

Università degli Studi di Torino
Scuola di Dottorato
XXXVI ciclo



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**Antiproton production measurement for indirect Dark Matter
search at the AMBER experiment at CERN**

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Davide Giordano

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Abstract

The AMBER (Apparatus for Meson and Baryon Experimental Research) experiment is a newborn particle physics experiment located in the North Area at CERN. The beam accelerated by the Super Proton Synchrotron (SPS) impinges on a fixed target in the Experimental Hall N2 and the AMBER spectrometer allows the particle identification and track reconstruction of the particles produced in the collisions. The AMBER collaboration submitted in June 2019 a Proposal in order to establish a "New QCD facility at the M2 beam line of the CERN SPS". This thesis work fits in one of proposed measurement concerning the study of proton-induced antiproton production cross sections for indirect dark matter searches.

Evidence strongly suggests that most of the universe's matter is non-baryonic and electrically neutral, commonly referred to as Dark Matter (DM) due to its lack of electromagnetic interactions. A leading candidate for DM is the Weakly Interacting Massive Particle (WIMP), which is believed to decay or annihilate into standard model particles and appear as distortions in the spectra of rare cosmic ray components like positrons, antiprotons and heavier (anti-)nuclei. One way to test this hypothesis is by studying Cosmic Ray (CR), particles that arrive at the top of the Earth's atmosphere. Indeed, the dominant part of the antiprotons in our galaxy originates from inelastic scattering of incoming cosmic rays off InterStellar Medium (ISM) nuclei at rest. In particular, the dominant reactions producing antiprotons involve Helium and proton and represents the background when searching for small contributions from exotic sources; in order to obtain a significant sensitivity to DM signals, it is then very important to achieve a small uncertainty on the prediction of cosmic anti-proton produced in the collision with proton and Helium.

The idea is to study the antiproton production cross sections in pHe scattering for projectile energies from several tens to a few hundreds GeV/ c . The AMBER experiment collected in 2023 precise data on pHe collision and in combination with similar measurements by LHCb in the TeV range, these data set represent the only available measurements with Helium. The new results are expected to allow for higher accuracy of the predicted natural flux of antiprotons in the galactic cosmic rays, especially in the relevant energy regime for space based spectrometer like AMS-02.

This thesis project is focused on the preparation and the first analysis of the 2023 data with beam momentum at 190 GeV/ c . In the first chapter, I provide an overview of the current scenario of the cosmic rays production and propagation mechanism and of the dark matter detection methods. Chapter two is dedicated to a description of the experimental apparatus, with a focus on the novelties of the 2023 setup. In chapter three the first tasks performed for the data analysis, which include the spectrometer alignment,

the data quality and stability studies, the luminosity estimation and lifetime correction, are discussed. In the fourth chapter, I estimate the efficiency of the hadron beam tagging with the CEDARs and provide the characterization of the RICH-1 detector used for the particle identification of hadrons produced in interactions. The fifth chapter contains a description of the work that I performed on the preparation of the MonteCarlo chain and on the MonteCarlo related studies like the description of the target and the trigger system in the spectrometer simulation and the extraction of the tracking efficiency. Finally, in the last chapter I present the first results from the 190 GeV/ c proton-helium collision, with the hadron spectra corrected for the acceptance of the apparatus and for the PID purity, compared to the expected shape predicted by the PYTHIA8 event generator.

*"The cosmos is within us, [...]
We are a way for the universe to know itself."*
From *Cosmos: A Personal Voyage*, Carl Sagan

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Chapter 1

Cosmic rays fluxes and Dark Matter

Multiple and concurring evidence indicates that the vast majority of the matter content of the universe is non baryonic and electrically neutral. This constituent of the universe is usually referred as Dark Matter (DM), for its lack of electromagnetic interactions. One of the most promising candidate for DM is the so-called Weakly Interacting Massive Particle (WIMP) which is foreseen to decay or annihilate into standard model particles, on top of the standard astrophysical component. One way to validate this hypothesis lies in the interpretation of particles arriving at top of Earth atmosphere, to which we refer as Cosmic Ray (CR). The study of CR is of crucial importance in the astrophysics scenario. It is currently established that the bulk of CRs is originated in our Galaxy from Supernova explosions. Nevertheless, the details on how they are accelerated and how they are confined in the magnetic and turbulent InterStellar Medium (ISM) are subject of ongoing debate.

While tentative to understand the origin of Cosmic Ray (CR) and how they propagate in our Galaxy are ongoing, DM hypotheses are constantly being tested in multi-messenger fluxes. The probability to form (anti-)nucleus and in particular (anti-)nuclei from standard interaction in the ISM is lower with respect to some DM models, which predict the formation of anti-nuclei without the suppression seen in standard particle collisions. For this reason, among the plethora of collected particles, the antiprotons, anti-deuterons and heavier anti-nuclei fluxes represent the golden channels to probe a possible DM signal. However, the disentanglement of such exotic signal from standard origin requires a vast knowledge of all the aspects of CR propagation and production. How they are generated, how they propagate in the Galaxy and how they interact with the interstellar medium are few of the many questions to be answered.

In this first chapter I briefly summarize the current understanding of the production mechanisms of cosmic rays and (anti-)nuclei and I provide a recap of the main physics processes influencing the particles trajectories in the InterStellar Medium (ISM). More focus in this chapter is placed on the antiprotons flux interpretation. For a correct interpretation of their flux, we need a better understanding of their production cross section.

The Apparatus for Meson and Baryon Experimental Research (AMBER) collaboration proposed in 2019 *"to establish a world-unique QCD facility by using the external M2 beam line of the CERN SPS in conjunction with a universal spectrometer that will use upgraded installations of the COMPASS experiment in the experimental hall EHN2"* [1]. The proposal was approved in 2020 and after a test run in 2022, eventually AMBER

collected the first data in April 2023 dedicated to the antiproton production cross section in pHe interactions. Along with the 2024 program, where AMBER will collect data at center of mass energies of $\sqrt{s} \sim 10\text{-}21$ GeV to measure production cross section in proton-proton and proton-deuterium collisions, the collaboration aims to contribute in the cosmic rays interpretation and improve the sensitivity to possible DM signals.

1.1 Origin of Cosmic Rays

It is firmly believed that the bulk of CRs arriving at the top of Earth atmosphere have Galactic origin. This belief is supported with observations of the diffuse high energy gamma-ray emission from the gaseous disk of our Galaxy, which is explained as result of decays of π^0 . The neutral pions are supposedly produced in the InterStellar Medium hadronic collisions. If the CRs were uniformly produced from outer Galaxies, we would observe similar diffusive gamma-ray emission also from nearby Galaxies. Observations with the Energetic Gamma Ray Experiment Telescope (EGRET), however, lead to the upper limit of the diffusive emission from the Small Magellanic Cloud to be a factor 5 smaller with respect to the expected flux if the CRs were evenly originated [2], demonstrating that the majority of CRs arriving at Earth are of galactic origin.

The energy spectrum of CR is a critical observable in the cosmic ray realm. We do observe a local spectrum of nuclei (mainly protons) arriving at top of Earth atmosphere which is consistent with a power law in rigidity R (momentum over charge) with a slope of roughly -2.7 , from the GeV scale to PeV [3]. Concerning the energy availability to maintain the cosmic rays population, the standard interpretation is that the only possible source is the explosion of supernovae (SN). Already in 1934, the pioneer studies of Baade and Zwicky [4, 5] suggested that a new class of novae, so-called supernovae, may be the expulsion centers of particles and heavier ions. Today, we have a theory supporting this belief, called diffusive shock acceleration (DSA), which describes how a relatively small number of particles flowing into the supernovae shock can be accelerated at ultra-relativistic energies, becoming the cosmic rays we detect [6, 7]. The two main components of cosmic rays sources are indeed supernova ejecta and interstellar material and dust grains swept-up in the expansion phase. The bulk of the former component is estimated by nucleosynthesis calculations, while ISM composition is known from observations of interstellar gas and dust. The mixing of the two components is crucial in the CR acceleration paradigm and defines the time scale of acceleration in the supernova remnant expansion [8]. The shock wave penetrates the surrounding plasma and charged particles near the shock front are trapped and accelerated multiple times by bouncing back and forth across the shock. The energy gained by particles as they cross the shock front depends on the difference in speed between the upstream and downstream material. It can be demonstrated that the resulting energy spectrum is a power law with similar index to the observed one at Earth.

The heavy elements appear to share essentially the same value of spectral index, the variety of whose probe nuclear processes not accessible from plasma studies, like mass mixing ratio of ejecta and ISM in the acceleration region and on the nucleosynthesis yields. Furthermore, the study of the elements and their isotope abundances is a golden channel to investigate processes that affect the generation and the propagation of these elements

in the Galaxy. The similar spectral index for the various elements is also a confirmation of the DSA theory: at the same rigidity, elements are accelerated in the same way by the shock wave, leaving the interpretation of the differences to local phenomena, not related to the source production.

The natural general division of CR is then based on their production mechanism: a particle may be produced directly by a source (like in the described mechanism of SN remnants) or produced in collisions in the ISM. In the first case, the CR are usually called *primary*, while in the second case as *secondaries*.

1.2 Propagation model

One of the most fundamental points in modeling CR fluxes is their propagation and acceleration in chaotic magnetic field. In pioneer studies the diffusion was successfully modeled especially in the Solar proximity, having local (in Galactic terms) cosmic ray interacting with Solar magnetic field and plasma. This approach was later used to explain so called Galactic Cosmic Rays (GCR) which face the problem of transport in the unknown galactic magnetic field. Solar cosmic rays (SCR), in contrary have the advantage to propagate in well known features of turbulence effects studied from direct measurement, making the interpretation of GCR far from being similarly successful. The approach later used and now widely accepted starts from the work of Fermi, which demonstrated how random magnetic irregularities scatter the particles and accelerate them. This random scattering was later interpreted as equivalent of a random walk in the magnetic field that was later associated to the spatial diffusion phenomenon.

The review of the main elements in the parametrization of the CR propagation starts by inspecting the galactic content, geometry and magnetic structure. The matter content is nowadays quite known thanks to multi-wavelengths surveys and is usually divided geometrically as Local Interstellar Medium (LISM) and more generally as ISM. The first one is an asymmetric bubble region around our Solar system of ~ 100 parsec containing hot and low density gas ($\sim 10^5 - 10^6$ K and $n \leq 0.005 \text{ cm}^{-3}$), whose kinematic properties have been identified from measured radial velocity of interstellar gas and with sight lines [9, 10]. However, apart a few species, CRs travel for hundreds of kpc and become sensible only to the smoothed properties of the ISM, being a rather homogeneous mixture of hydrogen (90%), helium (10%), ionized gas and dust. This let us consider, in general, a usual effective average density of ~ 1 particle per cm^3 . In the propagation model of the Galaxy, the matter content is usually contained in a diffusive volume where the density drops to zero outside and the particles are free to leave [11, 12]. The exact dimension of this volume is not known, but according to direct observation of neighbor galaxies [13], it should radially follow the galactic disk with more thickness. In most of the articles cited in this work, it is typically modeled as a cylinder with a certain radius (~ 20 kpc) and half height to be determined, sitting around $\sim 4 - 12$ kpc. Mathematically, this imposes boundary conditions for the matter density to be 0 at the edges of the volume. Fig. 1.1 shows a sketch of the halo with the main undergoing phenomena happening during CR transport.

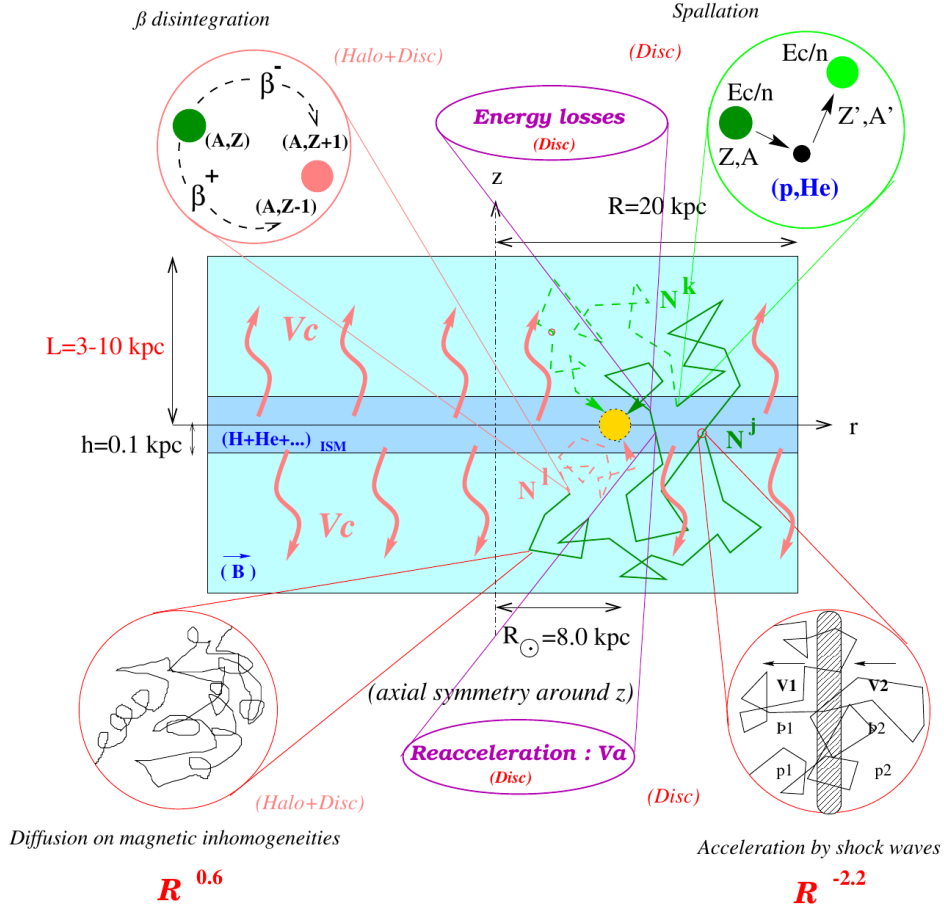


Figure 1.1: Sketch view of the Galaxy with some of the propagation processes. The thin central region is the galactic disk, with a half height of ~ 100 pc, which contains the ISM. The diffusive region includes the inner disk plus an outer region defined by the cylinder with ~ 20 kpc radius and half-height of $\sim 3-10$ kpc. The sun is located at 8 kpc distance from the center. Figure taken from [14]

Diffusive propagation

Since the charged CR are deflected in random directions by turbulent magnetic field, it is usually impossible to define where they are originated from, if not by tracking their electromagnetic radiation, like in Supernova remnants (SRN). This is the basic reason of the isotropy of observed CR approaching Earth with energies ≥ 10 GeV/c, with negligible deflection by Earth's field. Without the turbulent component, their path would be described by solving Lorentz force and follow spirals along magnetic field lines of the Sun or the interstellar gas (like in Fig. 1.2). With the turbulence effect, the magnetic field has

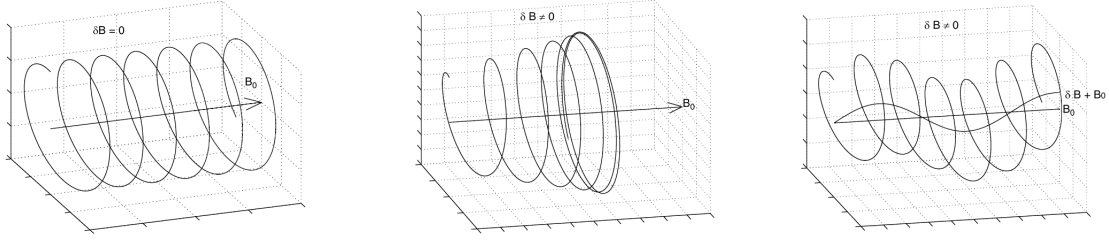


Figure 1.2: Particle propagation in different condition of magnetic field perturbation. From left to right: particle motion in an unperturbed system; parallel spatial diffusion due to parallel turbulence; guiding center of the helix following perturbed field lines. Figures taken from [15].

an additional perturbative term δB . The particles experience parallel and perpendicular scattering generating the diffusive motion described mathematically with diffusion coefficients. If one considers also the transverse component of magnetic field perturbations, it can be found that the particles experience parallel spatial diffusion, with guiding centers following magnetic field lines and creating a superposition of a gyrorotation and stochastic motion of the guiding centers. The two effects combined are described by a diffusion tensor D . Assuming null electric field, the diffusion equation governs the flux j of the particles based on the gradient of the particle density M as:

$$j(\vec{x}, t) = -D \nabla M(\vec{x}, t) \quad (1.1)$$

with D having anti-symmetric terms off diagonal to keep track of gradient and curvature effects.

For a complete formulation, the properties of the turbulent fields δB_i such as geometry, wave spectrum and the temporal behavior have to be specified. These features are taken into account with a magnetic correlation tensor, that in the most general form correlates two points in space in two time instants. It can be derived that the diffusion tensor can be expressed as a function of two turbulence properties:

- turbulence geometry
- wave spectrum

These two quantities are described with different models that present different degree of completeness:

- in the one dimensional formulation, the *slab model*, the geometry of turbulent fields depend only on z coordinate and the wave vectors are aligned parallel to the mean field;
- the 2D model is a function of only the perpendicular coordinates with wave vectors aligned perpendicular to the mean field;
- the composite model is a superposition of the 1D slab and the 2D where the three coordinates are taken into account, also called *slab composite model*.

The wave spectrum describes the wavenumber dependence, in accordance with solar wind observation, divided in three ranges: a large scale where the turbulence gains energy; a medium scale called inertial range where the energy is transferred to the small scales; and a small scale in which the turbulence loses energy by dissipation.

The picture becomes more complicated when considering the time evolution of the correlation tensor and dynamical turbulence effects start to appear. The various components of the tensor have now a dynamical correlation function, which describe the time evolution of the coefficients, that can be parametrized according to the model in different ways with a parameter called *Alfvén velocity*. The Alfvén velocity regulates the intensity of the dynamic effects and can have as well different parametrization. For instance, in a plasma wave turbulence model, the plasma waves are called indeed Alfvén waves. The Alfvén velocity must be estimated from fit to data and has usually values around ~ 30 km/s.

Electric fields, until now neglected because less intense, are however essential for momentum diffusion creating stochastic acceleration effects and must be taken into account for a full description of the CR propagation. The purpose of this section is, though, to give a glimpse on the main effects and the basic features of the framework to study CR fluxes. A rigorous description and derivation of the final formula can be found in [15] and will not be reported here.

Propagation equation

The presence of cosmic ray sources, such as supernova, inject particles at a certain location with a certain energy dependence via a *source term* $q(\vec{r}, p, t)$. The source term takes into account the spatial distribution of the sources of that particular CR species in the Galaxy, their energy spectrum and in the more general form depends also on the progenitor species in case the CR can be produced by spallation (secondary). In general, the source term of a primary CR can be factorized into three terms, a normalization term $q_{0,i}$ dependent from the particle species; the source spatial distribution $q_{r,z}(r, z)$ and the rigidity term $q_R(R)$ as ([16]):

$$q_i(\mathbf{x}, p) = q_i(r, z, R) = q_{0,i} q_{r,z}(r, z) q_R(R) \quad (1.2)$$

where r is the distance from the galactic center, z the height of the galactic cylinder, and the rigidity R being the momentum over charge Ze of the particle $R = pc/Ze$. A common description of the source distribution follows the radial distribution of supernovae and pulsars, that are responsible for the acceleration of the nuclei and their energy availability; while the rigidity spectrum $q_R(R)$ of emitted particles is determined by acceleration

processes and usually is parametrized with a power law [17] given by:

$$q_R(R) \propto (\mathcal{R})^{-\alpha} \quad (1.3)$$

with R the rigidity and α ranging in the interval 1.5-2.5. However, with the current precision achieved on CRs fluxes measurement up to 400 GV, the model of the rigidity dependence has been improved using a double broken power law function with three different slopes in three rigidity ranges (see for example [16, 18]).

The diffusive equation Eq. (1.1) is modified with the injection spectra and with the additional processes influencing the particles propagation. The density $\psi(\vec{r}, p, t)$ of a CR species at a certain time and position, traveling in the Galaxy, is described by the so called propagation equation [19]:

$$\begin{aligned} \frac{\partial \psi(\vec{r}, p, t)}{\partial t} = & q(\vec{r}, p, t) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) \\ & + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi \end{aligned} \quad (1.4)$$

This equation contains most of the effects like spatial diffusion, galactic wind, adiabatic energy losses and diffusion in momentum space. One can recognize the above mentioned spatial diffusion coefficient D_{xx} , momentum diffusion coefficient D_{pp} , convection velocity $\vec{V}$ and the CR density $\psi(\vec{r}, p, t)$ per unity of total particle momentum p at position $\vec{r}$.

Reacceleration and galactic wind

Once the CR are produced and accelerated gaining most of their energy, they may experience less important energy gains by either sporadic *reacceleration* or continuous processes. The first may happen when the CR scatters against a reaccelerating center like a supernova. This phenomenon is represented by the momentum diffusion coefficient D_{pp} , related to the velocity of turbulences in the plasma and the Alfvén velocity V_a by

$$\begin{aligned} D_{pp} & \propto p^2 V_a^2 / D_{xx} \\ D_{xx}(R) & = D_0 \beta^\eta \left(\frac{R}{R_0} \right)^\delta \end{aligned} \quad (1.5)$$

where the spatial diffusion coefficient D_{xx} has a typical form in which it is assumed spatially homogeneous, with a power law dependence on the rigidity R with respect to a reference rigidity R_0 and on the velocity of the particles β [20]. The proof of reacceleration was found thanks to the measured relative abundance of unstable isotopes by electronic capture. The probability of having orbital electrons is, indeed, highly dependent on energy and the relative abundances of stable and unstable isotopes are sensible to any changes in the particle energy. One of the first test of the rate of reacceleration was done using ^{49}V and ^{51}Cr abundances using Cosmic Ray Isotope Spectrometer on the ACE spacecraft [21, 22].

Another effect to consider, when dealing with CR transportation, is the so called *galactic* or *convective wind*. It is believed, from observations (e.g. [23]), that the medium responsible for diffusion is moving away from the galactic disk with a convection velocity

V. The net effect is the dilution of the energy of particles in the disc into a larger volume depending on the gradient of the convection velocity. The presence of this galactic wind in other galaxies triggered the question of its importance in the CR transport. In some studies [11, 12], the dynamical role of the CR in the halo was investigated and it was suggested that the halo could be divided into a lower part (< 1 kpc) and an upper part where there is a strong coupling between CRs and the hot interstellar medium with resonant generation of Alfvén waves as they escape the halo. In those papers, it was showed that a stationary outflows solution exists by modelling the magnetic structure as an ensemble of flux tubes composed of hot gas and CRs coming from below with ages in between $10^6 - 10^7$ years. This creates a pressure gradient that has an overall effects of momentum transfer from CRs to the gas via those Alfvénic-waves as a mediator, with the result to push away the gas from the disk into the halo [24].

As last point, one should consider the important role of CR *destruction* in the interstellar medium via nuclear interactions or decays, happening in time scale much shorter than the typical propagation time of several megayears. The main process happening is the so called *spallation*, where a nucleus, due to inelastic interaction, is fragmented. Heavier nuclei, having larger cross sections, break much more easily, but it turns out that the kinetic energy per nucleon is roughly conserved and the only information needed is a set of the fundamental inelastic cross sections. Actually, for the purpose of understanding the spallation rate of a certain species, from experimental nuclear physics point of view, only the total inelastic cross-section is needed: the main reason for studying a specific secondary production cross section is to study the source term ingredient for the production and propagation of secondary nuclei such as positrons, anti-deuterons and antiprotons. The secondary production cross section of antiprotons, in particular, will be discussed extensively in Sec. 1.4.1 and the experimental determination of this quantity will be the main focus of this work.

Summary of CRs phenomena

To summarize, a charged cosmic ray wandering in the Galaxy will be subject to a superposition of several processes. Its density at a certain position per unity of momentum is described by Eq. (1.4) that, depending on the model choice, will take care of:

- spatial diffusion from the random walk in the magnetostatic medium
- momentum diffusion due to reacceleration
- nuclear interaction (decay, destruction, energy loss, electron capture) with the interstellar medium
- production rate (for secondary species)

Each type of CR will thus carry different information about its production mechanism and the medium properties, given the important differences between the species in term of interaction with the medium.

1.3 (Anti-)nuclei production

The nuclei and anti-nuclei production is a constantly evolving research field, providing inputs on the formation of QCD bound states and on the background determination on searches of dark matter in space. An observation of light antinuclei, like anti-deuterons and anti-helium, of cosmic origin could in fact provide signature of dark matter particles annihilation on top of the standard astro-physical production. Nucleons are kept together inside light nuclei with a binding energy of ~ 1 MeV per nucleon [25, 26]. Their production is currently mainly described by phenomenological models such as the Statistical Hadronisation Model [27] and in a more simplified approach by the coalescence model, firstly introduced in [28].

According to the coalescence model [29] any (anti-)proton and (anti-)neutron pair can form an (anti-)deuteron if they are close enough in the momentum-position phase space. The foundations of this model rely on the definition of a *coalescence parameter* B_A defined as:

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A \bigg|_{\vec{p}_p = \vec{p}_A / A} \quad (1.6)$$

where E is the energy, p the momentum, A is the nuclei mass number and its yield $\frac{d^3 N_A}{dp_A^3}$ is related to the proton yield $\frac{d^3 N_p}{dp_p^3}$ by the coalescence parameter, typically of the order of ~ 160 MeV. When studying the (anti-)nuclei production at LHC energies, the isospin effects vanishes and the production of protons and neutrons is symmetric at mid-rapidity. Therefore only the proton yield is usually used in this formalism. The model can be implemented in a simplified way if the coalescence probability depends only on the momentum and not on the space distance of the nucleons. This is valid for example in small systems collision such as pp [30]. When colliding heavier nuclei, a larger system is created and the spatial distances become relevant. From the charged multiplicity classes one can infer the impact parameter and study the spatial and momentum dependence of the coalescence parameter [31].

The measurement of light anti-nuclei spectra in space has been identified as one of the most promising probe for exotic sources [32–34]. From ground particle experiments, it is known that any addition in the number of antinucleon in the antinuclei decreases their production by a factor 10^3 [35–37]. The probability of forming an (anti-)nucleus is thus much lower than the formation of the single (anti-)nucleon and gives access to a cleaner channel to probe other source hypotheses. In particular, great focus was placed in studying the anti-deuterons flux and formation mechanism. Some dark matter models predict, indeed, the formation of low energy anti-deuteron and its possible presence should appear as clean signal in the modeled flux [38]. It is important to note that the anti-deuterons production from dark matter particles annihilation or decays is related to the antiproton production as well. A dark matter candidate able to produce antideuteron should in fact produce also a large amount of antiprotons. At the moment such an exotic signal in the antiproton flux has not been disentangled yet. The advantage of using low-energy anti-deuterons signature is to have a complementary probe to the $\bar{p}$ channels but with very low background.

Exploring varied collision systems near the production threshold of light antinuclei is also essential for deciphering their creation mechanism in the Galaxy.

The NA61/SHINE experiment at CERN has successfully recorded diverse interactions, including pp interactions at various beam momenta (13 to 400 GeV/ c), along with other crucial datasets relevant to refining cosmic-ray models. Notably, the analysis of extensive pp datasets at 158 GeV/ c and 400 GeV/ c holds significant interest, particularly in examining light nuclei in different A-A datasets. These measurements serve as vital complements to existing findings from NA49 [39] and ALICE [30, 40], allowing for thorough testing of coalescence and thermal models in diverse settings. Additionally, NA61 recently divulged results of carbon fragmentation measurements [41], paving the way to other important results.

Moreover, ongoing studies on light antinuclei production by ALICE, employing a range of particle identification techniques, have been influential in constraining antinuclei production models. Future endeavors aim to expand the present understanding through the cross-section measurements of the produced antinuclei with the detector materials.

In addition, LHCb's focus on antideuteron production cross-section measurements in pp interactions in the very forward direction ($2 < \eta < 5$) using various detection tools is a unique and significant effort within this domain. This experimental approach aims to measure antideuterons in various collision scenarios, including prompt production in pp collisions, decays of heavy-hadrons, and fixed target collisions [42].

1.4 Interpretation of the antiprotons flux

Antimatter is usually not abundantly produced in ordinary astrophysical interactions, in contrary to some hypothesis of DM decays and annihilation, in which matter and antimatter are produced evenly. This means that, in principle, any exotic sub-process should appear as a faint distortion of the spectra from the expected secondary production, which has to be very precisely modelled using antimatter production data from experiments at accelerators. In order to disentangle any possible source of primary antiprotons in our Galaxy, a very precise knowledge of the production cross section of the antiprotons is thus mandatory.

Theoretical calculation on the expected secondary antiprotons flux were published already in the 1960s [43], before any experimental observation, that came only few years later with balloon based experiments, performing a first measurement of the cosmic-ray antiproton flux at momenta between 130 and 320 MeV/ c^2 [44] at the Top Of Atmosphere (TOA). The antiproton flux measurement campaign continued then in the 1990s and 2000s, with a great improvement in the collected data samples thanks to experiments like MASS, IMAX, CAPRICE, HEAT, BESS and AMS-01 [45–49], to arrive finally in the last decade to the results of PAMELA [50, 51] and of the state-of-the-art AMS-02 experiment [52, 53], on the International Space Station (ISS).

The most recent results on antiprotons flux show that the ratio of antiprotons over protons is rather flat as the rigidity increases (see Fig. 1.3). This was not expected, given the very different processes behind the production of the two species, and triggered extensive studies on the topic. Starting from the propagation features, various aspects of the breakthrough observations in spectra hardening find explanation in the context of spatial shifts in cosmic ray diffusion throughout the Galaxy. This contrasts with conventional propagation models that assume a consistent diffusion regime across all regions [54, 55]. In

addition, an increasingly strong emphasis is being placed on the *production cross section*, which started to have more and more a crucial role to disentangle the possible sources and become the keystone to eventually solve the puzzle.

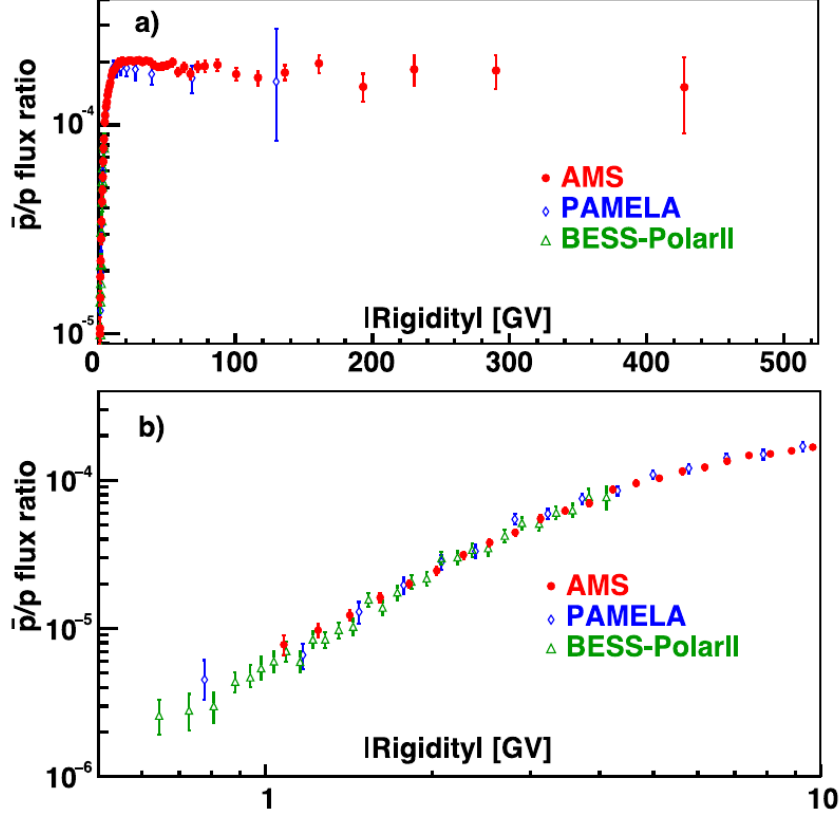


Figure 1.3: Antiproton over proton flux ratio measured by AMS-02, BESS-PolarII and PAMELA. The rigidity dependence of the flux of antiprotons is similar to proton one, in contrast to expected discrepancies due to the secondary nature of antiprotons. This flattening of the flux ratio triggered speculation on possible DM signals and extensive re-evaluation of injection fluxes, production cross section and propagation processes. Figure taken from [52].

In the CR framework, summarized by the propagation equation (Eq. (1.4)), the source term for a secondary species s (like the antiprotons), assuming completely secondary production, can be expressed as:

$$q_{ij}(T_s) = \int_{T_{th}}^{\infty} dT_i \, 4\pi \, n_{ISM,j} \, \phi_i(T_i) \, \frac{d\sigma_{ij}}{dT_s}(T_i, T_s) \quad (1.7)$$

where T_s is the secondary kinetic energy; $n_{ISM,j}$ the density of the ISM j -component; $\phi_i(T_i)$ the energy differential flux of the progenitor primary CR component i at kinetic energy T_i ; σ_{ij} is the nuclear cross section for $i + j \rightarrow s + X$ process and T_{th} is the threshold energy to produce the secondary. Antiprotons follow analogous physical pathways to protons, exhibiting a comparable mode of propagation. Yet, their opposite charge entails distinct behavior within the heliosphere. While traversing the Galaxy, antiprotons can engage

in another phenomenon—annihilation with interstellar matter nuclei. This interaction results in the absorption of the antiproton with a certain probability.

Due to the conservation of baryon numbers, antiprotons emerge only under specific conditions, necessitating collision energies sufficiently high to generate either a proton-antiproton pair directly or other baryon-antibaryon pairs, which subsequently decay into antiprotons. In the realm of collision energies conducive to antiproton production, nucleus-nucleus collisions are predominantly characterized by singular nucleon-nucleon interactions. The center-of-mass energy must exceed 4 proton mass equivalent. In the galactic frame, with the target particle nearly stationary, these collisions follow a fixed-target kinematics. The inclusive production rate of antiprotons in reactions such as $A + B \rightarrow \bar{p} + X$, where A and B represent the projectile and target nuclei, respectively, is determined by the inclusive, differential antiproton-production cross section.

The prevalent collision processes within our Galaxy arise from the composition of cosmic rays and the interstellar medium, predominantly involving pp , pHe , Hep , and $HeHe$ interactions. In Fig. 1.4 one can appreciate the relative contributions of other production channels, that represent a negligible fraction of the total antiproton source term ($< 10\%$).

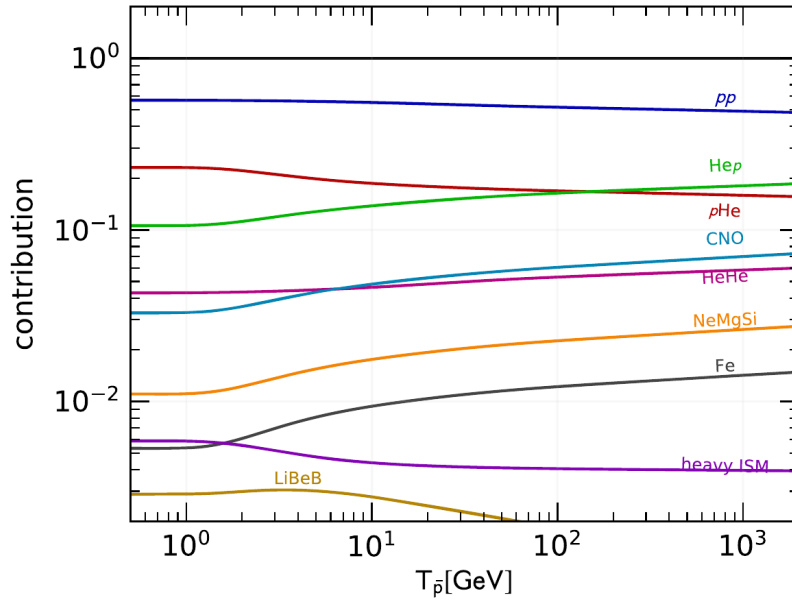


Figure 1.4: Main contributors to the antiproton source term as a function of the antiprotons momenta. Reactions involving proton and helium account for 80-90% of the total, depending on the kinetic energy of the antiprotons. Figure taken from [56].

In general, we can express the cross section to produce an antiproton according to the prompt or decay production:

$$\sigma = \sigma_{\bar{p}} + \sigma_{\bar{n}} \quad (1.8)$$

where the division separates the prompt antiprotons ($\bar{p}$) from the ones generated in long anti-neutrons decays ($\bar{n}$). A second subdivision is due if the corresponding hadron was promptly produced (^{0}) or if it was a product of an anti-hyperon decay ($^\Lambda$):

$$\sigma_{\bar{p},\bar{n}} = \sigma_{\bar{p},\bar{n}}^0 + \sigma_{\bar{p},\bar{n}}^\Lambda \quad (1.9)$$

The prompt production accounts for $\sim 40\%$ of the total antiprotons, another 40% comes from antineutron decay and the remaining 20% from antihyperon [57]. For the inclusive production of a certain hadron h in $p + p \rightarrow h + X$, it is usually convenient to express the cross section as a Lorentz invariant, defined as:

$$f_{pp \rightarrow h} = E_h \frac{d^3\sigma}{dp_h^3} = \frac{E_h}{\pi} \frac{d^2\sigma}{dp_L dp_T^2} \quad (1.10)$$

where E_h and p are the energy and momentum (L longitudinal and T transverse) of the hadron. The final cross section takes into account the contribution of antineutrons and antihyperon decays, plus the possible isospin asymmetry:

$$f = f_{\bar{p}}^0 (2 + \Delta_{IS} + 2\Delta_{\Lambda}) \quad (1.11)$$

Here, the factor 2 is due to the antineutrons decays, Δ_{Λ} and Δ_{IS} are respectively the antihyperon and isospin asymmetry enhancement factors. The production via antineutrons decays is usually not measured due to the long life of antineutrons. However, the total antiproton production cross section can be obtained by rescaling the prompt production as in Eq. (1.11), where the Δ_{Λ} can be estimated from pp data by computing the $\bar{\Lambda}/\bar{p}$ ratio and the Δ_{IS} from $\bar{n}/\bar{p}$ production ratios, as shown by Winkler work in Fig. 1.5. The Δ_{IS} will be commented more in detail in Sec. 1.4.4.

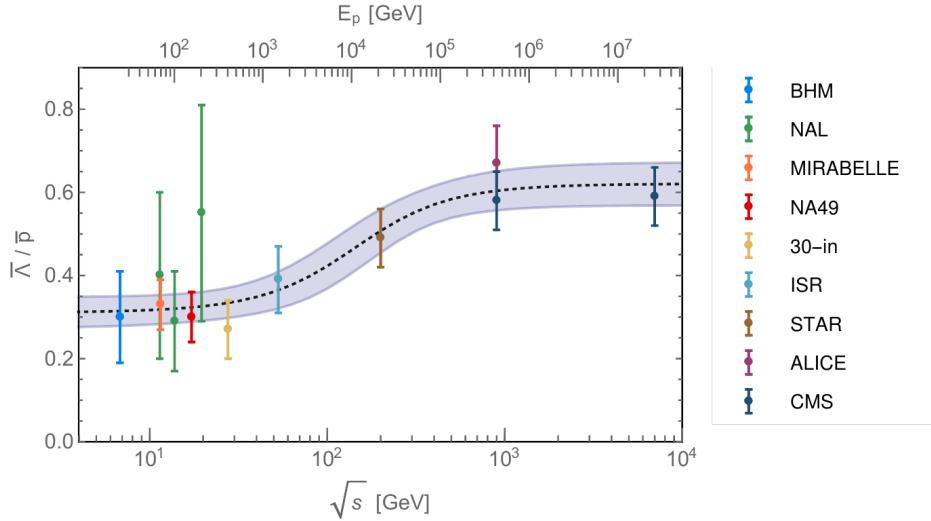


Figure 1.5: Antilambda over antiproton ratio from pp collision in different colliders and fixed target experiments. Error bands from the fit are also shown. This ratio is used to factorize the antiproton contribution from antihyperon decays in the cross section parametrization. Figure taken from [58].

In this formalism, two variables are typically used, that are the radial and Feynman scaling variables:

$$\begin{aligned} x_R &= \frac{E^*}{E_{\max}^*} \\ x_F &= \frac{p_L^*}{\sqrt{s}/2} \end{aligned} \quad (1.12)$$

with the starred quantities meaning in the center of mass frame. The maximum energy E_{max}^* of the antiproton produced can be calculated as (with $m_{X,min} = 3m_p$ for baryon number conservation in pp collision):

$$\begin{aligned}
 m_X^2 &= p_X^2 = (p_{p1} + p_{p2} - p_h)^2 \\
 &= s + m_h^2 - 2(p_{p1} + p_{p2}) \cdot p_h \\
 &= s + m_h^2 - 2\sqrt{s}E_h \\
 E_h &= \frac{s + m_h^2 - m_{X,min}^2}{2\sqrt{s}} \rightarrow E_{max}^* = (s - 8m_p^2)/(2\sqrt{s})
 \end{aligned} \tag{1.13}$$

1.4.1 Inputs from cross section measurements

Cosmic ray antiprotons are produced mainly from scattering with ISM, namely protons and Helium. Their flux depends on the production, scattering and annihilation cross sections and the propagation features. Errors induced by propagation models can be neglected when dealing with relative flux uncertainties, so that the primary uncertainty in the secondary antiproton source term stems from uncertainties within the inclusive cross sections utilized for its determination. While efforts have been made to evaluate antiproton production cross sections using Monte Carlo generators [59, 60], estimating uncertainties in the underlying hadronization models remains challenging, especially in the low-energy regime without a reliable theoretical description of soft hadronic processes. Even though the parton parton interactions can be described by QCD computations, with parton distribution function well measured in deep inelastic scattering experiments, the fragmentation and final hadronization are dominated by soft QCD processes and can not be calculated a priori for light quarks. In this sense, experimental data play a crucial role in providing hadrons spectra for models tuning and exploring the fragmentation functions via semi-inclusive deep inelastic scattering.

Despite the high precision modeling of proton-proton scattering in the LHC era, current collider experiments like CMS and ATLAS lack coverage in the high-rapidity region of the phase space where most antiprotons are produced. Additionally, the energy scales at cosmic ray experiments significantly differ from those of operating colliders like the LHC, with AMS-02 detecting antiprotons produced at energy scales below the collider energies. Data regarding proton-proton scattering relevant to this energy range were collected primarily in the 1970s and early 80s. Different approaches and effort has been made to describe the production cross sections. Prior to the last decade, after the first parametrization for the pp scattering [61], the latest parametrization [62] fitted these data but exhibits considerable discrepancies, making it challenging to determine the differential cross section. The uncertainties in old published data, especially regarding the feed-down where a fraction of antiprotons originates from the decay of strange hyperons, further complicate data interpretation due to difficulties in the separation of the reconstructed secondaries vertices in these old detectors.

1.4.2 pp channel

The NA49 experiment at CERN significantly improved this situation by providing high-phase-space coverage and precise data on antiproton production, addressing the feed-

down issue using micro vertex detection and precision tracking [39]. Some analyses were triggered by the availability of this new data set (e.g. [57, 58, 63]) addressing for the first time isospin violation and hyperon-induced production, aspects not considered in earlier parametrizations. In [63], the authors explore and prescribed the optimal antiprotons phase space to measure with collider and fixed target experiments so that the error on the nuclear cross section propagated on the source term matches the flux data errors (see Fig. 1.6).

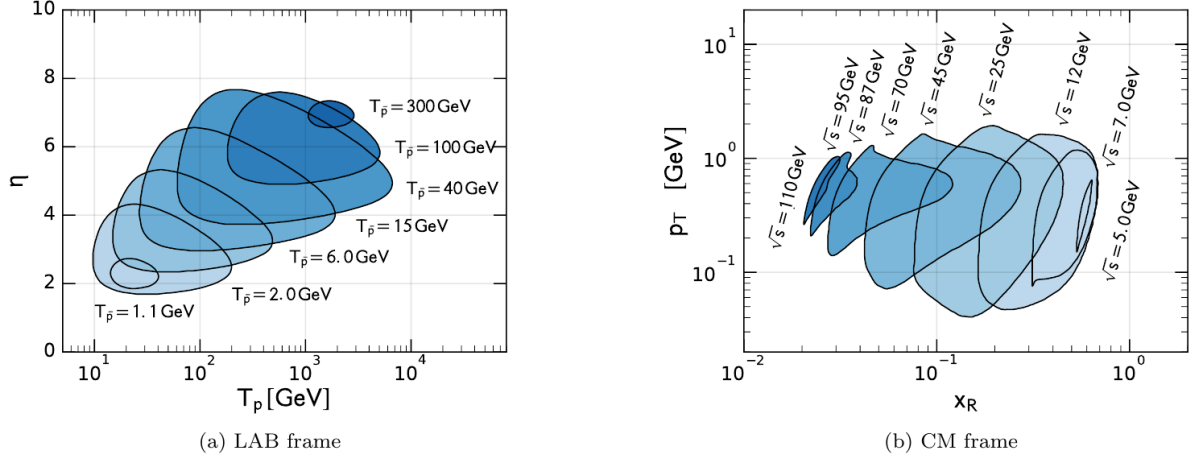


Figure 1.6: Optimal antiprotons phase space to be covered by an exemplary experiment for pp collisions for different energies. The contour are obtained by asking a 3% precision on the measurement of the cross section in order to match experimental flux precision on the source term for antiprotons. On the left with laboratory variables, on the right with center of mass variables. Figure taken from [64].

Following the same effort, more recently, the NA61 experiment [65] published results on the antiproton cross-section measurements at various CM energies ($\sqrt{s} = 7.7, 8.8, 12.3, 17.3$ GeV) in pp collisions [66], extending data to lower center of mass energy compared to NA49. However, as suggested in [56], in order to constrain the pp source term for $T_{\bar{p}} < 5 \text{ GeV}/c$, additional low-energy data are necessary. The currently available cross-section measurements below $s \sim 7 \text{ GeV}$ have large systematic uncertainties, making a good determination challenging.

1.4.3 pHe channel

Until few years ago only MC approach and parametrizations ([62]) based on A (atomic number) dependence of the cross section were used for the flux estimation of antiprotons, because no experimental data existed on the inclusive reaction $p + He \rightarrow \bar{p} + X$. Though, the increasing precision of the fluxes data triggered a general re-tuning of the whole CR framework, including stressing the importance of cross section data for the main production channels such as the reactions involving Helium. At the moment, the only data available on $p + He \rightarrow \bar{p} + X$ are those collected in May 2016 by LHCb ([67]) operating in fixed-target mode with the SMOG device at 6.5 TeV ($\sqrt{s} = 110 \text{ GeV}$, pseudo-rapidity range $2 < \eta < 5$ and momentum range $12 < T_{\bar{p}} < 110 \text{ GeV}/c$).

The availability of new data set was promptly used in new and improved parametrization like in Donato et al. [56] demonstrating, however, that the covered phase space in that production channel is not enough to allow for a standalone parametrization, requiring a rescaling from pp data. Following the same "recipe" concept of [63], the authors provided the optimal phase space for measurements in pHe reactions, as shown in Fig. 1.7.

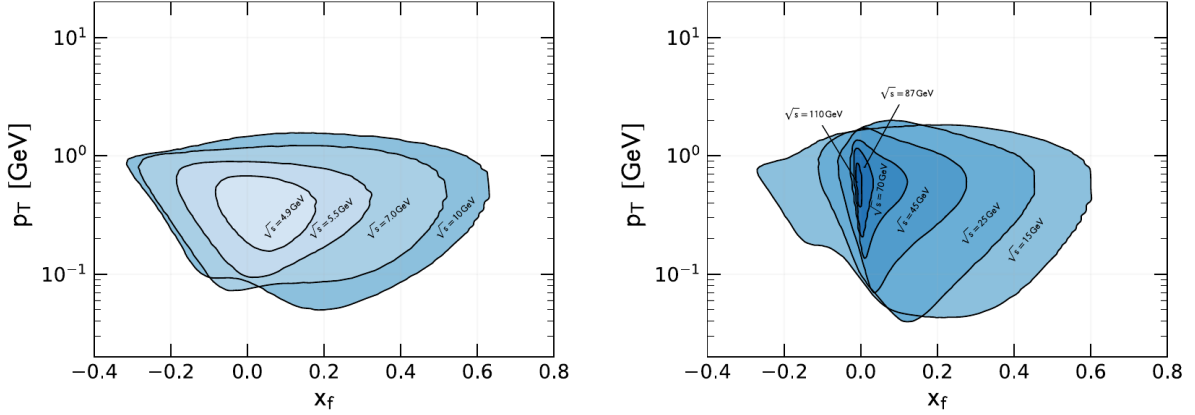


Figure 1.7: Antiprotons phase space to be covered at 3% precision by an experiment for pHe collisions in order to match the uncertainty of AMS-02. The axis variables are defined in Eq. (1.12). The two plots differ for the energy scale. Figure taken from [56].

Furthermore, a study [68] on the consistency of the antiprotons spectra with a secondary astrophysical origin demonstrated that, even by using the improved parametrization of [56] and [58], the current understanding of the cross section and the propagation features can not resolve any potential signal of exotic primary source in the CR antiproton spectrum. In Fig. 1.8 it can be appreciated how one of the most recent parametrizations of the cross section still induce uncertainties in the energy range of AMS-02 of 10-15%. More inputs from accelerator based experiments with capabilities in energy range of AMS-02 are needed.

1.4.4 Isospin symmetry violation

While antiprotons generated through direct hadronization or the decay of antihyperons in collisions are subjects directly investigable via accelerator-based experiments, the involvement of antineutrons remains entirely unexplored in experimental settings. Typically, the assessment of antineutron generation in collisions relies solely on theoretical principles founded upon isospin symmetry.

However, NA49 data at $\sqrt{s} = 17.3 \text{ GeV}$ indicates an enhanced production of antineutrons compared to antiprotons (see Fig. 1.9), leading to the non solved question regarding the production asymmetry of isospin pair $p\bar{n}$ and $\bar{p}n$. Few works [69, 70] suggested that this asymmetry originates from isospin effects and until now this remains one of the biggest source of uncertainties for low energy parametrization of the cross section for CRs interpretation, given that almost half of the CR antiprotons arrive from antineutrons decays. In those works, the antiproton multiplicity was found higher in neutron proton scattering compared to proton proton, which only differs in the third component

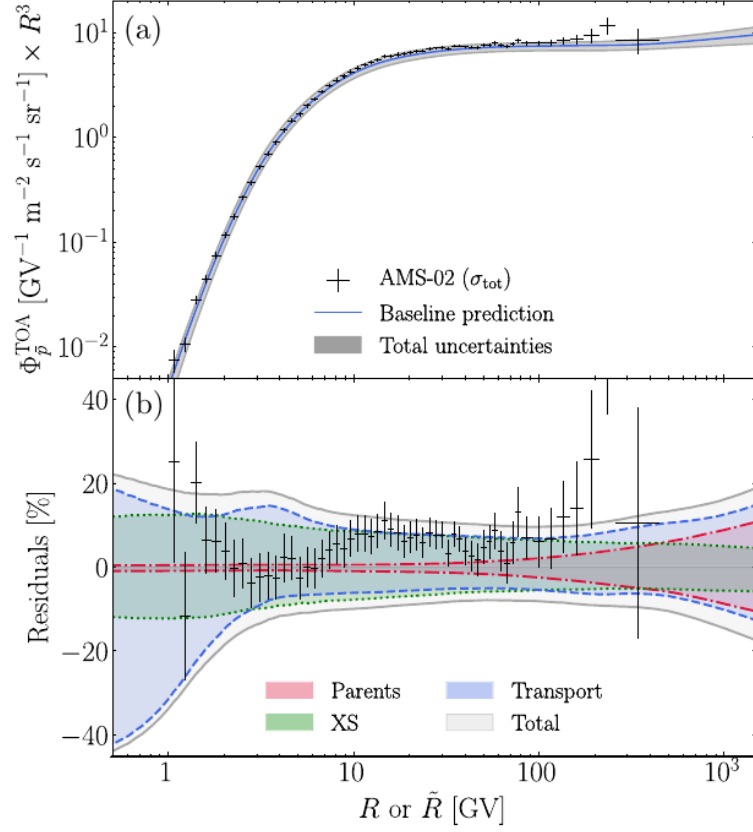


Figure 1.8: Antiprotons flux measured at TOA from AMS-02. Top figure: Baseline prediction (not a fit) for antiprotons flux created using latest parametrization of cross section, compared with AMS-02 data. Bottom: residuals as a function of rigidity. An excess is visible between 10 and 50 GV. Errors on propagation and cross section do not allow for a statistical valid excess. Figure adapted by the author from [68].

of isospin of the initial state. The asymmetry has its maximum at $x_F \sim 0$ of roughly

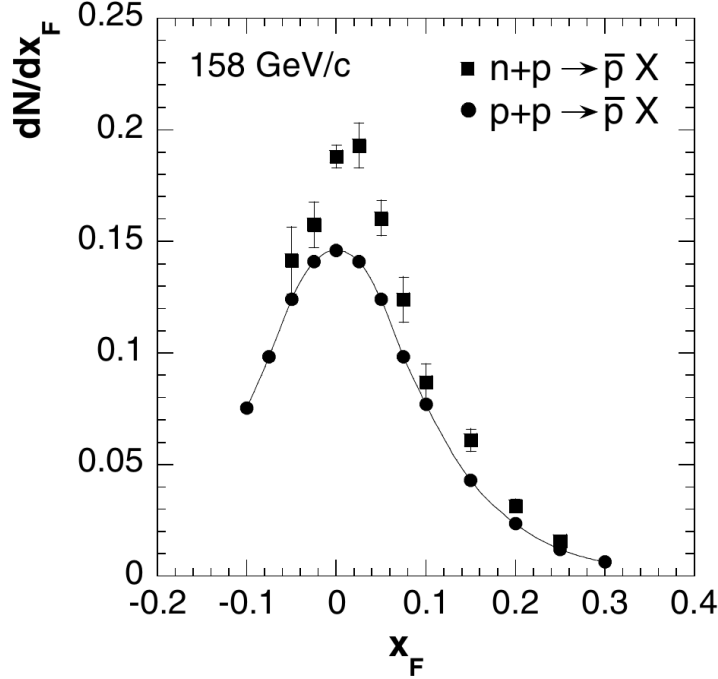


Figure 1.9: Antiproton yields as a function of x_F as measured in NA49. The antiproton production seems favoured in pn collisions especially at $x_F \sim 0$, where a $\sim 40\%$ increase in the production rate is visible. The data from NA49 represent the only data available on the production asymmetry due to possible isospin effects. Figure taken from [69].

$\sim 50\%$, consequently resulting in an enhanced production of antiprotons with respect to isospin symmetry consideration. However, the production asymmetry seems to disappear when dealing with higher center of mass energy. For instance in the work of Winkler ([58]), the author used data from fixed target NA49 and other collider experiments like PHENIX [71], STAR [72], CMS [73], and ALICE [40], to constrain not only the values of this asymmetry as previously done ([57]), but also its dependence on the collision energy, as can be seen in Fig. 1.10. In that work, the determination of the isospin factor, defined as $\Delta_{\text{IS}} = f_{\bar{n}}^0/f_{\bar{p}}^0 - 1$ (with $f_{\bar{n}}^0$ and $f_{\bar{p}}^0$ being the prompt-production cross section of antineutrons and antiprotons), was extracted from data by modeling the x_F -multiplicity dependence of the antiprotons into a projectile and target component, weighted with the number of interacting nucleons and the neutron to nucleon numbers of the colliding particles. It is clear from this parametrization that the errors associated to the low energy regime, due to the scarcity of data, becomes huge below ~ 50 GeV, directly afflicting the final source term predictions.

1.5 Dark Matter search

Dark Matter is usually introduced with the studies of Zwicky on the redshift of galaxies in the Coma cluster [74], followed by a plethora of experimental evidences in the galactic rotation curves measured with 21-cm emission, from which it is possible to infer the

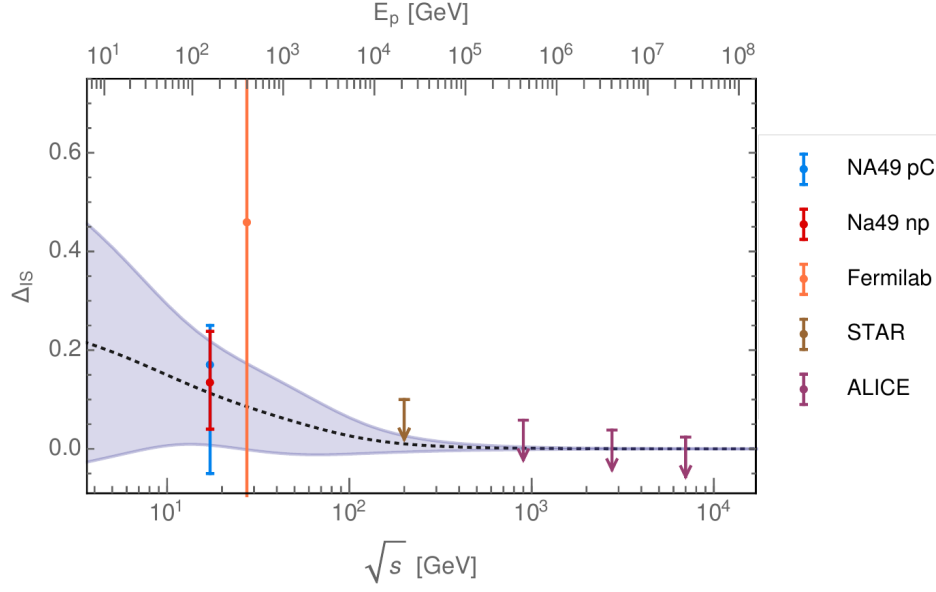


Figure 1.10: Isospin factor dependence on collision energy in different experiments. Error bands from the fit are also shown. The isospin factor $\Delta_{IS} = f_{\bar{n}}^0/f_{\bar{p}}^0 - 1$ is calculated from the projectile and target proton-neutron composition. The extrapolation of the energy dependence is used in the cross section parametrization and induces relevant errors in the low energy regime, where only NA49 data points are available with reasonable uncertainty. Figure taken from [58].

galaxies matter distributions [75–80]. To summarize the discoveries, it was the observation of a flat rotation curve to persuade the scientific community that vast amount of non visible matter (or even called “*low luminosity material*”) is present in the outer regions of the Galaxy to which we now refer as *Dark Matter*. From observations and global fit of cosmological datasets collected by the Wilkinson Microwave Anisotropy Probe (WMAP) we can infer the abundance of DM to be around $\Omega_{DM}h^2 \simeq 0.112$ (where $\Omega = \rho/\rho_c$, with ρ being an energy density and ρ_c the critical energy density of the universe $1-3 \cdot 10^{-26} \text{ kg/m}^3$) [81].

The explanations of the DM origin and composition followed a century of development and are now divided in few macro categories, of which only the particle interpretation will be elaborated more here:

- baryonic nature (massive astrophysical compact halo objects (MACHO) [82, 83], primordial black holes (PBH) [84, 85] and re-evaluations of the baryonic budget of the universe [81, 86]);
- modified gravity frameworks (developments of the modified Newtonian dynamics (MOND) approach [87–89]);
- new particle models (neutrinos, supersymmetry, axion, weakly interactions...);

As described in the historical review of dark matter by Bertone and Hooper [90], prior to the last few decades particle physics did not contribute in astrophysics field until

an increasing number of particle physicist became interested in cosmology and brought major interest to the new particle hypothesis of the dark matter. The use of the "dark" term, initially referred to the variety of astrophysical non-visible material, left space to the current common usage of the word related to a certain particle candidate trying to solve the dark matter puzzle. In the particle interpretation framework, the standard model neutrinos were one of the most promising candidates to account for long-lived, neutrally charged and non-strongly interacting particle. After the first pioneering studies of Gershtein and Zeldovich [91], the neutrino hypothesis was largely studied during the year in the scenarios where the dark matter particle could either be hot (relativistic) or cold (non-relativistic) during structure formation. The two cases predict different results in the cluster formation mechanism. With the neutrino being light hot thermal relics, via N-body simulation it was demonstrated that a neutrino-dominated universe and more generally any hot DM particle candidate could not account for the observed total DM component [92].

When *supersymmetry* (SUSY) theories [93,94] began to circulate, it seemed very natural that, if any of the several new neutral and non-strongly interacting s-particles would be stable and sufficiently abundant, it could influence the evolution and chemical composition of the universe. The success that the SUSY approach had is also due to the fact that it does not rely entirely on the dark matter puzzle. Actually, the ability to explain some aspects of it, is part of its framework and gives the theory a "generality" feature strengthening its validity.

Always in the context of beyond standard model theories, Peccei and Quinn showed that the introduction of a spontaneously breaking U(1) symmetry in the QCD could dynamically solve the CP-violation effect [95], implying the existence of a Nambu-Goldstone boson to which we refer as *axion* [96,97]. The production mechanism of the axion in the early universe was largely debated and constraints on its mass were placed to 10^{-5} eV so that it could account for the observed dark matter density, becoming one of the most promising candidates for the DM explanation.

Last but not least, the deduction that the non visible mass of the universe was non baryonic and with cold origins (in cosmology term), led to the general concept of the Weakly Interacting Massive Particle (WIMP) [98,99], that makes pair with the axion to be the non-baryonic cold DM candidate. The starting point of the WIMP paradigm is a new undiscovered candidate particle χ , long-lived and weakly interacting in thermal equilibrium. When the temperature of the universe is much larger than the mass of the particle m_χ , the conversion into lighter particles trough annihilation rapidly happen and viceversa. As soon as the temperature drops below the m_χ value, the number of χ drops exponentially with a certain annihilation rate dependent on the averaged product of the freeze-out annihilation cross section and relative velocity of a χ pair $\langle\sigma v\rangle_{fo}$. By solving the Boltzmann transport equation, governing the number density evolution of a certain species according to its interaction mechanism, one can find in units of the critical density:

$$\Omega_\chi h^2 \simeq 0.1 \times \left(\frac{\langle\sigma v\rangle_{fo}}{3 \cdot 10^{-26} \text{ cm}^3 \text{ s}^{-1}} \right)^{-1} \quad (1.14)$$

The result is valid for any thermal χ of any masses. If we plug in a cross section annihilation of the order of magnitude of the weak scale ($\sim 10^{-26}$), this simple result shows that a

new weakly interacting and long-lived particle can have an abundance comparable to the current DM density ($\Omega_{DM} h^2 \simeq 0.112$). This very fortunate coincidence sometime is referred as "WIMP miracle". In the context of SUSY theories, the lightest supersymmetric particle (LSP), in particular the neutralino, is usually studied as WIMP candidate.

This WIMP paradigm is currently one of the most probed and experimentally tested. The experimental search of WIMP can be done mainly in three ways: by producing it or directly and indirectly detect it. Schematically pictured in Fig. 1.11, these three methods put complementary constraints on the hypothesis.

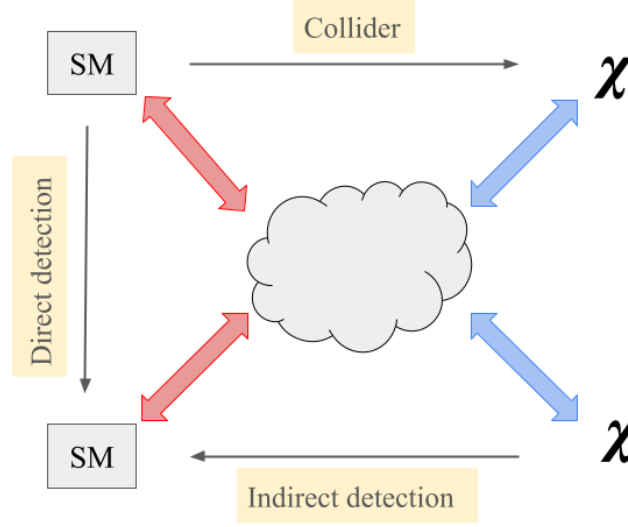


Figure 1.11: DM detection channels. In colliders, standard models particles may produce Dark Matter particles; in direct detection experiments, the interaction of DM with ordinary matter is measured; in indirect detection methods we search for products of annihilation or weak decays into standard model particles.

The *production* mechanism at accelerators aims to measure the DM production in high energy interactions. Since the DM is invisible to our detectors, the general idea is to measure the missing transverse momentum for example in jet production. A simplified model [100] assumes that χ is a Dirac fermion and its interaction with standard model particle is mediated by a heavy vector, axial-vector, scalar or pseudo-scalar boson. More complete models contain mediators which interact with more particles, introducing additional modes in nuclear interactions and in the relic density calculations.

The *direct* approach exploits possible scattering of the χ candidate with ordinary matter. The scattering rate is described by:

$$\frac{dR}{dE_{nr}} = \frac{\rho_0 M}{m_N m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma}{dE_{nr}} dv \propto \exp\left(-\frac{E_{nr}}{E_0} \frac{4m_\chi m_N}{(m_\chi + m_N)^2}\right) F^2(E_{nr}) \quad (1.15)$$

where m_N , m_χ and M are respectively the masses of the target nucleus, of the WIMP and of the detector; E_{nr} is the nuclear recoil energy, σ is the interaction cross section and $F(E_{nr})$ is the nuclear form factor. The other parameters like ρ and $f(v)$ account for the local DM density and velocity distribution. The nuclear recoil energy depends on the mass

of the nucleus. By integrating the Eq. (1.15) over E_{nr} one obtains the expected number of events by a certain experiment in its life time with a given sensitive detector volume. This reaction is typically studied in underground low-background laboratories, where the transferred energy of the χ to the nuclei of large masses of matter is transformed in measurable signals via ionization or scintillation [101]. The scattering cross section is expressed with a spin dependent and a spin independent part, according to scalar or axial-vector structure. In the spin-dependent results it is usually assumed that the WIMP couples to only neutrons or only protons, so that experiments using target nuclei with odd number of protons or neutrons may probe WIMP-proton or WIMP-neutron interactions. The experiments can be divided in big categories according to the material used as probe, that defines the limits of detection and the potential spin-dependence of the cross section [102]. The variety of detection techniques includes cryogenic detectors [103, 104], liquid noble elements like Xenon and Argon either in 1-phase or 2-phases [105–107], scintillating crystals [108–110], bubble chambers and directional detectors [111]. In these experiments there is always a trade-off between signal sensitivity, amount of sensitive material, background rate and the DM mass range probed. Any positive measurement in direct detection experiments would provide an unambiguous confirmation of the particle nature of DM. So far, there were no clear DM detection and more stringent limits are constantly put on the scattering cross section, as in Fig. 1.12.

The last way to detect DM is the *indirect* detection, which uses the possible decay and annihilation channels of the candidate particle into standard model particles that we can detect via multi-messenger cosmic rays analysis. A typical analysis of DM signal in CR fluxes follows the approach described in the “PPPC 4 DM ID” [113]. It starts with the choice of the DM density profile, where several models are available, driven by observations and numerical calculation. The most used profiles in literature are the Navarro-Frenk-White (NFW) [114] and the Moore [115]. These models are usually converging at the same density value at Earth location and differ when approaching the galactic halo center, with the consequence of being more or less sensible to signals from the inner part of the Galaxy, as shown in Fig. 1.13. The flux production comes from the DM annihilation and decay cross sections parametrized into some primary channels like e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$, $q\bar{q}$, $\gamma\gamma$, hh , $\nu\bar{\nu}$ or via a new boson mediator that decays into standard model leptons. The hadronization is then simulated with physics generator and happens at the production point, leading to the fluxes of hadrons and (anti-)nuclei. The transportation of the CR is simulated with propagation codes (e.g. GALPROP [116], DRAGON [117]) that solve numerically the propagation equation Eq. (1.4) according to the choices of the features like the diffusion coefficient shape and parameters, the diffusion volume dimension, profile of the magnetic field in the Galaxy and many other characteristics. In literature three set of parameters called MIN, MED, MAX are often used, that lead to the minimal, median or maximal flux of CR from DM annihilation.

In particular for antiprotons, in case of DM nature origin, the transport equation is modified with a source term (described for a purely secondary CR species by Eq. (1.7))

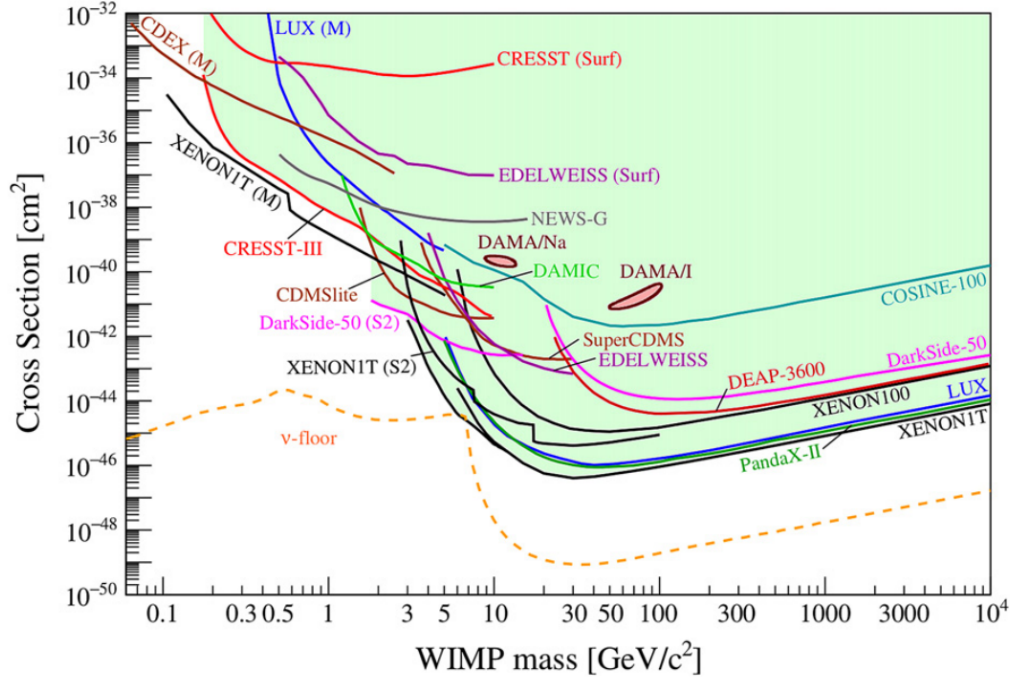


Figure 1.12: Current limits to spin-independent WIMP scattering cross section at different DM masses hypothesis for various direct detection experiments. 'Surf' means operated at ground level. The ν -floor indicated here is calculated according to [112] and identifies the region where direct detection experiment become sensible to neutrino detection. This is relevant for experiments without directional sensitivity, as neutrino background can closely mimic a WIMP signal. Here the ν -floor is calculated for a Ge target. Figure taken from [102].

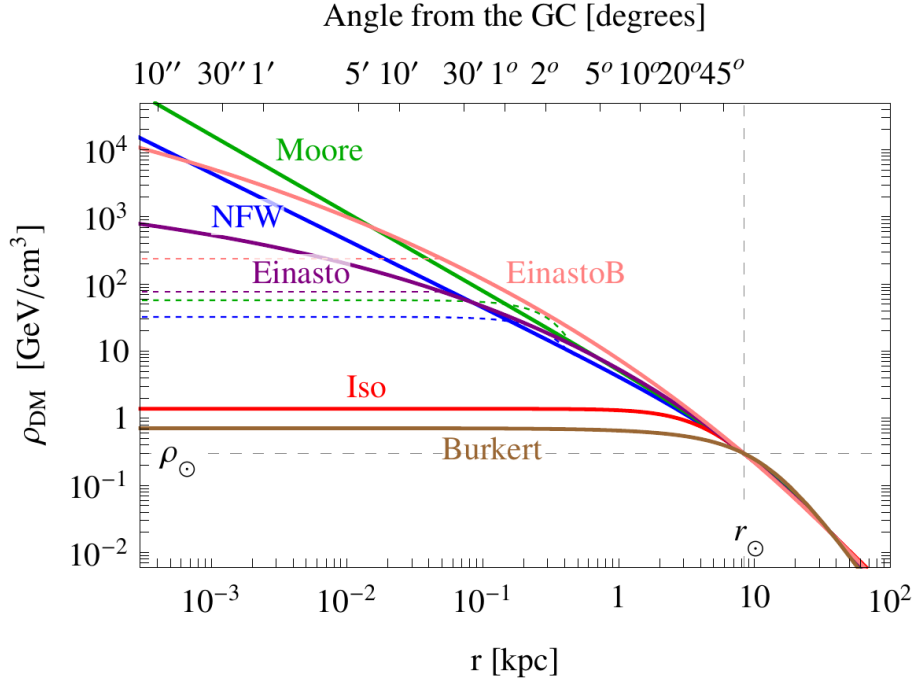


Figure 1.13: Dark matter density profiles as functions of the distance from the galactic center, according to different models. The models converge at Earth location, but have different dependence near the galactic center, becoming more or less sensible in probing that region. Figure taken from [113].

defined as following:

$$\begin{aligned}
 q &= \frac{1}{2} \left(\frac{\rho}{M_{\text{DM}}} \right)^2 f_{\text{inj}}^{\text{ann}}, \quad f_{\text{inj}}^{\text{ann}} = \sum_f \langle \sigma v \rangle_f \frac{dN_{\bar{p}}^f}{dE} \quad (\text{annihilation}) \\
 q &= \left(\frac{\rho}{M_{\text{DM}}} \right) f_{\text{inj}}^{\text{dec}}, \quad f_{\text{inj}}^{\text{dec}} = \sum_f \Gamma_f \frac{dN_{\bar{p}}^f}{dE} \quad (\text{decay})
 \end{aligned} \tag{1.16}$$

with the index f running over all possible ways to produce antiprotons from DM. Many studies, after the release of antiproton data from AMS-02, investigated the significance of a possible DM contribution with $m_{\text{DM}} \sim 80$ GeV in the excess measured in the $R = 10 - 20$ GV range. In [118, 119] the spectrum of antiprotons is fitted with a DM decaying into $b\bar{b}$ using a NFW density profile, as in Figs. 1.14 and 1.15. These studies show that a DM candidate with mass in $\sim 60-80$ GeV and $\langle \sigma v \rangle \sim 3 \cdot 10^{-26} \text{ cm}^3/\text{s}$ is statistically preferred with a significance higher than $\sim 4\sigma$. Nevertheless, other papers suggest that, even if a robust statistical excess is present, a deeper understanding of the signal requires an improved knowledge of the antiprotons production cross section and an accurate modeling of the solar modulation at low rigidities. In [120] the authors show that the choice of the parametrization of the antiproton production cross section has a large impact on the DM significance, leading to a 5% error on the source term solely due to the cross section uncertainty. The largest errors stem from the normalization, due to the uncertainty on the determination of the luminosity. Furthermore, the scaling of the cross

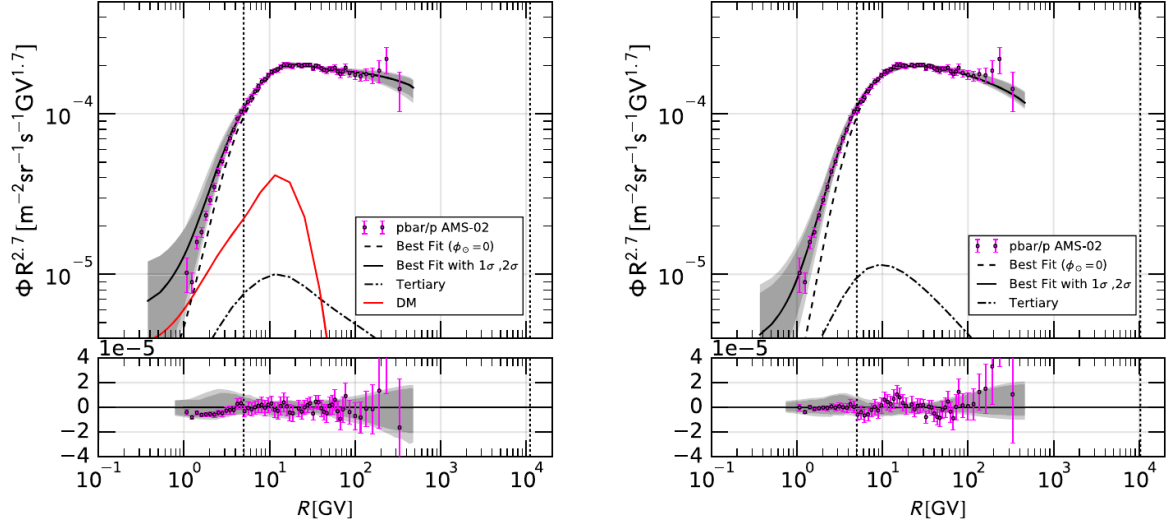


Figure 1.14: Comparison of the fit to the antiproton over proton flux with and without DM signal, on the left and on the right respectively. The DM hypothesis seems favoured by statistical test with masses around 80 GeV. Here 'tertiary' means inelastically scattered secondaries. Figure taken from [119].

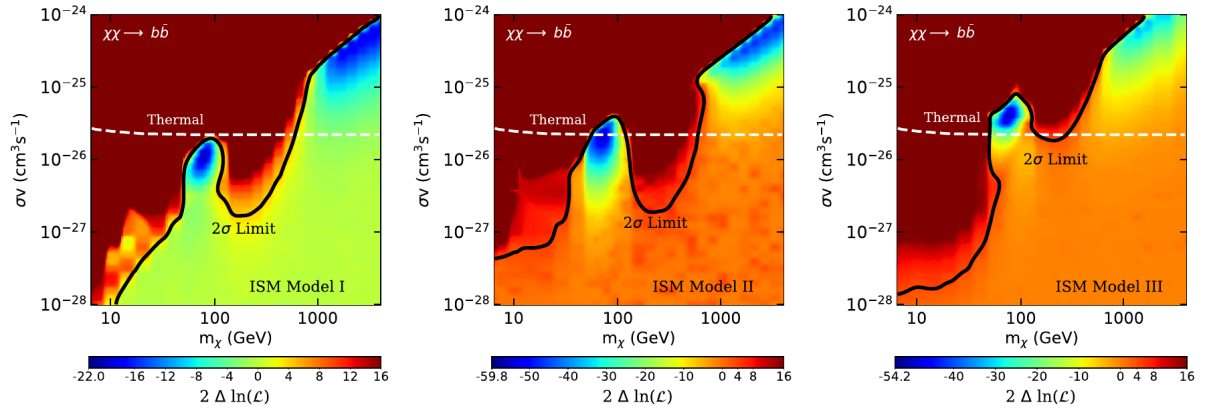


Figure 1.15: Impact of annihilating DM in the antiproton/proton fit in different scenarios of propagation. From left to right: different ISM models. The white line indicates the thermal cross section as a reference for a thermal relic. A thermal DM candidate with mass in 60-80 GeV is favoured with statistical significance over 4.5σ . A $\sim \text{TeV}$ scale DM is also disfavoured depending on the ISM model. Figure taken from [118].

section is broken at lower energies, due to the lack of data, making the extrapolation less reliable. As a last example, in [121] even more importance is placed on the correlation of the uncertainties from flux measurements, especially in absorption cross sections in the experimental apparatus, which reduce the significance of the antiproton excess and could lead to "fake" DM signals. The story of DM discovery with precise flux measurements is to be continued...

Chapter 2

The 2023 pHe AMBER setup

This chapter is devoted to comprehensively describe the experimental apparatus and to give more details on the peculiarities of the **2023 setup** dedicated to the $p+{}^4He \rightarrow \bar{p}+X$ studies, with a focus on the key detectors of the measure, namely:

- the CEDARs for beam proton identification
- the ${}^4He$ target
- the RICH-1 for the PID of antiprotons in the final state
- the trigger setup

The operations performed specifically for this run preparation, namely the alignment of the CEDARs, the RICH-1 beam pipe removal and the trigger elements movements are described as well. A 3D visualization of the spectrometer from the simulation software is visible in Fig. 2.1.

Since the AMBER spectrometer in 2023 was for most part identical to the COMPASS spectrometer, the majority of the technical information reported here are taken from the COMPASS technical papers like [122], [123], [124], to which I refer for more detailed information.

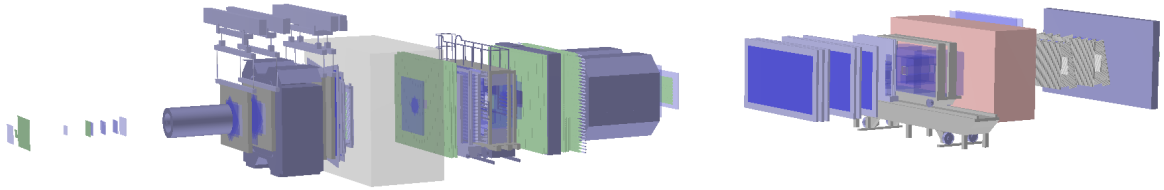


Figure 2.1: 3D visualization of the AMBER spectrometer. The beam enters from the left.

2.1 Beamline

The spectrometer is located in the Experimental Hall 2 (EHN2) at the SPS at CERN and uses the M2 beam line for the delivery of a secondary beam. A schematic view of the M2

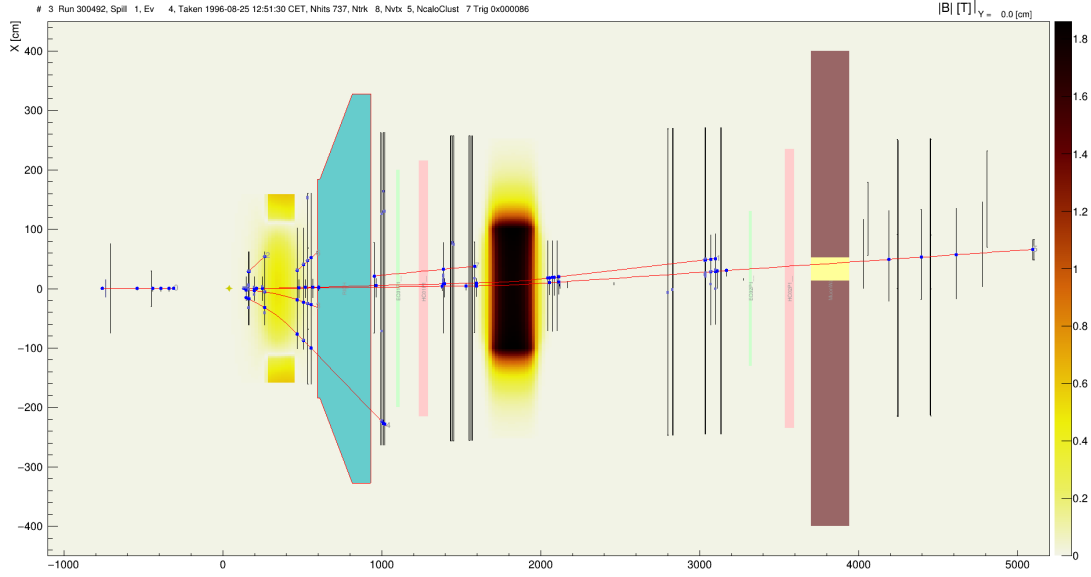


Figure 2.2: Top view of the AMBER spectrometer with a real data event display. The intensity of the magnetic field is color-coded on the right. The x axis is pointing up and the y axis is perpendicular to the picture. The z coordinate goes from left to right.

beamline, which is 1.13 km long, is shown in Fig. 2.3.

The beamline can be operated in three different basic modes:

- muon beam at high intensity ($\sim 10^8$ p/spill) at typical momentum of 160 GeV/c, from hadrons decay. This is obtained by placing absorbers on the beam path, so that only muons can survive;
- hadron beam at high intensity ($\sim 10^8$ p/spill) from 60 up to 280 GeV/c.
- electrons beam at low intensity ($\sim 10^4$ p/spill). Obtained by placing a dedicated electron target and removing the absorbers out of the beam path;

These three modes can be achieved by shooting the primary proton beam from SPS at 400 GeV/c on a production target (T6) with variable thickness. The products of interaction are collected and selected through the hadron absorbers and the intensity can be adjusted with TAX elements and by varying the T6 settings.

For the purpose of the antiproton production cross section, the beam line was set to hadron configuration at an intensity of roughly 10^5 p/spill. At the SPS, one spill corresponds to a delivery of particles lasting ~ 5 seconds. Typically during the 2023 run we had a supercycle of 2 spills every ~ 30 seconds. This intensity has been chosen in order to prevent a high DAQ dead time and to avoid the pre-scaling of the trigger rate. The hadron beam composition is reported in Tab. 2.1.

2.1.1 CEDAR

The secondary hadron beam delivered to the AMBER experiment is a mixture of protons, pions and kaons. In order to measure a proton induced reaction in the Helium target, it

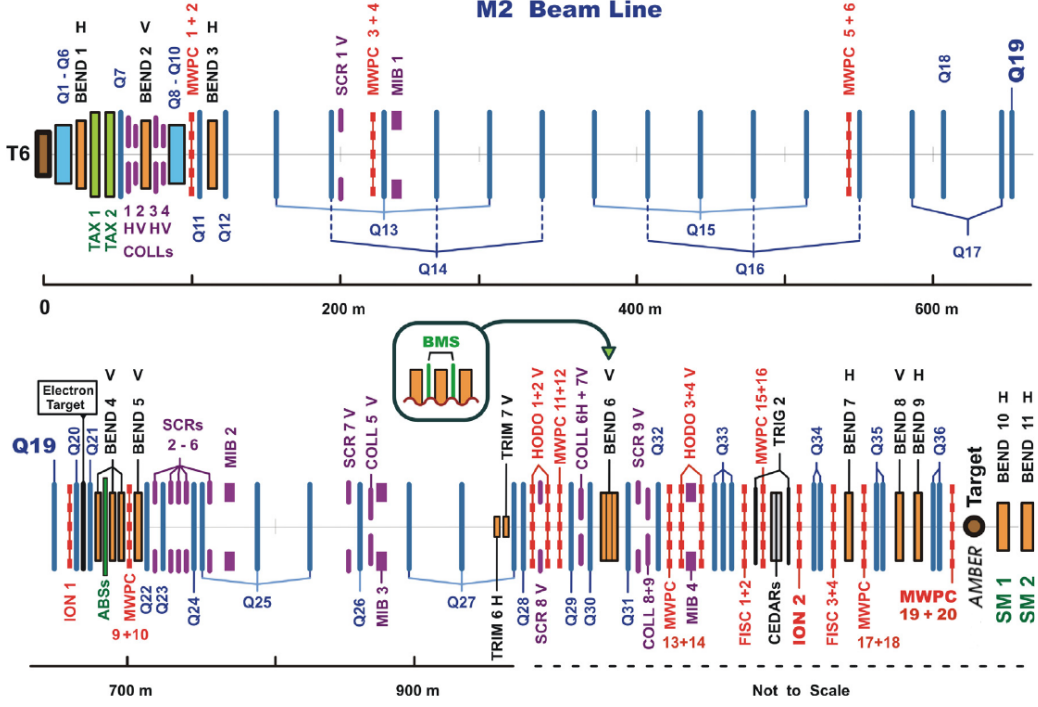


Figure 2.3: A schematic view of M2 beam line, where the relative position of the CEDARs, the target and the two spectrometer magnets are visible. Figure adapted by the author from [123].

Beam mom. [GeV/c]	Positive beams			Negative beams		
	π^+	K^+	p	π^-	K^-	$\bar{p}$
100	0.618	0.015	0.367	0.958	0.018	0.024
160	0.360	0.017	0.623	0.966	0.023	0.011
190	0.240	0.014	0.746	0.968	0.024	0.008
200	0.205	0.012	0.783	0.969	0.024	0.007

Table 2.1: The hadron beam composition at different momenta at the M2 beam line [123, 125]

is mandatory to identify the particle hitting the target. For this purpose two Cherenkov Detector with Achromatic Ring focus (CEDAR) type-N [126, 127] were placed ~ 40 m upstream the target.

The working principle of a CEDAR is illustrated schematically in Fig. 2.4. A beam particle crossing the detector radiator gas with momentum above a certain threshold (see appendix A for the production mechanism of the Cherenkov light) will emit light that is collected into 8 PMTs. The CEDARs used have a central part 6 m long filled with gaseous Helium in a range of pressure between 10 and 14 bars, depending on the particle to be tagged.

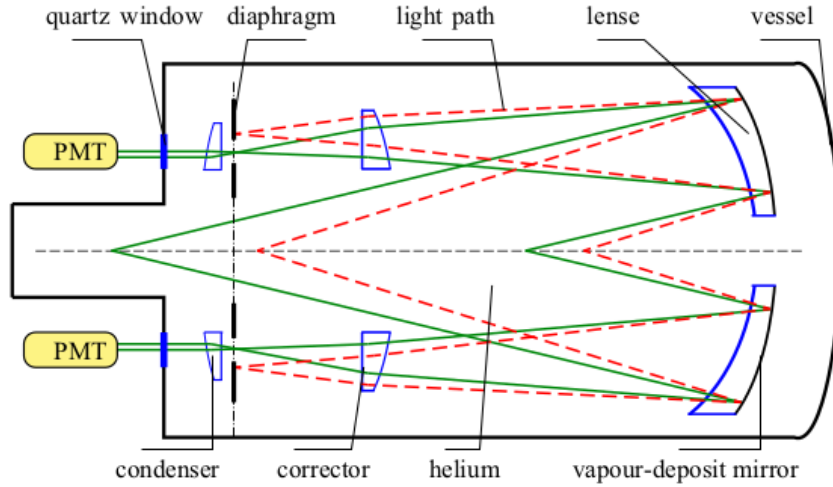


Figure 2.4: Working principle of a CEDAR counter. A particle crossing the gas radiator with a velocity larger than the speed of light in the medium, emits Cherenkov photons which are reflected by two mirrors and then focused by a system of lenses on the PMTs, through a quartz window. Figure taken from [123]

Once the beam line optics is tuned for a certain momentum, we can assume that particles of the same type will emit Cherenkov photons with the same angle. Therefore, by tuning the radiator gas pressure, and consequently the refractive index, inside the vessel and the diaphragm aperture it is possible to tag the desired type of particle in the hadron beam (kaon, pion or proton). With the correct settings only the photons produced by the protons will be focused on the PMTs and will leave a clear signal with large multiplicity.

Several effects, however, can smear the photons rings and alter the expected detector performance. Optical aberrations, chromatic dispersion, inhomogeneity of the refractive index, beam divergence, misalignment and multiple scattering are all incoherent effects and contribute to limit the ring resolution. Since the refractive index stability is directly correlated to any pressure or temperature gradient, the CEDARs underwent an upgrade of the thermal housing system in 2018 (along with an upgrade of the front-end electronics with iTDC readout and new PMTs [1]). Even though at equilibrium no pressure gradient is expected, a better control of the temperature along the system ensures better stability and performances. The multiple scattering limits the minimum momentum at which it

is possible to perform Particle Identification (PID), because for lower momenta an higher pressure is required to compensate the decrease of the ring radius. Moreover any beam divergence at the CEDAR entrance results in the production of a photons ring which does not match the diaphragm geometry, thus degrading the detection efficiency and the purity.

A summary sketch of the possible effects on photon ring smearing is shown in Fig. 2.5.

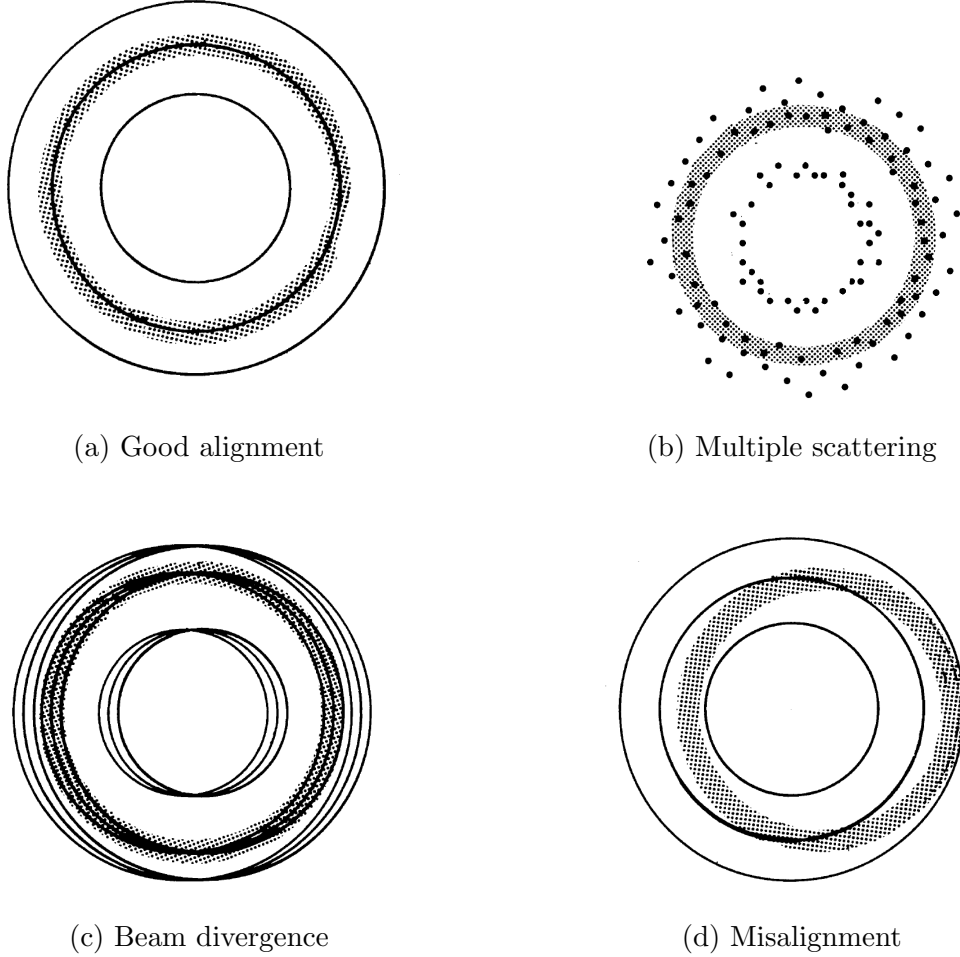


Figure 2.5: Different effects affecting the CEDAR performances in the diaphragm plane. The grey area is the diaphragm opening. The 3 rings correspond to different particle types. Figures taken from [127]

For the reason explained above, a dedicated procedure for the CEDAR alignment with respect to the beam axis has been developed and it is described in the following section.

CEDAR alignment in 2023

In the 2023 run both CEDARs were tuned to identify protons, which is the dominant component in the positive beam for momenta higher than $\sim 120\text{-}130$ GeV/ c . In order to find the optimum pressure setting, a scan of the signal rate versus pressure was performed at each beam momentum, as shown in Fig. 2.6. The three peaks correspond, from left

to right, to the pion, the kaon and the proton components of the positive hadron beam. Because protons have ~ 2 -6 times the mass of kaons and pions respectively, at the same momentum the proton radius is larger and very well resolved with almost no risk of contamination from pions or kaons (the efficiency and purity will be studied anyhow in detail in Sec. 4.1). The visible plateau is due to the fact that for a certain diaphragm aperture, there is a range of accepted Cherenkov ring radii. Increasing the pressure, the ring of a certain particle becomes larger, until it comes out of the detector acceptance and the count rate drops. The diaphragm aperture has then to be optimized accordingly to the beam particles we want to select. For example, to resolve the kaon from the pion peak a very narrow aperture has to be set which allows to be very selective on the ring radius. To select the protons, whose peak is well separated, it is not needed to set a very small diaphragm aperture. For the data collected in 2023 at 190 GeV/ c a safe value of 0.87 mm with a pressure set in the middle of the pressure scan plateau at 10.66 bar was chosen.

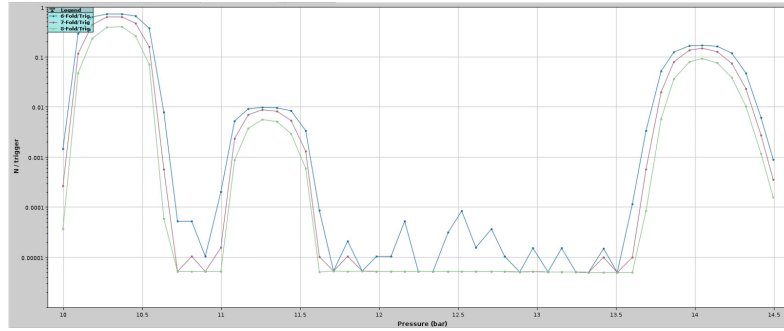


Figure 2.6: A typical pressure scan with the positive hadron beam at 60 GeV/ c with the three signal peaks. On the vertical axis the number of counts normalized on a beam trigger rate at CEDAR position; on the horizontal axis the pressure range. The three peaks correspond, from left to right, to pion, kaon and proton particles. Different colors for different many-fold requirement on the PMTs multiplicity. The width of the plateaus is determined by the diaphragm aperture.

The alignment of CEDARs is obtained by carrying out a first pressure scan and checking at which pressure each PMT reaches its maximum rate. If there is misalignment, the maximum rate peak of a single PMT will be shifted in pressure with respect to the others, depending on the direction of misalignment. This shift observed in relation with the single PMT position allows to determine the alignment correction to be applied to the CEDAR. An example of this procedure can be seen in Fig. 2.7. To give an idea of the orders of magnitude, the evolution of the plot is obtained by moving the CEDAR of several hundreds of micrometers to account for a relative differences in the peaks position of ~ 0.1 bar. This method allows to be very precise and independent from the single PMT efficiency, because only the pressure of the maximum count rate for each PMT has to be taken into account.

The final positions and settings of the two CEDARs in the different data taking periods of 2023 can be found in Tab. 2.2 and Tab. 2.3.

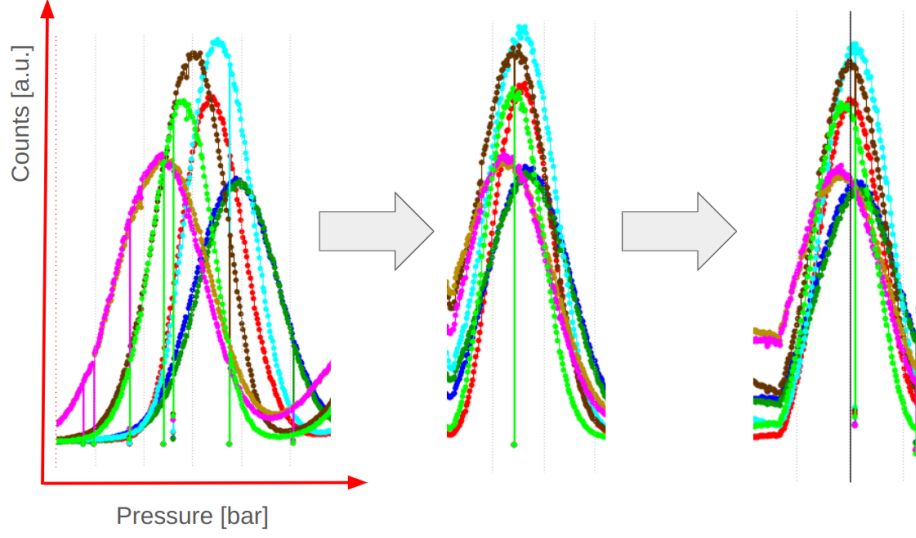


Figure 2.7: Pressure scan for individual PMTs (different colors means different PMTs, 8 total). The evolution of the plot are two consecutive iteration of alignment after correcting the physical position of the CEDAR.

Period name	Beam mom. [GeV/c]	CE01			
		Diaphr. [mm]	Press. [bar]	X [mm]	Y [mm]
W01	190	0.87	10.66	0.06	2.77
W02-W03	60	2.11	14.07	0.06	1.4
W04	100	1.51	11.64	0.3	2.87
W05	250	0.53	10.5	0.3	2.87
W06	160	1.21	10.8	0.3	2.87
W07	80	2.43	12.42	0.45	2.94

Table 2.2: Summary of CEDAR 1 diaphragm opening, positions and pressures in the different periods of 2023.

Period name	Beam mom. [GeV/c]	CE02			
		Diaphr. [mm]	Press. [bar]	X [mm]	Y [mm]
W01	190	0.75	10.56	-1.68	1.27
W02-W03	60	2.11	13.96	-1.68	1.4
W04	100	1.43	11.55	-1.29	1.37
W05	250	0.6	10.41	-1.29	1.37
W06	160	0.75	10.72	-1.29	1.37
W07	80	2.49	12.32	-1.16	1.4

Table 2.3: Summary of CEDAR 2 diaphragm opening, positions and pressures in the different periods of 2023.

2.2 Target

The AMBER run in 2023 came just after the last data taking run of COMPASS in 2022 dedicated to the study of the nucleon structure via Semi-Inclusive Deep Inelastic Scattering (SIDIS) process with a negative muon beam impinging on a polarized LiD target [128–130]. In order to optimize the technical swap between the two experiments, it was decided to use the same target platform and structure, with few modifications.

The COMPASS SIDIS target consists in polarized LiD material divided in two cells positioned in the mixing chamber (an epoxy tube) filled with liquid ^4He to keep the temperature at ~ 60 mK. The mixing chamber is then surrounded by dipole and solenoid magnets, used for the longitudinal and transverse polarization of the target material via dynamic nuclear polarization [131], in which the polarization of electrons is transferred to the nucleons in the target using microwave radiation, and maintained with the Helium at low temperature.

In 2023 both target magnets were not necessary and switched off. The polarized LiD material was also removed so that the mixing chamber could be used as a target filled with only ^4He , as in Fig. 2.8. The resulting usable target for the measure has the shape of a 140 cm long cylinder with a radius of ~ 3.6 cm.

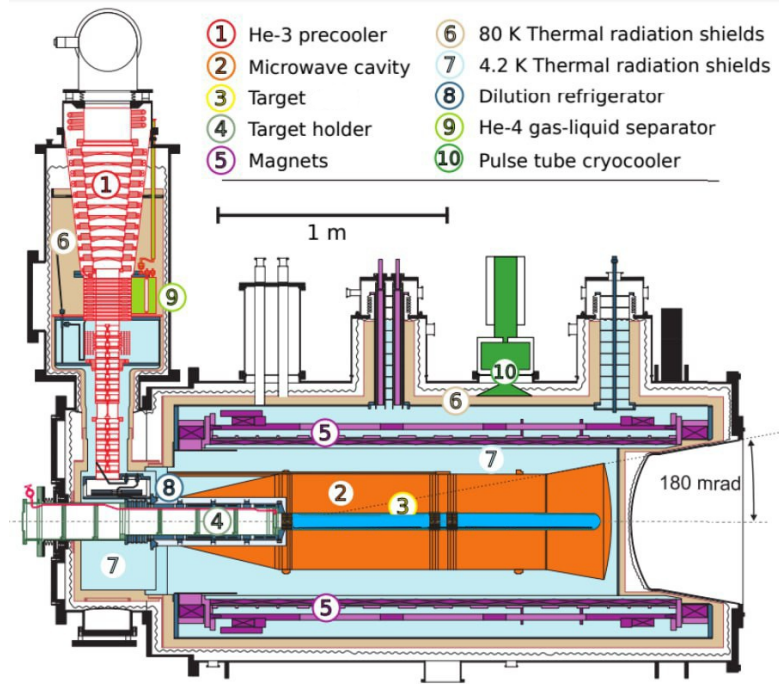


Figure 2.8: Sketch view of the COMPASS 2022 polarized target used for the AMBER 2023 run. In blue (3) the helium bath of the mixing chamber used as target. The beam enters from the left. Figure adapted by the author from [132]

2.3 Trackers

The particle flux varies depending on the position along the spectrometer. For this reason, detectors with different characteristics are used to cover different regions. Most of the large area detectors have a central hole corresponding to the trajectory of the non-interacting beam. The detectors are divided in three categories: the very small area trackers (VSAT), the small area trackers (SAT) and the large area trackers (LAT).

Very Small Area Trackers

For a distance up to ~ 3 cm from the beam axis, the area is covered by the very small area trackers. In this region the particle rate is very high ($10^5/s/mm^2$) thus VSATs have excellent time and position resolutions. The detectors involved are scintillating fibers (SciFi) and silicon microstrip detectors.

The SciFi detectors are the smallest ones in the spectrometer and their size vary between $\sim 16cm^2$ and $\sim 144cm^2$. The best characteristic of this kind of detectors is their time resolution of $350 \sim 450$ ps. In 2023 nine stations were placed along the entire apparatus. The active area is increasing with the distance from the target starting from $3.9 \times 3.9cm^2$ up to $12.3 \times 12.3cm^2$. The corresponding number of channels varied between 192 and 462 per detector plane. A single plane of SciFi is obtained by overlapping several layers of fibers as in Fig. 2.9.

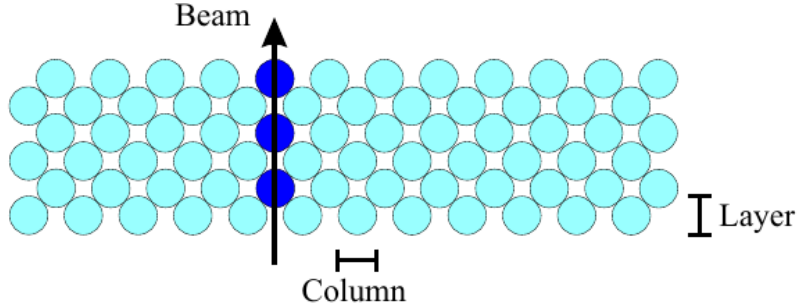


Figure 2.9: Single plane of a SciFi station. The number of layers varies with the station number. Figure taken from [122]

The silicon microstrip tracking system consists of three stations upstream of the target, which are used as a beam telescope. Since silicon detectors suffer from radiation damage exposure, to reduce the radiation damage all silicon stations are cooled down with liquid nitrogen to temperatures below 200 degrees Kelvin. One station comprises two silicon detectors with a stereo angle of 5° between their respective strip orientations to resolve multi track hit ambiguities. Each detector consists of a $300\mu m$ thick silicon sensor with an active area of $50 \times 70mm^2$. The signals are picked up on both sides, by 1280 strips on the n -side and 1024 perpendicularly oriented strips on the p -side. The spacial resolution is in the range of $4-6 \mu m$ when two strips are hit. When only one strip is hit, the resolution is in the range $7-11 \mu m$. The time resolution is about $1.4-1.8 ns$. The measured efficiency is above 99%.

Small Area Trackers

Distances from the beam axis larger than 2.5cm are covered by medium size detectors which combine good spatial resolution ($< 100 \mu\text{m}$), high rate capability ($\sim 10^4/\text{s}/\text{mm}^2$) and minimal material budget: Micro-Mesh Gaseous Structure (MicroMega) and Gas Electron Multipliers (GEM) detectors are used.

In Sec. 2.3 is illustrated the working principle of a MicroMega detector. There are three MicroMega stations in front of SM1 in the LAS, each one is composed by four detectors with different orientations: horizontal, vertical and two rotated by $\pm 45^\circ$ with respect to the vertical. Each plane has an active area of $40 \times 40 \text{ cm}^2$ with a dead zone of 5 cm in diameter for the nominal beam region. In total 1024 channels per detector resulted in a spacial resolution of $90 \mu\text{m}$ and a time resolution of 9 ns. The electrons produced by the ionization of a charged particles passing in the drift volume are drifted towards a metallic micro mesh. The mesh separates the drift area from an amplification gap where electrons are accelerated producing an avalanche of electron-ion pairs. The signal is read out by strip with a pitch of $360\text{--}420 \mu\text{m}$.

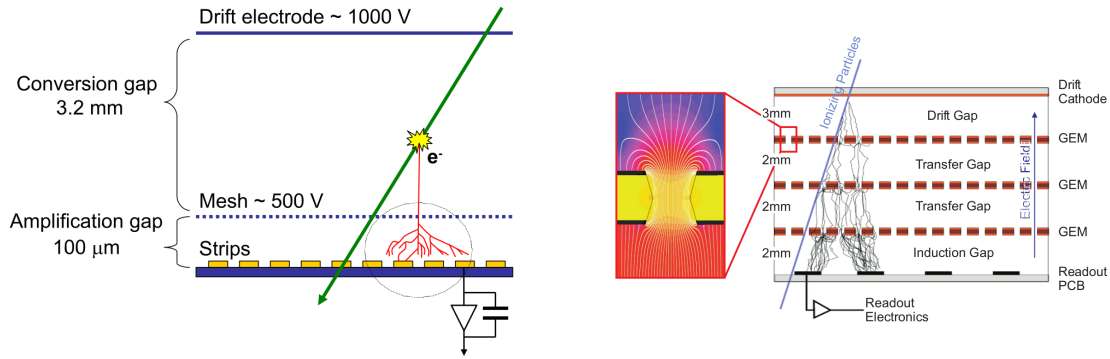


Figure 2.10: Working principles of GEMs (right) and MicroMega (left). Figures taken from [122].

The GEMs are, as the MicroMegas, Multi Pattern Gaseous Detector (MPGD). A GEM is a thin polyimide foil ($50 \mu\text{m}$) with Cu cladding on both sides, into which numerous microholes ($\sim 10^4/\text{cm}^2$) with a diameter of $70 \mu\text{m}$ have been chemically etched using lithographic techniques. The GEM detection principle is shown in Sec. 2.3: it is composed by three GEM amplification stages which are separated by thin grids of 2mm height. Across each foil a high voltage (several hundreds V) is applied to generate the avalanche multiplication of electrons through the holes. From the last GEM layer, the electron cloud produces the signal and is read by 2×768 orthogonal strips with a pitch of $400 \mu\text{m}$. The active area covers a surface of $31 \times 31 \text{ cm}^2$. The detection efficiency is $\sim 97\%$ with a spatial and time resolution of $\sim 70 \mu\text{m}$ and 12 ns respectively. The inner region, where beam intensity is too high, was object of an upgrade: the region was divided in 32×32 pixels with a pitch of 1 mm replacing the strips there. The rest of the $10 \times 10 \text{ cm}^2$ was covered with conventional strips. Four pixel GEM were distributed in two stations along the spectrometer in front and behind SM2.

Large Area Trackers

The large angle trackers have to provide a good spatial resolution while efficiently covering all the spectrometer acceptance. Detectors involved for this purpose are Drift Chambers, stations of Straw Drift Tubes and Multi-Wire Proportional Chamber (MWPC). Each DC consists of eight layers of wires with four different inclinations: vertical horizontal and rotated $\pm 20^\circ$ with respect to the vertical direction. Two DCs were mounted upstream SM1 (also called small DCs) and two downstream (large DCs). All of the DCs have a central dead zone of 30cm. The central dead zone can be activated for alignment purposes and was kept active with the 2023 low intensity beam. The average spatial resolution of a single DC layer is $270\mu\text{m}$ and the efficiency is above 95%.

The only station of straw detector consists in 2 couples of X-Y planes and two rotated planes (U-V). This station is located after SM1. The Straw tube drift chamber span even larger areas covering large scattering angles of $15 - 200$ mrad. It is composed of by two layers of straw tubes with different diameter, the smaller with 6.14 mm for the inner region the larger with 9.65 mm for the outer region.

MWPC consists of a plane of parallel sense wires enveloped by two cathode planes which can also be wire planes or simple metal sheets. There are three types of MWPC installed in the spectrometer, each type with a different number of layers: A-type, consists of three layers vertical and two tilted by $\pm 10^\circ$ with respect to the vertical axis; A^* -type has four layers, 3 identical to the A-type and an additional one orientated horizontally. These detectors have an active area of $178 \times 120\text{cm}^2$. The B-type is composed of two double layers detectors with opposite orientation fixed together, but only three layers are read out (the vertical layer and the two tilted ones). The active area is $178 \times 180\text{cm}^2$. All layers have a wire length of about 1m, a wire diameter of $20\mu\text{m}$ and a pitch of 2mm and are enclosed on both sides by graphite-coated Mylar foils. The central dead zone of each detector increases with respect to the detector position (the diameter varies from 16 to 22 cm). The average spatial resolution of the chambers is 1.6mm.

2.4 RICH-1

The RICH-1 is a ring-imaging Cherenkov detector with 3m long C_4F_{10} radiator, 21 m^2 Vacuum Ultra Violet (VUV) reflective mirror system and 5.6m^2 active detector surface. RICH-1 is capable of identifying pions, kaons and up to 40-45 GeV/c and protons up to 60-70 GeV/c. RICH sits in the first stage of the spectrometer. An aluminum structure is used as vessel. The vessel has a length of 3 m, a width of 6 m and a height of about 5 m. The hydro-static pressure of the radiator gas are held by the front and rear windows, which are built with minimum material budget due to their presence in the spectrometer acceptance: each one is a sandwich of two aluminum foils and a layer of rigid foam, for a total of $2\%X_0$. This radiation length is reduced to $0.6\%X_0$ where the beam is passing.

The RICH is used with focusing technique, the principals of this technique are illustrated in fig. Fig. 2.11. This implies the installation of the 21 m^2 VUV mirror wall to focalize the Cherenkov photons produced. Photon detectors are placed roughly on the focal plane of the mirror. The mirror wall is divided into two spherical surfaces of 6.6 m radius that have a mosaic formation composed of 116 spherical mirror units: 68

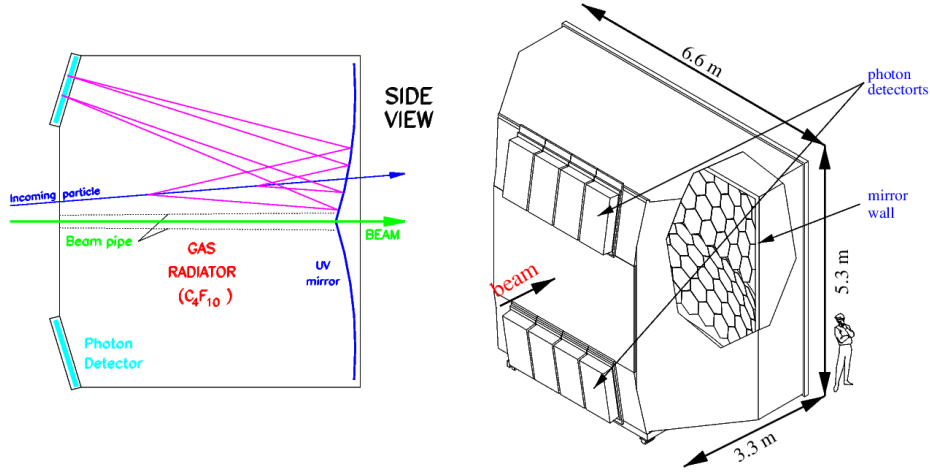


Figure 2.11: RICH-1 is used with focusing technique. Cherenkov photons are reflected by mirror and detected by photosensors on the backwall. Figure taken from [122]

hexagons with 522 mm of diagonal and 48 of different sizes to avoid overlap pattern near borders. The reflecting surface consists of an 80 nm thick Al layer deposited on a 7 mm thick borosilicate glass substrate and covered by a 30 nm thick MgF_2 protective layer. Each mirror has been fully characterized before installation: each mirror has a radius of 6606 ± 20 mm, a 95% energy spot size of 1.65 ± 0.45 mm, a surface roughness r.m.s. of 1.26 ± 0.11 nm and a VUV reflectance of 83 – 87% in the range between 165 and 200 nm [133]. As the mirrors have their centre of curvature located outside of the RICH, they have been individually aligned inside the RICH-1 vessel using the theodolite autoreflection method: the theodolite axis is oriented along the straight line joining its centre and the centre of the nominal mirror sphere (reference line); the mirror is then rotated until a laser beam along the reference line is reflected back on the same line. This procedure provides an accuracy of about 0.1 mrad. Since this procedure implies long and risky operations, in order to frequently monitor the mirror alignment during data taking an original on-line mirror alignment method has been developed and implemented in 2007 [134, 135].

In many physics programs, e.g. the measurement of the absolute cross-section of specific hadron species, the absolute values of the RICH efficiencies for the identified hadrons are required. Any fluctuation related to efficiencies will smear the precision of the measurement by enlarging the systematic error. The efficiencies are functions of the phase-space, but the stability of these values over the entire phase-space is at the core of such precision measurements. This can not be achieved without highly efficient and stable Cherenkov photon detection system, where both functionalities are important; namely, detection of signal photons and background rejection. In its original version the RICH-1 used as Photon Detector (PD) eight MWPC with a 576×1152 mm² active area, each equipped with two square CsI-coated photocathodes, segmented in pads. All the MWPCs with CsI photocathodes have been tested in the laboratory. They provide gain between 10^5 and 10^6 , but in the experimental environment they can be stably operated only at gain not exceeding 5×10^4 due to occasional electrical instabilities [133]. In 2006, to

overcome the problem of low PID efficiency for very forward particles, to provide higher rate capability and to get rid of the large uncorrelated background, the MWPCs with CsI photocathodes in the central region have been replaced by a fast detection system based on Multi-Anode PhotoMultipliers Tube (MAPMT)s coupled to individual fused silica lens telescopes and read out via sensitive front-end digital electronics and high resolution TDCs. In front of the MAPMTs a light concentration system transmitting photons with wavelength in the range from 200 to 700 nm with a wide angular acceptance provides a large image reduction (a factor 7.3 in area) with minimal distortion, and complies with the space limitations at the detector (11.5 cm total length). It consists of individual optical telescope for each MAPMT, made of two fused silica lenses (Fig. 2.12): a plano-convex field lens, placed in the focal plane of the mirrors and a biconvex condenser lens with one aspherical surface, providing a large demagnification with reduced image distortions. The image is projected to the plane of the MAPMT photo-cathode with a total spot size r.m.s. of 1 mm, to be compared to the 4.5 mm pitch of the MAPMT pixels [133].

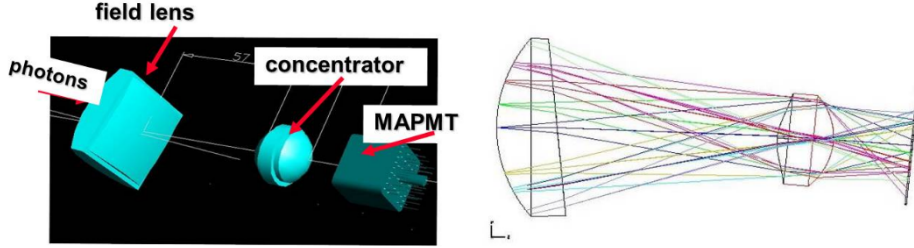


Figure 2.12: Artistic view of fused silica lens telescope. Figure taken from [133]

Central part of the RICH-1 is therefore equipped with MAPMT based PDs. Nevertheless, presence of magnetic field plays a crucial role in the detection of single photo-electron signal. Cases where RICHes are to be operated in vicinity of the magnetic field and large area are to be covered at an affordable cost, gaseous detectors are the only choice. This RICH has MWPC employed in the periphery. Despite of the fact that the MWPC have served brilliant performances over the years, they have their intrinsic limitations, which hamper the stability of the RICH largely. The occasional discharges of the detectors compel to operate them at a lower operating voltage, which results into lower working gain and hence difficulties in signal photon detection and background suppression. Motivated with such demands, in 2016 four of the twelve MWPCs have been upgraded with hybrid PDs based on Multi Pattern Gaseous Detector (MPGD) technology. The main goals of the upgrade were to achieve better stability, higher gain, similar single photon resolution, similar number of photons per ring and fast signal rising times compared to the MWPC. A complete characterisation of the newly installed detectors have demonstrated its advanced features. A simplified map of the different types of PDs used is shown in Fig. 2.13.

The RICH-1 is equipped with a beam pipe crossing all the radiator as in Fig. 2.14. The main goals of the beam pipe are to reduce the material length along the beam path and to reduce the pile up on the PDs due to the high interaction rate of the beam particles with the medium. The original beam pipe of 150 μm of stainless steel was replaced in

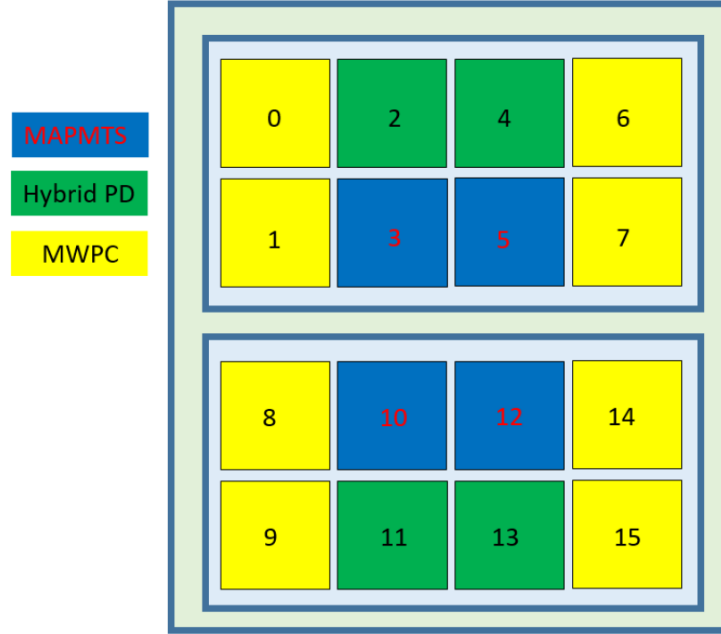


Figure 2.13: Map of PD used in the RICH-1. The scheme is not in scale. Figure taken from [136]

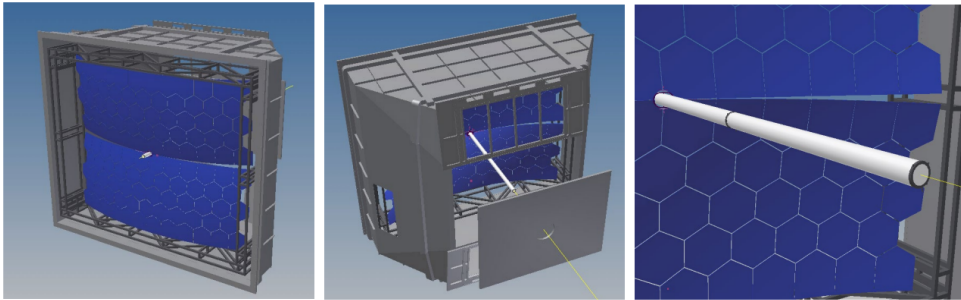


Figure 2.14: Beam pipe visualization in white. Mirror elements are displayed in blue. Figure taken from [133]

2012 by a lighter pipe of metalized BoPET. Starting from 2023 data taking, given the low intensity beam and in order to extend the phase space of charged particles produced at very small angle, the beam pipe was removed.

2.5 Trigger system in 2023

Since the goal of the 2023 measurements is an inelastic inclusive cross section, it was decided to opt for a minimum bias trigger, saving all the inelastic events in the target and removing most of the non-interacting beam particles crossing the spectrometer. This is obtained using the following elements displaced as in Fig. 2.15:

- beam trigger (BT) $\rightarrow$ to tag a beam particle before entering the target. A logical coincidence between two planes of scintillating fibers upstream the target (~ 7.5 m distance), namely SciFi01X and SciFi02Y.
- beam killers 1 and 2 (BKs) $\rightarrow$ to veto the non-interacting beam particles along the spectrometer. The single beam killer is made of a plastic scintillating disk of 3.5 cm radius. BK1 was placed at ~ 25 m and BK2 ~ 32 m after the target.
- VETO $\rightarrow$ to remove beam halo. The veto system is composed of three hodoscopes before the target, i.e. plastic scintillator slabs organized in different geometries before the target.

The final *physics trigger* is then obtained with the logical operation $BT+!BK+!VETO$ (with BK meaning the coincidence between the two beam killers).

A *random trigger* is also used during the whole data taking. The random signal is produced by measuring the β decay of a ^{22}Na source located in another building with respect to the experimental hall to ensure a complete unbiased signal. This trigger is used for example to determine the incoming flux of particles or other quantities that need an unbiased estimation.

The random trigger and the minimum bias physics trigger explained above are the only 2 triggers used for the 2023 data taking. A typical trigger mix with tentative and accepted rates is visible in Sec. 2.5.

Beam killers alignment

The position of the beam killers in the plane perpendicular to the beam axis was optimized to be centered on the beam trajectory. With the beam already tuned to enter the spectrometer as parallel as possible to the target, a position scan was performed moving the beam killers on the transverse coordinates in order to find the maximum intensity with the beam completely inside the scintillating disk (see Fig. 2.16).

For each beam momentum, the BK position set in the data taking is the one at which the BK count rate is maximized. The procedure is repeated for the X and Y coordinates of each beam killer and the final values used are reported in Tab. 2.5. The traversing path through the spectrometer was tuned to follow the same trajectory for all beam momenta. This was achieved by scaling magnets currents (and consequently the magnetic field intensity).

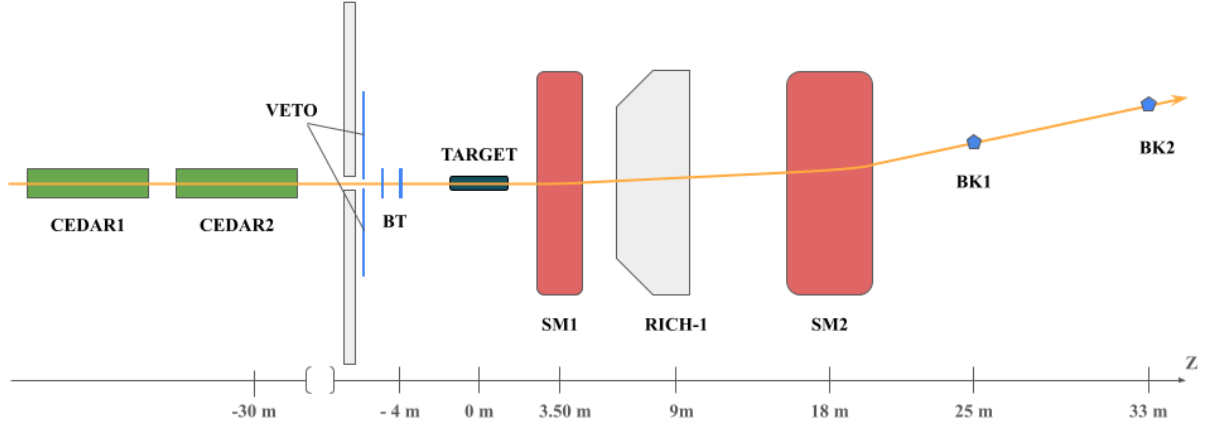


Figure 2.15: Schematic top view of the trigger elements (in blue) with some of the spectrometer parts for reference. A non-interacting beam particle (in orange) passes through the whole spectrometer and leaves signals in the beam trigger (BT) and in the two beam killers (BK) as in the picture. Not in scale.

Trigger element	Short name	Division factor	In rate	Out rate
Beam Trigger with Beam Killer condition and Veto	BT+!BK+!V	1	100,840	100,840
Beam Trigger with Beam Killer condition	BT+!BK	0	115,469	0
Beam Killer	BK	0	119,866	0
Inner Veto	VI	0	21,892	0
Beam Trigger	BT	0	233,812	0
HALO2 Trigger (VO1 AND HO04)	HALO2	0	6,791	0
True Random	TRand	1	16,609	16,609

Table 2.4: Exemplary trigger mix counts (per spill) for run number 300666 of period W01 (beam at 190 GeV/c).

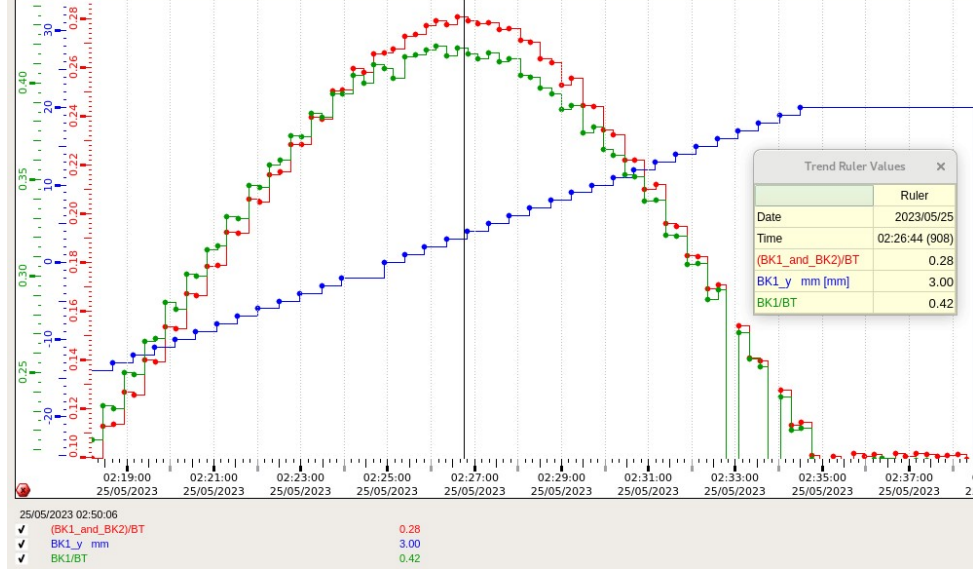


Figure 2.16: Position scan of the Y coordinate (in blue) of BK1. The position is adjusted via software at fixed intervals. In this case the maximum intensity (green line) is reached with a shift of 3 mm along the Y axis. The BK1 counts are normalized on the beam trigger counts in order to be independent from any beam intensity variation. Screenshot of the AMBER Detector Control System.

Period name	Beam mom. [GeV/c]	BK1 X [mm]	BK1 Y [mm]	BK2 X [mm]	BK2 Y [mm]	SM1 [A]	SM2 [A]
W01	190	86	5	157	4	2500	4800
W02-W03	60	82	3	157	3	935	1130
W04	100	86	3	157	3	1000	2360
W05	250	67	1	118	1	2500	4800
W06	160	86	2	157	2	1813	3870
W07	80	89	-2.5	157	-3.0	960	1835

Table 2.5: Summary of beam killers position in the different periods of 2023.

2.6 Data storage and reconstruction

Each triggered event is collected by the Data AcQuisition (DAQ) system locally and moved to the Cern Archive Tape (CTA) for the long term storage. The analysis of the raw data is made possible thanks to the reconstruction and simulation softwares that are inherited and maintained together with the COMPASS collaboration.

2.6.1 Reconstruction

The event by event reconstruction is performed by COmpass ReConstruction AnaLysis software package (CORAL) that handles the various stages of this process. The inputs to CORAL can either be real raw data collected by the experiment or the output of the Monte Carlo (MC) software. The two inputs differs mainly for the very first stage of data handling: the MC data undergo the *digitization* of the detector response and hits are produced based on particle trajectories and resolution, while in real data the detector information is *decoded*. The second phase is the *clustering*, where detector channels that were fired by the same particle are grouped together according to different mechanisms to get a better determination of particle position or parameters. The geometry of the detectors is read from a file called *detectors.dat*, which is produced either by alignment procedure (Sec. 3.2.1) or by MC description of the setup.

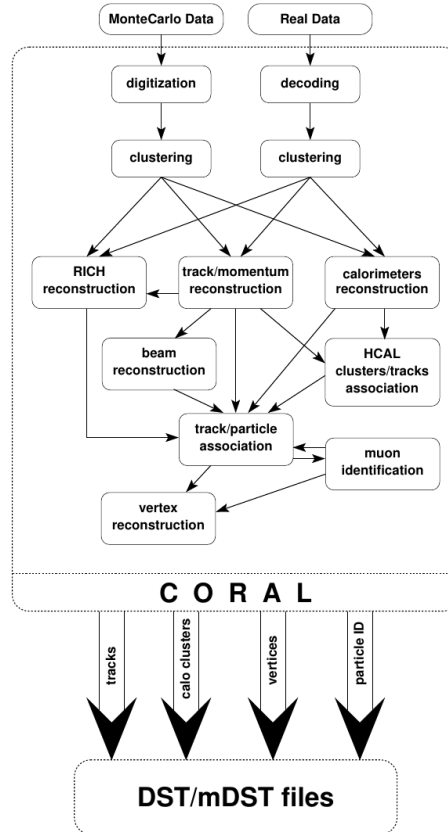


Figure 2.17: Reconstruction software scheme. Figure taken from [122]

After clusters are produced, the tracking algorithm (TRAFFIC) uses the tracking

detectors information to reconstruct the tracks and determine their momenta. Three phases can be identified: pattern recognition, bridging and fitting. Once track segments are found in the various zones of the spectrometer, they are bridged over to build full tracks. A Kalman filter ([137, 138]) is used to fit the tracks, to best estimate their parameters using also the information encoded in the material and magnetic field maps.

RICH-1 reconstruction algorithm uses information from the tracking to compute the Cherenkov angle associated to each track and the best hypothesis of identification. A specific software package called RICHONE handles this detector inside CORAL and takes care of clustering in the Photon Detector.

In the final phase, the vertex of interaction is found firstly by computing a point of closest approach. The tracks removed because too far from the candidate vertex are excluded from the second search performed with an inverse Kalman filter algorithm. The accuracy on the vertex location found with this method is about 0.1 mm in the transverse plane and from 5 mm to 15 mm in the longitudinal coordinate, with the worse being more upstream the target.

The reconstructed information is stored eventually in the form of Data Summary Tape (DST or miniDST) that can be analyzed with higher level tool like PHysics Analysis Tool (PHAST) based on ROOT framework [139].

2.6.2 Simulation

The experimental setup is simulated with Total Geometry And Tracking (TGEANT) [140], a GEANT-4 ([141]) based software specifically created for COMPASS and now customized for AMBER. Apart from implementing the GEANT4 features concerning the particle transport and interactions, the reconstruction of TGEANT data with CORAL mimics almost everything of the experimental environment, including detector efficiencies, material distribution, trigger, detectors response and beam condition. The shooting particle is typically a stable particle, given the generator supports it, and the generation of secondaries from primary interaction with the setup material may use several plug in:

- PYTHIA 6 [142];
- PYTHIA 8 [143];
- LEPTO [144];
- HEPGen++ [145];
- elastic only
- internal generator
- cosmic muons

The simulated data sample follow roughly the same path as real data towards the reconstruction. The final output is again a DST to be analyzed with PHAST. The complete tool set for data analysis is thus composed by:

- TGEANT → setup and physics simulation

- CORAL $\rightarrow$ event reconstruction of real data and MC data
- PHAST $\rightarrow$ higher level analysis of DST
- ROOT $\rightarrow$ general histogramming

Chapter 3

Analysis of the 2023 pHe data

In this chapter, I describe the operations performed on the monitoring of detectors, their alignment and the stability of the data collected. The Helium target tomography and the lifetime corrections of DAQ and VETO system are also presented for use in the following chapters.

3.1 Data sample

AMBER collected data for the antiproton production cross section between April and June 2023 with a commissioning phase of 1 month. As described in Sec. 1.4.1, the desired reaction to be measured is:

$$p + {}^4\text{He} \rightarrow \bar{p} + X$$

obtained with a positive hadron beam impinging on a liquid helium-4 target. In order to measure this reaction, we need an identification of protons in the beam with the CEDARs and an inclusive measurements of antiprotons in the final state. The products of interactions are tracked with the AMBER spectrometer and their identification relies on the performances of the RICH-1. The final goal is the measurement of the double differential cross section of the process in the momentum-polar angle plane.

The preparation for the run included some hardware and software operations. A part of them has already been described in Chap. 2, but they will be resumed here because useful to the discussion of the data analysis.

- RICH-1 beam pipe removal (Sec. 5.7)
- trigger elements alignment (Sec. 2.5)
- target filling (Sec. 2.2)
- CEDARs alignment and tuning (Sec. 2.1.1)
- general commissioning of the spectrometer

After the completion of detector commissioning, the physics data taking started on 19th May 2023. In about 2 months we collected a considerable data sample at six different beam momenta. A summary of the collected statistics in number of spills can be found

Period name	Beam mom. [GeV/c]	Collision energy $\sqrt{s_{NN}}$ [GeV]	Start Date	End Date	Number of spills
W02-W03	60	10.7	24.05	30.05	37000
W07	80	12.3	17.06	25.06	13400
W04	100	13.8	01.06	11.06	13700
W06	160	17.3	14.06	17.06	8500
W01	190	18.9	19.05	24.05	11000
W05	250	21.7	11.06	14.06	7300

Table 3.1: Summary of the data taking periods, with the collected statistic in number of spills, ordered by increasing beam momentum.

in Tab. 3.1. In this work the data analysis will concentrate on period W01 (190 GeV/c), which will be the first result on pHe collisions at the AMS-02 energy scale and will serve as basis for the analysis of the other collected data.

3.2 Stability studies

The operation performance of the spectrometer is monitored during the whole period of data taking. In general the stability of the detectors is ensured by a proper commissioning and maintenance, but it can happen that failures and errors influence a good running of the whole apparatus, especially considered the amount of instruments involved. For this reason a stability analysis is performed to ensure that the data sample to be analyzed has been collected with stable condition. This is typically achieved by the following steps:

1. online monitoring during data taking
2. spill by spill analysis
3. run stability study

The online monitoring allows us to identify channel by channel possible problems on detectors. This is usually done directly during data taking, but the results can be used as well for later stages to identify possible sources of instabilities. Then a rejection based on macro/tracking variables is performed at spill level. Eventually one can analyze whole runs to check the stability of physics variables.

3.2.1 Spectrometer alignment

Before proceeding with the reconstructed data and perform more advanced analysis, the alignment of the spectrometer is required. I carried out the alignment task during and immediately after the data taking in order to provide reliable and robust tracking performances. Actually, the complexity of the alignment procedure makes this task quite challenging, depending on the physics requirements and the general status of the reconstruction software, and it is typically carried out in parallel to the physics analysis to to solve potential issues with tracking or data reconstruction.

The alignment procedure in AMBER follows the principles developed in COMPASS [146, 147] and aims to find the true position of tracking detectors starting from survey campaign done before data taking or from construction design. I have performed the alignment procedure on the following stations, on the 2023 data sample at 190 GeV/c, for a total of more than 200 detector planes:

- Scintillating Fibers (FI01, FI02, FI15, FI03, FI04, FI05, FI55, FI06, FI07, FI08)
- GEMs (GM01, GM02, GM03, GM04, GM05, GM06, GM07, GM08, GM09, GM10)
- pixelized GEMs (GP02, GP03)
- small Drift Chamber (DC00, DC01)
- big Drift Chamber (DC04, DC05)
- Multi-Wire Proportional Chamber (PS01, PA01, PA02, PA03, PA04, PA05, PA06, PA11, PB01, PB02, PB03, PB04, PB05, PB06)
- Straw Detector (ST03)
- RichWall (DR01, DR02)
- Silicon detectors (SI01, SI02, SI03)
- W45 (DW01, DW02, DW03, DW04, DW05, DW06)
- MuonWall A (MA01, MA02)
- Micro-Mesh Gaseous Structure (MP01, MP02, MP03)

Each detector station consists of several planes which give different projections of the particle trajectory. In general each station is built in such a way to give an unambiguous position. The unique name of a plane is composed of the detector type (e.g. GM), the station number (01), the coordinate measured (X) and the layer number (1), resulting for instance in *GM01X1*. The X and Y projections correspond to the horizontal and vertical coordinates, while U and V layers indicate in general an inclination with respect to the X and Y (in the range between 10-45 degrees). The center of the plane, the pitch between sensitive elements, the dimension, the rotation, the dead zones and other informations are then coded into a table (called *detectors.dat*) needed to run real data and MC reconstruction instances.

Principle of the alignment method

The final goal of the alignment is to minimize the *residuals* distribution of each plane, defined as the distance between the particle hit on the plane and the reconstructed hit point. The expected residual distribution shape is a superposition of effects like the detector intrinsic resolution, the uncertainty on the tracking and the misalignment of the plane position. A perfect shape would be a Gaussian centered in 0, with standard deviation matching the detector resolution.

Each plane has at least three degrees of freedom to be tuned (center position, rotation and translation along beam axis). A traditional and simple method to address the task is to use the average of residuals to determine the alignment parameters a posteriori. This is a biased approach because the local fit of tracks depends on the set of alignment parameters itself. Also, detector inefficiencies and reiteration of the method will lead to an even more biased result. For example, the simple residual method can not disentangle the geometrical shift from the drift velocity shift in a drift detector. This method has the advantage to be quick, since only the determination of the local parameters is needed.

One of the best and most reliable methods to address the alignment is, instead, to minimize the χ^2 of a function ΔU that depends linearly on tracks parameters (*local parameters* α_t) **and** the alignment parameters (*global parameters* α_a) simultaneously.

$$\chi^2 = \sum_{i=1}^{n_{\text{track}}} \sum_{j=1}^{n_{\text{det}}} \frac{[\Delta U(u_{ij}, \alpha_{it}, \alpha_a)]^2}{\sigma_j^2} \quad (3.1)$$

with σ_j the resolution of detector j and u_{ij} the hit position of the i -track in the j -detector. It can be demonstrated that the minimization of this χ^2 is doable with analytic solution by asking null partial derivatives over parameters. The procedure leads to the inversion of a matrix that can easily reach thousands of rows and columns, due to more than 250 detector planes with 3 parameters each plus 4 parameters per track. The computation time for this inversion would be definitely too long. The special structure of the the matrices, however, with one set of global alignment parameters and many sets of local ones can be reduced to a solvable size with a general solution proposed and derived by Volker Blobel and implemented in a software bundle called *Millepede* [148, 149]. The AMBER spectrometer alignment framework relies on the Millepede algorithm.

Definition of quality criteria

The definition of the alignment parameters in AMBER is done by first defining three reference systems:

- Main Reference System (MRS). The z axis is oriented along the beam; the y axis is vertical and oriented upward; the x axis is horizontal and perpendicular to the other two axes. The origin is placed roughly in the middle of the target position.
- Detector Reference System (DRS). The DRS is defined for each plane. It has the origin in the center of the detector and the z axis is defined as in the MRS. Two other axes u and v are defined to be respectively perpendicular and parallel to the sensitive elements of the detector, so that the u coordinate is the coordinate measured by the plane.
- Wire Reference System (WRS). This reference has the origin in the lowest sensitive element in the plane. The axes are oriented as in the MRS.

In the DRS, we can then identify 4 parameters that will be used for the alignment procedure:

- δu , u coordinate offset

- $\delta\theta$ rotational offset
- δz longitudinal offset along z axis
- δp pitch offset (distance between two sensitive elements)

In principle also other parameters like the angle between the u, v axes and the z axis should be taken into account to accurately tune the detector position. The reconstruction software, however, assumes that each plane is perfectly perpendicular to the beam axis and can not handle tilts.

The fundamental estimator of the alignment quality of a plane is represented by the residual distributions. The residual is defined for each track in the DRS as:

$$\Delta u = u_{\text{hit}} - u_{\text{track}} \quad (3.2)$$

and may be *biased* or *unbiased*, depending respectively if the plane was used in the track reconstruction or not. Ideally the unbiased residuals show the true misplacement of the plane. However, not many detectors can be excluded from tracking at the same time, resulting in a slow procedure, while the biased residuals have the advantage of a fast processing and give a general overview of the alignment status. But especially in the first stages of alignment, an unbiased approach is preferable, with few planes at a time included in the procedure.

The distribution of residuals Δu as a function of u and v coordinates can be related to the alignment parameters:

- the average value of Δu is linked to the δu offset;
- the slope of Δu vs u is sensitive to the pitch and longitudinal offset parameters;
- the Δu vs v is eventually related to the $\delta\theta$ rotational offset;

For perfectly aligned detector, the three estimator (average Δu and the slopes against u and v) should be 0.

More advanced studies on the alignment quality involve some macro variables like number of reconstructed tracks per event, χ^2 tracks distribution, number of reconstructed vertices per event or physics quantities (e.g. K_0^S mass and width). A part from the physics ones, the other quantities have not an expected value but can be used to track any improvement in different iterations of the procedure. Eventually, (pseudo-)efficiencies may reveal large inter plane tensions and are used as an indicator of problems in the tracking for those planes.

The alignment procedure in 2023

The whole procedure is iterative and requires many steps to be completed. The initial input is a preliminary *detectors.dat* built from survey measurements or from previous years. In 2023, the starting point was the last period of 2022 COMPASS run, with the additional survey of a few detectors that were moved in specifically for the Amber run. During the data taking, dedicated alignment runs are taken for each beam momentum, corresponding to a different configuration of the two spectrometer magnets, SM1 and

SM2, current setting, and for every major movement of any detector position during maintenance operations. The runs used for alignment are of three main types, in this order:

1. muon beam data with both magnets SM1 and SM2 off (*aloff*).
2. muon beam data with SM1 and SM2 ON (*alon*) in the same configuration of the physics run.
3. physics data.

The first data set used requires the minimum bias possible and this is achieved by switching off the magnets. The AMBER spectrometer is indeed naturally divided in 5 zones (before target, target-SM1, SM1-SM2, SM2-muon filter, muon filter-beam dump). In the magnets off configuration the tracks are roughly straight while crossing the spectrometer and minimum bias is introduced in bridging over the various zones. The beam is typically defocused as much as possible to better illuminate the detectors.

A second sample is taken again with the same beam condition but with the magnets as in the physics final configuration. This ensures a smoother transition between the *aloff* and physics data. Several effects are introduced when switching on the magnets due to the fringe field, especially in the proximity of SM1 (Fig. 3.1):

- some support structures are slightly magnetic and the planes near the magnets move when the magnet is turned on;
- magnetic field changes the trajectories of drift electrons in drift detectors;

resulting in an offset in the residuals distribution larger than the detector resolution, as visible in Fig. 3.3. The bending of the electron drifting is usually handled by introducing a *Lorentz angle* correction, which represent the angle between the electric field lines and the electron drift velocity. The detectors affected by this effect are mainly the GEMs and MicroMega near SM1 (GM01,GM02,GM03 and MP01, MP02, MP03).

Eventually, some detectors are not properly illuminated with the magnets off and are out of the beam path: the *alon* data allows us to introduce those detectors in the alignment procedure.

The final data sample is the physics data which has the peculiarity to better illuminate the large angle detectors and provide additional information. For example the effect of the temperature on the support structure dilatation and contraction is very well visible in the residual monitoring in physics data and is very useful to track pathological cases. In both magnets ON cases the minimization procedure is more complicated with respect to the reconstruction of straight tracks and for this reason the algorithm is modified to include a linear deviation into the tracks reconstruction.

After collecting the data sample as described above, the 2023 alignment followed a typical approach. First of all a pair of detectors with X and Y planes have been chosen as references for the absolute alignment, called pivots. They are GM04X/Y and GM10X/Y. In fact the GEMs are good candidates to start with, because have very good resolution and cover an intermediate acceptance with overlapping regions with other detectors in both LAS and SAS. Once the pivots are chosen, it is important to let their position untouched,

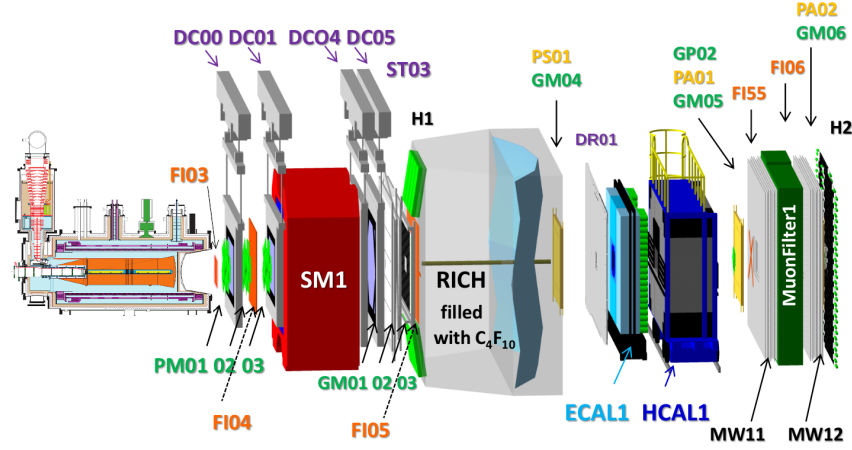


Figure 3.1: Side view of the LAS. The most precise detectors (GEMs GM01,02,03 and MicroMega MP01,02,03) in the proximity of the magnet suffer from the fringe field and show misalignment when switching from *aloff* to *alon*.

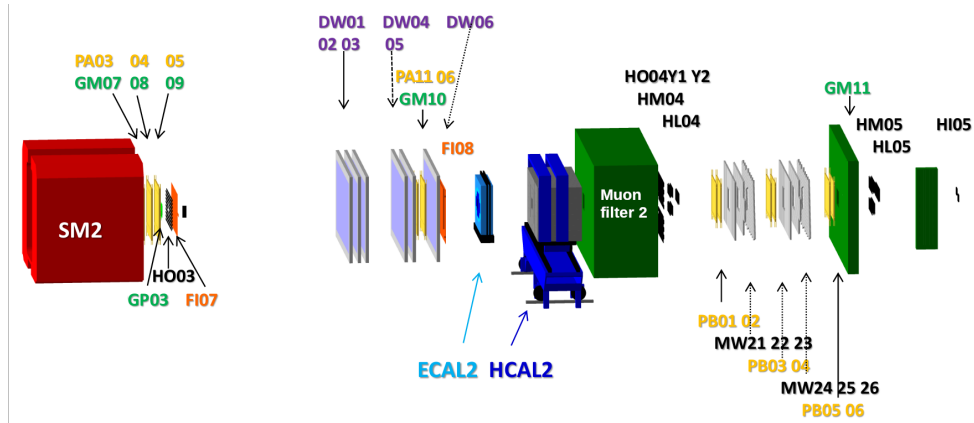


Figure 3.2: Side view of the SAS. The fringe field of SM2 is low compared to SM1 and the GEMs in the vicinity suffer less the induced movement. The large area SAS detectors are included in the alignment procedure only after the successful completion of the small and middle size detectors alignment in the LAS.

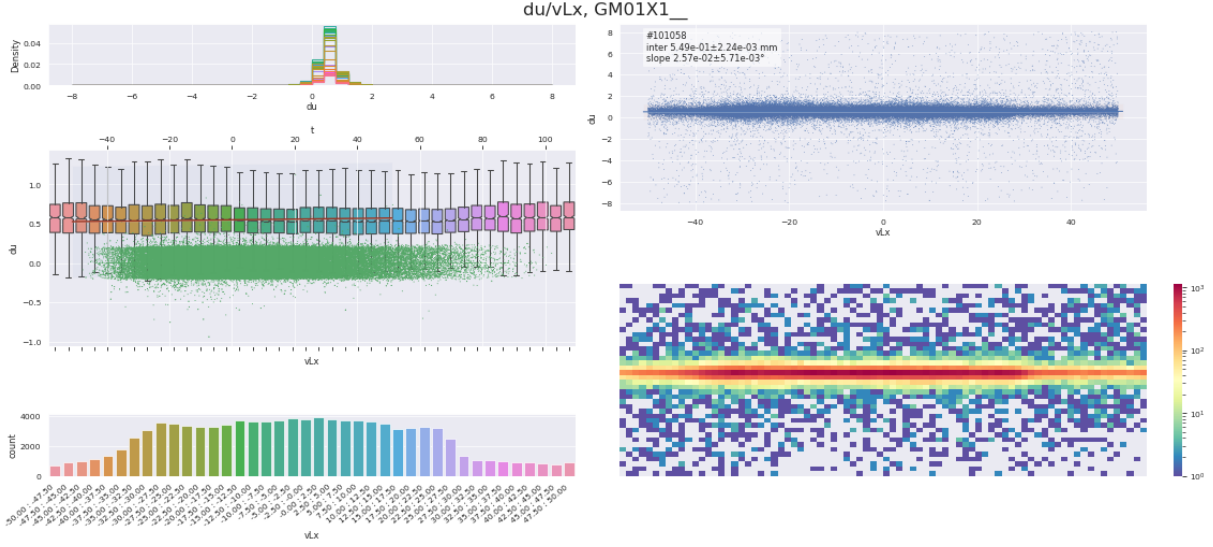


Figure 3.3: Residuals plots for GM01X1 in *alon* data. *mm* units. Its position was aligned with *aloff* data. Top left: δu distribution, top right: δu vs v , middle left: different representation of δu vs v divided in zones along v , bottom left: hit multiplicity in the different v zones of the detectors, bottom right: color coded 2D residual map. A shift on the δu residuals is clearly visible of the order of 0.5 mm, to be corrected with the *alon* data set.

at least before completion of a first round of alignment, as they are the fundamental reference for all the other detectors. The following iterations foresee to add detectors of the same type to provide comparable tracking features (acceptance and resolution). The remaining GEMs were added one by one. At the very beginning plane by plane, but once the tracking becomes more robust, it is possible to add one full station per each iteration. After having all the GEMs aligned, I proceeded to include the pixel GEM (GPs) and later the MicroMega (MPs). Both this kind of detectors have the outer region composed of strips and the central region of pixels. The MP pixels are, for historical reason, treated differently in the alignment framework and need also a so called "v-align" which will be discussed later. The small angle reconstruction is then completed by plugging in the SciFi planes to have also a beam reconstruction before the target. In this first part of the procedure, the silicons are also included, but assuming a worse spatial resolution with respect to their real one, to accommodate eventual misalignment and allow for track reconstruction in the bias procedure. The silicons alignment will be then optimized with an unbiased method, together with all the beam telescope, once the rest of the spectrometer alignment is completed.

The medium size detectors alignment is performed by including the DCs, the MWPCs and the Straws. It is possible to use also the drift-like detectors without $R(T)$ calibrations, but at the price of a worse spatial resolution. Finally, the large area detector like RichWall, MuonWall and DW, are included.

The alignment procedure is quite challenging, due to the large number of tracking planes. In general there is always the risk at any step that the minimization falls into a local minimum, resulting for example in subtle tensions between neighboring planes that

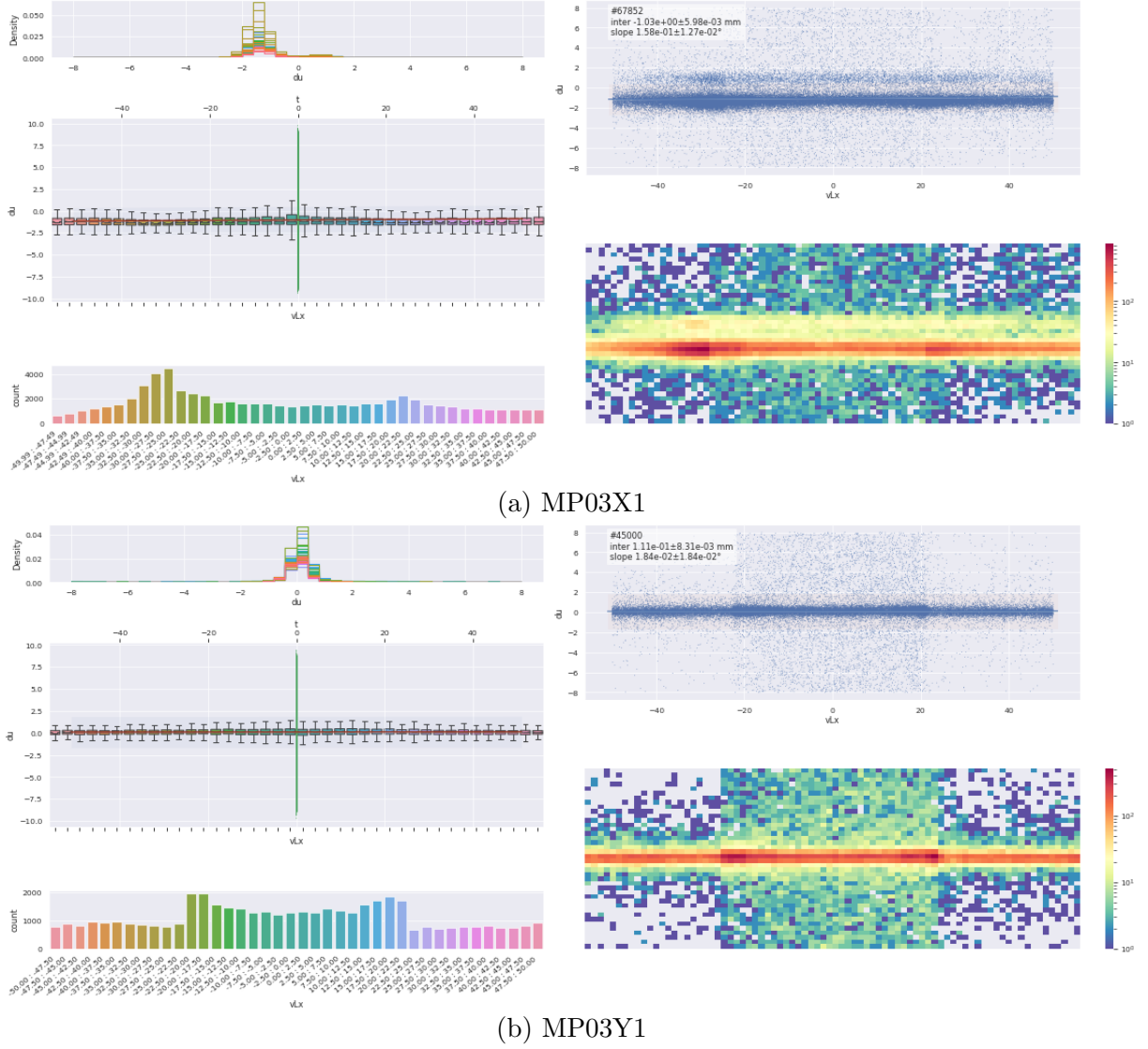


Figure 3.4: Residuals plots for different planes of MP03 after switching to *alon* data. *mm* units. Plot description as in Fig. 3.3. The Lorentz effect on the drift electrons is clearly visible on the X plane, that is the magnetic field bending direction, while on Y almost no effect is present.

are difficult to disentangle when approaching the late stages of the procedure. As a golden rule, the pitch and rotation parameters should be addressed only at later stage. The risk of using δu plus $\delta\theta$ or even δp as alignment parameters in the first stages is to find local minima or to correct with higher order correction before it is needed. At the beginning of the procedure a safe approach is to use only δu as free parameter, fixing all the others.

To give a quick overview, a typical single iteration for the alignment of one detector plane consists in:

1. reconstructing some data with the current spectrometer setup (the plane to be aligned is included or excluded in the tracking depending on the biased or unbiased approach)
 - (a) choosing the free global parameters
 - (b) minimizing the parameters space
 - (c) computing the residuals
2. updating the *detectors.dat* file with shifts, rotations and pitch adjustment needed
3. checking the alignment quality
4. repeating the entire procedure. In critical cases it is recommended to repeat an identical iteration to be sure that the minimum is indeed reached.

Typically I used a biased approach with a set of iterations meant to minimize in the order the following parameters $\delta u \rightarrow \delta u \rightarrow \delta u + \delta\theta \rightarrow \delta u + \delta\theta$. However, very precise planes like silicon detectors required unbiased treatment to determine their position.

3.2.2 Bad spill rejection

The delivery of particles in the experimental hall is provided by SPS in form of particles packages called *spills* and the spill structure dictates the DAQ intervals of data acquisition. More detail on the beam line in Sec. 2.1.

The spill by spill analysis aims to identify and reject spills that deviate too much with respect to the neighboring samples (in time). A tool to perform this analysis was developed for COMPASS, but, given the slightly different setup and especially the different physics program, I developed a new tool for the AMBER antiproton cross section measurement. The criteria used for defining bad/good spills are based on macro-variables which account for detectors and tracking performances and trigger rates. These macro variables are computed per spill and used as estimators of stability:

- n. primary vertices per event
- n. outgoing particles per event
- n. outgoing tracks per event
- n. particles from primary vertices per event
- n. particles from primary vertices per vertex

- n. hits of beam particles per event
- n. hits of outgoing particles per particle
- sum of χ^2 of outgoing particles per particle
- sum of χ^2 of primary vertices, per primary vertex
- physics trigger rate normalized to random trigger rate
- n. Cherenkov photons in RICH-1 per particle
- average θ_{CH} in RICH-1 per particle
- multiplicity per event in CEDAR1
- multiplicity per event in CEDAR2
- ratio of multiplicity in CEDARs per event

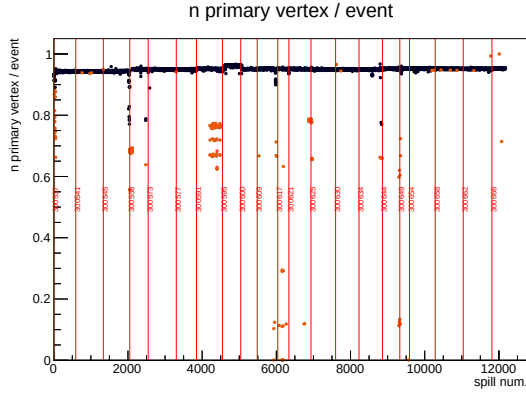
For each spill, the neighboring 1200 spills are grouped (spill num. ± 600) and represent the local (in time) population of good spills. If a spill is at the edge of the data taking period, the population is adjusted to accommodate the same total number of spills. For each variable, the standard deviation of the local population is extracted. We can define an interval of $\pm 5\sigma$ around the value of the variable of the spill examined (the number of σ can be tuned for each variable, depending on the stability of it). The spill is marked as bad if the number of neighbors within this σ interval is below 250. Empty spills are marked bad as well. One can appreciate the result of this procedure in Fig. 3.5, where few of the variables are shown as function of the unique spill number. The unique spill number is created from the run number and the spill number in the run, and simply represents the chronological order of the spills.

For period W01, the statistic loss due to bad spills rejection is at the level of 10%.

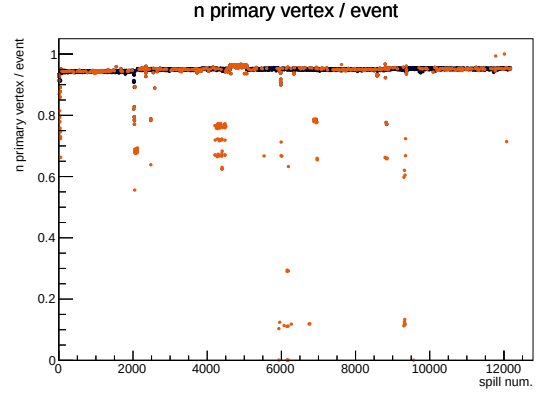
3.2.3 Run stability study

After the bad spill rejection, I performed an higher order stability check on a run by run level. This approach is based on physical quantities and it is more sensible to possible alignment issues and magnetic field. The quantities used in this case are the reconstructed mass, width and number of the so called V_0 s produced (K_0^S and $\Lambda/\bar{\Lambda}$). These particles decay via weak interaction and their decay vertices can be spatially resolved from a primary vertex. The weak decay vertex selection is achieved by using the following cuts:

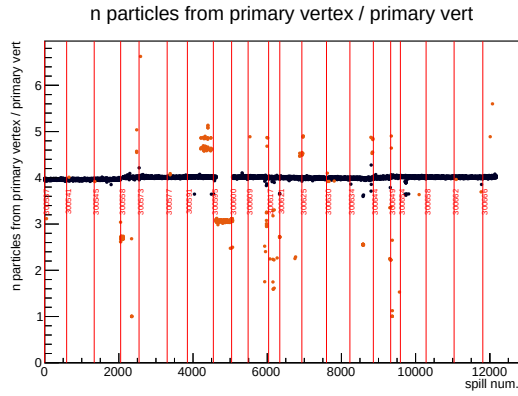
- bad spill list applied
- primary vertex exists in the target region (see Sec. 2.2)
- a secondary vertex exists
- exactly 2 outgoing tracks of opposite charges from secondary vertex
- the two tracks are not connected to a primary vertex



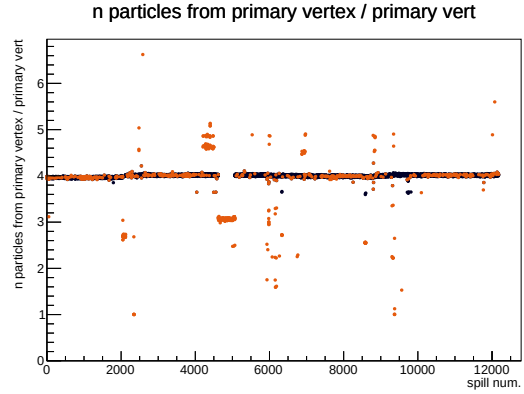
(a) Bad spill selected by number of primary vertex per event



(b) Bad spills selected from all the variables.



(c) Bad spills selected by average number of particles from primary vertices.



(d) Bad spills selected from all the variables.

Figure 3.5: Bad spill selection for two of the variables used in the stability check study. In (a) and (c) the orange points are spills marked as bad by the specific variables. Black points are good spills, again according to the single variable. The final bad spills rejection is performed including the results obtained on all the variables used as stability estimators, as visible in (b) and (d). Around spill number 4500 there is a bulk of ~ 300 spills rejected due to a problem on the trigger timing.

Hadrons	Decays	
	Channel	BR
K_0^S	$\pi^+\pi^-$	$(69.20 \pm 0.05)\%$
$\Lambda(\bar{\Lambda})$	$p\pi^- (\bar{p}\pi^+)$	$(63.9 \pm 0.5)\%$

Table 3.2: Summary of decays channels of the V_0 s. Values taken from [150].

- primary-secondary vertex separation: $\Delta Z(PV - SV) > 2\sigma$
- $\cos \theta_{coll} < 0.9996$. Where the θ_{coll} is the angle between the primary-secondary vertex direction and the decaying particle direction. This ensures that these 2 vectors are collinear
- outgoing tracks cross less then $10X_0$ (radiation length), to filter out muons
- last measured point (Z_{last}) of outgoing tracks is downstream SM1, to ensure a well reconstructed momentum
- momentum of outgoing tracks larger than 1 GeV/c, for a good reconstruction
- p_t of the produced particles with respect to the decaying one are larger than $23MeV/c$, to remove electrons

After this selection, according to the main decaying channels listed in Tab. 3.2, the different combinations of final state particles $\pi^+\pi^-$, $\pi^+\bar{p}$ and π^-p are formed to build up the Lorentz Vector of the decaying particle.

The resulting invariant mass spectra are then fitted with two gaussians to account for the two spectrometers and a first order polynomial for the background. The stability estimator such as resonance width, number of resonances and mass of the particles are extracted from the fit.

The difference between the nominal mass of K_0^S (and Λ) and the reconstructed mass is shown as a function of the run number in Fig. 3.6. In general there are no critical runs. However this estimator can give a glimpse also on the alignment quality and the accuracy of the reconstructed momentum of the tracks.

The reconstructed mass is then studied more in detail in bins of the primary vertex position along Z and separating the tracks which cross the whole spectrometer (LAS + SAS) from the ones which stop in between SM1 and SM2 (LAS). The separation in Z_{vtx} bins shows a trend of the accuracy as a function of the target length. This is due to the topology of the events decaying more downstream and to the different acceptance of the spectrometer depending where the particles are produced. Concerning the separation of tracks in SAS and LAS, we observe a better accuracy of a factor 5 of the SAS with respect to the LAS. This is actually expected, considering the longer lever arm for reconstruction and the combination of SM1 and SM2 in determining the momentum. Again, the run stability is well established and no runs are rejected.

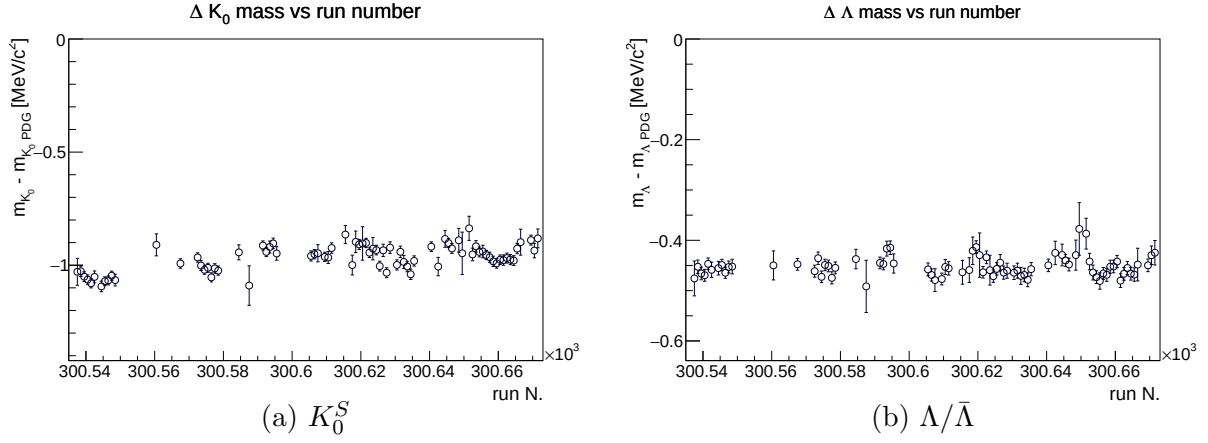


Figure 3.6: Difference of the reconstructed mass of V_0 s with respect to the mass from the PDG. Overall the difference is less than 0,2 % for K_0^S and less than 0,02 % for Λ .

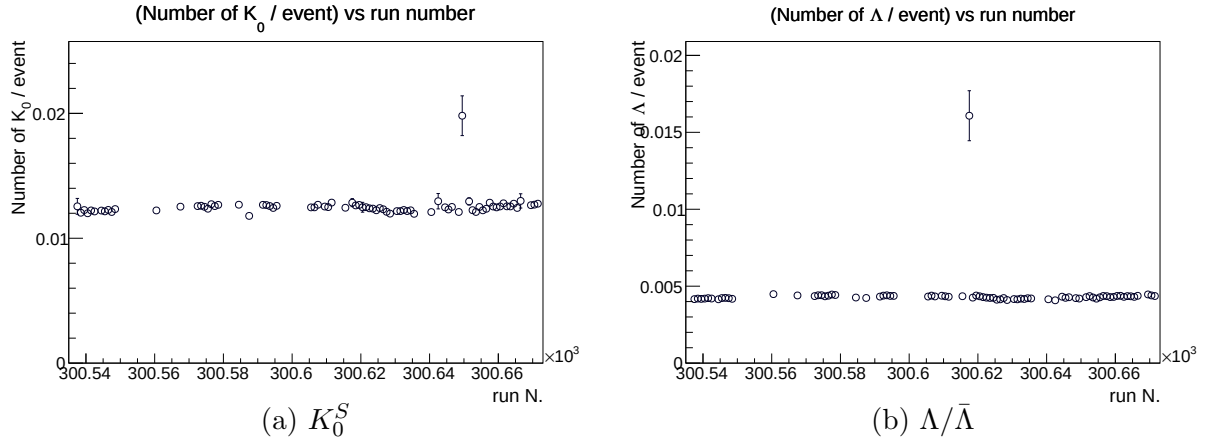


Figure 3.7: Stability of the V_0 s number per event. The count is normalized on the total number of primary vertex in the target. Two runs have problem in the fit, but are not discarded.

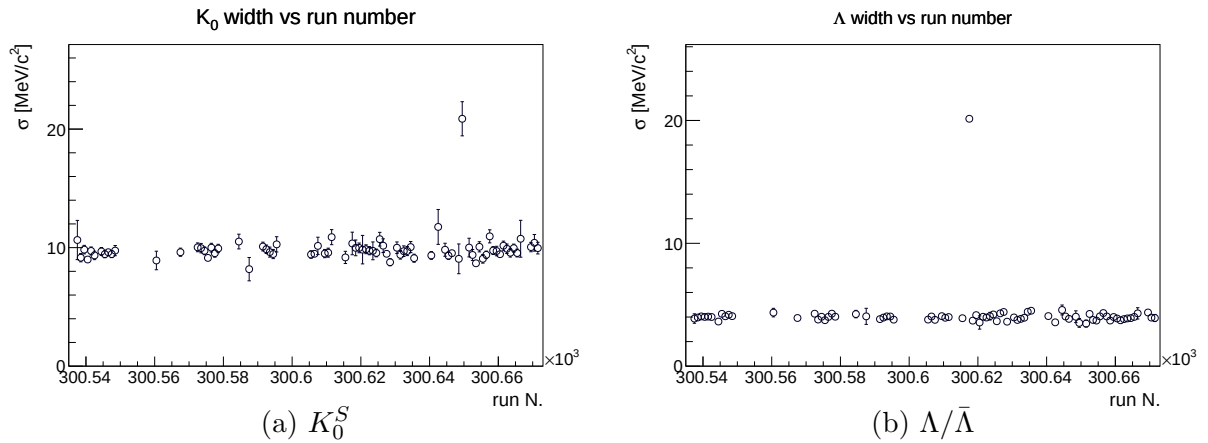


Figure 3.8: The width of the resonance is obtained by adding in quadrature the σ of the two gaussians fits of the invariant mass distribution. Two runs have problem in the fit, but are not discarded.

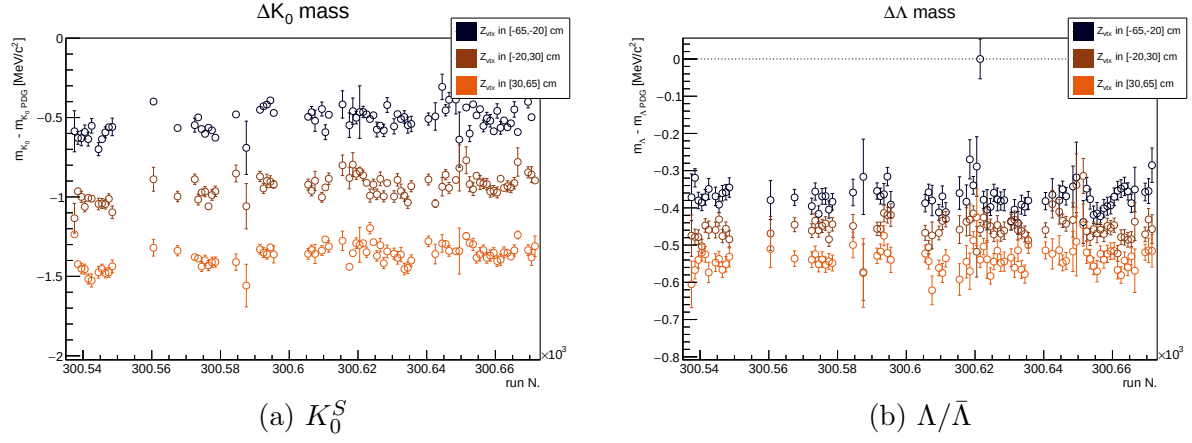
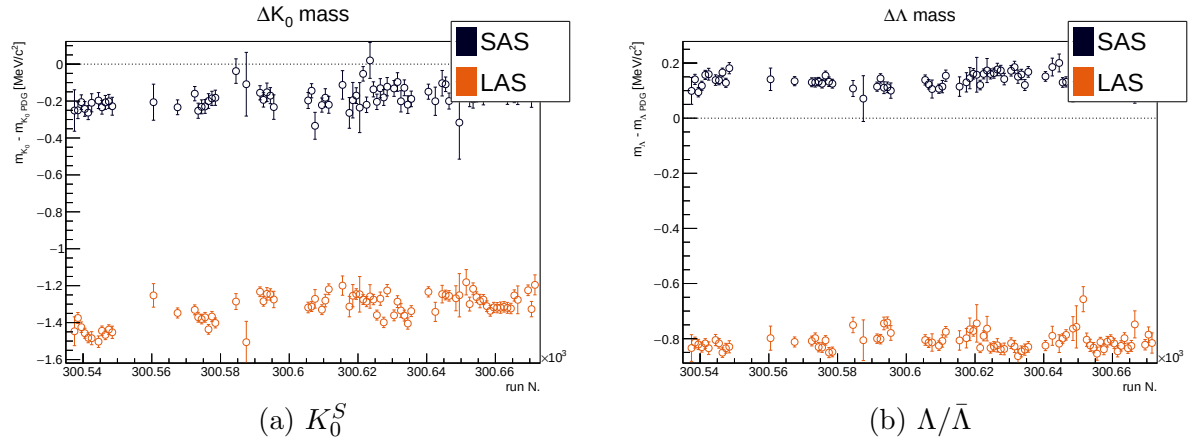
Figure 3.9: Run stability studies in bins of primary vertex Z_{vtx} position.

Figure 3.10: Run stability studies separating SAS and LAS tracks.

3.3 Study of the He target size and position

The determination of the target position and dimension is crucial for several aspects of this analysis. First of all, the interactions of the proton beam with the helium target are selected requiring that the primary vertices are inside the target volume. In order to minimize the systematic error induced by interactions with other target materials (e.g. the mixing chamber or the general support structure of the target, see Sec. 2.2), the exact dimension of the main Helium Target volume has to be determined. Furthermore, the correct target position is needed for the precise estimation of the incoming proton flux to derive the luminosity. Finally the most precise as possible target geometry has to be encoded in the Monte Carlo for applying proper corrections.

The mixing chamber contains the helium used as target material. It is made of epoxy and has a radius of roughly 3.6 cm. To identify the mixing chamber we can exploit the interactions with it: even if the radius is much larger with respect to the beam spot (of ~ 2 cm), with enough statistics it is possible to identify a circumference in the XY distribution of vertices due to the smaller interaction length of the epoxy. The data sample used for this study is selected with a minimum bias cut by rejecting the bad spills and asking for a primary vertex in the event. To ensure a better reconstruction of the vertex, the number of associated outgoing tracks is requested to be larger or equal than 3.

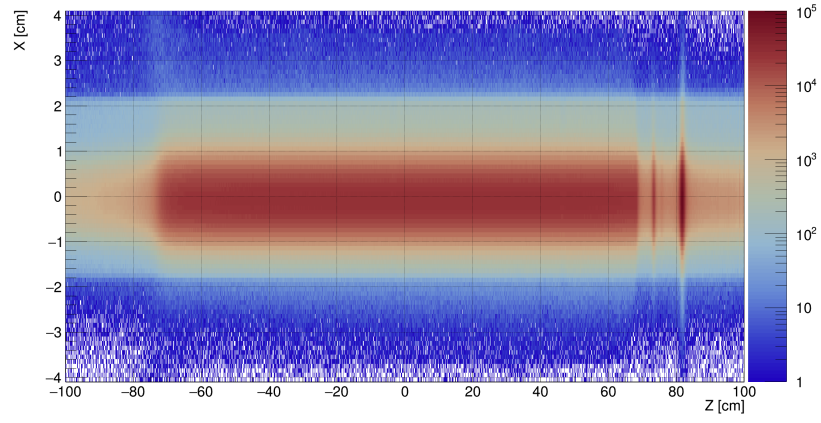
First of all, we need to identify the target region along Z by looking at the Z vertex distribution. The nominal length of the target is 140 cm, from -70 cm to 70 cm, with the center of the Main Reference System roughly in the middle. The target region is clearly visible in Fig. 3.11 between the nominal coordinates. To be on the safe side, we will limit the target region in between -65 cm and 65 cm.

On the plane perpendicular to the Z axis, the XY vertex distribution obtained with the same selection above is shown in Fig. 3.12, where a ring with a radius of ~ 3.6 cm is visible. If we divide this plot into slices of the azimuthal angle φ , we can study the evolution of the radius as a function of the angle. By plotting the cumulative distribution of the distances to the center as in Fig. 3.13, a peak is visible around the expected value. The example in the picture is for a particular bin in z and angle. The peak is fitted with a polynomial background and a gaussian, whose mean value is taken as estimator of the mixing chamber radius in that bin of z and angle. We can compute then the modulation of the radius as a function of the azimuthal angle. The general equation of a non centered circumference in polar coordinates is:

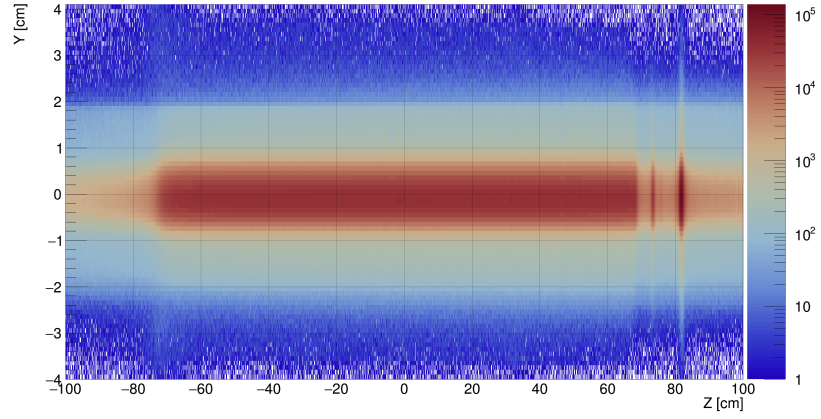
$$r^2 - 2rr_0 \cos(\varphi - \phi_0) + r_0^2 = \rho^2 \quad (3.3)$$

where $r = \sqrt{x^2 + y^2}$ and φ are the polar coordinates of a point $P(x = r\cos(\varphi), y = r\sin(\varphi))$, r_0 and ϕ_0 are the coordinates of the center of the circumference and ρ is the circumference radius as in Fig. 3.14.

The target was divided in 6 bins in Z with 5 bins in angle each. The results of the radius fit as a function of the angle are shown in Fig. 3.15 for one of the z bin. A clear modulation is visible, indicating that the mixing chamber is slightly off-centered; the small offset has to be determined from the fit parameters, as described above. From the extracted parameters we can, eventually, study the inclination of the target along the z axis and any variation of the radius.



(a) XZ



(b) YZ

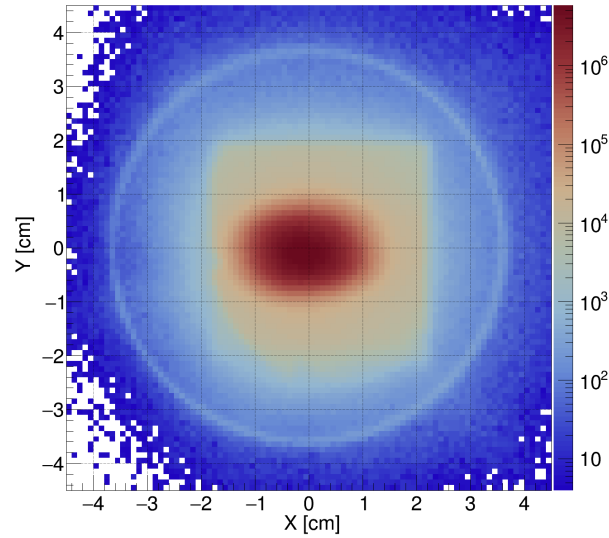
(c) XY (integrated over $Z \in [-65, 65]$ cm)

Figure 3.11: Tomography of the target cell with the primary vertices position in the different projections. The mixing chamber circumference is clearly visible in the X-Y coordinates plane with a radius of ~ 3.6 cm. Also the sub-structure of the 2×2 cm² fiber detector is visible. The endcaps of the target are visible at $Z = \pm 70$ cm. Reduced sample.

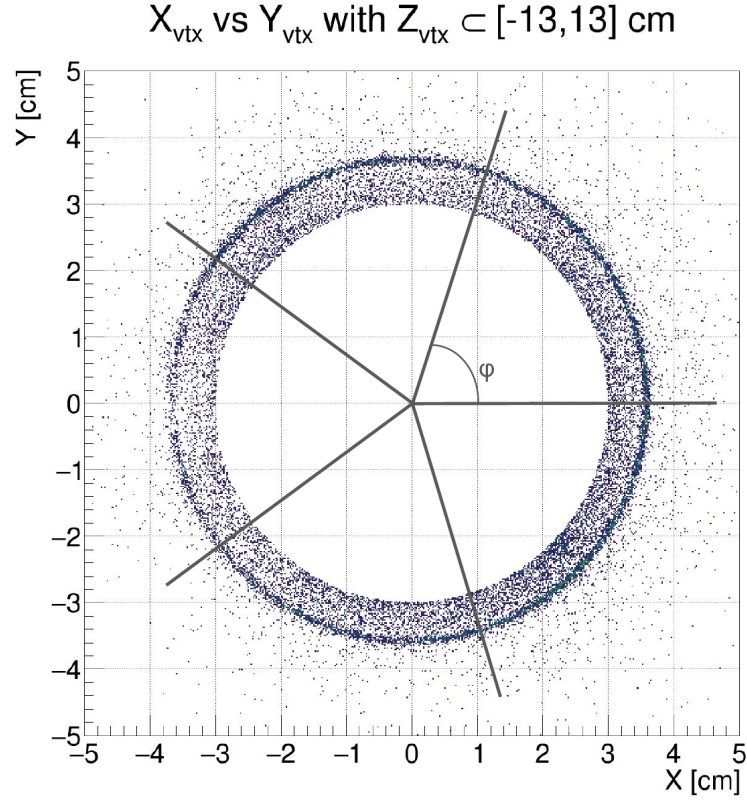


Figure 3.12: Vertex distribution in the XY plane in a particular Z bin. The missing hole in the middle is artificial, to save some processing time and has no impact on the extrapolation. The φ slices used for the radius modulation study are indicated with lines.

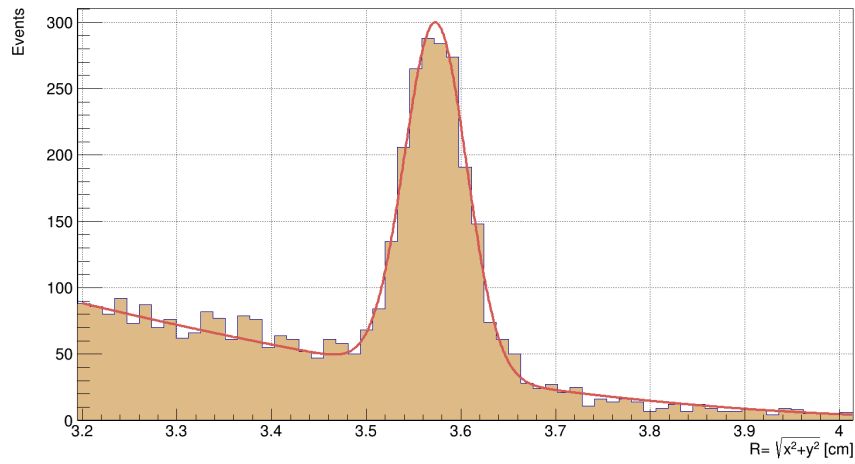


Figure 3.13: The larger interaction rate with the epoxy of the mixing chamber is visible in the radial distribution at ~ 3.6 cm. In this picture, the radial distribution of vertices in one bin of Z and azimuthal angle is shown.

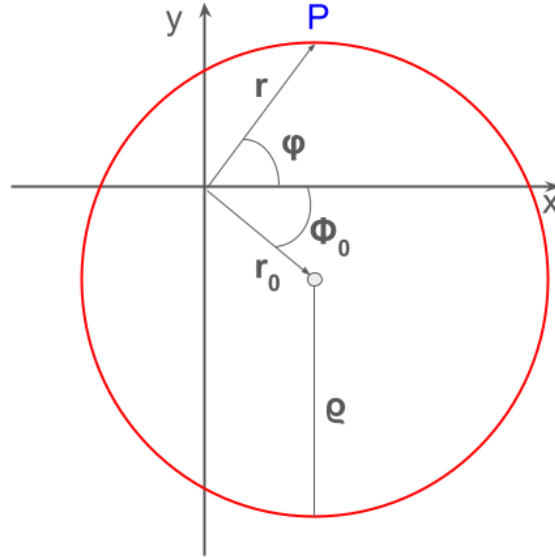


Figure 3.14: Circumference in polar coordinates.

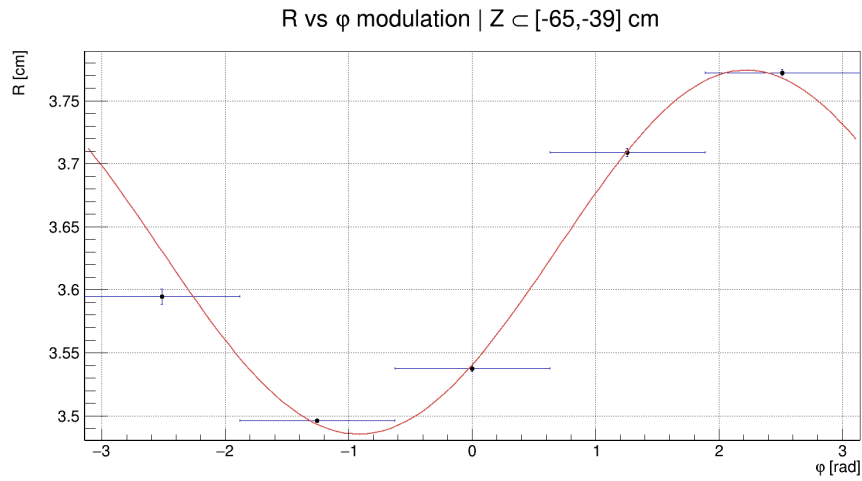


Figure 3.15: Modulation of target radius with the azimuthal angle in the first bin considered along Z. A clear modulation is visible, indicating an off-centered target.

The X and Y coordinates of the target center as a function of Z are shown in Fig. 3.16. In general we observe a tilt in X of less than 1 mm and in Y of about 1.2 mm over the 1.40 m target length. The value of the radius is quite stable, with minor dependence on z (< 0.5 mm).

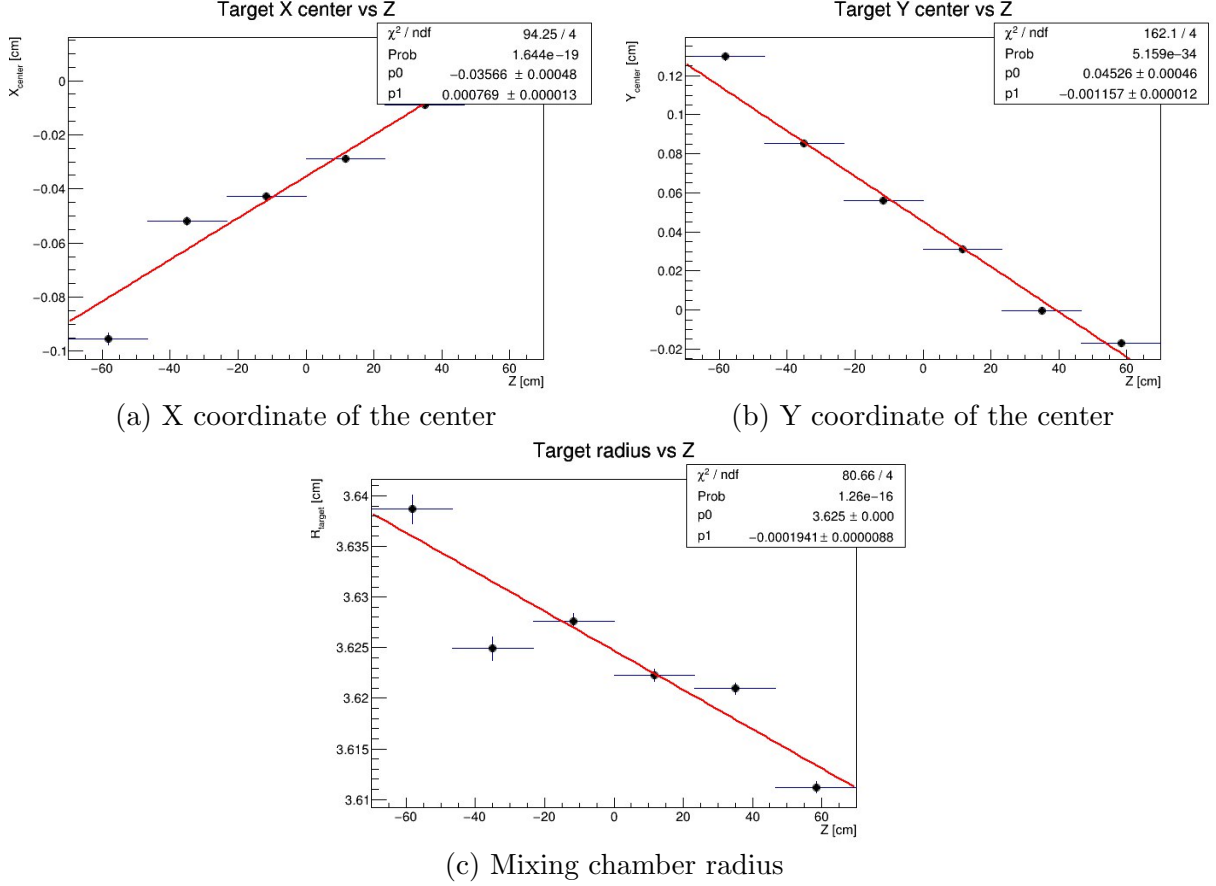


Figure 3.16: Coordinates of the target center along Z. The target is inclined roughly of ~ 1.2 mm along X and Y over a total length of 140 cm. The radius can be considered constant (< 0.3 mm fluctuation).

The final conditions to apply in order to select interactions with the liquid helium-4 inside the mixing chamber are then:

- $R_{vtx} < 3.4$ cm
- $Z_{vtx} \subset [-65, 65]$ cm

3.4 Luminosity estimate

We are interested in the antiproton production cross section. The cross section for any nuclear process can be linked to the rate of events for that process by a quantity called *luminosity* [151]. The luminosity measures the ability of a particle experiment to produce

a certain number of interactions. This quantity is de facto the proportionality term between the cross section σ and the rate of events observed:

$$\frac{dR}{dt} = \mathcal{L} \cdot \sigma \quad (3.4)$$

and it is thus measured in $cm^{-2}s^{-1}$. By integrating over time, i.e. summing up all the desired events recorded, we then deal with the integrated luminosity $\mathcal{L}_{int}$:

$$\begin{aligned} N_{events} &= \mathcal{L}_{int} \cdot \sigma \\ \mathcal{L}_{int} &= \int_0^T \mathcal{L}(t') dt' \end{aligned} \quad (3.5)$$

measured in cm^{-2} , expressing the number of collisions per unit area. This section is devoted to the extraction of the integrated luminosity, while the selection of antiproton events, in the formula above N_{events} , is addressed in Chapter 6.

The integrated luminosity can be calculated as the product of the target areal density ρ_T and the number of incident beam particles N_{beam} :

$$\begin{aligned} \mathcal{L}_{int} &= \rho_T \cdot N_{beam} \\ \rho_T &= \frac{\rho_{^4He} \cdot N_A \cdot l \cdot A_{^4He}}{M_{^4He}} \end{aligned} \quad (3.6)$$

where the subscript ^4He refers to liquid helium-4, $\rho_{^4He}$ is the density in g/cm^3 , N_A is the Avogadro number, l is the target length, M is the molar mass in g/mol and $A_{^4He}$ the number of nucleons (4). Most of the properties of the liquid helium-4 needed for the formula are summarized in Tab. 3.3. The usable target length was extracted from data

Quantity	Value	Units	Value	Units
Atomic number	2			
Atomic mass	4.002602(2)	$g \text{ mole}^{-1}$		
Specific gravity	0.1249	$g \text{ cm}^{-3}$		
Mean excitation energy	41.8	eV		
Minimum ionization	1.936	$MeV \text{ g}^{-1}cm^2$	0.2418	$MeV \text{ cm}^{-1}$
Nuclear collision length	51.8	$g \text{ cm}^{-2}$	415.1	cm
Nuclear interaction length	71.0	$g \text{ cm}^{-2}$	568.4	cm
Pion collision length	79.5	$g \text{ cm}^{-2}$	636.2	cm
Pion interaction length	103.6	$g \text{ cm}^{-2}$	829.5	cm
Radiation length	94.32	$g \text{ cm}^{-2}$	755.2	cm
Critical energy	208.25	MeV (for e-)	203.34	MeV (for e+)
Molière radius	9.60	$g \text{ cm}^{-2}$	76.90	cm
Plasma energy $\hbar\omega_p$	7.20	eV		
Muon critical energy	2020.	GeV		
Boiling point @ 1 atm	4.220	K	-268.9	C
Index of refraction (Na D)	1.024			

Table 3.3: Physical properties of the liquid helium-4. Values taken from [150]

in Sec. 3.3 and has the value of 130 cm, resulting in a value of $\rho_T = 9.772 \cdot 10^{24} \text{cm}^{-2}$.

In order to extract the number of beam particles we can use the random trigger (described in Sec. 2.5) to open a fixed time gate Δt_{RT} in which we can count the number of tracks. This method was developed by EMC experiment [152] and provides an unbiased evaluation of the flux. The resulting N_{beam} is eventually calculated from the flux $\Phi_{RT}(i)$ for the i-spill, expressed as a function of the number of tracks in the time window ($N_{RT,tracks}$), the number of random trigger attempts ($N_{RT,att}$) and the selected time in spill window Δ_{TIS} as:

$$\begin{aligned} N_{beam}(i) &= \Phi_{RT}(i) \cdot \Delta_{TIS} \\ \Phi_{RT}(i) &= \frac{N_{RT,tracks}(i)}{N_{RT,att}(i) \cdot \Delta t_{RT}} \end{aligned} \quad (3.7)$$

The time gate for the track reconstruction is set software-wise in the CORAL option file equal to $[-5,5]$ ns. In general, the time of a reconstructed track is given by a weighted average of the associated hits time, with a weight based on the resolution of the detectors crossed by the track. For a beam track, the time is mainly given by the hits on the SciFis of the beam telescope, due to the higher time resolution with respect to the Silicons. For random trigger events, the expected beam track time distribution is rather flat, whether the physics trigger events should have a peak around 0. This is because the physics trigger in this data set is basically a beam trigger: just after a beam track leaves hits in the beam telescope we have also the fired trigger (if no VETOs fired). In principle, the time of the hits is calculated with respect to the first trigger arrived, so-called *Master Trigger*. For the luminosity estimate we ask for the random trigger to be the master trigger. However, it was found that whenever a physics trigger (PT) is overlapped with random triggers (RT), the time of tracks is calculated with respect to the physics one, even if arrived later. This behavior was not seen in previous COMPASS studies [153] where the percentage of master random triggers overlapping with physics trigger was less than 1%. Nevertheless, in our data set the triggers follow roughly this composition:

Trigger	Percentage [%]
All	100
RT master	11.75
PT master	88.25
RT master and PT	0.049
RT and PT master	0.048
RT inclusive	11.79
PT inclusive	88.30
PT and RT	0.097
RT exclusive	11.70
PT exclusive	88.20

Table 3.4: Trigger mixture for data taking period W01 in 2023.

The random master trigger events, needed for the luminosity, are roughly the 11% of the total sample. By checking the beam reconstruction in those events, only 14% have a beam track reconstructed and half of these do have a physics trigger. This means that the

overlapping of a master random trigger with a beam track reconstructed and a physics trigger is of the order of 50%: definitely a more important effect with respect to the past studies. The tracks time distributions with the various combination of triggers are visible in Fig. 3.17. It is not yet clear whether the problem may be mitigated at software level

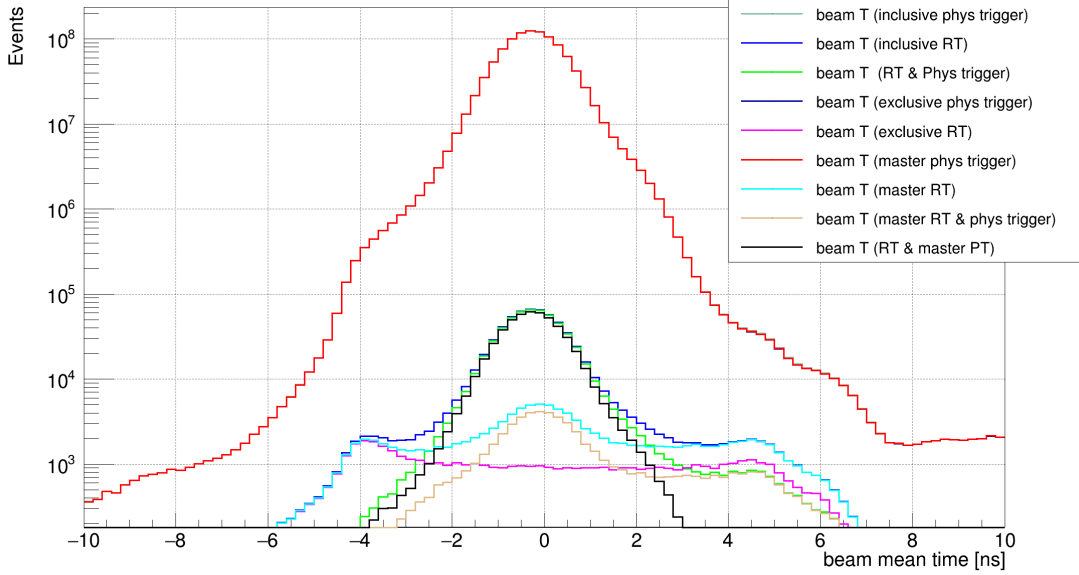


Figure 3.17: Beam track times with different requirement of trigger condition. The exclusive random trigger distribution (violet) is the one used for the luminosity estimate. The other distributions are biased by the physics trigger timing.

or not and it is an open issue for this analysis. I tried to implement different solutions by playing with the trigger setting precision and by isolating the problematic events and calculating the time of tracks with respect to the TDC information of the first trigger. However, this task was not finalized before the completion of this thesis. A work-around for the luminosity estimate is to select exclusive random trigger events with reconstructed beam track. This will bias the final estimation and will not be possible to compute the final cross section in an accurate way, but will give the order of magnitude of the integrated luminosity.

Given these constraints, for the flux estimation only reconstructed beam proton tracks crossing the whole target length in exclusive random trigger events are selected. This is ensured by using the following cuts:

- good runs and spills selection as in Sec. 3.2.2;
- time in spill window between [1.2,5.4] s (as in the final event selection);
- exclusive random trigger;
- beam time between [-3,3] ns. The time distribution is visible in Fig. 3.18;
- number of hits in beam telescope $N_{hits,FI} \geq 4$ and $N_{hits,SI} \geq 10$ (as in the final events selection);

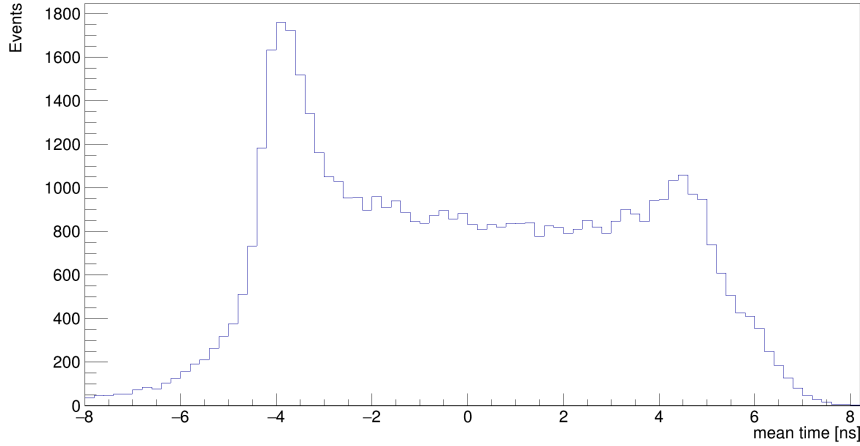


Figure 3.18: Beam tracks time distribution selected with random trigger as exclusive trigger. The time interval for beam selection is between $[-3, 3]$ ns to avoid edge effects.

- proton tagging with CEDARs as defined in Sec. 4.1 ($CE_{1,mult} \geq 6$ and $CE_{2,mult} \geq 6$);
- beam track extrapolated through the whole target. This is done to ensure the full target crossing. The beam profile upstream and downstream the target is visible in Fig. 3.19;

The flux estimated with this method is not influenced like the physics trigger by the VETO system life time. For this reason, we have to correct for the VETO lifetime to make it coherent with the selection of physics events. While the correction for the DAQ dead time is not needed because the random trigger and the physics trigger are affected by it in the same way.

The integrated luminosity estimate, with the exclusive random trigger events, is of the order $\sim 10 \text{ nb}^{-1}$ (with expected statistical error of $\sim 6 \%$), as visible in Fig. 3.21.

3.5 Lifetime correction

The DAQ and trigger system can only accept a limited amount of triggers per second due to hardware and software limitation. This leads to the concept of *dead time* (DT) which expresses the relative amount of time in which the DAQ is busy and valid events can not be recorded. The complementary of the dead time is the *life time* (LT). These quantities are not simulated in the MC and must be estimated to account for the fraction of events lost. Two kinds of lifetime have to be measured: the DAQ LT and VETO LT. The physics trigger logic has, indeed, the VETO system in the mix and it is influenced by both DTs, for which we have to apply a correction. During data taking several scalers continuously read the triggers attempted and accepted; they will be used for the estimation of these correction factors.

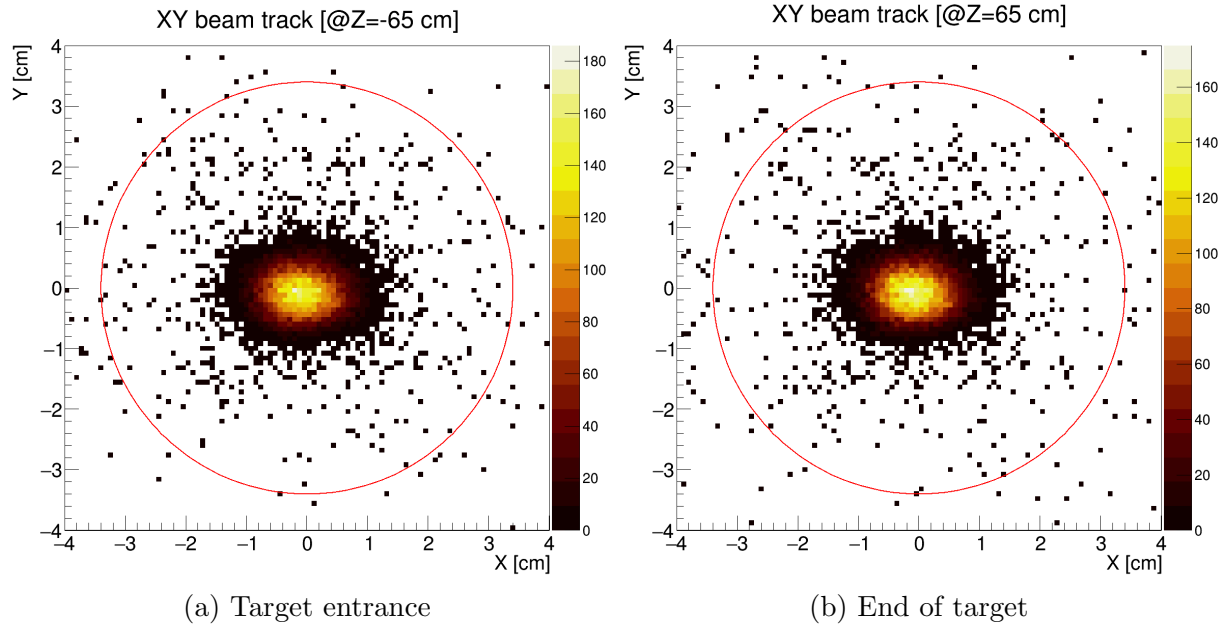


Figure 3.19: Profile distribution of the beam tracks at the target entrance and exit before cut on the target radius.

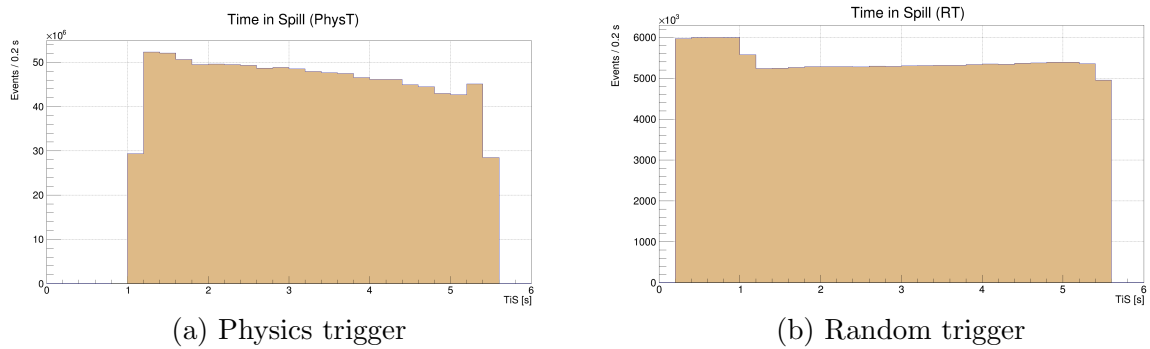


Figure 3.20: Event time in spill distribution from physics and random triggers. The start of the spill is visible at ~ 1.2 s in the physics trigger distribution, while the random trigger populates from 0 to the end of the spill time.

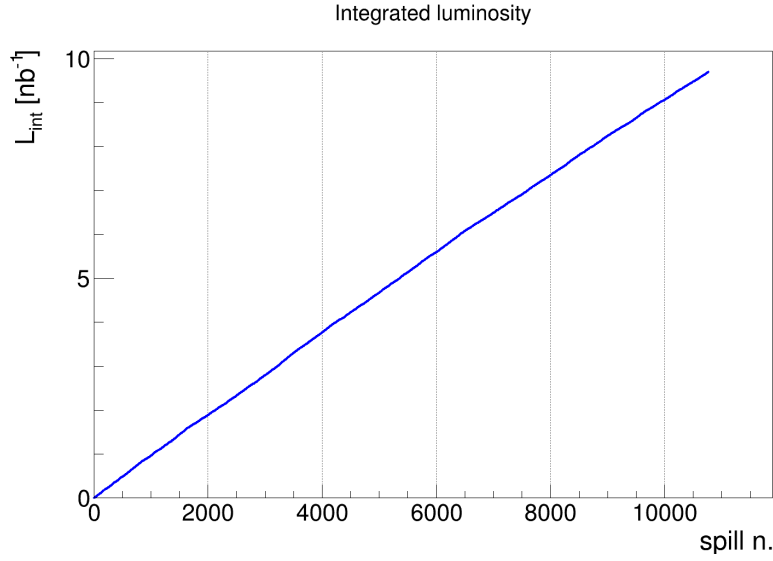


Figure 3.21: Integrated luminosity as a function of spills number in data taking period W01. The selection is based on exclusive random trigger events.

3.5.1 DAQ

A schematic view of the trigger propagation is visible in Fig. 3.22. When the system

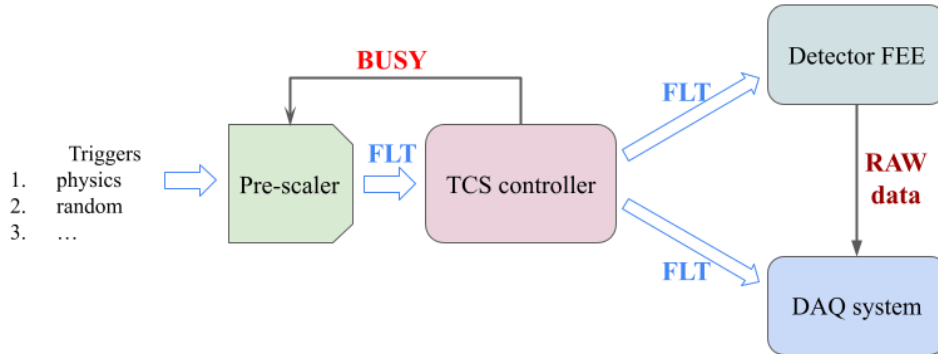


Figure 3.22: Simplified DAQ block scheme.

receives a First Level Trigger (FLT), the signal is propagated to the front end electronics and eventually to the DAQ system. During this operation, the Trigger Control System (TCS) sends a BUSY signal to the trigger pre-scaler that prevents other FLT to be sent to the TCS. It is the BUSY signal which essentially causes the dead time which can be estimated using the scalers information of the number of FLT attempted and accepted. In principle the DT does not depend on the type of trigger. We can then use the attempted FLT and random trigger (RT) to obtain two independent estimates, which will be useful for the study of the systematic error of the life time correction.

The scaler used in 2023 is called HMSC1. The relevant quantities are obtained in the following way:

- ch. 13 $\rightarrow$ FLT attempted, N_{att}^{FLT} ;

- ch. 2 $\rightarrow$ RT attempted, N_{att}^{RT} ;
- from data file $\rightarrow$ FLT accepted, N_{acc}^{FLT} ;
- from data file $\rightarrow$ RT accepted, N_{acc}^{RT} ;

The DAQ dead time is defined as:

$$DT_{DAQ}^{RT} = \frac{N_{acc}^{RT}}{N_{att}^{RT}} \quad (3.8)$$

$$DT_{DAQ}^{FLT} = \frac{N_{acc}^{FLT}}{N_{att}^{FLT}}$$

and the life time as

$$LT_{DAQ} = 1 - DT_{DAQ} \quad (3.9)$$

The life time is computed spill by spill on a data sample of events selected with:

- good run and spills selection as in Sec. 3.2.2;
- time in spill window between $[t_1 = 1.2, t_2 = 5.4]$ s (as in the final event selection);

The scaler readings are reset at every spill, so that the effective counts within the time in spill window used for the i -channel are simply defined by:

$$N_{ch<i>} = HMSC1_{ch<i>}(t_2) - HMSC1_{ch<i>}(t_1) \quad (3.10)$$

The final trend as a function of the spill number is visible in Fig. 3.23. In the plot, the two different estimates with random trigger and first level trigger are shown. The lifetime

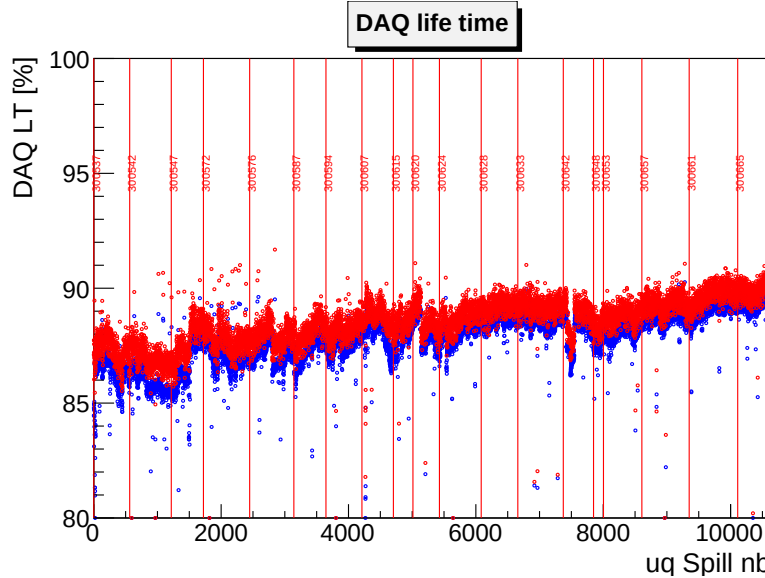


Figure 3.23: DAQ lifetime estimated with RT (red) and FLT (blue) methods. Some of the run numbers are reported for reference next to the red lines.

increases with the spill number because the beam intensity was not perfectly constant.

The primary proton beam intensity on T6 target was slightly decreasing with time and consequently the physics trigger rate as well. The correction will be thus applied on a spill by spill level. The difference in the estimates is computed spill by spill and plotted in Fig. 3.24. Overall the systematics associated to this estimation is less than 1%.

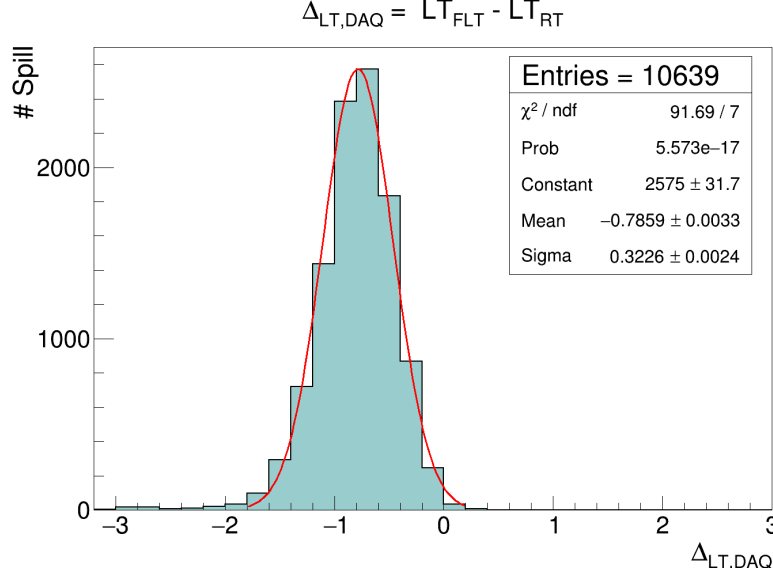


Figure 3.24: Difference between the DAQ lifetime estimated with random trigger and first level trigger. Distribution fitted with a gaussian.

3.5.2 VETO

Random coincidences between the physics trigger and the veto system induce dead time in the trigger system. A method developed to estimate the VETO life time is described in [154]. The basic idea is to measure the occurrences of the random coincidences by delaying the VETO signal before the anti-coincidence with the physics trigger. The VETO is thus split before any logical operation: one line will be used for the final trigger decision, while the other will be delayed. In this way we can set up one channel of the scaler to count the number of occurrences of the delayed veto with physics trigger and another channel to count the physics trigger standalone.

- ch. 15 $\rightarrow$ phys trigger ($BT+!BK+!VETO_{del}$) accepted with delayed VETO, $N_{VETO,del}^{phys}$;
- ch. 27 $\rightarrow$ phys trigger ($BT+!BK$) attempted, N_{att}^{phys} ;

The VETO lifetime is then defined as $N_{VETO,del}^{phys}/N_{att}^{phys}$. The dependence of the lifetime with the spill number is visible in Fig. 3.25. The values is overall stable at 99.5%.

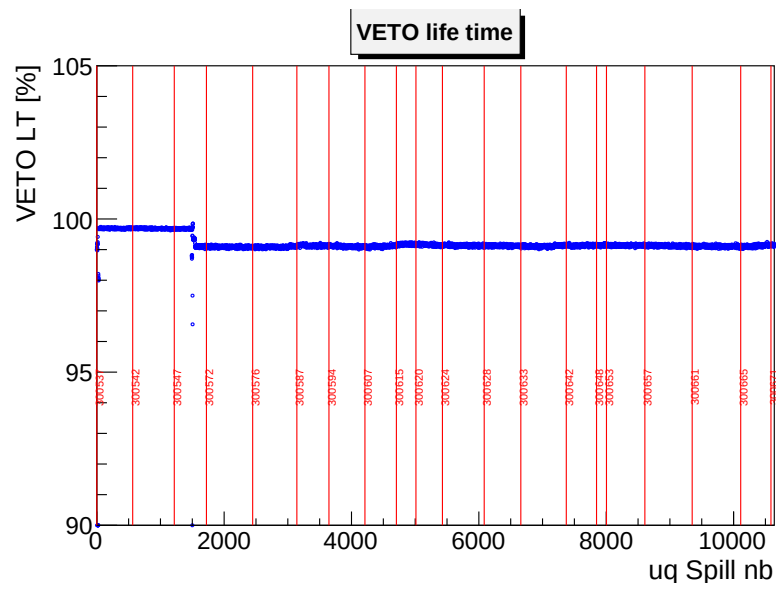


Figure 3.25: VETO lifetime estimated with physics trigger. Some of the run numbers are reported for reference next to the red lines. During the first ~ 1800 spills the VETO trigger had bad timing, resulting in a lower efficiency.

Chapter 4

Study of the PID of CEDARs and RICH-1

In general, particles are identified by their mass and electrical charge. The mass cannot be measured directly and 2 other quantities must be measured: momentum, kinetic energy and/or velocity. By exploiting the basic relation:

$$m = \frac{p}{c\beta\gamma} \quad (4.1)$$

it is possible to fully identify the particle (β is the ratio v/c and $\gamma = E/mc^2$). Curvature in a static magnetic field leads to the charge sign and the momentum value, while the β factor could be given by several methods: ionization energy loss, time of flight, Cherenkov radiation and transition radiation. The resolution on mass can be calculated by propagating the errors in eq. 4.1:

$$\left(\frac{dm}{m}\right)^2 = \left(\gamma^2 \frac{d\beta}{\beta}\right)^2 + \left(\frac{dp}{p}\right)^2 \quad (4.2)$$

To estimate the mass precisely we need a very good determination of momentum and velocity. If we assume that the determination of the momentum is precise enough, the mass resolution is led by the accuracy in the determination of the velocity. The differences between the masses of two particles m_1 and m_2 and same momentum p can be expressed as:

$$m_1^2 - m_2^2 = p^2 \frac{\Delta\beta (\beta_1 + \beta_2)}{c^2 (\beta_1 \cdot \beta_2)^2} \quad (4.3)$$

where $\Delta\beta = |\beta_1 - \beta_2|$. Assuming $\beta_1, \beta_2 \sim \beta$:

$$\frac{\Delta\beta}{\beta} = \frac{(m_1^2 - m_2^2) \cdot c^2}{2p^2} \quad (4.4)$$

indicating that the beta resolution becomes important at higher momenta. In AMBER, a beta resolution of the order of 10^{-5} is required for identifying particles in the spectrometer up to 60 GeV/c and of the order of $\sim 10^{-6}$ for beam particles. In our setup, the β factors of beam tracks and spectrometer tracks are measured respectively by the CEDARs and RICH-1 detector via Cherenkov light. Their PID efficiency is studied and discussed in this chapter.

4.1 CEDAR tagging efficiency

The identification of the beam particle is performed by using the CEDAR detectors installed upstream the target. In 2023 we set the pressures of both the two CEDARs in such a way to positively tag the protons in the beam (a description of the procedure is in Sec. 2.1.1). At 190 GeV/c, the protons signal is very well separated from pion and kaons and we can obtain an almost pure sample of protons. The efficiency of the tagging is evaluated for each CEDAR by looking at the PMTs many-fold multiplicity and using the other CEDAR to select the proton with the highest purity possible (8-fold). In order to follow the same beam track selection as in the final events selection (details in Sec. 6.1), the performance plots for CEDAR were created with the following requirements:

1. time in spill in selected window
2. beam tracks exists and is well reconstructed (cut on the minimum number of hits in the beam telescope)
3. vertex exists
4. the extrapolated beam track passes through the entire target

The result of this study is shown in Fig. 4.1. The many-fold tagging is very efficient for CEDAR2 where even with the 8-fold we can obtain an efficiency of 94%. Possibly due to intrinsic inefficiencies of the PMTs or misalignment issues, CEDAR1 was less efficient. However, up to 7-fold the efficiency of CEDAR1 is above 95% and can be perfectly used in this framework.

The combined efficiency of the system CEDAR1+CEDAR2 is plotted in Fig. 4.2, on the left. In this figure the many-fold occurrences are also shown, on the right plot. It is clearly visible that the proton tagging is efficient with 7-8 fold in CE2 and 6-8 in CE1, while the $\sim 21\%$ multiplicity at 0 fold in CE1 and CE2 is due to the positive hadron beam composition at 190 GeV/c, which is made of $\sim 75\%$ protons and remaining 25% of pions and a small fraction of kaons.

For the final event selection, in order to save both statistic and purity of the protons sample, we require:

- CE1 many-fold ≥ 6
- CE2 many-fold ≥ 6

with a tagging efficiency of 96%. The systematic associated to this cut will be described in the final chapter. In this work a dedicated study of the sample purity is not included. For this kind of study special data collected at the end of the Run, with one CEDAR set on pion/kaon pressure-peak, the other on proton, have to be used.

4.2 RICH-1 characterization and PID efficiency

A detailed description of the detector is given in Sec. 2.4. Some of the basic definitions that will be used in this work, like efficiency, contamination and purity, are intrinsic

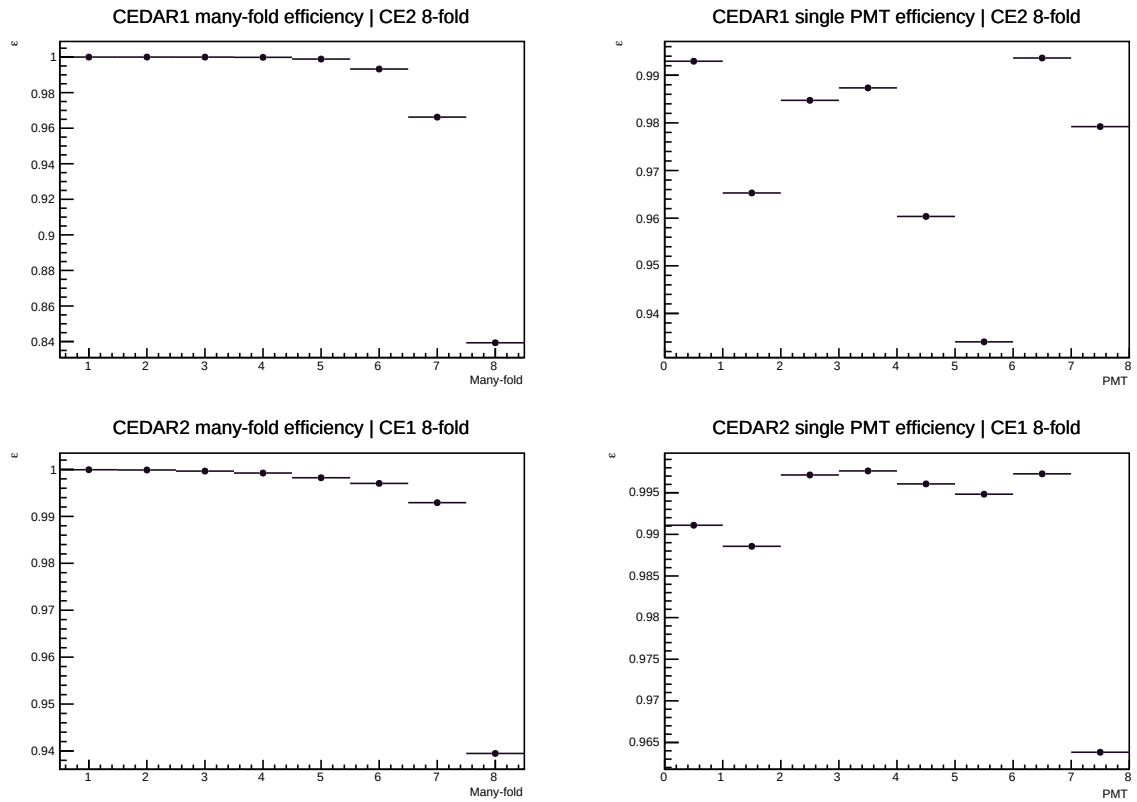


Figure 4.1: CEDARs many fold efficiency and single PMT efficiency obtained by requiring a 8-fold signal multiplicity on the other CEDAR.

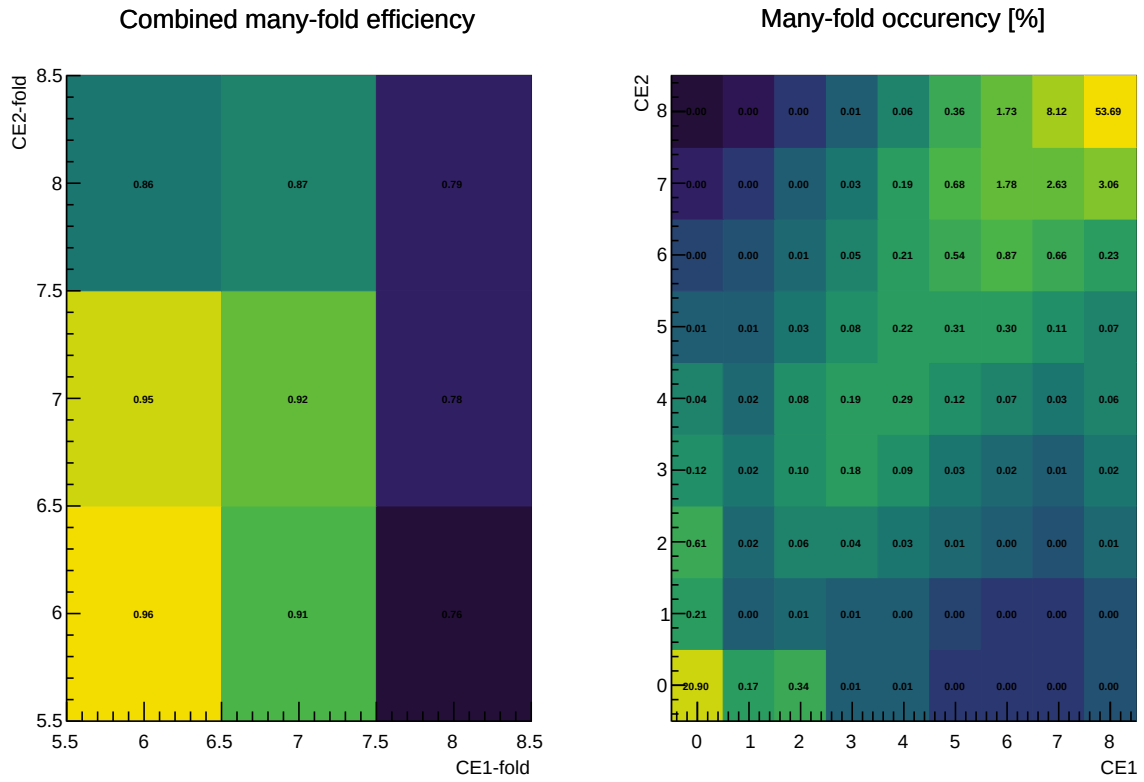


Figure 4.2: On the left: (CEDAR1+CEDAR2) combined many-fold efficiency; on the right: many-fold occurrences in percentage from 1 to 100 %.

characteristics of any PID device. A wrong identification will fail in identifying the particle A (*inefficiency*) or will classify the particle B as A (*contamination*). The efficiency in the identification of a particle of type A is given by the ratio of the number of particles recognized as type A ($N_{A,identified}$), divided by the total number of particles of type A ($N_{A,total}$).

$$\varepsilon_{A \rightarrow A} = \frac{N_{A,identified}}{N_{A,total}} \quad (4.5)$$

while contamination is given by the ratio of the number of wrongly identified particles, to the total number of particles.

$$\varepsilon_{B \rightarrow A} = \sum_{B, B \neq A} \frac{N_{A,identified}^B}{N_{A,total}} \quad (4.6)$$

The characterization of the RICH-1 is thus a crucial step in the determination of the antiproton production cross section because it is the main and only detector used for the PID of the final state hadrons. An overview needed for understanding the RICH detection principles and the Cherenkov radiation features can be found in appendix A, to which many of the formula and assumption will refer.

The characterization of the AMBER RICH-1 consists in two main steps:

1. refractive index and background map extraction
2. efficiency estimation

where the refractive index is extracted from data itself and is needed for the second step.

4.2.1 Refractive index extraction

The refractive index, combined with the momentum measurement, is connected with the Cherenkov angle measurement and used to deduce the particle's mass for PID. Alternatively, by assuming the mass of the particle emitting the photons, we can estimate the refractive index of the radiator from each individual photon. The refractive index at a specific temperature and pressure, within a particular wavelength range, is expected to remain relatively constant from event to event. It's important to note, however, that the refractive index of the radiator is influenced by temperature and pressure, following the Lorentz-Lorenz equation:

$$\frac{n^2 - 1}{n^2 + 2} \propto \frac{p(\text{atm})}{T(\text{K})} \quad (4.7)$$

Given the fluctuation of temperature across the various days and nights of data taking, its value must be determined from data day by day. The monitoring and the extraction of the refractive index are based on the assumption that in the RICH-1 vessel there are no temperature or pressure gradients. These quantities are constantly monitored but they are assumed to be constant inside the vessel.

RICH-1 requires two different refractive indices for gaseous detectors (UV wavelength) and for the MAPMTs (visible wavelength VS). The dependence on the wavelength is shown in Fig. 4.3. The ring χ^2 is computed with ring angles translated into UV standard

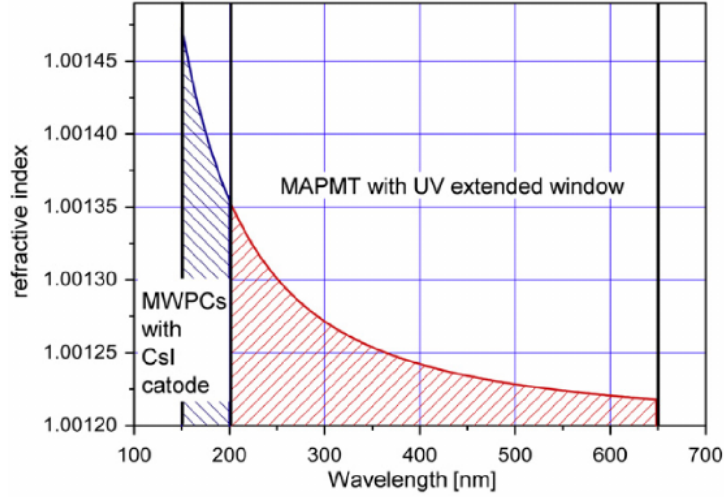


Figure 4.3: Measured C_4F_{10} refractive index versus light wavelength. Figure taken from [155].

and the further likelihood functions computation take into account the local refractive index. The average refractive index is a convolution of several effects and can be inferred from large statistic. The usual way to express its value is in *part per million* (ppm) units as $n - 1$:

$$(n - 1) = \frac{\sqrt{p^2 + m^2}}{\cos \theta_{CH} \cdot p} - 1 \quad (4.8)$$

Knowing the momentum and the Cherenkov angle, the UV index can be thus extracted from MAPMTs photons data assuming a mass hypothesis. In the recent COMPASS history, due to different triggers and setup condition, the events were pion dominated in momentum range of 40-100 GeV/c and this interval was usually chosen for the $n - 1$ extraction with pion mass hypothesis. The momentum range is chosen in order to have Cherenkov angle saturated for a certain species. In fact, as long as we work in a region where the slope $d\theta_{ch}/dp$ is flat or very small, the extraction of the refractive index is almost independent from the momentum determination uncertainties. On the contrary, if we were working in high slope region, any small uncertainty on the momentum will result in a spoiled value of the refractive index. If we take the 40-100 GeV/c interval, where pion Cherenkov angle is saturated at ~ 50 mrad, and apply the above equation to one run of the 2023 data set using pion mass hypothesis we obtain the plot in Fig. 4.4, where the peak is fitted with a gaussian and a first order polynomial. The gaussian width is around 103 ppm, only slightly larger compared with previous years values below < 100 ppm. The major change with respect to previous extraction concerns the mean value of 1211 ppm. Typically the RICH-1 visible (VS) refractive index has values fluctuating between 1245-1280 ppm [156]. This discrepancy suggests a problem either on alignment, or in the tracks sample. In the first case, possibly due to a bad momentum reconstruction, the refractive index calculated with Eq. (4.8) is spoiled. In the second case, if we have contamination in the sample, from other non-saturated particles, the estimation is biased. The calculation of the refractive index depends, indeed, on a mass assumption and we

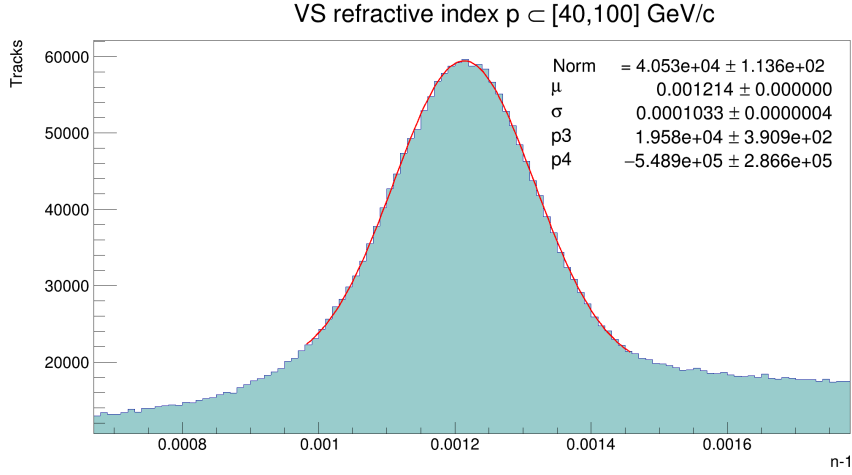


Figure 4.4: Refractive index ($n-1$) extracted from photons collected in MAPMT associated to tracks with pion mass hypothesis and momentum range in $[40,100]$ GeV/ c . Fit function is a gaussian plus a first order polynomial. The first 3 parameters refer to the gaussian normalization, mean and width.

assumed pion mass in the mass hypothesis. We can check the sample properties with a ROOT-tree produced by the RICHONE software package with dedicated options in CORAL. In this tree one can access the single photons information. We can look at the θ_{CH} of the single photons as a function of the momentum of the associated track, as in Fig. 4.5a. In the momentum range considered (40-100 GeV/ c) we notice indeed a large number of non saturated photons in the proton band. These proton-like tracks, under pion mass hypothesis, will bias the $n - 1$ population, making it broader and with a smaller mean value. Varying the range we observe a sensible shift in the mean value and width, as shown in Fig. 4.5b. Therefore, it was decided to shift the momentum range to higher values and use a proton mass hypothesis, given the proton enriched sample. The final range used is between 110-160 GeV/ c , in order to reach a good compromise between the loss of statistics and the required characteristics of the sample. One way to check the quality of the refractive index extraction is by plotting the squared mass of tracks computed using Eq. (A.7) as a function of the momentum. Ideally the computed mass should follow a straight line with a spread along the mass axis following a quadratic dispersion as in Eq. (A.8). The result obtained for tracks coming from a primary vertex inside the target is shown in Fig. 4.6. In Fig. 4.6a where the refractive index was not properly tuned, a bending effect with increasing momentum is clearly visible. While in Fig. 4.6b, the straight lines indicate a proper tuning.

The refractive index is computed at CORAL level. For the purpose of these operations and in order to optimize the momentum range, new dedicated options were created to be used in the CORAL reconstruction scheme:

- momentum range for MAPMT $n-1$ extraction (default: 40-100 GeV/ c):
RICHONE `n-1LimitsPbar [ 0 - 1 ] 110. 160.;`
- mass hypothesis for $n-1$ extraction (default: pion mass):
RICHONE `n-1MassPbar 0.93827;`

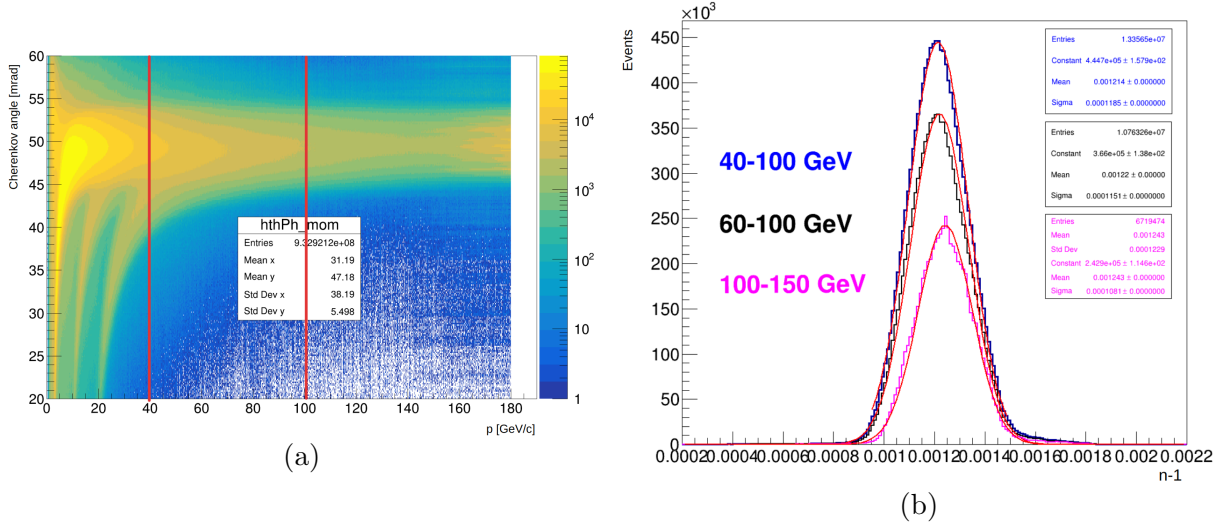


Figure 4.5: In picture (a): Cherenkov angle of single photons associated to a track versus momentum of the track. The momentum range between 40 and 100 GeV/c selects also a considerable amount of protons that do not have angle saturation. In (b): different momentum range choices show an important shift in the extracted values.

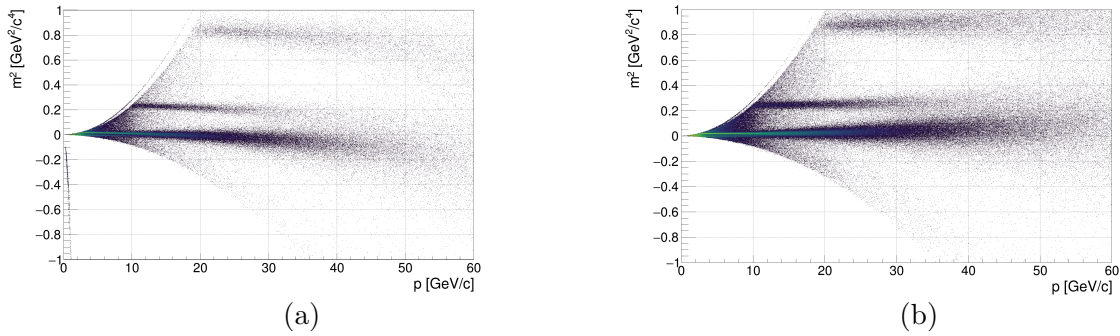


Figure 4.6: Mass squared of particles calculated from the Cherenkov angle as a function of momentum. Before (a) and after (b) the optimization of the momentum range for the refractive index extraction. Three population are visible, corresponding to pion, kaons and protons. With the refractive index extracted at 40-100 GeV/c the tracks have a bias towards smaller masses due to an underestimate of the refractive index (left). When using 110-160 GeV/c for the extraction and a proton mass hypothesis, the mass plots shows straight tracks (right), indicating a better estimate.

- overwrite db entries for refIndex (default: no):
`RICHONE overWriteDBindex;`

The final refractive index value and single photon resolution as a function of the run number for the data taking period W01 are shown in Fig. 4.7.

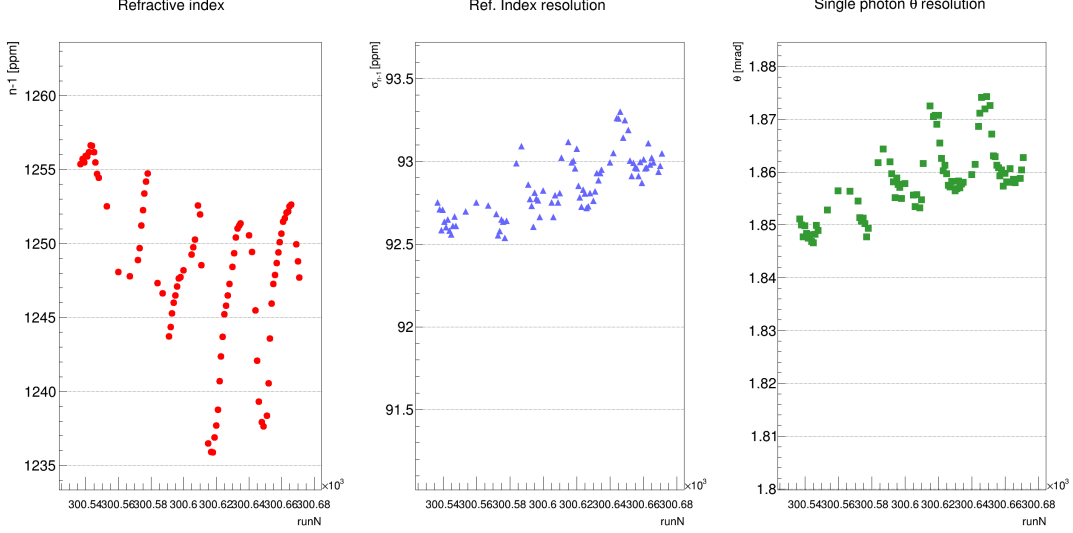


Figure 4.7: Refractive index, resolution and single photon resolution dependence with the run number. The oscillations are caused by the temperature and pressure gradients between day and night.

Alongside with the refractive index, also a so-called *background map* of the RICH is extracted from data. This map will be used later to construct the likelihood formalism. The background is parameterized from the cluster distribution on the photon detectors surface and represents the average number of photons per event on a certain pixel, taken from all triggers type, to describe correlated and uncorrelated background. The average occupancy is normalized on the number of events and provides an average indication on how likely that pixel is going to fire. This procedure was studied when COMPASS had higher trigger rates with respect to this data taking, without the possibility to study the background on an event by event basis. This is one of the topics to be addressed to improve this measurement result. The background map extracted from period W01 is visible in Fig. 4.8.

4.2.2 PID method

The PID relies on an extended maximum likelihood (EML) method, the details of which are described in appendix B. The likelihood functions $\mathcal{L}_M$ for each mass hypothesis M

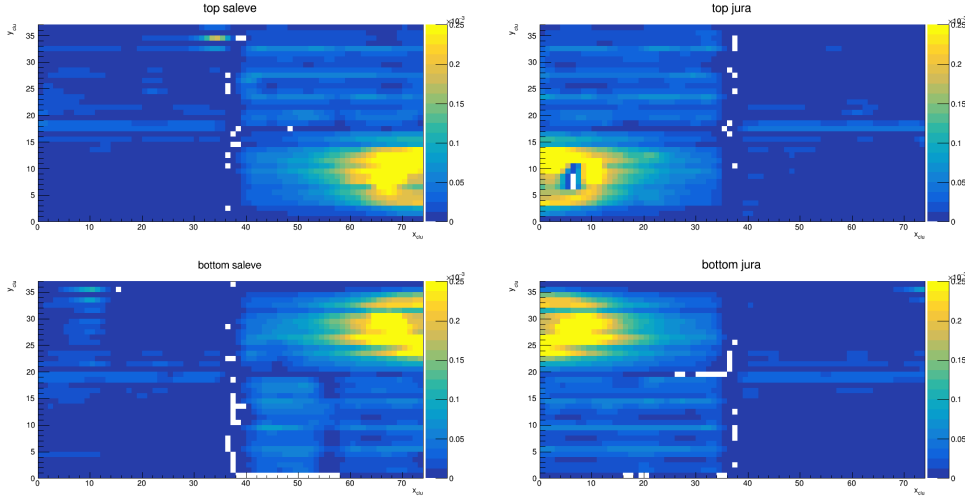


Figure 4.8: Background map for data taking period W01. The map shows the cluster distribution normalized on the number of events, in the different photon detector zones. Jura and Saleve indicate respectively the positive and negative direction of the X axis in the Main Reference System.

depend on a signal s_M and a background term b :

$$\begin{aligned} \mathcal{L}_M &= \exp[-(S_M + B)] \prod_{j=1}^N f_M(\theta_j, \varphi_j) \\ f_M(\theta, \varphi) &= s_M(\theta, \varphi) + b(\theta, \varphi) \\ s_M(\theta_j, \varphi_j) &= \frac{S_0}{\sigma_{\theta j} \sqrt{2\pi}} \exp\left[-\frac{1}{2} \frac{(\theta_j - \Theta_M)^2}{\sigma_{\theta j}^2}\right] \varepsilon_D(\theta_j, \varphi_j) \end{aligned} \quad (4.9)$$

where the signal density term $s_M(\theta, \varphi)$ is described by a gaussian distribution in the $\theta - \varphi$ plane with single photon resolution $\sigma_{\theta, j}$; S_0 is the expected number of photons according to Eq. (A.9); Θ_M is the expected Cherenkov angle for a particle of mass M and momentum p and the index j runs over all the photons associated to the track. The background $b(\theta, \varphi)$ is obtained from the background map already discussed and it is a common term for each mass hypothesis. The $\mathcal{L}_M$ are then computed for the various mass hypothesis (e , μ , π , K , p) plus the background (that has the characteristic of having $s_M = 0$). Each photons has also a certain probability $\varepsilon_D(\theta_j, \varphi_j)$ to reach the detector that takes into account the possibility to be absorbed in the medium or lost in the holes between mirror elements. This function was modified in particular for this data because it was accounting for the presence of the beam pipe that was removed prior data taking. The capital letters terms S_M and B are the integral over θ and φ of the lowercase letters terms:

$$\begin{aligned} S_m &= \int s_m(\theta, \varphi) d\theta d\varphi \\ B &= \int b(\theta, \varphi) d\theta d\varphi \end{aligned} \quad (4.10)$$

integrated over a fiducial region of 70 mrad, larger than the maximum Cherenkov angle detectable by the photons detectors.

After the normalization phase, to a first approximation one could take the largest likelihood to be the candidate of the good hypothesis. But to overcome the case in which many hypotheses are similar, the likelihoods ratio is taken in to account. If these ratio is above a defined value, the identification is positive. Each particle type has a momentum threshold for producing Cherenkov light, according to Eq. (A.2). In the RICH-1 with C_4F_{10} radiator the thresholds are about:

- π 2.5 GeV/ c
- K 9 GeV/ c
- p 18 GeV/ c

The protons emit Cherenkov light only above 18 GeV/ c , constraining the phase space covered with active identification above that threshold. There is a region in momentum, however, in which pions and kaons do emit Cherenkov photons, while protons do not. This region is in between the kaon and proton threshold. There, we can use the RICH in so-called "VETO mode" exploiting the high efficiency in pion and kaon identification at those momenta. Two scenarios are possible: a proton may pass without leaving any light and all the likelihoods will be 0, or some photons may be detected and the likelihoods are computed. The phase space for PID is thus divided in two (plus one) regions:

- $p \in [p_{thr,K}, p_{thr,p}]$ GeV/ c . Below proton momentum threshold. Active identification for K and π . VETO mode for p
- $p \in [p_{thr,p} - \delta, p_{thr,p} + \delta]$ GeV/ c . Overlapping zone. Active identification for π and K . The proton candidates must satisfy the likelihood ratio selection criteria required for both below and above proton momentum threshold.
- $p \in [p_{thr,p}, 60]$ GeV/ c . Above proton momentum threshold. Active identification for all particles.

The intermediate region is added to ensure continuity between the above and below proton thresholds regions. It is possible to perform proton identification under momentum threshold by requiring that all the likelihoods are 0 (no photons are detected and the likelihoods are not computed) or that the particle is not identified as a pion nor as a kaon, with their hypotheses tested versus the background using the ratios $LH(\pi)/LH(bkg)$ and $LH(K)/LH(bkg)$.

The minimum momentum used in this analysis lies just above the kaon threshold at 10 GeV/ c . The electron hypothesis is usually not taken into account above 10 GeV because the electrons Cherenkov angle saturates after a few GeV and becomes undistinguishable from π and μ . Therefore, the likelihood of electrons is not used in this analysis.

Likelihood tuning

For the cross section computation we need to know the true number of the hadrons detected. The goal of the likelihood tuning for this analysis is not to maximize the purity or the efficiency for a particular hadron species, but rather to estimate as best as possible

	$\pi^{+/-}$	$K^{+/-}$	$p(\bar{p})$	
Momentum range	$p > p_{\pi,thr}$	$p > p_{K,thr}$	$p_{K,thr} < p < p_{p,thr}$	$p > p_{p,thr}$
LH(i)/LH(π)	-	> 1.06	-	> 1.06
LH(i)/LH(K)	> 1.06	-	-	> 1.06
LH(i)/LH(P)	> 1.06	> 1.06	-	-
LH(i)/LH(Bkg)	> 1.25	> 1.25	-	> 1.25
	-	-	not π or K	-
LH(π)/LH(Bkg)	-	-	< 2.5	-
LH(K)/LH(Bkg)	-	-	< 2.5	-

Table 4.1: Starting values for LH ratios cuts.

each probability of identification or misidentification. This is a crucial correction factor to obtain the final hadron multiplicity number which will enter in the cross-section formula.

With the RICH-1 correctly tuned for what concerns the refractive index and the background parametrization, we can look into the likelihood distributions for different samples of π , K and protons. These populations can be selected by kinematic cuts on momentum and expected Cherenkov angle. For a certain mass m , the expected angle θ_C is computed as:

$$\cos \theta_C = \frac{\sqrt{p^2 + m^2}}{n \cdot p} \quad (4.11)$$

By selecting an interval of $\theta_C \pm 0.0004$ rad (that is about 3 times the resolution on the fitted Cherenkov angle) we can access clean population of π , K and protons as in Fig. 4.9c. With the populations separated, the ratio of the likelihoods can be studied. Especially the ones related to the π - K separation under the proton threshold can be used for a cross-check of the quality of the RICH calibration and of the validity of the likelihood ratio approach for PID. In Fig. 4.10 one can appreciate, indeed, the clean separation of pion and kaon samples, when plotting $LH(\pi)$ versus $LH(K)$. The two populations lie above and below the line of 1, that represent the region where no separation is possible.

The likelihoods ratios are displayed also in Figs. 4.11 and 4.12, with the pion, kaon and proton samples shown in different colors. From these distributions we can infer a starting point for the ratios cut values. For example, a good trade-off for the pion and kaon identification can be obtained with the cuts shown in Tab. 4.1:

4.2.3 PID efficiency matrix

The final step in the RICH-1 characterization is to extract the identification and misidentification probabilities. These probabilities can be grouped in the so-called RICH-1 PID efficiency matrix:

$$M_{RICH}^{+/-}(p, \theta) = \begin{pmatrix} \epsilon(\pi \rightarrow \pi) & \epsilon(K \rightarrow \pi) & \epsilon(p \rightarrow \pi) \\ \epsilon(\pi \rightarrow K) & \epsilon(K \rightarrow K) & \epsilon(p \rightarrow K) \\ \epsilon(\pi \rightarrow p) & \epsilon(K \rightarrow p) & \epsilon(p \rightarrow p) \\ \epsilon(\pi \rightarrow X) & \epsilon(K \rightarrow X) & \epsilon(p \rightarrow X) \end{pmatrix} \quad (4.12)$$

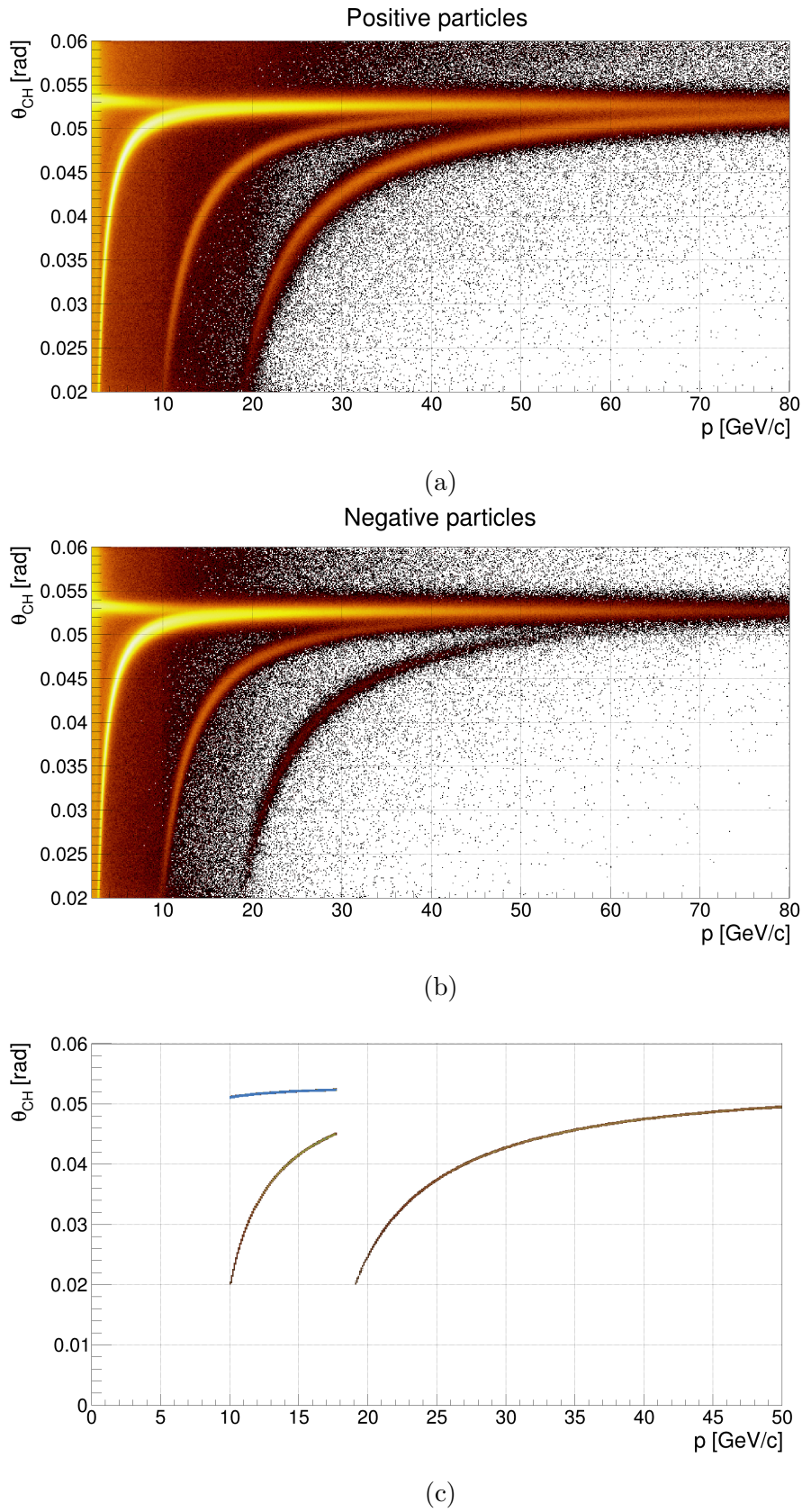


Figure 4.9: Cherenkov angle versus momentum for positive particles (top) and negative particles (middle). On the bottom, a selection of tracks based only on kinematic cuts on momentum and Cherenkov angle is shown, where pion, kaon and proton bands are visible from left to right.

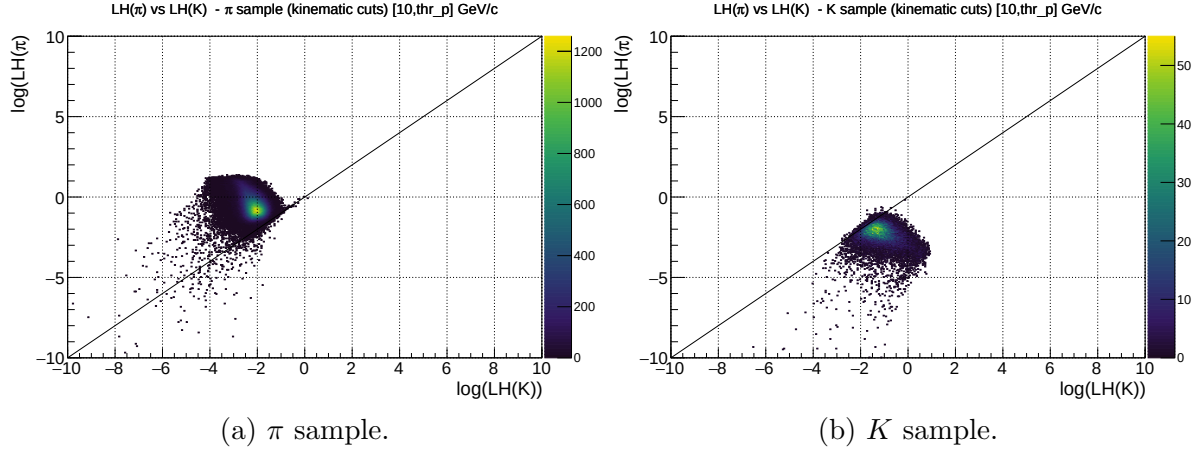


Figure 4.10: Log-likelihood of pions versus kaon hypothesis for the populations of pions and kaons. The line indicates ratio equal 1. We can observe a net separation, as we expect by a correct RICH tuning.

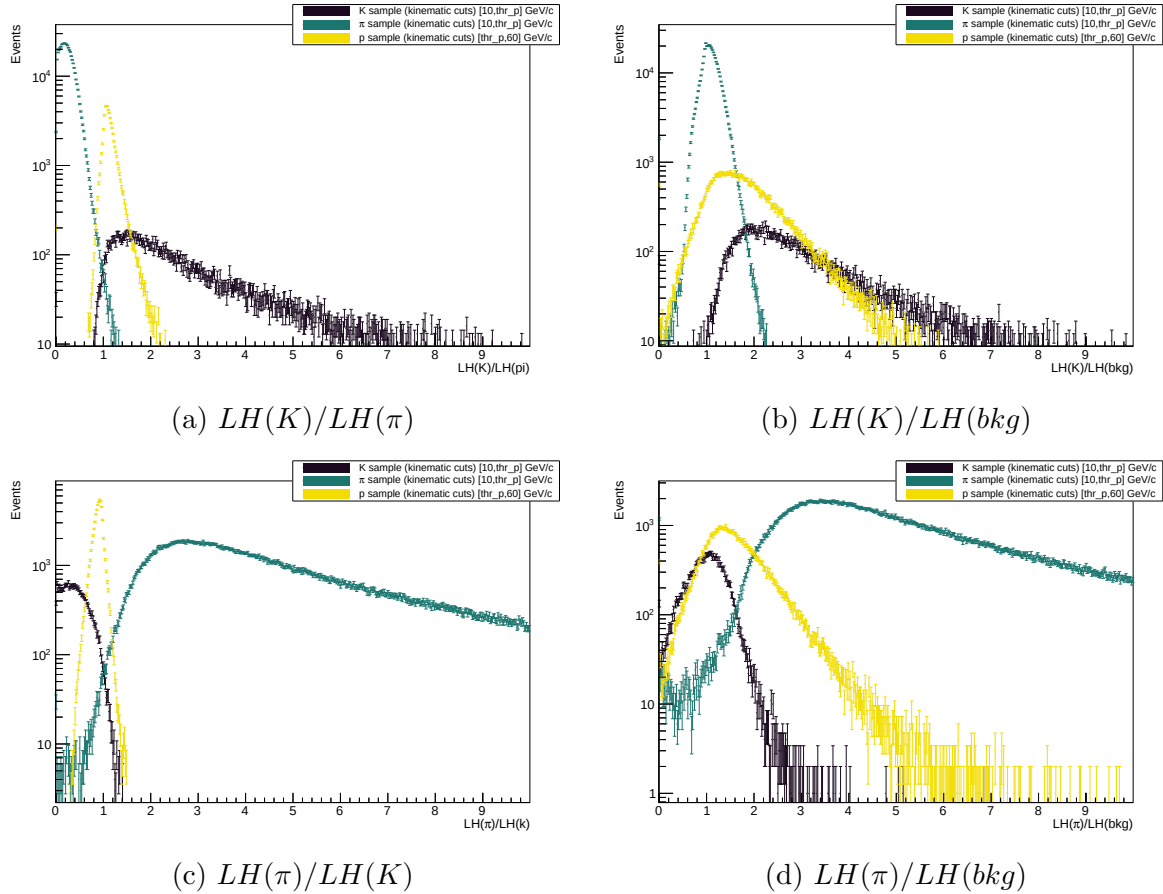


Figure 4.11: Likelihood ratios for the three different populations selected with kinematic cuts only. Black points: kaons; green: pions; yellow: protons.

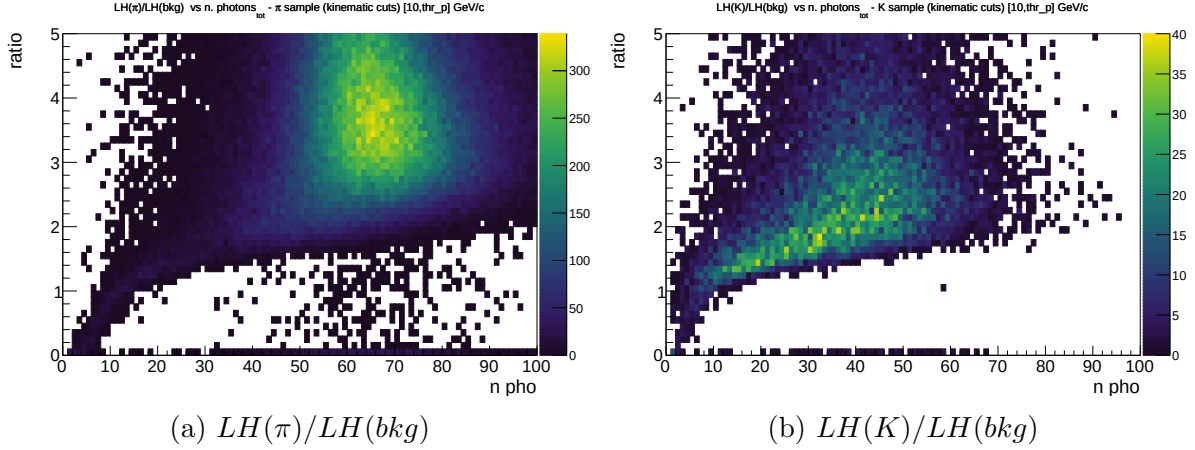


Figure 4.12: $LH(i)/LH(bkg)$ for pions and kaons under proton threshold as a function of the number of detected photons. This ratio will be used for the identification of proton under threshold.

Hadrons	Decays	
	Channel	BR
K_S	$\pi^+\pi^-$	$(69.20 \pm 0.05)\%$
ϕ	K^+K^-	$(48.9 \pm 0.5)\%$
$\Lambda(\bar{\Lambda})$	$p\pi^- (\bar{p}\pi^+)$	$(63.9 \pm 0.5)\%$

Table 4.2: Summary of the V_0 s decay channels. Values taken from [150].

where the bottom row represents the probability of not identifying a particle; the diagonal of the sub-matrix gives the probability to correctly identify a particle species and the off-diagonal elements are the misidentification probabilities. The matrix is filled for positive and negative particles and for each kinematic bin considered. In the matrix formalism we can define two vectors containing the true numbers of hadrons (N_{true}^h) and the measured number of identified hadrons (N_{id}^h):

$$N_{id}^h = \begin{pmatrix} N_{meas}^\pi \\ N_{meas}^K \\ N_{meas}^p \end{pmatrix}; \quad N_{true}^h = \begin{pmatrix} N_{true}^\pi \\ N_{true}^K \\ N_{true}^p \end{pmatrix} \quad (4.13)$$

The true number of hadrons, needed for the cross section measurement, can be linked to the measured number as:

$$N_{true}^h = M_{RICH}^{-1} \cdot N_{id}^h \quad (4.14)$$

where the M_{RICH} is the sub-matrix without the non-identification probabilities. The calculation of N_{true}^h will be then the result of the unfolding of the raw hadron spectra using the RICH matrix.

The identification and misidentification probabilities are estimated from the data using a track sample coming from the decay of the V_0 secondary vertices ($\Lambda, \bar{\Lambda}, K^0, \phi$) shown in Tab. 4.2). After the selection of the secondary vertices, the whole procedure for the estimation of the PID performances is the following:

1. derive the invariant mass spectra of decay products with different PID hypotheses
2. fit the spectra to extract the number of decaying particles
3. compute the PID matrix

Invariant mass spectra

With respect to the approach already described in Sec. 3.2.3 for the analysis of the V0s performed for the run stability study, the ϕ selection requires a different method, as this particle decays strongly after traveling 10^{-23} cm. Its decay vertex can not be spatially disentangled from a primary vertex. The ϕ candidates are thus selected in an inclusive way by looping over all outgoing pairs of oppositely charged tracks, with the application of the following cuts:

- bad spill list applied
- primary vertex exists in the target region (see Sec. 2.2)
- tracks cross less than $10X_0$ (radiation length), to filter out muons
- last measured point (Z_{last}) of outgoing tracks is downstream SM1, to ensure a well reconstructed momentum
- p_t of the produced particles with respect to the decaying one is larger than $23\text{MeV}/c$, to remove electrons

After collecting the V0s, we can build the so-called Armenteros-Podolanski plot [157] to illustrate the kinematics of the resonances candidates. By plotting the p_T of one of the two produced particles, versus the asymmetry in laboratory longitudinal momentum of the two particles (α), the typical arc shapes are forming as shown in Fig. 4.13.

$$\begin{aligned}\alpha &= \frac{p_l^+ - p_l^-}{p_l^+ + p_l^-} \\ p_l &= p \cos \theta \\ p_T &= p \sin \theta\end{aligned}\tag{4.15}$$

with θ being the angle between the directions of the V0 and the produced particles.

With the statistics collected, the phase space of the V0s sample from the data collected in period W01 is divided into:

- 9 bins in momentum [10, 12, 14, 17, 21, 25, 30, 40, 47, 60] GeV/c
- 2 bins of polar angle [0.01, 0.03, 0.18] rad

Per each kinematic bin, 5 invariant mass ($M^2 = (p_1 + p_2)^2$) spectra are computed from the momenta of the V0 candidates decay products. Each spectrum has one identified V0 decay product, the second particle is tested against the following five different identification hypotheses:

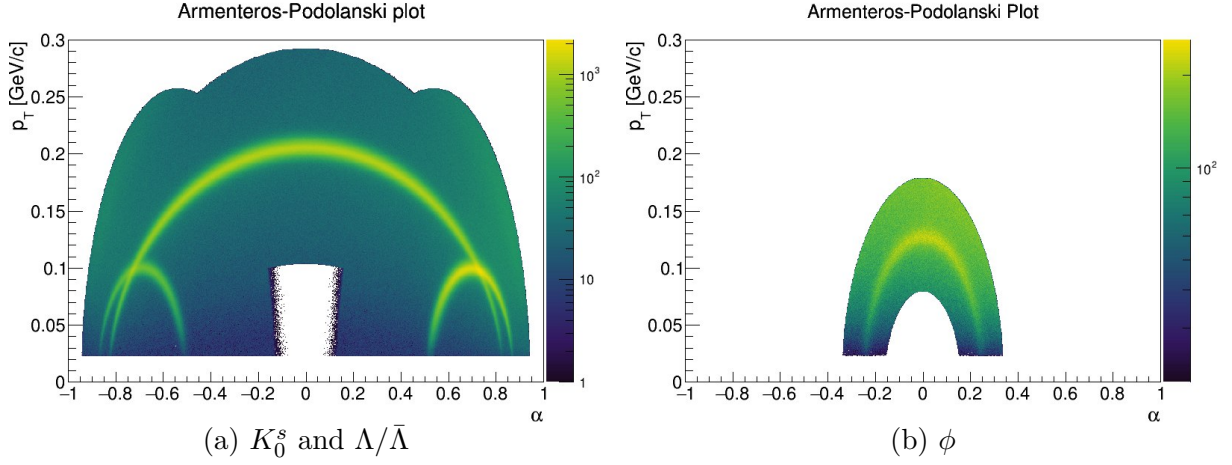


Figure 4.13: Armenteros-Podolanski plot for the selected two body decays. On the left, the main arc is the population of K_0^s candidates, with the two smaller arcs for Λ and $\bar{\Lambda}$. On the right, the ϕ arc is visible.

1. no identification requested
2. identified as π
3. identified as K
4. identified as p
5. no identification was possible

Some of the obtained invariant mass spectra are shown as examples in Fig. 4.14. The fit of these plots allows us to extract the probability of correctly or wrongly identifying a particle. As an example: suppose we want to study the probability to correctly identify a proton. This is given by the number of correctly identified protons divided by the total number of protons:

$$\epsilon(p \rightarrow p) = \frac{N(p \rightarrow p)}{N(p)} \quad (4.16)$$

Using the Λ spectra, we ask for the negative particle to be a π^- . Since there is a 1:1 correspondence between the number of Λ and the number of protons, the numerator of this computation can be associated to the number of reconstructed Λ resonances with the positive particle identified as proton, while the denominator is estimated from the total number of Λ :

$$\begin{aligned} N(p \rightarrow p) &= N_\Lambda(p\pi^-) \\ N(p) &= N_\Lambda \end{aligned} \quad (4.17)$$

Here, the particle type in the parenthesis indicates a PID request on the track. Similarly, the misidentification probability is given by:

$$\begin{aligned} \epsilon(p \rightarrow K^+) &= \frac{N(p \rightarrow K)}{N(p)} = \frac{N_\Lambda(K^+\pi^-)}{N_\Lambda} \\ \epsilon(p \rightarrow \pi^+) &= \frac{N(p \rightarrow \pi)}{N(p)} = \frac{N_\Lambda(\pi^+\pi^-)}{N_\Lambda} \end{aligned} \quad (4.18)$$

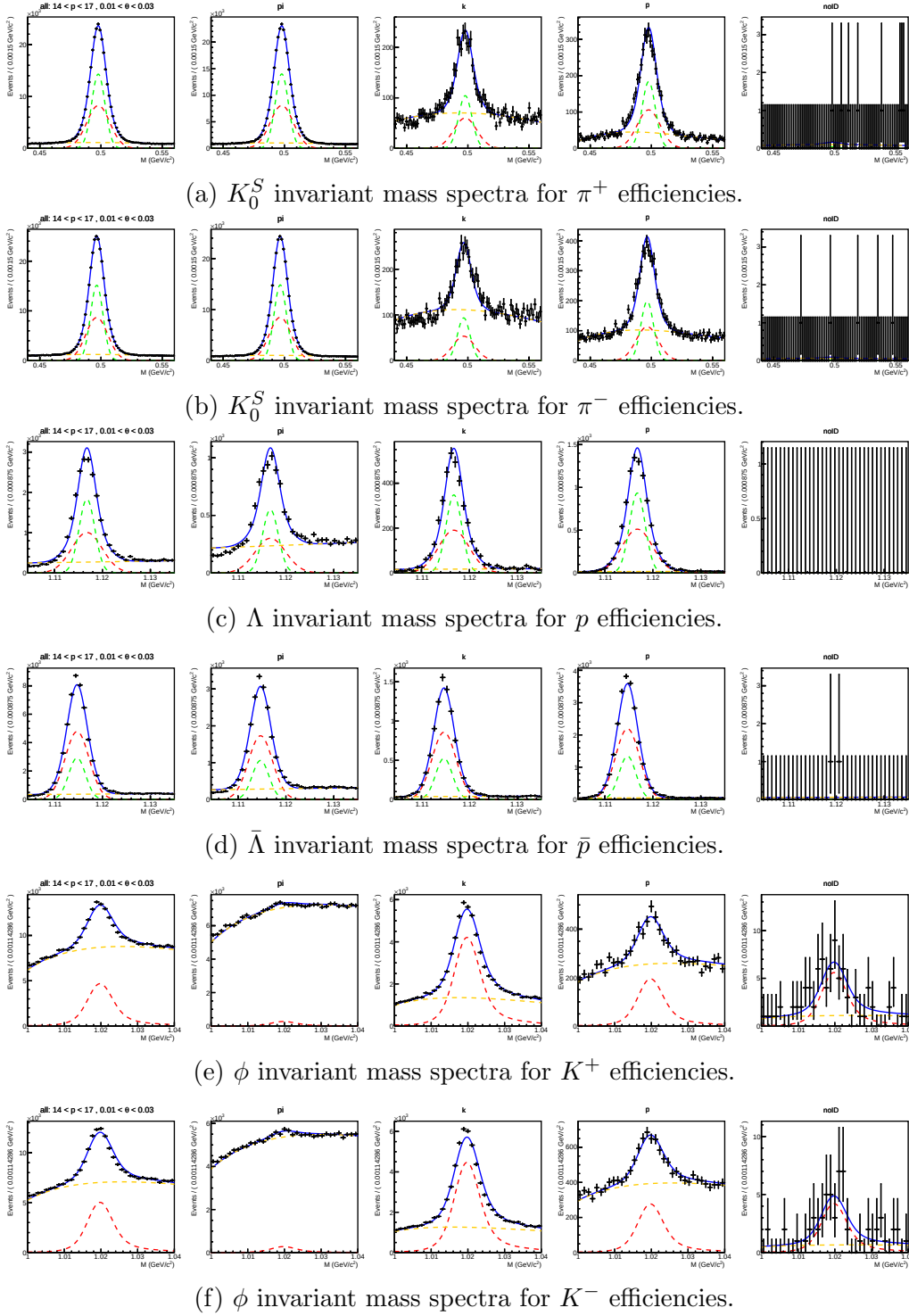


Figure 4.14: Invariant mass spectra for particles with $14 < p < 17$ GeV/c and $0.01 < \theta < 0.03$ rad. From left to right different identification hypotheses on the positive particle is assumed: no hypothesis, pion, kaon, proton, not identified.

	K_0^S	Λ or $\bar{\Lambda}$	ϕ
Total	$F(x) = N_{sig}f_{sig}(x) + N_{bgk}f_{bgk}(x)$		
Signal	2 Gaussian*	2 Gaussian*	$\text{BW}(\mu, \sigma_2) \otimes \text{G}(\mu, \sigma_2)$
Background	$1 + ax + b(2x^2 - 1) + c(4x^3 - 3x)$	$(x - x_{th})^n \times \exp(-a(x - x_{th}))$ with $x_{\text{threshold}} = m_p + m_\pi$	$(x - t)^m \exp(-a(x - t))$ with $t = 2m_K$
(*) composed as: $f_{\text{sig}}(x) = \delta \text{G}(\mu, \sigma_1) + (1 - \delta) \text{G}(\mu, \sigma_2); \delta \in [0, 1]$			

Table 4.3: Summary of fit functions used for fitting the V_0 spectra.

For each fit, a general constraint is placed on the total number of resonances, e.g. in the Λ case:

$$N_\Lambda = N(p \rightarrow \pi) + N(p \rightarrow K) + N(p \rightarrow p) + N(p \rightarrow X) \quad (4.19)$$

where the $N(p \rightarrow \pi)$, $N(p \rightarrow K)$, $N(p \rightarrow p)$ and $N(p \rightarrow X)$ are the results of a simultaneous fit of the 5 samples with fit functions summarized in Tab. 4.3.

The final results of the identification and misidentification probabilities divided in bins are visible in Fig. 4.15. The error on the matrix elements are calculated via error propagation with the covariance matrix u of the fit:

$$\sigma_\epsilon = \sqrt{\sum_{j=1}^m \left(\frac{\delta\epsilon}{\delta N(i \rightarrow j)} \right)^2 \cdot u_{jj} + 2 \sum_{j=1}^{m-1} \sum_{k=j+1}^m \left(\frac{\delta\epsilon}{\delta N(i \rightarrow j)} \frac{\delta\epsilon}{\delta N(i \rightarrow k)} \cdot u_{jk} \right)} \quad (4.20)$$

The identification of π is high ($> 97\%$) up to 40 GeV/ c , as expected, due to clean separation of the Cherenkov angle from protons and kaons. The π identification drops to 0 as soon as the kaon and pion Cherenkov bands overlap at roughly 45 GeV/ c . The probability goes into the not identification, rather than misidentification into kaons.

The kaons probabilities show some misidentification near the kaon threshold in the very first bin at 10-12 GeV/ c . In this range the pions are nearly at saturation, and the misidentification into pions is not expected, as the number of photons produced by pions should be around ~ 60 , while a true kaon near threshold is supposed to produced very few photons. The reason could lie in the selection of the Φ . The inclusive selection may have a fraction of pion contamination, and we are wrongly assuming the kaon hypothesis for these particles. This issue will be investigated in future works.

The RICH-1 is very efficient in identifying the protons above thresholds (> 18 GeV/ c), also due to the clear separations of the bands from pions and kaons. Under threshold the identification is based on the veto approach, and shows the major fluctuations between polar angle bins. This could be related to the RICH-1 background description.

In general the discrepancies between polar angles are mainly driven by the lack of illumination of the decay particles in the outer regions of the RICH-1. In the future, the efficiency extraction could be improved with more statistics by merging two periods of data taking, namely W01 (190 GeV/ c) and W05 (250 GeV/ c), that have same magnets configuration.

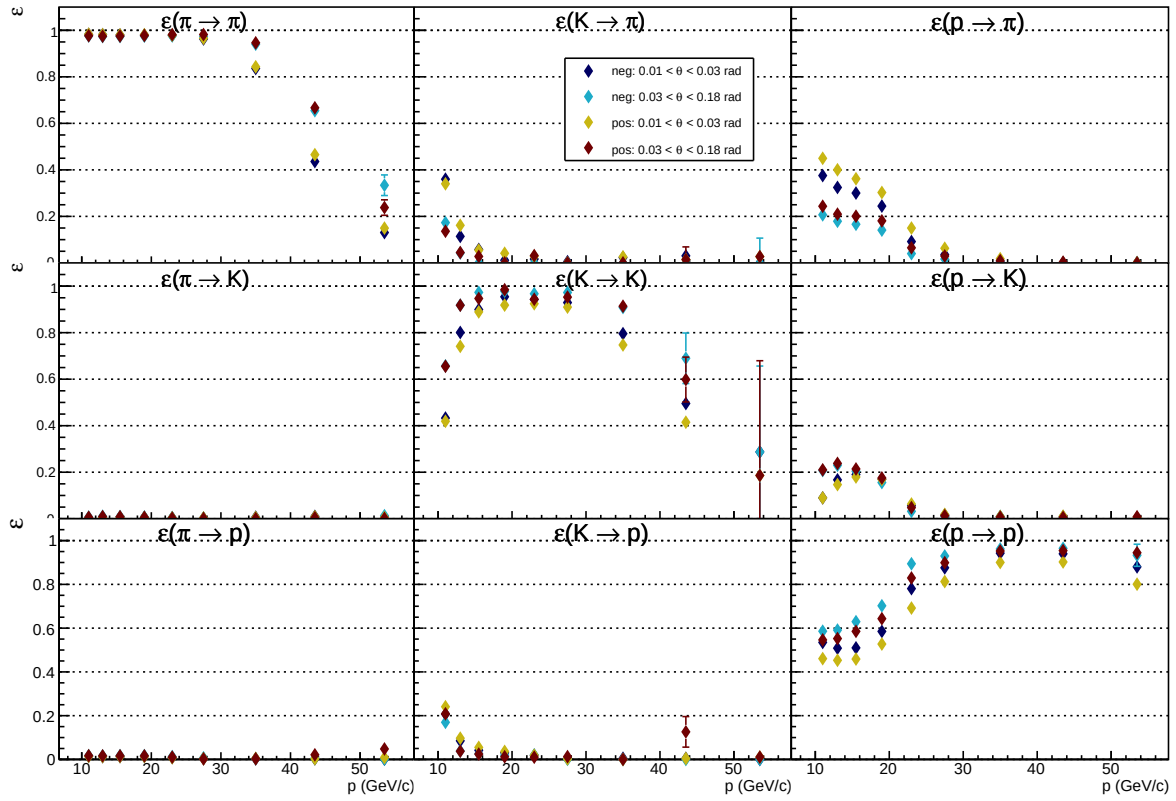


Figure 4.15: PID matrix for positive and negative particles in different bins of momenta and polar angle, divided by particles charge.

Chapter 5

Monte Carlo studies

The Monte Carlo preparation is another crucial step towards the final cross section measurement. The MC let us introduce correction factor for the tracks detection geometrical acceptance and for the efficiency of the reconstruction and event selection. Some of the effects in real data condition, like DAQ and VETO lifetime, CEDAR and RICH-1 PID efficiency, are not simulated and require dedicated work to extract correction factor for the cross section. Other experimental features, like tracking detector efficiency, beam profile, trigger efficiency and the simulation of physics interactions, are included in the MC simulation with TGEANT and used to compute the geometrical acceptance corrections.

In this section the main changes applied to the MC chain (mainly geometry and settings) for the 2023 measurement are presented. The acceptance correction factor will be discussed later in Sec. 6.2.

5.1 Beam File

The beam particle in the simulation is a proton of fixed energy, with different momentum, depending on the data taking period to be simulated (see Tab. 3.1). In COMPASS run with muon beam, the beam momentum was measured by the Beam Momentum Station, situated along the beam line approximately 100 meters upstream of the experimental hall. This beam spectrometer measures the momentum of incoming particles on an event-by-event basis. It is composed of a magnet and two sets of tracking stations, which are made of scintillator hodoscopes and a scintillating fiber detector [122]. However, the hadron beam is provided with less than 1% uncertainty on the momentum [158, 159], sufficiently accurate for the purpose of this measurement and does not need a dedicated measure. In 2023, considering also that the presence of the BMS would degrade the beam condition before entering the experimental hall, it was removed.

The shooting particle momenta is, thus, fixed and also its type. We can, however, simulate the spatial distribution of the beam entering the experimental hall by sampling the beam distribution from real data. The extraction from real data uses random triggers to select proton beam tracks well reconstructed in the beam telescope without associated vertex of interaction. The parameters of the tracks are extracted at the first SciFi station available in the hall, that is SciFi01 positioned at ~ -760 cm. This procedure is applied with a TiS cut as in the data selection. The final cuts applied are:

- *TiS* window [1.2,5.4] s;
- random trigger events;
- CEDAR tagging;
- defined time of track;
- no vertex associated;
- number of hits in the beam telescope as in the final event selection;
- track parameters extrapolated at -760 cm;

The result is a file called *beamfile* in which each line represents a beam particle selected from real data and its information like X and Y position and divergence at the SciFi location. This file is extracted with the latest alignment used for data production and is then plugged into the simulation framework to mimic the beam condition. Eventually, TGEANT reads this file randomly for the beam initial placement and direction.

5.2 Target

The target used, described in Sec. 2.2, has been implemented into the TGEANT framework. From the operational point of view, TGEANT was designed with a specific target backend class that lets the user create a new target and easily place it into the framework. In particular, the starting point was the polarized COMPASS target class that was modified to account for the 2023 differences. I started by removing the polarized *LiD* material from the target holder. Then the target volume is created by filling the mixing chamber with liquid helium. The concept is illustrated in Fig. 5.1b and the target drawn in OGL geometry is shown in Fig. 5.1a.

The resulting target is a 140 cm long helium tube with 3.6 cm radius, described in the `T4LHETarget` class. In 2023 we collected data with empty target for background studies and for this reason I created an empty target class `T4EmptyTarget2023` as well.

5.3 Trigger

In a proper setup simulation, also the trigger has to be included to take into account possible biases and study the feature of events that will or will not trigger in real data condition. The trigger setup, described in Sec. 2.5, is simply made by an anti-coincidence between a beam trigger and the veto signals. As for the target, the implementation relies on a backend class. I implemented the trigger logic into `T4TriggerPbar2023` class by looping on the detectors hits (for SciFi) and on 'trigger-like' hits for beam killers and vetos. The beam trigger (BT) is thus created by the time coincidence between hits on the fibers of FI01Y1 and FI02X1 (as in real data) and the veto signal by a time coincidence between VETO detectors. The position of the two beam killers depend on the simulated data taking period. In fact their position was tuned for every beam momentum and the corresponding current set in the two spectrometer magnets SM1 and SM2.

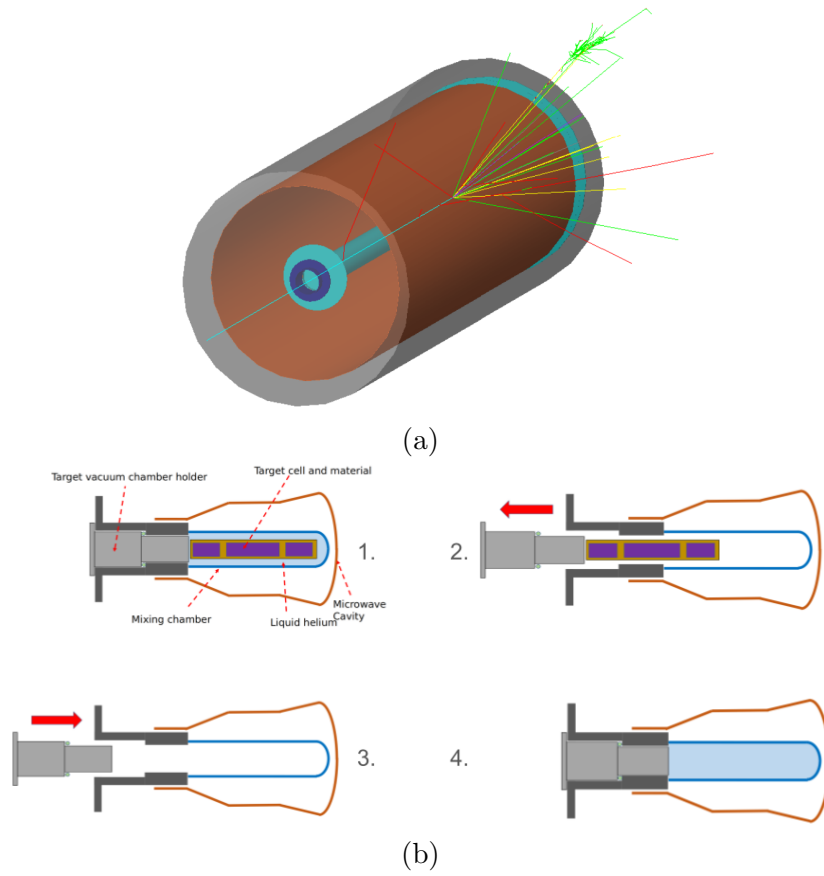


Figure 5.1: Top: target geometry in TGEANT. Bottom: sketch of operation performed for the target changeover from COMPASS to AMBER, figure adapted by the author from [160].

5.4 Event generator

The generation of events is handled by PYTHIA8 [143]. For the current analysis we are interested in inclusive production of hadrons in primary inelastic events and no specific processes are investigated. The PYTHIA parametrization used is the Monash 2013 [161] with the following processes activated:

- SoftQCD:inelastic $\rightarrow$ includes non diffractive, single diffractive and double diffractive processes;
- SoftQCD:elastic $\rightarrow$ includes only elastic process ($AB \rightarrow AB$);

One data sample was produced with inelastic process flag to check the agreement of the MC data with the real data sample and was used to calculate the acceptance correction. The elastic process was activated to study the contamination into the inelastic event selection.

5.5 Detector efficiencies

The tracking detector efficiency simulation plays an important role in extracting the acceptance corrections. The intrinsic efficiency of a plane can not be described a priori and it needs an empirical approach, starting from data.

In general the approach may be biased or unbiased, respectively if the examined tracking plane is contributing to the track fitting or not in the efficiency evaluation method. In the first case, the efficiency extracted is called *pseudo-efficiency*, while if the extraction is unbiased, it is called *true efficiency*. In both cases the efficiency is calculated comparing the illumination of a plane with the number of hits found on that plane. A sample of reconstructed tracks from real data is used to create a 2D map of expected hits on the reference plane. By looking at how many times an hit is associated to a track, one can compute the efficiency as a function of the position on the plane. One of the differences between biased and unbiased lies in the accuracy of the efficiency estimate. In the biased procedure, indeed, the hits on the examined plane affect the tracking algorithm that will use those hits to reconstruct tracks passing near the hit location. In some cases this could cause fake hit association to a track and spoil the efficiency determination. The idea is sketched in Fig. 5.2. The other difference is the computing time needed to extract the efficiencies of more than 250 planes. For the unbiased procedure one should reconstruct the same data sample a number of times equal to the number of planes and this requires a lot of computation time. Also, the performances of the detectors can be variable in time, due to readout errors or other issues. In order to reproduce as best as possible the real data condition, one should take into account this time-dependent changes and also mix pseudo and real efficiency to get the overall best tradeoff in terms of accuracy and computing time.

For the purpose of this thesis work, I have extracted the true efficiencies of all the tracking detectors from a couple of runs in period W01 that were identified as representative for the entire period. From the technical point of view, after having selected the desired data sample, the extraction is performed in the following way:

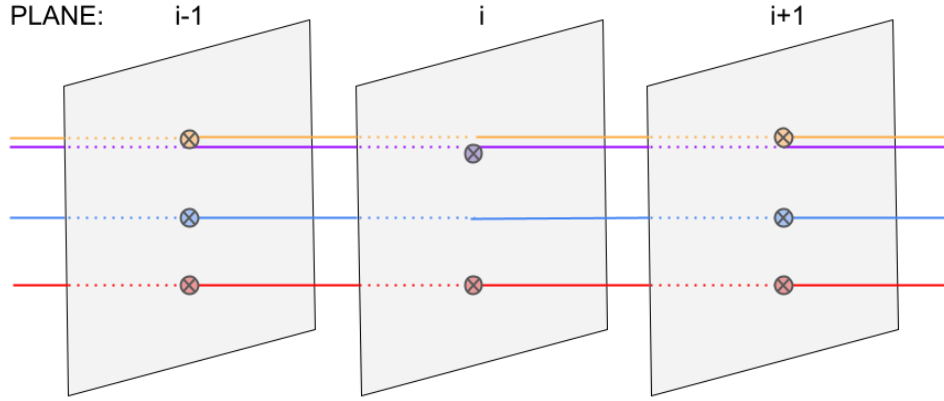


Figure 5.2: The contribution of the tracking plane to the track fitting alters the efficiency evaluation in the cases where several hits are located around the intersection point of a track. If the evaluation is unbiased, in the middle plane the neighboring hit is not used in the track fitting (orange track) and a real (in-)efficiency is returned. If the evaluation is biased, the near hit biases the fitting (violet) and an higher pseudo-efficiency is returned. The blue and red tracks would give same results both in the efficiency and in the pseudo-efficiency approach, without the ambiguities from neighboring hits.

- add the desired plane to the list of disabled trackers in the CORAL option file (*TraF DetNameOff*)
- add the option to save extrapolated parameters of the tracks at the plane location (*TraF SmoothDet*)
- reconstruct some data
- analyze the found/expected hits patterns
- compute 2D map of detector
- smooth the efficiency map [145]
- plug in the efficiency values into a SQLite database file for later MC reconstruction

Examples of efficiency maps are visible in Fig. 5.3, for one MWPC plane and one GEM plane.

For the future development of this analysis and for the sake of a more precise measurement, a broader selection of runs used as data sample for efficiencies extraction is desirable to better reproduce the spectrometer behavior in real data condition.

5.6 CEDAR implementation

The CEDAR detectors are not implemented into the TGEANT framework. Even though their simulation is not particularly needed for the physics case of the antiproton production cross section, it can be insightful and helpful for the Drell-Yan physics program of

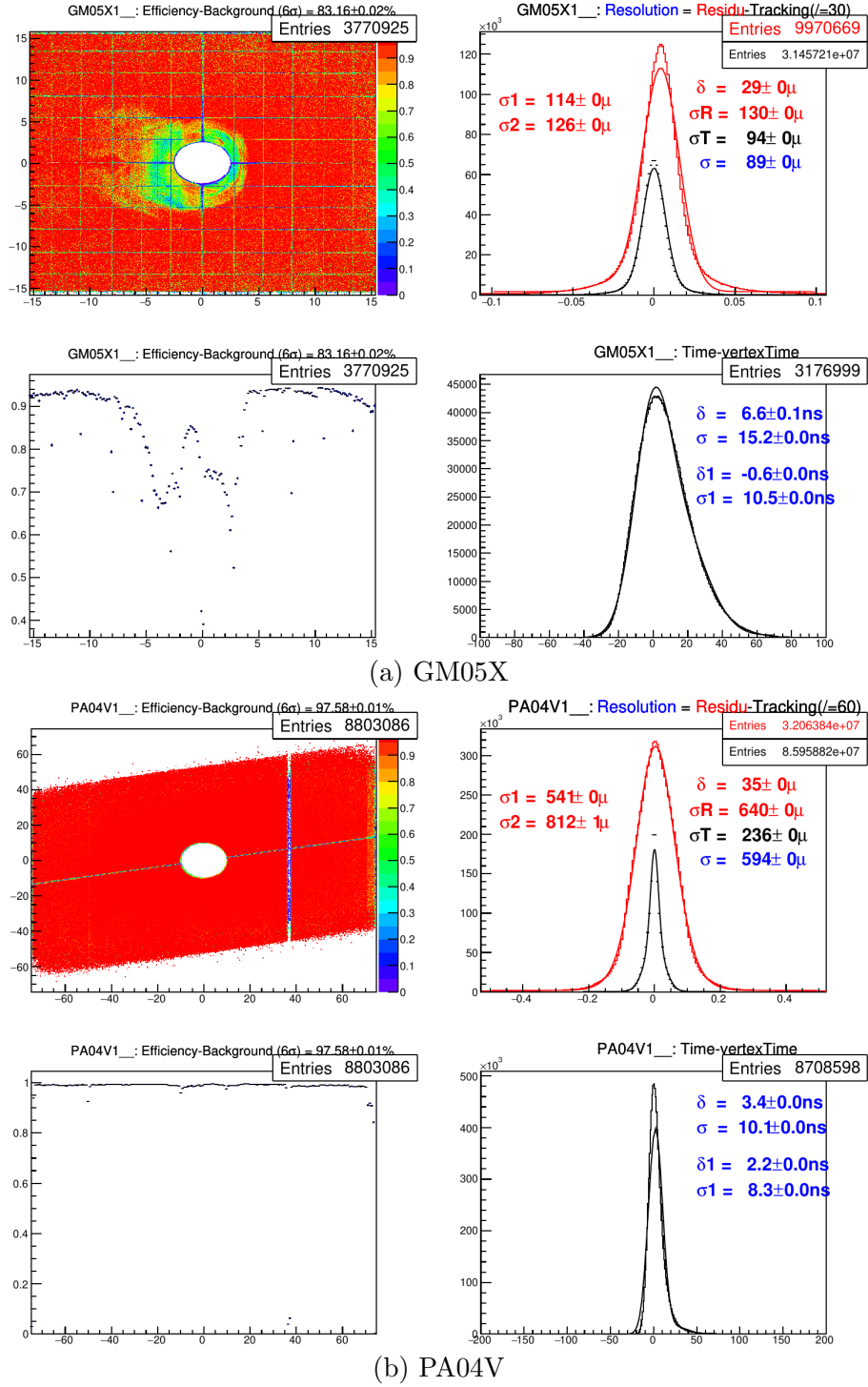


Figure 5.3: Example of performances studies on a GEM and an MWPC plane. In both figures (a) and (b) the following plots are shown: Top left: efficiency map; top right: residual distribution; bottom left: efficiency profile; bottom right: time calibration check. Some ageing effects are visible in the center of GM05X.

AMBER, where high intensity ($\sim 10^7$ p/s) hadron beam is used. At fixed energy, the pion and kaon Cherenkov rings have small radius difference. In order to separate the rings, one needs precise tracking and characterization to keep under control the effect of divergence of the beam at the CEDAR entrance. The low intensity hadron beam for the 2023 antiproton production cross-section run together with the requirement of proton tagging makes the beam particle identification easier with respect to the DY physics program.

For the CEDAR simulation it was decided to use an already existing standalone C++ software and implement it in the TGEANT framework. The standalone software was developed several years ago by Flavio Tosello in Torino and takes care of producing the photons in the radiator and collecting them in the PMTs, provided the input of a beam particle. I implemented this bundle into the TGEANT framework by using the GEANT4 fast simulation model (FSM) via the `G4VFastSimulationModel` class [162]. The fast simulation allows to manage the propagation of the particles and the response of the detector and it is typically used for example in the shower simulation for calorimeters. The parametrization of the particle propagation in this framework is use-case dependent and can be realized in many sub-volumes of the detector or in an assembly of volumes (in Geant4 formalism called respectively mass geometry and parallel geometry). From the technical point of view, one has to add the `G4FastSimulationManagerProcess` object to the physics list of the simulation and create the desired detector class inheriting the `G4VFastSimulationModel` members, in this case `T4CedarFSM`. Then the following class functions are overridden:

- `G4bool IsApplicable(const G4ParticleDefinition *)` defines for which particle the model is valid (proton, pion or kaon);
- `G4bool ModelTrigger(const G4FastTrack &)` allows to implement kinematic checks on the tracks triggering the model;
- `void DoIt(const G4FastTrack &, G4FastStep &)` is invoked when the model has triggered and it is where the parametrization is implemented;

The general geometry of the CEDAR is coded in a simple way within a geometry class `T4CedarDet`, where one can find the geometry description, the region definition for the FSM and an object containing all the structs needed to run the standalone software. A single CEDAR is described in a naive way as a vessel of steel filled with helium with a small plane at the entrance simulating the entrance window, to which the FSM is linked. The collection of CEDARs is stored into `T4Cedar`. When a proton, pion or kaon particle passes through the triggering region, the custom simulation software is called with the inputs describing all the beam particle characteristics like momentum, divergence and position. The output of the call is a struct named `NPEPMT`, where all the information on the Cherenkov photons generated and the photo-electron generated/collected are stored. However, in order to limit the output file size, only the position of photo-electron in the PMT reference frame and the number of pads fired is stored into the ASCII output of TGEANT. The output of TGEANT is then processed by CORAL, as in the standard workflow, where I implemented the decoding of the CEDAR MC digits and the creation of TGEANT hits as well. An example of event display for CEDAR is visible in Fig. 5.5.

The implementation of the CEDAR simulation has several points that can be improved in the future for the DY physics case:

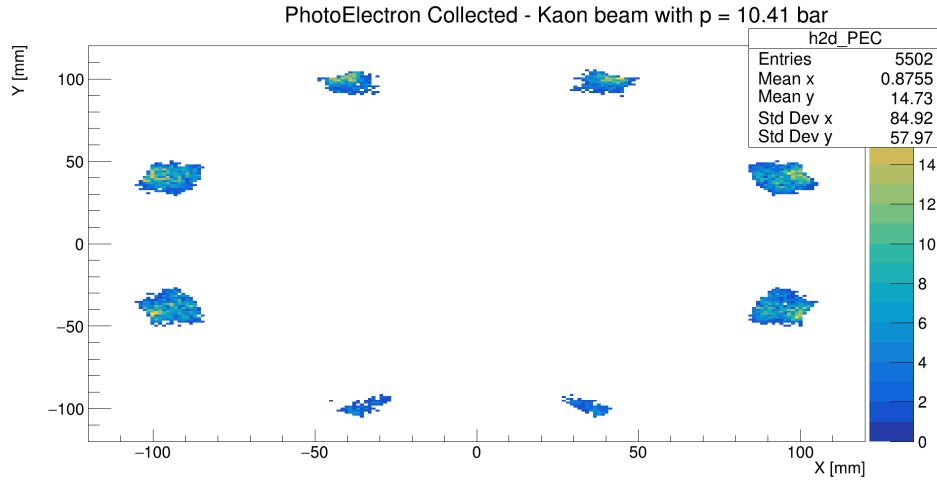


Figure 5.4: An example of the CEDAR response simulation. Position of the collected photoelectrons created with the ASCII information from TGEANT.

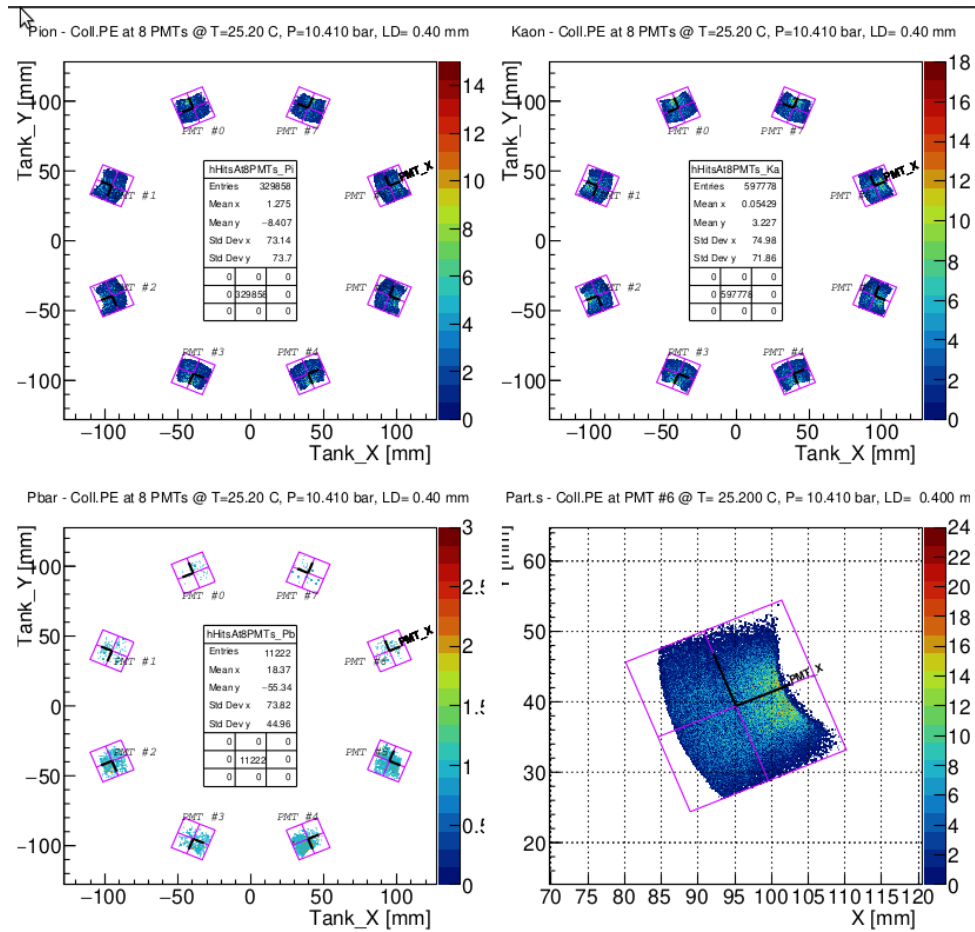


Figure 5.5: An example of the CEDAR response simulation. Position of the collected photoelectrons produced by the standalone software.

1. import the CAD drawing of the CEDAR for a proper geometry and material description;
2. include mechanism to collect photons from the secondaries produced by the beam particle interacting with the radiator gas;
3. include the beamline magnets elements and the transport matrix of the beam, needed to propagate the beam particle in the beamline to provide better divergence description at CEDAR entrance.

5.7 RICH-1 beam pipe removal

The RICH-1 acceptance defines the phase space in which PID is performed. The acceptance of this detector is mainly defined by the geometrical dimension, the mirror dead zones and by the beam pipe. Particle entering the RICH at small angle and passing through the beam pipe have a reduced fraction of photons collected. In the cases when the particle path is completely contained inside the beam pipe no photons are detected at all. By removing the beam pipe, we can increase the phase space covered for the PID and consequently expand the final phase space of the measured cross section in the very forward direction. A dedicated study of the impact of removing the RICH-1 beam pipe was carried out to evaluate how much the phase space of charged particles would be extended and also which would be the increase in the detector occupancy. The beam pipe geometry and scope is discussed in Sec. 2.4 and some photos of the operation can be seen in Fig. 5.6.

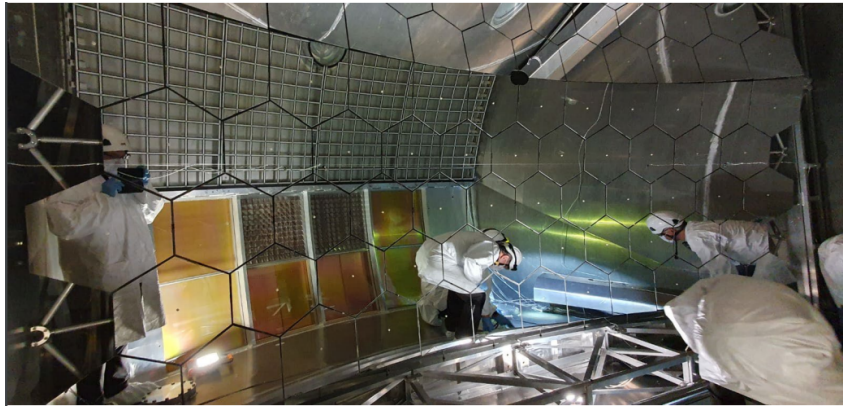


Figure 5.6: Inside the RICH-1 vessel during beam pipe removal operation. [163]

The original purpose of the beam pipe was to reduce the pile up of the high intensity muon beam. However, in the 2023 low intensity hadron run the incoming particle rate was of the order of 30 kHz and the beam pipe removal became an option to be considered.

The simulations were performed at 60, 190 and 250 GeV/ c proton beam momenta in order to cover the interval between the maximum and minimum energy available. The results shown in the following plots are related to the MC truth. Transverse momentum vs momentum distribution of antiproton reaching the RICH-1 entrance can be seen in Figs. 5.7 to 5.9. The 2D plots show that the removal of the beam pipe would extend

the phase space coverage for those antiprotons produced at momenta larger than 20-30 GeV/ c with $p_T < 0.2 - 0.3$. The MC results also show that the beam pipe cuts a fraction of antiprotons at lower momenta and low p_T , in the overlapping region. In numbers, if

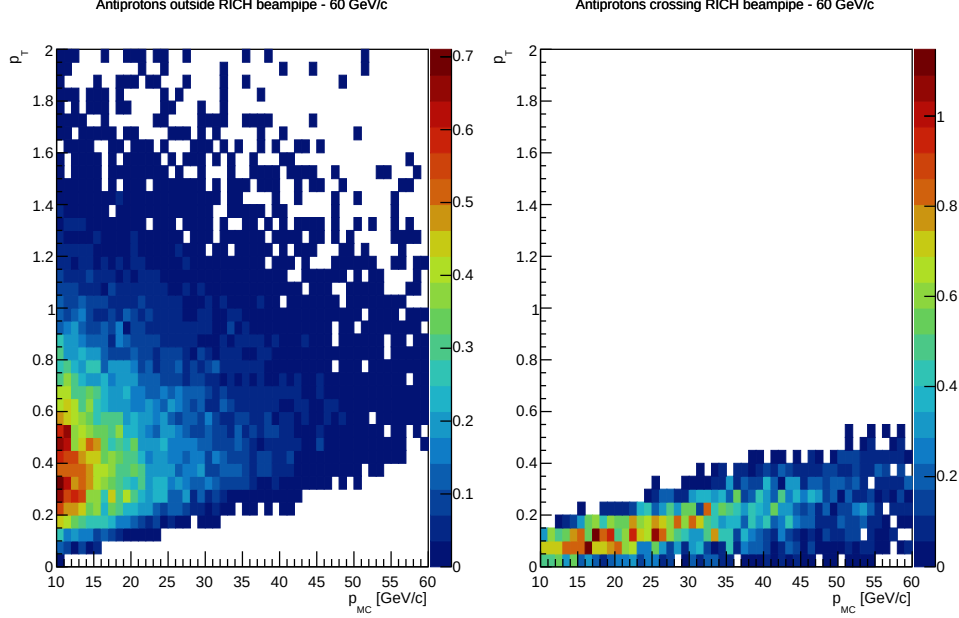


Figure 5.7: Transverse momentum vs momentum for antiprotons produced with 60 GeV/ c beam. Left: particles crossing RICH radiator outside the beam pipe; right: crossing the beam pipe.

we remove the beam pipe, we would gain between 5 – 10% of total antiprotons depending on the energy considered.

While the gain in phase space is clear, the increased occupancy of the detector could have negative effect on the general performances. The multiplicity of charged particles above their respective momentum thresholds for producing Cherenkov light was considered as an estimator of potential saturation of the detector. The multiplicity of particles entering the RICH without crossing the beam pipe can be appreciated in Fig. 5.10. The average multiplicity is ~ 5 tracks with a median of 6. On the other side, one can see in Fig. 5.11 the average number of particles per event entering the beam pipe region for the different beam momentum. In average, by removing the pipe, there would be ~ 0.7 tracks more per event. With this projection, the detector performances are not degraded, with the benefit of a larger phase space coverage.

5.8 2022 test run

A test run for the antiproton production cross section took place from November 9th to November 14th 2022, using the polarised LiD COMPASS target and a positive hadron beam with an intensity of about $5 \cdot 10^5$ p/s. The different target introduced some limits mostly because when compared to the liquid-He the LiD target is more dense by a factor

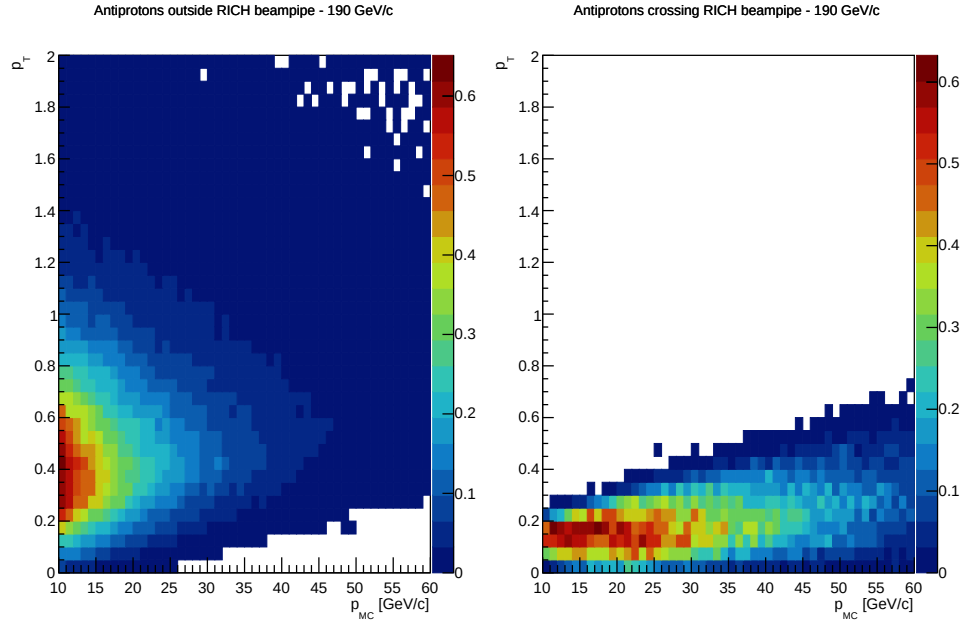


Figure 5.8: Transverse momentum vs momentum for antiprotons produced with 190 GeV/ c beam. Left: particles crossing RICH radiator outside the beam pipe; right: crossing the beam pipe.

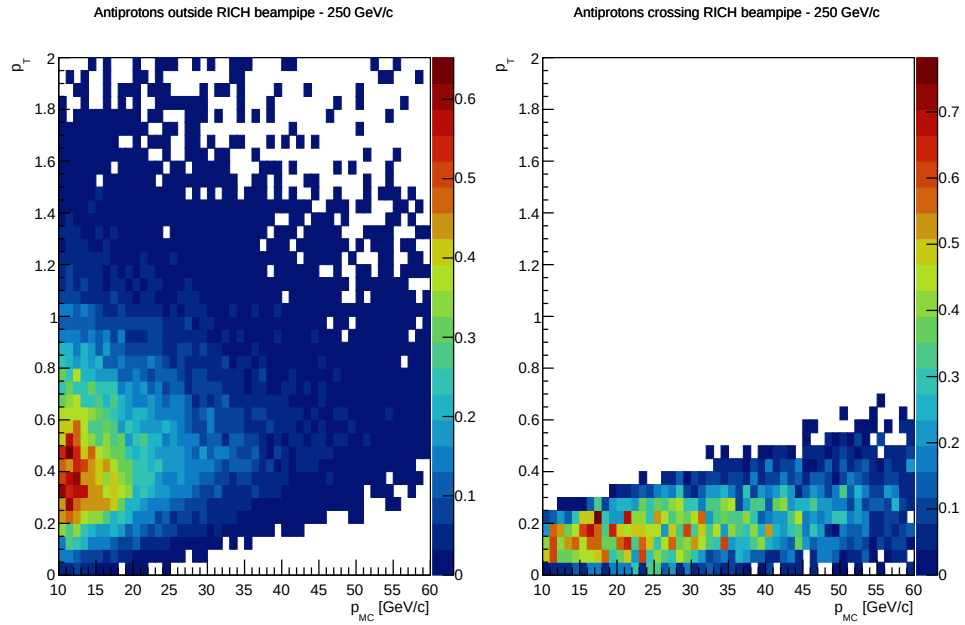


Figure 5.9: Transverse momentum vs momentum for antiprotons produced with 250 GeV/ c beam. Left: particles crossing RICH radiator outside the beam pipe; right: crossing the beam pipe.

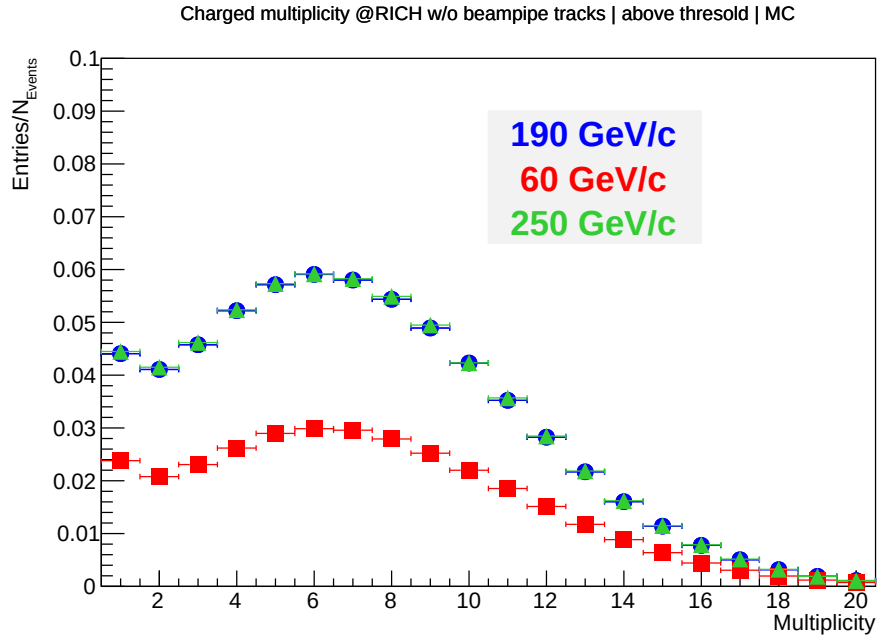


Figure 5.10: Charged multiplicity distributions of particles producing Cherenkov light in the radiator outside the beam pipe. Different colors refer for the different beam momenta.

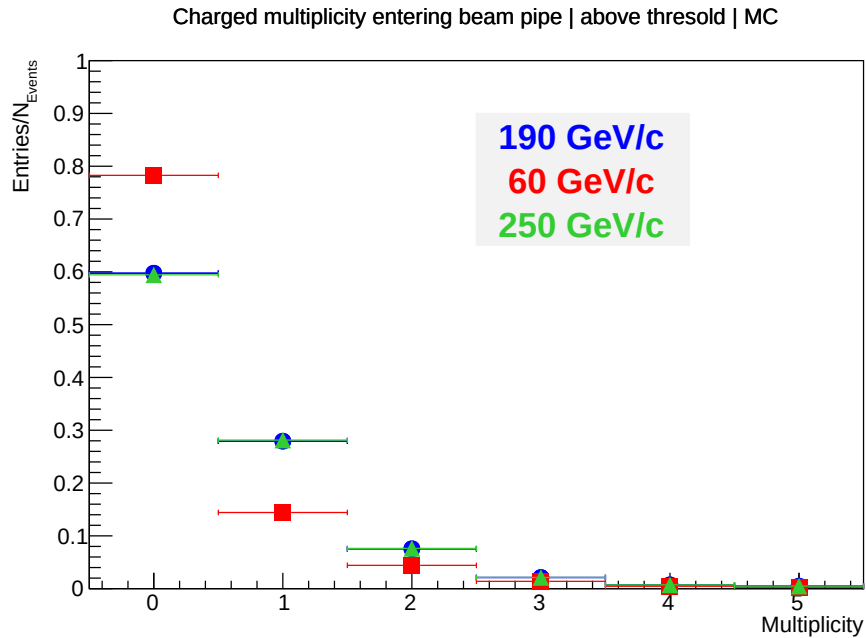


Figure 5.11: Charged multiplicity distributions of particles producing Cherenkov light crossing the full beam pipe.

3. The larger density was compensated by pre-scaling the trigger. The experiment was operated with the minimum-bias trigger then used also for the 2023 run. Data were collected at four different beam momenta between 60 and 250 GeV/ c and consequently with different spectrometer magnets (SM1 and SM2) current settings. The main difference with the final setup of 2023 is the beam killer positioning. Before the test run, I produced a small MC sample with a non-interacting beam to check the position of the beam at the beam killer locations (BK1 at $Z=25$ m and BK2 at $Z=33$ m), as shown in Fig. 5.12. The beam killers are motorized and the idea was to move the beam killers to follow the beam path using the nominal current of the spectrometer magnets (2500 A for SM1 and 4800 A for SM2). For many of the beam momenta, however, the nominal bending power was larger than the possible movement of the beam killer and it was decided to scale the magnet currents to keep the beam in the spectrometer acceptance.

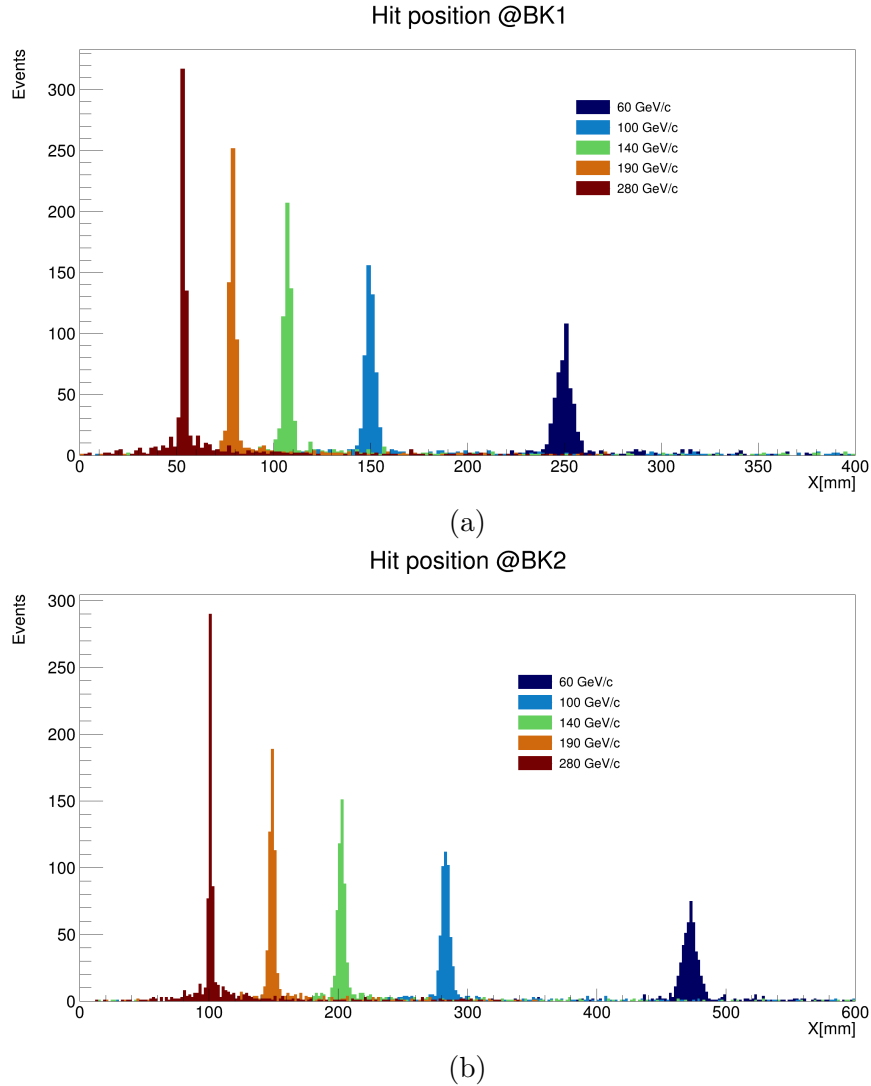


Figure 5.12: Beam spot location on the X axis at the two beam killers Z positions.

The position of the beam killers was then finalized performing a scan of the counting rates as a function of the position along x - and y -axis for each configuration shown in

Tab. 5.1.

Beam momentum [GeV/ c]	SM1 [A]	SM2 [A]	BK1 (x, y) [mm]	BK2 (x, y) [mm]
60	936	0	(102, 6.0)	(180, 5)
60	936	1500	(103, 7.5)	(139, 5)
60	2500	0	(45, 7.7)	(59, 5)
100	1562	2500	(107, 6.0)	(188, 5)
190	2500	4800	(85, 0.0)	(155, 0)
250	2500	4800	(67, 11.0)	(118, 11)

Table 5.1: The different configurations tested in the November 2022 Test Run are shown in this table.

Chapter 6

Extraction of hadron spectra

This chapter is devoted to the extraction of hadrons spectra in pHe collision with a positive hadron beam at 190 GeV/ c in the AMBER experiment. The data sample used is period W01, the same used in the previous chapters for the detectors efficiencies and correction factors estimation. The bins size of the phase space is optimized from the MC and the acceptance correction is calculated in bins of Z vertex position, momentum and transverse momentum for pions, kaons and protons. The number of identified hadrons is unfolded for the RICH-1 PID matrix and computed as a function of momentum and p_T in the laboratory frame. The unfolded spectra are eventually corrected for the geometrical acceptance.

The true number N_{true}^h of a certain hadron species $h = \pi, K, p$ in the AMBER apparatus is obtained from the identified number of hadrons N_{id}^h with the following relation:

$$N_{true}^h = \frac{N_{id}^h}{\varepsilon}; \quad \text{with} \quad N_{id}^h = N_{measured}^h \cdot \frac{\gamma}{\epsilon_{RICH}} \quad (6.1)$$
$$\varepsilon = A \cdot \epsilon_{DAQ} \cdot \epsilon_{VETO}$$

where ε includes the acceptance $A = \epsilon_{geom} \cdot \epsilon_{tracking}$ and the lifetime correction of DAQ and VETO. The number of identified hadrons accounts for the purity γ of the measured h sample and for the efficiency of the RICH in identifying that species ϵ_{RICH} . The term A is generally called acceptance and it is estimated from the MC in Sec. 6.2. The lifetimes of DAQ and VETO were already extracted in Sec. 3.5. The convolution of RICH purity and efficiency is computed by inverting the RICH matrix as in Eq. (4.14).

6.1 Real data event selection

The measured number of hadrons $N_{measured}^h$ is computed after a selection of inelastic events in the helium target. After the data reconstruction with CORAL, the cuts applied to select the inelastic events from real data are enumerated here:

1. bad runs and spills are rejected

The spill rejection is discussed in Sec. 3.2.2 and the bad runs in Sec. 3.2.3. The two rejection lists are coherent with the flux estimation and all the other analysis presented in this work;

2. trigger mask has physics trigger bit fired

The trigger mask provides a bit map of triggers fired. The trigger required is bit 1, that is our physics trigger, made of the anti-coincidence between a beam trigger and the VETO detectors. A more detailed description is provided in Sec. 2.5.

3. TiS is in $[1.2, 5.4]$ s time window

A typical spill lasts ~ 4 seconds. With the physics trigger used in this data taking the event rate is $\sim 10^5 ev/spill$. Each event has the Time in Spill (TiS) information indicating the event time with respect to the start of the spill. The same time window is used in the flux estimation. An example of TiS distribution is visible in Fig. 6.1;

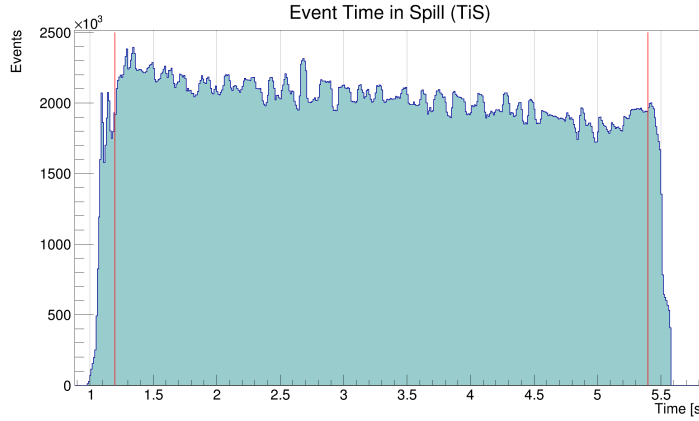


Figure 6.1: Distribution of the event time in spill for physics trigger. The red lines indicate the start and stop cut applied for the selection of physics events. Reduced sample.

4. primary vertex exists and is tagged by CORAL as best;

5. primary vertex position is inside the liquid helium target

The primary vertex is requested to be inside the target volume. The distribution of vertices is visible in Fig. 3.11. Size and geometry of the target are discussed in Sec. 3.3. The final cut is a cylinder parallel to the beam with Z dimension $\subset [-65, 65]$ cm and radius of 3.4 cm;

6. multiplicity of CEDAR1 and CEDAR2 is larger than 6

The hadron tagging in the beam is provided by the CEDAR detectors. An overview of their efficiency is given in Sec. 4.1. The required PMTs multiplicity is at least 6 on both CEDARs;

7. beam track is well reconstructed in the beam telescope

The number of reconstructed beam tracks per event follows the distribution shown in Fig. 6.2a. The beam intensity was kept low in order to avoid event pile-up. However, we observe that $\sim 0.2\%$ of events have multiple beam tracks reconstructed. What happens is that a beam track interacting in the beam telescope region could produce a certain number of secondary tracks, which create additional hits in the

beam telescope. These hits cause the reconstruction of fake beam tracks due to a loose cut in CORAL, where a beam track is reconstructed if it has at least 2 hits in SciFi detectors and 3 hits in Silicons. The distributions of the number of hits in the beam telescope, for all the events and for events with multiple beams reconstructed, are visible in Figs. 6.2b and 6.2c. The bulk of good reconstructed beam tracks is visible in the top right corner of the plot, with hits in the SciFis larger than 6 and larger than 11 in the silicons, while a second population can be appreciated around 4-6 silicon hits and few SciFis hits. In order to remove this second population of fake beam tracks, the CORAL criteria is kept, but we apply a stricter condition in PHAST ensuring that the beam track is well reconstructed along the whole beam telescope. The final selection accepts beams with at least 4 hits on the SciFis of the beam telescope and 10 on the Silicons.

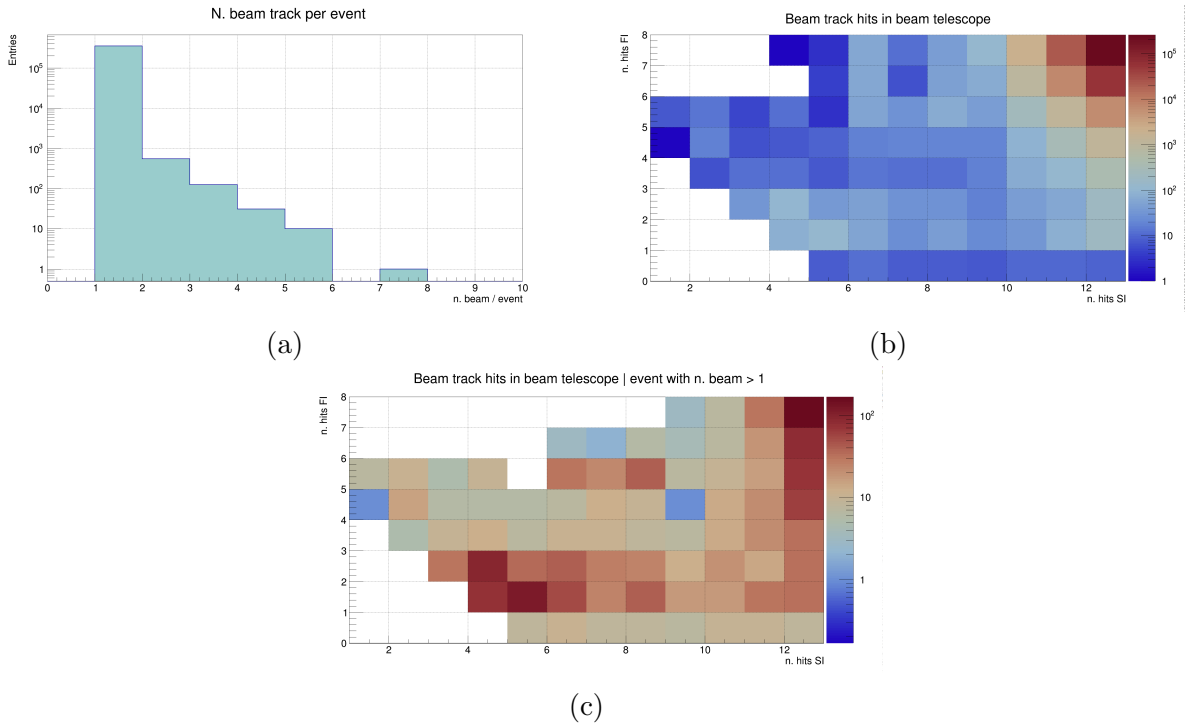


Figure 6.2: In (a) number of beam tracks reconstructed per event; (b): hits distribution per beam track in the beam telescope; (c): hits distribution per beam track in the beam telescope for events with multiple beam tracks reconstructed. Reduced sample.

8. beam track pass through whole target length

In order to ensure the same condition used for the flux estimate, the beam track is extrapolated at the entrance and exit of the target. The entrance and exit position must satisfy the target dimension cut.

9. primary vertices with only one outgoing track are excluded;

The impact of all the selection cuts is quantified in Tab. 6.1.

Cut name	Number of events	Fraction
All events	1216139648	100 %
Physics trigger	1069971648	87.9 %
TiS window	1011486080	83.2 %
Primary vertex found in target	574395136	47.2 %
Beam track reconstructed	572238080	47.1 %
Beam track in target	572198336	47.1 %
proton tag with CEDAR	414567360	34.1 %
primary vertex with ≥ 2 outgoing tracks	311962720	25.7 %

Table 6.1: Cut flow of events in data taking period W01.

6.1.1 Tracks selection

The track selection follows minimum criteria to ensure a good reconstruction of the hadron candidates. From all the vertex selected in inelastic events, the outgoing tracks passing the following cuts constitute the raw sample of hadrons:

1. $\chi^2/ndf < 10$
the reduced χ^2 must be smaller than 10 to ensure proper reconstruction;
2. the radiation length crossed is $X/X_0 < 10$
The radiation length cut is applied to exclude muons from the sample;
3. First and last measured point are respectively before and after SM1
This cut ensures a proper momentum reconstruction of the particles. The first spectrometer is located roughly at 3.50 m after the target. The cut applied is $Z_{first} < 350$ cm and $Z_{last} > 350$ cm;
4. track can be extrapolated to the RICH;
5. track has RICH information;
6. defined mean time;
7. at RICH entrance, momentum in $[10, 60]$ GeV/ c and polar angle in $[0.01, 0.18]$ rad
The phase space is the same as in the RICH matrix extraction.

The sample size after the cut flow is reported in Tab. 6.2.

Cut name	Number of tracks	Fraction [%]
All tracks	2026243712	100
$\chi^2/ndf < 10$	1934083584	95.5
$Z_{first} < Z_{SM1}$ and $Z_{last} > Z_{SM1}$	1824707200	90.1
$X/X_0 < 10$	1788087040	88.2
track has RICH data	1725605120	85.2
$p \in [10, 60]$ GeV/ c and $\theta \in [0.01, 0.18]$ rad	442409408	21.8

Table 6.2: Cut flow for tracks in inelastic events for period W01.

6.2 Acceptance correction

The apparatus simulation takes into account the efficiency of tracking detectors, the beam characteristics and the general response of detectors to the passage of the particles. From MC it is possible to estimate the performances of the reconstruction software, the geometrical limitation of the spectrometer and the cuts' impact on the real data selection. The resulting correction factor is generally called *acceptance* and it is a convolution of the following effects:

1. Geometrical acceptance of the spectrometer;
2. Efficiencies of detectors;
3. Efficiencies of trigger;
4. Efficiencies of analysis cuts;
5. Tracking resolution and efficiency.

A schematic view of the Monte Carlo and real data processing is shown in Fig. 6.3.

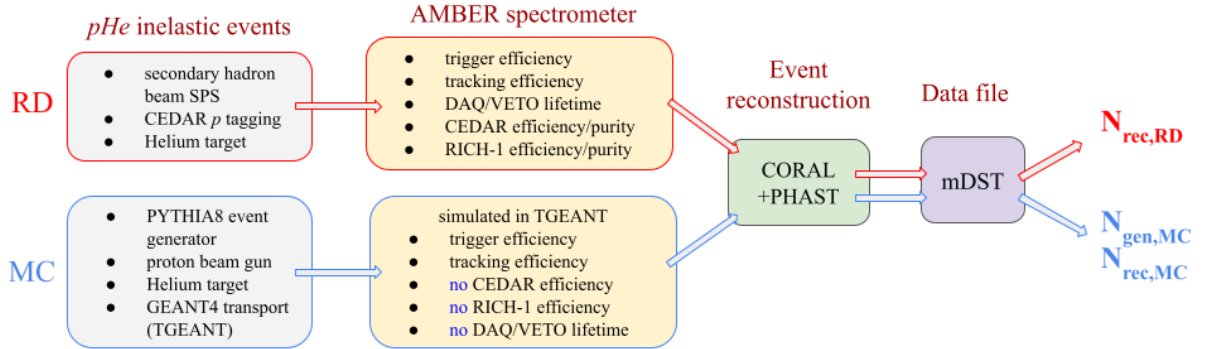


Figure 6.3: Block representation of the MC and real data processing. In the MC the CEDAR and RICH-1 efficiency and DAQ/VETO deadtime are not simulated.

In order to estimate the acceptance correction, the interaction events are simulated with PYTHIA8 event generator within the TGEANT framework (see Chap. 5). I will refer to this simulated sample as *generated* sample. These events are then processed by the reconstruction software CORAL, whose output is almost identical to the real data processing and can be analyzed with the same tools. The output of this chain is called *reconstructed* sample, to which it is applied almost the same selection as the real data processing. The reconstructed sample mimics the real data condition, because it is subject to all the effects mentioned before. The acceptance correction is then calculated from the ratio of MC reconstructed events N_{rec}^{MC} over the MC generated events N_{gen}^{MC} . The correction is computed as a 3-dimensional quantity in bins of momentum p , transverse

momentum p_T and position of the interaction vertex along the z-axis Z_{vtx} as:

$$A^h(Z_{vtx}, p, p_T) = \frac{N_{rec}^{MC,h}(Z_{vtx}, p, p_T)}{N_{gen}^{MC,h}(Z_{vtx}, p, p_T)} \quad (6.2)$$

where the superscript h indicates that the correction is computed separately per hadron species.

6.2.1 Generated sample selection

The selection of events leading to the $N_{rec}^{MC,h}(Z_{vtx}, p, p_T)$ is done with the following cuts:

1. primary vertex is in target region $Z_{vtx} \in [-65, 65]$ cm and $r < 3.4$ cm
2. beam track is found
3. charged particles with $p \in [10, 60]$ GeV/c are selected

The selected primary vertices are shown in Fig. 6.4 for X, Y and Z projections. As an example, the phase space covered by negative hadrons produced in the selected events is shown in Fig. 6.5, with the transverse momentum in the center of mass frame as a function of the rapidity $y = \frac{1}{2} \ln \frac{E+p_z c}{E-p_z c}$. The limits on momentum are needed to select the same kinematic properties of the reconstructed sample. The effect of this cut is visible in the phase space plot, where the population of hadrons is confined into arc-shape bands.

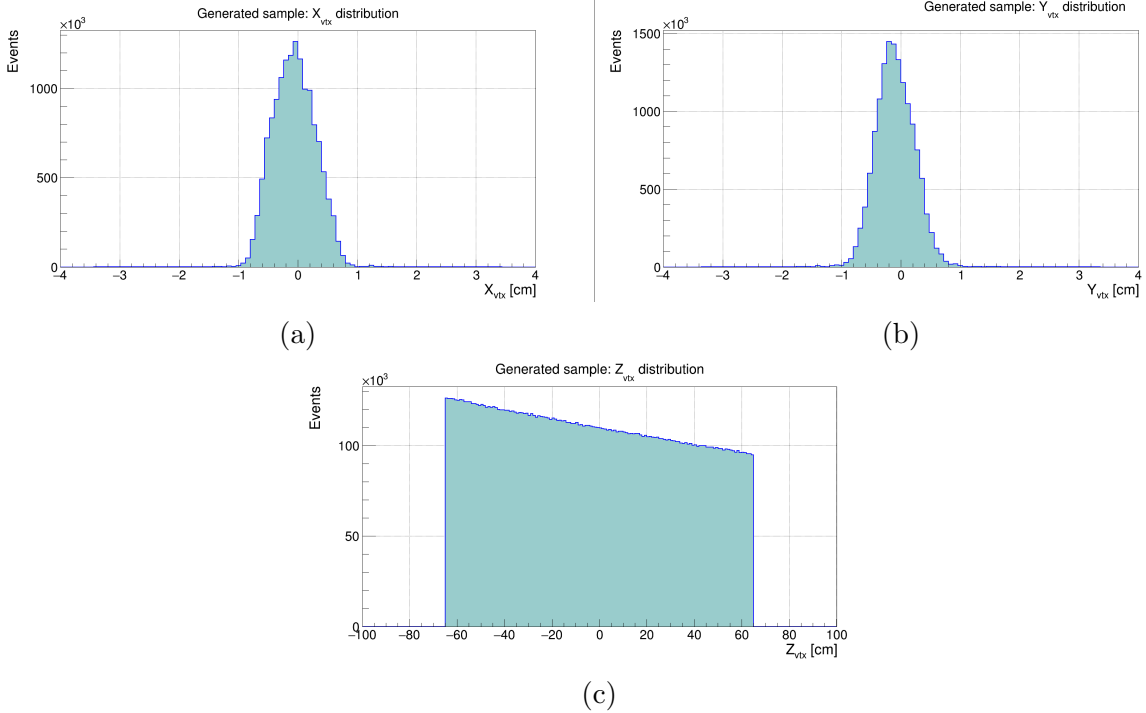


Figure 6.4: Generated vertices distributions.

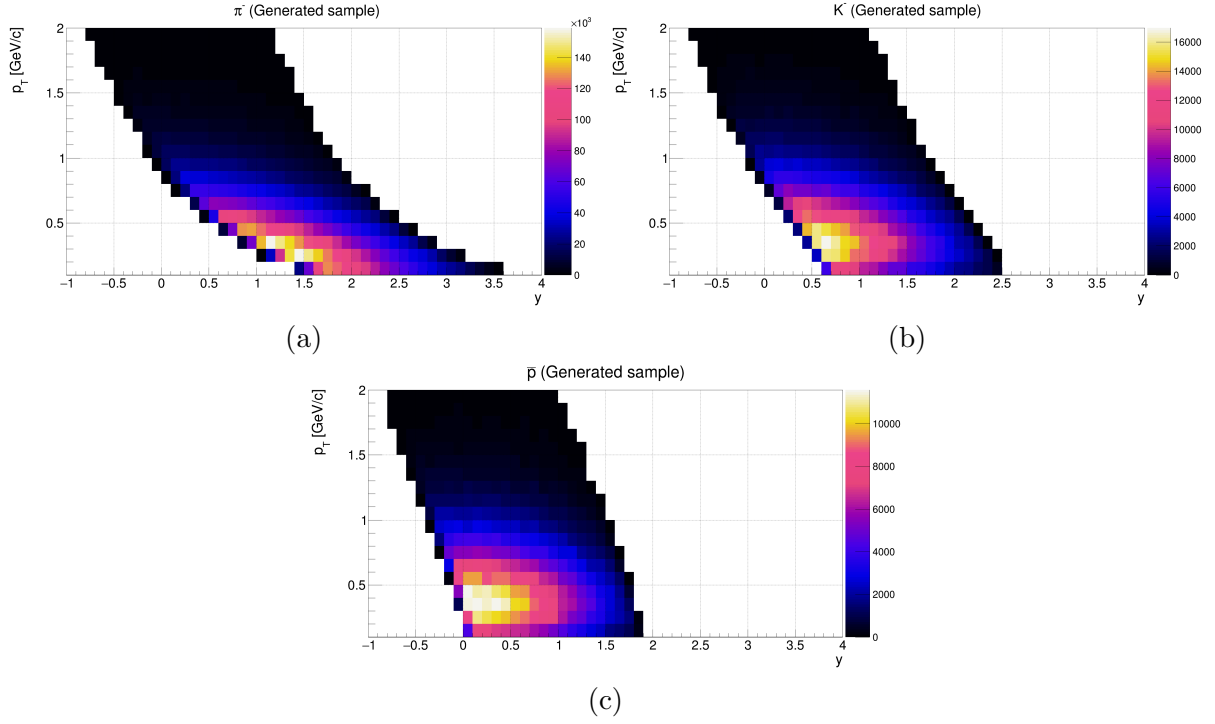


Figure 6.5: Transverse momentum vs rapidity in center of mass frame for negative hadrons (generated sample)

6.2.2 Reconstructed sample selection

The MC reconstructed selection follows almost the same criteria of the real data selection (see Sec. 6.1). The only differences are related to the bad spills and time in spill selection and to the CEDAR cuts and the RICH-related cuts. The hadron species are identified using the MC truth.

The cuts applied to the reconstructed sample are the following:

1. trigger mask has physics trigger bit fired;
2. primary vertex exists and is tagged by CORAL as best;
3. location of primary vertex is inside the liquid helium target;
4. beam track is well reconstructed in the beam telescope;
5. beam track pass through whole target;
6. vertices with tracks multiplicity of 1 are skipped;

The outgoing tracks from primary vertices are selected if:

1. tracking $\chi^2/ndf < 10$;
2. radiation length crossed $X/X_0 < 10$;
3. first and last measured point are respectively before and after SM1;

4. defined mean time;
5. at the RICH entrance, momentum in $[10, 60]$ GeV/ c and polar angle in $[0.01, 0.18]$ rad;

6.2.3 MC/RD comparison

I checked the reliability of the simulation by comparing the reconstructed MC sample with the RD sample for some of the relevant variables in the spectrometer reference frame. The results are visible in Fig. 6.6. In general the shape of the momentum and azimuthal angle distributions are reproduced very well. The p_T comparison shows the most discrepancies. The origin of which could reside at the physics generator level. The position of primary vertex along z is also matching the RD distribution below few percent difference, while the X and Y vertex shapes are strongly dependent on the beamfile input of the MC and are not perfect at the edges of the distributions, mainly due to the low statistic from the beamfile extraction procedure (Sec. 5.1). However, the central part of the beam spatial features is well reproduced for the Y, and with a 20 % maximum difference for the X. These quantities were checked in different bins of Z_{vtx} and all keep the same behavior in the different target zones.

6.2.4 3D acceptance results

The binning used for the acceptance calculation is determined after a study on the resolution in reconstructing the momentum and its transverse component. I checked the resolutions using the reconstructed sample and by comparing the tracks' reconstructed momentum with the MC truth. From the distributions of $\Delta p = p^{rec} - p^{gen}$ and $\Delta p_T = p_T^{rec} - p_T^{gen}$ we can take the RMS and average value, to which I will refer respectively as *resolution* and *bias*. The study is performed in different bins of momentum and transverse momentum, Z_{vtx} coordinate and for the 3 hadron species considered (π, K, p). As an example, in one of the vertex bins the bias and resolutions are displayed in Fig. 6.8 for pions, in Fig. 6.9 for kaons and in Fig. 6.7 for protons. The RMS and mean of the variable being checked are studied as a function of the generated variable, while the division in bins of the other variables is taken from reconstructed information. In general the bias does not show particular kinematic dependence and is rather flat. The resolution decreases naturally with momentum, but the relative precision is stable. In the edges of the phase space the resolutions show a bending knee, possibly due to lower statistics with respect to the other bins. However, the very last points can be extrapolated from the previous ones and do not alter the results of this study.

The variables checked have the following minimum and maximum values (among all the bins studied):

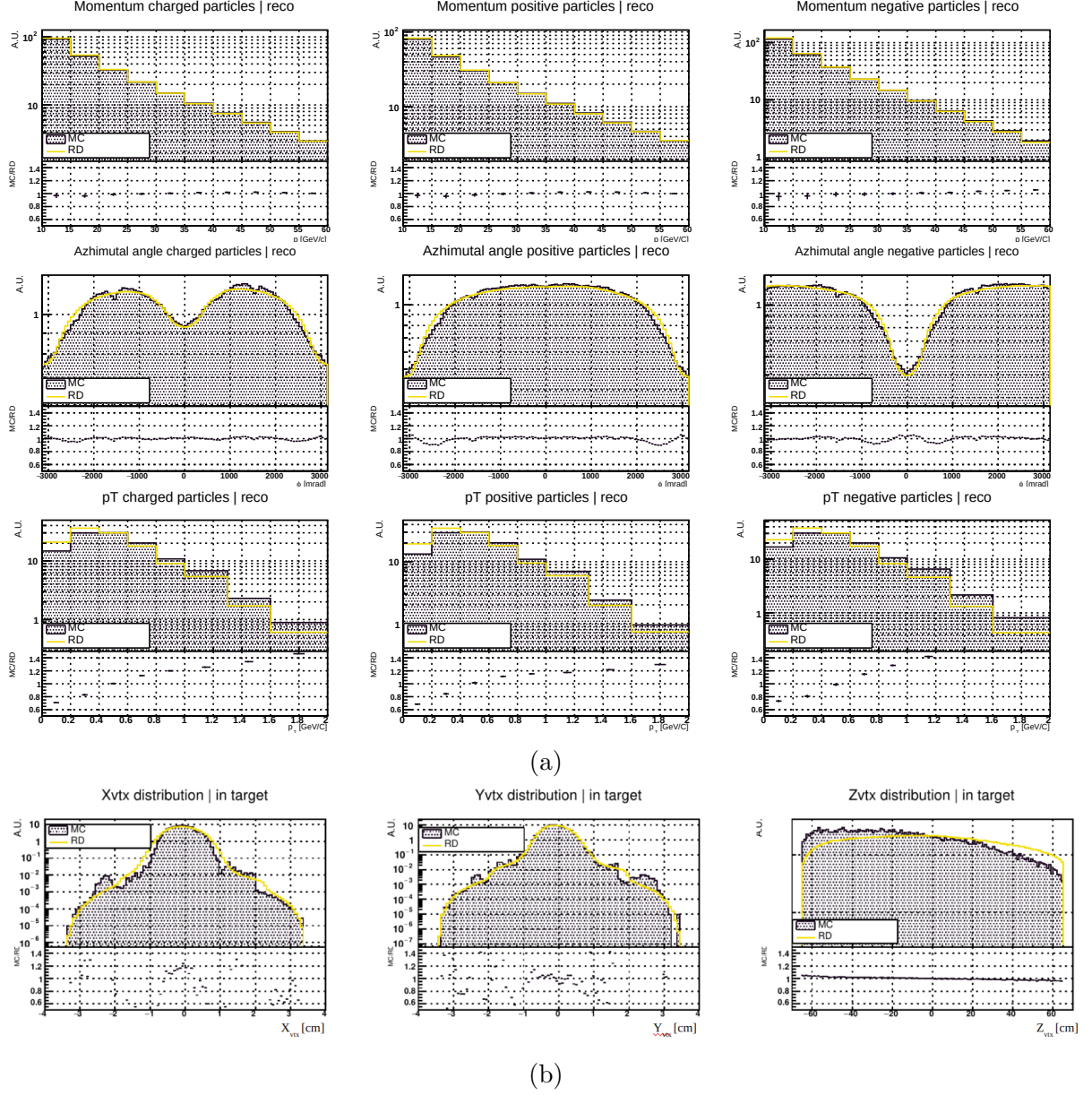
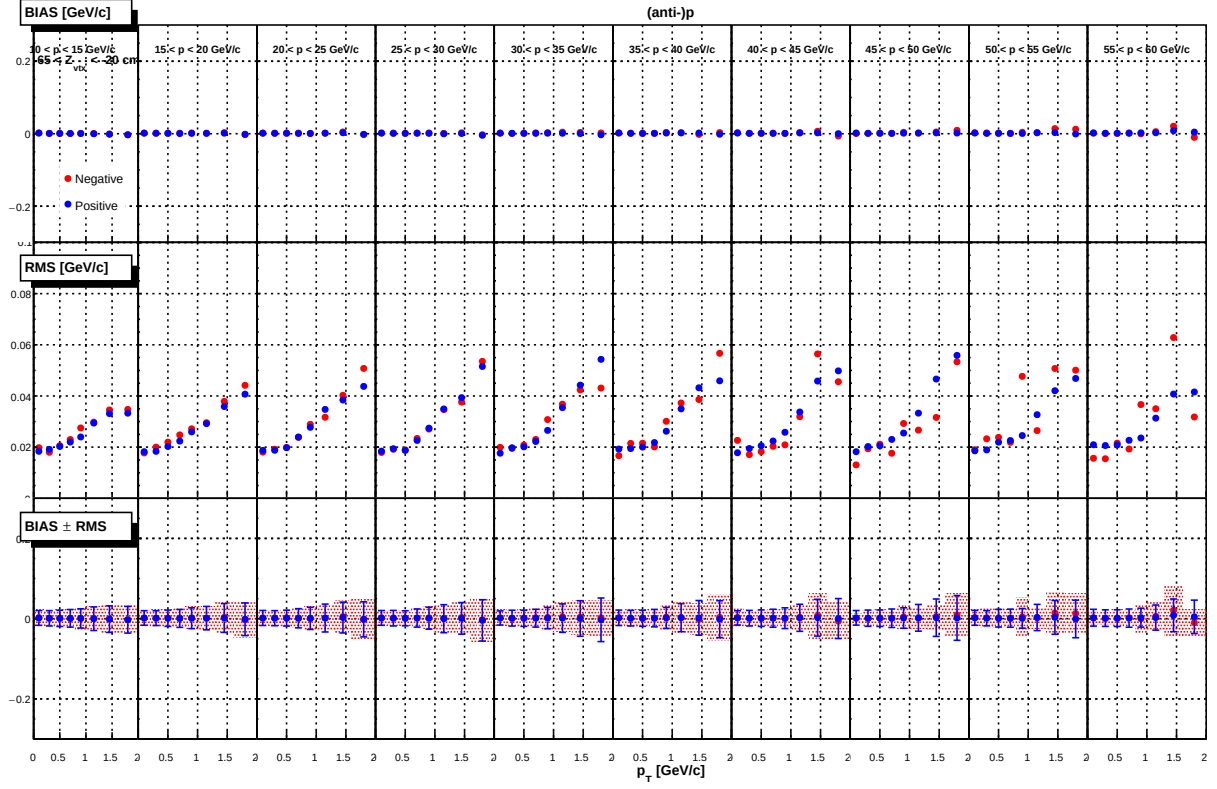
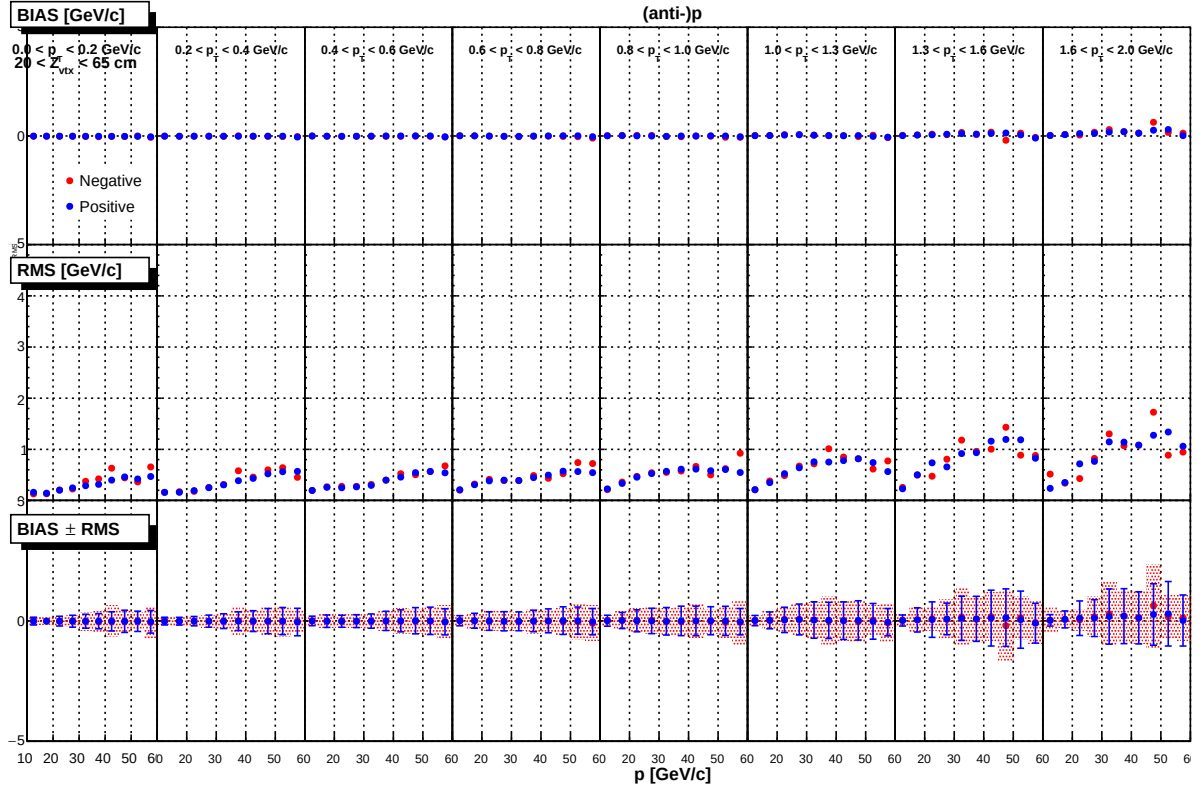


Figure 6.6: Comparison between reconstructed MC and RD. The histograms are normalized to an arbitrary value. In figure (a) the columns are, respectively from left to right, total selected tracks, positive and negative. On the first row, the momenta are compared. In the second row the azimuthal angle ϕ , and on the third row the p_T . In figure (b) one can compare the primary vertices position. At the bottom of each plot, the ratio MC/RD per each bin is shown.

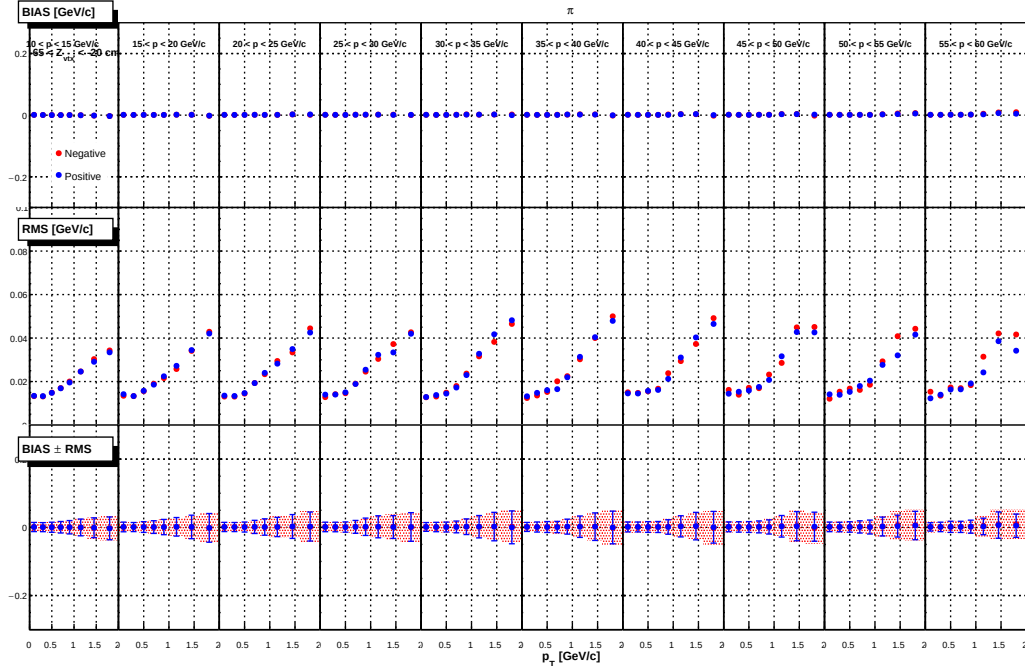


(a)

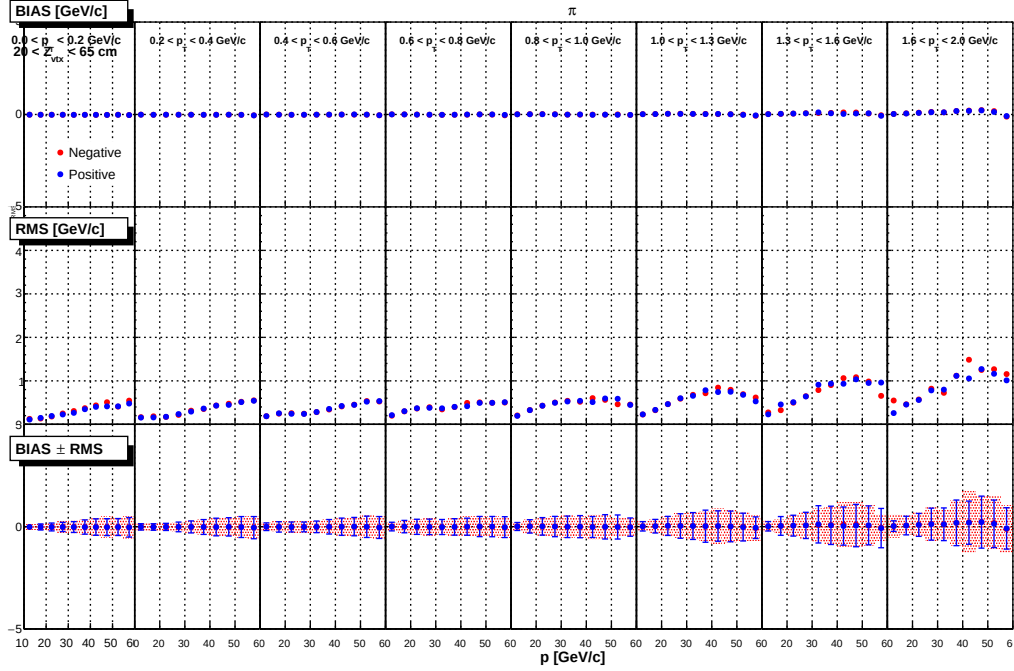


(b)

Figure 6.7: Proton and antiprotons bias and resolution in reconstructing the momentum and p_T in a particular Z_{vtx} region indicated on top left corner. Top: the different columns indicate different momentum bins; bottom: columns indicate different p_T bins. Red color is referred to negative particles, blue color to positive particles.

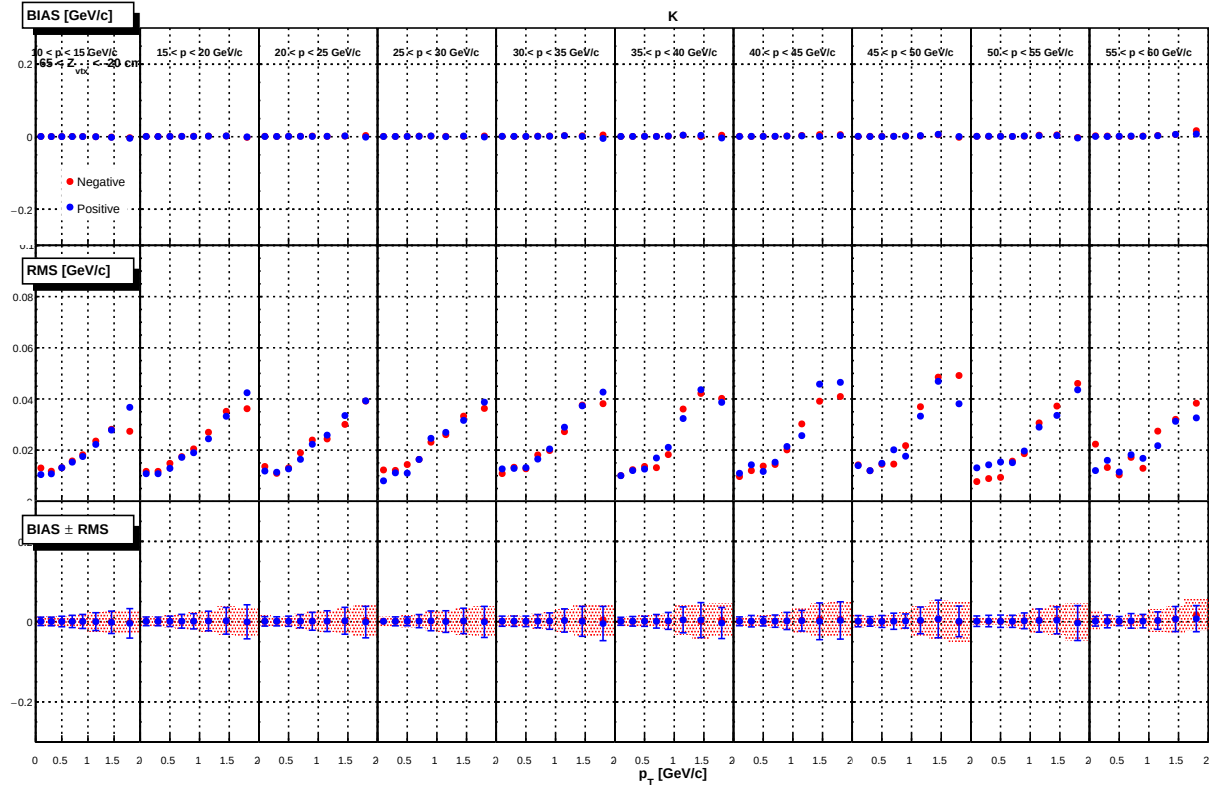


(a)

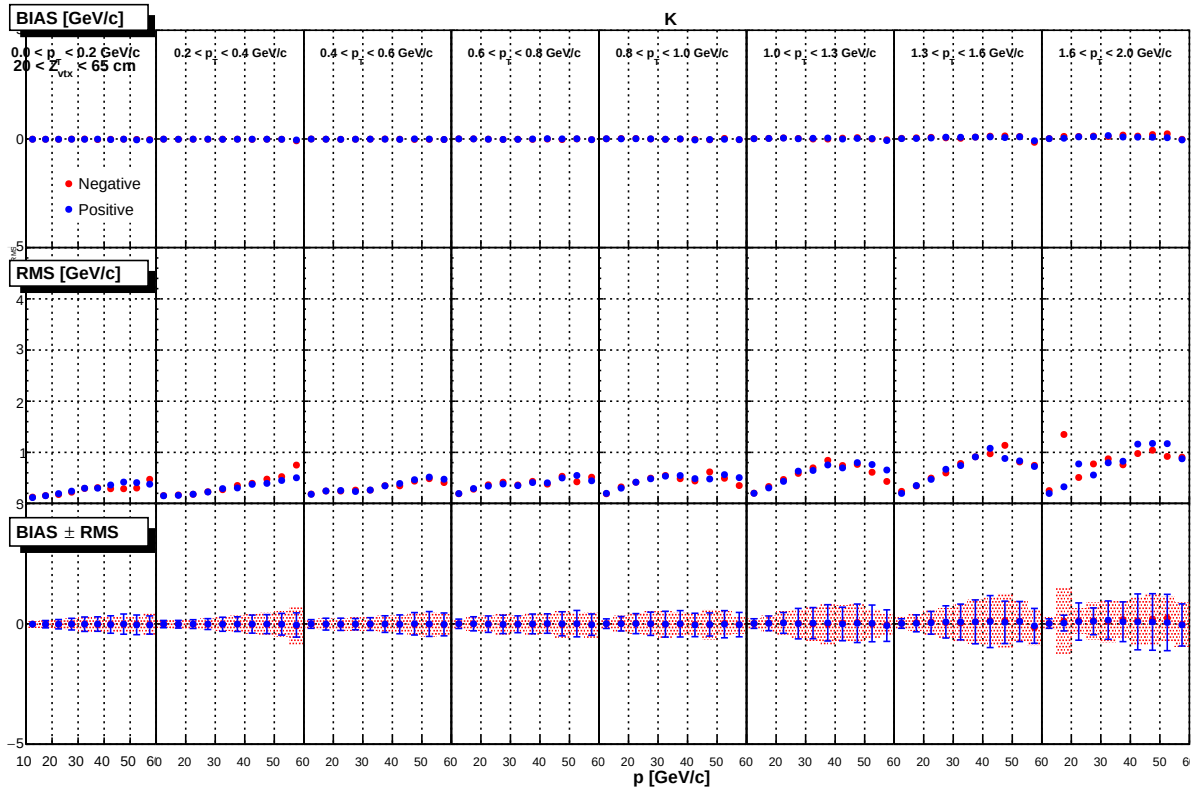


(b)

Figure 6.8: $\pi^{+/-}$ bias and resolution as in Fig. 6.7



(a)



(b)

Figure 6.9: Kaons bias and resolution as in Fig. 6.7

Particle	p bias [GeV/c]		p RMS [GeV/c]		p_T bias [GeV/c]		p_T RMS [GeV/c]	
	Min	Max	Min	Max	Min	Max	Min	Max
π	-0.1	0.3	0.1	1	-0.003	0.01	0.03	0.05
k	-0.2	0.7	0.1	2	-0.005	0.02	0.03	0.05
p	-0.7	1	0.1	2	-0.01	0.02	0.04	0.06

Table 6.3: Particle Momentum and Transverse Momentum Bias and RMS Values.

Considering the results of this study on resolution and bias and the statistics of the generated MC sample, I have chosen the following binning in momentum and p_T :

- 9 bins in momentum with a 5 GeV/c width
[10, 15, 20, 25, 30, 35, 40, 45, 50, 60] GeV/c
- 8 bins in p_T of variable width, larger than the minimum resolution
[0., 0.2, 0.4, 0.6, 0.8, 1.0, 1.3, 1.6, 2.0] GeV/c

The acceptance calculation results are shown in 1D projections in Figs. 6.10 to 6.12 for the different particle types, for $-20 < Z_{vtx} < 20$ cm. The profiles show a flat dependence along momentum for p_T above 0.8 GeV/c with an acceptance of ~ 0.6 , while we do observe a strong dependence for smaller p_T ranges. In general the positive tracks are better reconstructed by $\sim 5\%$. For the different particles species the acceptance is similar and show same behavior. At low p_T and momenta larger than 45 GeV/c the number of reconstructed particles drop to 0 and the acceptance correction as well.

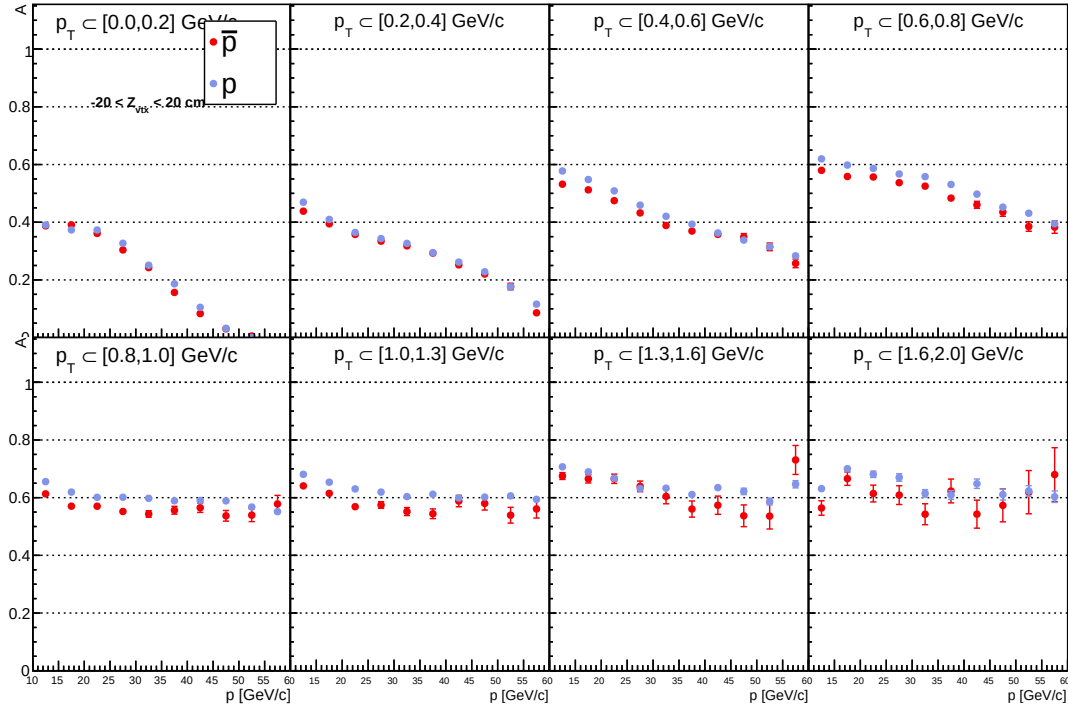


Figure 6.10: Acceptance correction for protons and antiprotons.

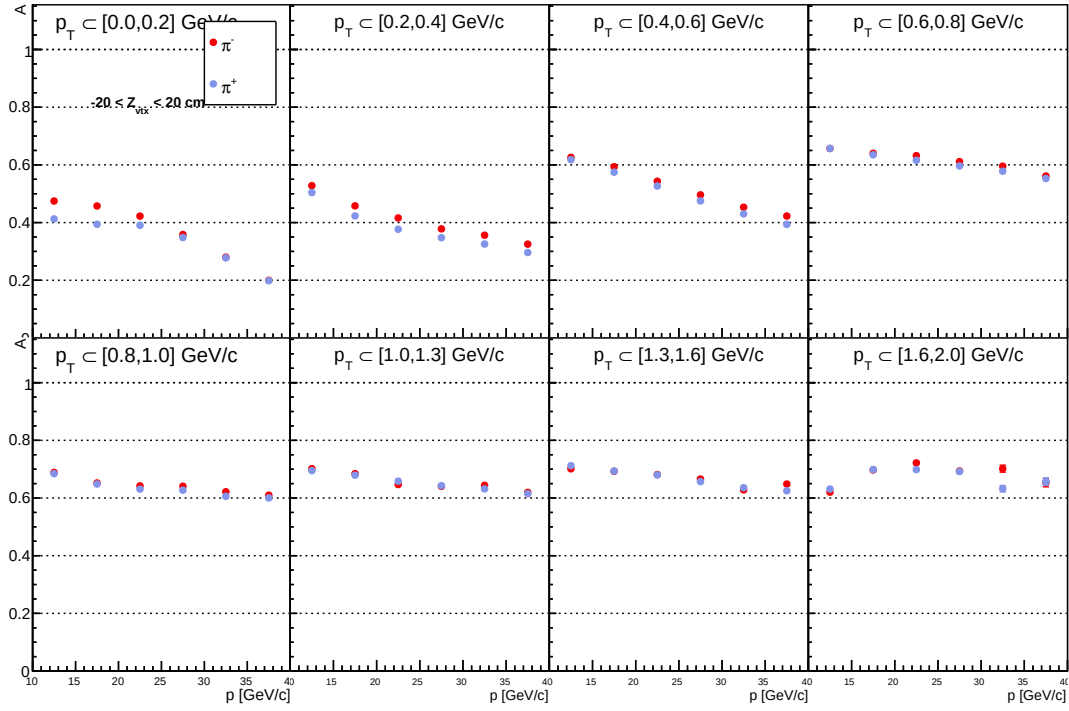


Figure 6.11: Acceptance correction for pions.

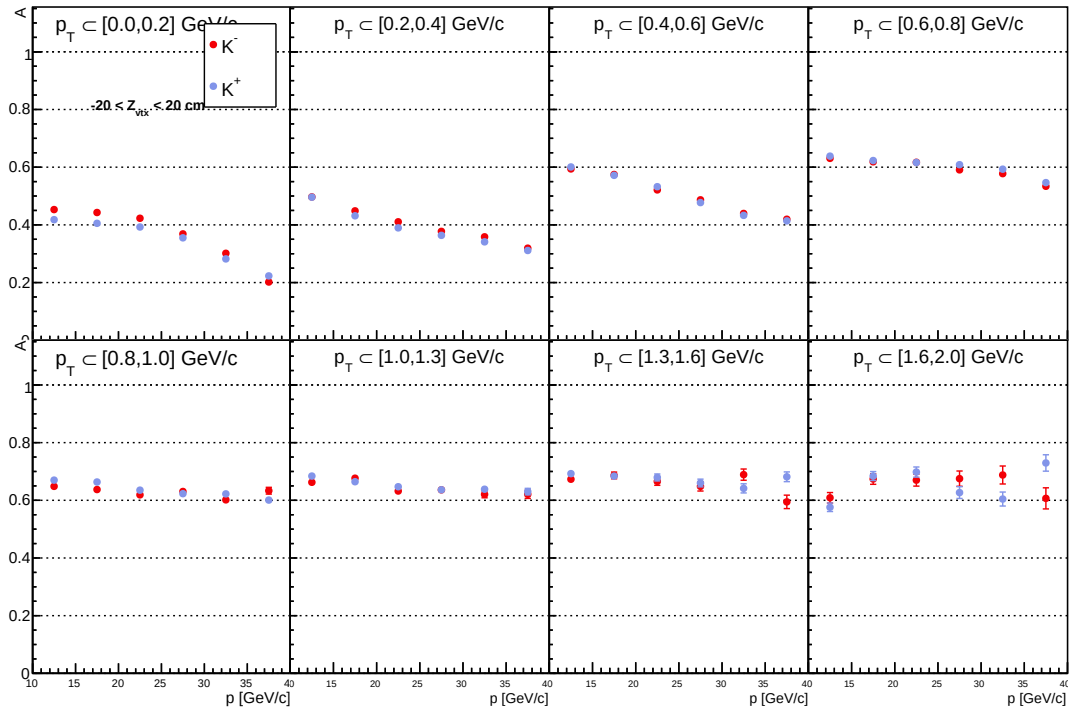


Figure 6.12: Acceptance correction for kaons.

For a better visualization, the 2D generated and reconstructed sample, along with their ratio, are shown in Fig. 6.13 for antiprotons as an example. The ratio of protons over antiprotons acceptance are displayed in Fig. 6.14. This ratio is rather stable at 1, but shows some discrepancies at the edges of the phase space.

6.3 RICH unfolded spectra results

The identified hadron spectra are corrected event by event for the RICH unfolding according to the following relation:

$$N_h^{true} = M_{RICH}^{-1} \cdot N_h^{id} \quad (6.3)$$

with N_h^{true} being the true number of hadrons and N_h^{id} the identified number of hadrons h . The inversion of the RICH matrix is a non-linear operation and the 3x3 inverted elements M_{ij}^{-1} have covariances $\text{cov}(M_{\alpha\beta}^{-1}, M_{ab}^{-1})$ that can be written in terms of the non-inverted covariances [164] as:

$$\text{cov}(M_{hr}^{-1}, M_{hr}^{-1}) = \sum_{i,j,k,l=0}^3 M_{hi}^{-1} M_{jr}^{-1} M_{hk}^{-1} M_{lr}^{-1} \text{cov}(M_{ij}, M_{kl}) \quad (6.4)$$

with

$$\text{cov}(M_{ij}, M_{kl}) = [\sigma_M]_{ij}^2 \delta_{ik} \delta_{jl} \quad (6.5)$$

This relation is used to calculate the statistical error σ_h on the number of identified hadron N_h^{true} as:

$$\sigma_h^2 = \sum_{i=1}^{N_h} \sigma_{RICH,i}^2 = \sum_{i=1}^{N_h} \left[\text{cov}(M_{hr}^{-1}, M_{hr}^{-1}) + (M_{hr}^{-1})^2 \right] \quad (6.6)$$

with M_{hr} the element of the RICH matrix for hadron h from RICH identified hadron r .

The hadron spectra are shown in Figs. 6.15 to 6.17, for positive and negative particles.

The errors propagation from the matrix inversion highly affects the higher p_T bins, where the PID efficiency matrix is not well known due to the poor illumination of the detector from V0 decays and consequently the limited statistics.

6.3.1 Systematics effects from likelihood cuts

Following the approach in [165, 166], one can study the RICH-induced systematic effects by using different likelihoods cuts and comparing their impacts on the extracted spectra. Two methods are used to compute this estimate. The first one by creating two new sets of likelihoods, namely *loose* and *tight* and compare the effect on the hadron multiplicities. The second way is to vary the identification and misidentification probabilities within the statistical error associated and look at the final impact on data. Both methods are taken into account, leading respectively to $\sigma_{sys}^{RICH,LH}$ and $\sigma_{sys}^{RICH,stat}$.

The new sets for *loose-tight* approach are listed in Tab. 6.4. The label tight and loose are intended with respect to the likelihoods used during the spectra unfolding (see Tab. 4.1).

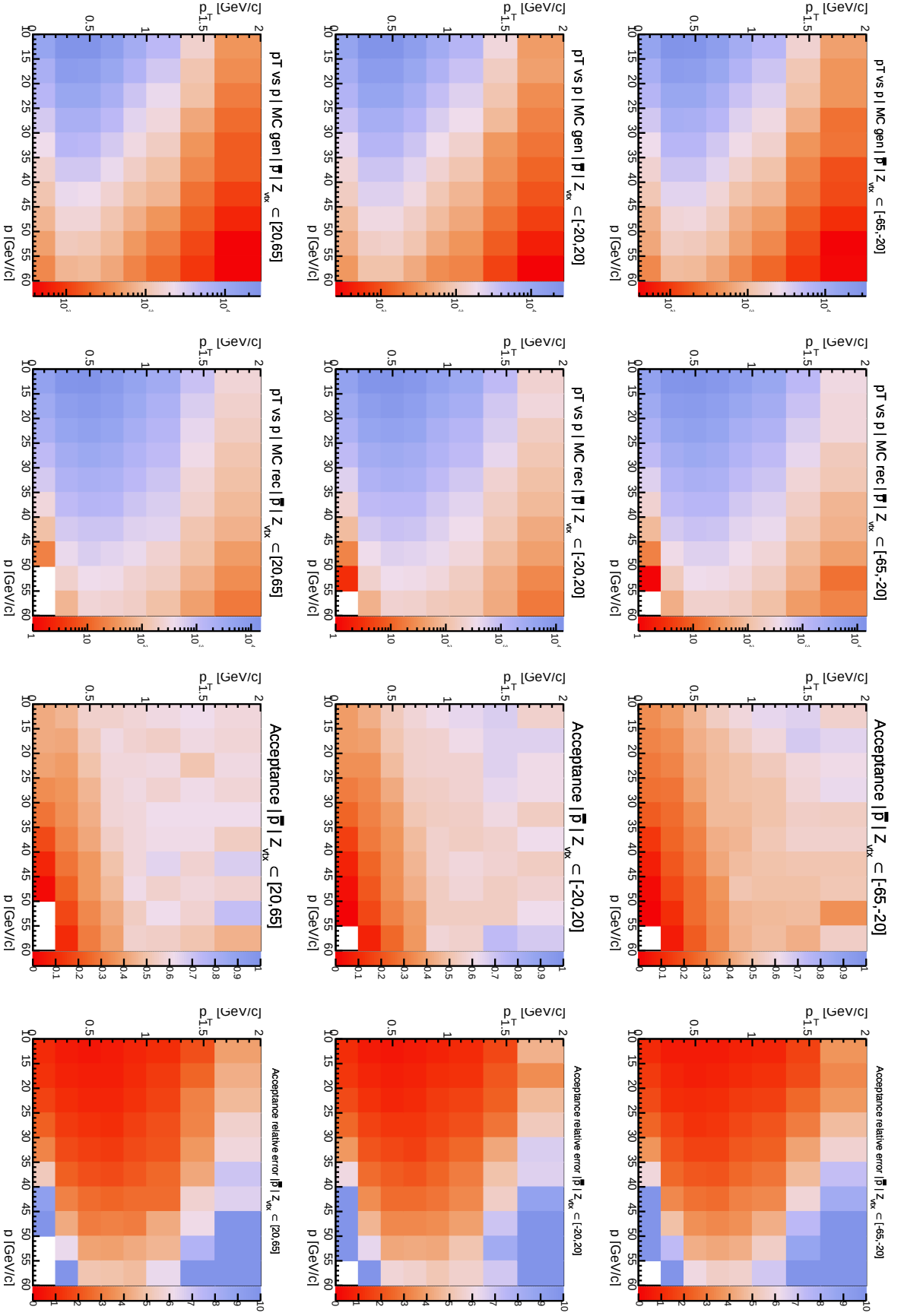


Figure 6.13: From top to bottom: different bins of Z_{vtx} . From left to right: 2D phase space of generated and reconstructed antiprotons, acceptance corrections and the relative error in percentage on the acceptance. The relative error plots has the maximum at 10%, blue-ish in the color scale, to better visualize the discarded bins due to the high uncertainty.

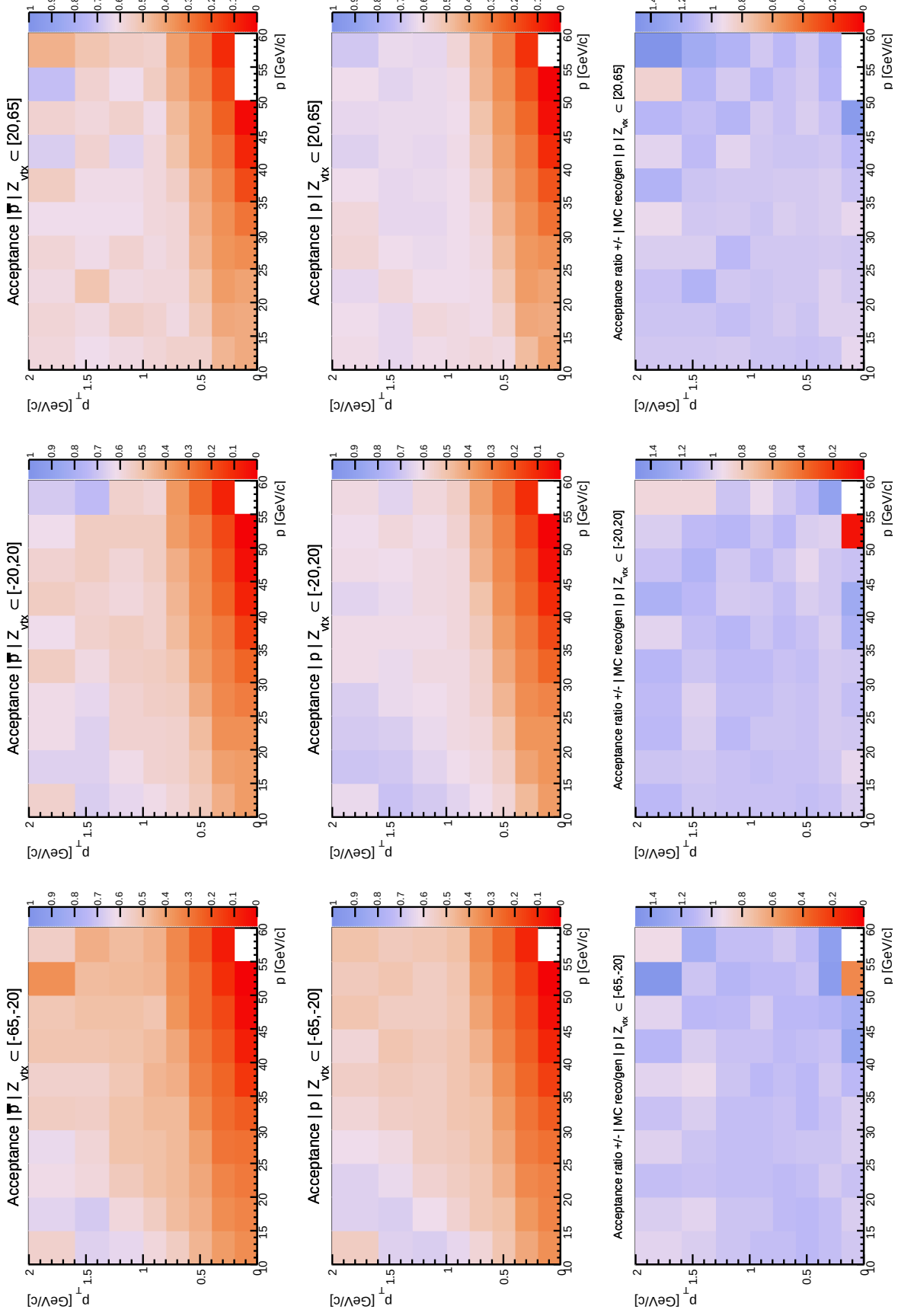
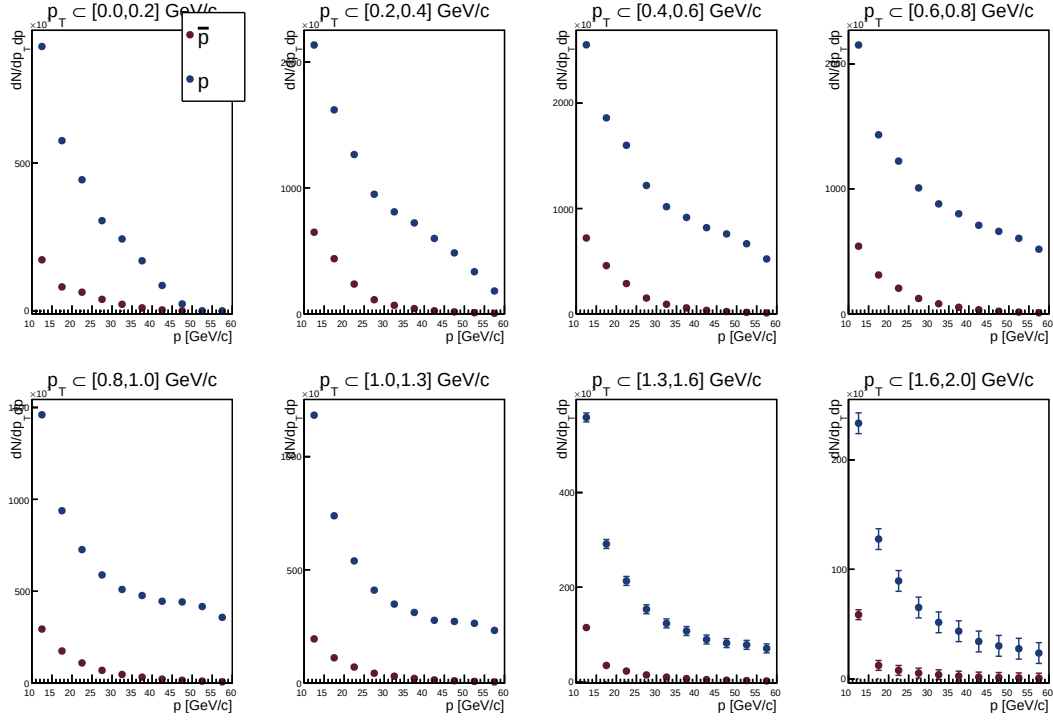
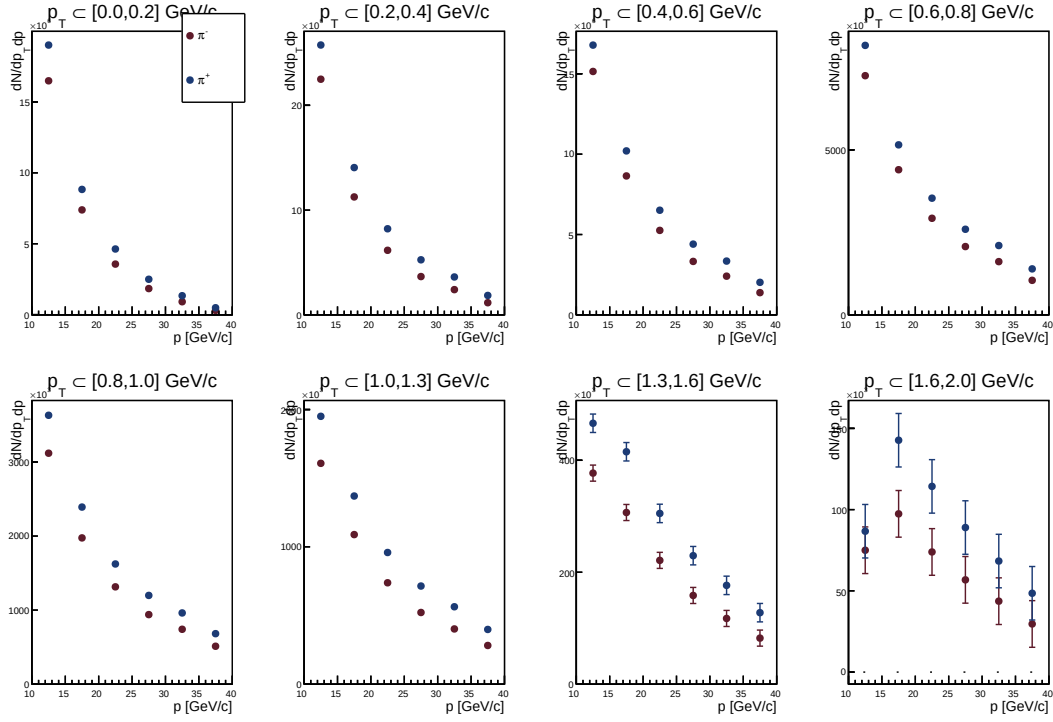
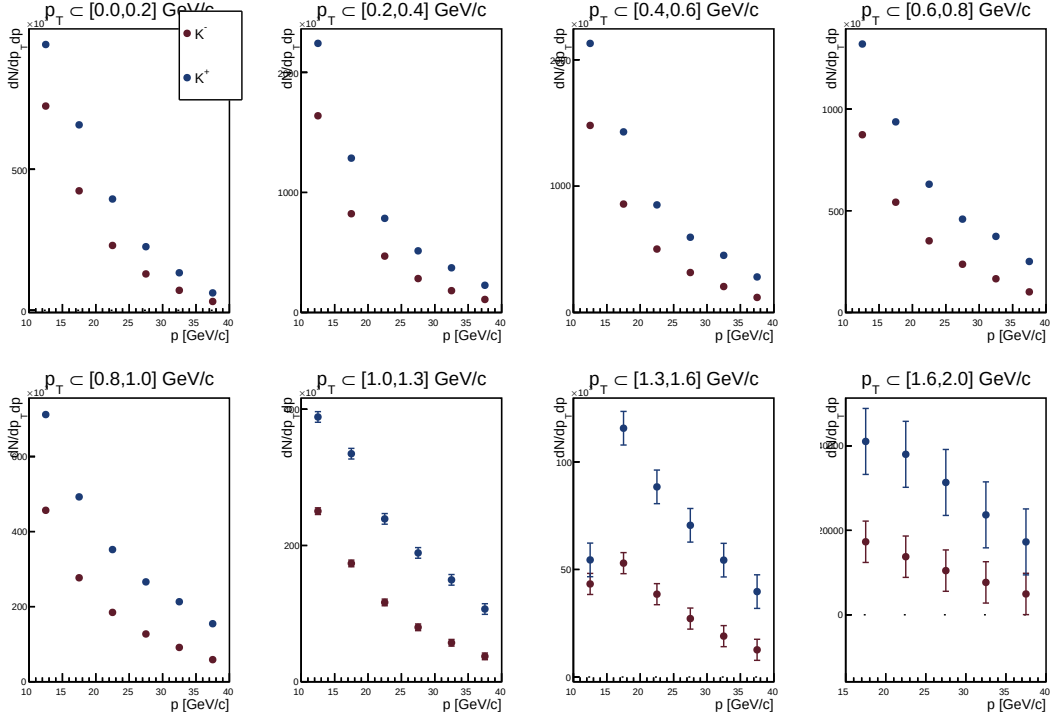


Figure 6.14: From top to bottom: 2D acceptance for antiprotons, protons and their ratio. From left to right: different bins of Z_{vtx} .

Figure 6.15: p and $\bar{p}$ raw spectra unfolded for RICH purity.Figure 6.16: $\pi^{+/-}$ raw spectra unfolded for RICH purity.

Figure 6.17: $K^{+/-}$ raw spectra unfolded for RICH purity.

	Loose			Tight		
	π	K	$p(\bar{p})$	π	K	$p(\bar{p})$
$LH(i)$	-	> 1.01	> 1.01	-	> 1.11	> 1.11
$LH(\pi)$	-	> 1.01	> 1.01	-	> 1.11	> 1.11
$LH(i)$	> 1.01	-	> 1.01	> 1.11	-	> 1.11
$LH(K)$	> 1.01	> 1.01	-	> 1.11	> 1.11	-
$LH(p)$	> 1.01	> 1.01	> 1.01	> 1.11	> 1.11	> 1.11
$LH(i)$	> 1.20	> 1.20	> 1.20	> 1.35	> 1.35	> 1.35
$LH(bkg)$	-	-	$< 2.6(2.6)$	-	-	$< 2.4(2.4)$
$LH(K)$	-	-	$< 2.6(2.6)$	-	-	$< 2.4(2.4)$
$LH(\pi)$	-	-	$< 2.6(2.6)$	-	-	$< 2.4(2.4)$
$LH(bkg)$	-	-	$< 2.6(2.6)$	-	-	$< 2.4(2.4)$

Table 6.4: Different cuts used to evaluate systematic effects from the LH used in the RICH matrix evaluation.

The RICH efficiencies are extracted again for both cases and the differences with respect to the nominal values are shown in Figs. 6.18 and 6.19. The loose cuts are characterized by high efficiency in pion identification. The misidentification probabilities differ of a few percent with respect to the nominal ones. Largest differences are for momentum under proton PID threshold, meaning that the main difference is related to the disentanglement of the particles hypothesis with respect to the background. Also, the under threshold proton identification relies on the efficiency in identifying the pions and kaons and changes accordingly. In the tight set we can see the opposite behavior. Pions and kaons are less likely to be identified and it translates into higher misidentification probability.

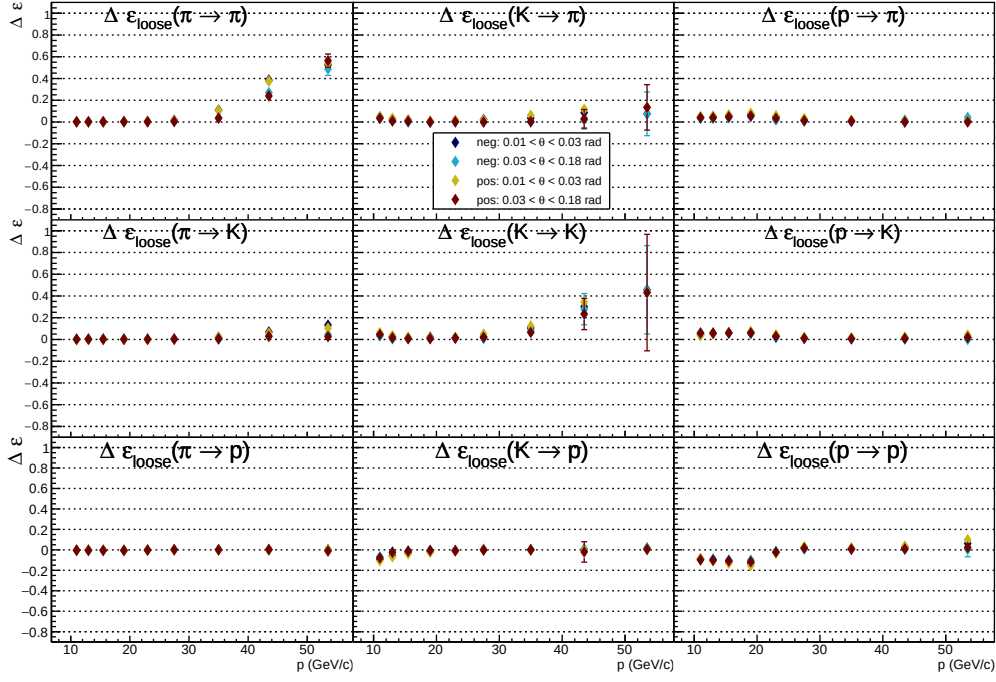


Figure 6.18: Difference on the absolute values of efficiencies for loose likelihood cuts with respect to nominal ones. Different colors mean positive/negative particles and different θ bins.

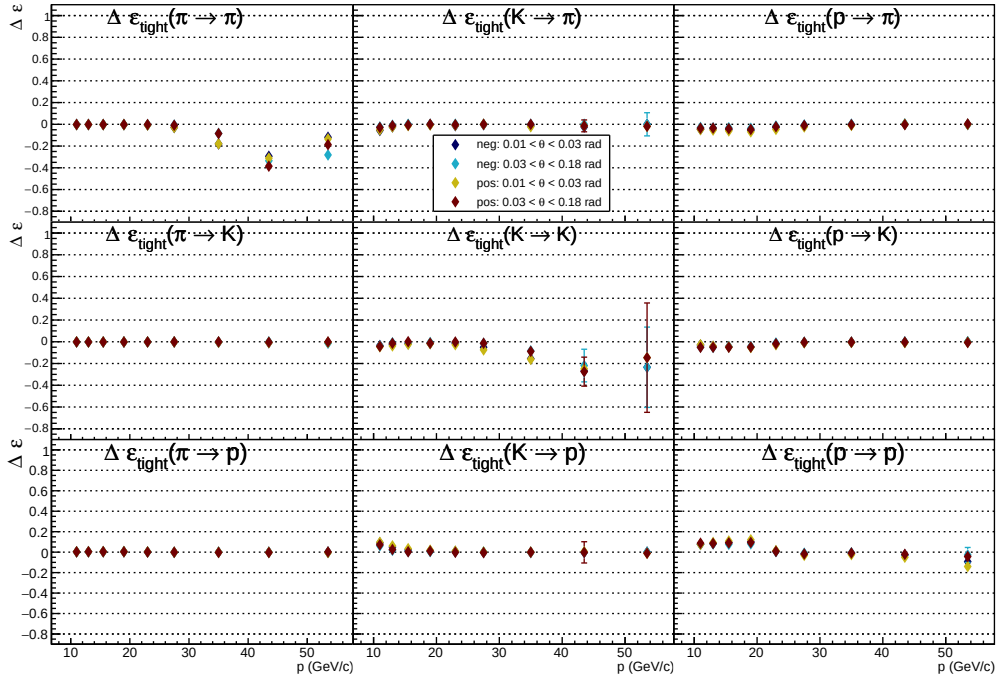


Figure 6.19: Difference on the absolute values of efficiencies tight likelihood cuts with respect to the nominal ones. Different colors mean positive/negative particles and different θ bins.

With the new cuts I extracted again the hadrons spectra with loose and tight requirements and compared to the nominal ones. The systematics effects from the likelihoods cuts are estimated by taking the maximum difference either in the loose or in the tight set according to:

$$\sigma_{\text{sys}}^{\text{RICH}_{LH}} = \text{MAX} \left(|N_{\text{raw}}^{h^{\pm}, \text{loose}} - N_{\text{raw}}^{h^{\pm}}|, |N_{\text{raw}}^{h^{\pm}, \text{tight}} - N_{\text{raw}}^{h^{\pm}}| \right). \quad (6.7)$$

Another possible source of errors lie in the matrix element calculation. For this reason, I performed a study by varying the efficiencies within their statistical uncertainty calculated with Eq. (4.20) and created two matrices according to:

$$M_{\text{RICH}}^{\pm} = \begin{pmatrix} \epsilon(\pi \rightarrow \pi) \pm \sigma_{\epsilon(\pi \rightarrow \pi)} & \epsilon(K \rightarrow \pi) \mp \sigma_{\epsilon(K \rightarrow \pi)} & \epsilon(p \rightarrow \pi) \mp \sigma_{\epsilon(p \rightarrow \pi)} \\ \epsilon(\pi \rightarrow K) \mp \sigma_{\epsilon(\pi \rightarrow K)} & \epsilon(K \rightarrow K) \pm \sigma_{\epsilon(K \rightarrow K)} & \epsilon(p \rightarrow K) \mp \sigma_{\epsilon(p \rightarrow K)} \\ \epsilon(\pi \rightarrow p) \mp \sigma_{\epsilon(\pi \rightarrow p)} & \epsilon(K \rightarrow p) \mp \sigma_{\epsilon(K \rightarrow p)} & \epsilon(p \rightarrow p) \pm \sigma_{\epsilon(p \rightarrow p)} \end{pmatrix} \quad (6.8)$$

where the identification probabilities span in $\pm\sigma$ and the misidentification probabilities in $\mp\sigma$ to keep the total probability to 1. Again, from the 2 matrices we can compute 2 hadron spectra. The largest difference is taken as systematic error as:

$$\sigma_{\text{sys}}^{\text{RICH}_{\text{stat}}} = \text{MAX} \left(|N_{\text{raw}}^{h^{\pm}, +} - N_{\text{raw}}^{h^{\pm}}|, |N_{\text{raw}}^{h^{\pm}, -} - N_{\text{raw}}^{h^{\pm}}| \right) \quad (6.9)$$

The final systematic error associated to the hadron spectra, induced by the RICH matrix, is the maximum between $\sigma_{\text{sys}}^{\text{RICH}_{\text{stat}}}$ and $\sigma_{\text{sys}}^{\text{RICH}_{LH}}$ and is visible in Figs. 6.20 to 6.22 for the three hadron species.

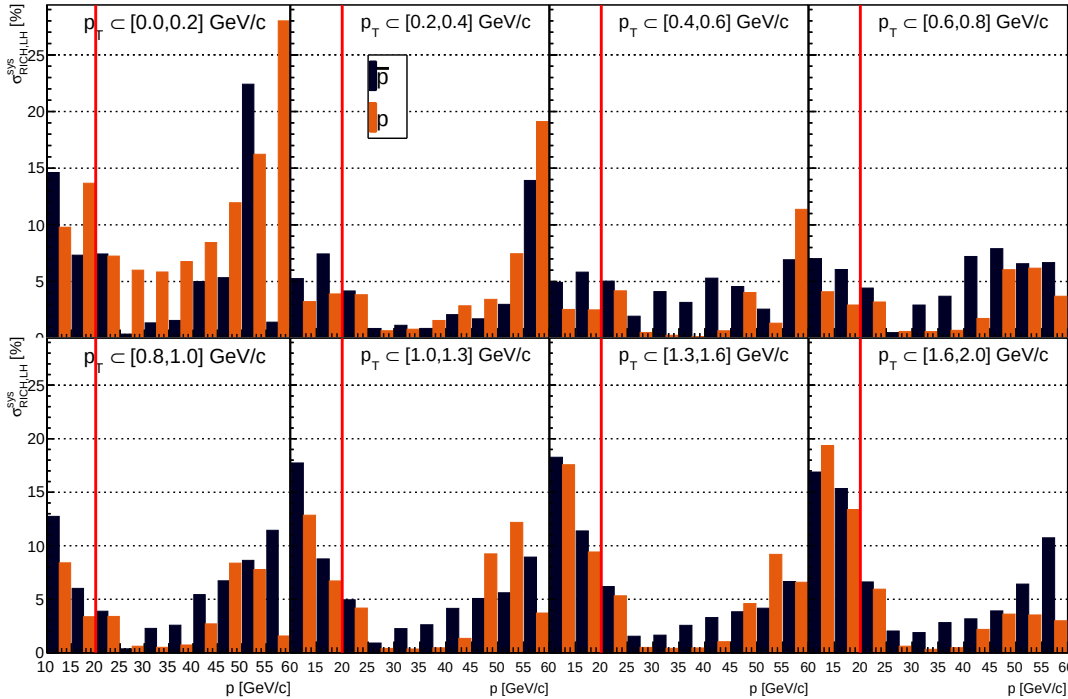


Figure 6.20: Systematic error on the proton and antiproton spectra induced by the choice of the the RICH likelihood cuts and statistical fluctuation of the efficiency values. The red line at the proton Cherenkov threshold indicate the change from VETO mode to active identification in the RICH-1.

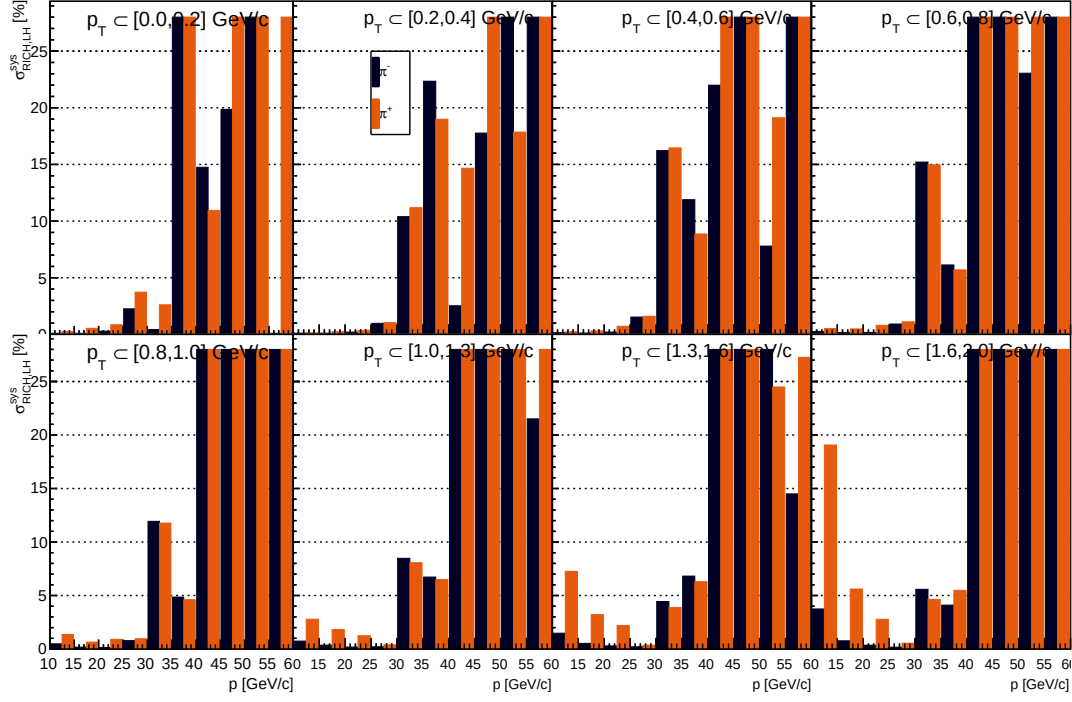


Figure 6.21: As in Fig. 6.20, for pions.

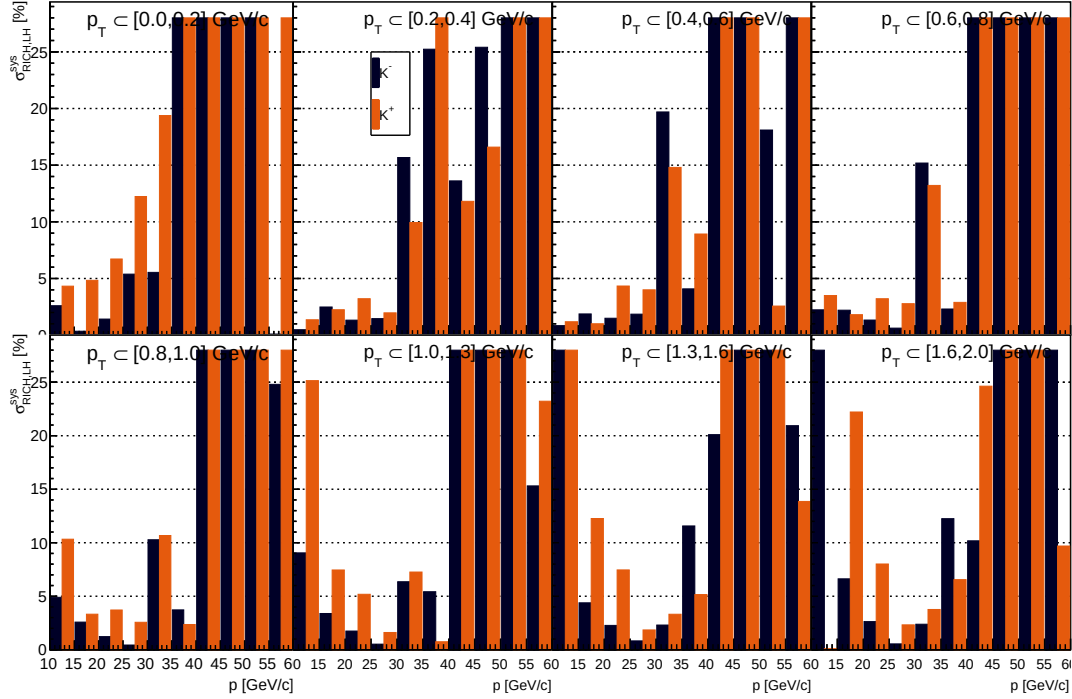


Figure 6.22: As in Fig. 6.20, for kaons.

The error induced by the choice of the likelihoods cuts is below few percent for pions

and kaons in the majority of the bins considered. The error increases dramatically at higher momenta where the separation of kaons and pions is no longer possible due to Cherenkov angle saturation. For this reason the bins with momenta larger than 40 are excluded in the future plots.

The errors on protons and antiprotons is contained in between 0-10 % in both the above and below threshold (18 GeV/c) identification for p_T in 0.4-1.0 GeV/c. The edges of the momentum interval are the most affected by the RICH-1 uncertainties, especially in the under threshold identification where the RICH-1 is used in 'veto' mode and errors reach 20 % in some bins. The most challenging bin of the phase space is at $p_T < 0.2$ GeV/c, where the acceptance is lower and the reconstruction of the tracks is more difficult. The identification in that region is less reliable.

6.4 Corrected spectra and shape comparison with event generator

The RICH-unfolded spectra are corrected for the acceptance and shown in Figs. 6.23 to 6.25. The plots are not normalized because deeper studies are needed to compare flux-normalized plots and the final cross sections.

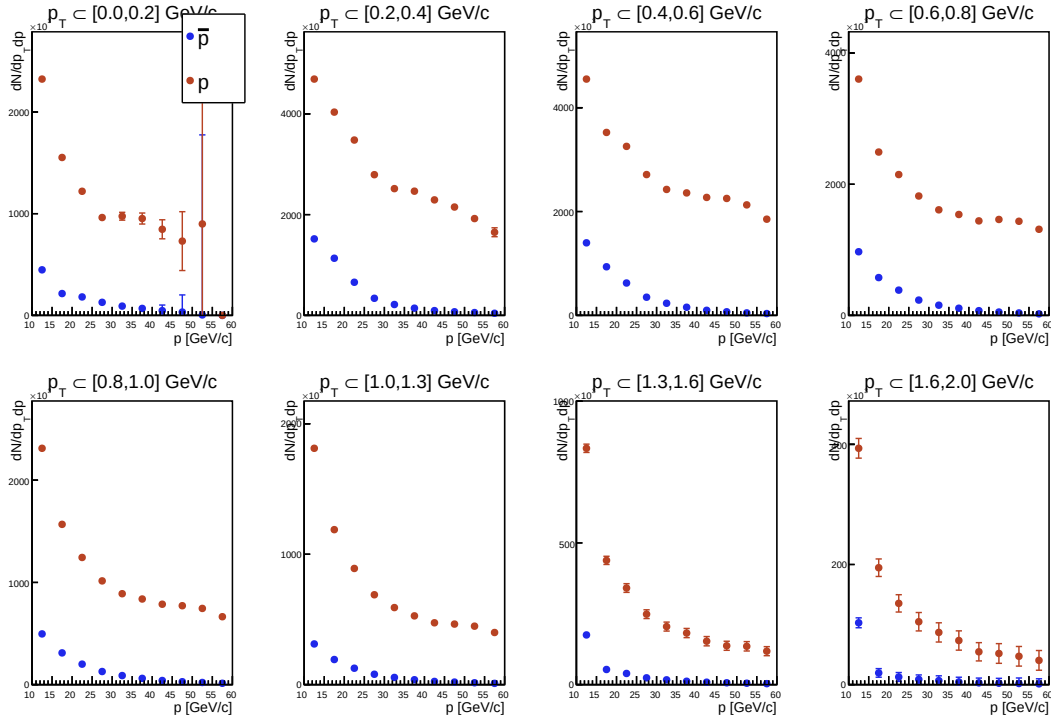


Figure 6.23: Unfolded proton spectra corrected for acceptance and PID efficiency. Only statistical uncertainty is shown, propagated from counting, RICH PID matrix and acceptance.

The shape of the hadron spectra is compared, in Figs. 6.26 to 6.28, with the PYTHIA8 event generator shape prediction. The comparison is only at the shape level and the plots

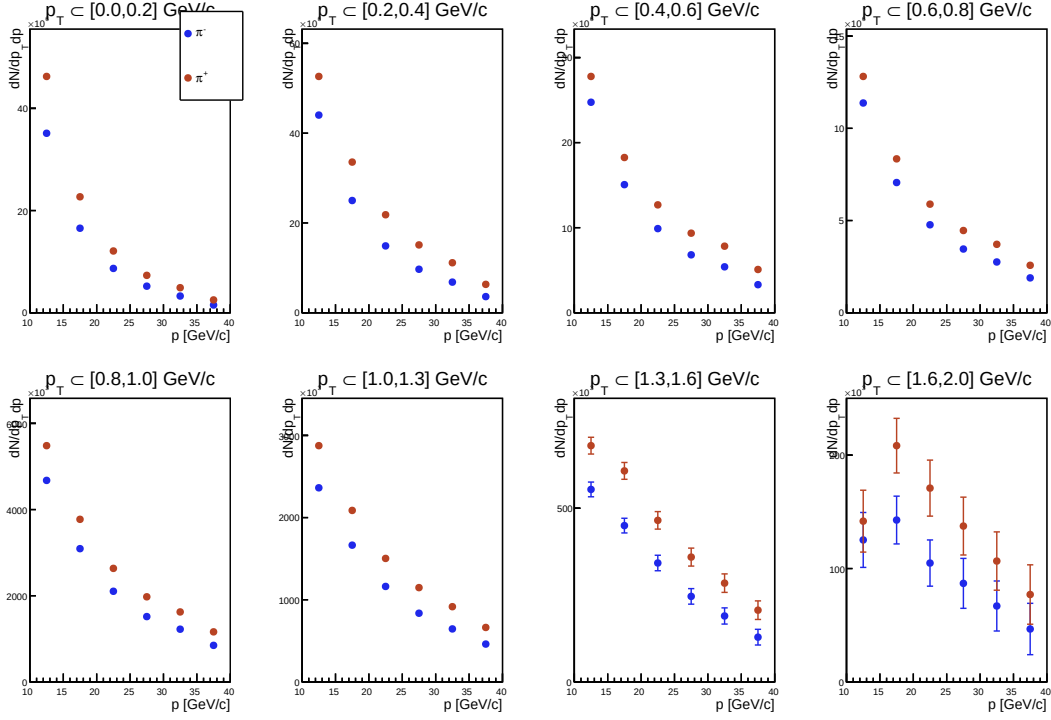


Figure 6.24: Unfolded pions spectra corrected for acceptance and PID efficiency. Errors as in Fig. 6.23.

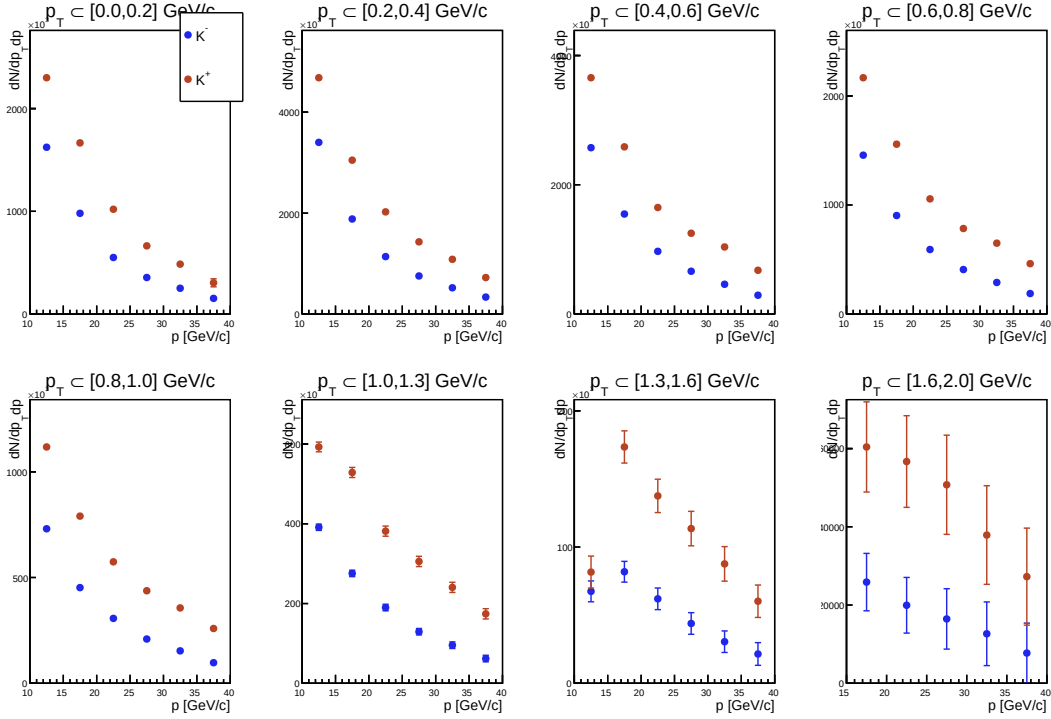


Figure 6.25: Unfolded kaons spectra corrected for acceptance and PID efficiency. Errors as in Fig. 6.23.

are arbitrary normalized over the integral of the entries. The bins with uncertainties larger than 10% from the acceptance or from the systematic of the PID matrix are covered respectively by red and blue bands. The blue errors on the single data points represent the statistical uncertainty propagated from the counting, the PID matrix elements and the acceptance. In green, the statistical plus the systematic uncertainty from the RICH PID matrix evaluated in the previous section. As a general comment, the shape prediction is in line with the experimental data for pions and kaons. The comparison show the most discrepancies for the proton production, possibly due to some misidentification of pions/kaons at higher momenta. The high transverse momentum region, even if with high relative uncertainties, show a good agreement of the central values.

In Figs. 6.29 to 6.31 the ratio of negative/positive identified particles is shown along the prediction of the PYTHIA8 model. The generator seems to overestimate the production of the negative hadrons with respect to their positive counterpart, especially for pions and kaons. For proton and antiprotons the agreement is better but this behavior can be found again in the high transverse momentum region. The predicted shape is also well reproduced by the data. The errors on the data points include the statistical uncertainties and the systematic effects of the PID matrix.

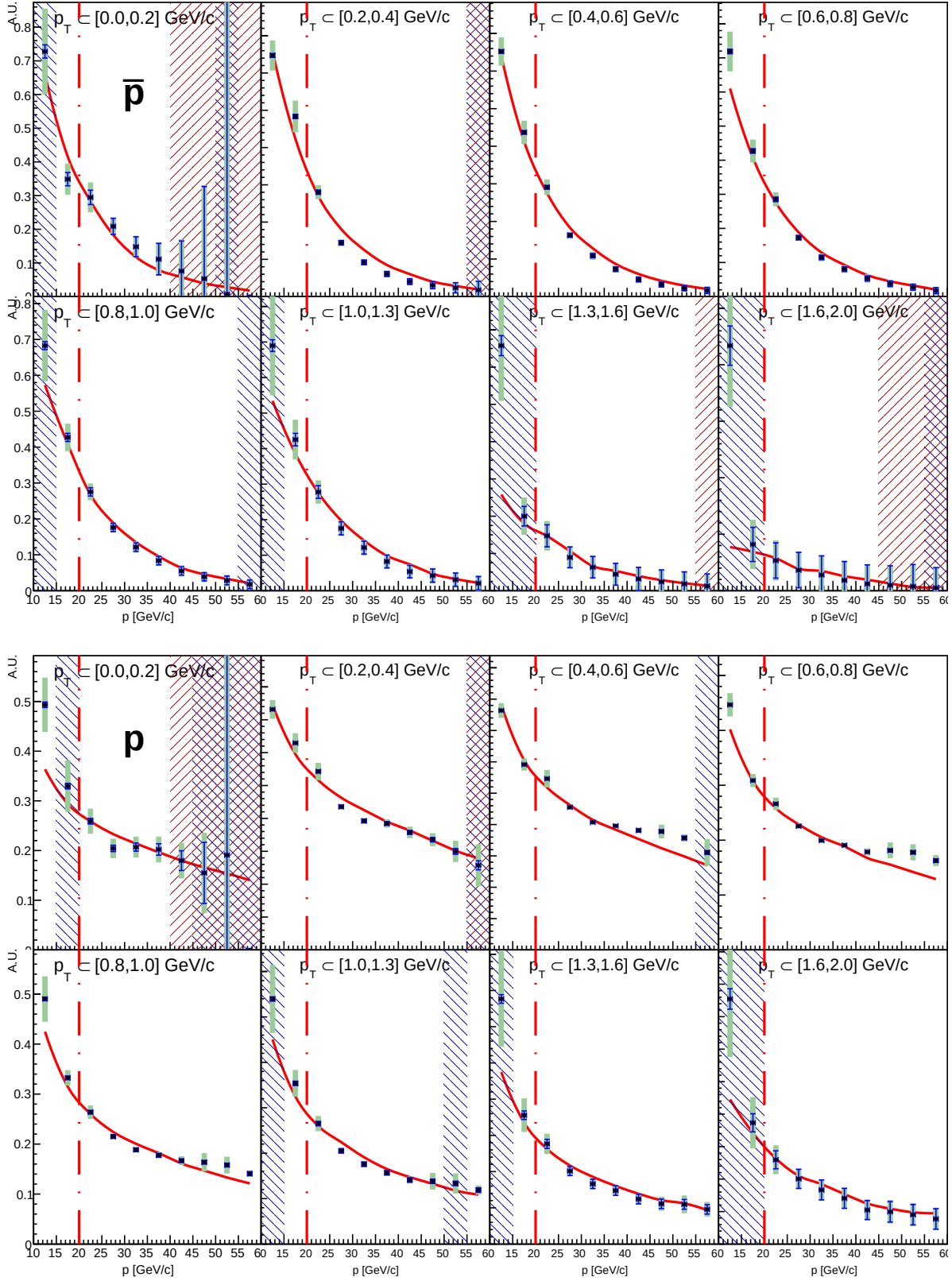


Figure 6.26: Protons/antiprotons spectra in bins of momentum and transverse momentum in laboratory frame. In red, a shape prediction from the generated MC sample. The bands represent bins in which the acceptance (red) and the RICH-1 systematic (blue) become larger than 10%. The dashed vertical red line indicates the proton Cherenkov threshold and the change of identification algorithm.

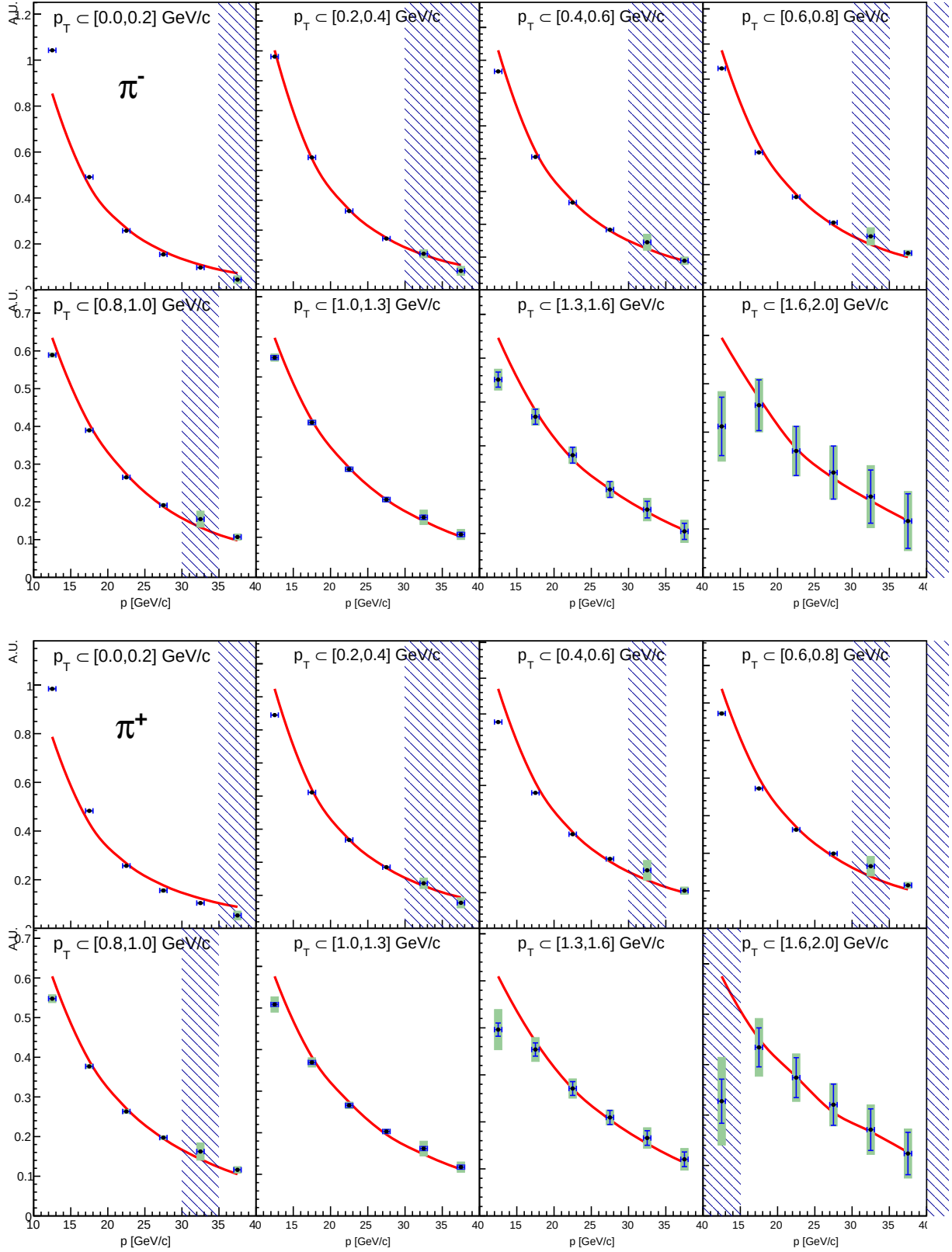


Figure 6.27: Pions spectra in bins of momentum and transverse momentum in laboratory frame. In red, a shape prediction from the generated MC sample. The bands represent bins in which the acceptance (red) and the RICH-1 systematic (blue) become larger than 10%.

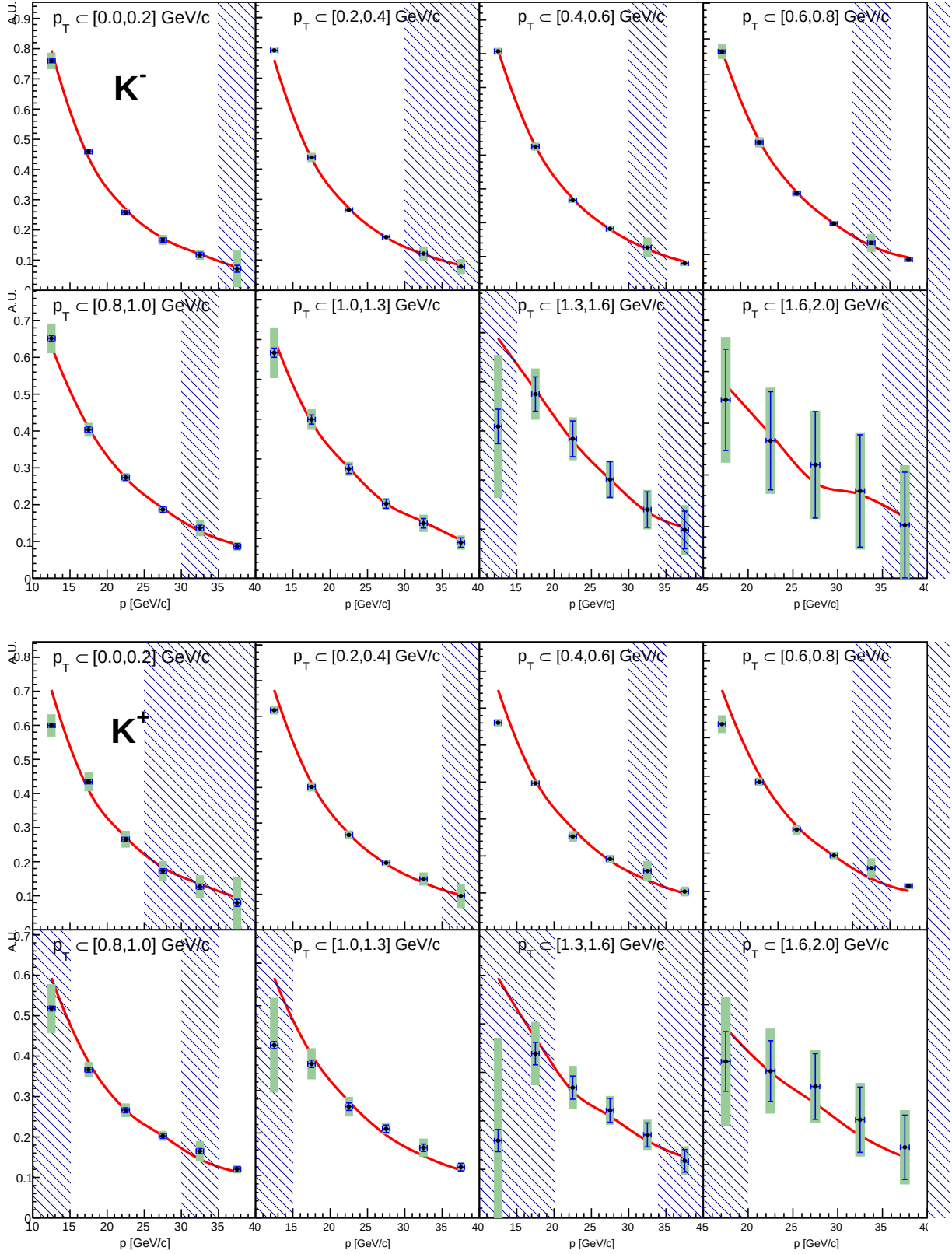


Figure 6.28: Kaons spectra in bins of momentum and transverse momentum in laboratory frame. In red, a shape prediction from the generated MC sample. The bands represent bins in which the acceptance (red) and the RICH-1 systematic (blue) become larger than 10%.

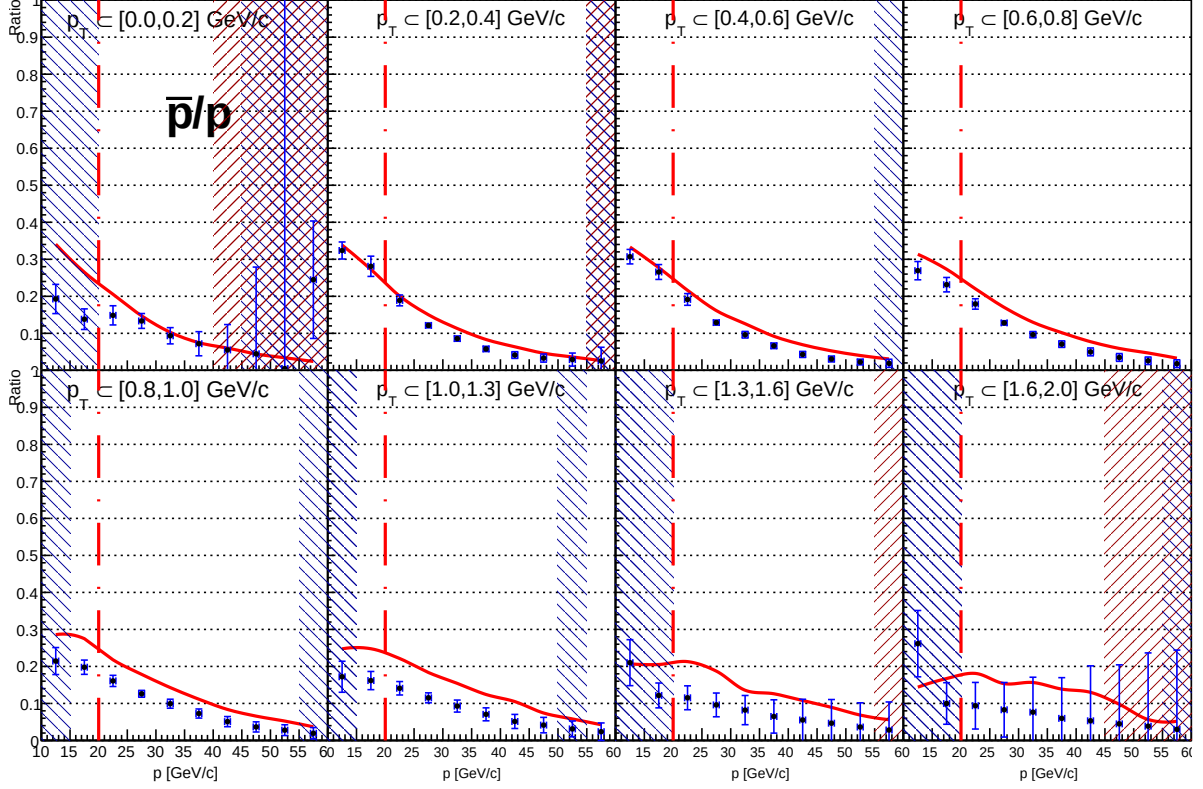


Figure 6.29: Ratio of $\bar{p}/p$ in bins of momentum and transverse momentum in laboratory frame. In red, a prediction from the generated MC sample. The vertical bands represent bins in which the acceptance (red) and the RICH-1 systematic (blue) become larger than 10%. The dashed vertical red line indicates the proton Cherenkov threshold and the change of identification algorithm. The real data as well the generated sample suffer of low statistic at high transverse momentum. The errors on the data points include the statistical uncertainties and the systematic effects of the PID matrix.

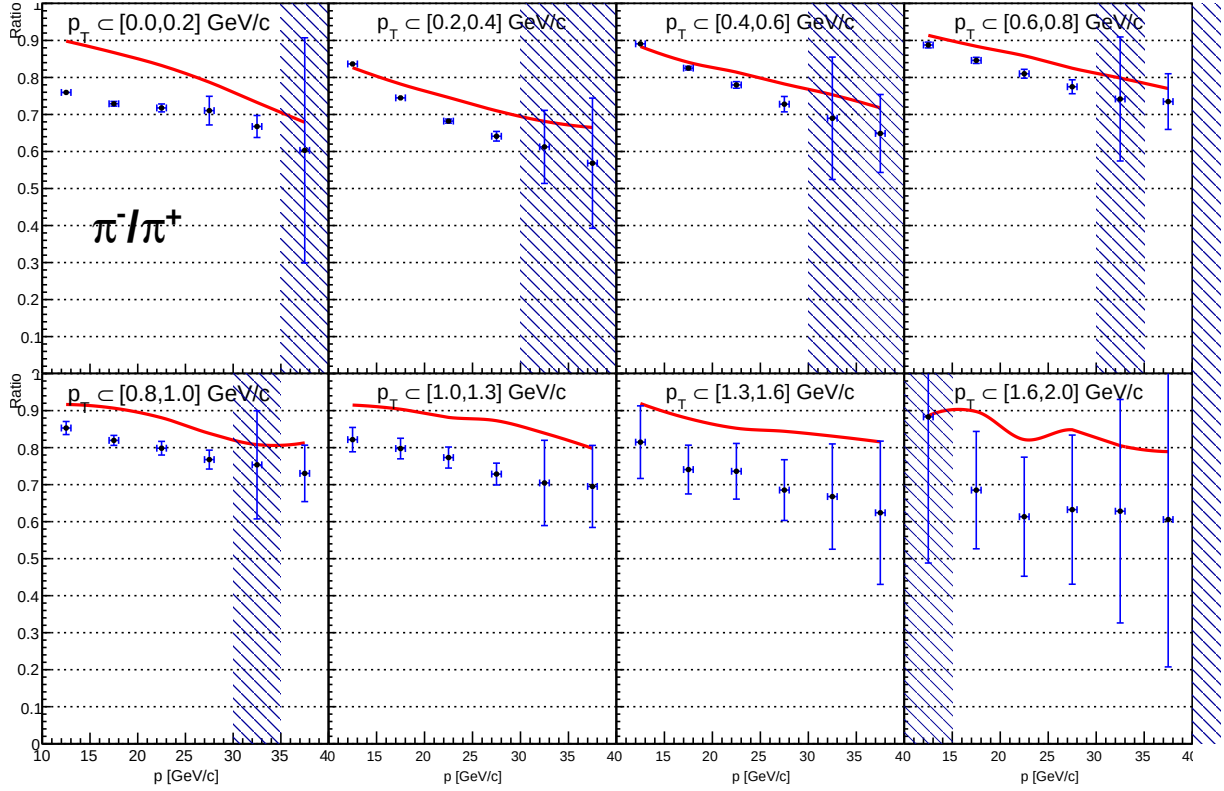


Figure 6.30: Ratio of π^-/π^+ in bins of momentum and transverse momentum in laboratory frame. In red, a prediction from the generated MC sample. The vertical bands represent bins in which the acceptance (red) and the RICH-1 systematic (blue) become larger than 10%. The real data as well the generated sample suffer of low statistic at high transverse momentum. The errors on the data points include the statistical uncertainties and the systematic effects of the PID matrix.

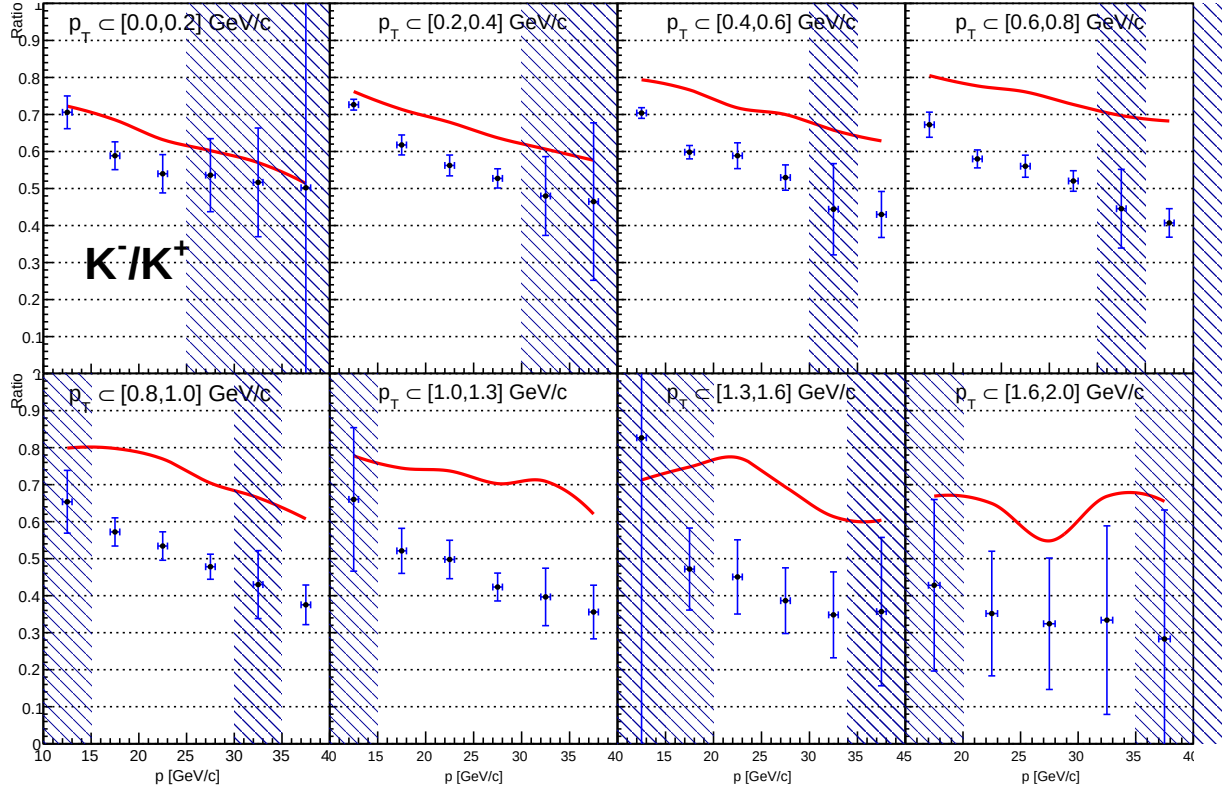


Figure 6.31: Ratio of K^-/K^+ in bins of momentum and transverse momentum in laboratory frame. In red, a prediction from the generated MC sample. The vertical bands represent bins in which the acceptance (red) and the RICH-1 systematic (blue) become larger than 10%. The real data as well the generated sample suffer of low statistic at high transverse momentum. The errors on the data points include the statistical uncertainties and the systematic effects of the PID matrix.

Summary

The precision study of cosmic rays fluxes is a crucial aspect of modern astrophysics. In order to disentangle possible exotic signal in the cosmic antimatter fluxes, a better understanding of the underlying production processes are needed. The AMBER experiment, with the 2023 proton-helium data and 2024 proton-hydrogen and proton-deuterium, will contribute to lower the uncertainties on the current extrapolations and models describing the antiproton production cross sections.

The work described in this thesis represents my contribution to the development of an analysis strategy of the data collected in 2023 by AMBER. By studying the interactions of a positive hadron beam at 190 GeV/ c on the liquid helium target, the results obtained with this work showed that the AMBER spectrometer is capable of performing this measurement with sufficient precision and pave the way to a methodology for the future analysis of the data collected by AMBER at the other energies (60, 80, 100, 160, 250 GeV/ c) and of the 2024 data sample. The protons in the hadron beam are well separated from the pions and the kaons with the CEDAR tagging based on the PMTs multiplicity. The target was precisely localized with a tomography based on the study of the primary vertices position. The produced hadrons are identified with the RICH-1, whose efficiency and the induced systematic uncertainty were evaluated for pions, kaons and protons. Finally the first hadron spectra and the ratio of antiproton over proton have been obtained and are presented in this thesis.

My work during my PhD was entirely dedicated to the different phases of this physics program at AMBER, from the preparation of the 2022 test run, to the activity done as detector expert on MPWCs and Richwall, to grant stable run conditions, to the analysis of the data collected in period W01, at 190 GeV/ c . On the analysis side, I took responsibility of all the aspects from setting up the reconstruction of the data and the alignment of the spectrometer, to the characterization of detectors and the final extraction of the hadron spectra. The final results have room for improvement on many of the topics addressed in this work. In order to obtain the cross section, a background estimation with the data collected with empty target must be carried out. Furthermore, more work has to be devoted to the refinement of the Monte Carlo simulation of the apparatus, both by producing a larger sample of simulated data with different generators and by studying the re-interactions rate that contaminates the final prompt sample. The results showed in this work present only the systematics effect of the RICH-1 PID matrix that are, nevertheless, the expected major contributions to the final error.

The analysis of all the periods of 2023 data taking is foreseen in the near future. Together with the data that will be collected in 2024 in $p-p$ and $p-D$, they will provide exciting results on the production mechanism of antiprotons and as well pions and kaons.

Appendix A

Cherenkov radiation and RICH technique principles

Consider a charged particle moving in a dielectric medium with refractive index n , with a velocity β faster than c/n (c is the light velocity). This particle emits an electromagnetic radiation at a given angle θ_C with respect to the trajectory in that medium. This angle follows the law:

$$\cos\theta_C = \frac{1}{n\beta} \quad (\text{A.1})$$

A quantum description of this phenomenon predicts an additional term in Eq. (A.1) which will be neglected for this discussion. A qualitative description of the mechanism is the following: when the charged particle passes across the dielectric the molecules in the vicinity of the track become polarized due to the electric field generated by the particle. If the velocity of the particle is lower than the velocity of light in the medium the molecules have time to relax back to the original position and shape due to the transient nature of this polarization state. The situation is symmetric in both azimuth and along the axis and so the radiated wavelets interfere destructively. However if the speed of the particle exceeds the velocity of light in the medium the interference becomes constructive leading to a nonzero field intensity at a long distance. From Huygens's construction as in Fig. A.2, it is visible that the radiation will be emitted at a particular angle along the track, which is the angle given by equation Eq. (A.1) and owing to an azimuthal symmetry; each elemental section will be circular if projected on a plane transverse to the direction of the charged track, with different radii depending on the distance from the plane (Fig. A.1).

Since $0 < |\cos\theta_C| < 1$ and $\cos\theta_C = \frac{1}{n\beta}$, there is a lower threshold limit for the particle's momentum which is given by:

$$p_{th} = \frac{m}{\sqrt{n^2 - 1}} \quad (\text{A.2})$$

or equivalently, expressed as Lorentz factor γ_t :

$$\gamma_{th} = \left(1 - \frac{1}{n^2}\right)^{-1/2} \quad (\text{A.3})$$

So the range in which a particle can produce signal (Cherenkov photons) is determined by the mass and the refractive index of the medium. For any practical use, the spectral

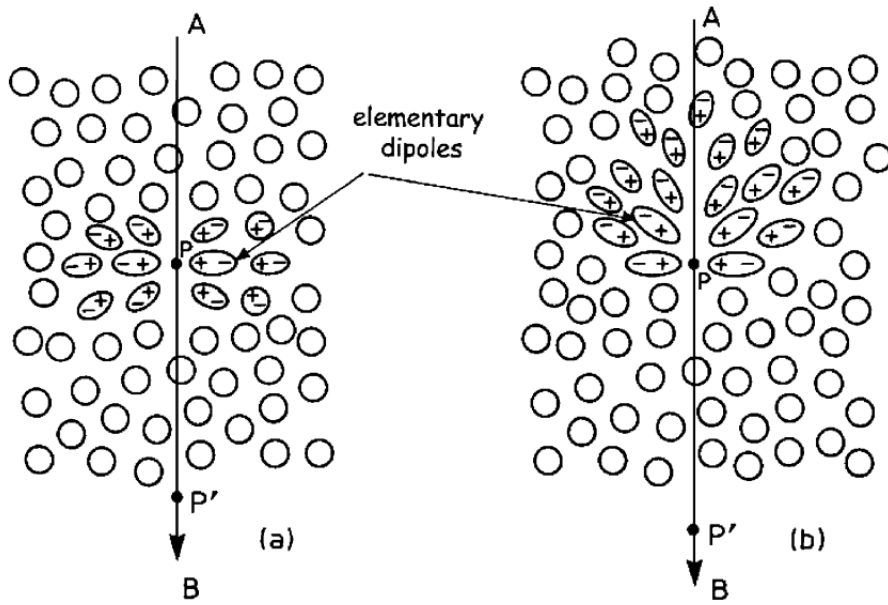


Figure A.1: Polarization of the dielectric medium traversed by a negatively charged particle at a velocity respectively smaller (a) and larger (b) than the local speed of light. [167]

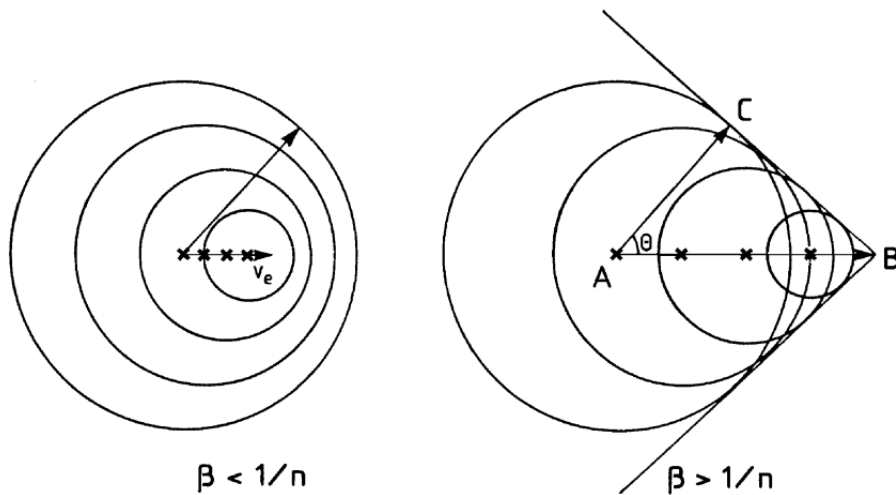


Figure A.2: Huygens's construction of Cherenkov radiation. [167]

dependence must be taken into account with the Frank e Tamm equation which describes the energy loss per unit length of a relativistic charged particle with Z charge:

$$\frac{d^2W}{dx d\omega} = \frac{Z^2 e^2 \omega}{c^2} \left(1 - \frac{1}{\beta^2 n^2(\omega)} \right) \quad (\text{A.4})$$

with a dependence of the n-index from ω for the chromatic abberation. Integrating over the length and the frequency, the number of Cherenkov photons emitted with energy $\hbar\omega$ is given by:

$$N = \frac{L Z^2 \alpha}{c} \int \left(1 - \frac{1}{\beta^2 n^2(\omega)} \right) d\omega \quad (\text{A.5})$$

which can be approximated to

$$N \sim 370 Z^2 \left(1 - \frac{1}{n^2} \right) \quad (\text{A.6})$$

assuming that the number of photon per unit length and per unit energy (eV) is constant.

A Ring Imaging Cherenkov detector exploits the measurement of the Cherenkov emitted photons angle of the charged tracks to identify the particle with the β or the mass calculated from the measurement of the Cherenkov angle, provided the refractive index n and the momentum. From Eq. (A.1):

$$\begin{aligned} \cos \theta_C &= \frac{1}{n\beta} \\ \beta &= \frac{p}{E} = \frac{p}{\sqrt{p^2 + m^2}} \\ \cos \theta_C &= \frac{\sqrt{p^2 + m^2}}{n \cdot p}; \\ m^2 &= p^2 \cdot (n^2 \cos^2 \theta_C - 1) \end{aligned} \quad (\text{A.7})$$

Since at high momenta the radius of Cherenkov ring increases, it is mandatory to minimize the errors on θ_C to have a good separation between particles masses. On the beta factor, the error is directly given by propagation of errors in Eq. (A.1). The error on n index is related to the gas temperature and pression and to the emitted Cherenkov radiation wavelength emitted by Cherenkov radiation. We get:

$$\left(\frac{\sigma_\beta}{\beta} \right)^2 = (\tan \theta_C \sigma_{\theta_C})^2 + \left(\frac{\sigma_n}{n} \right)^2$$

In a Cherenkov radiator with light gas, the refractive index is usually reported as (n-1) and expressed in ppm (10^{-6}). Any term smaller with respect to 1 ppm is neglected. Finally, from simple propagation in Eq. (A.7), the error on masses is given by :

$$\left(\frac{\sigma_{m^2}}{m^2} \right)^2 = \left(2m^2 \frac{\sigma p}{p} \right)^2 + \left(p^2 \frac{2\theta_C \sigma_{\theta_C}}{(n-1)-1} \right)^2 + \left([2p^2 - (p\theta_C)^2] \frac{\sigma_{(n-1)}}{[(n-1)-1]^2} \right)^2 \quad (\text{A.8})$$

It is thus clear that with increasing momentum the resolution on masses is deteriorated. In principle from each Cherenkov photon we can get an estimation of the particle

mass; nevertheless if the estimation is performed by a reconstructed Cherenkov ring, the associated error on theta is reduced by a factor $\sqrt{N}$. In the general case in which Cherenkov photons are emitted in a frequency range where the refractive index is approximately constant, the number of photon produced is given by the Frank and Tamm equation seen in Eq. (A.5). In a compact way:

$$\begin{aligned} N &= N_0 L \sin^2 \theta_c \\ N_0 &= \frac{2\pi\alpha}{\hbar} \int dE \epsilon \times QE \times T \times R \end{aligned} \quad (\text{A.9})$$

where ϵ is the single electron detection efficiency, QE stands for the quantum efficiency of the photon detector, T for the transmission coefficient, R for the reflectivity of the mirror and L for the length of the detector. N_0 is also called the figure of merit of the detector. The energy limits in the integral are defined on the bottom edge by the photo-ionization threshold and on the top edge by the medium transparency.

The saturation is reached when $\beta \rightarrow 1$ and θ becomes asymptotically maximum. The $\theta_{C,max}$ is related to the minimum threshold value expressed as Lorentz factor (Eq. (A.3)):

$$\begin{aligned} N_{max} &= N_0 L \sin^2 \theta_{C,max} \\ \sin^2 \theta_{C,max} &= \frac{1}{\gamma_{th}^2} \\ N_{max} &= \frac{N_0 L}{\gamma_{th}^2} \end{aligned} \quad (\text{A.10})$$

So the fraction of Cherenkov photon produced is expressed as:

$$\frac{N}{N_{max}} = \frac{\sin^2 \theta}{\sin^2 \theta_{C,max}} \quad (\text{A.11})$$

Finally, we can derive an upper limit in momentum to separate two particles species. Two particles emitting Cherenkov photons at angles θ_1 and θ_2 with masses m_1 and m_2 , have a separation power defined by $n_\sigma = (\theta_2 - \theta_1)/\sigma_\theta$. From Eq. (4.4) and Eq. (A.1):

$$\begin{aligned} \delta\beta &= \frac{\sin \theta}{n \cos^2 \theta} \delta\theta = \frac{\tan \theta}{n \cos \theta} \delta\theta = \tan \theta \beta \delta\theta \\ \frac{\delta\beta}{\beta} &= \frac{(m_1^2 - m_2^2) \cdot c^2}{2p^2} = \tan \theta \delta\theta \\ p_{1,2,up} &= \left(\frac{\Delta m^2 \sqrt{N_{ph}}}{2 \tan \theta n_\sigma \sigma_\theta} \right)^{1/2} \end{aligned} \quad (\text{A.12})$$

where $\Delta m^2 = m_1^2 - m_2^2$, $\theta = \frac{\theta_1 + \theta_2}{2}$ and the error on θ is rescaled by a factor $\sqrt{N_{ph}}$ [167].

Appendix B

The Extended Maximum Likelihood

PID algorithm of COMPASS RICH-1 relies on an extended maximum likelihood (EML) approach. In this section this method will be briefly described

A set of m unknown parameters $\{a_1, \dots, a_m\}$ is estimated by maximising the likelihood (LH) in eq. B.1 (or its logarithm) based on N data values $\{\theta_1, \dots, \theta_N\}$ measured:

$$L = \prod_{i=1}^N p(\theta_i; a_1, \dots, a_m) \quad (\text{B.1})$$

with the $p(\theta_i; a_1, \dots, a_m)$ the probability density for the sampling variable x . The estimators $\hat{a}_i$ are the solutions of the equations:

$$\sum_i \frac{\partial \ln p(\theta_i; a_1, \dots, a_m)}{\partial a_j} = 0 \quad \forall j \quad (\text{B.2})$$

In the classical maximum likelihood method the integral of $p(\theta_i)$ over the entire range of x is normalised to unity; the relaxation of this requirement leads to the extended maximum likelihood method, where the $p(\theta_i)$ function is replaced by $P(\theta_i)$ function normalised as:

$$\int d\theta P(\theta_i; a_1, \dots, a_m) = \mathcal{N}(a_1, \dots, a_m) \quad (\text{B.3})$$

The interpretation of eq. B.3 is that $P(\theta_i; a_1, \dots, a_m)$ describes not only the shape of the expected distribution in θ but also its size. The observed number of events N will be in general fluctuating, governed by Poisson statistics, while $\mathcal{N}(a_1, \dots, a_m)$ is the total number of events expected over the whole range of observation. This approach can be useful in cases when events occur randomly and their total number can fluctuate during a certain period of data taking. The observed number of events may be relevant to the quantities being estimated, and the incorporation of the actual value N improves the estimate of the parameters [168]. In our case, we estimate the likelihood for every track and for each mass hypothesis, using each emitted Cherenkov photon as an event. The number of photons, and thus of the events, is randomly varying for each track; the true number of photons is a crucial information in the estimation of PID likelihood. In principle if we could divide our photon detectors surface in bin of infinitesimal width, where the probability of having

more than one event per bin is negligible, we could write the probabilities for 0 and 1 event given by Poisson statistics:

$$\begin{aligned} P_0 &= e^{-\Delta\theta P(\theta)} \\ P_1 &= \Delta\theta P(\theta) e^{-\Delta\theta P(\theta)} \end{aligned} \quad (\text{B.4})$$

The extended likelihood $\mathcal{L}$ is a combined probability for all the data sample:

$$\mathcal{L} = \prod_i \Delta\theta P(\theta_i) \prod_j e^{-\Delta\theta P(\theta_j)} \quad (\text{B.5})$$

where the first term is the product over all bins containing 1 event and the second over all bins. As we were said before, if the bins are infinitesimally small we are in the limit $\Delta\theta \rightarrow d\theta$. The first term becomes $\prod_i d^N\theta P(\theta_i)$ (the $d^N\theta$ term is there just to remind that these are probability densities and not real probabilities); the second one becomes:

$$e^{-\sum_j \Delta\theta P(\theta_j)} \rightarrow e^{-\int P(\theta) d\theta} = e^{-\mathcal{N}}$$

We get the following expression for the $\mathcal{L}$:

$$\begin{aligned} \mathcal{L} &= e^{-\mathcal{N}} \prod_i P(\theta_i) \\ \ln \mathcal{L} &= \sum_i \ln P(\theta_i) - \mathcal{N} \end{aligned} \quad (\text{B.6})$$

It is evident that increasing the number of events both the terms in eq. B.6 will increase. By maximising the $\mathcal{L}$, we can find the estimators values that are solutions of:

$$\sum_{i=1}^N \frac{\partial \ln P(\theta_i; a_1, \dots, a_m)}{\partial a_j} - \frac{\partial \mathcal{N}}{\partial a_j} = 0 \quad \forall j \quad (\text{B.7})$$

Another derivation is given: if $P(\theta)$ predicts a total number of events $\mathcal{N}$, the observed number N is given by Poisson statistics with this mean value. The total probability of a sample in eq. B.1 is modified in the following way:

$$\mathcal{L} = \frac{e^{-\mathcal{N}}}{N!} \prod_{i=1}^N P(\theta_i) \quad (\text{B.8})$$

since the standard probabilities is related to the extended one by:

$$P(\theta) = \mathcal{N} p(\theta) \quad (\text{B.9})$$

The two derivations discussed above lead to the same result with the only difference of a factor $N!$. Since one is usually maximising the $\mathcal{L}$, the $N!$ makes no difference and can be forgotten.

Acronyms

AMBER Apparatus for Meson and Baryon Experimental Research.

CEDAR Cherenkov Detector with Achromatic Ring focus.

CERN Conseil Européen pour la Recherche Nucléaire.

COMPASS COmmon Muon Proton Apparatus for Structure and Spectroscopy.

CORAL COmpass Reconstruction AnaLysis software package.

CR Cosmic Ray.

DAQ Data AcQuisition.

DC Drift Chamber.

DM Dark Matter.

FLT First Level Trigger.

GEM Gas Electron Multipliers.

ISM InterStellar Medium.

LAS Large Angle Spectrometer.

LH Likelihood.

MAPMT Multi-Anode PhotoMultipliers Tube.

MC Monte Carlo.

MicroMega Micro-Mesh Gaseous Structure.

MPGD Multi Pattern Gaseus Detector.

MWPC Multi-Wire Proportional Chamber.

PD Photon Detector.

PHAST PHysics AnalysiS Tool.

PID Particle Identification.

PMT PhotoMultiplier Tube.

RICH Ring Imaging CHerenkov.

SAS Small Angle Spectrometer.

SciFi Scintillating Fibers.

SPS Super Proton Synchrotron.

TDC Time to Digital Converter.

TGEANT Total Geometry And Tracking.

TOA Top Of Atmosphere.

WIMP Weakly Interacting Massive Particle.

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Acknowledgements

I would like to thank, first of all, my supervisor Prof. Michela Chiosso for the boundless freedom she gave me concerning the scientific work, for the informal working environment and the complete dedication and empathy to listen at problems and helping when needed. My journey with her started already during my bachelor degree in 2018 and I could not choose a better supervisor and group to work with. Thanks for believing in me since the beginning, for me that means everything.

I would like to thank the other members of group in Torino with which I had the pleasure to work with: Prof. Daniele Panzieri, Dr. Maxim Alexeev, Dr. Antonio Amoroso, Dr. Oleg Denisov and Dr. Bakur Parsamyan. Each one taught me something and improved my being as scientist and person.

Although his journey with the Torino group was relatively short, thanks to Dr. Filippo Delcarro, with whom I shared not only physics: it is also thanks to him that we all returned in one piece from our motorcycle raids in the Moroccan desert.

Special mention to my fellow and friend Chiara Alice with which I shared every moment in the office and many outside. The "spasso-ufficio" would not exists without you: I am in debt for for your company, support and friendship. Thank you.

I can not help but thanks as well my collaboration colleagues that helped me the most (and were overly bothered with my problems) and from which I absorbed most of the knowledge on how to operate the spectrometer hardware and software wise: Dr. Chandradoy Chatterjee, Dr. Christian Dreisbach, Renat Dusaev, Dr. Thomas Poeschl, Dr. Marcin Stolarski and Benjamin Moritz Veit. Particularly thanks to Dr. Vincent Andrieux for his endless support and patience. From you guys I learned how to be a physicist and you made the amount of work during data taking much more enjoyable.

Thanks to all the extraordinary people with which I could exchange few words at CERN.

I want to thanks also my lifelong friends in Racconigi and Torino. I am lucky to have many: thanks for bringing me down to Earth and sharing wonderful memories.

Finally, since the opportunity to thank them in a serious way does not happen that often, I want to express my most sincere gratitude to my parents and my family, that supported me by being always present during the years (thanks also for the food and accommodation. Great service, I will put 5 stars on TripAdvisor). The long path to the PhD starts, actually, from the choice of the University career almost 10 year ago. They allowed me to take this path in life, not without doubts, but trusting my determination and inclination for discovery. I hope I have returned the affection I received by making them understand, through hard work and endless passion, that at the end of the day there is nothing else that makes me feel better than this. Having a satisfied son with his life is, I guess, a great achievement for a parent.

Ringraziamenti

Desidero ringraziare, innanzitutto, la mia supervisor Prof.ssa Michela Chiosso, per la libertà che mi ha concesso sul lavoro, l'ambiente di lavoro informale e per la completa dedizione ed empatia nell'ascoltare i problemi e nell'aiutare quando necessario. Il mio percorso con lei è iniziato già durante la laurea triennale nel 2018 e non potevo scegliere un supervisor e un gruppo migliore con cui lavorare. Grazie per aver creduto in me fin dall'inizio, per me questo significa tutto.

Vorrei ringraziare gli altri membri del gruppo di Torino con cui ho avuto il piacere di lavorare: Prof. Daniele Panzieri, Dr. Maxim Alexeev, Dr. Antonio Amoroso, Dr. Oleg Denisov e Dr. Bakur Parsamyan. Ognuno di loro mi ha insegnato qualcosa e ha migliorato il mio essere scienziato e persona.

Nonostante il suo viaggio con il gruppo di Torino sia stato relativamente breve, grazie al Dr. Filippo Delcarro, con cui ho condiviso non solo la fisica: è anche grazie a lui che siamo tornati tutti interi dalle nostre scorribande in moto nel deserto marocchino.

Una menzione speciale alla mia collega e amica Chiara Alice, con cui ho condiviso praticamente ogni momento in ufficio e molti fuori. Lo "spasso-ufficio" non esisterebbe senza di lei: sono in debito per la tua compagnia, il tuo sostegno e la tua amicizia. Grazie.

Non posso fare a meno di ringraziare anche i miei colleghi della collaborazione che mi hanno aiutato di più (e sono stati tartassati eccessivamente dai miei problemi) e dai quali ho assorbito la maggior parte delle conoscenze sullo spettrometro e sul suo funzionamento hardware e software: Dr. Chandradoy Chatterjee, Dr. Christian Dreisbach, Renat Dusaev, Dr. Thomas Poeschl, Dr. Marcin Stolarski and Benjamin Moritz Veit. In particolare, grazie al Dr. Vincent Andrieux per il suo infinito sostegno e la sua pazienza. Da voi ho imparato come dovrebbe essere un fisico e senza di voi l'incredibile mole di lavoro durante la presa dati sarebbe stata meno divertente.

Grazie a tutte le persone straordinarie con cui ho potuto scambiare qualche parola al CERN.

Vorrei ringraziare anche i miei amici di una vita a Racconigi e a Torino. Sono fortunato ad averne tanti: grazie per riportarmi coi piedi per terra e per aver condiviso bellissimi ricordi.

Infine, poiché l'opportunità di ringraziarli in modo serio non capita spesso, voglio esprimere la mia più sincera gratitudine ai miei genitori e alla mia famiglia, che mi hanno sostenuto e sono sempre stati presenti durante gli anni (grazie anche per il cibo e l'alloggio. Ottimo servizio, metterò 5 stelle su TripAdvisor). Il lungo percorso verso il dottorato inizia, in realtà, dalla scelta della carriera universitaria quasi 10 anni fa. Mi hanno permesso di intraprendere questo percorso di vita, non senza dubbi, ma fidandosi della mia determinazione e inclinazione alla scoperta. Spero di aver ricambiato l'affetto ricevuto facendo capire loro, attraverso il duro lavoro e la passione, che in fin dei conti non c'è nient'altro che mi faccia sentire meglio di questo. Avere un figlio soddisfatto della sua vita credo sia un grande risultato per un genitore.