State-of-the-art extractions of pion parton distributions

Patrick Barry (Jefferson Lab)

Light Cone 2021: Physics of Hadrons on the Light Front

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What do we want?

To study the makeup of nuclear matter

Building blocks of nature are quarks and gluons

What’s the problem?

Quarks and gluons are not directly measurable!

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

Game plan

What to do:

- Define a structure of hadrons in terms of quantum field theories
- Identify theoretical observables that factorize into non-perturbative objects and perturbatively calculable physics
- Perform global QCD analysis as structures are universal and are the same in all processes

Complicated Inverse Problem

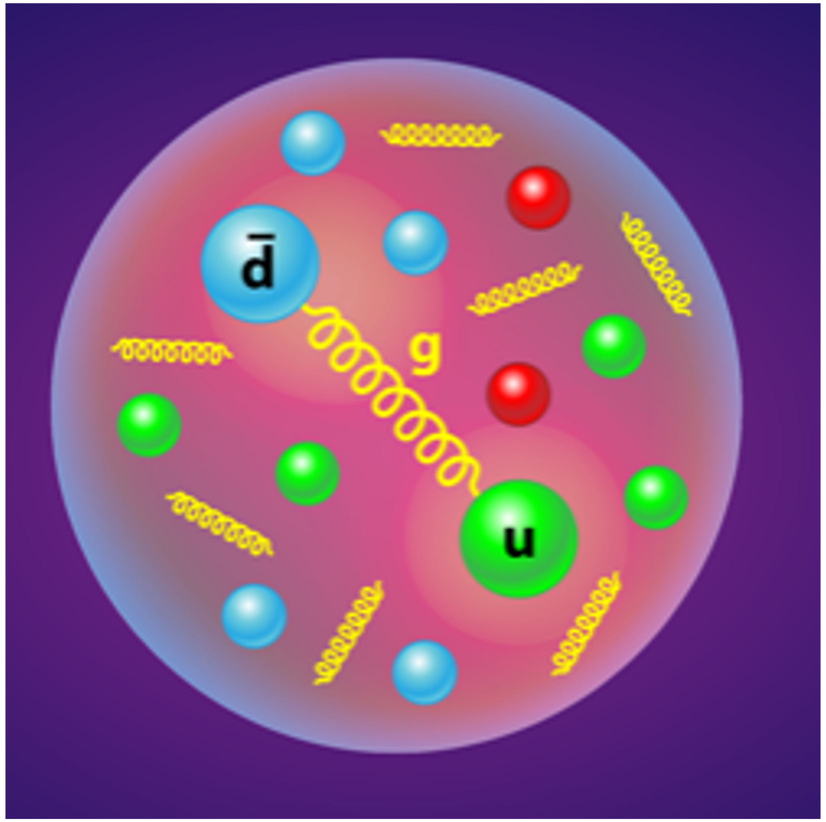
- Factorization theorems involve convolutions of hard perturbatively calculable physics and non-perturbative objects

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

- Parametrize the non-perturbative objects and perform global fit

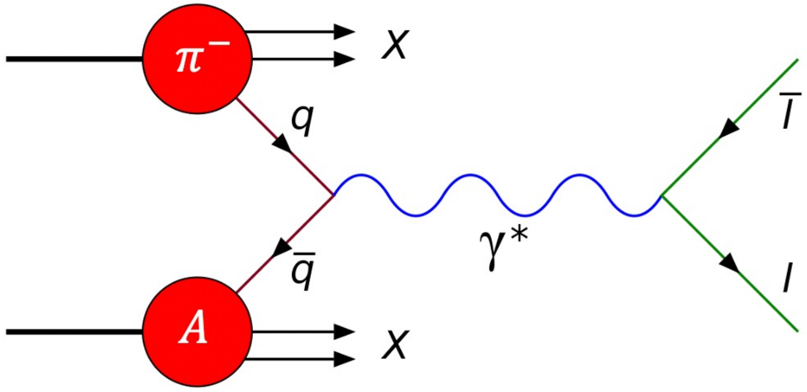
Pions

- 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

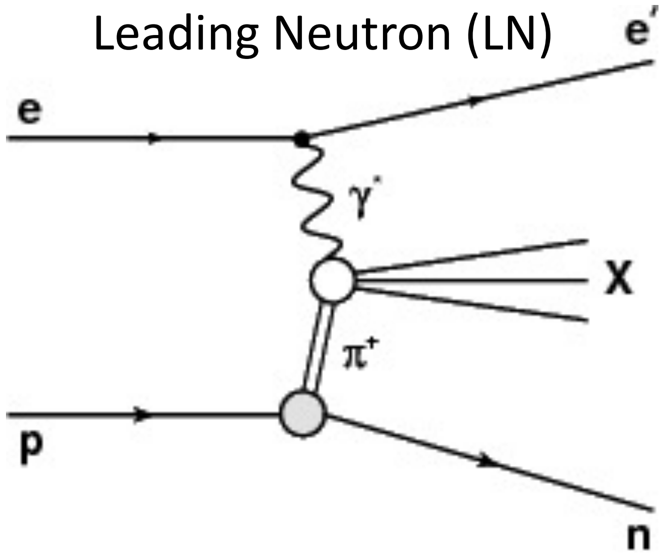


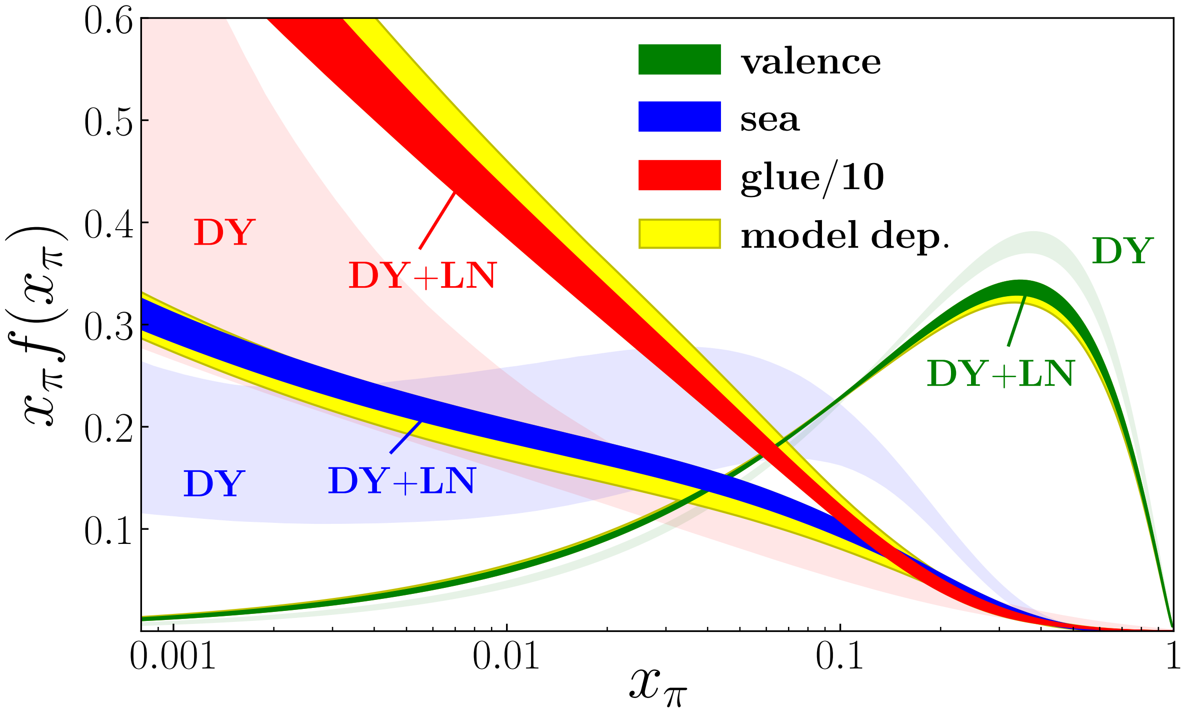
Experiments to probe pion structure

Drell-Yan (DY)



Leading Neutron (LN)





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

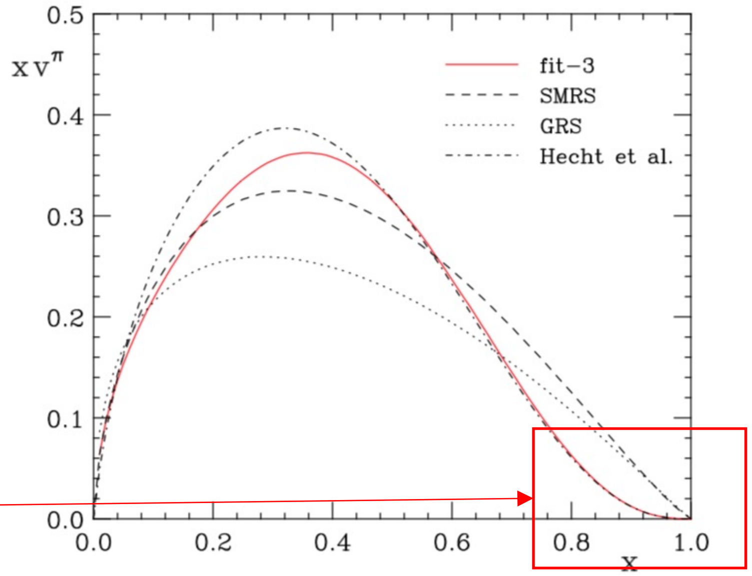
Featured in Physics

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

- Generally, the parametrization lends a behavior as $x_\pi \to 1$ of the valence quark PDF of $q_v(x) \propto (1-x)^\beta$
- For a fixed order analysis, we find $\beta \approx 1$
- Debate whether $\beta = 1$ or $\beta = 2$
- Aicher, Schaefer Vogelsang (ASV) found $\beta = 2$ with threshold resummation



ASV valence PDF

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

Threshold Resummation in Pion Drell-Yan

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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]

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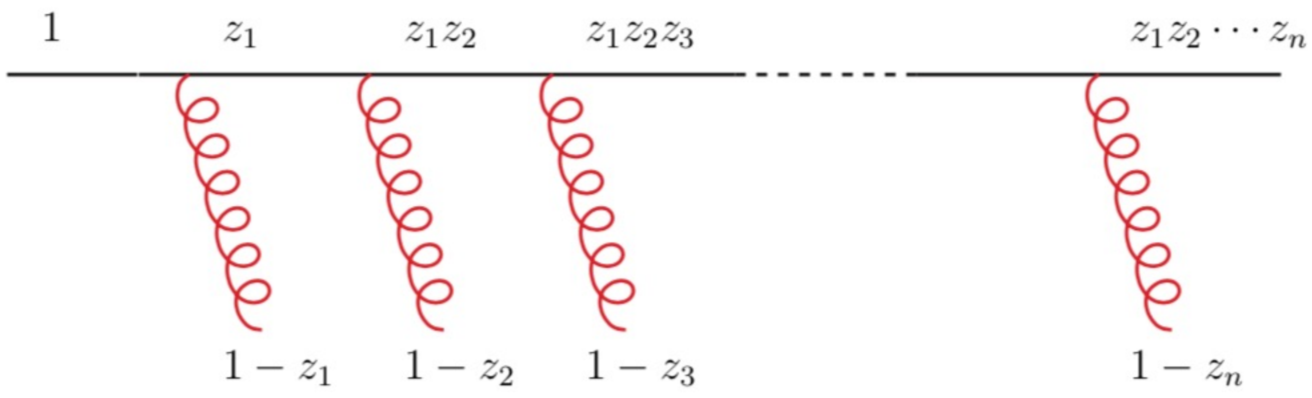
Soft gluon resummation in DY



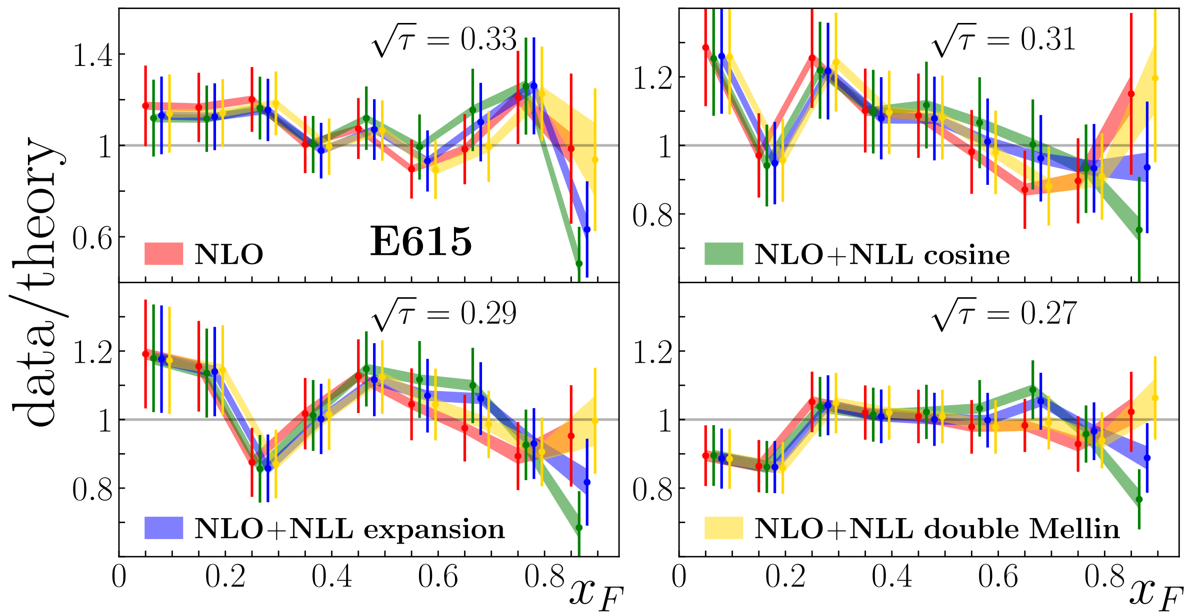
- Fixed-target Drell-Yan notoriously has large-x_F contamination of higher orders
- Large logarithms may spoil perturbation
- Focus on corrections to the most important $q\bar{q}$ channel
- Resum contributions to all orders of α_s

Methods of resummation

- Resummation is performed in conjugate space
- Drell-Yan data needs two transformations
- We can perform a Mellin-Fourier transform to account for the rapidity
  - A cosine appears while doing Fourier transform; options:
    1) Take first order expansion, cosine ≈ 1
    2) Keep cosine intact
- Can additionally perform a Double Mellin transform
- Explore the different methods and analyze effects
- Double Mellin transform is theoretically cleaner and sums up terms appropriately

Data and theory comparison

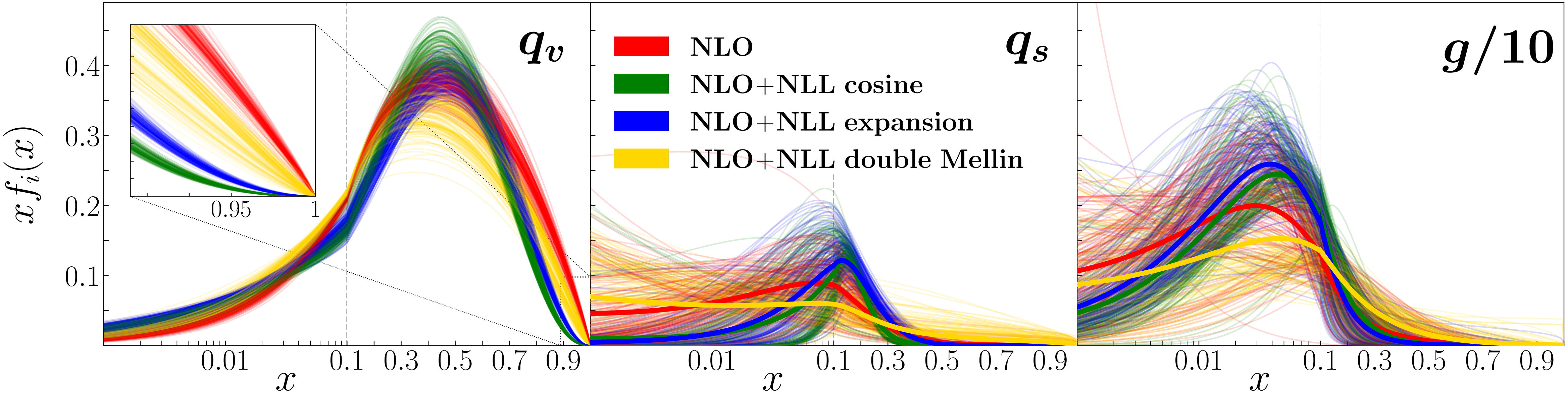
- Cosine method tends to overpredict the data at very large x_F
- Double Mellin method is qualitatively very similar to NLO
- Resummation is largely a high-x_F effect



Method	χ^2/npts
NLO	0.85
NLO+NLL cosine	1.29
NLO+NLL expansion	0.95
NLO+NLL double Mellin	0.80

Slightly disfavored

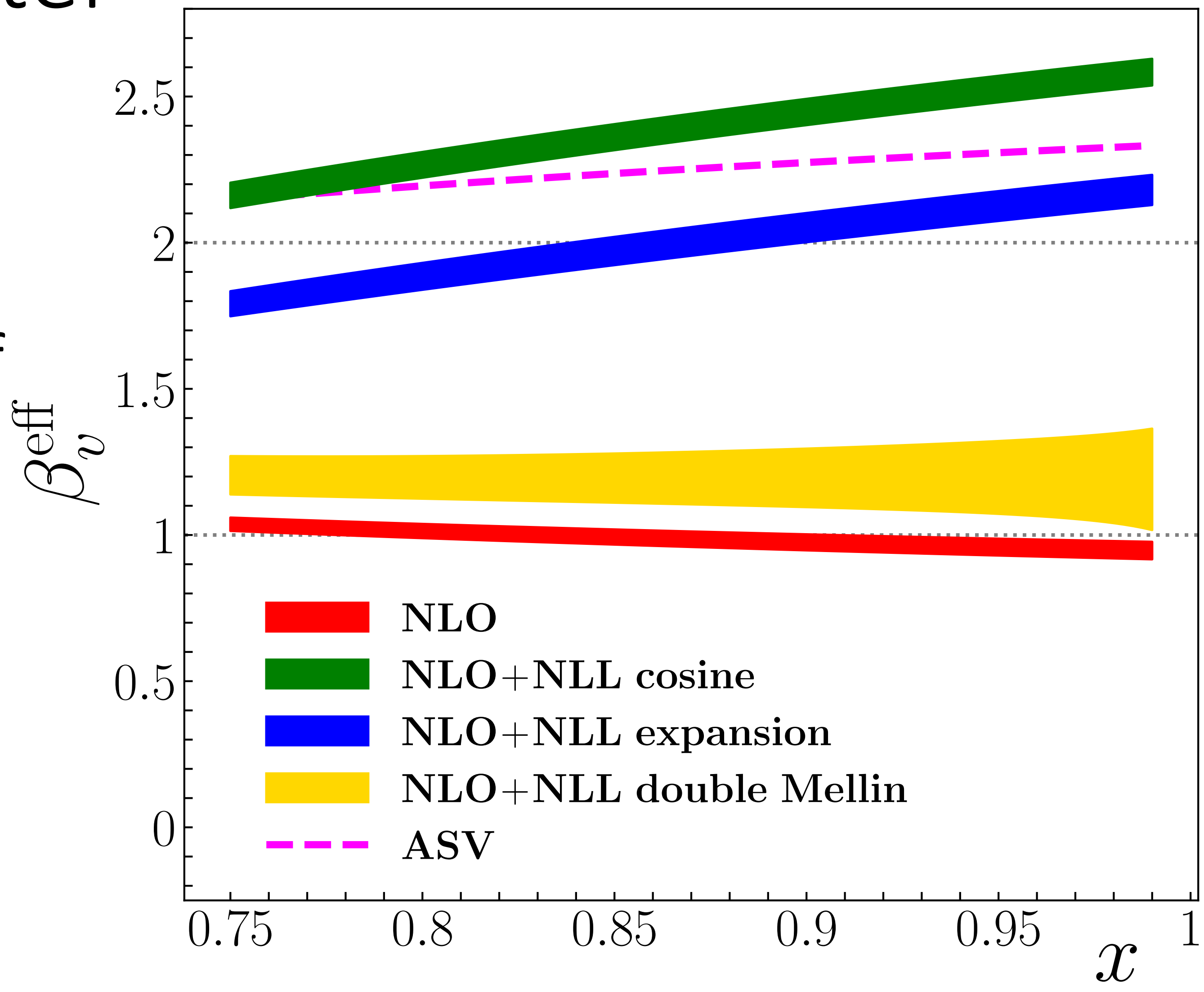
Resulting PDFs



- Large x behavior of q_v **highly sensitive** to method of resummation

Effective β_v parameter

- $q_v(x) \sim (1-x)^{\beta_v^{\rm eff}}$ as $x \to 1$
- Threshold resummation does not give universal behavior of $\beta_v^{\rm eff}$
- NLO and double Mellin give $\beta_v^{\rm eff} \approx 1$
- Cosine and Expansion give $\beta_v^{\rm eff} > 2$



Introducing lattice QCD data in global analysis

PCB, C. Egerer (Jefferson Lab), J. Karpie (Columbia), W. Melnitchouk (Jefferson Lab), C. Monahan (William & Mary, Jefferson Lab), K. Orginos (William & Mary, Jefferson Lab), Jian-Wei Qiu (Jefferson Lab), D. Richards (Jefferson Lab), N. Sato (Jefferson Lab), R. S. Sufian (William & Mary, Jefferson Lab), S. Zafeiropoulos (Aix Marseille Univ.)

Observable

- Lattice calculation is the **reduced** pseudo Ioffe time distribution (reduced pseudo-ITD)

$$\mathfrak{M}(\nu, z^2) = \frac{\mathcal{M}(\nu, z^2)}{\mathcal{M}(0, z^2)}$$

"Ioffe time"

$$\boxed{\nu = p \cdot z}$$

- The UV divergences arising from choosing the spacelike z cancel from taking the ratio at the rest frame $p_z = 0$ (light-like z does not have these divergences)
- Make use of the "good lattice cross section," which has convolution structure like experimental observables

Fitting the Data and Systematic Effects

$$\mathrm{Re}[\mathfrak{M}(\nu, z^2)] = \int_0^1 dx\, q_v(x, \mu_{\mathrm{lat}}) \mathcal{C}^{\mathrm{Rp-ITD}}\left(x\nu, z^2, \mu_{\mathrm{lat}}\right) + z^2 B_1(\nu) + \frac{a}{|z|} P_1(\nu) + e^{-m_\pi (L-z)} F_1(\nu) + \ldots,$$

Valence quark distribution in pion

Wilson coefficients for matching

Systematic Effects to parametrize

- $z^2 B_1(\nu)$: power corrections
- $\frac{a}{|z|} P_1(\nu)$: lattice spacing errors
- $e^{-m_\pi (L-z)} F_1(\nu)$: finite volume corrections

Other potential systematic corrections the data is not sensitive to

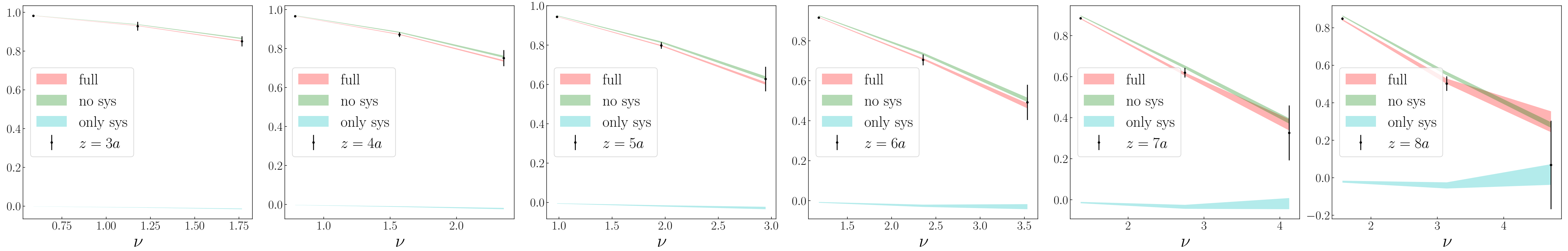
Resulting χ^2_{red}

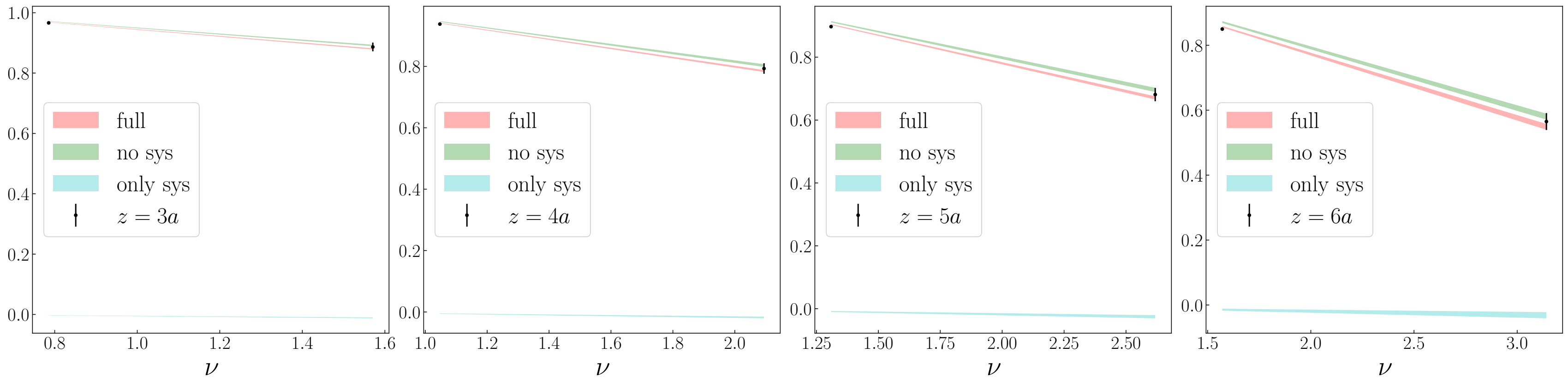
- Scenario A: only experimental data
- Scenario B: include lattice data without fitting systematic effects
- Scenario C: Include systematics

		Scenario A		Scenario B		Scenario C	
Process	Experiment	N_{dat}	χ^2_{red}	N_{dat}	χ^2_{red}	N_{dat}	χ^2_{red}
DY	E615	61	0.82	61	0.82	61	0.82
	NA10 (194 GeV)	36	0.53	36	0.54	36	0.55
	NA10 (286 GeV)	20	0.81	20	0.79	20	0.88
LN	H1	58	0.35	58	0.39	58	0.37
	ZEUS	50	1.48	50	1.69	50	1.61
Rp-ITD	a127m415L	–	–	18	1.06	18	1.07
	a127m415	–	–	8	2.63	8	1.50
Total		**225**	**0.80**	**251**	**0.92**	**251**	**0.88**

Fits to the data

Larger lattice volume





Smaller lattice volume

- Systematic effects shown in blue, are very small at low momentum and Ioffe time, ν

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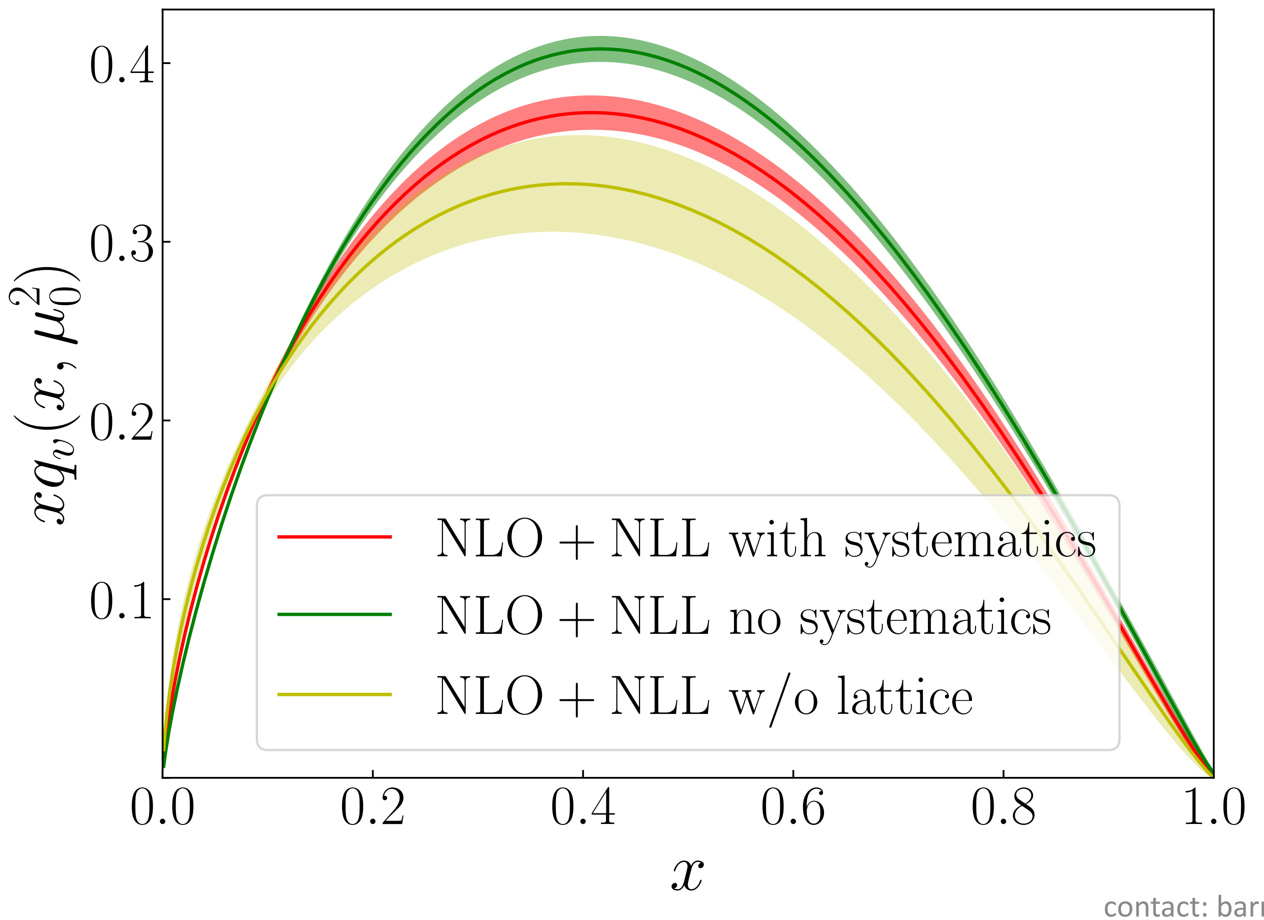
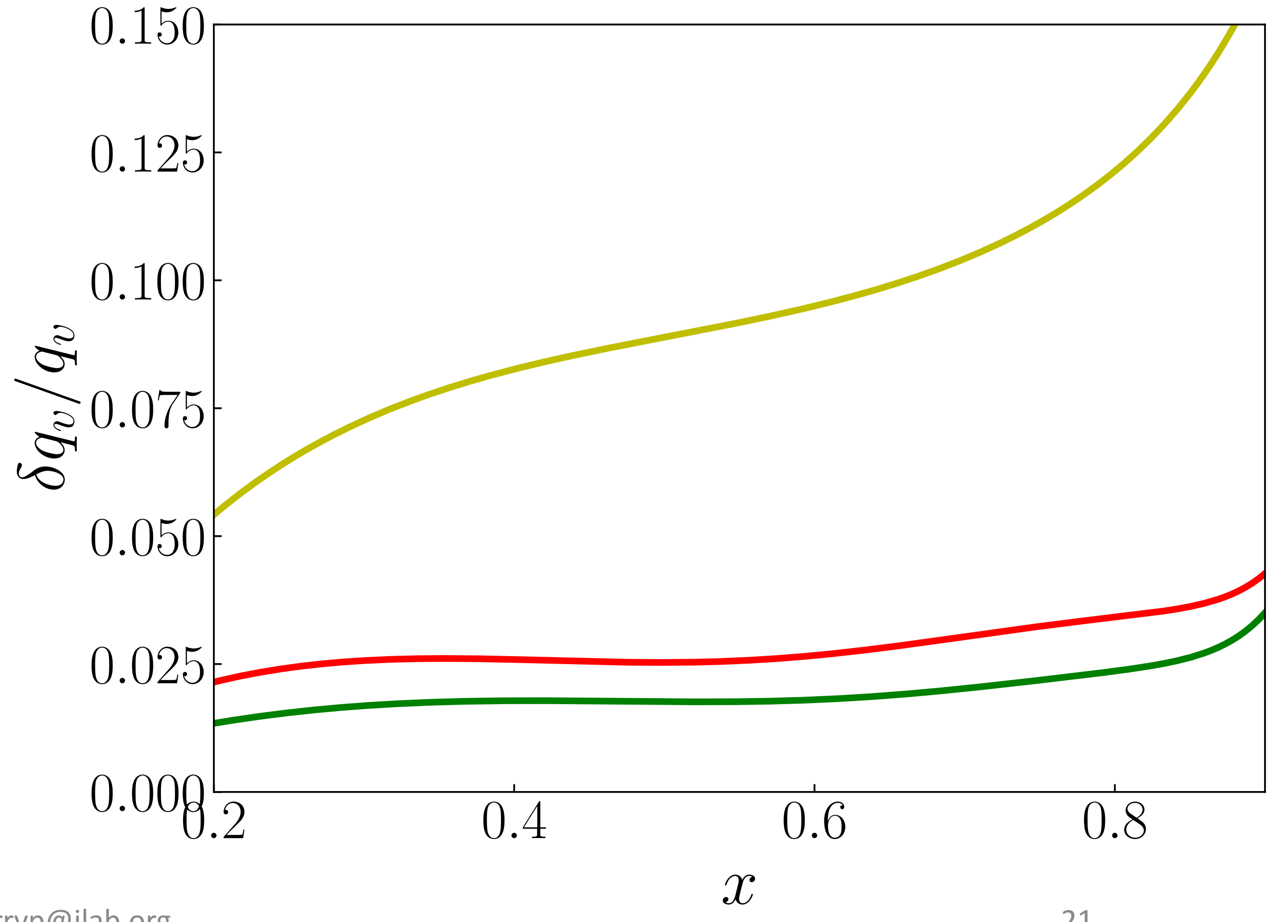
Effect on q_v^π

- Sizeable effect even when including systematics



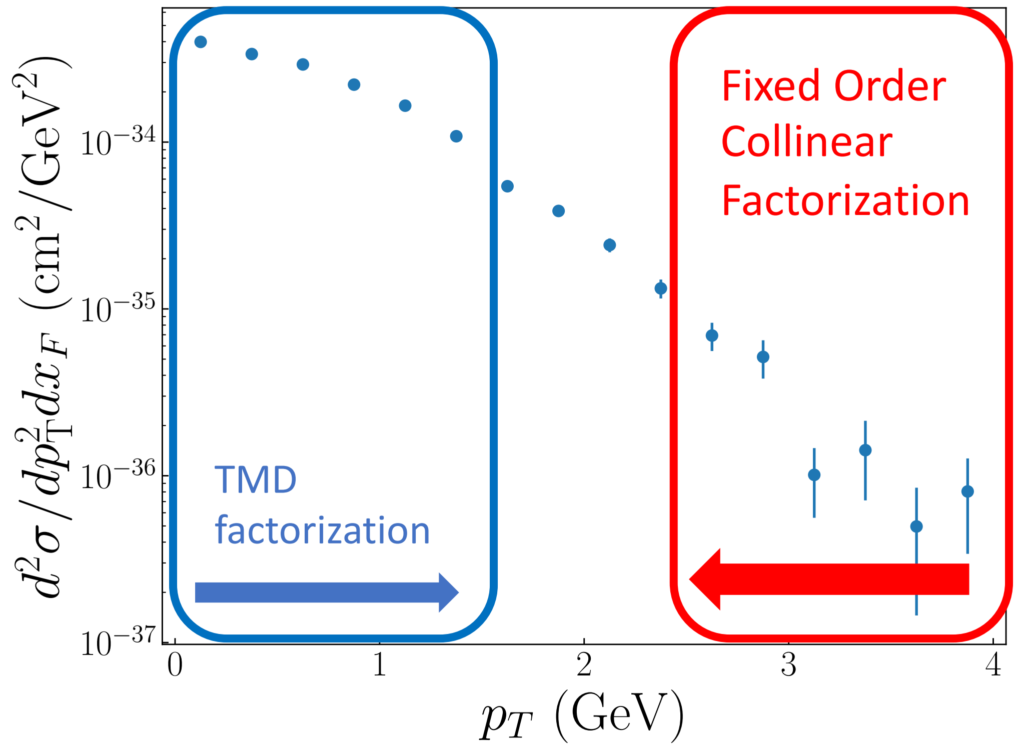


Transverse Momentum Dependent Drell-Yan

PCB, N. Y. Cao (Harvard), W. Melnitchouk (Jefferson Lab), N. Sato (Jefferson Lab), L. Gamberg (Penn State Berks), E. Moffat (Penn State Berks), A. Prokudin (Penn State Berks, Jefferson Lab)

p_{T}-dependent spectrum for pion data

- Small-p_{T} data – TMD factorization – partonic transverse momentum
- Large-p_{T} data – collinear factorization – recoil transverse momentum

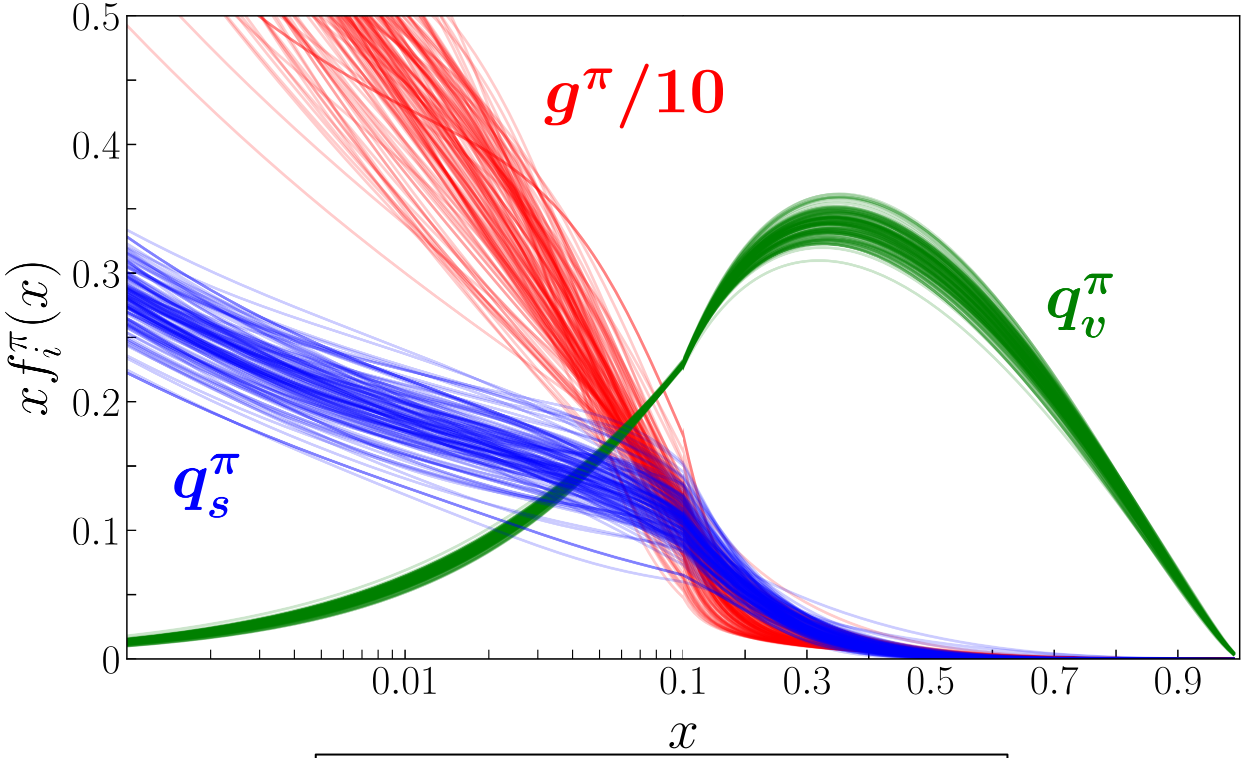


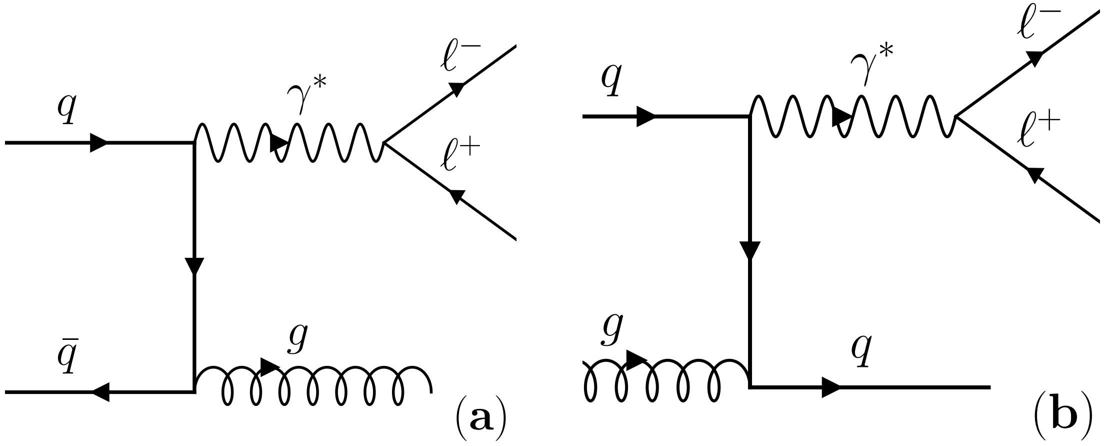
E615 πW Drell-Yan

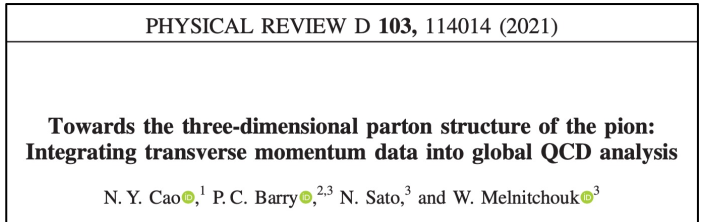
Phys. Rev. D **39**, 92 (1989).

JAM20 Pion PDFs

Fixed Order Analysis






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]

- For the first time, we included large p_{T}-dependent Drell-Yan data, which follows collinear factorization
- Large p_{T} does not dramatically affect the PDF
- Successfully describe data with a scale $\mu = p_{\mathrm{T}}/2$

TMD factorization in Drell-Yan

- In small-p_T region, Use the CSS formalism for TMD evolution

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

Collinear pion PDF

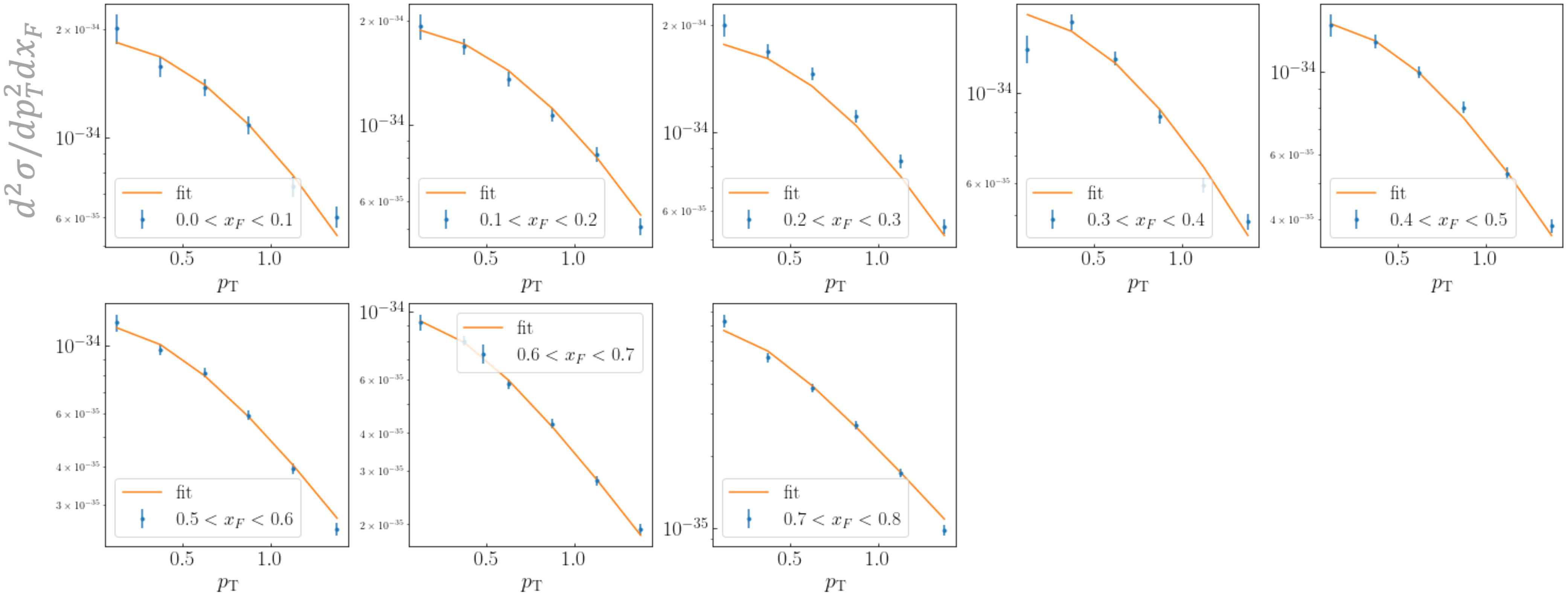
Non-perturbative TMDs to extract

- Fit non-perturbative TMDs to pion-induced E615 data

Single Fits in low energy Drell-Yan

- Perform single fits of non-perturbative TMD functions to pA and πA data

E615 πA



Future Experiments

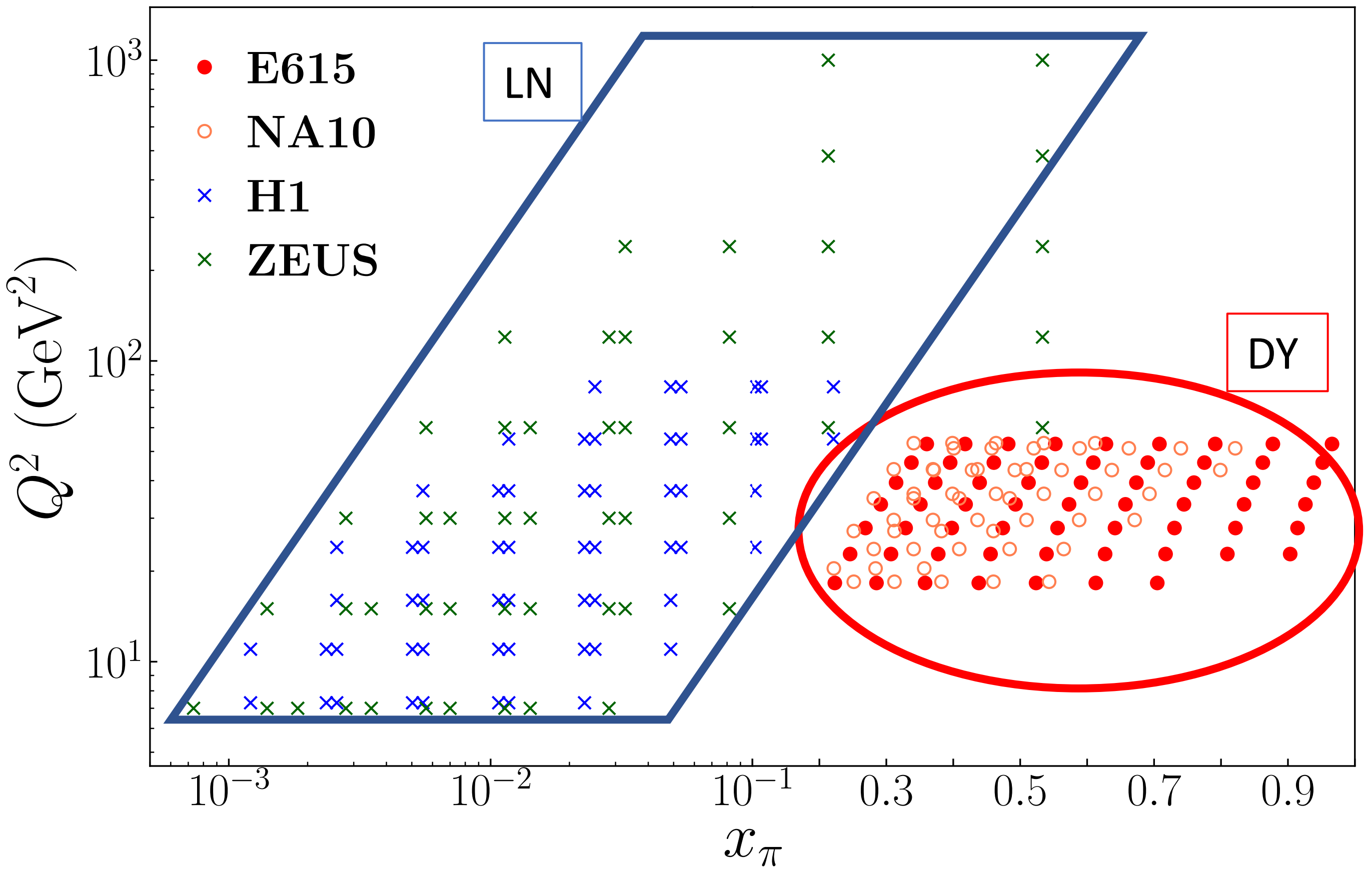
Datasets -- Kinematics

- Large x_π -- Drell-Yan (DY)
- Small x_π -- Leading Neutron (LN)
- Not much data overlap
- In DY:

$$x_\pi = \frac{1}{2}\left(x_F + \sqrt{x_F^2 + 4\tau}\right)$$

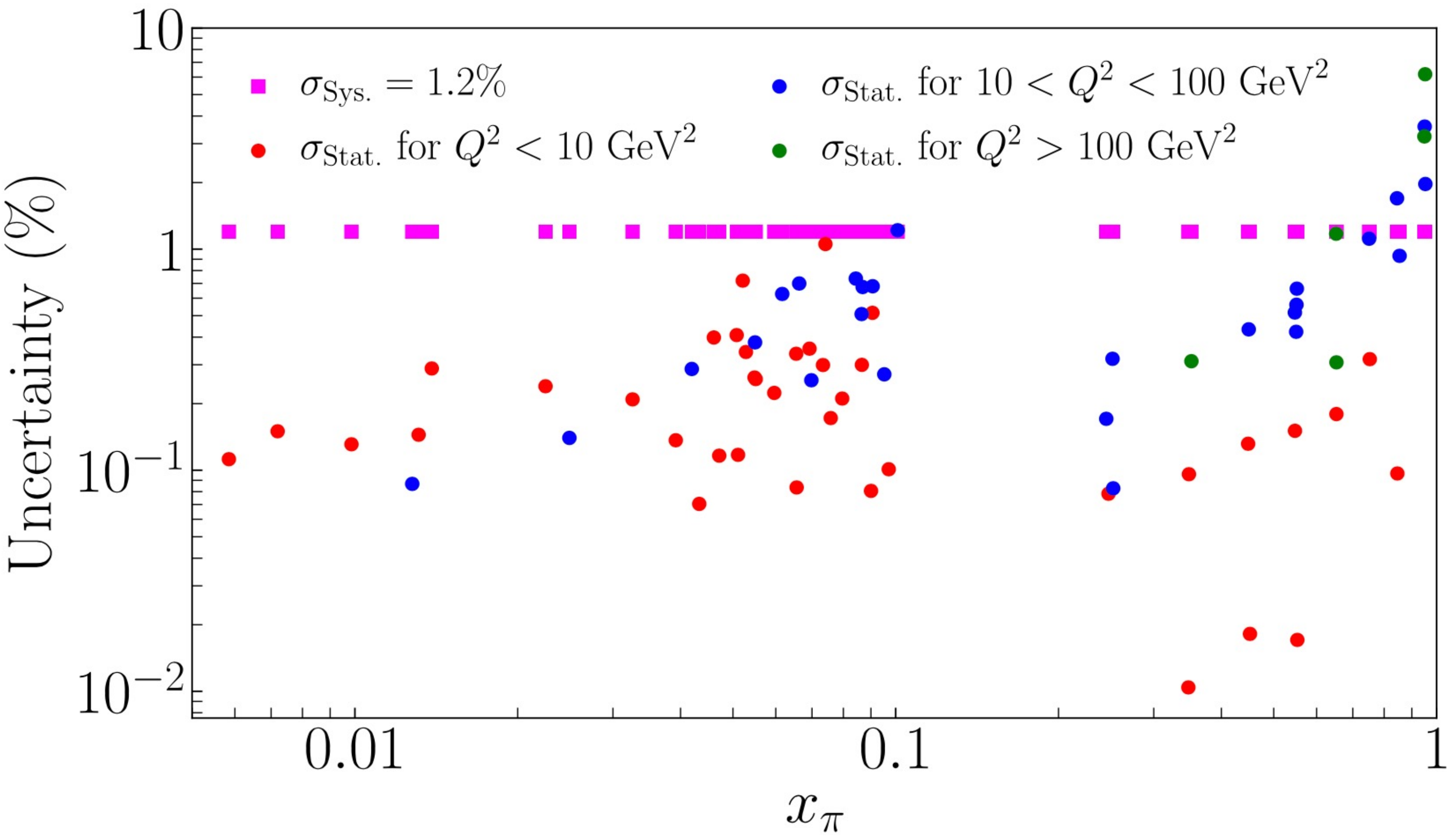
- In LN:

$$x_\pi = x_B / \bar{x}_L$$



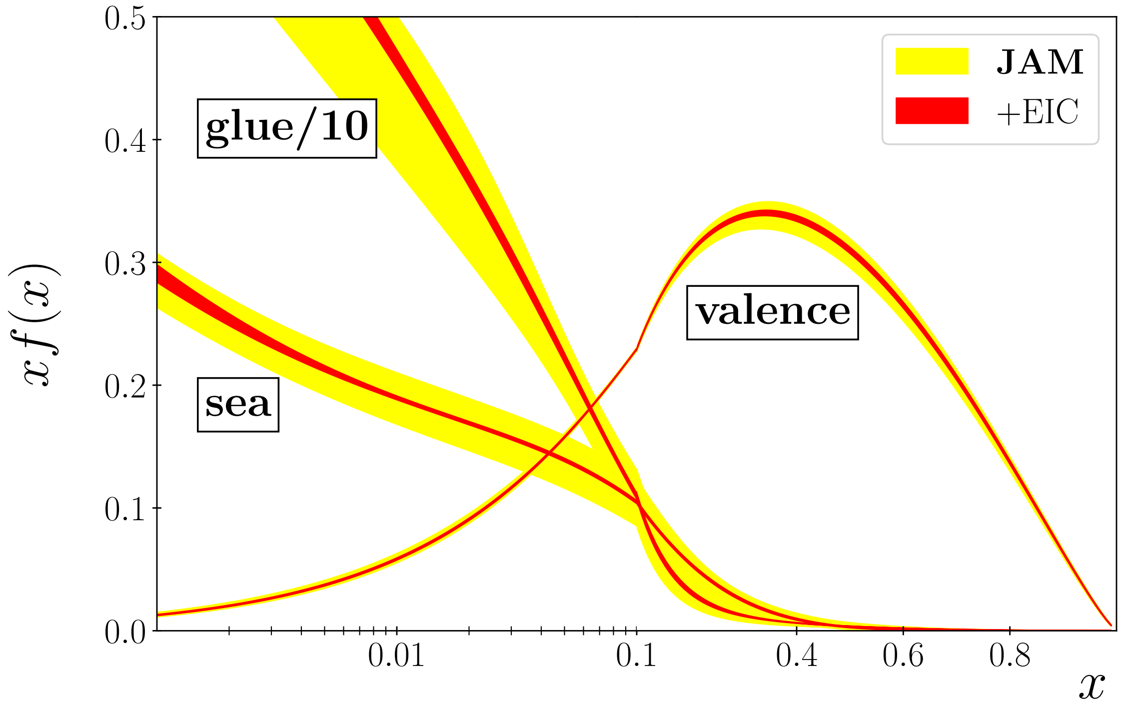
EIC kinematics and uncertainties

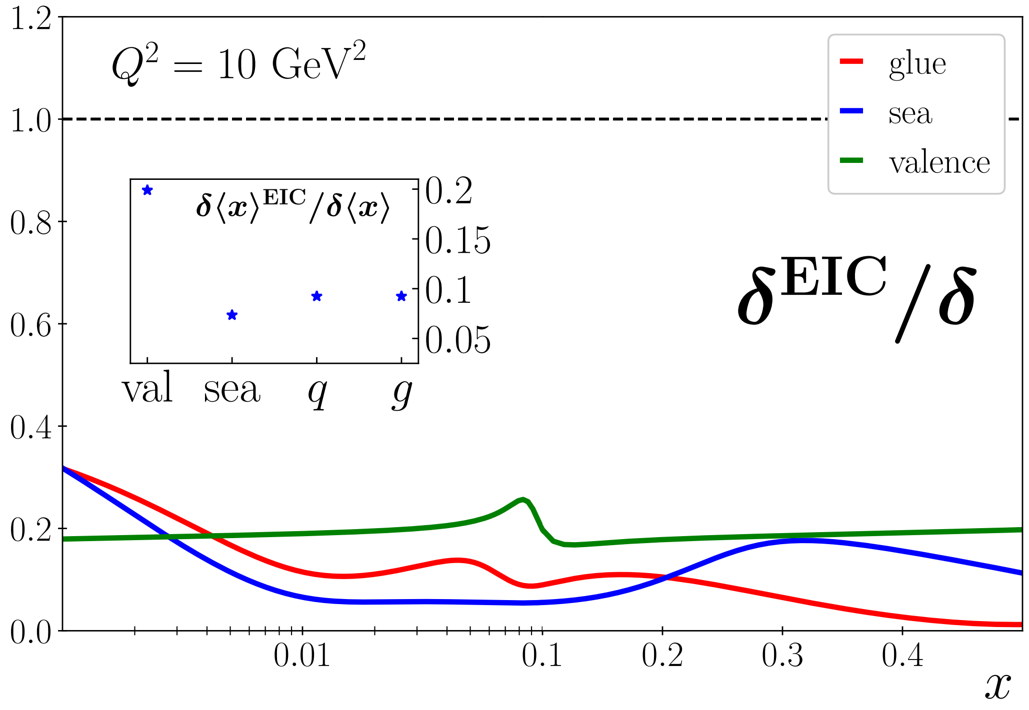
- Uncertainties are dominated by systematics
- Large range in x_π, Q^2 to overlap Drell-Yan and leading neutron regions



EIC Impact on Pion PDFs

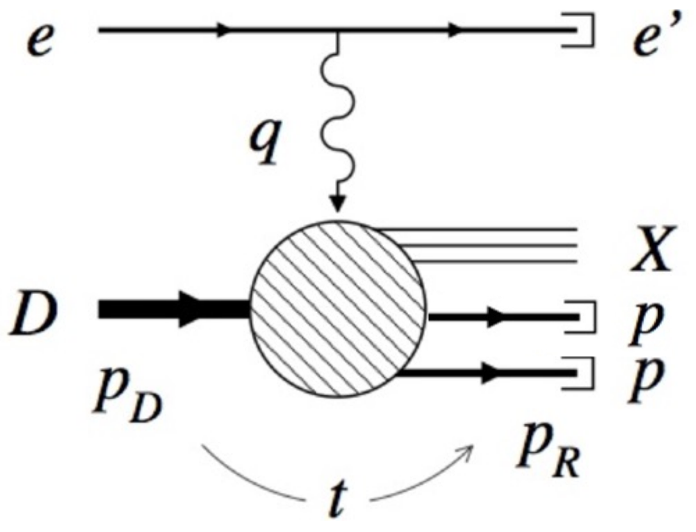
- Statistical uncertainties are small compared with HERA because of larger luminosity – systematics dominate
- $s = 5400$ GeV^2, 1.2% systematic uncertainty, integrated $\mathcal{L} = 100$fb^{-1}





Future Experiments

- TDIS experiment at 12 GeV upgrade from JLab, which will tag a proton in coincidence with a spectator proton
- Gives leading proton observable, complementary to LN, but with a fixed target experiment instead of collider (HERA)



- Proposed COMPASS++/AMBER also give π-induced DY data
- Both π^+ and π^- beams on carbon and tungsten targets

Conclusions

- Behavior of large-x valence distribution with double Mellin threshold resummation $q_v(x \to 1) \propto (1-x)^1$
- The marriage between lattice and experimental data sheds light on the pion PDF itself as well as systematics associated with the lattice
- Successful description of large-p_{T} Drell-Yan data from the pion
- Successfully have performed single fits to low- p_{T} of both pion TMD and collinear PDFs and Monte Carlo is underway