Determination of unpolarized TMD distributions from the fit of Drell-Yan and SIDIS data at N^{4}LL

ART25
IPARCOS-UCM-25-018
[2503.11201]

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Abstract

This work extends the previous analysis of transverse momentum dependent (TMD) distributions ART23 [1] by including SIDIS measurements in addition to those of the Drell-Yan process. As a result, we provide a simultaneous extraction of the unpolarised TMD parton distribution functions (PDFs), the unpolarised TMD fragmentation functions (FFs) and the Collins-Soper kernel (CS) from a global phenomenological analysis. The theoretical framework is based on leading power TMD factorisation to N^{4}LL perturbative accuracy.

Formulation of TMD distributions

The TMDPDFs are independent distributions, which appear as matrix elements in the factorisation of Drell-Yan processes of small transverse momentum q_T [2], and which contain non perturbative information about the probed hadron's three-dimensional structure. The TMD and the collinear distributions are, however, related in the limit of small transverse distances b – the Fourier conjugated variable to the transverse momentum. This matching between TMDs and collinear distributions is used to formulate the TMD distributions as their perturbative part – determined by the collinear PDFs – and a non-perturbative ansatz f_{NP} – to be constrained by the data:

$$f_{1,f}(x,b) = \int_x^1 \frac{dy}{y} \sum_{f'} C_{f\to f'}\left(y, L(b,\mu_{\text{OPE}}), \alpha_s(\mu_{\text{OPE}})\right) q_{f'}\left(\frac{x}{y}, \mu_{\text{OPE}}\right) f_{\text{NP}}^f(x,b). \quad (1)$$

One major difference between TMDPDFs and their collinear counterpart is their dependence not only on a single factorisation scale μ_F, but also on a second energy scale ζ. The dependence of the distributions on these two scales is given by the evolution equations

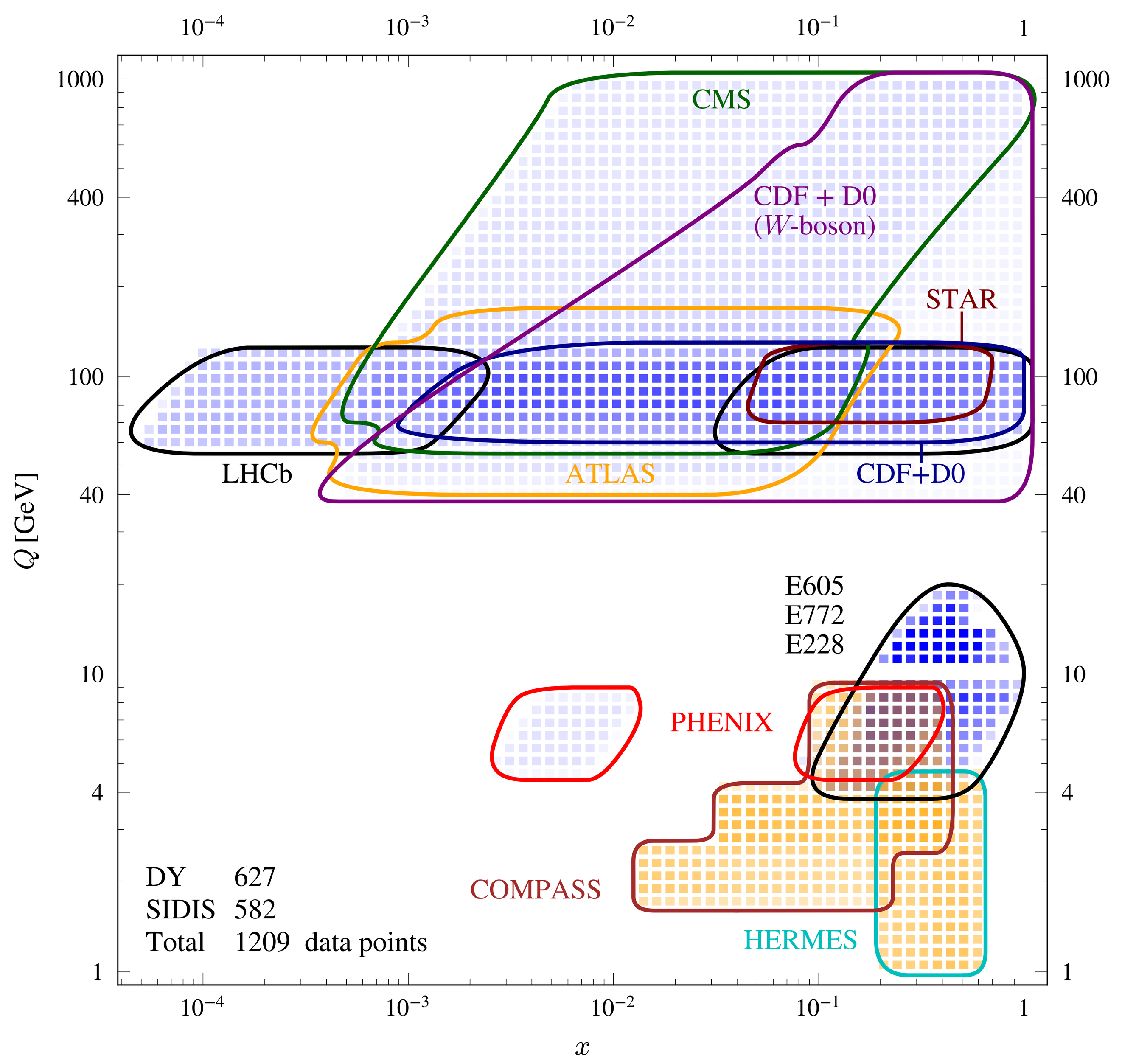
$$\mu_F^2 \frac{d}{d\mu_F^2} f(x,b;\mu_F,\zeta) = \frac{\gamma_F(\mu_F,\zeta)}{2} f(x,b;\mu_F,\zeta), \quad (2)$$

$$\zeta \frac{d}{d\zeta} f(x,b;\mu_F,\zeta) = -\mathcal{D}(b,\mu_F) f(x,b;\mu_F,\zeta). \quad (3)$$

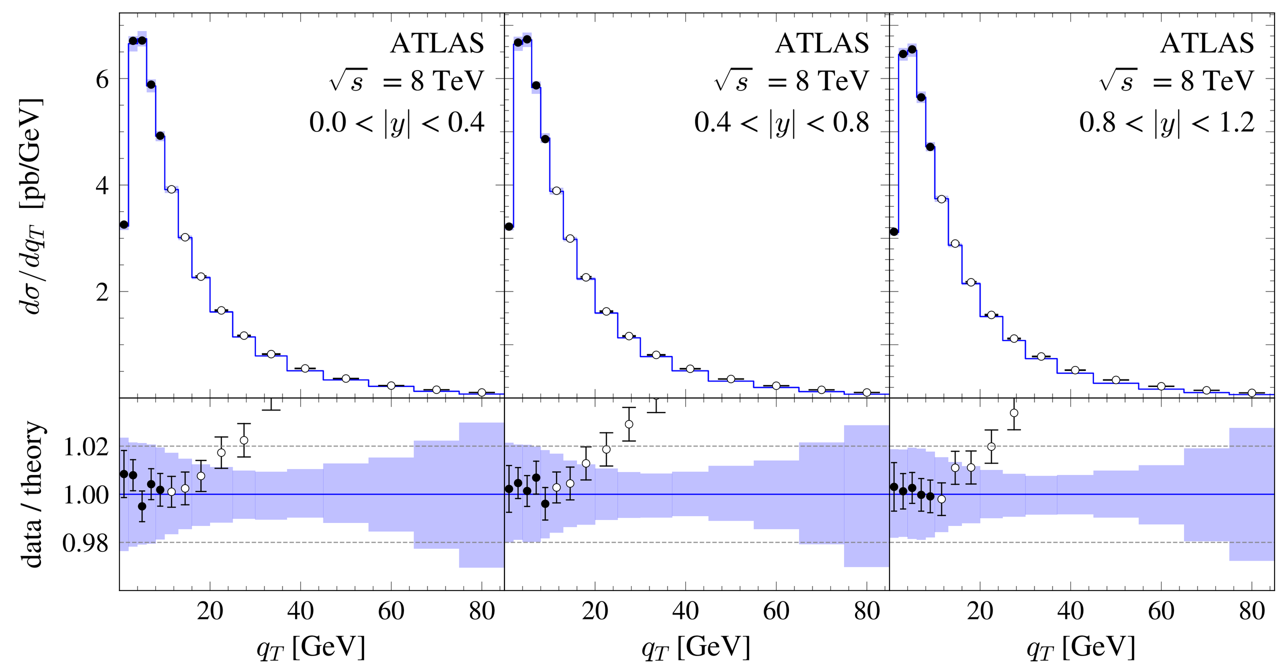
The function γ_F is perturbative, while the CS ($\mathcal{D}$) is not and, hence, its determination is part of the phenomenological extraction. In our framework, we define the ansatz (1) to hold at the saddle point induced by the equations (2) & (3), implicitely defining its energy scales. Furthermore, this technical definition decorrelates the parameters of the TMD distributions and the CS.

Data review

The data from the Drell-Yan process used in the fit covers a range in resolution scale Q from 4 GeV – in fixed target experiments at Fermilab – up to 1000 GeV – in scattering events measured at the LHC. The most precise data is contributed by the ATLAS collaboration at a centre-of-mass energy of 13 TeV and a precision at the permille level. The other half of the data are contributed from SIDIS measurements, provided by the HERMES and COMPASS experiments. These data allow for the extraction of pion- and kaon-TMDFFs. Additionally, the SIDIS process helps in separating the quark flavours.



Kinematic phase space in momentum fraction x and virtuality Q covered by the data used in the fit



Experimental data and theoretical prediction of the q_T spectrum for the Drell-Yan process at $\sqrt{s} = 8$ TeV measured in various bins of rapidity y in the ATLAS experiment

Factorised cross section

The parton distributions determine the outcome of the cross section. As an illustration, in the Drell-Yan process the differential unpolarised cross section is given as a convolution of two unpolarised TMDPDFs f_1:

$$\frac{d\sigma}{dQ^2 dy dq_T^2} = \frac{2\pi\alpha_{\text{em}}^2}{3N_c s Q^2}\left(1+\frac{q_T^2}{2Q^2}\right)\sum_f C_{\text{DY}} \int_0^\infty db\, b\, J_0(bq_T)\left(\frac{Q^2}{\zeta(b)}\right)^{-2\mathcal{D}(b,Q)} f_{1,f}(x_1,b) f_{1,\bar{f}}(x_2,b). \quad (4)$$

Non perturbative input

The matching (1) requires the collinear distributions, which themselves are non-perturbative objects and first need to be determined, e.g., from a fit. ART25 employs the results MSHTPDF20 [3] and MAPFF1.0 [4] for the collinear PDFs and FFs, respectively.
The non-perturbative ansatzes used in this work are listed below. They feature a simplistic functional form, and flavour and hadron dependence in their parameters. Last of which are new developments, possible due to increasing precision in both theory and experiment.

$$f_{\text{NP}}^f(x,b) = \cosh^{-1}\left(\left(\lambda_1^f(1-x)^{\lambda_3} + \lambda_2^f x\right) b\right) \quad (5)$$

$$f \in \{u, \bar{u}, d, \bar{d}, sea\}$$

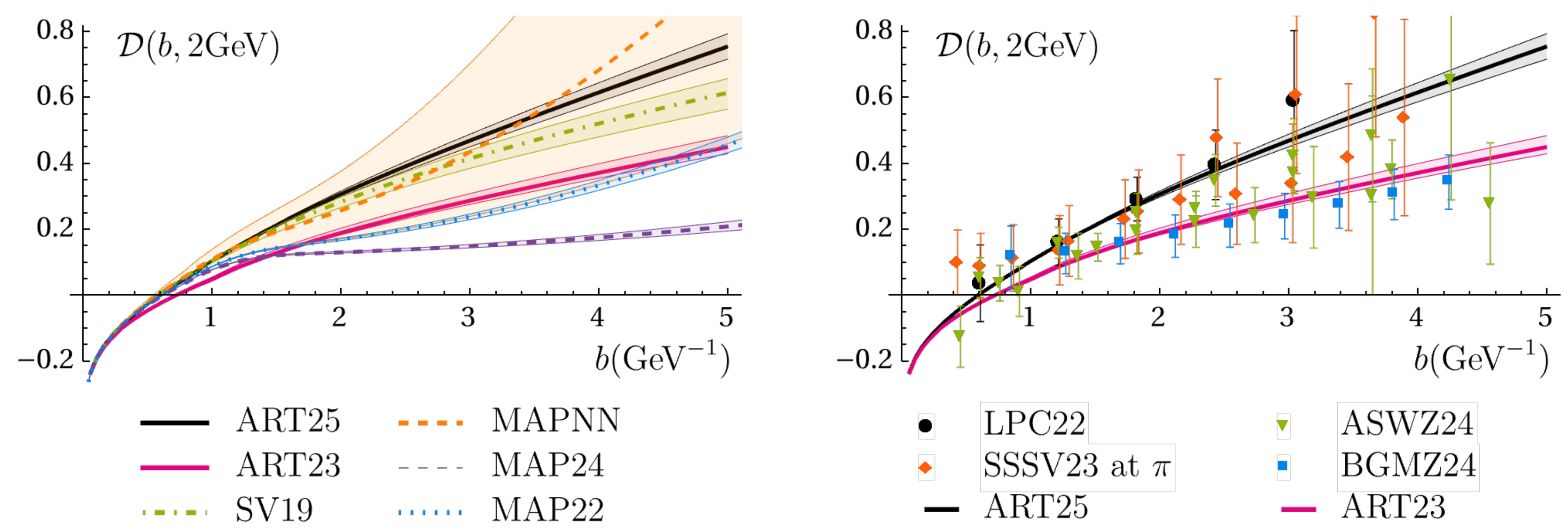
$$d_{\text{NP}}^{f,h}(z,b) = \cosh^{-1}\left(\eta_0^h(1-z)\frac{b}{z}\right)\left(1+\eta_1^{\{h,f\}}\frac{b^2}{z^2}\right) \quad (6)$$

$$h \in \{\pi^\pm, K^\pm\} \qquad f \in \{u, \bar{d}, \bar{u}, sea\} \text{ for } h = \pi^+$$

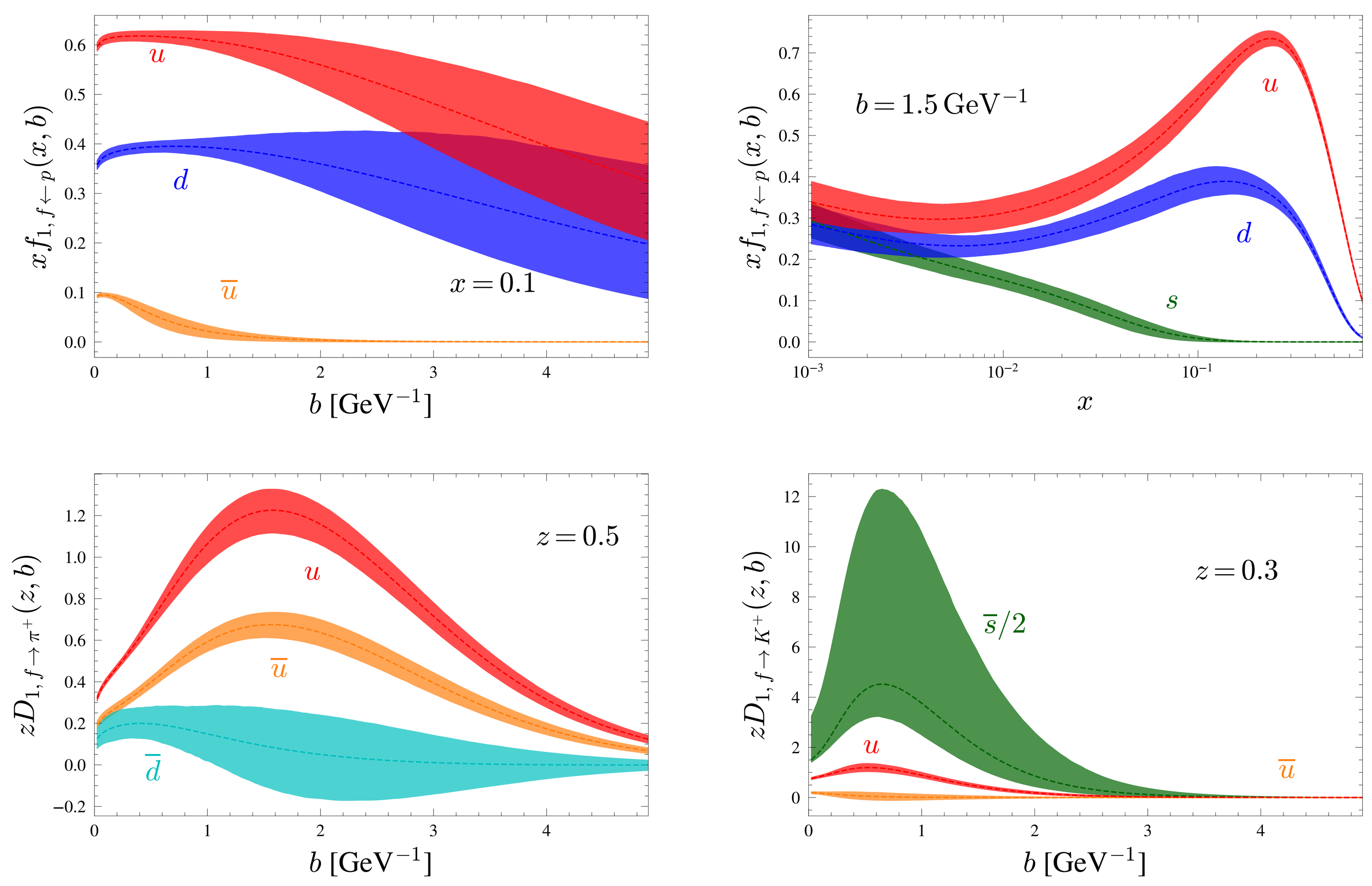
$$\mathcal{D}(b,\mu) = \mathcal{D}_{\text{small-b}}(b^*,\mu) + c_0 b b^* + c_1 b b^* \ln\left(\frac{b^*}{B_{\text{NP}}}\right) \quad (7)$$

Results

We obtain an ensamble of predictions, each thereof resulting of a fit with a replica of the collinear distributions and a replica of the data. Displayed are the average and the 68% CI of these results. The extracted values provide a very good description of the data over whole range of available kinematics and achieve a $\chi^2/N_{\text{data}} = 1.05$ at the input of a total of 22 free parameters.
Shown below is a selection of the obtained results for the CS and the TMD distributions. The uncertainty obtained for the CS remains small at larger values of b as an artefact of the fit, as the data is most sensitive to the region $b \leq 1.5$ GeV.



Obtained CS compared with other phenomenological extractions (left) and with results from lattice QCD (right).



Resulting TMD distributions for different quark flavours: the TMDPDFs displayed by their b dependence (top left) and their x dependence (top right), the pion TMDFF (bottom left) and the kaon TMDFF (bottom right) displayed for their b dependence.

References

[1] Valentin Moos et al. "Extraction of unpolarized transverse momentum distributions from the fit of Drell-Yan data at N^{4}LL". In: JHEP 05 (2024), p. 036. DOI: 10.1007/JHEP05(2024)036. arXiv: 2305.07473 [hep-ph].

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[3] S. Bailey et al. "Parton distributions from LHC, HERA, Tevatron and fixed target data: MSHT20 PDFs". In: The European Physical Journal C 81.4 (Apr. 2021). DOI: 10.1140/epjc/s10052-021-09057-0.

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