Extraction of Transverse Momentum Distributions from semi-inclusive DIS and Drell-Yan data.

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We present a first attempt at a global extraction of unpolarized partonic transverse momentum dependent (TMD) distributions and fragmentation functions from a simultaneous fit of data measured in semi-inclusive deep-inelastic scattering, Drell–Yan and Z boson production. This analysis is performed in the low transverse momentum region, at leading order in perturbative QCD, implementing TMD evolution at NLL accuracy. We test the agreement between our results and the recently published COMPASS data for muon-deuteron SIDIS multiplicities, and discuss their inclusion in a future global fit with a higher accuracy.

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1. Introduction

Parton distribution functions describe the internal structure of the nucleon in terms of its elementary constituents, quarks and gluons. Transverse momentum dependent distributions and fragmentations functions (TMDs) carry fundamental information on the intrinsic motion of partons and the correlation between the nucleons spins and momenta, including however also the dependence on transverse momentum components $k_\perp^2$ and thus providing a full three-dimensional picture of hadrons in momentum space.

In this contribution to the proceedings, based on [1] to which we refer for a more detailed discussion, we focus only on the unpolarized TMD PDF $f_1^q(x, k_\perp^2, Q^2)$ and the unpolarized TMD FF $D_1^{q \to h}(z, P_{hT}^2, Q^2)$, with a flavor independent analysis. We take into consideration three processes: semi-inclusive DIS, and Drell–Yan processes (DY), both with the production of virtual photons and Z bosons. Many observables in hadronic hard scattering experiments are related to PDFs and FFs, in a way specified by factorization theorems (see, e.g., Refs. [2, 3]). These theorems also illustrate the universality of PDFs and FFs (i.e., the fact that they are the same in different processes) and their evolution equations. Availability of measurements of different processes in different experiments makes it possible to test the reliability of factorization theorems and extract PDFs and FFs through so-called global fits.

2. Formalism

In one-particle SIDIS, a lepton ℓ with momentum l scatters off a hadron target N with mass M and momentum P. In the final state, the scattered lepton momentum l' is measured together with one hadron h with mass M_h and momentum P_h. The available data refer to SIDIS hadron multiplicities; in the single-photon-exchange approximation, the multiplicities can be written as (see Ref. [4] for details):

$$m_N^h(x, z, |\boldsymbol{P}_{hT}|, Q^2) = \frac{d\sigma_N^h/(dx\,dz\,d|\boldsymbol{P}_{hT}|\,dQ^2)}{d\sigma_{DIS}/(dx\,dQ^2)} \simeq \frac{2\pi |\boldsymbol{P}_{hT}| F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2)}{F_T(x, Q^2)} \tag{2.1}$$

where x, y, z and γ are the usual kinematic variables, $\boldsymbol{P}_{hT}$ is the component of $\boldsymbol{P}_h$ transverse to $\boldsymbol{q}$, $Q^2 = -q^2 = -(l - l')^2)$ and ε is the polarization ratio of the virtual photon.

The semi-inclusive cross section can be factorized in terms of TMDs only in the kinematic limits $M^2 \ll Q^2$ and $\boldsymbol{P}_T^2 \ll Q^2$. Moreover, in the present analysis, we will take into account all powers of the form $\alpha_S^n L^{2n} \approx 1$ (Leading Logarithms –LL) and $\alpha_S^n L^n \approx 1$ (Next-to-Leading Logarithms – NLL). With this accuracy, only the contribution $F_{UU,T}$ is relevant in our study.

In our study we neglect the terms $\mathscr{H}_{UU,T}$, denoting the NLO hard scattering part, and $Y_{UU,T}$, introduced to ensure a matching to the perturbative fixed-order calculations at higher transverse momenta. In order to apply TMD evolution equations, we need to calculate the Fourier transform of the part of $F_{UU,T}$ involving TMDs. The structure function thus reduces to

$$F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2) \approx 2\pi \sum_a \int_0^\infty d\xi_T\, \xi_T J_0\big(\xi_T |\boldsymbol{P}_{hT}|/z\big)\, \tilde{f}_1^a(x, \xi_T^2; Q^2)\, \tilde{D}_1^{a \to h}(z, \xi_T^2; Q^2) \tag{2.2}$$

A similar discussion can be made for a Drell–Yan process, where two hadrons A and B with momenta P_A and P_B collide at a center-of-mass energy squared $s = (P_A + P_B)^2$ and produce a virtual photon or a Z boson plus hadrons. The differential cross sections can be analyzed in terms of structure functions F_{UU}^1 and F_{UU}^2 [5, 6]. Similarly to the SIDIS case, in the kinematic limit $q_T^2 \ll Q^2$ and not including the hadron masses the structure function F_{UU}^2 can be neglected. With the choices discussed for the SIDIS case, the structure function F_{UU}^1 can be expressed as a Fourier transform:

$$F_{UU}^1(x_A, x_B, \boldsymbol{q}_T^2, Q^2) = \sum_a \int_0^\infty \frac{d\xi_T}{2\pi} \xi_T J_0(\xi_T |\boldsymbol{q}_T|) \tilde{f}_1^a(x_A, \xi_T; \mu^2) \tilde{f}_1^{\bar{a}}(x_B, \xi_T; \mu^2). \qquad (2.3)$$

In order to include measurement taken at different energy scales, we implement the formalism for TMD evolution in our model, containing the connection between TMDs at different values of the hard scale of the process. Following the formalism of Refs. [3, 7], the evolved unpolarized TMD distribution at LO in configuration space for a parton flavor a at a scale Q^2 can be written as

$$\tilde{f}_1^a(x, \xi_T^2; Q^2) = f_1^a(x; \mu_b^2) \, e^{S(\mu_b^2, Q^2)} \cdot e^{g_K(\xi_T)\ln(Q^2/Q_0^2)} \, \tilde{f}_{1\mathrm{NP}}^a(x, \xi_T^2) \qquad (2.4)$$

where $f_1^a(x; \mu_b^2)$ is the usual collinear distribution function, evaluated at the initial energy scale μ_b. According to Refs. [8, 9, 10], for the nonperturbative Sudakov factor we make the traditional choice $g_K(\xi_T) = -g_2 \xi_T^2/2$ with g_2 a free parameter. Finally, we parametrize the intrinsic nonperturbative parts of the TMDs as the normalized linear combination of a Gaussian and a weighted Gaussian:

$$\tilde{f}_{1\mathrm{NP}}^a(x, \xi_T^2) = \frac{1}{2\pi} e^{-g_{1a}\frac{\xi_T^2}{4}} \left(1 - \frac{\lambda g_{1a}^2}{1 + \lambda g_{1a}} \cdot \frac{\xi_T^2}{4} \right), \qquad (2.5)$$

$$\tilde{D}_{1\mathrm{NP}}^{a \to h}(z, \xi_T^2) = \frac{g_{3a \to h} e^{-g_{3a \to h}\frac{\xi_T^2}{4}} + (\lambda_F/z^2) g_{4a \to h}^2 \left(1 - g_{4a \to h}\frac{\xi_T^2}{4} \right) e^{-g_{4a \to h}\frac{\xi_T^2}{4}}}{2\pi z^2 \left(g_{3a \to h} + (\lambda_F/z^2) g_{3a \to h} \right)} . \qquad (2.6)$$

Based on the analyses of Refs. [11, 12], we defined the Gaussian width of the TMDs to be dependent on their fractional momentum:

$$g_1(x) = N_1 \frac{(1-x)^\alpha x^\sigma}{(1-\hat{x})^\alpha \hat{x}^\sigma}, \qquad\qquad g_{3,4}(z) = N_{3,4} \frac{(z^\beta + \delta)(1-z)^\gamma}{(\hat{z}^\beta + \delta)(1-\hat{z})^\gamma}, \qquad (2.7)$$

where α, σ, $N_1 \equiv g_1(\hat{x})$ with $\hat{x} = 0.1$ and β, γ, δ, $N_{3,4} \equiv g_{3,4}(\hat{z})$ with $\hat{z} = 0.5$ are free parameters. In total we need 11 free parameters to describe our model, defined more in depth in [1].

3. Data analysis and results

In our work we included a wide range of measurements taken from semi-inclusive DIS, Drell-Yan at low energy and Z boson production.

To avoid issues relative to known errors in the normalization of Compass data, we divided every data point by the value of the first point of their bin, excluding them from the d.o.f counting. The application of the TMD formalism to SIDIS depends on the capability of identifying the current fragmentation region, we identify it by operating a cut on z only, namely $0.2 < z < 0.74$. Another

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requirement for the applicability is the presence of two separate scales in the process, Q^2 and P_{hT}^2, which should satisfy the condition $P_{hT}^2/z^2 \ll Q^2$. We implement this condition by imposing $Q^2 > 1.4$ GeV^2 and restricting our fit to the small transverse momentum region. With those kinematic cuts we have 6252 points from COMPASS , 1514 from HERMES, 203 from Drell-Yan experiments and another 90 from Z boson production, for a total of 8059 data points.

Our fit is based on the replica methodology, a Monte Carlo approach that consists in creating $\mathscr{M}$ replicas of the data points, by shifting independently each data point *i* by a Gaussian noise with the same variance as the measurement. A minimization procedure is applied to each replica separately, using MINUIT.

The overall quality of our fit is good, with a global χ^2/d.o.f. $= 1.55 \pm 0.05$. Uncertainties are computed as the 68% confidence level (C.L.) from the replica methodology. The number of degrees of freedom (d.o.f.) is given by the number of data points analyzed, reduced by the number of free parameters (i.e. 11 free parameters) and the number of points used as normalization. With the adopted kinematic cuts, we included regions where TMD factorization could be questioned, but we checked that our results describe very well the regions where TMD factorization is supposed to hold. The χ^2/d.o.f. can be improved up to 1.02 restricting the kinematic cuts, without changing the parameters. In addition, we tested the stability of our distribution shape agianst different possible choices for collinear pdf distributions, alternative kinematic cuts and including normalization also for HERMES .

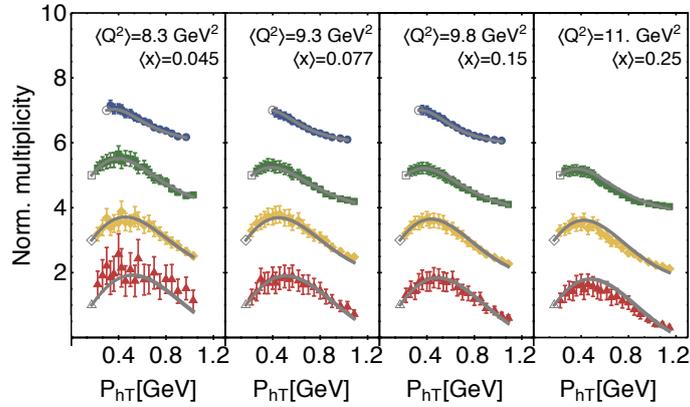## 4. Preliminary analysis of recently published SIDIS COMPASS data

Figure 1: Updated COMPASS multiplicities [13], as a function of the transverse momentum of the detected hadron P_{hT} at different $\langle x \rangle$, $\langle z \rangle$, $\langle Q^2 \rangle$ bins. Grey bands represent the 68% confidence level of the theoretical curves obtained from the minimization of 50 data replicas. Each $\langle z \rangle$ bin has been shifted for clarity by an offset.

Recently COMPASS collaboration has published a new semi-inclusive measurement of charged hadron multiplicities from muon-deuteron DIS [13]. Comparing this dataset to the one used in our previously discussed analysis [14], we observe that they cover a wider kinematical range, reaching in x up to 0.4 instead of 0.12, in Q^2 up to 81 GeV^2 instead of 10 GeV^2 and in P_{hT}^2 up to 3 GeV^2 instead of about 1 GeV^2. Even if the data points are reduced in quantity they have a much higher

statistics, leading to a significantly decreased systematic uncertainties on the normalization of the P_{hT}^2-integrated multiplicities. This feature could be an important improvement for our analysis, considering that at the moment it seems to be necessary to normalize each x, z, Q^2 bin of COM-PASS data.

We conducted a preliminary study of this new data set to test its agreement with the result obtained in our previous global fit. As a first step we compared the recent COMPASS data with the theoretical curves obtained from the 200 groups of parameters extracted from the minimization of the already discussed data replicas. In this case we obtained a χ^2 value of 1.91 if we considered only the COMPASS measurements, and a value of 2.01 if we also included Drell–Yan and Z boson production data. These initial results suggest that the parameters obtained in the previous fit are able to describe also the new one, as can be observed in Fig. 1, even if not as accurately as before. After this initial exploration we repeated our global minimization on 50 replicas of the new data set. After minimizing we obtained a parameter space similar to the published one, able to describe the experimental measurements quite accurately ($\chi^2 = 1.71$ with 3922 d.o.f.). Finally we tested the necessity of the bin normalization for the improved data. A preliminary comparison without minimization and using the parameters obtained from previous fits showed a worse agreement with the measurements. Even repeating the minimization process at the moment we are not able to achieve the results of our previous analysis. There are different issues that could be the cause of this behaviour, we noticed that including this data our results became more sensitive to the value of *z*, producing notably different theoretical curves if we choose the starting or the mid value of a *z* bin. This sensitivity can be explained observing how the shape of the FF changes in relation to *z* and considering that the *z* bin are now twice larger than before; integrating the multiplicities on the entire *z* bin range instead of evaluating them for the average value could solve this issue.

We observed also that the updated data seem to be less stable with regards to the kinematic cuts applied, and it could be necessary to resize the kinematic range in order to find an area with greater stability.

Finally, we are implementing in our future analysis higher order corrections to exclude that discrepancies between our model and the data could come from an incomplete description of the process.

5. Conclusions

In this work we demonstrated for the first time that it is possible to perform a simultaneous fit of unpolarized TMD PDFs and FFs to data of SIDIS, Drell–Yan and Z boson production at small transverse momentum collected by different experiments.

Using a replica methodology we extracted unpolarized TMDs using 8059 data points with 11 free parameters, obtaining an average χ^2/d.o.f. of 1.55 ± 0.05. Most of the discrepancies between data and theory come from the normalization and not from the transverse momentum shape.

Preliminary studies on the recently published COMPASS sets of multiplicities suggest that they are compatible with our results, however further consideration on the normalization and the description of the *z* dependence are necessary for a future improved global fit.

Acknowledgments

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