

JLUO Annual Meeting

June 23-25, 2026



First simultaneous global QCD analysis of kaon and pion parton distributions with lattice QCD constraints

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2026 JLUO Annual Meeting

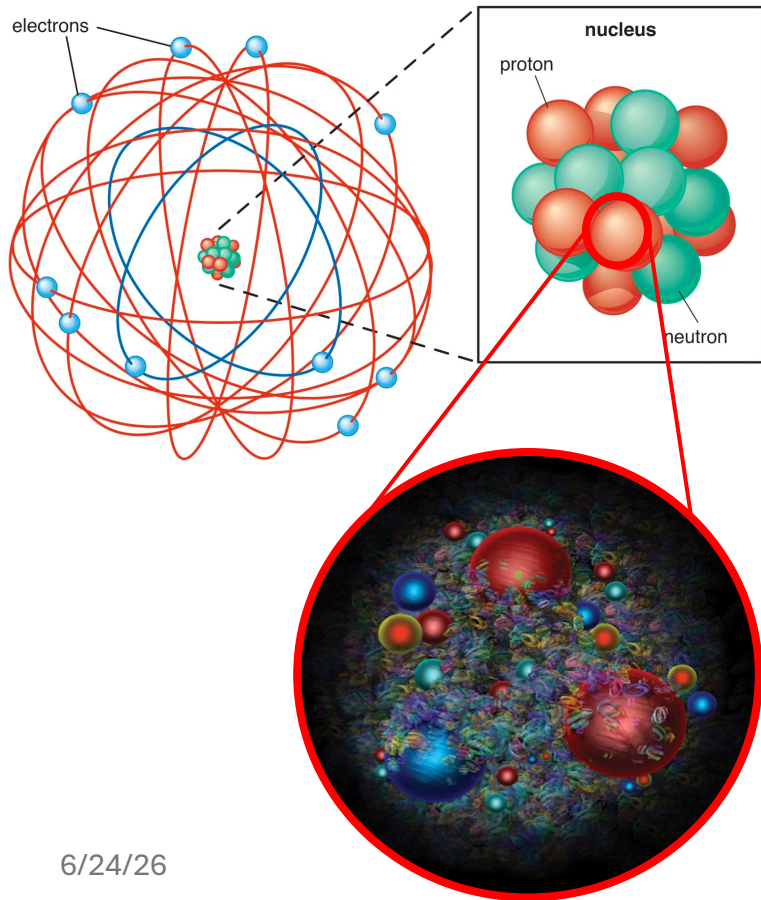
June 24th, 2026

arXiv:2510.11979; accepted into PRD

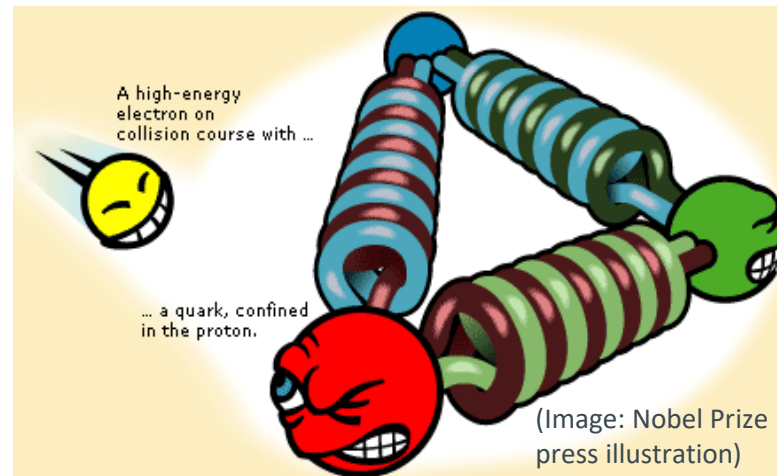


Why is femtoscale imaging important?

- Visible matter of the universe is made up of atoms \supset nucleons \supset quarks and gluons



- Related with fundamental scientific problems such as origins of color confinement and mass

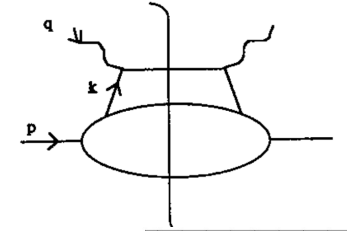


How do we image?

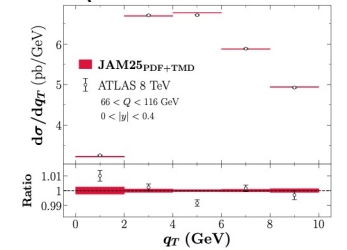
$$\frac{d\sigma}{d\Omega} \propto \mathcal{H} \otimes f = \int_x^1 \frac{d\xi}{\xi} \mathcal{H} \left(\frac{x}{\xi} \right) f(\xi)$$

- Confined nature of quarks and gluons ➤ Perform **inference** of structure from data
- Observables must be **factorizable** within controllable approximations
- Develop a **global QCD** analysis framework
- **Computation** is what allows us to rigorously achieve these goals

Theory



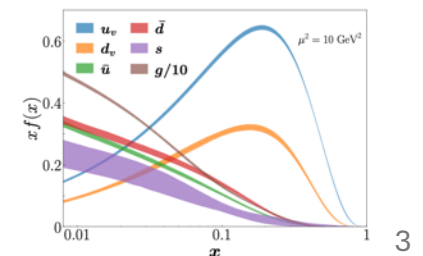
Measurement



Computation

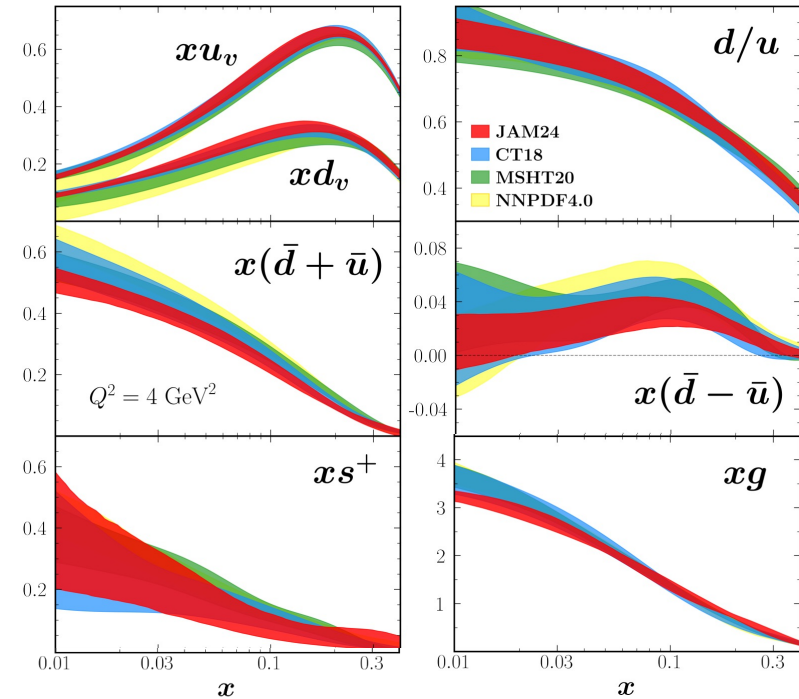
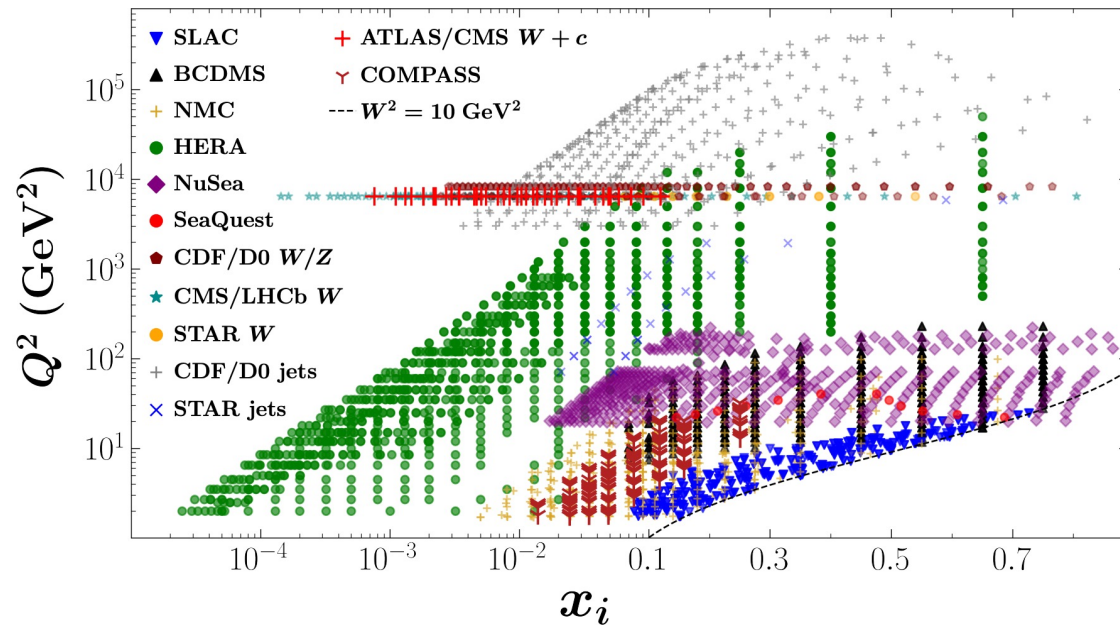


Inferred structure



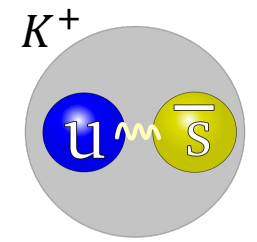
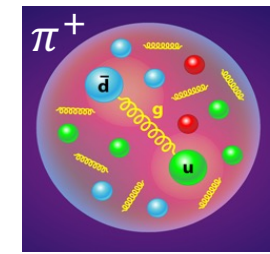
What do we know about structures?

- Most familiar description of hadron structure: longitudinal momentum distributions, especially in the proton



T. Anderson, et al., Phys. Rev. D **112**, 094011 (2025).

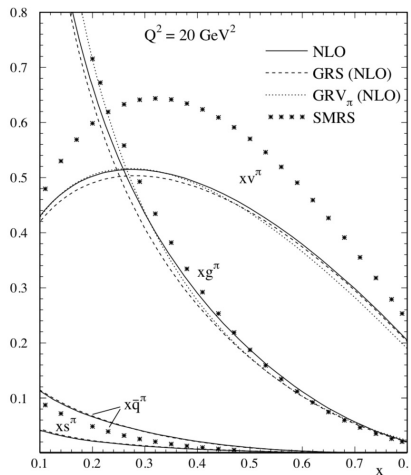
Other structures - Mesons



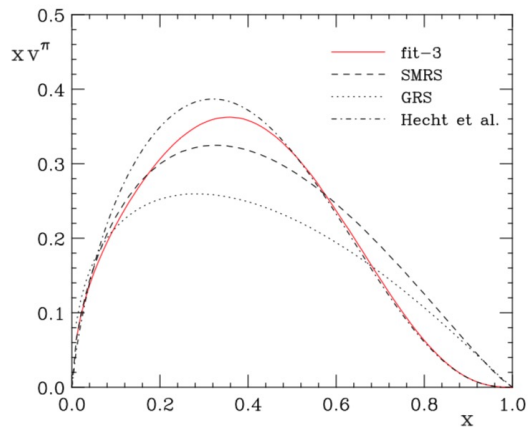
- We want to learn about QCD through the structure of hadrons
- Does it make sense to *only* study proton structure? **NO!**
- **Mesons** offer importance of emergent phenomena of QCD such as
 - How is mass generated?
 - How do quarks and gluons arrange themselves within hadrons?
 - Why is there confinement?
- Allows for another probe of confinement scales in quark-gluon bound systems

Pion structure in phenomenology

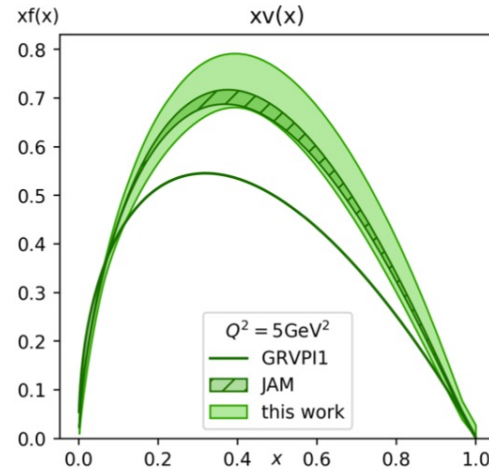
- Historically, pion distributions have been extracted from fixed target πA data
 - Drell-Yan (DY) $\pi A \rightarrow \mu^+ \mu^- X$
 - Prompt photon $\pi A \rightarrow \gamma X$



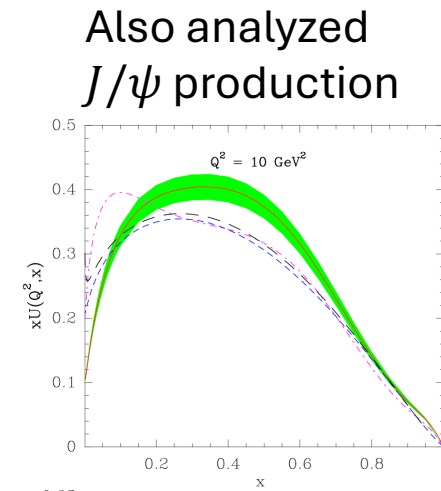
GRS, GRV, and SMRS



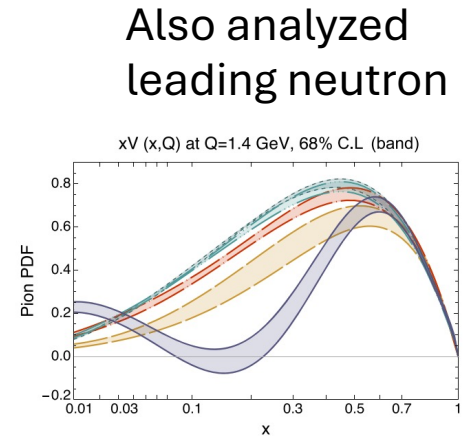
ASV valence PDF



xFitter



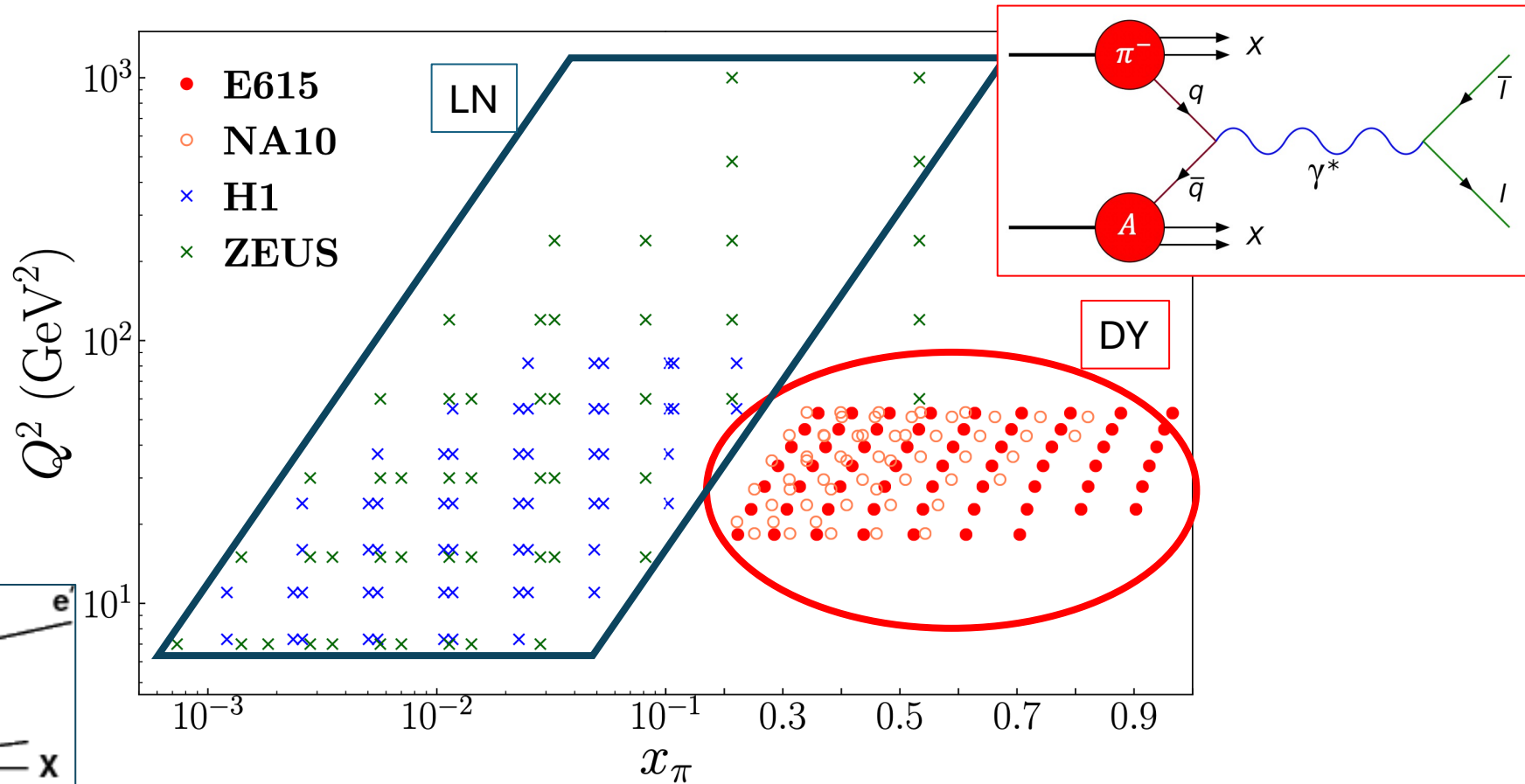
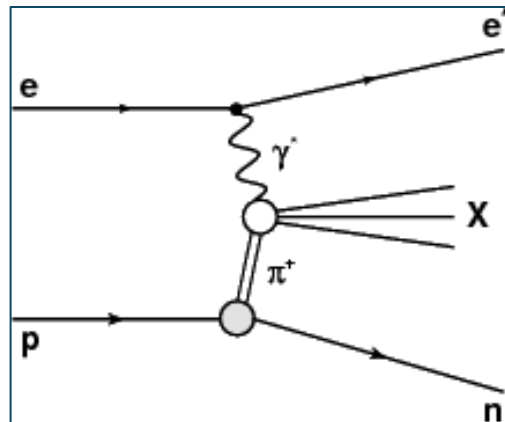
Statistical modeling

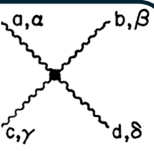


FantoPDF

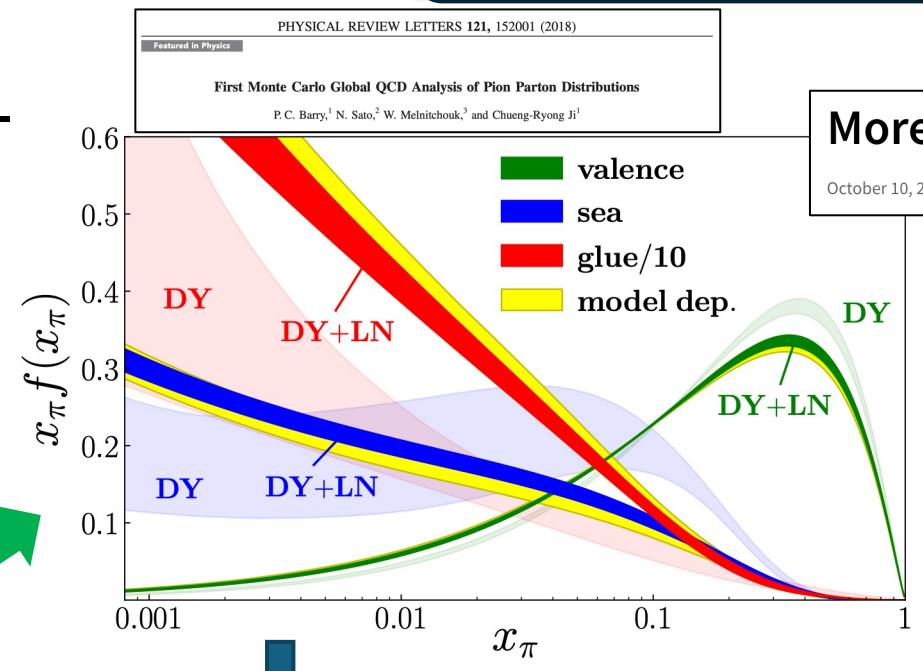
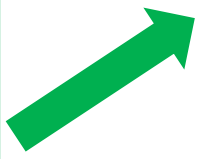
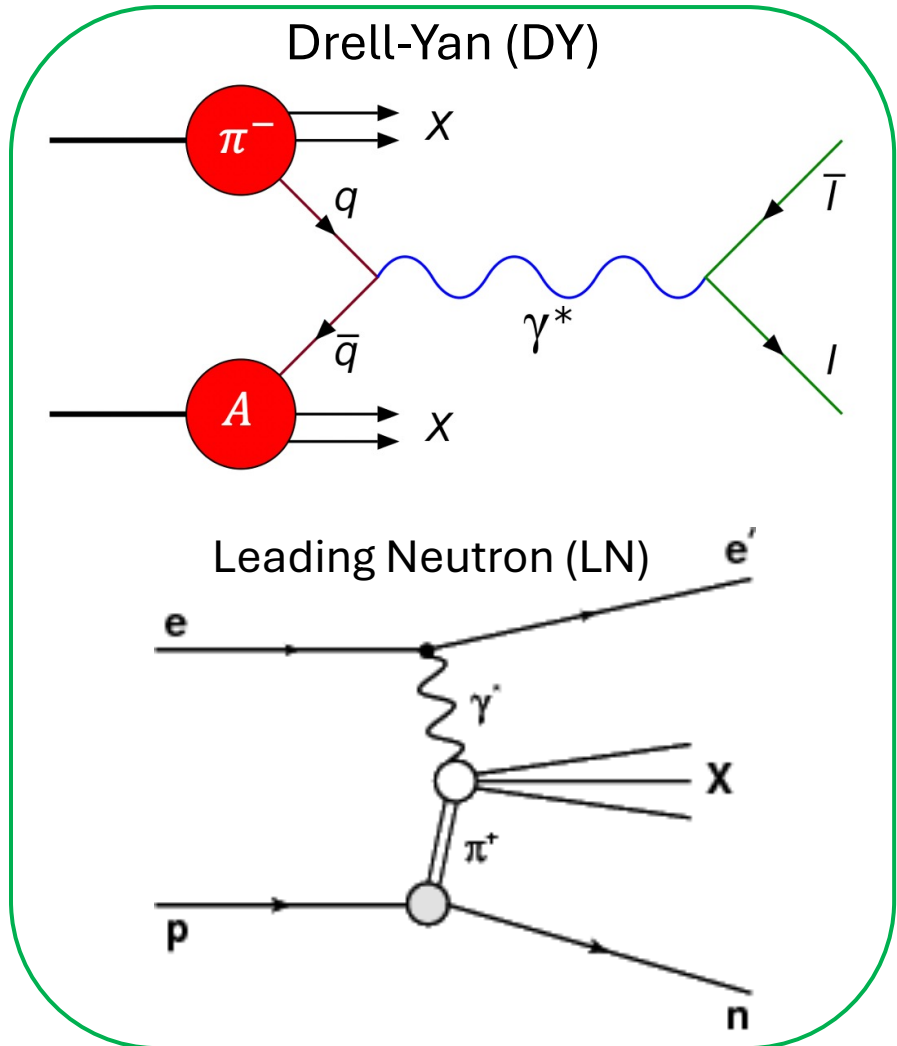
Available datasets for pion structures

- Much less available data than in the proton case



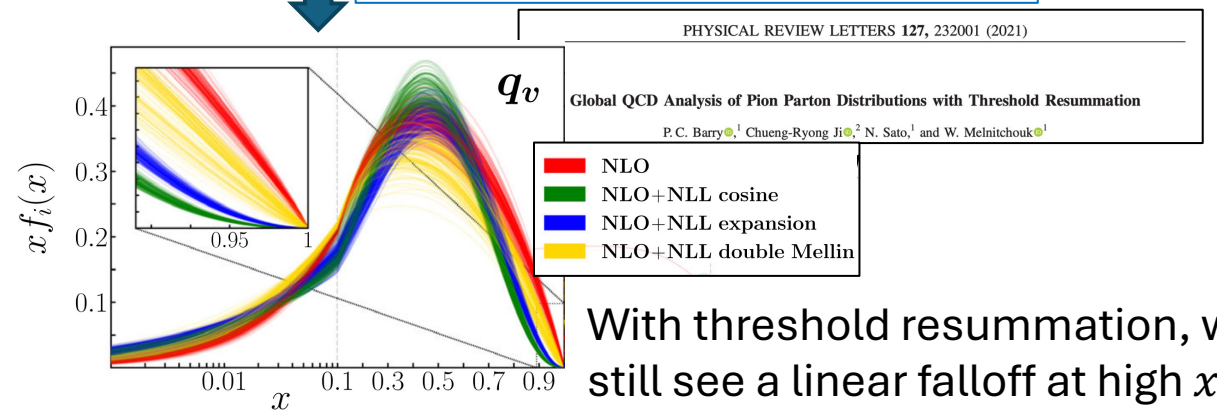


Pion PDF analyses



More Gluons in the Pion
October 10, 2018 • *Physics* 11, s117

Threshold resummation in DY



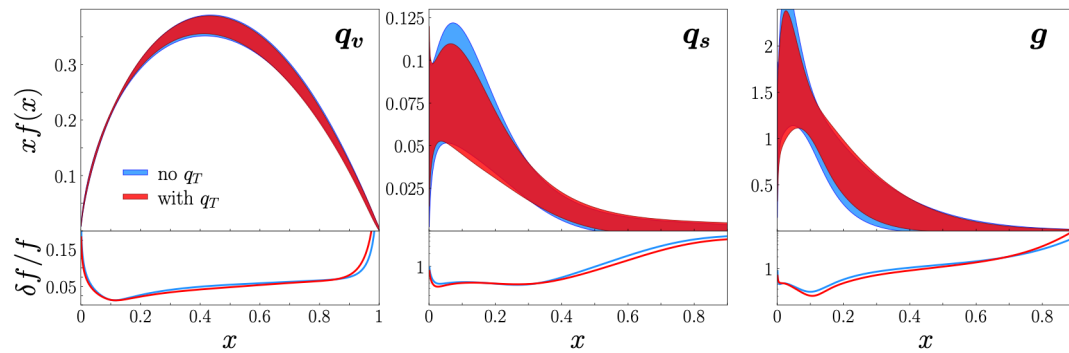
With threshold resummation, we still see a linear falloff at high x

Brief aside on q_T -dependent Drell-Yan

- Small and large q_T -dependent data do not affect much the pion PDFs

PHYSICAL REVIEW D 108, L091504 (2023)
 Letter
 Tomography of pions and protons via transverse momentum dependent distributions
 P. C. Barry^{1,2}, L. Gamberg³, W. Melnitchouk^{1,4}, E. Moffat^{1,2}, D. Pitonyak⁵, A. Prokudin^{1,2} and N. Sato¹

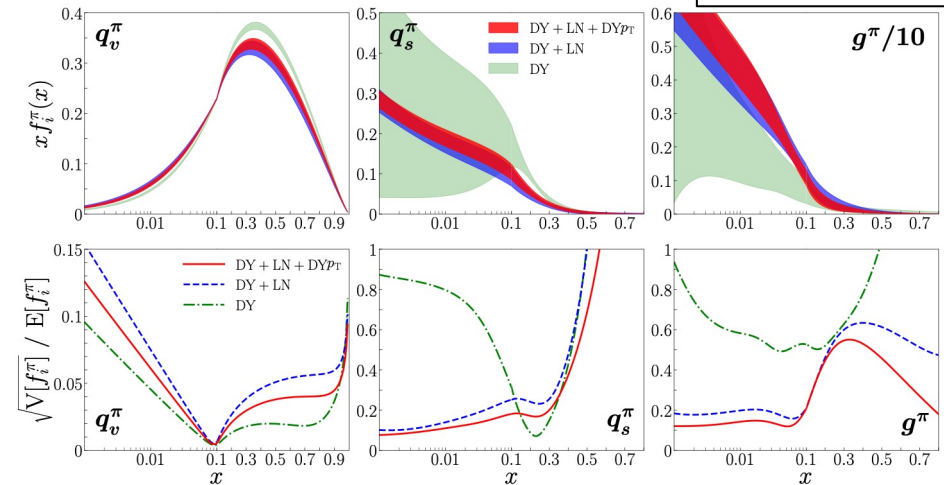
Small q_T (TMD)



Explicit quark PDFs in the operator product expansion

Large q_T (collinear)

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. Cao¹, P. C. Barry^{2,3}, N. Sato¹ and W. Melnitchouk³
 Jefferson Lab Angular Momentum (JAM) Collaboration



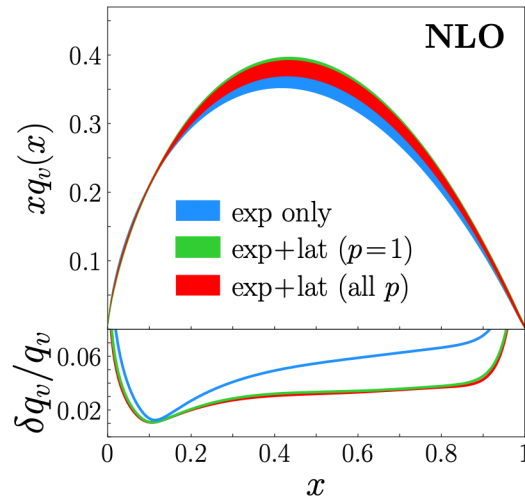
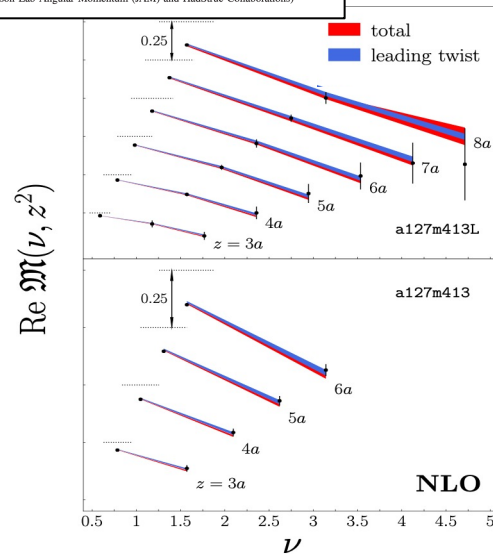
Preferred scale choice is $\mu = p_T/2$

Incorporating lattice QCD data

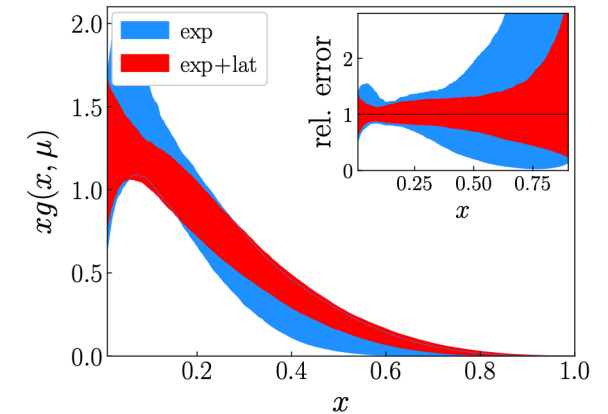
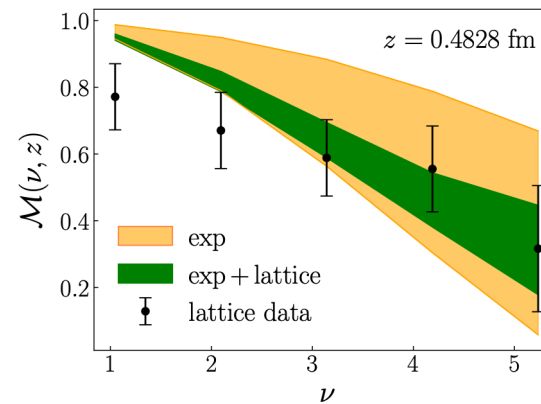
- Lattice calculations of reduced Ioffe time pseudodistributions complement existing experimental data

PHYSICAL REVIEW D 105, 114051 (2022)
 Complementarity of experimental and lattice QCD data on pion parton distributions
 P. C. Barry¹, C. Egerer¹, J. Karpie², W. Melnitchouk^{1,3}, C. Monahan^{1,3}, K. Orginos^{1,3}, Jian-Wei Qiu^{1,3}, D. Richards¹, N. Sato¹, R. S. Sufian^{1,3} and S. Zafeiropoulos⁴
 (Jefferson Lab Angular Momentum (JAM) and HadStruc Collaborations)

Valence sector



Gluon sector



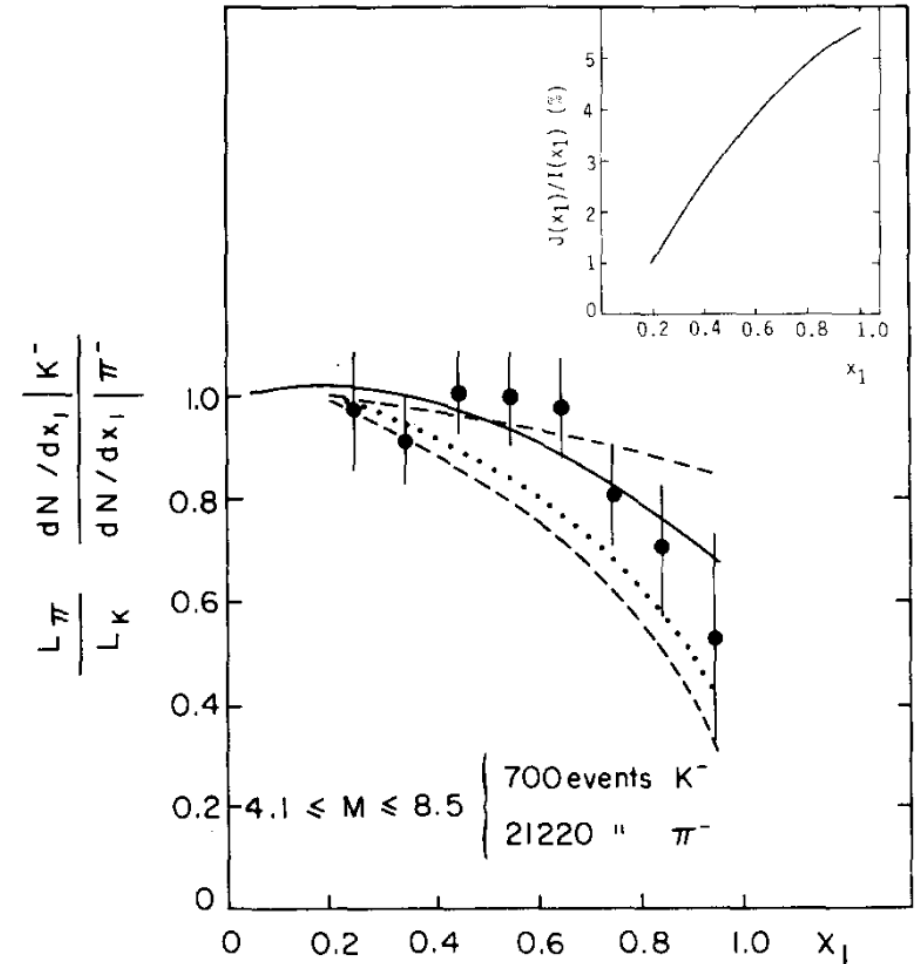
Provides large- x constraints on the gluon

Good, PCB, Lin, Melnitchouk, NieMiera, Sato; 2507.22730

Increased precision for valence distribution

Experimental data for kaons

- In 1980, the NA3 collaboration published results of kaon-induced Drell-Yan (DY) cross sections
- Presented as a ratio of kaon-induced to pion-induced DY cross sections as a function of x_1
- Both the K^- and π^- beams were incident on a platinum target
- Only 700 measured K^- events!
- Expected dominance of the valence-valence flavor combinations



J. Badier, et al., Phys. Lett. B **93**, 354 (1980)

Phenomenological analyses of kaon PDFs

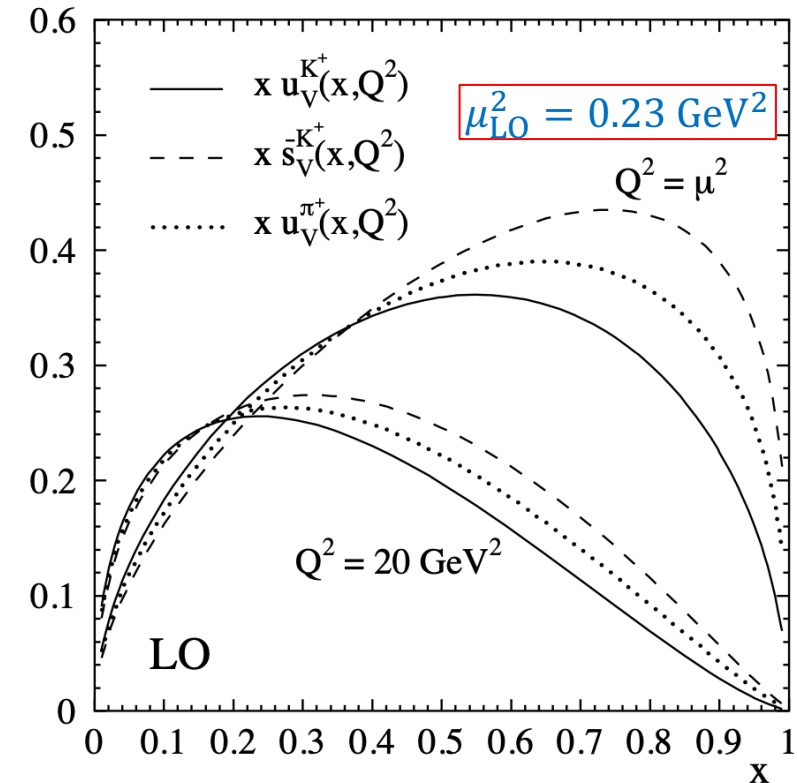
- Glück, Reya, and Stratmann (GRS) fitted the NA3 DY according to

$$u_v^{K^+}(x) = N_u(1-x)^{\kappa} v^{\pi}(x)$$

$$\bar{s}_v^{K^+}(x) = v^{\pi}(x) - u_v^{K^+}(x)$$

with influence from their pion PDF results

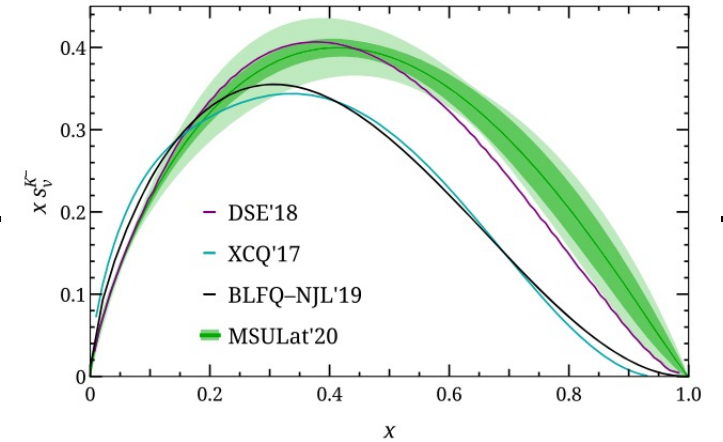
- More recently, a statistical model for parametrization has additionally used J/ψ production to constrain the gluon distribution [Bourelly, Buccella, Chang, and Peng, Phys. Lett. B **848**, 138395 \(2024\).](#)



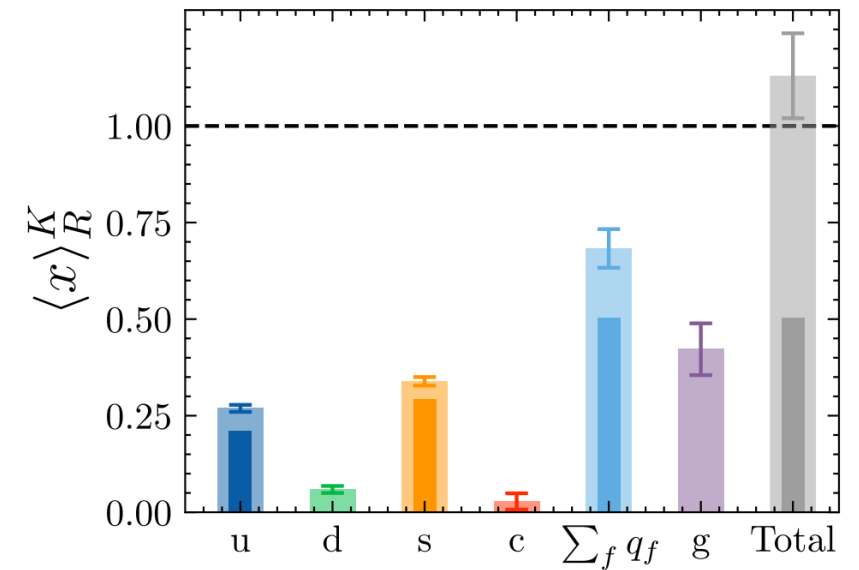
GRS, Eur. Phys. J C **2**, 159 (1998)

Lattice QCD efforts

- Lattice QCD plays a key role in constraining kaon PDFs where experimental data are limited
- Examples include:
 - Valence quark distributions from LaMET from MSULat (also gluon distributions)
 - Mellin moments of kaon PDFs from ETMC (up to $\langle x^3 \rangle$)
- We use the ETMC moments as constraints in our global analysis of kaon and pion PDFs



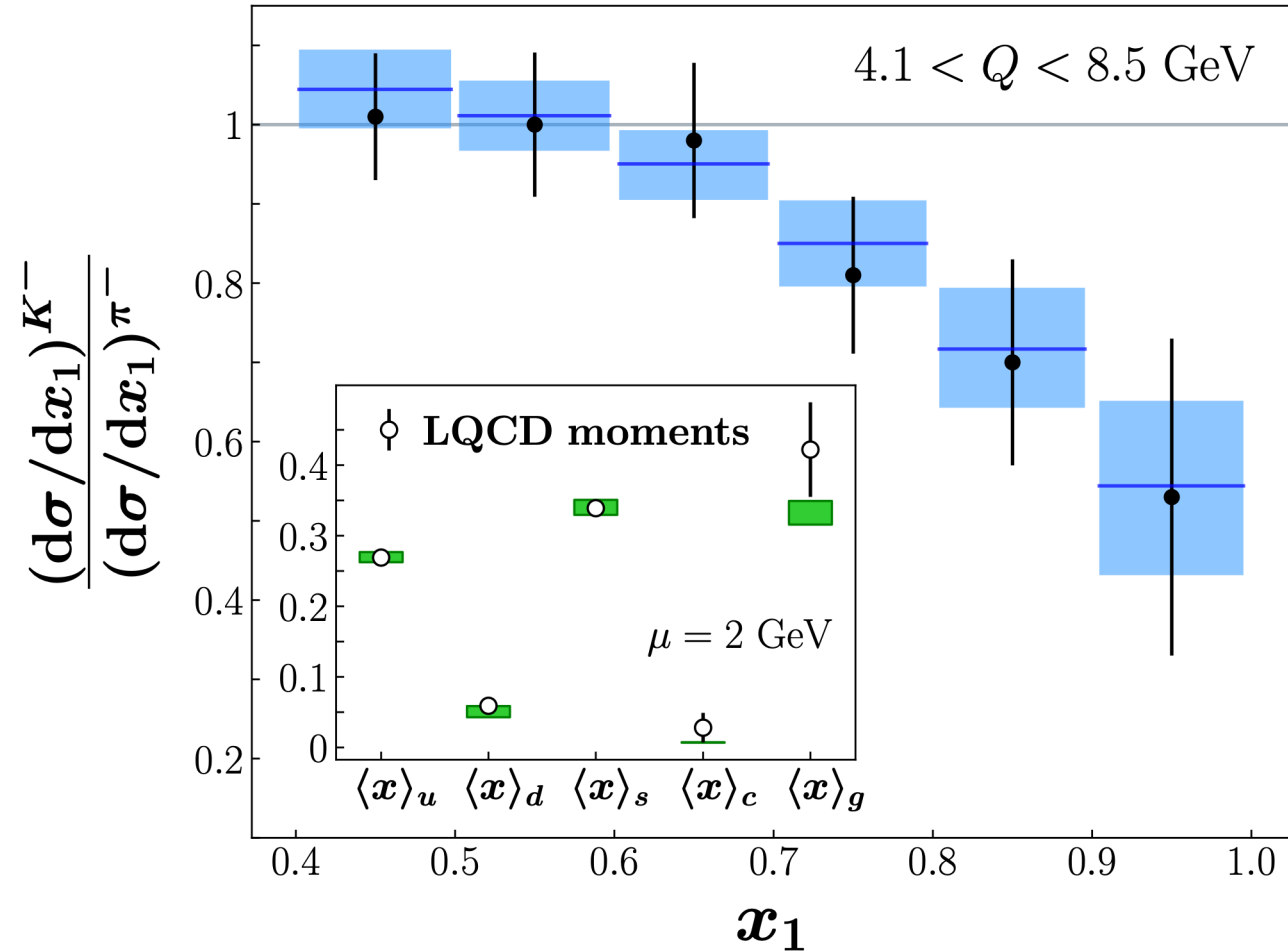
MSULat, Phys. Rev. D **103**, 014516 (2021).



ETMC Phys. Rev. Lett. **134**, 131902 (2025).

Data and theory agreement

- Because of large errors on the NA3 data, we achieve $\chi^2/N_{pts} = 0.08$
- Precision of quark LQCD moments leads to smaller fitted $\langle x \rangle_g$ than the lattice
- Additional $\langle x \rangle^\pi$ and higher moments used
 - Higher moments were not calculated at physical point



Lattice QCD moments

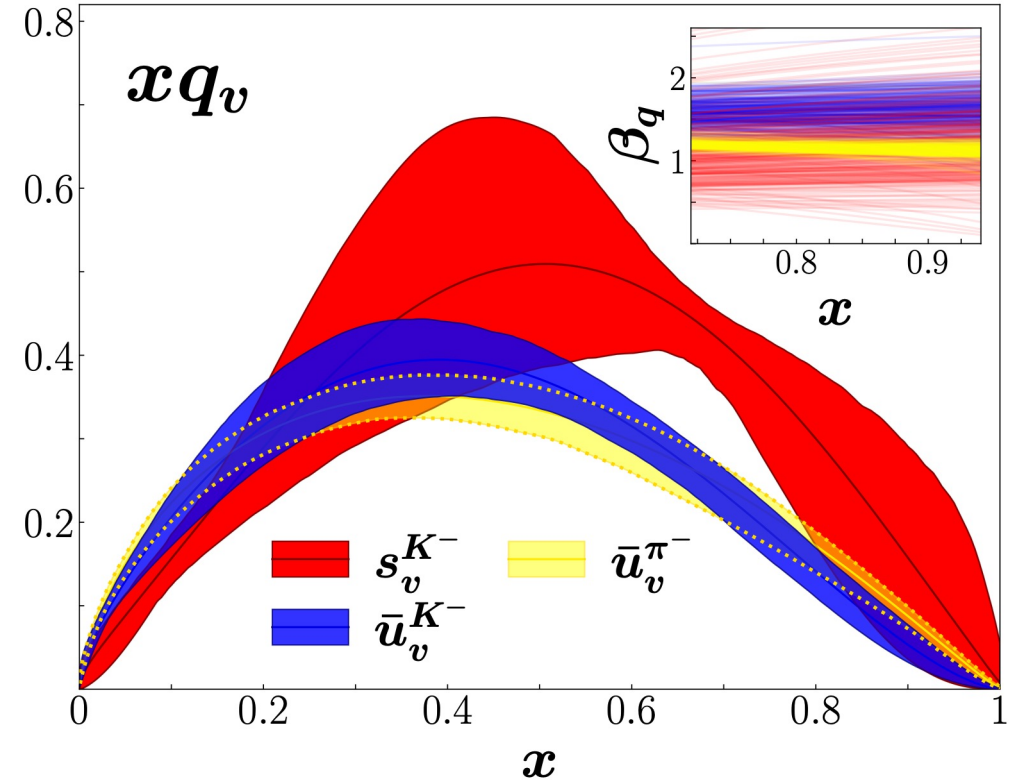
- Good agreement with all LQCD moments for pion and kaon, including $\langle x^2 \rangle$ and $\langle x^3 \rangle$
- ETMC reports similar gluon momentum fractions for the pion and kaon
- We find $\langle x \rangle_g^K < \langle x \rangle_g^\pi$
 - Gluonic contribution to mass is $\frac{3}{4} \langle x \rangle_g$
 - 1/3 mass for pion, but 1/4 mass for the kaon

Moment	<i>kaon</i>		<i>pion</i>	
	ETMC	JAM	ETMC	JAM
$\langle x \rangle_u$	0.269(9)	0.269(7)	0.249(28)	0.256(10)
$\langle x \rangle_d$	0.059(9)	0.051(8)	0.249(28)	0.256(10)
$\langle x \rangle_s$	0.339(11)	0.340(11)	0.036(15)	0.040(10)
$\langle x \rangle_c$	0.028(21)	0.0071(3)	0.013(16)	0.0092(6)
$\langle x \rangle_g$	0.422(67)	0.333(17)	0.402(53)	0.439(28)
$\langle x^2 \rangle_u$	0.096(3)	0.089(4)	0.110(14)	0.090(4)
$\langle x^2 \rangle_s$	0.139(2)	0.137(4)	—	—
$\langle x^3 \rangle_u$	0.033(6)	0.050(3)	0.024(18)	0.052(2)
$\langle x^3 \rangle_s$	0.073(5)	0.082(5)	—	—

Resulting PDFs

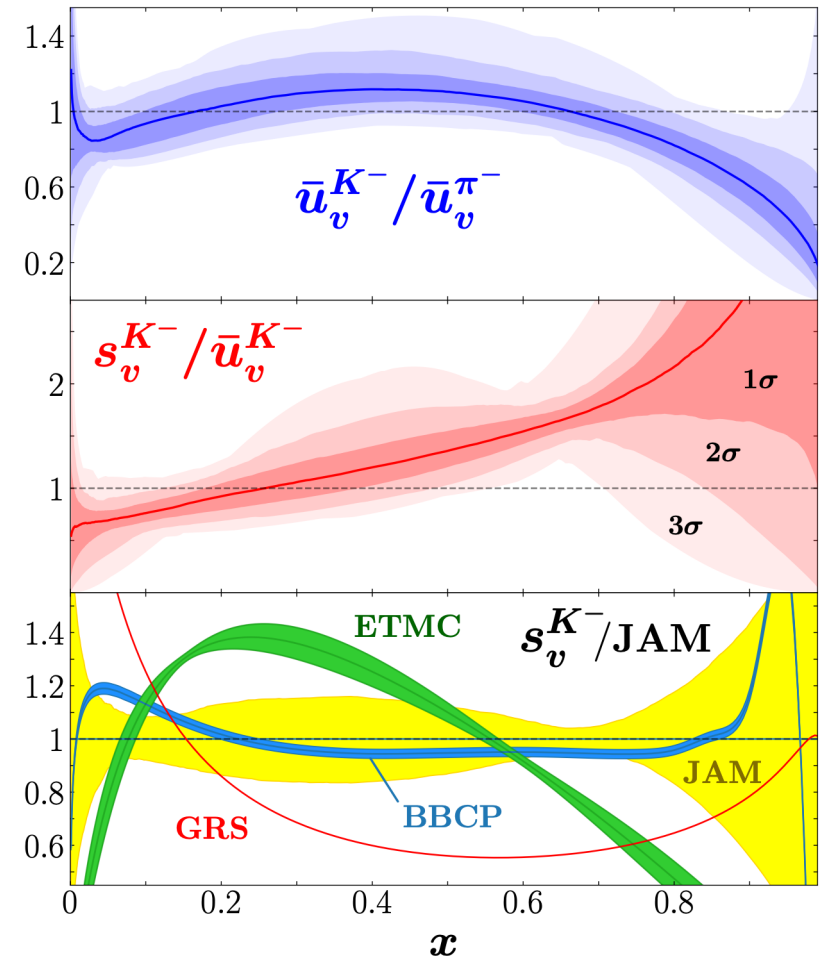
- The strange valence, largely constrained by the lattice moments, gives a noticeably larger signal at intermediate x , in accordance with the lattice moments
- β_q is not necessarily at an integer value for any valence distribution

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



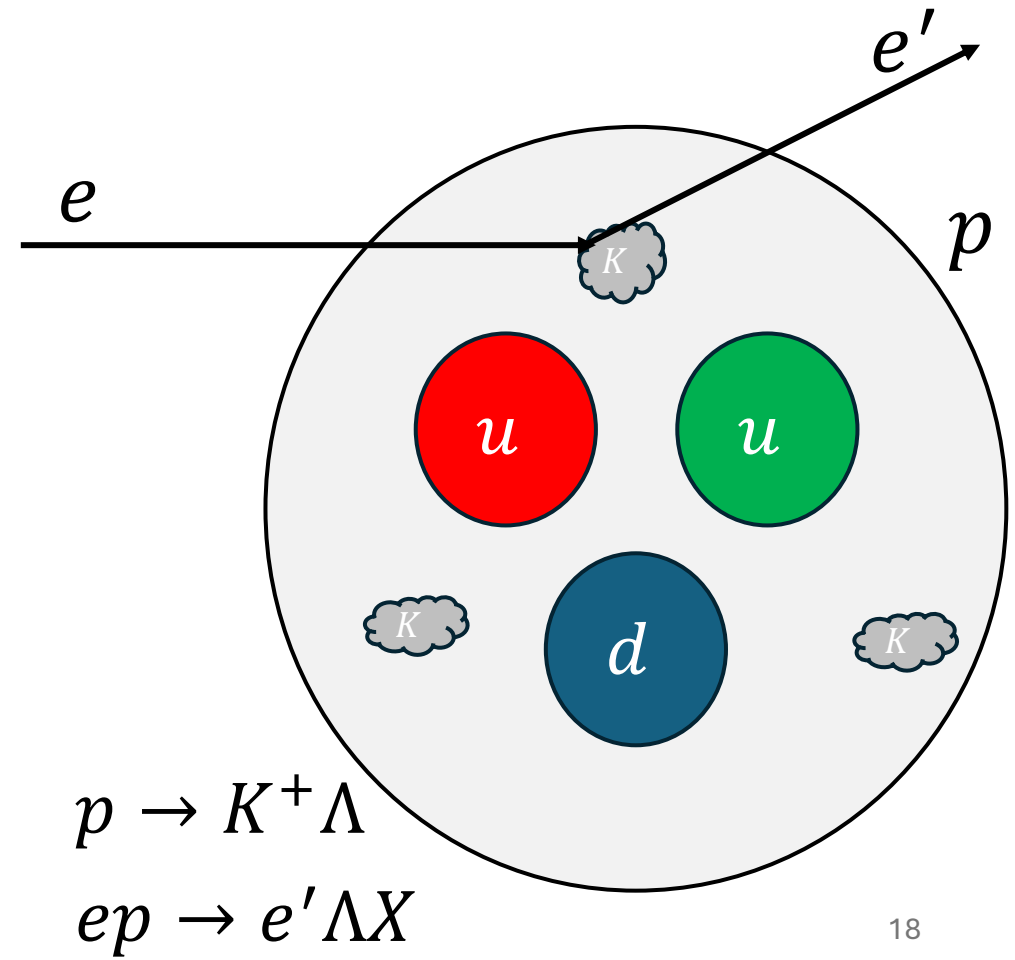
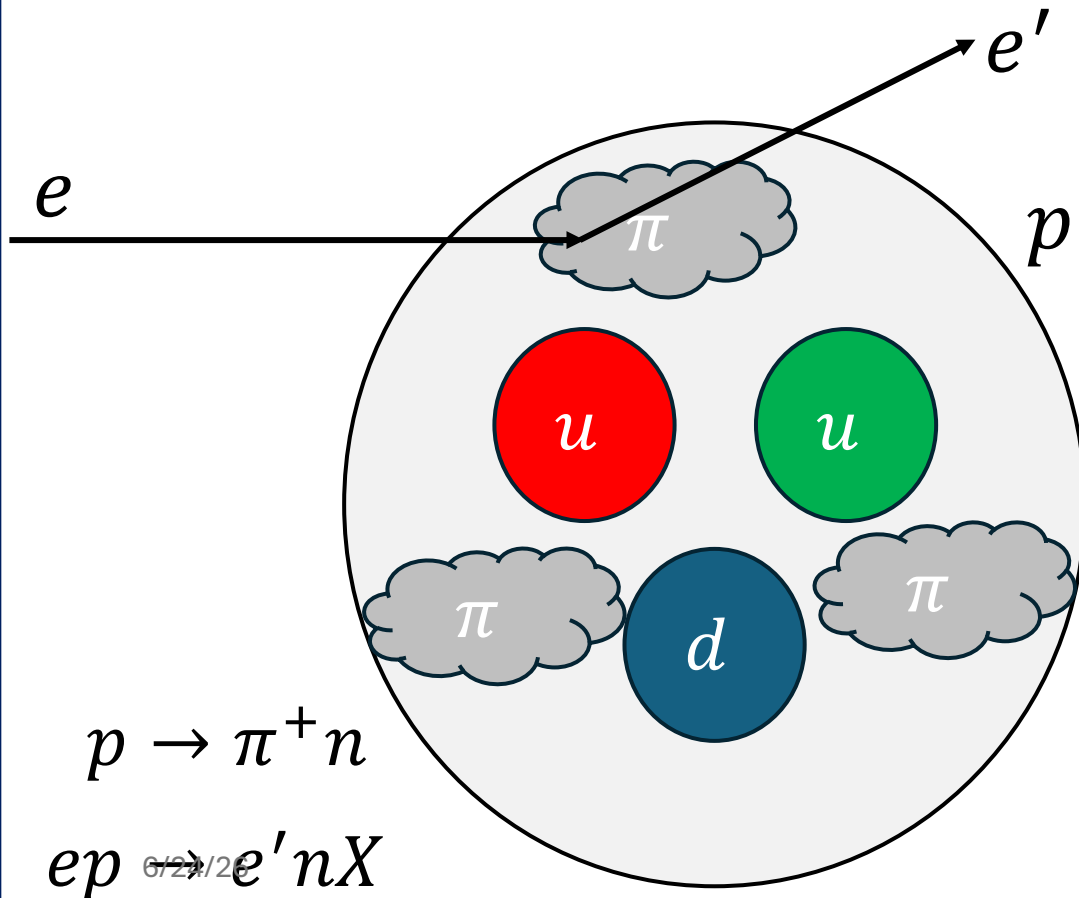
Ratios of PDFs

- $\bar{u}_v^{K^-} / \bar{u}_v^{\pi^-}$ reflects the NA3 experimental data
 - Consistent with 1 and drops off at large x
- $s_v^{K^-} / \bar{u}_v^{K^-}$ is ≈ 2 at $x = 0.8$
- Ratio of the $s_v^{K^-}$ to the experimental + lattice JAM result
 - Experimental-only analyses (GRS, BBCP)
 - Lattice QCD-only analysis (ETMC)



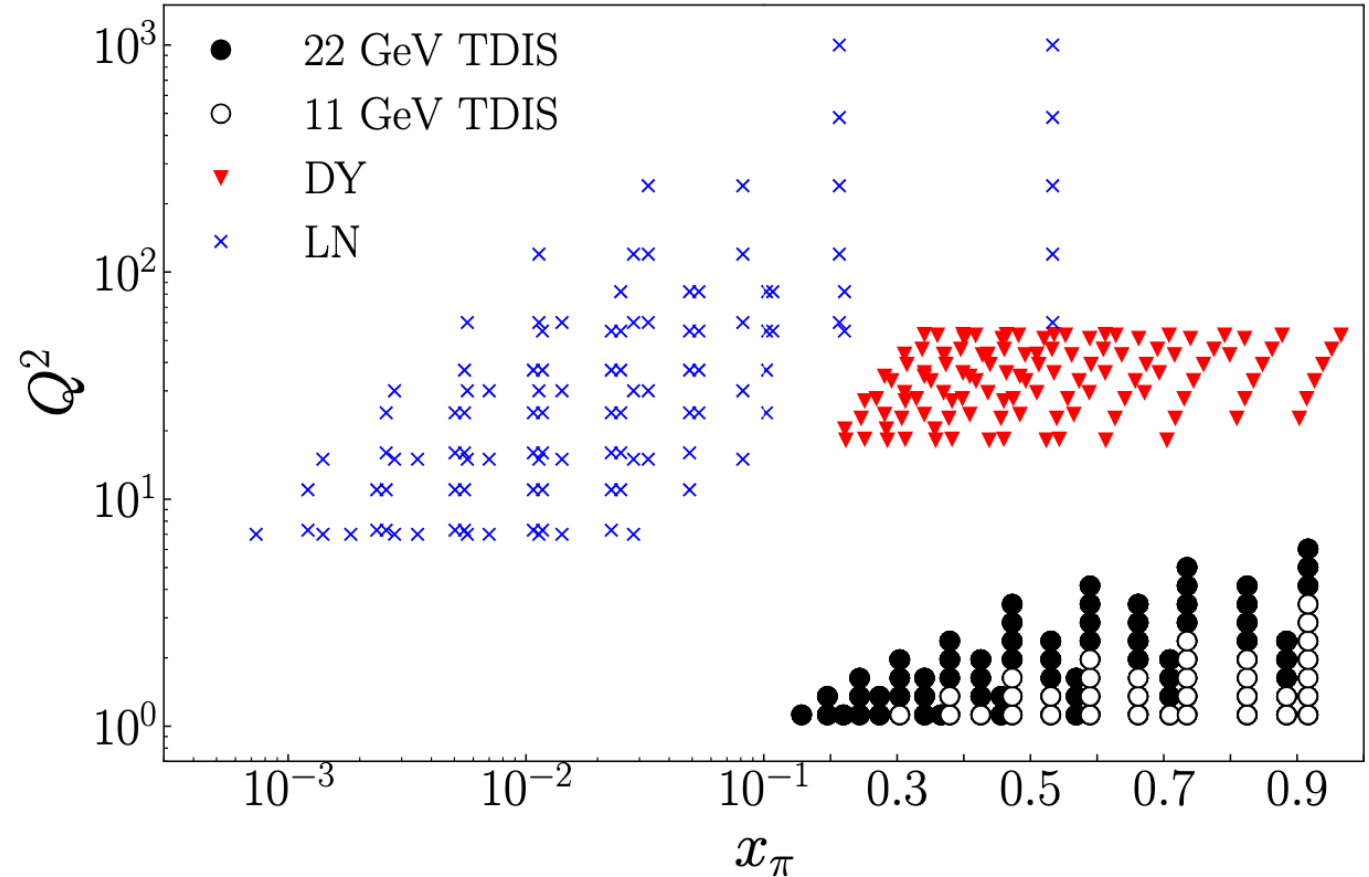
Pions and kaons at JLab

- Tagged DIS can access pion and kaon structure from the proton's virtual meson cloud

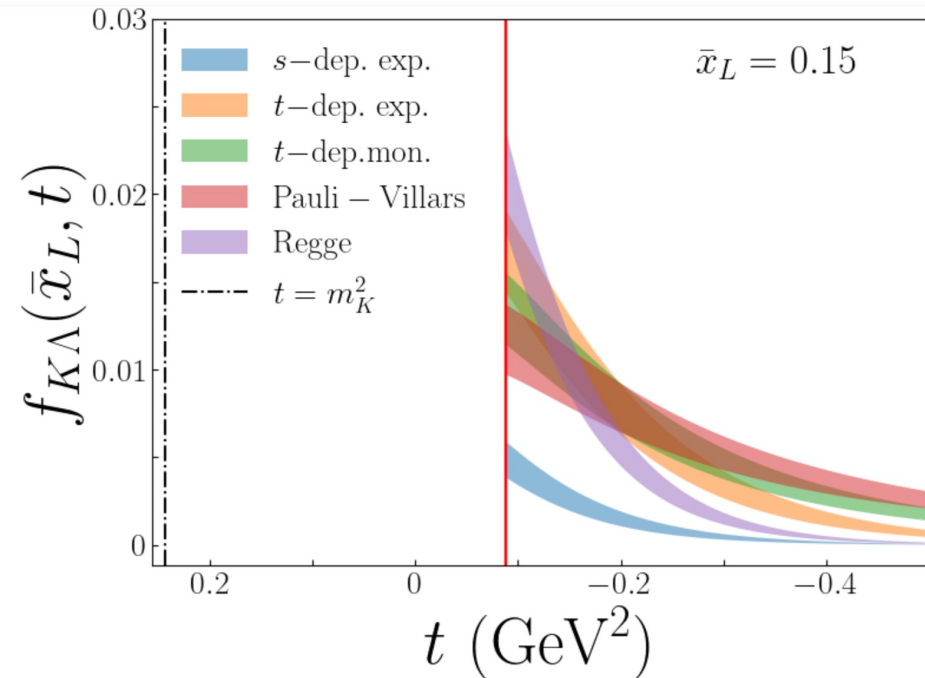
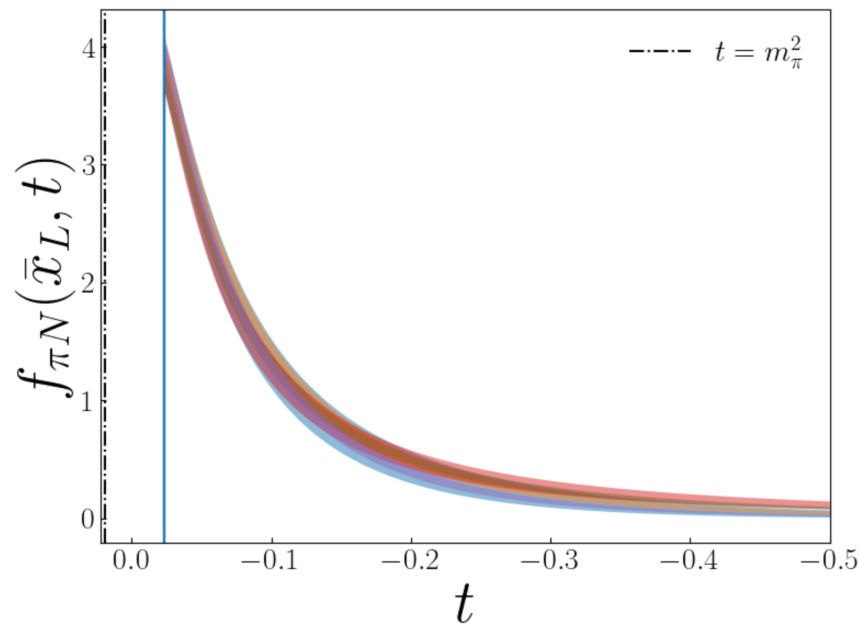


Future kinematics

- With JLab 11 and 22 GeV, we can achieve overlap between DY and TDIS measurements
- However, we must be **careful** how to interpret these data!
 - Resonance region at low W_π^2



Relative pion and kaon fluxes



- The counts for the kaon TDIS will be ≈ 2 orders of magnitude less than for pions
- Need high luminosity machine!

Backup Slides

Note about E615 πA Drell-Yan data

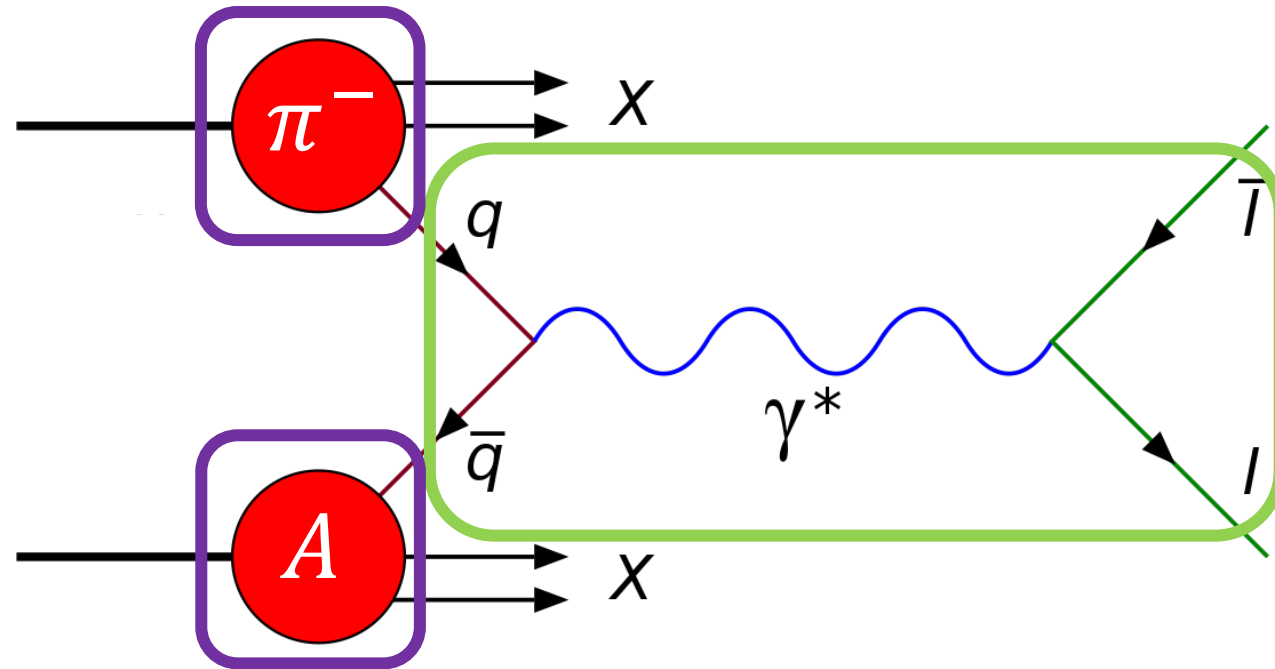
- Provides both $\frac{d\sigma}{dx_F d\sqrt{\tau}}$ (p_T -integrated) **and** $\frac{d\sigma}{dx_F dp_T}$ (p_T -dependent)
 - Large constraints on π **collinear PDFs** from p_T -integrated
 - Large constraints on π **TMD PDFs** from p_T -dependent
- Projections of same events \Rightarrow correlated measurements
- They have the **same luminosity** uncertainty, so they have the **same overall normalization** uncertainty
- To account for this, we *equate* the fitted normalizations of the two otherwise independent measurements
 - No other guidance from experiment how the uncertainties are correlated

Note on collinear DY theory

- When equating the normalizations, we found
 - **Agreement** when using **NLO** theory on the **collinear** observables
 - **Tension** when using **NLO+NLL** threshold resummed theory on the **collinear** observables
- We note that in the OPE part of the **TMD** formalism, we use **NLO** accuracy
 - We do not use any *threshold enhancements* on the **p_T -dependent** observables

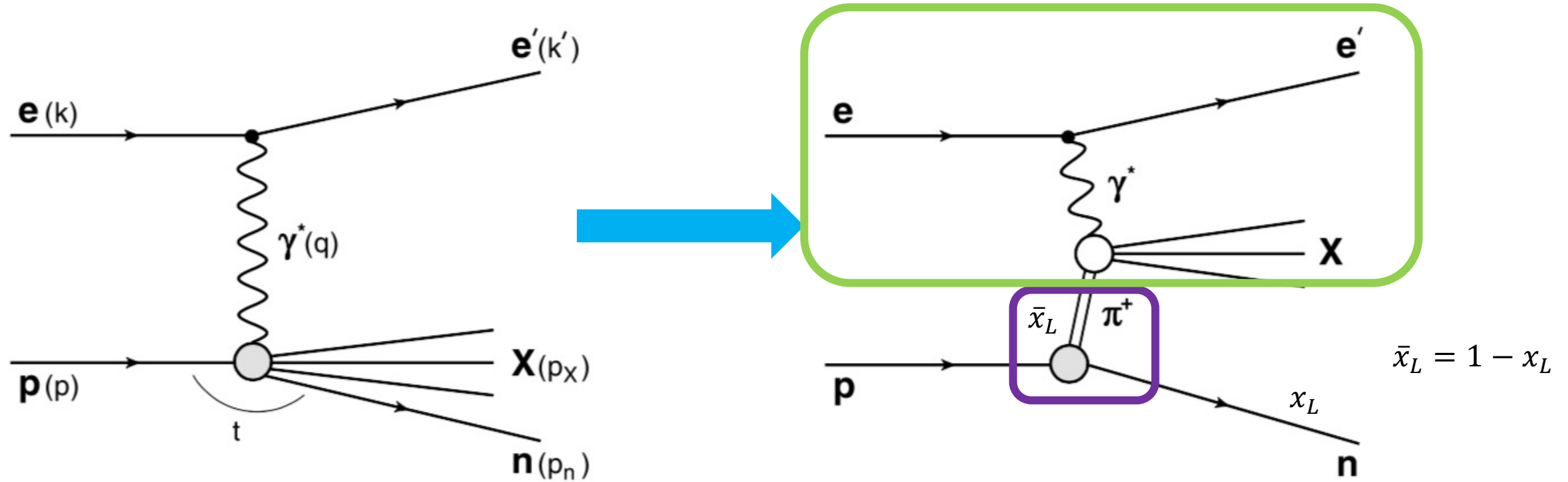
Drell-Yan (DY)

$$x_\pi = \sqrt{\frac{Q^2}{S}} e^{+Y} \quad x_A = \sqrt{\frac{Q^2}{S}} e^{-Y}$$



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

Leading Neutron (LN)



$$\frac{d\sigma}{dx dQ^2 d\bar{x}_L} \propto f_{p \rightarrow \pi^+ n}(\bar{x}_L) \sum_i \int_{x/\bar{x}_L}^1 \frac{d\xi}{\xi} C_i(\xi) f_i^\pi \left(\frac{x/\bar{x}_L}{\xi}, \mu^2 \right)$$

How to relate PDFs with lattice observables?

- Make use of good lattice cross sections and appropriate matching coefficients

$$\begin{aligned}\Sigma_{n/h}(\nu, z^2) &\equiv \langle h(p) | T \{ \mathcal{O}_n(z) \} | h(p) \rangle \\ &= \sum_i f_{i/h}(x, \mu^2) \otimes C_{n/i}(x\nu, z^2, \mu^2) \\ &\quad + \mathcal{O}(z^2 \Lambda_{\text{QCD}}^2)\end{aligned}$$

- Structure just like experimental cross sections – good for global analysis

Fitting the Data and Systematic Corrections

Valence quark distribution in pion

Wilson coefficients for matching

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

Integration lower bound is 0

Systematic corrections 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

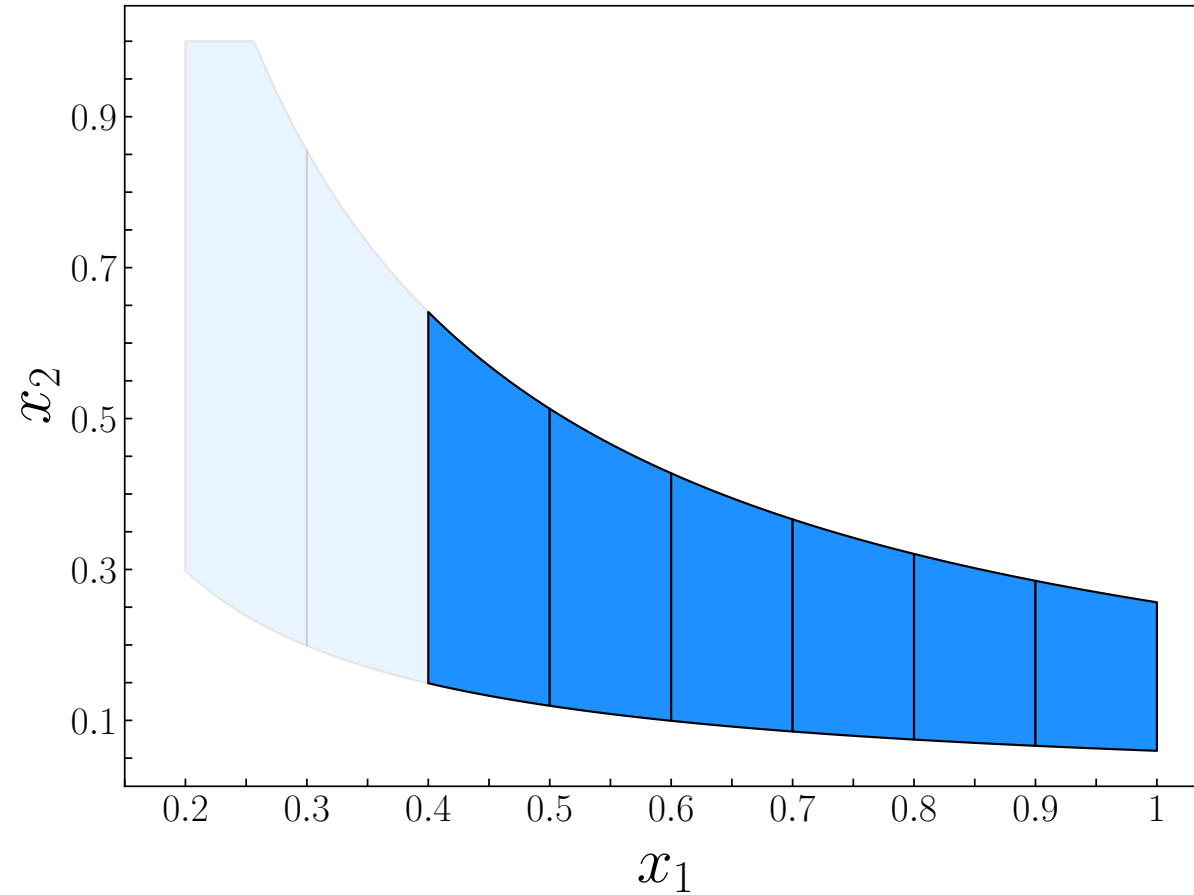
Drell-Yan cross section

(recall $N = L\sigma$)

- Data are presented as $\frac{L_\pi}{L_K} \frac{dN/dx_1|_{K^-}}{dN/dx_1|\pi^-}$, which is $\frac{d\sigma/dx_1^{K^-}}{d\sigma/dx_1^{\pi^-}}$
- We compute the numerator and denominator according to the integral over x_2 of $\frac{d\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9Q^2} \sum_{i,j} [C_{i,j} \otimes f_{i/h_1} \otimes f_{j/h_2}](x_1, x_2; \mu^2)$,
- We use NLO+NLL theory in the DY hard coefficient $C_{i,j}$
- The range of x_2 for each x_1 is given as $\frac{Q_{\min}^2}{sx_1} \leq x_2 \leq \frac{Q_{\max}^2}{sx_1}$

NA3 kinematics

- We integrate over x_2 and perform a bin averaging in bins of x_1
- The range of Q is $4.1 \text{ GeV} \leq Q \leq 8.5 \text{ GeV}$
- We remove the two lowest bins of x_1 because $x_F < 0$
 - In NA10 paper, “*In view of possible reinteraction effects, [the uncertainties are comparable to, or even larger, than the statistical errors] for the points with $x_F < 0$.*”



Methodology

- The first step was to try using the GRS parametrization, by equating the sea quark distributions in the pion and kaon along with the gluon
 - Implies that the momentum fractions of the total valence distributions in the pion and kaon must be the same
- However, in doing so, we are unable to simultaneously fit the experimental data and LQCD moments
- Instead, we set a proportionality of the sea quark and gluon

$$q_{sea}^K = N_{sea} q_{sea}^\pi \qquad g^K = N_g g^\pi$$

and the normalization of the sea quark is fixed by the momentum sum rule