Tomography of pions and protons via TMDs

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In collaboration with: Leonard Gamberg, Wally Melnitchouk, Eric Moffat, Daniel Pitonyak, Alexei Prokudin, Nobuo Sato

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arXiv:2302.01192

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Tomography of pions and protons via transverse momentum dependent distributions

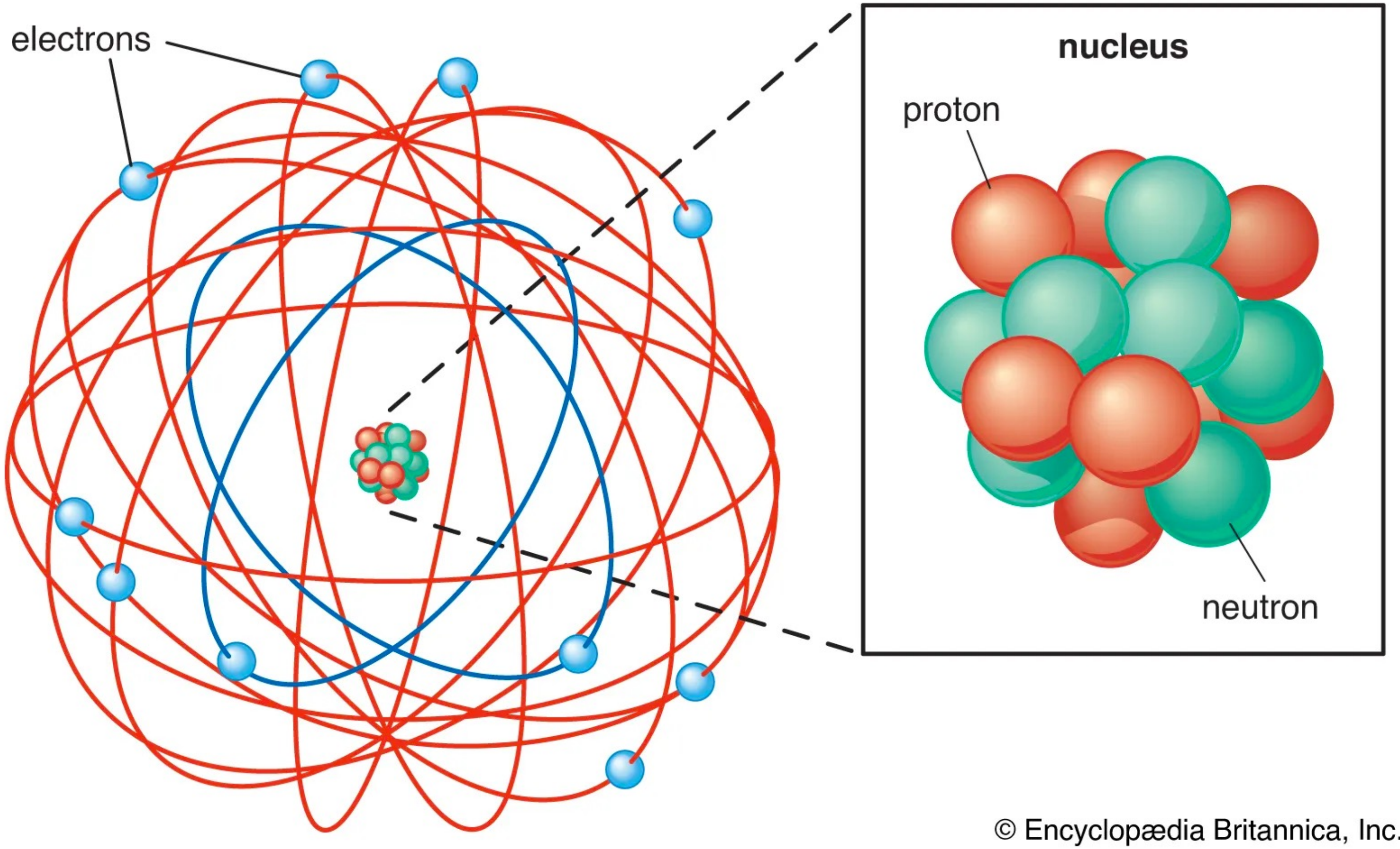
P. C. Barry,[1] L. Gamberg,[2] W. Melnitchouk,[1,3] E. Moffat,[2,4] D. Pitonyak,[5] A. Prokudin,[1,2] and N. Sato[1]
(**Jefferson Lab Angular Momentum (JAM) Collaboration**)
[1] *Jefferson Lab, Newport News, Virginia 23606, USA*
[2] *Division of Science, Penn State Berks, Reading, Pennslyvania, 19610, USA*
[3] *CSSM and CDMPP, Department of Physics, University of Adelaide, Adelaide 5000, Australia*
[4] *Physics Division, Argonne National Laboratory, Lemont, Illinois 60439, USA*
[5] *Department of Physics, Lebanon Valley College, Annville, Pennsylvania 17003, USA*

(Dated: February 3, 2023)

We perform the first simultaneous extraction of parton collinear and transverse degrees of freedom from low-energy fixed-target Drell-Yan data in order to compare the transverse momentum dependent (TMD) parton distribution functions (PDFs) of the pion and proton. We demonstrate that the transverse separation of the quark field encoded in TMDs of the pion is more than 5σ smaller than that of the proton. Additionally, we find the transverse separation of the quark field decreases as its longitudinal momentum fraction decreases. In studying the nuclear modification of TMDs, we find clear evidence for a transverse EMC effect. We comment on possible explanations for these intriguing behaviors, which call for a deeper examination of tomography in a variety of strongly interacting quark-gluon systems.

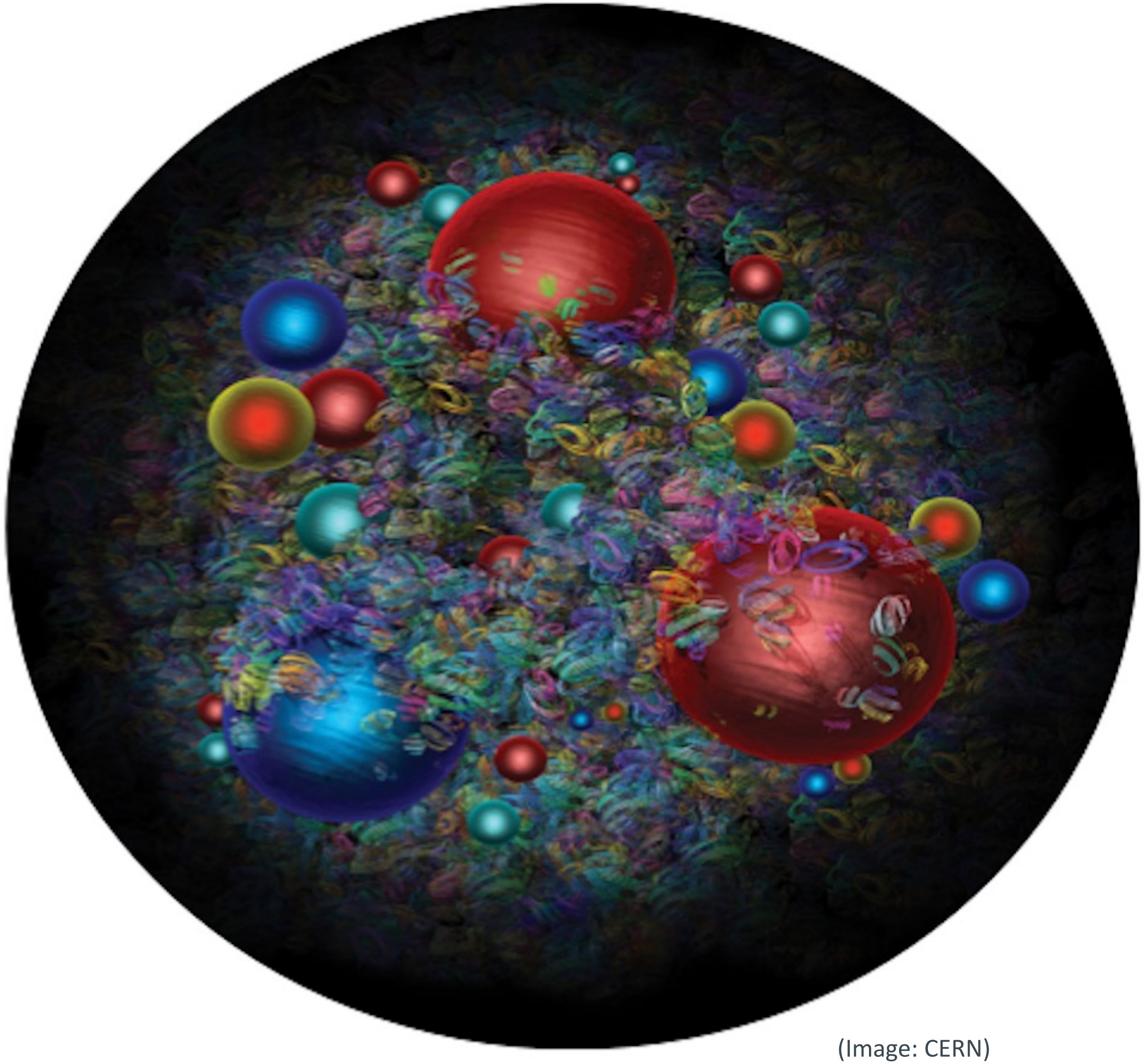
Motivation

- All visible matter is made up of atoms
- The mass of these atoms are largely from the nucleus
- The nucleus is made up of protons and neutrons



Motivation

- In turn, these protons and neutrons are made of quarks and gluons
- We want to study the structure of the nuclear matter



(Image: CERN)

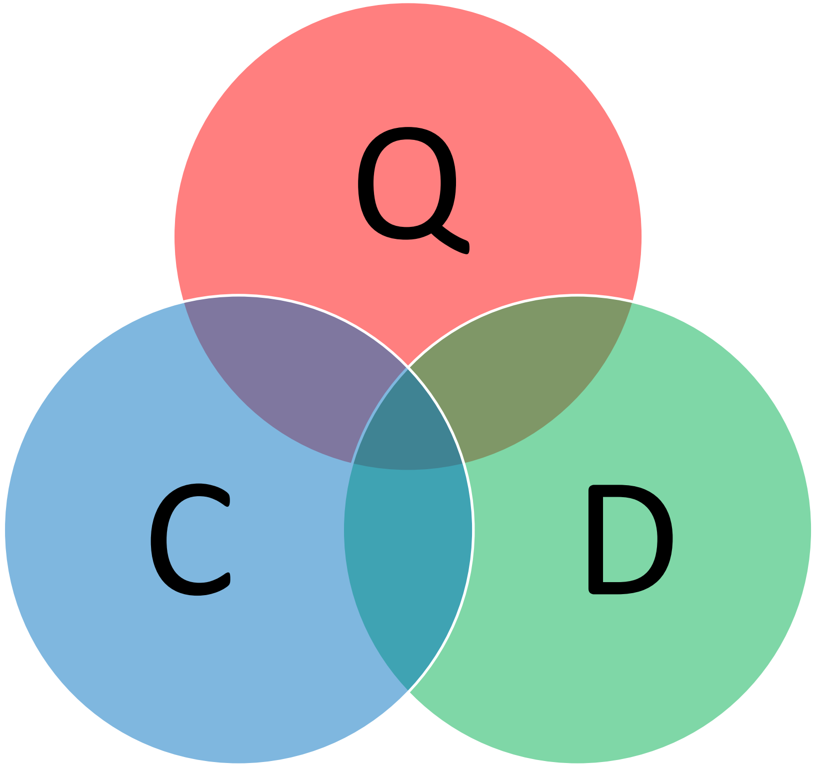
What's the problem?

Quarks and gluons are not directly measurable because of color confinement!

Have to be inferred from experimental data

How to handle this

- We make use of QCD, which allows us to study the structure of hadrons in terms of partons (quarks, antiquarks, and gluons)
- Use factorization theorems to separate hard partonic physics out of soft, non-perturbative objects to quantify structure



Game plan

What to do:

- Define a structure of hadrons in terms of quantum field theories
- Identify physical observables that can be theoretically factorized with controllable approximations, or factorizable lattice QCD observables
- Perform global QCD analysis as structures are universal and are the same in all processes

Complicated Inverse Problem

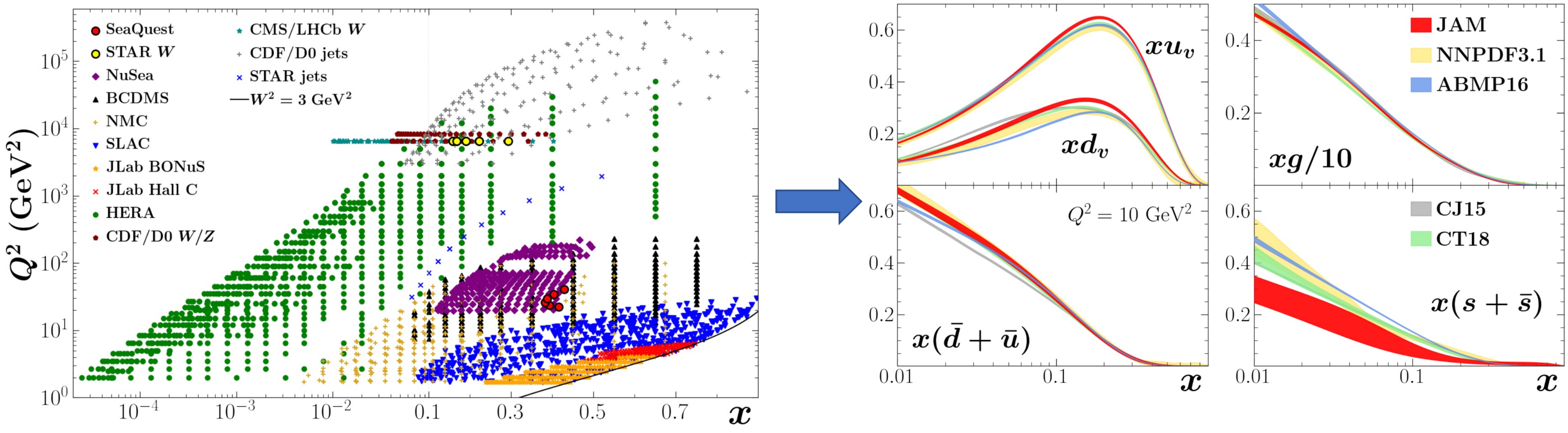
- Factorization theorems involve convolutions of hard perturbatively calculable physics and non-perturbative objects

$$\frac{d\sigma}{d\Omega} \propto \mathcal{H} \otimes f = \int_x^1 \frac{d\xi}{\xi} \mathcal{H}\left(\frac{x}{\xi}\right) f(\xi)$$

- Parametrize the non-perturbative objects and perform global analysis

What do we know about structures?

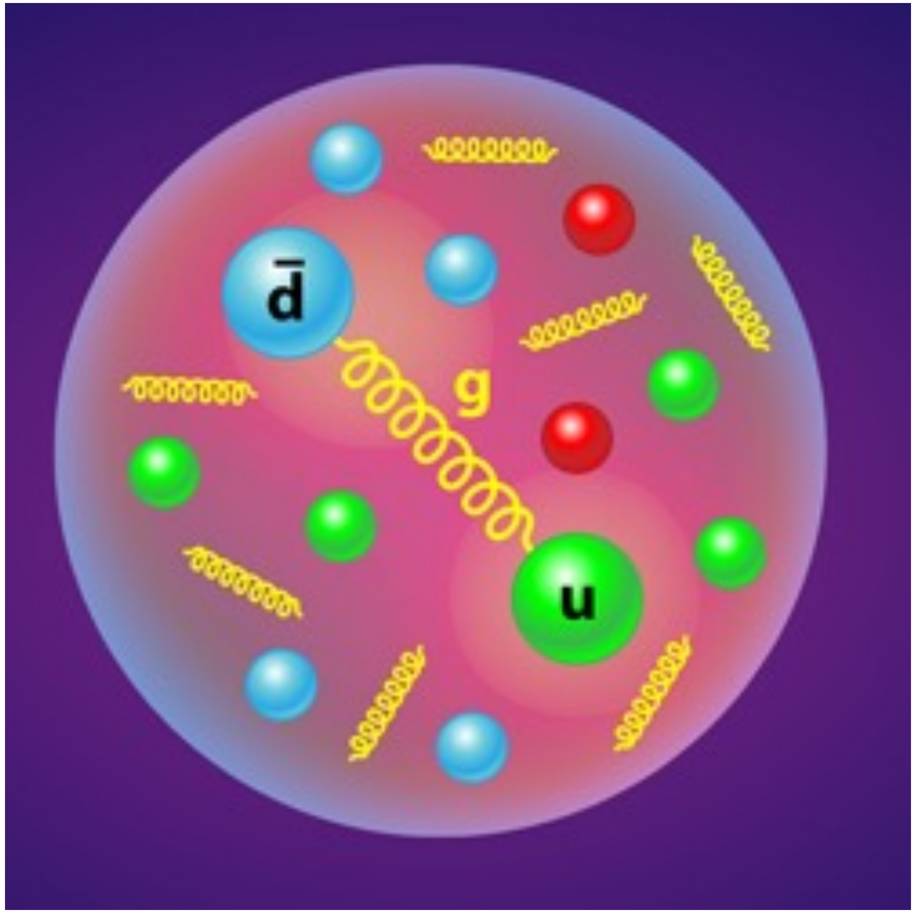
- Most well-known structure is through longitudinal structure of hadrons, particularly protons



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

Other structures?

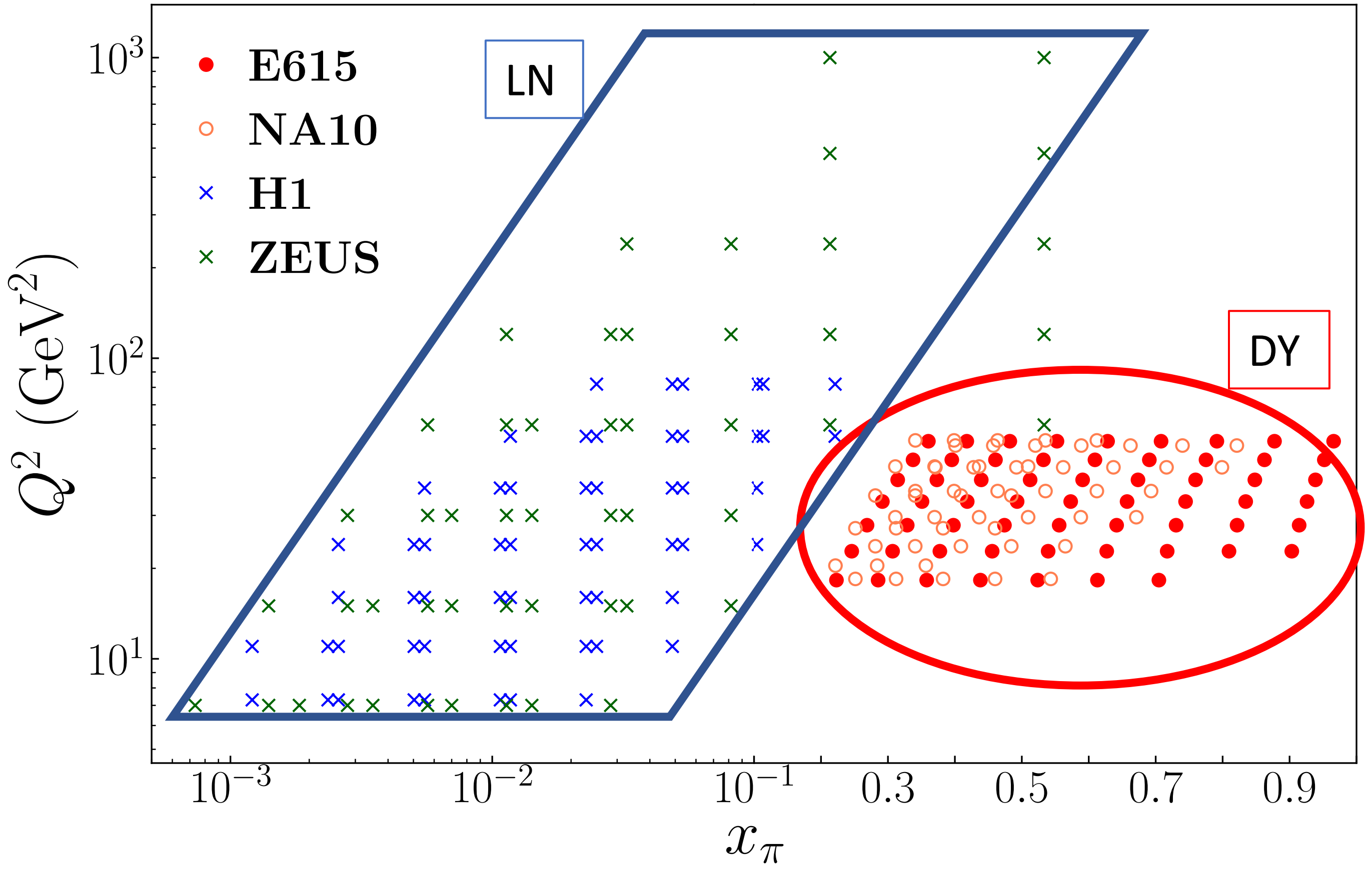
- To give deeper insights into color confined systems, we shouldn’t limit ourselves to proton structures
- Pions are also important because of their Goldstone-boson nature while also being made up of quarks and gluons



Available datasets for pion structures

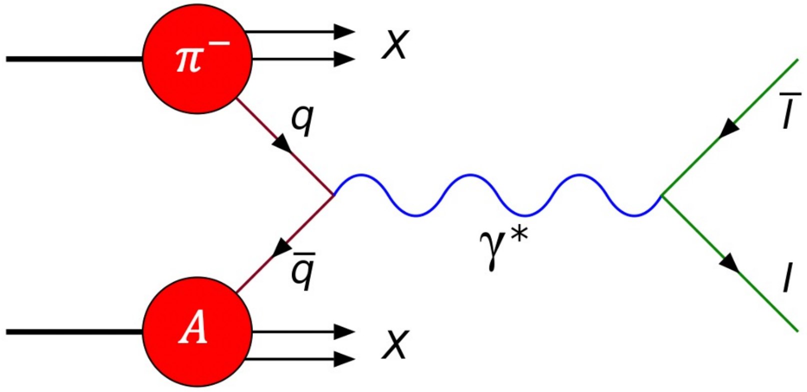
- Much less available data than in the proton case

- Still valuable to study

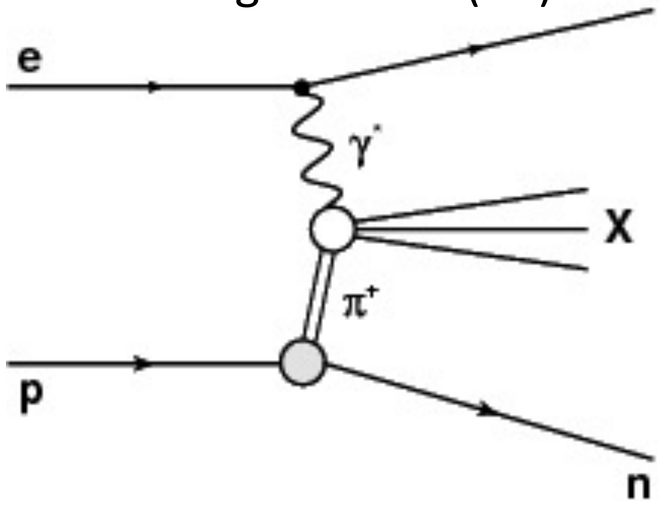


Pion PDFs in JAM

Drell-Yan (DY)



Leading Neutron (LN)

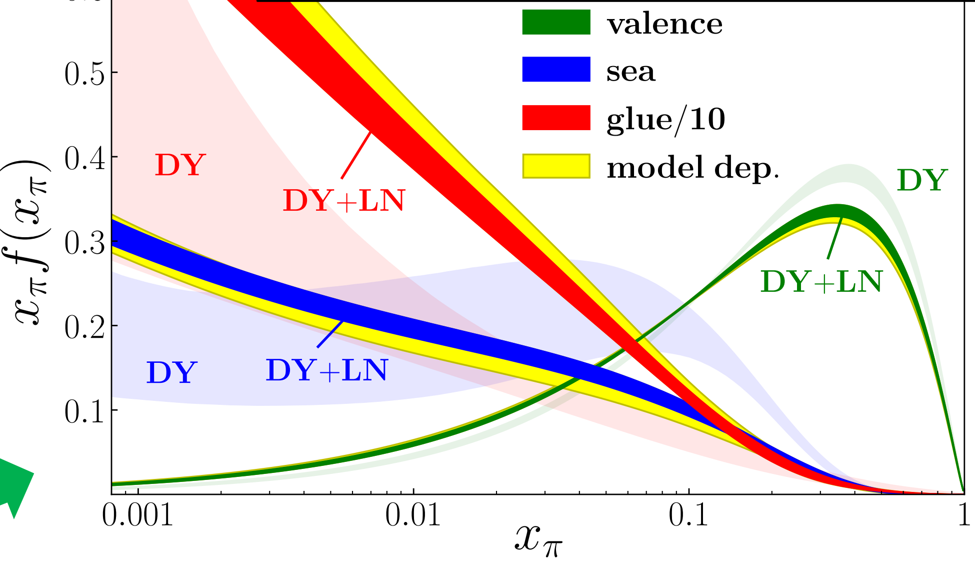


PHYSICAL REVIEW LETTERS **121**, 152001 (2018)

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]

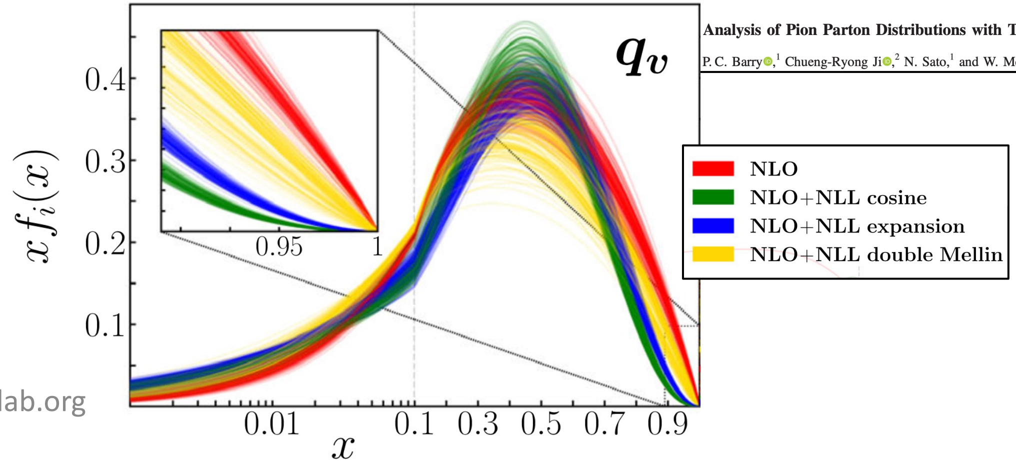


Threshold resummation in DY

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]



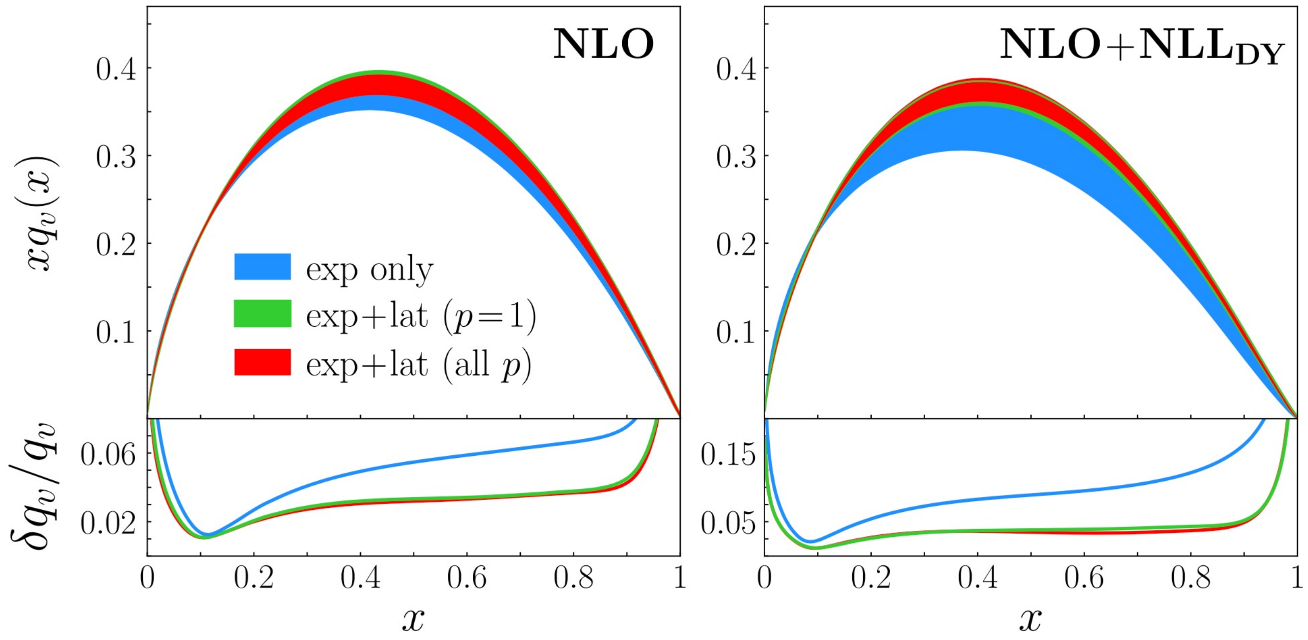
Pion PDFs from lattice + experimental data

PHYSICAL REVIEW D **105**, 114051 (2022)

Complementarity of experimental and lattice QCD data on pion parton distributions

P. C. Barry,[1] C. Egerer,[1] J. Karpie,[2] W. Melnitchouk,[1] C. Monahan,[1,3] K. Orginos,[1,3] Jian-Wei Qiu,[1,3] D. Richards,[1] N. Sato,[1] R. S. Sufian,[1,3] and S. Zafeiropoulos[4]

(Jefferson Lab Angular Momentum (JAM) and HadStruc Collaborations)

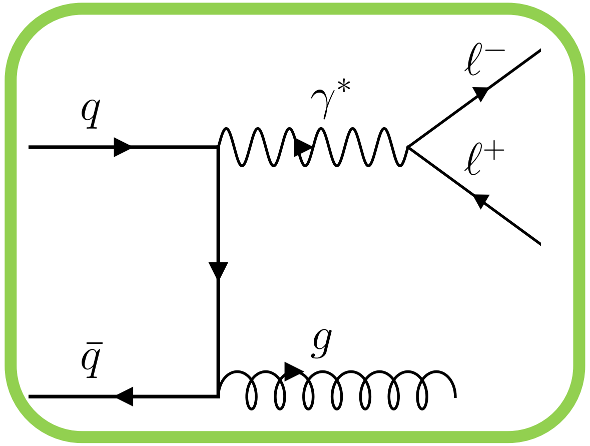


- The inclusion of lattice QCD data along with experimental data can also help us to reveal pion structure

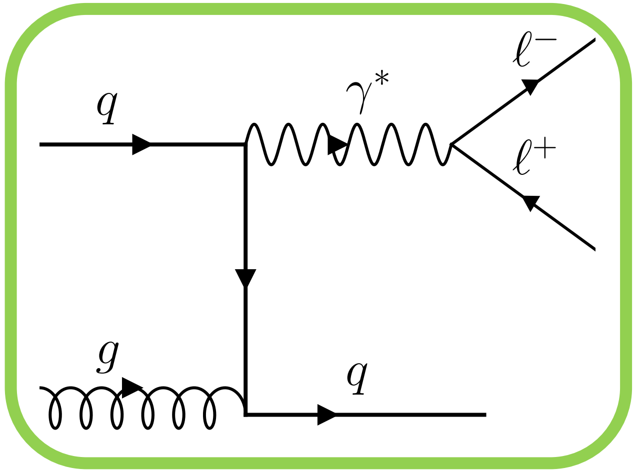
Large transverse momentum

- p_T dependent DY in **collinear factorization**

$$\frac{d\sigma}{dQ^2 dY dq_T^2} = \frac{4\pi\alpha^2}{9Q^2 S} \sum_{i,j} e_q^2 \int_{x_\pi^0}^1 dx_\pi f_i^\pi(x_\pi, \mu) f_j^A(x_A, \mu) \times \frac{d\hat{\sigma}_{i,j}}{dQ^2 d\hat{t}}$$



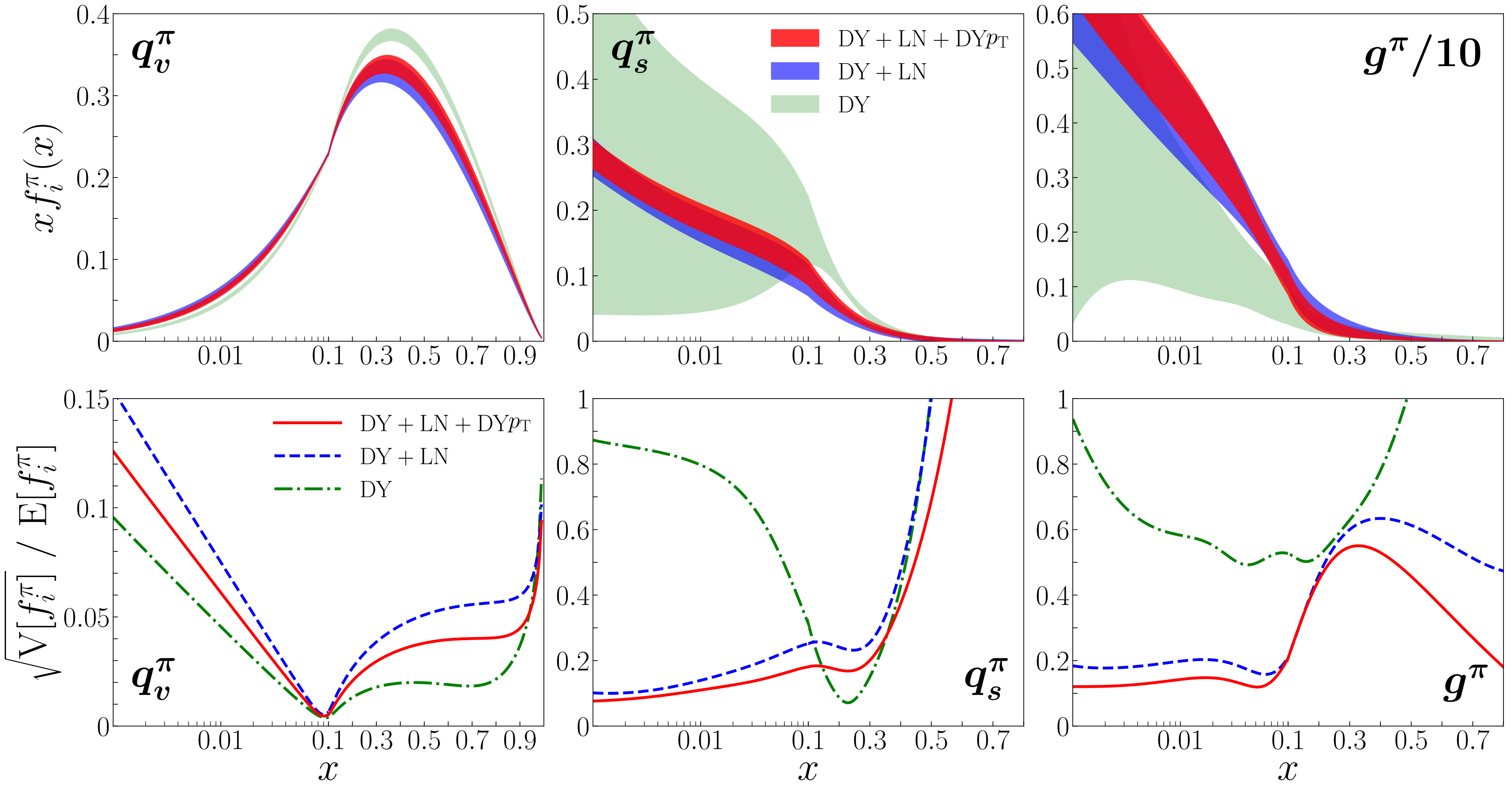
$q\bar{q}$ channel example



qg channel example

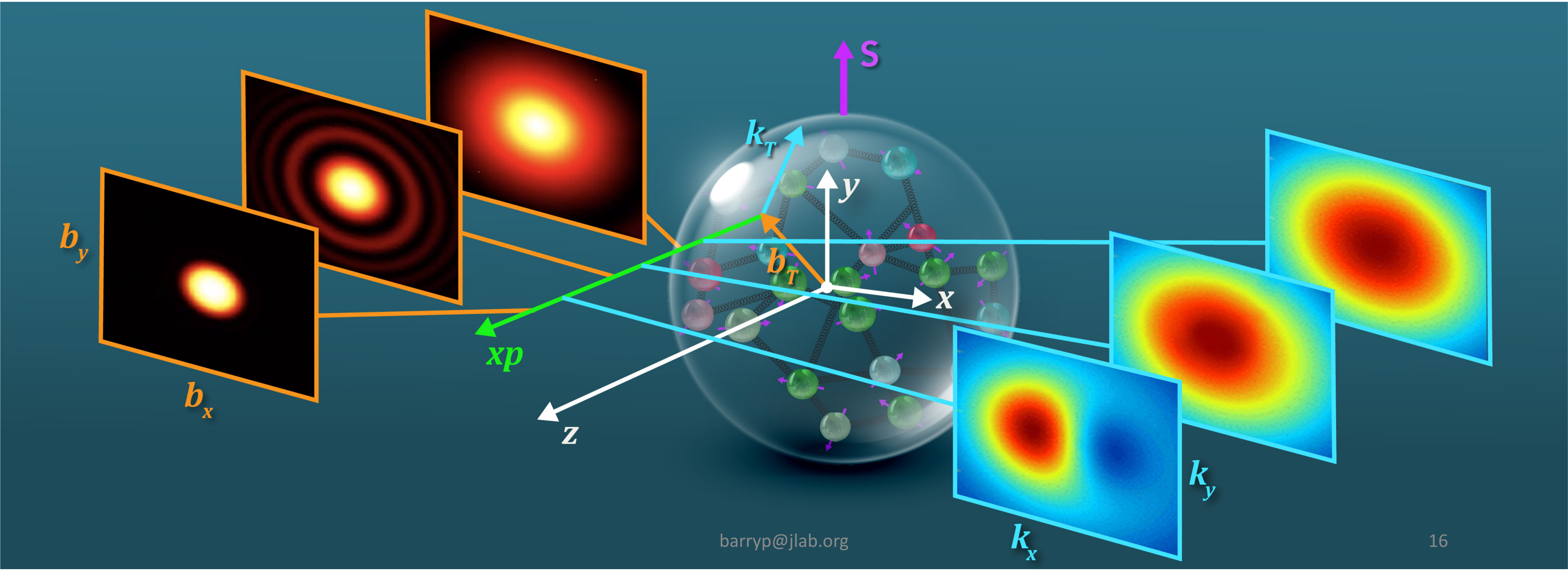
Effects of Each Dataset

- Not much impact from the transverse-momentum dependent DY data



3D structures of hadrons

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



Unpolarized TMD PDF

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

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

- $\boldsymbol{b_T}$ 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

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

Evolution equations for the TMD PDF

$$\frac{\partial \ln \tilde{f}_{q/\mathcal{N}}(x, b_T; \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = \tilde{K}(b_T; \mu)$$

Collins-Soper (CS) kernel

Rapidity scale

Has its own renormalization group equation

$$\frac{\mathrm{d}\tilde{K}(b_T; \mu)}{\mathrm{d}\ln \mu} = -\gamma_K\left(\alpha_S(\mu)\right)$$

Anomalous dimension of CS kernel

$$\frac{\mathrm{d}\ln \tilde{f}_{q/\mathcal{N}}(x, b_T; \mu, \zeta)}{\mathrm{d}\ln \mu} = \gamma_f(\alpha_S(\mu)) - \frac{1}{2}\gamma_K(\alpha_S(\mu)) \ln \frac{\zeta}{\mu^2}$$

Renormalization scale

Anomalous dimension of TMDPDF

Small b_T operator product expansion

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

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

- where $\tilde{C}$ are the Wilson coefficients, and $f_{q/\mathcal{N}}$ 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.

$$e^{-g_{q/\mathcal{N}(A)}(x,b_T)} = \frac{\tilde{f}_{q/\mathcal{N}(A)}(x, b_T; \mu, \zeta)}{\tilde{f}_{q/\mathcal{N}(A)}(x, b_*; \mu, \zeta)} e^{g_K(b_T; b_{\max}) \log\left(\sqrt{\zeta}/Q_0\right)}$$

Full description of the TMD

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

- Have individual pieces that are sensitive to low-b_T spectrum (perturbative) and the high-b_T (non-perturbative)

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?

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

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

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

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

Perturbative pieces

Non-perturbative pieces

Non-perturbative piece of the CS kernel

Nuclear TMD PDFs

- The TMD factorization allows for the description of a quark inside a nucleus to be $\tilde{f}_{q/A}$
- However, the intrinsic non-perturbative structure will in-principle change from nucleus-to-nucleus
- Want to model these in terms of protons and neutrons as we don't have enough observables to separately parametrize different nuclei

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

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

and

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

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

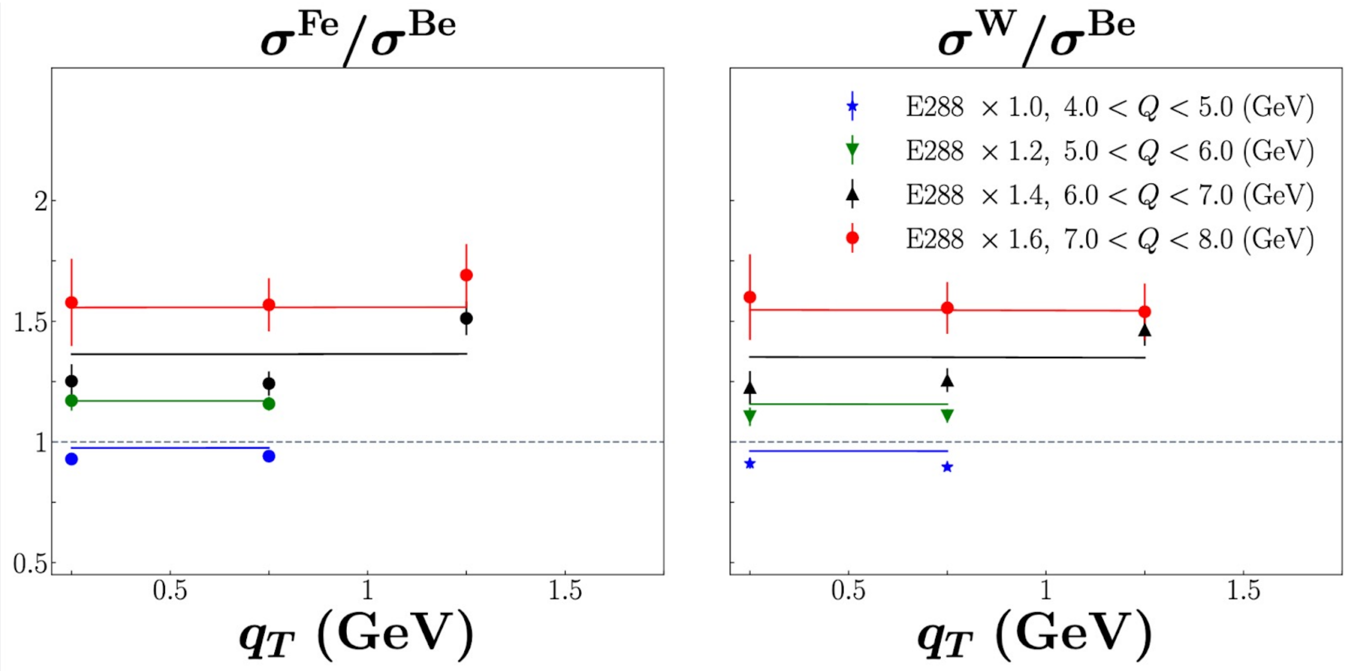
Datasets in the q_T-dependent analysis

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 $q_T^{\max} < 0.25\, Q$

A few words on nuclear dependence

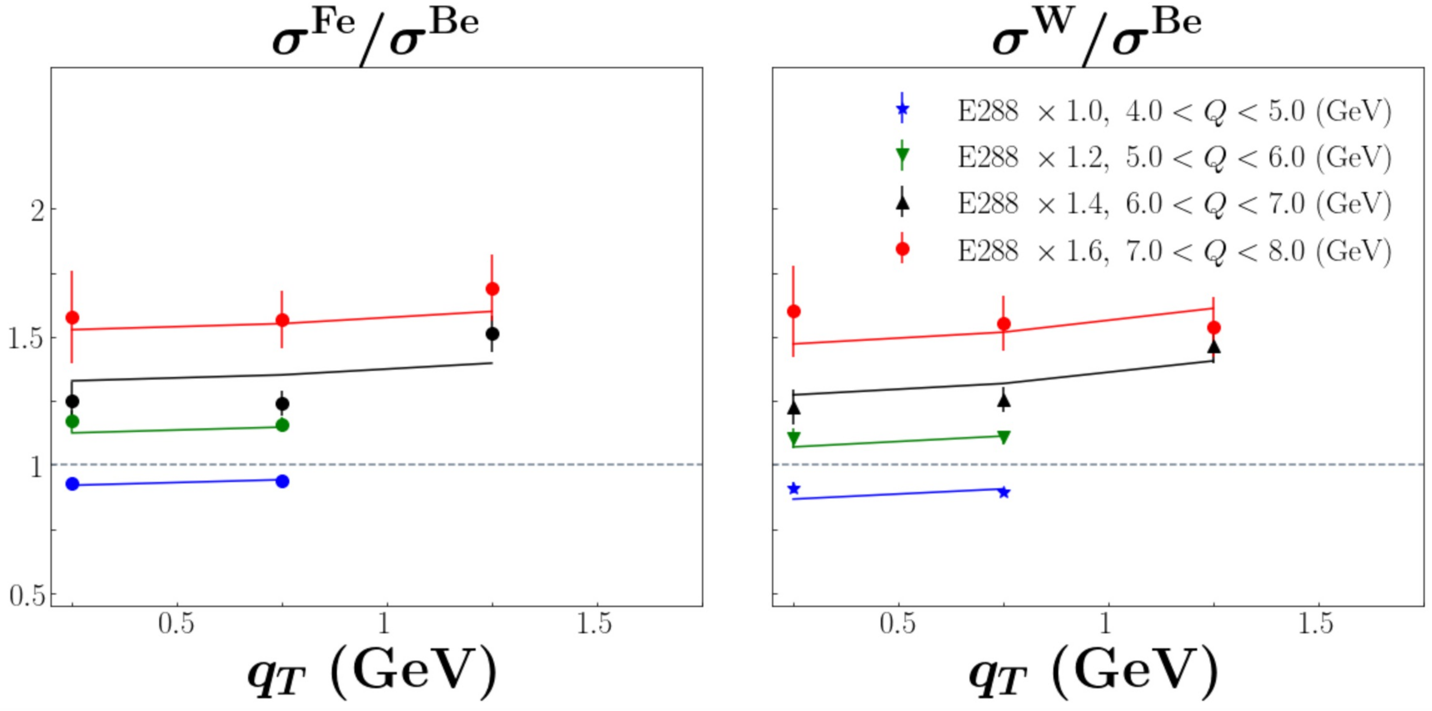
- The ratios from the E866 experiment provided a look to nuclear effects in TMDs as well as the importance of nuclear collinear effects
- Ignoring any nuclear corrections in TMDs and collinear PDFs



col	obs	tar	npts	chi2/npts	Z-score
E866	ratio	Fe/Be	10	2.2	2.16
E866	ratio	W/Be	10	3.51	3.67

Including nuclear dependence

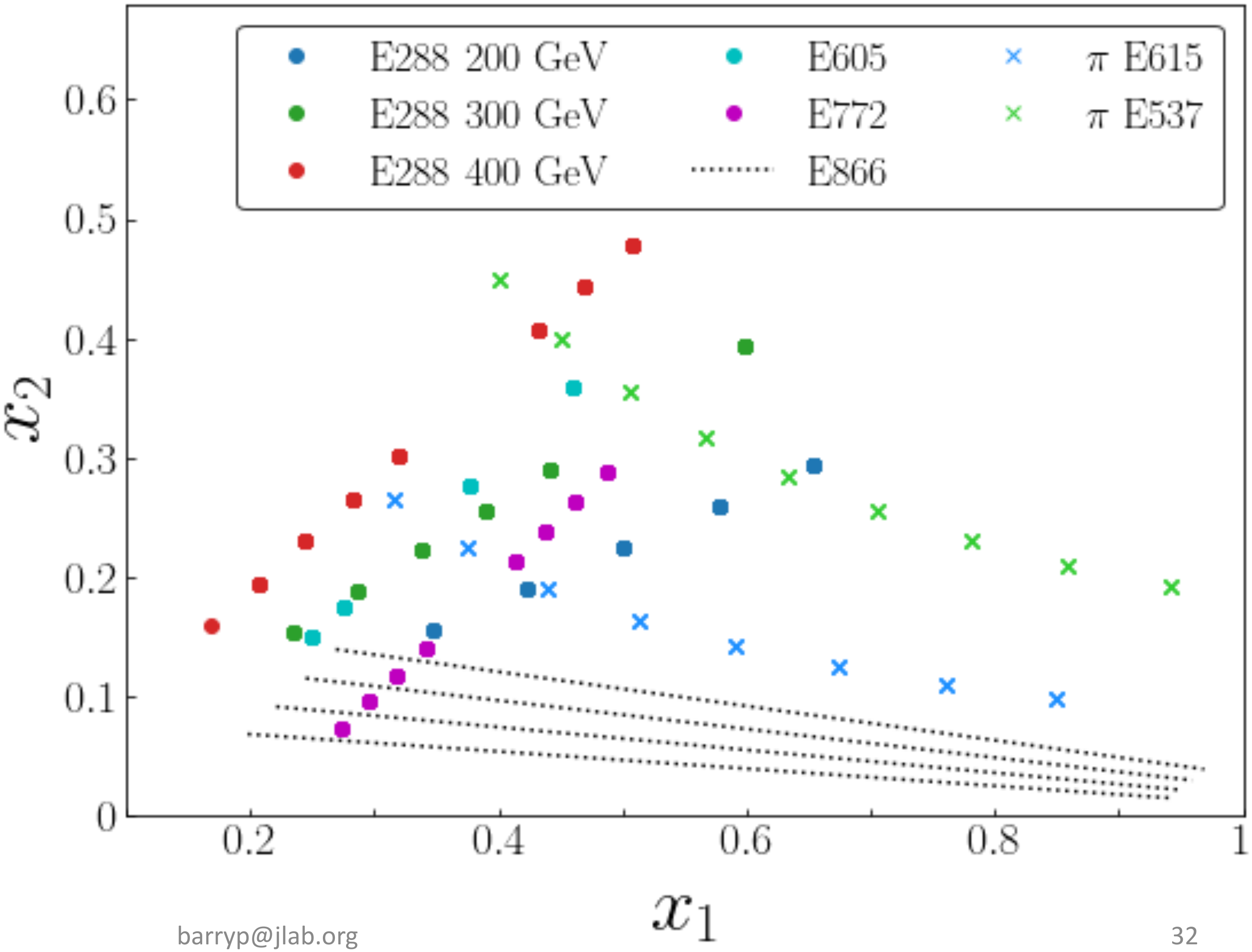
- Better description when including the nuclear dependence in the collinear PDF and TMD



col	obs	tar	npts	chi2/npts	Z-score
E866	ratio	Fe/Be	10	1.11	0.4
E866	ratio	W/Be	10	0.92	0.04

Kinematics in x_1, x_2

- Using the kinematic mid-point from each of the bins, we show the range in x_1 and x_2



Parametrizations of the TMDs

- First perform single fits of these data to explore various aspects
- Many types of parametrizations have been used in the past
- For the "intrinsic" non-perturbative TMD, we perform fits with each of the following

Gaussian

$$\exp(-g_{q/N}(x, b_T)) = \exp\left(-g_q(x, A)\, b_T^2\right) \,,$$

Exponential

$$\exp(-g_{q/N}(x, b_T)) = \exp\left(-g_q(x, A)\, b_T\right) \,,$$

Gaussian-to-Exponential

$$\exp(-g_{q/N}(x, b_T)) = \exp\left(-g_q(x, A)\, \frac{b_T^2}{\sqrt{1 + B_{NP}(x) b_T^2}}\right) \,,$$

Parametrizations

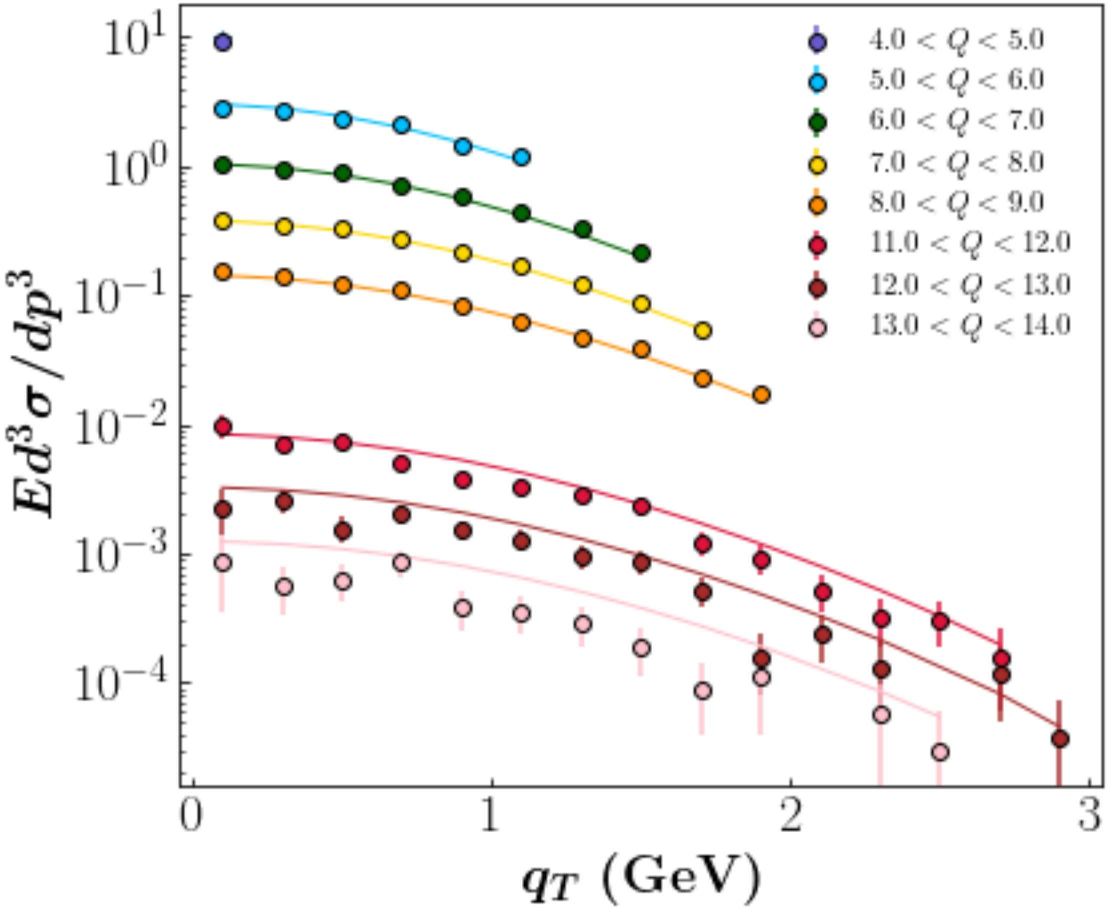
- We can test whether or not the x-dependence is important for these functions (it is!)
- For these g_q functions, we have the following

$$g_q(x, A) = |g^q + g_2^q x + g_3^q (1-x)^2|(1 + g_1(A^{1/3} - 1)) \ ,$$
$$B_{NP}(x) = b_{NP} x^2 \ ,$$

- 4 free parameters for each scheme (5 for Gaussian-to-Exponential)
- We may also open up these for each flavor in the proton (u, d, and sea) and for the pion (val, sea)

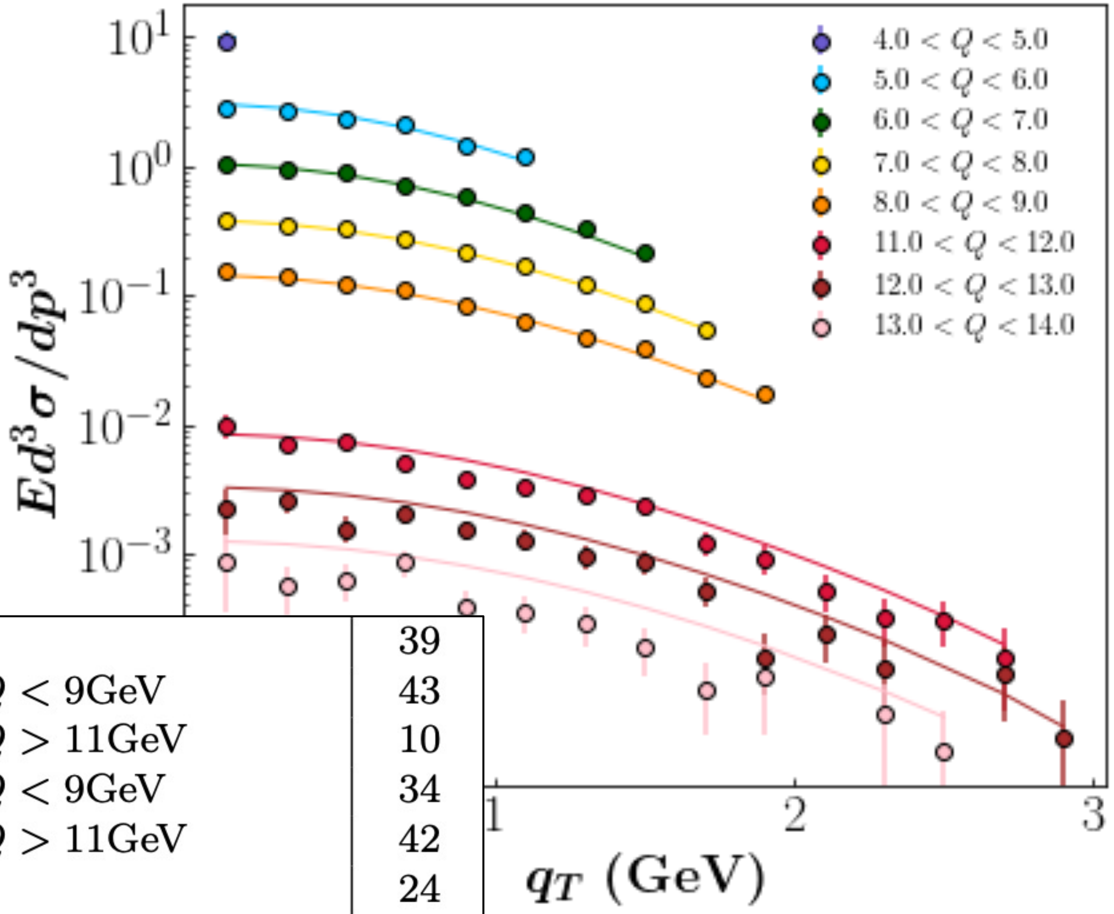
Problem describing data

- The E288 400 GeV data are difficult to describe the same above and below the Υ resonance
- Theory overpredicts data when $Q > 11\text{GeV}$



Problem describing data

- The E288 400 GeV data are difficult to describe the same above and below the Υ resonance
- Theory overpredicts data when $Q > 11\text{GeV}$
- Could treat as separate datasets – separate normalizations:



E228-200	39
E228-300 $Q < 9\text{GeV}$	43
E228-300 $Q > 11\text{GeV}$	10
E228-400 $Q < 9\text{GeV}$	34
E228-400 $Q > 11\text{GeV}$	42
E772	24
E605 $Q < 9\text{GeV}$	21
E605 $Q > 11\text{GeV}$	32

MAP parametrization

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

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

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

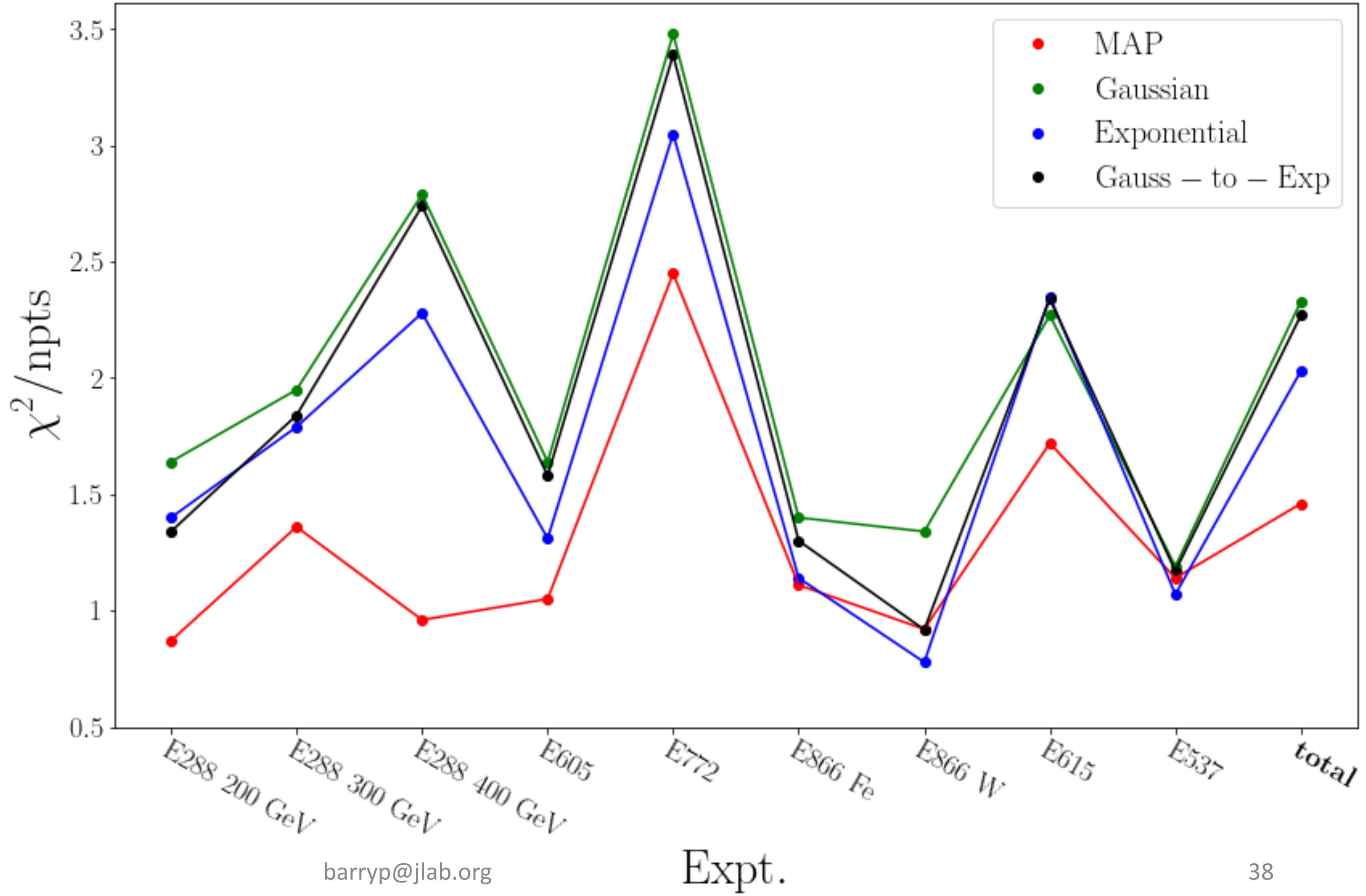
$$\boxed{g_K(\boldsymbol{b}_T^2) = -g_2^2\, \frac{\boldsymbol{b}_T^2}{2}}$$

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

- MAP gives best overall
- How significant?



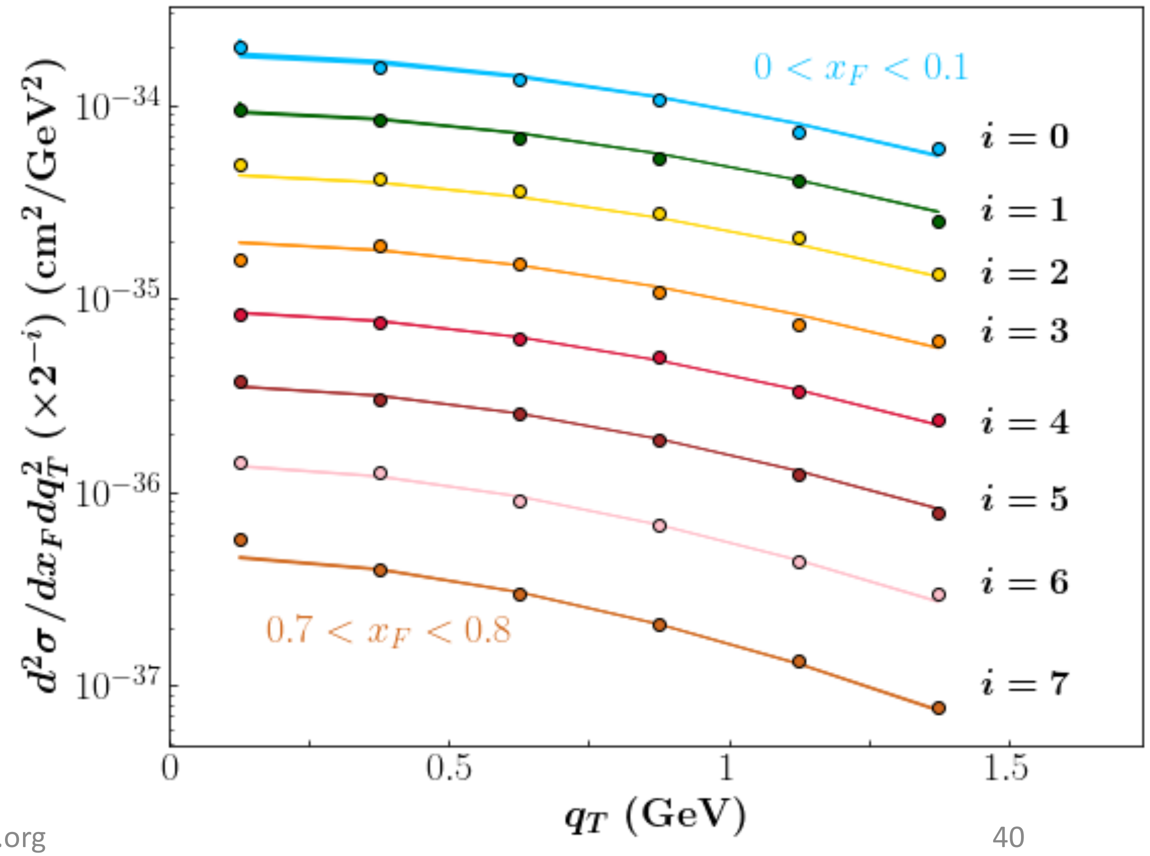
Perform the Monte Carlo

- We use the MAP parametrization
- Now, we can include the pion collinear PDF and its collinear datasets
- Include an additional 225 collinear data points
- Simultaneously extract
    1. Pion TMD PDFs
    2. Pion collinear PDFs
    3. Proton TMD PDFs
    4. Nuclear dependence
    5. Non-perturbative CS kernel

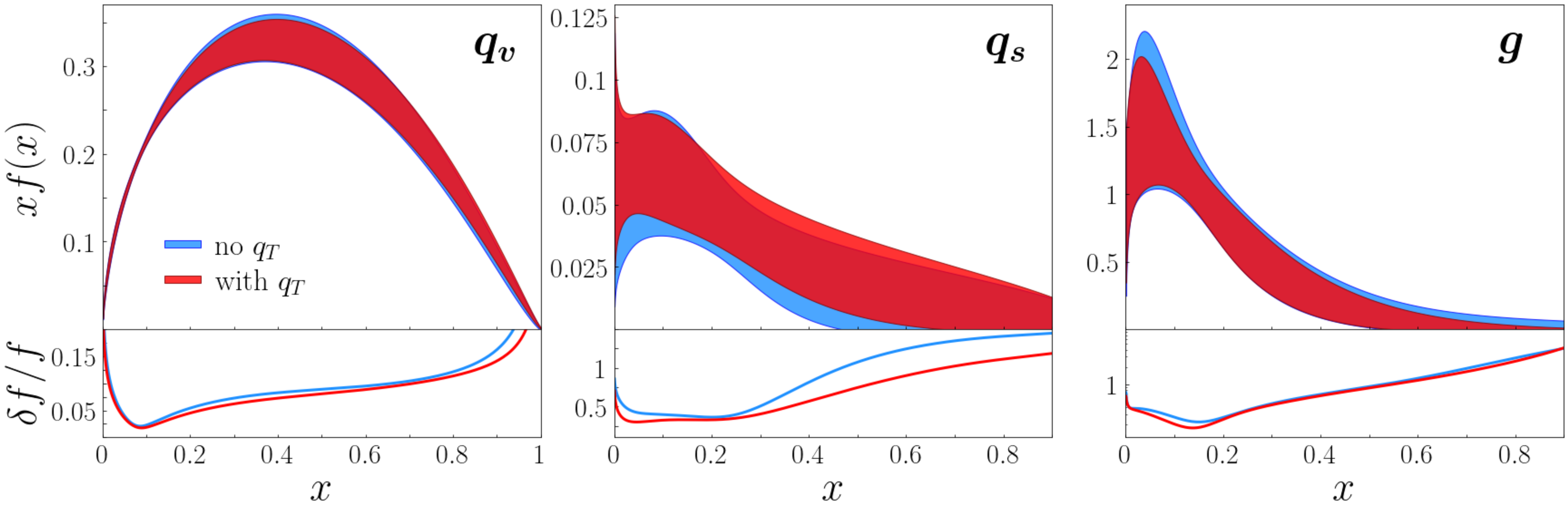
Data and theory agreement

- 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

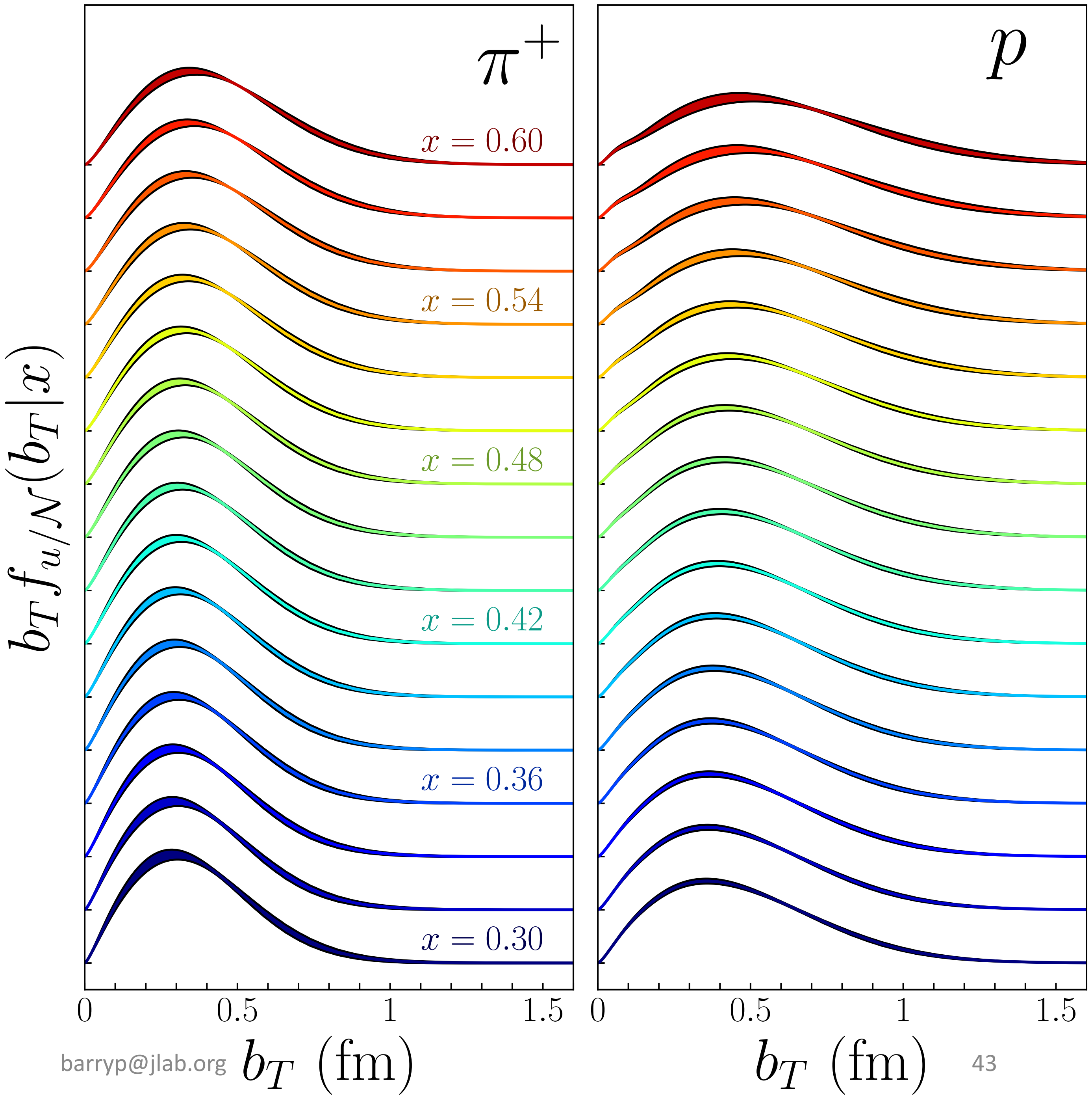
Conditional density

- We define a quantity in which describes the ratio of the 2-dimensional density to the integrated, b_T-independent number density, dependent on “b_T given x”

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

Resulting TMD PDFs of proton and pion

- Shown in the range where pion and proton are both constrained
- Broadening appearing as x increases
- Up quark in pion is narrower than up quark in proton



Average b_T

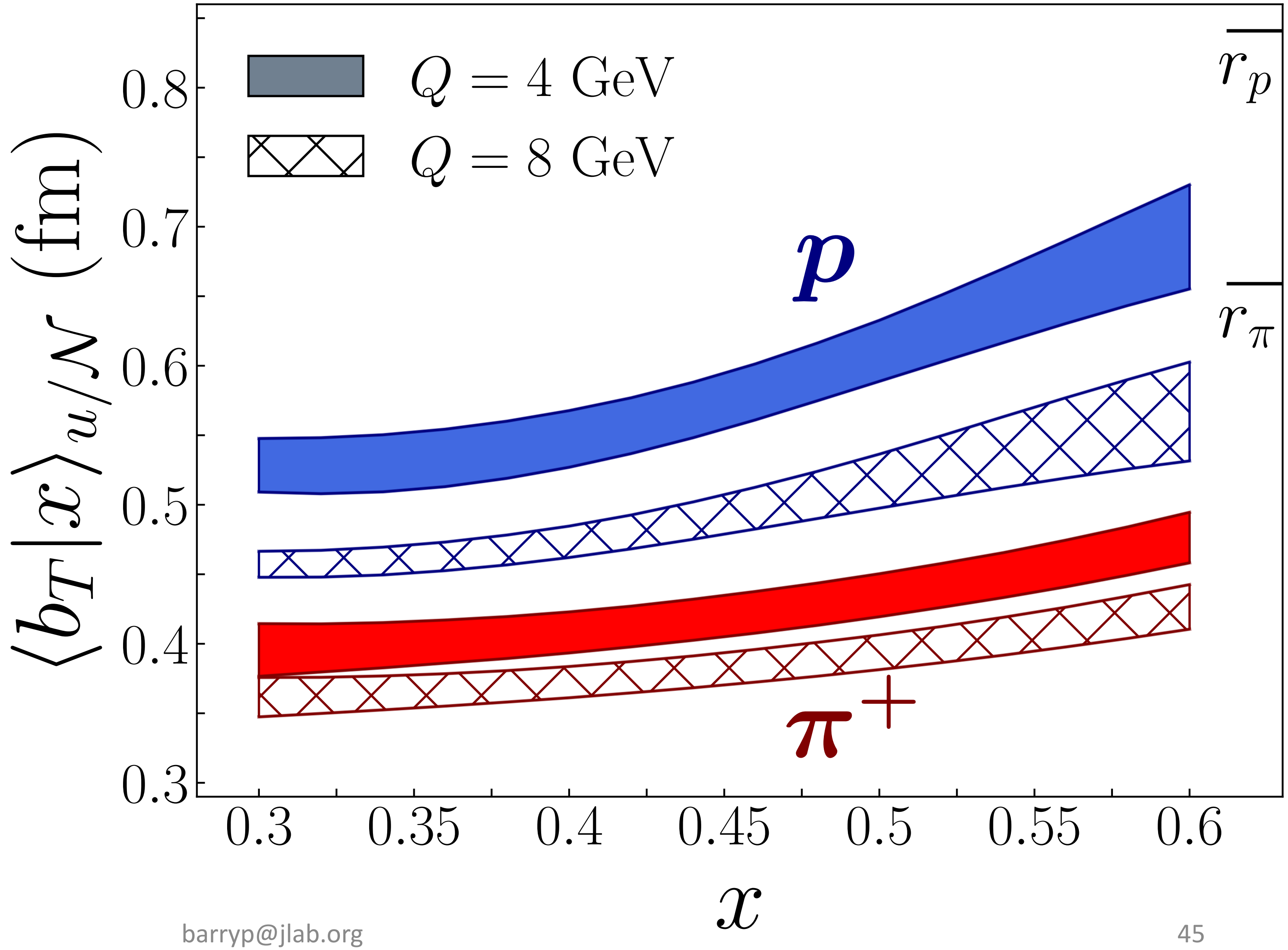
- The conditional expectation value of b_T for a given x

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

- Shows a measure of the transverse correlation in coordinate space of the quark in a hadron for a given x

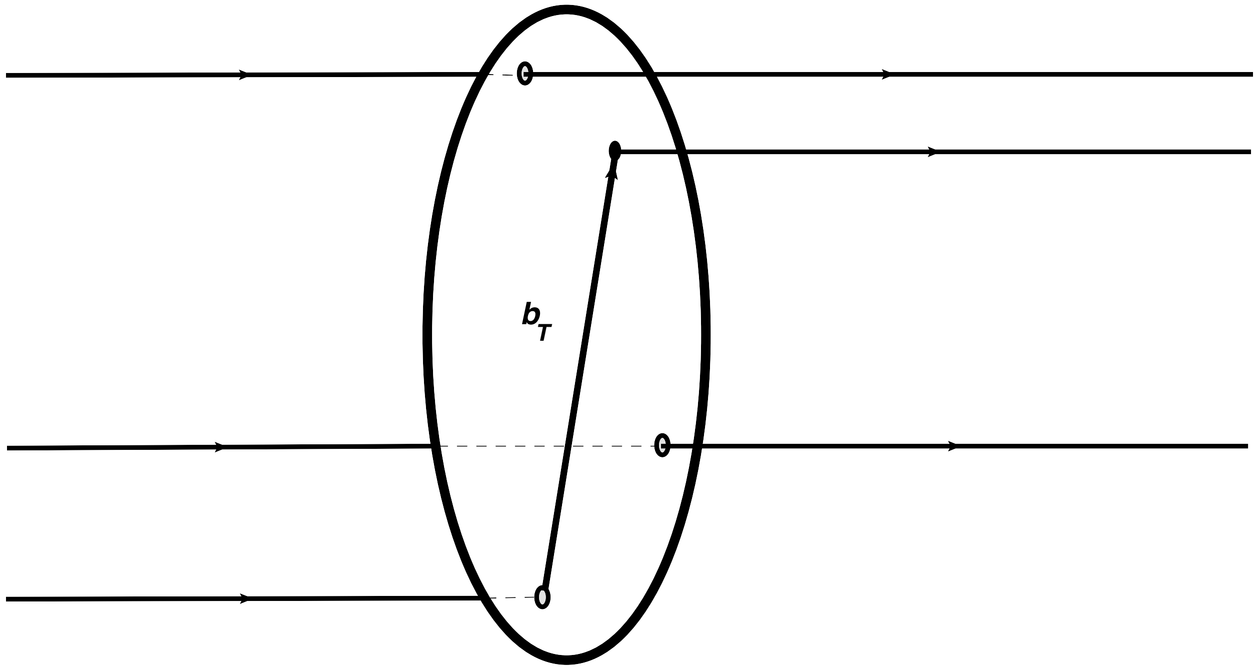
Resulting average b_T

- Pion's $\langle b_T|x\rangle$ is $5.3 - 7.5\sigma$ smaller than proton in this range
- Decreases as x decreases



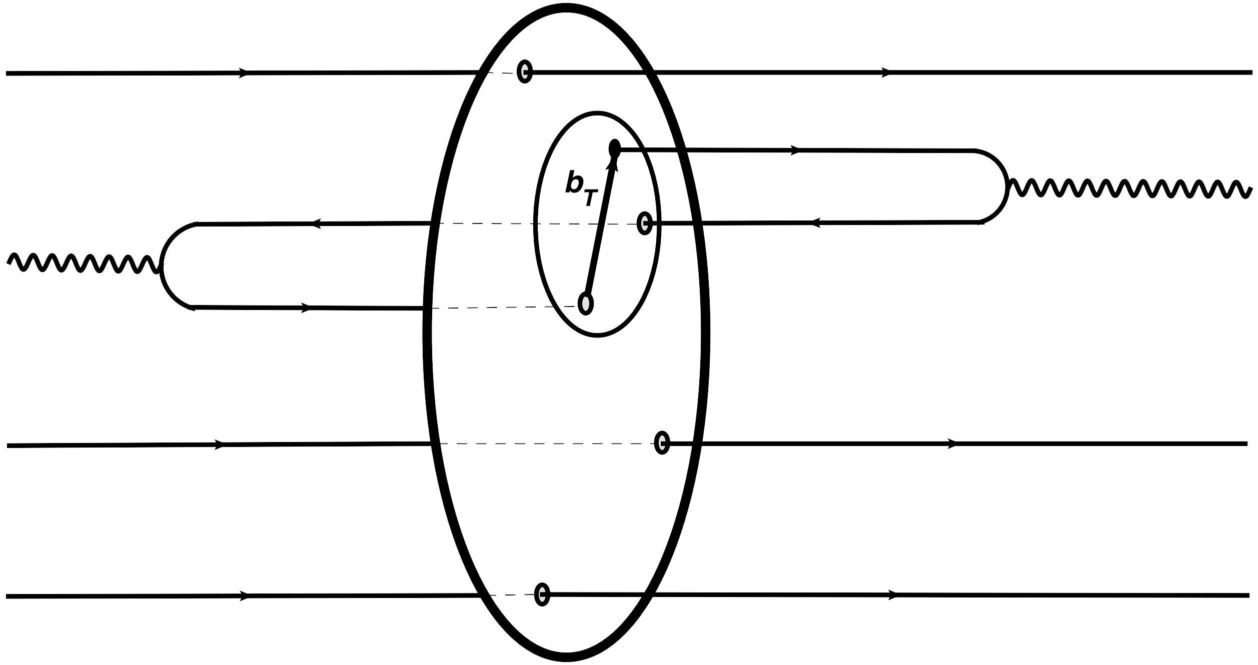
Possible explanation

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



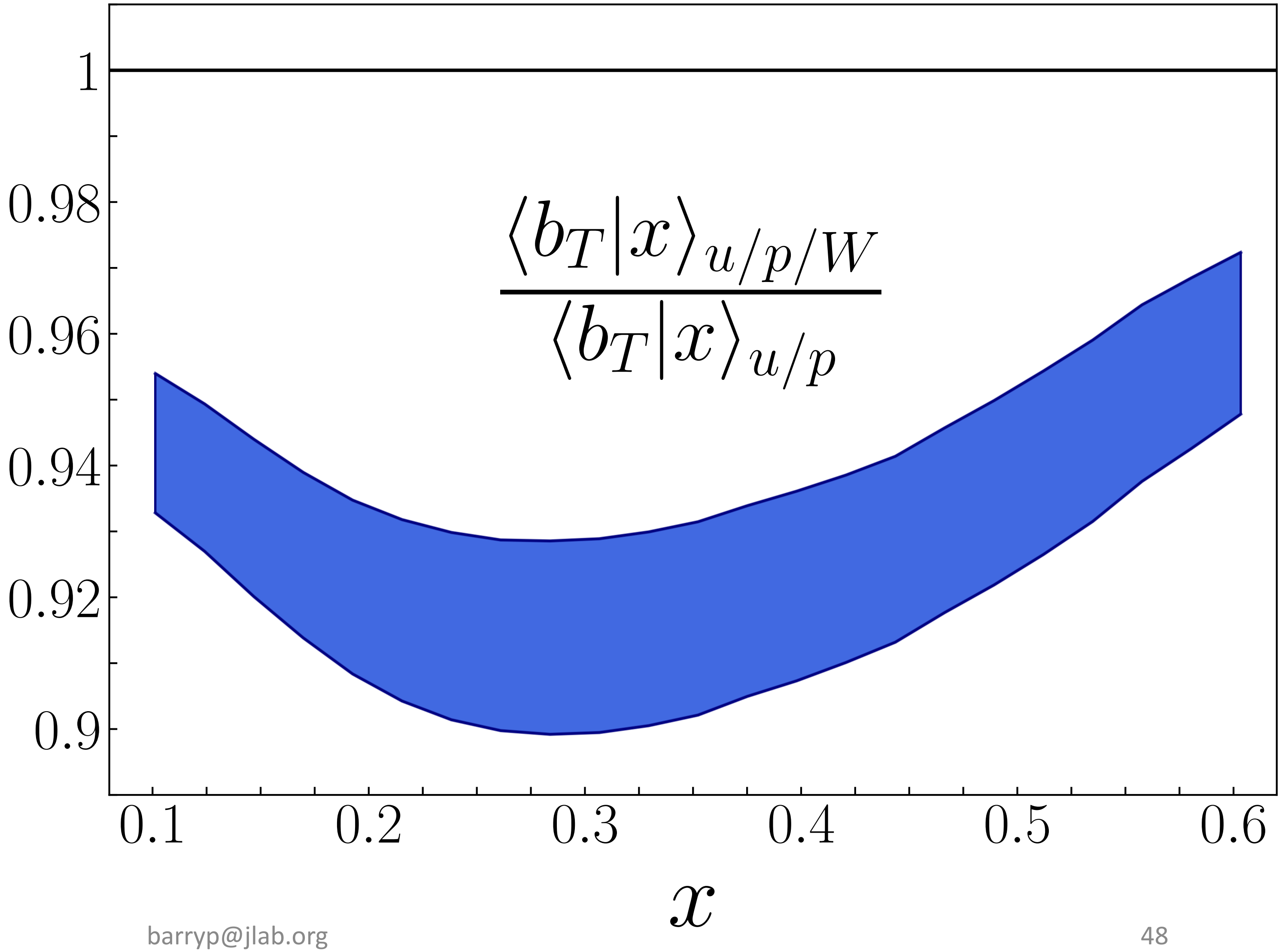
Possible explanation

- 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



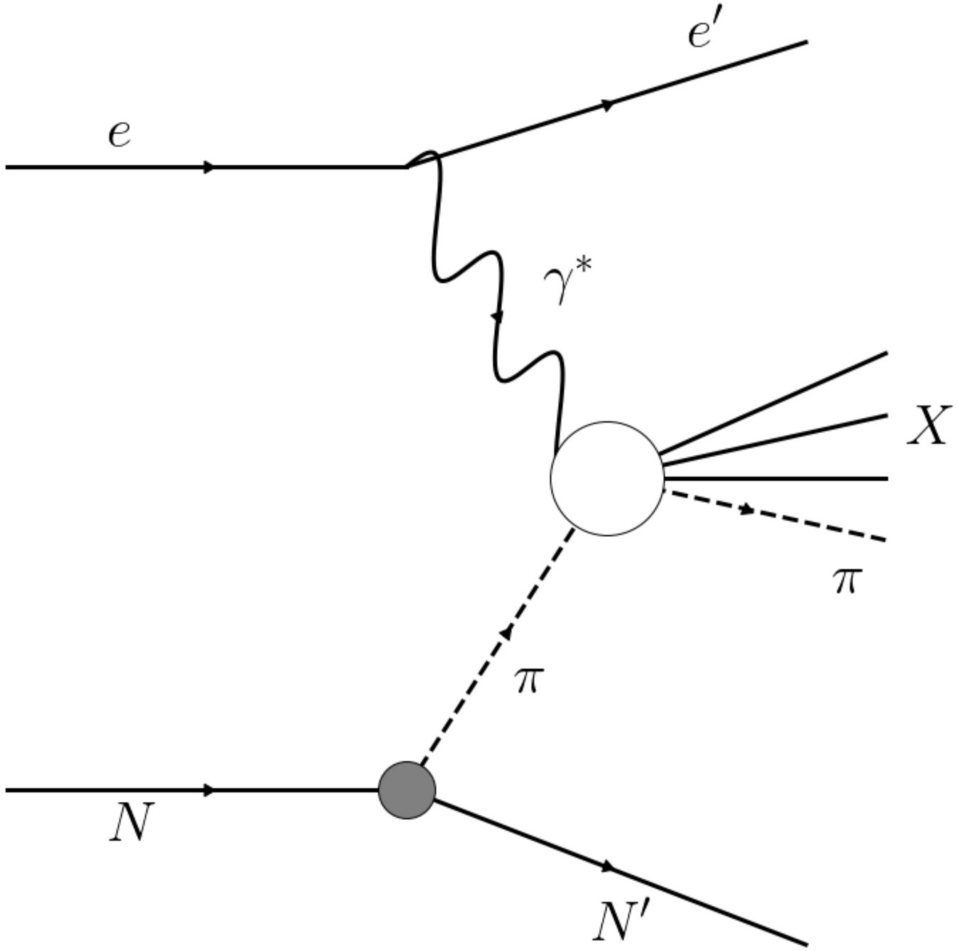
Outlook

- Future studies needed for theoretical explanations of these phenomena
- Important to study various hadronic systems to provide a more complete picture of strongly interacting quark-gluon systems emerging from QCD
- Lattice QCD can in principle calculate any hadronic state – look to kaons, rho mesons, etc.
- Future tagged experiments such as at EIC and JLab 22 GeV can provide measurements for neutrons, pions, and kaons

Future experiment – pion SIDIS

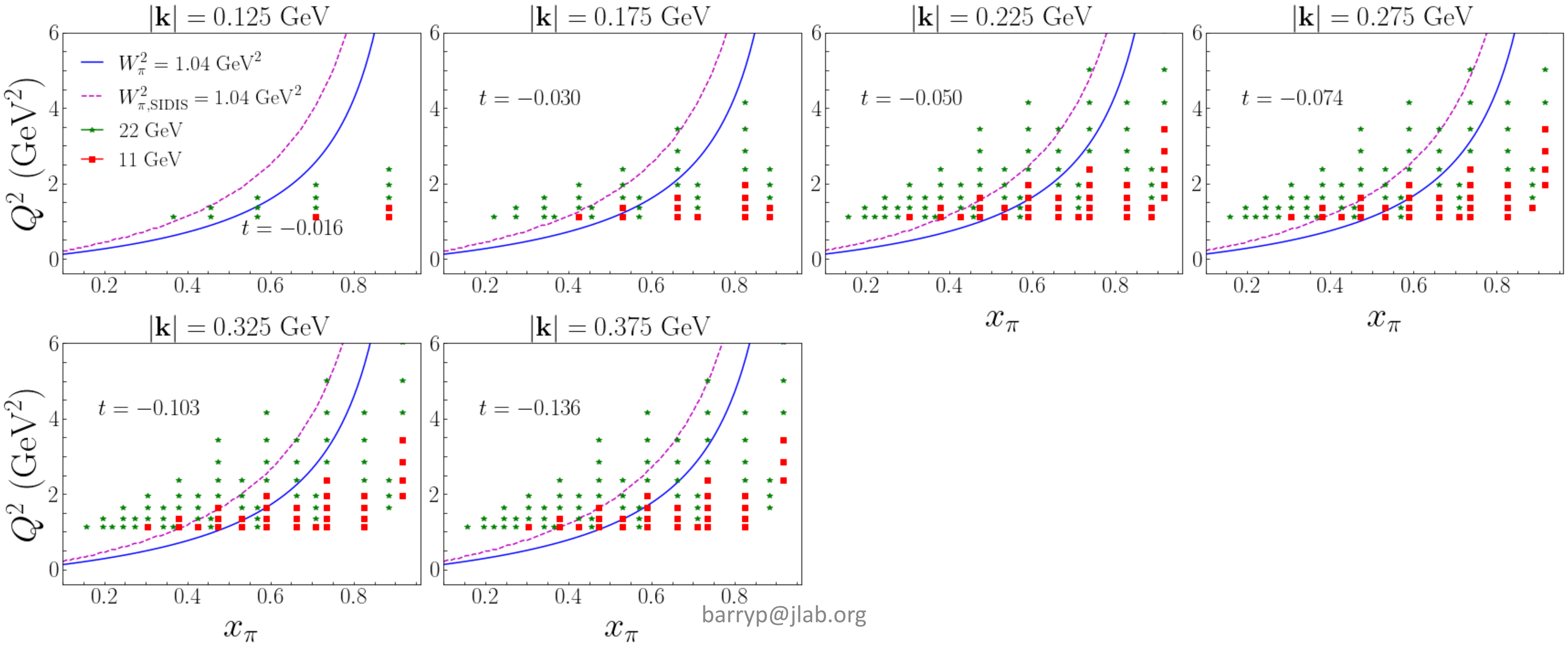
$$eN \to e'N'\pi X$$

- Measure an outgoing pion in the TDIS experiment
- Gives us another observable sensitive to pion TMDs
  - Needed for tests of universality



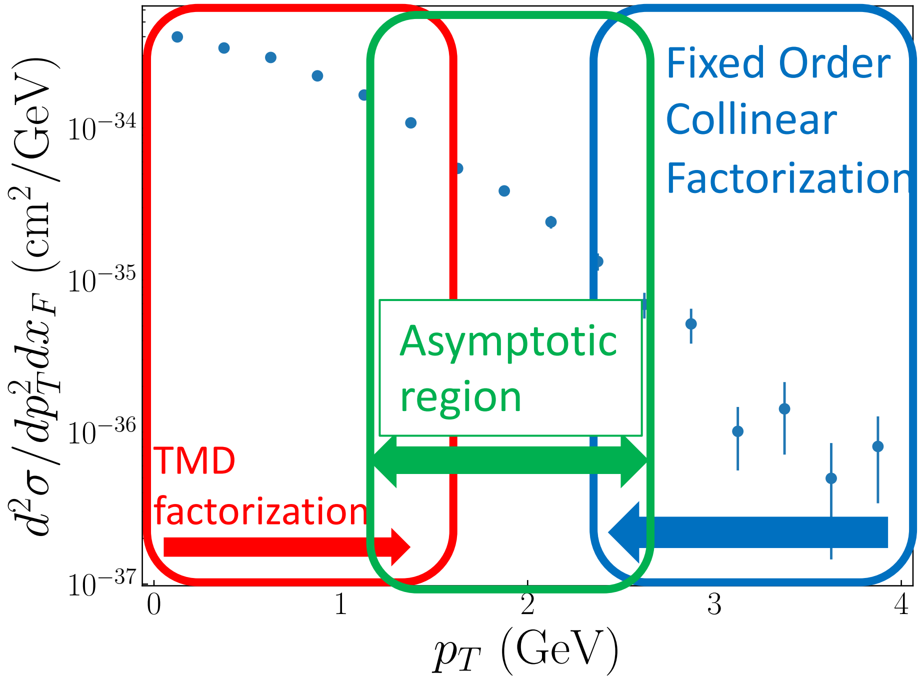
Kinematics with 11 GeV

- Still a cut on $W_\pi^2 = 1.04\ \text{GeV}^2$, but SIDIS requires more phase space
- Hardly anything available with $z = 0.2$, $P_{h,T} = 0.2$ GeV



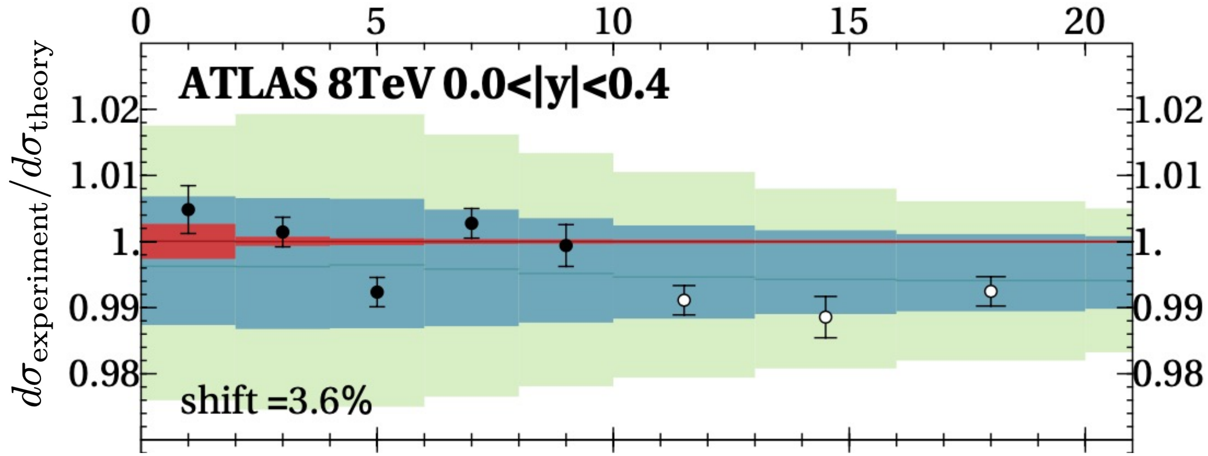
Future work – entire q_T range

- We have shown the ability to perform a global analysis separately of the large-q_T and small- q_T regions in the pion
- Tackle the challenging "asymptotic region"
- Can we combine these analyses in the π-sector?



Future work – High energy PDF+TMD

- From Bury, et al. arXiv:2201.07114



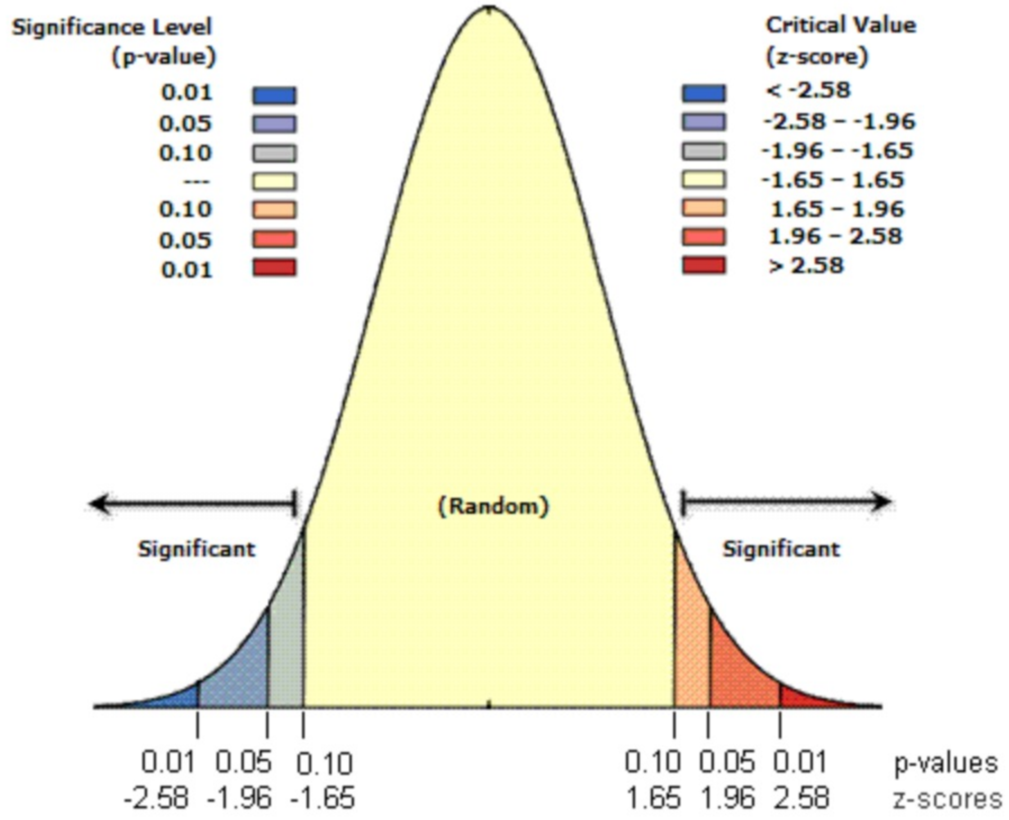
- The outer green band is the uncertainty from MSHT20 PDFs
- Red band is the statistical uncertainty from the data
- Important information about PDFs in this regime!

Backup

Z-scores

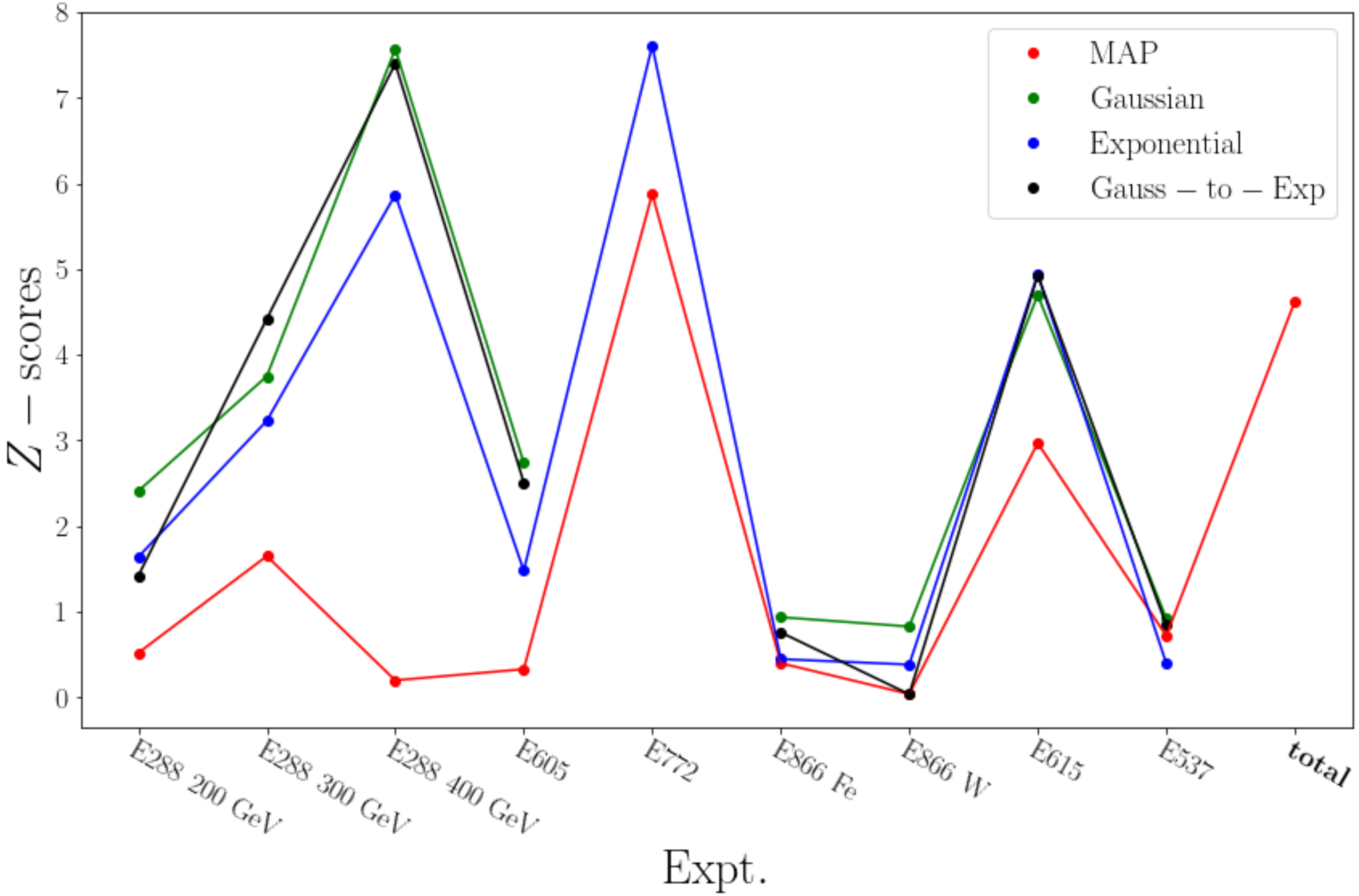
- A measure of significance with respect to the normal distribution
- Null hypothesis is the expected χ^2 distribution

$$Z = \Phi^{-1}(p) \equiv \sqrt{2}\,\mathrm{erf}^{-1}(2p - 1).$$



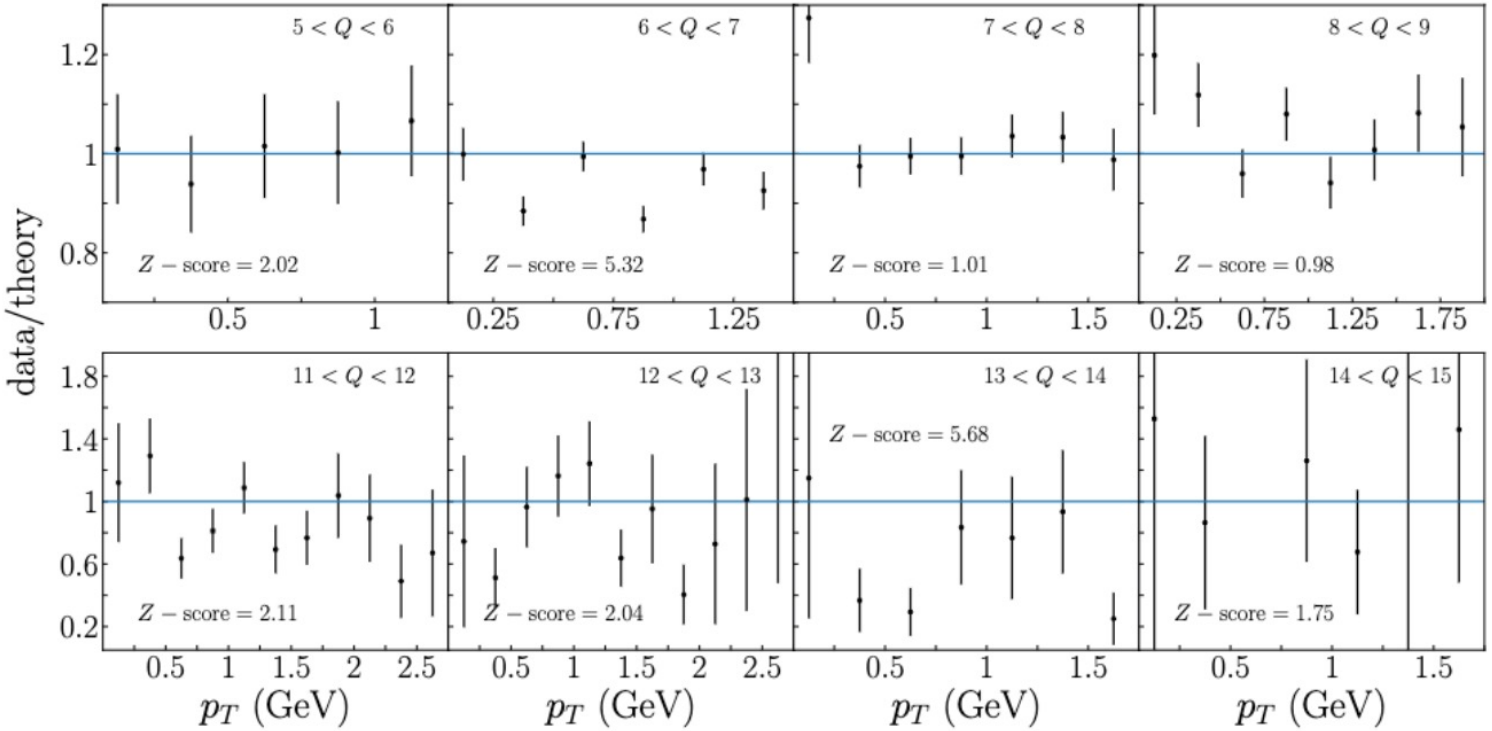
Z-scores

- Example of significance of the χ^2 values with respect to the expected χ^2 distribution



E772 data

- Let’s take a look at the data and theory agreement
- Data do not always follow the general trend and uncertainties appear underestimated



The Collins-Soper (CS) kernel

- From the simultaneous πA and pA analysis, which uses the same CS kernel, we compare with the lattice-generated data