Simultaneous extraction of collinear and transverse momentum dependent parton densities in the pion

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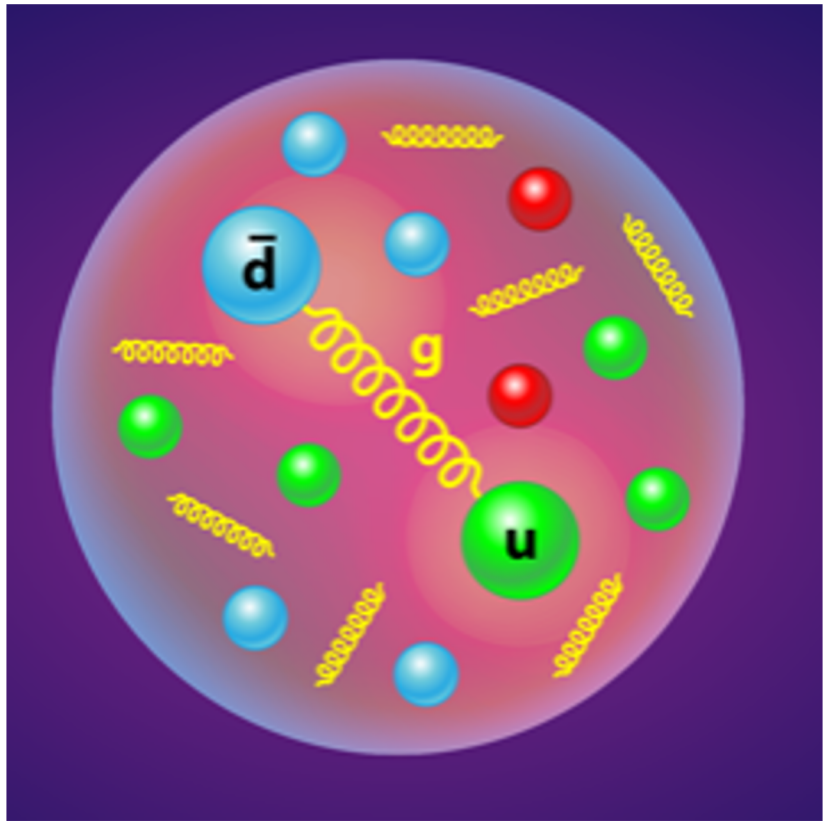
Motivation

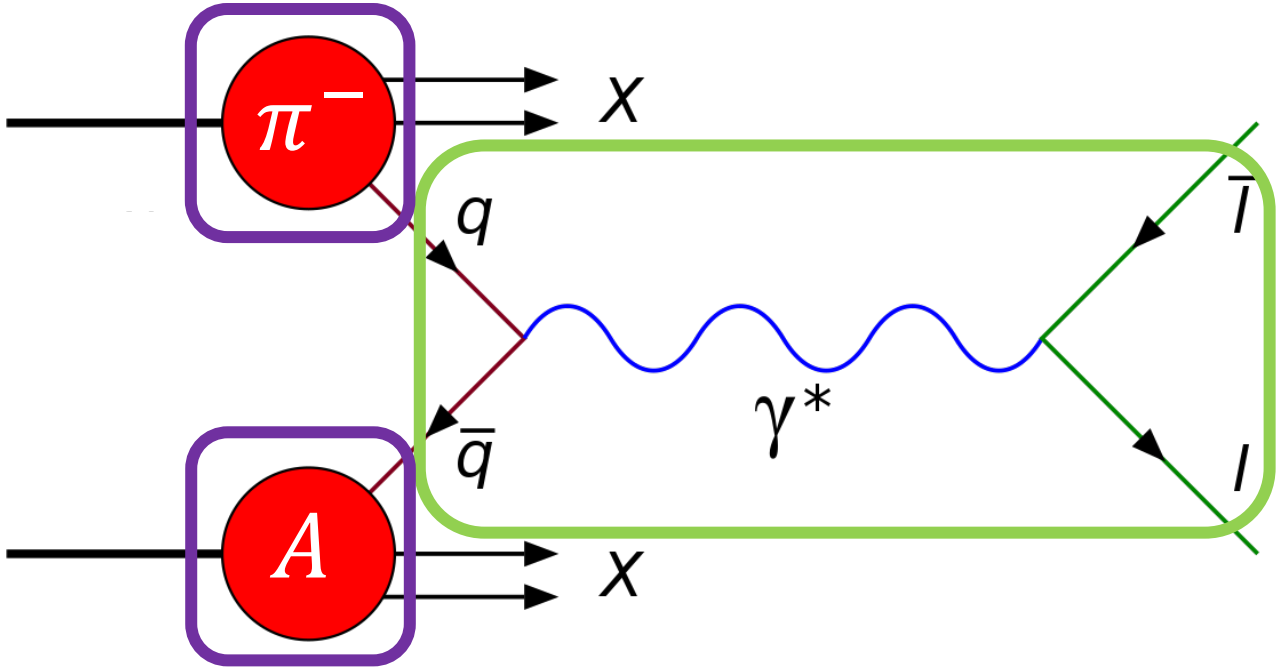
- QCD allows us to study the structure of hadrons in terms of partons (quarks, antiquarks, and gluons)
- Identify physical observables that can be factorized in theory with controllable approximations
- Perform global QCD analysis as structures are universal and are the same in all processes

Pions

- Pion is the Goldstone boson associated with spontaneous symmetry breaking of chiral $SU(2)_L \times SU(2)_R$ symmetry
- Lightest hadron
- Made up of q and $\bar{q}$ constituents



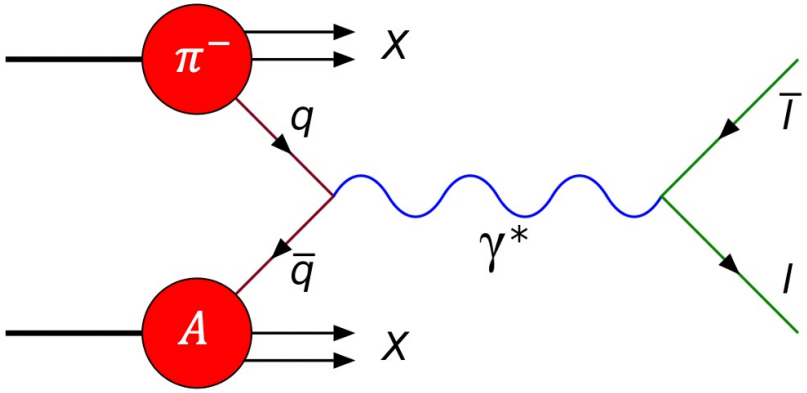
Drell-Yan (DY)



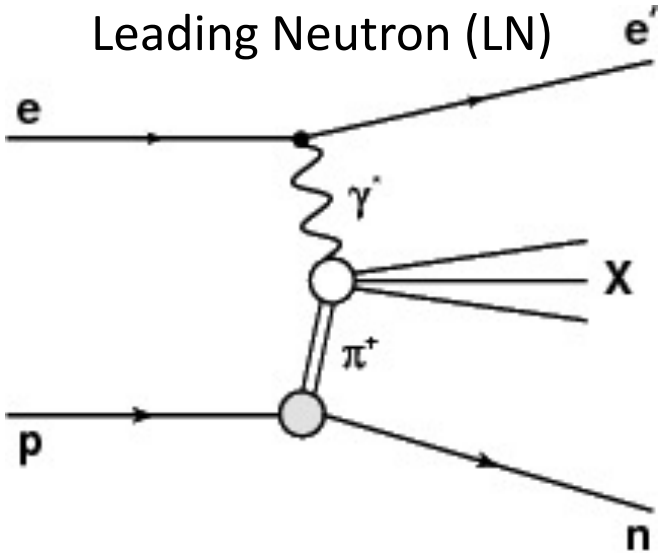
$$\sigma \propto \sum_{i,j} f_i^{\pi}(x_\pi, \mu) \otimes f_j^{A}(x_A, \mu) \otimes C_{i,j}(x_\pi, x_A, Q/\mu)$$

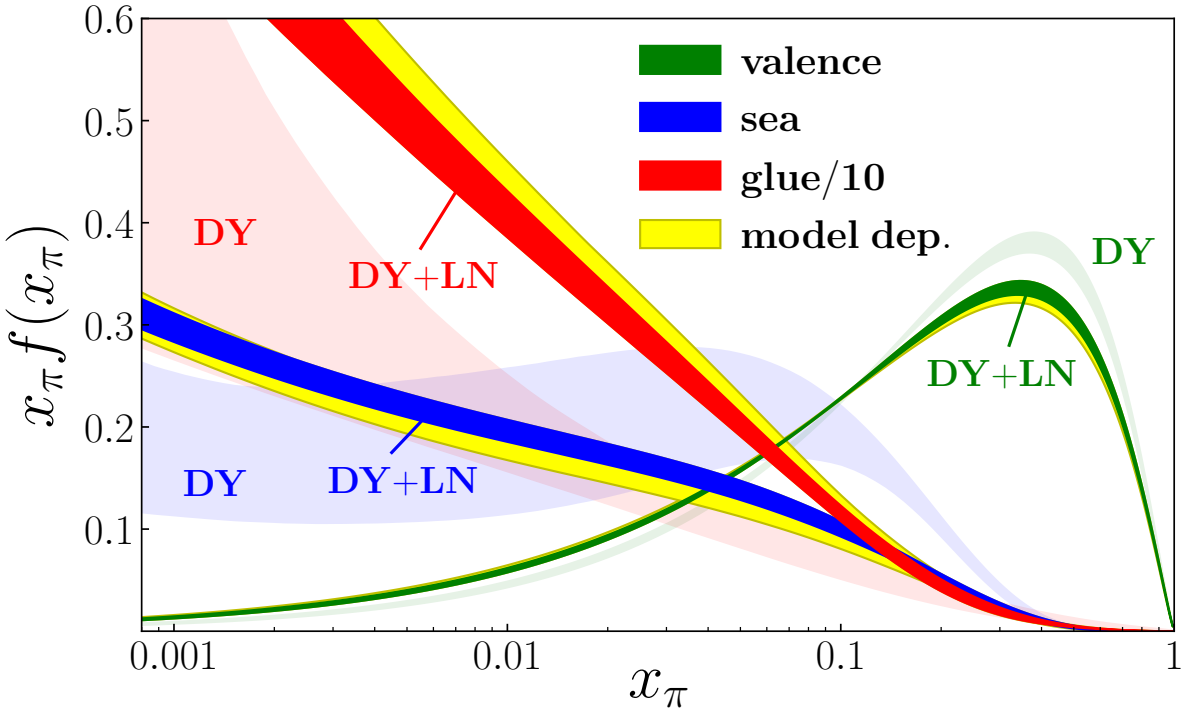
Experiments to Probe Pion Structure

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

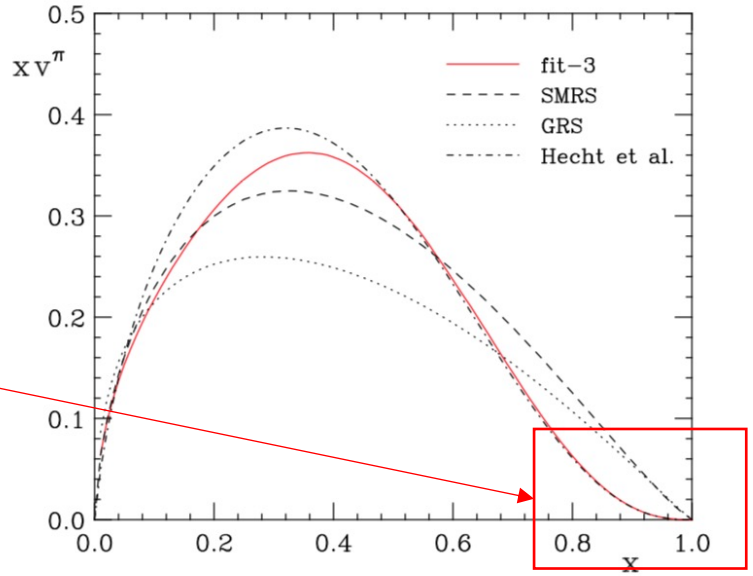
P. C. Barry,[1] N. Sato,[2] W. Melnitchouk,[3] and Chueng-Ryong Ji[1]

Large-x_π behavior

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

<u>Phenomenologically</u>

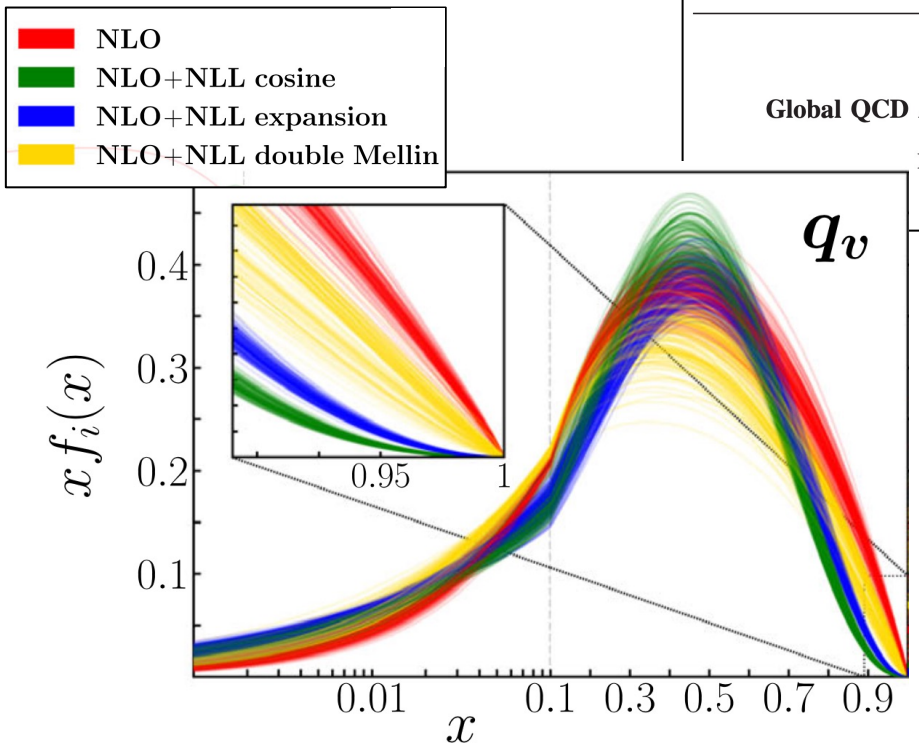
- Fixed order analyses find $\beta \approx 1$
- Aicher, Schaefer Vogelsang (ASV) found $\boxed{\beta = 2}$ with threshold resummation



ASV valence PDF

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

JAM analysis with threshold resummation



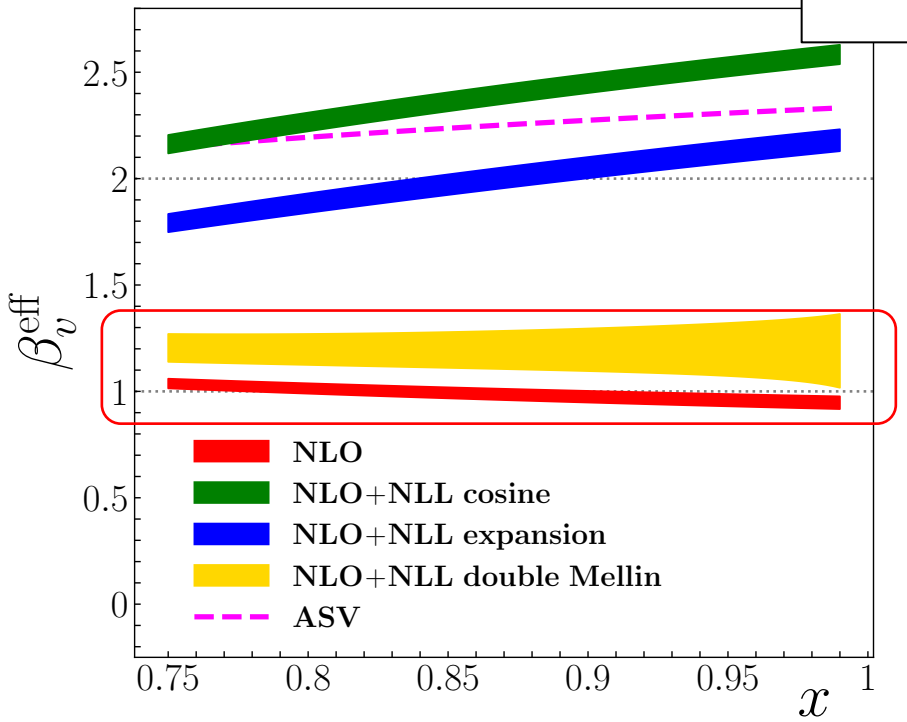
PHYSICAL REVIEW LETTERS **127,** 232001 (2021)

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)

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

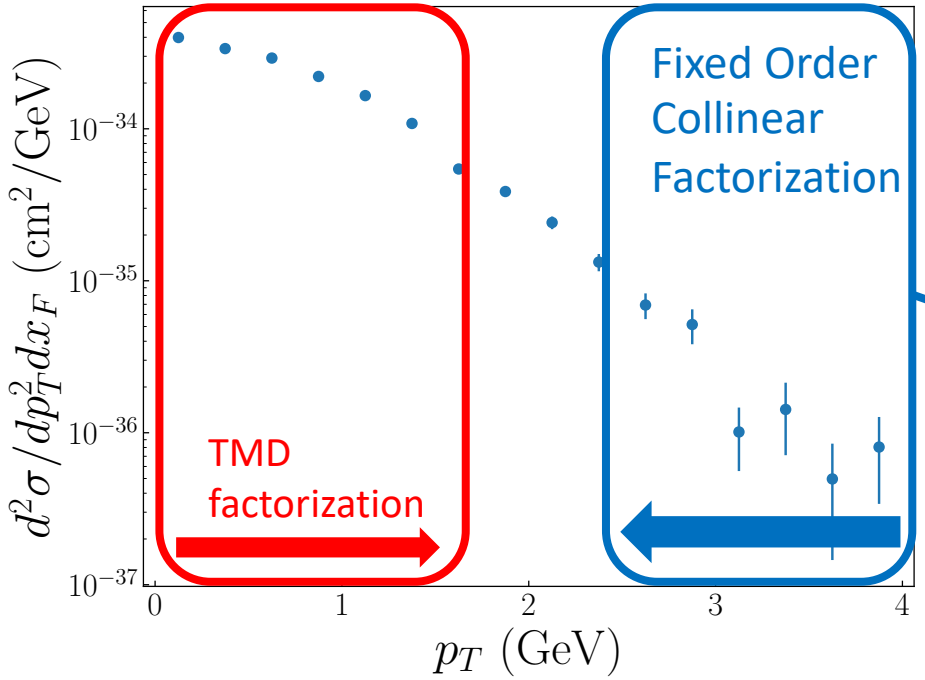


For more details, attend my talk in WG1 on Tuesday at 5:30pm

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

What about the transverse dimension?

- Available q_T-dependent Drell-Yan data from E615 Phys. Rev. D **39**, 92 (1989).
- Fixed Target data (no collider pion data)



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

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[3]*Jefferson Lab, Newport News, Virginia 23606, USA*

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

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

TMD factorization in Drell-Yan

- In small-q_{T} region, Use the Collins-Soper-Sterman (CSS) formalism

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

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

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

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

Collinear pion PDF

Use NLO, N^{2}LL perturbative expansions

Non-perturbative TMDs to extract

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

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

- Can these data constrain the pion collinear PDF?

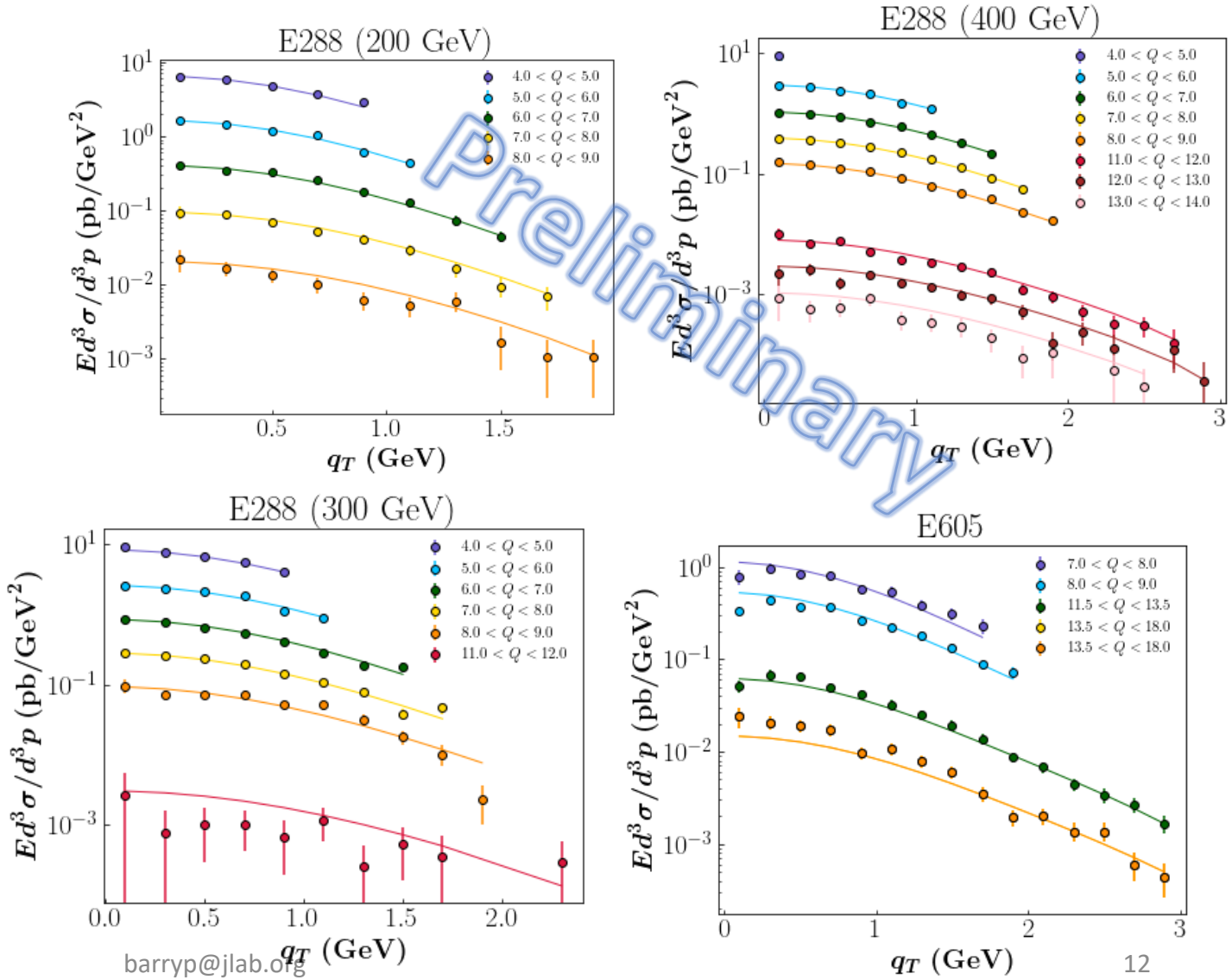
Strategy for simultaneous analysis

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

*Avoid Υ resonance in $9 < Q < 11$GeV

Description of pA data

- Proton PDFs from the recent JAM analysis including MARATHON data
- Nuclear PDFs from EPPS16



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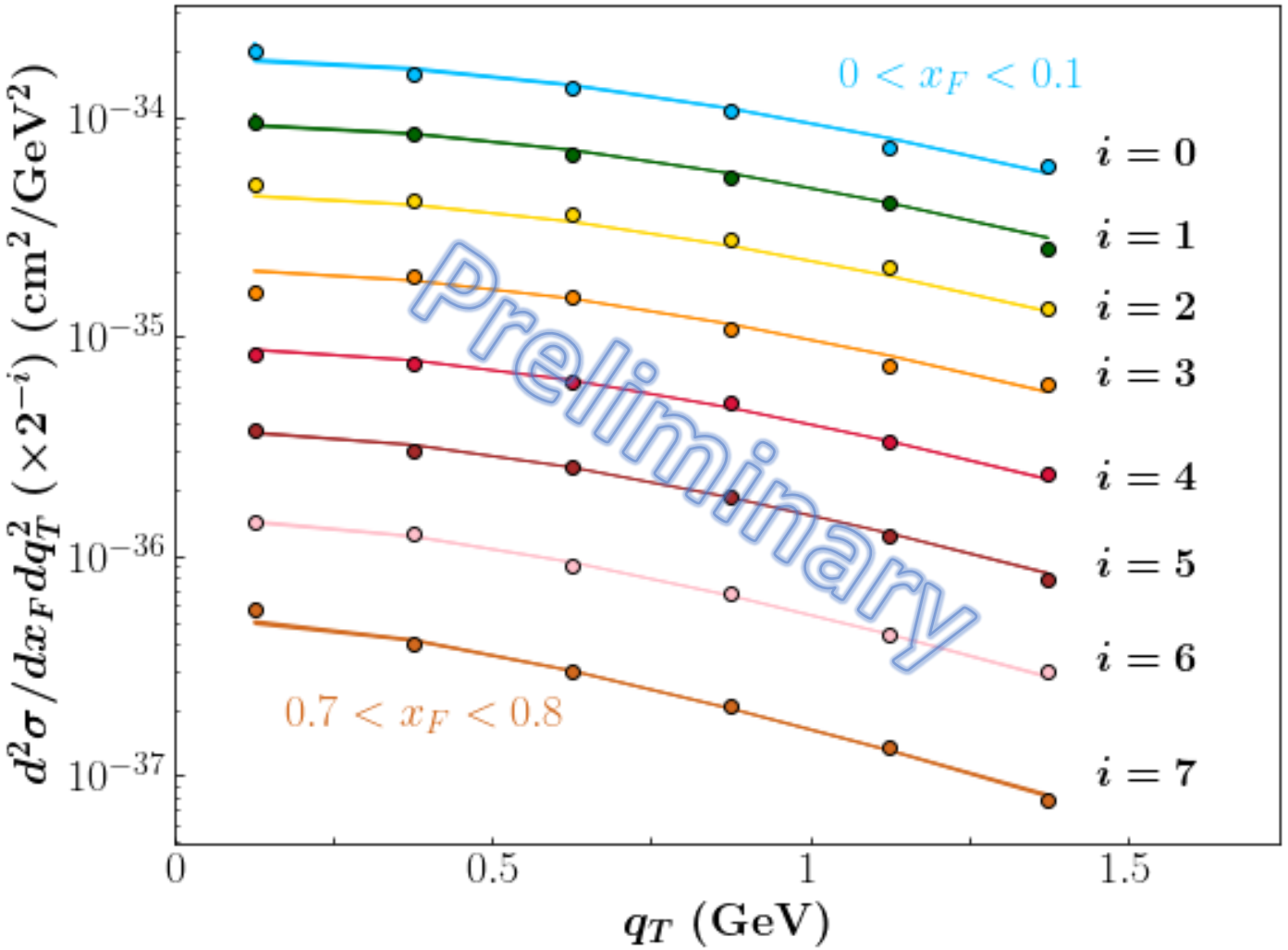
Process	Drell-Yan $\pi\, W \to \mu^+\mu^- X$	Leading neutron $ep \to e'n\, X$	q_T-dependent Drell-Yan $\pi\, W \to \mu^+\mu^- X$
Observable	$d^2\sigma/dx_F d\sqrt{\tau}$	$F_2^{\mathrm{LN}}, r = F_2^{\mathrm{LN}}/F_2^{\mathrm{inc}}$	$d^2\sigma/dx_F dq_T$
Experiment	E615, NA10	H1, ZEUS	E615, E537

*Avoid Υ resonance in $9 < Q < 11$GeV

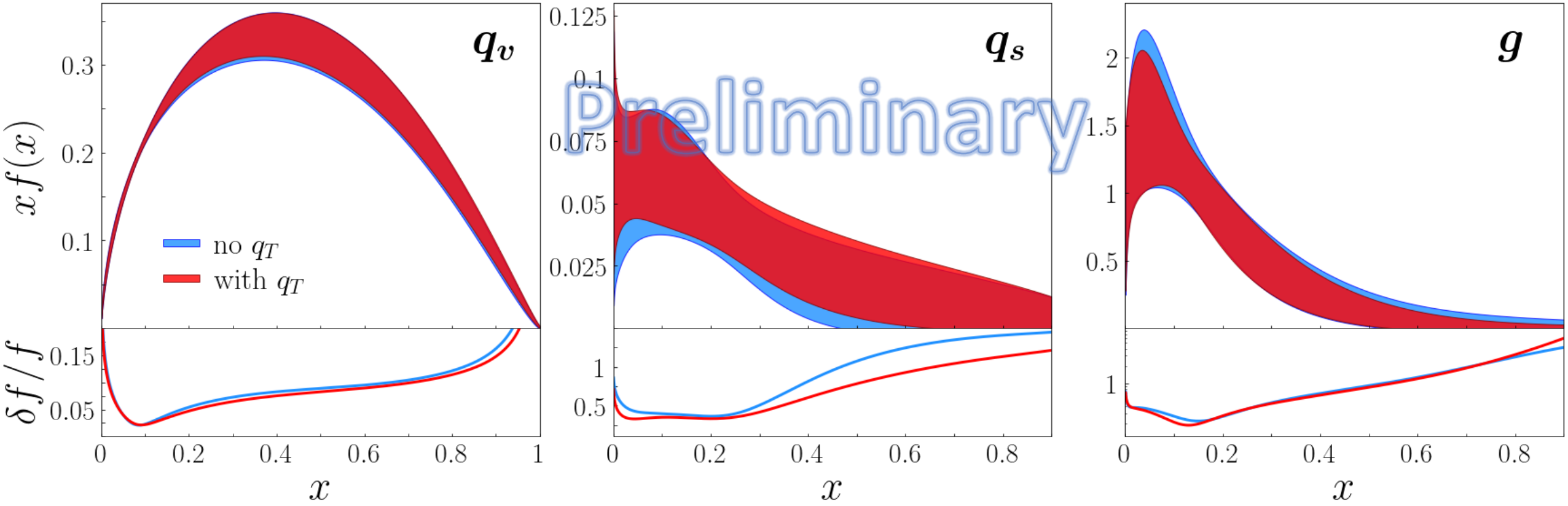
Description of πA data

- Well describe the E615 data in the (x_F, q_T) spectrum: $\chi^2/\mathrm{npts} = 1.45$
- Can also describe rest of the experimental data: $\chi^2_{\mathrm{tot}}/\mathrm{npts} = 0.93$



Impact on PDFs

- Similar to the case without inclusion of q_T-dependent DY, but with more constrained sea quark

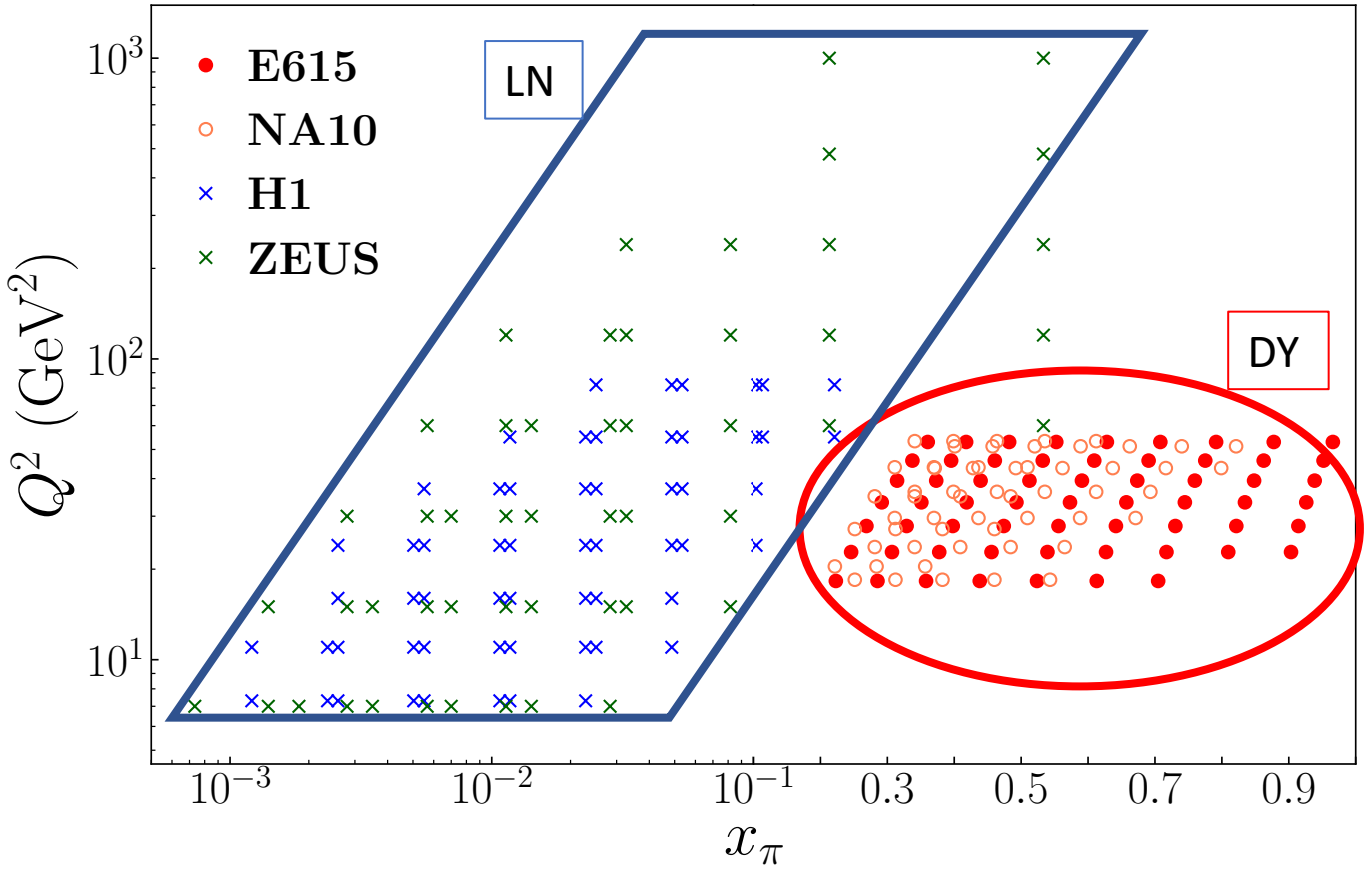


Conclusions

- We have made strides in collinear pion PDF phenomenology by introducing available datasets and theoretical advances
- Inclusion of q_T-dependent DY data slightly constrains the sea quark distribution
- Extend framework to LHC data and nucleon PDFs
  - Use different methodologies – CSS, Qiu-Zhang, zeta-prescription
  - Can these precise data constrain nucleon PDFs?

Backup Slides

Datasets -- Kinematics



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

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

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

$$g_{\mathrm{sea}/p}(x, b_T) = a_1^{\mathrm{sea}} x^{a_2^{\mathrm{sea}}} b_T^2$$

pion

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

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

Correlations

- Shown is the correlation of the parameters
- $a_1^\pi, a_3^\pi, a_5^\pi$ are TMD parameters, rest are collinear
- Notice the lack of correlation between TMD parameters and PDF parameters