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Global extraction of partonic transverse momentum distributions from semi-inclusive deep inelastic scattering and Drell-Yan data

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Abstract.
We discuss 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. To connect data at different scales, we use TMD evolution at next-to-leading logarithmic accuracy.

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 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. Similarly to the more common collinear distributions, TMDs are not purely perturbative quantities, they cannot be easily computed from first principles but have to be extracted from experimental measurements to have a complete determination.
Many observables in hadronic hard scattering experiments are related to PDFs and FFs, in a way specified by factorization theorems (see, e.g., Refs. [1, 2]). 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, that connect the different values that the distributions assume when the hard scale of the process change. 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.

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In this contribution to the proceedings, based on [3] to which we refer for details, we focus only on the unpolarized TMD PDF $f_1^q(x, k_\perp^2)$ and the unpolarized TMD FF $D_1^{q\to h}(z, P_{hT}^2)$, with a flavor independent analysis. We take into consideration three kinds of processes: semi-inclusive DIS, and Drell–Yan processes (DY) with the production of virtual photons and Z bosons.

2. Formalism

2.1. Semi-inclusive DIS

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 and taking 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 – NNL), the multiplicities can be written as (see Ref. [4] for details):

$$m_N^h(x, z, |\boldsymbol{P}_{hT}|, Q^2) = \frac{d\sigma_N^h/(dxdzd|\boldsymbol{P}_{hT}|dQ^2)}{d\sigma_{DIS}/(dxdQ^2)} \simeq \frac{2\pi|\boldsymbol{P}_{hT}|F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2), Q^2)}{F_T(x, Q^2)} \tag{1}$$

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 – NNL). With this accuracy, only the contribution $F_{UU,T}$ is relevant in our study. This function can be expressed in terms of TMD PDFs and FFs using the factorized formula for SIDIS [5]:

$$F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2) = \sum_a \mathcal{H}_{UU,T}^a(Q^2; \mu^2) \times \int d\boldsymbol{k}_\perp \, d\boldsymbol{P}_\perp \, f_1^a\big(x, \boldsymbol{k}_\perp^2; \mu^2\big) \, D_1^{a\to h}\big(z, \boldsymbol{P}_\perp^2; \mu^2\big) \\ \cdot \delta\big(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp\big) + Y_{UU,T}\big(Q^2, \boldsymbol{P}_{hT}^2\big) + \mathcal{O}\big(M^2/Q^2\big) \, . \tag{2}$$

Here, $\mathcal{H}_{UU,T}$ is the hard scattering part; the term $Y_{UU,T}$ is introduced to ensure a matching to the perturbative fixed-order calculations at higher transverse momenta. In this analysis we neglect this term, leaving a detailed treatment of the matching to the high $P_{hT}^2 \approx Q^2$ region to future investigations.
In order to apply TMD evolution equations, we need to calculate the Fourier transform of the part of Eq. (2) involving TMDs. The structure function thus reduces to

$$F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2) \approx 2\pi \sum_a \int_0^\infty d\xi_T \, \xi_T \cdot J_0\big(\xi_T|\boldsymbol{P}_{hT}|/z\big) \tilde{f}_1^a\big(x, \xi_T^2; Q^2\big) \tilde{D}_1^{a\to h}\big(z, \xi_T^2; Q^2\big) \tag{3}$$

where we introduced the Fourier transforms $\tilde{f}_1^a\big(x, \xi_T; Q^2\big)$ and $\tilde{D}_1^{a\to h}\big(z, \xi_T; Q^2\big)$ of the TMD PDF and FF, respectively.

2.2. Drell–Yan processes

In a Drell–Yan process, 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 boson then decays into a lepton-antilepton pair. The experimental cross sections can be analyzed in terms of structure functions [6, 7]:

$$\frac{d\sigma}{dQ^2 \, dq_T^2 \, d\eta} = \sigma_0^{\gamma,Z}\left(F_{UU}^1 + \frac{1}{2}F_{UU}^2\right). \tag{4}$$

where $\sigma_0^{\gamma,Z}$ are the elementary cross sections for the process. Similarly to the SIDIS case, in the kinematic limit $q_T^2 \ll Q^2$ and neglecting 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:

$$F_{UU}^1(x_A, x_B, \boldsymbol{q}_T^2, Q^2) = \sum_a \mathcal{H}_{UU}^{1a} \int_0^\infty \frac{d\xi_T}{2\pi} \xi_T \, J_0(\xi_T |\boldsymbol{q}_T|) \cdot \tilde{f}_1^a(x_A, \xi_T; \mu^2) \; \tilde{f}_1^{\bar{a}}(x_B, \xi_T; \mu^2). \quad (5)$$

2.3. TMDs and their evolution
Following the formalism of Refs. [2, 8], the unpolarized TMDs at LO in configuration space for a parton flavor a at a certain scale μ^2 can be written as

$$\widetilde{f}_1^a(x, \xi_T^2; Q^2) = f_1^a(x; \mu_b^2) \; e^{S(\mu_b^2, Q^2)} \cdot e^{g_K(\xi_T) \ln(Q^2/Q_0^2)} \; \widetilde{f}_{1\mathrm{NP}}^a(x, \xi_T^2) \quad (6)$$

$$\widetilde{D}_1^{a\to h}(z\xi_T^2; Q^2) = D_1^{a\to h}(z; \mu_b^2) \; e^{S(\mu_b^2, Q^2)} \cdot e^{g_K(\xi_T) \ln(Q^2/Q_0^2)} \; \widetilde{f}_{1\mathrm{NP}}^{a\to h}(z, \xi_T^2) \quad (7)$$

where $f_1^a(x; \mu_b^2)$ and $D_1^{a\to h}(z; \mu_b^2)$ are the usual collinear distribution and fragmentation functions, evaluated at the initial energy scale μ_b, which is chosen such that at $Q_0 = 1$ GeV there are no evolution effects.

The Sudakov exponent S can be generally written as

$$S(\mu_b^2, \mu^2) = -\frac{1}{2} \int_{\mu_b^2}^{\mu^2} \frac{dk_T^2}{k_T^2} \left[A\left(\alpha_s(k_T)\right) \ln\left(\frac{Q^2}{k_T^2}\right) + B\left(\alpha_s(k_T)\right) \right]. \quad (8)$$

Following Refs. [9, 10, 11], 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:

$$\widetilde{f}_{1\mathrm{NP}}^a(x, \xi_T^2) = \frac{1}{2\pi} e^{-g_{1a} \frac{\xi_T^2}{4}} \left(1 - \frac{\lambda g_{1a}^2}{1 + \lambda g_{1a}} \cdot \frac{\xi_T^2}{4}\right), \quad (9)$$

$$\widetilde{D}_{1\mathrm{NP}}^{a\to h}(z, \xi_T^2) = \frac{g_{3a\to h} e^{-g_{3a\to h} \frac{\xi_T^2}{4}} + \left(\lambda_F/z^2\right) g_{4a\to h}^2 \left(1 - g_{4a\to h} \frac{\xi_T^2}{4}\right) e^{-g_{4a\to h} \frac{\xi_T^2}{4}}}{2\pi z^2 \left(g_{3a\to h} + \left(\lambda_F/z^2\right) g_{3a\to h}\right)}. \quad (10)$$

Based on the analyses of Refs. [12, 13], we consider that the Gaussian width of the TMDs depends on their fractional momentum, according to

$$g_1(x) = N_1 \frac{(1-x)^\alpha \; x^\sigma}{(1-\hat{x})^\alpha \; \hat{x}^\sigma}, \qquad g_{3,4}(z) = N_{3,4} \frac{(z^\beta + \delta) \; (1-z)^\gamma}{(\hat{z}^\beta + \delta) \; (1-\hat{z})^\gamma}, \quad (11)$$

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.

3. Data analysis and results

In our work we included a wide range of measurements taken from semi-inclusive DIS [14, 15], Drell-Yan at low energy [16, 17] and Z boson production [18, 19, 20, 21].
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 $0.2 < z < 0.74$.

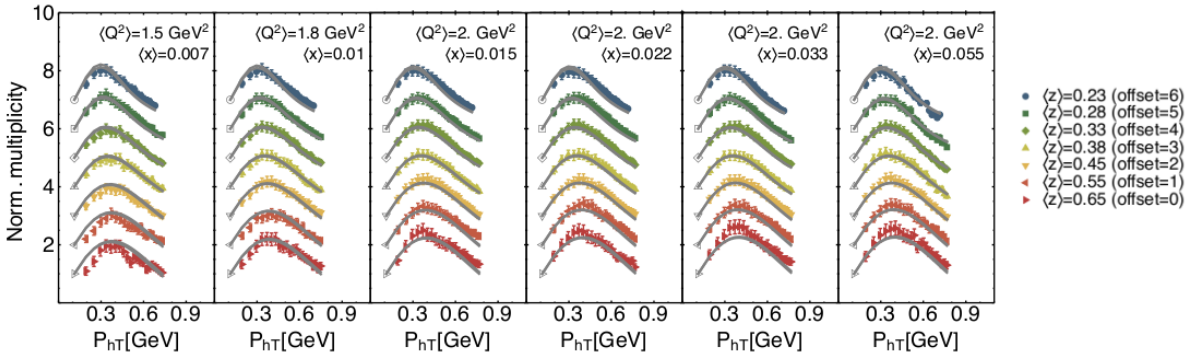

Figure 1: HERMES multiplicities for the process $ep \to ep + X$ as a function of the transverse momentum of the detected hadron P_{hT} at different $\langle x\rangle$, $\langle z\rangle$, $\langle Q^2\rangle$ bins. Each $\langle z\rangle$ bin has been shifted for clarity by an offset.

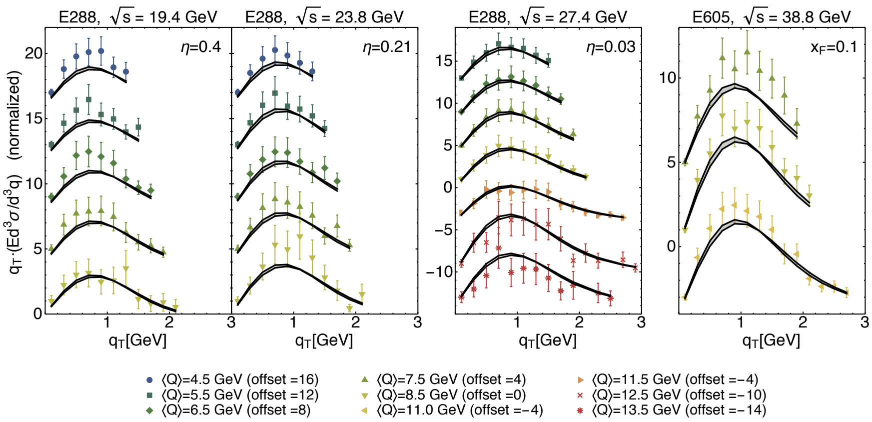

Figure 2: DY cross section as a function of the qT of the virtual photon for different values of $\sqrt{s}$ and $\langle Q\rangle$. For clarity, each $\langle Q\rangle$ bin has been normalized and then shifted by an offset.

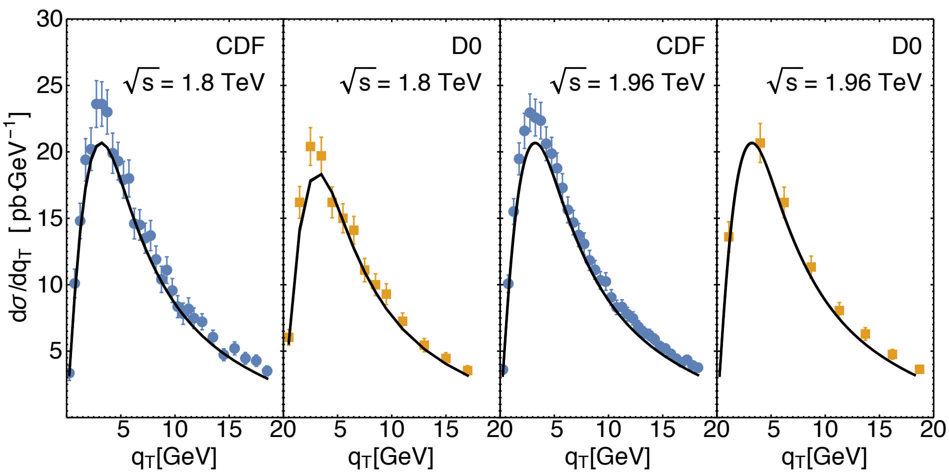

Figure 3: Cross section for the process $\bar{p}p \to ZX$ as a function of the transverse momentum q_T of the Z boson, for different energies of the CDF and D0 experiments at the Tevatron.

Another 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 $\mathcal{M}$ 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 (8059), reduced by the number of free parameters in the error function (i.e. 11 free parameters).

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 Tab. 1 the values obtained for the fit parameters are presented.

For SIDIS at Hermes off a proton, most of the contribution to the χ^2 comes from events with a π^+ in the final state and the bins with the worst agreement are at low Q^2. The main reason for the large χ^2 at Hermes is probably a normalization difference. SIDIS at Compass involves scattering off deuteron only, $D \to h^\pm$, and we identify $h \equiv \pi$. The quality of the agreement between theory and Compass data is better than in the case of pion production at Hermes, mainly because our fit is essentially driven by the Compass data and the observable that we fit in this case is a normalized multiplicity.

In regard to the low energy Drell–Yan data we observe that they have large error bands. This is why their χ^2 values are rather low compared to the other data sets. The agreement is also good for Z boson production. The statistics from Run-II is higher, which generates smaller experimental uncertainties and higher χ^2, especially for the CDF experiment.

For illustration, in Fig. 1 a selection of our results is compared with the Compass experimental data for the production of positively charged hadrons at different $\langle x \rangle$, $\langle z \rangle$ bins, as a function of the transverse momentum of the final hadron P_{hT}. The bands are computed as the 68% confidence level envelope of the full sets of fit curves from all the 200 replicas.

Results from DY and Z-boson productions are presented in Figs. 2 and 3, respectively.

4. 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 experimental data and theory comes from the normalization and not from the transverse momentum shape. This issue could probably be addressed in future studies adopting a framework with an higher order of accuracy. This analysis could be further improved by considering different functional forms for the nonperturbative elements.

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Table 1: 68% confidence intervals of best-fit values for TMD parameters at $Q = 1$ GeV.

TMD PDFs	g_1 [GeV^2]	α	σ		λ [GeV^{-2}]	
	0.28 ± 0.06	2.95 ± 0.05	0.17 ± 0.02		0.86 ± 0.78	
TMD FFs	g_3 [GeV^2]	β	δ	γ	λ_F [GeV^{-2}]	g_4 [GeV^2]
	0.21 ± 0.02	1.65 ± 0.49	2.28 ± 0.46	0.14 ± 0.07	5.50 ± 1.23	0.13 ± 0.01

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