

First Simultaneous Analysis of Transverse Momentum Dependent and Collinear Parton Distributions in the Proton

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We present the first simultaneous global QCD analysis of unpolarized transverse momentum dependent (TMD) and collinear parton distribution functions (PDFs) in the proton. Our Letter incorporates data from deep-inelastic scattering, Drell-Yan, inclusive weak boson, W + charm, and jet production involving PDFs, as well as TMD Drell-Yan and Z-boson production data from fixed target and collider experiments sensitive to both TMD and collinear distributions. The analysis is performed at next-to-next-to-leading logarithmic accuracy for QCD resummation in TMD observables and next-to-leading order for observables described in collinear factorization. The combined analysis improves knowledge of both TMD and collinear PDFs, particularly in the sea-quark sector, providing a consistent simultaneous description of the aforementioned observables.

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Introduction—Over the past half century significant effort has been devoted to studying the internal structure of nucleons in terms of their fundamental quark and gluon constituents within the theory of quantum chromodynamics (QCD) [1]. Probing the nucleon’s internal structure relies on experimental and phenomenological input, employing QCD factorization theorems [2–7] to separate observables into perturbative hard parts and nonperturbative functions encoding structure information. In addition, evolution equations derived from factorization theorems resum large process-independent logarithmic contributions from the collision-induced radiation and connect observables at different scales. Accordingly, measurements from fixed

target and collider experiments are synergistic, together enabling detailed studies of perturbative and nonperturbative QCD dynamics.

The most well-known nonperturbative functions are the unpolarized collinear parton distribution functions (PDFs) [8–15]. In recent years there has been increased focus on the nucleon’s three-dimensional structure, encoded in transverse momentum dependent (TMD) parton distribution functions [16–20] (referred to as “TMDs” in this Letter). While PDFs depend only on the longitudinal parton momentum fraction x , TMDs are in addition sensitive to the parton’s transverse momentum $k_T \equiv |\mathbf{k}_T|$. The study of TMDs has yielded many phenomenological successes, where key nonperturbative inputs to the unpolarized and polarized TMDs and the Collins-Soper (CS) kernel have been inferred [21–40].

The main motivation for this Letter is based on the connection between PDFs and TMDs. The latter can be expressed in the space of $b_T \equiv |\mathbf{b}_T|$, the Fourier conjugate to $\mathbf{k}_T$, $\tilde{f}(x, b_T) = \int d^2\mathbf{k}_T e^{-i\mathbf{b}_T \cdot \mathbf{k}_T} f(x, \mathbf{k}_T)$. While TMD and collinear factorizations are formally distinct, the TMD operator for $\tilde{f}(x, b_T)$ matches onto the operator for the PDF $f(x)$ in the small- b_T limit, as formalized by the

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operator product expansion (OPE) [4,7,35,41–45] and by integral relations [46–48], which enables explicit construction of the TMDs from collinear PDFs.

In this Letter, we perform the first simultaneous global QCD analysis of collinear PDFs and TMDs of the proton utilizing data from deep-inelastic scattering (DIS), Drell-Yan (DY), inclusive weak boson, W + charm, and jet production, as well as TMD-sensitive DY and Z -boson production data from fixed target and collider experiments. This Letter establishes a new paradigm in which collinear PDFs and TMDs are extracted simultaneously, allowing for improved determination of these universal QCD functions and a more consistent theoretical description of observables sensitive to PDFs and TMDs.

Theoretical formalism—TMD factorization [4,7,49–53] describes the DY process, $h_1 h_2 \rightarrow \ell^+ \ell^- X$, in the region of small transverse momentum q_T of the produced lepton pair relative to its invariant mass Q . In this regime, the measured cross section has been described in the Collins-Soper-Sterman formalism [4] and recently presented in terms of TMDs [7,18,20,54]. The cross section for proton-proton collisions differential in Q^2 , rapidity y of the lepton pair, and q_T is given by

$$\frac{d^3\sigma}{dQ^2 dy dq_T^2} = \sigma_0 \mathcal{P} \sum_q c_q^2(Q) \mathcal{H}_{q\bar{q}}^{\text{DY}}(Q, \mu) \int \frac{d^2 b_T}{(2\pi)^2} e^{ib_T \cdot q_T} \times \tilde{f}_{q/p}(x_1, b_T; \mu, \zeta) \tilde{f}_{\bar{q}/p}(x_2, b_T; \mu, \zeta), \quad (1)$$

where the sum over q runs over all quarks and antiquarks with electroweak charges c_q^2 . Here, $\mathcal{P}$ is the fiducial factor that takes into account experimental cuts on the momenta of the detected leptons [22,24], $\sigma_0 \equiv 4\pi^2 \alpha^2 / 9Q^2 s$ with s the center of mass energy squared of the reaction, $\mathcal{H}_{q\bar{q}}^{\text{DY}}$ is the hard coefficient function, and $x_{1(2)} = (Q/\sqrt{s})e^{+(-)y}$ are the partonic momentum fractions. Two scales, μ and ζ , regularize the ultraviolet and rapidity divergences, respectively, and are conventionally chosen to be $\mu^2 = \zeta = Q^2$ to optimize the perturbative convergence. Each TMD satisfies the CS equations [20,55], which govern the dependence on these scales, and several frameworks exist for implementing their solutions (see Chapter 4 of Ref. [20] and references therein).

In our Letter we utilize the ζ -prescription [27,56] for TMD evolution. A defining feature of the ζ -prescription is that it uses the null-evolution line $[\mu, \zeta_\mu(b_T)]$ as the reference scale, defined by

$$\Gamma(\mu) \ln\left(\frac{\mu^2}{\zeta_\mu(b_T)}\right) - \gamma_V(\mu) = 2\mathcal{D}(b_T; \mu) \frac{d \ln \zeta_\mu(b_T)}{d \ln \mu^2}, \quad (2)$$

where γ_V is the anomalous dimension of the vector form factor [55,57], and Γ is the cusp anomalous dimension [58–63]. The CS kernel $\mathcal{D}$ [7,20,36,41] determines the rapidity scale evolution of the TMD,

$$\mathcal{D}(b_T; \mu) = \mathcal{D}_{\text{pert}}(b^*; \mu^*) + \int_{\mu^*}^{\mu} \frac{d\mu'}{\mu'} \Gamma(\mu') + \mathcal{D}_{\text{NP}}(b_T). \quad (3)$$

Here, $\mathcal{D}_{\text{pert}}$ is a perturbatively calculable component that describes the small- b_T behavior [64–66], and $\mathcal{D}_{\text{NP}}$ is a nonperturbative component that dominates the large- b_T region. The matching between the small- and large- b_T regions is controlled via b^* , where $b^*(b_T) = b_T / \sqrt{1 + b_T^2/B_{\text{NP}}^2}$ with fixed $B_{\text{NP}} = 1.5 \text{ GeV}^{-1}$ and $\mu^* = 2e^{-\gamma_E}/b^*(b_T)$. The nonperturbative component is extracted from the data, as discussed below.

In the ζ -prescription [27,56], the selection of the scale for TMDs is replaced by the selection of the equipotential line, for which we choose a line passing through the saddle point of the evolution field. A TMD at a given set of scales (μ, ζ) is then given by

$$\tilde{f}_{q/p}(x, b_T; \mu, \zeta) = \tilde{f}_{q/p}(x, b_T) \left(\frac{\zeta}{\zeta_\mu(b_T)} \right)^{-\mathcal{D}(b_T; \mu)}, \quad (4)$$

where $\tilde{f}_{q/p}(x, b_T)$ is the so-called optimal TMD. This function is obtained by utilizing the OPE relation of TMDs and PDFs at small b_T [7,35,41–45] and modeling its nonperturbative large- b_T behavior,

$$\tilde{f}_{q/p}(x, b_T) = \sum_{f'=q,\bar{q},g} [C_{q/f'}(x, b_T; \mu_{\text{OPE}}) \otimes f_{f'/p}(x; \mu_{\text{OPE}})] \times f_{\text{NP}}^q(x, b_T), \quad (5)$$

where $f_{f'/p}$ is the collinear PDF for flavor f' , and f_{NP}^q is a nonperturbative function that encodes large- b_T behavior. The $\otimes$ symbol represents the convolution integral, $C \otimes f \equiv \int_x^1 (d\xi/\xi) C(x/\xi) f(\xi)$. Setting the scale $\mu_{\text{OPE}} = 2e^{-\gamma_E}/b_T + 2 \text{ GeV}$ [36] minimizes logarithmic corrections and avoids the Landau pole at large b_T .

To align with the next-to-leading order treatment of the collinear observables in this analysis, the Wilson coefficients $C_{q/f'}$ entering Eq. (5) are taken at $\mathcal{O}(\alpha_s)$ [7,55]. Following the standard logarithmic counting [20,22], we implement next-to-next-to-leading logarithmic (NNLL) accuracy for TMDs. Specifically, we use Γ at $\mathcal{O}(\alpha_s^3)$, and γ_V and $\mathcal{D}_{\text{pert}}$ at $\mathcal{O}(\alpha_s^2)$ precision, while the hard factor $\mathcal{H}_{q\bar{q}}^{\text{DY}}$ in Eq. (1) is at $\mathcal{O}(\alpha_s^2)$. We plan to extend the perturbative accuracy to higher orders in the future, as inclusion of next-to-next-to-leading order corrections can further improve the description of the collinear-sensitive data [67].

Phenomenological framework—The data used in this analysis include DIS from BCDMS [68], NMC [69,70], SLAC [71], Jefferson Lab [72–75], and HERA [76]; DY lepton-pair production from the Fermilab NuSea [77] and SeaQuest [78] experiments; $W^\pm$ -lepton asymmetries from CMS [79–82] and LHCb [83,84] at the LHC and STAR

[85] at RHIC; reconstructed Z/γ^* and $W^\pm$ asymmetries from the Tevatron [86–89]; $W+$ charm production [90–92] from the LHC; and jet production data from the Tevatron [93,94] and RHIC [95]. We note that while state-of-the-art purely collinear analyses include q_T -integrated LHC Z -boson production data [9,10,12], our emphasis is on the inclusion of their q_T -dependent counterparts, which we describe using the TMD formalism. Our baseline PDF set does not include these high-precision q_T -integrated measurements and is therefore comparatively less constrained. A relatively low cut on DIS data of $W^2 > 3.5 \text{ GeV}^2$ allows sensitivity to quark distributions in the large- x region.

For the processes described above we utilize the $\overline{\text{MS}}$ renormalization scheme, with the strong coupling α_s evolved numerically using the QCD β -functions with boundary condition $\alpha_s(M_Z) = 0.118$ at the Z -boson mass. The PDFs are evolved to next-to-leading logarithmic accuracy solving the DGLAP evolution equations [2,3,96,97] using Mellin-space techniques in the zero-mass variable flavor scheme. The input scale μ_0 is set to the charm quark mass, $m_c = 1.28 \text{ GeV}$ [98]. The collinear PDFs are parametrized at μ_0 using the shape function

$$f(x; \mu_0) = N x^\alpha (1-x)^\beta (1 + \gamma \sqrt{x} + \delta x), \quad (6)$$

which historically was motivated by Regge theory [99,100] for α and quark counting rules [101,102] for β , although in modern QCD analyses these are treated as completely free parameters. The shape-modifying factor with the parameters γ and δ adds flexibility in the intermediate- x region [103]. A total of 35 parameters are used for the $u_v, d_v, \bar{u}, \bar{d}, s, \bar{s}$, and g flavors, while heavy quark distributions are generated through evolution. As usual, the number and momentum sum rules are imposed to constrain the normalization parameters for the u_v, d_v, s , and g PDFs. We additionally include contributions from higher twist effects, target mass corrections, and off-shell effects that are important in describing the high- x DIS data [15,105].

In this analysis, we use q_T -dependent DY data from both fixed target and collider experiments. The fixed target inputs are from the E288 experiment [106] taken with 200, 300, and 400 GeV proton beams on a copper (Cu) target, the E605 experiment [107] taken on a Cu target, and the E772 experiment [108] using a deuterium target. For the high-energy collider datasets, we analyze absolute cross sections, including $p\bar{p}$ data from the Tevatron integrated in rapidity, comprising two datasets from CDF [109,110] at 1.8 and 1.96 TeV and D0 [111] at 1.8 TeV. We also use LHC pp data taken around the Z boson peak: ATLAS [112] at 8 TeV and CMS [113] at 13 TeV binned in rapidity, and LHCb data [84,114,115] at 7, 8, and 13 TeV integrated over large rapidity, $2 \leq y \leq 4.5$. Finally, pp data from the STAR 510 GeV [116] and PHENIX 200 GeV runs [117] at RHIC are also included.

For consistency between our theoretical formalism and the experimental data, we impose kinematic cuts for the TMD-sensitive data such that $q_T/Q < 0.2$, and at least one of $q_T^2/Q^2 < 2\sigma$ or $q_T < 10 \text{ GeV}$ is satisfied, where σ is the experimental relative uncorrelated uncertainty [36,37]. This yields 436 points for the q_T -dependent DY data, which together with the 4279 points for collinear observables, amounts to a total dataset of 4715 points.

For the parametrization of the nonperturbative ingredients of the TMDs, we follow Ref. [36] and take

$$f_{\text{NP}}^q(x, b_T) = \cosh \{ [\lambda_1^q (1-x) + \lambda_2^q x] b_T \}^{-1}, \quad (7)$$

where $\lambda_{1,2}^q$ are free parameters for $u, d, \bar{u}, \bar{d}$, and $q_{\text{sea}} = s = \bar{s} = c = \bar{c} = b = \bar{b}$. The nonperturbative part of the CS kernel is parametrized as

$$\mathcal{D}_{\text{NP}}(b_T) = b_T b^* [c_0 + c_1 \ln(b^*/B_{\text{NP}})], \quad (8)$$

where c_0 and c_1 are free parameters. This parametrization is motivated by the expected exponential decay of TMDs and a linear dependence of the Collins-Soper kernel at large b_T [103,118,119].

Since the fixed-target data involve nuclei, we relate the TMDs for the nucleus to the bound proton and neutron TMDs by $\tilde{f}_{q/A} \equiv (Z/A)\tilde{f}_{q/p} + (1-Z/A)\tilde{f}_{q/n}$

TABLE I. χ^2/N_{pts} and Z -score values for the PDF only (baseline PDF) and TMD only (baseline TMD+LHC) analyses compared with the combined TMD + PDF analysis (JAM25_{PDF+TMD}).

Process	N_{pts}	χ^2/N_{pts} (Z-score)	
Collinear		PDF only	TMD + PDF
DIS—fixed target	2501	1.02(+0.82)	1.02(+0.59)
—HERA	1185	1.27(+6.01)	1.27(+6.11)
DY	205	1.27(+2.54)	1.26(+2.50)
W - ℓ asymmetry	70	0.80(−1.20)	0.78(−1.35)
W asymmetry	27	1.12(+0.51)	1.13(+0.53)
Z rapidity	56	1.09(+0.55)	1.11(+0.60)
Jets	198	1.00(+0.00)	0.98(−0.13)
$W + c$	37	0.65(−1.66)	0.62(−1.84)
Total collinear	4279	1.10(+4.31)	1.09(+4.14)
TMD		TMD only	TMD + PDF
DY—E288, E605, E772	224	1.36(+3.44)	1.31(+3.02)
—CDF, D0	80	1.06(+0.45)	1.11(+0.71)
—STAR, PHENIX	12	1.15(+0.47)	1.20(+0.60)
—ATLAS	30	2.07(+3.29)	1.78(+2.55)
—CMS	64	1.18(+1.03)	0.92(−0.39)
—LHCb	26	0.53(−1.97)	0.50(−2.12)
Total TMD	436	1.27(+3.72)	1.20(+2.76)
Total	4715		1.10(+4.79)

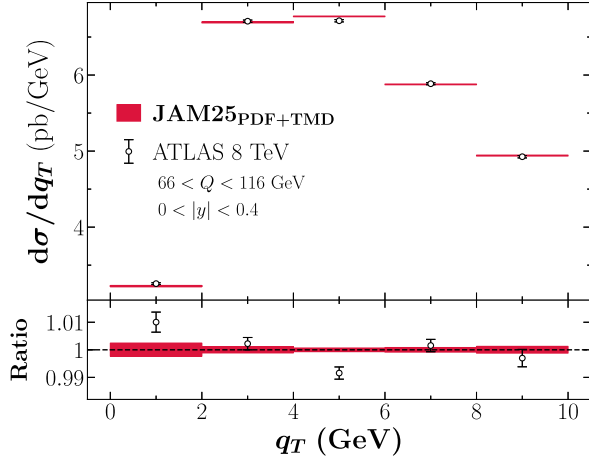


FIG. 1. Comparison of a representative bin of the ATLAS 8 TeV data with the JAM25_{PDF+TMD} analysis at the 68% CI.

for a nucleus with mass number A and atomic number Z . We do not include additional nuclear effects in this analysis; nuclear TMD effects have previously been studied [34,120] and will be incorporated in future work. In all we have 12 parameters for the TMD sector, which together with the 35 collinear PDF shape parameters and the 12 higher-twist and off-shell parameters, gives a total of 59 parameters that need to be inferred from the data. This constitutes a computational challenge that requires a high-performance computing effort due to the lengthy calculation involved, particularly for the OPE.

For our global analysis we use the Bayesian Monte Carlo methodology developed by the JAM Collaboration [15,97,105,121–141], generating $\mathcal{O}(1000)$ replicas to accumulate sufficient statistics to compute approximate credible intervals (CIs) for the collinear and TMD PDFs. We also filter replicas with large posterior Z -scores, where $Z = \Phi^{-1}(p) \equiv \sqrt{2}\text{erf}^{-1}(2p - 1)$, with the p value of the resulting χ^2 computed relative to the expected χ^2 distribution.

Results—We perform the Bayesian Monte Carlo analysis for four different scenarios: (1) baseline PDF: collinear PDFs inferred from collinear observables only;

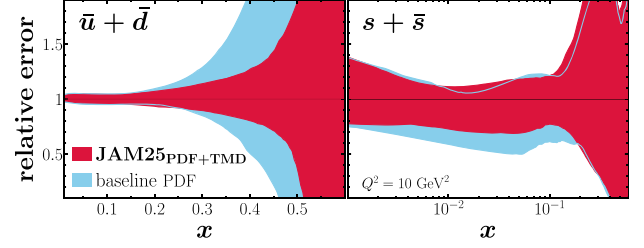


FIG. 2. Comparison of relative errors for collinear $\bar{u} + \bar{d}$ (left panel) and $s + \bar{s}$ (right panel) PDFs between the baseline PDF (blue) and JAM25_{PDF+TMD} (red) analyses at $Q^2 = 10 \text{ GeV}^2$ for 95% CIs.

(2) baseline TMD: TMDs inferred from the q_T -dependent fixed target DY, Tevatron, and RHIC data, with PDF replicas fixed to the baseline PDF set. This allows PDF uncertainties to be propagated into the extracted TMDs; (3) baseline TMD +LHC: TMDs inferred using in addition LHC TMD-sensitive data, with TMD priors taken from baseline TMD and PDFs fixed from baseline PDF. This allows us to assess the impact of LHC data; and (4) **JAM25_{PDF+TMD}**: full simultaneous PDF and TMD inference set, combining all collinear-sensitive and TMD-sensitive data considered in this Letter.

The resulting agreement with the data is shown in Table I, where the quoted values of χ^2 and Z -scores are computed using the average theory over the ensemble of replicas. The combined analysis leads to an improvement in the description of the experimental measurements, especially for the q_T -dependent DY data where the Z -score reduces by ≈ 1 unit from 3.72 to 2.76, while the collinear-sensitive datasets remain stable with a Z -score reduction of only 0.17. The improvement in χ^2/N_{pts} is greatest for ATLAS data (from 2.07 to 1.78) and CMS (from 1.18 to 0.92). We stress that the ATLAS data are extremely precise, and all modern extractions fitting only DY data have relatively large χ^2 values [25,36,38].

In Fig. 1, we show the data and theory comparison for the $0 \leq |y| \leq 0.4$ bin of the ATLAS data, as well as the data-to-theory ratio. We note the subpercent precision of the data and our ability to describe the data to within 1%.

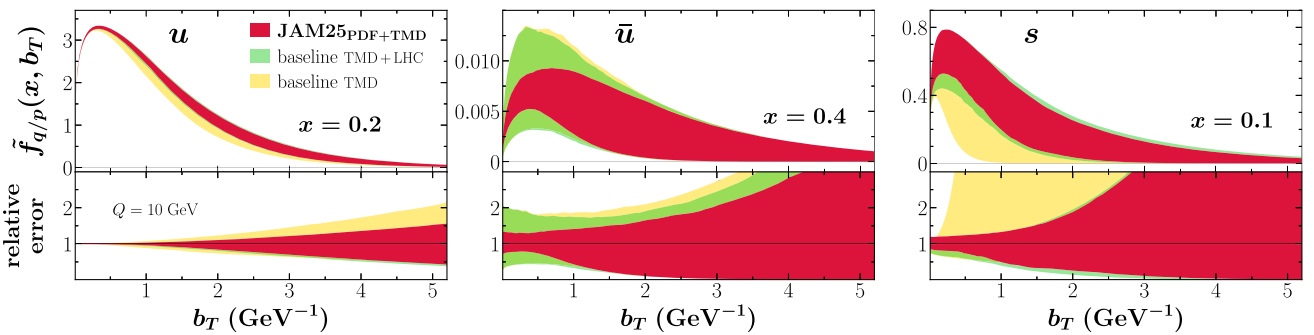


FIG. 3. TMDs $\tilde{f}_{q/p}(x, b_T)$ (upper panels) and ratios to the mean values of $\tilde{f}_{q/p}$ (bottom panels) as functions of b_T for u , $\bar{u}$, and s quarks at fixed $x = 0.2, 0.4$, and 0.1 , respectively, and $Q = 10 \text{ GeV}$. The JAM25_{PDF+TMD} results (red) are compared with the baseline TMD (yellow) and baseline TMD+LHC (green) analyses for 95% CIs.

We additionally achieve a high degree of consistency of normalization coefficients for all q_T -dependent DY datasets, with all fitted normalization factors being within 1σ of the reported normalization uncertainty, except in the case of ATLAS and CMS where the agreement is within 3σ .

In Fig. 2, we present the $\bar{u} + \bar{d}$ and $s + \bar{s}$ PDFs from the baseline PDF and JAM25_{PDF+TMD} analyses as errors relative to the mean value of the combined PDF + TMD analysis. We observe a significant reduction in the uncertainties for the $\bar{u} + \bar{d}$ PDFs for $x \gtrsim 0.3$, largely influenced by the fixed target q_T -dependent DY data, and a modest reduction in the strange quark sector for $10^{-3} \leq x \leq 0.2$ due to the LHC data. While the magnitude of the light sea decreases at large x , since the relative uncertainty increases, we have verified that the reduction persists for the absolute uncertainty of $x(\bar{u} + \bar{d})$. The reduction in uncertainty of the $s + \bar{s}$ PDFs is consistent with the inclusion of the collinear-sensitive LHC data as observed in Ref. [142]. The comparable reduction obtained from the q_T -integrated LHC data indicates that this constraint on the strange PDF is not unique to the TMD-sensitive data. Rather, the similar effect observed in our PDF + TMD analysis as in the purely collinear analysis [142] supports the consistency of these two theoretical frameworks.

The improvement of the uncertainties on the extracted TMDs is demonstrated in Fig. 3, where we show $\tilde{f}_{q/p}(x, b_T)$ for $q = u, \bar{u}$, and s at $Q = 10$ GeV and $x = 0.2, 0.4$, and 0.1 , respectively, where the impact of the PDF + TMD combined analysis is most prominent. The constraints on the u and s quark TMDs come largely from the LHC data, as shown by the uncertainty reduction from the yellow to green bands. However, these bands for the $\bar{u}$ TMD are rather similar, indicating that it is largely constrained by the fixed target q_T -dependent DY data, with the LHC data playing a minor role. Our simultaneous analysis of TMDs and PDFs has the strongest impact on the $\bar{u}$ and s quark TMDs, particularly at $b_T \lesssim 1$ GeV⁻¹. Interestingly, although the combined analysis significantly impacts both sectors, we find only weak statistical correlation between the PDF and TMD parameters (see Supplemental Material for details [103]).

In Fig. 4, we show the extracted CS kernel from Eq. (3) at $Q = 10$ GeV. One can see that the inclusion of the LHC data significantly constrains its values below $b_T = 1.5$ GeV⁻¹. In addition, the extractions of the CS kernel from the JAM25_{PDF+TMD} and baseline TMD + LHC analyses are largely compatible. This shows that there is a significant decorrelation between the CS kernel and PDFs. The inset of Fig. 4 compares the CS kernel at $Q = 2$ GeV to the lattice QCD results from Ref. [143]. Our results are in excellent agreement with the lattice QCD data, as well as other phenomenological extractions [22,25,36–38] (not shown in Fig. 4).

Outlook—Our simultaneous extraction of proton TMDs and PDFs, obtained from a large collection of observables

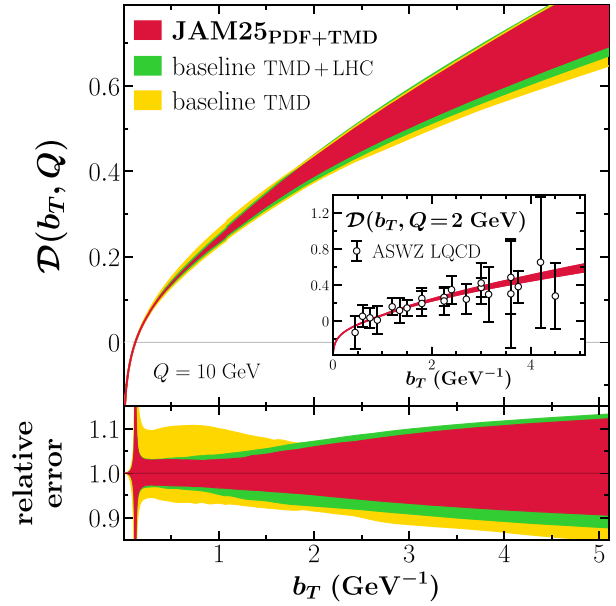


FIG. 4. Collins-Soper kernels $\mathcal{D}(b_T, Q)$ at $Q = 10$ GeV at 95% CIs, with notations as in Fig. 3. The inset compares the 68% CI JAM25_{PDF+TMD} results with lattice QCD (ASWZ LQCD) data at $Q = 2$ GeV [143]. (The lattice data were originally presented in Ref. [143] as $\gamma_q \equiv -2\mathcal{D}$).

ranging from low-energy fixed target experiments to high-energy LHC data, opens a new frontier for QCD studies of nucleon structure. The observed reductions in PDF and TMD uncertainties, especially in the sea-quark sector, together with improvements in the Collins-Soper kernel, highlight the potential for a unified phenomenological treatment of TMD and collinear physics in future simultaneous global QCD analyses.

In the future, we will extend our phenomenological framework to include large transverse momentum data that are also sensitive to collinear PDFs [133,144], and perform precision studies of the QCD strong coupling [145]. Our ultimate goal is to carry out a comprehensive phenomenological study that additionally includes observables sensitive to hadronization effects via semi-inclusive annihilation in e^+e^- and semi-inclusive DIS reactions from existing Belle, Jefferson Lab, HERMES, and COMPASS experiments, preparing for the future Electron-Ion Collider [146]. This Letter paves the way to test and validate the universality of reconstructed nonperturbative hadron structures that emerge in QCD from GeV to TeV scales.

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Data availability—The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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