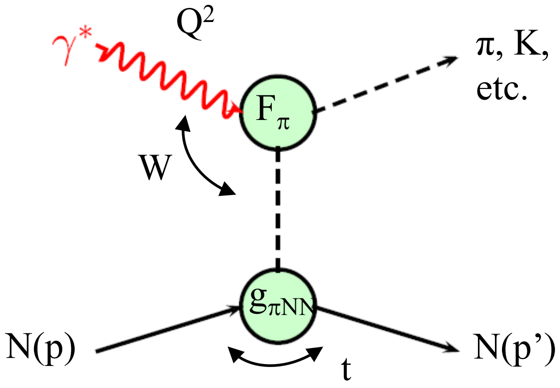
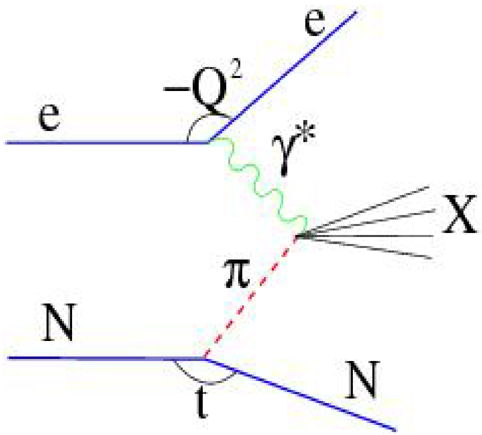
Experimental Overview on Future Experiments for Pion/Kaon Structure (EIC & JLab)





Tanja Horn

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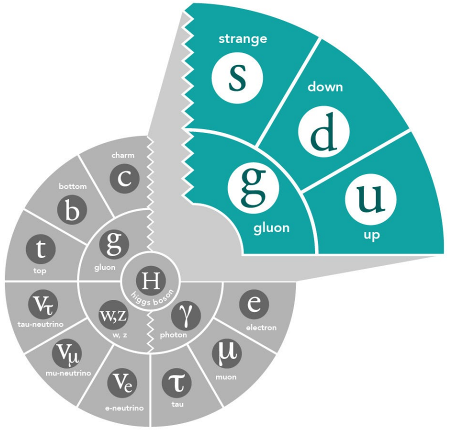
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Supported in part by NSF grants PHY2309976 and PHY2012430

PAW'24 Physics at AMBER International Workshop

Chateau de Bossey, Mar 18-20, 2024

The Incomplete Hadron: Mass puzzle

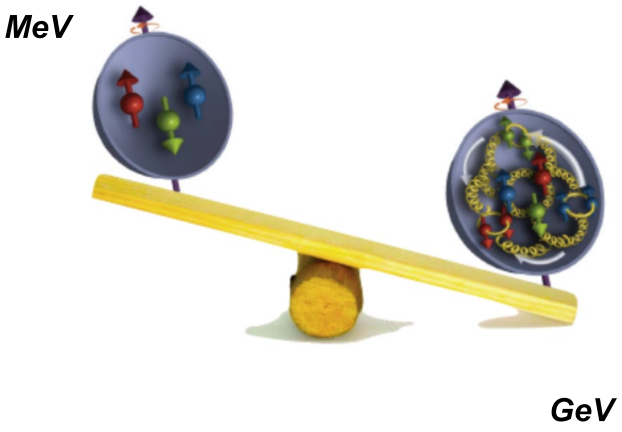


Proton: Mass ~ 940 MeV (~1 GeV)
Most of mass generated by dynamics

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

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

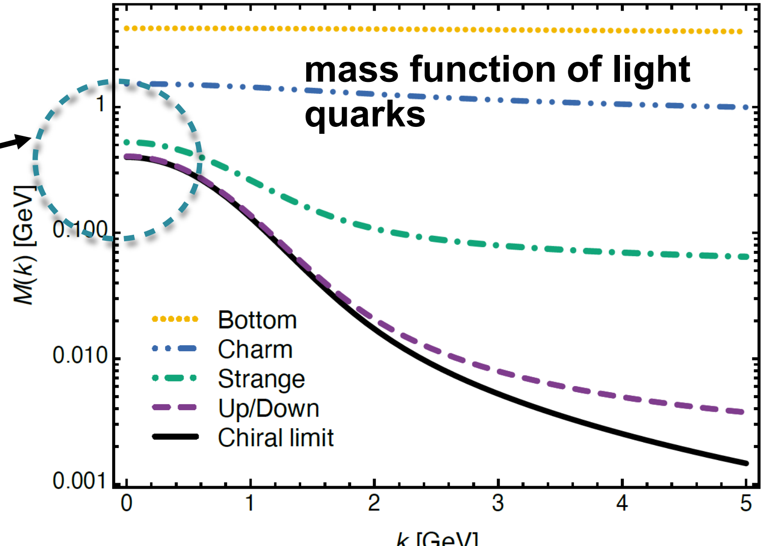
"Mass without mass!"



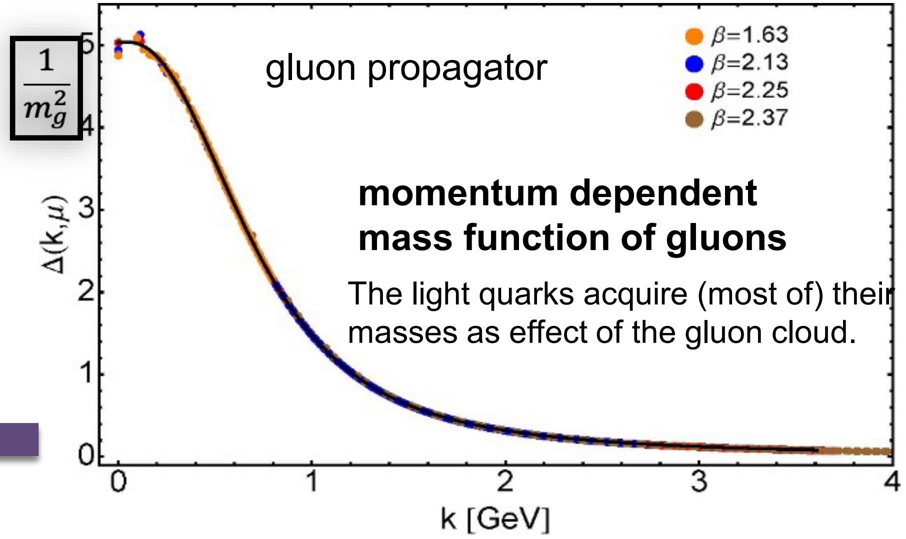
Visible world: mainly made of light quarks – its mass emerges from quark-gluon interactions.

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

Rapid increase in mass due to gluon cloud



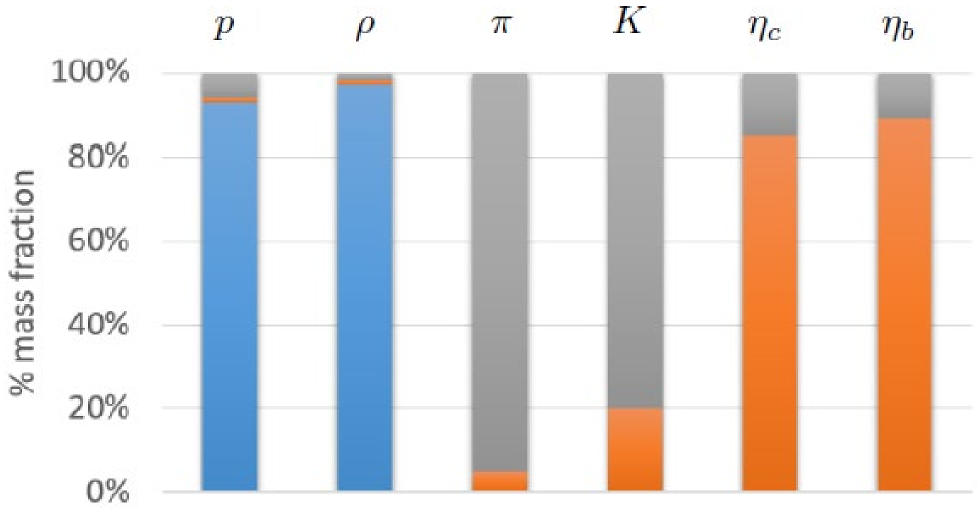
C. D. Roberts, Symmetry ***12, (2020)*** *1468*



Insights into Hadron Structure and Mass through Mesons

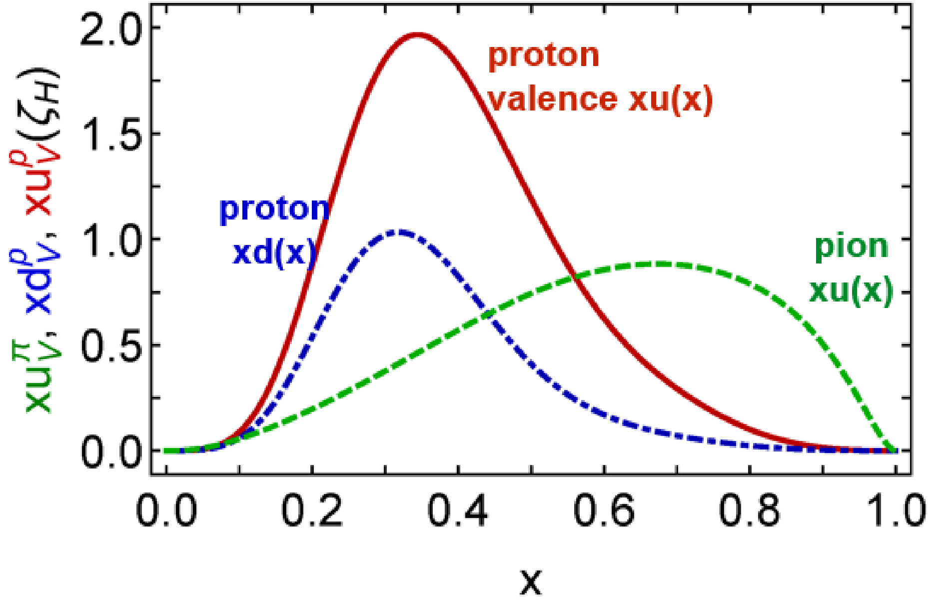
Understanding pion/kaon is vital to understand the **dynamic** generation of hadron mass and offers unique insight into EHM and the role of the Higgs mechanism

*K. Raya, A. Bashir, D. Binosi, C.D. Roberts, J. Rodriguez-Quintero, arXiv:2403.00629v1 (**2024**)*



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

D. Binosi, Few Body Systems **63** (**2022**) 42



Mass budget for mesons and nucleons are vastly different

- Proton (and heavy meson) mass is large in the chiral limit – expression of emergent hadronic mass
- 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

Pion/proton valence quark distributions are also very different

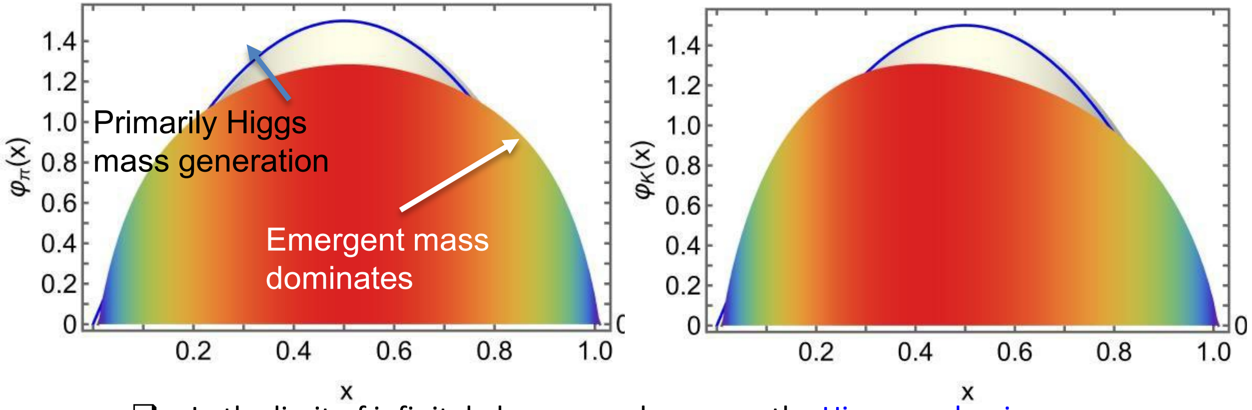
→ Difference between meson PDFs: direct information on emergent hadron mass (EHM)

Light Mesons and EHM

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*

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

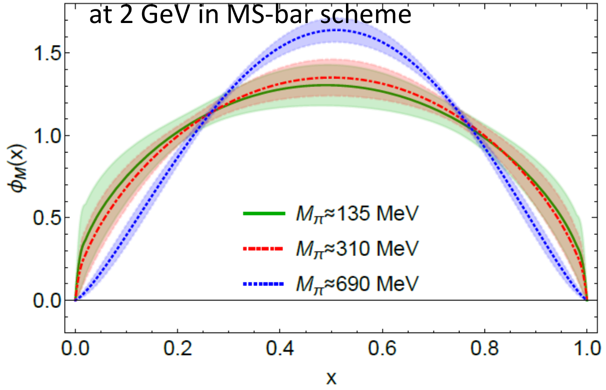


- ❑ In the limit of infinitely-heavy quark masses, the Higgs mechanism overwhelms every other mass generating force, and the PDA becomes a δ-function at x = ½.
- ❑ The DA for the light-quark pion is a broad, concave function, a feature of emergent mass generation.
- ❑ Kaon DA is asymmetric around the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

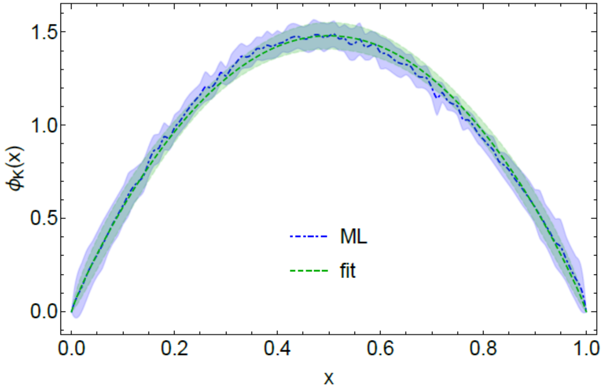
Strong synergy with lattice QCD

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

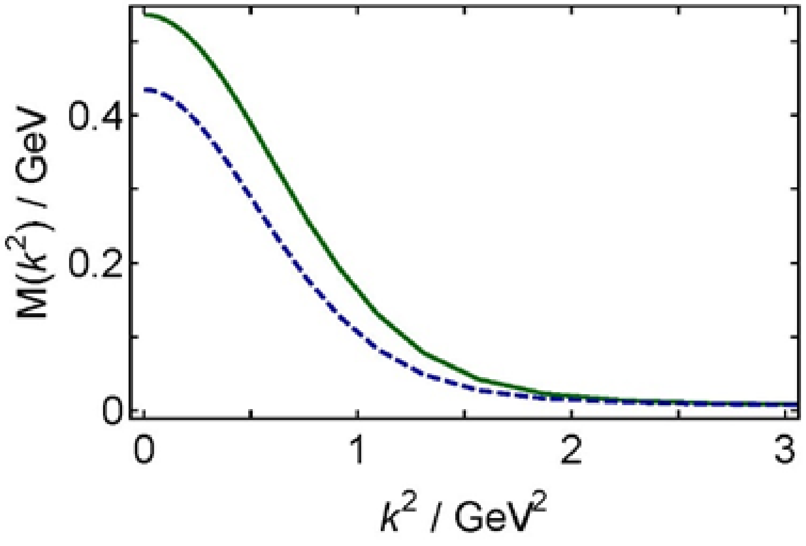


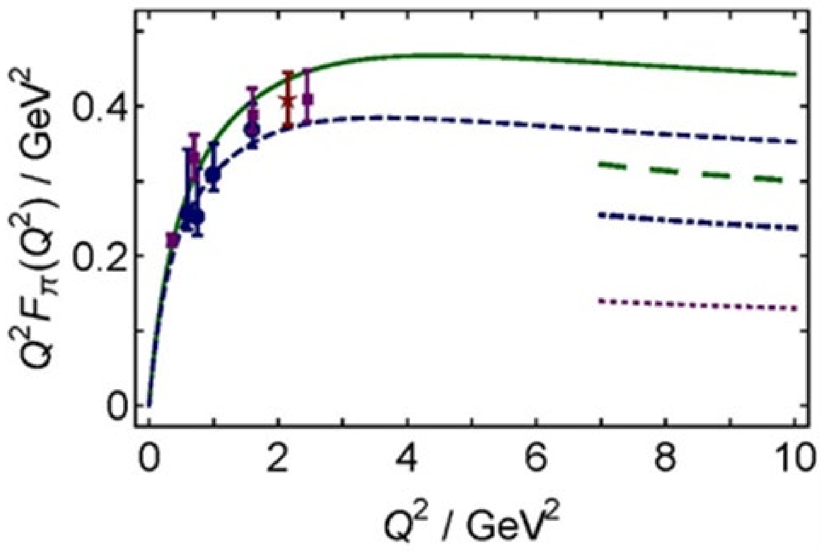
Fit to lattice data for kaon, and using machine learning approach

- ➢ 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 Mass

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





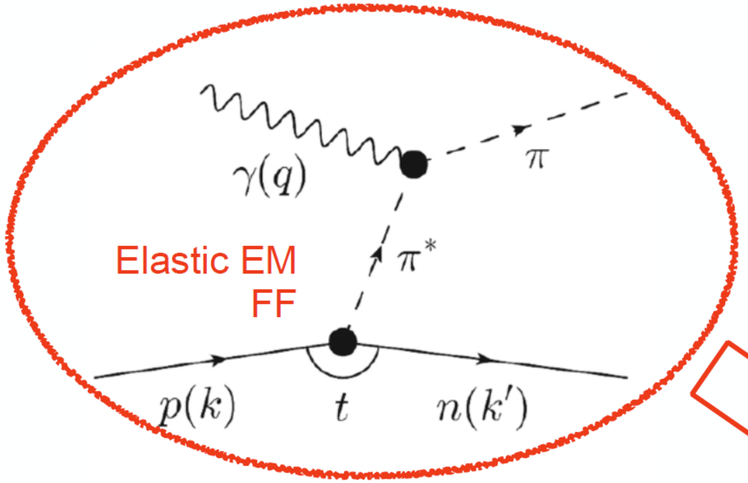
A.C. Aguilar et al., Eur. Phys. J. A ***55*** *(**2019**) 10, 190*

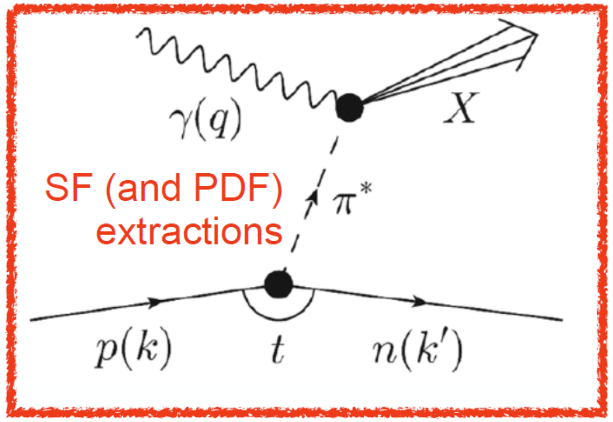
<u>Left panel</u>. Two dressed-quark mass functions distinguished by the amount of DCSB: emergent mass generation is 20% stronger in the system characterized by the solid green curve, which describes the more realistic case. <u>Right panel</u>. $F_\pi(Q^2)$ obtained with the mass function in the left 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

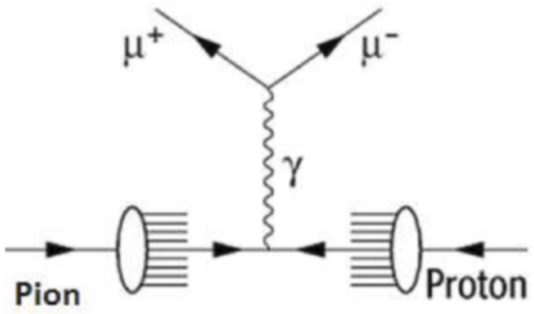
Hard scattering from virtual meson cloud of nucleon





Drell-Yan

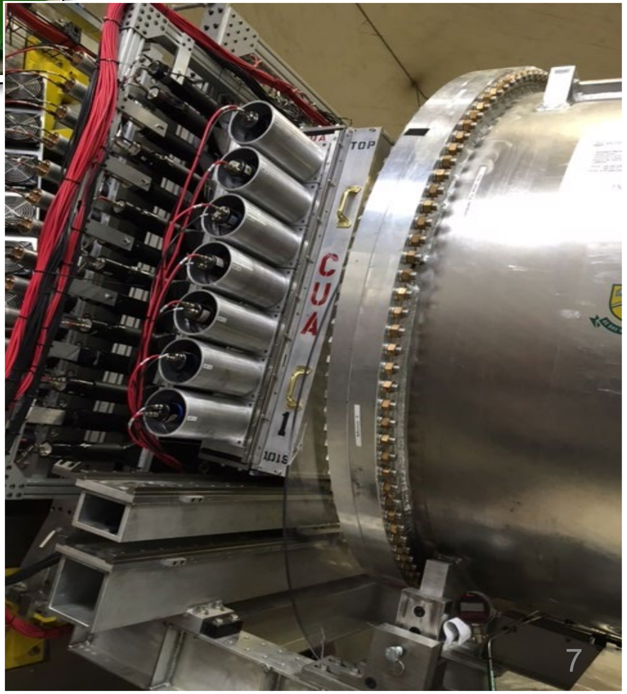
Quark of pion (e.g.) annihilates with anti-quark of proton (e.g.), virtual photon decays into lepton pair



- **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

Exclusive Meson Experiments in Hall C @ 12 GeV JLab

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

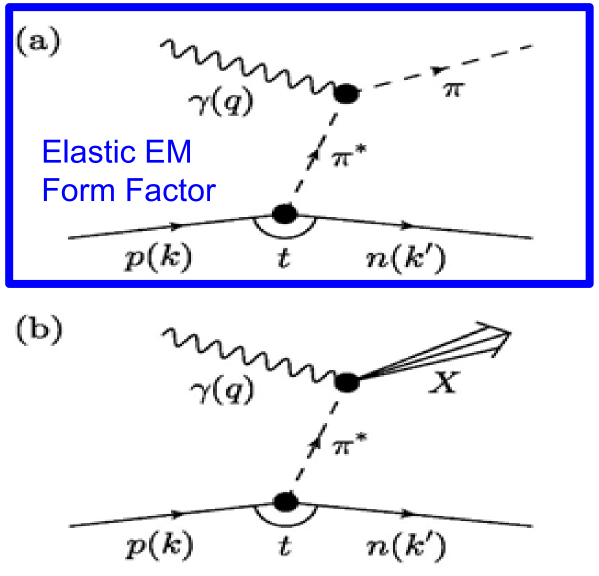


- CEBAF 10.9 GeV electron beam and SHMS small angle capability and controlled systematics are essential for precision measurements to higher Q^2
- Focusing spectrometers fulfill the L/T separation requirements
- Dedicated key SHMS Particle Identification detectors for the experiments
  - Aerogel Cherenkov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

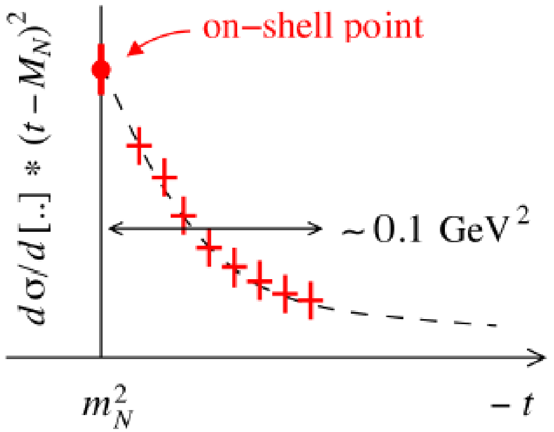
T. Horn, H. Mkrtchyan, et al., Nucl.Instrum.Meth.A **842** (**2017**) 28-47

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*



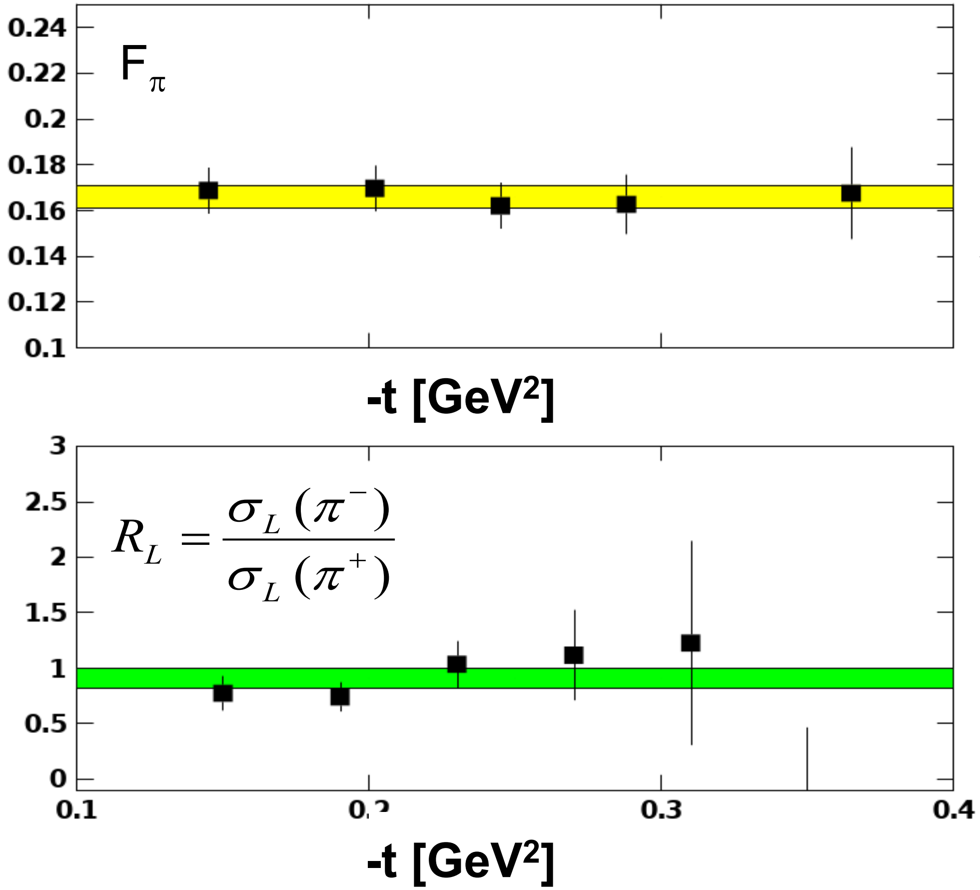
- To **check these conditions** are satisfied empirically, one can **take data covering a range in *t*** and compare with phenomenological and theoretical expectations.

- **Theoretical calculations found that for $-t \leq 0.6\ (0.9)\ \mathrm{GeV}^2$, 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*

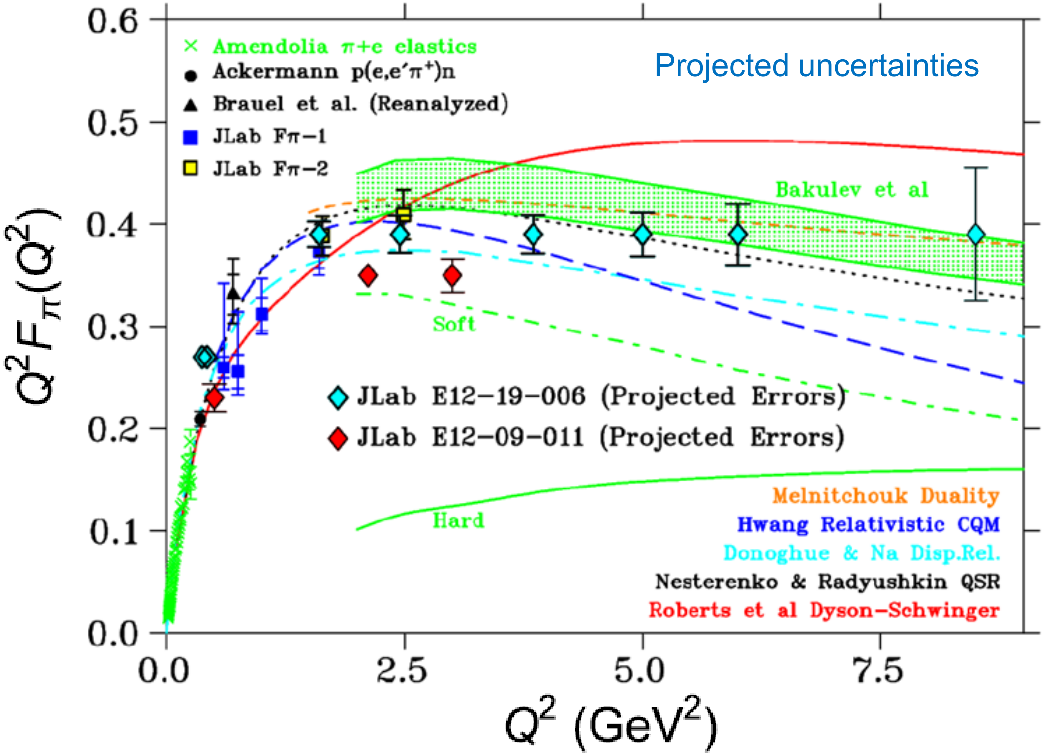
*G. Huber et al, PRL**112** (**2014**)182501*

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

PionLT/KaonLT Program at 12 GeV JLab Overview

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

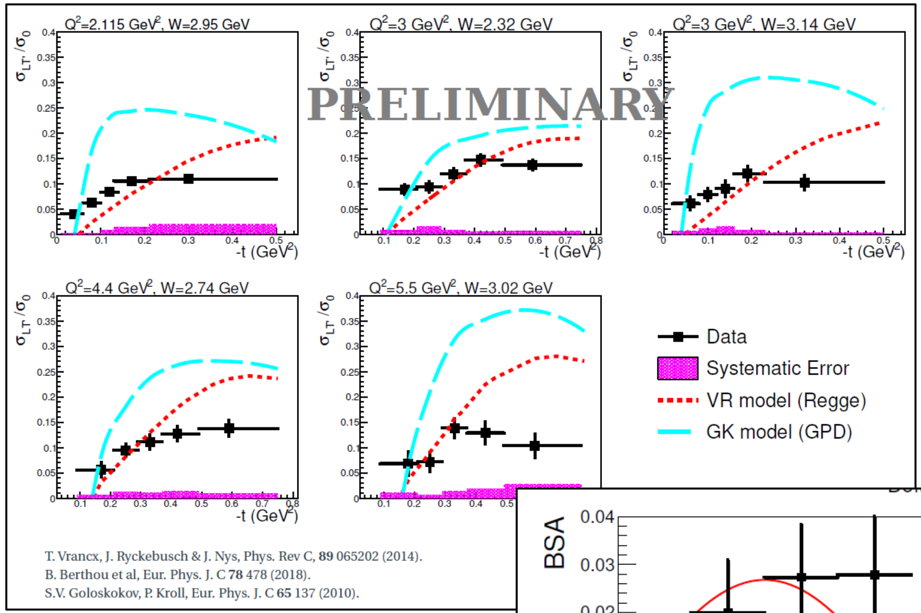
- ➢ L/T separated cross sections at fixed x=0.3, 0.4, 0.55 up to Q^2=8.5 GeV^2
- ➢ Pion form factor at Q^2 values up to 8.5 GeV^2
- ➢ Additional data from *KaonLT* experiment



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

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

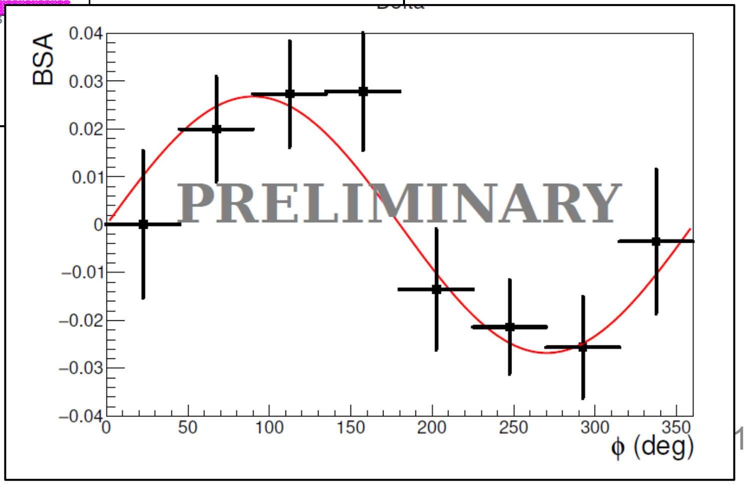
- ➢ Highest Q^2 for L/T separated kaon electroproduction cross section
- ➢ First separated kaon cross section measurement above W=2.2 GeV



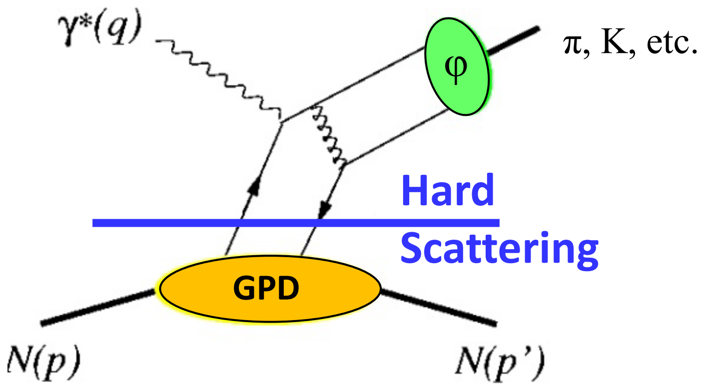
Spokespersons: Tanja Horn (CUA), Garth Huber (URegina), Pete Markowitz (FIU)

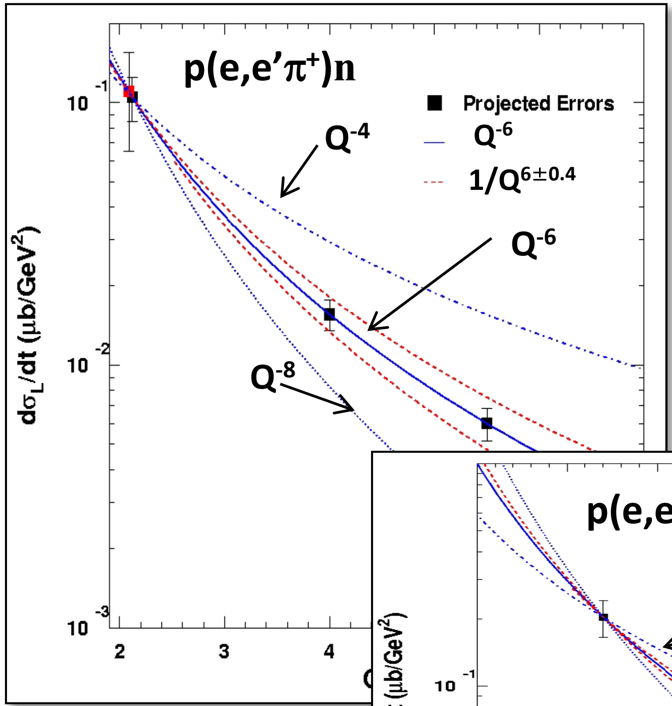
$$p(e, e'\pi^+)n/\Delta^0$$

- Preliminary results on beam single-spin asymmetries
- Next: LT separated cross sections (later in 2024)
- If warranted by data: kaon form factor extraction



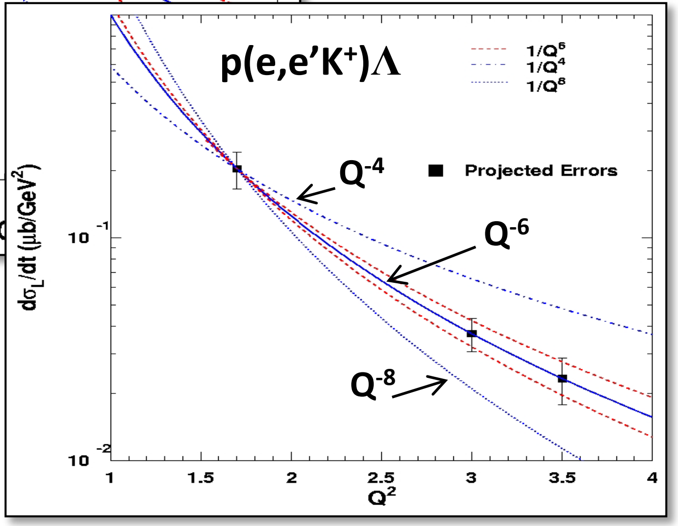
L/T Separated π^+/K^+ Cross Sections with 12 GeV JLab





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

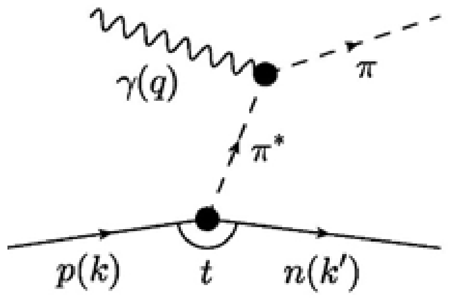
Fit: $1/Q^n$



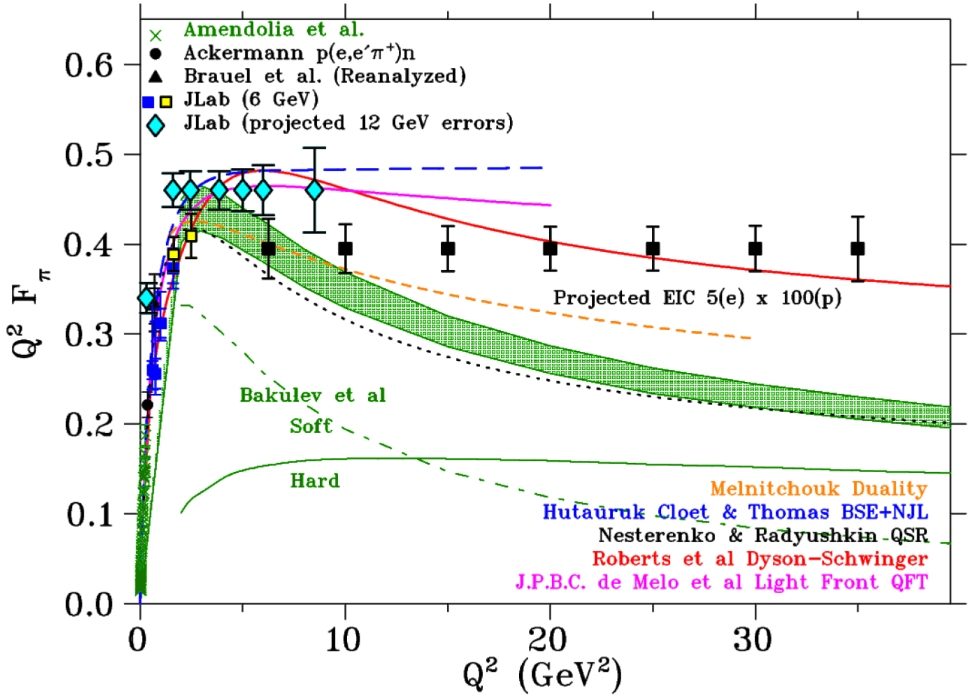
- One of the most stringent tests of the reaction mechanism is the Q^2 dependence of cross section
  - –σ_L scales to leading order as Q^{-6}
  - –σ_T does not
- Need to validate the reaction mechanism for reliable interpretation of the GPD program – key are precision longitudinal-transverse (L/T) separated 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

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



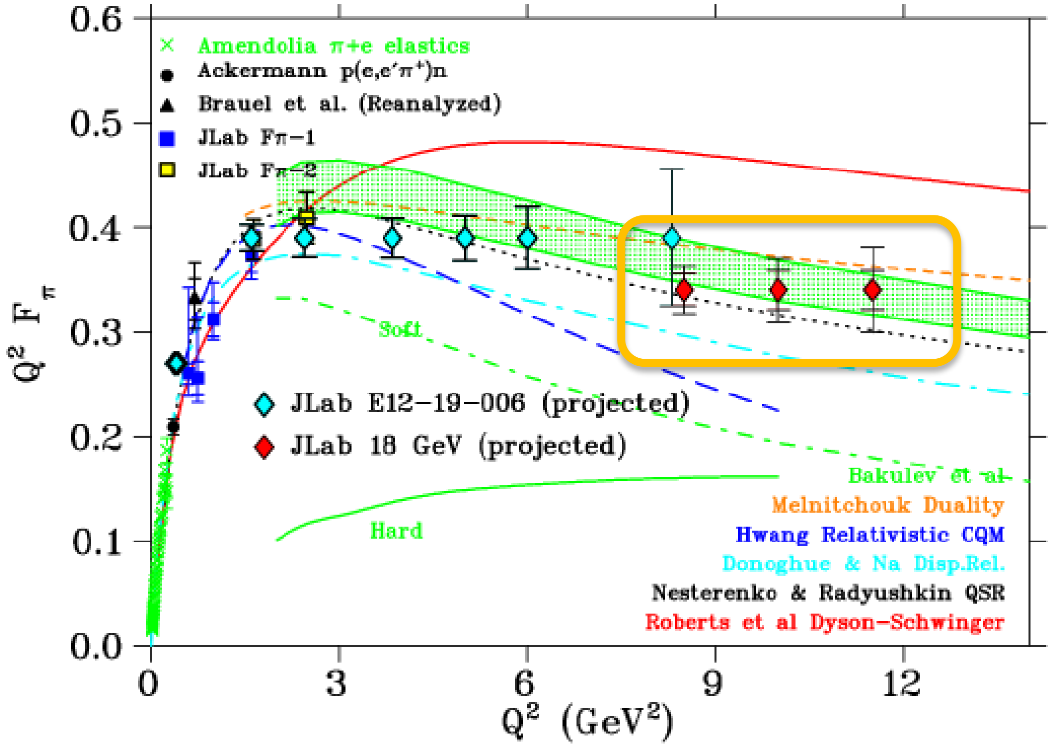
- ❑ Assumed 5 GeV(e^-) x 100 GeV(p) with an integrated luminosity of 20 fb^{-1}/year, and similar luminosities for d beam data
- ❑ R=σ_L/σ_T assumed from VR model and assume that π pole dominance at small t confirmed in ^{2}H π^-/π^+ ratios
- ❑ Assumed a 2.5% pt-pt and 12% scale systematic uncertainty, and a 100% systematic uncertainty in the model subtraction to isolate σ_L

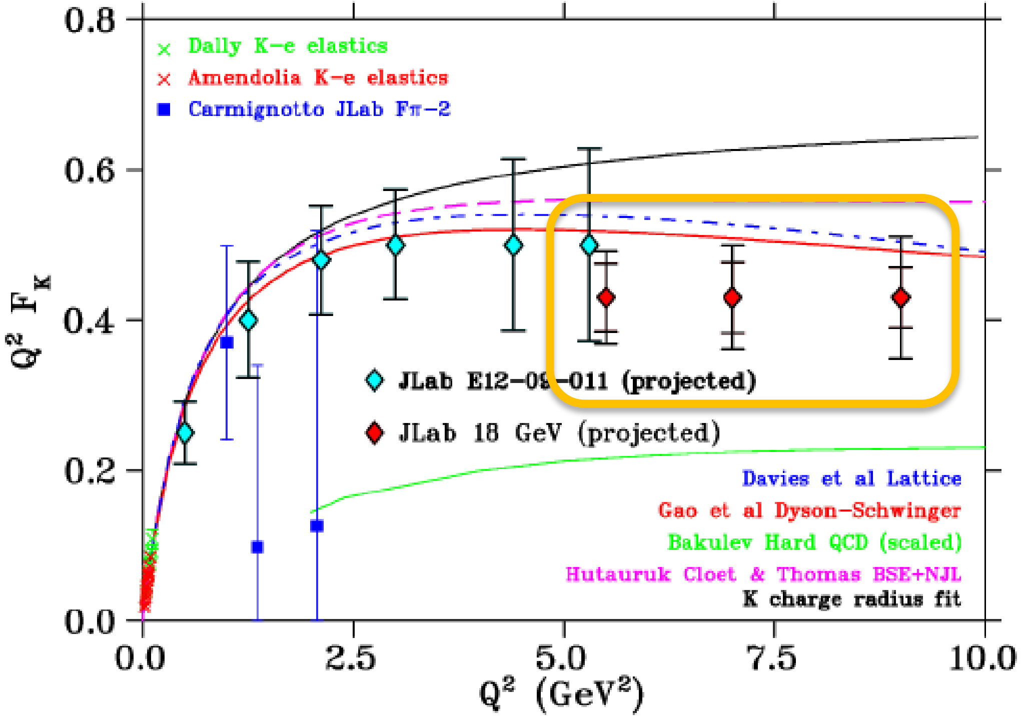
Can we measure the kaon form factor at EIC? Or only through L/T separations emphasizing lower energies? Not clear – needs guidance from JLab 12- GeV.

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)

Projections based on 50 days of beam time

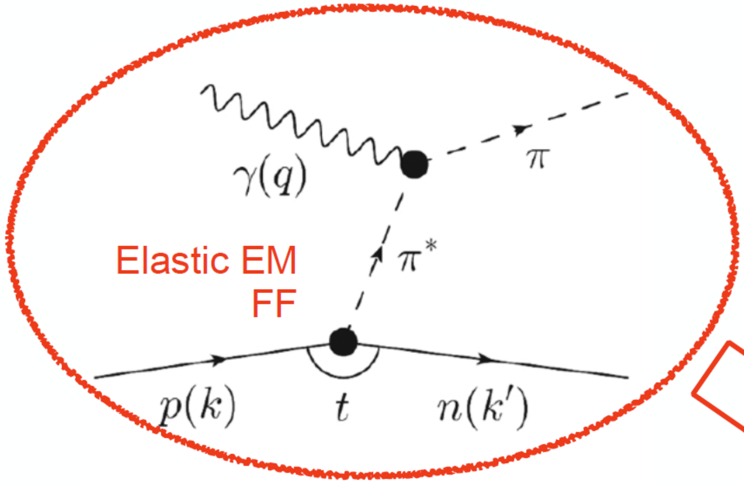


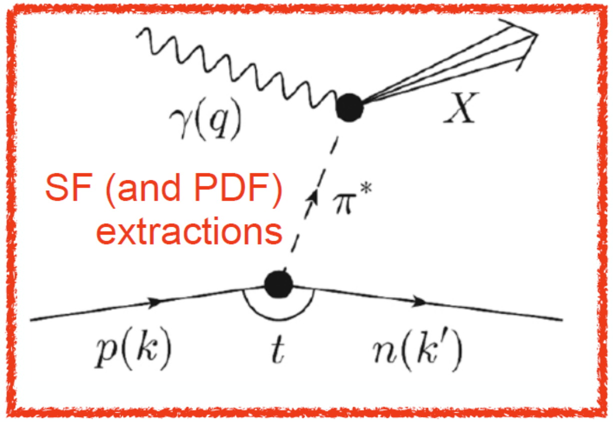


Accessing Pion/Kaon Structure Information

Sullivan

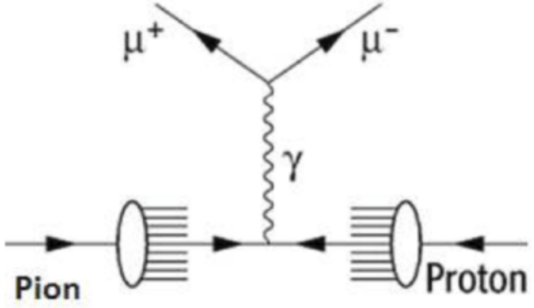
Hard scattering from virtual meson cloud of nucleon





Drell-Yan

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



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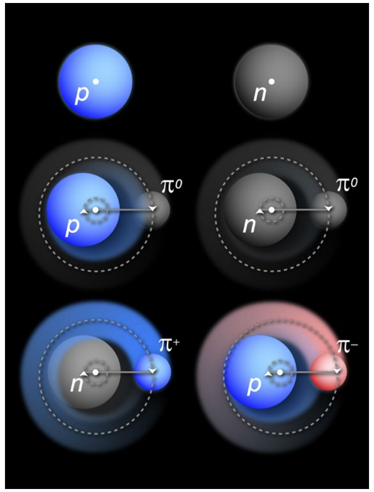
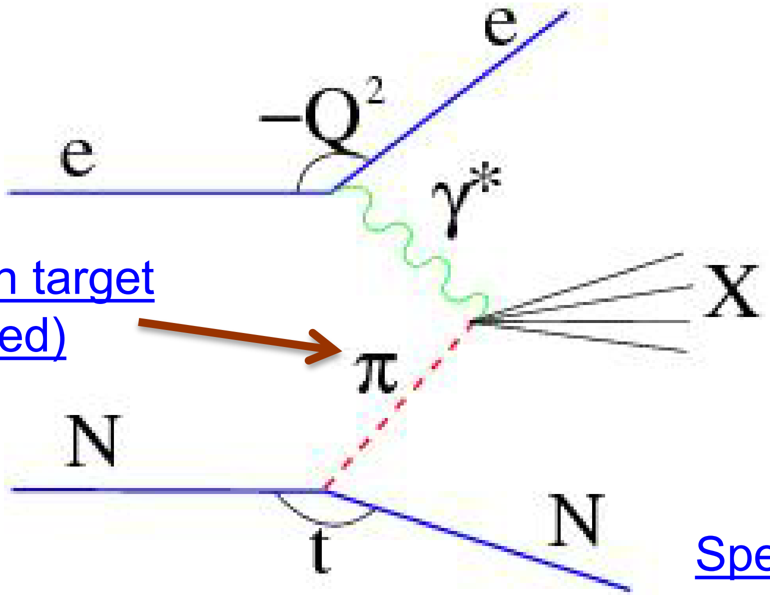
Physics Objects for Pion/Kaon Structure Studies



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

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

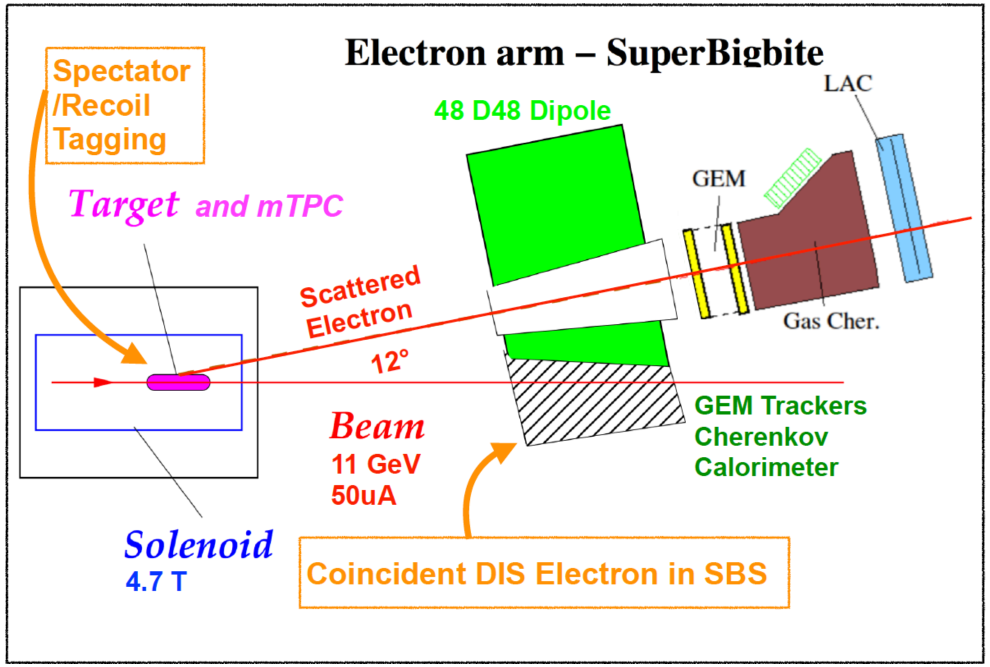
Tagged structure function
a direct measure of the mesonic content of nucleons

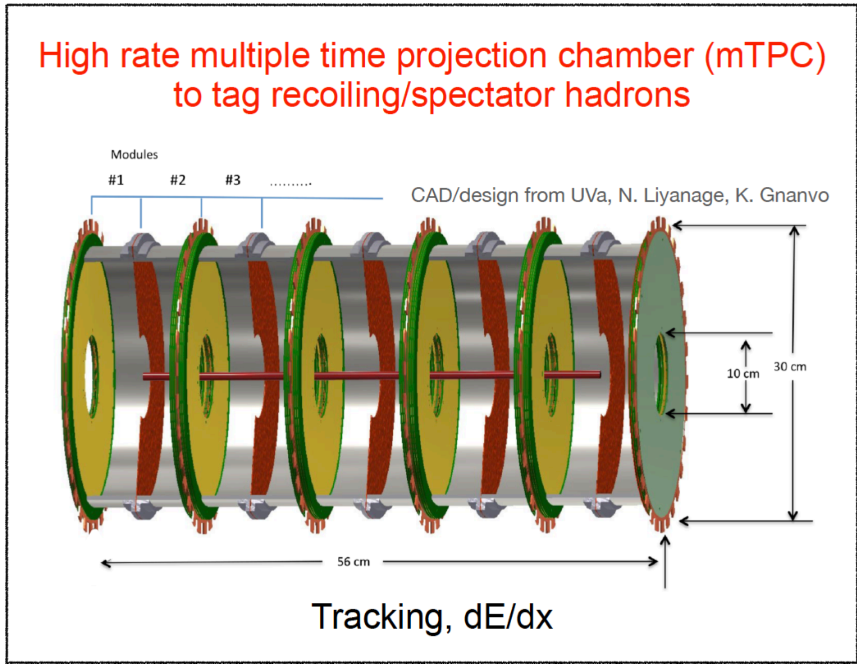
$$F_2^T(x,Q^2,z,t) = \frac{R^T}{\Delta z\Delta t}F_2^p(x,Q^2).$$

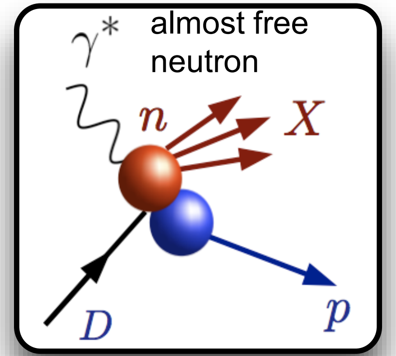
Tagged DIS can be used to tag the "meson cloud"

Spectator Tagging – well established technique at JLab

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







Deuteron Spectator proton (backward going slow proton)

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

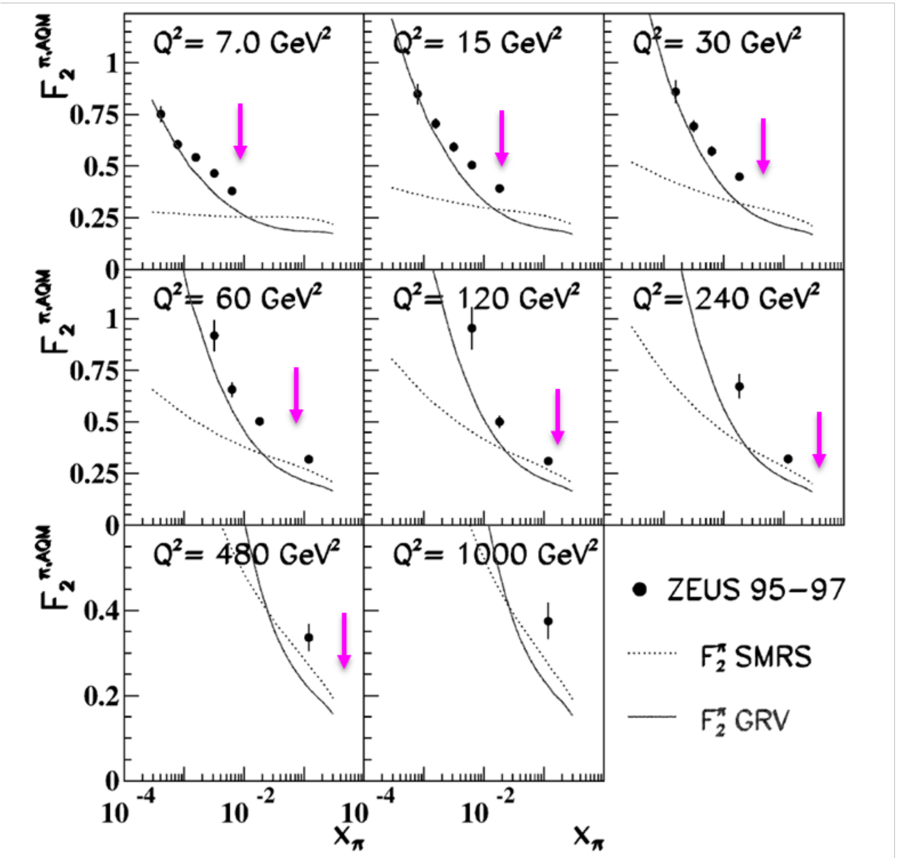
- TDIS will be a pioneering experiment that will be the first direct measure of the mesonic content of nucleons.
- The techniques used to extract meson structure function will be a necessary first step for future experiments

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

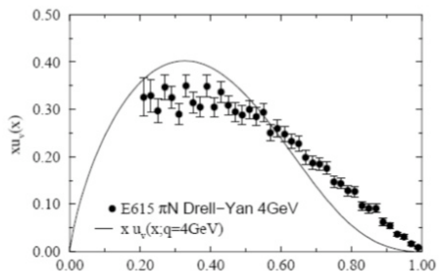


EIC kinematic reach down to a x = few 10^{-3}
Lowest x constrained by HERA
DESY 08-176 JHEP06 (2009) 74

DY: Large x Structure of the Pion

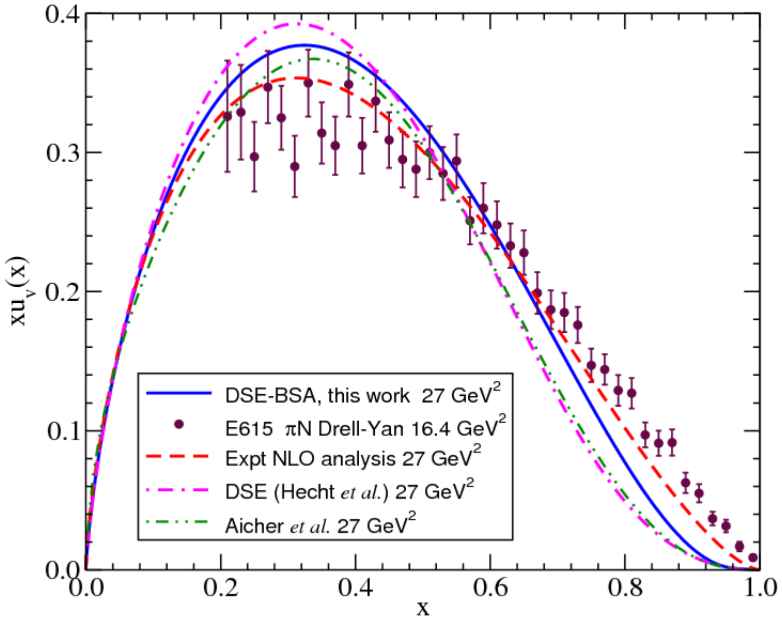
Initial observations:

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



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

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



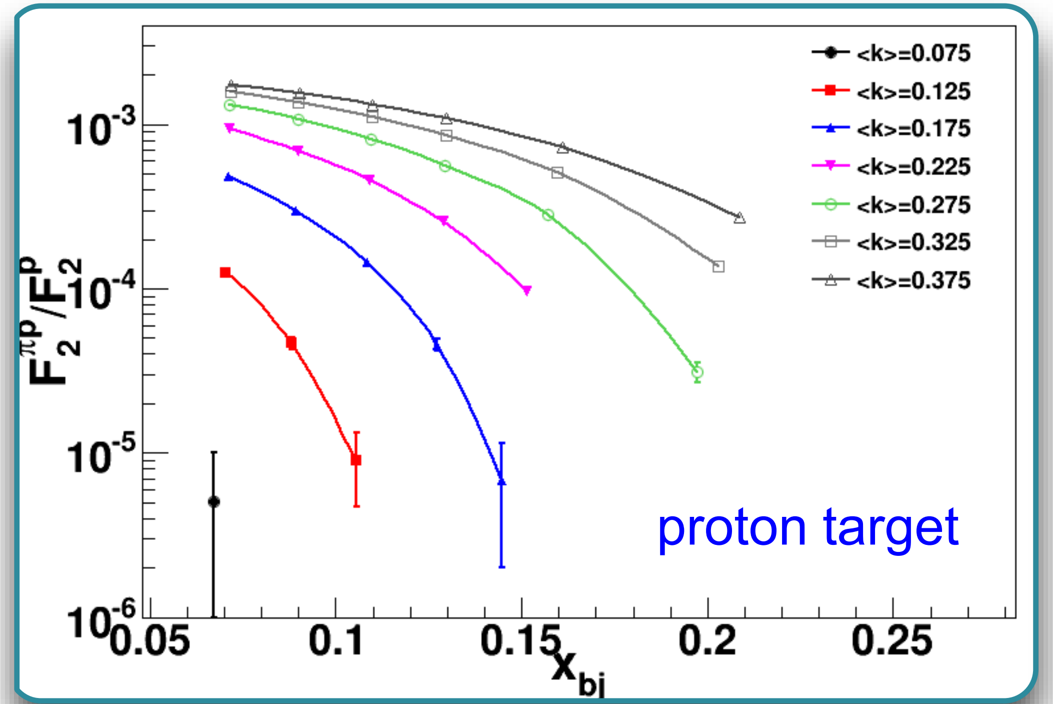
[C.D. Roberts, IRMA Lect. Math. Theor. Phys. 21 (2015) 355; arXiv:1203.5341 (2012)]

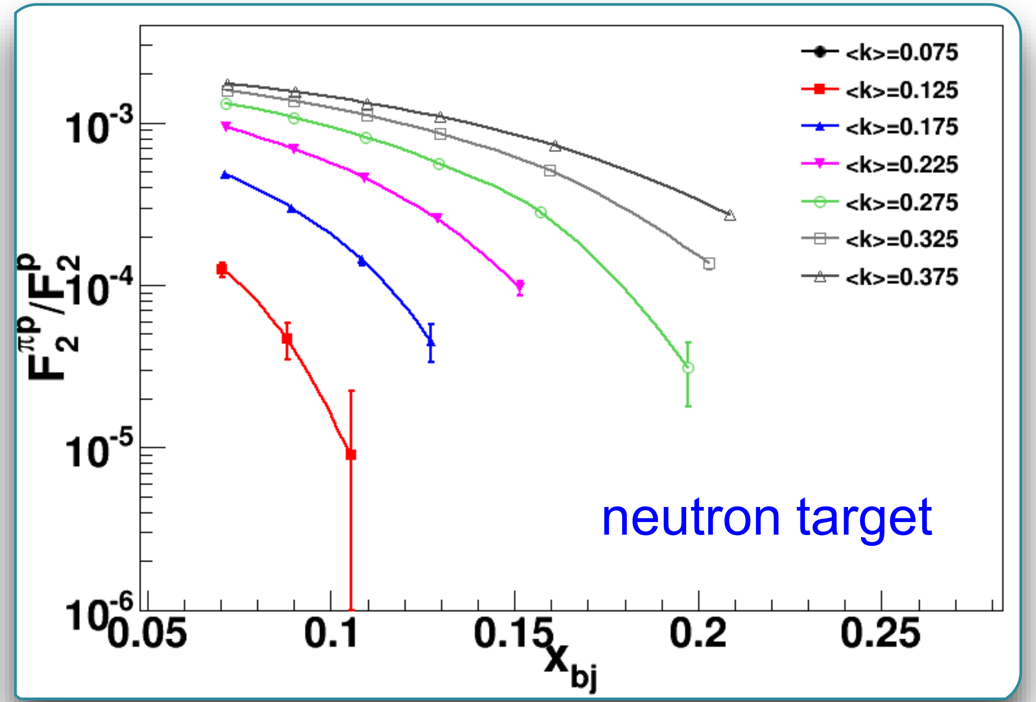
- ❑ Model tensions, pQCD, Dyson-Schwinger, Light Front, Instanton,…
- ❑ NLO gluon resummation effects

[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

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

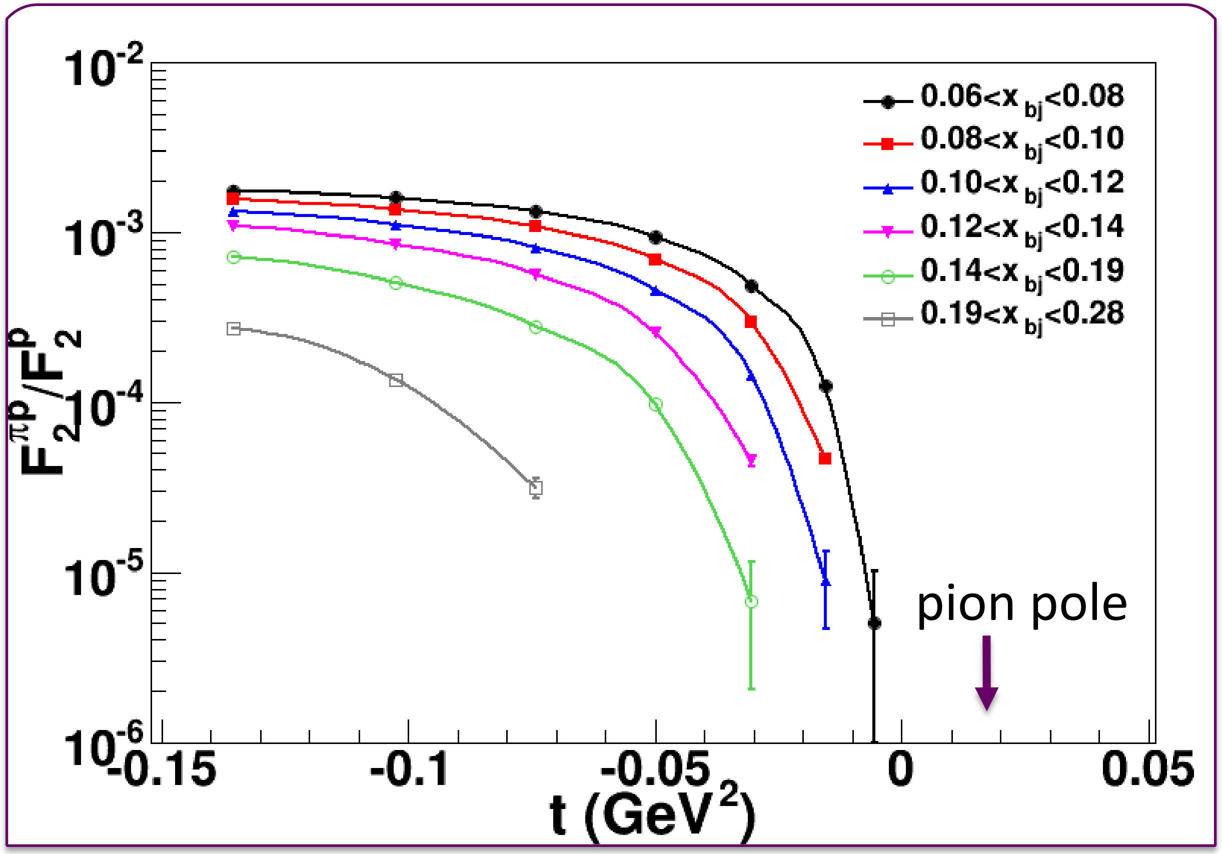
some kinematic limits:

- 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|

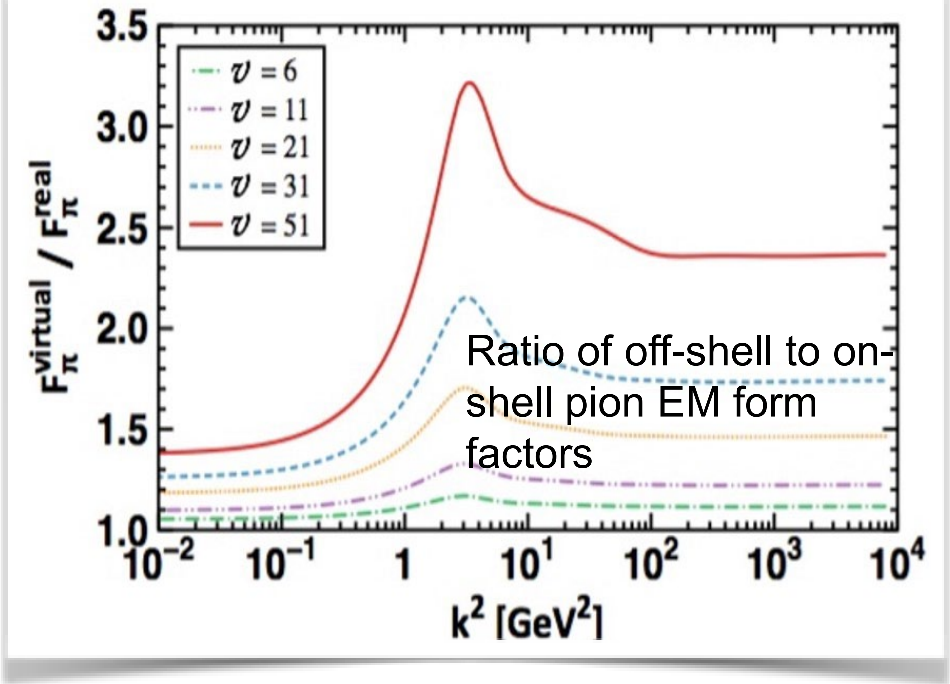


virtuality-independent form factor implies virtuality-independent pion structure function

virtuality ν = 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

TDIS in Hall A with SBS:

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

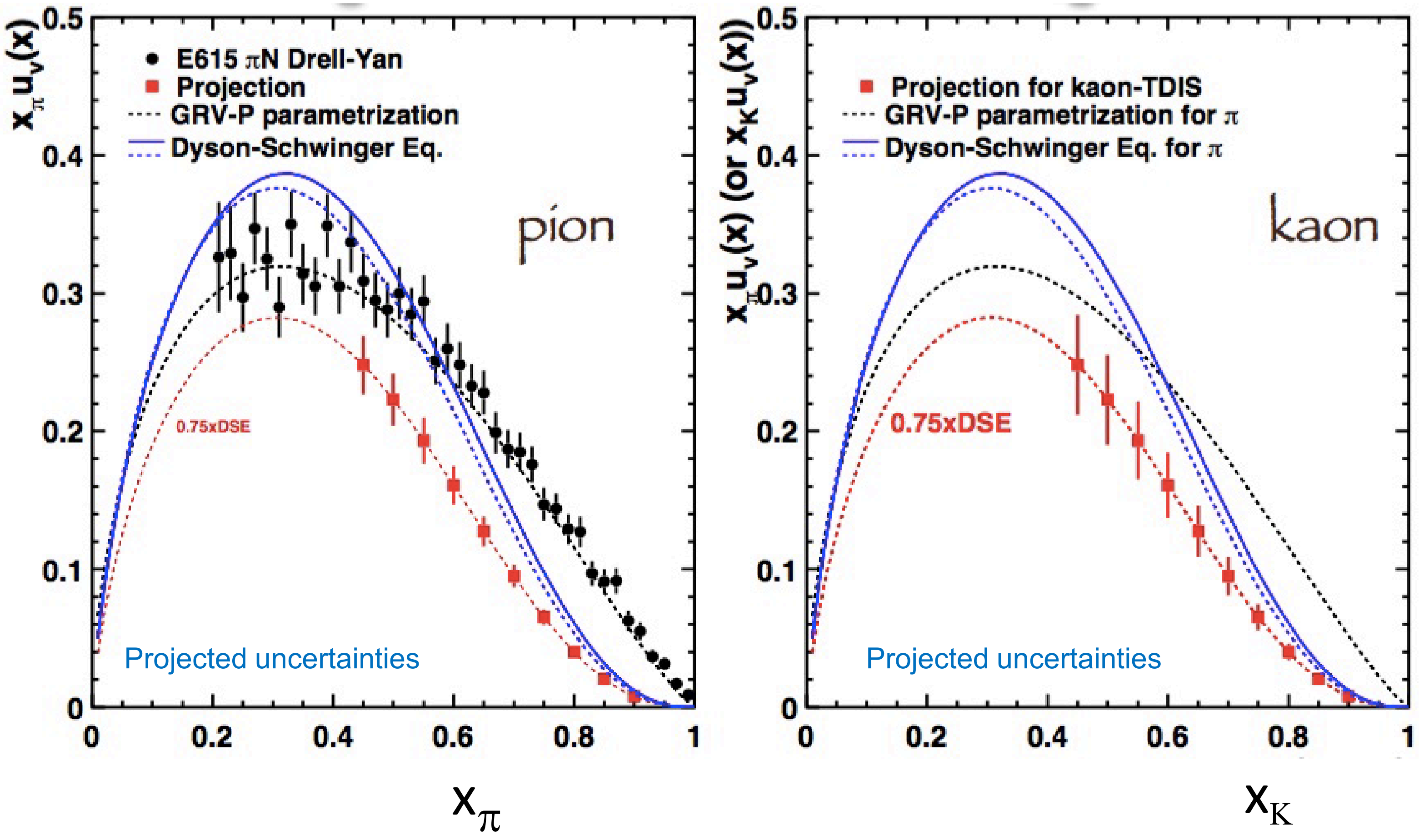
✓Large acceptance
~70 msr

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

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

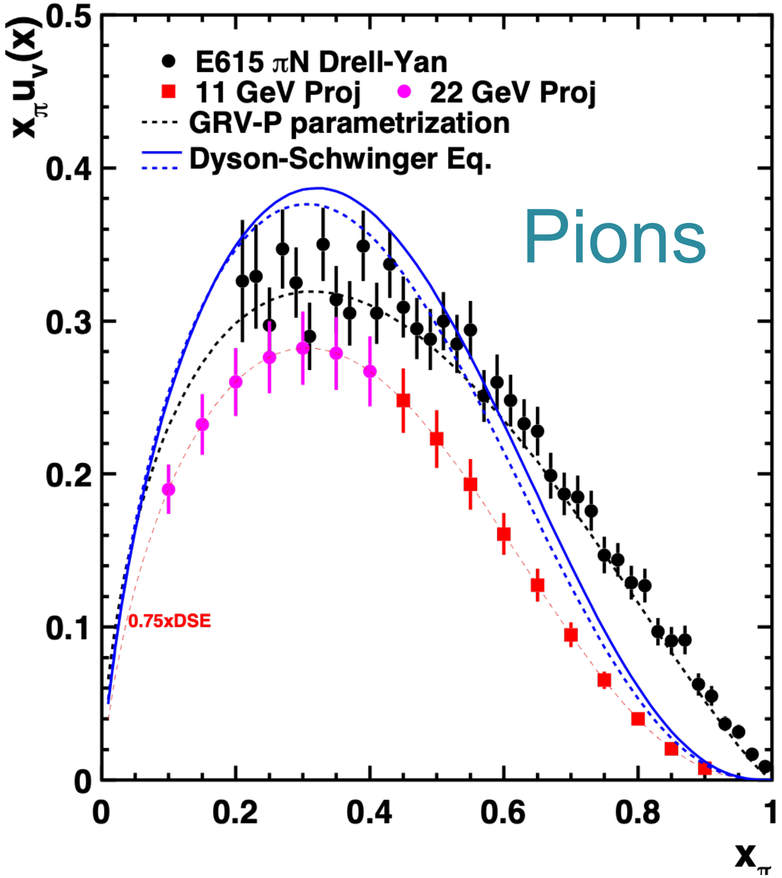


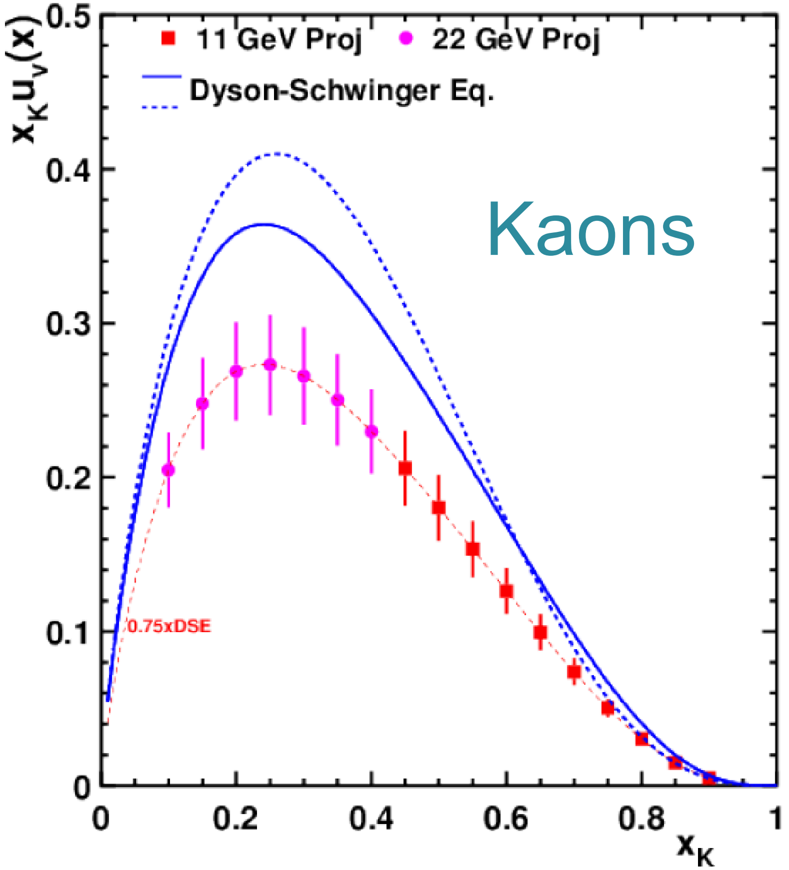
Essentially no kaon data currently

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

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)





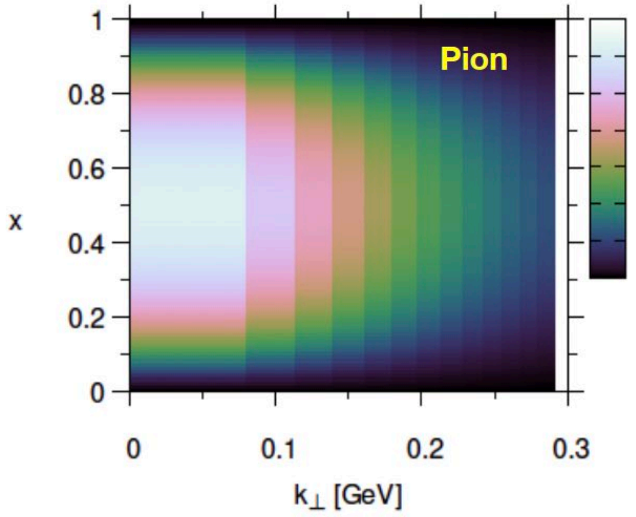
Adding a new constraint in the kinematics enables the study of π resonances

- 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

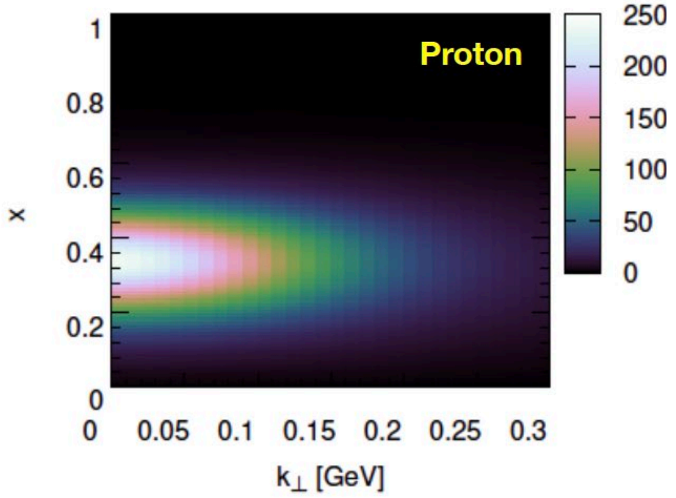
JLab 22 GeV: Opportunities for TDIS π, K Structure

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)

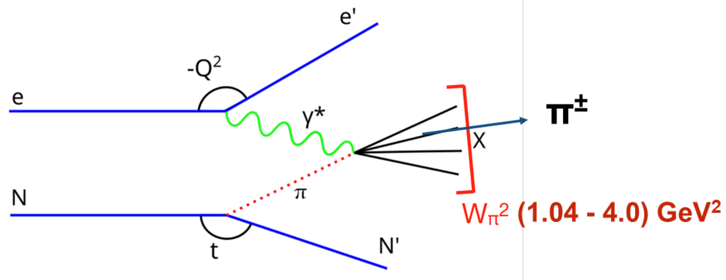
PRD 105, L071505 (2022); PRD 104, 114012 (2021) E. Ydrefore & T. Frederico

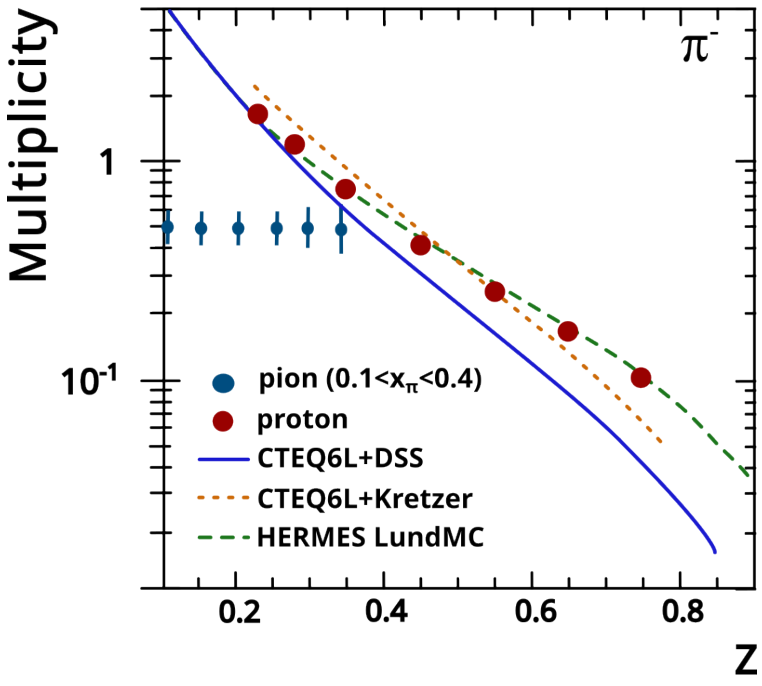


Pion TMDs from
Bethe-Saltpeter equation



Proton TMDs from
Light-Front Model



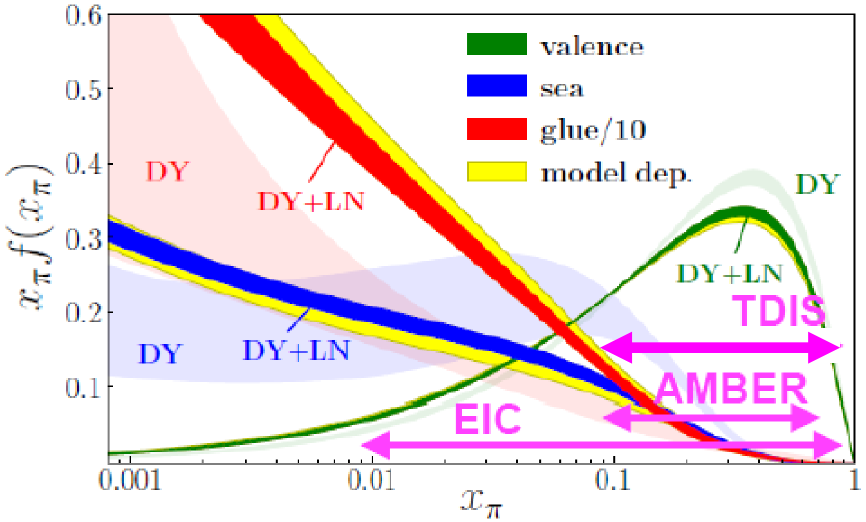


Significant x-broadening of Pion TMDs compared to proton TMDs

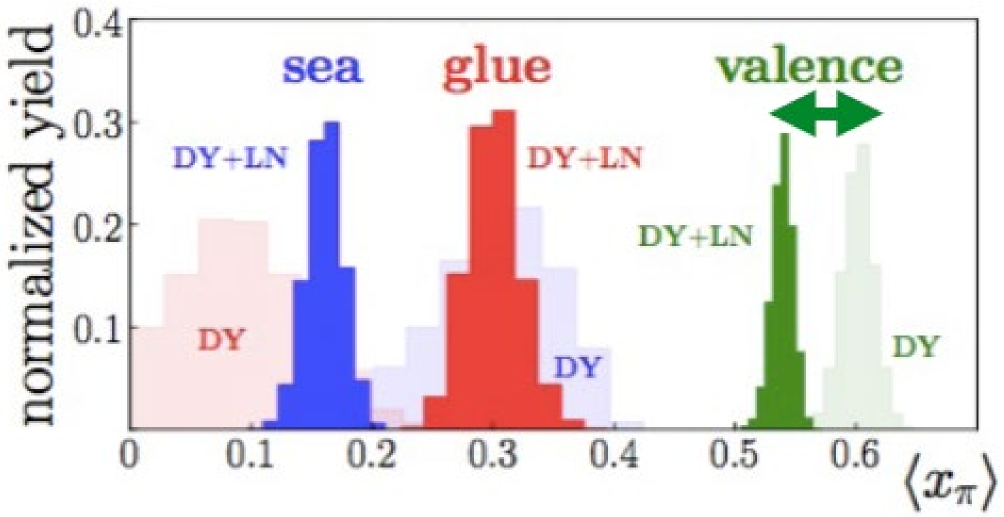
- ❑ TDIS with 22 GeV beam also enables access to TMDs
- ❑ Measurement of SIDIS from a pion target – requires additional instrumentation for detection of an additional pion (ongoing effort)

Global PDF Fits and Demand for more Data

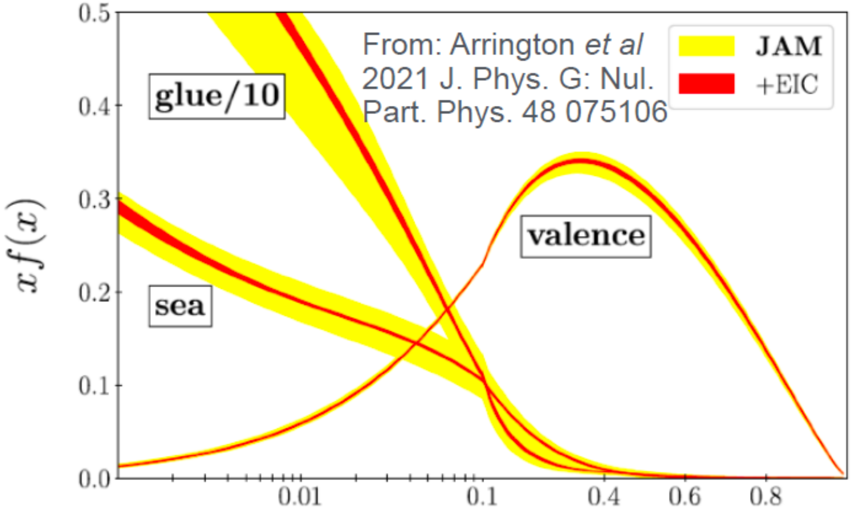
- ❑ Combined Leading Neutron/Drell-Yan analysis for PDF fitting, with novel MC techniques for uncertainties (JLab JAM)
- ❑ Non-overlapping uncertainties – tension at large x



Mom. Fraction carried by sea/glue/valence



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

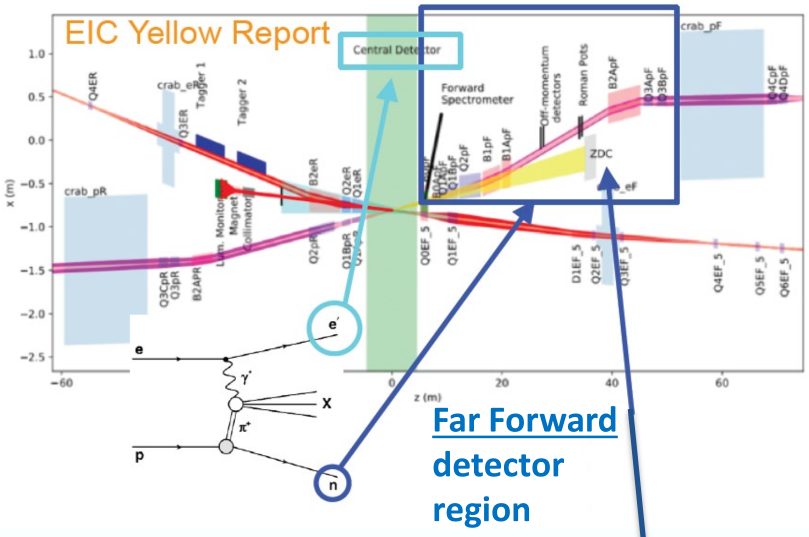


- ❑ Yet, different basis light front quantization (BFLQ) technique finds agreement in PDF evolution between DY and DIS

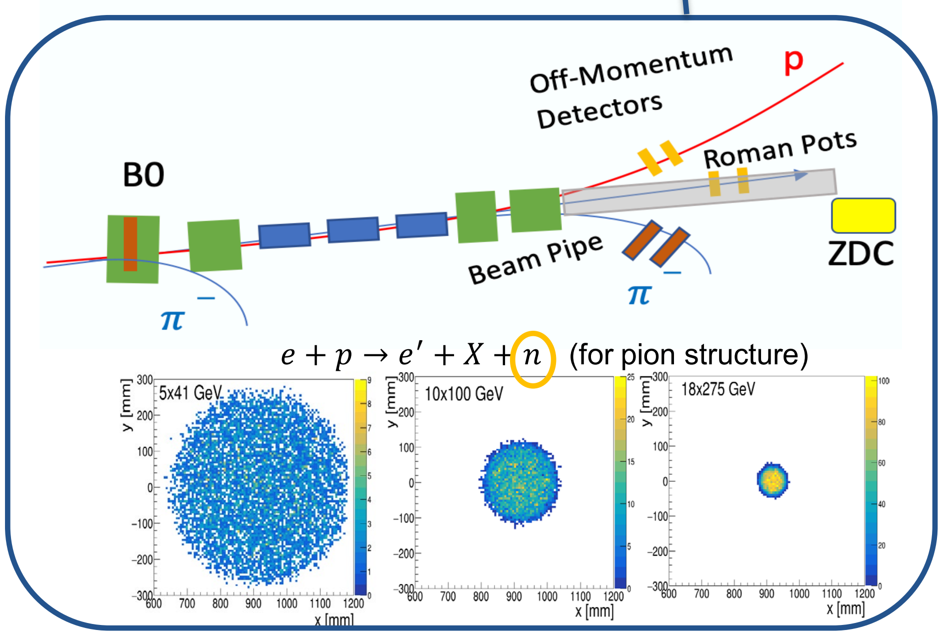
  J. Lan, C. Mondal, S. Jia, X. Zhao, J.P. Vary, arXiv:1907.01509 (2019)
  - ➢ More data needed
- ❑ **Excellent opportunity for more data with EIC**
  - ➢ Kinematic bridge between HERA and high-x with wide coverage in x

EIC and Sullivan Process SF Measurements

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

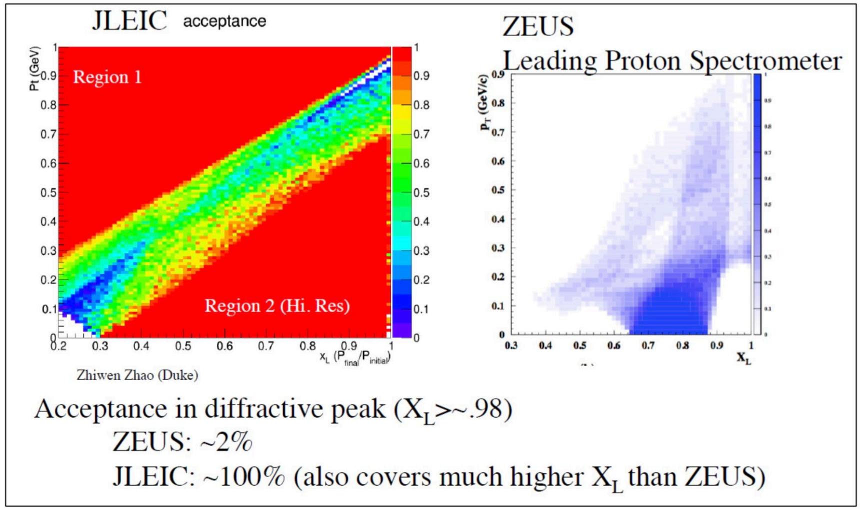


- EIC design well suited for HERA-style pion/kaon SF measurements
- Scattered electron detected in the central detector
- Leading hadrons → large fraction of initial beam energy → far forward detector region
  - ZDC particularly important (reaction kinematics and 4 momenta)

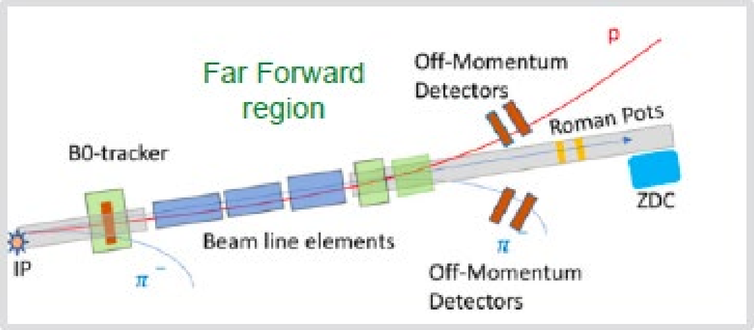


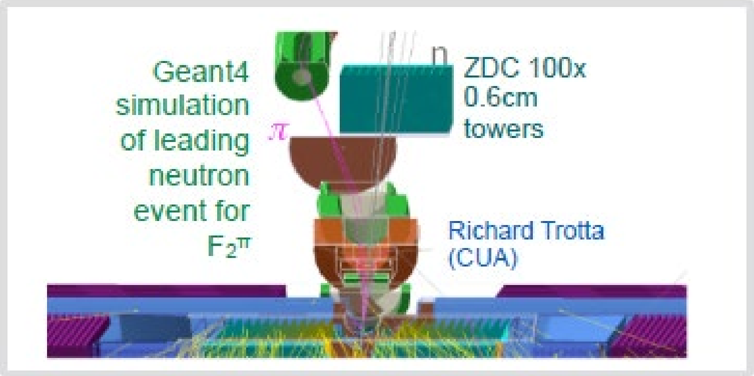
Huge gain in acceptance for forward tagging….

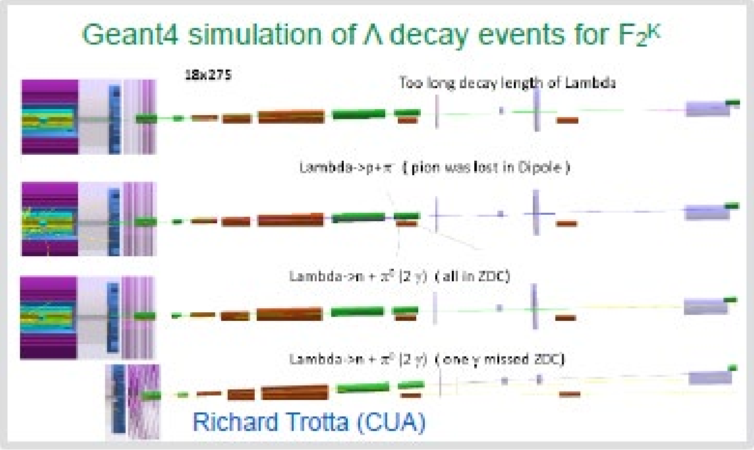
Example: acceptance for p' in e + p → e' + p' + X

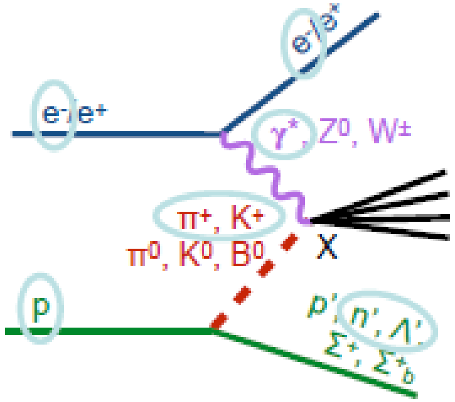


EIC Pion/Kaon SF Measurements









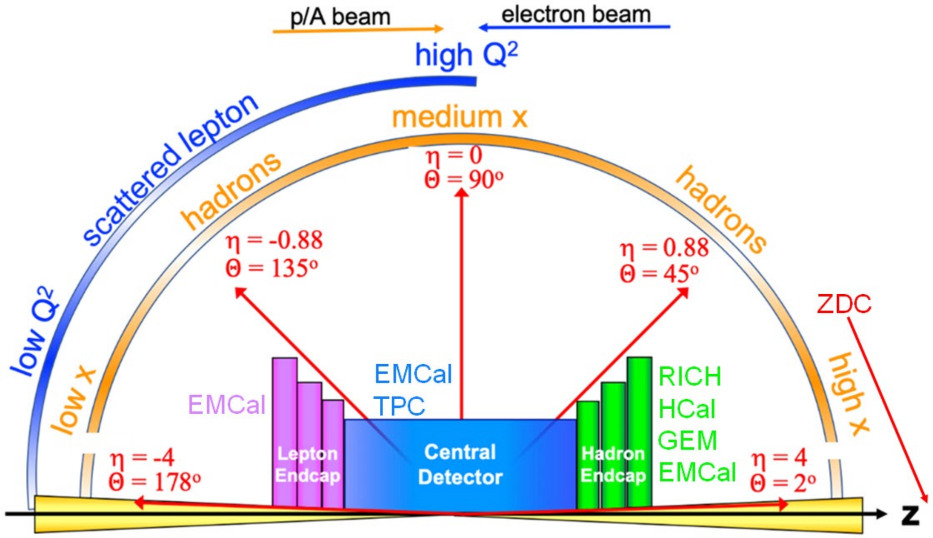
- ❑ Custom fast MC event generator (R. Trotta, CUA) and G4 for detector acceptance/response
- ❑ Focus so far: ep and measuring cross section at small-t for
  - ○ F_2^{π} (π^+) tagged by n
  - ○ F_2^{K} (K^+) tagged by Λ^0 decay
- ❑ Settings e x p(GeV): 5x41, 5x100, 10x100, 10x135, 18x275

Detector requirements:

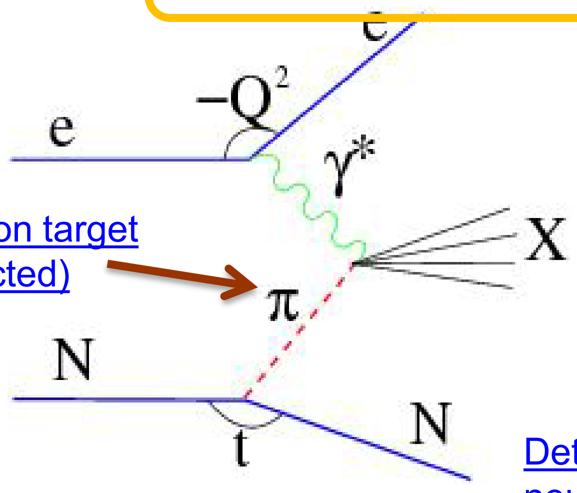
- ○ **For π-n:**
  - ➢ Lower energies (5 on 41, 5 on 100) require at least 60 x 60 cm^2
  - ➢ For all energies, the neutron detection efficiency is 100% with the planned ZDC
- ○ **For π-n and K^+/Λ:**
  - ➢ All energies need good ZDC angular resolution for the required -t resolution
  - ➢ High energies (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 Detector and SF Measurements

Scattered Electron



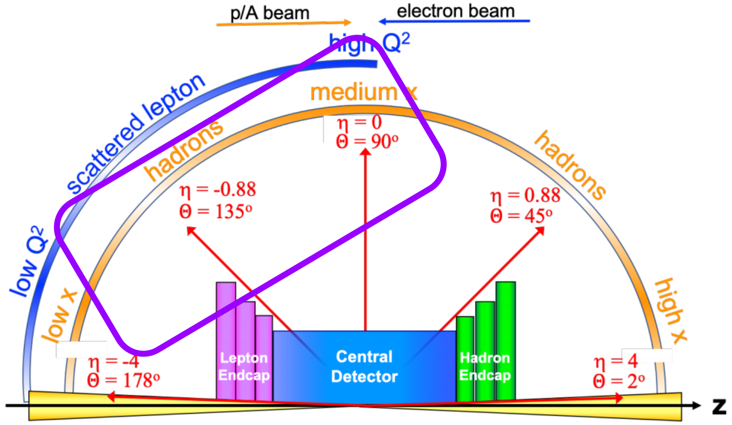
Detect scattered electron

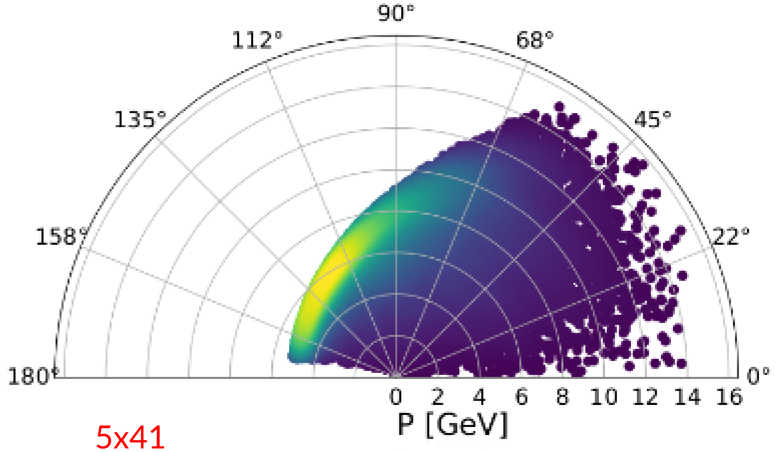


DIS event – reconstruct x, Q^2, W^2, also M_X (W_π) of undetected recoiling hadronic system

Pion/Kaon target (undetected)

Detect "tagged" neutron/lambda

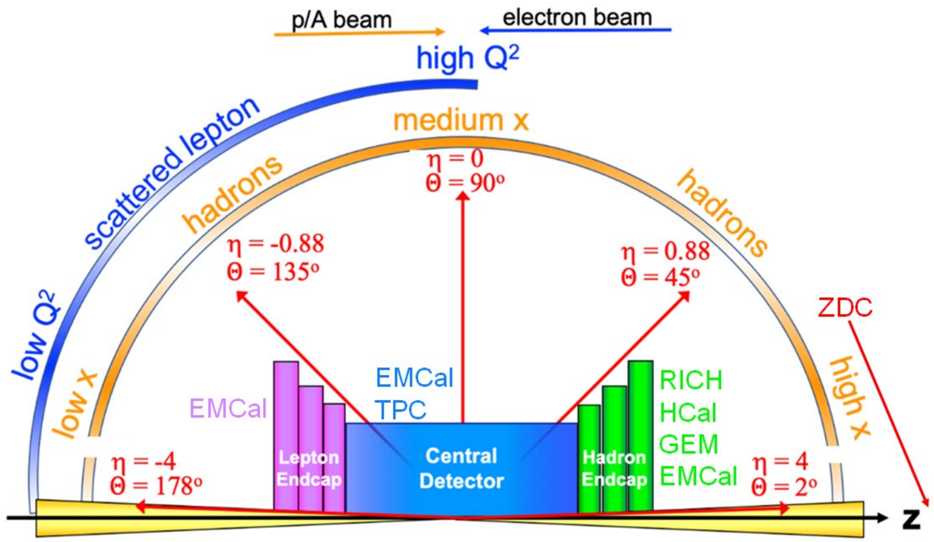




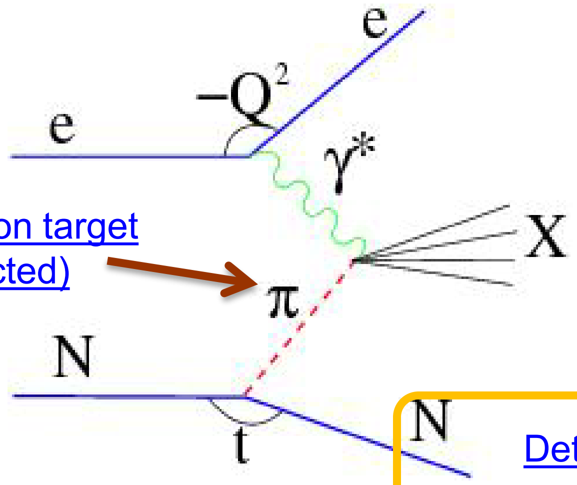
5x41

EIC Detector and SF Measurements

Leading Baryon



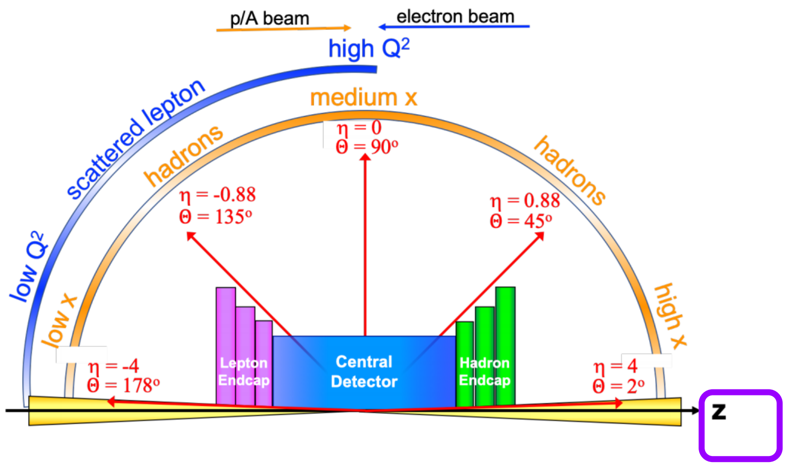
Detect scattered electron



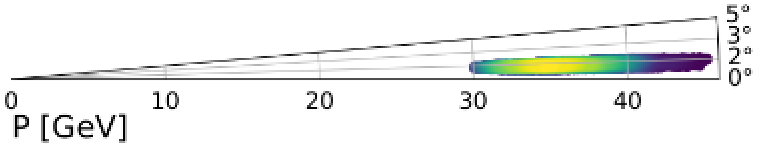
DIS event – reconstruct x, Q^2, W^2, also M_X (W_π) of undetected recoiling hadronic system

Pion/Kaon target (undetected)

Detect "tagged" neutron/lambda

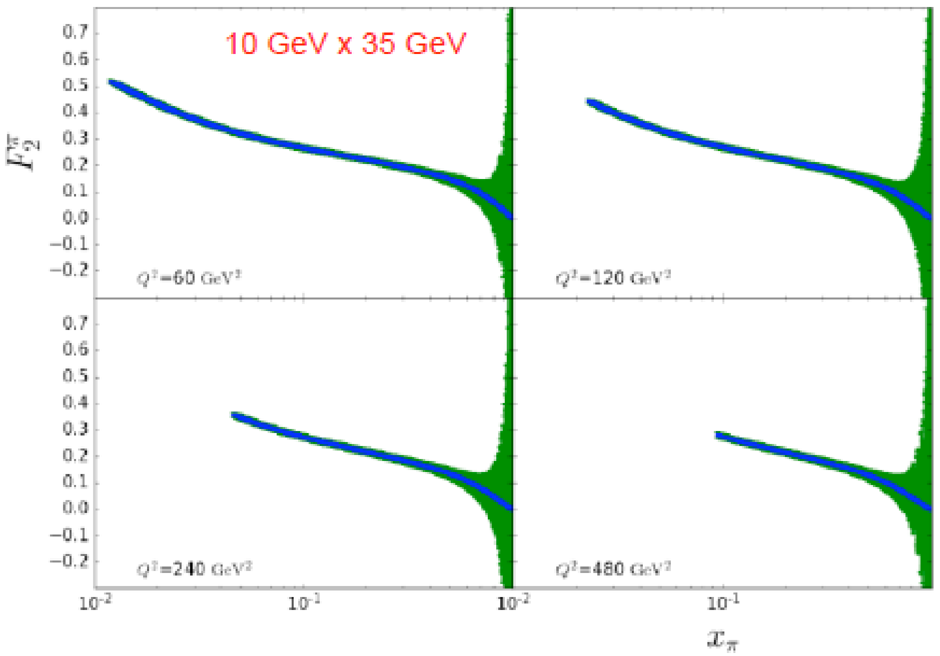


Baryon (neutron lambda) at very small forward angles and nearly the beam momentum



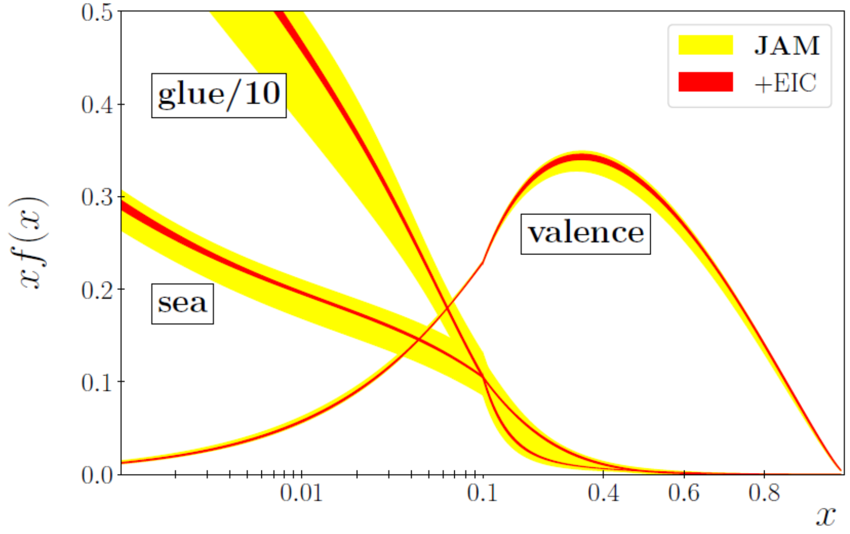
5x41

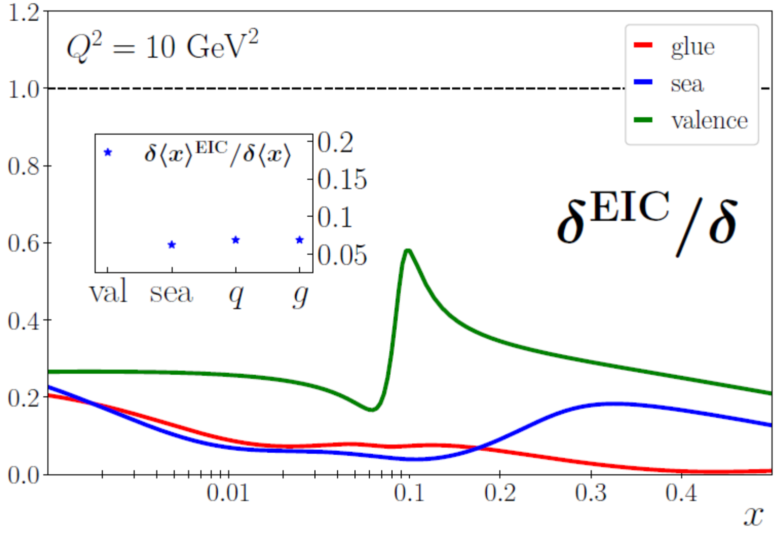
EIC Pion SF Projections



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



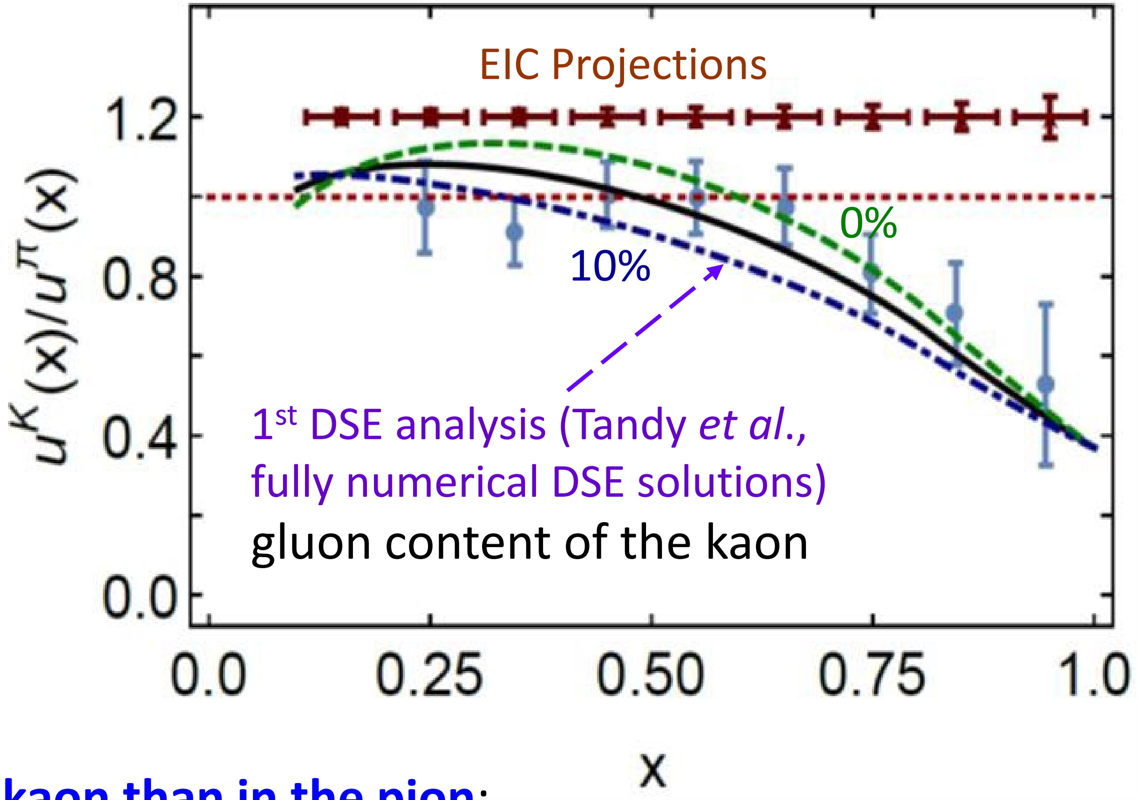


Kaon structure functions – gluon pdfs

Based on Lattice QCD calculations and DSE calculations:

- ➢ Valence quarks carry 52% of the pion's momentum at the light front, at the scale used for Lattice QCD calculations, or ~65% at the perturbative hadronic scale
- ➢ At the same scale, valence-quarks carry ⅔ of the kaon's light-front momentum, or roughly 95% at the perturbative hadronic scale

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



Thus, at a given scale, there is far **less glue in the kaon than in the pion**:

- ❑ heavier quarks radiate less readily than lighter quarks
- ❑ heavier quarks radiate softer gluons than do lighter quarks
- ❑ Landau-Pomeranchuk effect: softer gluons have longer wavelength and multiple scatterings are suppressed by interference.
- ❑ Momentum conservation communicates these effects to the kaon's u-quark.

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 $e + p \to e' + X + n$ (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 $e + p \to e' + X + \Lambda/\Sigma^0$ (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 $(\text{GeV}/c)^2$.	• Need to uniquely determine exclusive process $e + p \to e' + \pi^+ + n$ (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 $(\text{GeV}/c)^2$.	• Need to uniquely determine exclusive process $e + p \to e' + K + \Lambda$ (low $-t$) • L/T separation at CM energy ~10-20 GeV • 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 behavior?	Behavior 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

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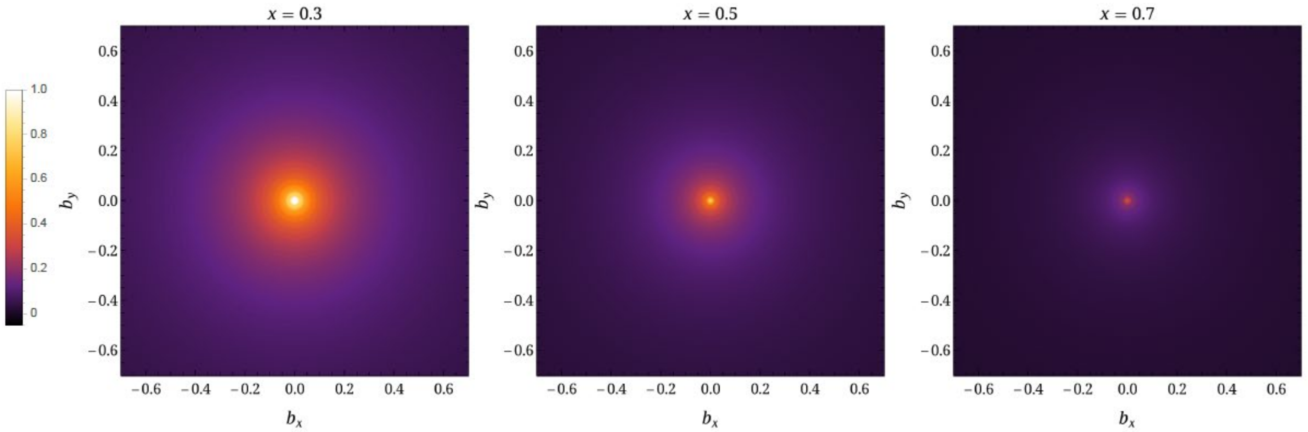
EIC Meson Structure Functions – further observables

Science Question	Key Measurement[1]	Key Requirements[2]



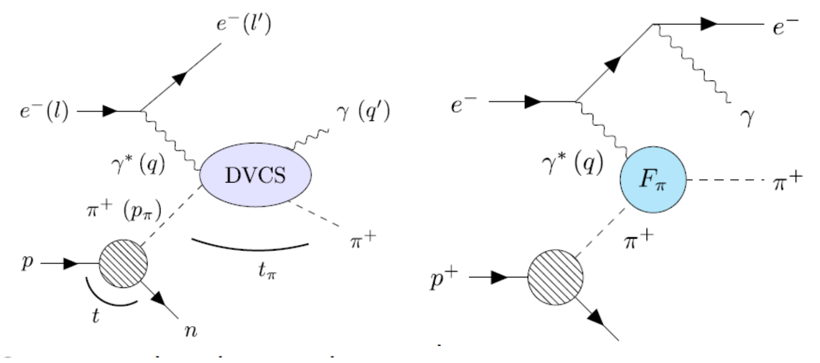
Can we even do SIDIS or DES off meson target?

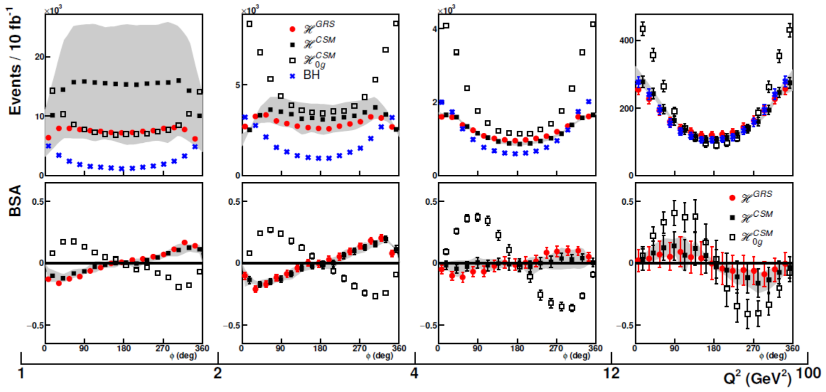
More speculative observables		
What is the trace anomaly contribution to the pion mass?	Elastic J/Ψ production at low W off the pion.	• Need to uniquely determine exclusive process $e+p \to e' + J/\Psi + \pi^+ + n$ (low $-t$) • High luminosity (10^{34+} cm^{-2} sec^{-1}) • CM energy ∼70 GeV
Can we obtain 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 $e+p \to e' + \gamma + \pi^+ + n$ (low $-t$) • High luminosity (10^{34+} cm^{-2} sec^{-1}) • 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 SIDIS off pion $e+p \to e' + h + X + n$ (low $-t$) • High luminosity (10^{34}cm^{-2} sec^{-1}) • $e+p$ 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

Science Question	Key Measurement[1]	Key Requirements[2]





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

More speculative observables		
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 $e+p \to e' + J/\Psi + \pi^+ + n$ (low $-t$) • High luminosity (10^{34+}cm^{-2} sec^{-1}) • CM energy $\sim$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 $e+p \to e' + \gamma + \pi^+ + n$ (low $-t$) • High luminosity (10^{34+}cm^{-2} sec^{-1}) • CM energy $\sim$10-100 GeV
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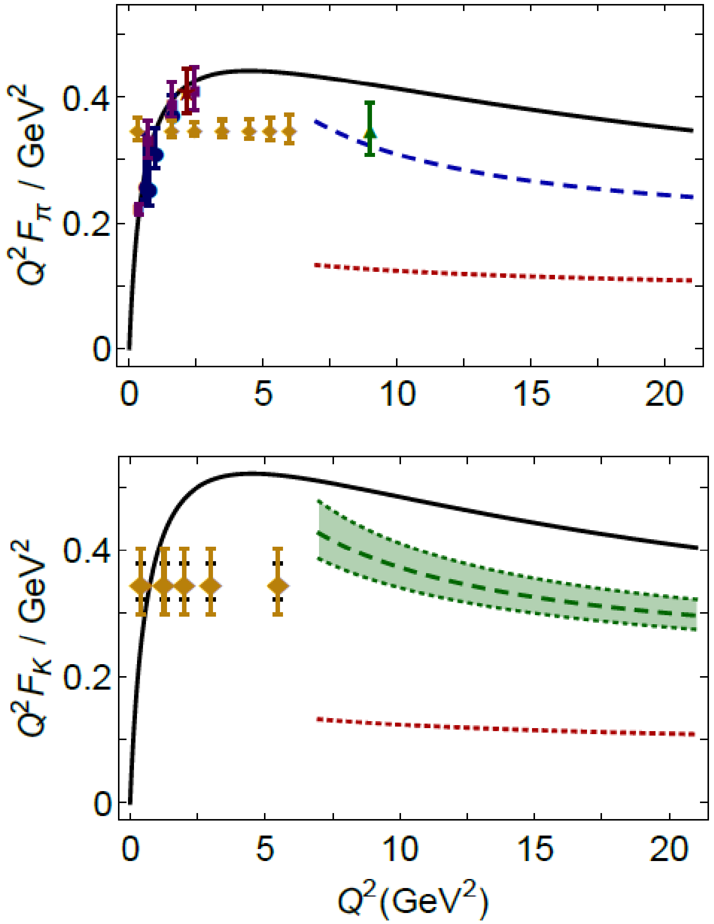
J. Arrington et al., J.Phys.G 48 (2021) 7, 075106

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
- A coherent effort is required among theory, phenomenology, computing, and experiment to complete our understanding of light meson structure
- 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/Q2 langscape for pion/kaon SF; Potential to provide definite answers on different gluon distributions in pion/kaon
- 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

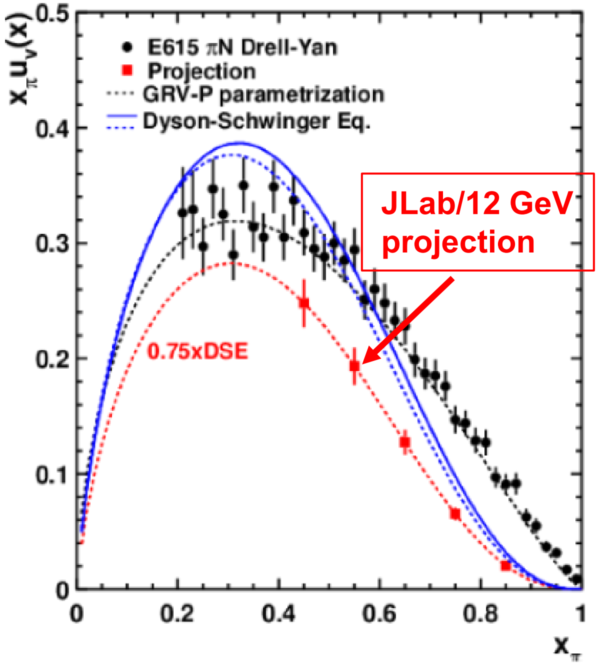
Summary Pion and Kaon Structure at 12 GeV and beyond

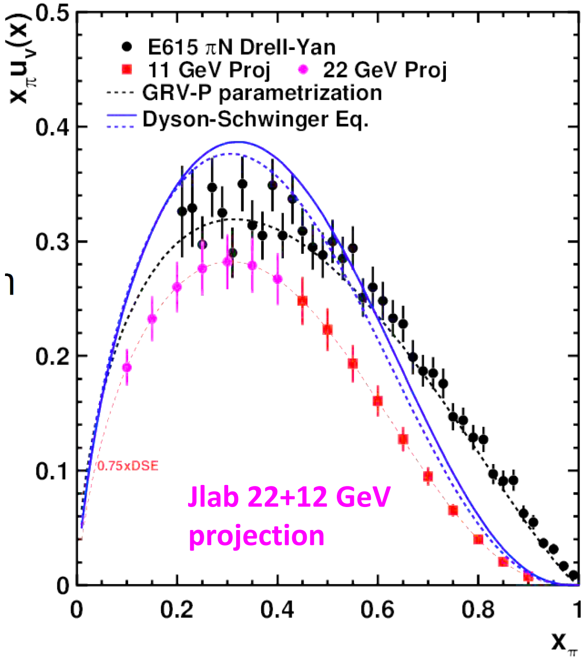
Jefferson Lab will provide, at its CM energy of 5 GeV, tantalizing data for the pion (kaon) form factor up to Q^2 ~ 10 (5) GeV^2, and measurements of the pion (kaon) structure functions at large-x (> 0.5) through the Sullivan process.



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

PR12-15-006



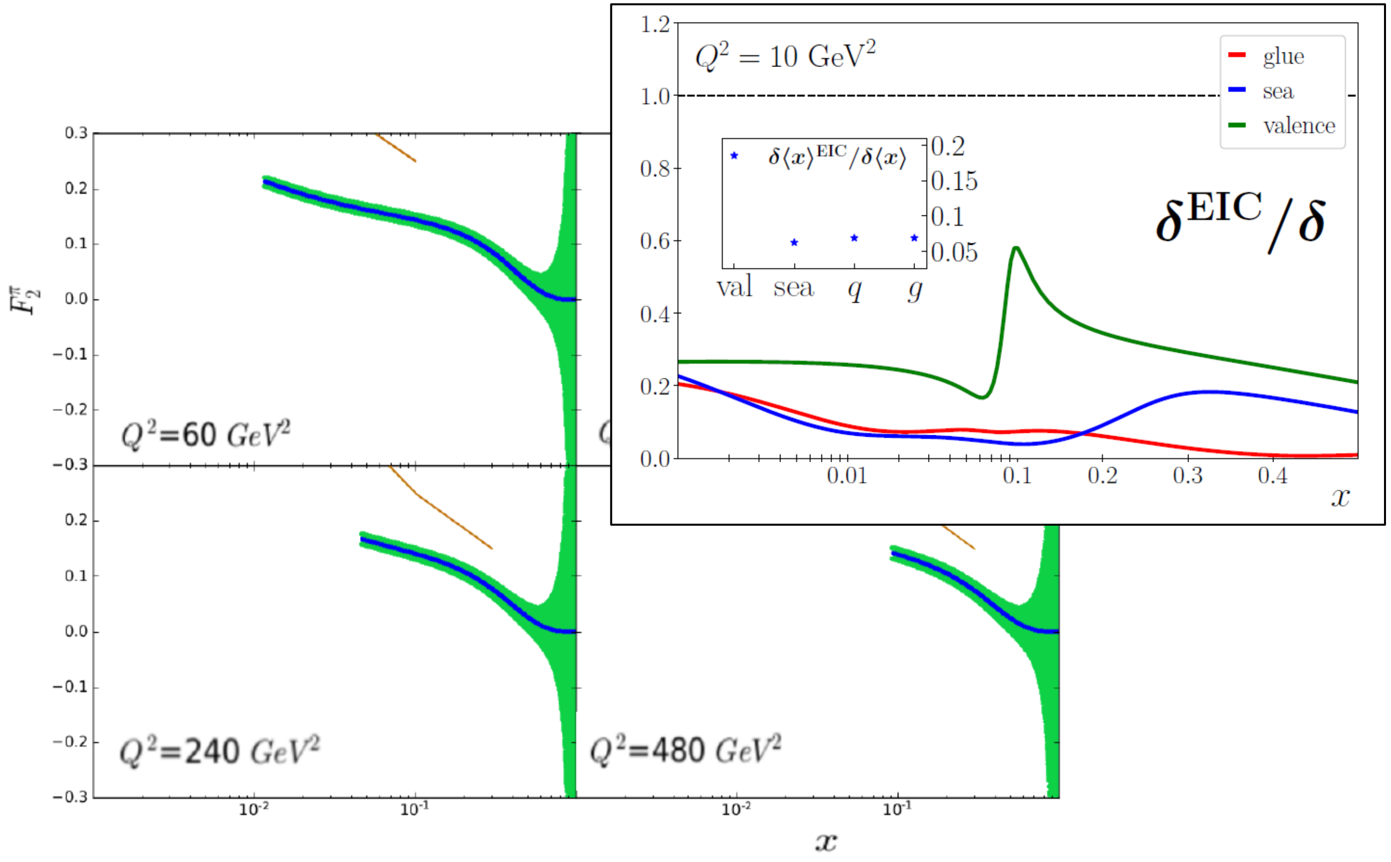


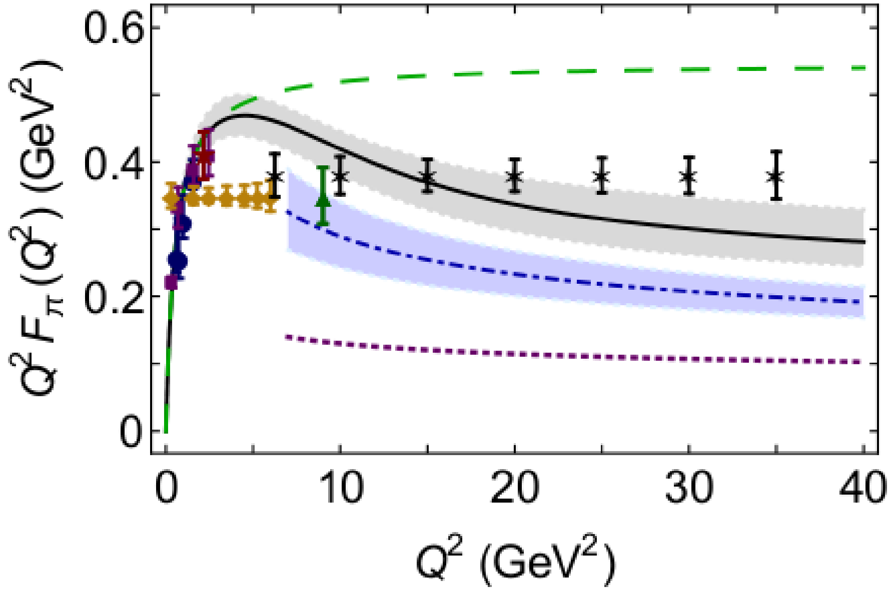
Pion SF – $(1-x)^1$ or $(1-x)^2$ dependence at large x?

and kaon

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.



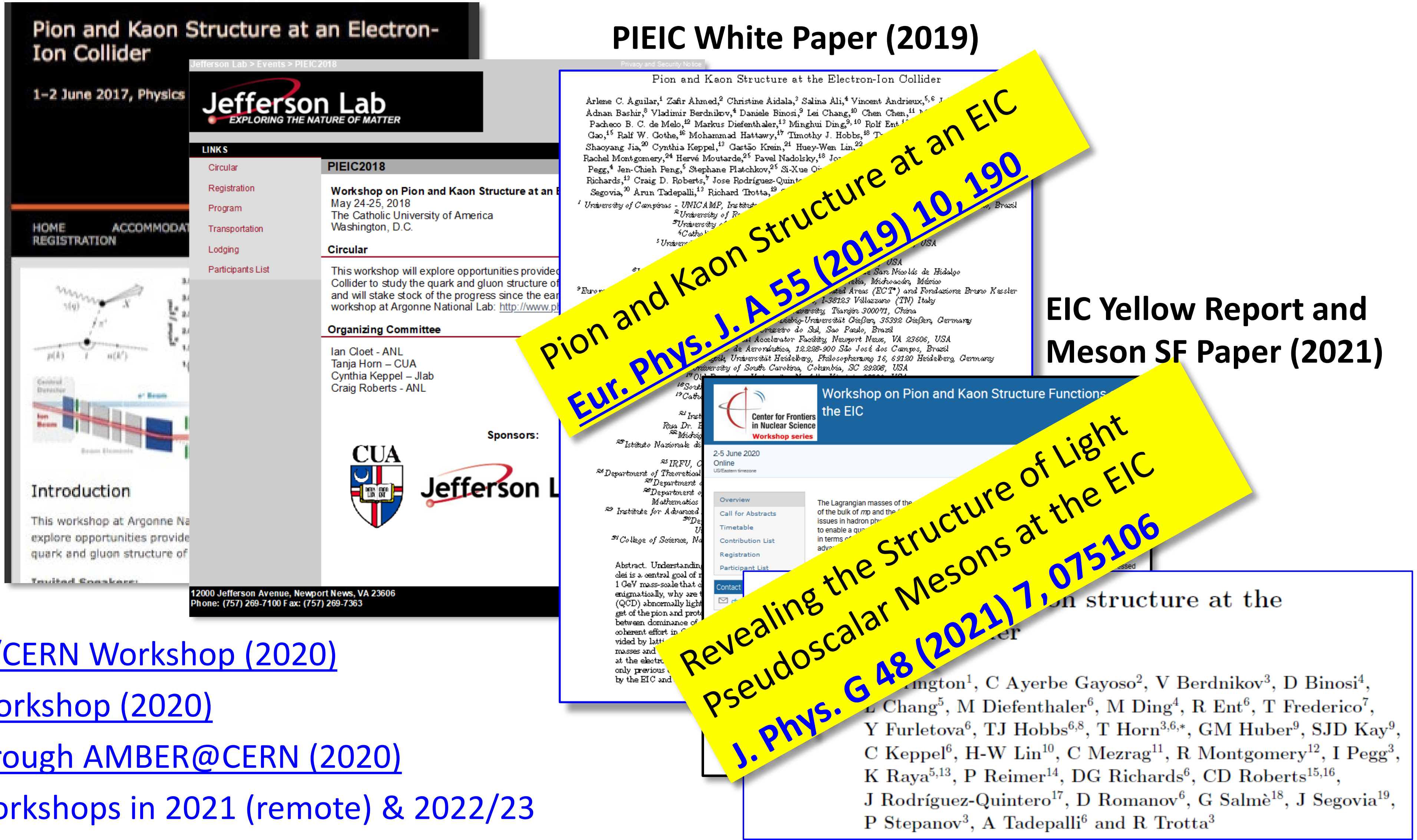


Pion and Kaon Structure at the EIC – History

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

PIEIC White Paper (2019)

EIC Yellow Report and Meson SF Paper (2021)

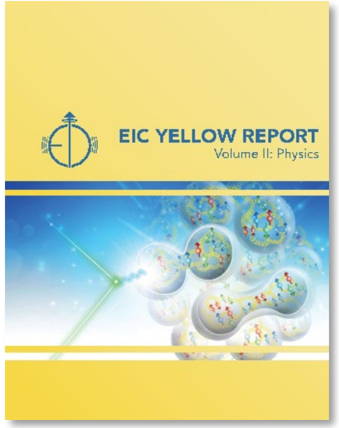


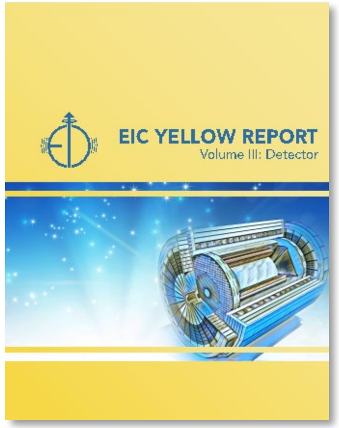
- ❑ AMBER/CERN Workshop (2020)
- ❑ CFNS Workshop (2020)
- ❑ EHM through AMBER@CERN (2020)
- ❑ ECT* Workshops in 2021 (remote) & 2022/23

Meson Structure Functions Working Group

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

- Meson SF WG: 27 members, 18 institutions, 10 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, Meson SF WG is likely to continue existing.



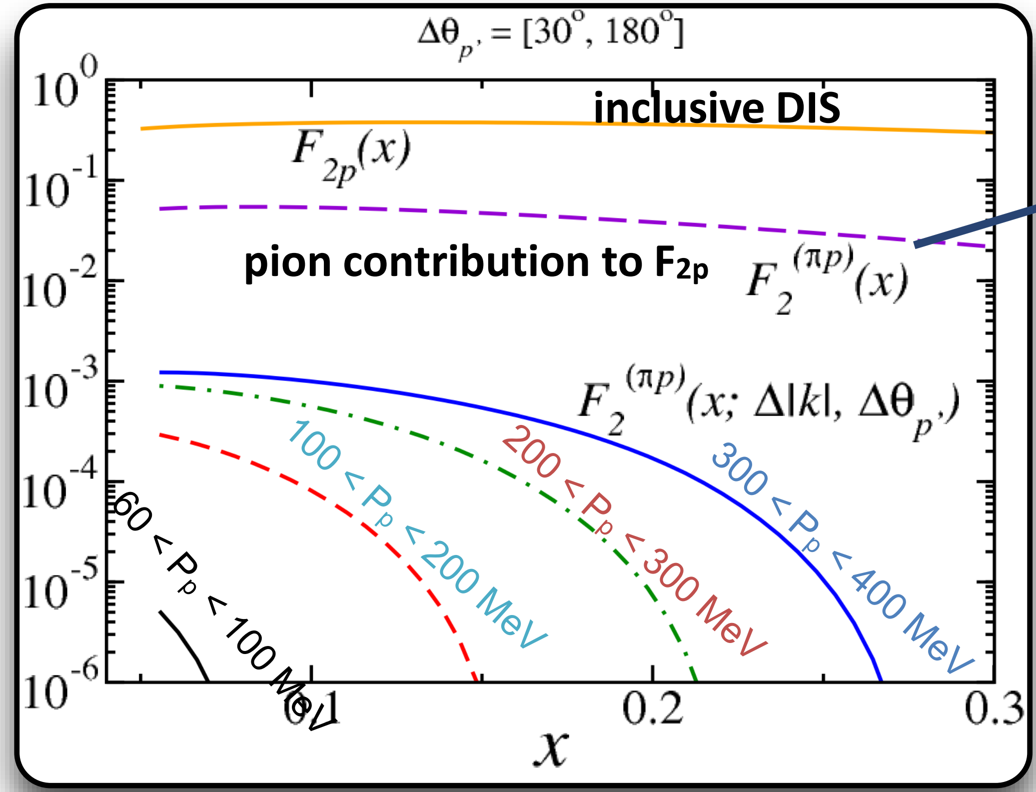


2022/23 Meson SF Meetings have been focused on Theory Progress and the next publication

- *Complementary of experimental and lattice QCD data on pion PDFs* by P. Barry - Link to the slides
- *Pion Structure explored in Minkowski Space* by T. Frederico - Link to the slides
- Pion GPD by C. Mezrag and M. Defurne - Link to the talk
- Pion and Kaons GPDs and gravitational form factors by Craig Roberts - Link to the talk
- Goals (experimental/theory) on the topic of TMDs

Meson SF Working group members:
John R. Arrington (LBNL), Carlos Ayerbe Gayoso (Mississippi State U), Patrick Barry (JLab), Adnan Bashir (U. Michoacán/Morelia, Mexico), Daniele Binosi (ECT*), Lei Chang (Nankai U.), Rolf Ent (Jlab), Tobias Frederico (Instituto Tecnologico de Aeronautica), Timothy Hobbs (FNAL), Tanja Horn (CUA), Garth Huber (U. Regina), Parada Hutauruk (Pukyong National University), Stephen Kay (U. Regina), Cynthia Keppel (Jlab), Bill Lee (W&M)), Shuije Li (LBNL), Huey-Wen Lin (MSU), Cedric Mezrag (CEA), Rachel Montgomery (U. Glasgow), Ian L. Pegg (CUA), Paul Reimer (ANL), David Richards (Jlab), Craig Roberts (Nanjing U.), Jorge Segovia (Universidad Pablo de Olavide), Arun Tadepalli (JLab), Richard Trotta (CUA), Ali Usman (U. Regina)

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



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

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

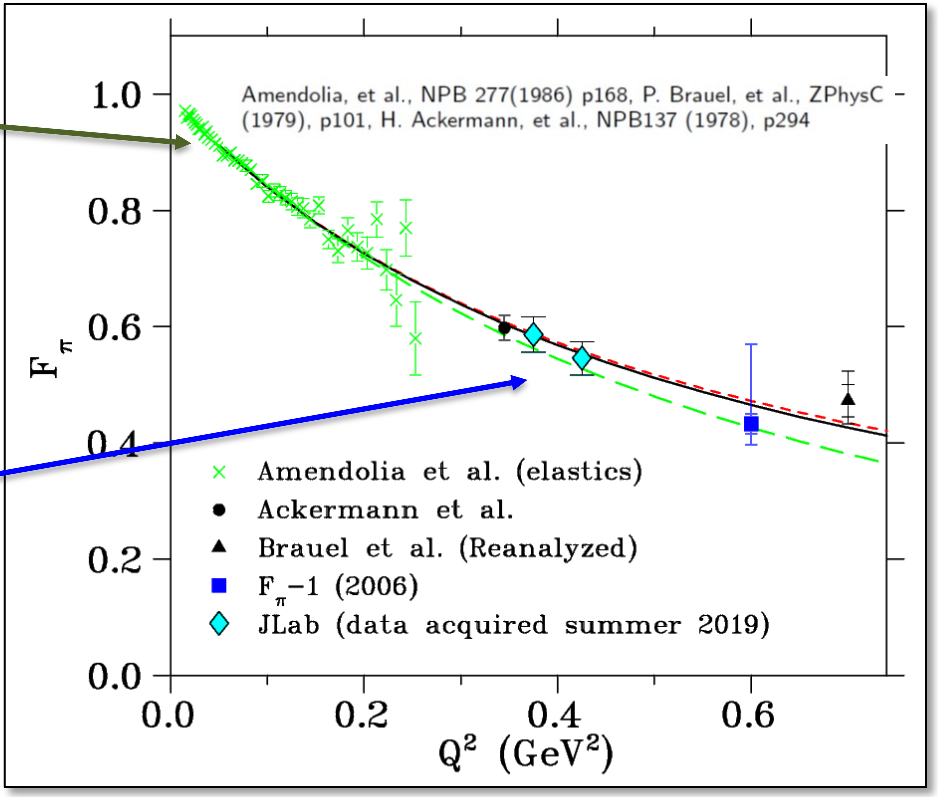
$$F_2^{(\pi N)}(x, z, k_\perp) = f_{\pi N}(z, k_\perp)\, F_{2\pi}\left(\frac{x}{z}\right)$$

Tagged SF　　pion "flux"　　Pion SF

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)

Experimental Determination of the π^+ Form Factor

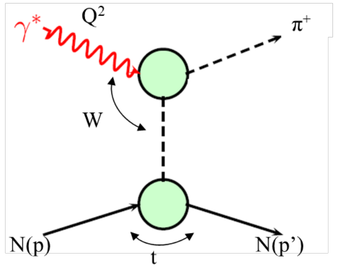


Through π-e elastic scattering

- At low Q^2, $F_{\pi+}$ can be measured directly via high energy elastic π^+ scattering from atomic electrons
  - CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV^2 *Amendolia et al, NPB277,168 (1986)*
  - These data used to constrain the pion charge radius: $r_\pi = 0.657 \pm 0.012$ fm

Through pion electroproduction

- At larger Q^2, $F_{\pi+}$ must be measured indirectly using the "pion cloud" of the proton via the *$p(e,e'\pi^+)n$ process*
  - At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L
  - In the Born term model, F_π^2 appears as



$$\frac{d\sigma_L}{dt} \propto \frac{-t}{(t-m_\pi^2)} g_{\pi NN}^2(t) Q^2 F_\pi^2(Q^2,t)$$

[In practice one uses a more sophisticated model]

Requirements:

- Full L/T separation of the cross section – isolation of σ_L
- Selection of the pion pole process
- Extraction of the form factor using a model
- Validation of the technique - model dependent checks