Global fit of unpolarized Transverse Momentum Distributions

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In this talk we present the latest results by the MAP Collaboration about the extraction of unpolarized quark Transverse-Momentum-Dependent Distributions (TMD PDFs) and Fragmentation Functions (TMD FFs) from global fits of Drell-Yan and Semi-Inclusive Deep-Inelastic Scattering (SIDIS) data sets.

31st International Workshop on Deep Inelastic Scattering (DIS2024)
8–12 April 2024
Grenoble, France

*Speaker

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1. Introduction

Mapping the multi-dimensional internal structure of hadrons is a crucial step for understanding the phenomena of confinement and hadronization. Transverse-Momentum-Dependent Distributions (TMDs) serve as examples of such multidimensional mappings, as they encapsulate information about the distribution of quarks within three-dimensional momentum space.

In recent years, the extraction of Transverse Momentum Dependent (TMD) parton distribution functions (PDFs) and fragmentation functions (FFs) from experimental data has reached a high level of sophistication. We now benefit from global analyses incorporating both Semi-Inclusive Deep-Inelastic Scattering (SIDIS) and Drell-Yan (DY) data at high perturbative accuracies [1–3]. These analyses employ a flavor-blind approach, imposing the same behavior across different flavors in transverse momentum. However, recent efforts have also explored TMDs using a flavor-dependent approach, albeit solely analyzing DY data [4, 5].

This contribution serves as a summary of the work presented in [6], where, for the first time, we analyzed TMDs by fitting data from both DY and SIDIS at the highest possible accuracy (N^{3}LL).

2. Formalism

In the TMD factorization framework [7], the differential cross-section for the Drell-Yan process $h_A(P_A) + h_B(P_B) \to \gamma^*(q)/Z + X \to \ell^+(l) + \ell^-(l') + X$ can be expressed as follows:

$$\begin{aligned}\frac{d\sigma^{DY}}{d|\boldsymbol{q}_T|dydQ} &\approx \frac{16\pi^2\alpha^2}{9Q^3}|\boldsymbol{q}_T|\frac{x_A x_B}{2\pi}\mathcal{H}^{DY}(Q;\mu)\\ &\times\sum_a c_a(Q^2)\int d|\boldsymbol{b}_T||\boldsymbol{b}_T|J_0(|\boldsymbol{q}_T||\boldsymbol{b}_T|)\hat{f}_{1A}^{a}(x_A,\boldsymbol{b}_T^2;\mu,\zeta_A)\hat{f}_{1B}^{\bar{a}}(x_B,\boldsymbol{b}_T^2;\mu,\zeta_B),\end{aligned} \tag{1}$$

where $\boldsymbol{q}_T$ and y respectively denote the transverse momentum and the pseudorapidity of the vector boson, Q is the invariant mass of the lepton pair, and $x_{A,B} = \frac{Q}{\sqrt{s}}e^{\pm y}$. Here, $\mathcal{H}^{DY}$ represents the hard function of the process. The term $\hat{f}_{1H}^{f}$ refers to the Fourier transform of the unpolarized TMD PDF of a quark with flavor f in a hadron H, depending on the longitudinal momentum fraction x_H, the Fourier-conjugate variable $\boldsymbol{b}_T$ (relative to $\boldsymbol{q}_T$), and the renormalization and rapidity scales μ and ζ.

The differential cross-section for unpolarized SIDIS at small transverse momentum is similarly articulated:

$$\begin{aligned}\frac{d\sigma^{\text{SIDIS}}}{dx\,dz\,d|\boldsymbol{q}_T|\,dQ} &= \frac{8\pi^2\,\alpha^2\,z^2\,|\boldsymbol{q}_T|}{x\,Q^3}\left[1+\left(1-\frac{Q^2}{xs}\right)^2\right]\frac{x}{2\pi}\mathcal{H}^{SIDIS}(Q,\mu)\\ &\times\sum_a e_a^2\int_0^{+\infty} d|\boldsymbol{b}_T||\boldsymbol{b}_T|J_0\big(|\boldsymbol{b}_T||\boldsymbol{q}_T|\big)\hat{f}_1^{a}(x,\boldsymbol{b}_T^2;\mu,\zeta_A)\,\hat{D}_1^{a\to h}(z,\boldsymbol{b}_T^2;\mu,\zeta_B),\end{aligned} \tag{2}$$

where x and z represent the light-cone fractions of the incoming and outgoing quarks' collinear momenta, respectively. The term $\hat{D}_1^{f\to h}$ denotes the Fourier transforms of the TMD FF for a quark with flavor f fragmenting into a hadron h, which shares the same variable dependencies as $\hat{f}_{1H}^{f}$ except that it depends on z rather than x.

3. Data

The TMD formalism is specifically applicable only in the small $\boldsymbol{q}_T$ region. Accordingly, we impose the following kinematic cuts for our analysis:

$$|\boldsymbol{q}_T|\,|_{\mathrm{DY/Z}} < 0.20\,Q, \quad |\boldsymbol{P}_{hT}|\,|_{\mathrm{SIDIS}} < \min\big[\,\min[0.2\,Q, 0.5\,zQ] + 0.3\,\mathrm{GeV},\ zQ\big]. \tag{3}$$

Our analysis includes 2031 data points meeting these criteria, comprising 484 from Drell-Yan processes sourced from FERMILAB fixed-target experiments, Tevatron, LHC, STAR, and PHENIX, and 1547 from the SIDIS process, sourced from COMPASS and HERMES datasets. Fig. 1 illustrates the kinematic coverage ($x - Q^2$) of the data utilized.

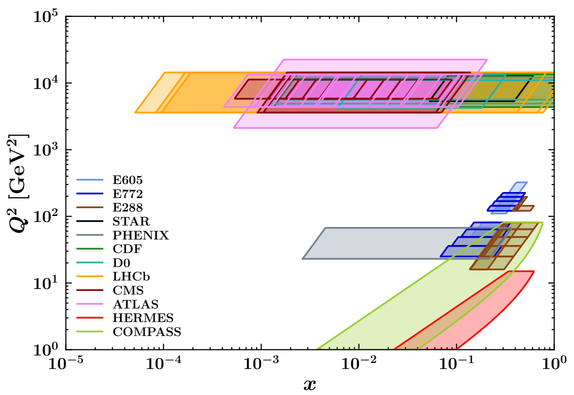

Figure 1: The $x - Q^2$ coverage of the experimental data used for the fit.

4. Results

The main result presented here, namely the extraction with a flavor-dependent approach of TMD PDFs for unpolarized quarks in the proton and TMD FFs for final pions and kaons (MAPTMD24) represents a significant upgrade compared to the MAPTMD22 fit and similar studies, since it is the first time that a global analysis of SIDIS and DY data with flavor dependence is performed. In this fit we parametrize the nonperturbative part of TMDs as

$$f_{1\,NP}(x, \boldsymbol{b}_T^2; \zeta, Q_0) = \frac{g_1(x)\, e^{-g_1(x)\frac{\boldsymbol{b}_T^2}{4}} + \lambda^2\, g_2^2(x)\left[1 - g_2(x)\frac{\boldsymbol{b}_T^2}{4}\right] e^{-g_2(x)\frac{\boldsymbol{b}_T^2}{4}} + \lambda_2^2\, g_3(x)\, e^{-g_3(x)\frac{\boldsymbol{b}_T^2}{4}}}{g_1(x) + \lambda^2\, g_2^2(x) + \lambda_2^2\, g_3(x)} \left[\frac{\zeta}{Q_0^2}\right]^{g_K(\boldsymbol{b}_T^2)/2}, \tag{4}$$

and similarly for the $D_{1\,NP}$

$$D_{1\,NP}(z, \boldsymbol{b}_T^2; \zeta, Q_0) = \frac{g_4(z)\, e^{-g_4(z)\frac{\boldsymbol{b}_T^2}{4z^2}} + \frac{\lambda_F}{z^2}\, g_5^2(z)\left[1 - g_5(z)\frac{\boldsymbol{b}_T^2}{4z^2}\right] e^{-g_5(z)\frac{\boldsymbol{b}_T^2}{4z^2}}}{g_4(z) + \frac{\lambda_F}{z^2}\, g_5^2(z)} \left[\frac{\zeta}{Q_0^2}\right]^{g_K(\boldsymbol{b}_T^2)/2}, \tag{5}$$

where both of them are constructed as the Fourier transform of the sum of a Gaussians and a Gaussian weighted by their transverse momentum.

We stress that these parametrizations use different parameters for different flavors, particular, for TMD PDFs we independently parametrize the following flavors: u, $\bar{u}$, d, $\bar{d}$, and *sea*, where *sea* includes s, $\bar{s}$, c, $\bar{c}$, b, and $\bar{b}$. For TMD FFs, we independently parametrize five different cases, as proposed in the exploratory study of Ref. [8] where charge conjugation and isospin symmetries had been assumed. In total, the MAPTMD24 fit involves 96 free parameters: 1 for the nonperturbative part of the Collins-Soper kernel, 50 (5 flavors $\times$10 parameters) for the nonperturbative part of the TMD PDFs, and 45 (5 channels $\times$9 parameters) for the nonperturbative part of the TMD FFs.

With this setup, we performed a fit of 100 Monte Carlo replicas of the experimental data and we obtained the global $\chi_0^2/N_{\text{dat}} = 1.08$, indicating that we are able to simultaneously describe the experimental data coming from both SIDIS and DY processes in an excellent way.

We observe that both the MAPTMD24 and MAPTMD22 extractions [3] describe the data in a comparably good way. Going into more detail, the MAPTMD24 extraction provides a better description of the DY data, especially the high-energy ones, while there is a slight deterioration in the description of the SIDIS data. In general, the comparison between experimental data and theoretical predictions for most of the included data sets shows a very good agreement for all experiments.

From the MAPTMD24 flavor dependent fit, we are able to obtain for each of the parametrized flavors, their corresponding TMD PDFs and FFs extracted at N^{3}LL accuracy.

Figure 2 displays the unpolarized TMD PDFs for the various independent flavors, as functions of the partonic transverse momentum $|\boldsymbol{k}_\perp|$ at $\mu = \sqrt{\zeta} = Q = 2$ GeV and $x = 0.1$ (left panel), $x = 0.01$ (central panel), and $x = 0.001$ (right panel).

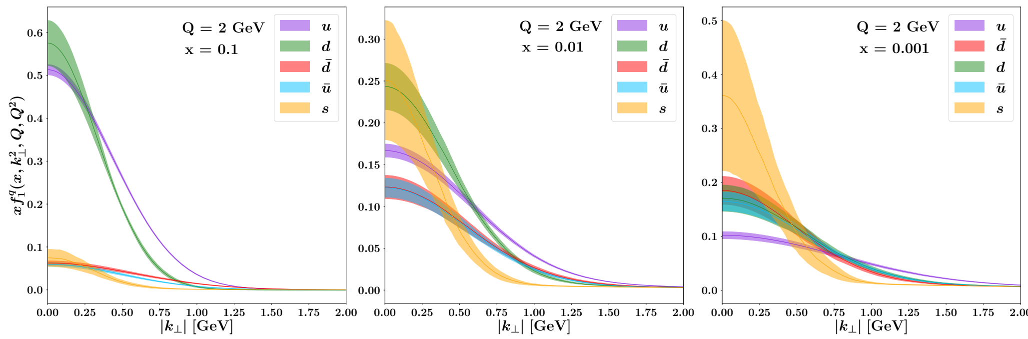

Figure 2: Comparison between the unpolarized TMD PDFs extracted in the MAPTMD24 fit with a flavor dependent approach, for a up (purple), anti-up (light blue), down (green), anti-down (red), and *sea* (orange) quark, as functions of the partonic transverse momentum $|\boldsymbol{k}_\perp|$ at $\mu = \sqrt{\zeta} = Q = 2$ GeV and $x = 0.1$ (left panel), $x = 0.01$ (central panel), and $x = 0.001$ (right panel). The uncertainty bands represent the 68% C.L.

We note that at $x = 0.1$ the contributions of the up and down quarks dominate. The d-quark TMD PDF is larger at low values of $|\boldsymbol{k}_\perp|$ and decreases more rapidly than the u-quark one. At small x, the contributions from the sea quarks increase and become dominant at low $|\boldsymbol{k}_\perp|$ values. Furthermore, at medium to low x the $\bar{u}$-quark and $\bar{d}$-quark TMD PDFs behave in a similar way, while the u-quark and d-quark ones are very different.

Moreover, the distribution of quarks not belonging to the valence content of the proton appears to be the least constrained with large uncertainty bands for all x values, as expected from the lack of experimental data directly sensitive to sea quarks. On the contrary, at larger x (left panel) the uncertainty bands of the TMD PDFs for up and down quarks are very narrow, due to the large amount of SIDIS data in combination with high-precision DY data. Finally, it is useful to remark that the uncertainties for all flavors increase as x decreases, confirming the need for experimental data in this kinematic region.

In Figs. 3,4, we display the unpolarized TMD FFs of the favoured and unfavoured channels for the fragmentation into a π^+ and K^+, respectively, as functions of the hadronic transverse momentum $|\boldsymbol{P}_\perp|$ at

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$\mu = \sqrt{\zeta} = Q = 2$ GeV and $z = 0.4$ (left panel), and $z = 0.6$ (right panel). We note that the favored fragmentation channel (in this example, $u \longrightarrow \pi^+$) dominates over the unfavored one. Also, both TMD FFs show a second bump at intermediate $|\boldsymbol{P}_\perp|$ which decreases in size at larger z.

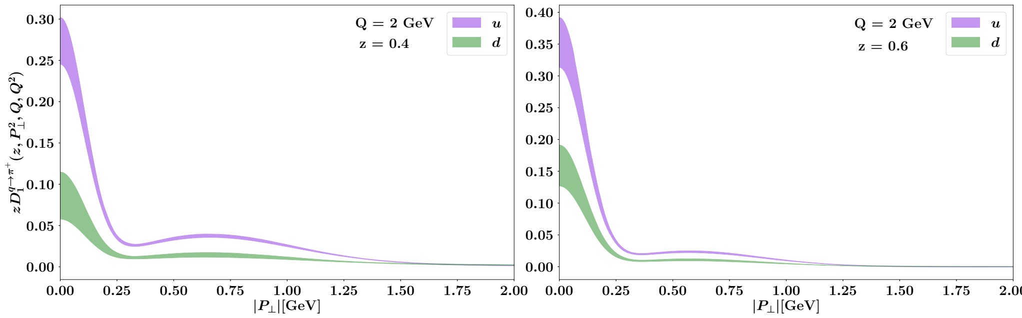

Figure 3: Comparison between the unpolarized TMD FFs for the fragmentation into a π^+ of up (purple) and down (green) quarks, extracted in the MAPTMD24 fit with a flavor dependent approach, as functions of the hadronic transverse momentum $|\boldsymbol{P}_\perp|$ at $\mu = \sqrt{\zeta} = Q = 2$ GeV and $z = 0.4$ (left panel), and $z = 0.6$ (right panel). The uncertainty bands represent the 68% C.L.

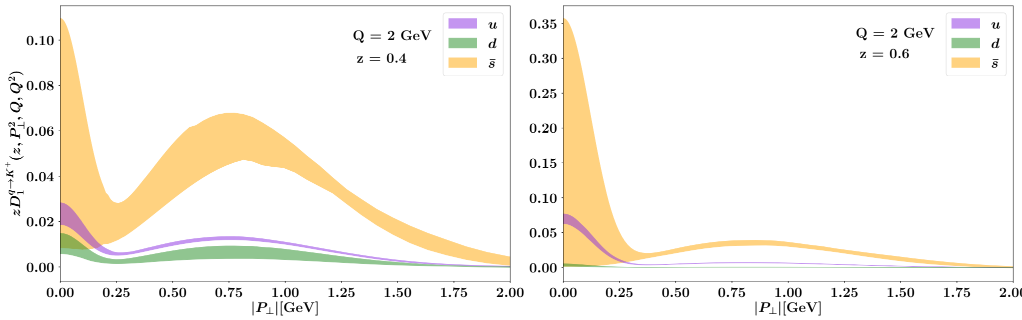

Figure 4: Comparison between the unpolarized TMD FFs for the fragmentation into a K^+ of up (purple), anti-strange (yellow) and down (green) quarks, extracted in the MAPTMD24 fit with a flavor dependent approach, as functions of the hadronic transverse momentum $|\boldsymbol{P}_\perp|$ at $\mu = \sqrt{\zeta} = Q = 2$ GeV and $z = 0.4$ (left panel), and $z = 0.6$ (right panel). The uncertainty bands represent the 68% C.L.

5. Conclusions

In this work, we performed an extraction of transverse-momentum-dependent parton distribution and fragmentation functions from a comprehensive set of 2031 experimental data points from the Drell-Yan (DY) process and semi-inclusive deep-inelastic scattering (SIDIS), with the main goal of unraveling the distinctions among different quark flavors. It is the first time that the flavor-dependent nature of Transverse Momentum Distributions (TMDs) is fully taken into consideration in a global fit.

Our study builds upon previous work by incorporating state-of-the-art theory results reaching N^{3}LL accuracy, and adopting the fitting framework used in our past works, available through the `NangaParbat` public code. This enabled an accurate portrayal of the flavor-specific characteristics of TMDs and their uncertainties, at least within the choices for prescriptions and functional forms that we adopted.

The extracted TMD PDFs and FFs offer valuable insights into the three-dimensional structure of hadrons, revealing distinctive flavor-dependent behaviors across different kinematic regimes. In particular, the u-quark

TMD PDF results to be the most constrained among all flavors, and it is the widest at small and intermediate x. On the other hand, an examination of TMD FFs demonstrates the importance of distinguishing between favored and unfavored channels, particularly evident for kaon fragmentations.

Overall, our study represents a significant step forward in the quest for a comprehensive understanding of the flavor-dependent structure of hadrons in momentum space, and paves the way for more refined theoretical predictions and improved interpretations of experimental phenomena in high-energy physics.

References

[1] A. Bacchetta, F. Delcarro, C. Pisano, M. Radici and A. Signori, *Extraction of partonic transverse momentum distributions from semi-inclusive deep-inelastic scattering, Drell-Yan and Z-boson production*, *JHEP* **06** (2017) 081, [1703.10157].

[2] I. Scimemi and A. Vladimirov, *Non-perturbative structure of semi-inclusive deep-inelastic and Drell-Yan scattering at small transverse momentum*, *JHEP* **06** (2020) 137, [1912.06532].

[3] MAP (Multi-dimensional Analyses of Partonic distributions) collaboration, A. Bacchetta, V. Bertone, C. Bissolotti, G. Bozzi, M. Cerutti, F. Piacenza et al., *Unpolarized transverse momentum distributions from a global fit of Drell-Yan and semi-inclusive deep-inelastic scattering data*, *JHEP* **10** (2022) 127, [2206.07598].

[4] M. Bury, F. Hautmann, S. Leal-Gomez, I. Scimemi, A. Vladimirov and P. Zurita, *PDF bias and flavor dependence in TMD distributions*, *JHEP* **10** (2022) 118, [2201.07114].

[5] V. Moos, I. Scimemi, A. Vladimirov and P. Zurita, *Extraction of unpolarized transverse momentum distributions from the fit of Drell-Yan data at N^{4}LL*, *JHEP* **05** (2024) 036, [2305.07473].

[6] MAP collaboration, A. Bacchetta, V. Bertone, C. Bissolotti, G. Bozzi, M. Cerutti, F. Delcarro et al., *Flavor dependence of unpolarized quark Transverse Momentum Distributions from a global fit*, 2405.13833.

[7] J. Collins, *Foundations of Perturbative QCD*. Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology. Cambridge University Press, 2011.

[8] A. Signori, A. Bacchetta, M. Radici and G. Schnell, *Investigations into the flavor dependence of partonic transverse momentum*, *JHEP* **11** (2013) 194, [1309.3507].