Opportunities at EIC for hadron structure studies

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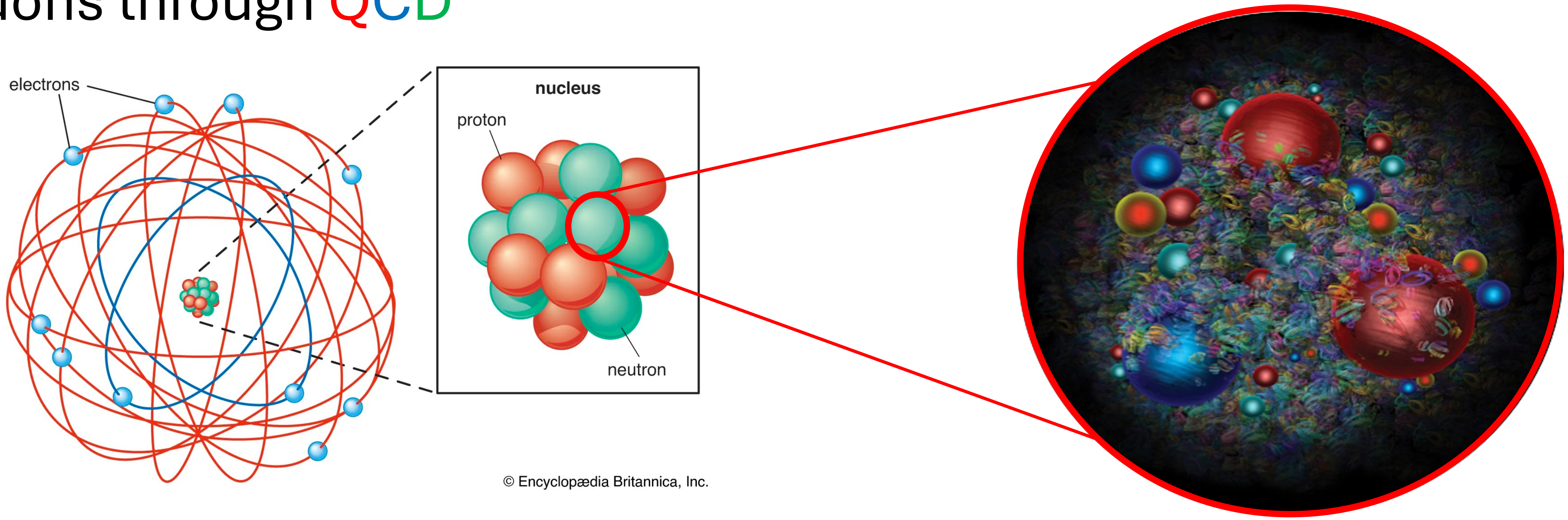
Motivation

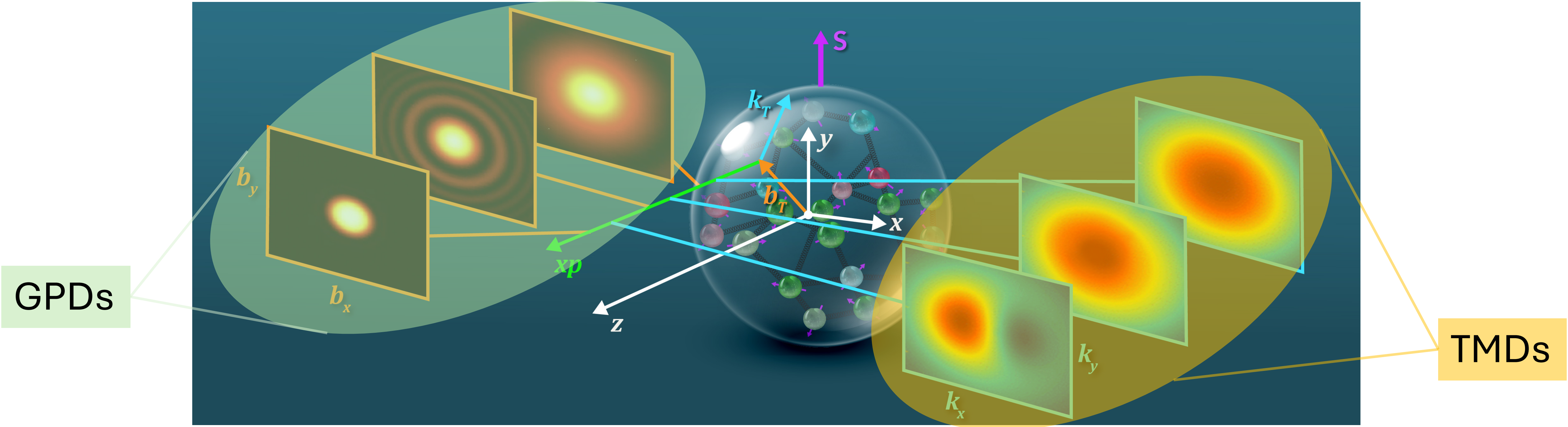
- We want to study the structure of hadrons in terms of quarks and gluons through QCD



- However, quarks and gluons are not directly observable and structures are unknown!

What are we looking for?

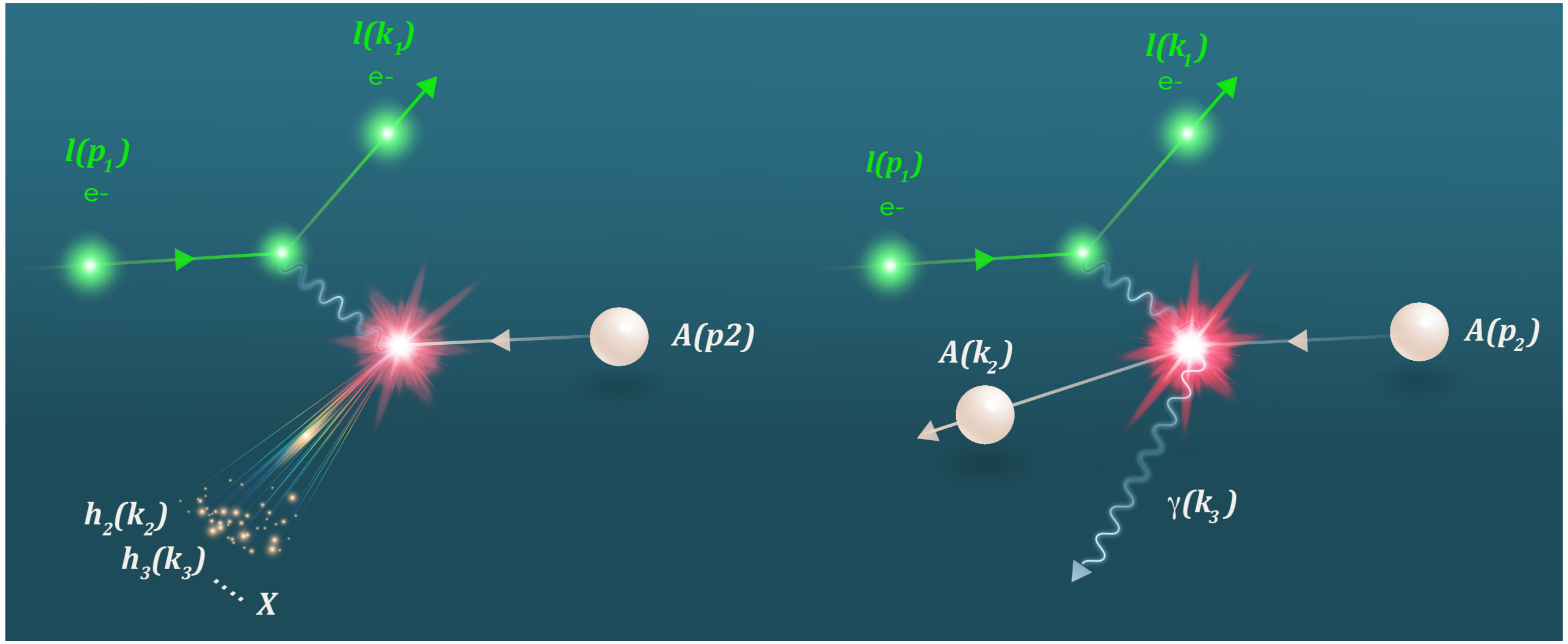
- Images of protons in coordinate and momentum space



- Nonperturbative functions such as TMDs and GPDs are defined in QFTs and describe the intrinsic *partonic structure of protons*

How do we do it?

- Through experimental data in factorizable processes in QCD
- Focus on electron-induced reactions that can be realized at JLab and future EIC



SIDIS – TMDs

DVCS – GPDs

1. Meson structures

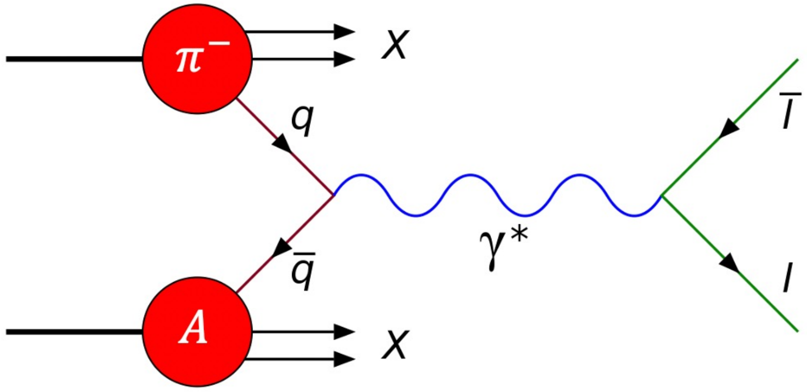
50 Years of QCD

Frontiers of QCD research in *Physical Review*

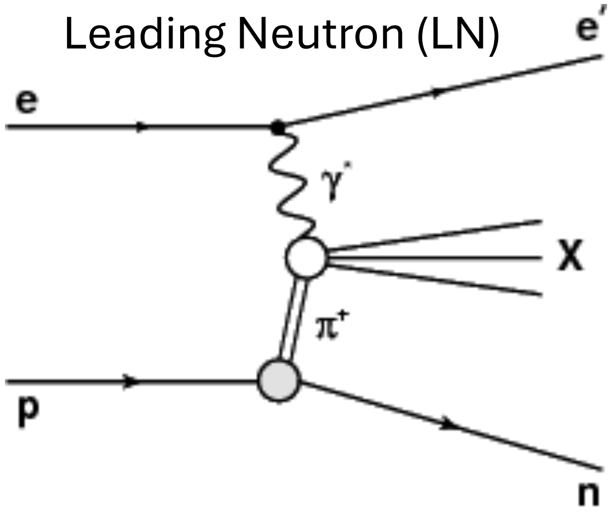
Precision determination of parton distribution functions:

Pion PDF analyses

Drell-Yan (DY)



Leading Neutron (LN)

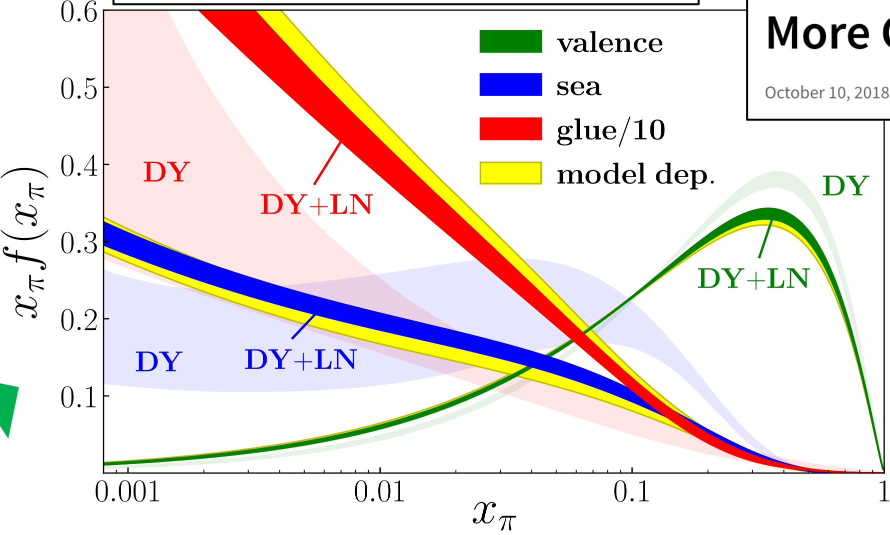


PHYSICAL REVIEW LETTERS **121,** 152001 (2018)

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]



More Gluons in the Pion

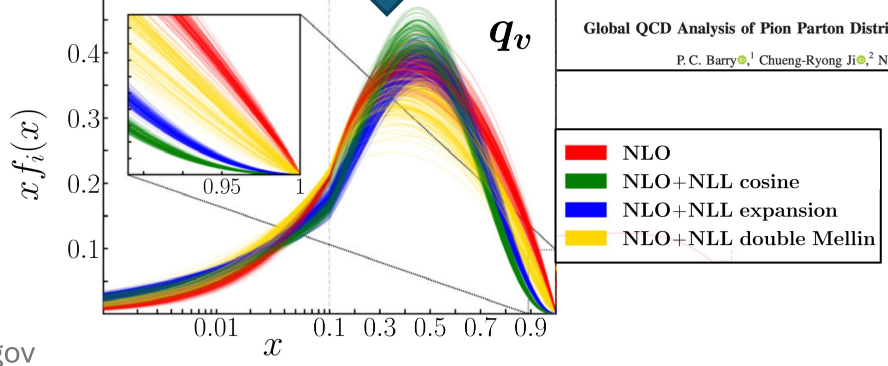
October 10, 2018 • *Physics* 11, s117

Threshold resummation in DY

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

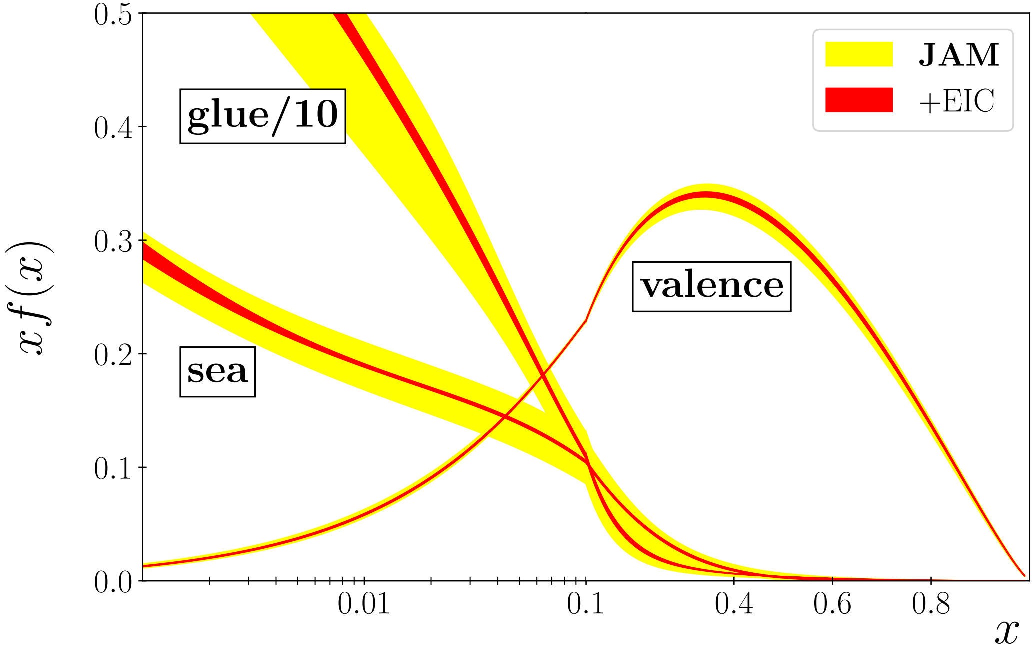
Global QCD Analysis of Pion Parton Distributions with Threshold Resummation

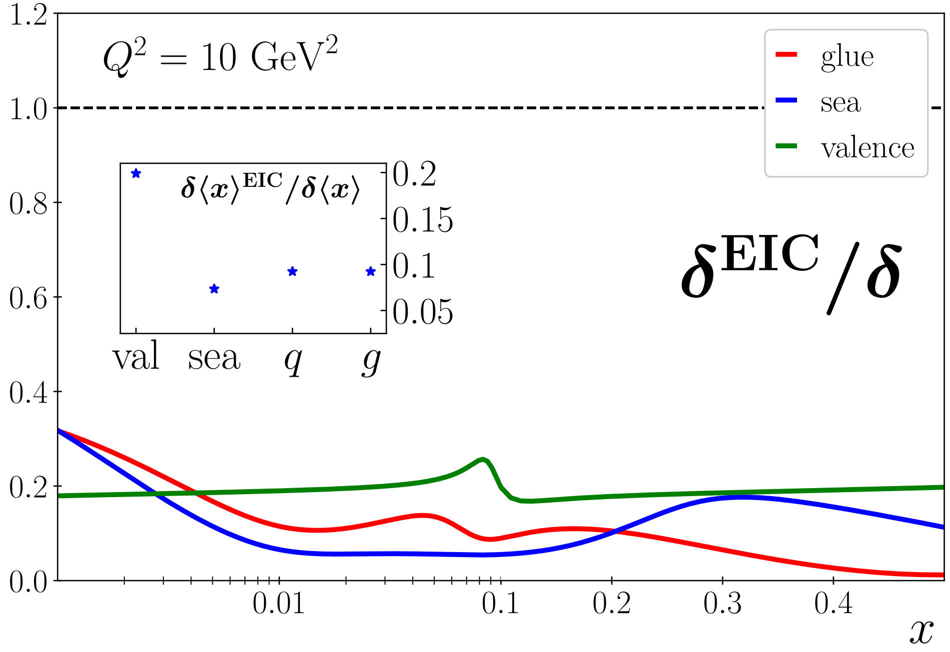
P. C. Barry,[1] Chueng-Ryong Ji,[2] N. Sato,[1] and W. Melnitchouk[1]



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}

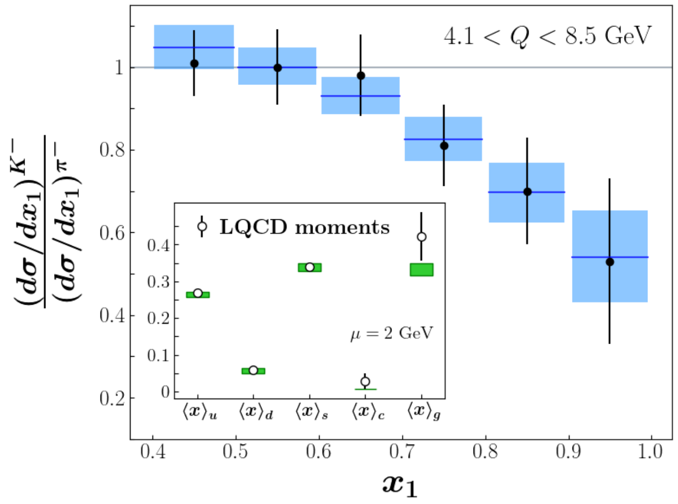




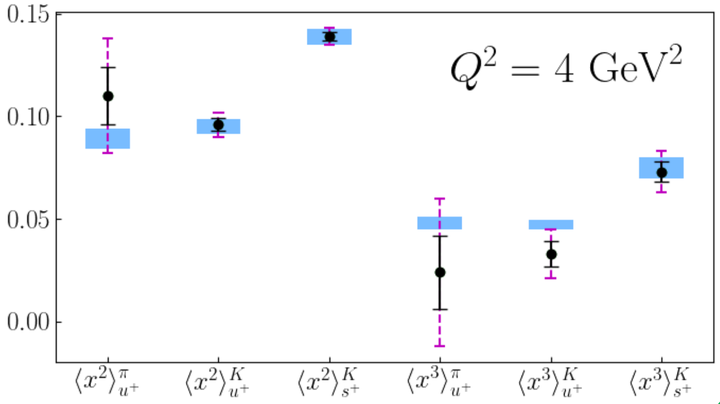
Abdul-Khalek, et al., Nuclear Physics A **1026**, 122447 (2022).

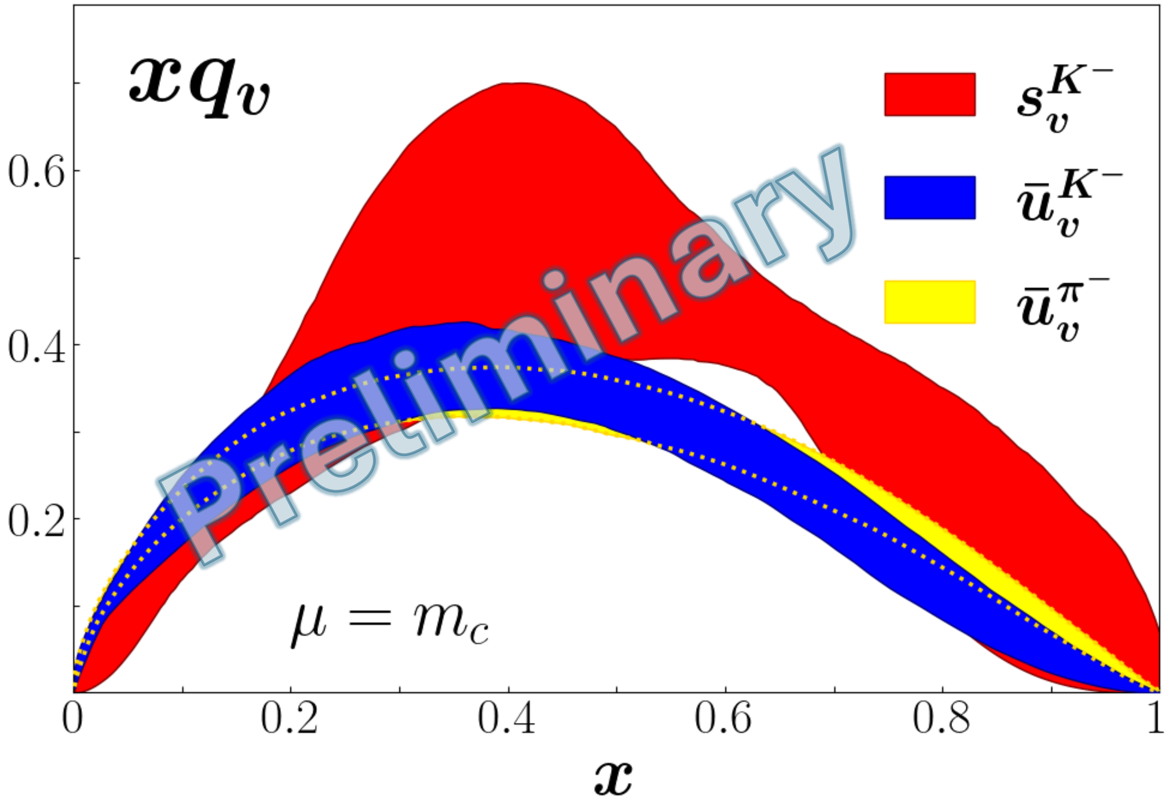
Kaon PDFs

NA3 data



LQCD data





Measurements of **leading hyperon** at EIC will be needed to access small-x PDFs

2. Transverse Momentum Distributions (TMDs)

Essential components of TMD phenomenology

Relation to k_T-space TMD

$$\tilde{f}_{q/\mathcal{N}}(x, b_T) = (2\pi)^2 \int d^2\boldsymbol{k}_T e^{-i\boldsymbol{b}_T \cdot \boldsymbol{k}_T} f_{q/\mathcal{N}}(x, k_T)$$

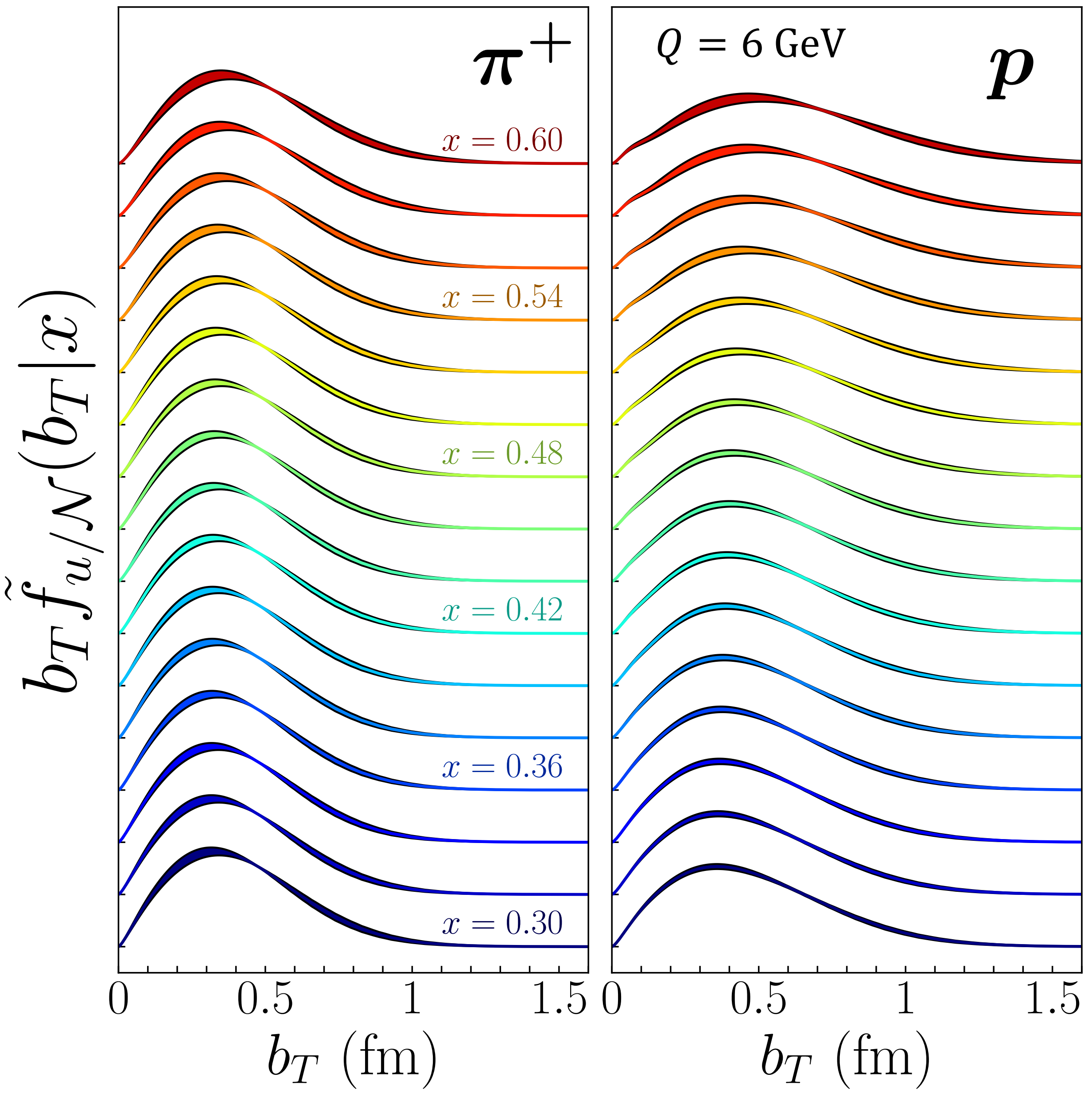
$$\tilde{f}(x, b_T; \mu_0, \zeta_0) = [C \otimes \boldsymbol{f}]\,(x, b_T; \mu_0, \zeta_0)\, f_{\mathrm{NP}}(x, b_T)$$

- Convenient to formulate TMDs in b_T-space (conjugate to k_T)
- Note the explicit dependence on the collinear PDF, while having an intrinsic non-perturbative TMD function
- Apply QCD evolution (has perturbative and non-perturbative components)

TMD PDFs of proton and pion

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

- Here we use fixed-target DY data
- Broadening in b_T-space appearing as x increases
  - $\Longrightarrow$Narrowing in k_T-space
- Up quark in pion is narrower than up quark in proton in b_T-space
  - $\Longrightarrow$ Broader in k_T-space



PCB, et al., PRD **108**, L091504 (2023).

Simultaneous Analysis of PDFs and TMDs

- Make use of high-energy precise datasets such as LHC
- Exploit the explicit dependence of the PDF on the TMD formalism and perform a global analysis to world TMD and collinear data

TMD				
			χ^2/N_{pts} (Z)	
Process	Experiment	N_{pts}	TMD-only	**TMD+PDF**
Fixed target DY	E288, E605, E772	224	1.36 (3.44)	**1.31 (3.02)**
TeVatron	CDF, D0	80	1.06 (0.45)	**1.11 (0.71)**
RHIC	STAR, PHENIX	12	1.15 (0.47)	**1.20 (0.60)**
LHC	ATLAS 8 TeV	30	2.07 (3.29)	**1.78 (2.55)**
	CMS 13 TeV	64	1.18 (1.03)	**0.92 (-0.39)**
	LHCb 7, 8, 13 TeV	26	0.53 (-1.97)	**0.50 (-2.12)**
TMD total		436	1.27 (3.72)	1.20 (2.76)

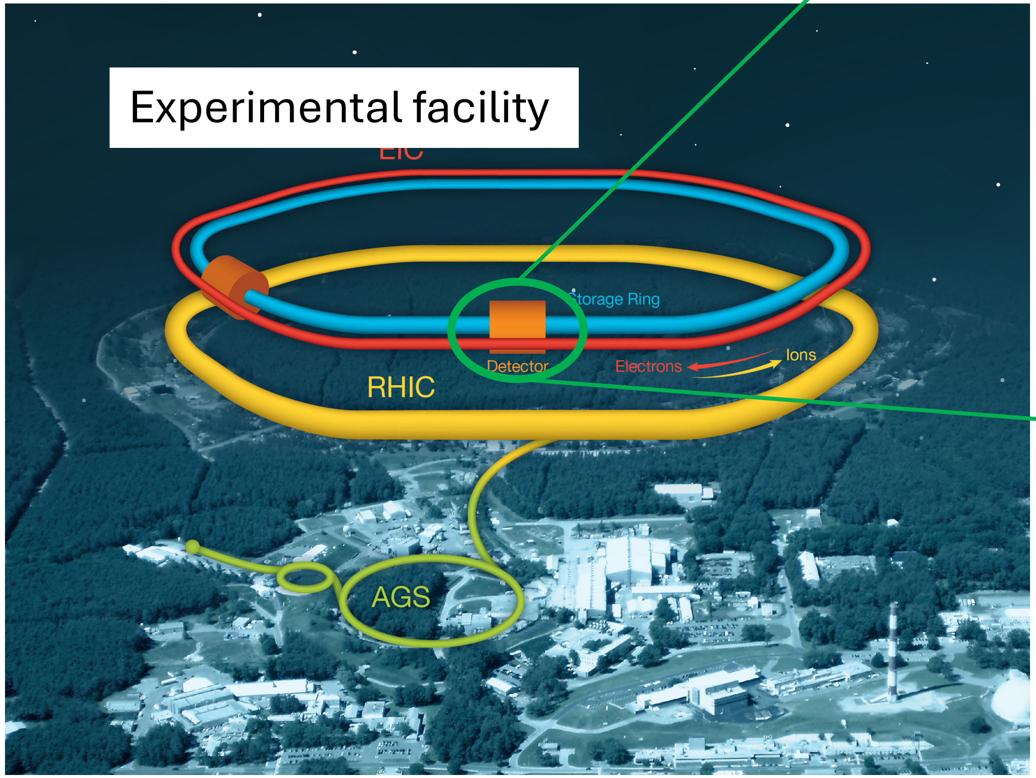
Collinear				
Process	Experiment	N_{pts}	PDF-only	**TMD+PDF**
DIS	SLAC, BCDMS, NMC, JLab	2501	1.02 (0.82)	**1.02 (0.59)**
	HERA	1185	1.27 (6.01)	**1.27 (6.11)**
Drell–Yan	E866, E906	205	1.27 (2.54)	**1.26 (2.50)**
W-lepton asymmetry	CMS, LHCb, STAR	70	0.80 (-1.20)	**0.78 (-1.35)**
W charge asymmetry	CDF, D0	27	1.12 (0.51)	**1.13 (0.53)**
Z rapidity	CDF, D0	56	1.09 (0.55)	**1.11 (0.60)**
Inclusive jets	CDF, D0, STAR	198	1.00 (0.00)	**0.98 (-0.13)**
W + charm	ATLAS, CMS	37	0.65 (-1.66)	**0.62 (-1.84)**
Collinear total		4279	1.10 (4.31)	1.09 (4.14)
Total		**4715**		**1.10 (4.79)**

Preliminary

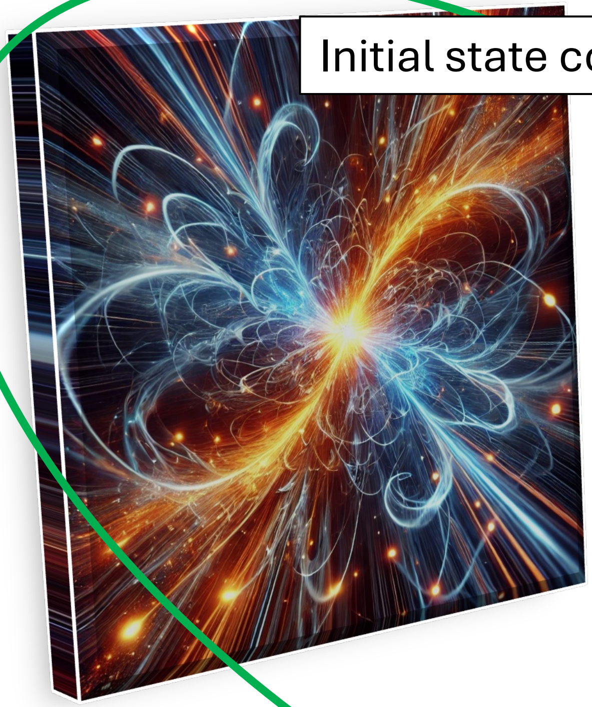
3. Event-level inference

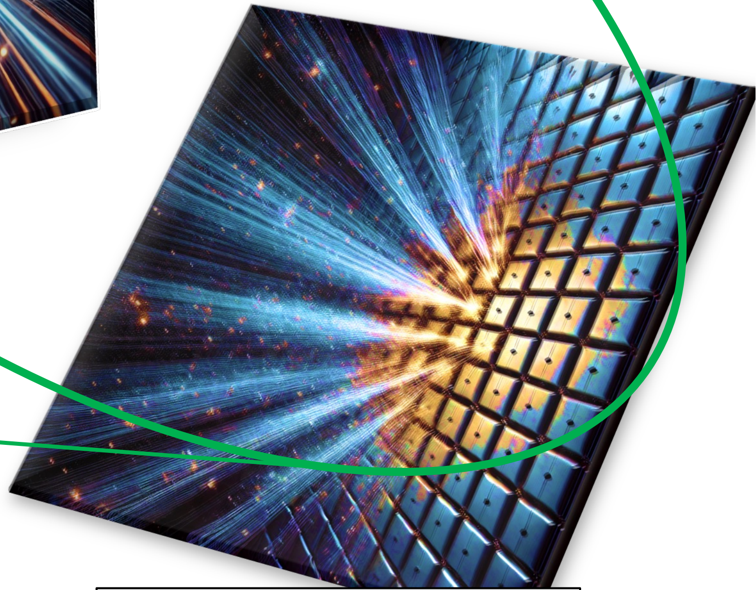
Observations from Experiment

Deep inelastic scattering: $ep \rightarrow e'X$



Initial state collisions



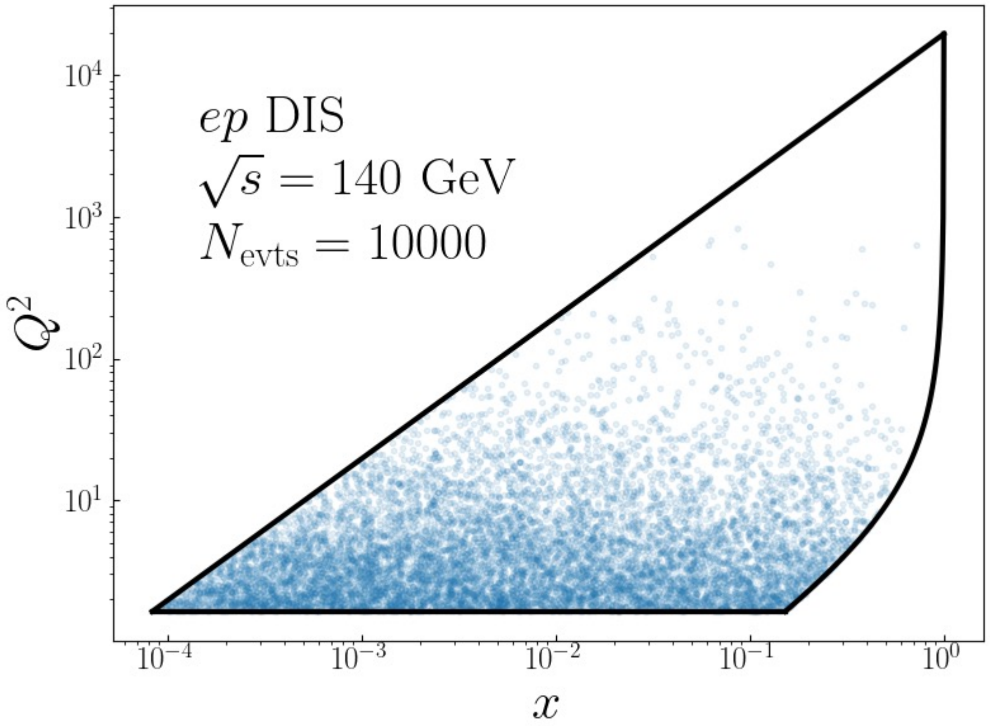


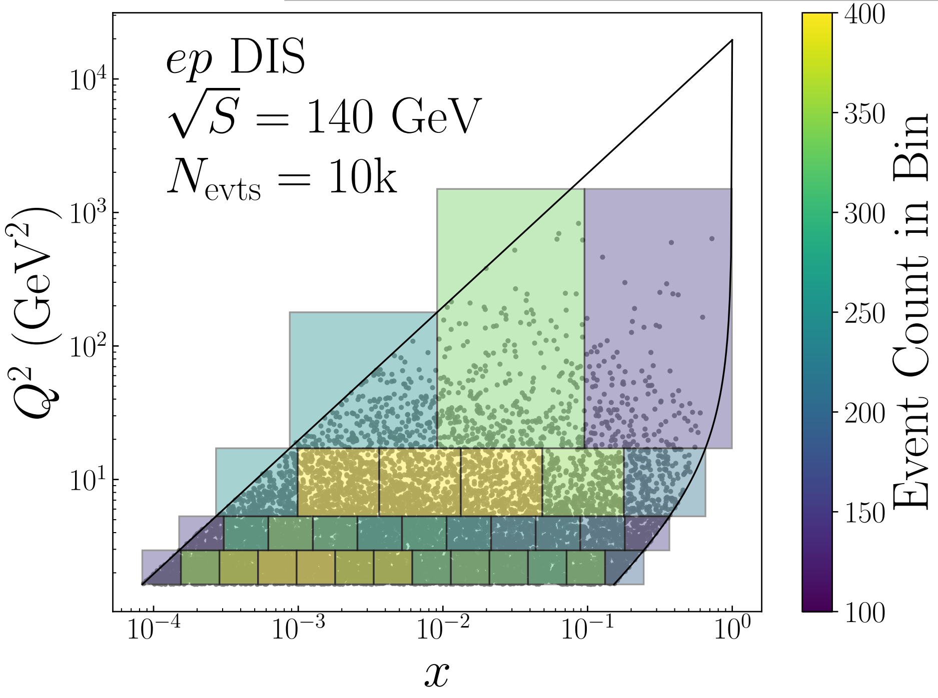
Final state detection

Presenting the data

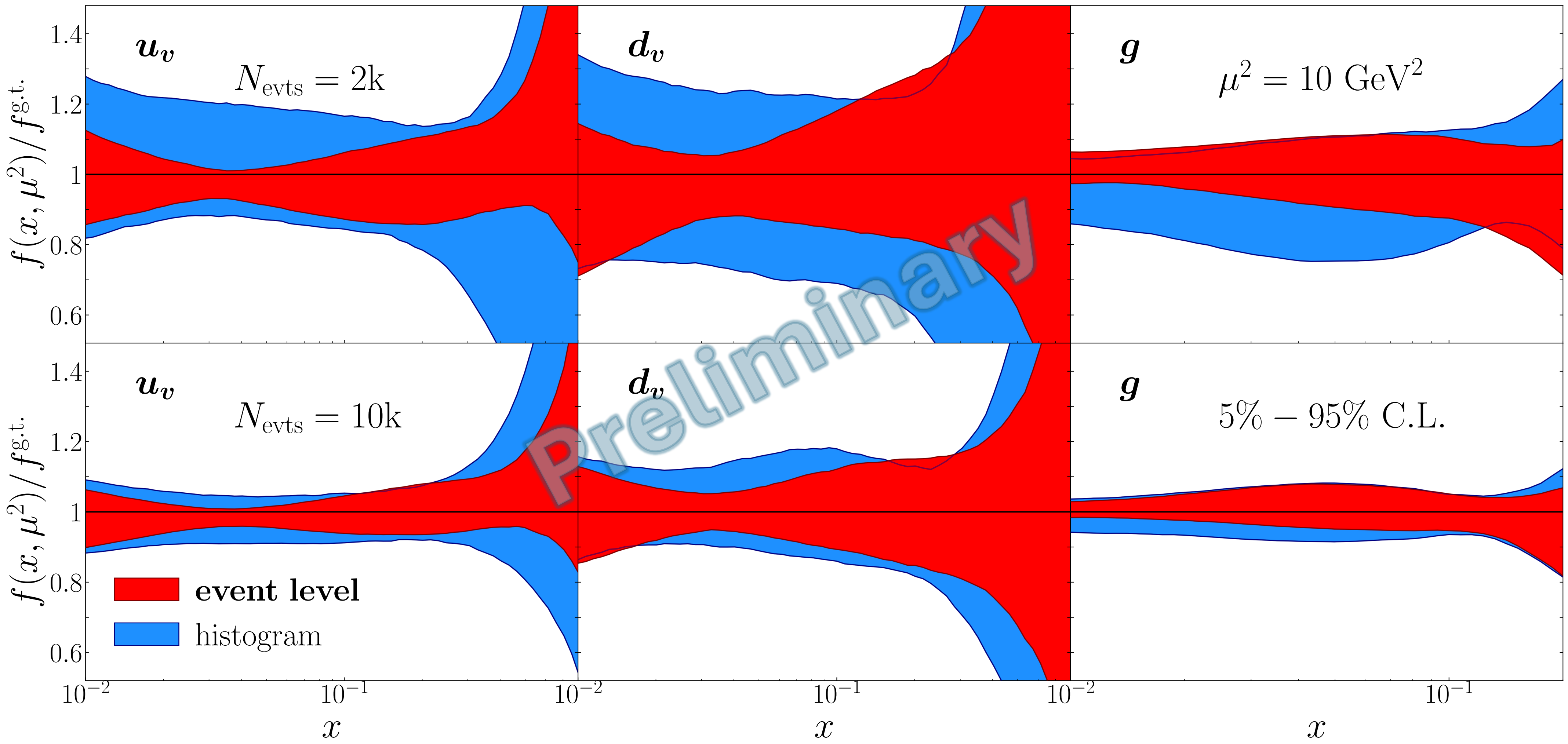
- Traditionally, detected events are binned in kinematic variables through histograms

Traditional approach – lose information by averaging





Resulting PDFs



EIC outlook

1. Leading baryon observables can improve our knowledge of **meson structures**, complementing existing Drell-Yan data and lattice QCD data
   - Tagged SIDIS – access to meson TMDs
2. SIDIS measurements at EIC can provide complementary high energy measurements to LHC data for **TMD extractions**
   - Simultaneous analysis of FFs and TMD FFs
3. Improve our knowledge of internal structure of hadrons through **event-level inference**
   - Next step is to analyze the effects of a detector