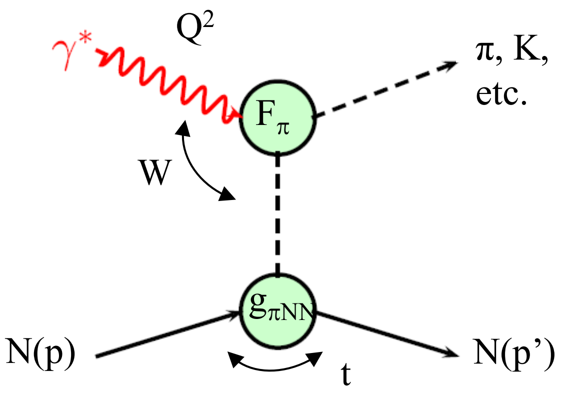
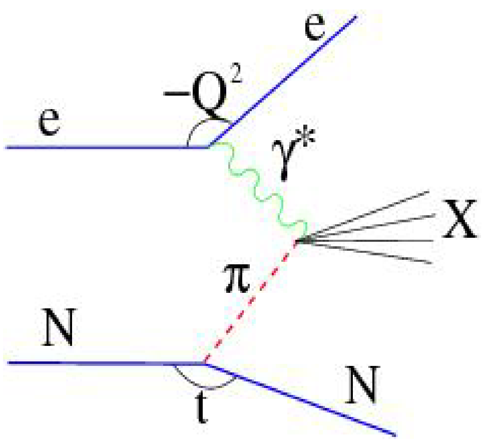
Pion and Kaon Structure – experimental overview (EIC & JLab)





Tanja Horn

THE CATHOLIC UNIVERSITY OF AMERICA

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Supported in part by NSF grants PHY2309976 and PHY2012430

Workshop on Parton Distribution Functions in the EIC era

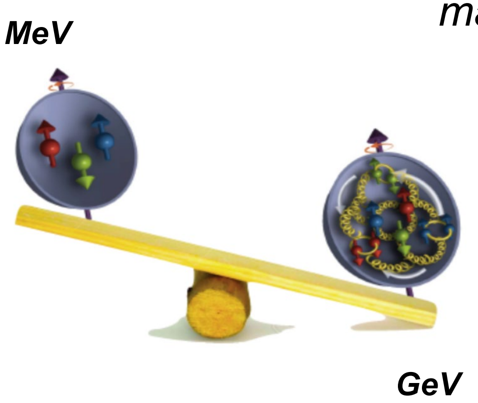
Institute of Physics, Academia Sinica, June 16-18, 2025

Outline

- ❑ Brief overview of the role of **meson structure** in understanding EHM and our visible Universe
- ❑ JLab 12 GeV and improving the $\pi^+/K^+/\pi^0$ electroproduction data set and tagged DIS
  - L/T separated cross sections and pion and kaon form factor extractions
  - Tagged DIS and resolving and cross-checking pion PDF issues at high-x; kaon SF extractions
- ❑ Exciting imminent opportunities to collect additional data for light mesons beyond JLab 12 GeV
  - ❑ JLab 22 GeV
  - ❑ Electron-Ion Collider (EIC)
- ❑ Ongoing efforts extending into 3D light hadron structure – GPDs and TMDs – in theory/experiment

What Do We Know: Mass of the Proton, Pion, Kaon

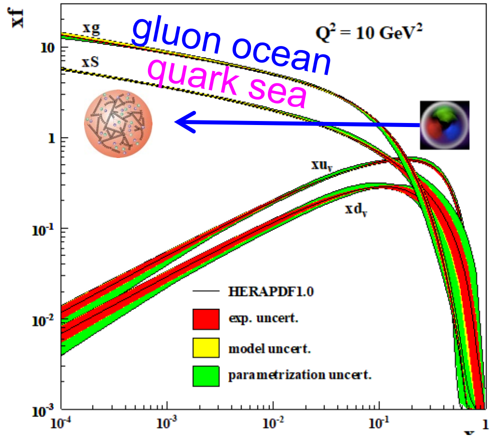
Visible world: mainly made of light quarks – its mass emerges from quark-gluon interactions.



Proton

Quark structure: uud
Mass ~ 940 MeV (~1 GeV)
Most of mass generated by dynamics.

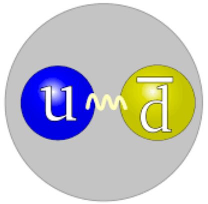
Gluon rise discovered by HERA e-p



Fraction of overall proton momentum carried by quark or gluons

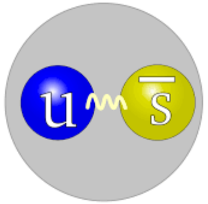
Pion

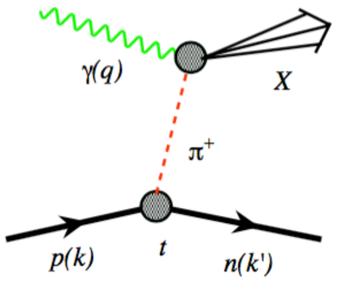
Quark structure: $u\bar{d}$
Mass ~ 140 MeV
Exists only if mass is dynamically generated.
Empty or full of gluons?



Kaon

Quark structure: $u\bar{s}$
Mass ~ 490 MeV
Boundary between emergent- and Higgs-mass mechanisms.
More or less gluons than in pion?





proton the EIC will allow determination of an important term contributing to the proton mass, the so-called "QCD trace anomaly"

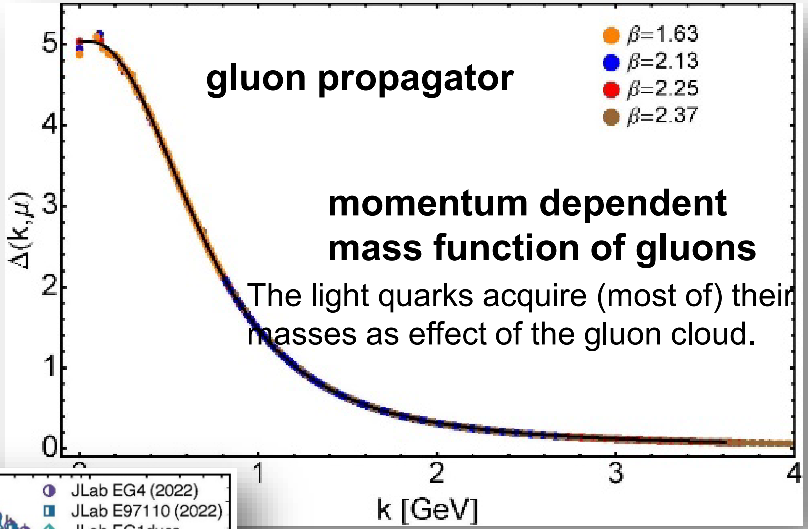
pion and the kaon the EIC will allow determination of the quark and gluon momentum contributions with the Sullivan process.

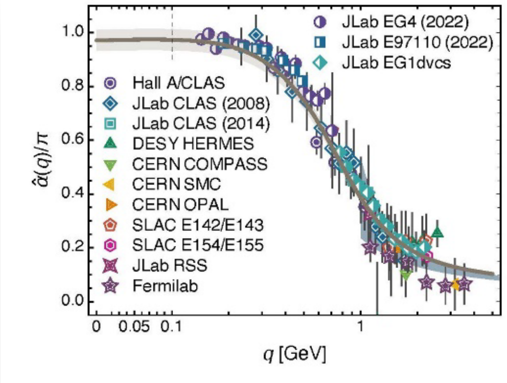
*C. Aguilar, …, T. Horn, et al., Pion and Kaon structure at the EIC, EPJA **55** (2019) 190.*
*J. Arrington, …, T. Horn, et al., Revealing the structure of light pseudoscalar mesons at the EIC, J. Phys. G **48** (2021) 7, 075106.*

Emergence of Hadron Mass (EHM)

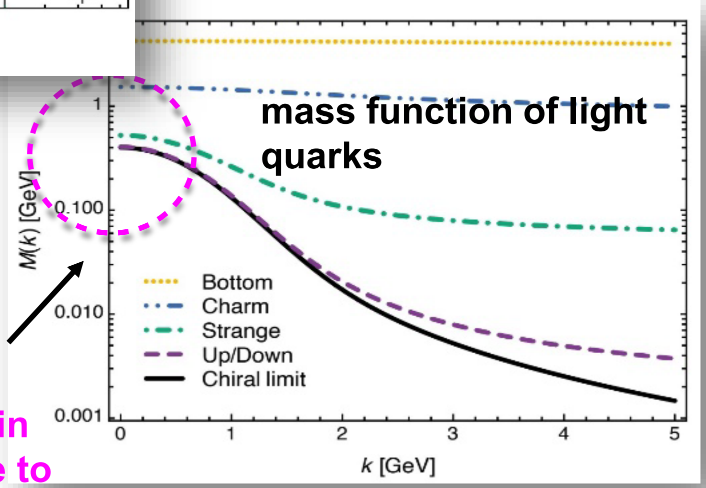
Adapted from C.D. Roberts at PAW24, Geneva, Switzerland, Mar 18-20, 2024

- Absent Higgs boson couplings, QCD Lagrangian is scale invariant
- Yet …
  - Massless gluons become massive
  - A momentum-dependent charge is produced
  - Massless quarks become massive
- EHM is expressed in
  EVERY strong interaction observable
- Challenge to Theory:
  Elucidate all observable consequences of these phenomena and highlight the paths to measuring them
- **Challenge to Experiment:**
  Test the theory predictions so that the boundaries of the Standard Model can finally be drawn





THREE PILLARS OF EHM



Rapid increase in mass due to gluon cloud

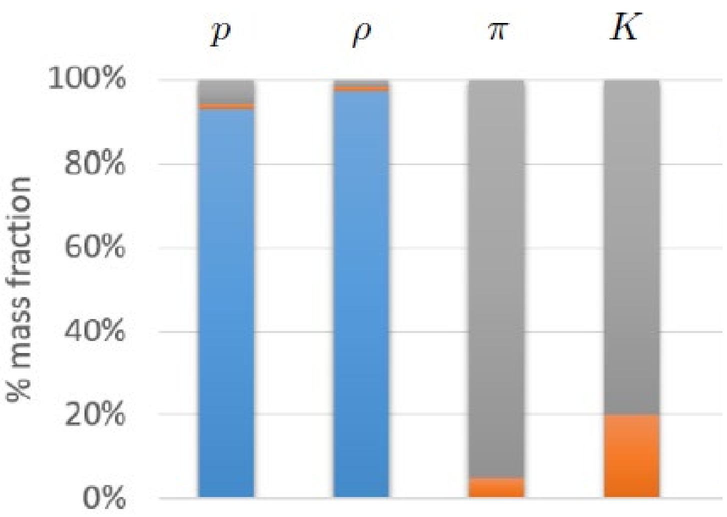
"Mass without mass!"

- ✓ *Process independent strong running coupling*
  Daniele Binosi *et al.*, arXiv:1612.04835 [nucl-th] Phys. Rev. D 96 (2017) 054026/1-7
- ✓ *Experimental determination of the QCD effective charge $\alpha_{g1}(Q)$.*
  A. Deur; V. Burkert; J.-P. Chen; W. Korsch, Particles 5 (2022) 171
- ✓ *QCD Running Couplings and Effective Charges,* Alexandre Deur, Stanley J. Brodsky and Craig Roberts, e-Print: 2303.00723 [hep-ph], Prog. Part. Nucl. Phys. **134** (2024) 104081

See also C. D. Roberts, D. Richards, T. Horn, L. Chang, Prog.Part.Nucl.Phys. ***120*** *(****2021****) 103883*

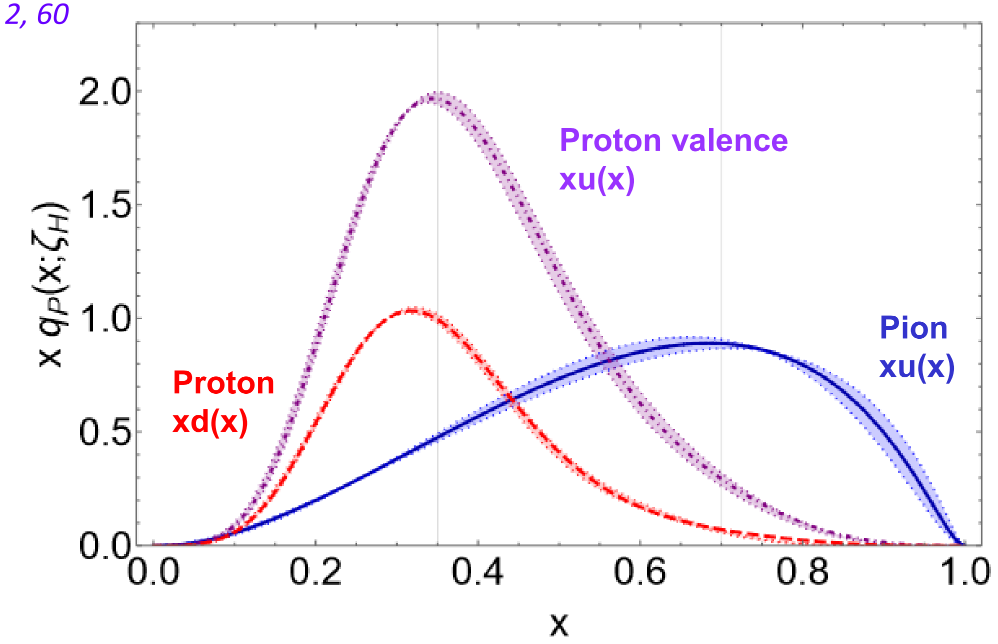
C. D. Roberts, Symmetry ***12****, (****2020****) 1468*

Insights into Hadron Structure and Mass through Mesons



❑ Emergent hadron mass (EHM)
❑ Interference of emergent hadron mass & Higgs mechanism
❑ Higgs mechanism

K. Raya, A. Bashir, D. Binosi, C.D. Roberts, J. Rodriguez-Quintero, Few Body Sust. ***65*** *(**2024**) 2, 60*



Mass budget for nucleons and mesons are vastly different

- Proton (and heavy meson) mass is large in the chiral limit – expression of Emergent hadronic mass (EHM)
- Pion/kaon: Nambu-Goldstone Boson of QCD: massless in the chiral limit
  - chiral symmetry of massless QCD dynamically broken by quark-gluon interactions and inclusion of light quark masses (DCSB, giving pion/kaon mass)
  - Without Higgs mechanism of mass generation pion/kaon would be indistinguishable

Valence quark distribution of proton/pion are also very different

→ **Difference between meson PDFs: direct information on emergent hadron mass (EHM)**

Understanding pion/kaon is vital to understand the **dynamic** generation of hadron mass and offers unique insight into EHM and the role of the Higgs mechanism

Light Mesons and EHM

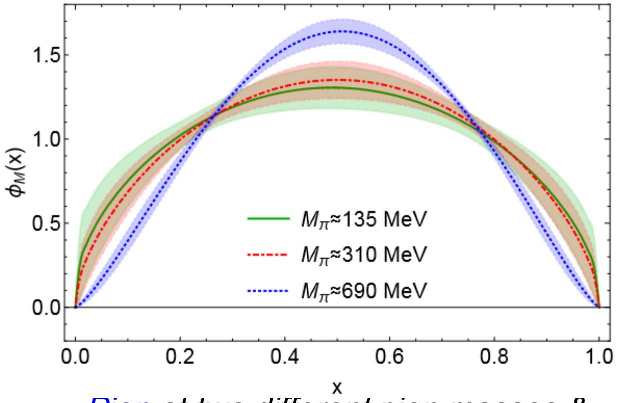
Pion and kaon distribution amplitudes (DA – $\phi_{\pi,K}$) are fundamental to our understanding of pion and kaon structure

- EHM is expressed in the x-dependence of the pion and kaon DA
- Pion DA is a direct measure of the dressed-quark running mass in the chiral limit

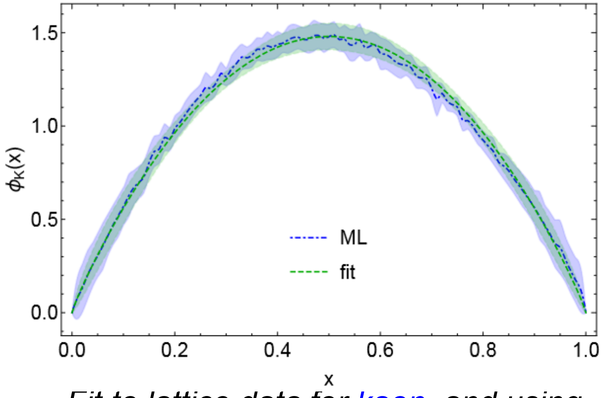
Strong synergy with lattice QCD

*R. Zhang et al., Phys. Rev. D **102** (2022) 9, 094519*

Calculations using meson-boosted momentum at P_z = 1,.73 GeV and renormalized at 2 GeV in MS-bar scheme

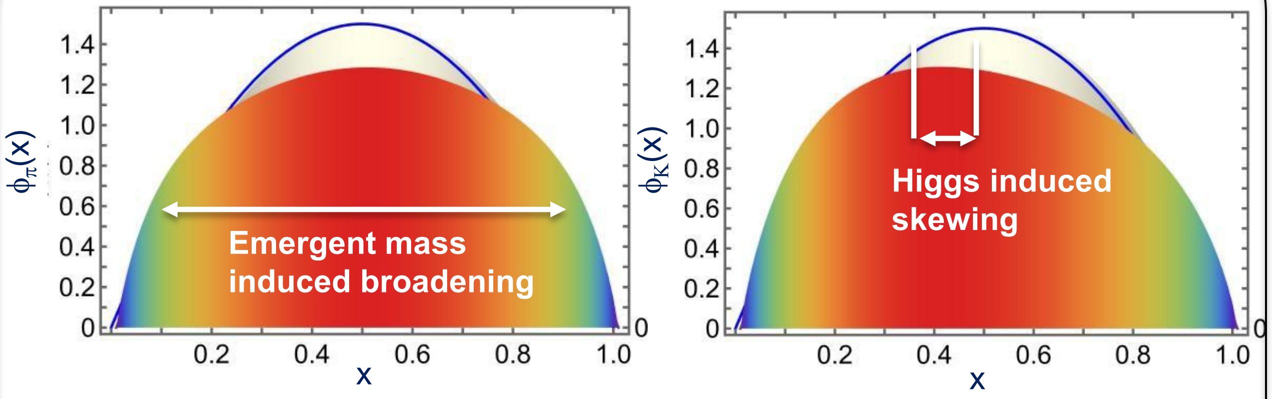


Pion at two different pion masses & extrapolated to the physical mass



Fit to lattice data for kaon, and using machine learning approach

*Insights into the Emergence of Mass from Studies of Pion and Kaon Structure, C.D. Roberts, D.G. Richards, T. Horn, L. Chang, Prog. Part. Nucl. Phys. **120** (**2021**) 103883/1-65*

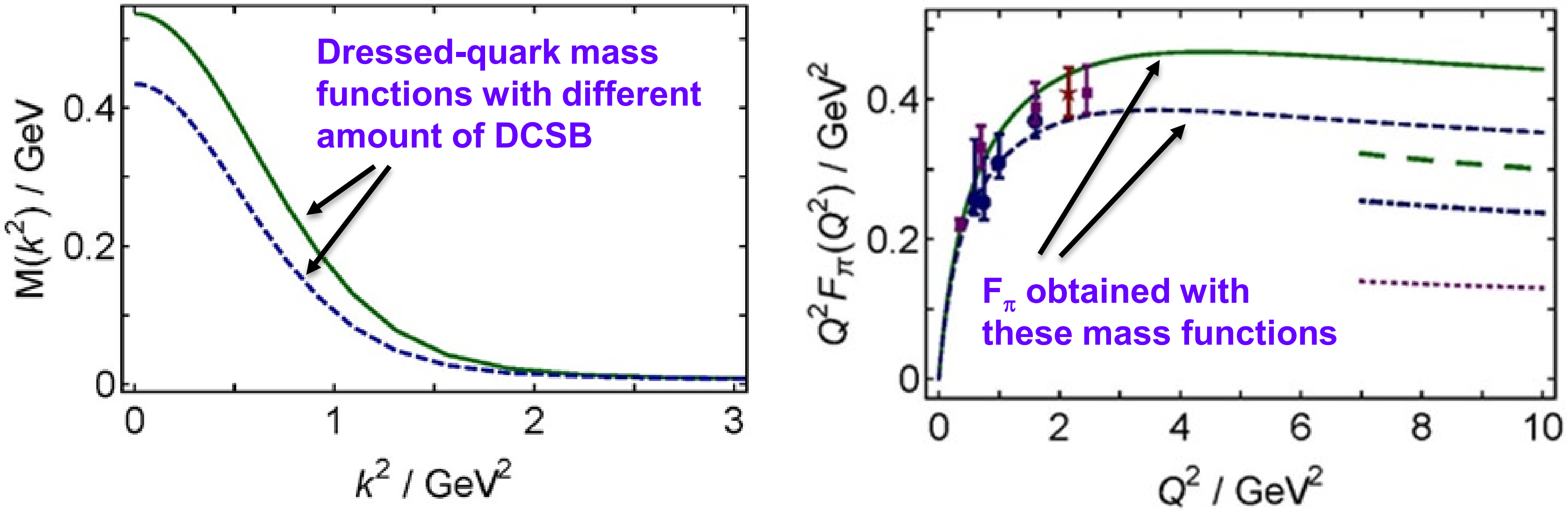


- In the limit of infinitely-heavy quark masses, the Higgs mechanism overwhelms every other mass generating force, and the PDA becomes a δ-function at x = ½.
- The DA for the light-quark pion is a broad, concave function, a feature of emergent mass generation.
- Kaon DA is asymmetric around the midpoint – signature of constructive interference between EHM and HB mass-generating mechanism

- Experimental signatures of the exact PDA form are, in general, difficult
- Understanding light meson structure requires collaboration of QCD phenomenology, continuum calculations, lattice, and experiment.

Pion Form Factors and Emergent Hadron Mass

There are several measurement observables (e.g., hadron elastic/transition form factors)



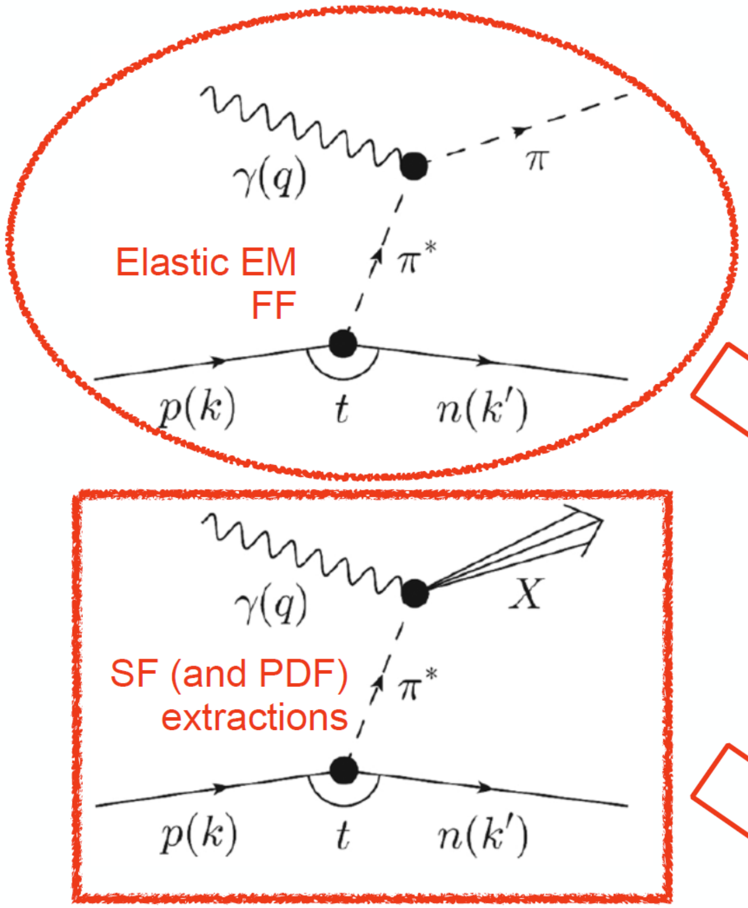
*A.C. Aguilar, …, T. Horn, et al., Eur. Phys. J. A **55** (**2019**) 10, 190*

<u>Left panel</u>. Two dressed-quark mass functions distinguished by the amount of DCSB: emergent mass generation is 20% stronger in the system characterized by the solid green curve, which describes the more realistic case. <u>Right panel</u>. $F_\pi(Q^2)$ obtained with the mass function in the left panel: r_π = 0.66 fm with the solid green curve and r_π = 0.73 fm with the dashed blue curve. The long-dashed green and dot-dashed blue curves are predictions from the QCD hard-scattering formula, obtained with the related, computed pion PDAs. The dotted purple curve is the result obtained from that formula if the conformal-limit PDA is used, $\phi(x)=6x(1-x)$.

Accessing Pion/Kaon Structure Information

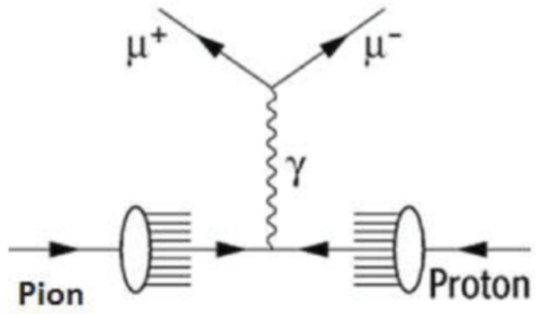
Sullivan

Hard scattering from virtual meson cloud of nucleon



Drell-Yan

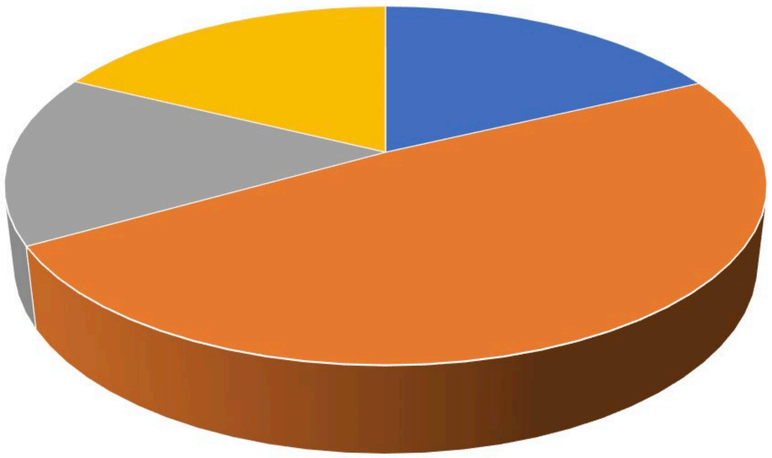
Quark of pion (e.g.) annihilates with anti-quark of proton (e.g.), virtual photon decays into lepton pair



- ❑ **Pion/Kaon elastic EM Form Factor**
  - Informs how EHM manifests in the wave function
  - Decades of precision F_π studies at JLab and recently completed measurement in Hall C for F_π and also F_K
  - EIC offers exciting kinematic landscape for FF extractions
- ❑ **Pion/Kaon Structure Functions**
  - Informs about the quark-gluon momentum fractions

Jefferson Lab and CEBAF

Approved 12 GeV program by PAC days



- Probe the structure of matter

  Complex **non-pQCD** problem which demands different approaches and measurements to access multiple observables

- Discover evidence for physics beyond the standard model

Hadron Spectra

1D-3D Nucleon Structure

Hadrons & Cold Nuclear Matter

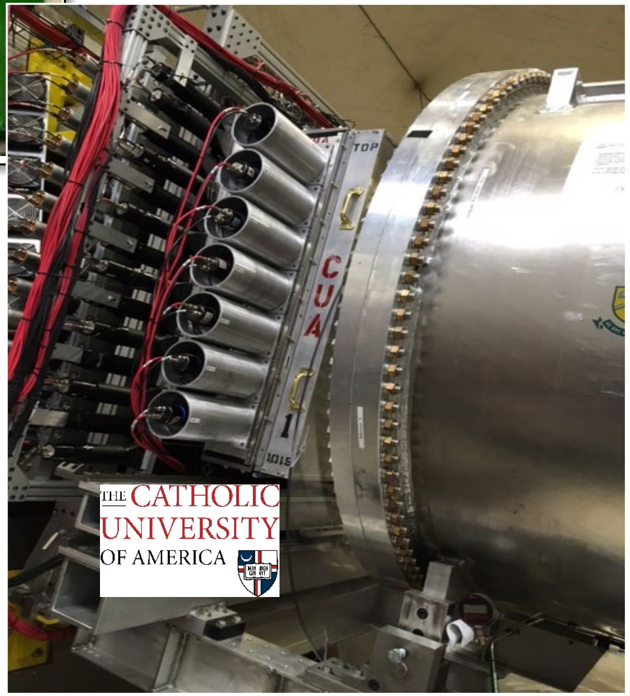
Test of SM & Fundamental Sym.

Hall C Deep Exclusive Charged Meson Experiments

Home of the precision cross section measurements through L/T and tagged DIS (TDIS)

Two experiments
- **PionLT** (E12-19-006)
- **KaonLT** (E12-09-011)

- CEBAF 10.9 GeV electron beam and SHMS small angle capability and controlled systematics are essential for precision measurements to higher Q^2
- Focusing spectrometers fulfill the L/T separation requirements
- Dedicated key SHMS Charged Particle Identification detectors
  - Aerogel Cherenkov – funded by NSF MRI (CUA)
  - Heavy gas Cherenkov – partially funded by NSERC (U Regina)



T. Horn, H. Mkrtchyan, et al., Nucl.Instrum.Meth.A **842** (**2017**) 28-47

Hall C Neutral Particle Spectrometer (NPS) Program

Relevant technologies for EIC (backward EMCal, B0 calorimeter)

e^- beam – small angle configuration

E12-13-010 - E12-06-114 - E12-13-007 – E12-23-014

- Exclusive Deeply Virtual Compton **on proton**
- SIDIS p(e,e',p^0) cross section.

  Map the transverse momentum dependence.

E12-22-006

- Exclusive Deeply Virtual Compton **on deuteron**

  Subtract the proton data from deuteron data to get neutron

Completed Run Group 1A in 2023/24

Large angle and other configuration

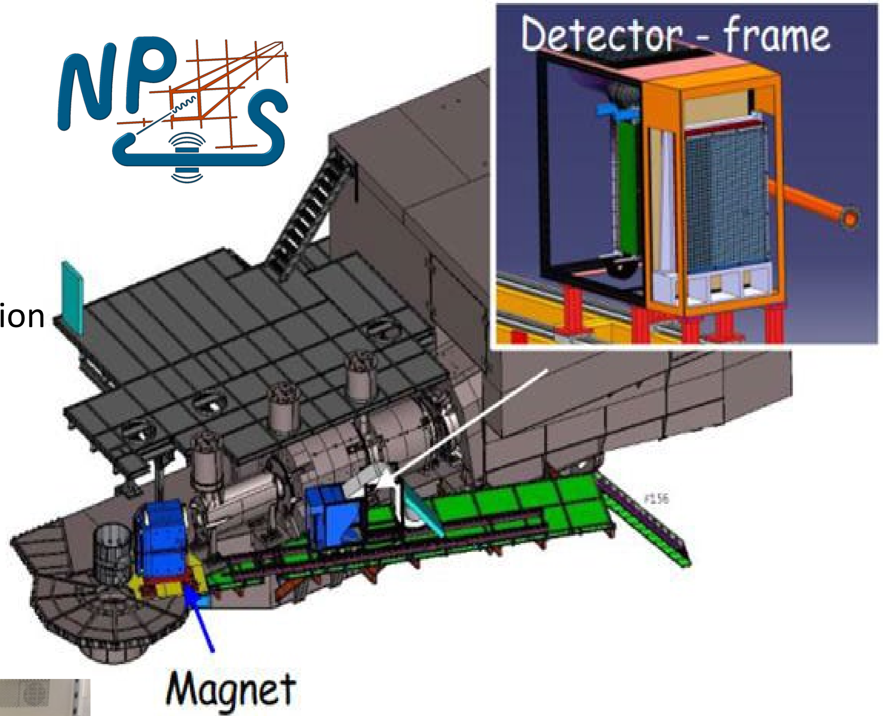
E12-14-003
- Wide-angle Compton Scattering

E12-14-005
- Wide Angle Exclusive π^0 Photoproduction

E12-17-008
- Polarization observables in WACS

E12-23-004
- Search for nonzero strange proton FF

C12-20-012 (standard + positron beam)
- DVCS using a positron beam



T. Horn, et al. Nucl.Instrum.Meth.A **956** (2020) 163375

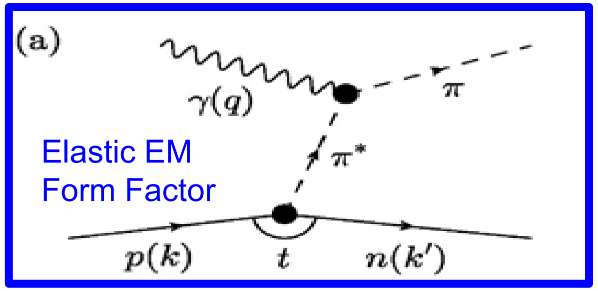
Neutral Particle Spectrometer (NPS) : Magnet with calorimeter

- **1080 Lead-Tungstate blocks** in Calorimeter to detect γ & π^0
- fADC250 with **streaming triggers**
- NPS attached to SHMS carriage to allow easy angle change. The calorimeter is on rails.

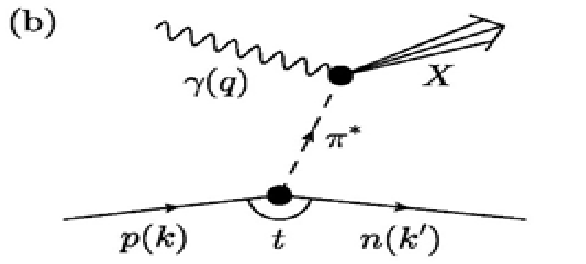
Miktat Imre and Carlos Domingues installing PMT/bases assemblies

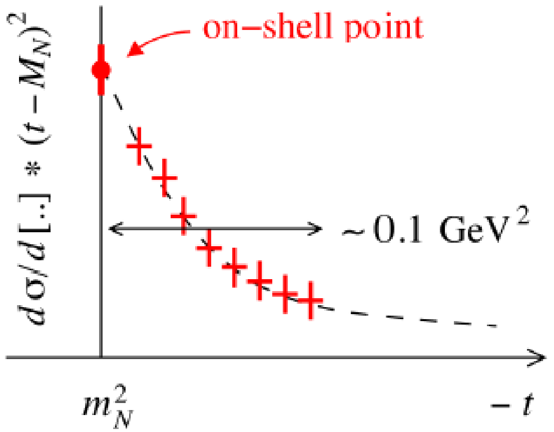
Accessing meson structure through the Sullivan Process

- The **Sullivan process can provide reliable access to a meson target** as t becomes space-like if the pole associated with the ground-state meson is the dominant feature of the process and the structure of the (off-shell) meson evolves slowly and smoothly with virtuality.



*S-X Qin, C. Chen, C. Mezrag, C.D. Roberts, Phys.Rev. C **97** (**2018**) 7, 015203*





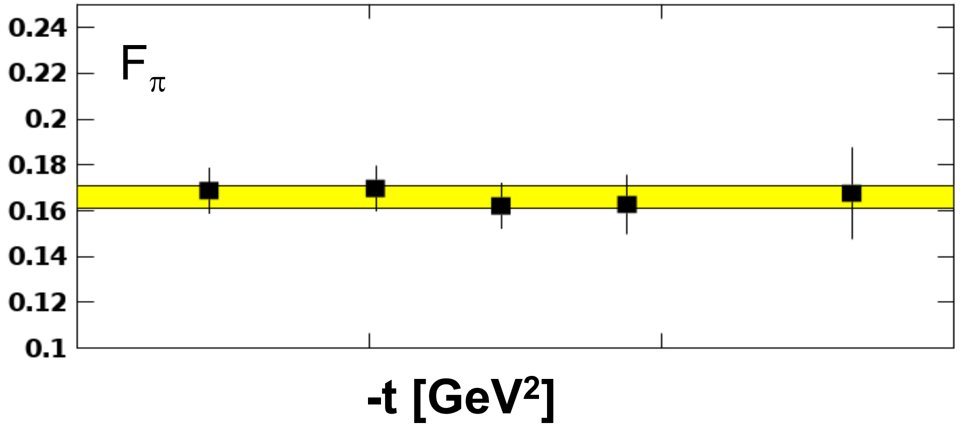
- To **check these conditions** are satisfied empirically, one can **take data covering a range in *t*** and compare with phenomenological and theoretical expectations.

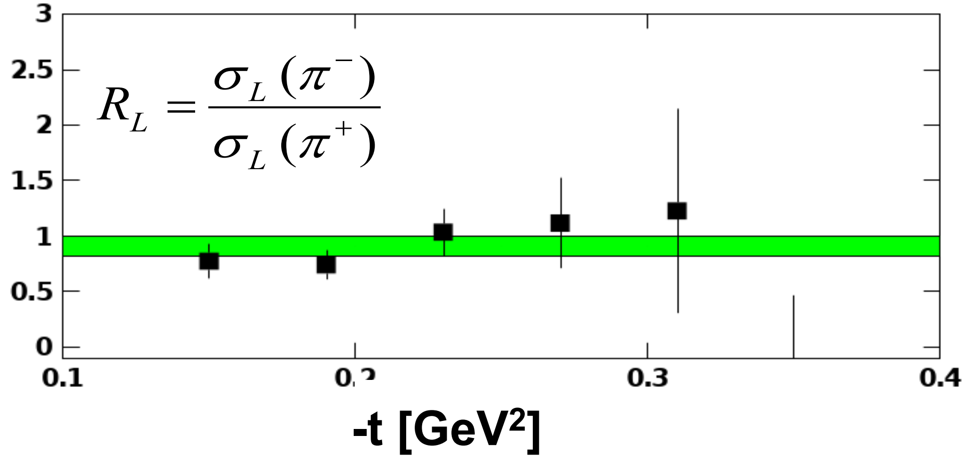
- **Theoretical calculations found that for $-t \leq 0.6$ (0.9) GeV^2, changes in pion (kaon) structure do evolve slowly** so that a well-constrained experimental analysis should be reliable, and the Sullivan processes can provide a valid pion target.

- Also **progress with elastic form factors – experimental validation**

Experimental Validation (Pion Form Factor example)

Experimental studies over the last decade have given *confidence* in the electroproduction method yielding the physical pion form factor





Experimental studies include:

- Take data covering a range in –t and compare with theoretical expectation
  - F_π values do not depend on -t – confidence in applicability of model to the kinematic regime of the data
- Verify that the pion pole diagram is the dominant contribution in the reaction mechanism
  - R_L (= $\sigma_L(\pi^-)/\sigma_L(\pi^+)$) approaches the pion charge ratio, consistent with pion pole dominance

*T. Horn, C.D. Roberts, J.Phys.G **43** (**2016**) 7, 073001*

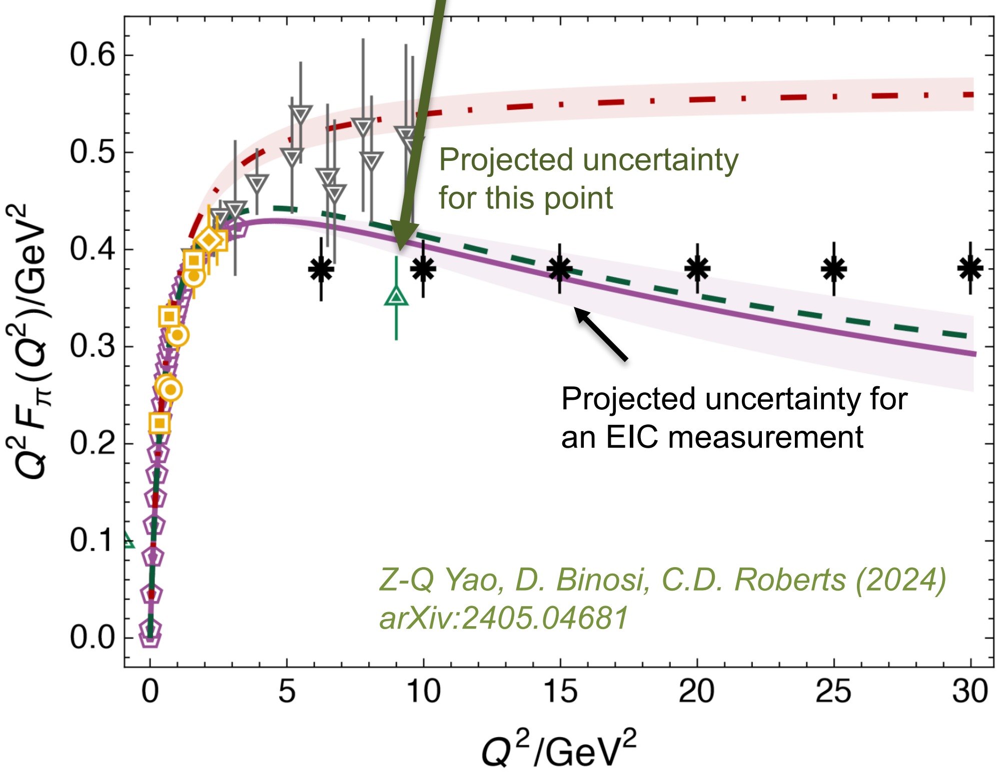
*G. Huber, …, T. Horn, et al, PRL**112** (**2014**)182501*

*R. J. Perry et al., PRC**100** (**2019**) 2, 025206*

Hall C – **Upcoming** Results PionLT/KaonLT Program

PionLT experiment (<u>completed in 2022</u>):

- ➢ L/T separated cross sections at fixed x=0.3, 0.4, 0.55 up to Q^2=8.5 GeV^2
- ➢ Pion form factor at Q^2 values up to 8.5 GeV^2
- ➢ Additional data from *KaonLT* experiment



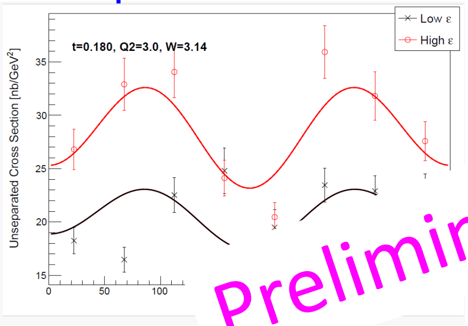
Spokespersons: Dave Gaskell (JLab), Tanja Horn (CUA), Garth Huber (URegina)

KaonLT experiment (<u>completed in 2018/19</u>):

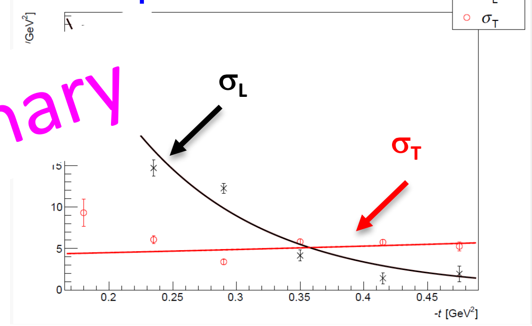
- ➢ Highest Q^2 for L/T separated kaon electroproduction cross section
- ➢ First separated kaon cross section measurement above W=2.2 GeV

Unseparated Cross Section

$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

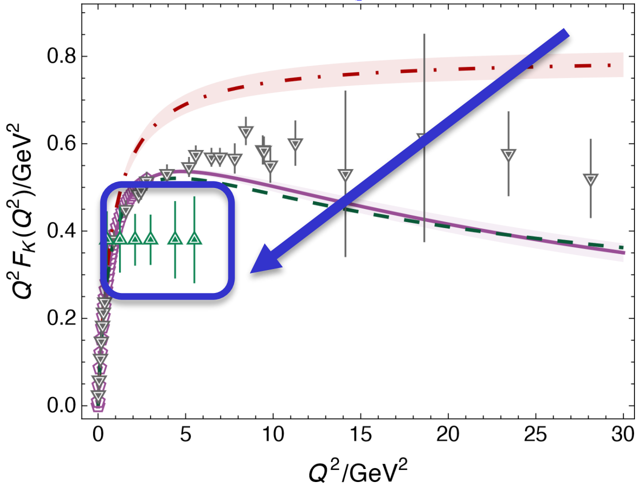


LT Separated Cross Section



- ○ First look at the unseparated and separated cross sections at Q^2=3 GeV^2, W=3.14 GeV
- ○ Separated cross sections have been extracted; KaonFF will follow if warranted by data

Projected Uncertainties for F_K



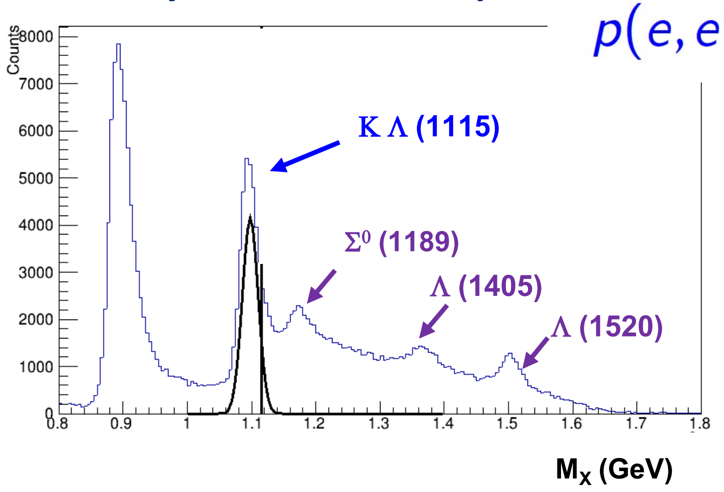
Spokespersons: Tanja Horn (CUA), Garth Huber (URegina), Pete Markowitz (FIU)

KaonLT (E12-09-011) Program – additional topics

Spokespersons: Tanja Horn (CUA), Garth Huber (URegina), Pete Markowitz (FIU)

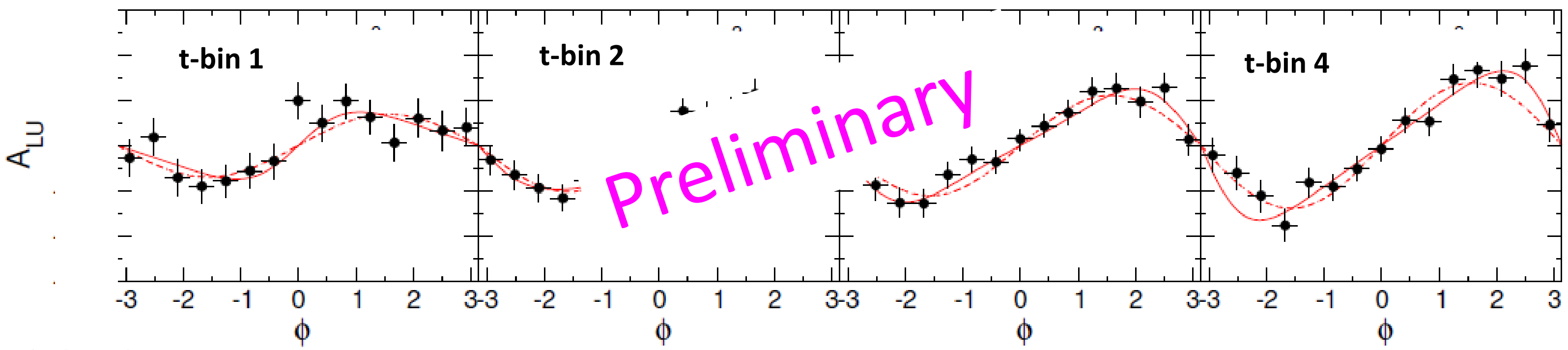
Grad. Students: Vijay Kumar (URegina), Richard Trotta (CUA), Ali Usman (URegina), A. Postuma (URegina)

Additional Physics Channels/Topics



$p(e,e'\pi^+)n/\Delta^0$

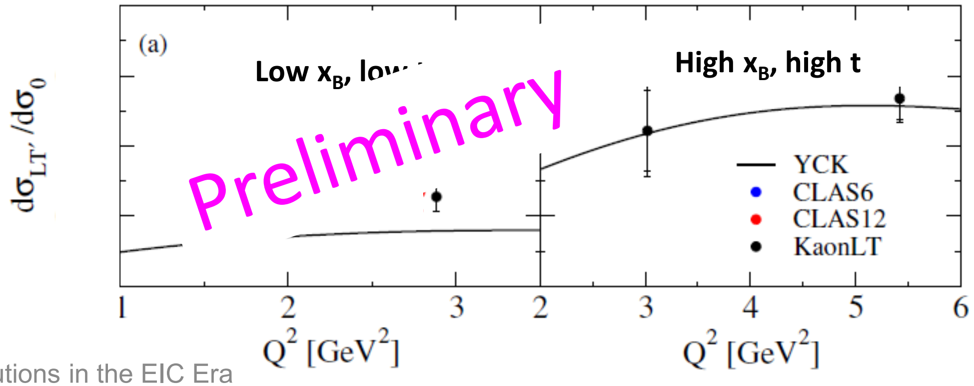
- KaonLT measured the beam spin asymmetry
- The t-dependence of $\sigma_{LT'}/\sigma_0$ was determined at fixed Q^2 and x_B over a range of kinematics above W>2 GeV
- Publication is in preparation – expected later this summer



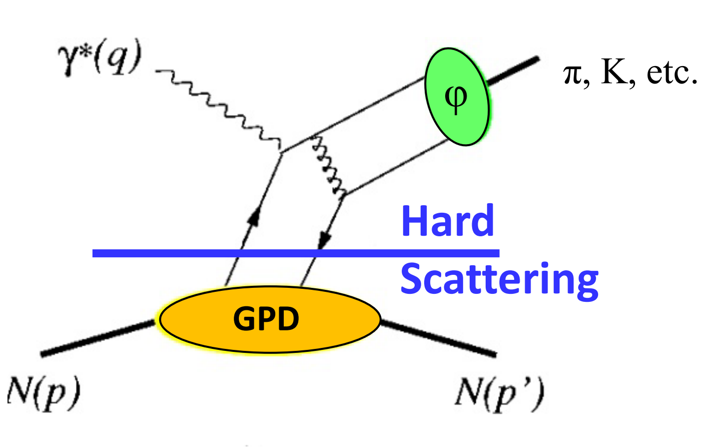
Regge and GPD Comparison of Beam Spin Asymmetry in Exclusive Pion Electroproduction

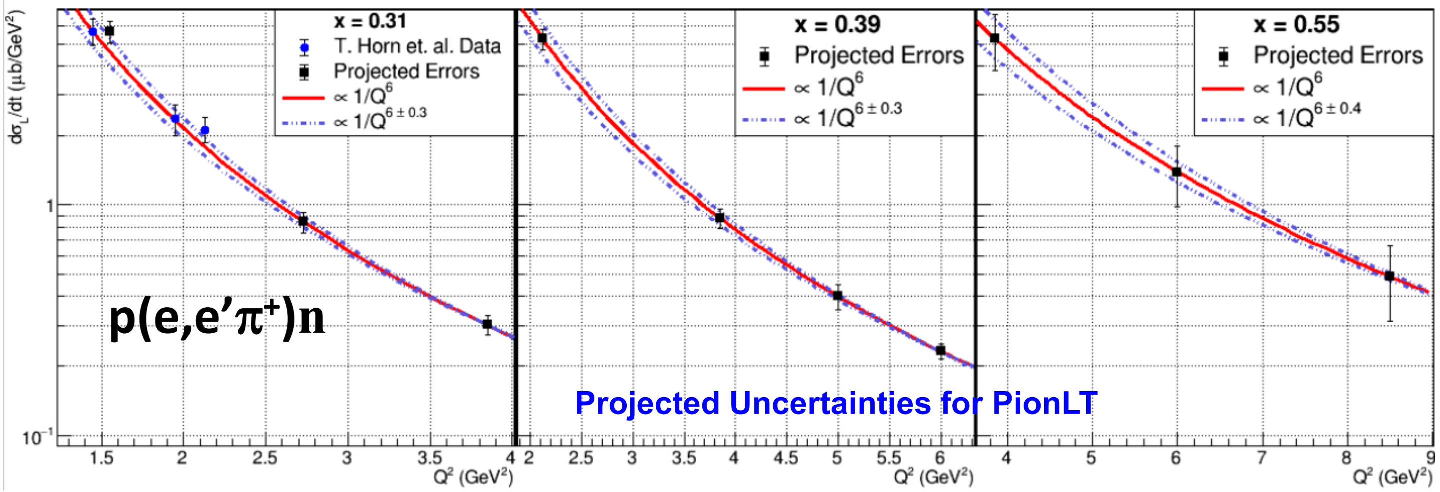
A.C. Postuma,[1] G.M. Huber,[1] T.K. Choi,[2] D. Gaskell,[3] N. Heinrich,[1] T. Horn,[4,3] M. Junaid,[1] S.J.D. Kay,[1,5] K.-J. Kong,[6] V. Kumar,[1] P. Markowitz,[7] J. Roche,[8] R. Trotta,[4] A. Usman,[1] B.-G. Yu,[6] S. Ali,[4] R. Ambrose,[1] D. Androic,[9] W. Armstrong,[10,11] A. Bandari,[12] V. Berdnikov,[4] H. Bhatt,[13] D. Bhetuwal,[13] D. Biswas,[14,15] M. Boer,[10,15] P. Bosted,[12] E. Brash,[16] A. Camsonne,[3] J.P. Chen,[3] J. Chen,[12] M. Chen,[17] M.E. Christy,[14] S. Covrig,[3] W. Deconinck,[12,18] M. Diefenthaler,[3] B. Duran,[10] D. Dutta,[13] M. Elaasar,[19] R. Ent,[3] H. Fenker,[3] E. Fuchey,[20] D. Hamilton,[21] J.O. Hansen,[3] F. Hauenstein,[22] S. Jia,[10] M.K. Jones,[3] S. Joosten,[11] M.L. Kabir,[13] A. Karki,[13] C. Keppel,[3] E. Kinney,[23] N. Lashley-Colthirst,[14] W.B. Li,[12,24] D. Mack,[3] S. Malace,[3] M. McCaughan,[3] Z.E. Meziani,[10,11] R. Michaels,[3] R. Montgomery,[21] M. Muhoza,[4] C. Munoz Camacho,[25] G. Niculescu,[26] I. Niculescu,[26] Z. Papandreou,[1] S. Park,[24] E. Pooser,[3] M. Rehfuss,[10] B. Sawatzky,[3] G.R. Smith,[3] H. Szumila-Vance,[3] A. Teymurazyan,[1] H. Voskanyan,[27] B. Wojtsekhowski,[3] S.A. Wood,[3] C. Yero,[7] J. Zhang,[17] and X. Zheng[17]

(KaonLT Collaboration)



L/T Separated π^+/K^+ Cross Sections with 12 GeV JLab

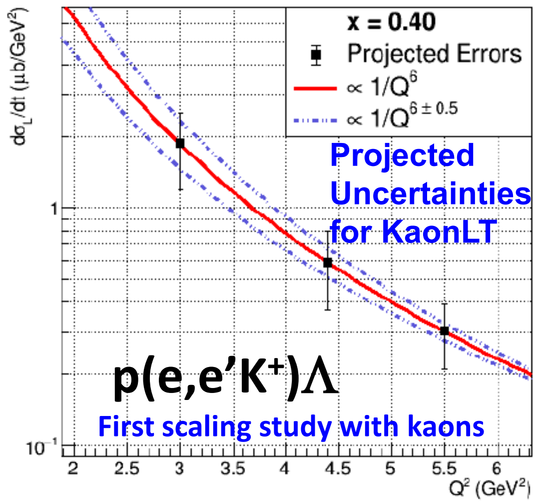




- One of the most stringent tests of the reaction mechanism is the Q^2 dependence of cross section
  - –σ_L scales to leading order as Q^{-6}
  - –σ_T does not

PionLT π^+: to Q^2~9 GeV^2
KaonLT K^+: to Q^2~6 GeV^2

Fit: $1/Q^n$



- Need to validate the reaction mechanism for reliable interpretation of the GPD program – key are precision longitudinal-transverse (L/T) separated data over a range of Q^2 at fixed x/t
  - **If σ_T is confirmed to be large, it could allow for detailed investigations of transversity GPDs. If, on the other hand, σ_L is measured to be large, this would allow for probing the usual GPDs**

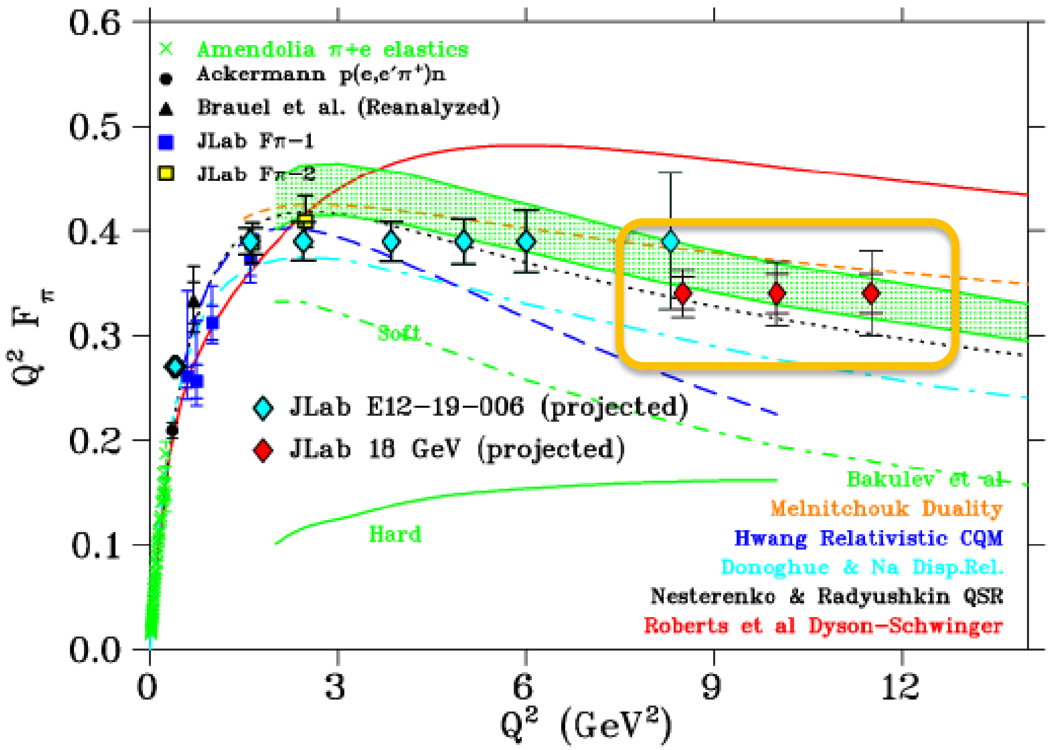
Q^{-n} scaling test range doubles with 18 GeV beam and HMS+SHMS

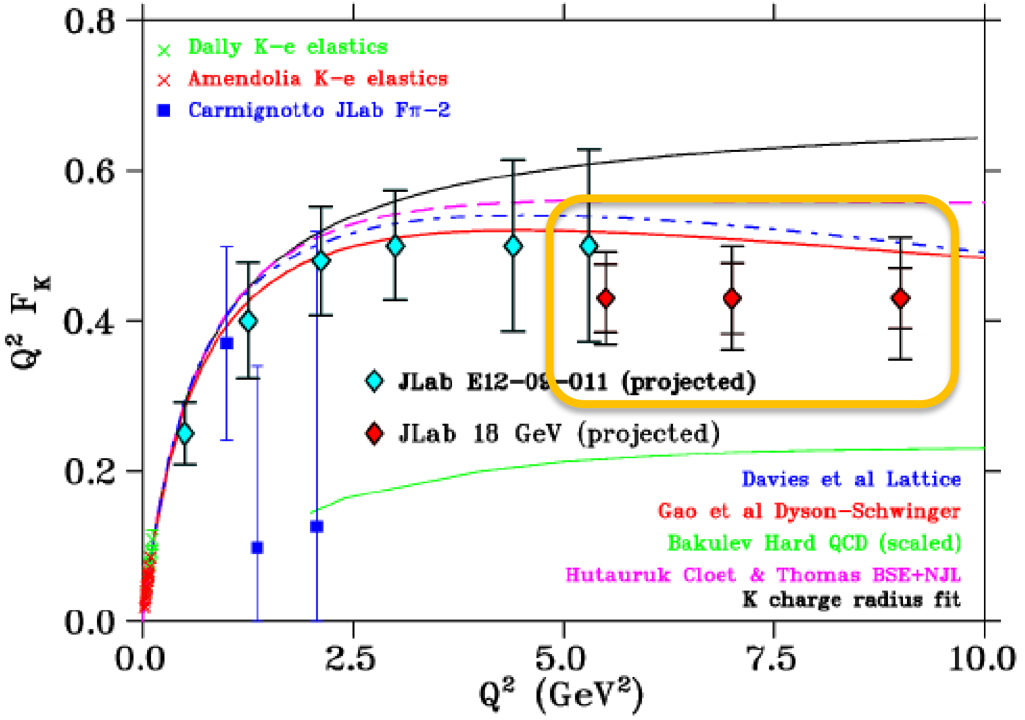
JLab 22 GeV: Opportunities for π, K form factors

Exclusive study group: Dave Gaskell (JLab), Tanja Horn (CUA), Garth Huber (URegina), Stephen Kay (U. York), Bill Li (Stonybrook U.), Pete Markowitz (FIU), et al.

Projections based on 50 days of beam time

A. Accardi,…, T. Horn, et al., “Strong Interaction Physics at the Luminosity Frontier with 22 GeV electrons at Jefferson Lab”, Eur. Phys. J. A **60** (2024) 9, 173



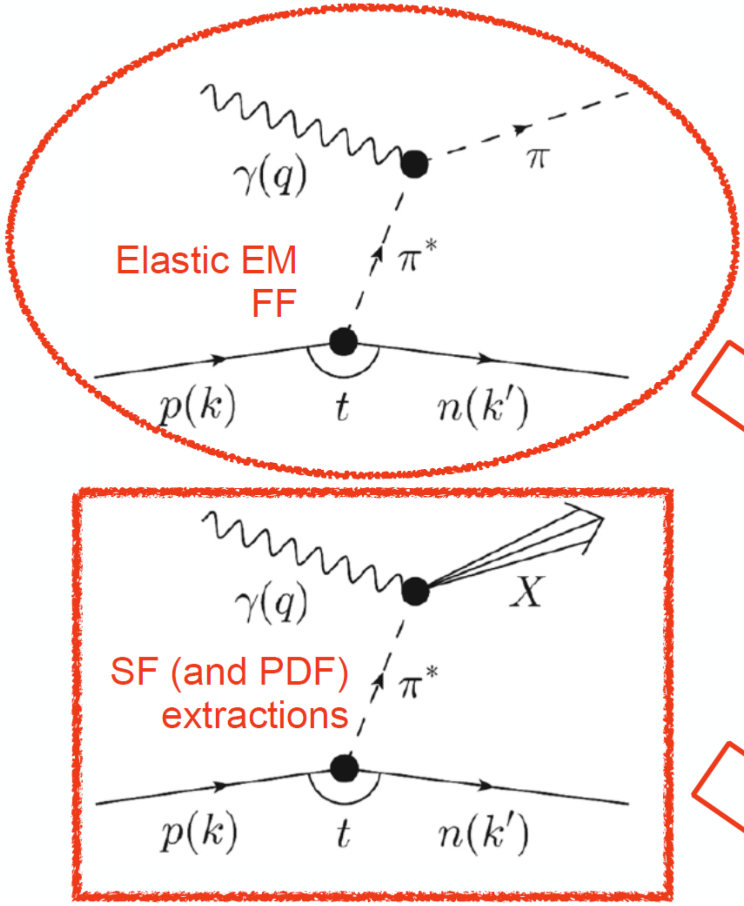


- ❑ Assume a staged energy upgrade with Phase 1 at 18 GeV and minor updates of SHMS, HMS PID, tracking, and DAQ
- ❑ Enables a significant increase in Q^2 reach of quality LT separations for DVMP – only possible in Hall C
- ❑ Interpretation of future data, e.g., EIC, depend on the extrapolation of LT data – maximizing the data set overlap of high priority

Accessing Pion/Kaon Structure Information

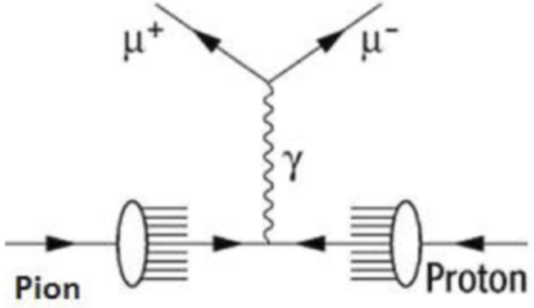
Sullivan

Hard scattering from virtual meson cloud of nucleon



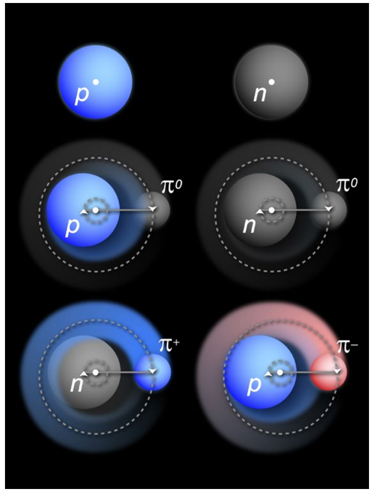
Drell-Yan

Quark of pion (e.g.) annihilates with anti-quark of proton (e.g.), virtual photon decays into lepton pair



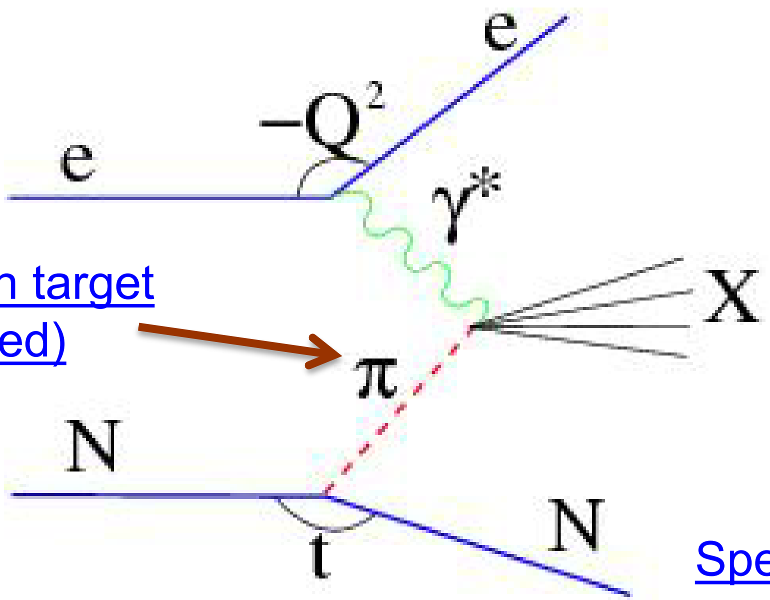
- **Pion/Kaon elastic EM Form Factor**
  - Informs how EHM manifests in the wave function
  - Decades of precision F_π studies at JLab and recently completed measurement in Hall C for F_π and also F_K
  - EIC offers exciting kinematic landscape for FF extractions
- **Pion/Kaon Structure Functions**
  - Informs about the quark-gluon momentum fractions

Physics Objects for Pion/Kaon Structure Studies



Sullivan process:
scattering from nucleon-meson fluctuations

Detect scattered electron



Pion/Kaon target (undetected)

DIS event – undetected recoiling hadronic system

Spectator "tagged" neutron/lambda

DIS event – reconstruct x, Q^2, W^2, also M_X of recoiling hadronic system

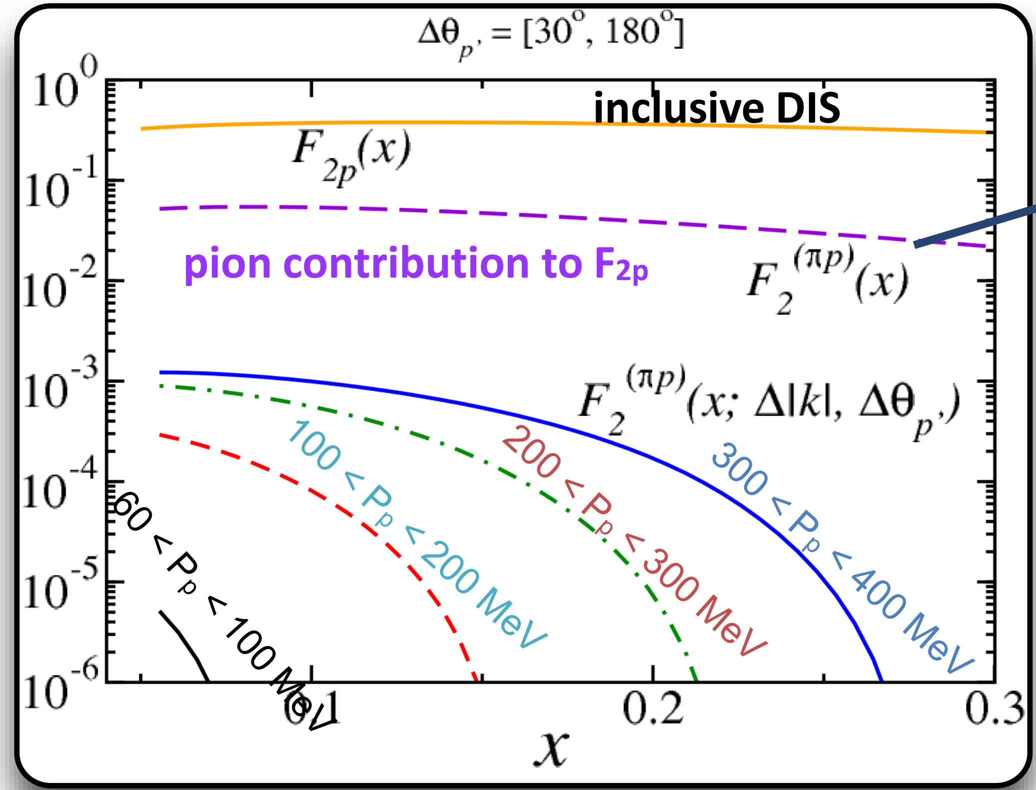
$$R^T = \frac{d^4\sigma(ep \to e'Xp')}{dxdQ^2dzdt} \Big/ \frac{d^2\sigma(ep \to e'X)}{dxdQ^2} \Delta z \Delta t \sim \frac{F_2^T(x, Q^2, z, t)}{F_2^p(x, Q^2)} \Delta z \Delta t.$$

Tagged structure function
a direct measure of the mesonic content of nucleons

$$F_2^T(x, Q^2, z, t) = \frac{R^T}{\Delta z \Delta t} F_2^p(x, Q^2).$$

Tagged DIS can be used to tag the "meson cloud"

Tagged Structure Functions can provide the magnitude of the mesonic content of the nucleon



Pion contribution dominates at JLab kinematics (with ~ 1% for P_p < 400 MeV/c)

$$F_2^{(\pi N)}(x) = \int_x^1 dz\, f_{\pi N}(z)\, F_{2\pi}\left(\frac{x}{z}\right),$$

light-cone momentum distribution of pions in the nucleon

$z = k^+/p^+$ - light cone momentum fraction of the initial nucleon carried by the virtual pion, where k is π 3-momentum = -p'

When tagging pion by detecting recoil proton

$$F_2^{(\pi N)}(x, z, k_\perp) = f_{\pi N}(z, k_\perp)\, F_{2\pi}\left(\frac{x}{z}\right)$$

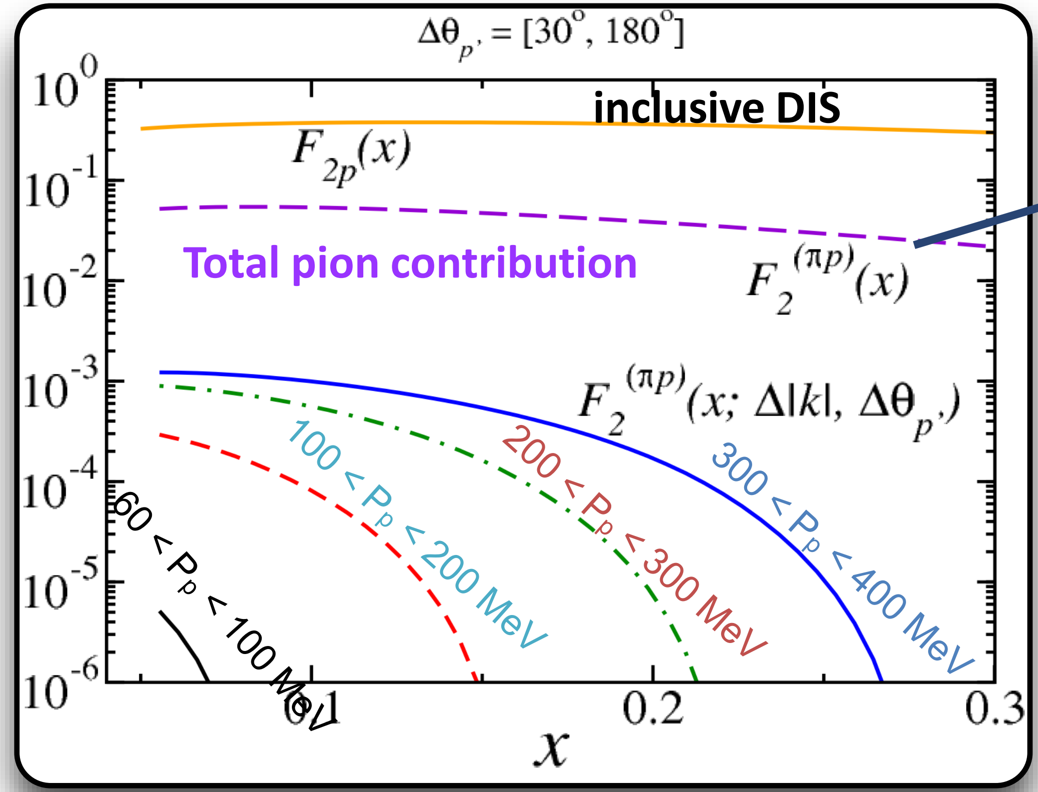
Tagged SF

pion "flux"

Pion SF

T. J. Hobbs, Few-Body Cyst. 56, 363–368 (2015);
H. Holtmann, A. Szczurek and J. Speth, Nucl. Phys. A 596, 631 (1996); W. Melnitchouk and A. W. Thomas, Z. Phys. A 353, 311 (1995)

Tagged Structure Functions can provide the magnitude of the mesonic content of the nucleon



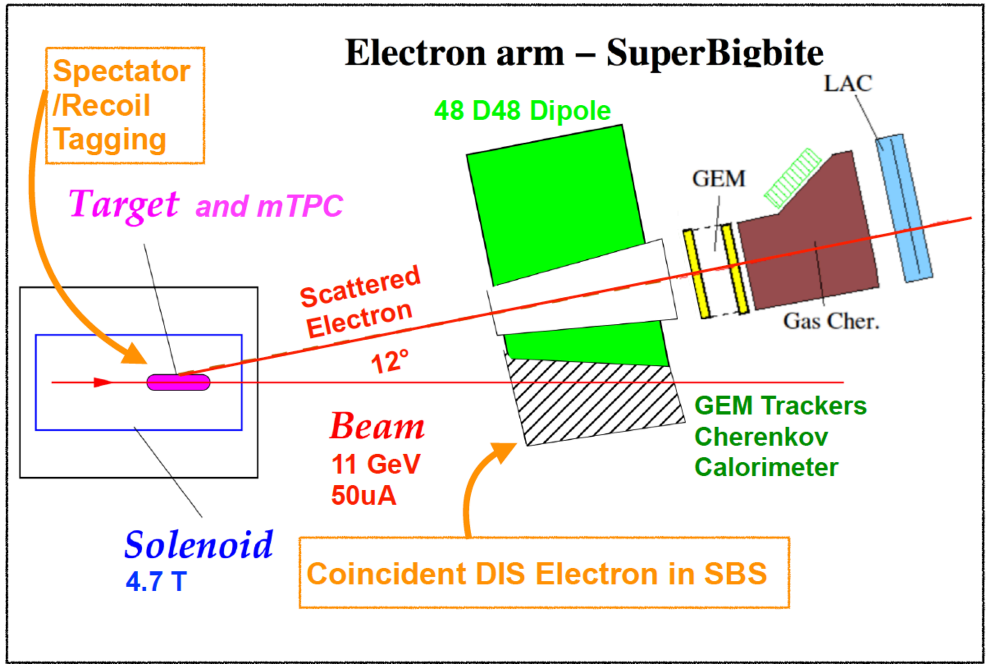
Pion Contribution dominates at JLab

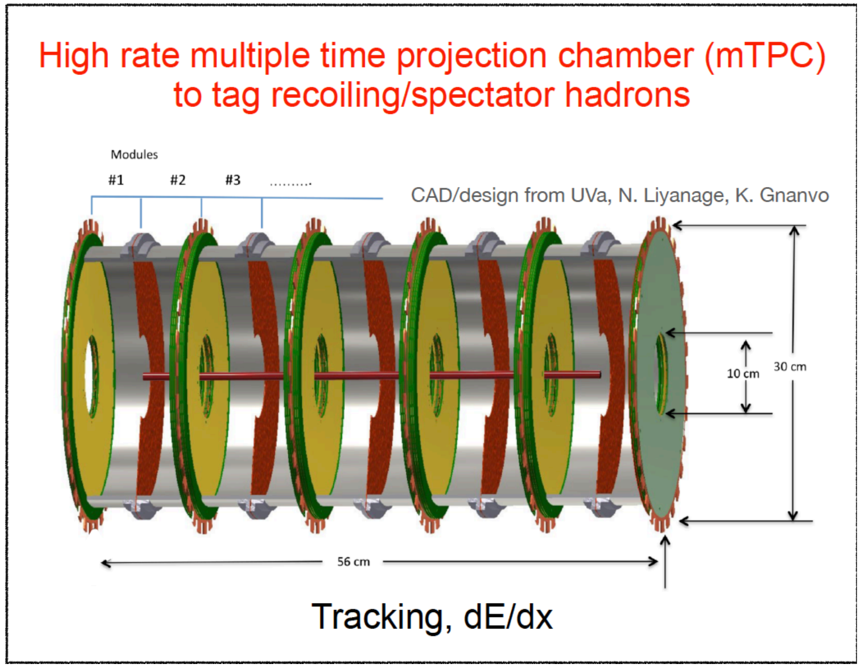
Pion contribution dominates at JLab kinematics (with ~ 1% for P_p < 400 MeV/c)

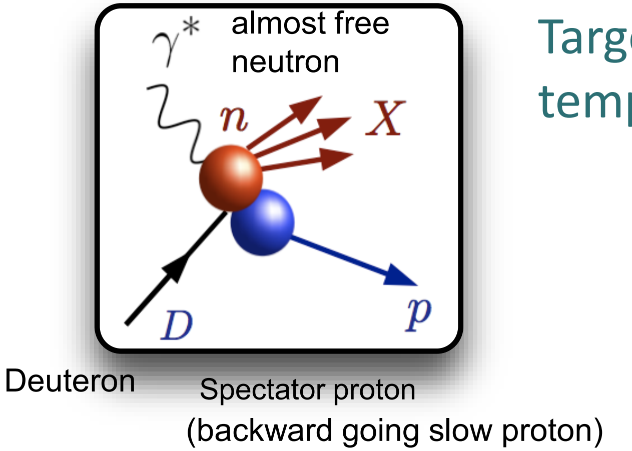
T. J. Hobbs, Few-Body Cyst. 56, 363–368 (2015); H. Holtmann, A. Szczurek and J. Speth, Nucl. Phys. A 596, 631 (1996); W. Melnitchouk and A. W. Thomas, Z. Phys. A 353, 311 (1995)

Spectator Tagging – well established technique at JLab

The TDIS experiment will use spectator tagging in a cylindrical recoil detector



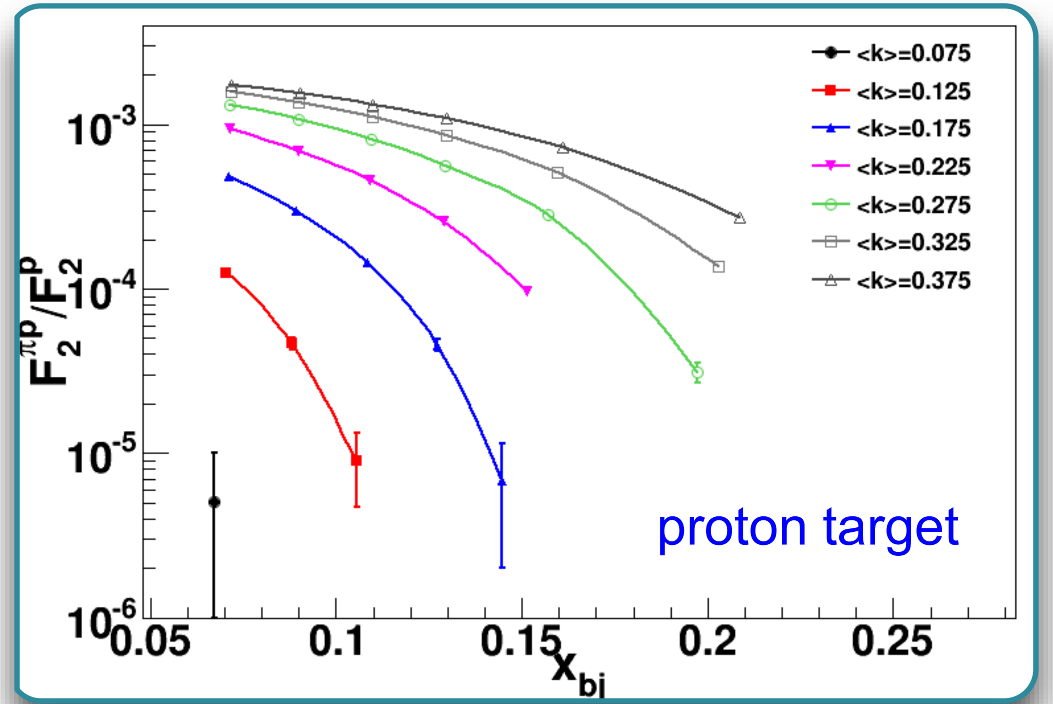


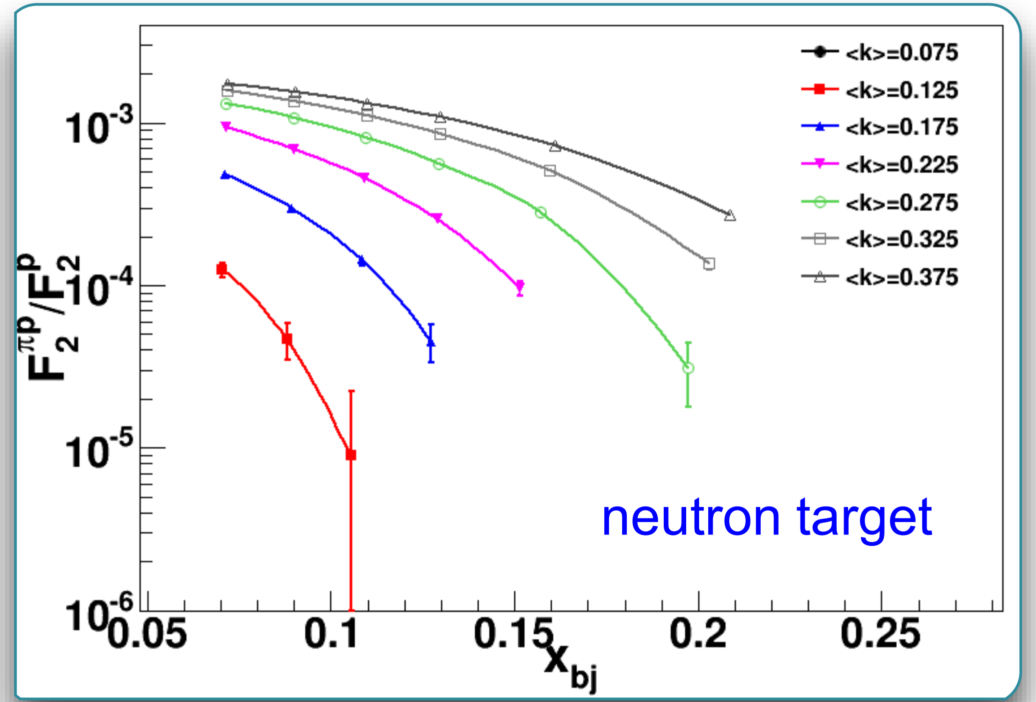


Target: 40 cm long, 25 um wall thickness Kapton straw at room temperature and 3 atm. pressure.

- TDIS will be a pioneering experiment that will be the first direct measure of the mesonic content of nucleons.
- The techniques used to extract meson structure function will be a necessary first step for future experiments

TDIS experiment will measure tagged structure functions





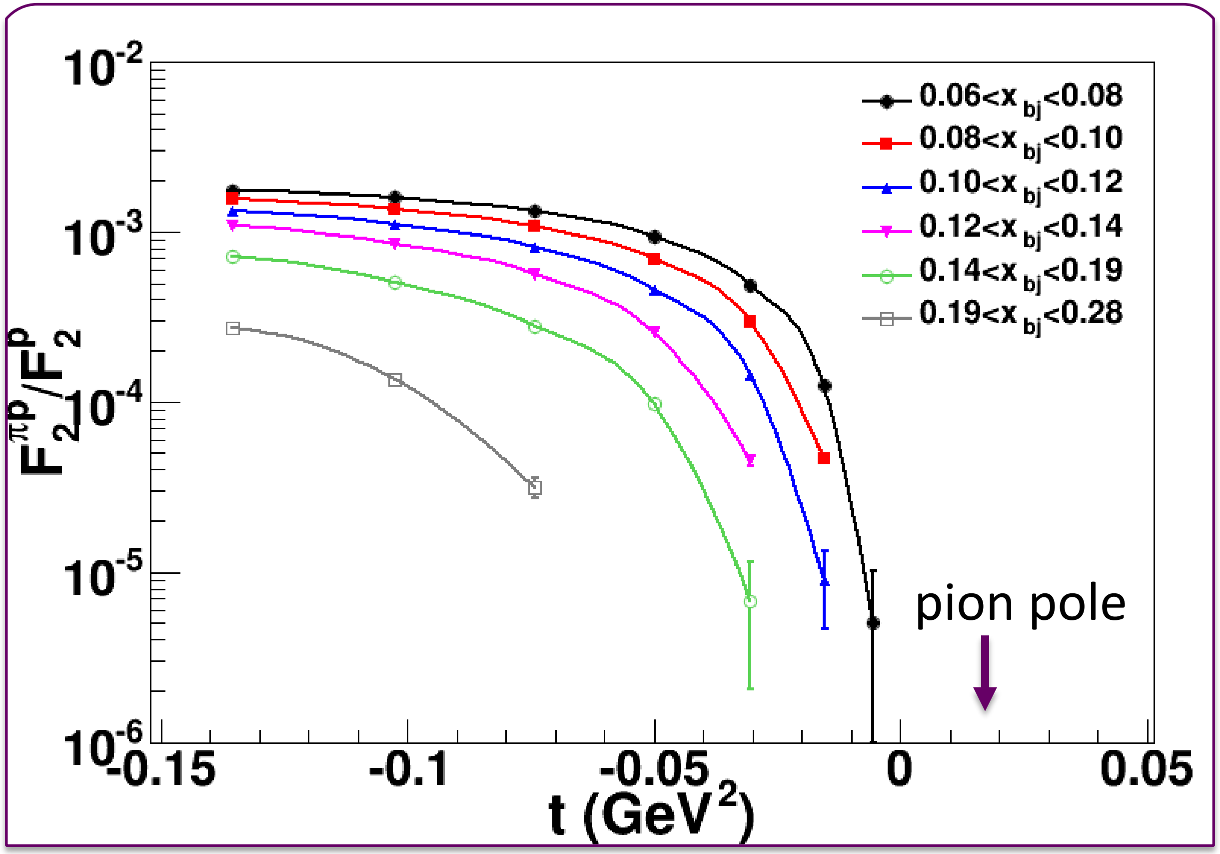
Full momentum range (collected simultaneously) - all momentum bins in MeV/c
Error bars largest at highest x points - at fixed x, these are the lowest t values

some kinematic limits:
- 150 < k < 400 MeV/c corresponds to z < ~0.2
- Also, x < z
- Low x, high W at 11 GeV means Q^2 ~2 GeV^2

TDIS experiment - pion structure function

It requires extrapolation to the pion pole

low momentum protons helps cover a range of low |t|

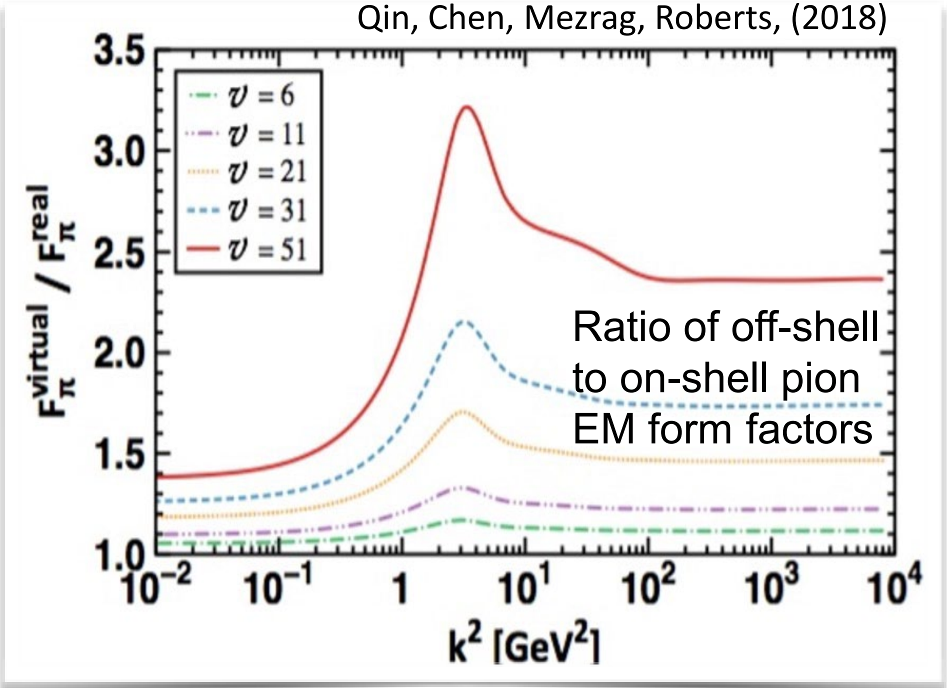


virtuality-independent form factor implies virtuality-independent pion structure function

virtuality $\boldsymbol{\nu}$ = 30 ⇒ t = -0.6 GeV^2

TDIS covers |t|= 0.01 - 0.16 GeV^2

Qin, Chen, Mezrag, Roberts, (2018)



The uncertainty in extrapolation to the pion pole within ~5% at JLab kinematics

Projected JLab TDIS Results for π, K Structure Functions

Jefferson Lab 12 GeV – experiment C12-15-006/006A

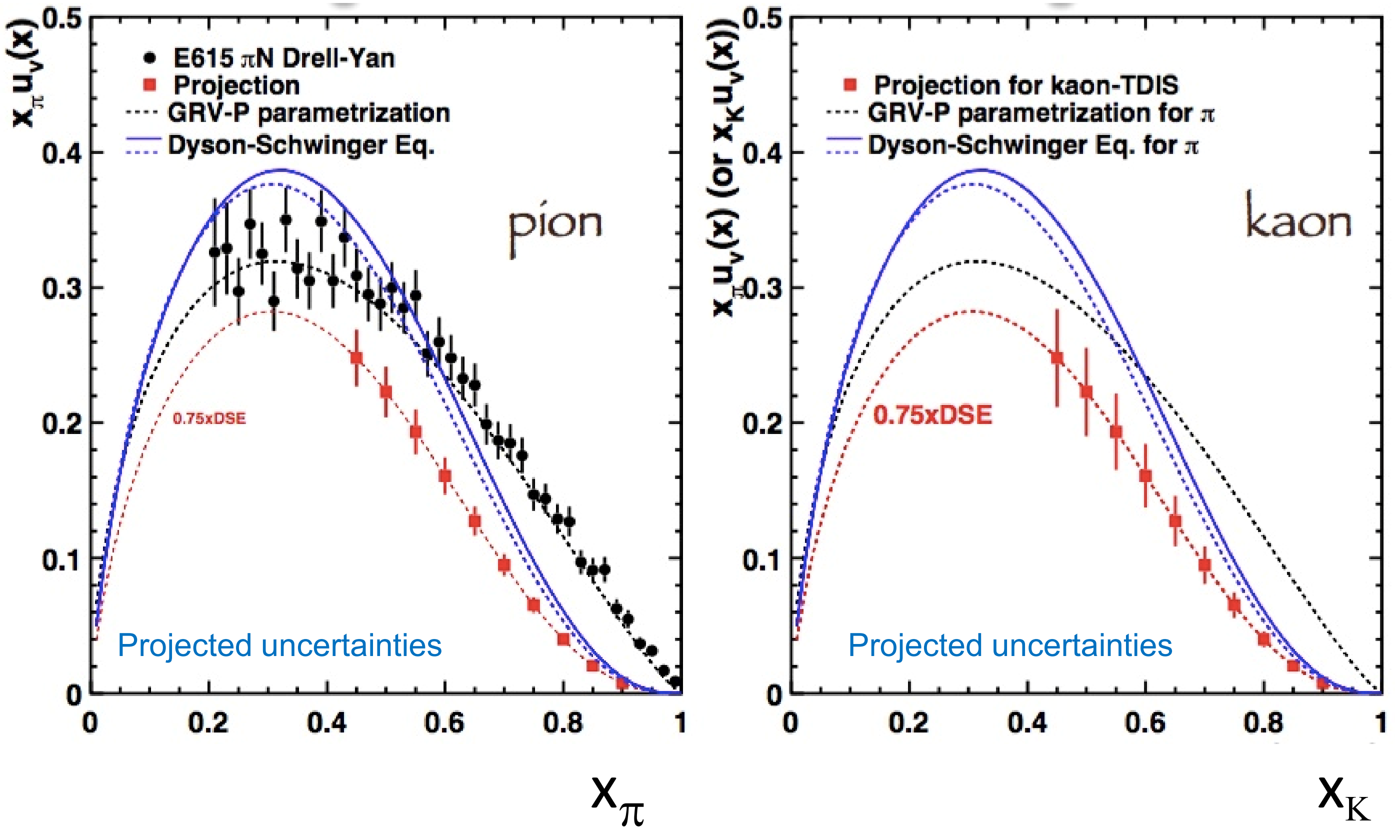
Spokespersons: D. Dutta, T. Horn, C. Keppel, P. King, N. Liyanage, R. Montgomery, K. Park, B. Wojtsekhowski,

TDIS with SBS:

✓High luminosity,
50 μAmp,
$\mathcal{L} = 3\text{x}10^{36}/\text{cm}^2\ \text{s}$

✓Large acceptance
~70 msr

Important for small cross sections



Pion and Kaon F2 SF extractions in valence regime

- Independent charged pion SF
- First kaon SF
- First neutral pion SF

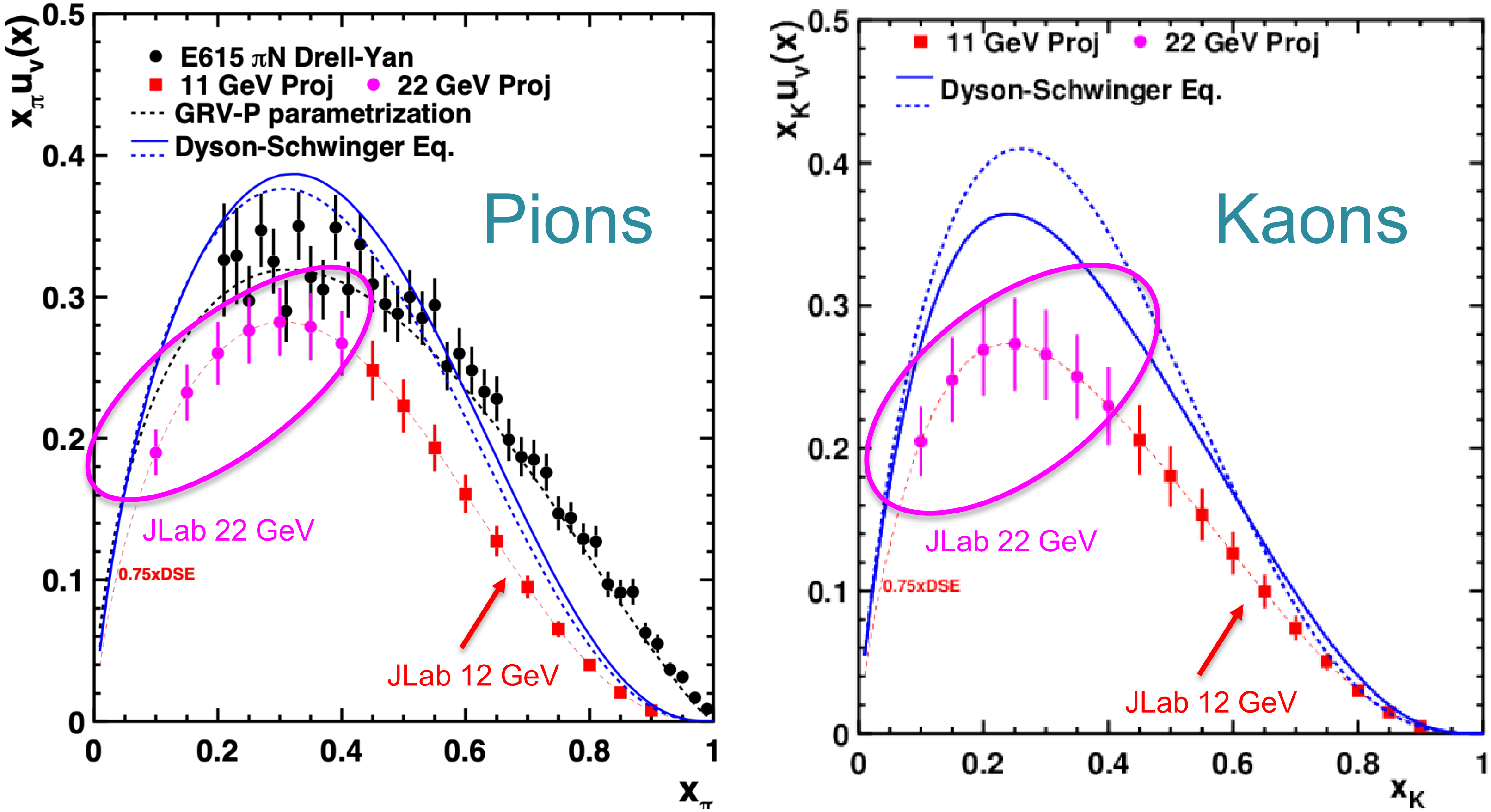
Projections based on phenomenological pion cloud model

T.J. Hobbs, Few Body Syst. 56 (2015) 6-9
J.R. McKenney et al., Phys. Rev. DD 93 (2016) 05011

Essentially no kaon data currently

JLab 22 GeV: Opportunities for TDIS π, K Structure

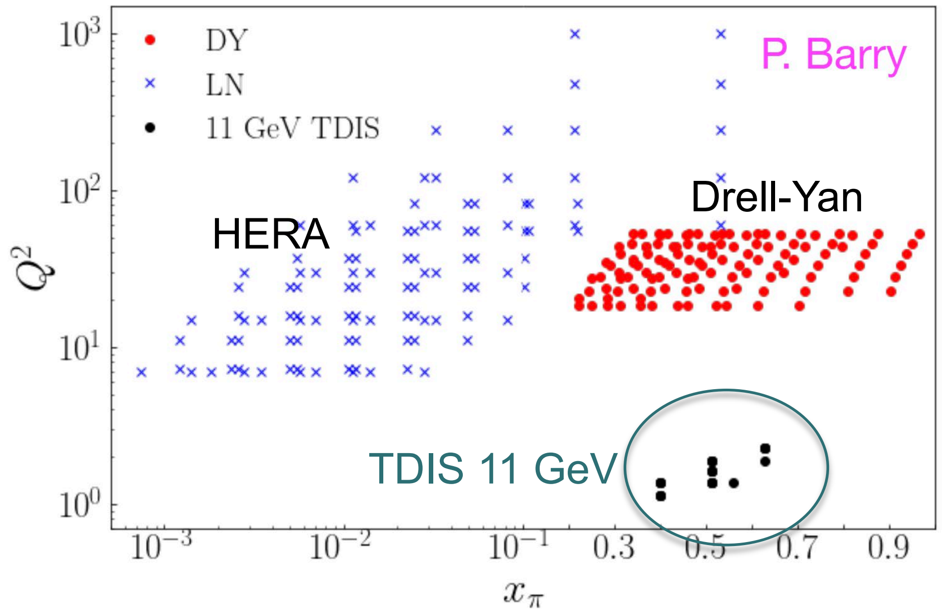
Tagged DIS in the JLab era study group: Dipangkar Dutta (MSU), Carlos Ayerbe-Gayoso, Rachel Montgomery (U. Glasgow), Tanja Horn (CUA), Thia Keppel (JLab), Paul King (OU), Rolf Ent (JLab), Patrick Barry (JLab)

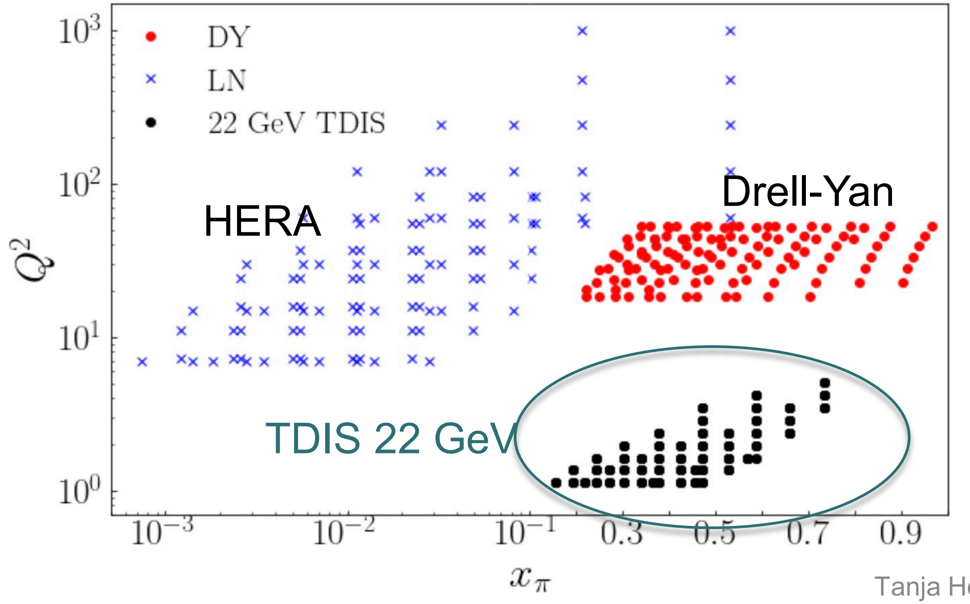


Adding a new constraint in the kinematics enables the study of π resonances

- The low-W^2 region was not measured at HERA – strength of resonances is unknown
- Wide kinematic coverage in TDIS to measure the resonance region

JLab 22 GeV: Opportunities for TDIS π, K Structure





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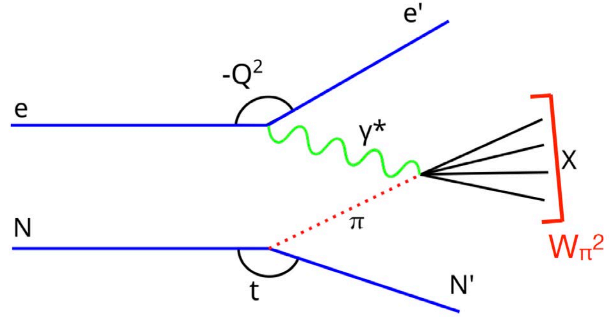
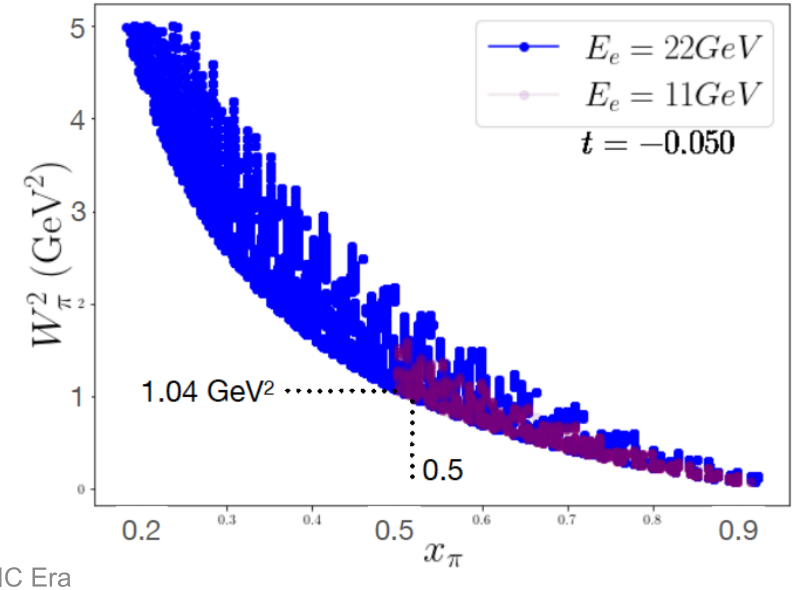


Using $W_\pi^2 > 1.04$ GeV^2 to remove $\boldsymbol{\rho}$ meson contribution would significantly reduce kinematic coverage at 11 GeV but not at 22 GeV

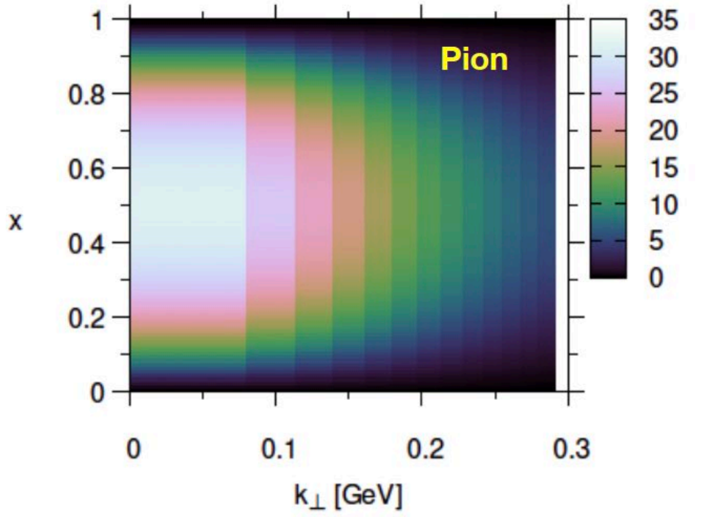


Based on simulations by P. Barry

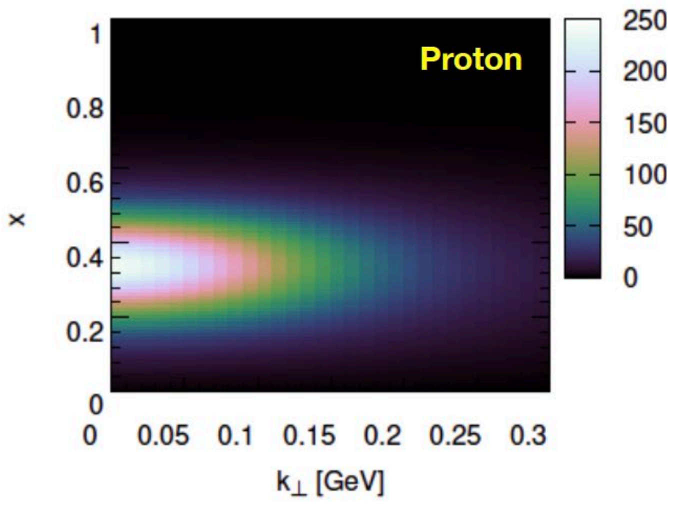
JLab 22 GeV: Opportunities for TDIS π, K Structure

Tagged DIS in the JLab era study group: Dipangkar Dutta (MSU), Carlos Ayerbe-Gayoso, Rachel Montgomery (U. Glasgow), Tanja Horn (CUA), Thia Keppel (JLab), Paul King (OU), Rolf Ent (JLab), Patrick Barry (JLab)

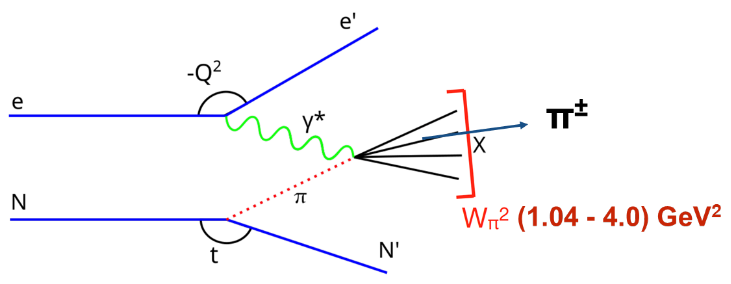
PRD **105**, L071505 (2022); PRD **104**, 114012 (2021) E. Ydrefore & T. Frederico

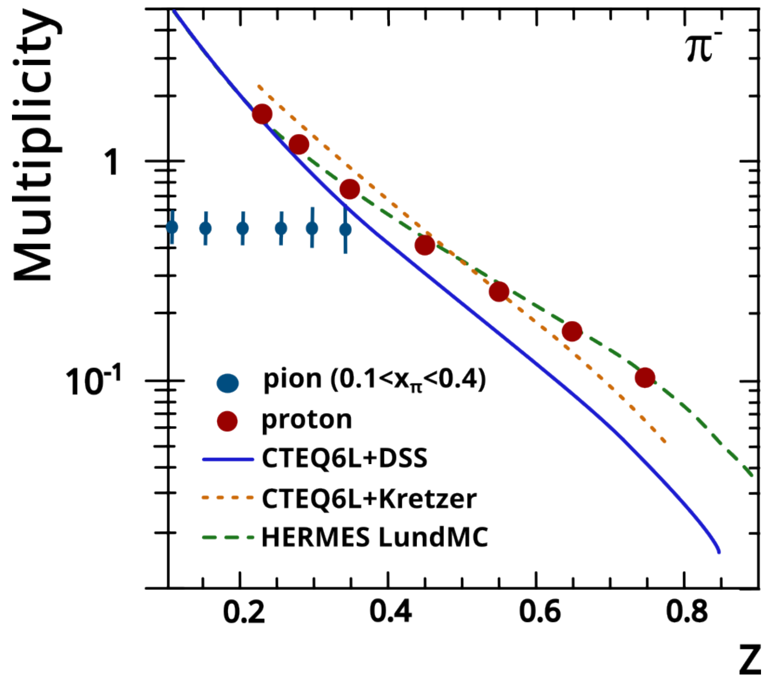


Pion TMDs from Bethe-Saltpeter equation



Proton TMDs from Light-Front Model



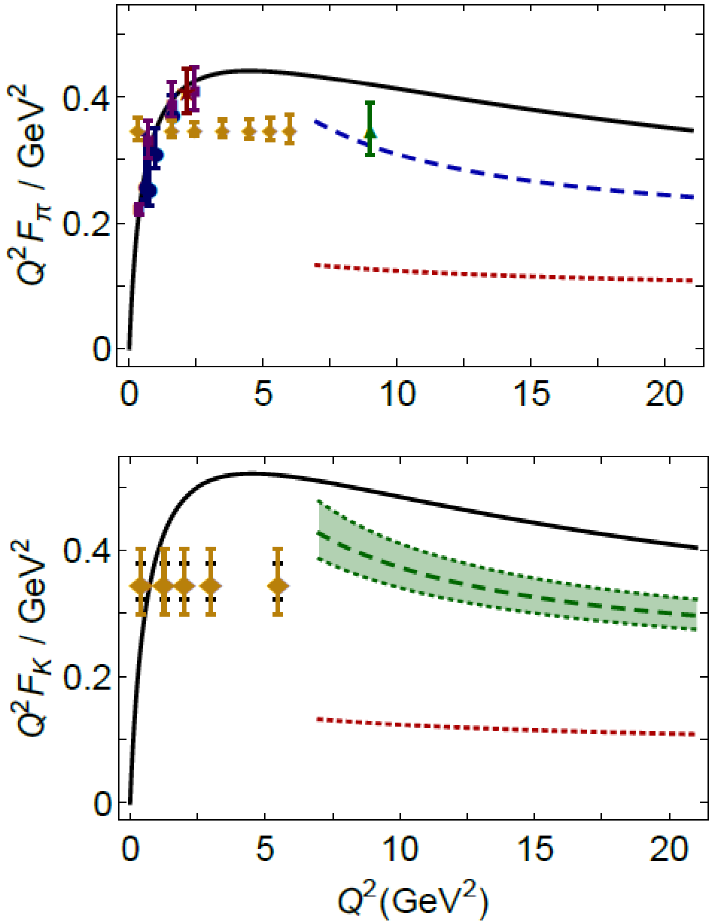


Significant x-broadening of Pion TMDs compared to proton TMDs

- TDIS with 22 GeV beam also enables access to TMDs
- Measurement of SIDIS from a pion target – requires additional instrumentation for detection of an additional pion (ongoing effort)

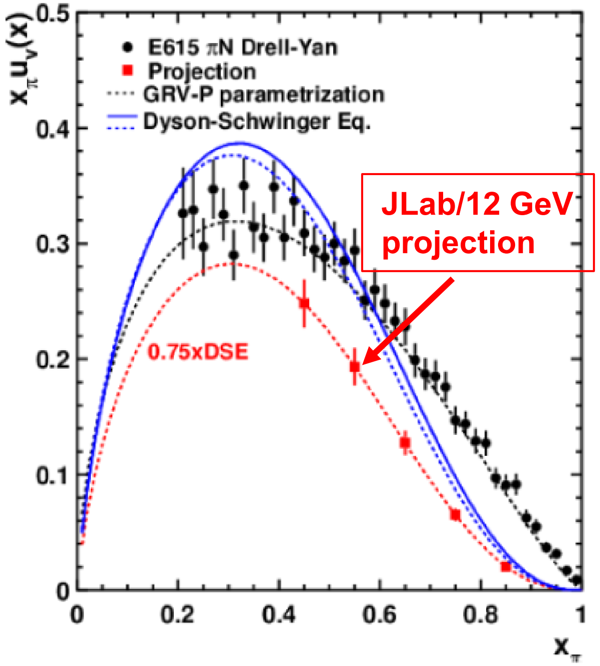
Pion and Kaon Structure at 12 GeV and beyond

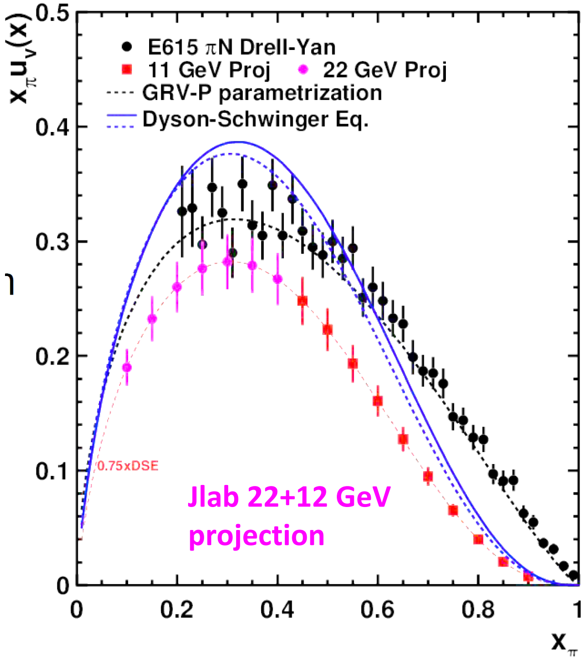
Jefferson Lab will provide, at its CM energy of 5 GeV, tantalizing data for the pion (kaon) form factor up to $Q^2 \sim 10$ (5) GeV^2, and measurements of the pion (kaon) structure functions at large-x (> 0.5) through the Sullivan process.



Pion FF – first quantitative access to hard scattering scaling regime?

PR12-15-006



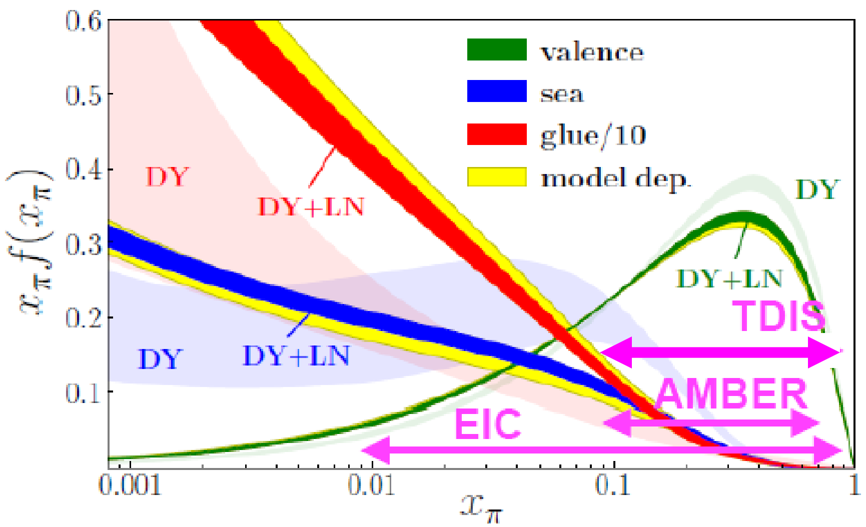


Pion SF – $(1-x)^1$ or $(1-x)^2$ dependence at large x?

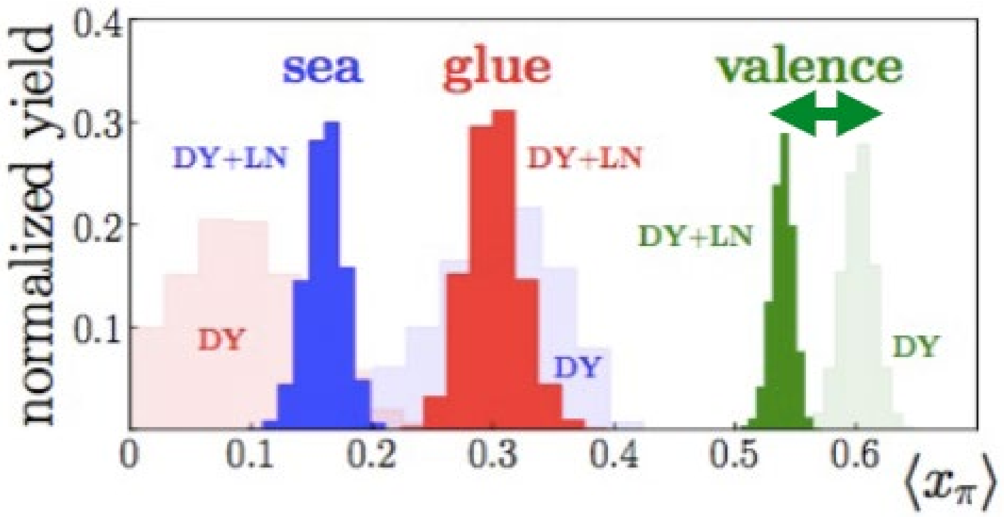
and kaon

Global PDF Fits and Demand for more Data

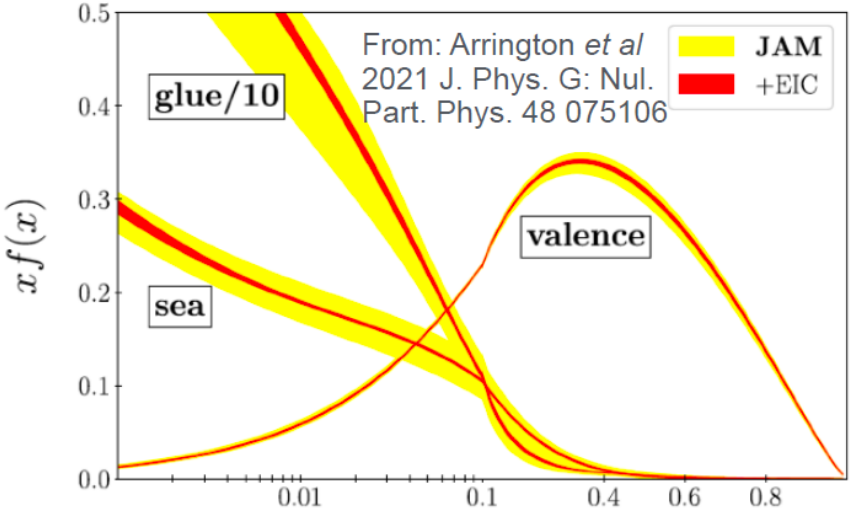
- Combined Leading Neutron/Drell-Yan analysis for PDF fitting, with novel MC techniques for uncertainties (JLab JAM)
- Non-overlapping uncertainties – tension at large x



Mom. Fraction carried by sea/glue/valence



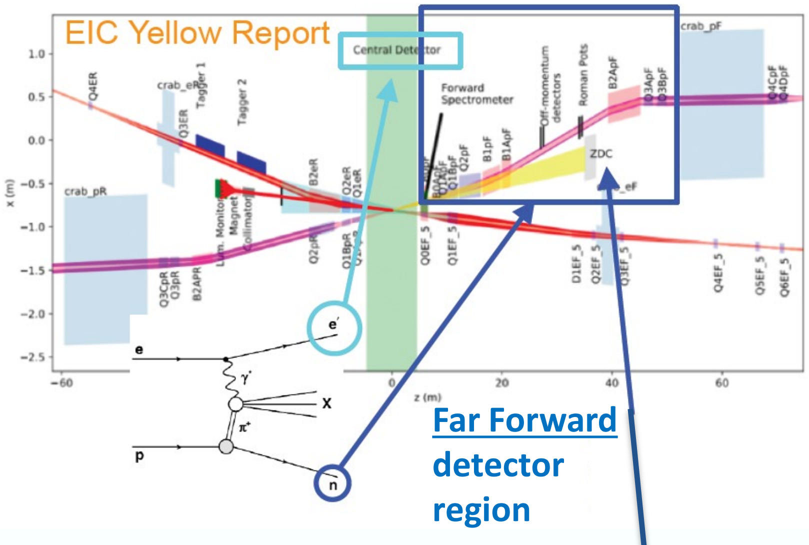
P.C. Barry, N. Sato, W. Melnitchouk, C-R Ji (JAM Collaboration), PRL 121 (2018) 152001



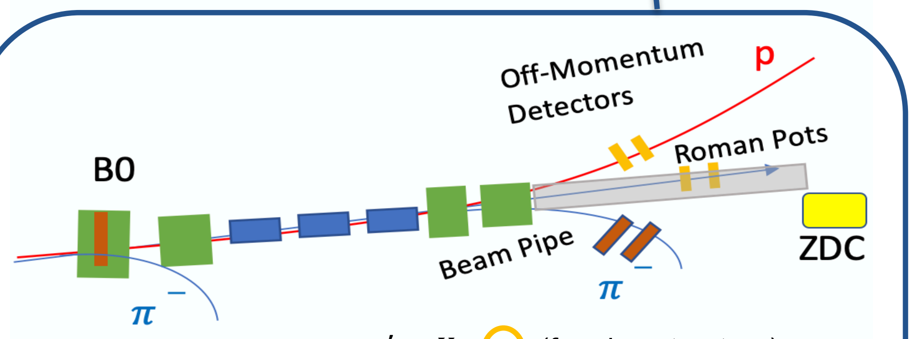
- Yet, different basis light front quantization (BFLQ) technique finds agreement in PDF evolution between DY and DIS
  J. Lan, C. Mondal, S. Jia, X. Zhao, J.P. Vary, Phys. Rev. D 101 (2020) 3, 034024
  - More data needed
- **Excellent opportunity for more data with EIC**
  - Kinematic bridge between HERA and high-x with wide coverage in x

EIC and Sullivan Process SF Measurements

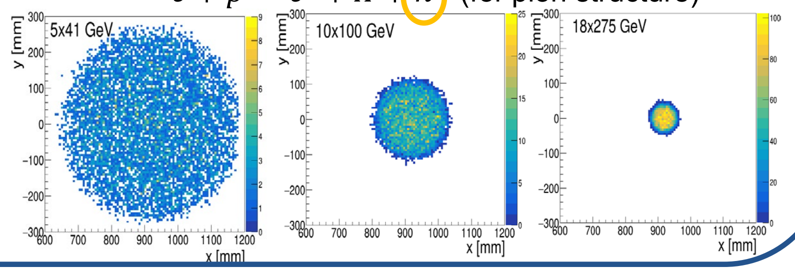
Good Acceptance for TDIS-type Forward Physics! Low momentum nucleons ***easier*** to measure!



- ❑ EIC design well suited for HERA-style pion/kaon SF measurements
- ❑ Scattered electron detected in the central detector
- ❑ Leading hadrons → large fraction of initial beam energy → far forward detector region
  - ZDC particularly important (reaction kinematics and 4 momenta)



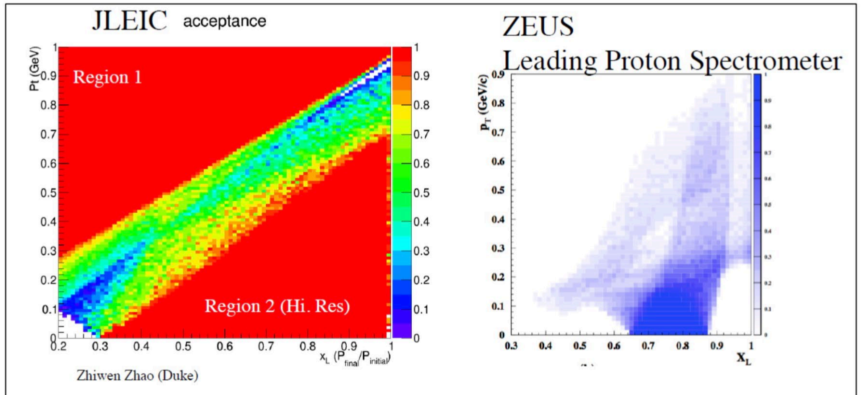
$e + p \rightarrow e' + X + n$ (for pion structure)



Huge gain in acceptance for forward tagging….

*R. Abdul Khalek, …, T. Horn, et al., Nucl. Phys. A **1026** (2022) 122447*

Example: acceptance for p' in e + p → e' + p' + X



Acceptance in diffractive peak (X_L>~.98)

ZEUS: ~2%

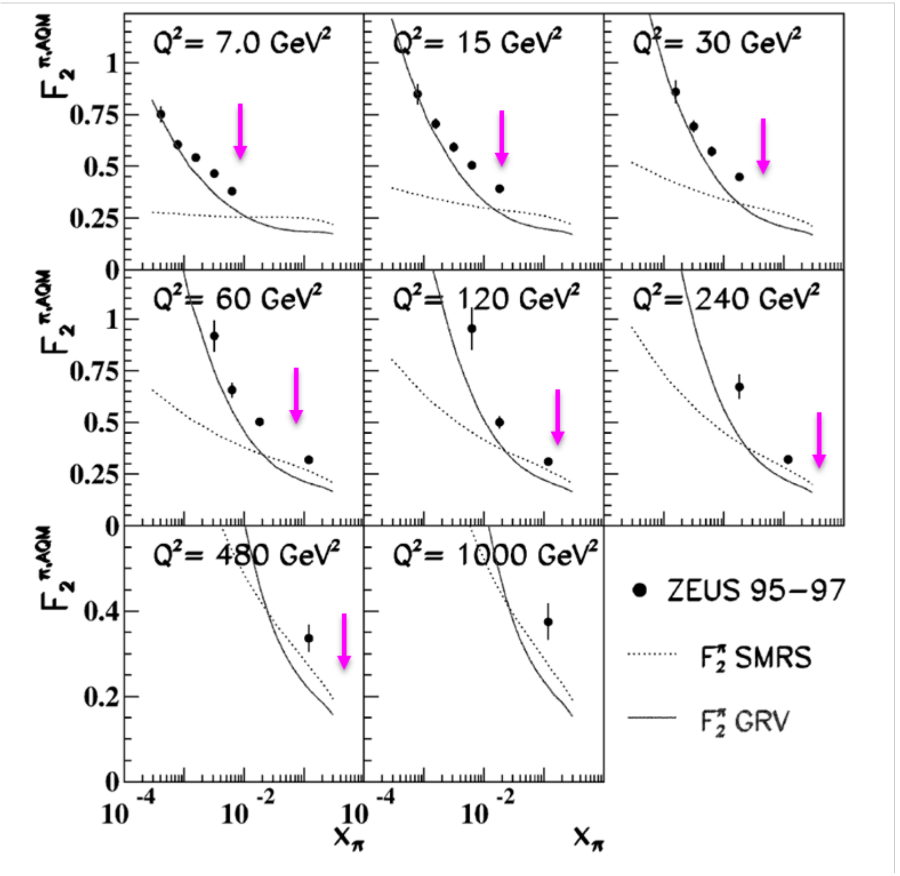
JLEIC: ~100% (also covers much higher X_L than ZEUS)

World Data on Pion Structure Function

HERA: showed Sullivan at low x

Pion sea region, low Bjorken x, high Q^2
$6<Q^2<100\,GeV^2$; $1.5e^{-4}<x<3.0e^{-2}$

~x_{min} for EIC



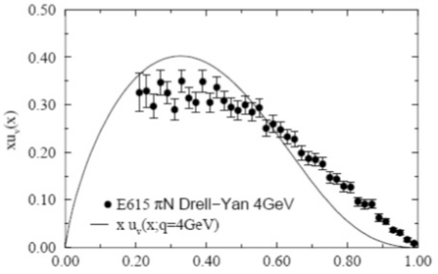
EIC kinematic reach down to a x = few 10^{-3}
Lowest x constrained by HERA leading n

DESY 08-176 JHEP06 (2009) 74

DY: Large x Structure of the Pion

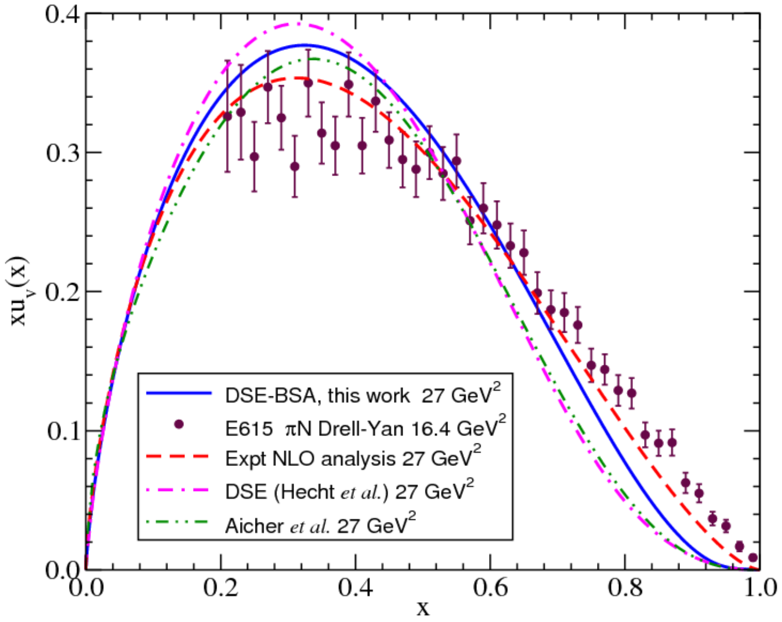
Initial observations:

- PDF ~ $(1-x_\pi)$ as x_π->1
- Agrees with structureless model
- Differs from pQCD prediction of $(1-x_\pi)^2$



$$\pi^- W \to \mu^+ \mu^- X$$

$$\sigma \propto \bar{u}(x_{\pi^-}) u(x_N)$$



- Model tensions, pQCD, Dyson-Schwinger, Light Front, Instanton,…
- NLO gluon resummation effects

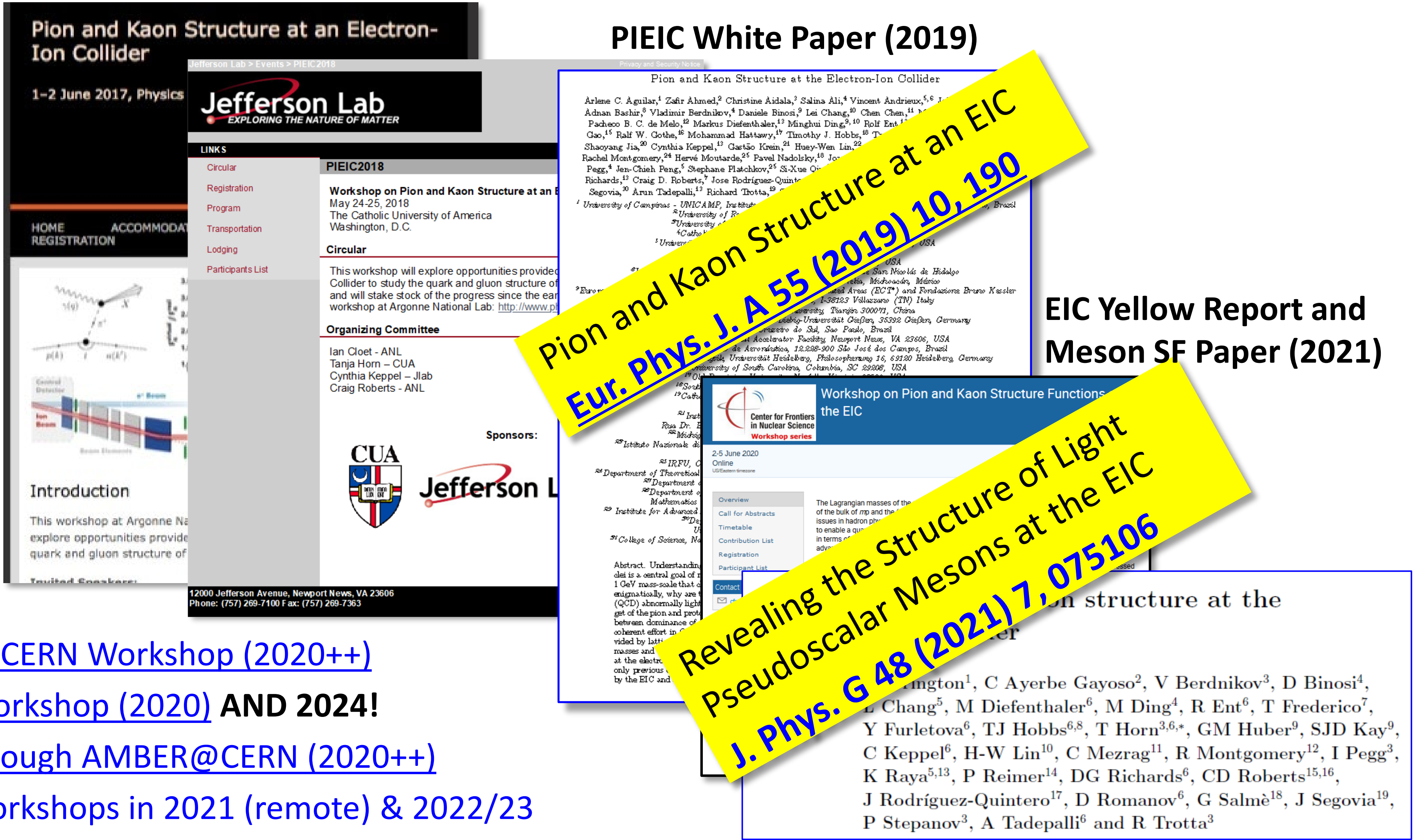
Aicher, Schäfer, Vogelsang, Phys. Rev. Lett. 105, 252003 (2010); L. Chang et al., Phys. Lett. B 737 (2014) 23

Jefferson Lab can provide important verification

C.D. Roberts, IRMA Lect. Math. Theor. Phys. 21 (2015) 355; arXiv:1203.5341 (2012)

Pion and Kaon Structure at the EIC – History

- ❑ PIEIC Workshops hosted at ANL (2017) and CUA (2018)
- ❑ ECT* Workshop: Emergent Mass and its Consequences (2018)



PIEIC White Paper (2019)

Pion and Kaon Structure at an EIC
Eur. Phys. J. A 55 (2019) 10, 190

EIC Yellow Report and Meson SF Paper (2021)

Revealing the Structure of Light Pseudoscalar Mesons at the EIC
J. Phys. G 48 (2021) 7, 075106

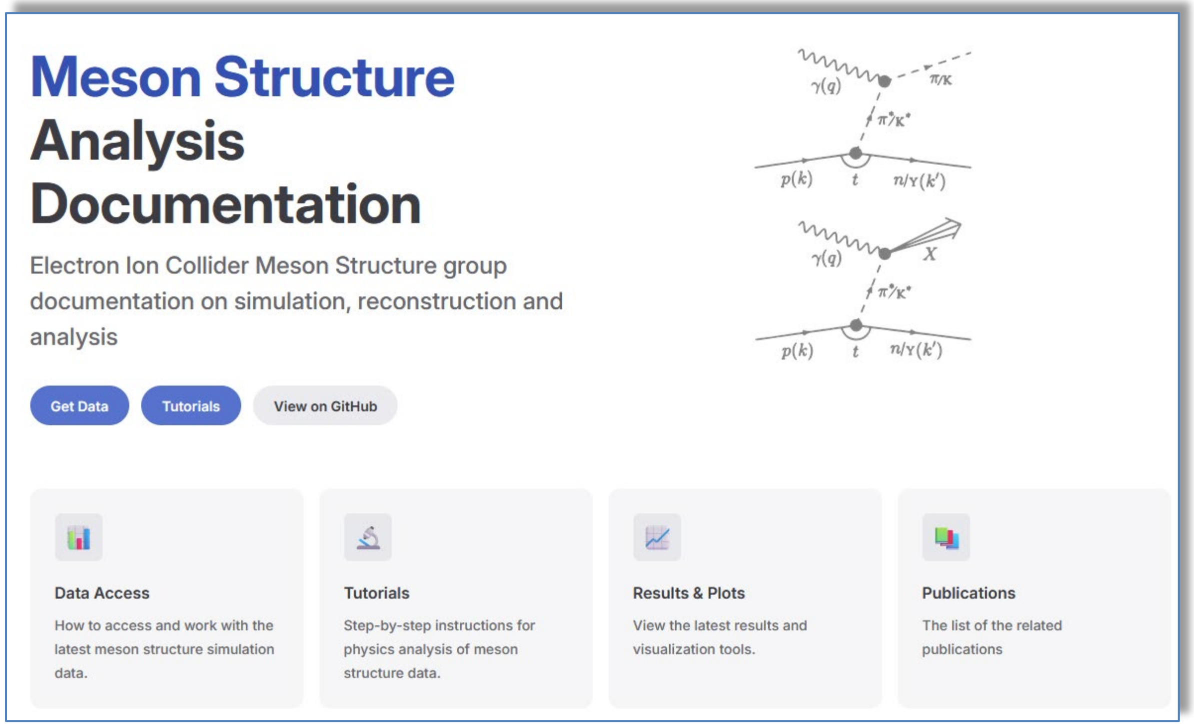
- ❑ AMBER/CERN Workshop (2020++)
- ❑ CFNS Workshop (2020) **AND 2024!**
- ❑ EHM through AMBER@CERN (2020++)
- ❑ ECT* Workshops in 2021 (remote) & 2022/23

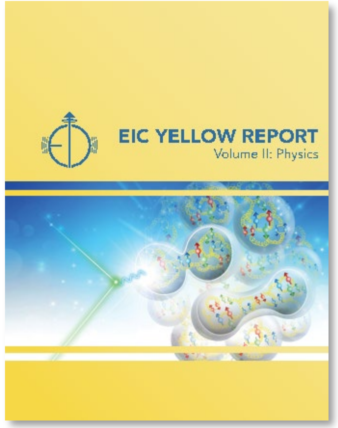
Meson Structure Functions Working Group

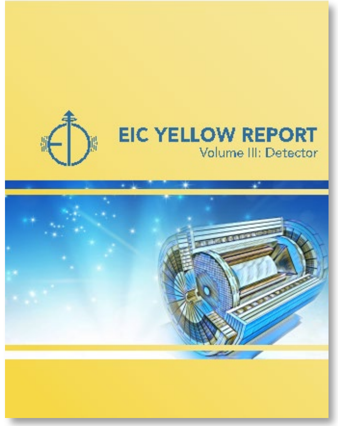
Formed in 2019 in context of the EIC User Group Yellow Report Effort

- Meson SF WG: 42 members, 25 institutions, 11 countries
- To join the Meson Structure Functions WG mailing list, contact T. Horn (hornt@cua.edu)
- Very successful effort, and lively discussions during YR effort and continuing since then with new efforts and publications

Meson SF Working group members:







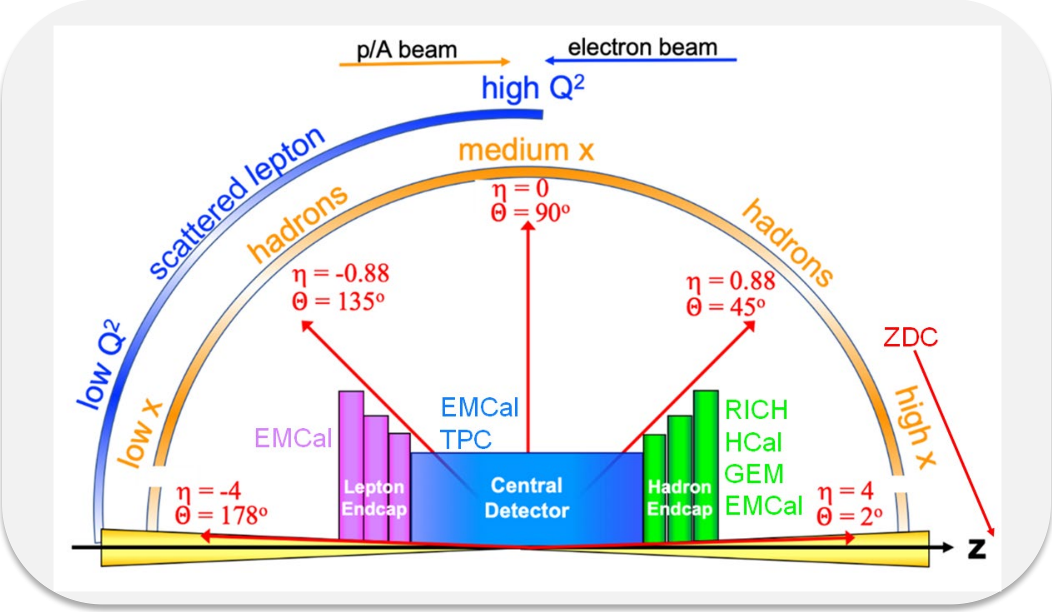
Recent WG discussions and theory publications

- Z-N. Xu et al., "*Kaon distribution functions from empirical information*", Phys. Lett. B **865** (2025) 13951
- W. Good et al., "*Towards the first gluon parton distribution from LaMET*", J. Phys. G **52** (2025) 3, 035105
- D-D. Cheng et al., "*Pion Boer Mulders function using a contact interaction*", Eur. Phys. J. C **85** (2025) 1, 115
- H-Y. Xing et al., "*Kaon and Pion Fragmentation functions*", e-Print: 2504.08142 [hep-ph]

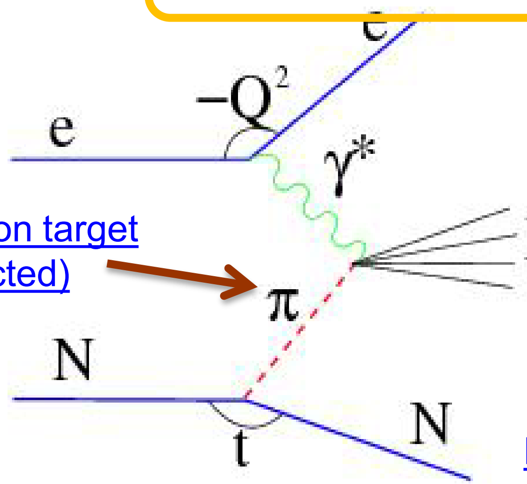
Recent experimental efforts focused on evaluating early science opportunities at EIC

EIC Detector and SF Measurements

Scattered Electron detected in the central detector



Detect scattered electron

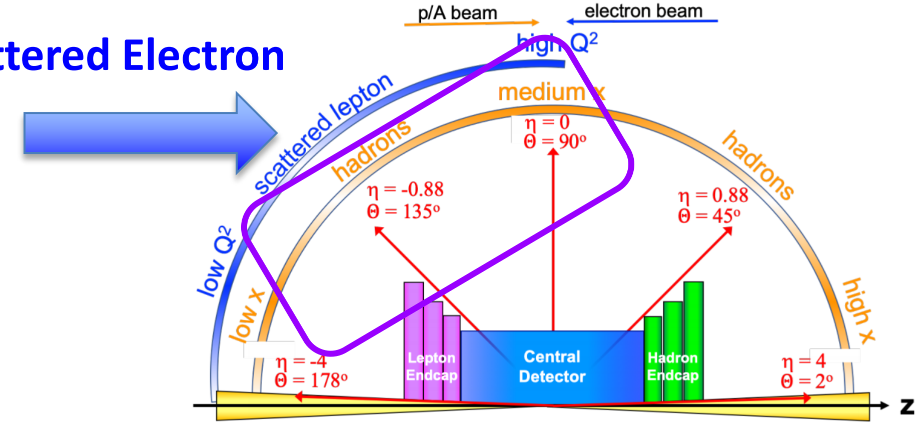


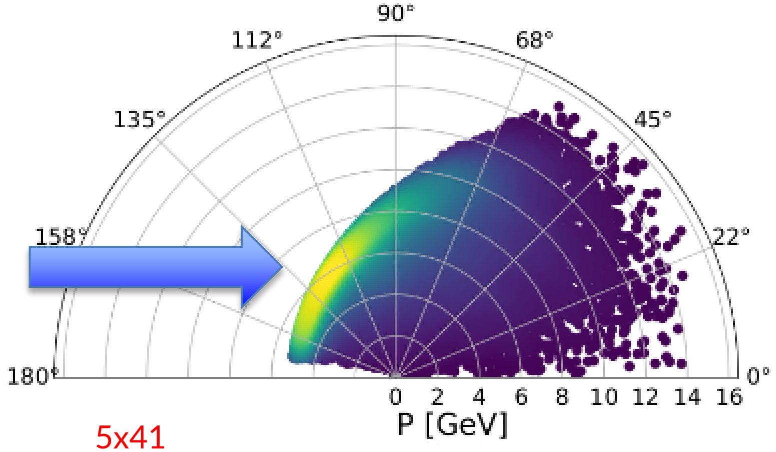
DIS event – reconstruct x, Q^2, W^2, also M_X (W_π) of undetected recoiling hadronic system

Pion/Kaon target (undetected)

Detect "tagged" neutron/lambda

Scattered Electron

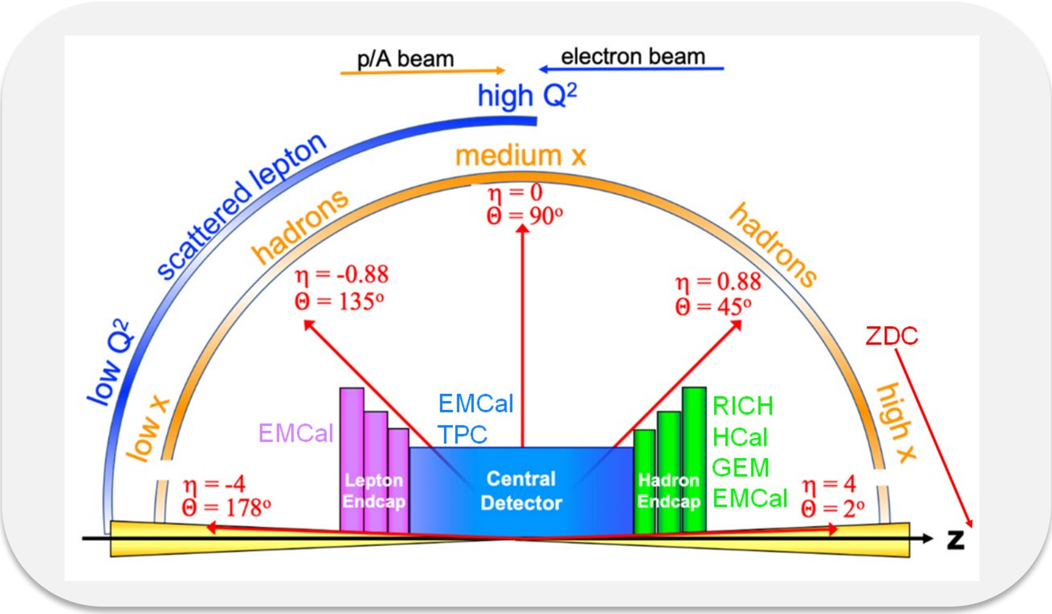


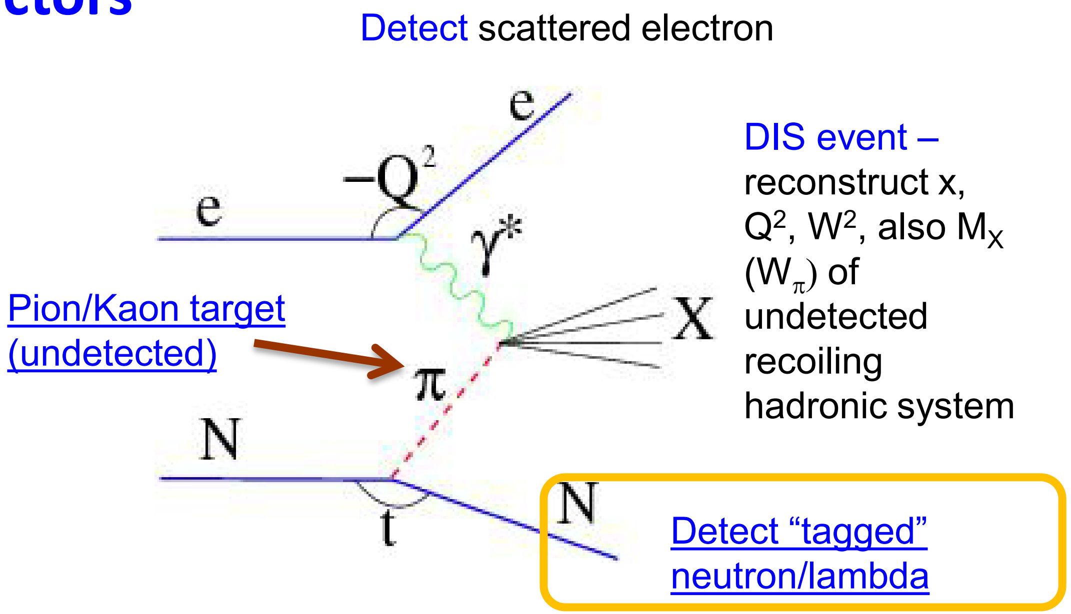


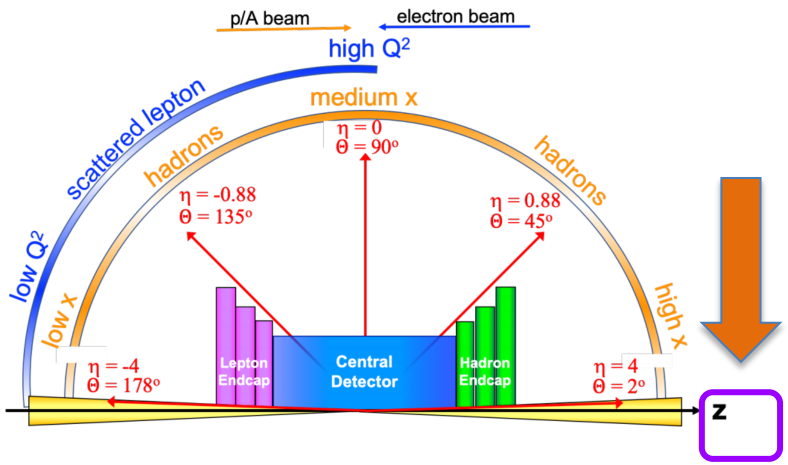
5x41

EIC Detector and SF Measurements

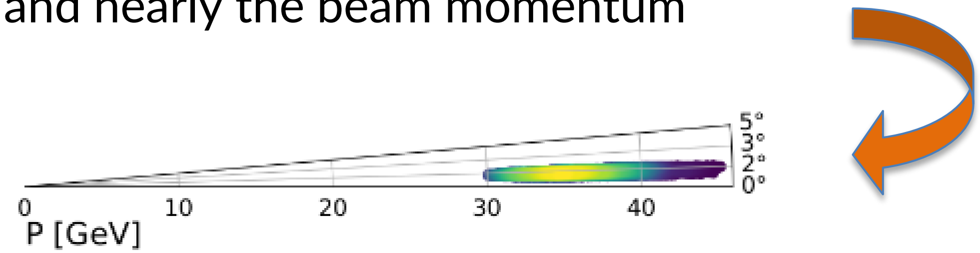
Leading Baryon detected in the Far Forward detectors





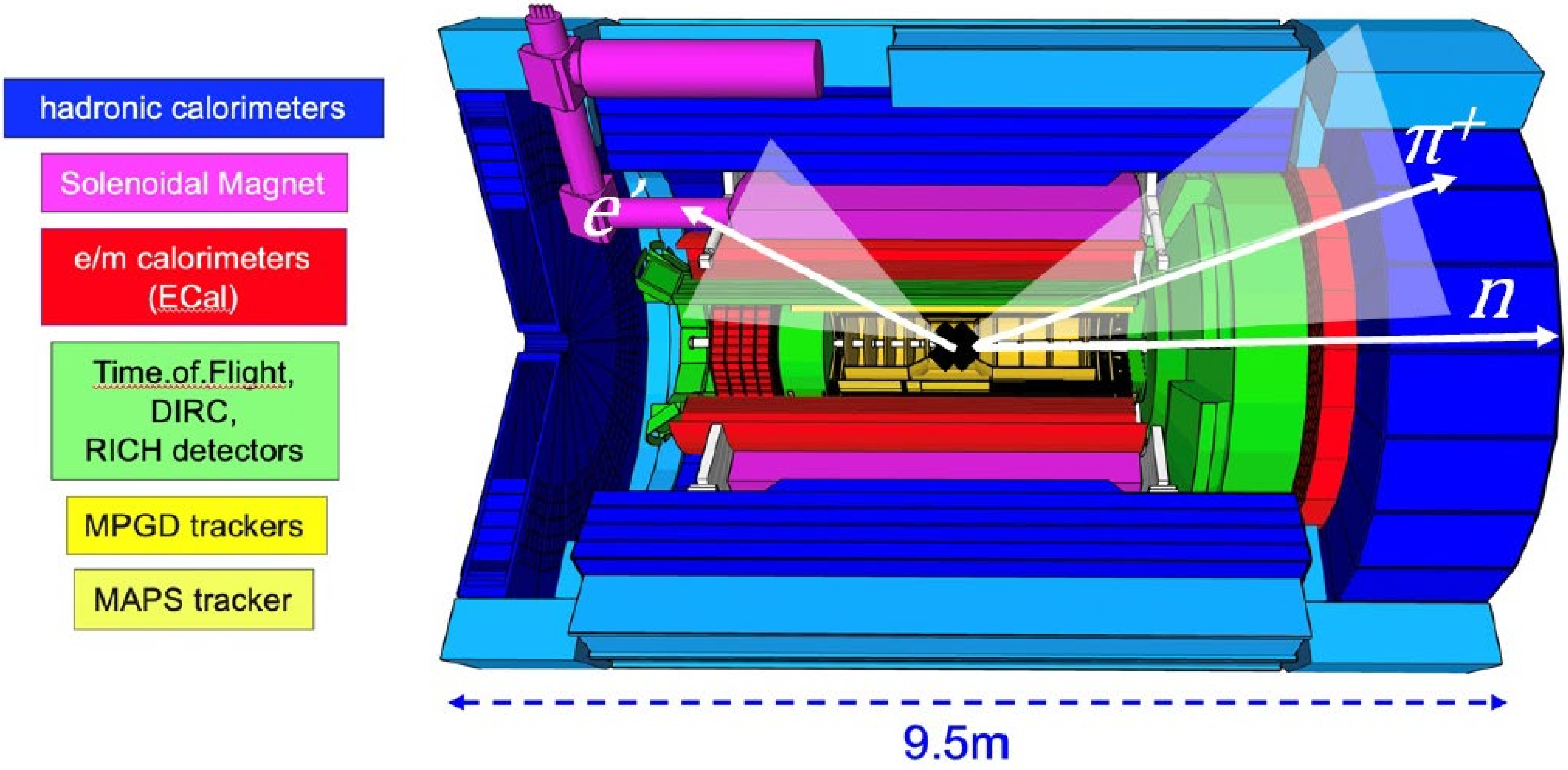


Baryon (neutron, lambda) at very small forward angles and nearly the beam momentum

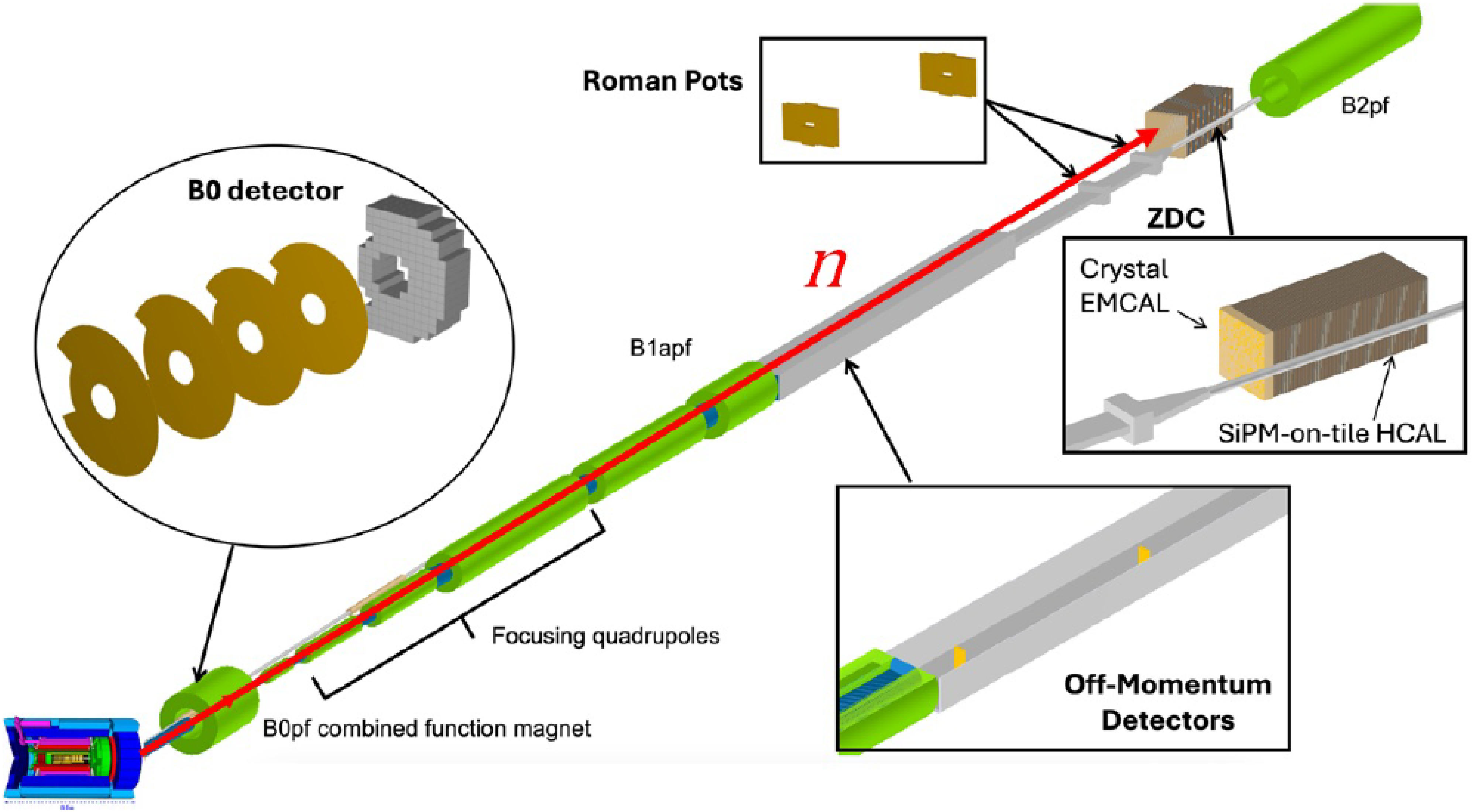


5x41

Kinematics Visualization with ePIC

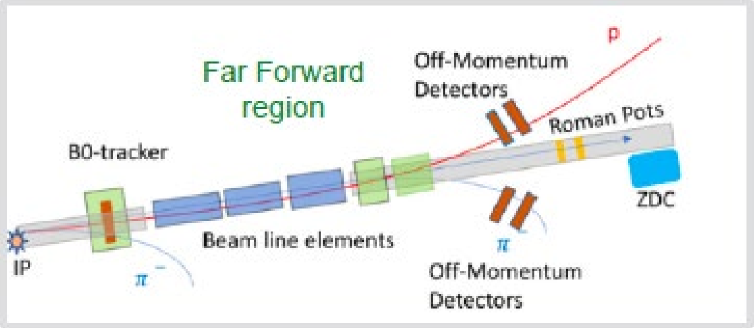


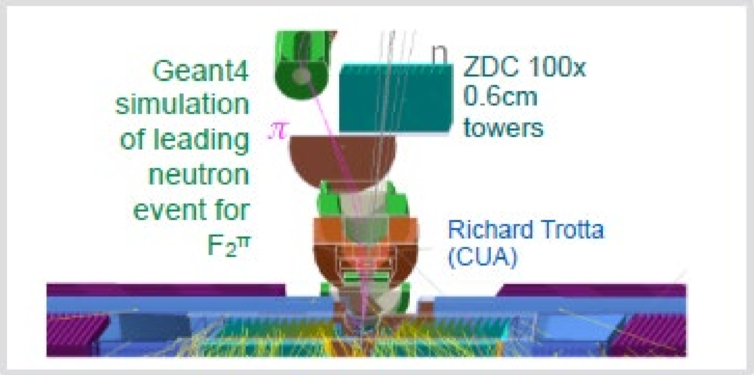
Kinematics Visualization with ePIC

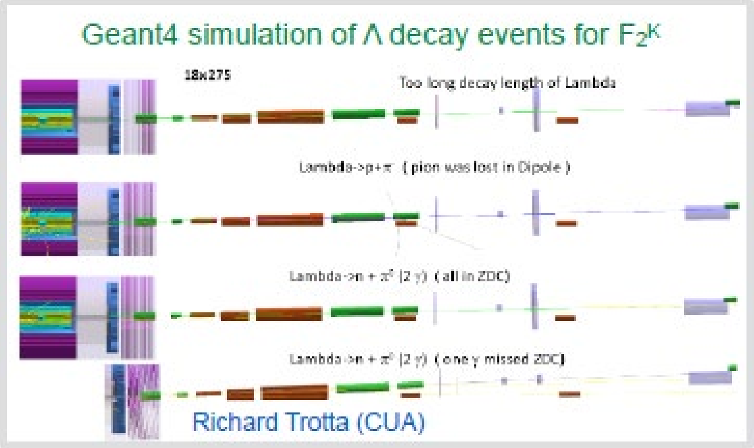


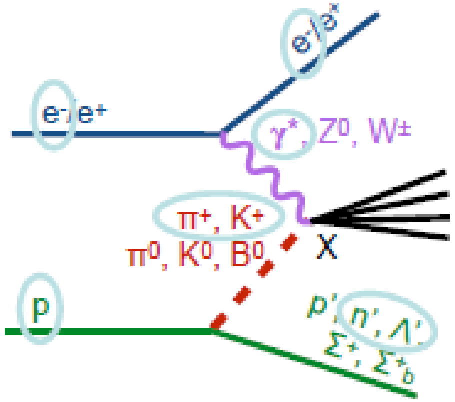
Central
Detector

EIC Pion/Kaon SF Measurements







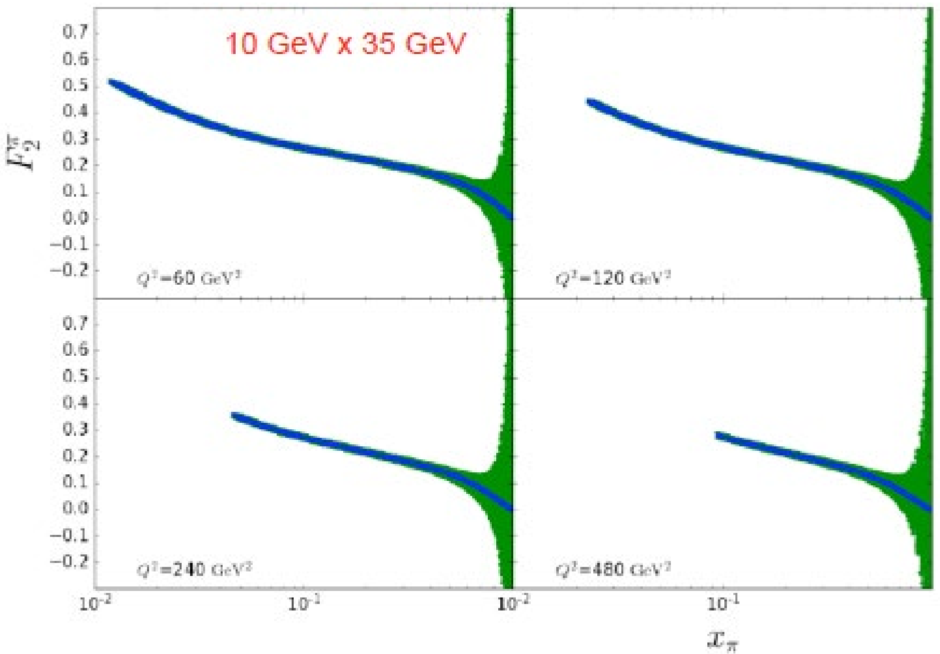


- ❑ Custom fast MC event generator (A. Singh, CUA) and G4 for detector acceptance/response
- ❑ Focus so far: ep and measuring cross section at small-t for
  - F_2^{π} (π^+) tagged by n
  - F_2^{K} (K^+) tagged by Λ^0 decay
- ❑ Settings e x p(GeV): 5x41, 5x100, 10x100, 10x135, 18x275

Detector requirements:

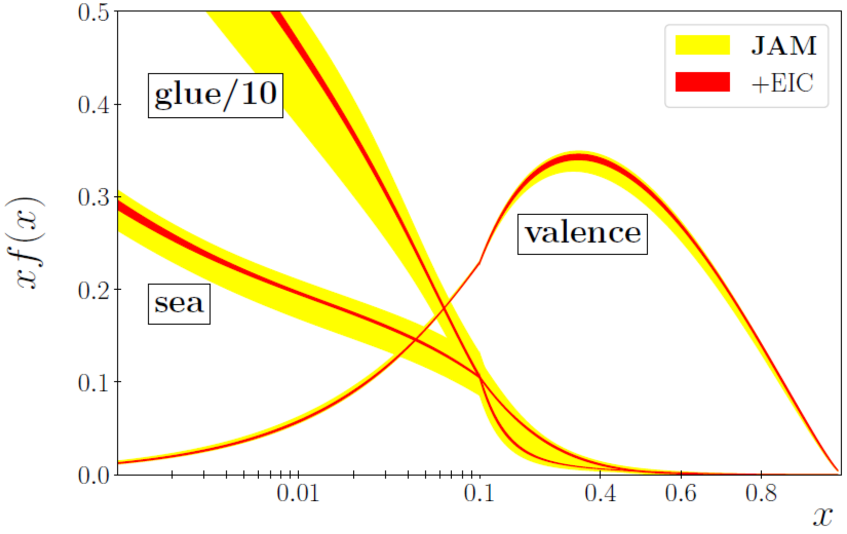
- **For π-n:**
  - Lower energies (5 on 41, 5 on 100) require at least 60 x 60 cm^2
  - For all energies, the neutron detection efficiency is 100% with the planned ZDC
- **For π-n and K^+/Λ:**
  - All energies need good ZDC angular resolution for the required -t resolution
  - High energies (10 on 100, 10 on 135, 18 on 275) require resolution of 1cm or better
- **K^+/Λ benefits from low energies (5 on 41, 5 on 100) and also need:**
  - $\boldsymbol{\Lambda \rightarrow n + \pi^0}$: additional high-res/granularity EMCal+tracking before ZDC – seems doable
  - $\boldsymbol{\Lambda \rightarrow p + \pi^-}$: additional trackers in opposite direction on path to ZDC – more challenging
- Standard electron detection requirements
- Good hadron calorimetry for good x resolution at large x

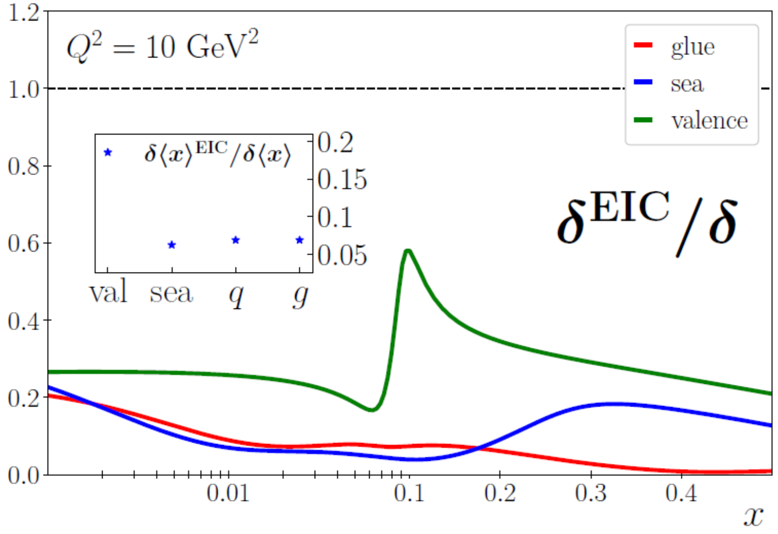
EIC Pion SF Projections



J. Arrington, …, T. Horn, et al., J.Phys.G **48** (**2021**) 7, 075106

- SF shown calculated at NLO using pion PDFs
- Projected data binned in x(0.001) and Q^2 (10 GeV^2)
  - Blue = projections
  - Green = uncertainties for luminosity 100 fb^{-1}
  - x-coverage down to 10^{-2}
  - Unprecedented mid-large x coverage, wide x/Q^2
- Similar SF analysis can be extended to the kaon (in progress) and expect similar quality
- Detailed comparison between pion/kaon and gluon contents possible with coverage and uncertainties
- Reduce uncertainties in global PDF fits

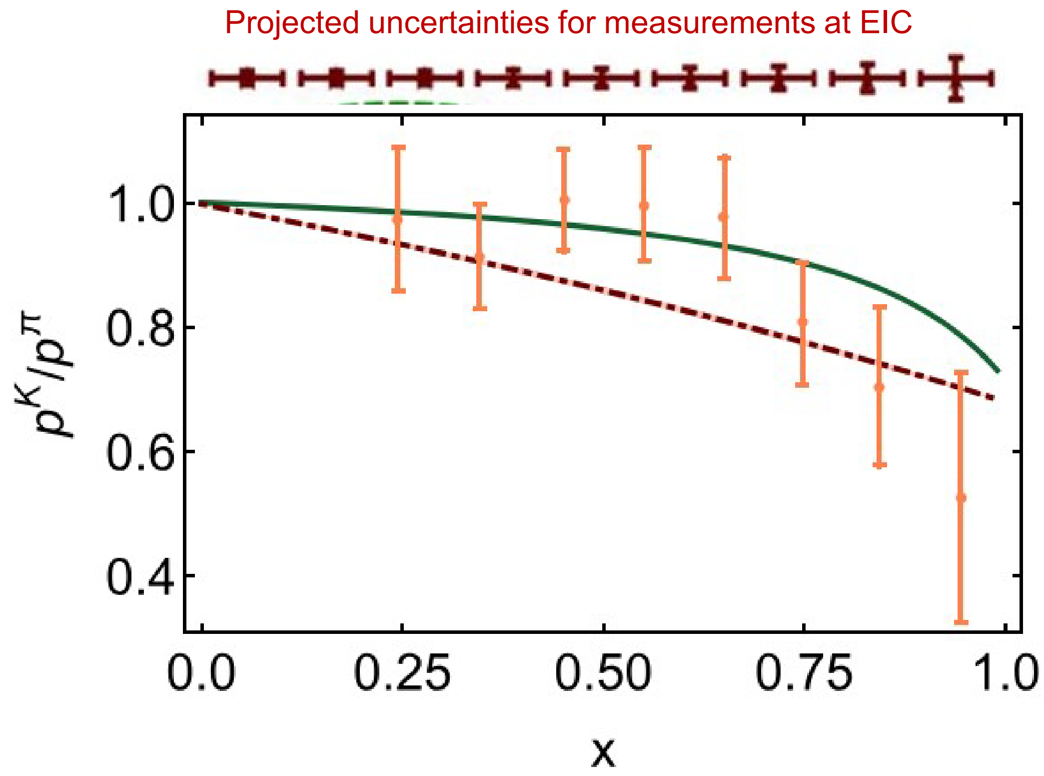




*R. Abdul Khalek, …, T. Horn, et al., Nucl. Phys. A **1026** (2022) 122447*

Kaon structure functions – gluon pdfs

- ❑ Based on Lattice QCD and DSE calculations the kaon glue and sea distributions are similar to those in the pion at the scale of existing measurements.
  - ➢ A calculation predicts that the gluon light-front momentum fraction in the kaon is ~ 1% less than that in the pion and the sea fraction is ~ 2% less *Z-F Ciu et al., Eur.Phys.J.C **80** (2020) 1064, 1*
- ❑ Differences exist between pion and kaon glue and sea on the valence quark domain, where the current quark mass is playing a role.
- ❑ EIC could provide data to shed light on this – projected uncertainties for the ratio are shown

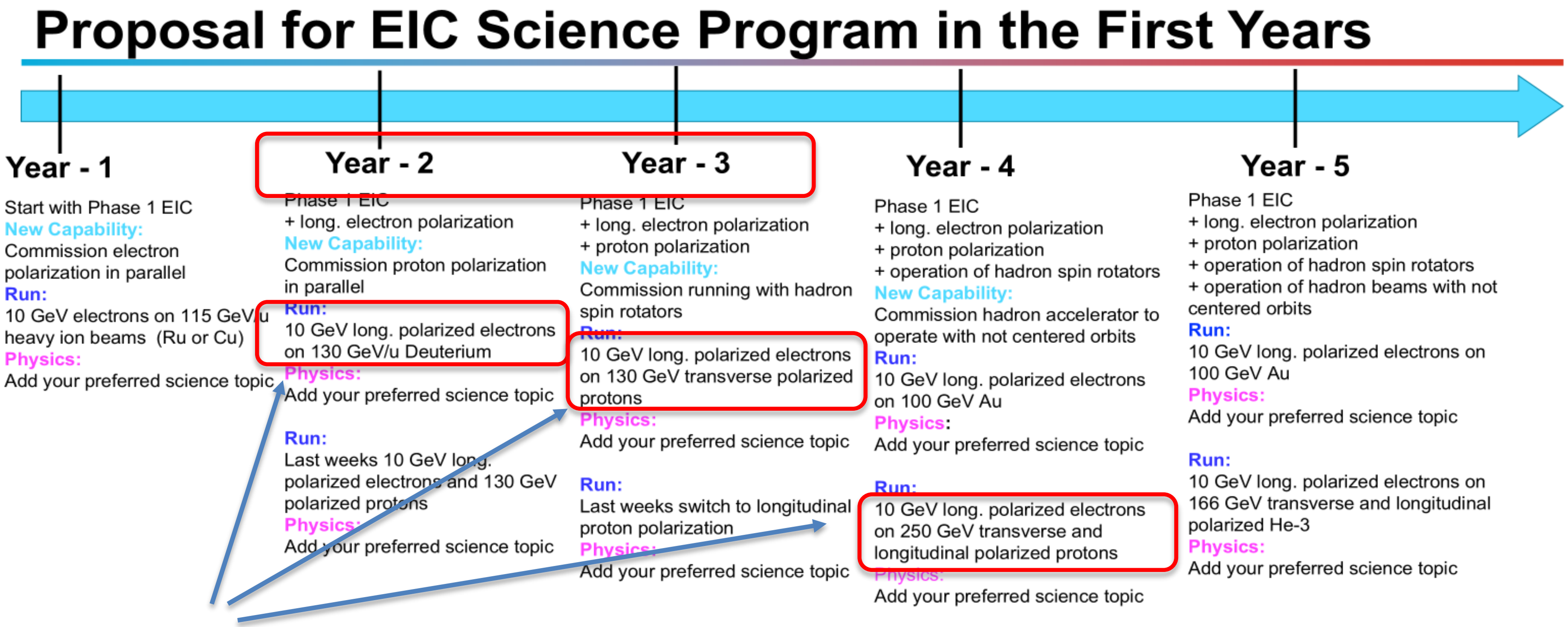


*Z-F Ciu et al., Eur.Phys.J.C **80** (2020) 1064, 1*

*A.C. Aguilar, …, T. Horn, et al., Eur.Phys.J.A **55** (2019) 10, 190*

EIC Early Running - Plans

- The early science program for EIC/ePIC is a current priority
- The proposed schedule has been presented and is evolving



Opportunities for light meson studies early on

Adapted from E.C. Aschenauer & R. Ent talk at ePIC UGM, Frascati 2025

EIC Early Running - Plans

- The early science program for EIC/ePIC is a current priority
- The proposed schedule has been presented and is evolving

Proposal for EIC Science Program in the First Years

Year - 5

Phase 1 EIC
+ long. electron polarization
+ proton polarization
+ operation of hadron spin rotators
+ operation of hadron beams with not centered orbits

Run:
10 GeV polarized electrons on 100 GeV Au

Physics:
Add your preferred science topic

Run:
10 GeV long. electrons on 166 GeV transverse and longitudinal polarized He-3

Physics:
Add your preferred science topic

Year - 6

Phase 1 EIC
+ long. electron polarization
+ proton polarization
+ operation of hadron spin rotators
+ operation of hadron beams with not centered orbits

New Capability:
Commission ESR & HSR at max. energy and beam currents

Run:
18 GeV long. polarized electrons on 275 GeV/u polarized (longitudinal & transverse) proton beams

Year - 7

Phase 1 EIC
+ long. electron polarization
+ proton polarization
+ operation of hadron spin rotators
+ operation of hadron beams with not centered orbits
+ operation of ESR & HSR at max. energy and beam currents

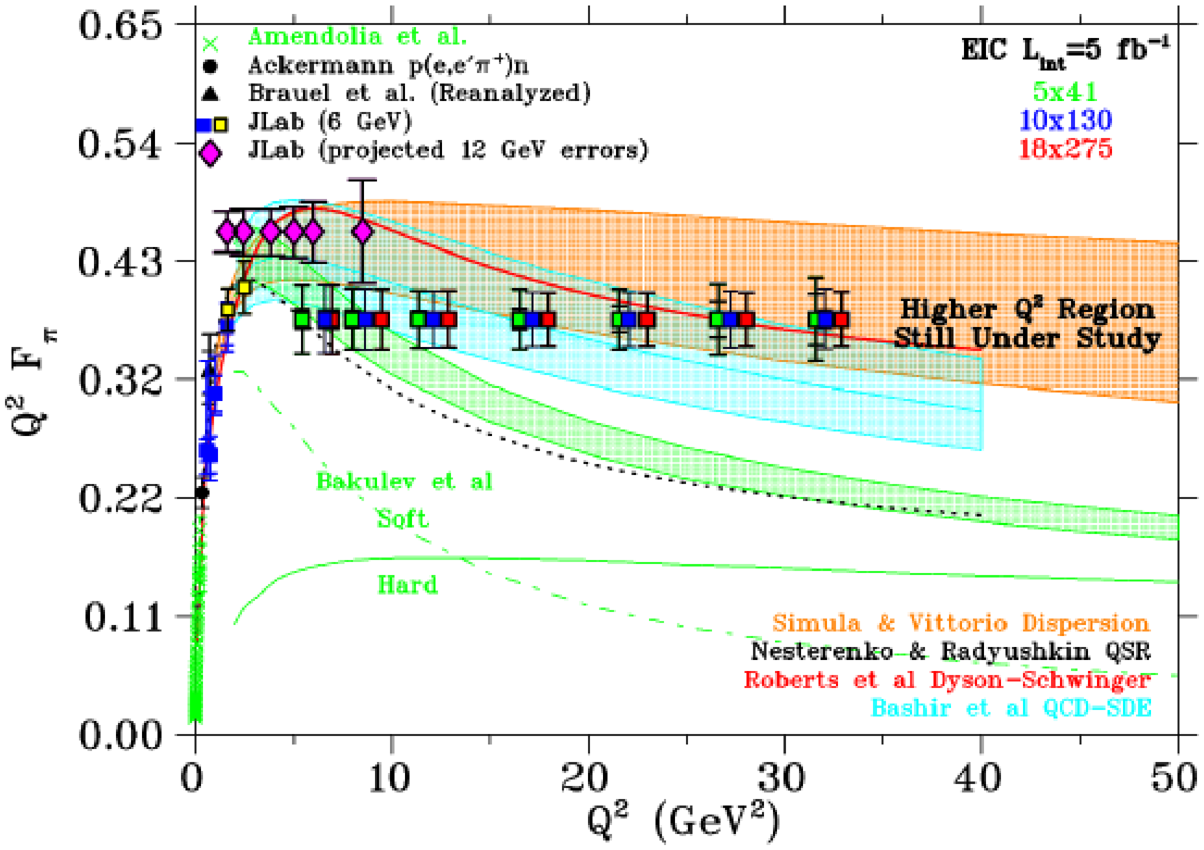
New Capability:
Operate HSR with 41 GeV bypass

Run:
5 GeV long. polarized electrons on 41 GeV transverse polarized proton beams

Adapted from E.C. Aschenauer & R. Ent talk at ePIC UGM, Frascati 2025

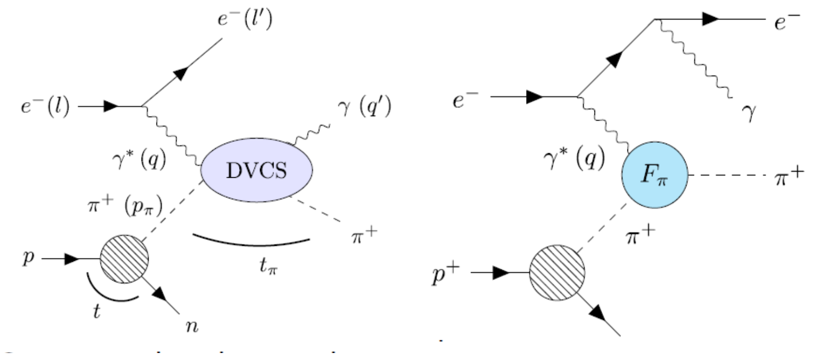
EIC Early Science Example: Pion Form Factor Projections

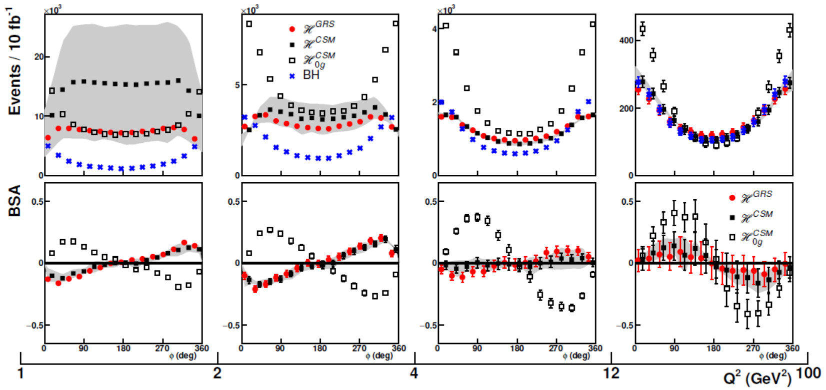
- ePIC opens up the high Q^2 regime
- Error bars represent real projected error bars
  - 2.5% point-to-point
  - 12% scale
  - $\delta R = R$ and $R = \sigma_L/\sigma_T$
  - R=0.13 – 0.14 at lowest –t (from VR model)
- Uncertainties dominated by R at low Q^2
- Statistical uncertainties dominate at high Q^2
- Even with the modest integrated luminosity in the early science program it looks promising
- How high in Q^2 will be possible?



The Pion in 3D – Spatial Imaging

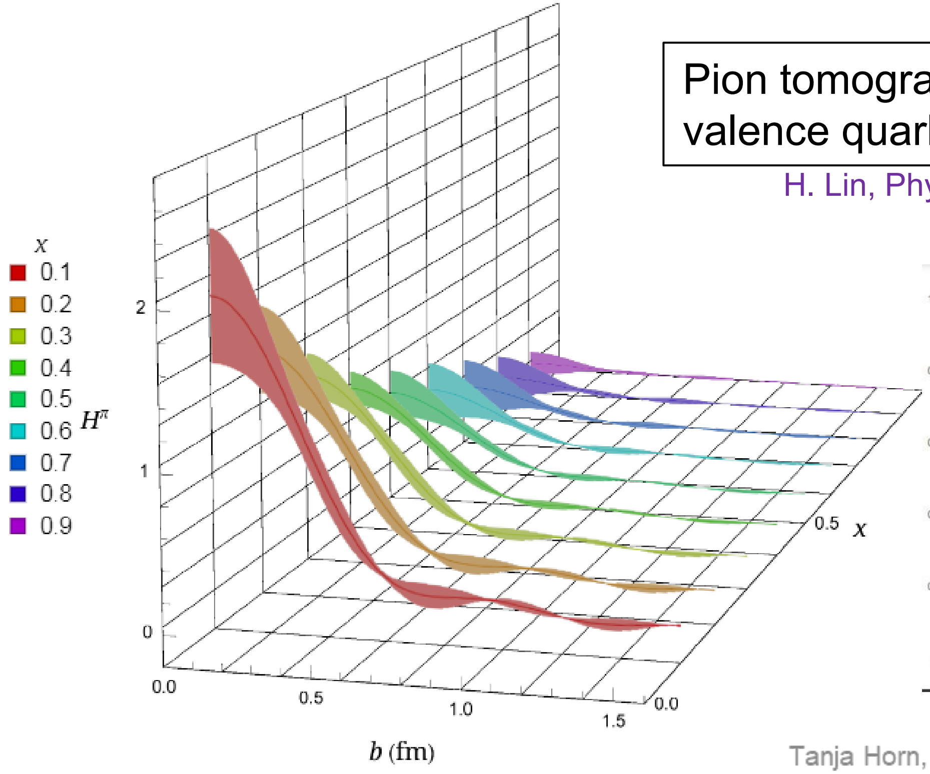
Lot of recent theory interest in the Sullivan process and calculations of meson structure





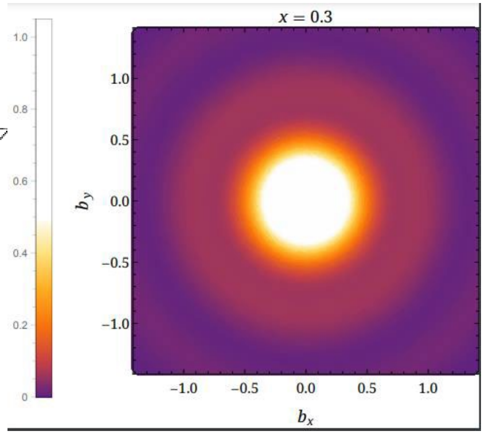
Sullivan DVCS seems measurable at the EIC

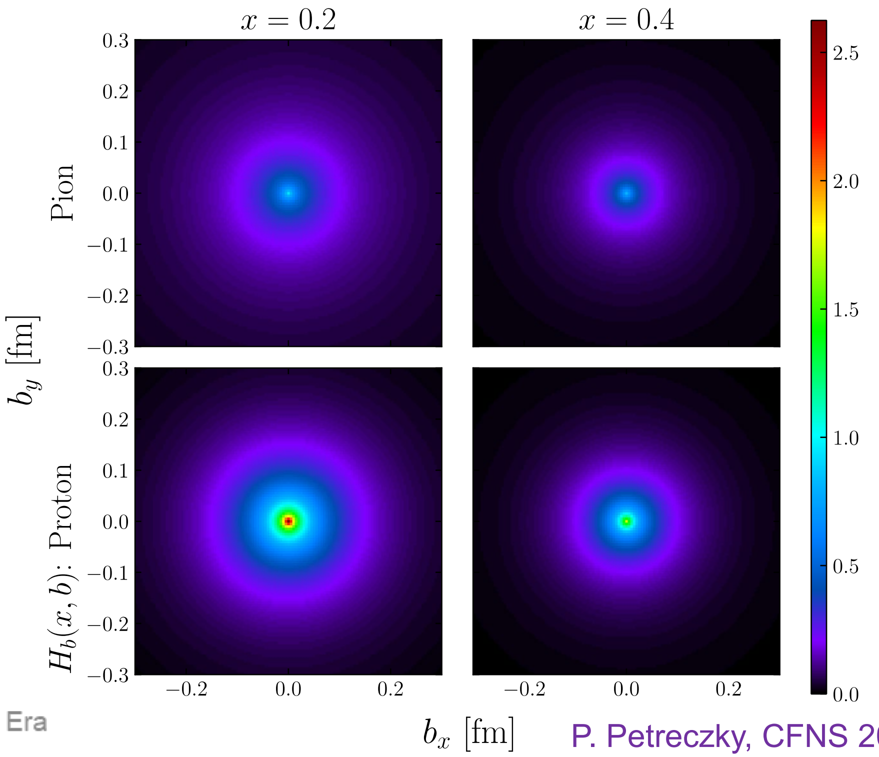
J.M.M. Chavez et al. Rev.Mex.Fis.Suppl. **3** (2022) 3, 0308099; Phys.Rev.Lett. **128** (2022) 20, 202501;Phys.Rev.D **105** (2022) 9, 094012



Pion tomography using the lattice – valence quark GPD results

H. Lin, Phys. Lett. B **846** (2023) 138181



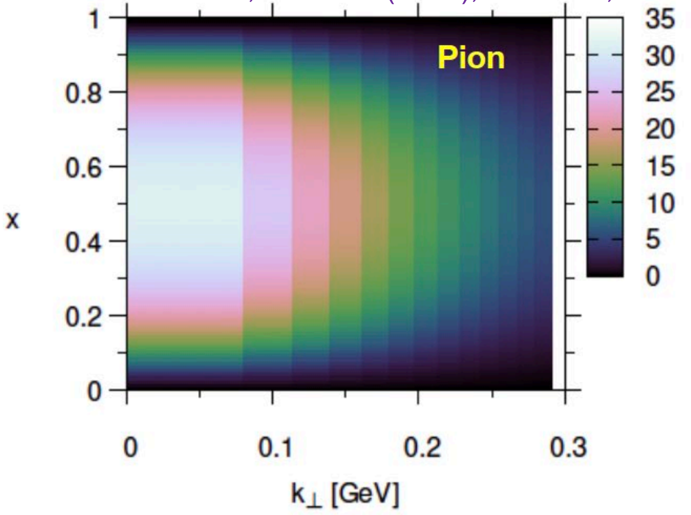


P. Petreczky, CFNS 2024 talk

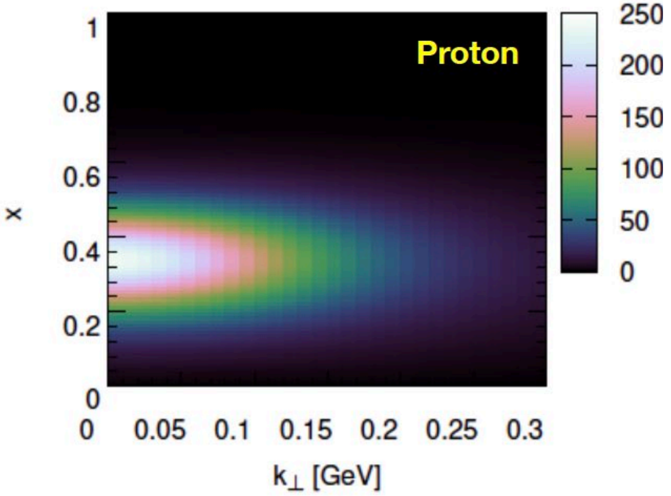
The Pion in 3D – Momentum Imaging

Lot of recent theory interest in the Sullivan process and calculations of meson structure

PRD **105**, L071505 (2022); PRD **104**, 114012 (2021) E. Ydrefore & T. Frederico

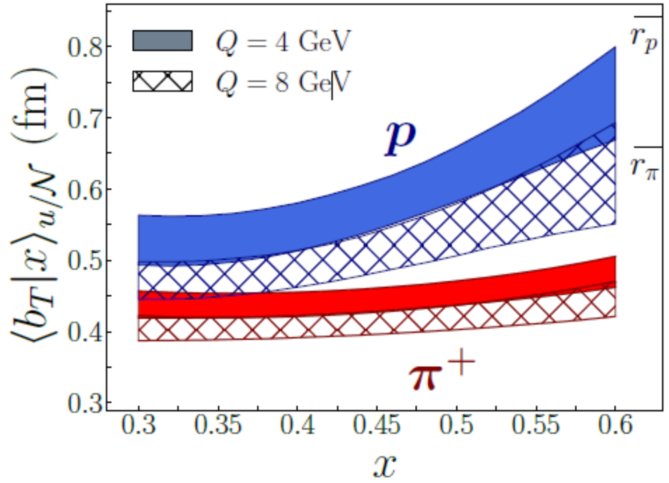


Pion TMDs from
Bethe-Saltpeter equation



Proton TMDs from
Light-Front Model

Significant x-broadening of Pion TMDs compared to proton TMDs



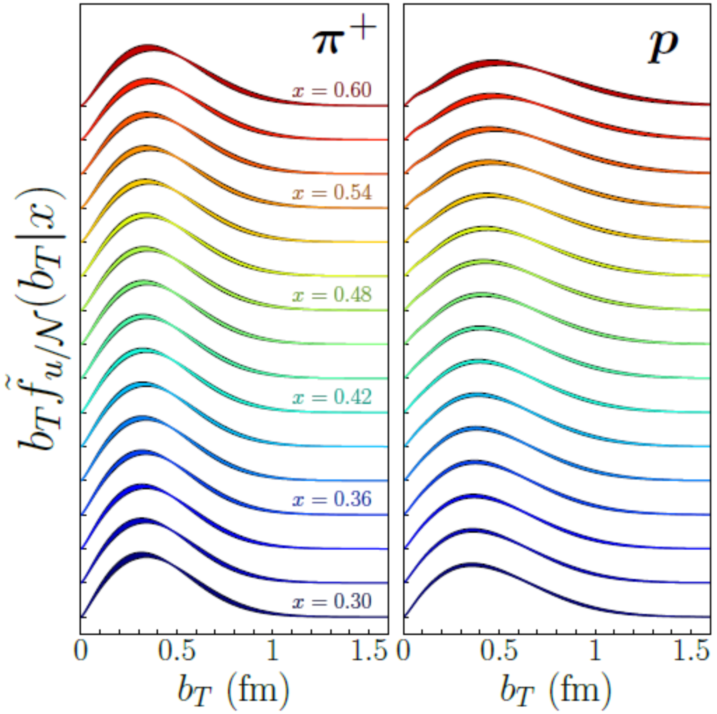
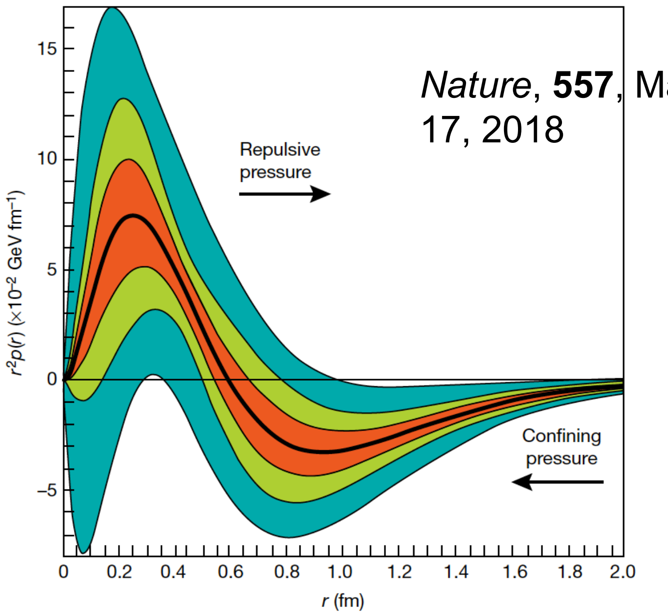
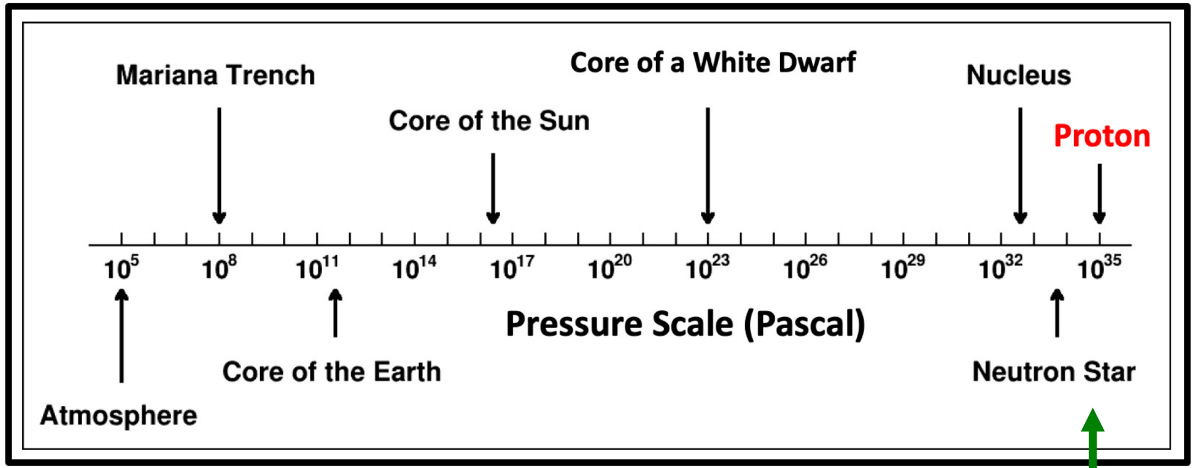


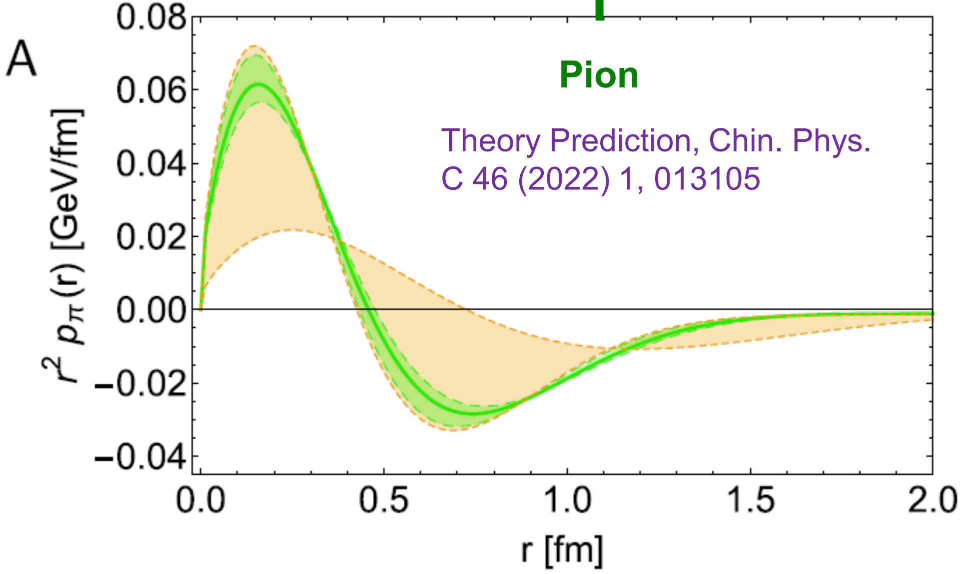
FIG. 1. The conditional TMD PDFs for the pion (**left**) and proton (**right**) as a function of b_T for various x values (indicated by color) evaluated at a characteristic experimental scale $Q = 6$ GeV. Each of the TMD PDFs are offset for visual purposes.

P. Barry, L. Gamberg, W. Melnitchouk, Moffat, Pitonyak, A. Prokudin, Phys. Rev. D **108** (2023) L0911504

Steps towards pressure distribution



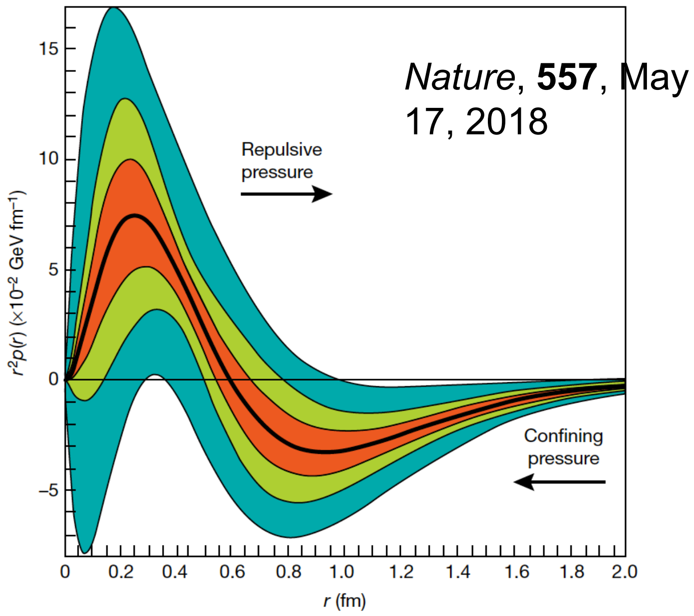


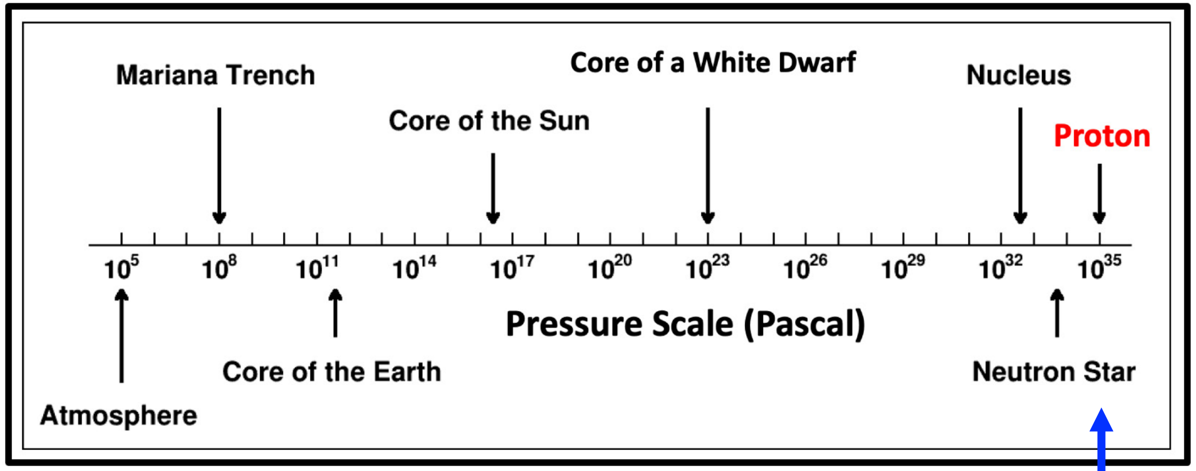


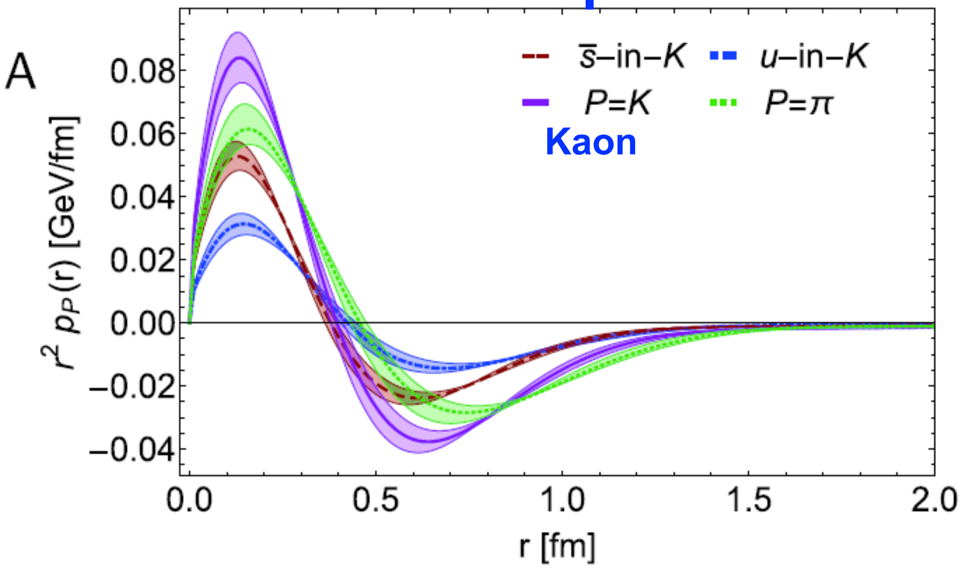
- **Pressure in the Proton**
  - First determination using DVCS (Deeply Virtual Compton Scattering) data
  - Interior pressure in proton is > pressure inside a neutron star! ***Who knew that!***
  - Lattice calculation motivates determination of gluon GPDs at EIC

Experimental prospects at EIC first discussed in J. Phys. G 48 (2021) 7, 075106 – further work ongoing

Steps towards pressure distribution







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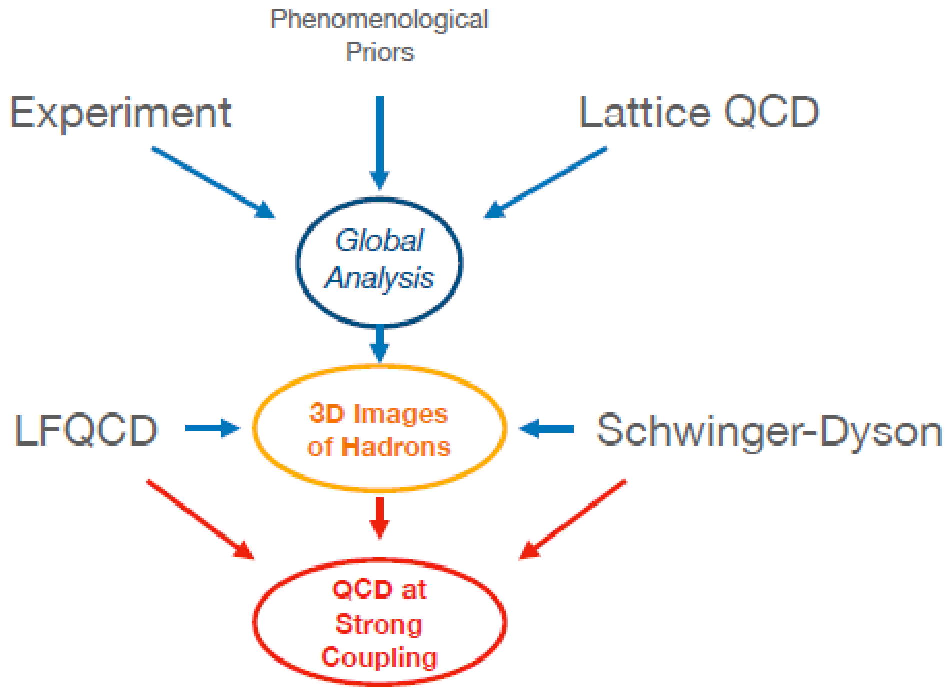
  - Lattice calculation motivates determination of gluon GPDs at EIC

Meson Structure – a Synergy of Experiment, QCD Phenomenology and Lattice QCD

This plot was made in the context of a large group of theorists and experimentalists working together on pion and kaon structure in a series of EIC-related workshops ("Pion and Kaon Structure at the EIC").This group continues to meet, with emphasis on the synergy of experiment, QCD theory and LQCD.

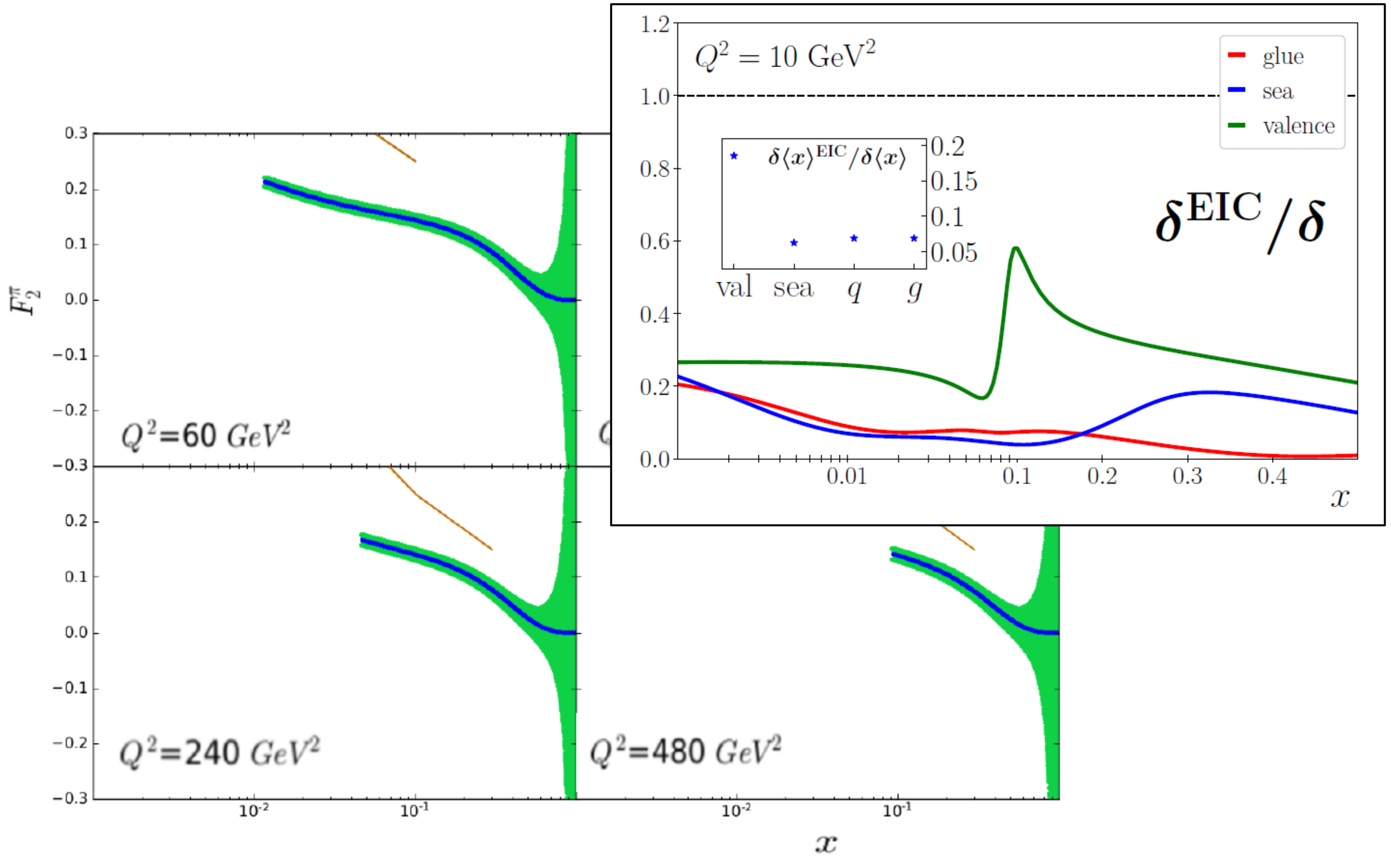
J. Phys. G 48 (2021) 7, 075106; arXiv:2102.11788

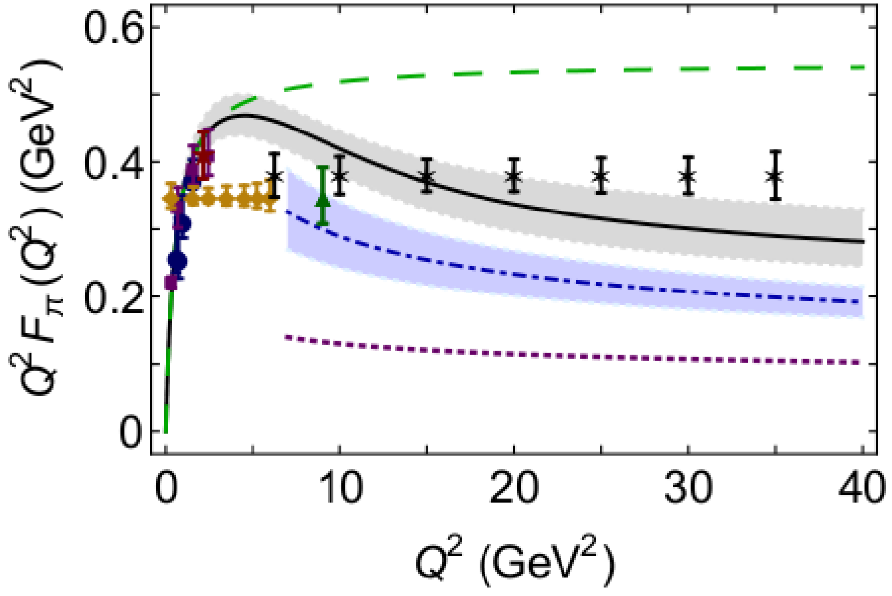


This will remain the theme, the mesons provide an excellent area to make progress in understanding and gaining intuition of how QCD works. The two-quark systems lend themselves for advanced QCD theory calculations of the QCD dynamics. The Sullivan process may (should!) provide the key data required for experimental validation.

Summary – Role of EIC

The unique role of EIC is its access to pion and kaon structure over a versatile large CM energy range, ~20-140 GeV. With its larger CM energy range, the EIC will have the final word on the contributions of gluons in pions and kaons as compared to protons, settle how many gluons persist as viewed with highest resolution, and vastly extend the x and Q^2 range of pion and kaon charts, and meson structure knowledge.





Summary

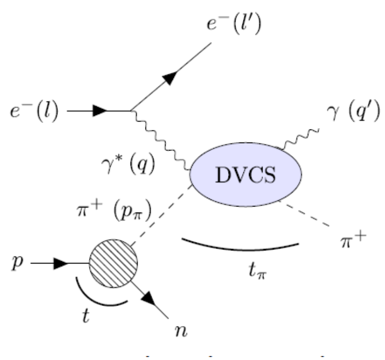
- Meson structure is essential for understanding EHM and our visible Universe
- The JLab 12 GeV era is going strong
  - Pion and kaon form factor extractions up to high Q2 possible (~9 and ~6 GeV2)
  - L/T separated cross sections important for transverse nucleon structure studies – may allow for accessing new type of GPDs
- JLab's approved program extends into 2030s (assuming ~30 weeks OPS/year) - There are very exciting imminent opportunities to collect additional data for light mesons
  - TDIS experiments provide data for resolving and cross-checking pion PDF issues at high-x and provides kaon SF extraction in an almost empty kaon structure world data set
- JLab will remain a critical facility for fixed target electron scattering at high luminosity
  - Laying the groundwork for an exciting role for CEBAF in the EIC era
  - TDIS @ 22 GeV JLab could offer new opportunities including possible SIDIS from pion target measurements
- Example of science from JLab to EIC: Meson structure is one of the Far Forward processes with major EIC Science and Detector Emphasis and is essential for understanding EHM and our visible Universe
  - Meson structure is non-trivial and data for pion and kaon structure functions is extremely sparse
  - JLab 12 GeV will dramatically improve the $\pi^+/K^+/\pi^0$ electroproduction data set
  - EIC - Potential game-changer for this topic due to large CM range (20-140 GeV); Large x/Q2 landscape for pion/kaon SF; Potential to provide definite answers on different gluon distributions in pion/kaon

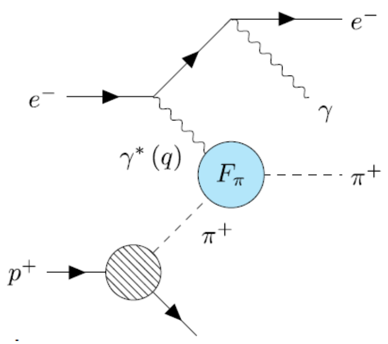
EIC Meson Structure Functions – Key Measurements

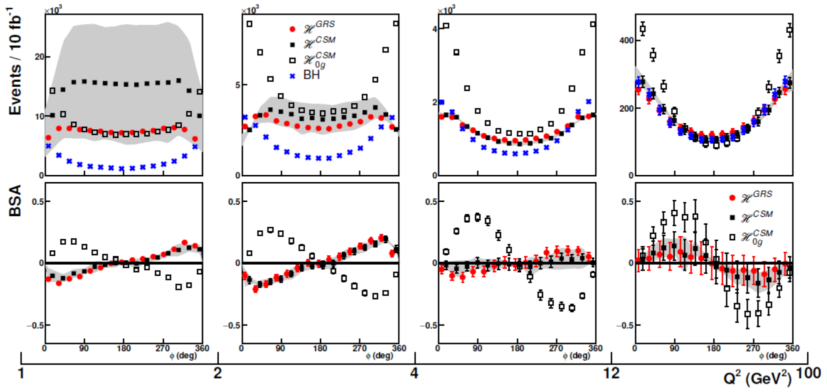
Science Question	Key Measurement[1]	Key Requirements[2]
What are the quark and gluon energy contributions to the pion mass?	Pion structure function data over a range of x and Q^2.	• Need to uniquely determine $e + p \rightarrow e' + X + n$ (low -t) • CM energy range ~10-100 GeV • Charged- and neutral currents desirable
Is the pion full or empty of gluons as viewed at large Q^2?	Pion structure function data at large Q^2.	• CM energy ~100 GeV • Inclusive and open-charm detection
What are the quark and gluon energy contributions to the kaon mass?	Kaon structure function data over a range of x and Q^2.	• Need to uniquely determine Λ, Σ^0: $e + p \rightarrow e' + X + \Lambda/\Sigma^0$ (low -t) • CM energy range ~10-100 GeV
Are there more or less gluons in kaons than in pions as viewed at large Q^2?	Kaon structure function data at large Q^2.	• CM energy ~100 GeV • Inclusive and open-charm detection
Can we get quantitative guidance on the emergent pion mass mechanism?	Pion form factor data for Q^2 = 10-40 (GeV/c)^2.	• Need to uniquely determine exclusive process $e + p \rightarrow e' + \pi^+ + n$ (low -t) • e-p and e-d at similar energies • CM energy ~10-75 GeV
What is the size and range of interference between emergent-mass and the Higgs-mass mechanism?	Kaon form factor data for Q^2 = 10-20 (GeV/c)^2.	• Need to uniquely determine exclusive process $e + p \rightarrow e' + K^+ + \Lambda$ (low -t) • L/T separation at CM energy ~10-20 GeV • e-p Λ/Σ^0 ratios at CM energy ~10-50 GeV
What is the difference between the impacts of emergent- and Higgs-mass mechanisms on light-quark behaviour?	Behaviour of (valence) up quarks in pion and kaon at large x	• CM energy ~20 GeV (lowest CM energy to access large-x region) • Higher CM energy for range in Q^2 desirable
What is the relationship between dynamically chiral symmetry breaking and confinement?	Transverse-momentum dependent Fragmentation Functions of quarks into pions and kaons	• Collider kinematics desirable (as compared to fixed-target kinematics) • CM energy range ~20-140 GeV

J. Arrington et al., J.Phys.G **48** (**2021**) 7, 075106

EIC Meson Structure Functions – further observables







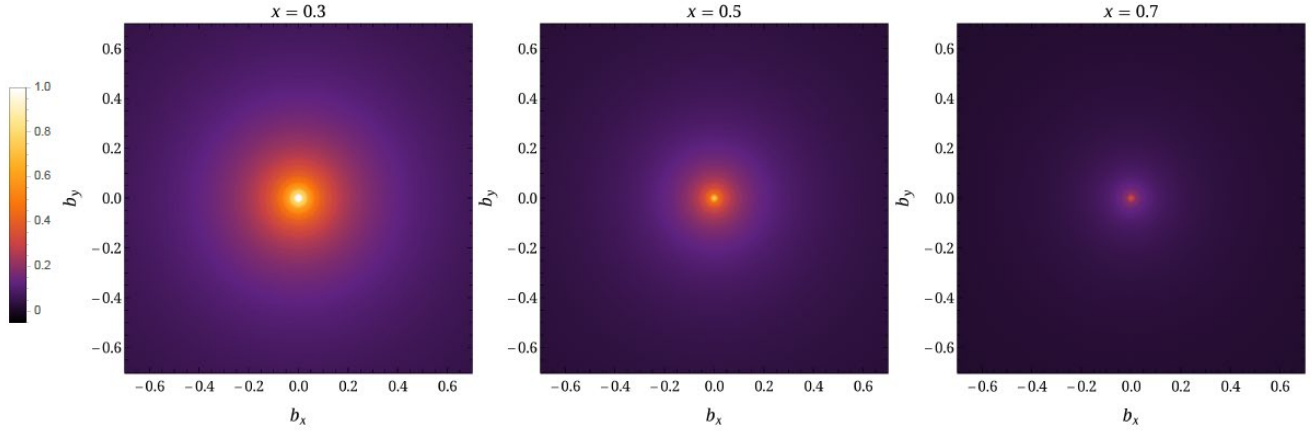
Sullivan DVCS seems measurable at the EIC

J.M.M. Chavez et al. Rev.Mex.Fis.Suppl. **3** (2022) 3, 0308099; Phys.Rev.Lett. **128** (2022) 20, 202501;Phys.Rev.D **105** (2022) 9, 094012

Science Question	Key Measurement[1]	Key Requirements[2]
What is the trace anomaly contribution to the pion mass?	Elastic J/ψ production at low W off the pion.	• Need to uniquely determine exclusive process $e + p \rightarrow e' + \pi^+ + J/\Psi + n$ (low -t) • High luminosity (10^{34}+) • CM energy ~70 GeV
Can we obtain tomographic snapshots of the pion in the transverse plane? What is the pressure distribution in a pion?	Measurement of DVCS off pion target as defined with Sullivan process	• Need to uniquely determine exclusive process $e + p \rightarrow e' + \pi^+ + \gamma + n$ (low -t) • High luminosity (10^{34}+) • CM energy ~10-100 GeV
Are transverse momentum distributions universal in pions and protons?	Hadron multiplicities in SIDIS off a pion target as defined with Sullivan process	• Need to uniquely determine scattered off pion: $e + p \rightarrow e + h + X + n$ (low -t) • High luminosity (10^{34}+) • e-p and e-d at similar energies desirable • CM energy ~10-100 GeV

J. Arrington et al., J.Phys.G 48 (2021) 7, 075106

EIC Meson Structure Functions – further observables



Can we even do SIDIS or DES off meson target?

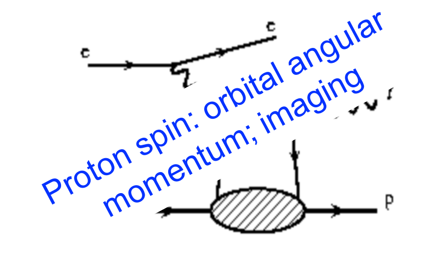
Science Question	Key Measurement[1]	Key Requirements[2]
What is the trace anomaly contribution to the pion mass?	Elastic J/ψ production at low W off the pion.	• Need to uniquely determine exclusive process $e + p \rightarrow e' + \pi^+ + J/\Psi + n$ (low -t) • High luminosity (10^{34+}) • CM energy ~70 GeV
Can we obtain tomographic snapshots of the pion in the transverse plane? What is the pressure distribution in a pion?	Measurement of DVCS off pion target as defined with Sullivan process	• Need to uniquely determine exclusive process $e + p \rightarrow e' + \pi^+ + \gamma + n$ (low -t) • High luminosity (10^{34+}) • CM energy ~10-100 GeV
Are transverse momentum distributions universal in pions and protons?	Hadron multiplicities in SIDIS off a pion target as defined with Sullivan process	• Need to uniquely determine scattered off pion: $e + p \rightarrow e + h + X + n$ (low -t) • High luminosity (10^{34+}) • e-p and e-d at similar energies desirable • CM energy ~10-100 GeV

J. Arrington et al., J.Phys.G 48 (2021) 7, 075106

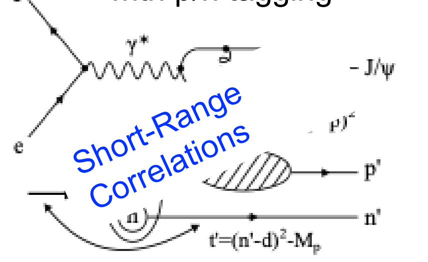
Far-Forward Physics at EIC

All these processes require the detection of protons, neutrons, photons and hadrons at small scattering angles → *MAJOR EIC science and detector emphasis*

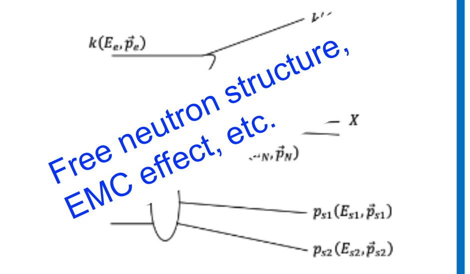
e+p DVCS



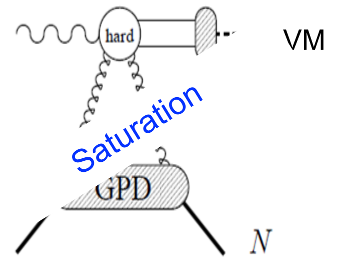
e+d exclusive J/Psi with p/n tagging



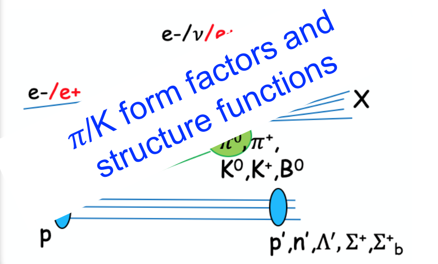
spectator tagging in light nuclei



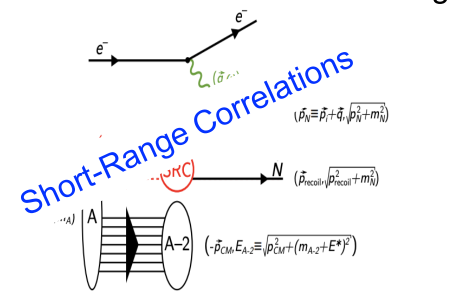
coherent/incoherent VM production in eA



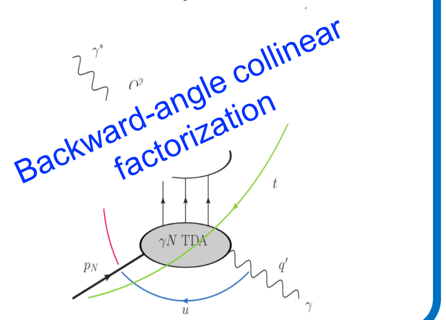
Sullivan process



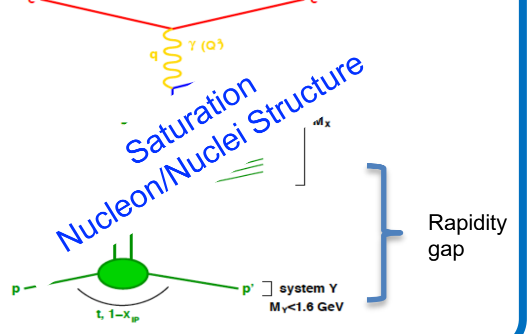
Quasi-elastic electron scattering



u-channel backward exclusive electroproduction



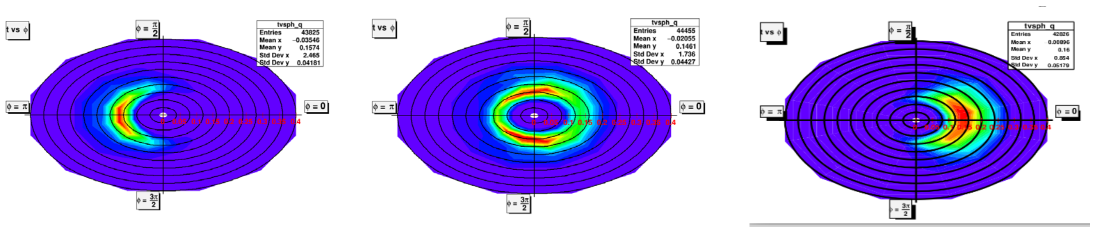
Diffraction



Look at this process in more detail as example of science from JLab to EIC

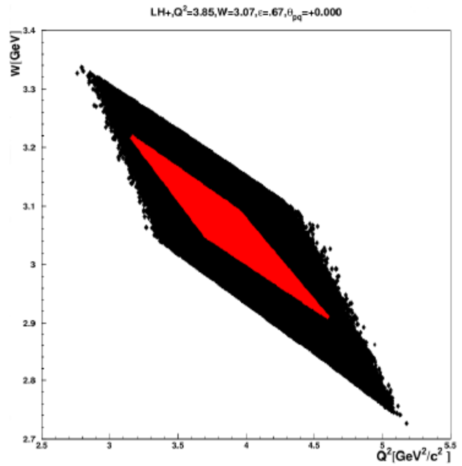
LT Separation Example

Three SHMS angles



The different pion/kaon arm (SHMS) settings provide the azimuthal angle (ϕ) distributions for a given t-bin

Two/three beam energies



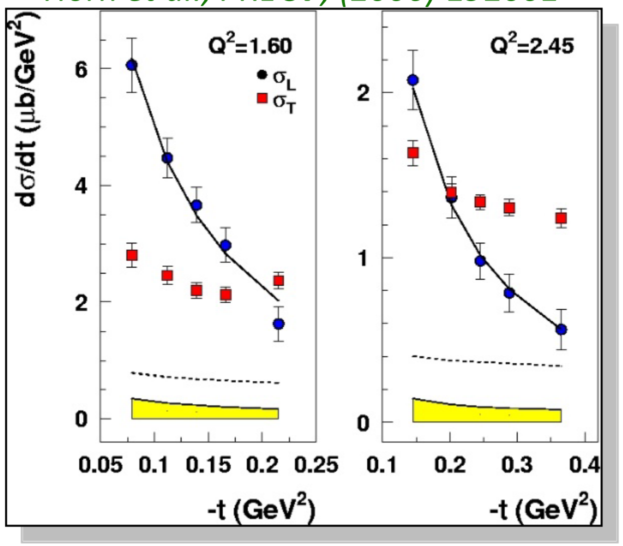
Define common (W, Q²) coverage at all beam energies (ε)

Extract σ_L by simultaneous fit of L, T, LT, TT using the measured azimuthal angle (ϕ) and knowledge of the photon polarization (ε)

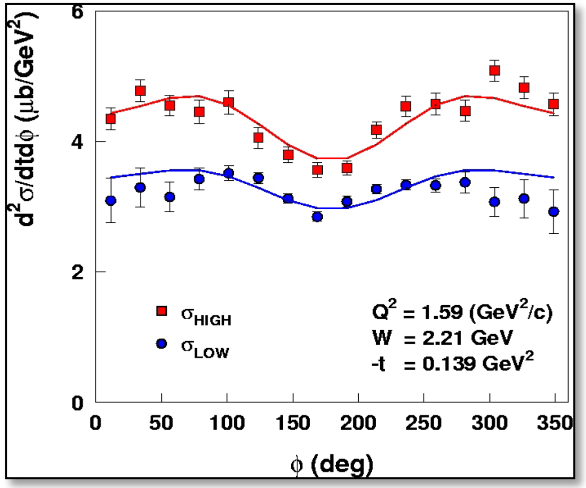
LT Separated Cross Section

- Note the need to control systematic uncertainty
- Only possible with focusing spectrometers

*Horn et al., PRL **97**, (2006) 192001*



Unseparated Cross Section



Physics Cross Section

$$2\pi \frac{d^2\sigma}{dt d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

KaonLT (E12-09-011) Program at 12 GeV Overview

Spokespersons: Tanja Horn (CUA), Garth Huber (URegina), Pete Markowitz (FIU)

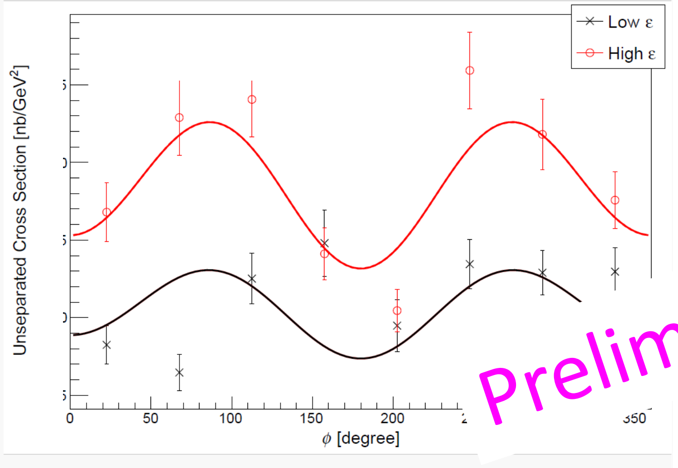
Grad. Students: Vijay Kumar (URegina), Richard Trotta (CUA), Ali Usman (URegina), A. Postuma (URegina)

Separated cross sections: L, T, LT, TT over a wide range of Q^2,and t

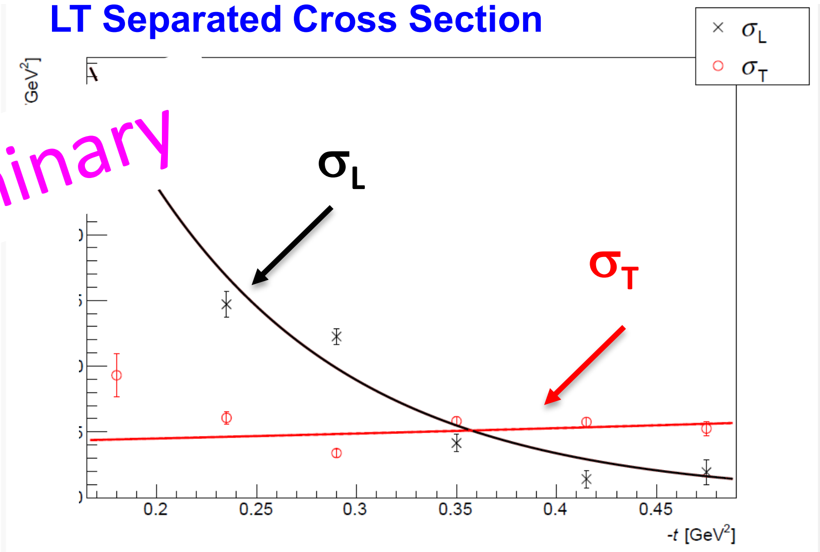
KaonLT experiment (completed in 2018/19):

- Highest Q^2 for L/T separated kaon electroproduction cross section
- First separated kaon cross section measurement above W=2.2 GeV
- Separated cross sections have been extracted – anticipate publication as soon as later this year; KaonFF will follow if warranted by data

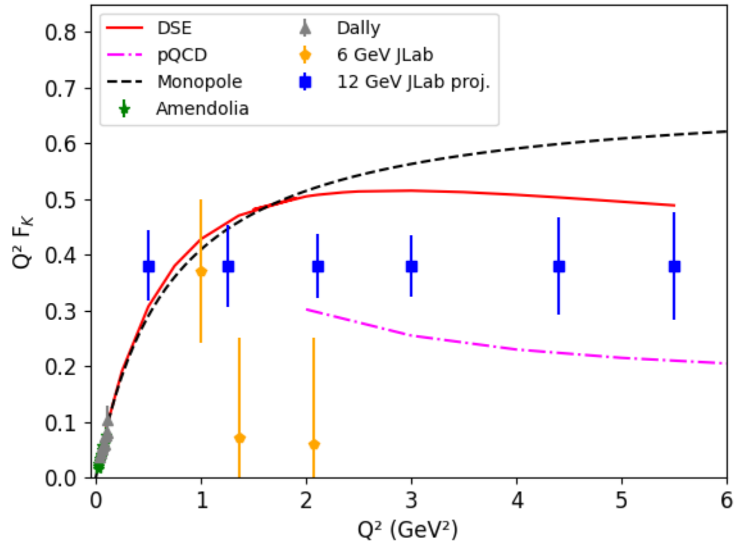
Unseparated Cross Section



LT Separated Cross Section



Projected Uncertainties for F_K



First look at the unseparated and separated cross sections at Q^2=3 GeV^2, W=3.14 GeV

$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$