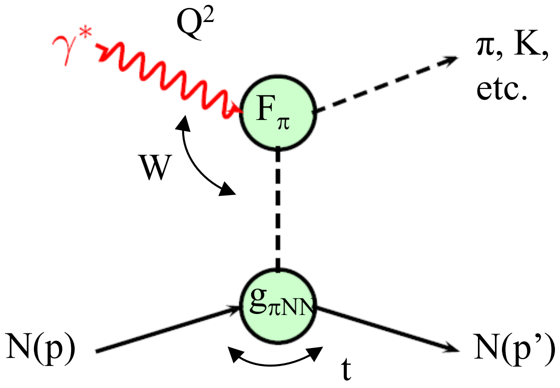
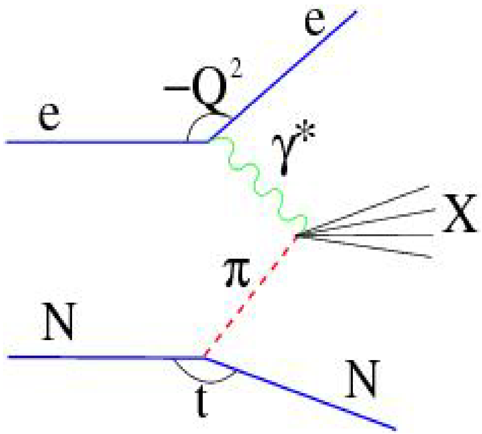
Overview on Experiments for Pion/Kaon Structure at JLab and EIC





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Thomas Jefferson National Accelerator Facility

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POETIC 2025

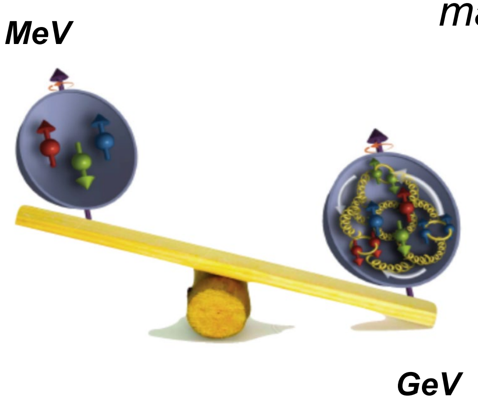
Florida International University, February 24-28, 2025

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
- ❑ Electron-Ion Collider (EIC) – a game changer
- ❑ Exciting imminent opportunities to collect additional data for light mesons beyond JLab 12 GeV
  - JLab 22 GeV
- ❑ Ongoing efforts extending into 3D light hadron structure – GPDs and TMDs – in theory/experiment

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

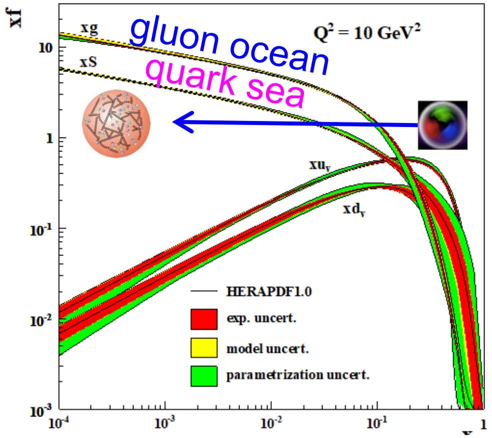
Visible world: mainly made of light quarks – its mass emerges from quark-gluon interactions.



Proton

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

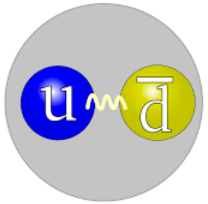
Gluon rise discovered by HERA e-p



Fraction of overall proton momentum carried by quark or gluons

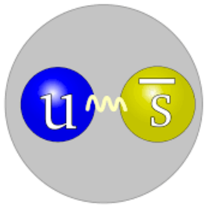
Pion

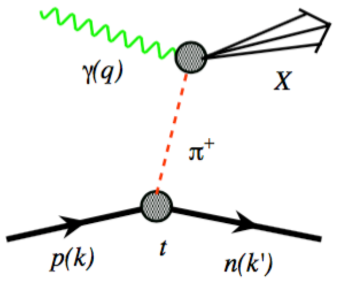
Quark structure: ud
Mass ~ 140 MeV
Exists only if mass is dynamically generated.
Empty or full of gluons?



Kaon

Quark structure: us
Mass ~ 490 MeV
Boundary between emergent- and Higgs-mass mechanisms.
More or less gluons than in pion?





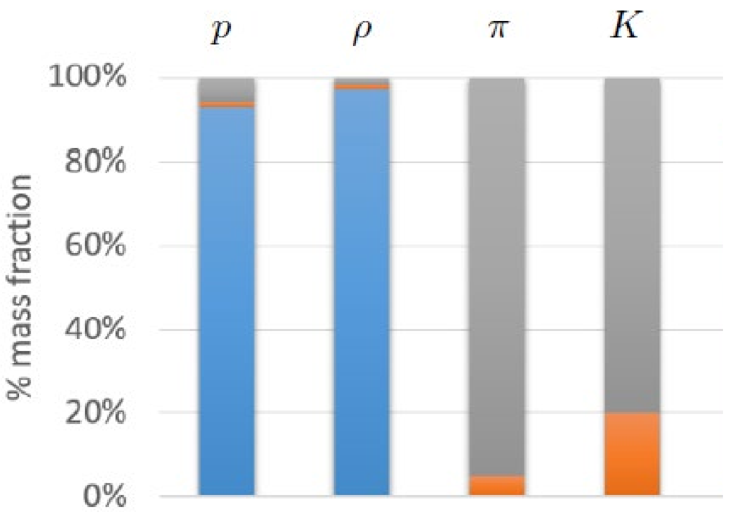
proton the EIC will allow determination of an important term contributing to the proton mass, the so-called "QCD trace anomaly"

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

*.C. Aguilar et al., Pion and Kaon structure at the EIC, arXiv:1907.08218, EPJA **55** (2019) 190.*
*J. Arrington et al., Revealing the structure of light pseudoscalar mesons at the EIC, arXiv:2102.11788, J. Phys. G **48** (2021) 7, 075106.*

Insight into Hadron Structure and Mass through Mesons

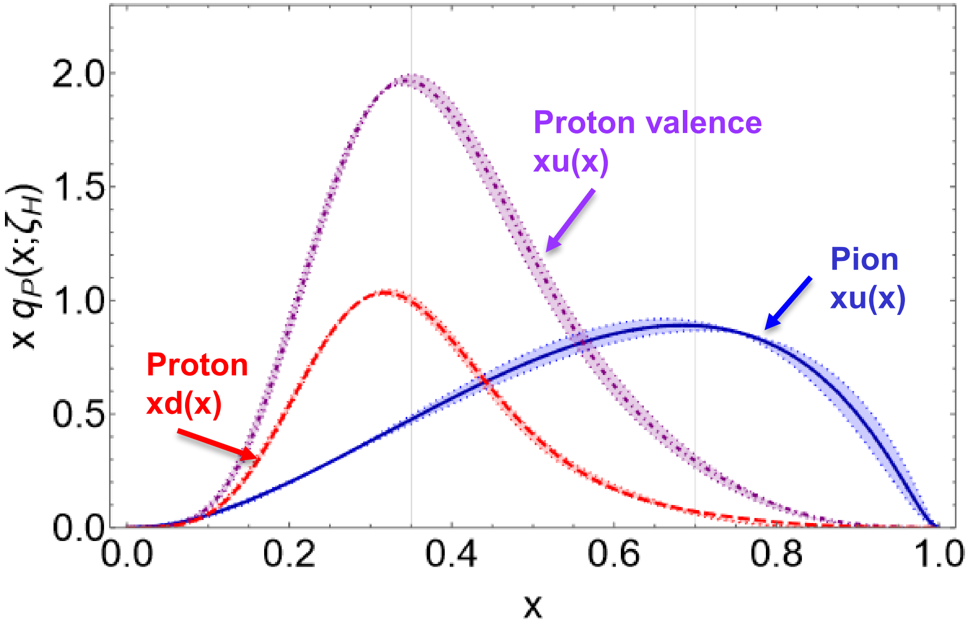
Understanding pion/kaon is vital to understand the **dynamic** generation of hadron mass and offers unique insight into EHM and the role of the Higgs mechanism



❑ 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 Syst. ***65*** *(****2024****) 2, 60*

Y. Lu, L. Chang, K. Raya, C. Roberts, J. Rodriguez-Quintero, PLB ***830*** *(****2022****) 137130/1-7*



Mass budget for nucleons and mesons are vastly different

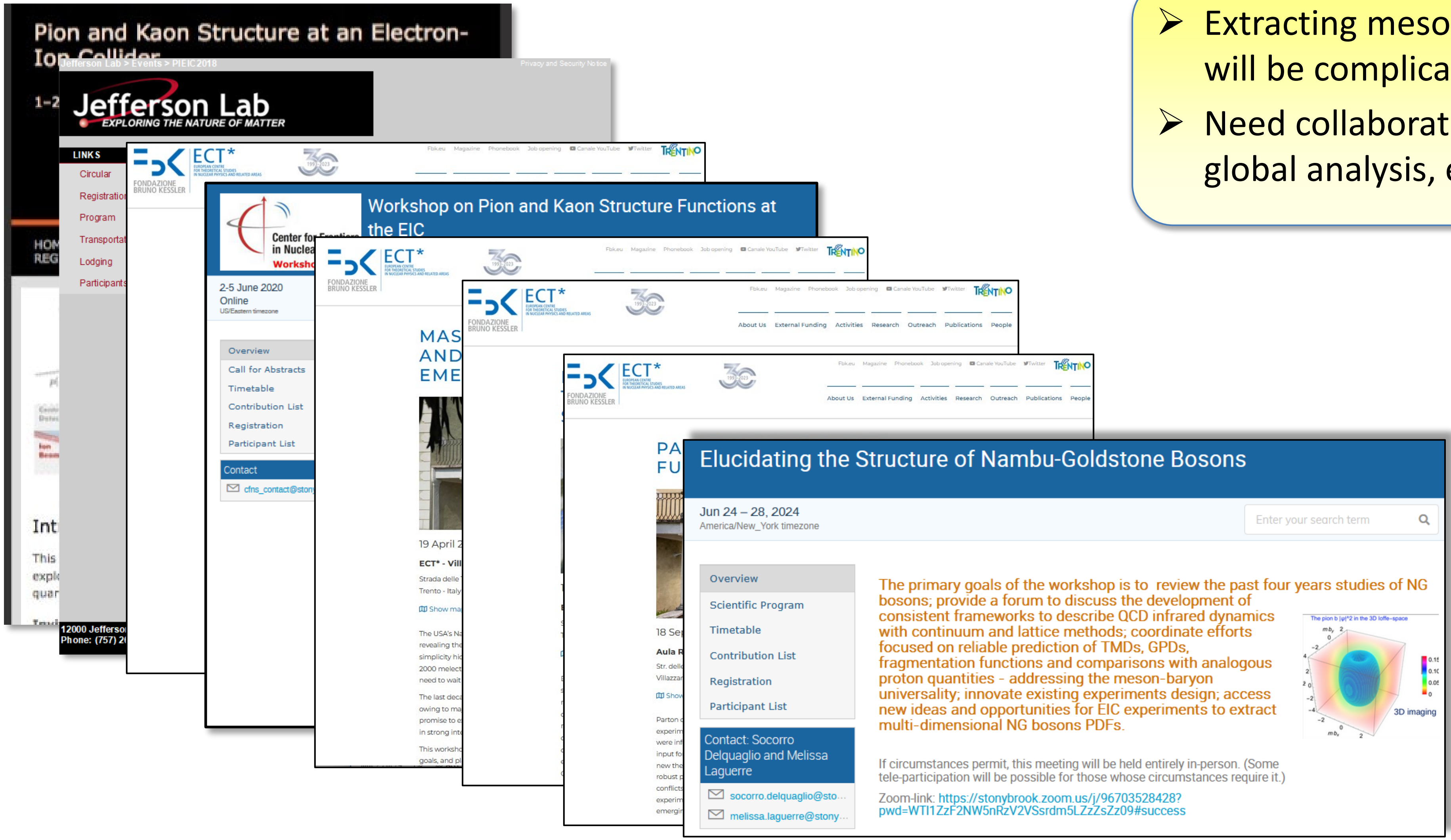
- Proton (and heavy meson) mass is large in the chiral limit – expression of Emergent hadronic mass (EHM)
- Pion/kaon: Nambu-Goldstone Boson of QCD: massless in the chiral limit
  - chiral symmetry of massless QCD dynamically broken by quark-gluon interactions and inclusion of light quark masses (DCSB,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

Notable difference between proton and pion valence quark distributions

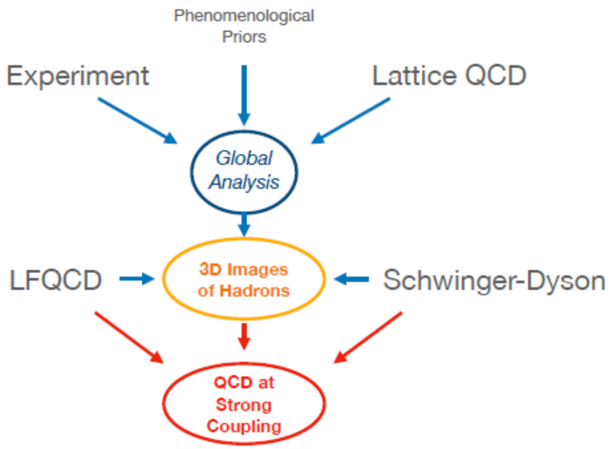
→ Difference between meson PDFs: direct information on emergent hadron mass (EHM)

Pion and Kaon Structure – Need for more data

- A lot of recent exciting theoretical developments on light meson structure in meson structure
- Many reports at workshops since 2018, e.g., the most recent CFNS workshop in 2024

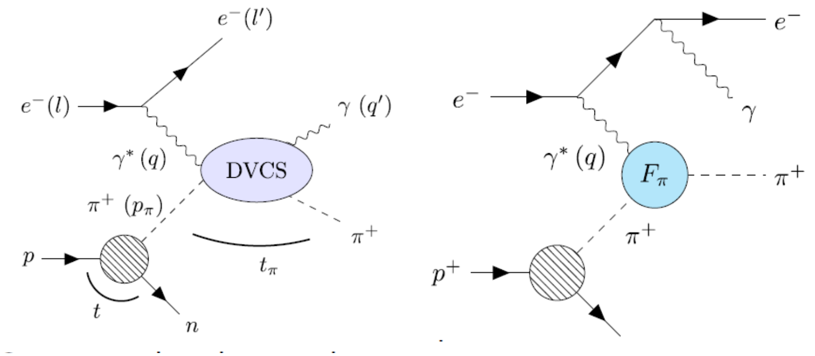


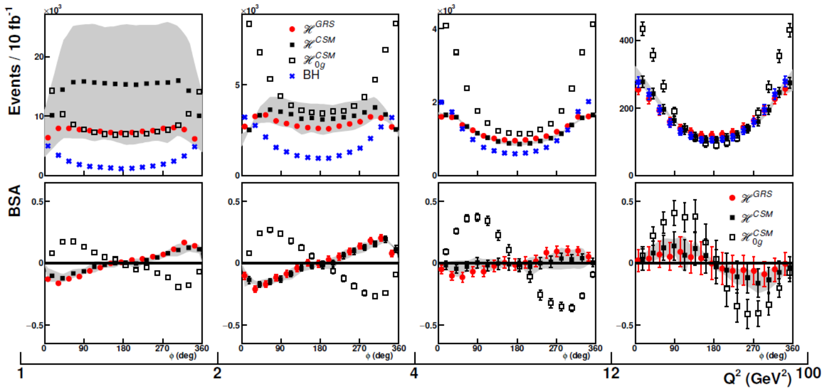
- Extracting meson PDFs and TMDs from data will be complicated
- Need collaboration between theory, lattice, global analysis, experiment



The Pion in 3D – Spatial Imaging

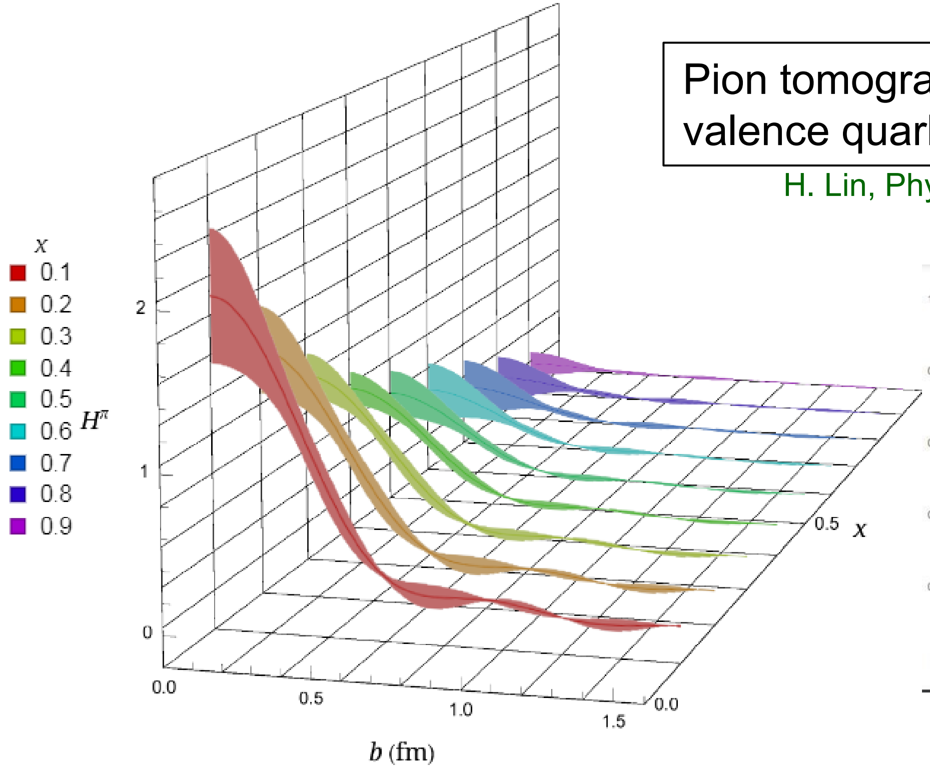
Lot of recent theory interest in the Sullivan process and calculations of meson structure





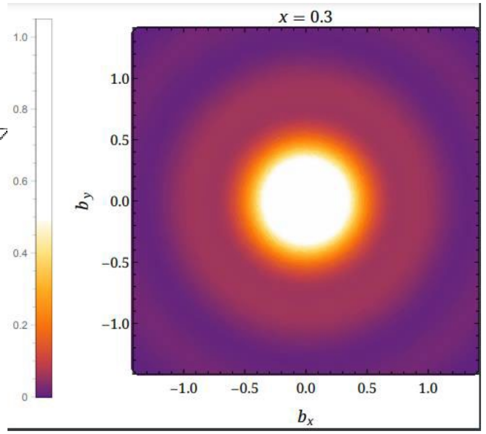
Sullivan DVCS seems measurable at the EIC

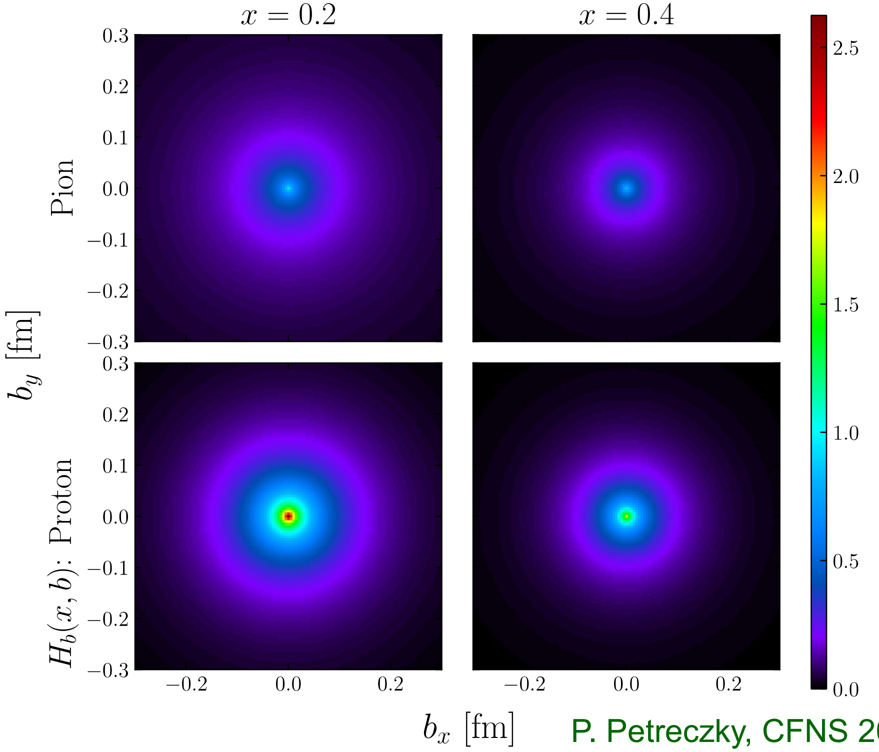
J.M.M. Chavez et al. Rev.Mex.Fis.Suppl. **3** (2022) 3, 0308099; Phys.Rev.Lett. **128** (2022) 20, 202501;Phys.Rev.D **105** (2022) 9, 094012



Pion tomography using the lattice – valence quark GPD results

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



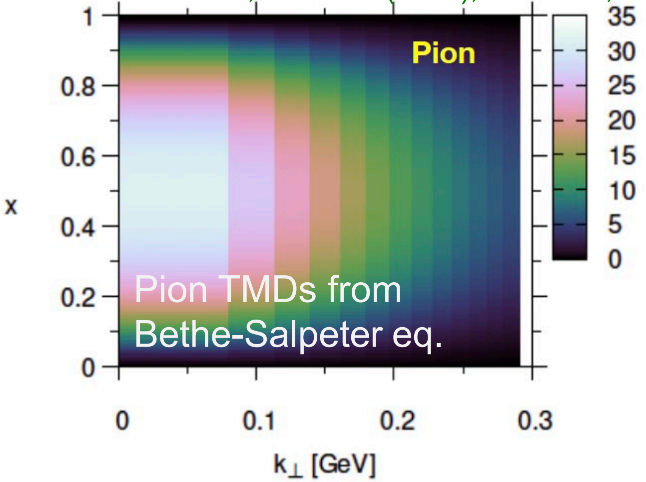


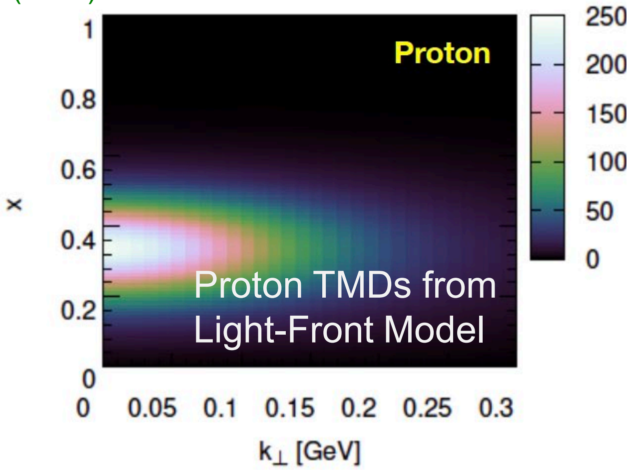
P. Petreczky, CFNS 2024 talk

The Pion in 3D – Momentum Imaging

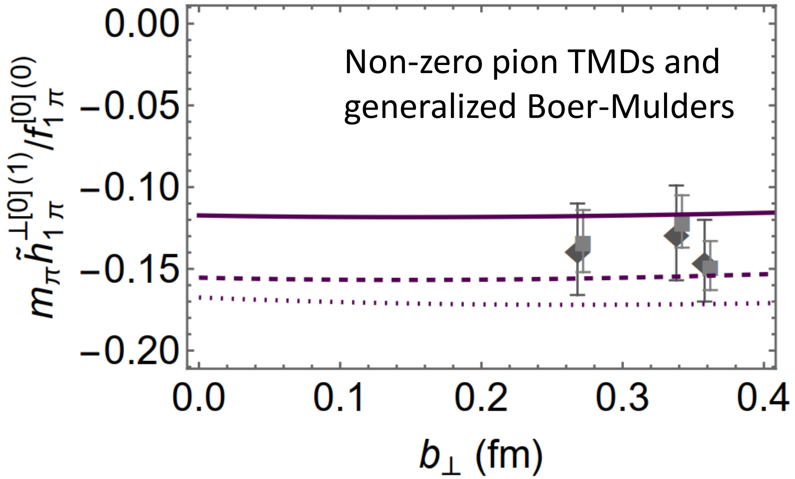
Lot of recent theory interest in the Sullivan process and calculations of meson structure

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

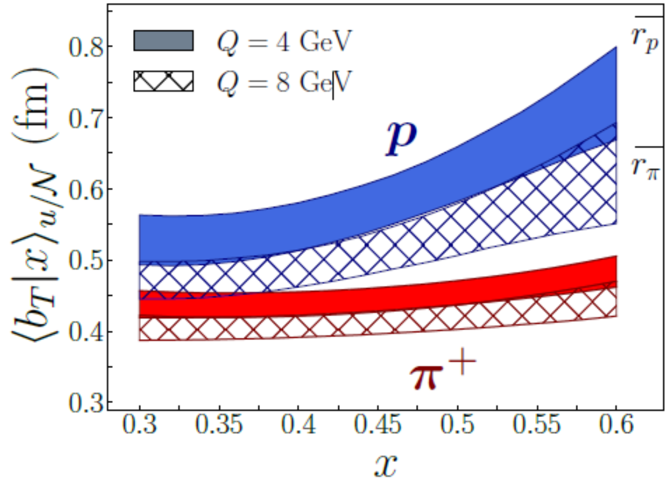




Significant x-broadening of Pion compared to proton TMDs



D.-D. Cheng, Z.-F. Cui, M. Ding, C.D. Roberts, S. Schmidt, Eur. Phys. J. C **85** (**2025**) 1, 115



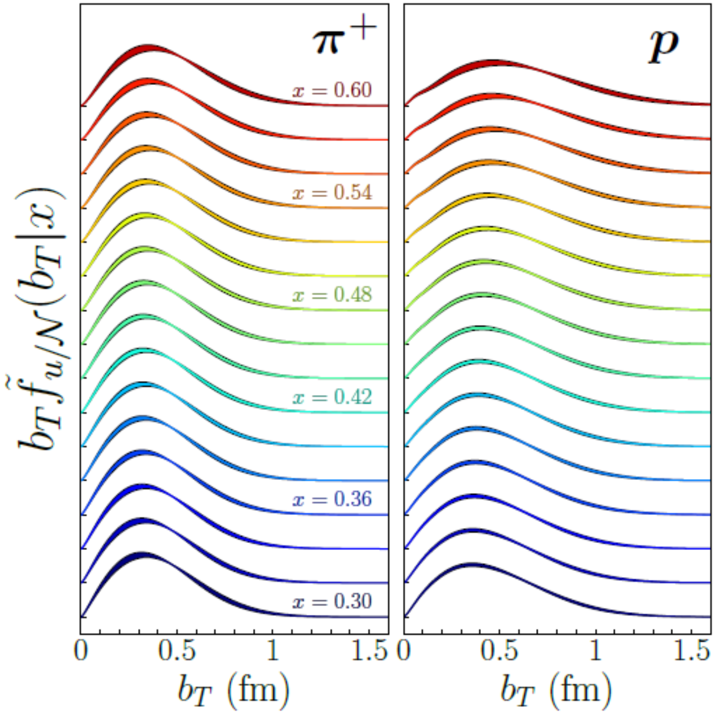


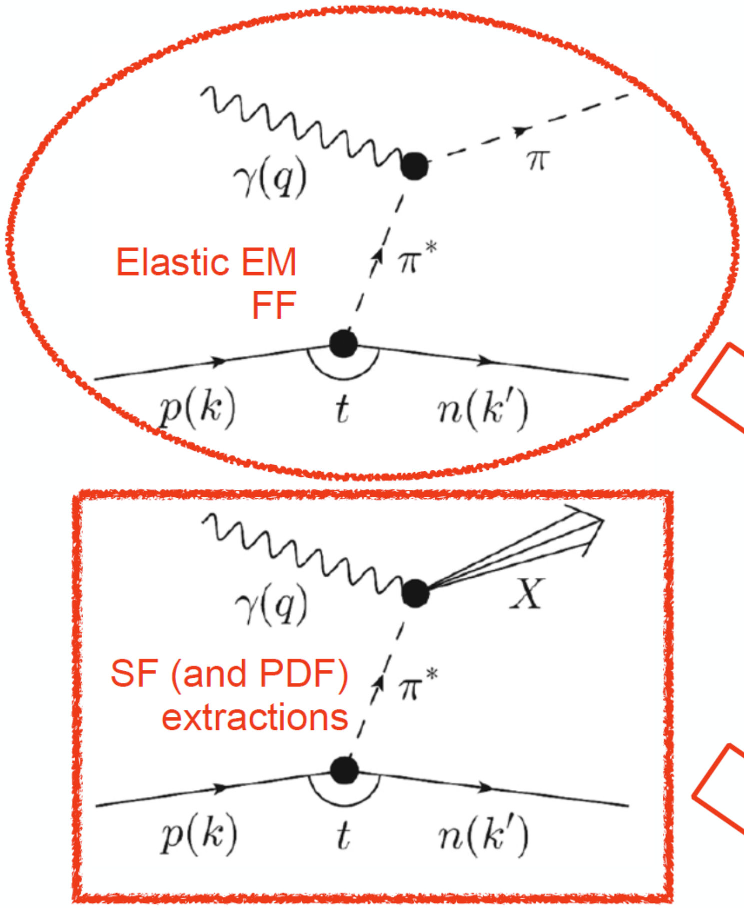
FIG. 1. The conditional TMD PDFs for the pion (**left**) and proton (**right**) as a function of b_T for various x values (indicated by color) evaluated at a characteristic experimental scale $Q = 6$ GeV. Each of the TMD PDFs are offset for visual purposes.

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

Accessing Pion/Kaon Structure Information

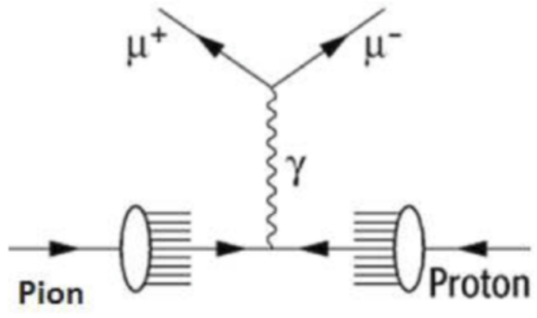
Sullivan

Hard scattering from virtual meson cloud of nucleon



Drell-Yan

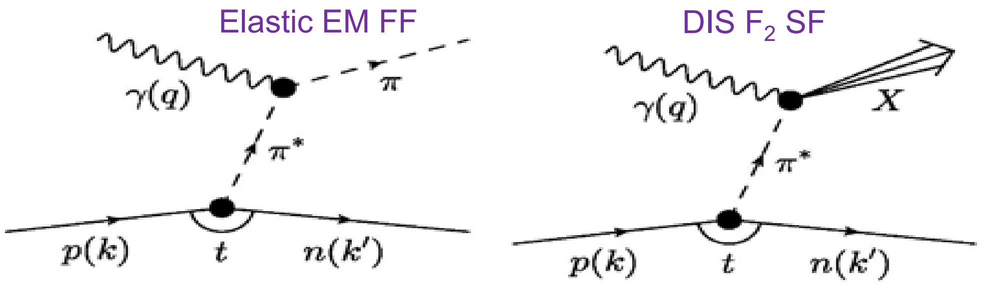
Quark of pion (e.g.) annihilates with anti-quark of proton (e.g.), virtual photon decays into lepton pair



- **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

Accessing meson structure through the Sullivan Process

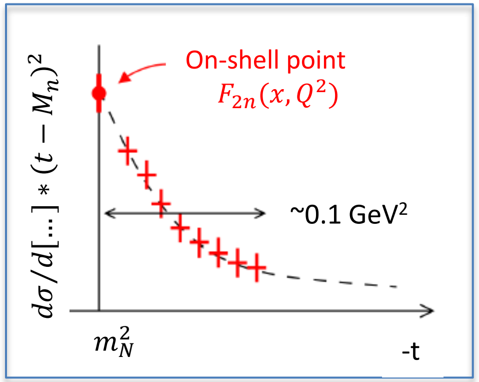
Sullivan Process



- The Sullivan process can provide reliable access to a meson target if meson pole dominant
- **Theoretical calculations found that for -t ≤ 0.6 (0.9) GeV², 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.

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

Progress with elastic FF: Experimental studies over the last decade have given *confidence* in the electroproduction method yielding the physical pion form factor

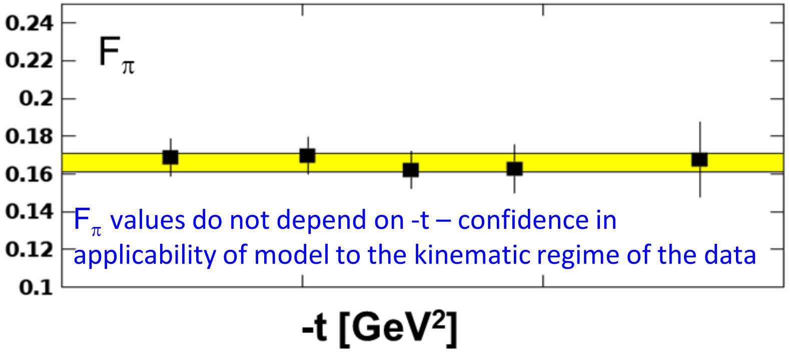


T. Horn, C.D. Roberts, J.Phys.G ***43*** *(**2016**) 7, 073001*

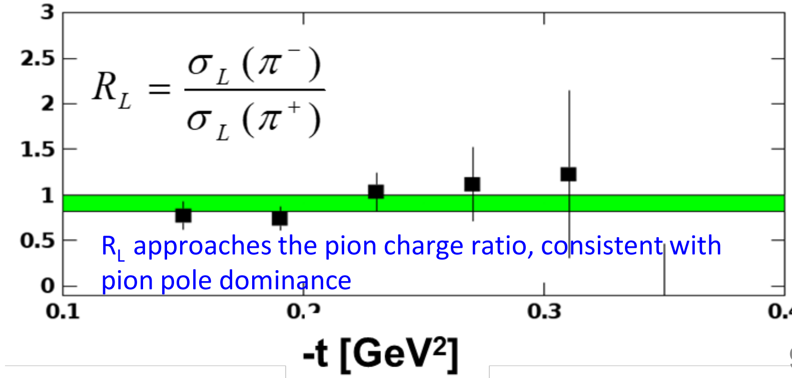
*G. Huber et al, PRL**112** (**2014**)182501*

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

Take data covering a range in –t and compare with theoretical expectation



Verify that the pion pole diagram is the dominant contribution in the reaction mechanism

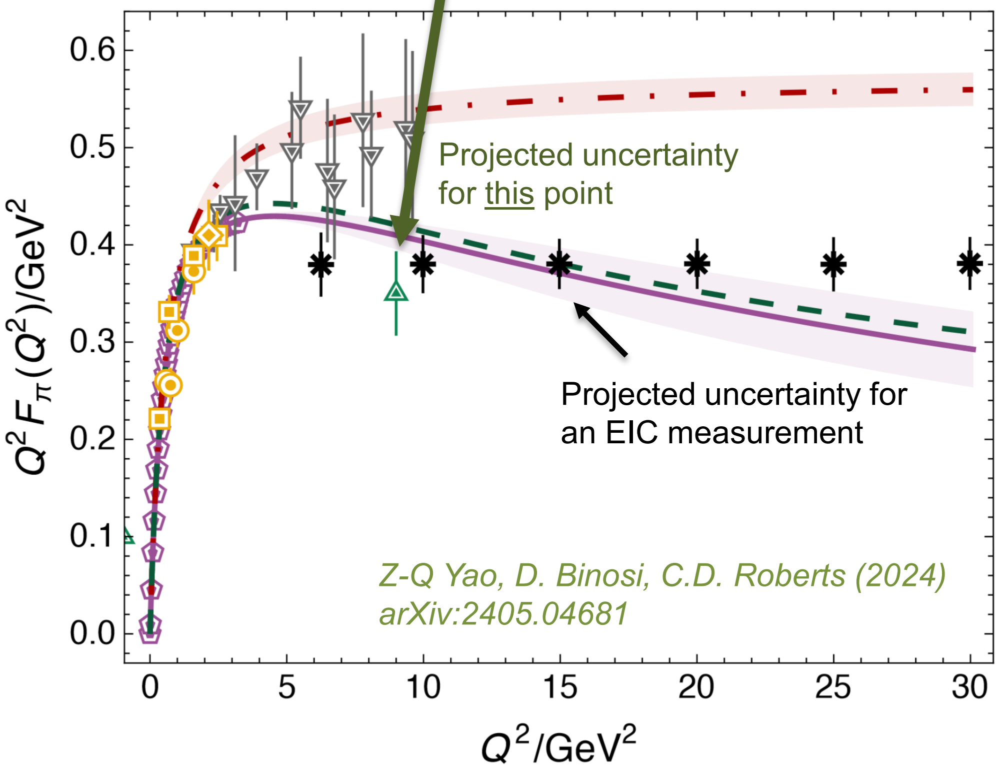


- To **check these conditions** are satisfied empirically, one can **take data covering a range in *t*** and compare with phenomenological and theoretical expectations.

Pion and Kaon Form Factor Measurements at JLab

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

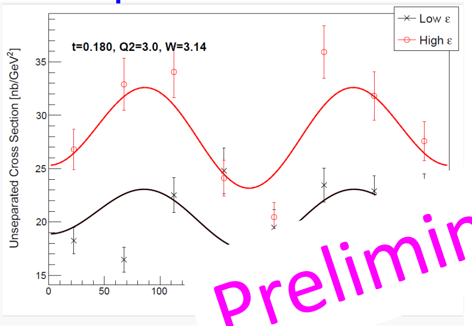


Spokespersons: Dave Gaskell (JLab), Tanja Horn (CUA), Garth Huber (URegina)

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

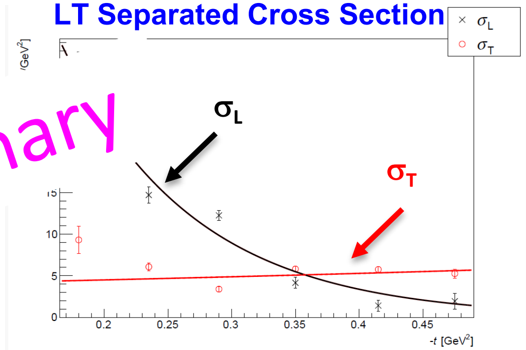
- Highest Q^2 for L/T separated kaon electroproduction cross section
- First separated kaon cross section measurement above W=2.2 GeV

Unseparated Cross Section



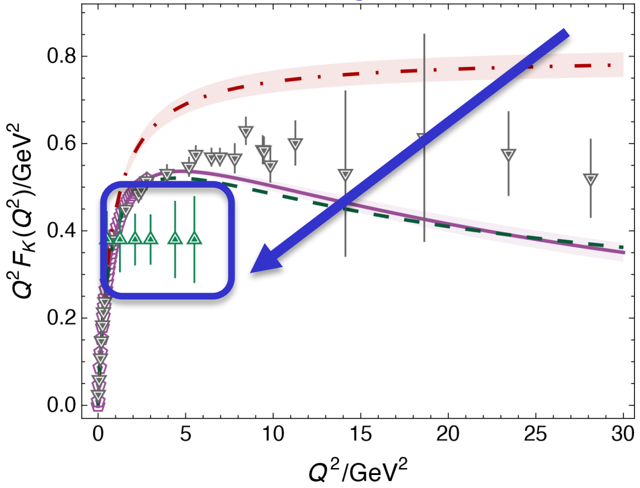
$$2\pi \frac{d^2\sigma}{dt d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)} \frac{d\sigma_{LT}}{dt} \cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$$

LT Separated Cross Section



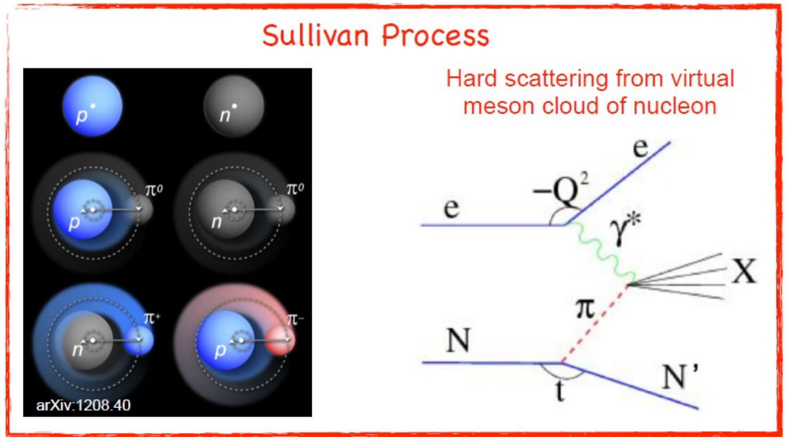
- First look at the unseparated and separated cross sections at Q^2=3 GeV^2, W=3.14 GeV
- Separated cross sections have been extracted; KaonFF will follow if warranted by data

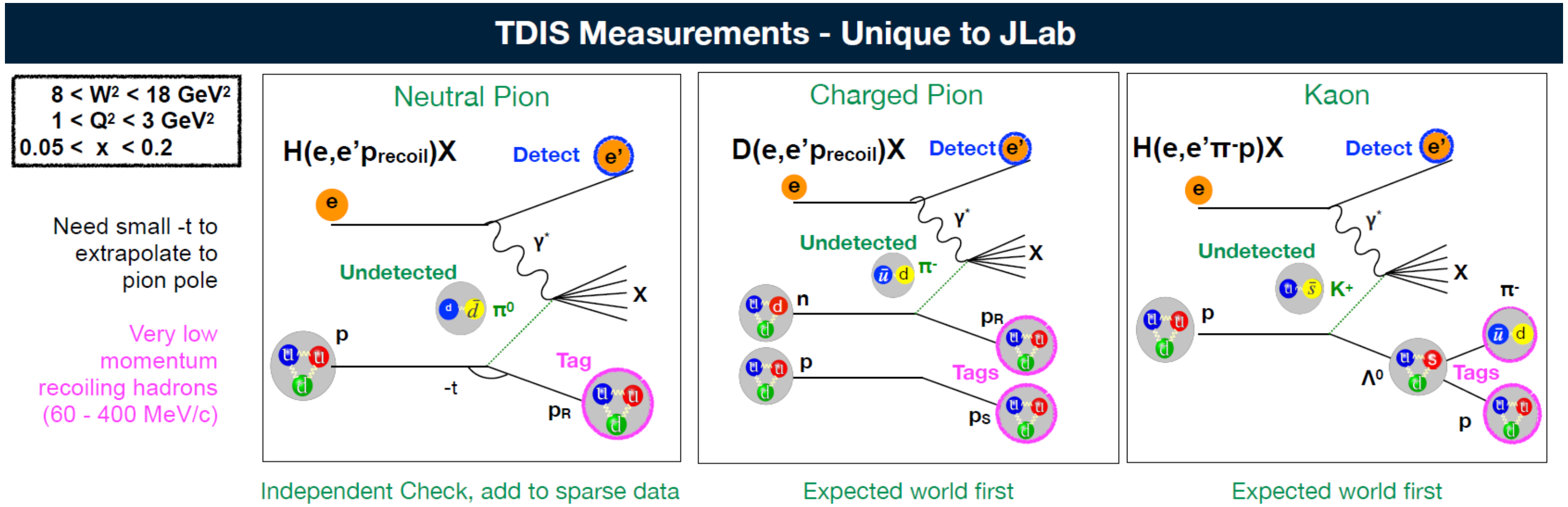
Projected Uncertainties for F_K



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

Pion and Kaon SF through TDIS Measurements at JLab





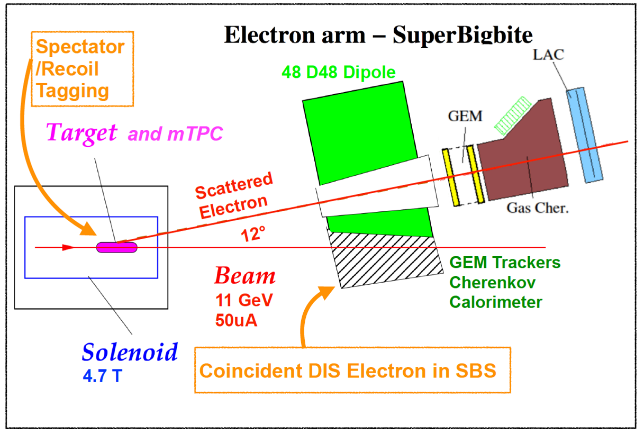
- Tag the "meson cloud" – need high luminosity
- Well-established technique, e.g., BONUS
- Pion flux contribution dominant in JLab kinematics

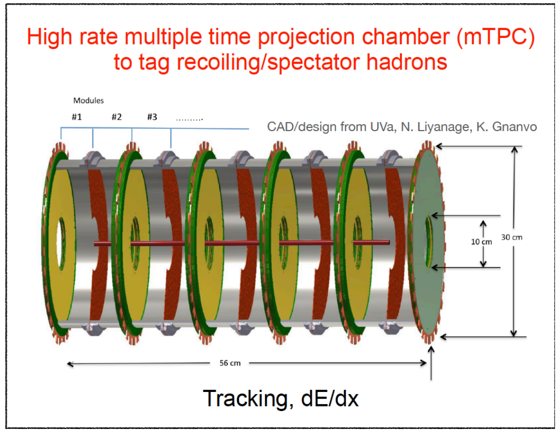
DIS event – reconstruct x, Q^2, W^2, also M_X of recoiling hadronic system

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

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

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





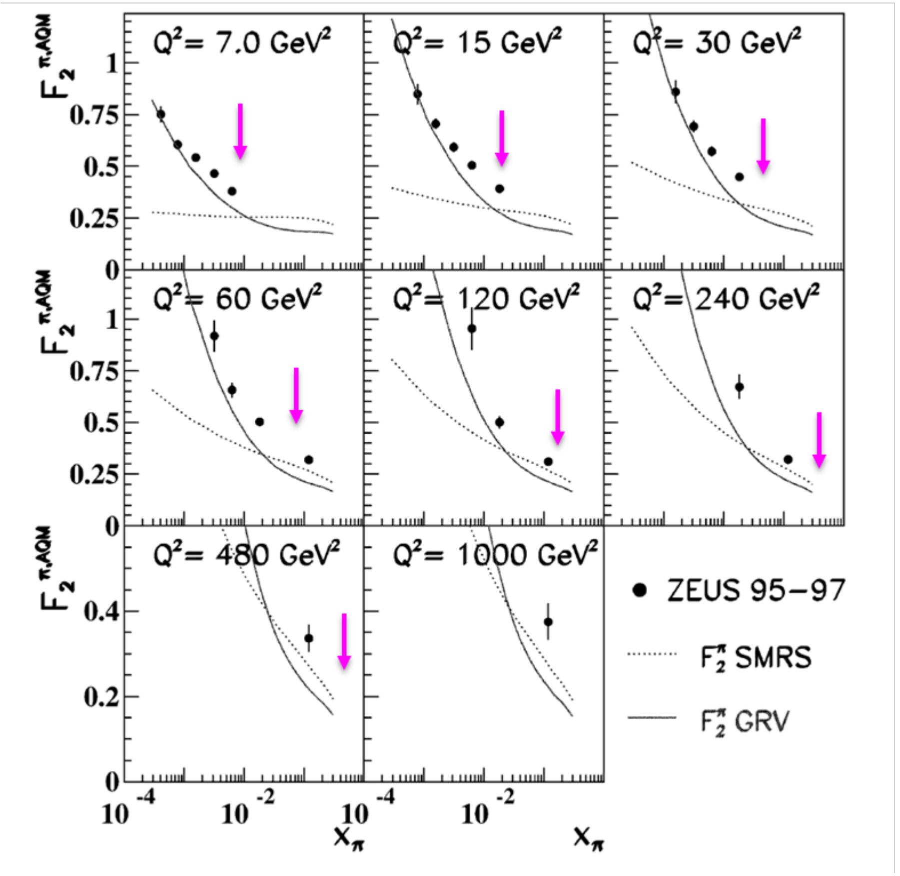
- TDIS will be a pioneering experiment that will be the first direct measure of the mesonic content of nucleons.
- The techniques used to extract meson structure function will be a necessary first step for future experiments

World Data on Pion Structure Function

HERA: showed Sullivan at low x

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

$\sim x_{min}$ for EIC



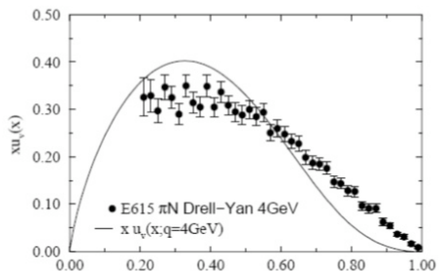
EIC kinematic reach down to a x = few 10^{-3}
Lowest x constrained by HERA leading n

DESY 08-176 JHEP06 (2009) 74

DY: Large x Structure of the Pion

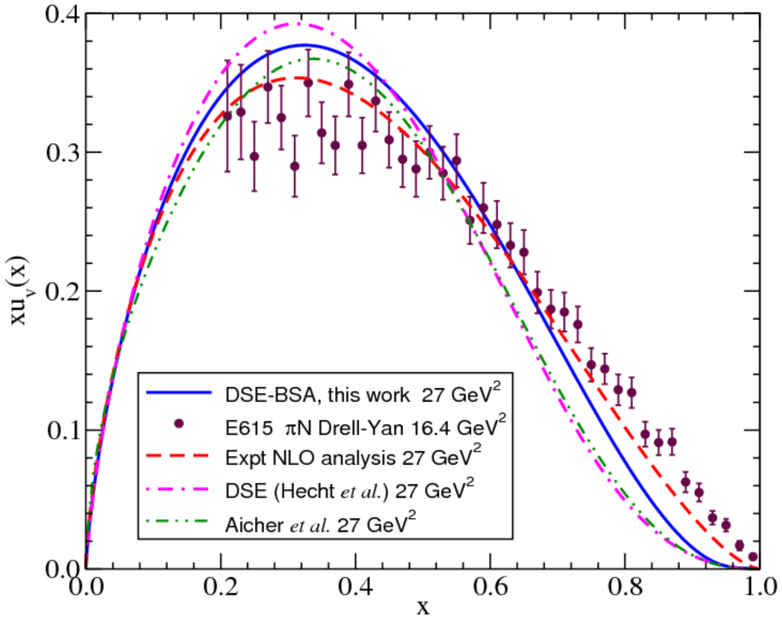
Initial observations:

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



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

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



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

- 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 TDIS can provide important verification

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:

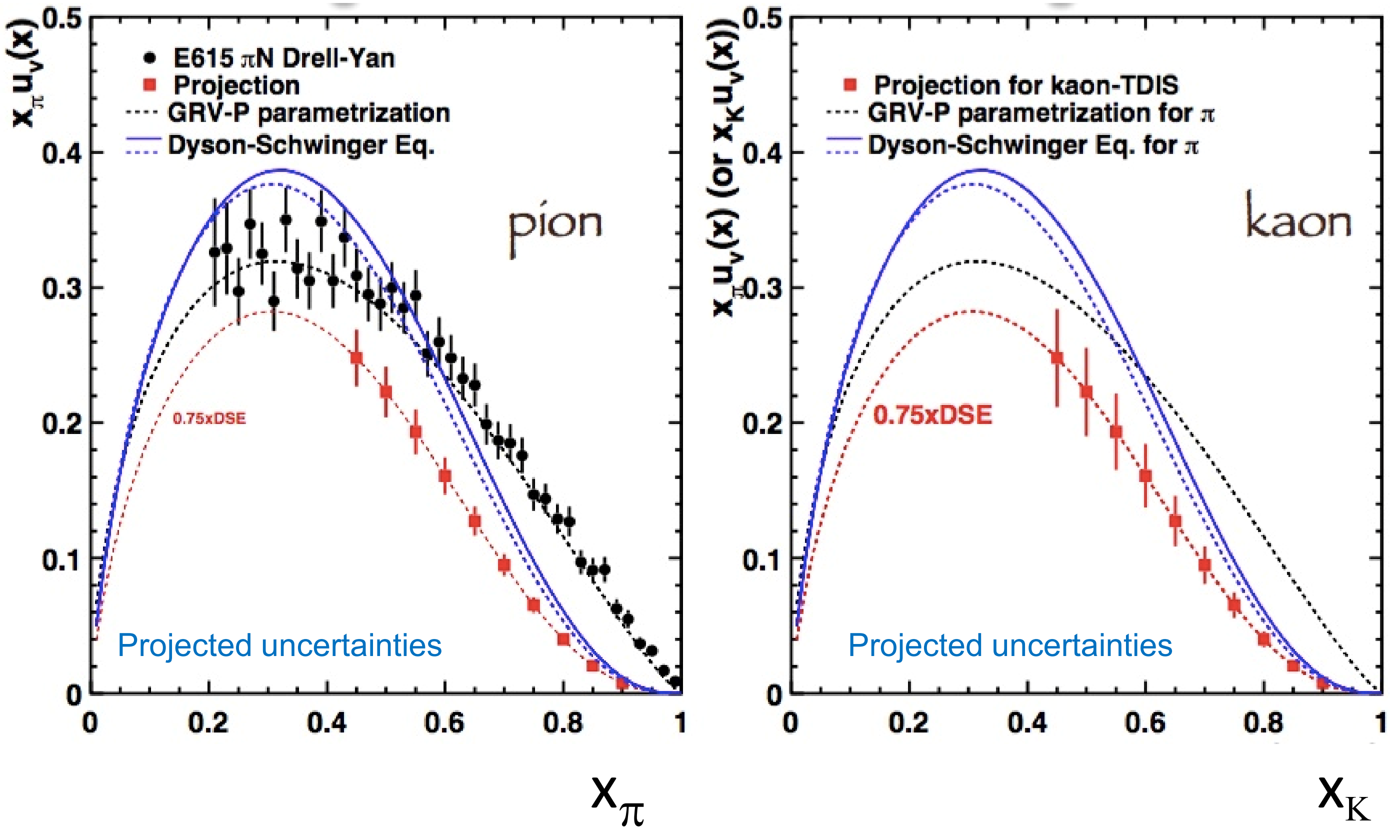
✓High luminosity,
50 μAmp,
$\mathcal{L}$ = $3x10^{36}/cm^2$ s

✓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

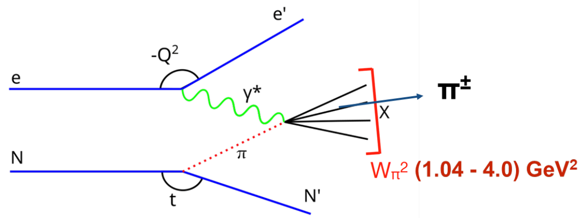


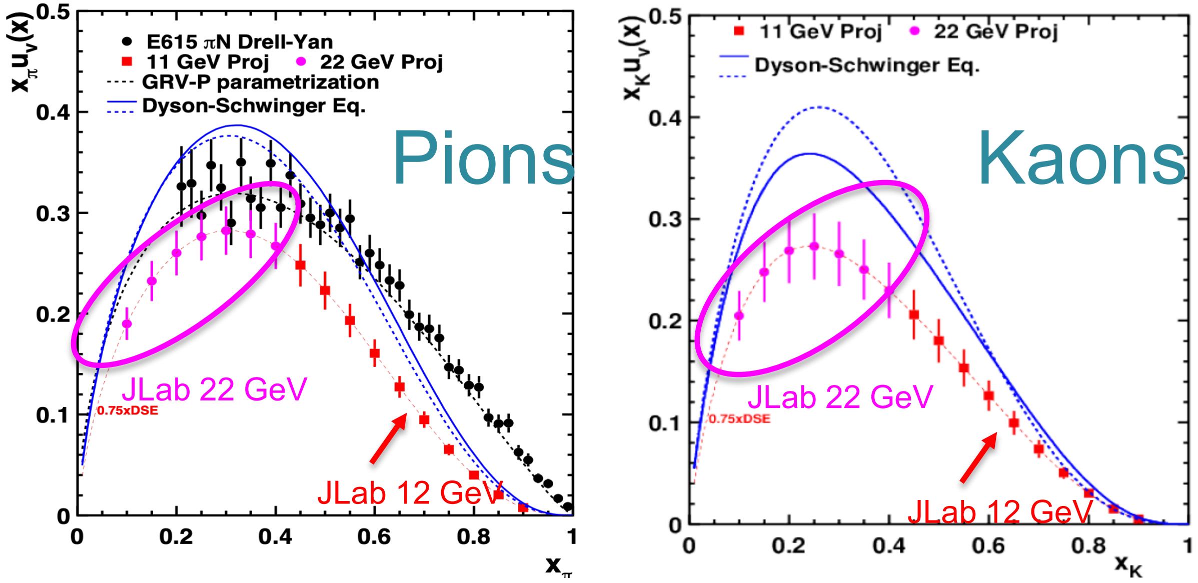
Projections based on phenomenological pion cloud model
T.J. Hobbs, Few Body Syst. 56 (2015) 6-9
J.R. McKenney et al., Phys. Rev. DD 93 (2016) 05011

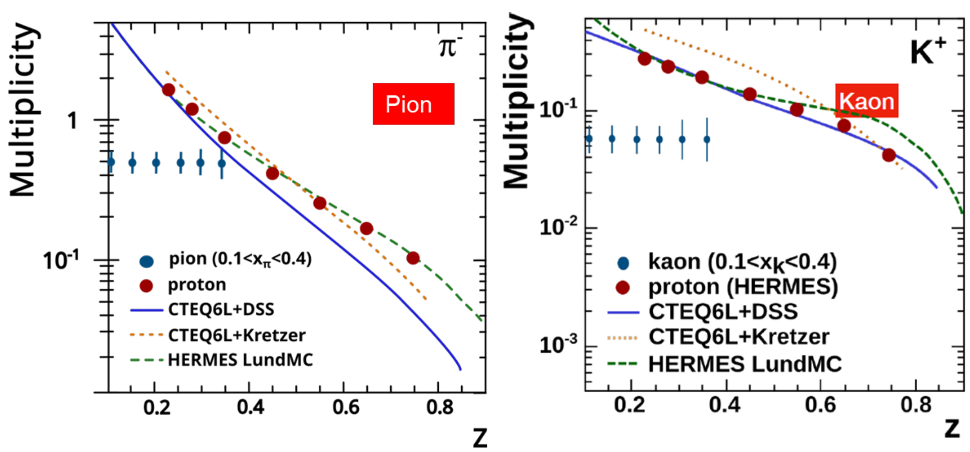
Essentially no kaon data currently

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)



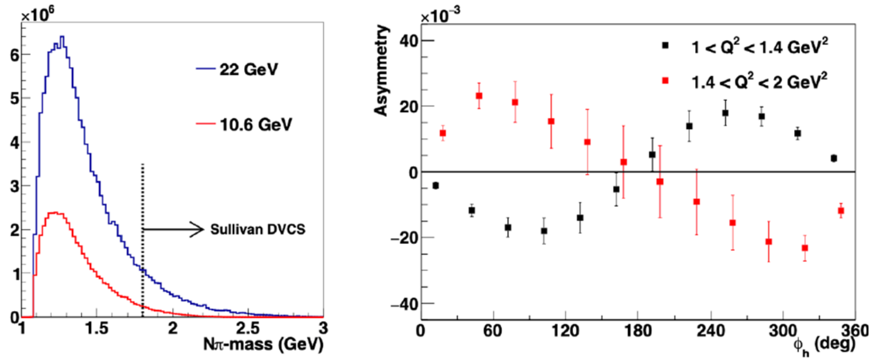




- TDIS with 22 GeV beam also enables access to TMDs
  - Measurement of SIDIS from a pion target – requires additional instrumentation for detection of an additional pion (ongoing effort)
- Higher statistics above the nucleon resonance cut would enable access to pion DVCS

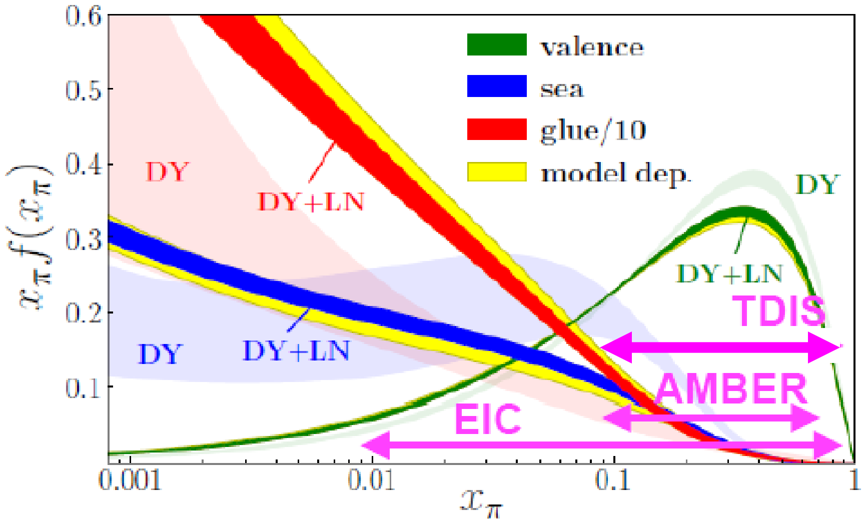
More stats above nucleon resonances cut

Assumed luminosity 3000fb⁻¹

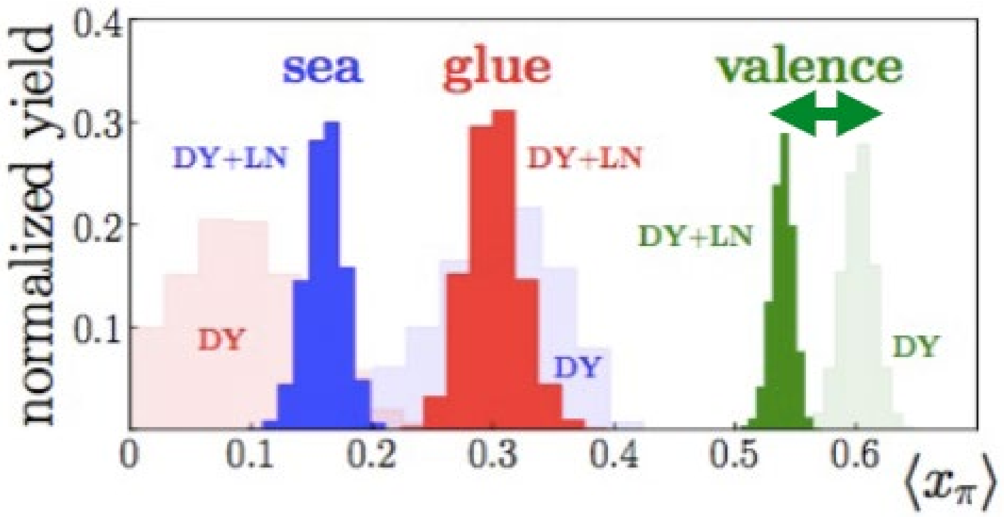


Global PDF Fits and Demand for more Data

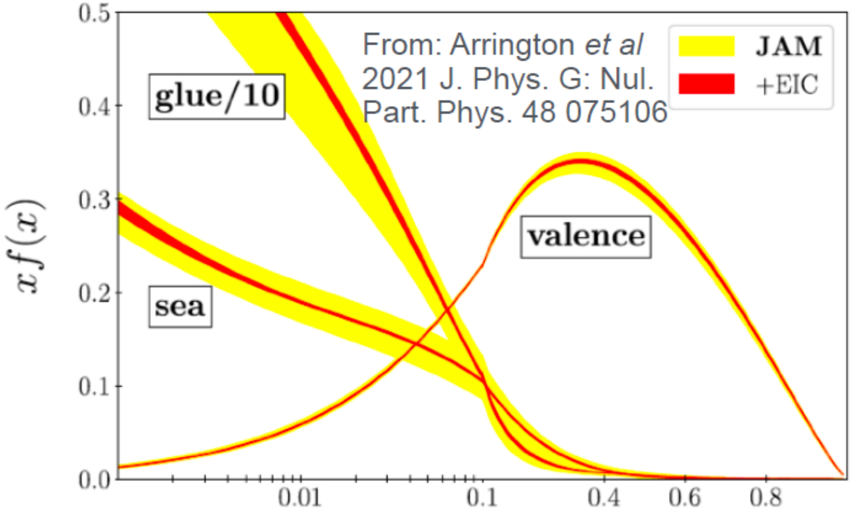
- Combined Leading Neutron/Drell-Yan analysis for PDF fitting, with novel MC techniques for uncertainties (JLab JAM)
- Non-overlapping uncertainties – tension at large x



Mom. Fraction carried by sea/glue/valence



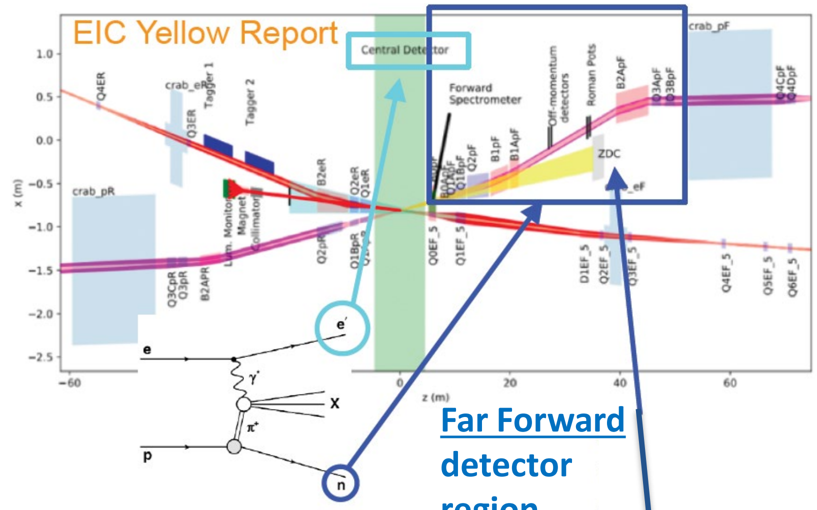
P.C. Barry, N. Sato, W. Melnitchouk, C-R Ji (JAM Collaboration), PRL 121 (2018) 152001



- 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, arXiv:1907.01509 (2019)
  - 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
  - Far-Forward detectors particularly important (reaction kinematics and 4 momenta)

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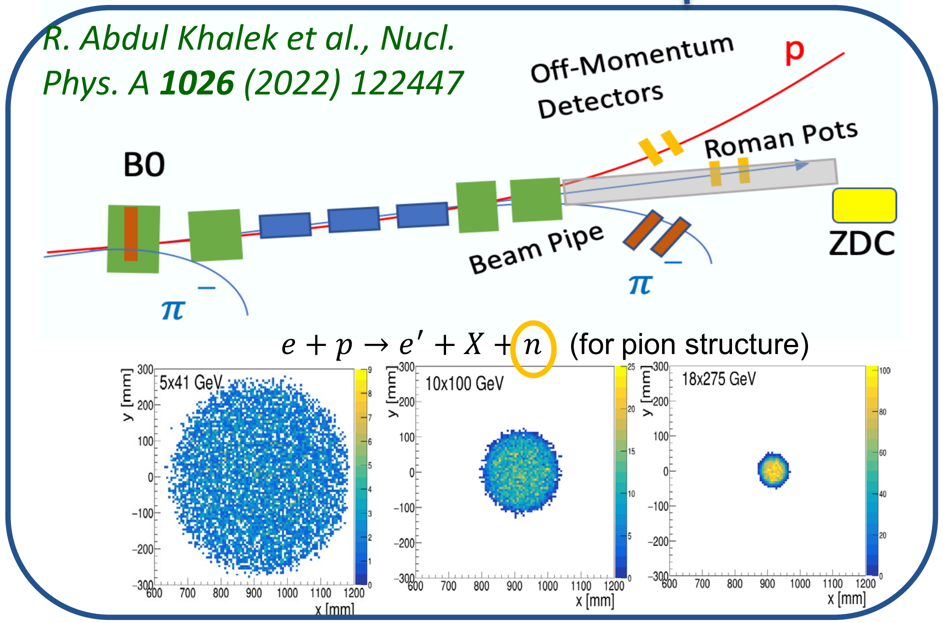
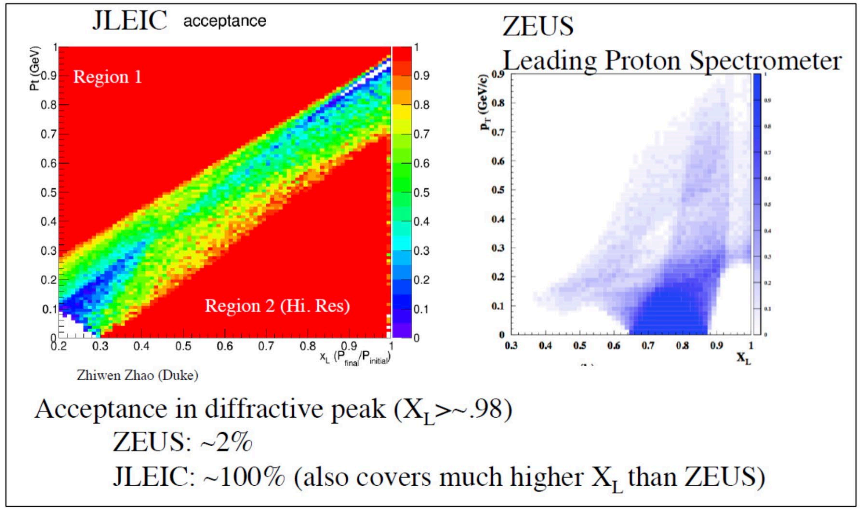


Far Forward detection region must detect the recoiling baryon and its decay products with sufficient precision to achieve the desired resolution for meson structure studies.

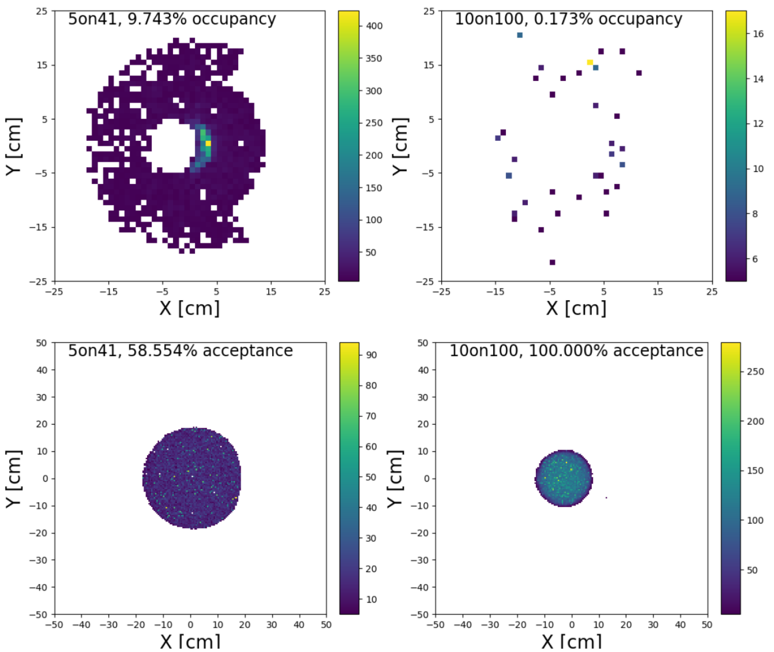
Example: acceptance for p' in e + p → e' + p' + X



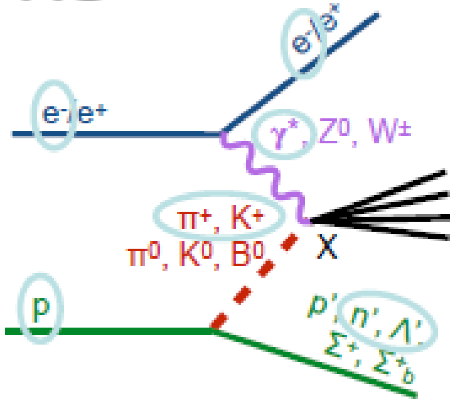
Huge gain in acceptance for forward tagging….

EIC Pion/Kaon SF – Experimental Considerations

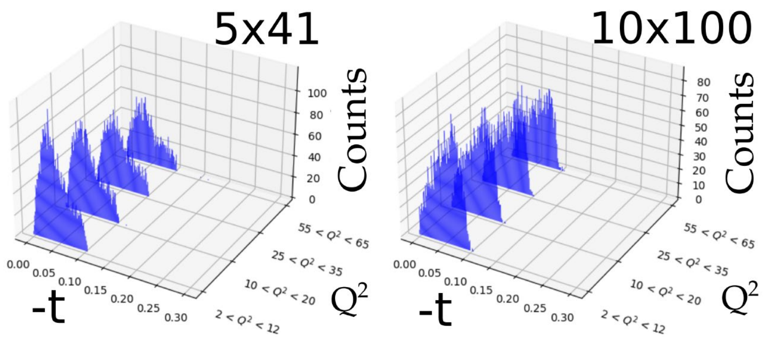
B0 occupancy and ZDC acceptance for leading neutron



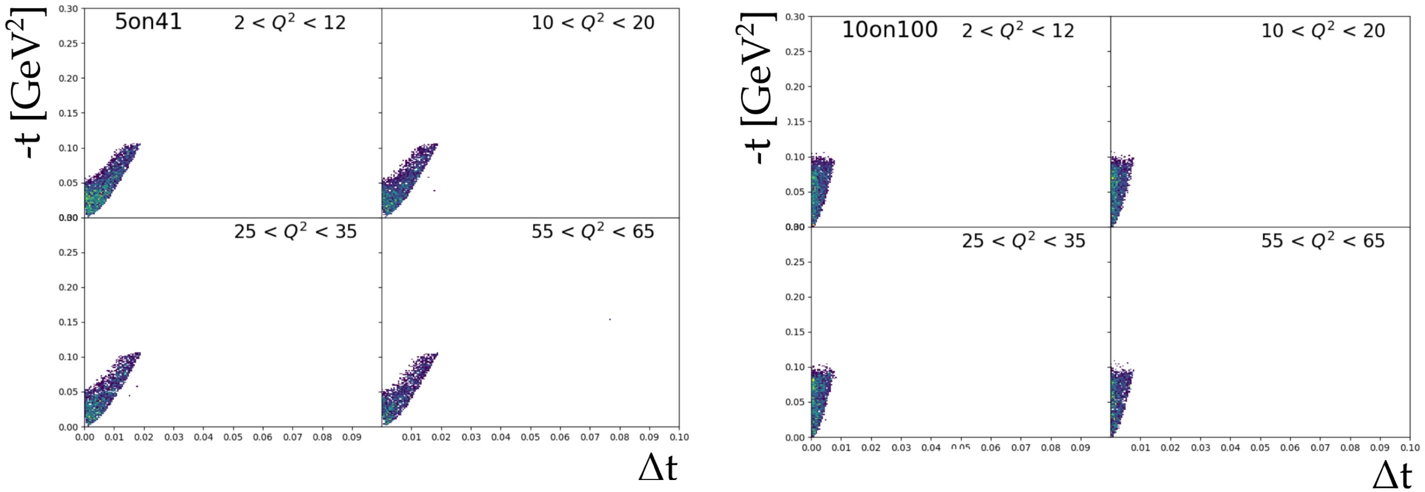
- For pion/kaon structure the kinematic phase space is: $(x,Q^2,-t)$. Acceptance and reconstruction resolution for the reaction particles is required
- Studies were conducted using the EIC_mesonMC event generator and G4 for detector acceptance and response and t-distributions, Dt vs t were obtained
- Focus so far: ep and measuring cross section 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



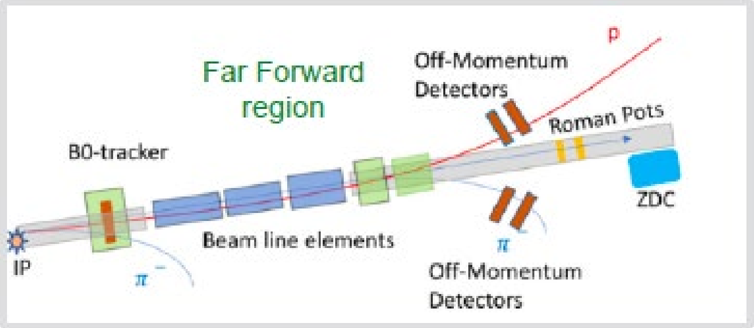
A. Bylinkin et al., NIMA 1052 (2023) 168238

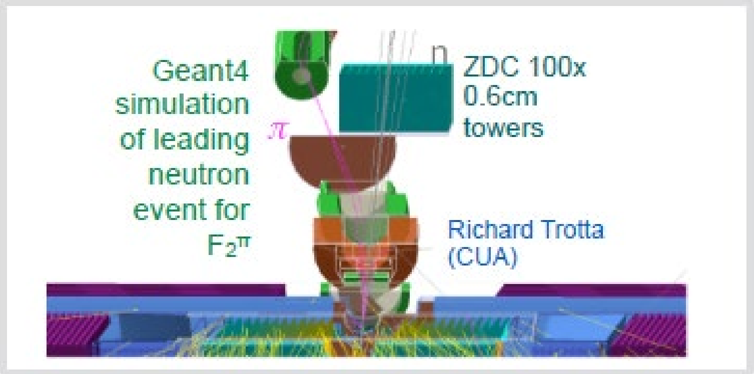


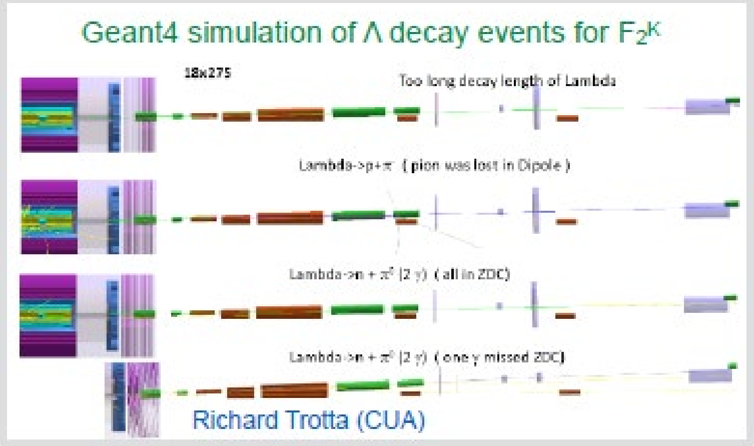
Reconstruction of –t from the detected π^+ and e^- tracks

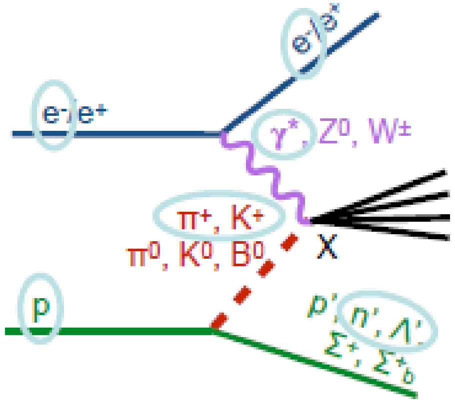


EIC Pion/Kaon SF Measurements





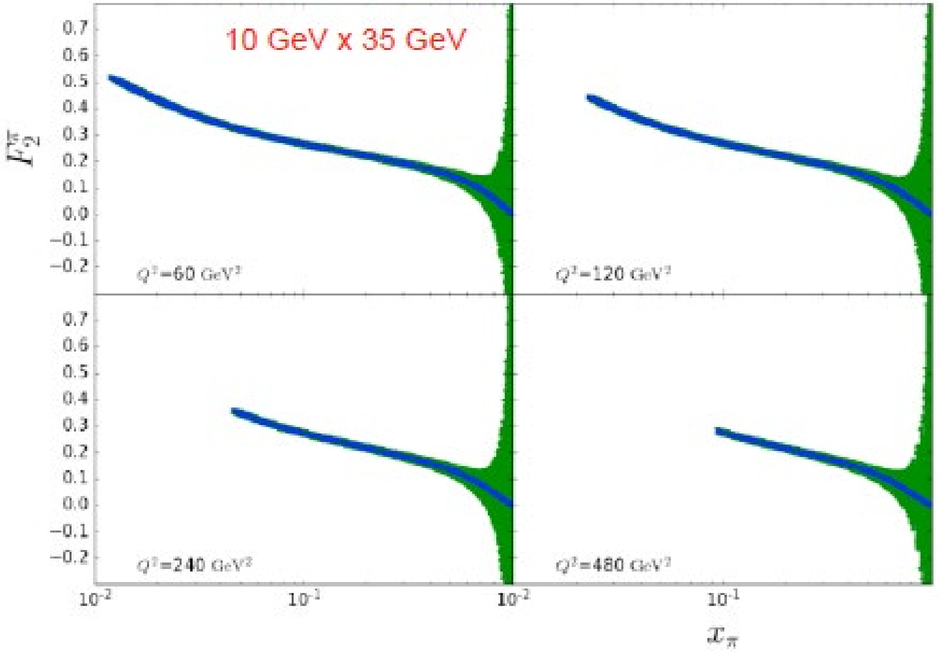




Detector requirements:

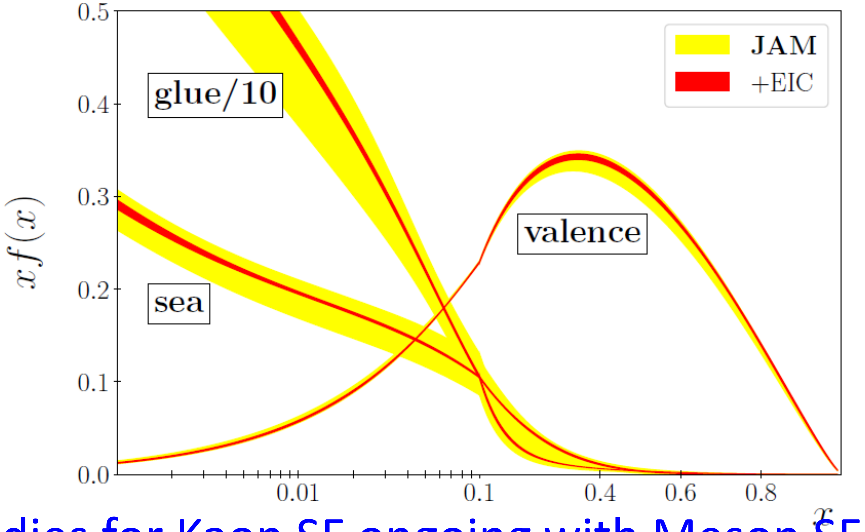
- **For π-n:**
  - Lower energies (5 on 41, 5 on 100) require at least 60 x 60 cm^2
  - For all energies, the neutron detection efficiency is 100% with the planned ZDC
- **For π-n and K^+/Λ:**
  - All energies need good ZDC angular resolution for the required -t resolution
  - High energies (10 on 100, 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:**
  - $\Lambda \rightarrow n + \pi^0$: additional high-res/granularity EMCal+tracking before ZDC – seems doable
  - $\Lambda \rightarrow p + \pi^-$: 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

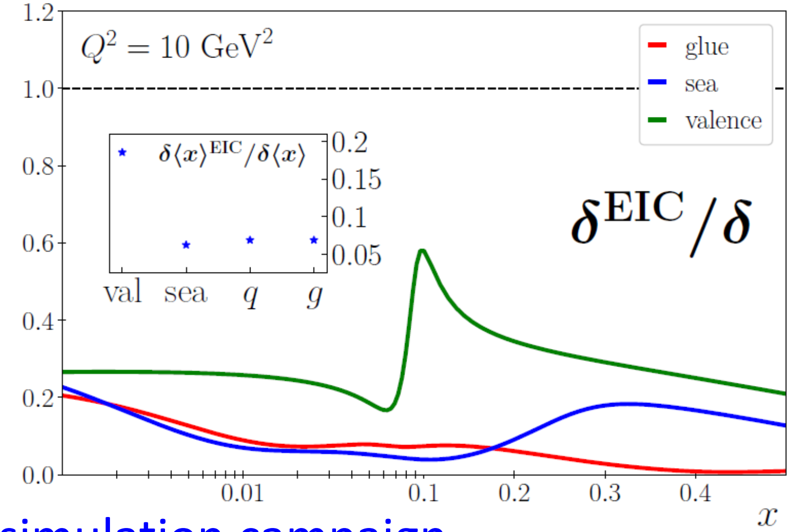
EIC Pion SF Projections



J. Arrington 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 et al., Nucl. Phys. A **1026** (2022) 122447*

Detailed studies for Kaon SF ongoing with Meson SF simulation campaign

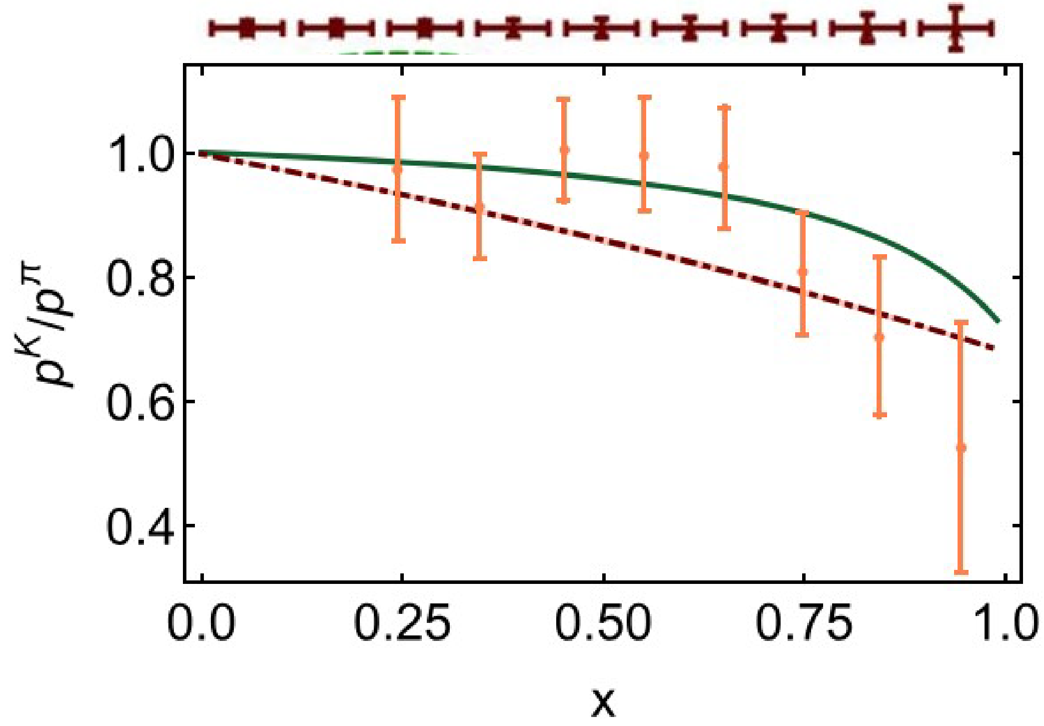
Kaon structure functions – gluon pdfs

- 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

Projected uncertainties for measurements at EIC

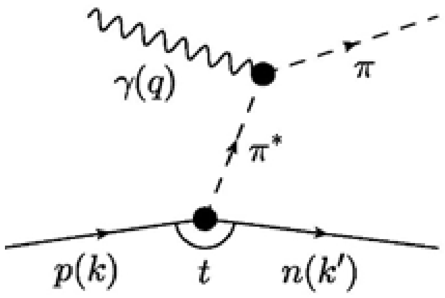


*Z-F Ciu et al., Eur.Phys.J.C **80** (2020) 1064, 1*

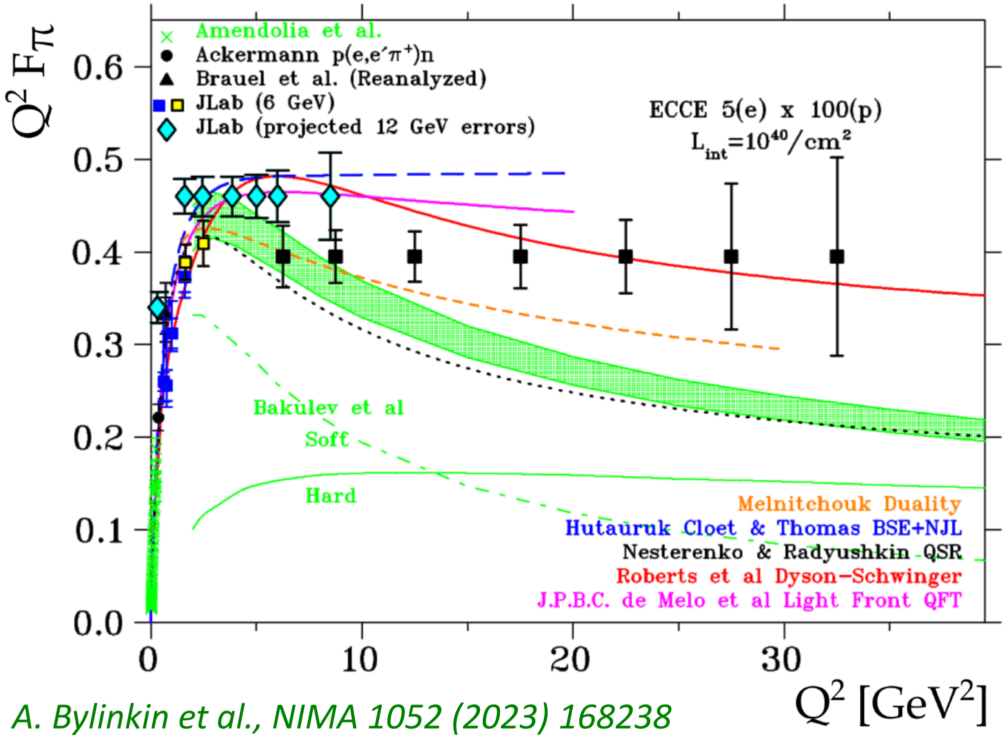
*A.C. Aguilar et al., Eur.Phys.J.A **55** (2019) 10, 190*

Detailed studies for Kaon SF ongoing with Meson SF simulation campaign

Pion Form Factor Prospects @ EIC



1. Models show a strong dominance of σ_L at small –t at large Q^2.
2. Assume dominance of this longitudinal cross section
3. Measure the π^-/π^+ ratio to verify – it will be diluted (smaller than unity) if σ_T is not small, or if non-pole backgrounds are large

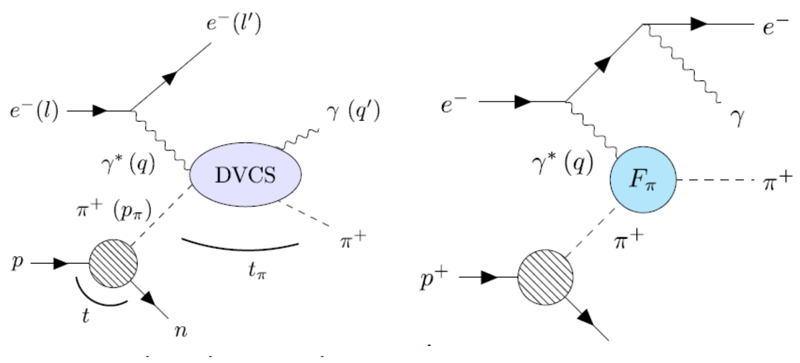


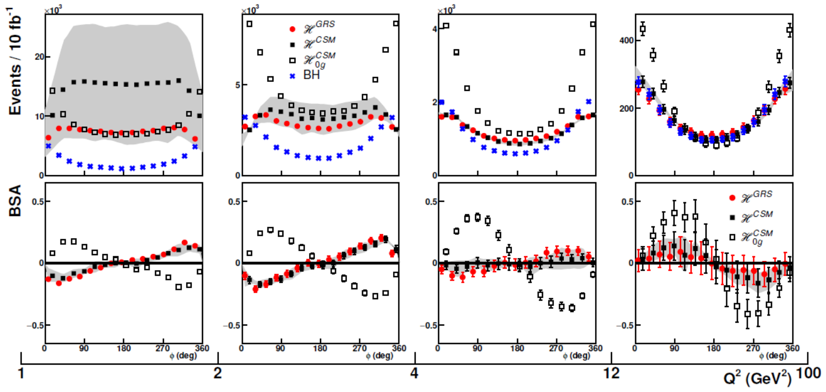
A. Bylinkin et al., NIMA 1052 (2023) 168238

- ❑ Assumed 5 GeV(e^-) x 100 GeV(p) with an integrated luminosity of 10 fb^{-1}/year, and similar luminosities for d beam data
- ❑ $R=\sigma_L/\sigma_T$ assumed from VR model and assume that π pole dominance at small t confirmed in ^2H π^-/π^+ ratios
- ❑ Assumed a 2.5% pt-pt and 12% scale systematic uncertainty, no systematic uncertainty in the model subtraction to isolate σ_L

Can we measure the kaon form factor at EIC? Or only through L/T separations emphasizing lower energies? Not clear – needs guidance from JLab 12- GeV.

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

Summary

- ❑ Meson structure is essential for understanding EHM and our visible Universe
  - ○ Meson structure is non-trivial and experimental data for pion and kaon structure functions is extremely sparse
- ❑ JLab 12 GeV will dramatically improve the $\pi^+/K^+/\pi^0$ electroproduction data set
  - ○ Pion and kaon form factor extractions up to high Q^2 possible (~9 and ~6 GeV^2)
  - ○ L/T separated cross sections important for transverse nucleon structure studies
- ❑ There are very exciting imminent opportunities to collect additional data for light mesons
  - ❑ TDIS @ 11 GeV JLab - provides 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
- ❑ EIC - Potential game-changer for this topic due to large CM range (20-140 GeV); Large x/Q^2 landscape for pion/kaon SF; Potential to provide definite answers on different gluon distributions in pion/kaon
  - ❑ Design of the far-forward region is important
  - ❑ Initial studies for pion SF; ongoing studies for kaon SF
- ❑ Ongoing efforts extending into 3D light hadron structure – GPDs and TMDs – in theory/experiment
  - ❑ TDIS @ 22 GeV JLab could offer new opportunities including possible SIDIS from pion target measurements