

$N - \bar{N}$ physics at GSI in single and double spin interactions

ASSIA COLLABORATION

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The new $\bar{p}^{(1)}p^{\uparrow}$ collider modes proposed for the HESR at GSI would provide new insights on the spin structure of the nucleon, even if only one of the two probes could be polarised. Drell-Yan processes are a powerful tool to access chirally odd parton distribution functions like transversity $h_1(x)$, without their convolution with fragmentation functions and without the suppression proper of the DIS experiments, in reactions where all the quarks taking part can be valence quarks. New insights on the relation of perturbative and non perturbative dynamics in hadron scattering could come in an earlier stage by the

mean of the PANDA spectrometer and of the present HESR design. Spin asymmetries in hadron production and nucleonic form factors are discussed as well.

Key words: spin physics, antiproton, parton distribution functions, transversity

1 Introduction

The new international facility foreseen at GSI, FAIR, offers excellent tools to deepen the knowledge of the nuclear and sub-nuclear matter, but not all the possibilities offered by such a facility had been explored at the very beginning: in particular the spin program was incomplete. Two spin related letters of intent had been submitted, from the ASSIA [1] and from the PAX collaboration [2], proposing different accelerator layouts: the former focused on the possibility to extract antiprotons, eventually polarised, from the new ring of the superconducting synchrotron SIS300 on a fixed polarised proton target; the latter suggested the interaction of the 15 GeV/c HESR polarised antiproton beam on a polarised fixed proton target, being the HESR features the ones originally foreseen to host the PANDA spectrometer.

Nowadays the GSI management is oriented to accept a scheme in which the HESR is modified in a $\bar{p}-p$ collider, with an s of at least 200 GeV^2 and a luminosity greater than 5×10^{31} . Again two different scenarios had been proposed: a scheme in which the HESR is transformed in an asymmetric collider, in which one of the beam has an energy of 15 GeV and the other one has an energy of 3.5 GeV, being the lower energy beam composed of protons in the PAX design and of antiprotons in the ASSIA design; a second scheme, proposed by ASSIA only [3], in which the HESR is transformed in a symmetric collider in which both the beams have an energy of 15 GeV. The asymmetric collider could reach an $s \approx 200 \text{ GeV}^2$, the symmetric collider could top $s \approx 900 \text{ GeV}^2$, with a luminosity of 5×10^{31} , for a marginal increase of the expenses if compared to the asymmetric design.

The key issue is the availability of a \bar{p} beam, with an energy and a luminosity suitable to investigate the spin structure of the nucleon. To achieve this goal, the quark and gluon distribution functions and the quark fragmentation functions are needed, at least at the first two leading twists, without integrating over the transverse momentum of the parton in the nucleon, in a wide range of the Bjorken kinematic variable x ; the selection between the two scenarios must account for the available center of mass energy, needed to span the desired kinematic region.

An excellent case to be studied is the Drell-Yan (DY) di-lepton production where protons and antiprotons annihilate in the initial state. An important role may be played also by the evaluation of the spin observables in hadron production. Here I shall concentrate on the relevant topics presented in the ASSIA LOI [1], that could be investigated within the framework of the new GSI facility. A complete experiment would require polarised antiprotons, but excellent physics, namely regarding transversity, can be performed also making use of unpolarised antiprotons and polarised protons.

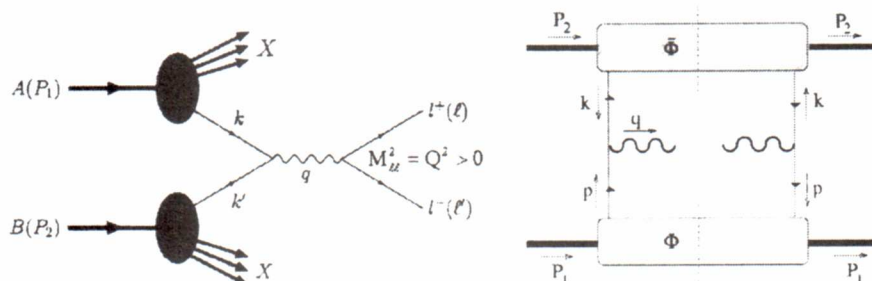


Fig. 1. Drell-Yan dilepton production.

2 Parton distribution functions

In the simpler case of collinear quarks inside the nucleon, or integrating over the transverse momentum of the quarks, the quark structure of the nucleon is completely described at the leading twist by three distribution functions: the unpolarised distribution $f_1(x)$, the longitudinal ($g_1(x)$) and the transverse ($h_1(x)$) polarised distributions.

If we admit a nonzero quark transverse momentum κ_\perp , at twist two and three the nucleon structure is described by eight parton distribution functions (PDF), among which some are κ_\perp -dependent functions: the distribution functions can be chirally even or odd, and this has prevented the chirally odd functions to be deduced from the historical data of DIS experiments. We will focus in the following on two κ_\perp -dependent distributions: $f_{1T}^\perp(x, \kappa_\perp^2)$ and $h_{1T}^\perp(x, \kappa_\perp^2)$, respectively the distribution functions of an unpolarised quark in a transversely polarised hadron, and of a transversely polarised quark inside an unpolarised parent hadron.

For a complete description of hadron production processes, the fragmentation functions are needed as well: a complete review of the theoretical and experimental aspects relative to the parton distribution and fragmentation functions can be found in [4].

3 Drell-Yan processes

The Drell-Yan production of lepton pairs $p\bar{p} \rightarrow l^+l^-X$ (Fig. 1a) is affected by low cross sections, but no contribution from quark fragmentation is related to the muon lines and hence the parton distribution functions can be directly accessed while other kinds of hard processes, like semi-inclusive deep-inelastic scattering (SIDIS), only provide the convolution of chirally odd distribution functions with unknown polarised quark fragmentation functions. Moreover chirally odd amplitudes, and hence transversity $h_1(x)$, can be investigated, since the two quark lines in the diagram of Fig. 1b are uncorrelated due to the two non-perturbative vertices, while in the data from the historical DIS experiments chirally odd amplitudes were

suppressed. Since an antiproton probe is involved, all the partons taking part in the production of muon pairs can be valence quarks, without the need of a sea quark like for example in the $p-p$ or in the $\pi-p$ scattering.

The two cited collaborations, ASSIA and PAX, differ on the choice of the selected leptons in the final state, respectively muons or electrons. We will focus herewith on the production of muon pairs $p\bar{p} \rightarrow \mu^+\mu^-X$, whose cross section, for a given di-muon mass M , is:

$$\frac{d^2\sigma}{dM^2 dx_F} = \frac{4\pi\alpha^2}{9M^2 s} \frac{1}{(x_1 + x_2)} \sum_a e_a^2 [f^a(x_1)f^{\bar{a}}(x_2) + f^{\bar{a}}(x_1)f^a(x_2)] \quad (1)$$

being the geometry and the kinematic variables the ones defined in [5], $x_{1,2} = \frac{M^2}{2P_{1,2}q}$ the fractions of the longitudinal momenta of the incoming hadrons carried by the quark and anti-quarks taking part in the annihilation into the virtual photon, the parameter $\tau = x_1x_2 = \frac{M^2}{s}$, and the summation being extended to the quark flavour a ($a = u, d, s$).

Cross section scales as $d^2\sigma/d\sqrt{\tau}dx_F \propto 1/s$, favouring low beam energies consistent with a selection of values of M ranging from 4 to 9 GeV/c² (the “safe” region), where the di-muon spectrum is essentially continuous without resonance effects from J/Ψ and Υ resonance families to disentangle in the data analysis; for greater M values cross section drops dramatically. Perturbative contributions may introduce additional terms in the formulæ for asymmetries; the importance of these contributions decreases with increasing s [6], and in the safe region it is definitely smaller than below the resonant peaks in the cross section. Data in the resonant regions should be collected as well, since there are arguments [7] in favour of the possibility of studying spin effects in the J/Ψ region, but only the safe region should be considered for the time being in order to extract the PDF.

It is important to investigate the PDF in a wide (x_1, x_2) region, that means asking for the τ parameter to range from 0 to 1. For a larger statistics, data from the complete safe region should be collected: the upper limit of 9 GeV/c² for M defines the highest \sqrt{s} needed for the complete τ region; also rejecting the events below the J/Ψ peak means to cut the allowed kinematic region, since a higher s means to access the very low x region. Continuous grey line hyperbola in Fig. 2b correspond to the minimum di-muon cut $M > 4$ GeV/c² for the values of s in the different scenarios: the operation of HESR with maximum energy on a fixed target as in its present design for the PANDA spectrometer, i.e. the former scenario proposed by PAX ($\sqrt{s} \approx 5.5$ GeV); the extraction of an antiproton beam from SIS300 on a fixed target, i.e. the former scenario proposed by ASSIA ($s \approx 80$ GeV/c²); the HESR asymmetric collider mode in the energy range suggested from the PAC committee ($s \approx 200$ GeV/c²); the HESR symmetric collider mode at $s \approx 900$ GeV/c² as proposed by ASSIA. One of the two last scenarios is clearly needed to access the very low x region.

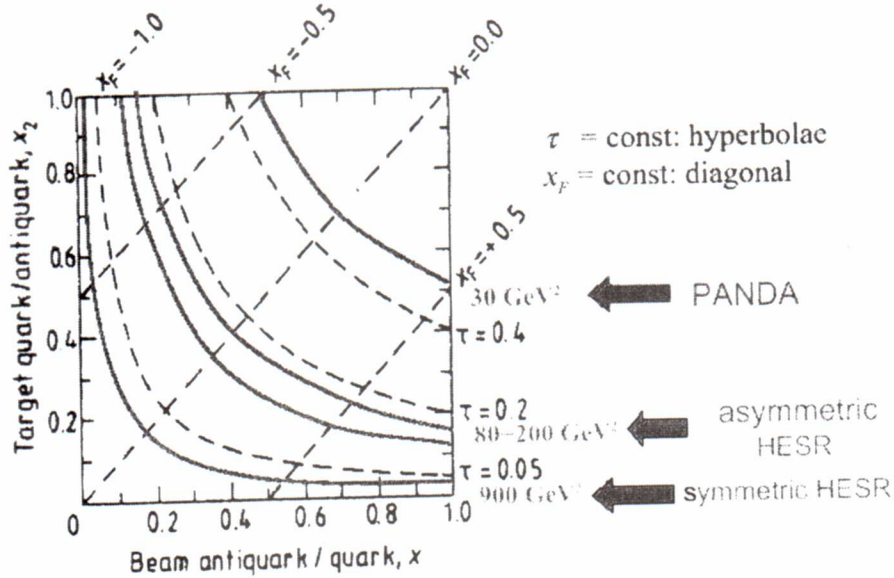


Fig. 2. Allowed (x_1, x_2) kinematic region in Drell-Yan processes: regions above the continuous grey line hyperbola correspond to the minimum di-muon cut $M > 4 \text{ GeV}/c^2$ for the s values in different scenarios, ranging from the presently HESR features actually foreseen for the PANDA spectrometer ($s \approx 30 \text{ GeV}$) to the HESR symmetric collider mode proposed by ASSIA ($s \approx 900 \text{ GeV}/c^2$) [3].

For spin studies, the ideal tool would be a beam and a target both polarised either longitudinally or transversely; in such a case the following asymmetries could be observed:

$$A_{LL} = \frac{\sum_a e_a^2 g_1^a(x_1) g_1^{\bar{a}}(x_2)}{\sum_a e_a^2 f_1^a(x_1) f_1^{\bar{a}}(x_2)} \quad (2)$$

$$A_{TR} = \frac{\sin^2 \theta \cos 2\phi}{1 + \cos^2 \theta} \frac{\sum_a e_a^2 h_1^a(x_1) h_1^{\bar{a}}(x_2)}{\sum_a e_a^2 f_1^a(x_1) f_1^{\bar{a}}(x_2)} \quad (3)$$

$$A_{LT} = \frac{2 \sin 2\theta \cos \phi}{1 + \cos^2 \theta} \frac{M}{\sqrt{Q^2}} \frac{\sum_a e_a^2 (g_1^a(x_1) y g_T^{\bar{a}}(x_2) - x h_L^a(x_1) h_1^{\bar{a}}(x_2))}{\sum_a e_a^2 f_1^a(x_1) f_1^{\bar{a}}(x_2)} \quad (4)$$

where the indices correspond to longitudinal and transverse polarisation of the target and of the beam respectively, and the polar (θ) and azimuthal (ϕ) angles are the ones defined in [5]; the validity of these formulæ depends strongly on the assumptions that s and Q^2 are large enough.

Although the availability of both a polarised beam and a polarised target seems to be the ideal case, even with unpolarised beam and target several information on the distribution functions can be extracted. For the completely unpolarised case, PQCD points to a cross section independent of the azimuthal angle, once

the acceptance is accounted for; experimental data [9] contradict this assumption. Recently [10] it has been pointed out that initial state interaction in the unpolarised Drell–Yan process could explain the observed asymmetries and be connected with the quark (anti-quark) T-odd distributions h_{1q}^\perp and $h_{1\bar{q}}$. For the $\bar{p}p \rightarrow \mu^+\mu^-X$ process, the measurement of the $\cos 2\phi$ contribution to the angular distribution of the di-muon pair provides the product $h_1^\perp(x_2, \kappa_\perp^2) \bar{h}_1^\perp(x_1, \kappa_\perp'^2)$.

This asymmetry can be evaluated also in the present HESR design by mean of the PANDA detector, where a polarised target cannot be installed because of the disturbance due to the magnetic field of the solenoid. The maximal antiproton beam energy foreseen for PANDA at HESR considerably reduces the reachable kinematic domain for the Bjorken x variable, preventing a systematic analysis of the very low x region; however the investigation with the PANDA spectrometer of the low di-muon mass region $1.5 \leq M \leq 2.5 \text{ GeV}/c$, still outside the resonant region and where the cross section is compatible with the cross section in the safe region, could offer access to a x region wider than the one accessible with the data in the safe-region only. Bianconi and Radici [11] have shown how very small $\cos 2\phi$ asymmetries, and even their dependence on the transverse momentum of the muon pairs, could be determined in this mass region and in the PANDA energy range. The possibility of investigating the transverse momentum dependence is crucial to probe the existence of a possible inversion of the trend in the energy dependence of the asymmetries, to balance soft and hard effects in this kind of processes.

Higher order perturbative corrections are expected to be sizeable in the lower energy range [6], and that's a clear complication in the effort of understanding the spin structure of the nucleon, but it becomes matter of investigation itself if the aim is to probe the limits of the factorisation techniques for the cross section and of the perturbative approach to the Drell–Yan channels in this energy range. Even the evaluation of the unpolarised Drell–Yan cross-section in the PANDA energy range could hence provide informations on the relation of perturbative and non perturbative dynamics in hadronic scattering, shedding light on the relationship between fixed orders, perturbative resummation and non perturbative dynamics [12].

In the case of a transversely polarised hydrogen target, ϕ_{S_1} being the azimuthal angle of the target spin in the frame of [5], the asymmetry for the two target spin states [13]:

$$A_T = |S_\perp| \frac{2 \sin 2\theta \sin(\phi - \phi_{S_1})}{1 + \cos^2 \theta} \frac{M}{\sqrt{Q^2}} \times \frac{\sum_a e_a^2 [x (f_1^{a\perp}(x_1) f_1^{\bar{a}}(x_2) + y h_1^a(x_1) h_1^{\bar{a}\perp}(x_2))]}{\sum_a e_a^2 f_1^a(x_1) f_1^{\bar{a}}(x_2)} \quad (5)$$

is $\propto h_1(x_2, \kappa_\perp^2) \bar{h}_1^\perp(x_1, \kappa_\perp'^2)$. The ideal approach would be to combine double spin measurements near the maximum value of the PDF with the investigation of SSA as a function of the Bjorken x to evaluate the x -dependence of the $h_1(x)$ function [11].

With unpolarised \bar{p} and polarised p , the κ_\perp -dependence of the quark distribution functions could be investigated. In particular, the measurement of the single

spin asymmetry (Eq. 5), in the absence of a polarised beam, is a unique tool to probe the κ_{\perp} effects. Recently, several papers have stressed the importance of measuring SSA in Drell–Yan processes [14, 15]; these measurements allow the determination of new non perturbative spin properties of the proton, like the Sivers function, which describes the azimuthal distribution of quarks in a transversely polarised proton [15].

The GSI PAC has suggested the hunt for $s \approx 200 \text{ GeV}/c^2$, the ASSIA collaboration propose a symmetric collider mode for HESR topping $s \approx 900 \text{ GeV}/c^2$; both energies provide access to a wide kinematic region suitable for the determination of the PDF. However there are further arguments favouring such high center of mass energies. A first advantage of the increased center of mass energy is the strongly reduced influence of the perturbative contributions from higher orders.

Moreover in a recent work, Bianconi and Radici [11] have tested with Montecarlo simulations the possibility to resolve among different functional behaviour of the PDF making use of the single spin asymmetry A_T for Drell–Yan events in the safe region only, in two different scenarios: the former one proposed by ASSIA (an antiproton beam from SIS300 on a fixed target), and the asymmetric collider mode of the HESR at $s \approx 200 \text{ GeV}/c^2$; even strongly different hypothesis on the functional behaviour could not be resolved in the former scenario, while this could be possible in the latter scenario at least in the lower x region. The situation is similar as far as the double spin asymmetry A_{TT} is concerned [16]: the higher energy $s \approx 200 \text{ GeV}/c^2$ is needed to resolve among the different functional behaviours of the PDF.

4 Further physics

As described in detail in [17], several other items can be investigated at the new facility of GSI. Plenty of data from Λ and $\bar{\Lambda}$ production are available in literature, and several theoretical models have been proposed both in a more classical quark approach and in a PQCD framework; two asymmetries, the analysing power A_N and the depolarisation (or spin transfer coefficient), D_{NN} , allow for the selection among the different predictions of the proposed theoretical models. A clear systematics appears in the depolarisation data: from negative values at low energy to positive values at higher energy, passing through an intermediate energy range in which the depolarisation is compatible with zero; new data at $s \approx 200 \text{ GeV}$ can bring additional information. Moreover, it has been shown [18] how the use of a polarised nucleon could allow the complete description of the spin structure of the exclusive production of Λ and $\bar{\Lambda}$ pairs; competing models reasonably well describing the cross-section of this reaction are unable to describe such spin observables as spin transfer from a polarised proton to Λ and to $\bar{\Lambda}$. Old data from LEAR do exist, new data on spin transfer and correlation coefficients at higher energies and momentum transfers will be easier interpreted in QCD based approaches and can help a better understanding of the spin dynamics in strong interactions.

The study of nucleon electromagnetic form factors is a powerful tool to investigate the nucleon structure; in particular the form factors in the time-like region (TL), which can be measured through the reactions $\bar{p} + p \leftrightarrow e^+ + e^-$, provide additional information on the nucleon structure with respect to the one that can be obtained by means of eN-scattering in the space-like region (SL).

The two regions, SL and TL, can be connected analytically through dispersion relations. The form factors data available extend mostly in the SL region; the TL data reach higher Q^2 , but are less precise: low statistics, imprecise measurements for cross-section (and only for protons and not for neutrons), and no spin effects investigated in the TL data. The reaction $\bar{p}p \rightarrow \mu^+\mu^-$ with polarised p (\bar{p}) can be an alternative means to study TL form factors measuring both the angular distributions of the differential cross-sections and of the analysing power. Theoretical models [17] provide for these quantities predictions very sensitive to the different underlying assumptions on the s -dependence of the form factors. The angular distribution of the produced leptons for the channels $\bar{p}p \rightarrow l^+l^-$ permits the separation of the electric (G_E) and magnetic (G_M) form factors. Moreover, an experimental proof of a large relative phase of proton G_E and G_M at relatively large momentum transfers in the TL region would be a strong indication of a different behaviour of these form factors.

5 Conclusion

An HESR $\bar{p}p$ collider mode at GSI, with a luminosity of $5 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ in the energy range $s \approx 200 \text{ GeV}^2$, or even $s \approx 900 \text{ GeV}^2$ as proposed by ASSIA, would provide excellent tools to investigate the nucleonic structure, even if only one of the two probes could be polarised. The experimental asymmetries described above in Drell–Yan di-muon production should not be suppressed as at higher energies, and higher order perturbative corrections proper of lower energies are expected to be negligible; by the mean of these asymmetries such an energy range should be suitable to resolve different functional behaviours of the PDF in a wide kinematic x -region.

Moreover, in a first stage the PANDA spectrometer could provide in its energy range new insights on the relationship between fixed orders, perturbative resummation and non perturbative dynamics, giving access at the same time to some κ_{\perp} -dependent PDF, although in a reduced (x_1, x_2) region.

Last but not least, the possibility to investigate in the same experiment both Drell–Yan lepton production and Λ production could be very useful to check and disentangle the different contributions to the asymmetries arising from the distribution and the fragmentation functions.

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