QCD Evolution Workshop 2023

Simultaneous extraction of collinear and TMD PDFs

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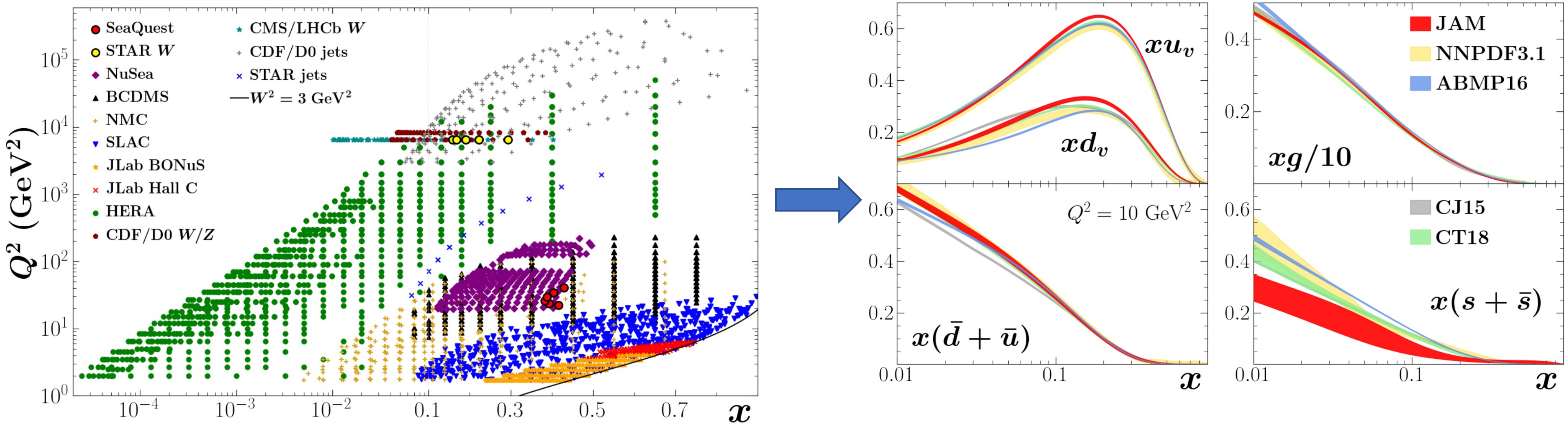
QCD Evolution Workshop 2023, Monday, May 22nd, 2023

Based in part on: arXiv:2302.01192

What do we know about structures?

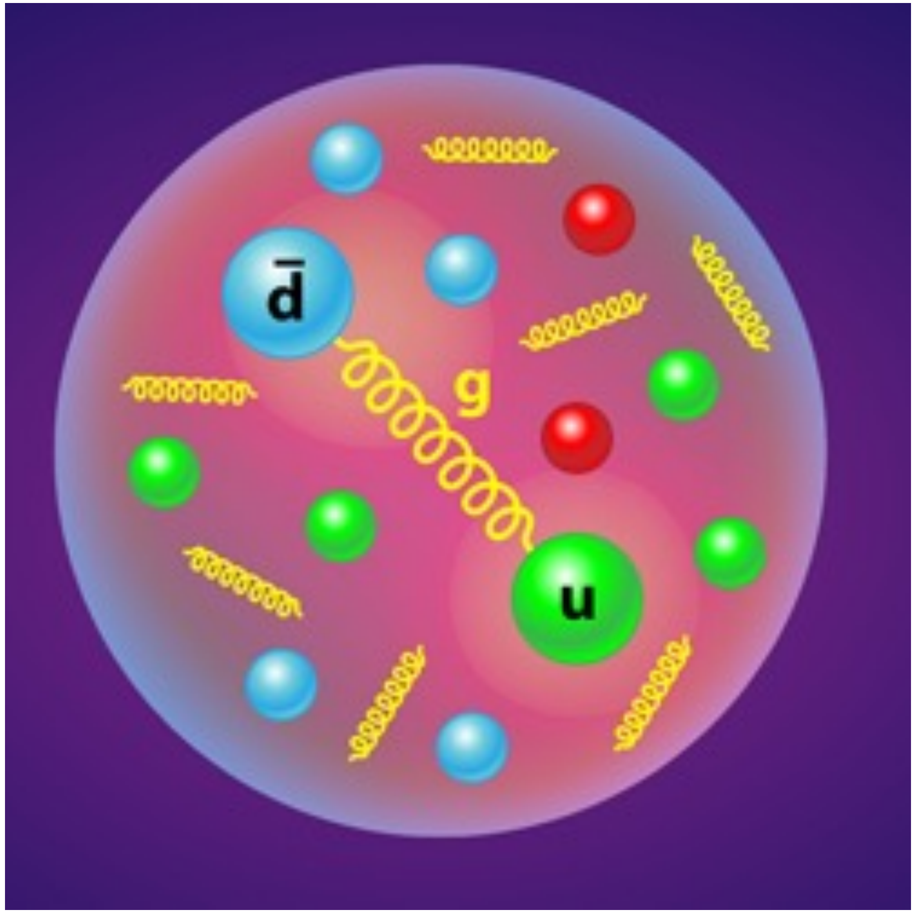
- Most well-known structure is through longitudinal structure of hadrons, particularly protons



C. Cocuzza, et al., Phys. Rev. D **104**, 074031 (2021)

Other structures?

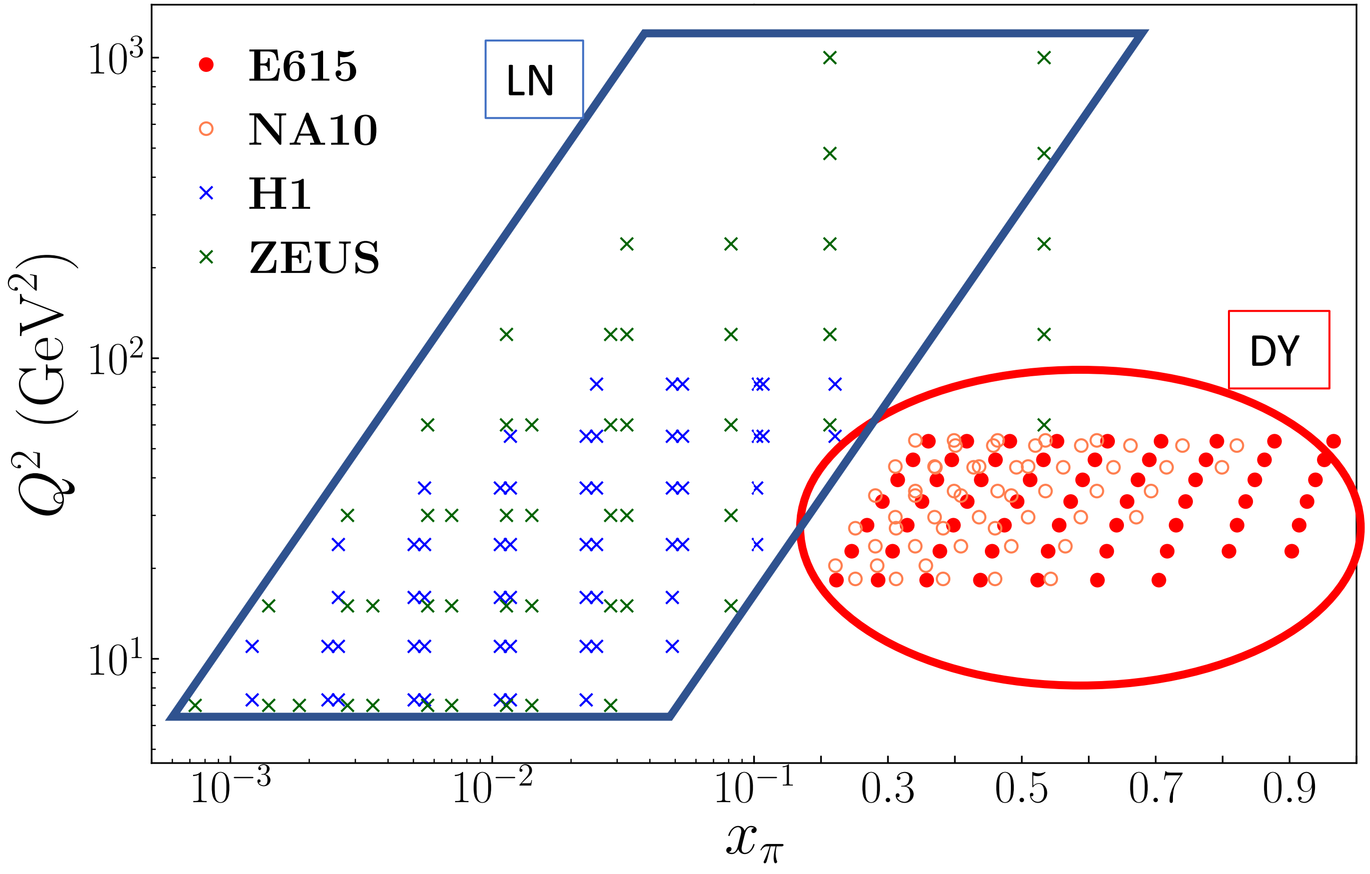
- To give deeper insights into color confined systems, we shouldn't limit ourselves to proton structures
- Pions are also important because of their Goldstone-boson nature while also being made up of quarks and gluons



Available datasets for pion structures

- Much less available data than in the proton case

- Still valuable to study



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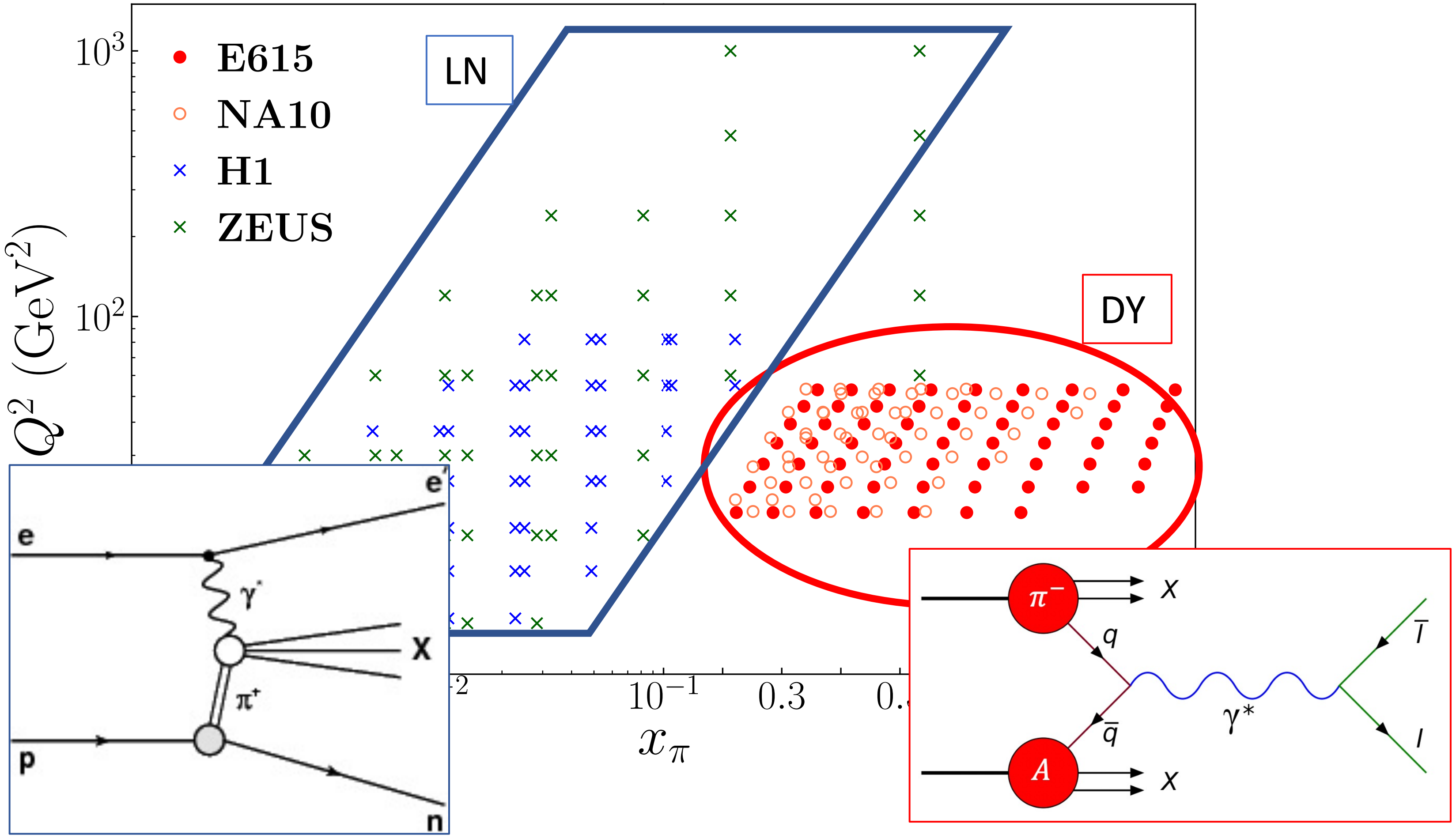
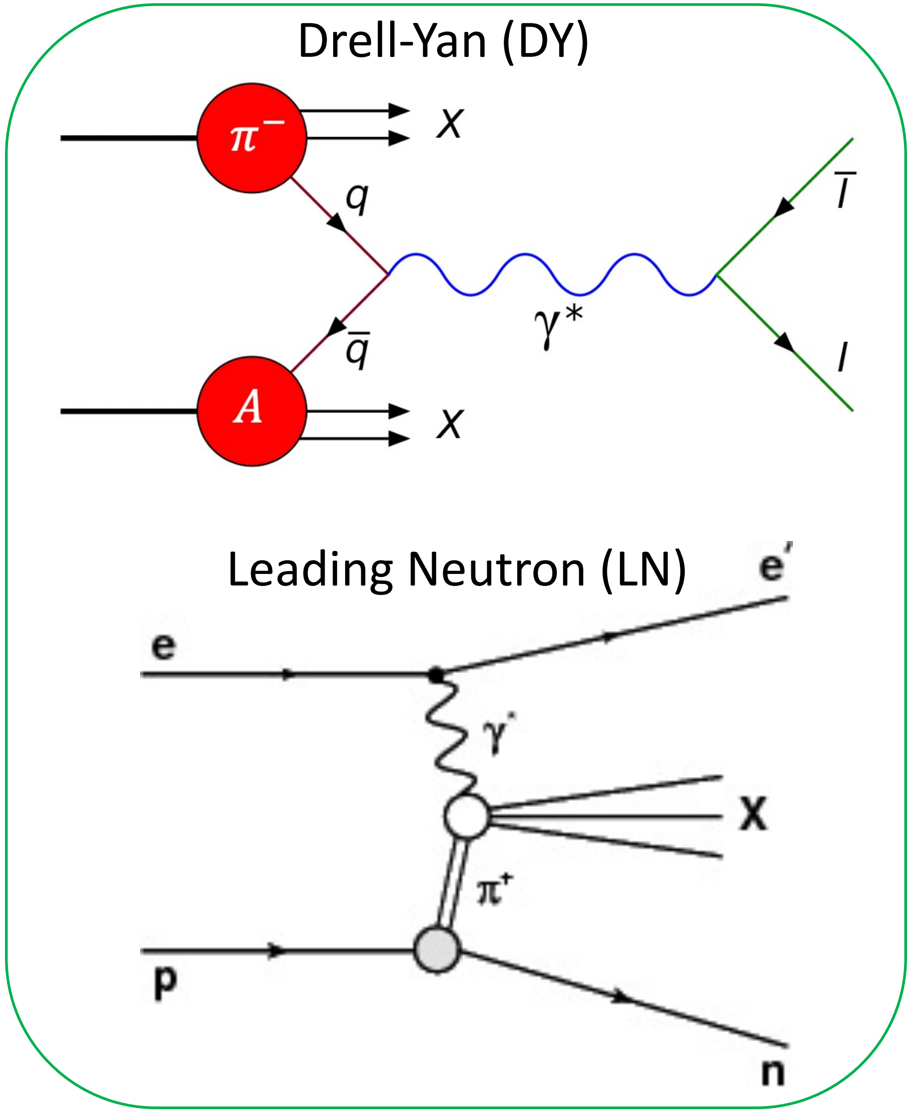


Pion PDFs in JAM

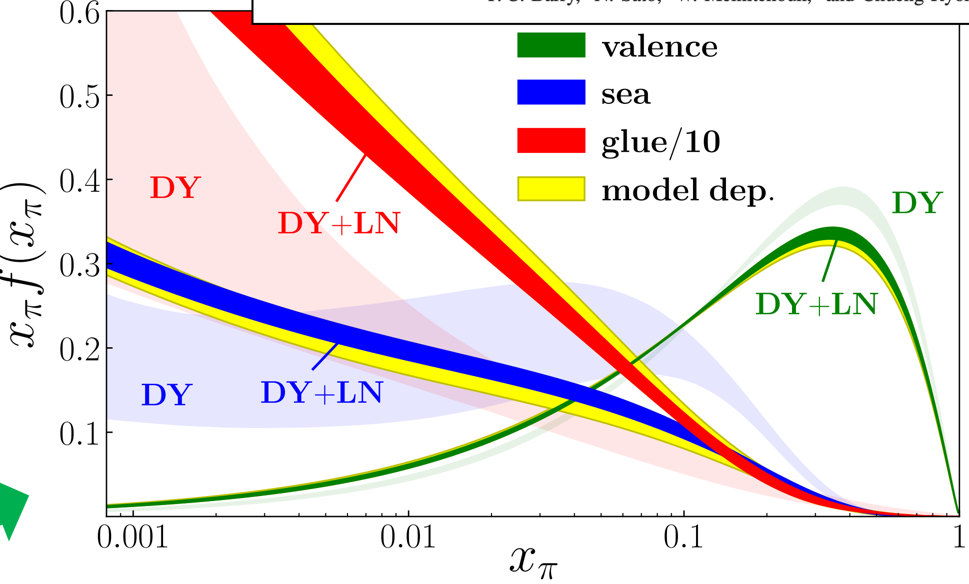


PHYSICAL REVIEW LETTERS **121**, 152001 (2018)

Featured in Physics

First Monte Carlo Global QCD Analysis of Pion Parton Distributions

P. C. Barry,[1] N. Sato,[2] W. Melnitchouk,[3] and Chueng-Ryong Ji[1]

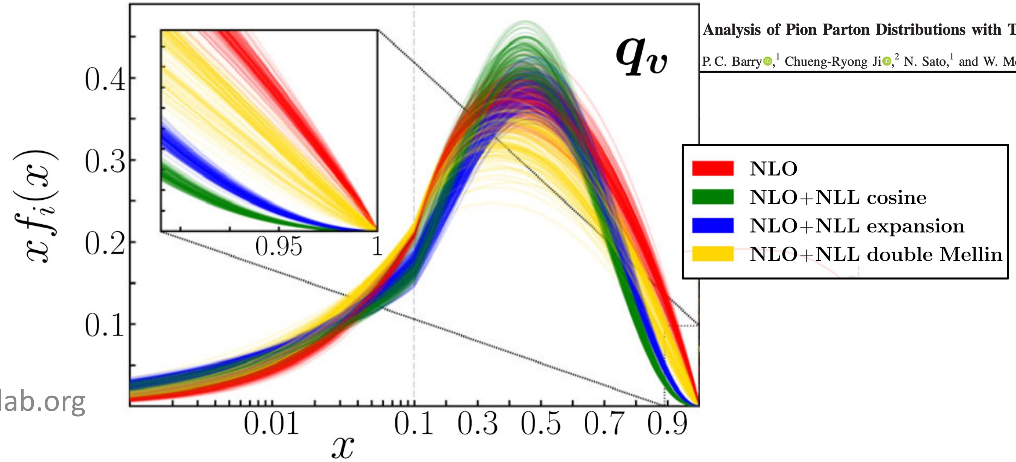


Threshold resummation in DY

PHYSICAL REVIEW LETTERS **127**, 232001 (2021)

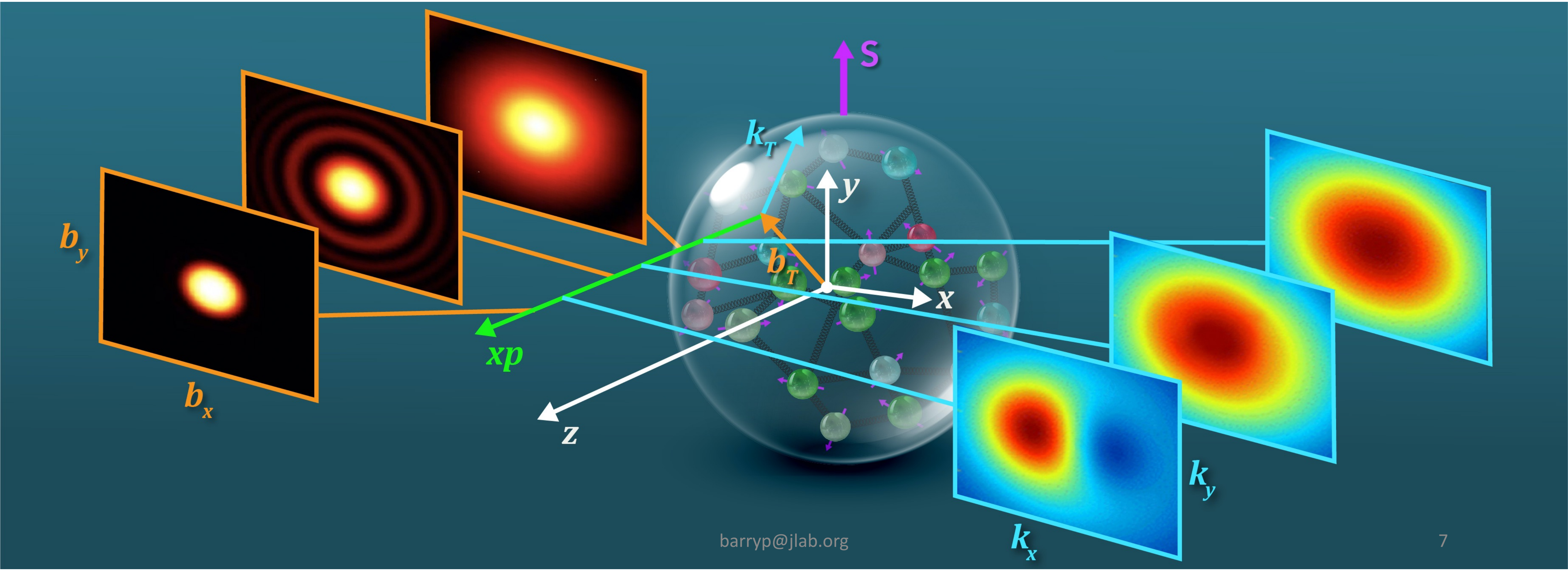
Analysis of Pion Parton Distributions with Threshold Resummation

P. C. Barry,[1] Chueng-Ryong Ji,[2] N. Sato,[1] and W. Melnitchouk[1]



3D structures of hadrons

- Even more challenging is the 3d structure through GPDs and TMDs



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, $\boldsymbol{k_T}$
- We can learn about the coordinate space correlations of quark fields in hadrons
- Modification needed for UV and rapidity divergences; acquire regulators: $\tilde{f}_{q/\mathcal{N}}(x, b_T) \to \tilde{f}_{q/\mathcal{N}}(x, b_T; \mu, \zeta)$

Factorization for low-q_T Drell-Yan

- Like collinear observable, a hard part with two functions that describe structure of beam and target
- So called "W"-term, valid only at low-q_T

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}\tau\mathrm{d}Y\mathrm{d}q_T^2} = \frac{4\pi^2\alpha^2}{9\tau S^2}\sum_q H_{q\bar{q}}(Q^2,\mu)\int \mathrm{d}^2 b_T\, e^{ib_T\cdot q_T} \times \tilde{f}_{q/\pi}(x_\pi, b_T, \mu, Q^2)\,\tilde{f}_{\bar{q}/A}(x_A, b_T, \mu, Q^2),$$

TMD PDF within the b_* prescription

$$\mathbf{b}_*(\mathbf{b}_T) \equiv \frac{\mathbf{b}_T}{\sqrt{1+b_T^2/b_{\max}^2}}.$$

Low-b_T: perturbative
high-b_T: non-perturbative

$$\tilde{f}_{q/\mathcal{N}(A)}(x, b_T, \mu_Q, Q^2) = \boxed{(C \otimes f)_{q/\mathcal{N}(A)}(x; b_*)}$$
$$\times \exp\left\{\boxed{-g_{q/\mathcal{N}(A)}(x, b_T) - g_K(b_T) \ln\frac{Q}{Q_0}} - \boxed{S(b_*, Q_0, Q, \mu_Q)}\right\}$$

Relates the TMD at small-b_T to the **collinear** PDF
$\Rightarrow$ TMD is sensitive to collinear PDFs

$g_{q/\mathcal{N}(A)}$: intrinsic non-perturbative structure of the TMD
g_K: universal non-perturbative Collins-Soper kernel

Controls the perturbative evolution of the TMD

Collins, Soper, Sterman, NPB **250**, 199 (1985).

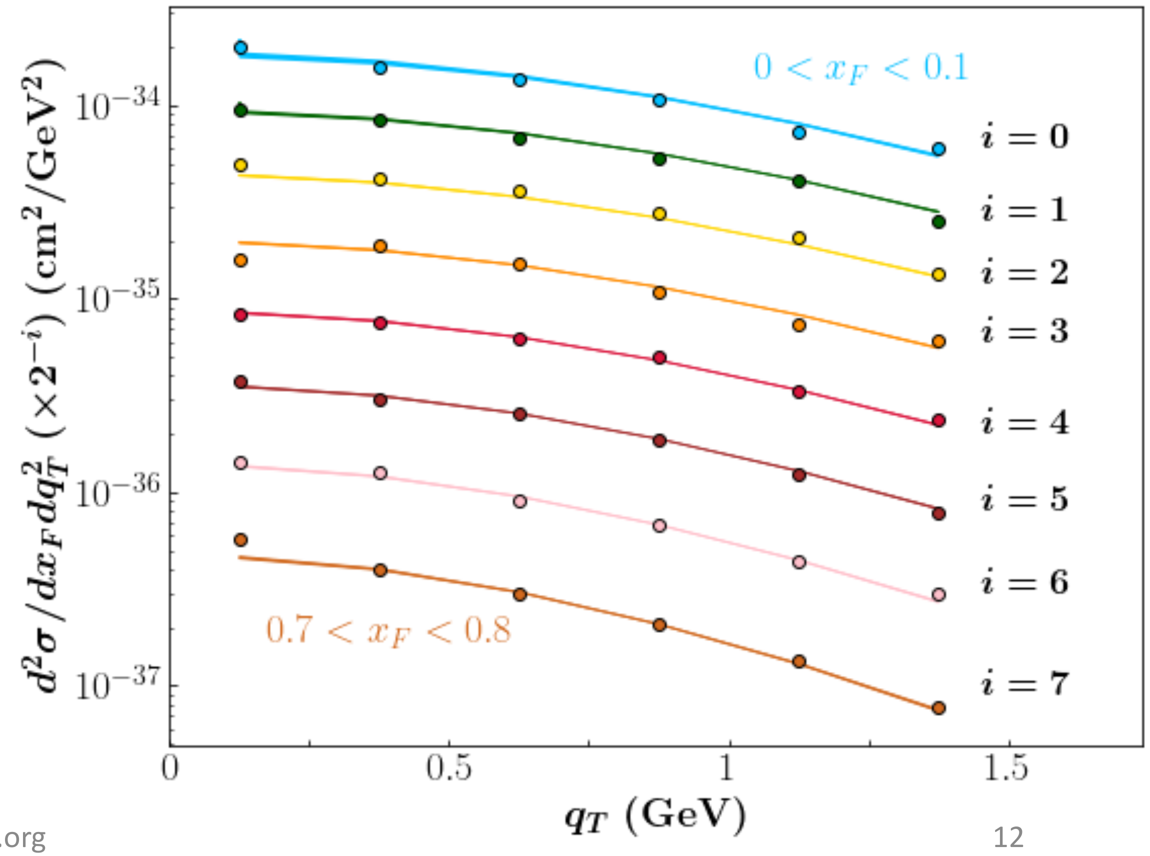
A few details

- Nuclear TMD model linear combination of bound protons and neutrons
  - Include an additional A-dependent nuclear parameter
- We use the MAP collaboration's parametrization for non-perturbative TMDs
  - Only tested parametrization flexible enough to capture features of Q bins
- Perform a **simultaneous global analysis** of pion TMD and collinear PDFs, with proton (nuclear) TMDs
  - Include both q_T-dependent and collinear pion data and fixed-target pA data

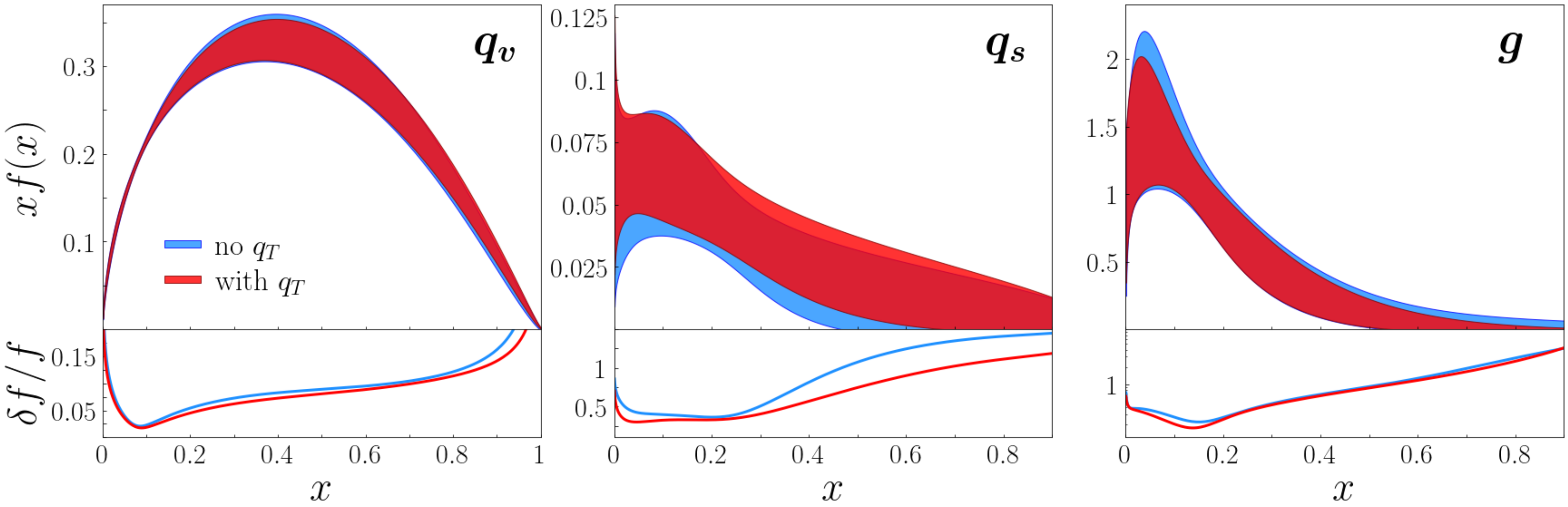
Data and theory agreement

- Fit both pA and πA DY data and achieve good agreement to both

Process	Experiment	$\sqrt{s}$ GeV	χ^2/np	Z-score
q_T-*integr. DY* $\pi W \to \mu^+\mu^- X$	E615 [37]	21.8	0.86	0.76
	NA10 [38]	19.1	0.54	2.27
	NA10 [38]	23.2	0.91	0.18
Leading neutron $ep \to e'nX$	H1 [73]	318.7	0.36	4.61
	ZEUS [74]	300.3	1.48	2.16
q_T-*dep.* pA *DY* $pA \to \mu^+\mu^- X$	E288 [67]	19.4	0.93	0.25
	E288 [67]	23.8	1.33	1.54
	E288 [67]	24.7	0.95	0.23
	E605 [68]	38.8	1.07	0.39
	E772 [69]	38.8	2.41	5.74
	E866 (Fe/Be) [70]	38.8	1.07	0.29
	E866 (W/Be) [70]	38.8	0.89	0.11
q_T-*dep.* πA *DY* $\pi W \to \mu^+\mu^- X$	E615 [37]	21.8	1.61	2.58
	E537 [71]	15.3	1.11	0.57
Total			1.15	2.55



Extracted pion PDFs

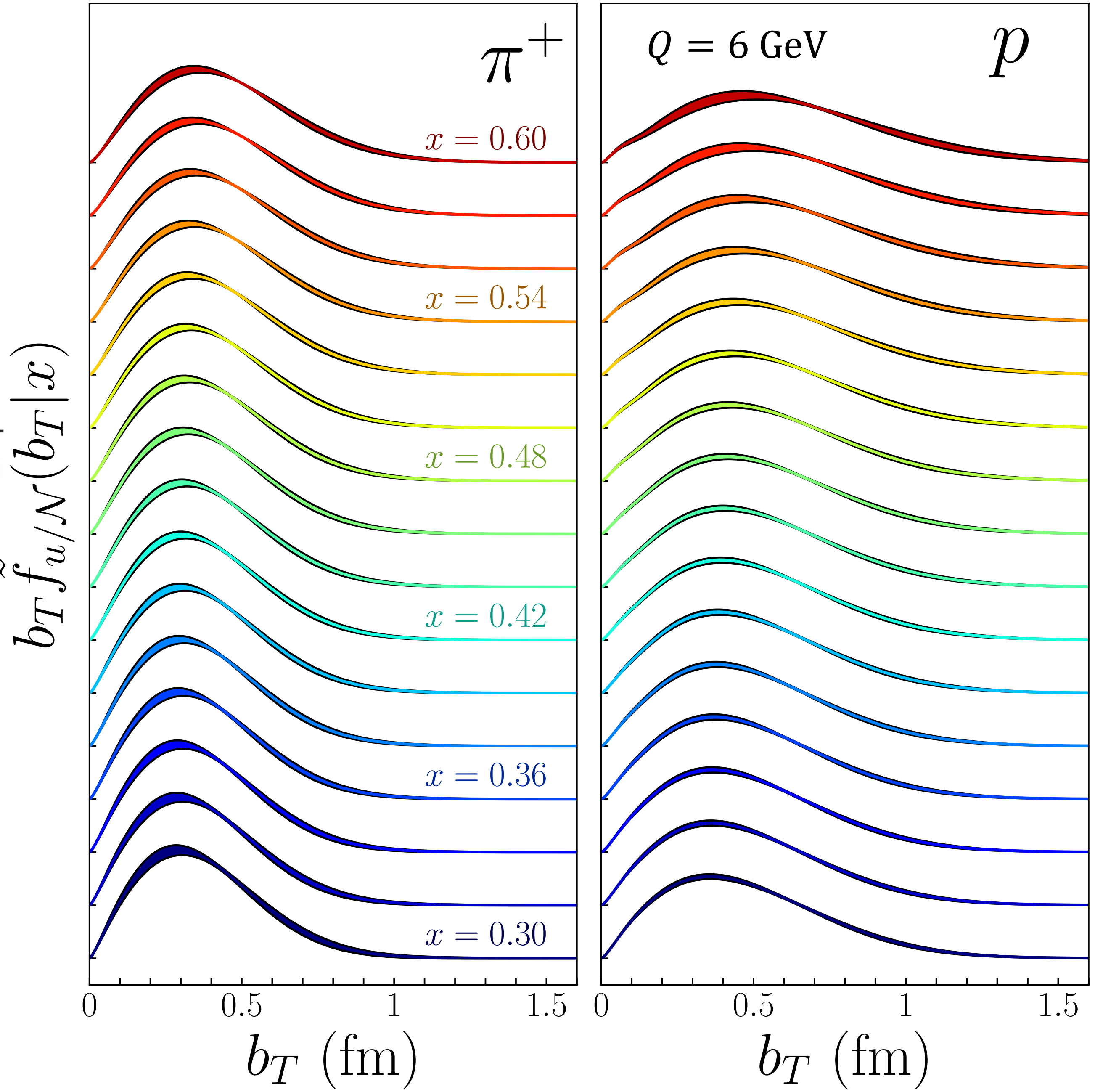


- The small-q_T data do not constrain much the PDFs

Resulting TMD PDFs of proton and pion

$$\tilde{f}_{q/\mathcal{N}}(b_T|x;Q,Q^2) \equiv \frac{\tilde{f}_{q/\mathcal{N}}(x,b_T;Q,Q^2)}{\int \mathrm{d}^2\boldsymbol{b}_T \tilde{f}_{q/\mathcal{N}}(x,b_T;Q,Q^2)}$$

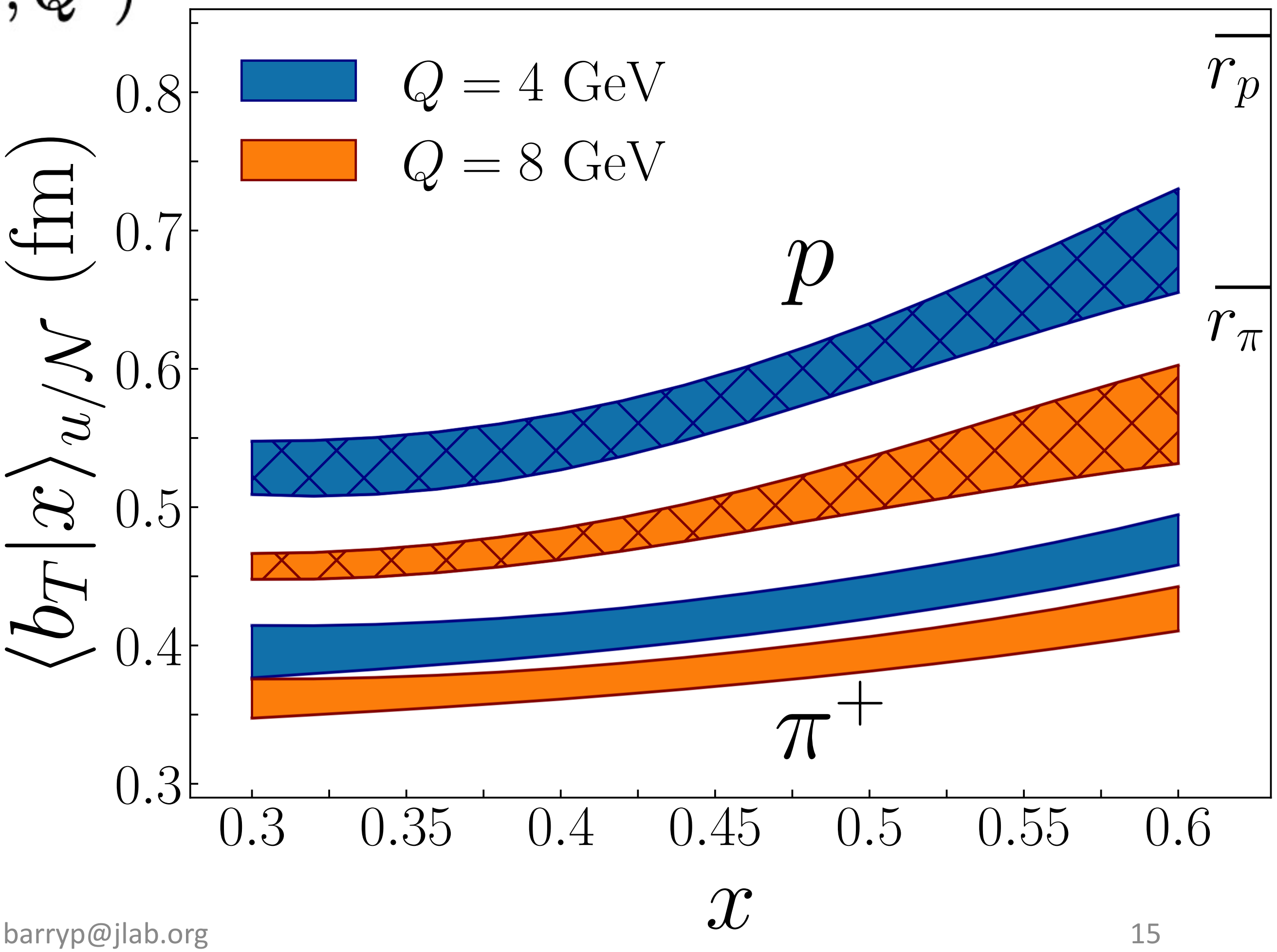
- Broadening appearing as x increases
- Up quark in pion is narrower than up quark in proton



Resulting average b_T

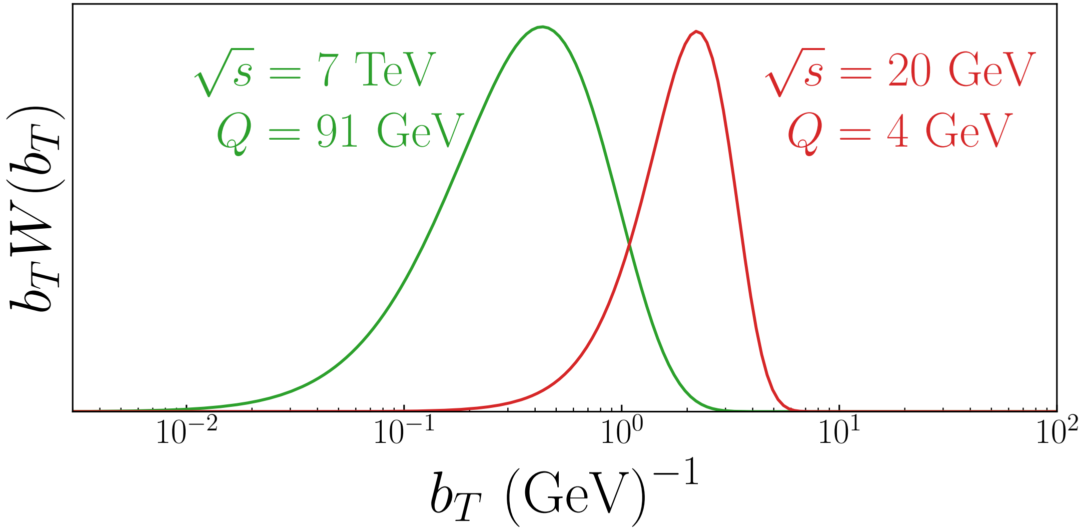
$$\langle b_T | x \rangle_{q/\mathcal{N}} = \int \mathrm{d}^2 \boldsymbol{b}_T \, b_T \, \tilde{f}_{q/\mathcal{N}}(b_T | x; Q, Q^2)$$

- Average transverse spatial correlation of the up quark in proton is $\sim$ 1.2 times bigger than that of pion
- Pion's $\langle b_T | x \rangle$ is $5.3 - 7.5\sigma$ smaller than proton in this range
- Decreases as x decreases



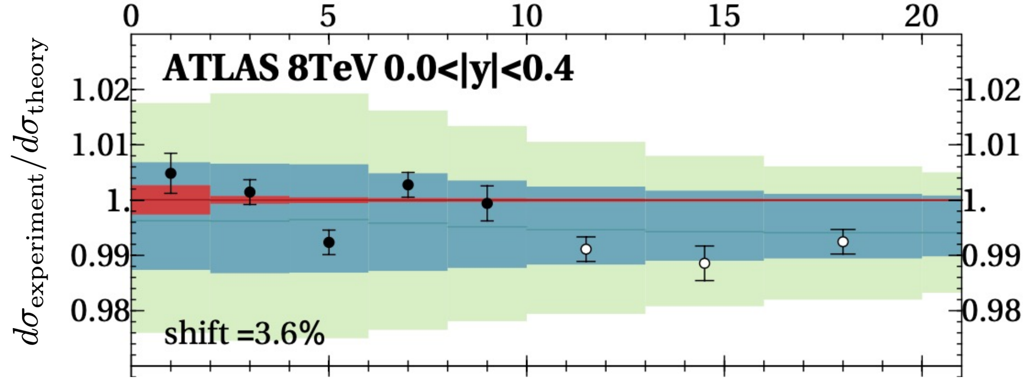
What about LHC energies?

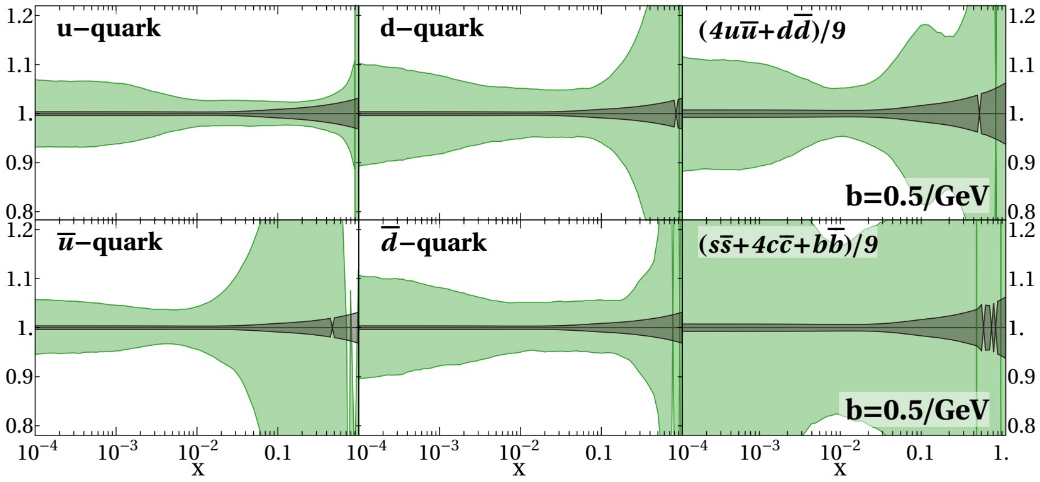
- Many studies have extracted TMDs from these data: Bertone, Scimemi, Vladimirov, JHEP **06** (2019). Bacchetta, et al. JHEP **10** (2022). etc.
- Fixed-target energies: sensitive to non-perturbative TMD structures
  - Large portion of $\widetilde{W}$ spectrum in large-b_T region
- LHC energies: sensitive to perturbative calculations
  - Have opportunity to study collinear distributions



High energy PDF uncertainties

- From Bury, et al. JHEP **118** (2022).





Moos, Scimemi, Vladimirov, Zurita, arXiv:2305.07473

- Studies about the uncertainties of the PDFs relative to data

Trust perturbative region

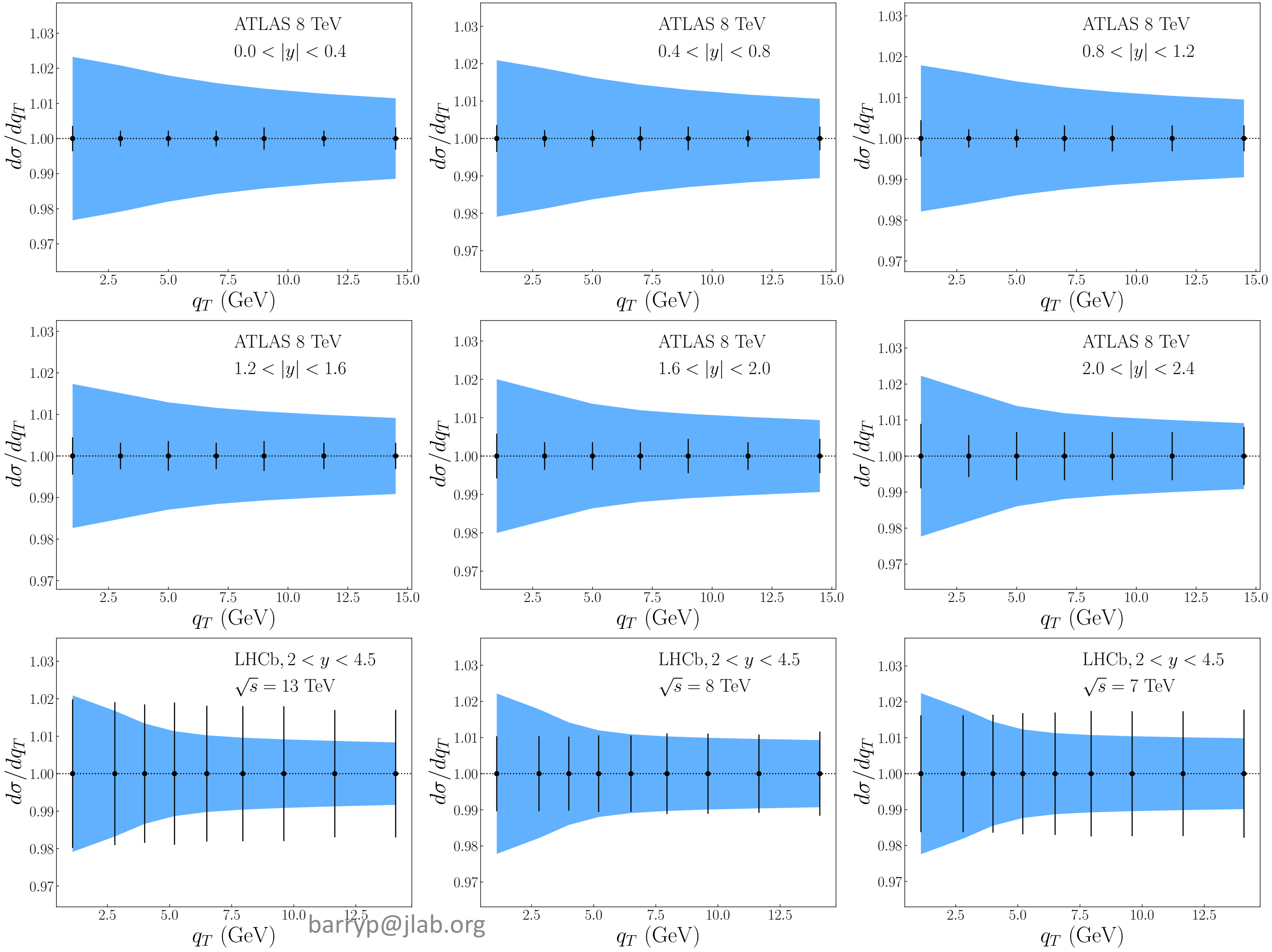
- Method to keep the $\widetilde{W}$ term unaltered by b_* mechanism up to a certain $b_{\max}$
- Non-perturbative effects kick in at $b_{\max}$
- Smooth function as 1st and 2nd derivatives are continuous at $b_{\max}$

$$
\begin{aligned}
\widetilde{W}(b_T, x_a, x_b, Q) &= \widetilde{W}_{\text{pert}}(b_T, x_a, x_b, Q) \quad \text{for} \quad b_T < b_{\max} \\
&= \widetilde{W}_{\text{pert}}(b_{\max}, x_a, x_b, Q) f_{\text{NP}}(b_T, b_{\max}, x_a, x_b) \quad \text{for} \quad b_T > b_{\max}
\end{aligned}
$$

Qiu, Zhang, PRD **63**, 114011 (2001).

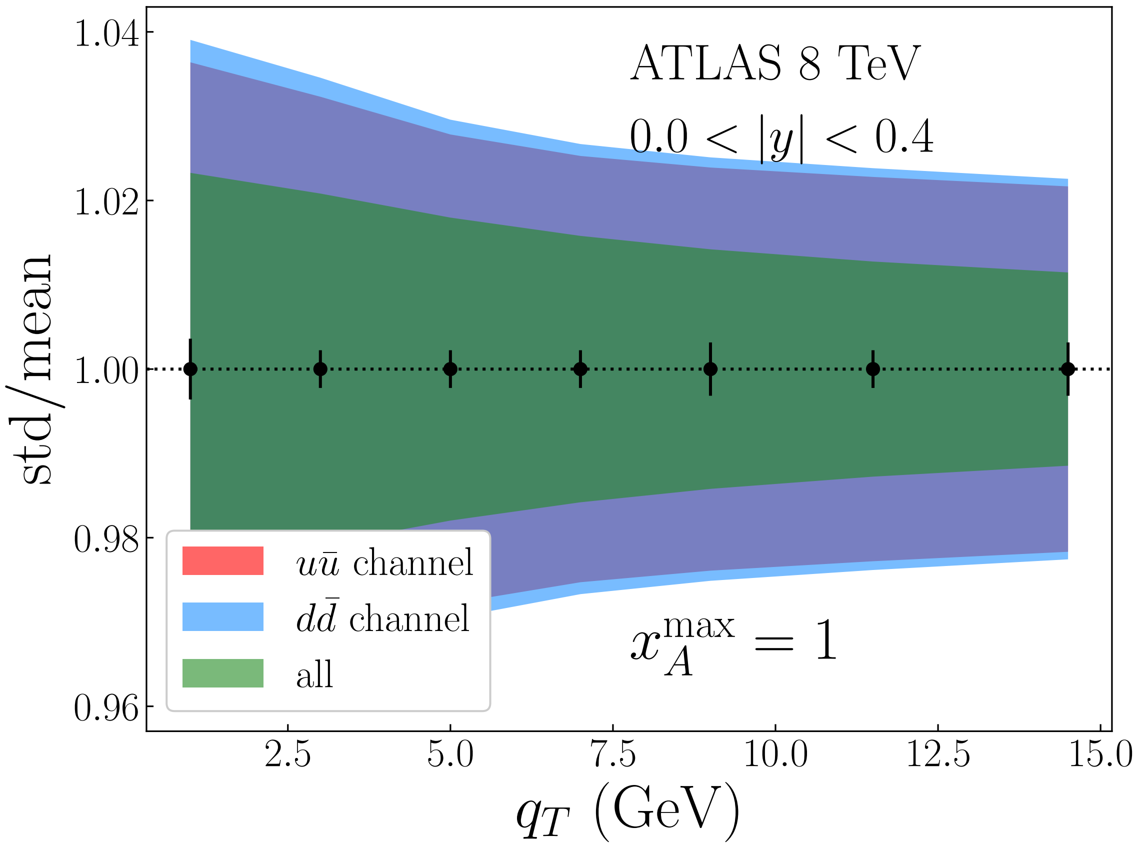
Uncertainties from JAM PDFs only

- Bands come from varying only the collinear PDFs
- High precision in ATLAS and LHCb data indicate potential constraining power



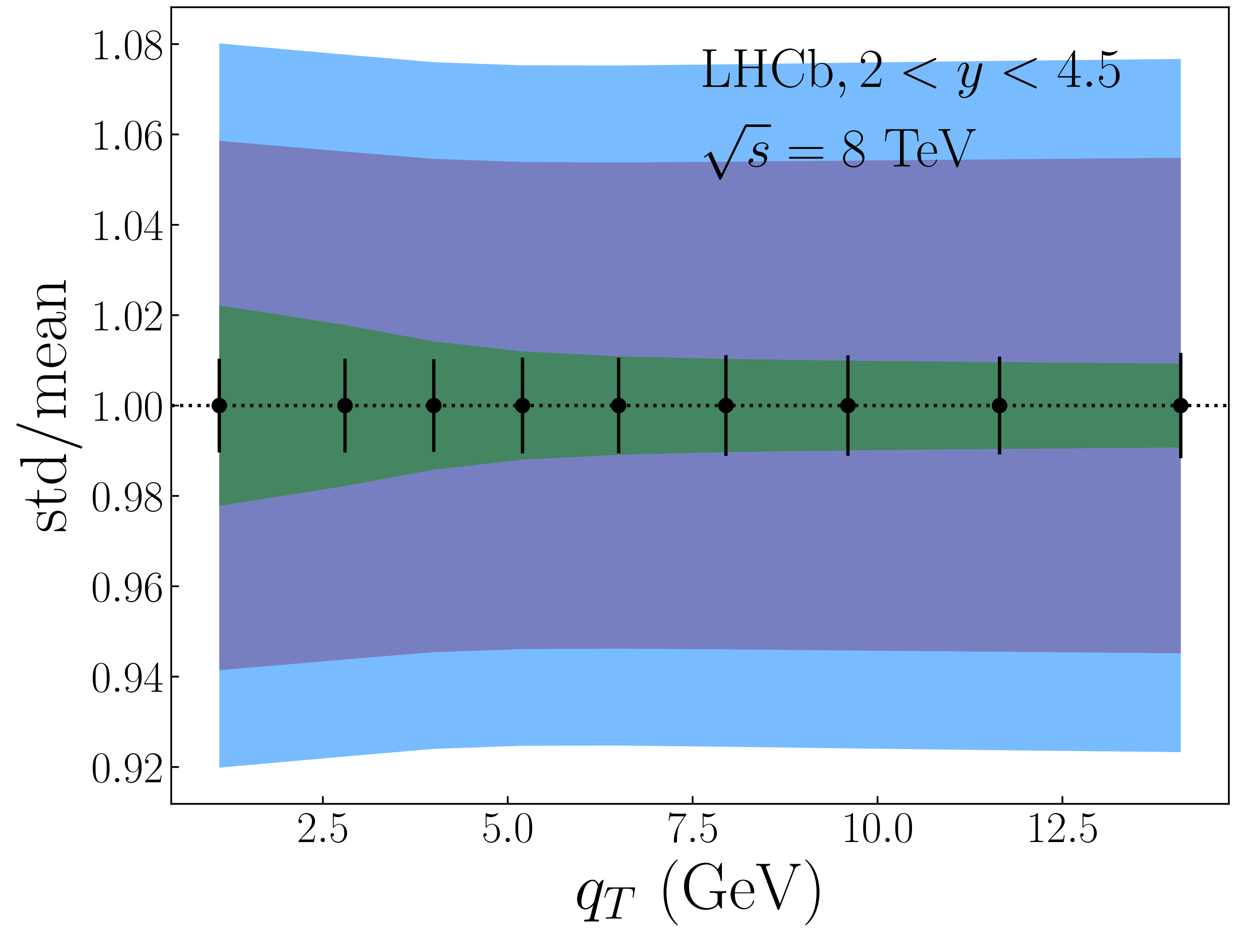
Individual quarks

- Green: full contributions
- Red (looks purple): contribution when u in beam PDF and $\bar{u}$ in target
- Blue: corresponding $d\bar{d}$



Sea quarks

- Large-x sea quarks carry large uncertainties
- Albeit the contributions are rather small



Outlook

- Further study various hadronic systems through:
  - Lattice QCD – look to kaons, rho mesons, etc.
  - Future tagged experiments - provide measurements for neutrons, pions, and kaons
- Finalize fits and perform simultaneous extractions of collinear and TMD PDFs
  - Examine the impact the low-q_T data have on the collinear PDFs
- Perform simultaneous analysis including W-boson production and analyze its mass

Backup

Small b_T operator product expansion

- At small b_T, the TMDPDF can be described in terms of its OPE:

$$\tilde{f}_{f/h}(x, b_T; \mu, \zeta_F) = \sum_j \int_x^1 \frac{d\xi}{\xi} \tilde{\mathcal{C}}_{f/j}(x/\xi, b_T; \zeta_F, \mu) f_{j/h}(\xi; \mu) + \mathcal{O}((\Lambda_{\mathrm{QCD}} b_T)^a)$$

- where $\tilde{C}$ are the Wilson coefficients, and $f_{j/h}$ is the collinear PDF
- Breaks down when b_T gets large

b_* prescription

- A common approach to regulating large b_T behavior

$$\mathbf{b}_*(\mathbf{b}_T) \equiv \frac{\mathbf{b}_T}{\sqrt{1 + b_T^2/b_{\max}^2}}.$$

Must choose an appropriate value; a transition from perturbative to non-perturbative physics

- At small b_T, $b_*(b_T) = b_T$
- At large $b_T, b_*(b_T) = b_{\max}$

Introduction of non-perturbative functions

- Because $b_* \neq b_T$, have to non-perturbatively describe large b_T behavior

Completely general – independent of quark, hadron, PDF or FF

$$g_K(b_T; b_{\max}) = -\tilde{K}(b_T, \mu) + \tilde{K}(b_*, \mu)$$

Non-perturbative function dependent in principle on flavor, hadron, etc.

$$e^{-g_{j/H}(x, \boldsymbol{b}_{\mathrm{T}}; b_{\max})} = \frac{\tilde{f}_{j/H}(x, \boldsymbol{b}_{\mathrm{T}}; \zeta, \mu)}{\tilde{f}_{j/H}(x, \boldsymbol{b}_*; \zeta, \mu)} e^{g_K(b_{\mathrm{T}}; b_{\max}) \ln(\sqrt{\zeta}/Q_0)}.$$

TMD factorization in Drell-Yan

- In small-q_T region, use the Collins-Soper-Sterman (CSS) formalism and b_* prescription

Can these data constrain the pion collinear PDF?

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2\,\mathrm{d}y\,\mathrm{d}q_\mathrm{T}^2} = \frac{4\pi^2\alpha^2}{9Q^2 s}\sum_{j,j_A,j_B} H_{j\bar{j}}^{\mathrm{DY}}(Q,\mu_Q,a_s(\mu_Q))\int\frac{\mathrm{d}^2\boldsymbol{b}_\mathrm{T}}{(2\pi)^2}e^{i\boldsymbol{q}_\mathrm{T}\cdot\boldsymbol{b}_\mathrm{T}}$$

$$\times\, e^{-g_{j/A}(x_A,b_\mathrm{T};b_{\max})}\int_{x_A}^1\frac{\mathrm{d}\xi_A}{\xi_A}\boxed{f_{j_A/A}(\xi_A;\mu_{b_*})}\,\tilde{C}_{j/j_A}^{\mathrm{PDF}}\left(\frac{x_A}{\xi_A},b_*;\mu_{b_*}^2,\mu_{b_*},a_s(\mu_{b_*})\right)$$

$$\times\, e^{-g_{\bar{j}/B}(x_B,b_\mathrm{T};b_{\max})}\int_{x_B}^1\frac{\mathrm{d}\xi_B}{\xi_B}f_{j_B/B}(\xi_B;\mu_{b_*})\,\tilde{C}_{\bar{j}/j_B}^{\mathrm{PDF}}\left(\frac{x_B}{\xi_B},b_*;\mu_{b_*}^2,\mu_{b_*},a_s(\mu_{b_*})\right)$$

$$\times\exp\left\{-\boxed{g_K}(b_\mathrm{T};b_{\max})\ln\frac{Q^2}{Q_0^2}+\tilde{K}(b_*;\mu_{b_*})\ln\frac{Q^2}{\mu_{b_*}^2}+\int_{\mu_{b_*}}^{\mu_Q}\frac{\mathrm{d}\mu'}{\mu'}\left[2\gamma_j(a_s(\mu'))-\ln\frac{Q^2}{(\mu')^2}\gamma_K(a_s(\mu'))\right]\right\}$$

Perturbative pieces

Non-perturbative pieces

Non-perturbative piece of the CS kernel

MAP parametrization

- A recent work from the MAP collaboration (arXiv:2206.07598) used a complicated form for the non-perturbative function

$$f_{1\,NP}(x, \boldsymbol{b}_T^2; \zeta, Q_0) = \frac{g_1(x)\, e^{-g_1(x)\frac{\boldsymbol{b}_T^2}{4}} + \lambda^2\, g_{1B}^2(x) \left[1 - g_{1B}(x)\frac{\boldsymbol{b}_T^2}{4}\right] e^{-g_{1B}(x)\frac{\boldsymbol{b}_T^2}{4}} + \lambda_2^2\, g_{1C}(x)\, e^{-g_{1C}(x)\frac{\boldsymbol{b}_T^2}{4}}}{g_1(x) + \lambda^2\, g_{1B}^2(x) + \lambda_2^2\, g_{1C}(x)} \left[\frac{\zeta}{Q_0^2}\right]^{\boxed{g_K(\boldsymbol{b}_T^2)/2}}, \quad (38)$$

$$g_{\{1,1B,1C\}}(x) = N_{\{1,1B,1C\}} \frac{x^{\sigma_{\{1,2,3\}}}(1-x)^{\alpha^2_{\{1,2,3\}}}}{\hat{x}^{\sigma_{\{1,2,3\}}}(1-\hat{x})^{\alpha^2_{\{1,2,3\}}}},$$

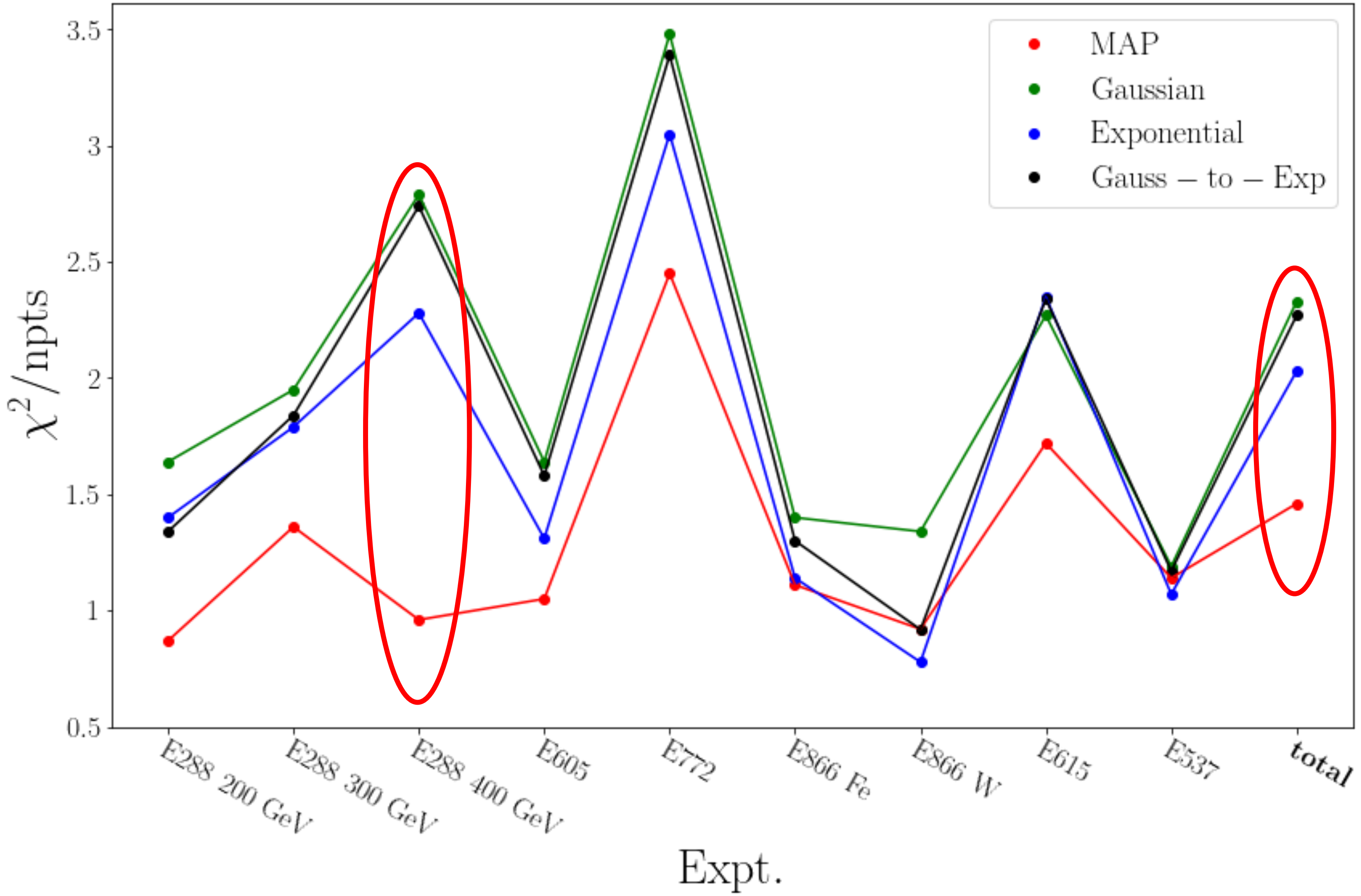
$$\boxed{g_K(\boldsymbol{b}_T^2) = -g_2^2\, \frac{\boldsymbol{b}_T^2}{2}}$$

Universal CS kernel

- 11 free parameters for each hadron! (flavor dependence not necessary) (12 if we include the nuclear TMD parameter)

Resulting χ^2 for each parametrization

- Tried multiple parametrizations for non-perturbative TMD structures
- MAP parametrization is able to describe better all the datasets



Nuclear TMD PDFs – working hypothesis

- We must model the nuclear TMD PDF from proton

$$\tilde{f}_{q/A}(x, b_T, \mu, \zeta) = \frac{Z}{A}\tilde{f}_{q/p/A}(x, b_T, \mu, \zeta) + \frac{A-Z}{A}\tilde{f}_{q/n/A}(x, b_T, \mu, \zeta)$$

- Each object on the right side independently obeys the CSS equation
    - **Assumption** that the bound proton and bound neutron follow TMD factorization
- Make use of isospin symmetry in that $u/p/A \leftrightarrow d/n/A$, etc.

Building of the nuclear TMD PDF

- Then taking into account the intrinsic non-perturbative, we model the flavor-dependent pieces of the TMD PDF as

$$(C \otimes f)_{u/A}(x) e^{-g_{u/A}(x,b_T)} \to \frac{Z}{A}(C \otimes f)_{u/p/A}(x) e^{-g_{u/p/A}(x,b_T)} + \frac{A-Z}{A}(C \otimes f)_{d/p/A}(x) e^{-g_{d/p/A}(x,b_T)}$$

and

$$(C \otimes f)_{d/A}(x) e^{-g_{d/A}(x,b_T)} \to \frac{Z}{A}(C \otimes f)_{d/p/A}(x) e^{-g_{d/p/A}(x,b_T)} + \frac{A-Z}{A}(C \otimes f)_{u/p/A}(x) e^{-g_{u/p/A}(x,b_T)}.$$

Nuclear TMD parametrization

- Specifically, we include a parametrization similar to Alrashed, et al., Phys. Rev. Lett **129**, 242001 (2022).

$$g_{q/\mathcal{N}/A} = g_{q/\mathcal{N}} \left(1 - a_{\mathcal{N}} \left(A^{1/3} - 1\right)\right)$$

- Where $a_{\mathcal{N}}$ is an additional parameter to be fit

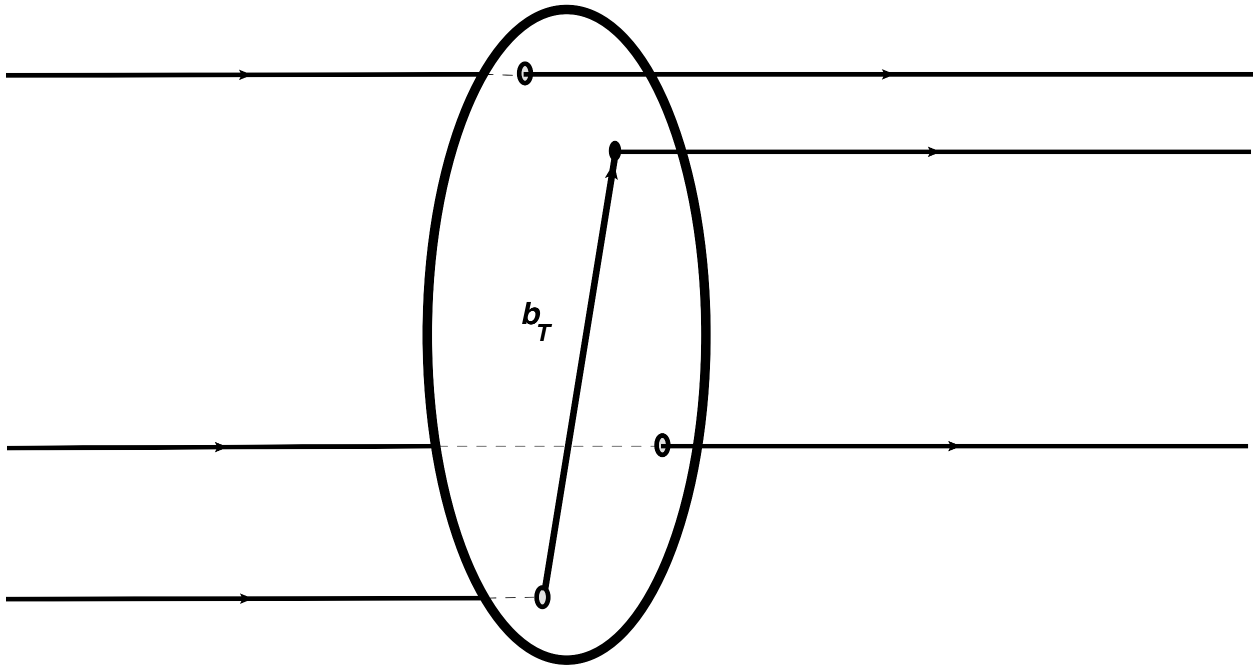
Datasets in the q_T-dependent analysis

Expt.	$\sqrt{s}$ (GeV)	Reaction	Observable	Q (GeV)	x_F or y	$N_{\text{pts.}}$
E288 [39]	19.4	$p + Pt \to \ell^+\ell^- X$	$E\mathrm{d}^3\sigma/\mathrm{d}^3\mathbf{q}$	$4 - 9$	$y = 0.4$	38
E288 [39]	23.8	$p + Pt \to \ell^+\ell^- X$	$E\mathrm{d}^3\sigma/\mathrm{d}^3\mathbf{q}$	$4 - 12$	$y = 0.21$	48
E288 [39]	24.7	$p + Pt \to \ell^+\ell^- X$	$E\mathrm{d}^3\sigma/\mathrm{d}^3\mathbf{q}$	$4 - 14$	$y = 0.03$	74
E605 [40]	38.8	$p + Cu \to \ell^+\ell^- X$	$E\mathrm{d}^3\sigma/\mathrm{d}^3\mathbf{q}$	$7 - 18$	$x_F = 0.1$	49
E772 [41]	38.8	$p + D \to \ell^+\ell^- X$	$E\mathrm{d}^3\sigma/\mathrm{d}^3\mathbf{q}$	$5 - 15$	$0.1 \le x_F \le 0.3$	61
E866 [50]	38.8	$p + Fe \to \ell^+\ell^- X$	R_{FeBe}	$4 - 8$	$0.13 \le x_F \le 0.93$	10
E866 [50]	38.8	$p + W \to \ell^+\ell^- X$	R_{WBe}	$4 - 8$	$0.13 \le x_F \le 0.93$	10
E537 [38]	15.3	$\pi^- + W \to \ell^+\ell^- X$	$\mathrm{d}^2\sigma/\mathrm{d}x_F\mathrm{d}q_T$	$4 - 9$	$0 < x_F < 0.8$	48
E615 [4]	21.8	$\pi^- + W \to \ell^+\ell^- X$	$\mathrm{d}^2\sigma/\mathrm{d}x_F\mathrm{d}q_T^2$	$4.05 - 8.55$	$0 < x_F < 0.8$	45

- Total of 383 number of points
- All fixed target, low-energy data
- We perform a cut of $q_T^{\max} < 0.25\,Q$

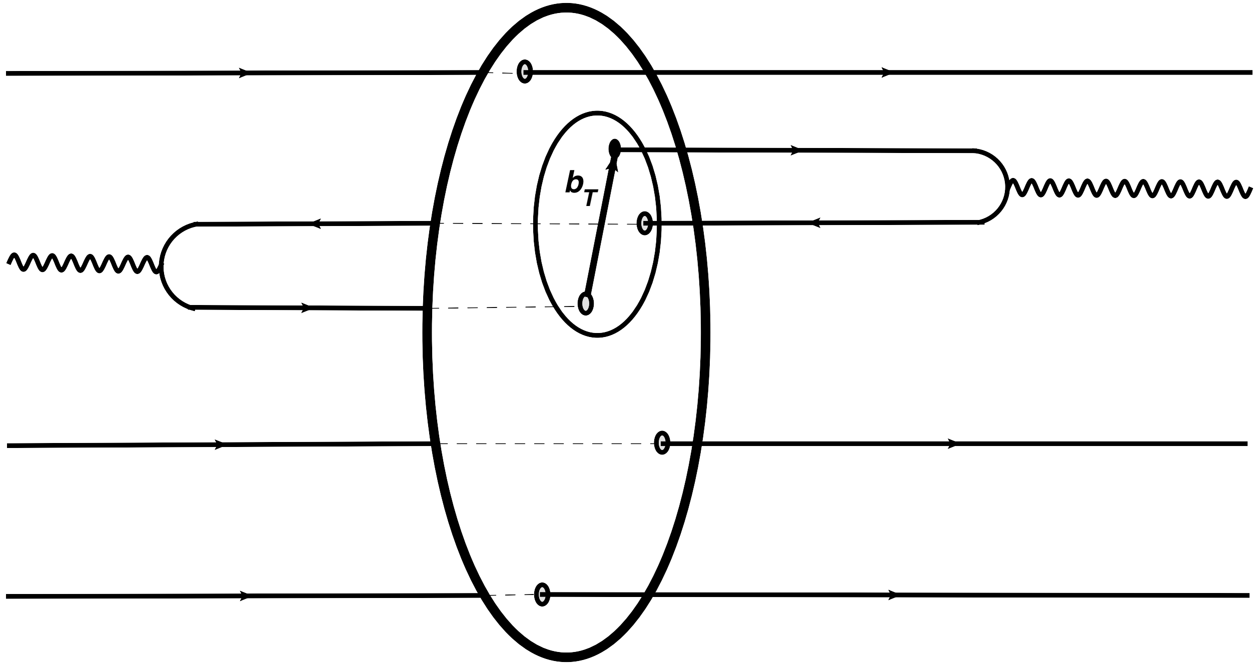
Possible explanation

- At large x, we are in a valence region, where only the valence quarks are populating the momentum dependence of the hadron



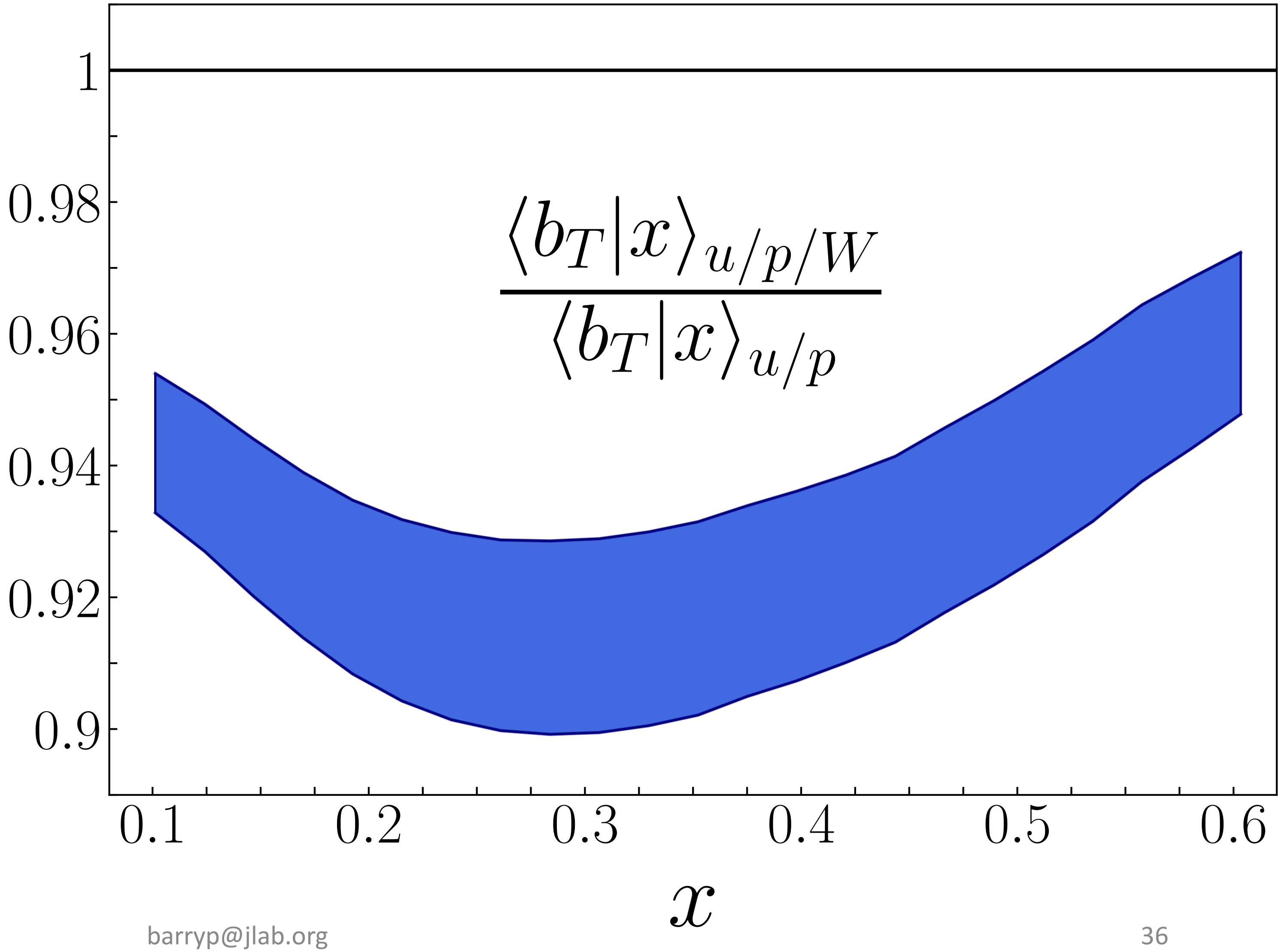
Possible explanation

- At small x, sea quarks and potential $q\bar{q}$ bound states allowing only for a smaller bound system



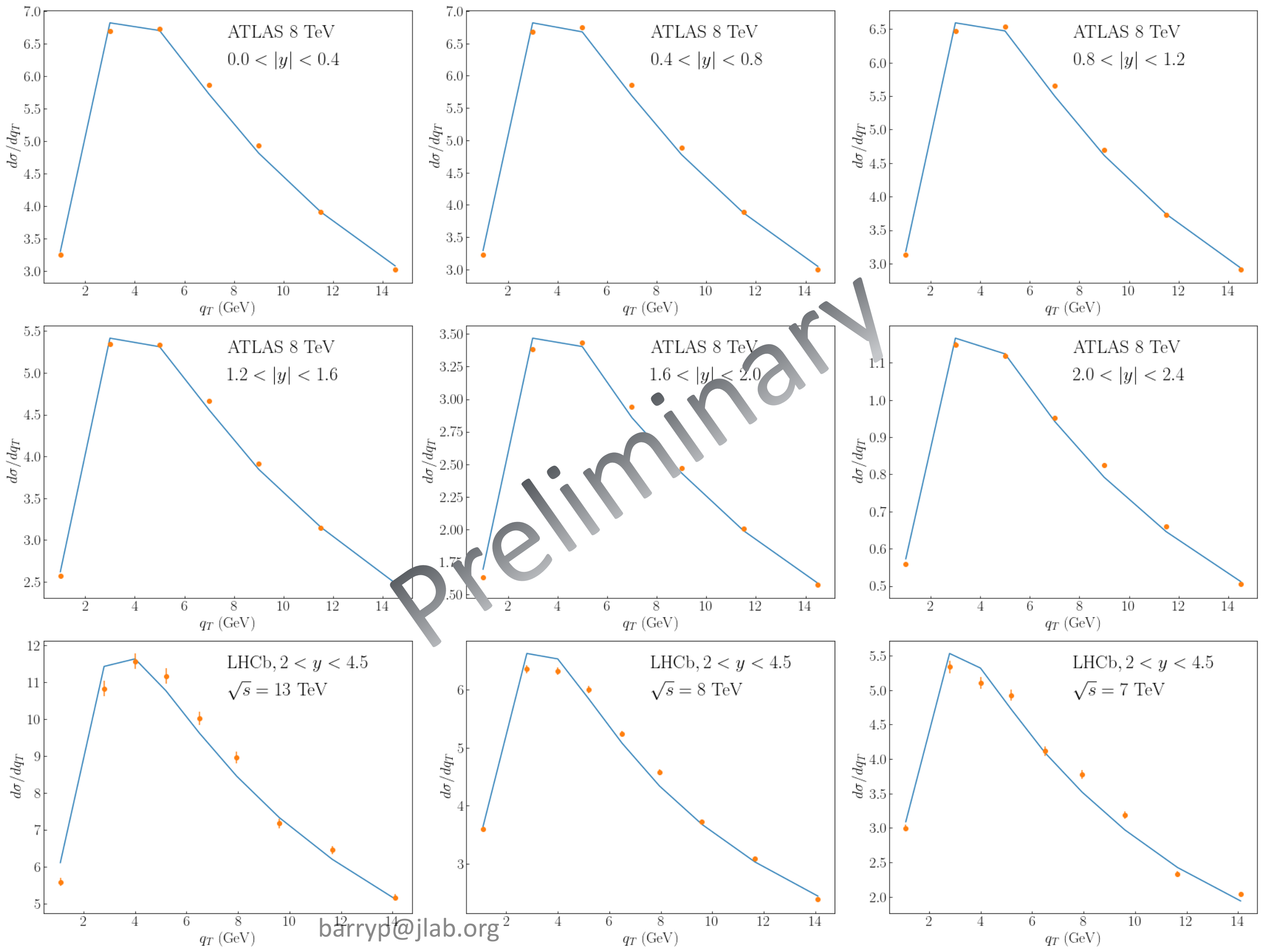
Transverse EMC effect

- Compare the average b_T given x for the up quark in the bound proton to that of the free proton
- Less than 1 by $\sim 5-10\%$ over the x range



Preliminary fit to ATLAS and LHCb

- Two free non-perturbative TMD parameters from fit
- Fix the collinear PDF
- $b_{\max} = 0.3\ \mathrm{GeV}^{-1}$



Contributions from each experiments

- Looking at percentage coming from specific quark channels