Simultaneous extraction of collinear and transverse momentum dependent parton densities using Drell-Yan data

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TMD Collaboration Meeting, Santa Fe, June 16th, 2022

Motivation

- QCD 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

Complicated Inverse Problem

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

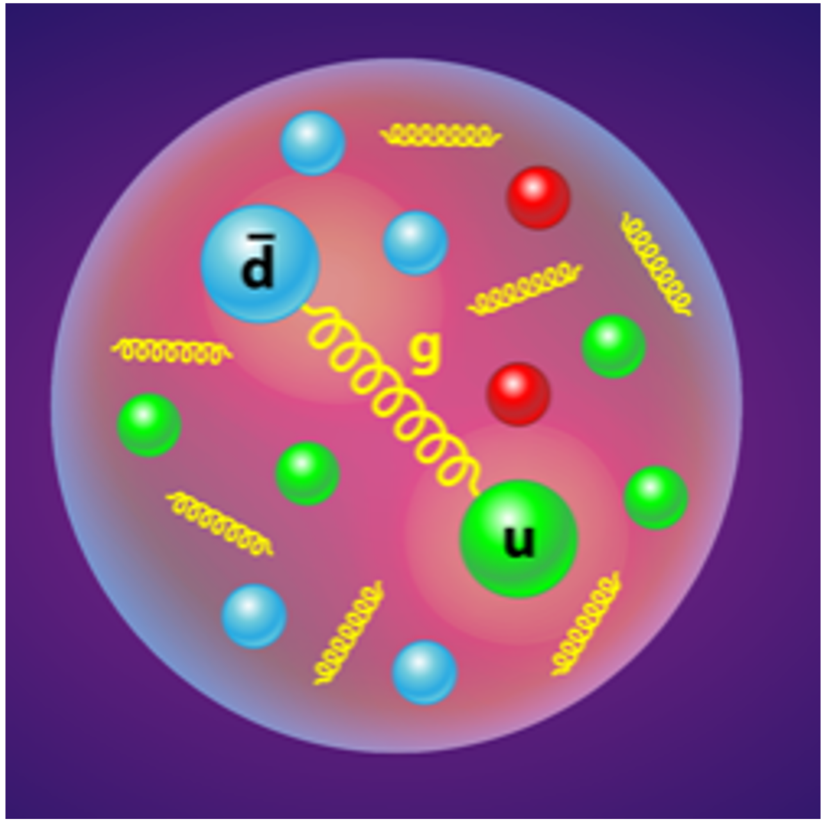
$$\frac{d\sigma}{d\Omega} \propto \mathcal{H} \otimes f = \int_x^1 \frac{d\xi}{\xi} \mathcal{H}\left(\frac{x}{\xi}\right) f(\xi)$$

- Parametrize the non-perturbative objects and perform global fit

Pions

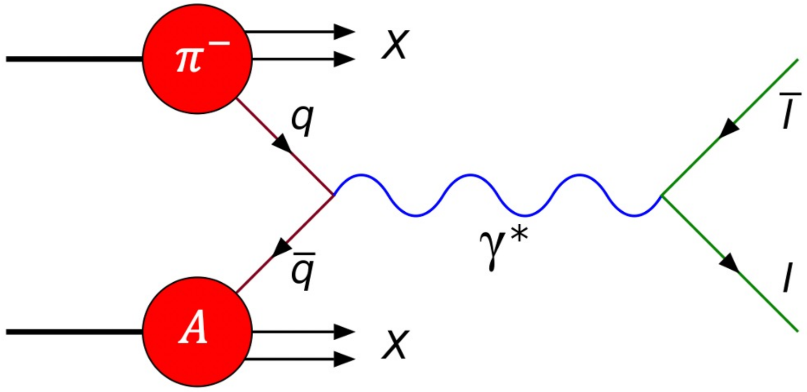
- Pion presents itself as a dichotomy

1. It is the Goldstone boson associated with spontaneous symmetry breaking of chiral $SU(2)_L \times SU(2)_R$ symmetry
2. Made up of quark and antiquark constituents

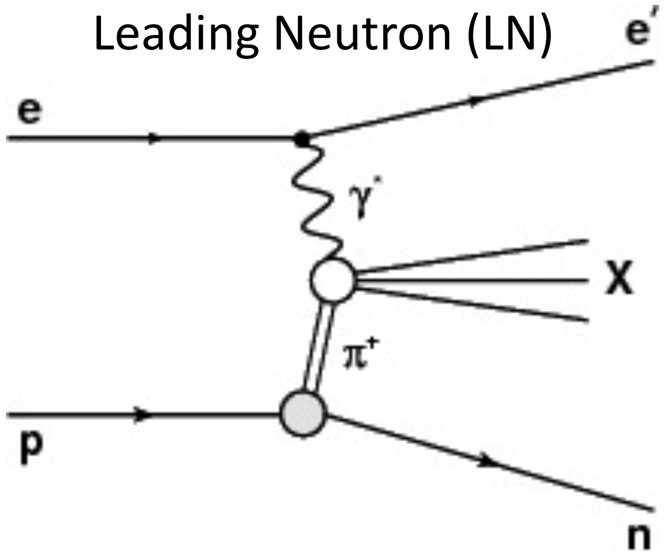


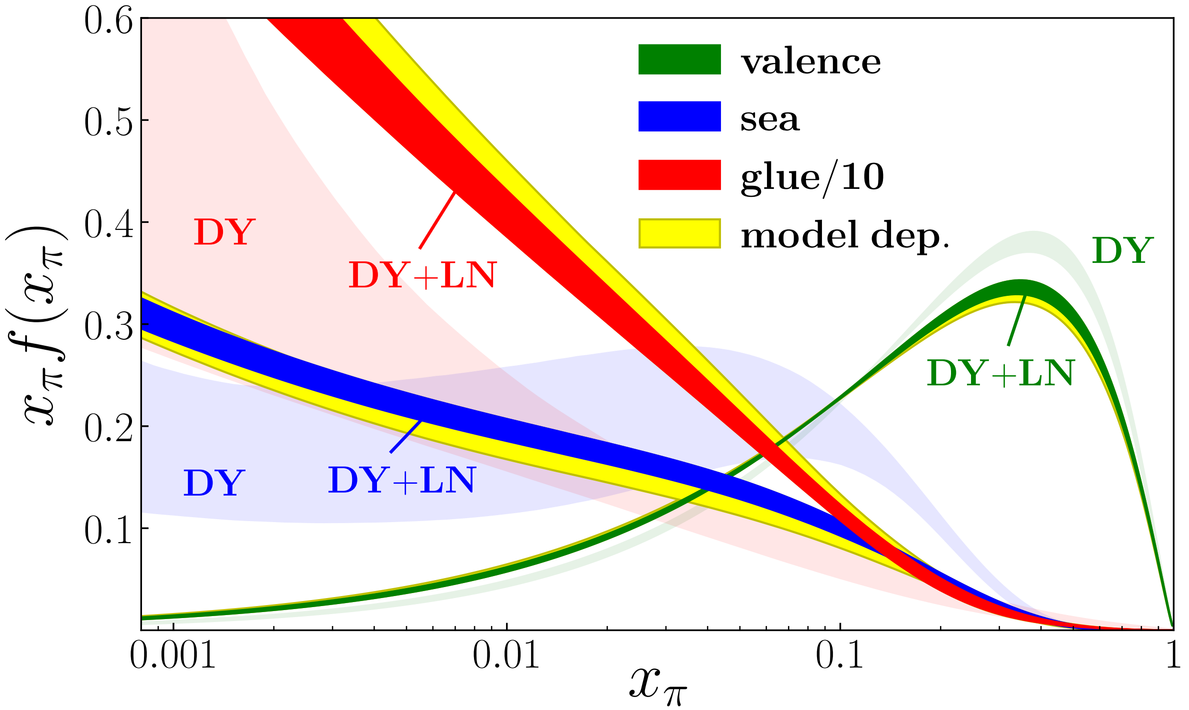
Experiments to Probe Pion Structure

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]

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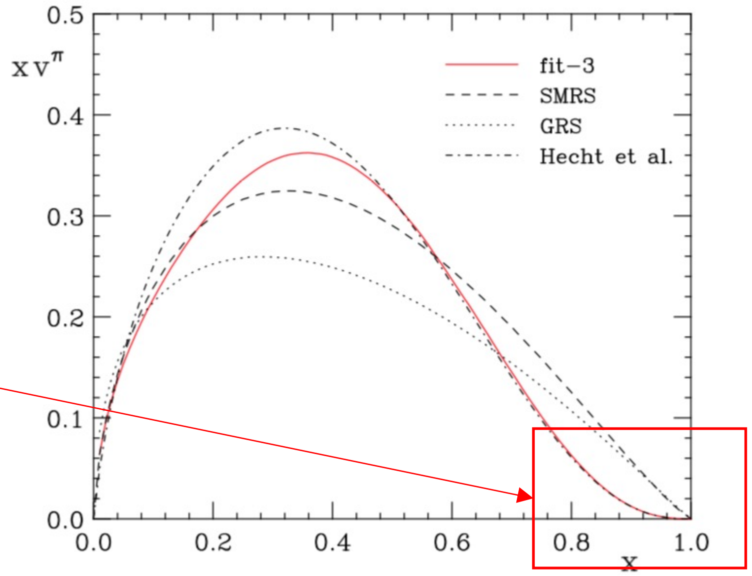
Large-x_π behavior

- Longstanding theoretical debates on $q_v(x) \propto (1-x)^\beta$ if $\beta = 1$ or $\beta = 2$

<u>Phenomenologically</u>

- Fixed order analyses find $\beta \approx 1$
- Aicher, Schaefer Vogelsang (ASV) found $\beta = 2$ with threshold resummation



ASV valence PDF

Phys. Rev. Lett. **105**, 114023 (2011).

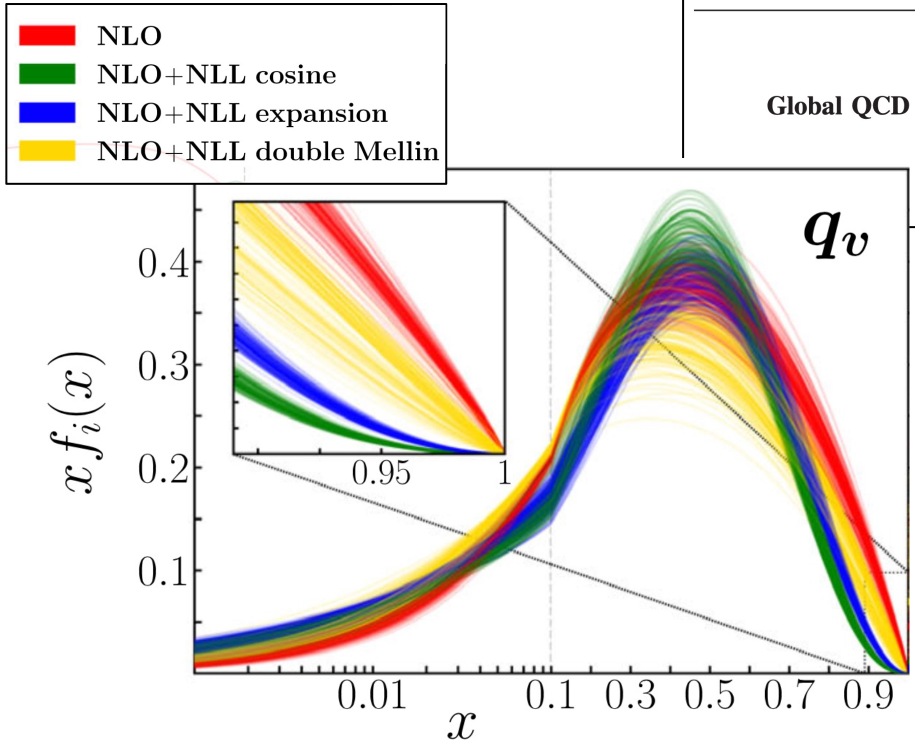
JAM analysis with threshold resummation

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

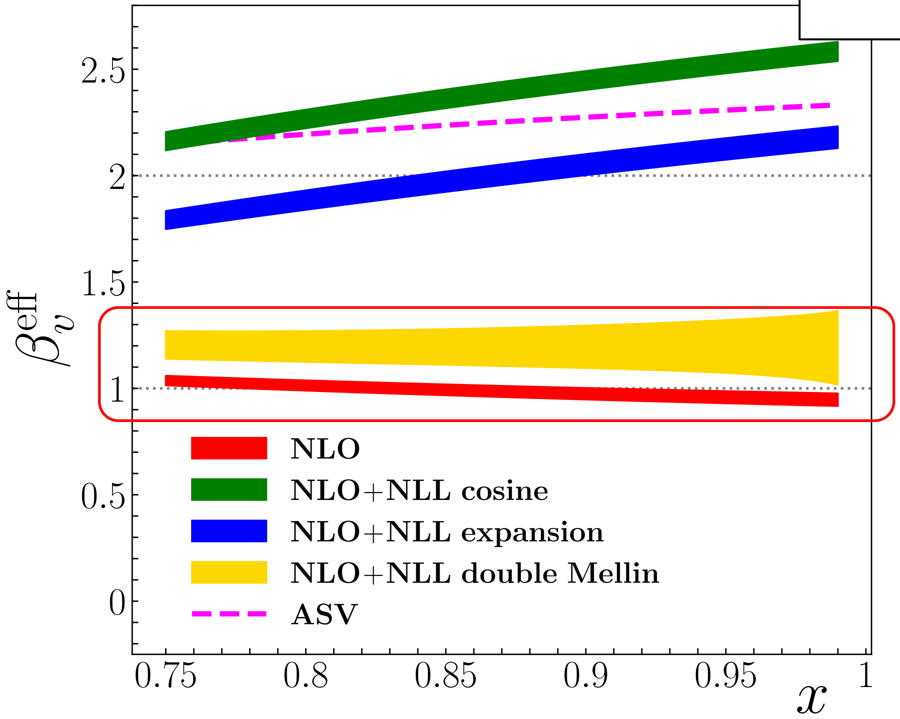
Global QCD Analysis of Pion Parton Distributions with Threshold Resummation

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

(JAM Collaboration)



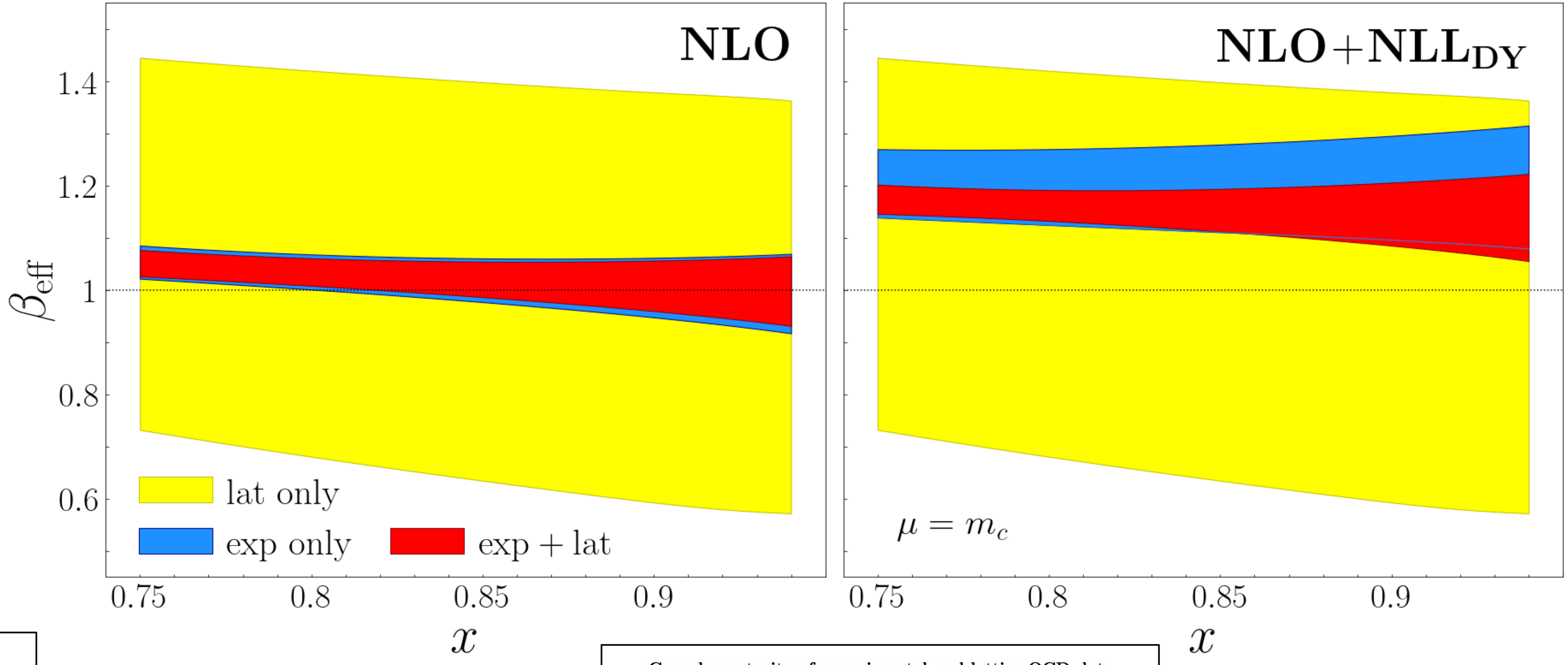
$$\beta_{\rm eff}(x,\mu) = \frac{\partial \log |q_v(x,\mu)|}{\partial \log(1-x)}$$



- Highly dependent on perturbative approach
- NLO and NLO+NLL double Mellin methods better on theoretical grounds

Inclusion of lattice QCD data

Including both experimental data and the reduced Ioffe time pseudo-distributions



Calculations from QCD do not predict $\beta_{eff} = 2$

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]

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[2] *Physics Department, Columbia University, New York City, New York 10027, USA*
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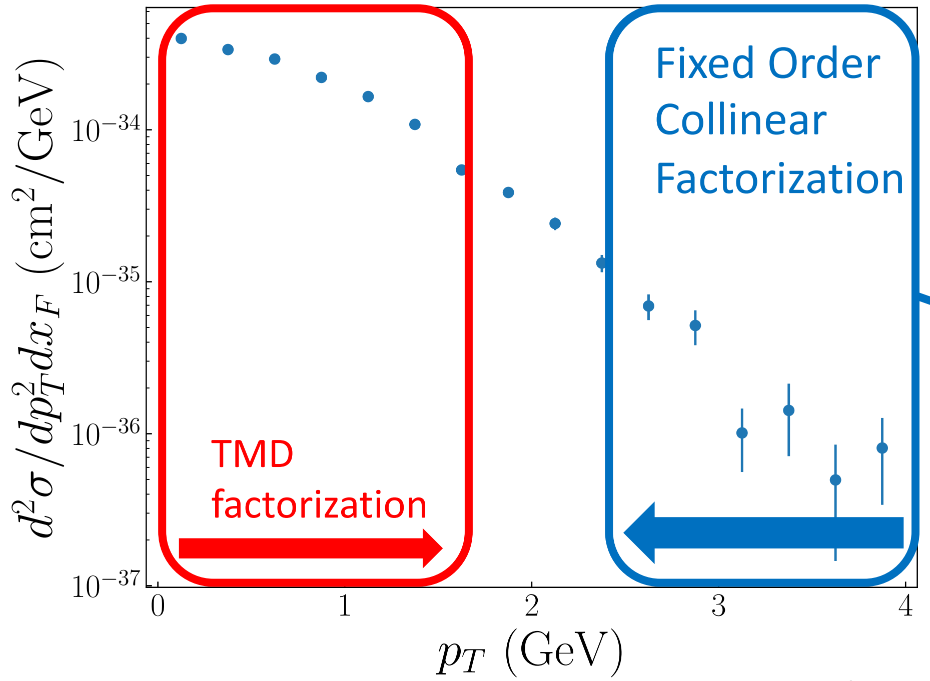
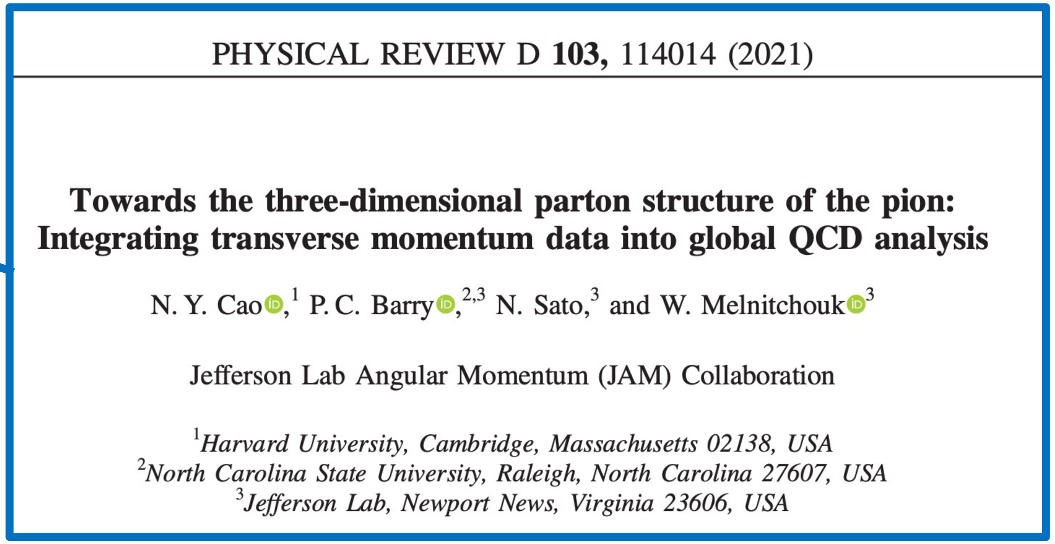
Jefferson Lab Angular Momentum (JAM) and HadStruc Collaborations

Recently accepted to PRD!

What about the transverse direction?

- The E615 π-induced fixed-target DY experiment measured the transverse momentum spectrum of the $\mu^+\mu^-$
- JAM was able to fit the large-q_T through collinear factorization





PHYSICAL REVIEW D **103,** 114014 (2021)

Towards the three-dimensional parton structure of the pion: Integrating transverse momentum data into global QCD analysis

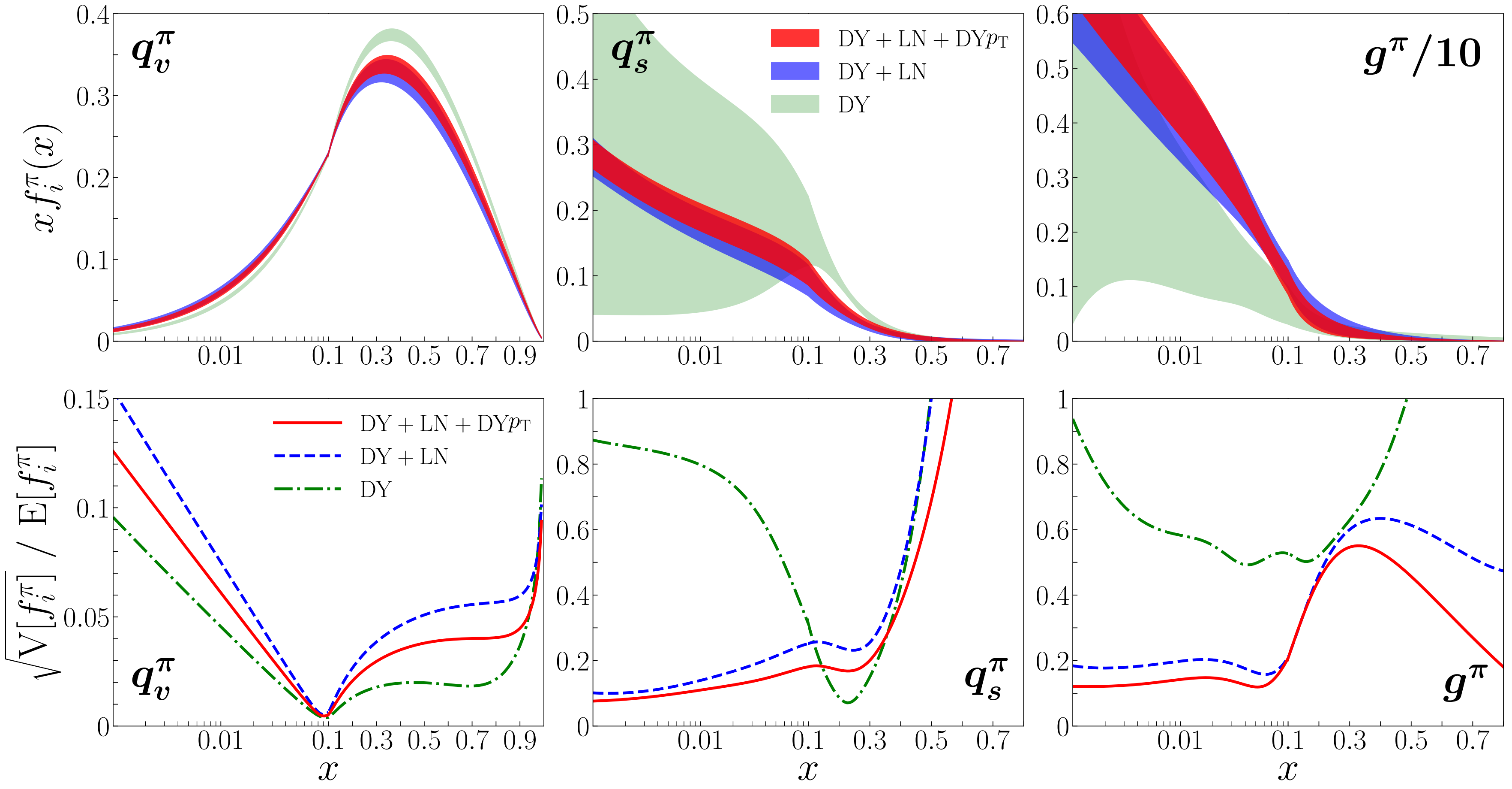
N. Y. Cao,[1] P. C. Barry,[2,3] N. Sato,[3] and W. Melnitchouk[3]

Jefferson Lab Angular Momentum (JAM) Collaboration

[1]*Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*North Carolina State University, Raleigh, North Carolina 27607, USA*
[3]*Jefferson Lab, Newport News, Virginia 23606, USA*

Effects of Each Dataset

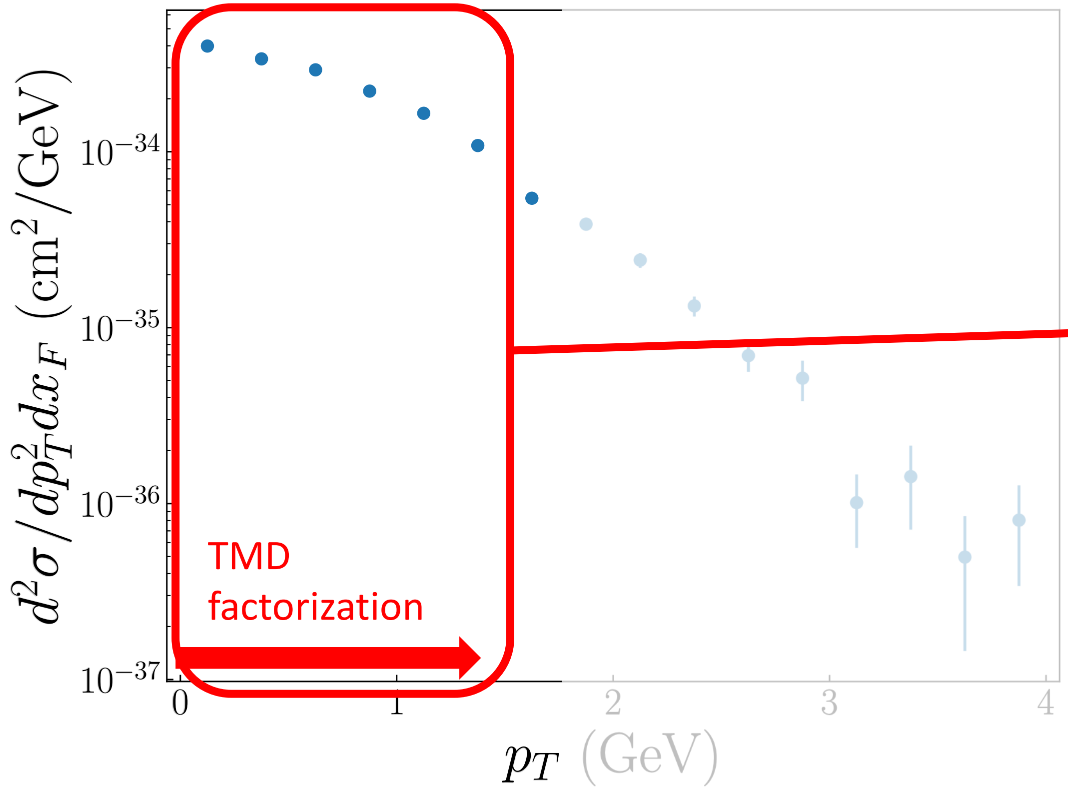
- Not much impact from the transverse-momentum dependent DY data
- Data are quite noisy statistically



Main Takeaways

- Despite the inclusion of the new dataset, the PDFs are not different from those extracted from DY and LN data
- Slight reduction in the uncertainties of the gluon at large x_π
- In describing the p_T-dependent DY data, the proper scale for the PDFs is $\mu = p_T/2$

What about the small-q_T?



- These data are much more precise
- Can they tell us anything about parton distributions?
- However, also sensitive to the TMDPDFs
- Vladimirov (JHEP **10**, 090 (2019)) was able to describe this region with π TMDPDFs

Factorization for low-q_T Drell-Yan

- Again, a hard part with two functions that describe structure of beam and target
- So called "W"-term

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

TMD factorization in Drell-Yan

- In small-q_{T} region, use the Collins-Soper-Sterman (CSS) formalism and b_* prescription

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

$$\mu_{b^*} = C_1/b_*$$

$$\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2\,\mathrm{d}y\,\mathrm{d}q_{\mathrm{T}}^2} = \frac{4\pi^2\alpha^2}{9Q^2 s} \sum_{j,j_A,j_B} H_{j\bar{j}}^{\mathrm{DY}}(Q,\mu_Q,a_s(\mu_Q)) \int \frac{\mathrm{d}^2\boldsymbol{b}_{\mathrm{T}}}{(2\pi)^2} e^{i\boldsymbol{q}_{\mathrm{T}}\cdot\boldsymbol{b}_{\mathrm{T}}} \\
\times e^{-g_{j/A}(x_A,b_{\mathrm{T}};b_{\max})} \int_{x_A}^{1} \frac{\mathrm{d}\xi_A}{\xi_A} f_{j_A/A}(\xi_A;\mu_{b_*})\, \tilde{C}_{j/j_A}^{\mathrm{PDF}}\left(\frac{x_A}{\xi_A}, b_*; \mu_{b_*}^2, \mu_{b_*}, a_s(\mu_{b_*})\right) \\
\times e^{-g_{\bar{j}/B}(x_B,b_{\mathrm{T}};b_{\max})} \int_{x_B}^{1} \frac{\mathrm{d}\xi_B}{\xi_B} f_{j_B/B}(\xi_B;\mu_{b_*})\, \tilde{C}_{\bar{j}/j_B}^{\mathrm{PDF}}\left(\frac{x_B}{\xi_B}, b_*; \mu_{b_*}^2, \mu_{b_*}, a_s(\mu_{b_*})\right) \\
\times \exp\left\{-g_K(b_{\mathrm{T}};b_{\max}) \ln\frac{Q^2}{Q_0^2} + \tilde{K}(b_*;\mu_{b_*}) \ln\frac{Q^2}{\mu_{b_*}^2} + \int_{\mu_{b_*}}^{\mu_Q} \frac{\mathrm{d}\mu'}{\mu'} \left[2\gamma_j(a_s(\mu')) - \ln\frac{Q^2}{(\mu')^2}\gamma_K(a_s(\mu'))\right]\right\}
\end{aligned}$$

TMD factorization in Drell-Yan

- In small-q_{T} region, use the Collins-Soper-Sterman (CSS) formalism and b_* prescription

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

$$\mu_{b^*} = C_1/b_*$$

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

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

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

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

Non-perturbative pieces

Perturbative pieces

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?

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

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

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

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

Non-perturbative pieces

Perturbative pieces

Strategy for simultaneous analysis

π-induced DY only for nuclear target – need a nuclear TMDPDF!

1. Perform single fit of TMDPDFs to available pA and πA data with $Q < 18$ GeV* to obtain the nuclear TMDPDFs
2. Perform the **first** Monte Carlo (MC) global QCD analysis on π PDFs and non-perturbative TMD functions

- We also introduce flavor dependence on the proton PDFs – u, d, and sea quarks
- The normalizations fitted are for the entire dataset – not individual bins

*Avoid Υ resonance in $9 < Q < 11$GeV

Strategy for simultaneous analysis

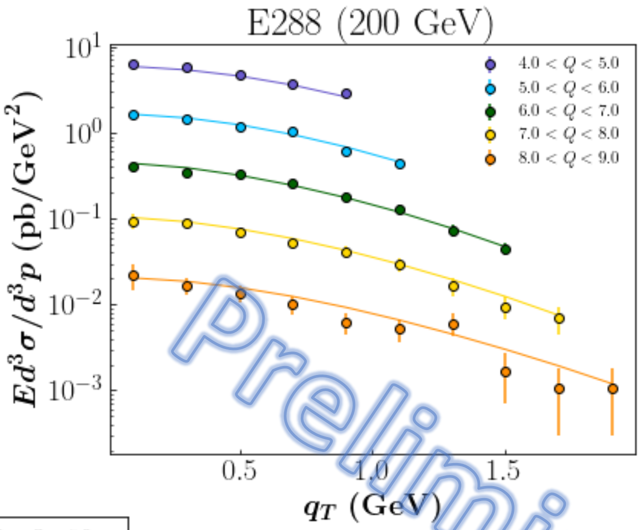
1. Perform single fit of TMDPDFs to available pA and πA data with $Q < 18$ GeV* to obtain the nuclear TMDPDFs
2. Perform the **first** Monte Carlo (MC) global QCD analysis on π PDFs and non-perturbative TMD functions

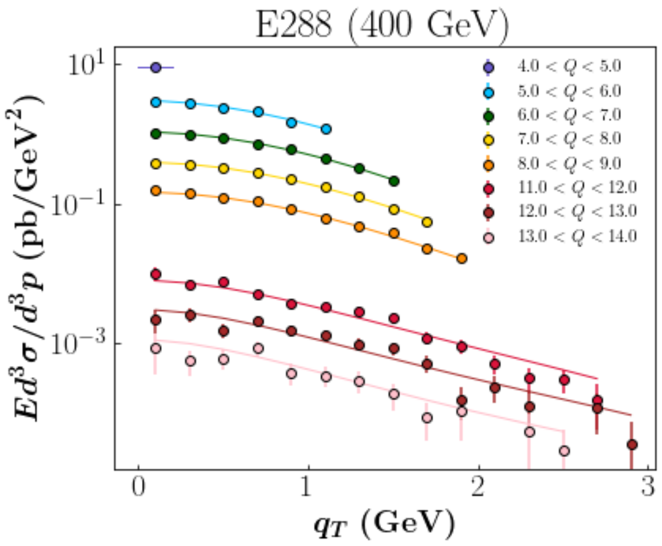
Process	Drell-Yan $\pi\, W \to \mu^+\mu^- X$	Leading neutron $ep \to e'n\, X$	q_T-dependent Drell-Yan $\pi\, W \to \mu^+\mu^- X$
Observable	$d^2\sigma/dx_F d\sqrt{\tau}$	$F_2^{\rm LN}, r = F_2^{\rm LN}/F_2^{\rm inc}$	$d^2\sigma/dx_F dq_T$
Experiment	E615, NA10	H1, ZEUS	E615, E537

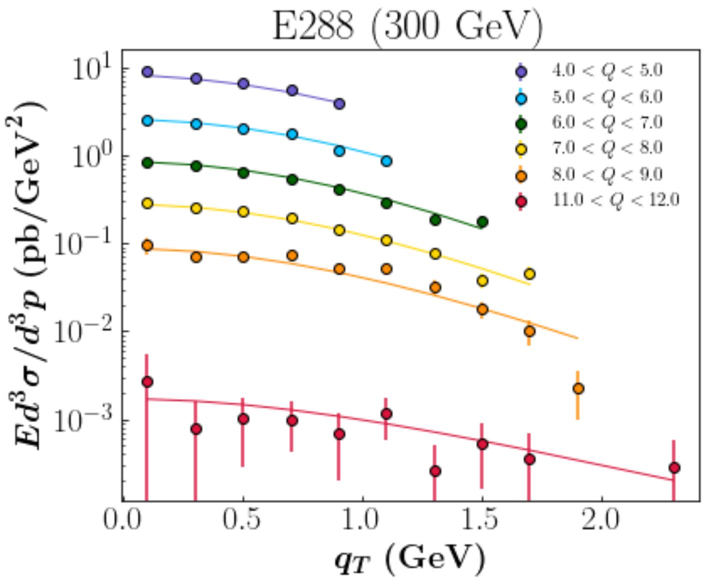
*Avoid Υ resonance in $9 < Q < 11$GeV

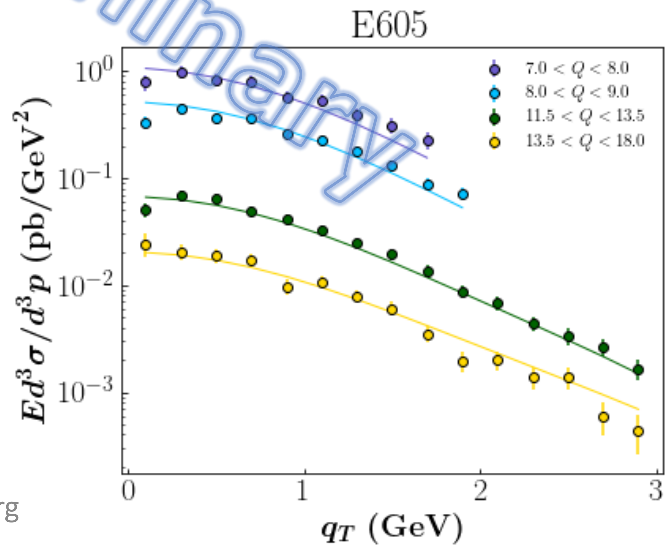
Description of pA data

- Extracted the TMDPDF of the proton using CT14nlo PDFs and EPPS16 nuclear PDFs



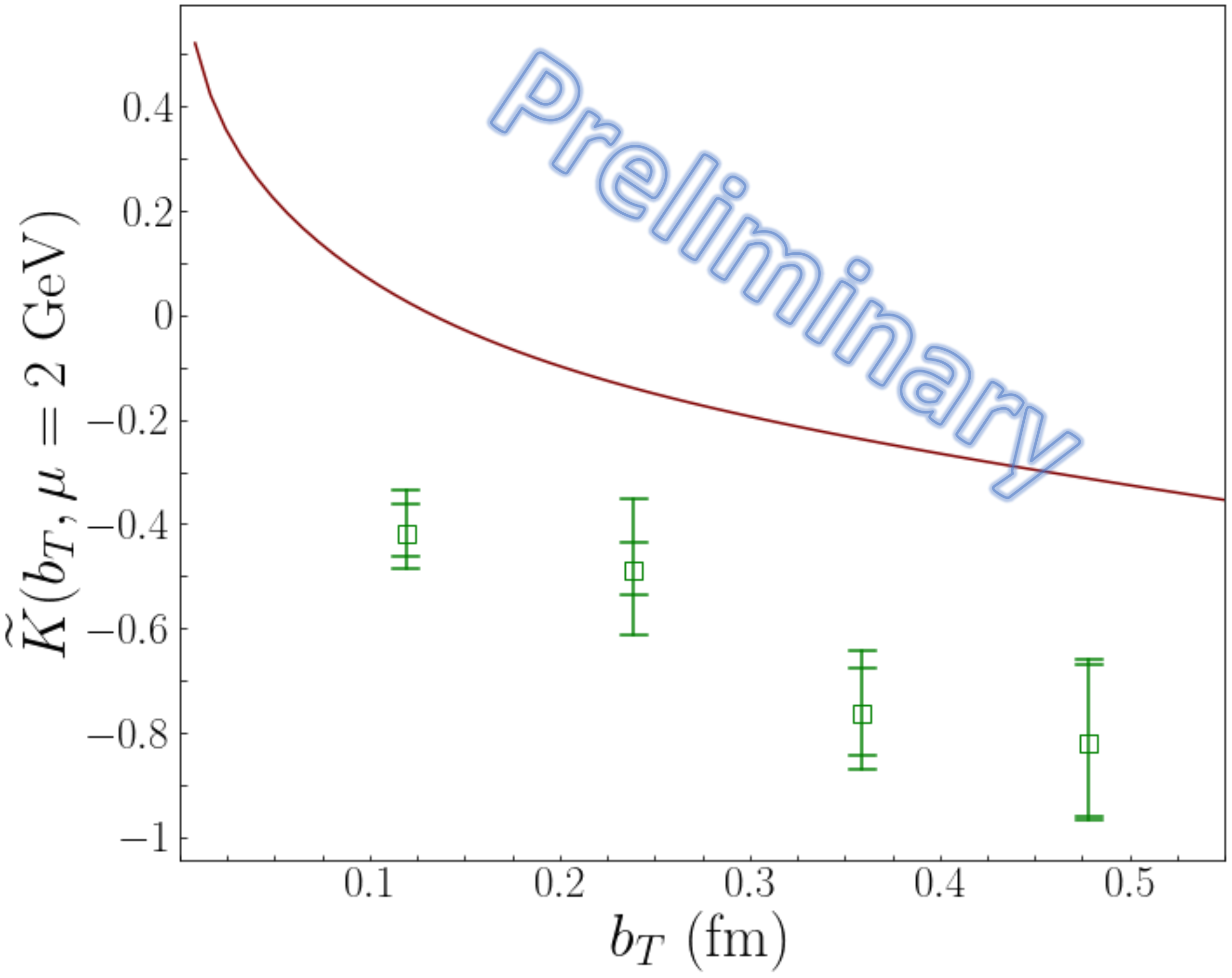






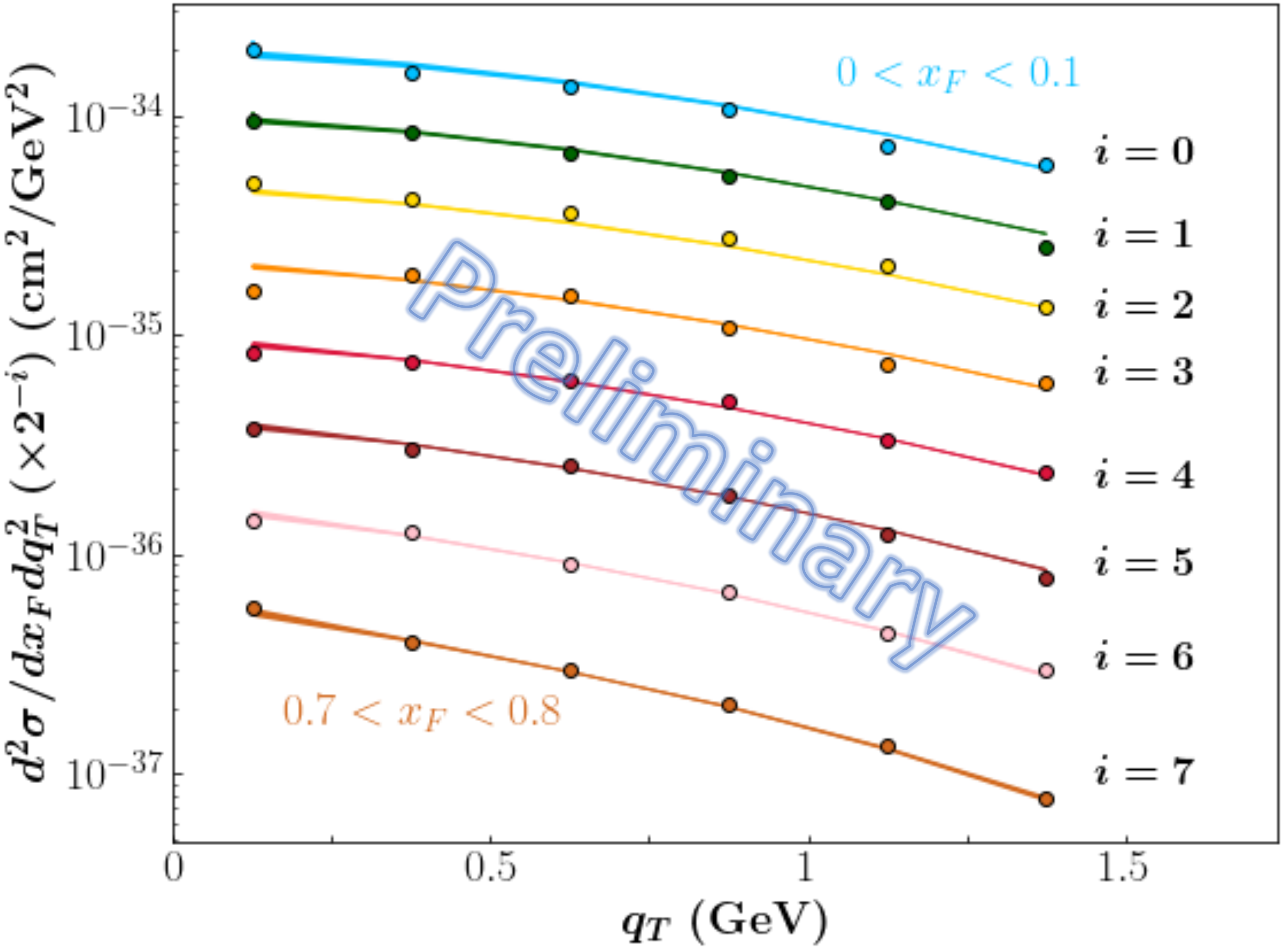
Two-hadron $\widetilde{K}$ extractions

- The Collins-Soper kernel is the most universal quantity in TMD physics
- No dependence on flavor, species, or type of TMD
- Extracted from single fit to both pA and πA data
- Green lattice points from Shanahan, et al., Phys. Rev. D **104**, 114502 (2021)



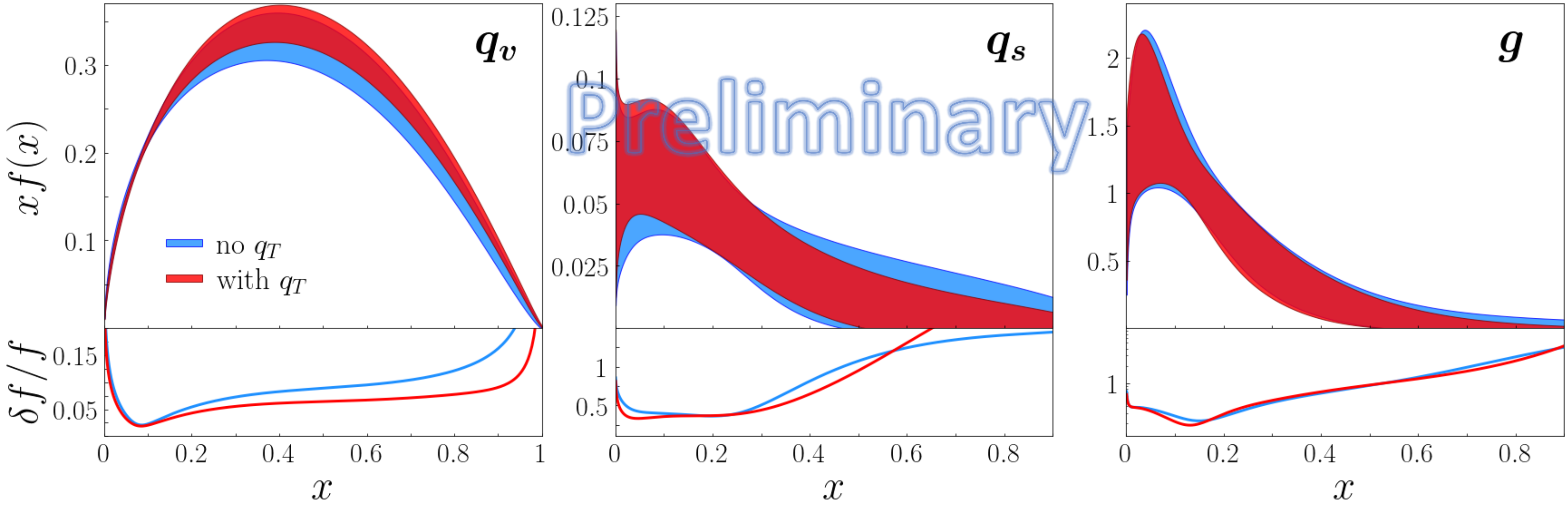
Description of πA data

- Well describe the E615 data in the (x_F, q_T) spectrum: $\chi^2/\text{npts} = 1.63$
- Can also describe rest of the experimental data: $\chi^2_{\text{tot}}/\text{npts} = 1.01$



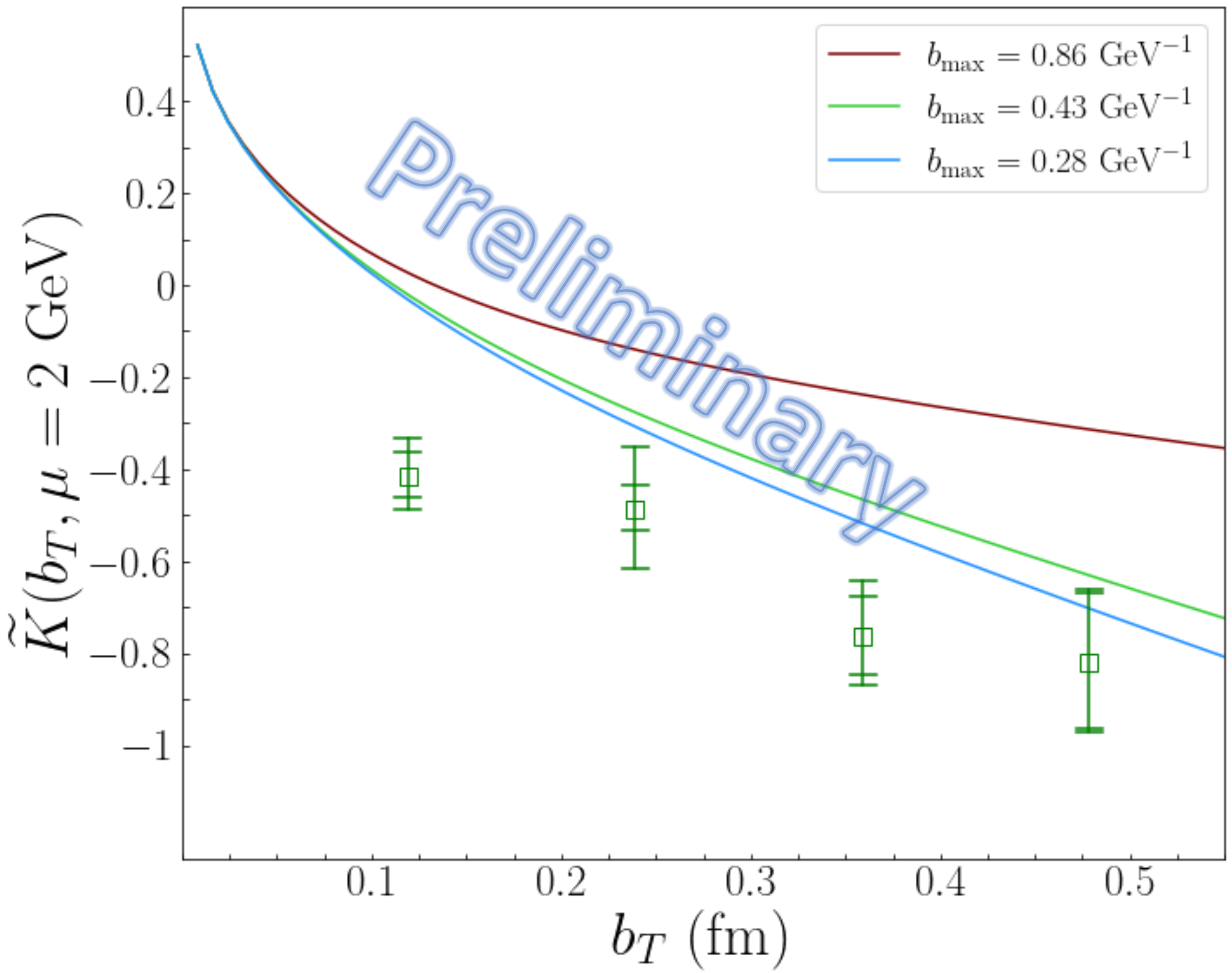
Impact on PDFs

- Slight reduction in uncertainties
- Overall very consistent with totally collinear analysis



Role of $b_{\max}$

- In principle, observables should be independent of $b_{\max}$
- Describes the transition between perturbative and non-perturbative structure
- Best fit with $b_{\max} = 0.86$
- Smaller $b_{\max}$, larger normalization difference in data



Next steps

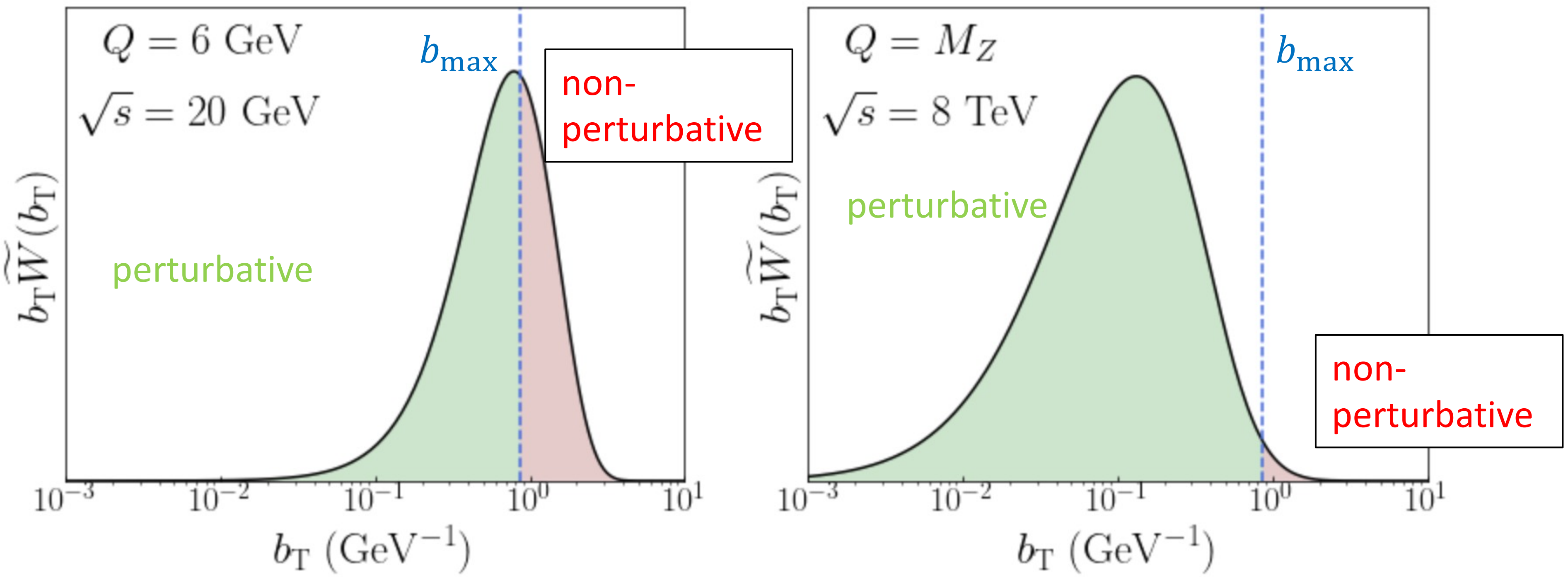
π-induced DY only for nuclear target – need a nuclear TMDPDF!

1. Perform single fit of TMDPDFs to available pA and πA data with $Q < 18$ GeV* to obtain the nuclear TMDPDFs
2. Perform the **first** Monte Carlo (MC) global QCD analysis on π PDFs and non-perturbative TMD functions
3. Simultaneous MC fit πA **and** pA data to obtain CS kernel

*Avoid Υ resonance in $9 < Q < 11$GeV

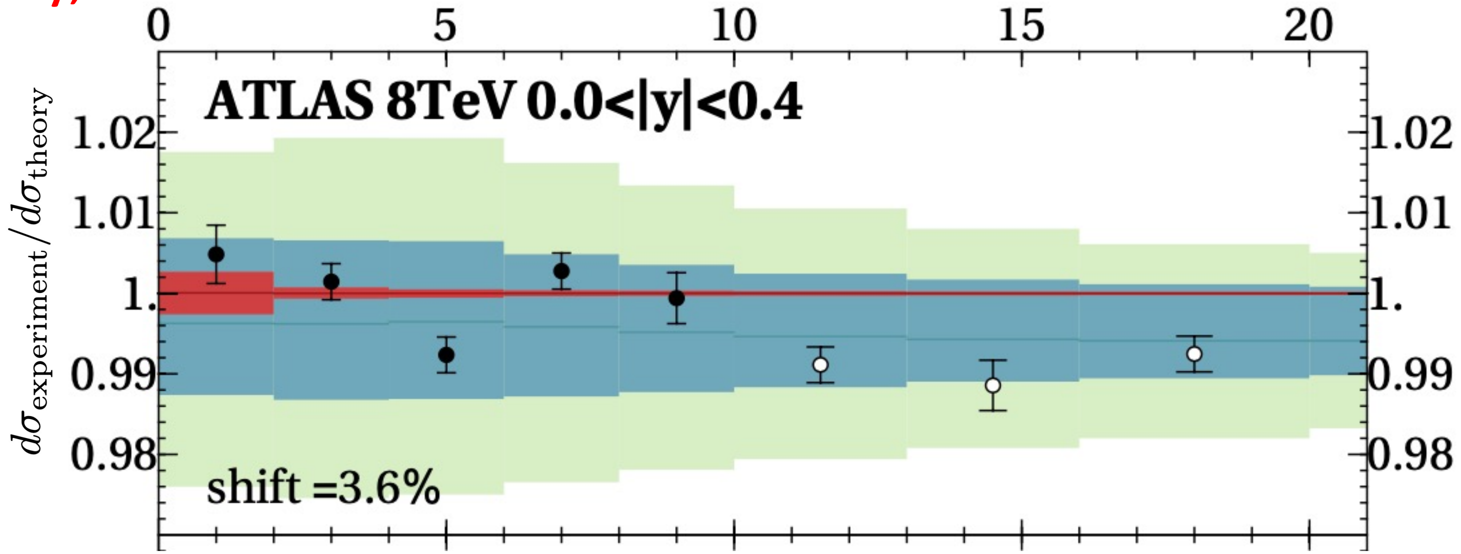
Extensions

- While fixed-target DY may not greatly probe the collinear PDFs, collider data at e.g. the LHC may have greater constraints



Can LHC constrain PDFs?

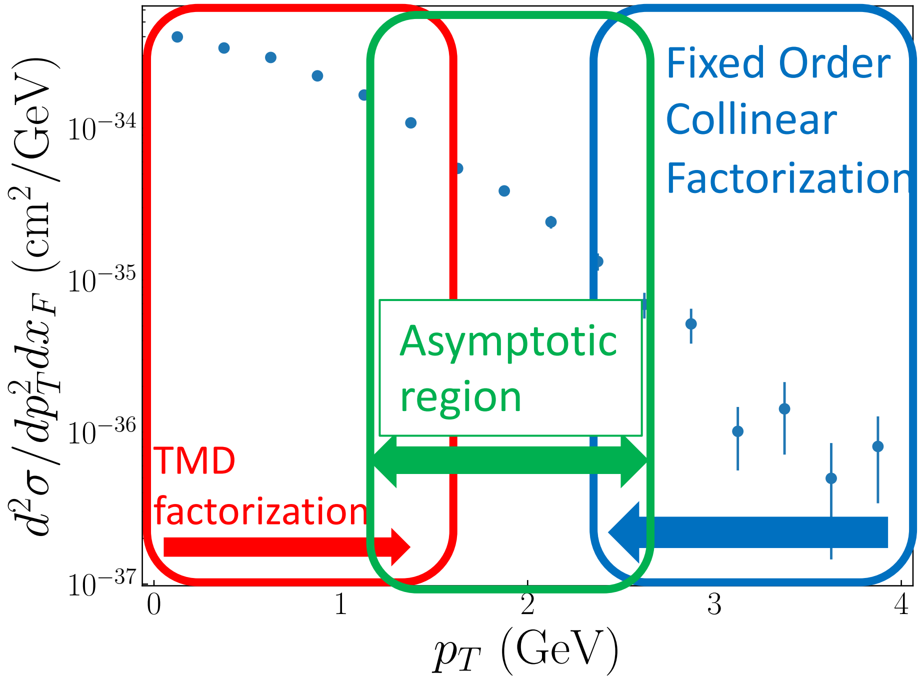
- From Bury, et al. arXiv:2201.07114



- The outer green band is the uncertainty from MSHT20 PDFs
- Red band is the statistical uncertainty from the data
- Largest uncertainty comes from PDF itself!

What about the entire q_T-spectrum?

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



Conclusions

- We have made strides in collinear pion PDF phenomenology by introducing available datasets and theoretical advances
- Inclusion of q_T-dependent DY data is consistent with collinear data
- Extend framework to LHC data and nucleon PDFs

Backup Slides

Perturbative orders

- We use NLO+N^{2}LL perturbative accuracy

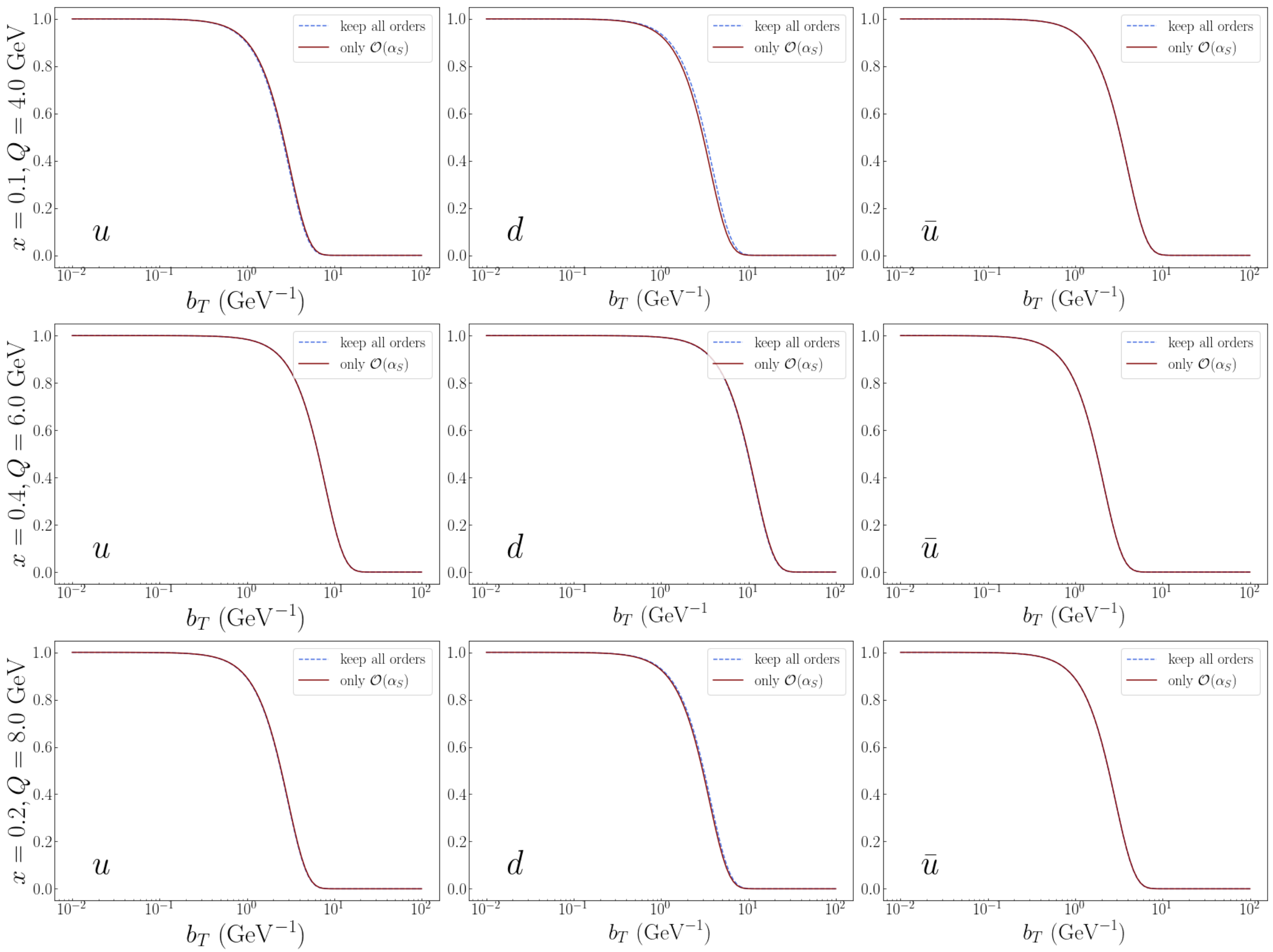
Function	Order
H	$\mathcal{O}(\alpha_S)$
$\tilde{C}^{\text{PDF}}$	$\mathcal{O}(\alpha_S)$
K and γ_F	$\mathcal{O}(\alpha_S^2)$
γ_K	$\mathcal{O}(\alpha_S^3)$

- But where are expansions appropriate?
- Consider the fixed order pieces:
  - Can multiply out each contribution
  - Can truncate to only accuracy by each piece

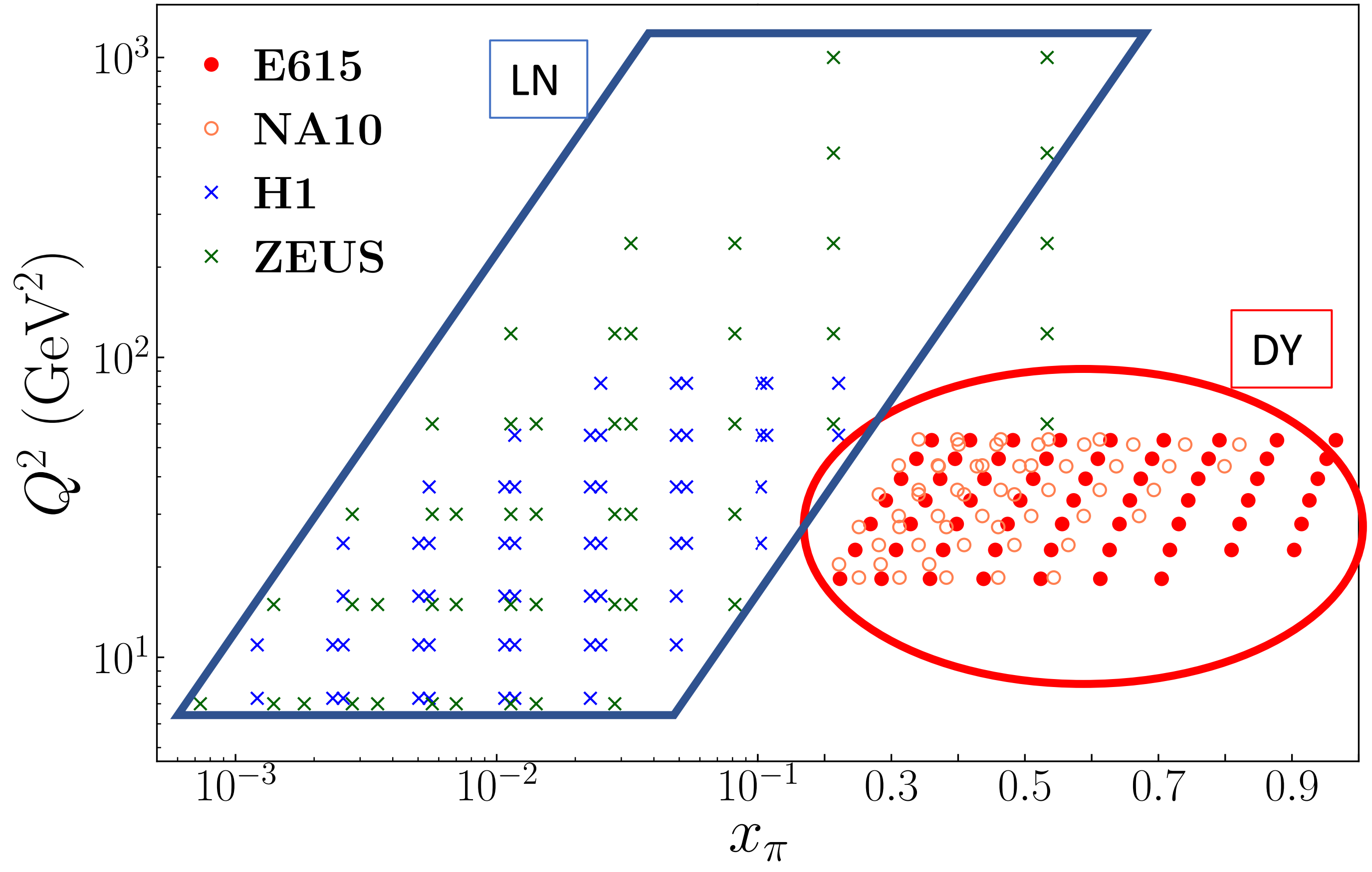
$$\sigma \propto H \ \text{OPE}_A \ \text{OPE}_B$$
$$\approx (1+\alpha_S \hat{H})(1+\alpha_S \widehat{\text{OPE}}_A)(1+\alpha_S \widehat{\text{OPE}}_B)$$
$$\approx 1+\alpha_S(\hat{H}+\widehat{\text{OPE}}_A+\widehat{\text{OPE}}_B)+\mathcal{O}(\alpha_S^2)$$

Perturbative orders

- Perform single fit to determine the effects on the non-perturbative objects
- Red and blue curves correspond to previous page
- Conclusion: no difference for these fixed-target kinematics



Datasets -- Kinematics



Bayesian Inference

- Minimize the χ^2 for each replica

Normalization parameter

$$\chi^2(\boldsymbol{a},\text{data}) = \sum_e \left(\sum_i \left[\frac{d_i^e - \sum_k r_k^e \beta_{k,i}^e - t_i^e(\boldsymbol{a})/n_e}{\alpha_i^e} \right]^2 + \left(\frac{1-n_e}{\delta n_e} \right)^2 + \sum_k \left(r_k^e \right)^2 \right)$$

- Perform N total χ^2 minimizations and compute statistical quantities

Expectation value $$\mathrm{E}[\mathcal{O}] = \frac{1}{N} \sum_k \mathcal{O}(\boldsymbol{a}_k),$$

Variance $$\mathrm{V}[\mathcal{O}] = \frac{1}{N} \sum_k \left[\mathcal{O}(\boldsymbol{a}_k) - \mathrm{E}[\mathcal{O}] \right]^2,$$

Nuclear TMDPDFs – working hypothesis

- Because no pW DY data exist, we must model the tungsten TMDPDF from proton

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

- Each object on the right side independently obeys the CSS equation
- Make use of isospin symmetry in that $u/p/A \leftrightarrow d/n/A$, etc.

Parametric form

- We perform a simultaneous extraction of collinear and transverse momentum dependent PDFs using collinear and p_T-dependent data

$$g_K(b_T, b_{\max}) = c_0 b_T b_*$$

Generic: $$g_{q/h}(x, b_T) = \frac{\left(a_1 + \left(A^{1/3} - 1\right)a_4\right)x^{a_2}(1-x)^{a_3} b_T^2}{\sqrt{1 + a_5 b_T^2}}$$

proton/nuclear

$$g_{u/p}(x, b_T) = a_1^u x^{a_2^u}(1-x)^{a_3^u} b_T^2$$

$$g_{d/p}(x, b_T) = a_1^d x^{a_2^d}(1-x)^{a_3^d} b_T^2$$

$$g_{\mathrm{sea}/p}(x, b_T) = \frac{\left(a_1^{\mathrm{sea}} + \left(A^{1/3} - 1\right)a_4^{\mathrm{sea}}\right)x^{a_2^{\mathrm{sea}}} b_T^2}{\sqrt{1 + a_5^{\mathrm{sea}} b_T^2}}$$

pion

$$g_{q/\pi}(x, b_T) = \frac{a_1^\pi x^{a_2^\pi}(1-x)^{a_3^\pi} b_T^2}{\sqrt{1 + a_5^\pi b_T^2}}$$

The data do not have sensitivity to flavor separation in the pion

Description of $p\bar{p}$ CDF data

- Using these proton TMD parameters and g_K, we show a good description of high energy CDF data