APS GHP 2025
Workshop

11th Workshop of the
APS Topical Group on
Hadronic Physics

Progress on the simultaneous analysis of collinear and transverse momentum parton distributions

Patrick Barry[1], Leonard Gamberg[2], Wally Melnitchouk[3], Eric Moffat[1], Daniel Pitonyak[4], Alexei Prokudin[2,3], Jianwei Qiu[3,5], Nobuo Sato[3], Alexey Vladimirov[6], Richard Whitehill[7]

[1]Argonne National Laboratory, [2]Penn State University – Berks, [3]Jefferson Lab, [4]Lebanon Valley College, [5]College of William and Mary, [6]Universidad Complutense de Madrid, [7]Old Dominion University

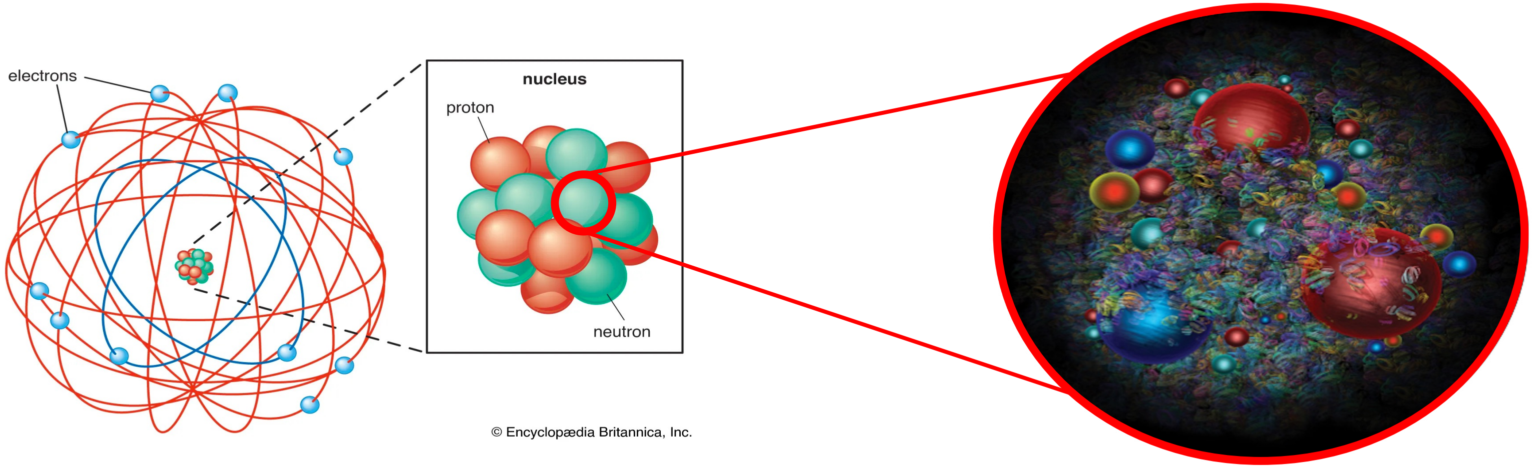
The 11th Workshop of the APS Topical Group on Hadronic Physics

March 14-16, 2025

barry@anl.gov

Motivation

- We want to study the structure of hadrons in terms of quarks and gluons through QCD



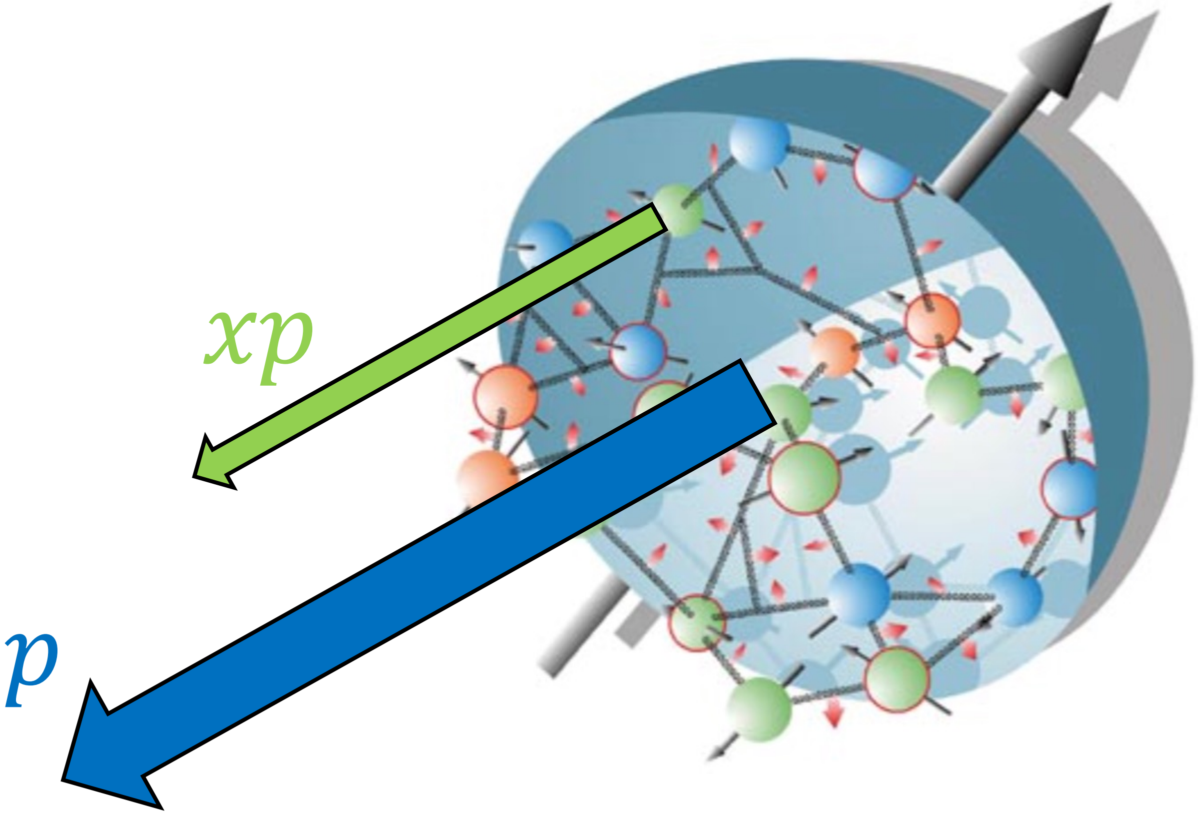
© Encyclopædia Britannica, Inc.

- However, quarks and gluons are not directly observable, and structures are unknown!
- We look to experimental observables to describe the structures in terms of universal objects

Collinear structure – parton distribution function (PDF)

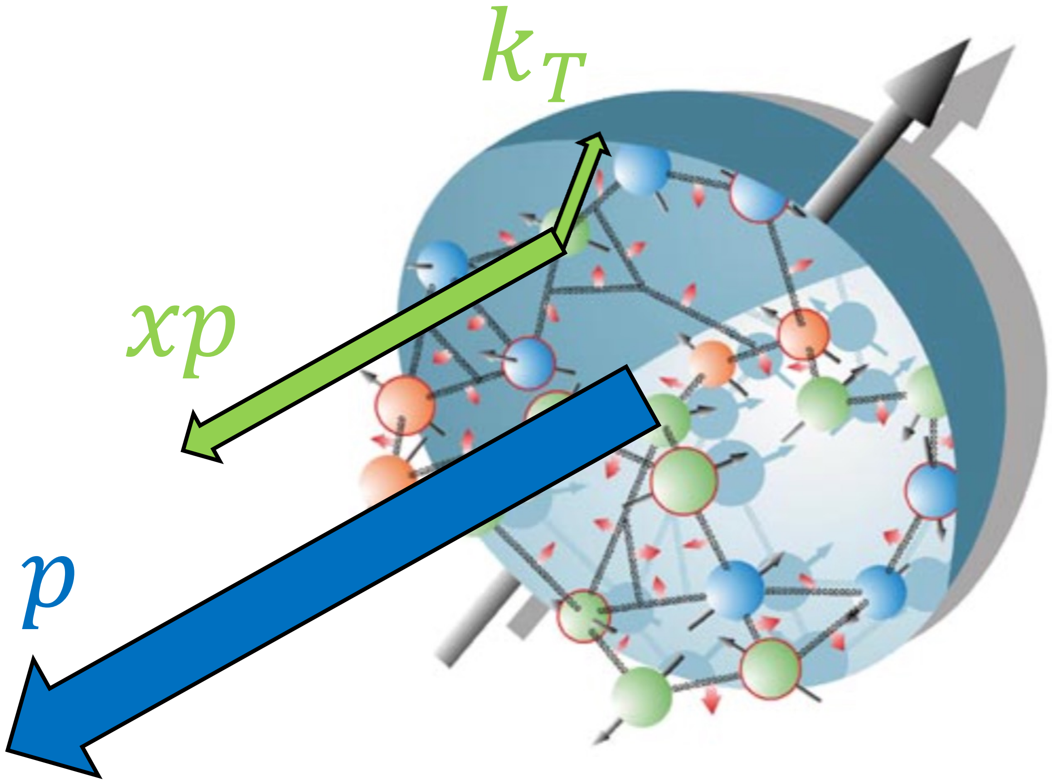
- Describes the collinear momentum distributions of quarks and gluons
- Partons have momentum along the direction of the hadron
- Evolution is descriped through DGLAP

$$\frac{\partial f(x,\mu^2;\boldsymbol{\theta})}{\partial \log \mu^2} = \int_x^1 dz\, \mathcal{P}\left(\frac{x}{z}, \alpha_S(\mu^2)\right) f(z,\mu^2;\boldsymbol{\theta})$$



Transverse Momentum Dependent distributions (TMDs)

- Encode both the collinear and transverse momentum carried by partons
- TMDs are related to collinear **PDFs** via Operator Product Expansion
- Both TMDs and PDFs can be extracted from variety of experimentally measured processes where factorization is applicable, such as Drell-Yan (DY)



$$\tilde{f}(x, b_T; \mu, \zeta) = [C \otimes \boldsymbol{f}](x, b_T; \mu_0, \zeta_0) \\ \times e^{S_{\text{evo}}(b_T; \mu, \mu_0, \zeta, \zeta_0)} f_{\text{NP}}(x, b_T)$$

Collins, Soper, Sterman Nucl. Phys. B **250**, 199, (1985).
Collins, Cambridge University Press, (2011).

Unpolarized TMD PDF

$$\tilde{f}_{q/\mathcal{N}}(x, b_T) = \int \frac{\mathrm{d}b^-}{4\pi} \, e^{-ixP^+b^-} \, \mathrm{Tr}\left[\langle \mathcal{N} \,|\, \bar{\psi}_q(b)\gamma^+\mathcal{W}(b,0)\psi_q(0) \,|\, \mathcal{N} \rangle\right]$$

$$b \equiv (b^-, 0^+, \boldsymbol{b_T})$$

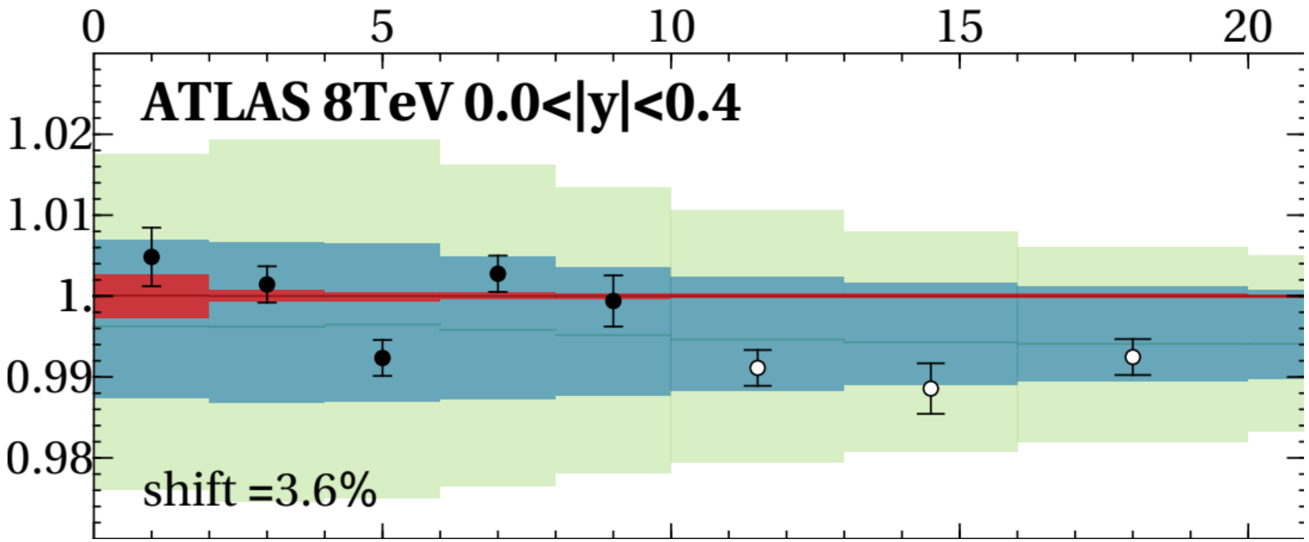
- $\boldsymbol{b_T}$ is the Fourier conjugate to the intrinsic transverse momentum of quarks in the hadron, $\boldsymbol{k_T}$
- Small $\boldsymbol{b_T}$: TMD can be described through the operator product expansion in terms of collinear PDFs
- Large $\boldsymbol{b_T}$: TMD has nonperturbative effects that must be determined from phenomenological analyses

barry@anl.gov

How sensitive are TMD observables to PDFs?

- Red: Bootstrapped fit with central PDFs
- Green: Unbootstrapped fit, varying the PDF replicas
- Blue: Weighted average
- **One needs to take a holistic approach and analyze both PDFs and TMDs simultaneously**

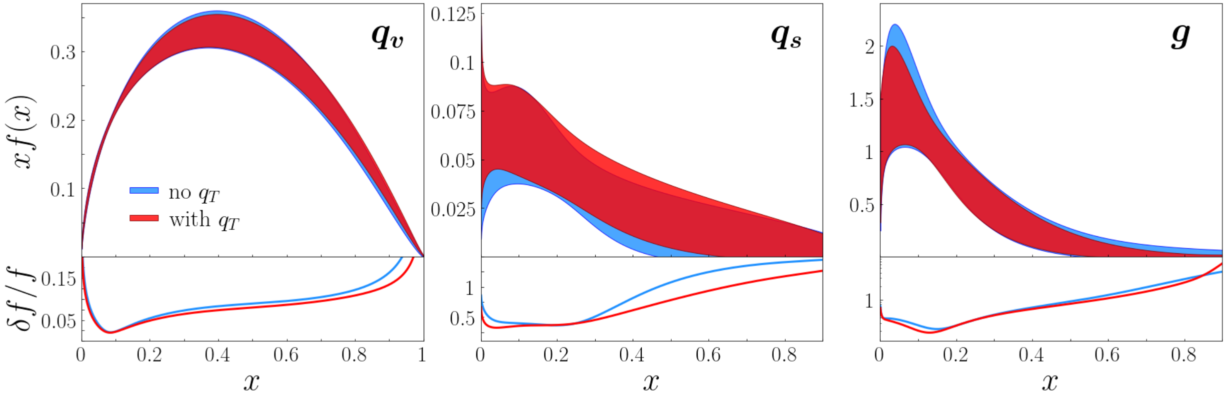
Bury, et al., JHEP **10**, 118 (2022).



barry@anl.gov

Can we learn about PDFs from TMD data?

- Viewing the uncertainties of the observables coming from the PDFs, there is potentially room for improvement on precision of PDFs
- How about for the pion?
- We extracted simultaneously the pion PDFs and TMDs



PCB, et al., PRD **108**, L091504 (2023).

- We found little change in the PDFs before and after the q_T-dependent DY data

Prospects of high-energy data for protons

- There are two major reasons to have hope for improvement of PDFs in the proton sector

1. LHC data are much more precise than their fixed-target low-energy counterparts
    - Peaks of the cross-section in the Z-boson region gather high statistics
2. High-energy data shifts the peak of the b_T-spectrum into the small b_T region, where the operator product expansion and perturbative evolution dominates

- Have to perform the **simultaneous** extraction of PDFs and TMDs from high-energy data to find out!

Transverse momentum dependent DY

- Full cross section over all q_T

$$\frac{d\sigma}{dQ^2dydq_T^2} = W(\boldsymbol{q}_T, Q) + Y(\boldsymbol{q}_T, Q) + O((m/Q)^c)\,,$$

- At small q_T, $W(q_T, Q)$ should be the dominant term

$$W(\boldsymbol{q}_T, Q) = \int \frac{d^2\boldsymbol{b}_T}{(2\pi)^2}\, e^{i\boldsymbol{q}_T\cdot\boldsymbol{b}_T}\, \widetilde{W}(\boldsymbol{b}_T, Q)\,.$$

$$\frac{d^3\sigma}{dQ^2dydq_T^2} = \frac{4\pi^2\alpha_{\rm em}^2}{9Q^2s}\underbrace{\mathcal{P}}_{\text{Fiducial volume factor}}\sum_j \underbrace{c_j^2(Q)}_{\text{Electro-weak couplings}}\underbrace{H_{j\bar{j}}^{\rm DY}(\mu, Q)}_{\text{Hard factor for DY}}\int\frac{d^2\boldsymbol{b}_T}{(2\pi)^2}e^{i\boldsymbol{q}_T\cdot\boldsymbol{b}_T}\underbrace{\tilde{f}_{q_j/\mathcal{N}}(x_1, b_T;\mu,\zeta)}_{\text{TMD for the beam}}\underbrace{\tilde{f}_{\bar{q}_j/\mathcal{N}}(x_2, b_T;\mu,\zeta)}_{\text{TMD for the target}},$$

barry@anl.gov

Input scale TMD

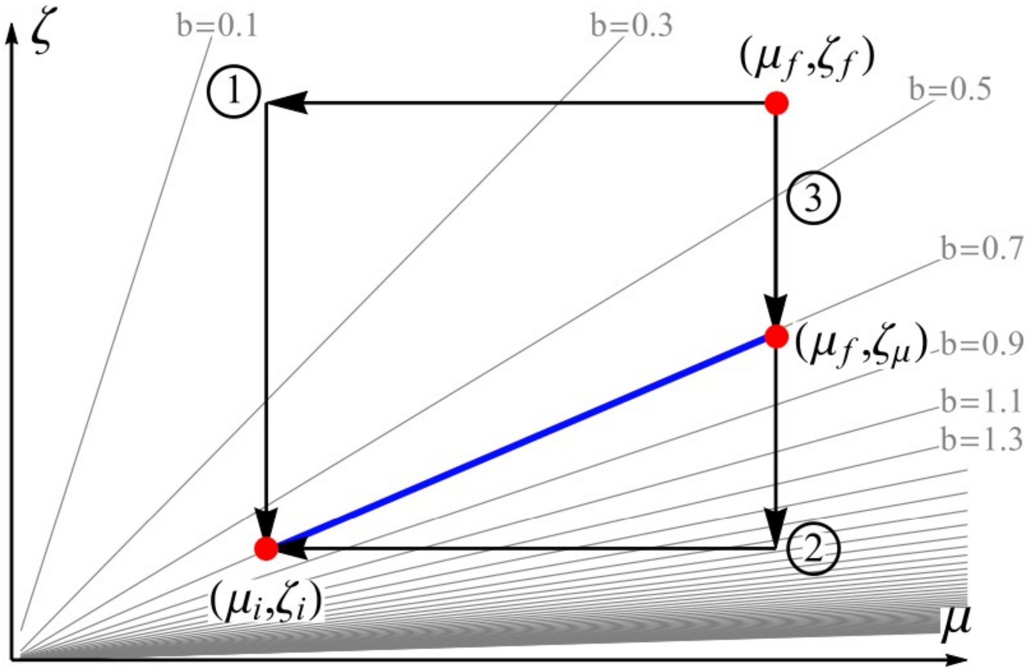
$$\tilde{f}_{q/\mathcal{N}}(x, b_T; \mu_0, \zeta_0) = f^{\mathrm{NP}}_{q/\mathcal{N}}(x, b_T) \sum_j \int_x^1 \frac{d\xi}{\xi} \tilde{\mathcal{C}}_{q/j}(x/\xi, b_T; \mu_0, \zeta_0) f_{j/\mathcal{N}}(\xi; \mu_0)$$

- f^{NP} describes the non-perturbative structure of the TMD at large-b_T
- Convolution is the operator-product expansion (OPE), which describes the small-b_T behavior
- Explicit dependence on the collinear PDF $f_{j/\mathcal{N}}$
- $\tilde{C}$ is perturbatively expanded in α_S
- Evolution in μ and ζ needs to take place to match with data

barry@anl.gov

Building the TMD in the ζ-prescription

- We need to evolve the TMD $\tilde{f}(x, b_T; \mu_0, \zeta_0) \rightarrow \tilde{f}(x, b_T; \mu_f, \zeta_f)$
- A few choices:
  1. Evolve $\zeta_0 \rightarrow \zeta_f$ at a fixed μ_i, then evolve $\mu_0 \rightarrow \mu_f$ at a fixed ζ_f
  2. Evolve $\mu_0 \rightarrow \mu_f$ at a fixed ζ_i, then evolve $\zeta_0 \rightarrow \zeta_f$ at a fixed μ_f
  3. Evaluate the TMD along the **null-evolution line**, where $\tilde{f}(x, b_T; \mu_0, \zeta_0) = \tilde{f}\left(x, b_T; \mu_f, \zeta_\mu\right)$, then evolve $\zeta_\mu \rightarrow \zeta_f$ at a fixed μ_f



Scimemi and Vladimirov, EPJ **C 78**, 89 (2019).

$$\left(\mu^2 \frac{\partial}{\partial \mu^2} + \left(\frac{\mu^2}{\zeta} \frac{d\zeta}{d\mu^2}\right) \zeta \frac{\partial}{\partial \zeta}\right) F(x, \boldsymbol{b}; \mu, \zeta) = 0.$$

TMD Evolution

- Since we evolve on the null-evolution line, no explicit evolution in μ has to be added, and we evolve in ζ according to

$$\tilde{f}_{q/\mathcal{N}}(x, b_T; \mu, \zeta = Q^2) = \left(\frac{Q^2}{\zeta_\mu(b_T)}\right)^{-\mathcal{D}(b_T,\mu)} \tilde{f}_{q/\mathcal{N}}(x, b_T; \mu_0, \zeta_0)$$

- $\mathcal{D}$ is the CS kernel, which has the following components

$$\mathcal{D}(b_T, \mu) = \mathcal{D}^{\text{pert}}(b_*, \mu_{b_*}) + \int_{\mu_{b_*}}^{\mu} \frac{d\mu'}{\mu'} \Gamma_{\text{cusp}}(\mu') + \mathcal{D}^{\text{NP}}(b_T)$$

$$b_* = \frac{b_T}{\sqrt{1 + \frac{b_T^2}{b_{\text{max}}^2}}}$$

$$\mu_{b_*} = \frac{2e^{-\gamma_E}}{b_*}$$

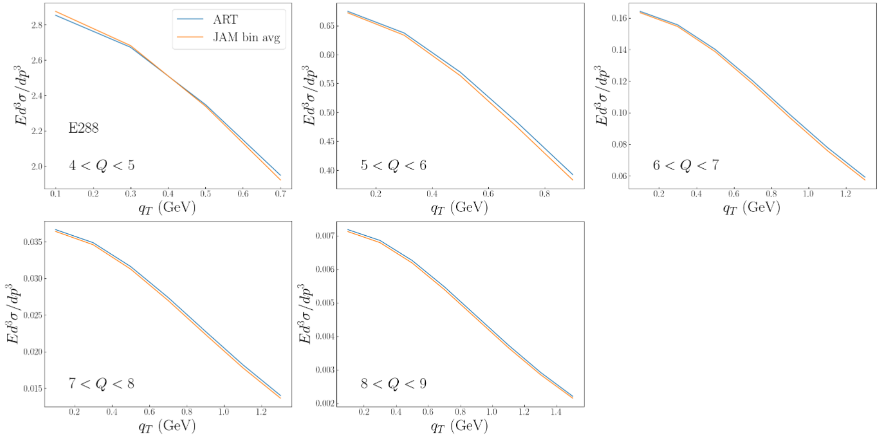
Described perturbatively

Non-perturbative description (large-b_T)

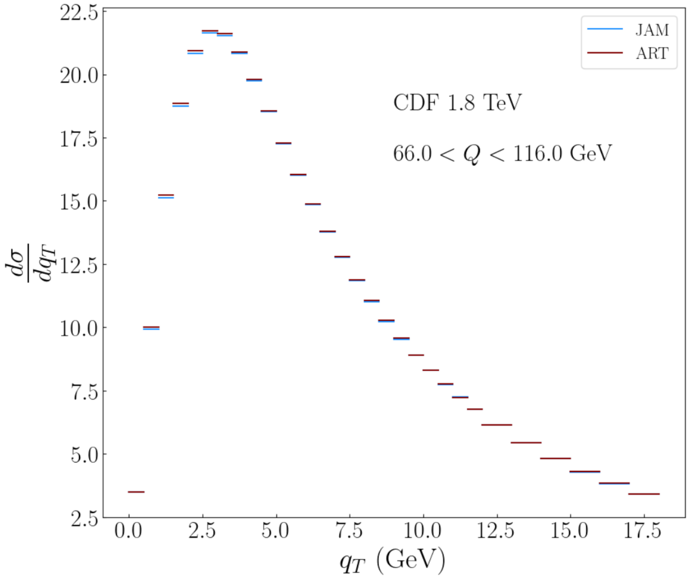
Implementing the ζ-prescription in JAM code

- We have spent time with the ART folks checking our JAM code against the arTeMiDe

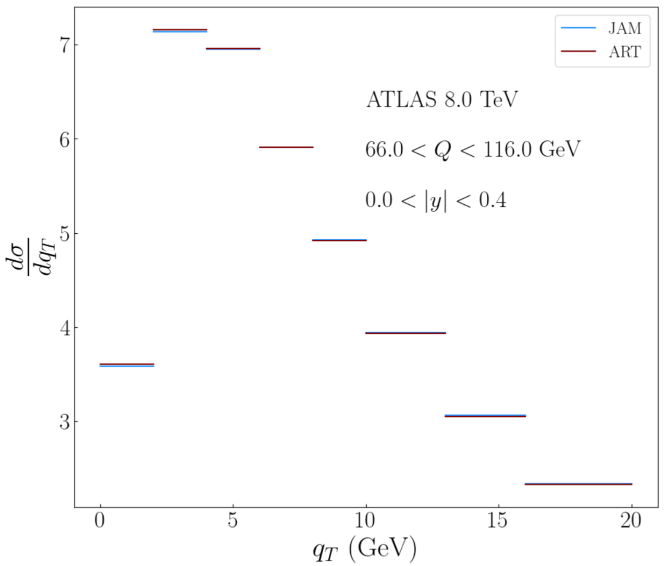
Low-energy regime



Collider - TeVatron



Collider - ATLAS

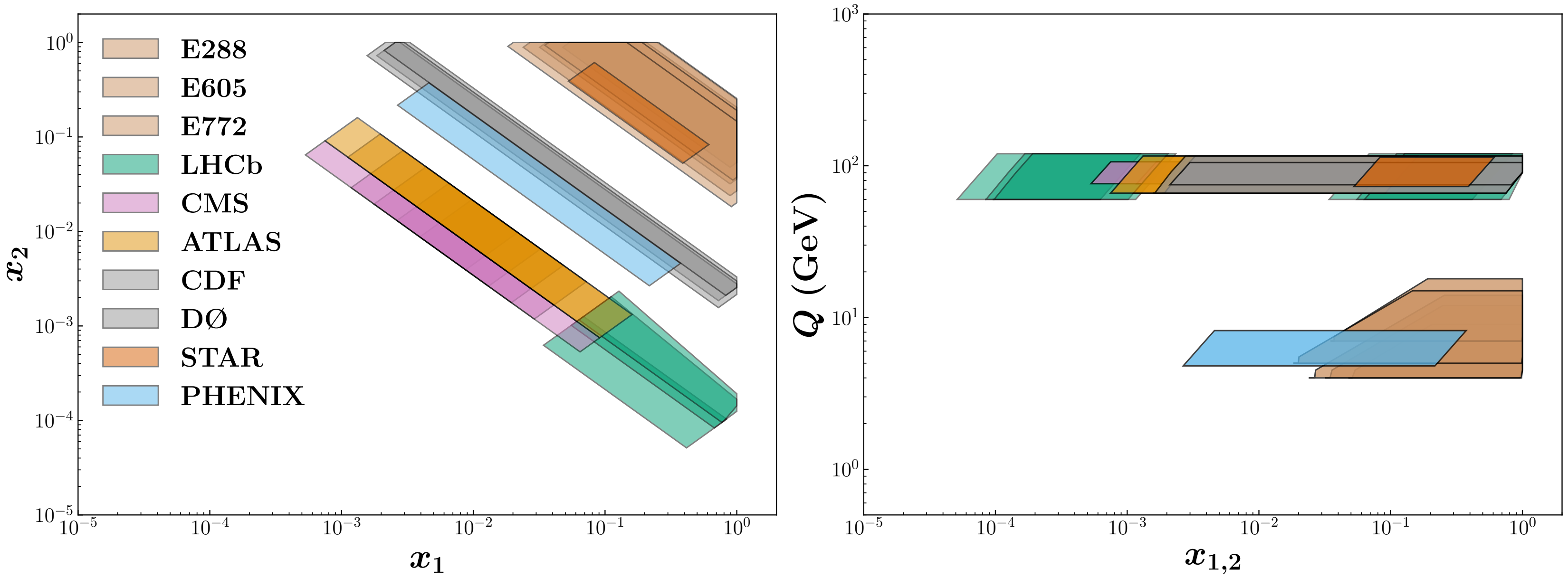


- Special attention paid to electroweak corrections and fiducial cuts

barry@anl.gov

Datasets and kinematics

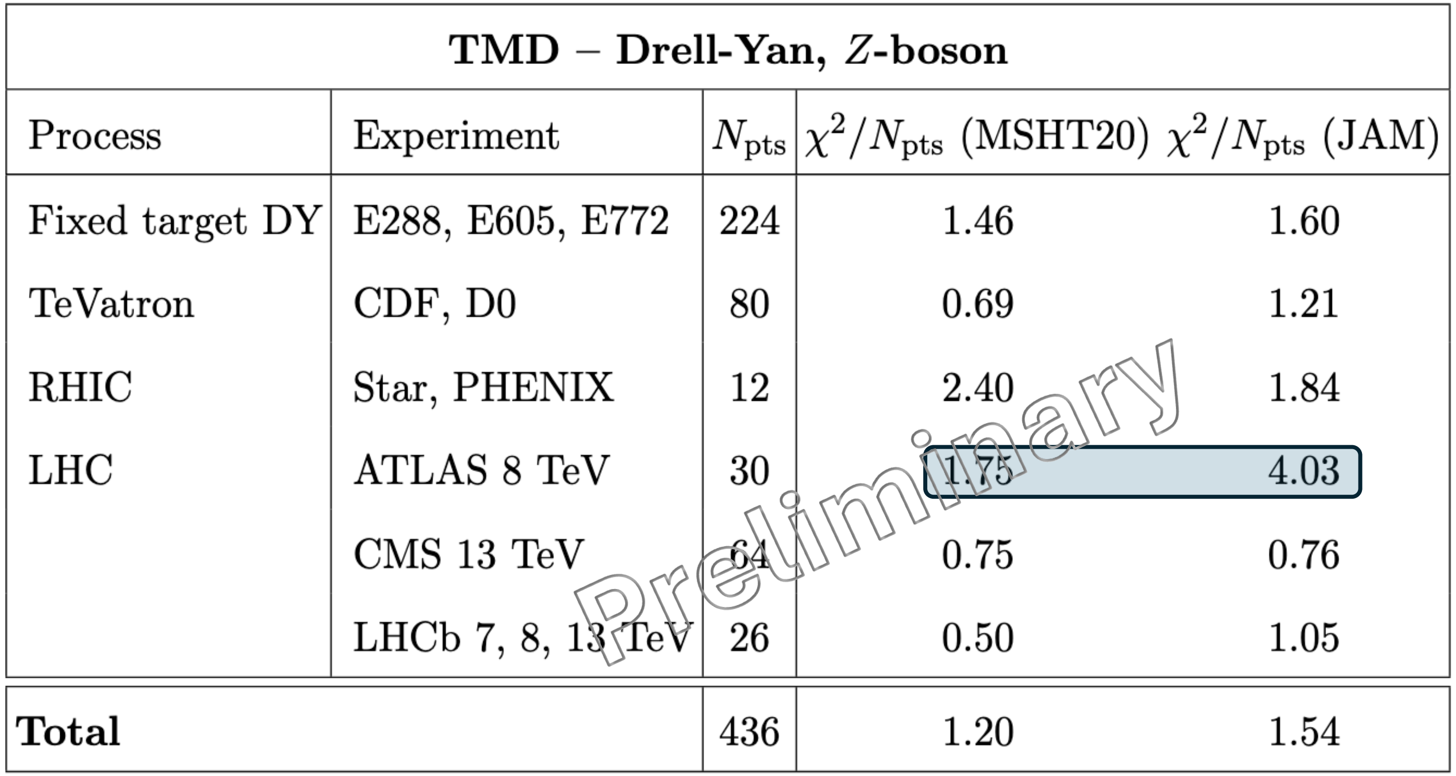
- Fixed-target low-energy datasets: more sensitivity to non-perturbative TMD structures
- Collider high-energy datasets: more sensitive to perturbative information while complementing the non-perturbative evolution in Q



barry@anl.gov

Fit results

- Using NLO+N2LL accuracy, we performed fits with the central replica for the MSHT20 PDFs (Bailey, et al., EPJ C **81**, 341 (2021).) and a JAM replica (Anderson, Melnitchouk,and Sato, 2501.00665 [hep-ph])
- We see that there can be improvement in the fit by improving the PDF set!



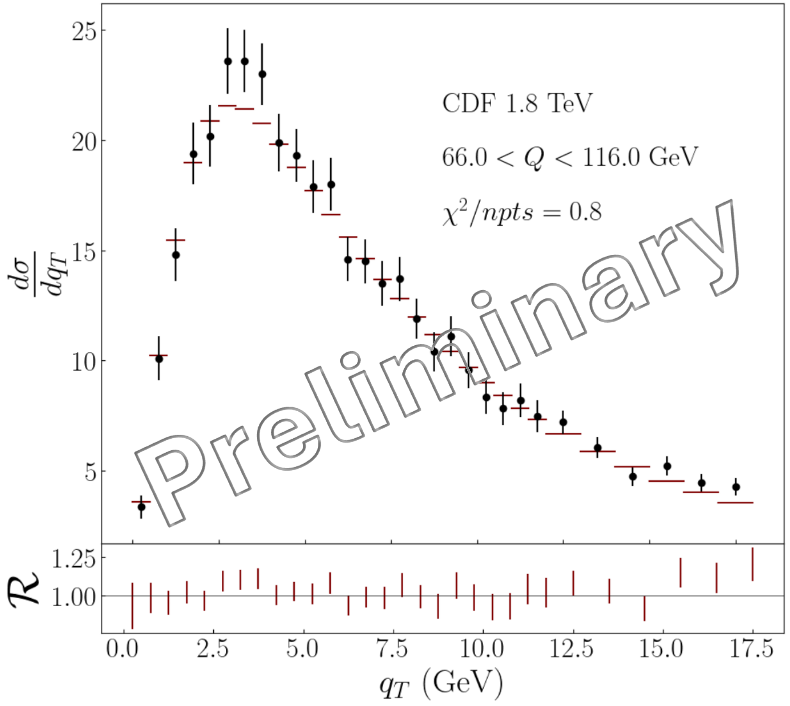
TMD – Drell-Yan, *Z*-boson

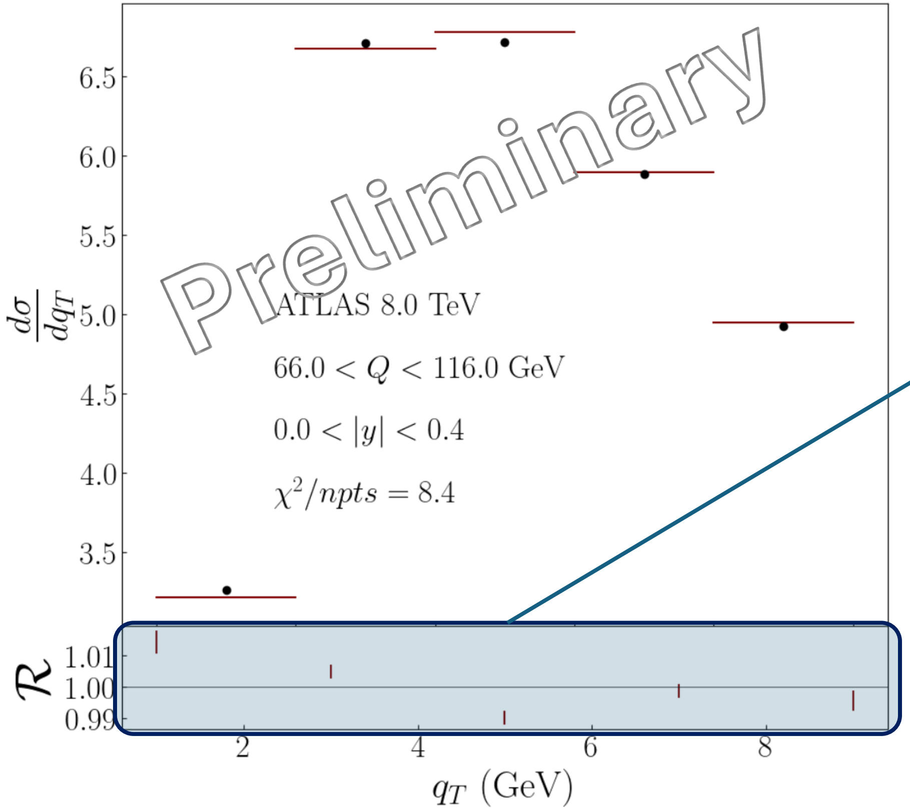
Process	Experiment	N_{pts}	χ^2/N_{pts} (MSHT20)	χ^2/N_{pts} (JAM)
Fixed target DY	E288, E605, E772	224	1.46	1.60
TeVatron	CDF, D0	80	0.69	1.21
RHIC	Star, PHENIX	12	2.40	1.84
LHC	ATLAS 8 TeV	30	1.75	4.03
	CMS 13 TeV	64	0.75	0.76
	LHCb 7, 8, 13 TeV	26	0.50	1.05
Total		436	1.20	1.54

barry@anl.gov

Agreement with the collider data

- Here, using the JAM PDFs





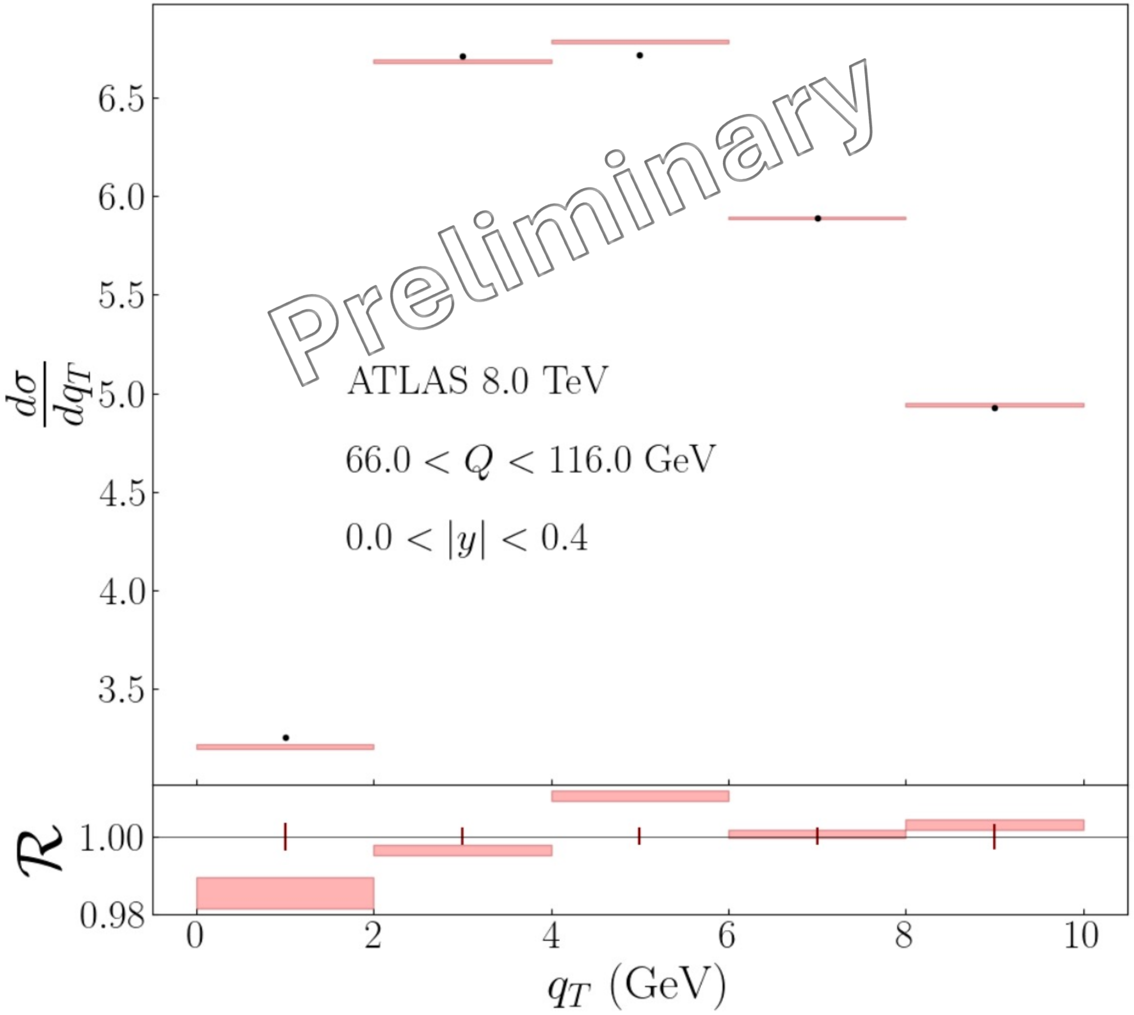
Sub-percent precision!

Extremely sensitive in the fit.

Can we improve our PDFs because of precision of data?

Uncertainties of JAM PDFs

- Here, we fix the non-perturbative function from the fit to a central JAM replica
- **Without fitting**, we vary the JAM PDFs and recompute the predictions for ATLAS
- Improvements needed on the PDFs and the overall procedure to extract TMDs and PDFs



barry@anl.gov

Conclusions and next steps

Summary

- We have demonstrated agreement in our codes with one of the leading phenomenological analysis groups
- We have performed preliminary fits to the low-energy and high-energy q_T-dependent Drell-Yan data

Next Steps

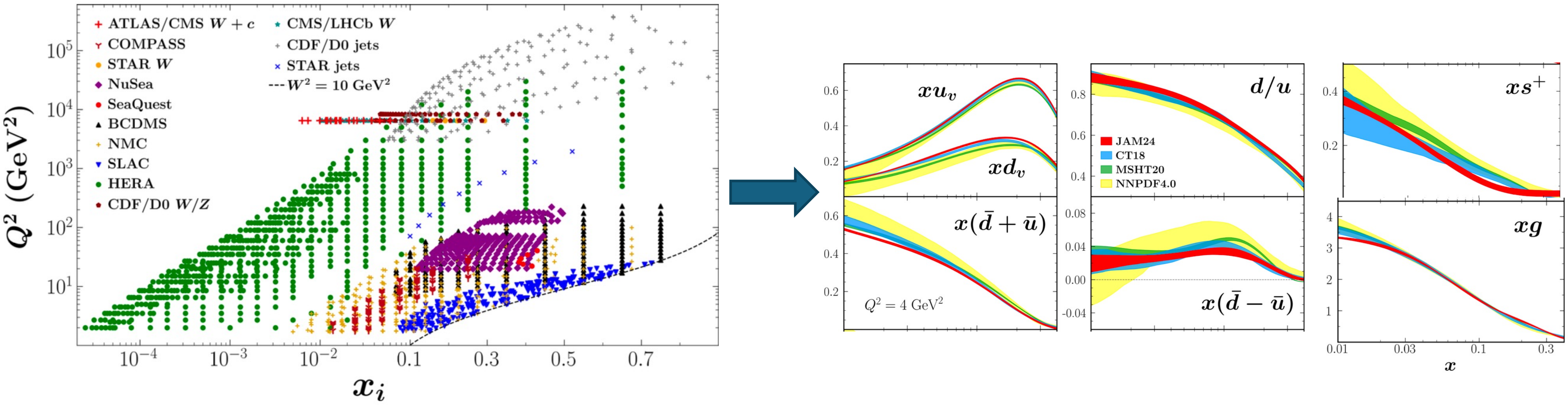
1. Perform fits of the TMDs over all JAM replicas
2. Incorporate the world collinear data and **open** the JAM PDFs in a simultaneous analysis
3. Understand the PDF dependence on various ingredients to the framework

barry@anl.gov

Backup Slides

What do we know about structures?

- Most well-known structure is through longitudinal structure of hadrons, particularly protons



Anderson, Melnitchouk, and Sato, 2501.00665 [hep-ph]

barry@anl.gov

Non-perturbative models for TMDs

- Fit λ_1 and λ_2 to this functional form for each of the following flavors: u, d, $\bar{u}$, $\bar{d}$, and $sea = s = \bar{s} = c = \bar{c} = b = \bar{b}$

$$f^{f}_{NP}(x,b) = \frac{1}{\cosh\left(\left(\lambda^{f}_{1}(1-x) + \lambda^{f}_{2}x\right)b\right)},$$

- For the CS kernel, we fit two additional parameters, c_0 and c_1 according to this functional form

$$\mathcal{D}_{\mathrm{NP}}(b) = bb^{*}\left[c_0 + c_1 \ln\left(\frac{b^{*}}{B_{\mathrm{NP}}}\right)\right],$$

Example of TMDs