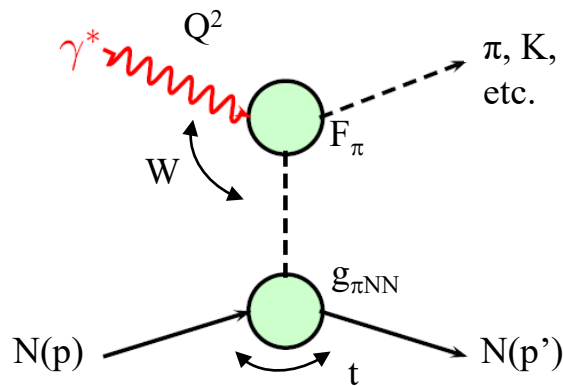
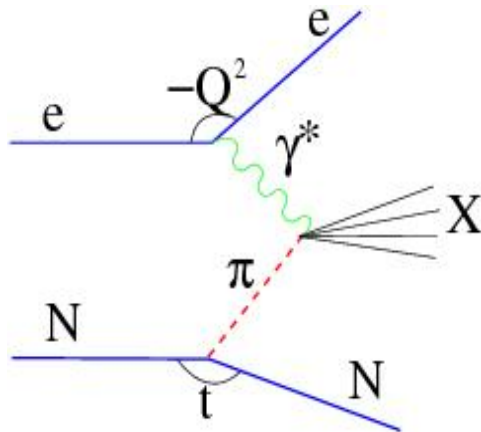


Experimental Access to Pion and Kaon Structure Functions



Tanja Horn



THE CATHOLIC
UNIVERSITY
OF AMERICA



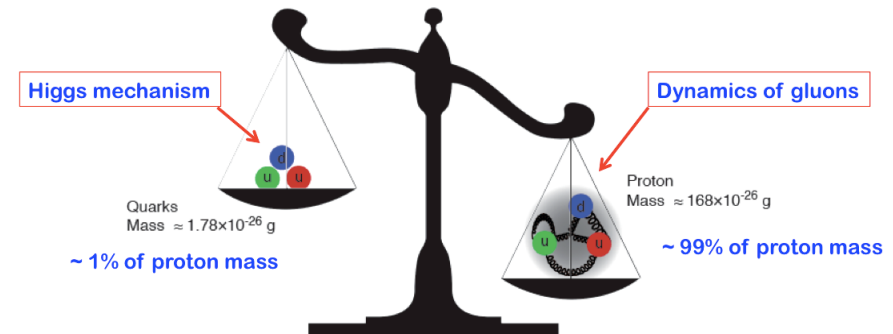
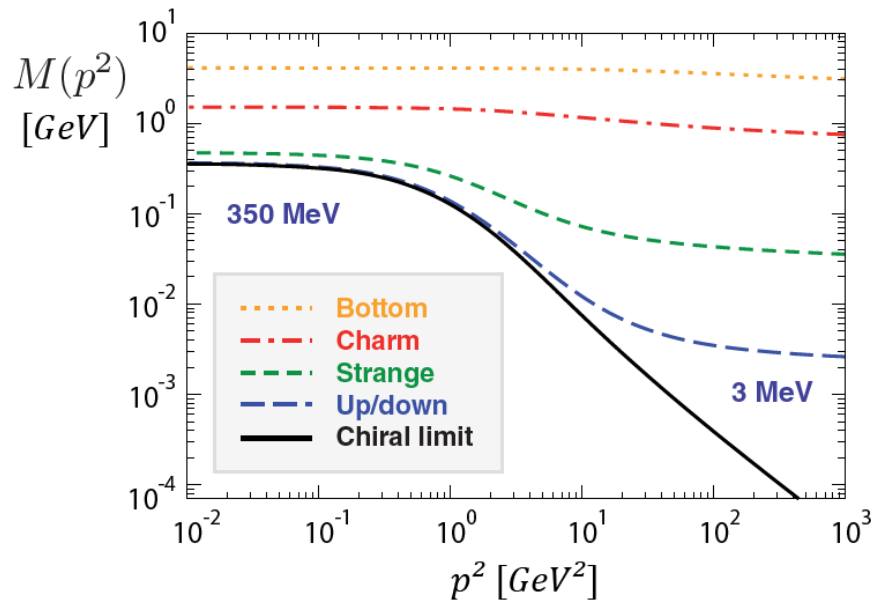
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Outline

- Accessing meson form factors through the Sullivan Process
 - Extraction from data and validation of the technique
 - F_{π^+} and F_{K^+} up to $Q^2 \sim 9$ and $\sim 6 \text{ GeV}^2$
- Accessing meson structure functions through the Sullivan process
 - JLab TDIS experiments
 - Opportunities at the EIC

The incomplete Hadron: Mass Puzzle

“Mass without mass!”



The light quarks acquire (most of) their masses as effect of the gluon cloud.

The strange quark is at the boundary - both emergent-mass and Higgs-mass generation mechanisms are important.

Proton: Mass ~ 940 MeV

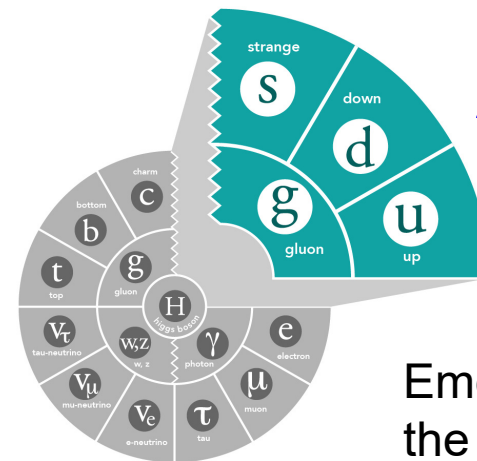
preliminary LQCD results on mass budget,
or view as mass acquisition by DCSB

Kaon: Mass ~ 490 MeV

at a given scale, less gluons than in pion

Pion: Mass ~ 140 MeV

mass enigma – gluons vs Goldstone boson



Emergent mass of
the visible universe

Origin of Mass of QCD's Pseudoscalar Goldstone Modes

- ❑ The pion is both the lightest bound quark system with a valence $\bar{q}q$ structure and a Nambu-Goldstone boson
- ❑ There are exact statements from QCD in terms of current quark masses due to PCAC [*Phys. Rep.* 87 (1982) 77; *Phys. Rev. C* 56 (1997) 3369; *Phys. Lett. B* 420 (1998) 267]

$$\begin{aligned} f_\pi m_\pi^2 &= (m_u^\zeta + m_d^\zeta) \rho_\pi^\zeta \\ f_K m_K^2 &= (m_u^\zeta + m_s^\zeta) \rho_K^\zeta \end{aligned}$$

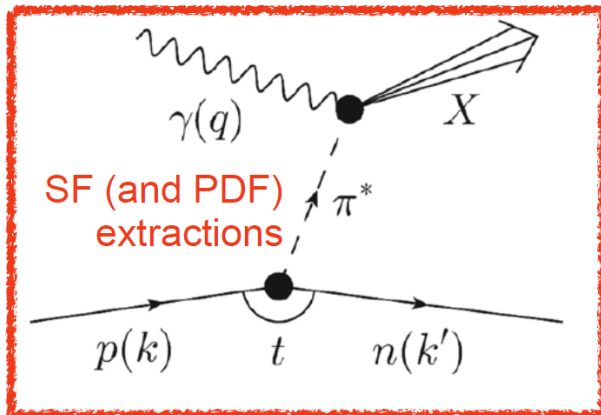
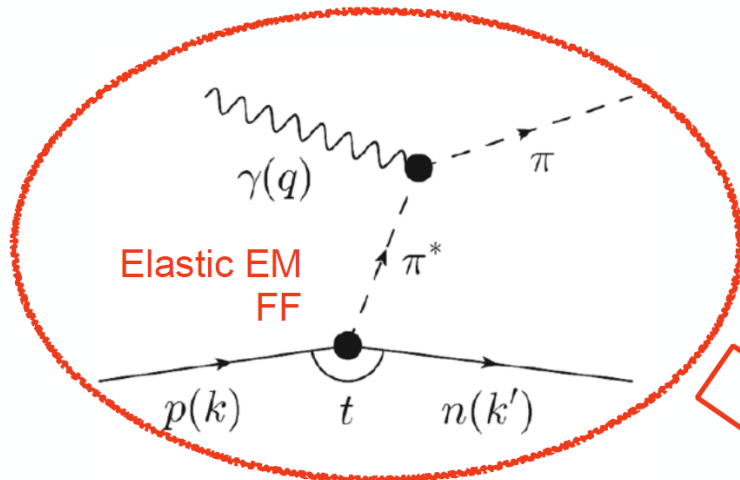
- ❑ Pseudoscalar masses are generated **dynamically**
 - From these exact statements, it follows the mass of bound states increases as \sqrt{m} with the mass of the constituents.
 - In contrast, in, e.g. the CQM, bound state mass rises linearly with constituent mass, e.g., with constituent quarks Q: in the nucleon $m_Q \sim \frac{1}{3}m_N \sim 310$ MeV, in the pion $m_Q \sim \frac{1}{2}m_\pi \sim 70$ MeV, in the kaon (with one s quark) $m_Q \sim 200$ MeV – **This is not real.**
 - In both DSE and LQCD, the mass function of quarks is the same, regardless what hadron the quarks reside in – **This is real.** It is the **Dynamical Chiral Symmetry Breaking (D χ SB)** that makes the pion and kaon masses light.

Understanding pion/kaon is vital to understanding dynamic generation of hadron mass

Accessing Pion/Kaon Structure Information

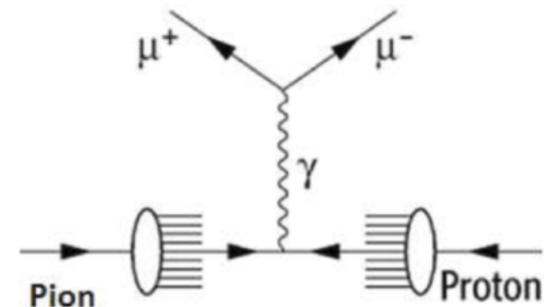
Sullivan

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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❑ Pion/Kaon elastic EM Form Factor

- Informs how emergent mass manifests in the wave function

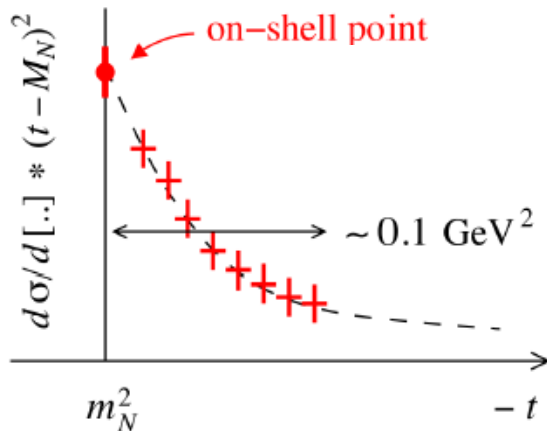
❑ Pion/Kaon Structure Functions

- Informs about the quark-gluon momentum fractions

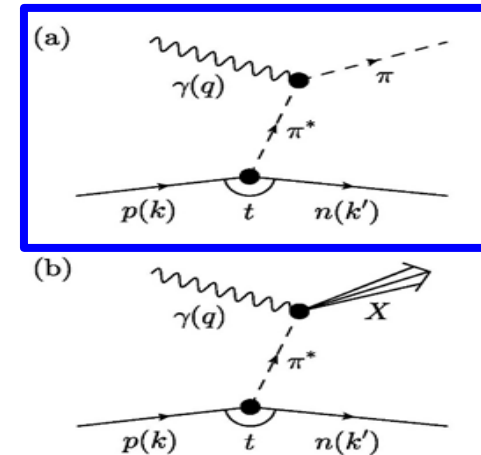
Accessing meson structure through the Sullivan Process

- ❑ 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) 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**

Meson Form Factors

❑ ***Pion and kaon form factors*** are of special interest in hadron structure studies

- The *pion* is the lightest QCD quark system and also has a central role in our understanding of the dynamic generation of mass - *kaon* is the next simplest system containing strangeness

*Clearest test case for studies of the transition
from non-perturbative to perturbative regions*

❑ Recent advances and future prospects in experiments

- Dramatically improved precision in F_π measurements

*12 GeV JLab data have the potential to
quantitatively reveal hard QCD's signatures*

❑ Form factor data and measurements go hand-in-hand with activities on theory side, e.g.

Distribution amplitudes – normalization fixed by pion wave function whose dilation from conformal limit is a signature of DCSB

The Pion in QCD

- At very large Q^2 , F_π can be calculated using perturbative QCD (pQCD)

$$F_\pi(Q^2) = \frac{4\pi C_F \alpha_s(Q^2)}{Q^2} \left| \sum_{n=0}^{\infty} a_n \left(\log \left(\frac{Q^2}{\Lambda^2} \right) \right)^{-\gamma_n} \right|^2 \left[1 + O \left(\alpha_s(Q^2), \frac{m}{Q} \right) \right]$$

- At asymptotically high Q^2 , the pion distribution amplitude becomes

$$\phi_\pi(x) \xrightarrow{Q^2 \rightarrow \infty} \frac{3f_\pi}{\sqrt{n_c}} x(1-x)$$

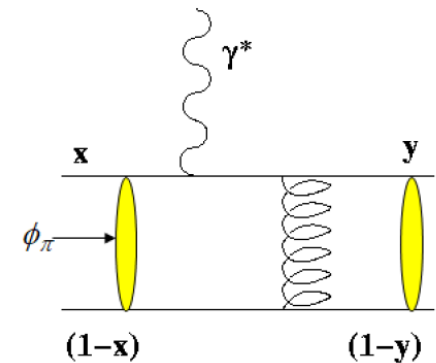
where $f_\pi^2 = 93 \text{ MeV}$ is the $\pi^+ \rightarrow \mu^+ \nu$ decay constant.

- and F_π takes the factorized form

$$F_\pi(Q^2) \xrightarrow{Q^2 \rightarrow \infty} \frac{16\pi\alpha_s(Q^2)f_\pi^2}{Q^2}$$

- This only relies on asymptotic freedom in QCD ($\partial\alpha_s/\partial\mu < 0$ as $\mu \rightarrow \infty$)
- $Q^2 F_\pi$ should behave as $\alpha(Q^2)$ even for moderately large Q^2

- F_π seems to be the best tool for experimental study of the nature of the quark-gluon coupling constant renormalization



Pion Structure with a more suitable DA

- ❑ Earlier pQCD derivation used normalization of F_π based on the conformal limit of the pion's twist 2 DA

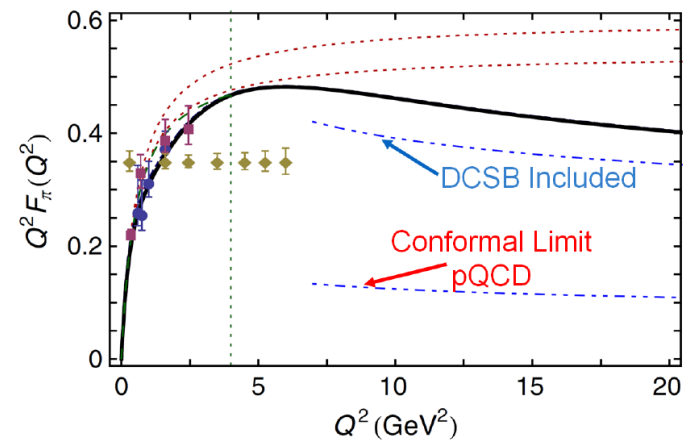
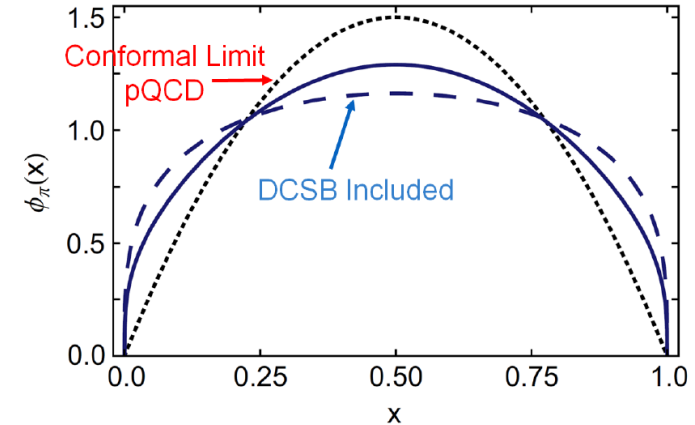
$$\phi_\pi^{cl}(x) = 6x(1-x)$$

- ❑ This results in an F_π that underpredicts the data by a factor of ~ 3

- ❑ Including the DSCB yields a pion DA

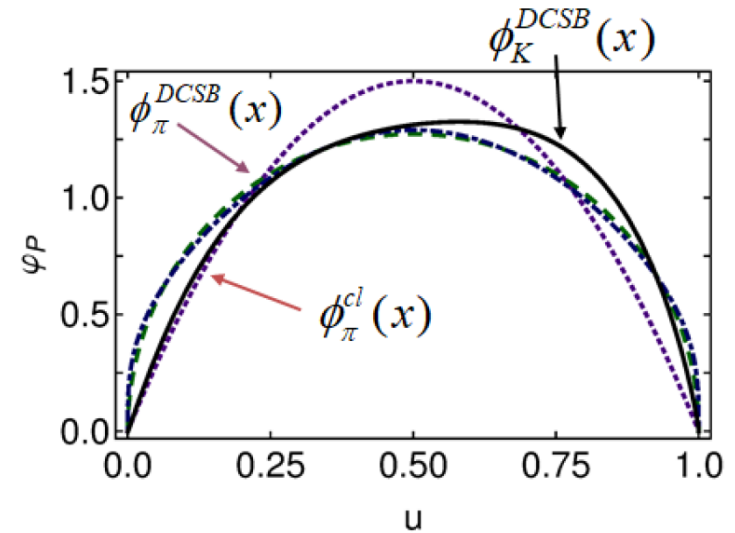
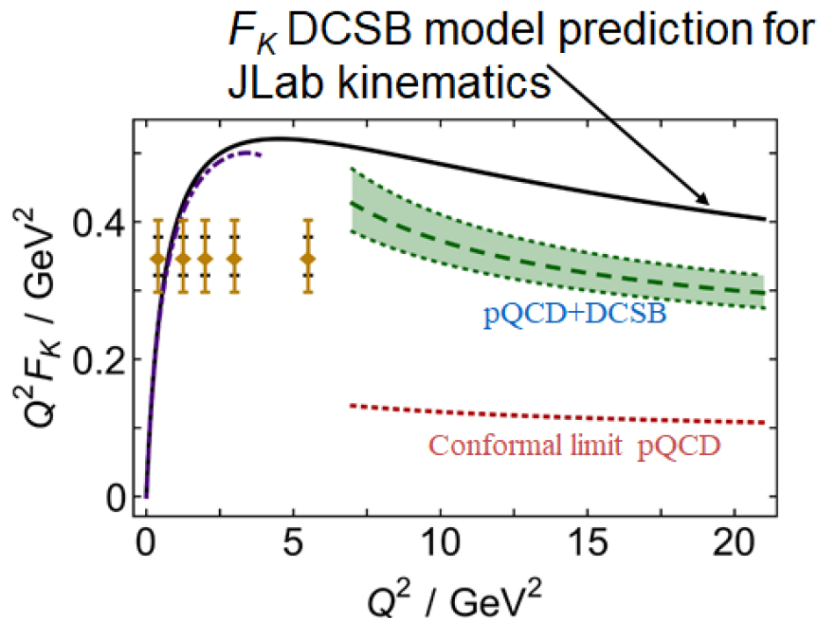
$$\phi_\pi(x) = \frac{8}{\pi} \sqrt{x(1-x)}$$

- ❑ Using this pion DA in the pQCD expression brings the resulting F_π much closer to the data
 - Underestimates the full calculation by $\sim 15\%$ for $Q^2 > 8 \text{ GeV}^2$



Kaon Structure with DCSB

- ❑ The charged kaon DA is broad, concave and asymmetric (similar to the pion)
- ❑ It is shifted with respect to the pion DA as the heavier s quark carried more bound state momentum than the u quark
 - Shift is less than one might expect based on the difference in current quark masses

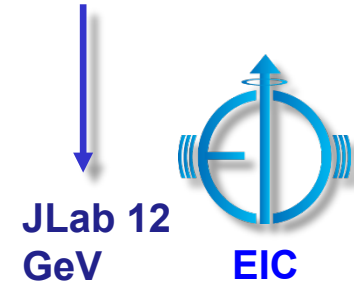


- ❑ Kaon form factor data are very sparse – experimentally extremely challenging
- ❑ JLab 12 GeV has the facilities to provide data up to $Q^2 \sim 5.5 \text{ GeV}^2$

Meson Production Data Evolution

Experiment

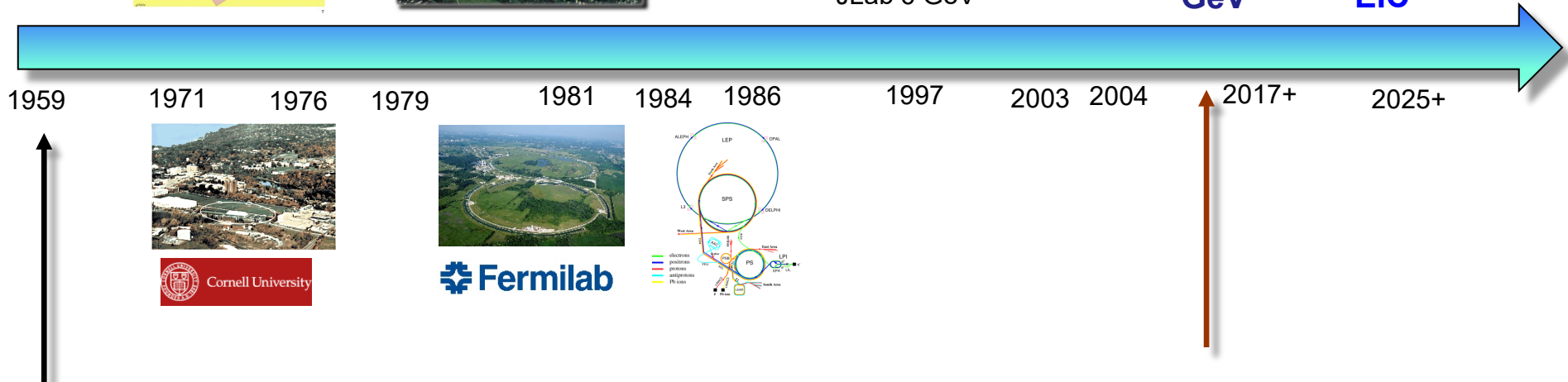
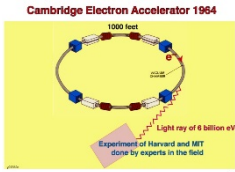
Capability to reliably access large Q^2 regime



Jefferson Lab



JLab 6 GeV



Theory

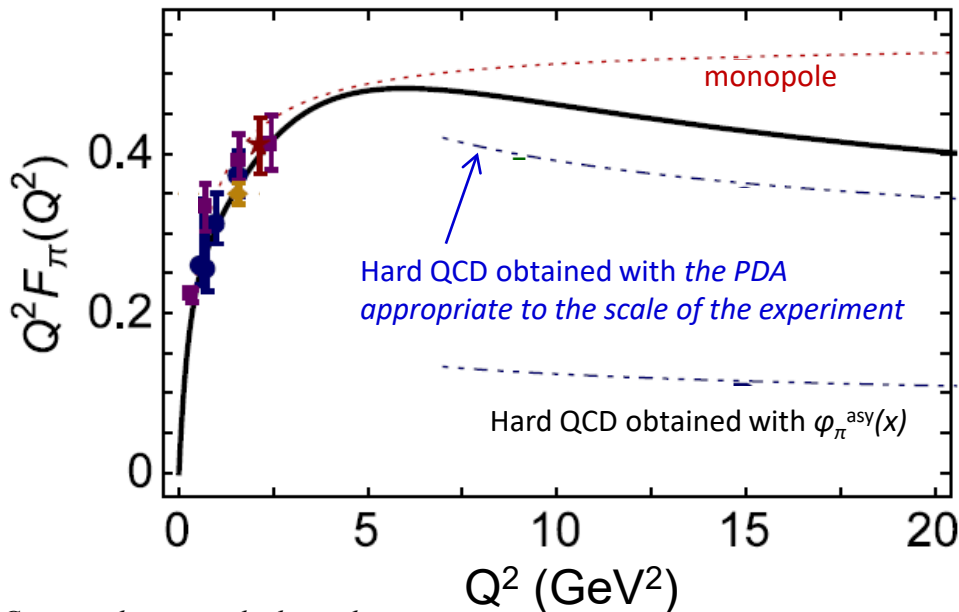
- Accessing the form factor through electroproduction
- Extraction of meson form factor from data
- Electroproduction formalism

Theory/Lattice/Global Fitting

Major progress on hadron structure calculations (also lattice and global fitting), e.g. large Q^2 behavior of meson form factor

Pion Form Factor at JLab 6 GeV

- ❑ The presently best F_π experimental data come from the successful Fpi-1, Fpi-2, and pionCT experiments at JLab 6 GeV
- ❑ Fpi was measured up to $Q^2=2.45 \text{ GeV}^2$
- ❑ *Factor* ~ 3 from hard QCD calculation evaluated with asymptotic valence-quark Distribution Amplitude (DA) – trend consistent with time like meson form factor data up to $Q^2=18 \text{ GeV}^2$

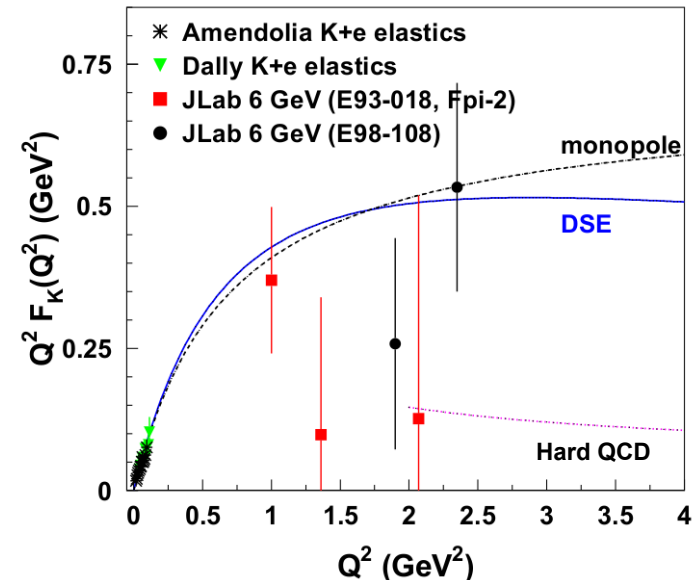


JLAB Fpi-1
JLAB Fpi-2
JLAB pionCT
DESY

*Compared to one calculation here
– there are others, e.g. Braun et al.*

Kaon Form Factor at JLab 6 GeV

- ❑ The Kaon Form factor was extracted from three JLab 6 GeV experiments measuring kaon electroproduction (E98-108, E93-018, Fpi-2)
- ❑ The extraction was opportunistic - none of these experiments were designed for F_K measurements
- ❑ F_K was extracted to $Q^2 \sim 2.1 \text{ GeV}^2$
- ❑ The method of extracting F_K from JLab data was successfully demonstrated and validated, but since the experiments were not dedicated for such measurements the data have limited lever arm and large error bars



[M. Carmignotto et al., Phys. Rev. C **97** (2018) no.2, 025204]

[F. Gao et al., Phys. Rev. D **96** (2017) no. 3, 034024]

Experimental Determination of the π^+ Form Factor

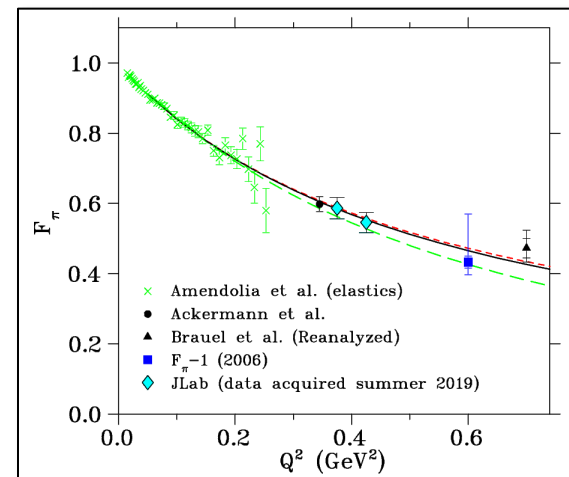
Through π -e elastic scattering

□ At low Q^2 , F_{π^+} 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 $Q^2 = 0.25 \text{ GeV}^2$
[Amendolia et al, NPB277,168 (1986)]
- These data used to constrain the pion charge radius: $r_\pi = 0.657 \pm 0.012 \text{ fm}$

□ The maximum accessible Q^2 is roughly proportional to the pion beam energy

- $Q^2 = 1 \text{ GeV}^2$ requires 1000 GeV pion beam



Amendolia, et al., NPB 277(1986) p168, P. Brauel, et al., ZPhysC (1979), p101, H. Ackermann, et al., NPB137 (1978), p294

Experimental Determination of the π^+ Form Factor

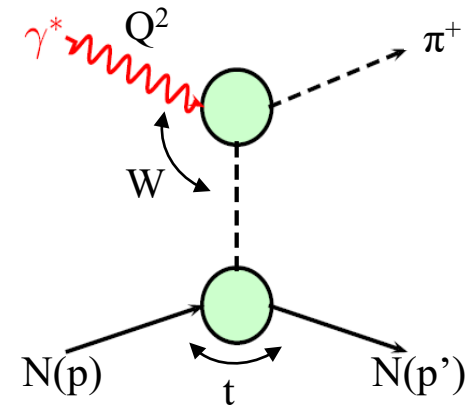
Through pion electroproduction

❑ At larger Q^2 , F_{π^+} 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

L/T Separation Example

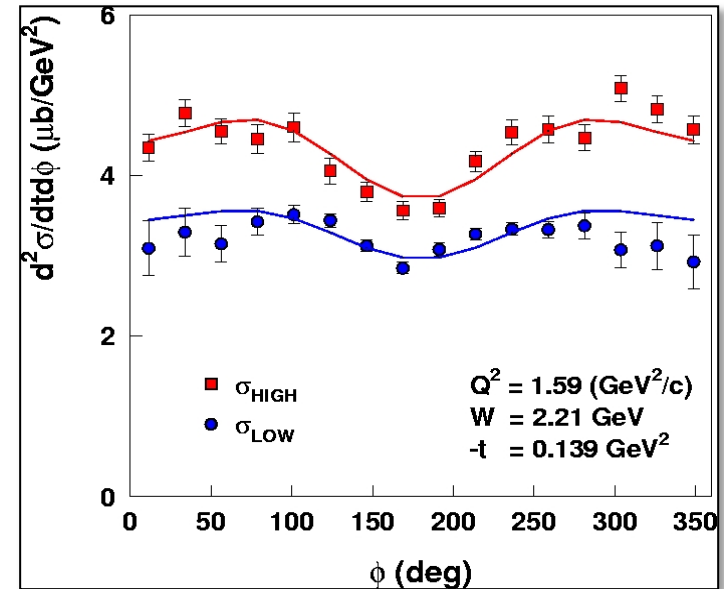
- σ_L is isolated using the Rosenbluth separation technique

- Measure the cross section at two beam energies and fixed W , Q^2 , $-t$
- Simultaneous fit using the measured azimuthal angle (ϕ_π) allows for extracting L, T, LT, and TT

- Careful evaluation of the systematic uncertainties is important due to the $1/\varepsilon$ amplification in the σ_L extraction

- Spectrometer acceptance, kinematics, and efficiencies

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



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

σ_L will give us F_π

Magnetic spectrometers a must for such precision cross section measurements

- This is only possible in Hall C at JLab

Using a model to extract of F_π from σ_L JLab data

- JLab 6 GeV F_π experiments used the VGL/Regge model as it has proven to give a reliable description of σ_L across a wide kinematic domain

[Vanderhaeghen, Guidal, Laget, PRC 57, (1998) 1454]

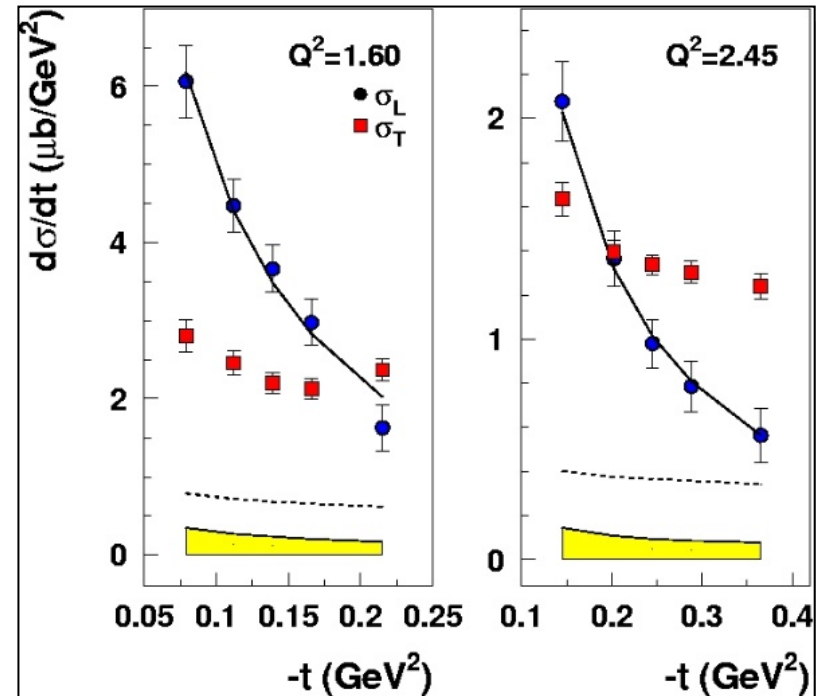
$$F_\pi(Q^2) = \frac{1}{1 + Q^2 / \Lambda_\pi^2}$$

Fit of σ_L to model gives F_π at each Q^2

- Separated L/T cross sections will be published, so F_π can be extracted using other models as they become available,

e.g. R. J. Perry et al., Phys. Rev. C 100 (2019) no. 2, 025206

[Horn et al., PRL 97, (2006) 192001]



$$\Lambda_\pi^2 = 0.513, 0.491 \text{ GeV}^2$$

$$\Lambda_\rho^2 = 1.7 \text{ GeV}^2$$

Validation: Electroproduction method consistency check

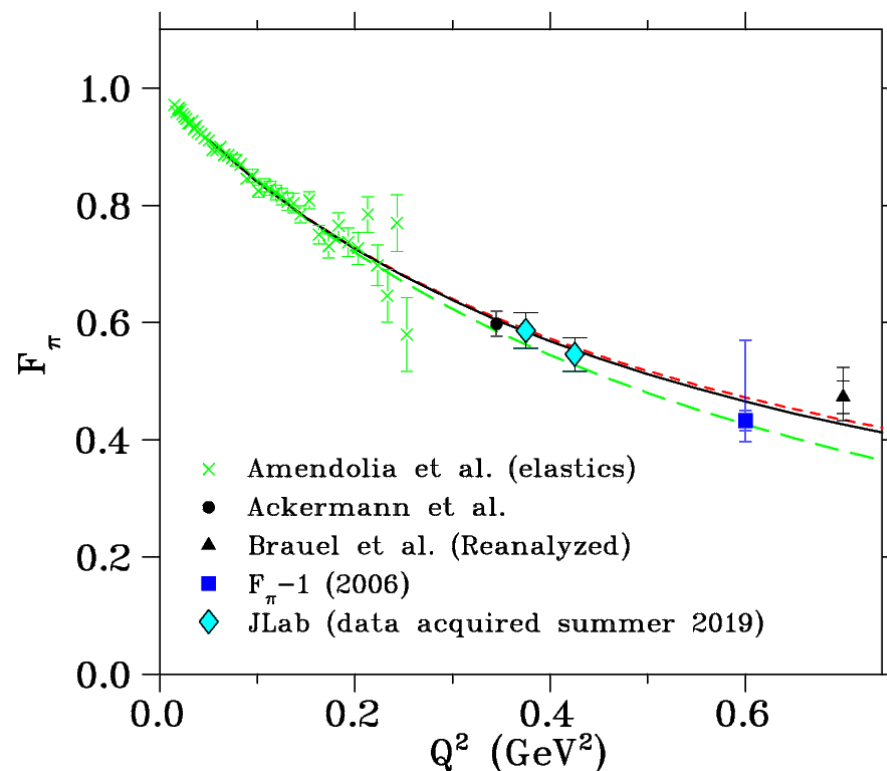
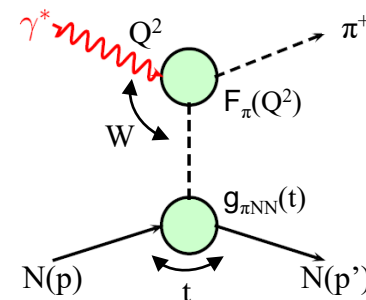
- Directly compare $F_\pi(Q^2)$ values extracted from very low $-t$ electroproduction with the exact values measured in elastic $e-\pi$ scattering

➤ JLab data: **blue**, re-analyzed DESY data: **black**

Method passes check: $Q^2=0.35 \text{ GeV}^2$
data from DESY consistent with limit
of elastic data within uncertainties

[H. Ackerman et al., NP B137 (1978) 294]

- More detailed tests with **12 GeV PionLT experiment** taking data at lower $-t$ (0.005 GeV^2)

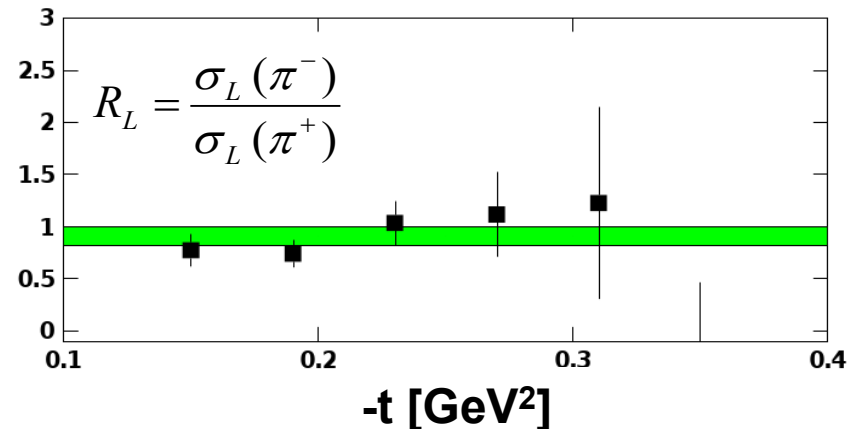
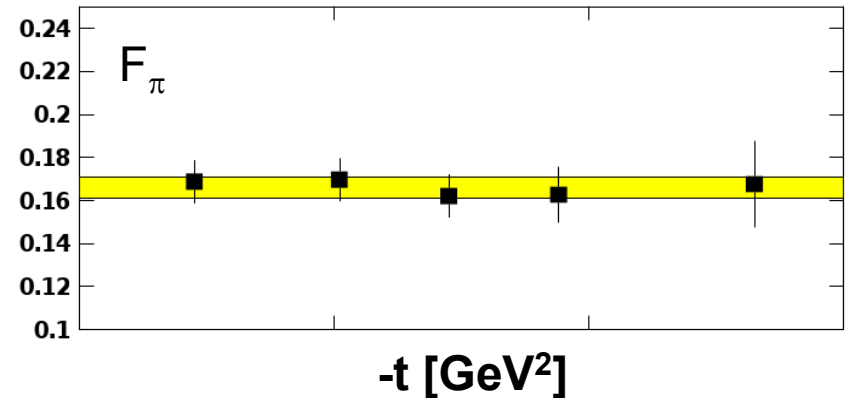


Experimental Validation (Pion Form Factor example)

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



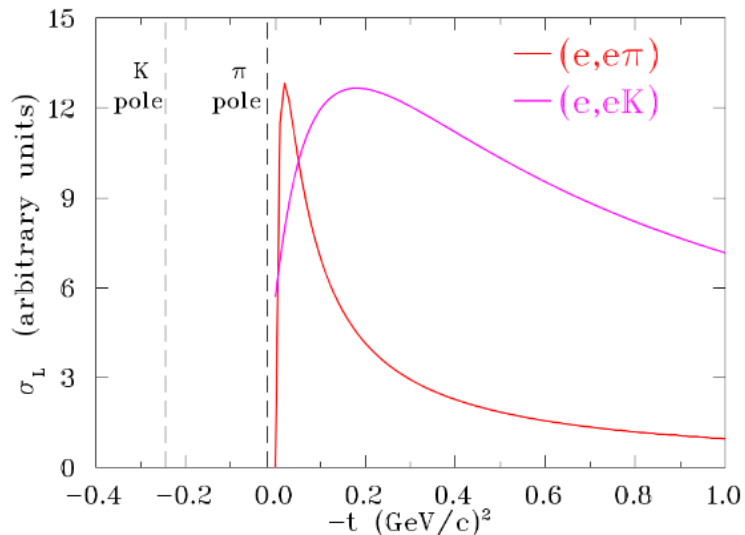
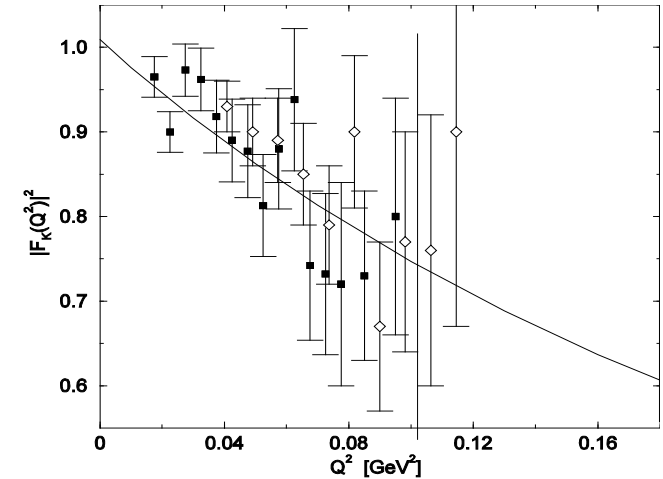
[G. Huber et al, PRL **112** (2014) 182501]

T. Horn, C.D. Roberts, J. Phys. G **43** (2016) no.7, 073001

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

Extension to systems containing strangeness: the K^+ Form Factor

- ❑ Similar to π^+ , elastic K^+ scattering from electrons used to measure charged kaon form factor at low Q^2
 - CERN SPS used 250 GeV kaons to measure form factor up to $Q^2 = 0.13 \text{ GeV}^2$ [Amendolia et al, PLB 178, 435 (1986)]
 - These data used to constrain the kaon RMS radius: $r_K = 0.58 \pm 0.04 \text{ fm}$



- ❑ Can “kaon cloud” of the proton be used in the same way as the pion to extract kaon form factor via $p(e, e' K^+) \Lambda$?

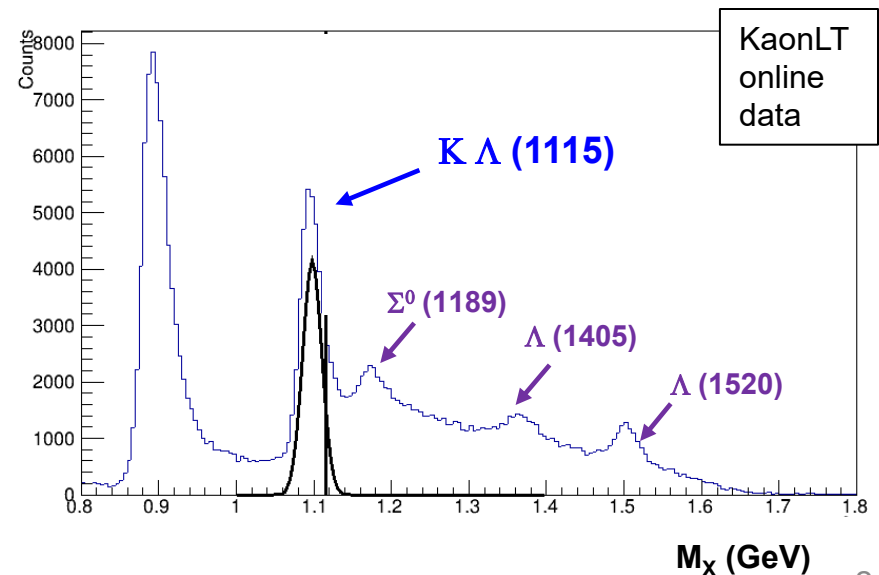
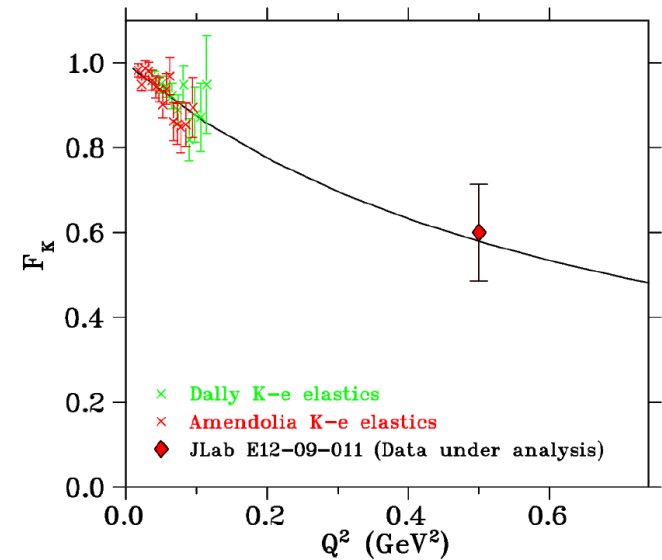
➤ *Need to quantify the role of the kaon pole*

K^+ Form Factor Validation

- Like for the pion, low Q^2 data are an important test
- The experiment allows for simultaneous studies of the Λ and Σ^0 channels
- Allows for performing pole dominance tests through the ratio

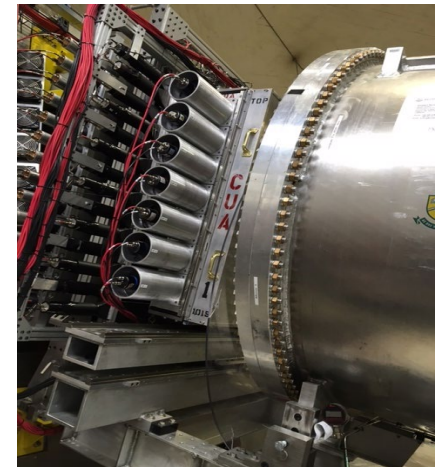
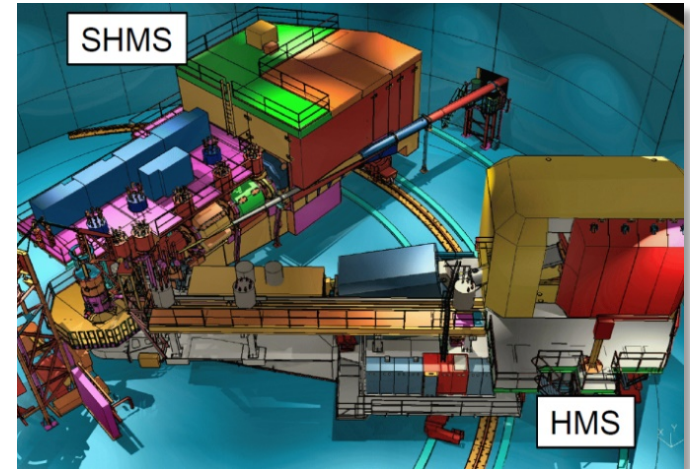
$$\frac{\sigma_L[p(e, e' K^+) \Sigma^0]}{\sigma_L[p(e, e' K^+) \Lambda^0]}$$

- Similar to the ratio of coupling constants $g_{pK\Lambda}^2/g_{pK\Sigma}^2$ if the t-channel exchange dominates



Exclusive Meson Experiments in Hall C @ 12 GeV

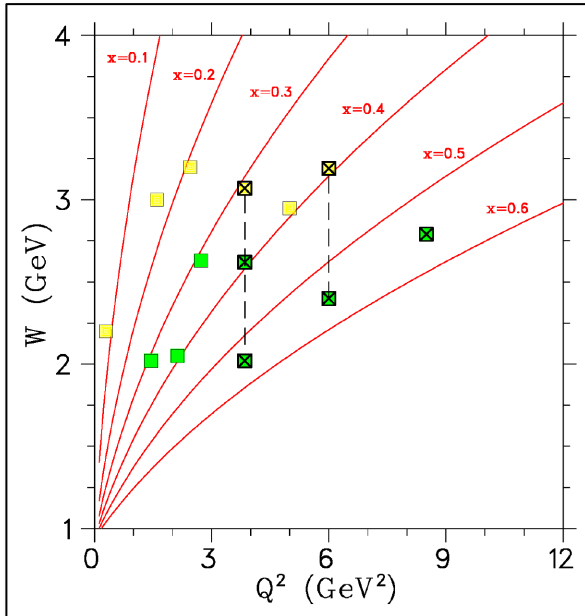
- ❑ CEBAF 10.9 GeV electron beam and SHMS small angle capability and controlled systematics are essential for extending precision measurements to higher Q^2
- ❑ New SHMS fulfills the meson experiments L/T separation requirements
 - Small forward-angle capabilities
 - Good angular reproducibility
 - Missing mass resolution
- ❑ 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)



PionLT (E12-19-006) Program at 12 GeV Overview

Spokespersons: D. Gaskell (JLab), T. Horn (CUA), G. Huber (URegina)

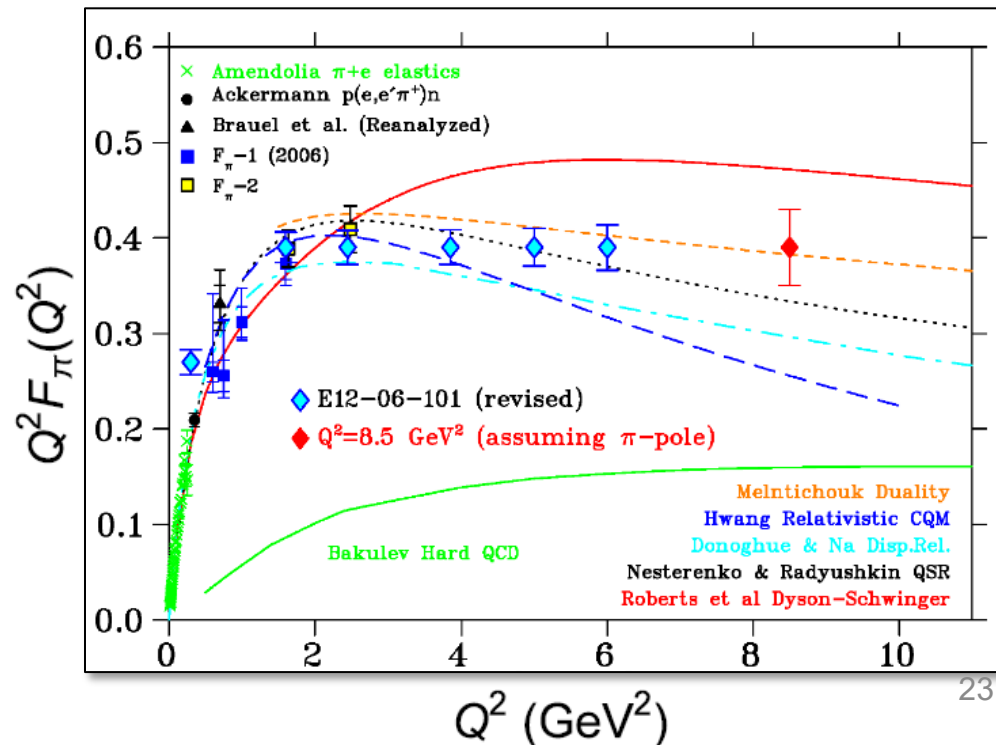
Grad. Students: J. Murphy (OU), A. Usman (URegina), J. Muhammed (URegina)



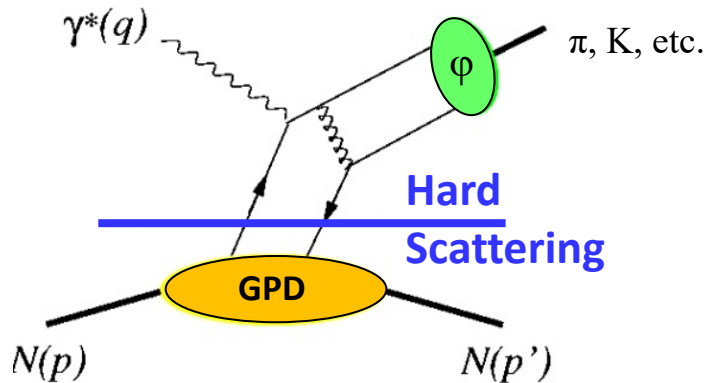
□ PionLT experiment features:

- L/T separated cross sections at fixed $x=0.3, 0.4, 0.55$ up to $Q^2=8.5$ GeV²
- Pion form factor at Q^2 values up to 6 GeV²
- Enables pion form factor extraction at $Q^2 = 8.5$ GeV², highest achievable at 12 GeV JLab

JLab 12 GeV experiments have the potential to access the perturbative scaling regime quantitatively – may also provide info on log corrections.



L/T Separated (e,e'π⁺/K⁺) Cross Sections with 12 GeV

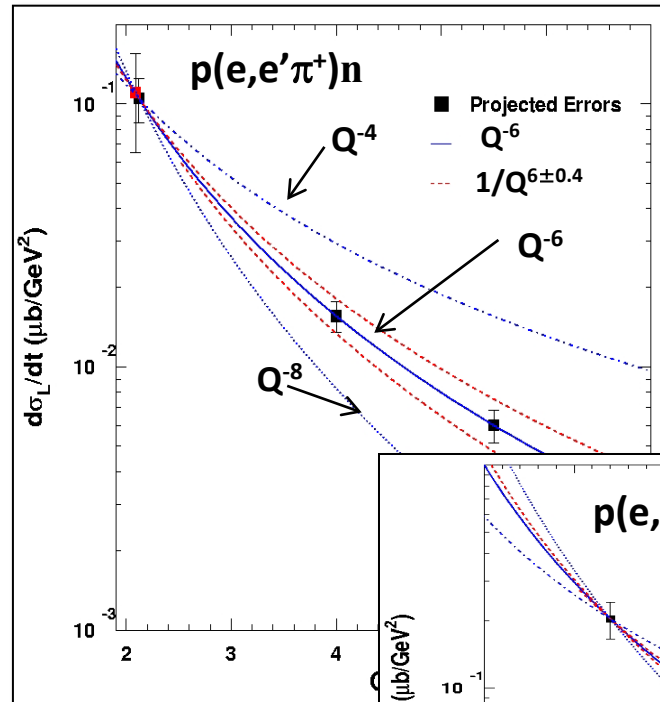


- One of the most stringent tests of the reaction mechanism is the Q^2 dependence of cross section

- σ_L scales to leading order as Q^{-6}
 - σ_T does not

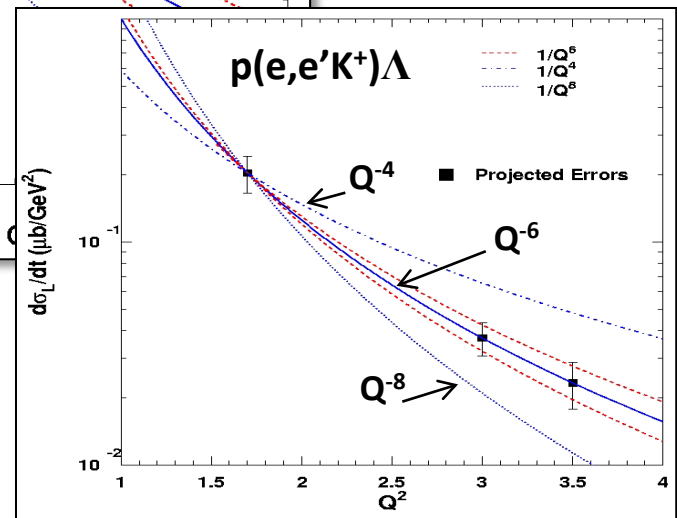
- Need to validate the reaction mechanism for reliable interpretation of the GPD program – key are precision longitudinal-transverse (L/T) separated data over a range of Q^2 at fixed x/t

- 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



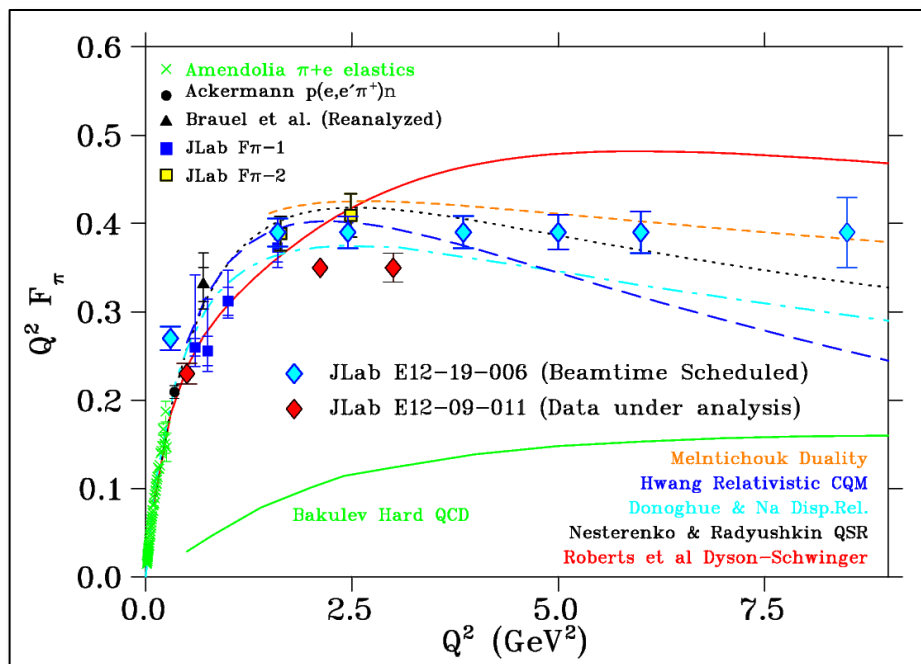
π^+ : to $Q^2 \sim 9 \text{ GeV}^2$
 K^+ : to $Q^2 \sim 6 \text{ GeV}^2$

Fit: $1/Q^n$



PionLT Program at 12 GeV: Outlook

- ❑ Low- Q^2 data taking for E12-19-006 completed in summer 2019
- ❑ Large part of data taking ongoing now (and in 2022)
- ❑ Additional data from KaonLT experiment (discussed next)



Setting	Low ϵ data	High ϵ data
$Q^2=0.375$	✓	✓
$Q^2=0.425$	✓	✓
$Q^2=1.45$ $W=2.02$	✓	✗
$Q^2=1.6$ $W=3.0$	✓	✗
$Q^2=2.12$ $W=2.05$	✓	✗
$Q^2=2.45$ $W=3.2$	✗	✗
$Q^2=2.73$ $W=2.63$	✗	✗
$Q^2=3.85$ $W=3.07$	✗	✗
$Q^2=5.0$ $W=2.95$	✗	✗
$Q^2=6.0$ $W=3.19$	✓	✗
$Q^2=8.5$ $W=2.79$	in progress	✗

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

Spokespersons: T. Horn (CUA), G. Huber (URegina), P. Markowitz (FIU)

Grad. Students: V. Kumar (URegina), A. Usman (URegina), R. Trotta (CUA)

Goals

- ❑ Separated cross sections as a function of Q^2 at $x_B=0.1, 0.25, 0.4$
- ❑ Separated cross sections as a function of $-t$ for kaon pole studies and possible kaon form factor extractions

Motivation

- ❑ Q^2 dependence for validating the hard exclusive reaction mechanism
 - First cross section data for Q^2 scaling tests with kaons
 - Highest Q^2 for L/T separated kaon electroproduction cross section
- ❑ t -dependence for validating the reaction mechanism
 - if warranted by data, extract the kaon form factor

KaonLT: Completed data taking in 2018/2019

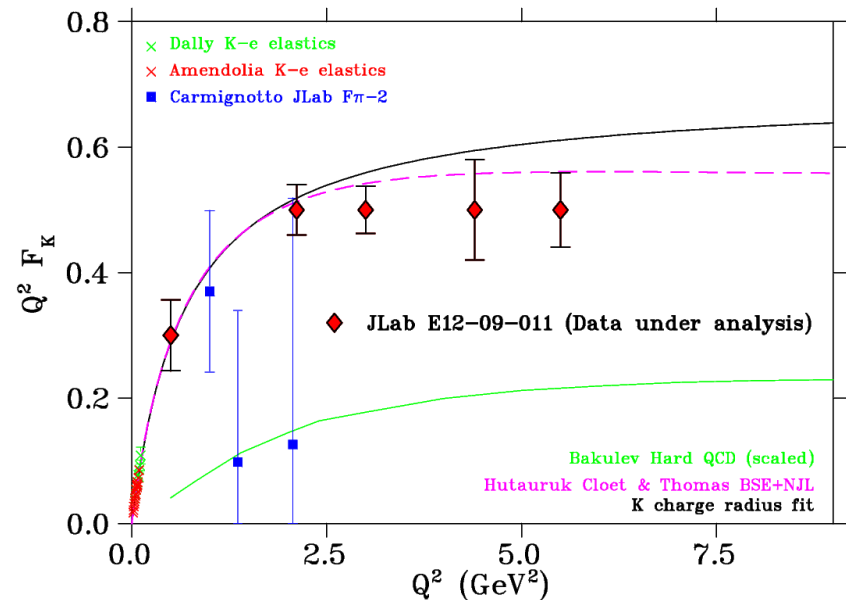
❑ Data taking completed end of Spring 2019 – analysis ongoing

❑ Physics analyses may include:

➤ **K^+ channel:** L/T separated Λ and Σ^0 cross sections, Q^{-n} dependence, coupling constants $g_{KN\Lambda}$, beam helicity asymmetry, $\Lambda(1405)$, $\Lambda(1115)$, $\Lambda(1520)$ cross sections

➤ **π^+ channel:** L/T separated cross sections, beam helicity asymmetry, n/Δ^0 ratios, Q^{-n} dependence

➤ **p channel:** $p(e,e'p)\rho/p(e,e'p)\omega$, $p(e,e'p)\phi$ ratios, as possible, cross sections and $p(e,e'p)\eta$ and $p(e,e'p)\eta'$, Q^{-n} dependence



Data collected

Q^2 (GeV ²)	W (GeV)	LT complete
5.5	3.02	✓
4.4	2.74	✓
3.0	3.14	✓
3.0	2.32	✓
2.115	2.95	✓
0.5	2.40	✓

Pion and Kaon Form Factors at the EIC

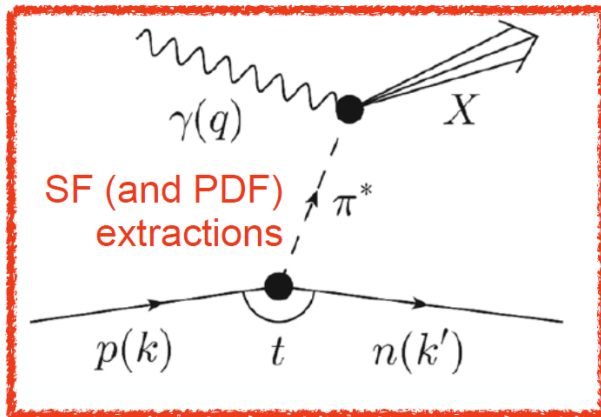
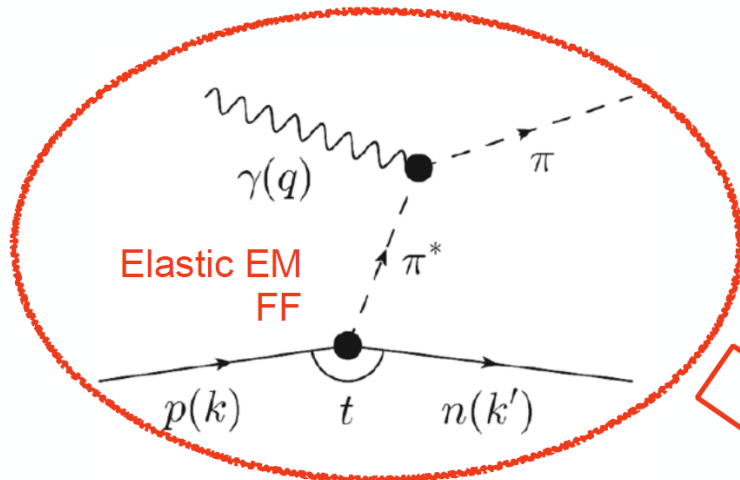
- JLab measurements push the Q^2 reach of data considerably
- Still can't answer some key questions regarding the emergence of hadronic mass however
- Can we get quantitative guidance on the emergent pion mass mechanism?
→ Need F_π data for $Q^2 = 10 - 40 \text{ GeV}^2$
- What is the size and range of interference between emergent mass and the Higgs-mass mechanism?
→ Need F_K data for $Q^2 = 10 - 20 \text{ GeV}^2$
- Beyond what is possible at JLab in the 12 GeV era
 - Need a different machine → **The Electron-Ion Collider (EIC)**

➤ **More on meson form factors at the EIC in the next section of this presentation**

Accessing Pion/Kaon Structure Information

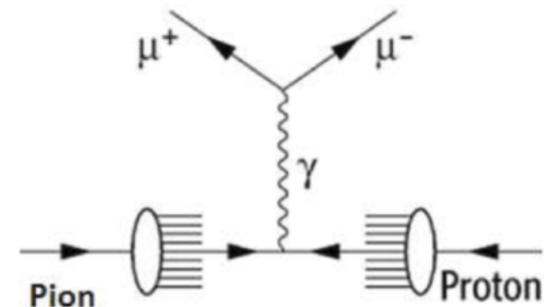
Sullivan

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

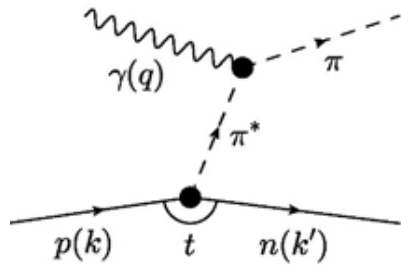
- Informs how emergent mass manifests in the wave function

❑ Pion/Kaon Structure Functions

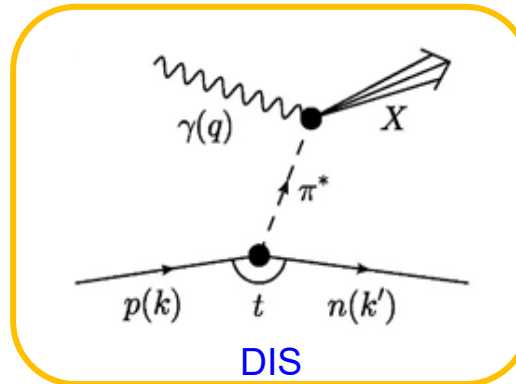
- Informs about the quark-gluon momentum fractions

Towards Pion/Kaon Structure Functions

- ❑ Similar as process used to measure the pion elastic form factors, isolate the One Pion Exchange Contribution also to measure pion structure functions



Elastic Form Factor



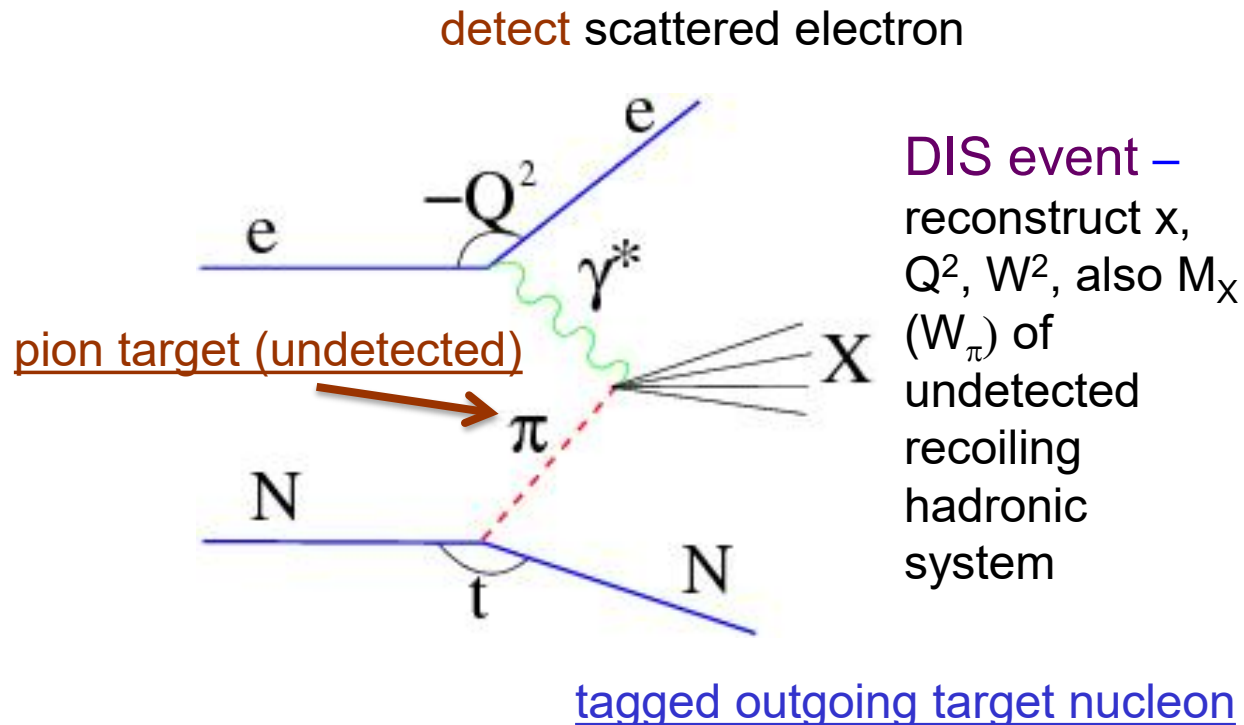
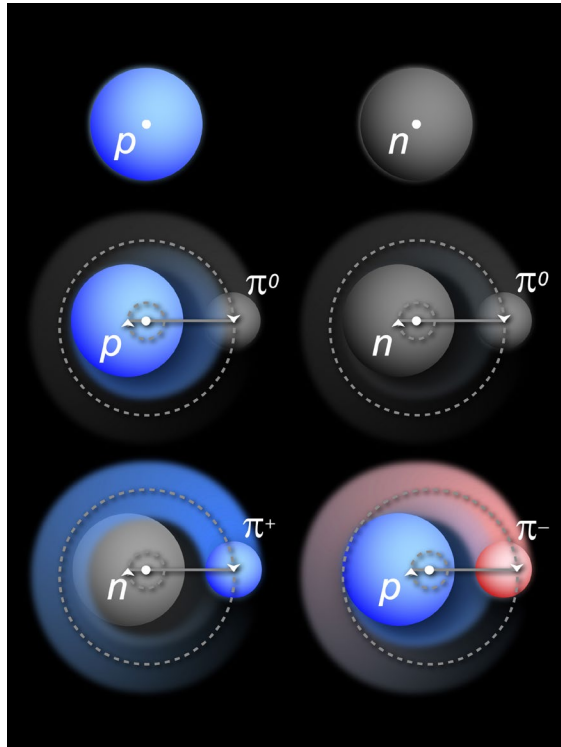
DIS

In the Sullivan process, the mesons in the nucleon cloud are virtual (off-shell) particles

- ❑ Sullivan was the first to consider the “Drell” process, with $\pi+X$ final states where m_X^2 grows linearly with Q^2
- ❑ A simple calculation gives the minimum momentum transfer squared $t_{min} = (q - k)_{min}^2 \rightarrow \infty$ as $Q^2 \rightarrow \infty$
 - The requirement of being near the pion pole at $t = m_\pi^2$ can never be satisfied and processes of this type play no role in the scaling region
- ❑ Similar consideration for offshellness as for meson FF – a well-constrained experimental analysis should be reliable in regions of $-t$

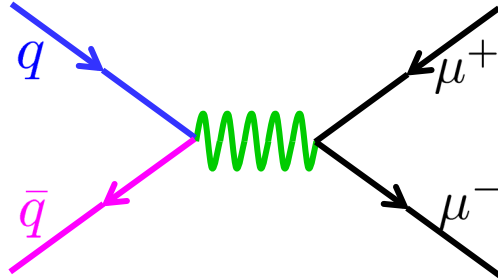
Tagged Deep Inelastic Scattering (TDIS)

- ❑ Use Sullivan process – scattering from nucleon-meson fluctuations



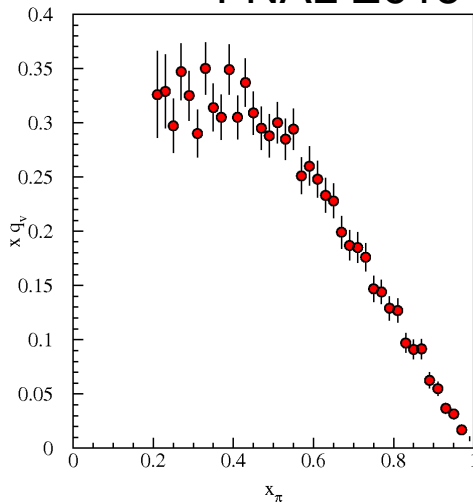
World Data on pion structure function F_2^π

Pion Drell-Yan

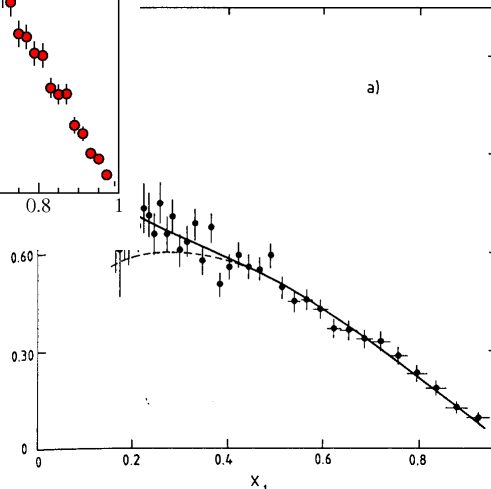


Data are very limited...

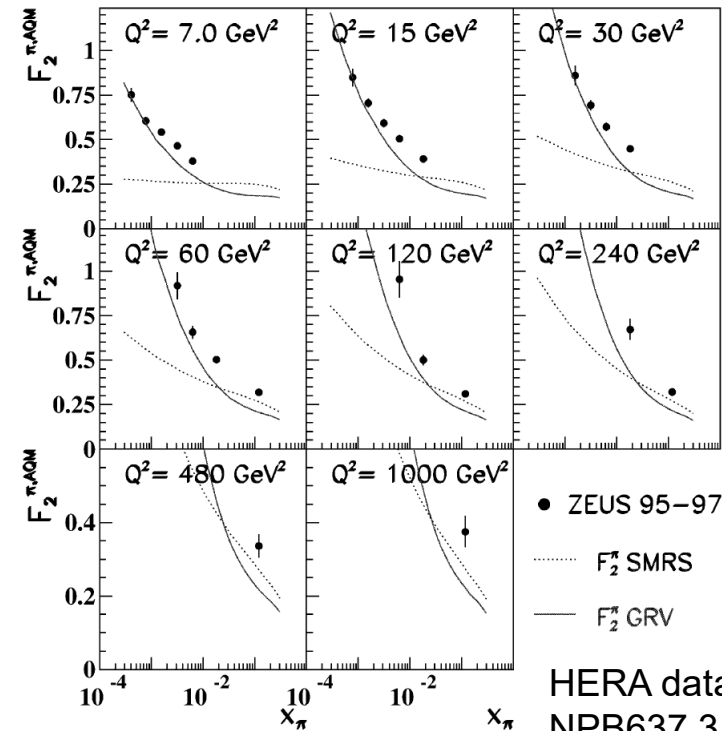
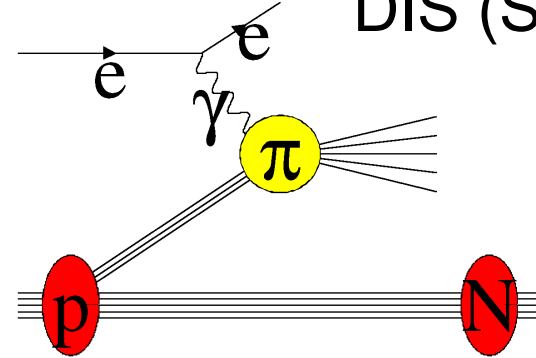
FNAL E615



CERN NA3

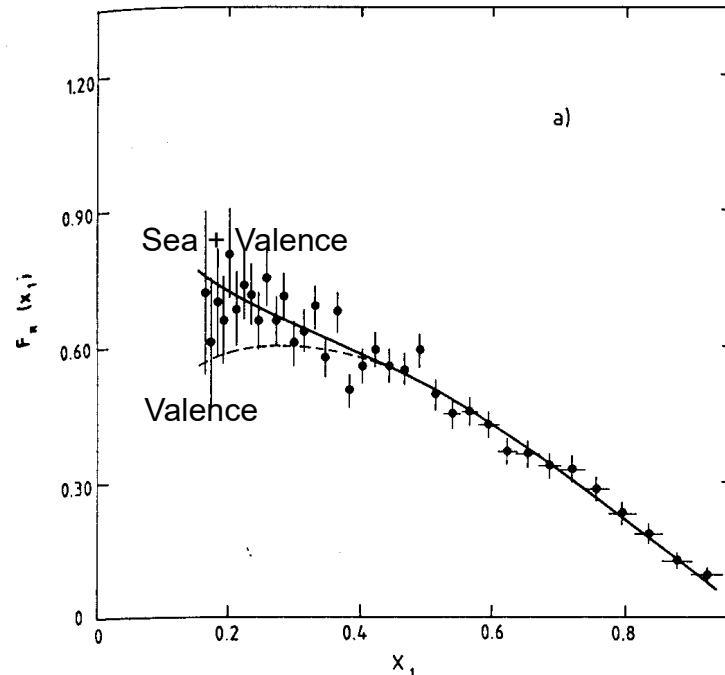


DIS (Sullivan Process)

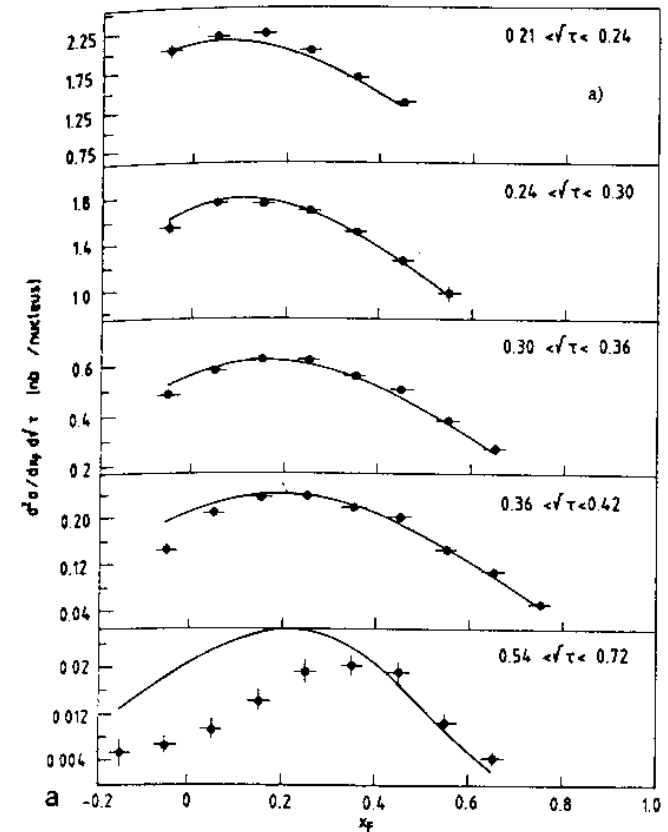


HERA data [ZEUS, NPB637 3 (2002)]

Pion Drell-Yan Data: CERN NA3 ($\pi^{+/-}$) NA10 (π^-)



NA3 200 GeV π^- data (also have 150 and 180 GeV π^- and 200 GeV π^+ data). Can determine pion sea!



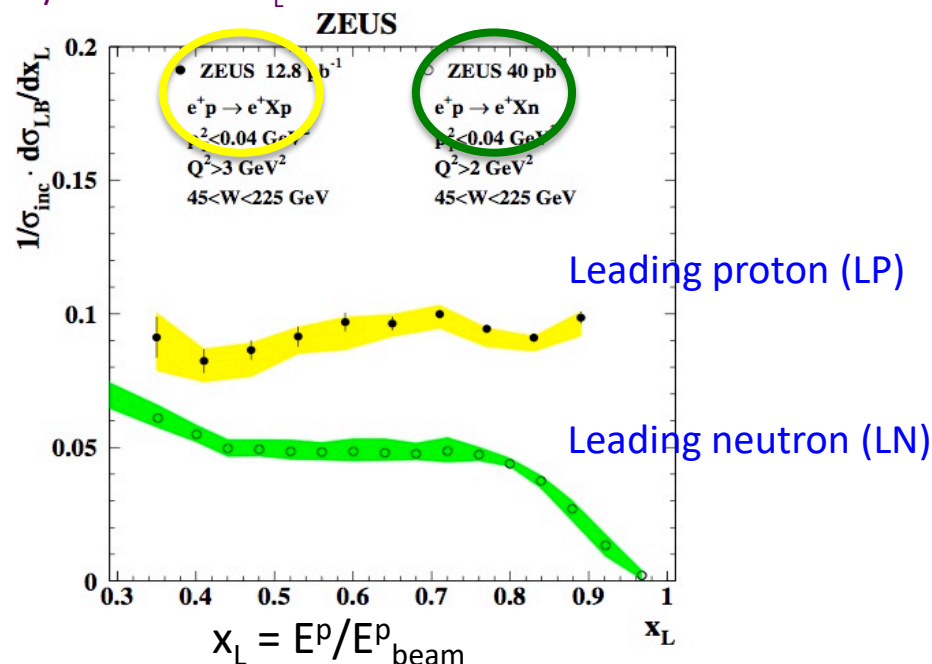
NA10 194 GeV π^- data

quark sea in pion is small – few %

$$Q_\pi^{\text{sea}} \equiv \int_0^1 x q_\pi^{\text{sea}}(x) dx = 0.01$$

Pion Structure Function from TDIS Measurements at HERA

Total yield for $0.35 < x_L < 0.9$



Pure isovector exchange

⇒ LP = 1/2 LN (isospin Clebsch-Gordon)

Data: LP ≈ 2LN

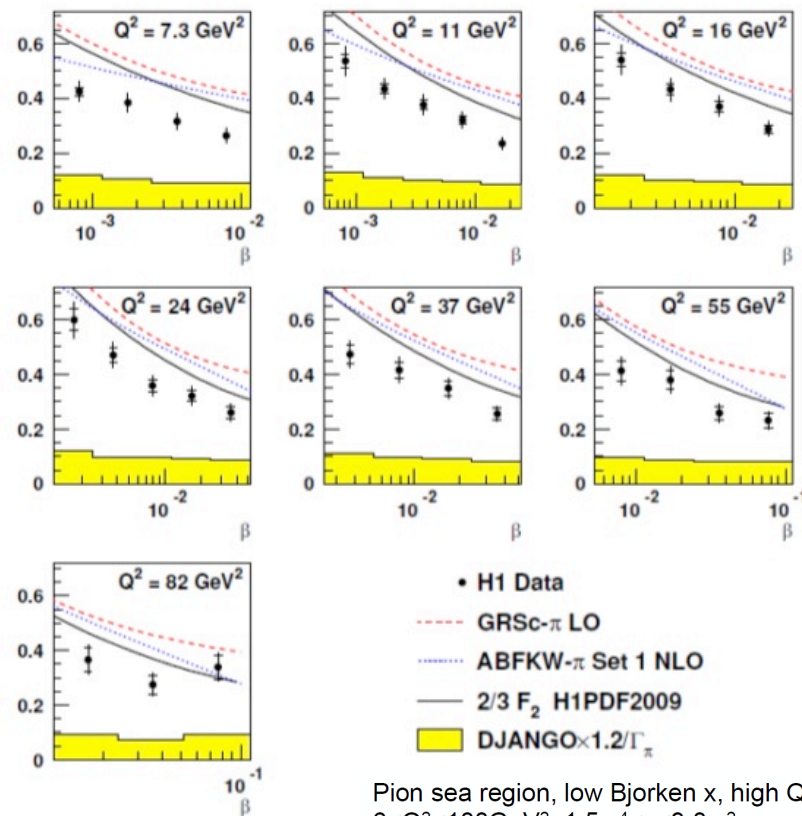
⇒ additional isoscalar exchanges for LP

Proton isoscalar events include diffractive scattering – *the neutral pion is buried*

Neutron events isovector only,
charged pions dominate

$F_2^{\text{LN}(3)}(x_L = 0.73)/\Gamma_\pi, \Gamma_\pi = 0.13$

H1



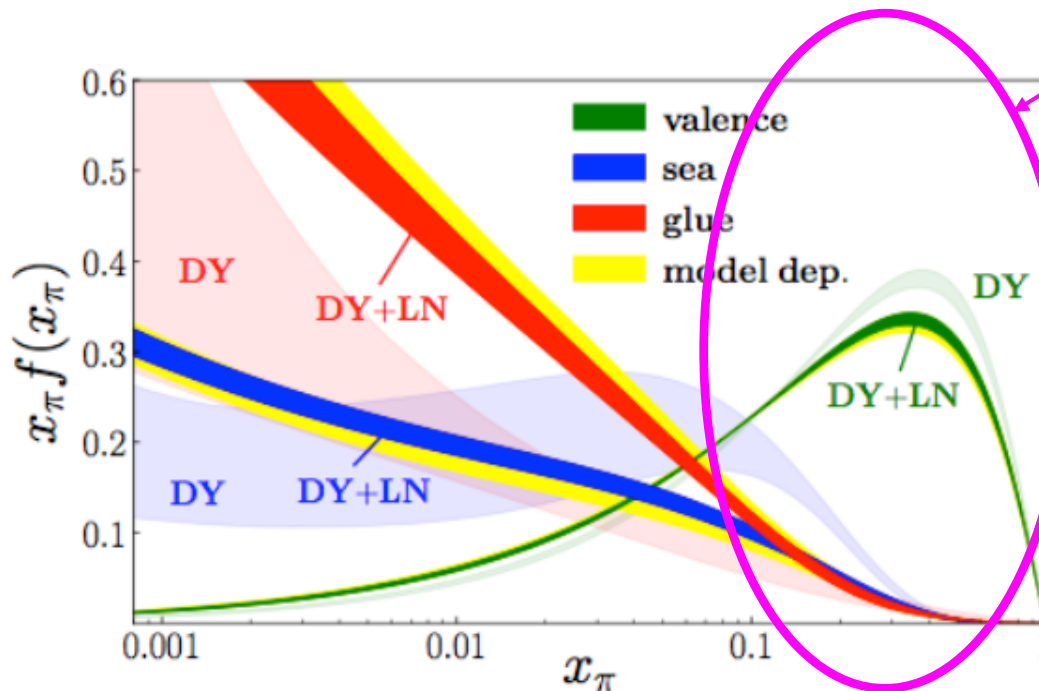
One pion exchange is the dominant mechanism

- *Can extract pion structure function*
- *In practice use in-depth model and kinematic studies to include rescattering, absorption, ...*

Global Fits: Pion and Structure Function

❑ First MC global QCD analysis of pion PDFs

- Using Fermilab DY and HERA Leading Neutron data



- ❑ JLab 12 GeV: Tagged Pion and Kaon TDIS
- ❑ Also prospects for kaon DY at COMPASS and pion and kaon LN at EIC

DY = πN Drell-Yan

LN = Leading Neutron

[Barry, Sato, Melnitchouk, Ji (2018, *Phys. Rev. Lett.* **121** (2018) no.15, 152001)]

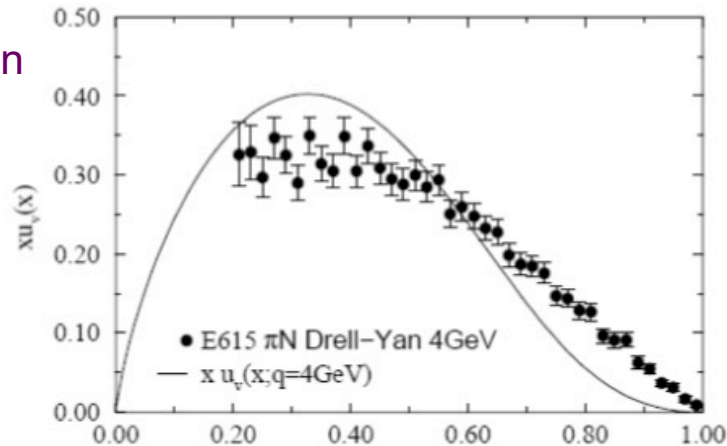
- Significant reduction of uncertainties on sea quark and gluon distributions in the pion with inclusion of HERA leading neutron data
- Implications for “TDIS” (Tagged DIS) experiments at JLab

Pion Structure Function from Drell-Yan: **Large x**

Large x Structure of the Pion

Initial observations:

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



FNAL E615, CERN NA3,10

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

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

$$x_\pi^x$$

❑ Model tensions, pQCD, Dyson-Schwinger, Light Front, Instanton,...

❑ Problems with data analysis?

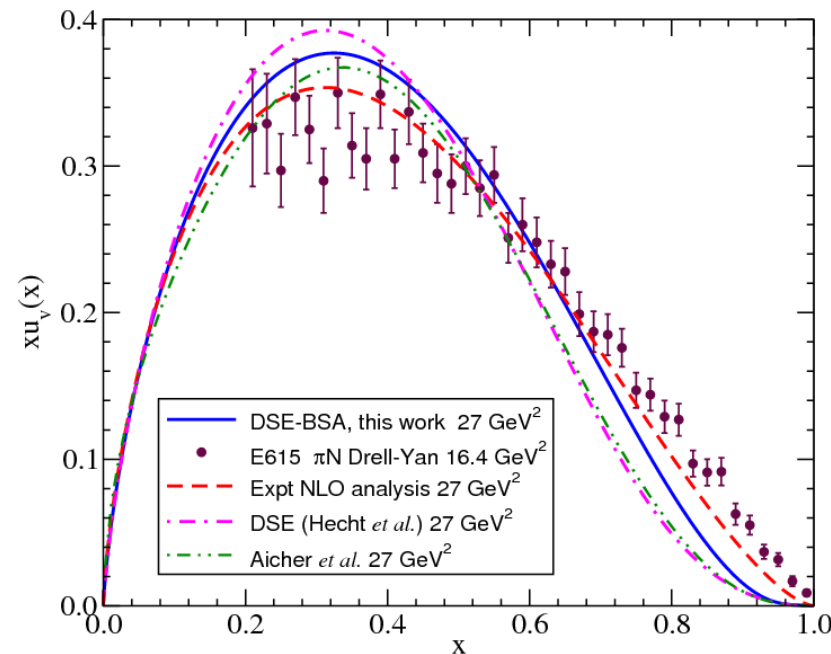
- NLO fit
- Improved proton PDFs
- Sea quark contribution
- More flexible extractions of PDFs

❑ Nuclear corrections needed?

❑ NLO gluon resummation effects

[Aicher, Schäfer, Vogelsang, Phys. Rev. Lett. 105, 252003 (2010)]

[L. Chang et al., Phys. Lett. B 737 (2014) 23]

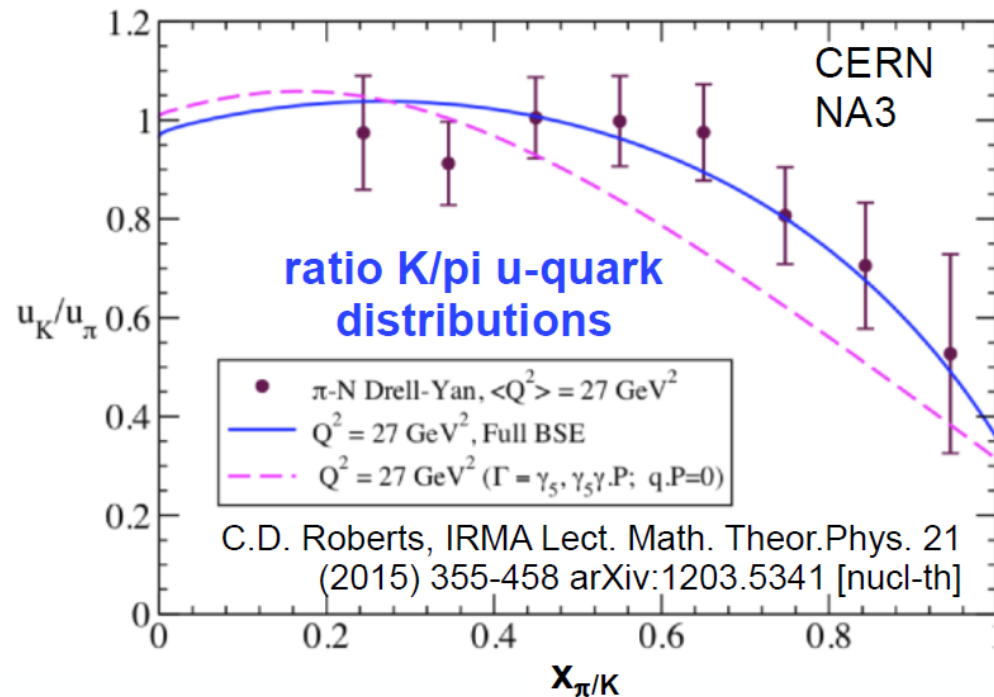


[C.D. Roberts, IRMA Lect. Math. Theor. Phys. 21 (2015) 355; arXiv:1203.5341 (2012)]

Jefferson Lab TDIS can provide important verification

Kaon Structure Function

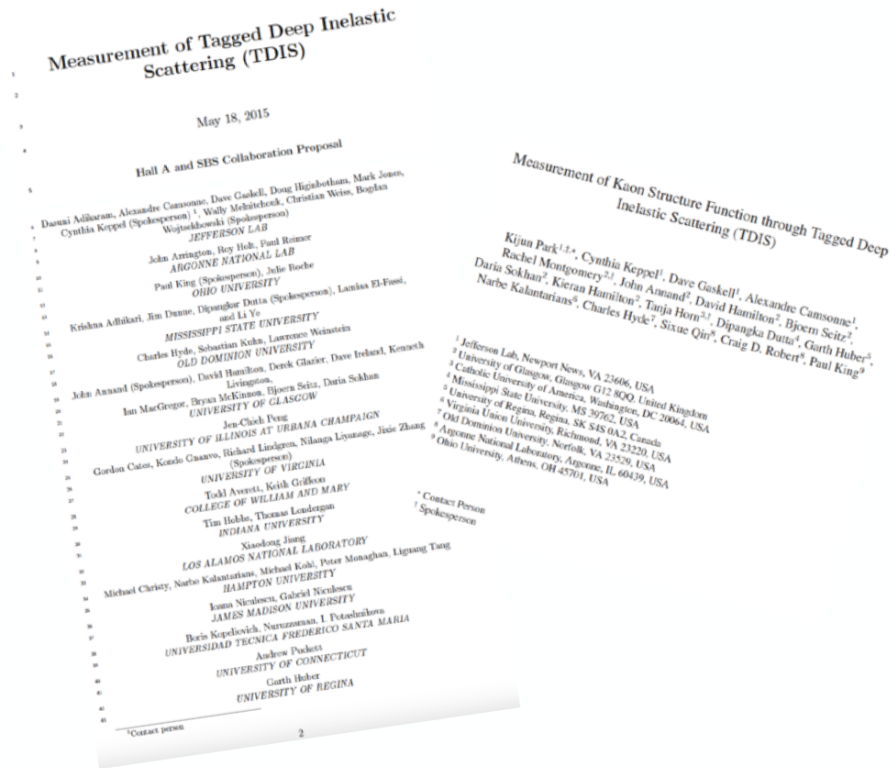
Practically no data...



*Jefferson Lab TDIS can provide important data,
and in particular at large x*

JLab 12 GeV Pion/Kaon TDIS Experiments (PR12-15-006)

Spokespersons: D. Dutta (MSU), C. Keppel (JLab), T. Horn (CUA), P. King (OU), N. Liyanage (UVA), R. Montgomery (U. Glasgow), K. Park (HU), B. Wojtsekhowski (JLab), J. Zhang (UVA)



Tagged Deep Inelastic Scattering (TDIS):

- ❑ Pion and Kaon F2 SF extractions in the valence regime
 - Independent charged pion SF
 - First neutral pion SF
 - First kaon SF

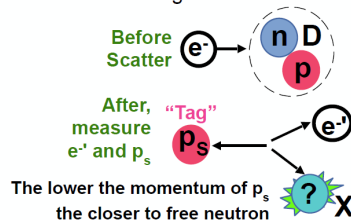
SIDIS measurement

- ❑ Spectator tagging - free pion/kaon targets not found in nature

Spectator Tagging at JLab

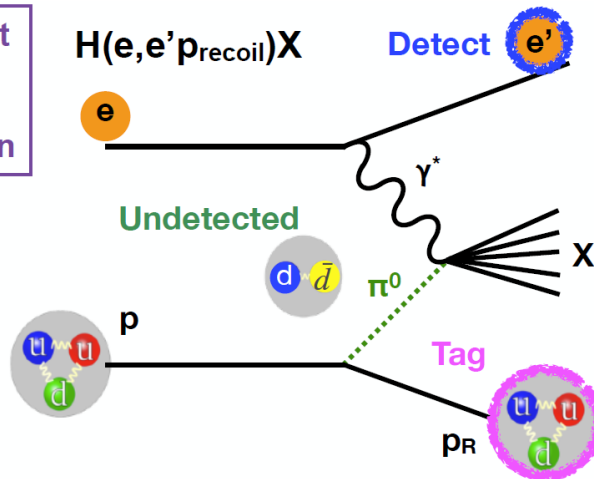
- ❑ BONUS – neutron valence structure, F2n input to global PDF fits
- ❑ BONUS12 – analysis underway

Effective free neutron target for BONUS/BONUS12

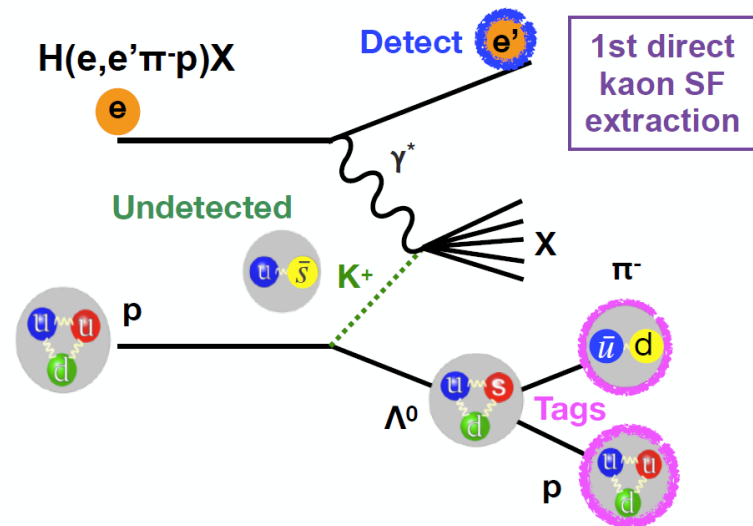


JLab 12 GeV Pion/Kaon TDIS Experiments (PR12-15-006)

1st direct
neutral
pion SF
extraction

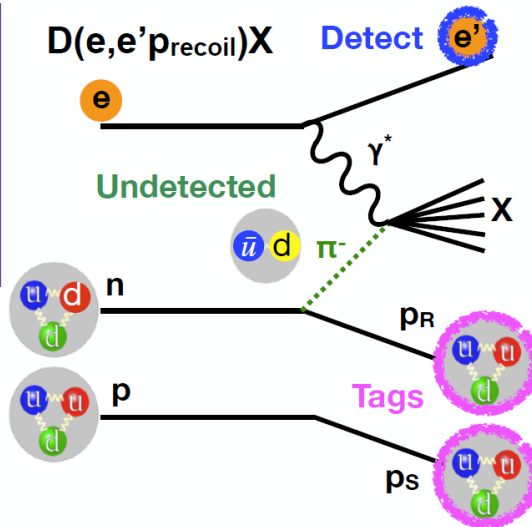


$H(e, e' \pi^- p) X$



1st direct
kaon SF
extraction

Resolve
QCD
model
tensions
for
charged
pion



$$\begin{aligned} 8 < W^2 < 18 \text{ GeV}^2 \\ 1 < Q^2 < 3 \text{ GeV}^2 \\ 0.05 < x < 0.2 \end{aligned}$$

- Novel detector essential for tagging very low momentum recoiling hadrons (60 - 400 MeV/c)

JLab Hall A TDis Experiment

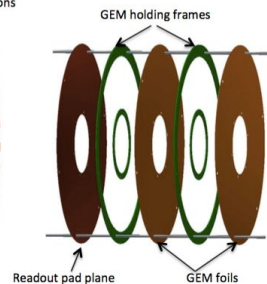
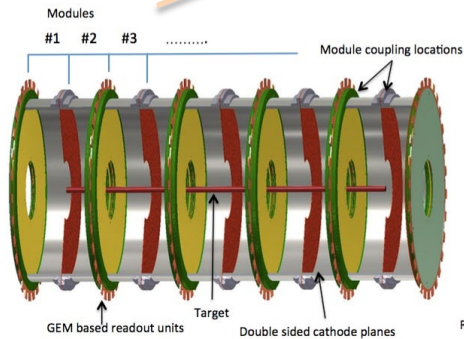
proton tag
detection in
GEM-based
mTPC at pivot



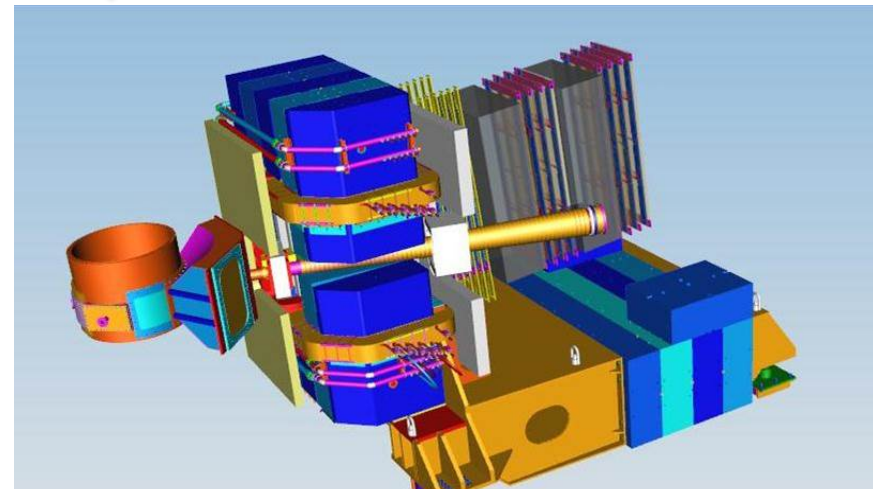
Hall A with SBS:

- ✓ High luminosity,
50 μAmp ,
 $\mathcal{L} = 3 \times 10^{36} / \text{cm}^2 \text{ s}$
- ✓ Large acceptance
 $\sim 70 \text{ msr}$

**Important for small
cross sections**



e- beam

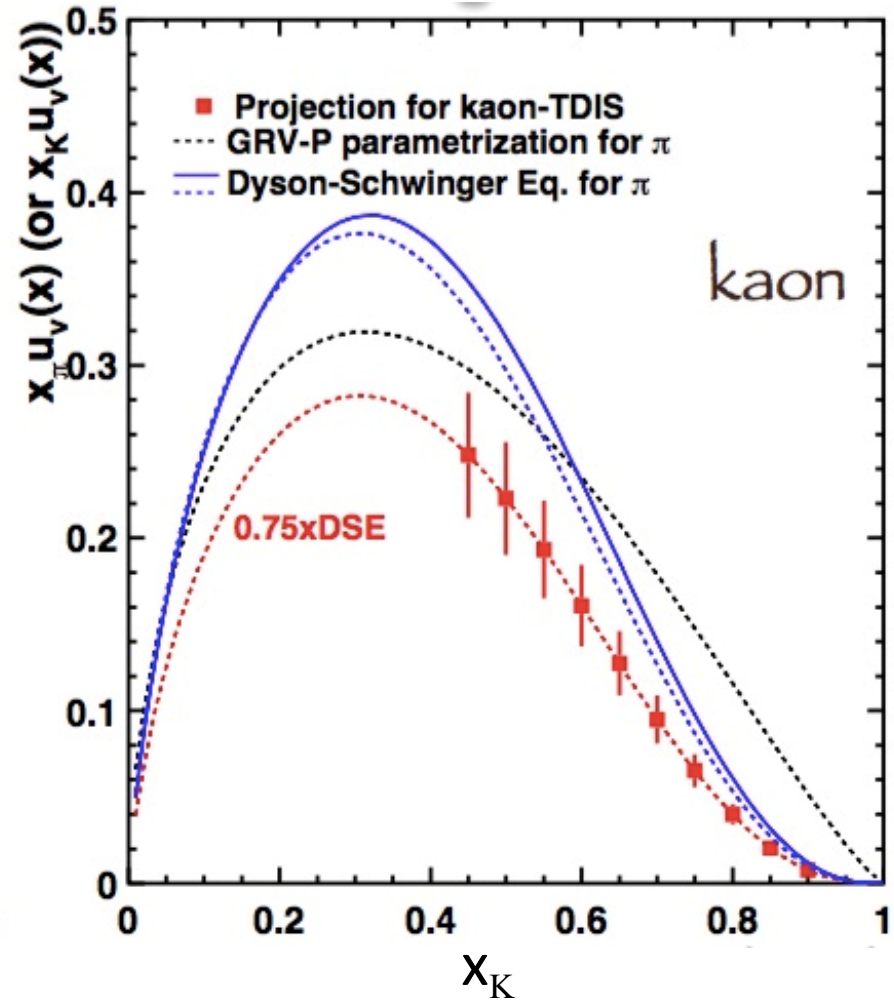
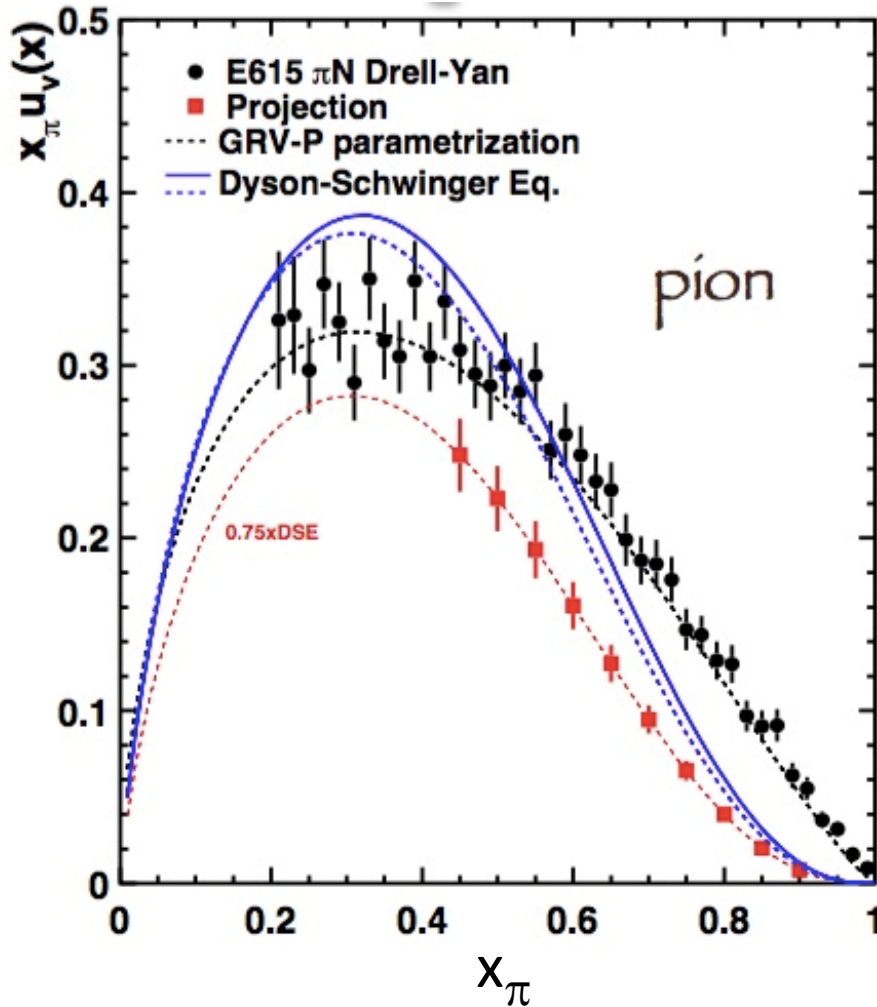


mTPC inside
superconducting
solenoid



Scattered electron detection in new Super
Bigbite Spectrometer (SBS)

Projected JLab TDIS Results for π , K Structure Functions

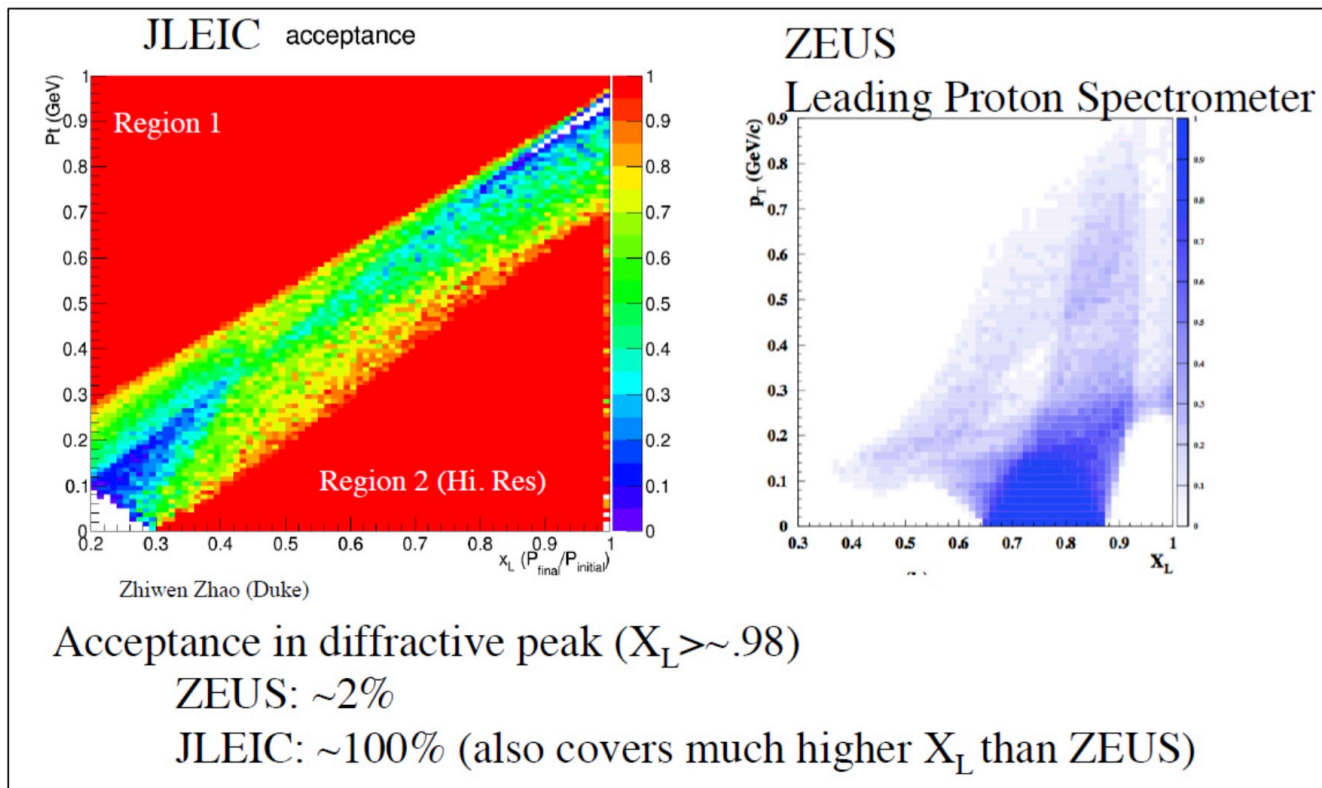


Essentially no data currently

Large Opportunity for Meson Structure Functions at the EIC

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

Example: acceptance for p' in $e + p \rightarrow e' + p' + X$



Huge gain in acceptance for forward tagging....

Pion and Kaon Structure at the EIC – History

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

Pion and Kaon Structure at an Electron-Ion Collider
1-2 June 2017, Physics

Jefferson Lab
EXPLORING THE NATURE OF MATTER

LINKS

- Circular
- Registration
- Program
- Transportation
- Lodging
- Participants List

PIEIC2018

Workshop on Pion and Kaon Structure at an EIC
May 24-25, 2018
The Catholic University of America
Washington, D.C.

Circular

This workshop will explore opportunities provided by the EIC to study the quark and gluon structure of the pion and kaon and will stake stock of the progress since the earlier workshop at Argonne National Lab: <http://www.pnpi.roma1.infn.it>

Organizing Committee

Ian Cloet - ANL
Tanja Horn - CUA
Cynthia Keppel - JLab
Craig Roberts - ANL

Sponsors:

CUA
Jefferson Lab

Introduction

This workshop at Argonne National Laboratory will explore opportunities provided by the EIC to study the quark and gluon structure of the pion and kaon.

Invited Speakers:

12000 Jefferson Avenue, Newport News, VA 23606
Phone: (757) 269-7100 Fax: (757) 269-7363

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 \(2020\)](#)
- ❑ [EHM through AMBER@CERN \(2020\)](#)
- ❑ ECT* Workshop in 2021 (remote) & 2022

Pion and Kaon Structure at the Electron-Ion Collider

Arlene C. Aguilar,¹ Zafir Ahmed,² Christine Aidala,³ Salma Ali,⁴ Vincent Andrieux,^{5,6} J. Adnan Bashir,² Vladimir Berdnikov,⁴ Daniele Binosi,³ Lei Chang,⁴⁰ Chen Chen,⁴¹ M. Pacheco B. C. de Melo,² Markus Diefenthaler,⁴³ Minghui Ding,^{9,40} Rolf Ent,⁶ T. Frederico,⁷ Gao,⁴⁵ Ralf W. Gothe,⁴⁶ Mohammad Hattawy,⁴⁷ Timothy J. Hobbs,⁴⁸ T. Horn,^{3,6,*} Y. Furlanova,⁶ Shaoyang Jia,⁴⁰ Cynthia Keppel,⁴⁹ Gastão Krein,²⁴ Huey-Wen Lin,¹⁰ J. Rodríguez-Quintero,¹⁷ Rachel Montgomery,²⁴ Hervé Moutarde,²⁵ Pavel Nadolsky,⁴⁰ J. Segovia,³⁰ Arun Tadealli,¹³ Richard Trotta,¹⁹ and D. Romanov,⁶

Workshop on Pion and Kaon Structure Functions at the EIC

Center for Frontiers in Nuclear Science
Workshop series

2-5 June 2020
Online

Overview

- Call for Abstracts
- Timetable
- Contribution List
- Registration
- Participant List
- Contact

The Lagrangian masses of the bulk of π and K mesons are issues in hadron physics to enable a quantum chromodynamics in terms of quarks and gluons.

Abstract. Understanding the structure of light pseudoscalar mesons is a central goal of nuclear physics. The EIC will provide a unique opportunity to study the quark and gluon structure of the pion and kaon at the electron-ion collider. The workshop will provide a platform for the exchange of ideas and information between the EIC and the meson physics community.

Participants: Arlington¹, C Ayerbe Gayoso², V Berdnikov³, D Binosi⁴, L Chang⁵, M Diefenthaler⁶, M Ding⁴, R Ent⁶, T Frederico⁷, Y Furlanova⁶, TJ Hobbs^{6,8}, T Horn^{3,6,*}, GM Huber⁹, SJD Kay⁹, C Keppel⁶, H-W Lin¹⁰, C Mezrag¹¹, R Montgomery¹², I Pegg³, K Raya^{5,13}, P Reimer¹⁴, DG Richards⁶, CD Roberts^{15,16}, J Rodríguez-Quintero¹⁷, D Romanov⁶, G Salmè¹⁸, J Segovia¹⁹, P Stepanov³, A Tadealli⁶ and R Trotta³

Meson Structure Functions Yellow Report Working Group

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

- Meson SF WG: 22 members, 13 institutions, 7 countries
- BlueJeans meetings every 2-3 weeks since January 2020
- To join the Meson Structure Functions WG mailing list, contact T. Horn (hornt@cua.edu)

- Within Yellow Report activities, part of the [EIC Diffractive Reactions & Tagging PWG](#)

- Very successful effort, and lively discussions, so Meson SF WG is likely to continue existing.

Meson SF Working group members:

John R. Arrington (LBNL), Carlos Ayerbe Gayoso (Mississippi State U), Daniele Binosi (ECT*), Lei Chang (Nankai U.), Rolf Ent (Jlab), Tobias Frederico (Instituto Tecnológico de Aeronautica), Timothy Hobbs (SMU), Tanja Horn (CUA), Garth Huber (U. Regina), Stephen Kay (U. Regina), Cynthia Keppel (Jlab), Bill Lee (W&M), Huey-Wen Lin (MSU), 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 Tadeepalli (JLab), Richard Trotta (CUA), Rik Yoshida (ANL)

The Physics Working Group is divided in the following subgroups:

➤ **Inclusive Reactions:** to join this group and its mailing list, contact **R. Fatemi**

➤ **Conveners:** **Renee Fatemi** (Kentucky), **Nobuo Sato** (JLab), **Barak Schmookler** (Stony Brook)

➤ **Semi-inclusive Reactions:** to join this group and its mailing list, contact **R. Seidl**

➤ **Conveners:** **Ralf Seidl** (RIKEN), **Justin Stevens** (W&M), **Alexey Vladimirov** (Regensburg), **Anselm Vossen** (Duke), **Bowen Xiao** (CCNU, China)

➤ **Jets, Heavy Quarks:** to join this group and its mailing list, contact **L. Mendez**

➤ **Conveners:** **Leticia Mendez** (ORNL), **Brian Page** (BNL), **Frank Petriello** (ANL & Northwestern U.), **Ernst Sichtermann** (LBL), **Ivan Vitev** (LANL)

➤ **Exclusive Reactions:** to join this group and its mailing list, contact **S. Fazio**

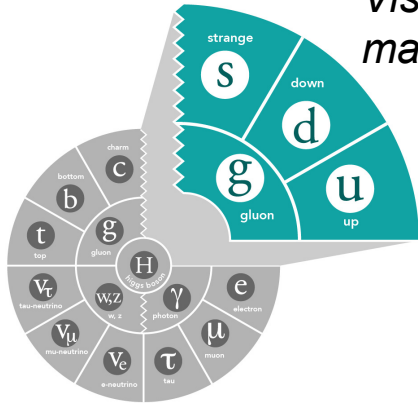
➤ **Conveners:** **Raphaël Dupré** (Orsay), **Salvatore Fazio** (BNL), **Tuomas Lappi** (Jyväskylä), **Barbara Pasquini** (Pavia), **Daria Sokhan** (Glasgow)

➤ **Diffractive Reactions & Tagging:** to join this group and its mailing list, contact **W. Cosyn**

➤ **Conveners:** **Wim Cosyn** (Florida), **Or Hen** (MIT), **Doug Higinbotham** (JLab), **Spencer Klein** (LBNL), **Anna Stasto** (PSU)

Mass of the Proton, Pion, Kaon

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



Proton

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

Gluon rise discovered by HERA e-p

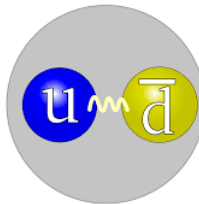
“Mass without mass!”



GeV

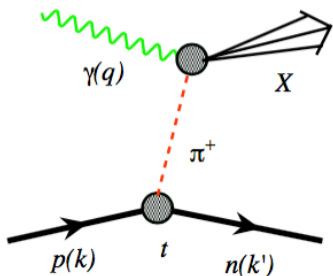
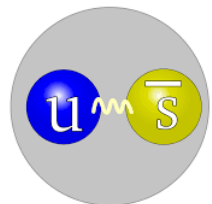
Pion

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?



For the proton the EIC will allow determination of an important term contributing to the proton mass, the so-called “QCD trace anomaly”
For the pion and the kaon the EIC will allow determination of the quark and gluon contributions with the Sullivan process.

A.C. Aguilar et al., Pion and Kaon structure at the EIC, *EPJA* **55** (2019) 190.

J. Arrington et al., Revealing the structure of light pseudoscalar mesons at the EIC, *J. Phys. G* **48** (2021) 7 075106.

C.D. Roberts, D. Richards, T. Horn, L. Chang, Insights into Emergence of Mass, *Prog. Part. NP* **120** (2021) 103883

Origin of Mass in the EIC Yellow Report

2.3 Origin of Nucleon Mass

Yellow Report, exec. summary, pages 9/10

See: R. Ent's talk on EIC Overview and Yellow Report

More than 99% of the mass of the visible universe resides in atomic nuclei, whose mass, in turn, is primarily determined by the masses of the proton and neutron. Therefore, it is of utmost importance to understand the origin of the proton (and neutron) mass, particularly how it emerges from the strong interaction dynamics. Interestingly, the proton mass is not even approximately given by summing the masses of its constituents, which can be attributed to the Higgs mechanism. Just adding the masses of the proton's valence quarks provides merely about 1% of the proton mass. While a QCD analysis leads to a more considerable quark mass contribution to the proton mass, the qualitative picture that the Higgs mechanism is responsible for only a small fraction of the proton mass is not altered. An essential role for a complete understanding of the proton mass is played by the trace anomaly of the QCD energy-momentum tensor [8–11]. It is precisely this essential ingredient for which the EIC can deliver crucial input through dedicated measurements of quarkonia's exclusive production (J/ψ and Υ) close to the production threshold.

Another way to address the emergence of mass is through the pion and kaon

The trace anomaly vanishes for the pion due to cancellations between competing effects in the chiral limit of vanishing quark masses. It is exact in the case of pions due to dynamical chiral symmetry breaking. For the kaon, the effect of the Higgs mechanism will play a more substantial role. This affects the shape and size of the pion (and kaon) wave function and has measurable implications for the various quark/gluon energy distributions and the form factor.

The Role of Gluons in the Chiral Limit

In the chiral limit, using a parton model basis: *the entirety of the proton mass is produced by gluons and due to the trace anomaly*

$$\langle P(p) | \Theta_0 | P(p) \rangle = -p_\mu p_\mu = m_N^2$$

In the chiral limit, for the pion ($m_\pi = 0$):

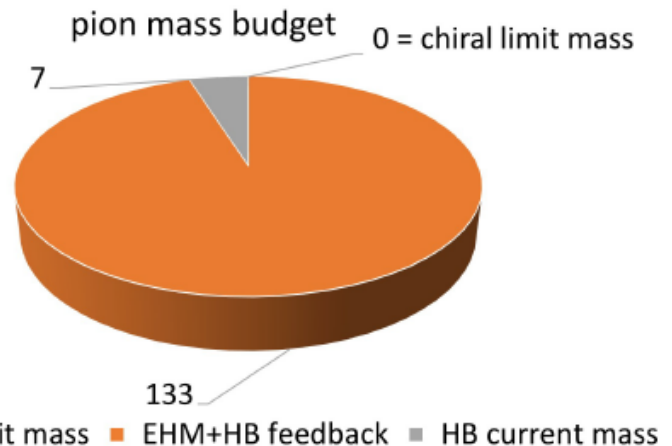
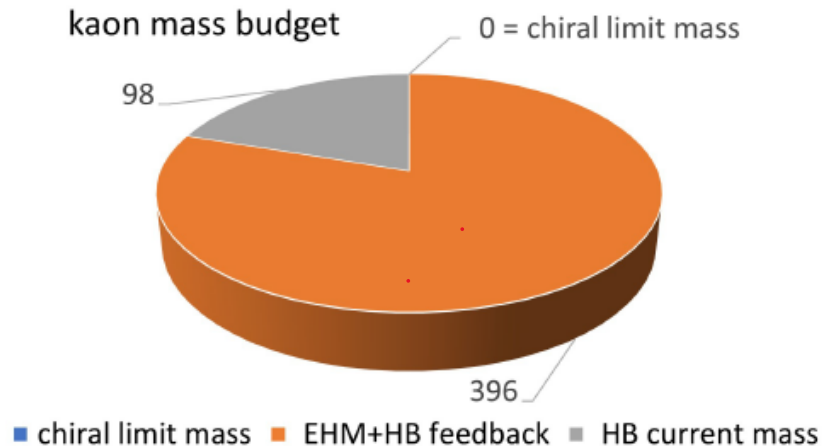
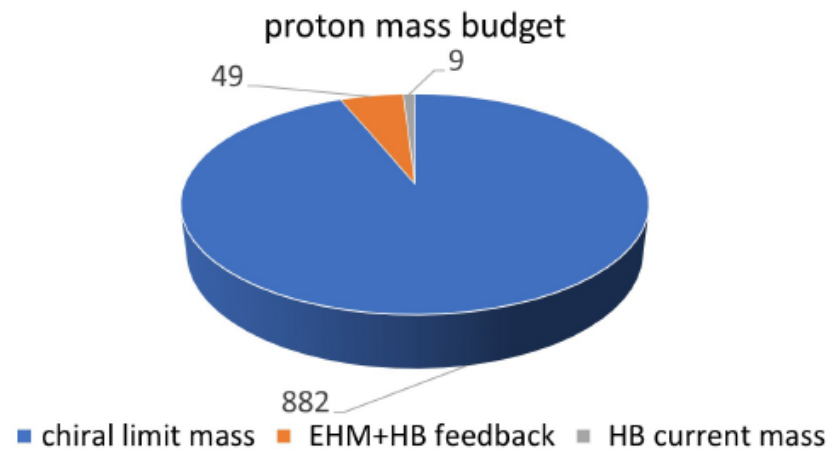
$$\langle \pi(q) | \Theta_0 | \pi(q) \rangle = -q_\mu q_\mu = m_\pi^2 = 0$$

in the chiral limit the gluons disappear and thus contribute nothing to the pion mass

This is unlikely as quarks and gluons still dynamically acquire mass – this is a universal feature in hadrons – so more likely a cancellation of terms leads to “0”

Nonetheless: are there gluons at large Q^2 in the pion or not?

Mass Budgets for the Proton, Kaon and Pion

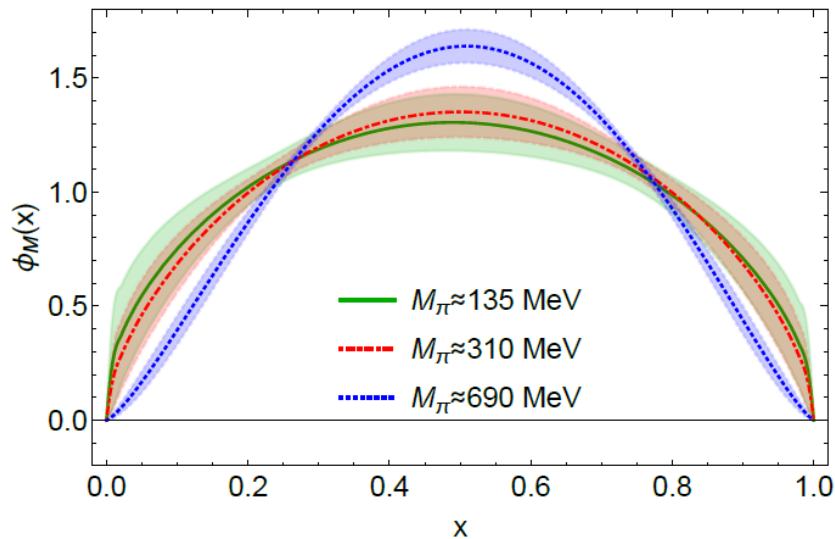


Strong Synergy with Lattice QCD

Huey-Wen Lin et al.

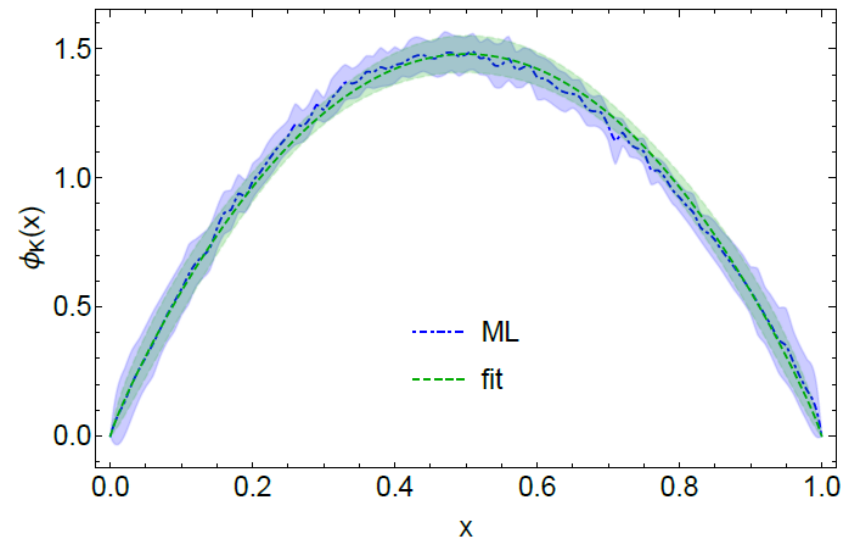
Parton distribution amplitudes

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



As the pion mass decreases, the distribution amplitude gets broader

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

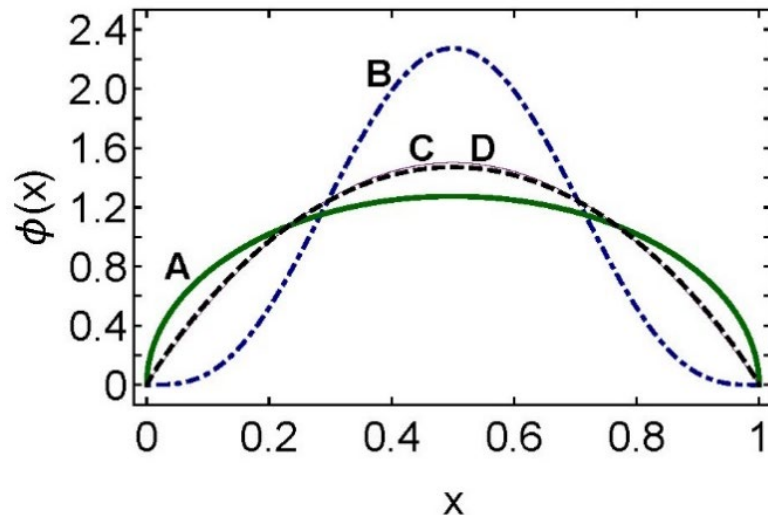


Note the slight asymmetry in the distribution amplitude around $x = 0.5$

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

Emergent- versus Higgs-Mass Generation

Twist-2 PDA at Scale $\zeta = 2 \text{ GeV}$



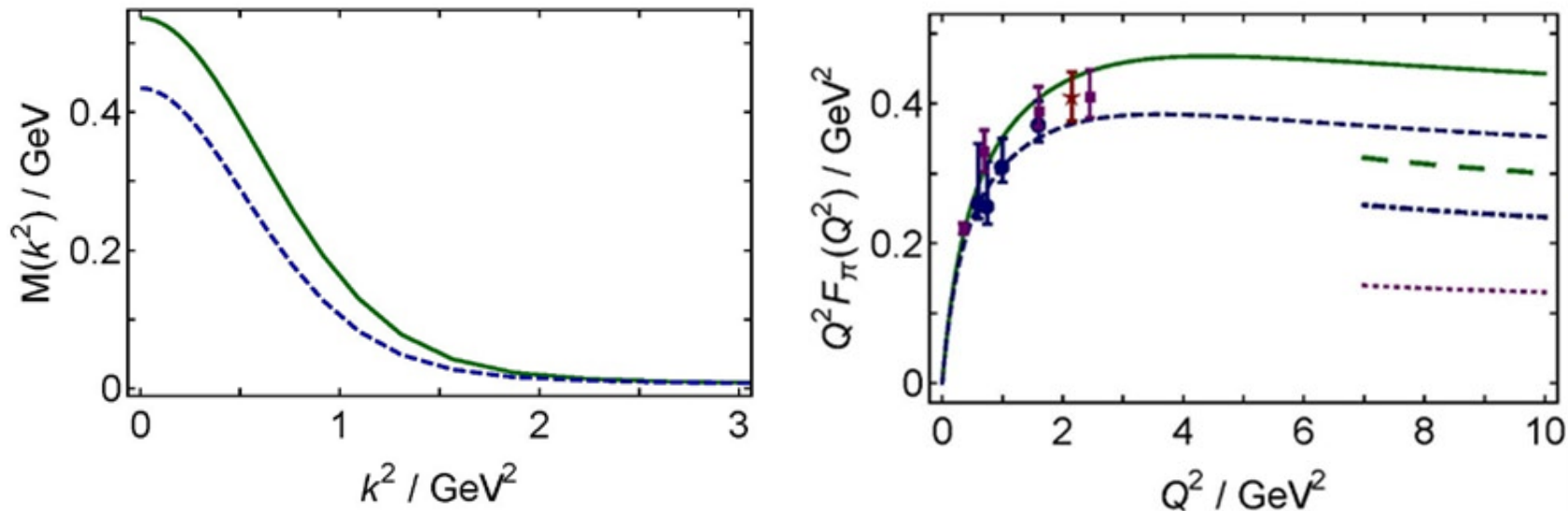
Unfortunately, experimental signatures of the exact PDA form are, in general, difficult.

- A** solid (green) curve – pion \Leftarrow emergent mass is dominant;
- B** dot-dashed (blue) curve – $\eta_c \Leftarrow$ primarily, Higgs mass generation;
- C** solid (thin, purple) curve – conformal limit result, $6x(1-x)$; and
- D** dashed (black) curve – “heavy-pion”, i.e., a pion-like pseudo-scalar meson ($\sim \eta_s$) in which the valence-quark current masses take values corresponding to a strange quark \Leftarrow the border, where emergent and Higgs mass generation are equally important.

- 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 $x = 1/2$.
- The sufficiently heavy η_c meson (**B**), feels the Higgs mechanism strongly.
- The PDA for the light-quark pion (**A**) is a broad, concave function, a feature of emergent mass generation.

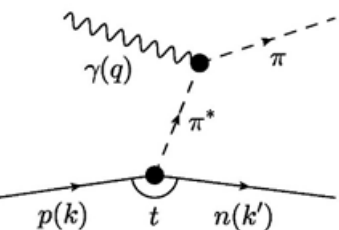
Pion Form Factor and Emergent Mass

Muyang Chen, Craig Roberts

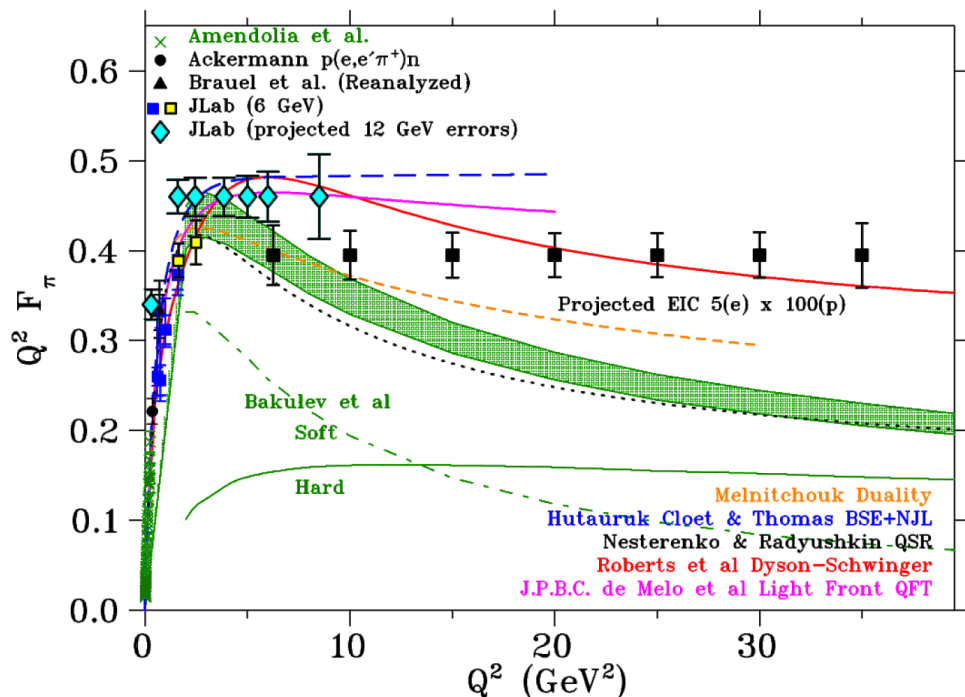


Left panel. Two dressed-quark mass functions distinguished by the amount of DCSB: emergent mass generation is 20% stronger in the system characterized by the solid green curve, which describes the more realistic case. Right panel. $F_\pi(Q^2)$ obtained with the mass function in the left panel: $r_\pi = 0.66$ fm with the solid green curve and $r_\pi = 0.73$ 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, $\phi(x)=6x(1-x)$.

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

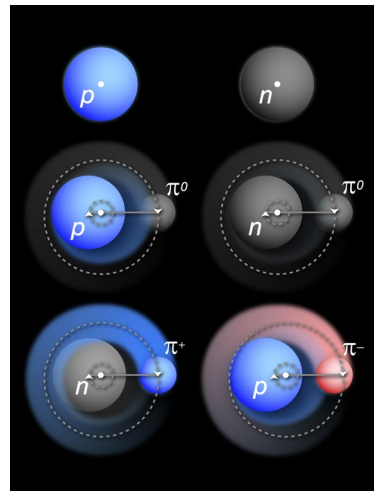


- Assumed 5 GeV(e^-) x 100 GeV(p) with an integrated luminosity of 20 $\text{fb}^{-1}/\text{year}$, and similar luminosities for d beam data
- $R = \sigma_L / \sigma_T$ assumed from VR model and assume that π pole dominance at small t confirmed in ^2H π^-/π^+ ratios
- Assumed a 2.5% pt-pt and 12% scale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

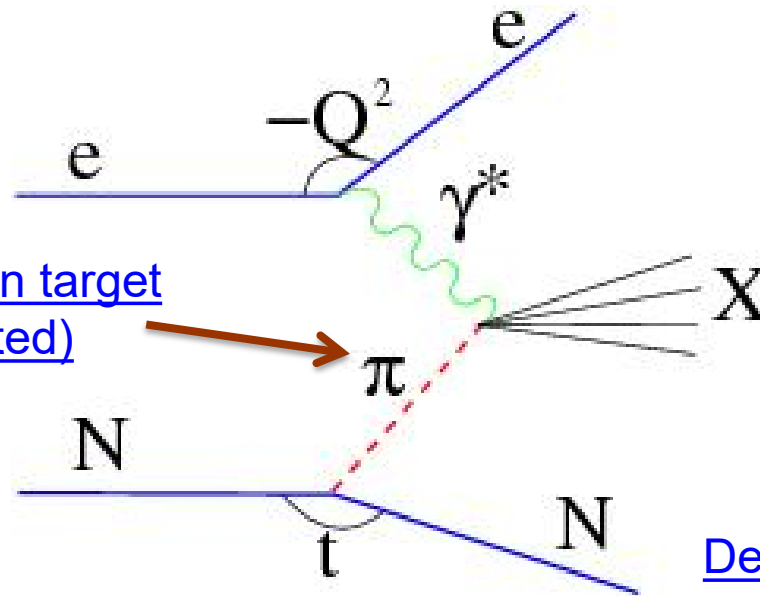
Can we measure the kaon form factor at EIC? Or only through L/T separations emphasizing lower energies? Not clear – needs guidance from JLab 12- GeV.

Physics Objects for Pion/Kaon Structure Studies

Sullivan process – scattering from nucleon-meson fluctuations



Pion/Kaon target
(undetected)



Detect scattered electron

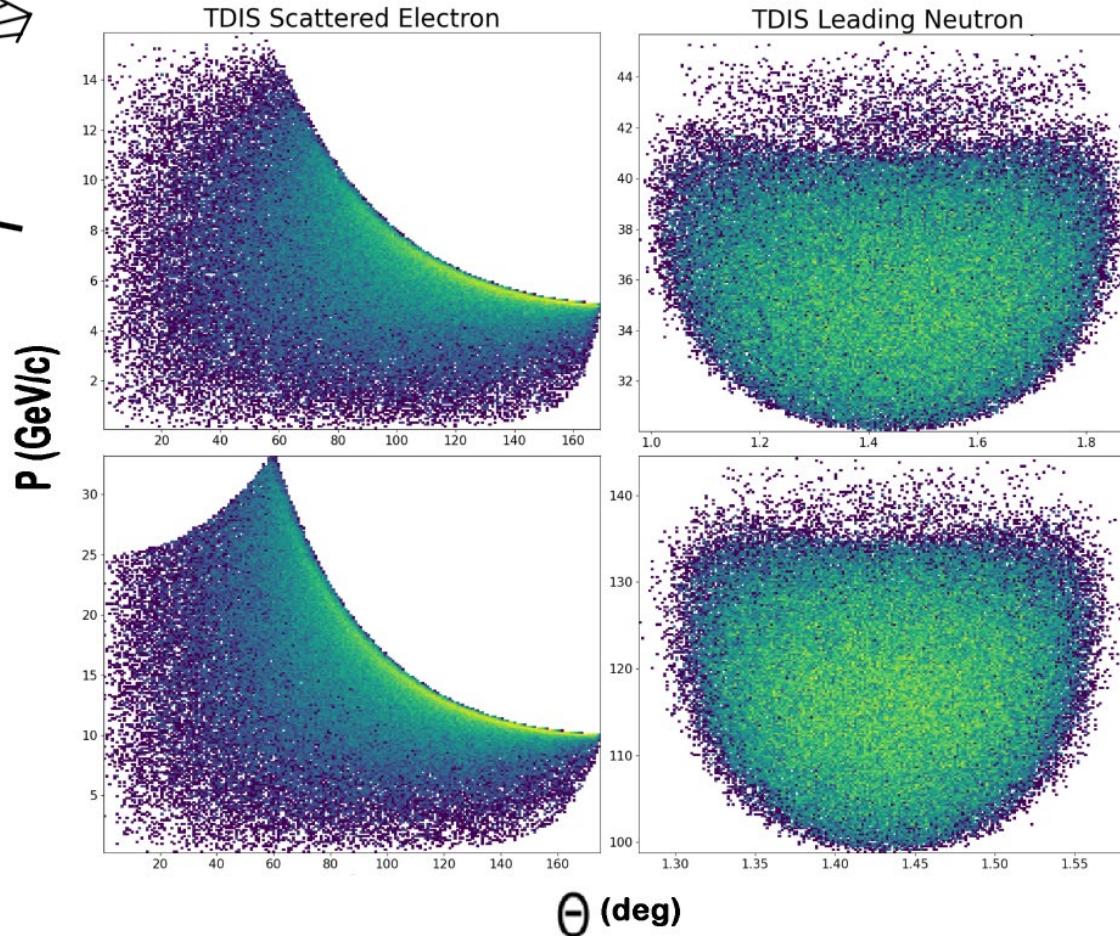
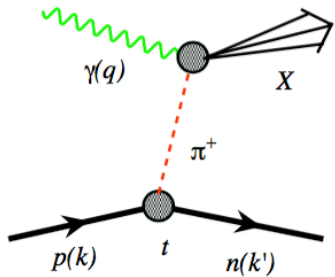
DIS event –
reconstruct x , Q^2 ,
 W^2 , also M_X (W_π)
of undetected
recoiling hadronic
system

Detect “tagged”
neutron/lambda

$$F_2^{LP(3)} = \sum_i \left[\int_{t_0}^{t_{min}} f_i(z, t) dt \right] F_2^i(x_i, Q^2)$$

“Flux factor”

EIC Meson Structure Kinematics



Electron x Proton
beam energies

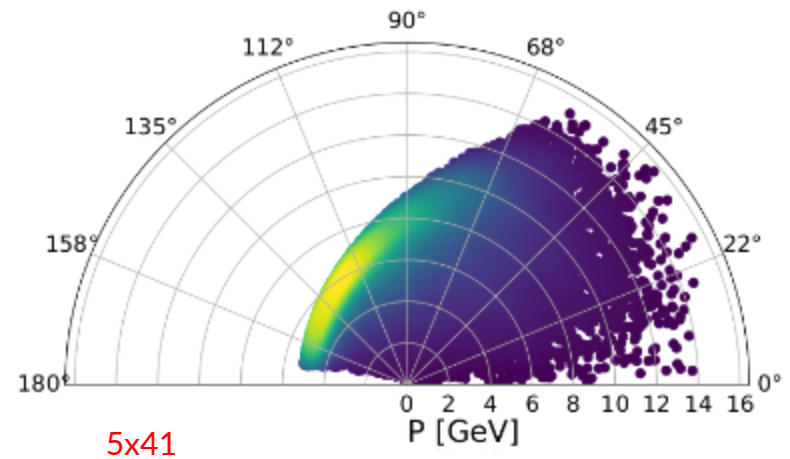
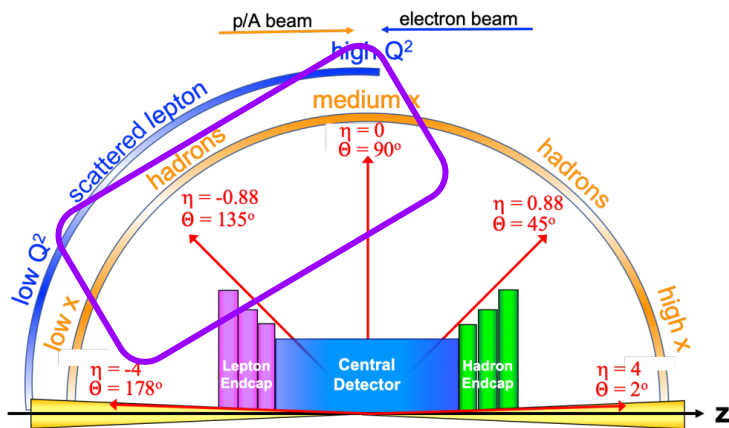
5 GeV x 41 GeV

10 GeV x 135 GeV

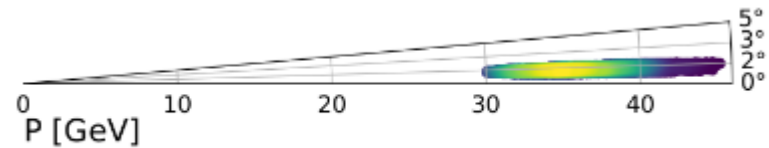
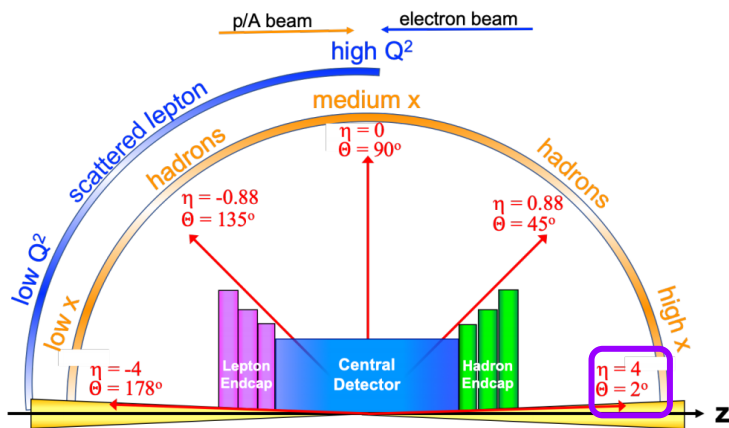
Scattered electron goes in EIC
central detector region

Leading neutron (or lambda) are at small
forward angles and carry most of the
proton beam momentum

Scattered Electron

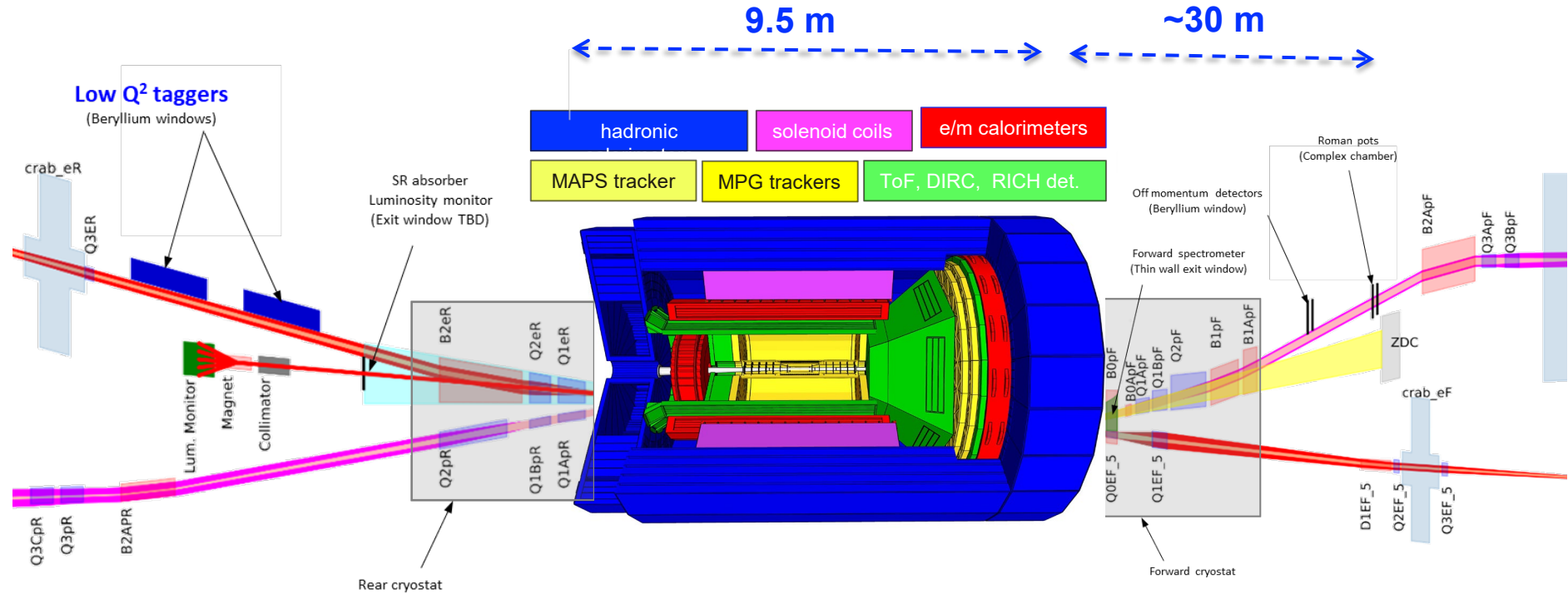


Leading Baryon

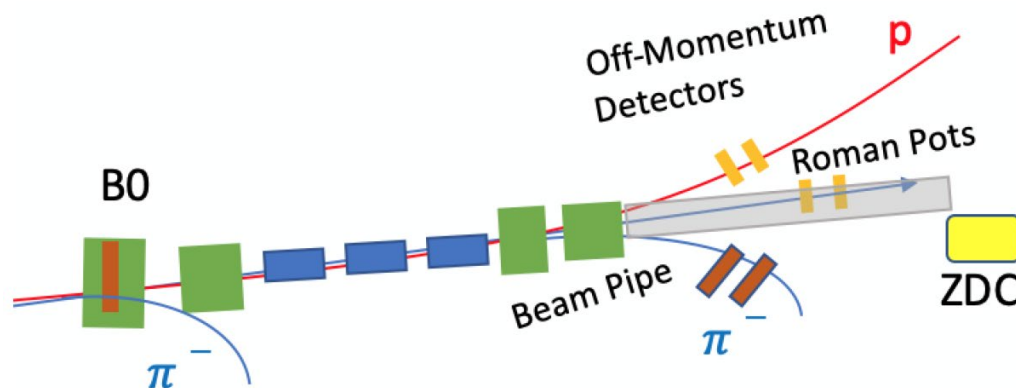


Baryon (neutron lambda) at very small forward angles and nearly the beam momentum

EIC Extended Detector integrated into the IR



Meson Structure: Summary of EIC Detector Requirements



❑ For π -n:

- Lower energies (5 on 41, 5 on 100) require at least $60 \times 60 \text{ cm}^2$
- 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

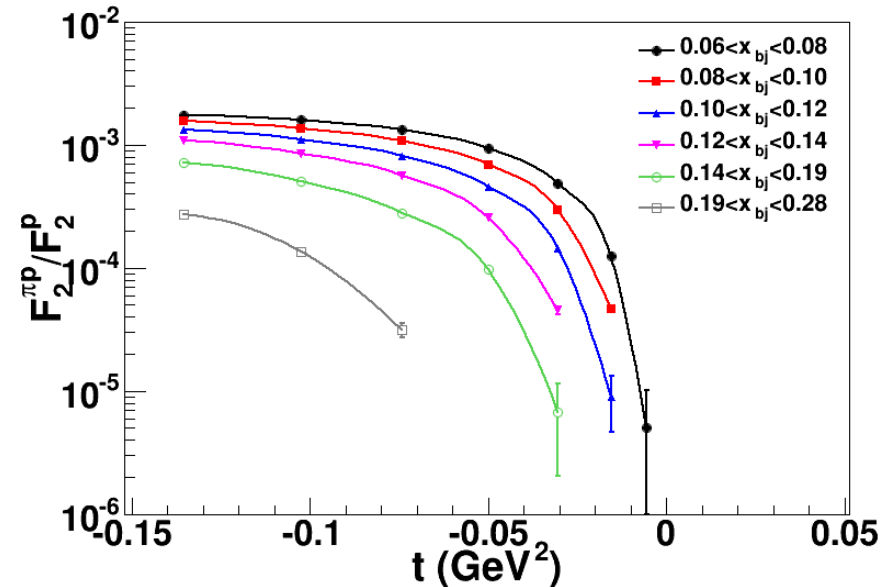
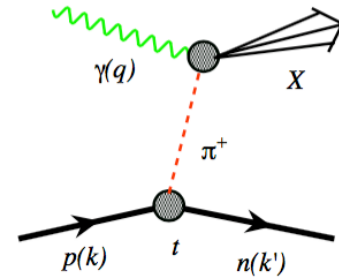
❑ Standard electron detection requirements

❑ Good hadron calorimetry for good x resolution at large x

EIC – Versatility and Luminosity is Key

Why would pion and kaon structure functions, and even measurements of pion structure beyond (pion GPDs and TMDs) be feasible at an EIC?

- $L_{\text{EIC}} = 10^{34} = 1000 \times L_{\text{HERA}}$
- Detection fraction @ EIC in general much higher than at HERA
- Fraction of proton wave function related to pion Sullivan process is roughly 10^{-3} for a small $-t$ bin (0.02).
- Hence, pion data @ EIC should be comparable or better than the proton data @ HERA, or the 3D nucleon structure data @ COMPASS
- If we can convince ourselves we can map pion (kaon) structure for $-t < 0.6$ (0.9) GeV^2 , we gain at least a decade as compared to HERA/COMPASS.



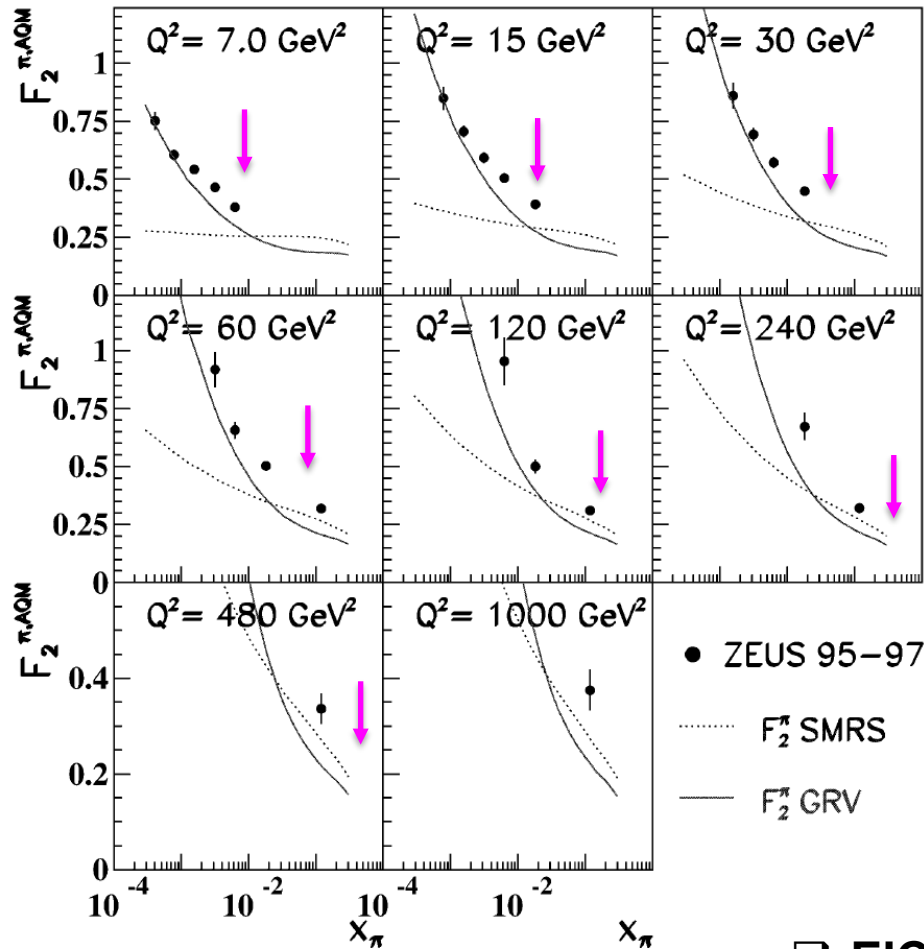
Ratio of the F_2 structure function related to the pion Sullivan process as compared to the proton F_2 structure function in the low- t vicinity of the pion pole, as a function of Bjorken- x (Jefferson Lab TDIS Collaboration, JLab Experiment C12-15-005)

World Data on pion structure function F_2^π

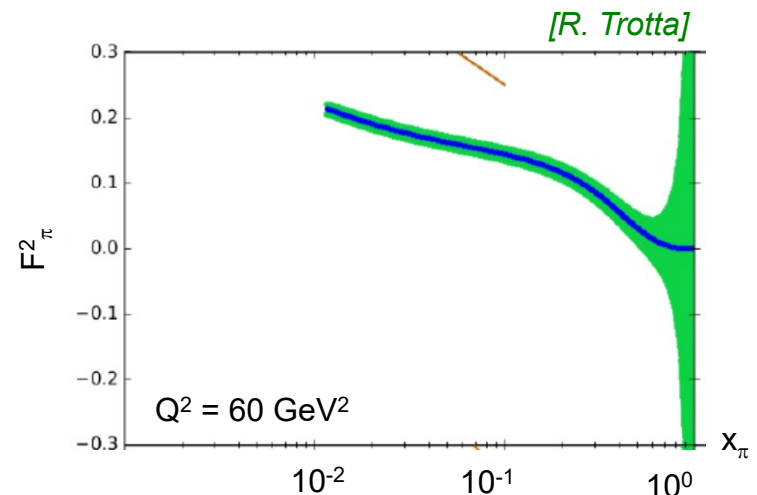
HERA

↓ $\sim x_{\min}$ for EIC

EIC

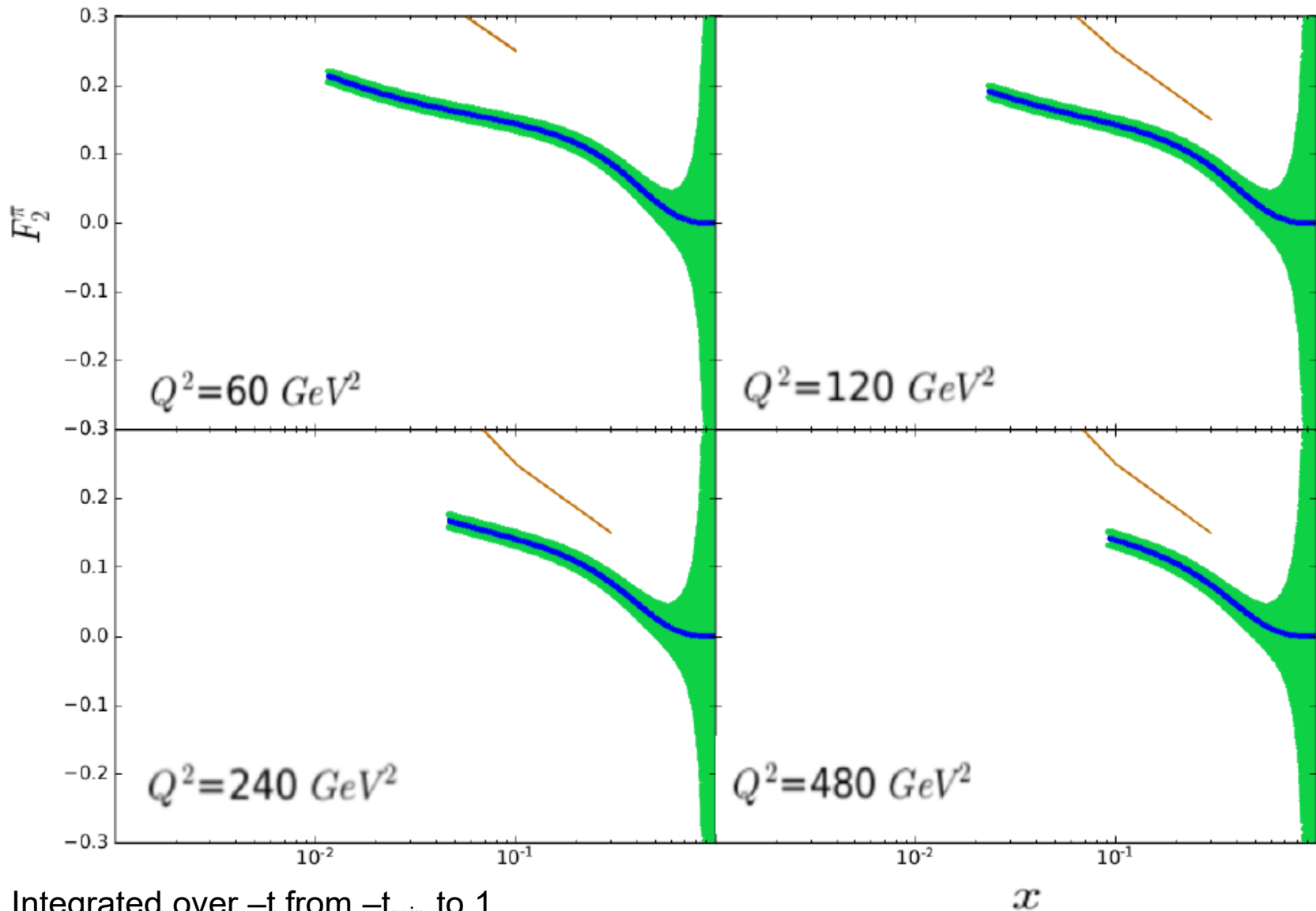


Here example for 5 GeV e^- and 100 GeV p

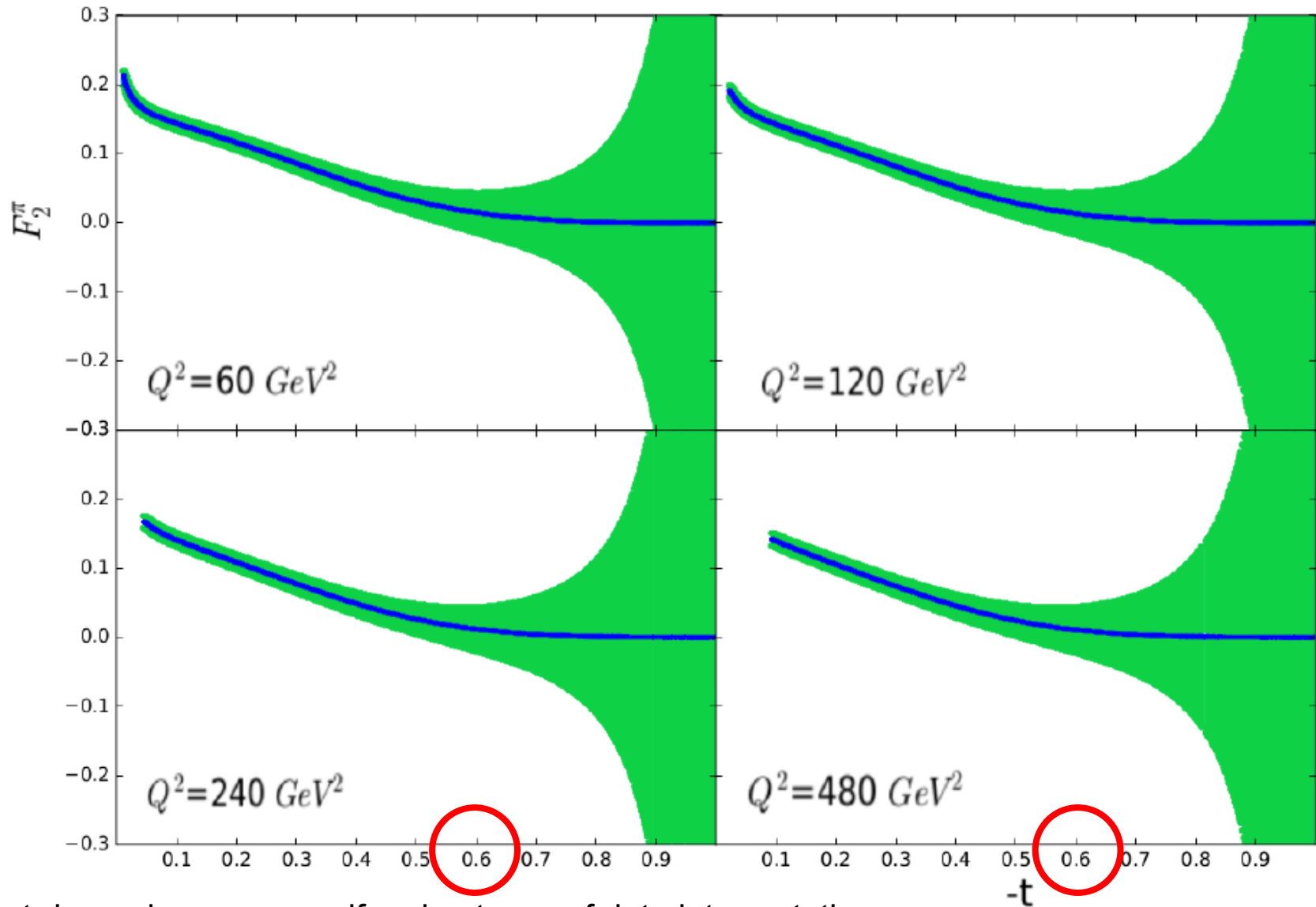


- ❑ EIC kinematic reach down to a $x = \text{few } 10^{-3}$
- ❑ Lowest x constrained by HERA

Pion Structure Function Projections vs x



Pion Structure Function Projections vs $-t$



t -dependence can verify robustness of data interpretation

Reduction of Pion 1-D Structure Information by EIC

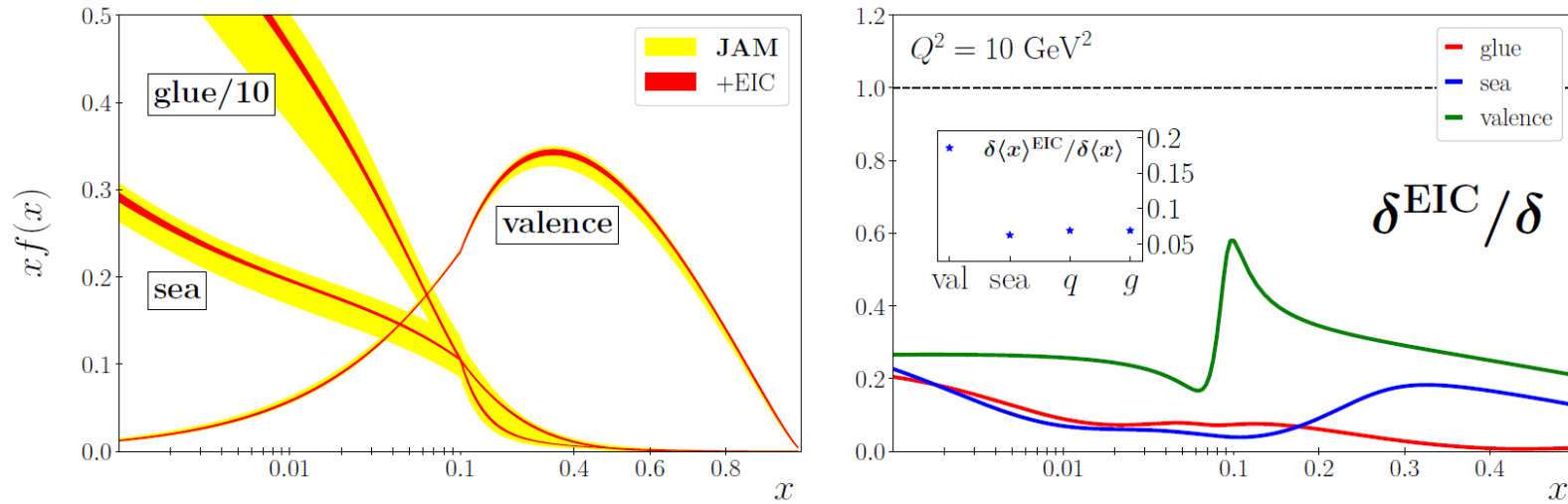


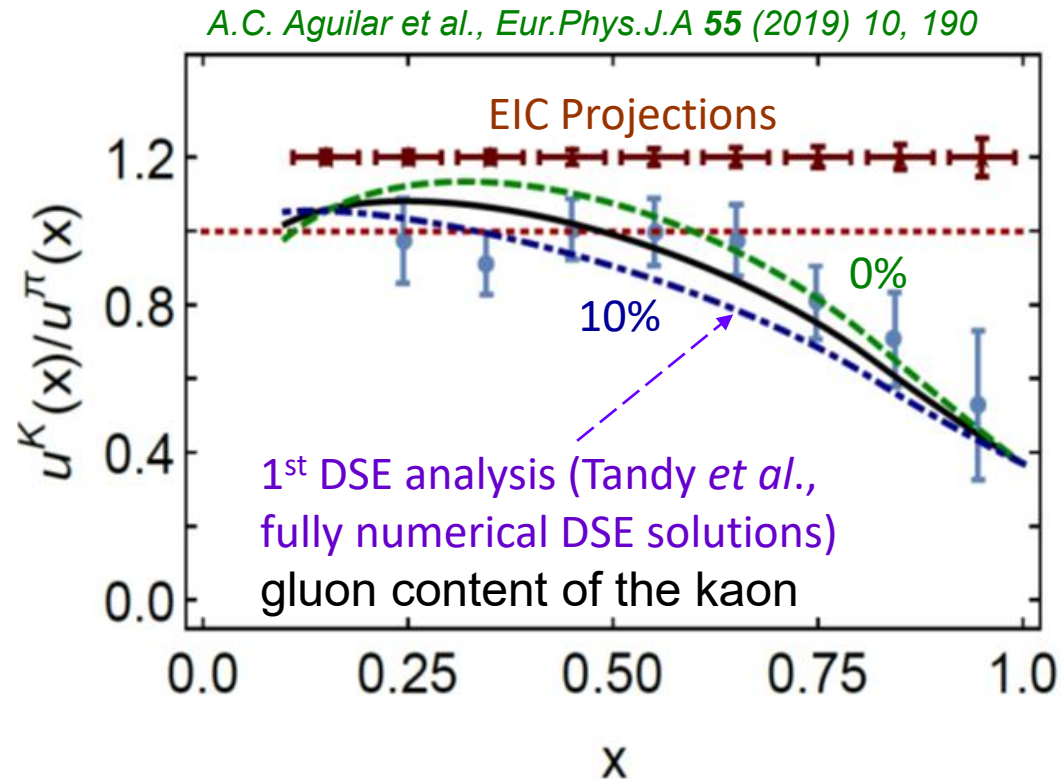
Figure 7.24: (Left): Comparison of uncertainties on the pion's valence, sea quark and gluon PDFs before (yellow bands) and after (red) bands inclusion of EIC data. (Right): Ratio of uncertainties with EIC data to without, $\delta^{\text{EIC}}/\delta$, for the valence (green line), sea quark (blue) and gluon (red) PDFs, assuming 1.2% systematic uncertainty, and (inset) the corresponding ratios of the momentum fraction uncertainties, $\delta\langle x \rangle^{\text{EIC}}/\delta\langle x \rangle$, for valence, sea, total quark and gluon PDFs [138], at a scale $Q^2 = 10 \text{ GeV}^2$.

*From EIC Yellow Report,
P. Barry, W. Melnitchouk, N. Sato et al.*

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 $\frac{2}{3}$ of the kaon's light-front momentum, or roughly 95% at the perturbative hadronic scale



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 Questions

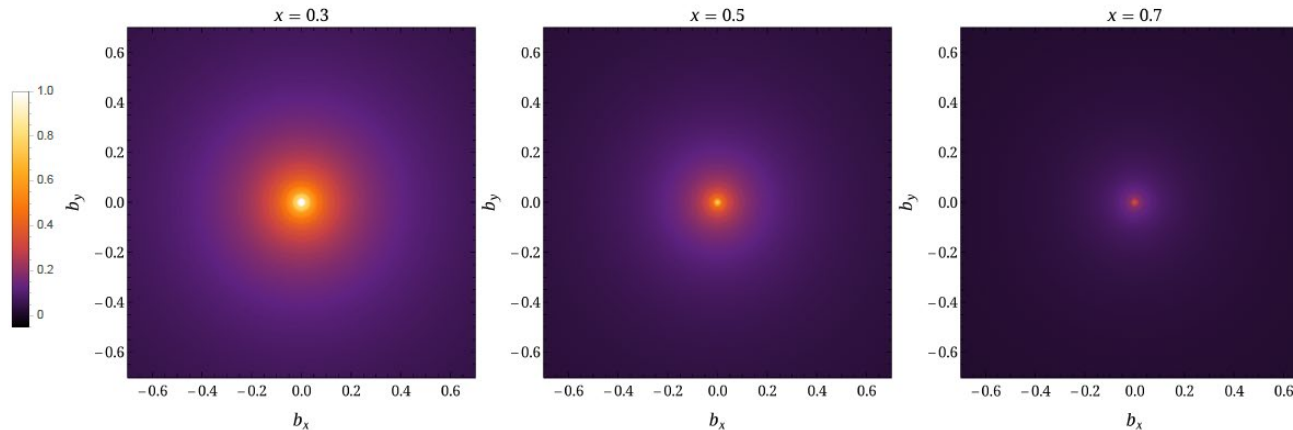
Science Question	Key Measurement[1]	Key Requirements[2]
What are the quark and gluon energy contributions to the pion mass?	Pion structure function data over a range of x and Q^2 .	<ul style="list-style-type: none"> • Need to uniquely determine $e + p \rightarrow e' + X + n$ (low $-t$) • CM energy range $\sim 10-100$ 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 .	<ul style="list-style-type: none"> • 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 .	<ul style="list-style-type: none"> • Need to uniquely determine $e + p \rightarrow e' + X + \Lambda/\Sigma^0$ (low $-t$) • CM energy range $\sim 10-100$ 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 .	<ul style="list-style-type: none"> • 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 .	<ul style="list-style-type: none"> • Need to uniquely determine exclusive process $e + p \rightarrow e' + \pi^+ + n$ (low $-t$) • $e + p$ and $e + D$ at similar energies • CM energy $\sim 10-75$ 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 .	<ul style="list-style-type: none"> • Need to uniquely determine exclusive process $e + p \rightarrow e' + K + \Lambda$ (low $-t$) • L/T separation at CM energy $\sim 10-20$ GeV • Λ/Σ^0 ratios at CM energy $\sim 10-50$ 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 .	<ul style="list-style-type: none"> • 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.	<ul style="list-style-type: none"> • Collider kinematics desirable (as compared to fixed-target kinematics) • CM energy range $\sim 20-140$ GeV

EIC – Meson Structure Questions

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
 $e + p \rightarrow e' + J/\Psi + \pi^+ + n$ (low $-t$)
- High luminosity ($10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$)
- CM energy $\sim 70 \text{ GeV}$

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
 $e + p \rightarrow e' + \gamma + \pi^+ + n$ (low $-t$)
- High luminosity ($10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$)
- CM energy $\sim 10\text{-}100 \text{ GeV}$

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
 $e + p \rightarrow e' + h + X + n$ (low $-t$)
- High luminosity ($10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$)
- $e + p$ and $e + D$ at similar energies desirable
- CM energy $\sim 10\text{-}100 \text{ GeV}$

Summary - Emergent Mass and Structure

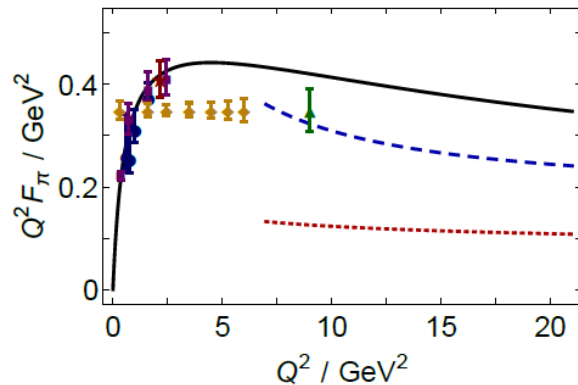
- ❑ Protons, neutrons, pions and kaons are the main building blocks of nuclear matter

If we really want to claim we understand hadron structure as relevant for the visible world, we HAVE to understand at least the pion, kaon, proton, neutron (and likely the Lambda) at the same level.

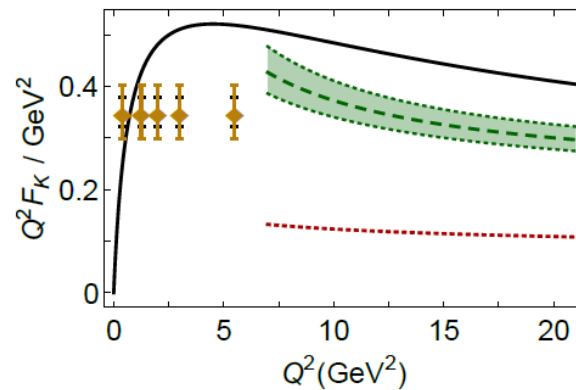
- ❑ Paradoxically, the lightest pseudoscalar mesons appear to be the key to the further understanding of the emergent mass and structure mechanisms.
 - These mesons, namely the pion and kaon, are the Nambu-Goldstone boson modes of QCD.
- ❑ Unraveling their exact partonic structure and interplay with the Higgs mass mechanism is a common goal of three independent methodologies – phenomenology with continuum QCD based approaches, Lattice QCD, and the global analysis of parton distributions – linked to experimental measurements of hadronic structure.

Summary Pion and Kaon Structure at 12 GeV

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.



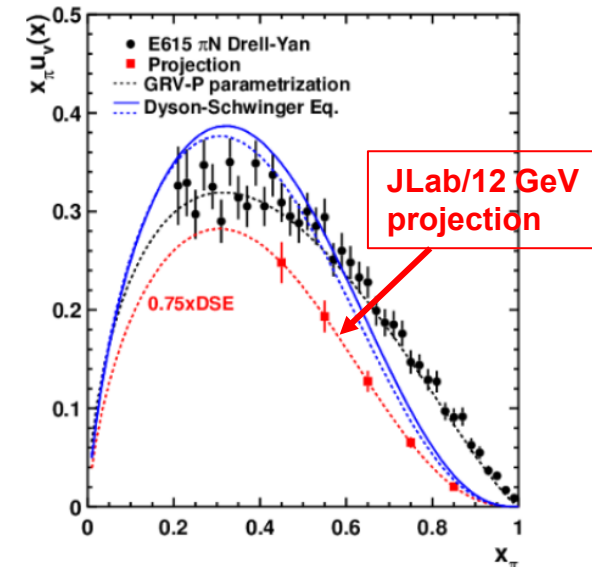
Pion FF – first quantitative access to hard scattering scaling regime?



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

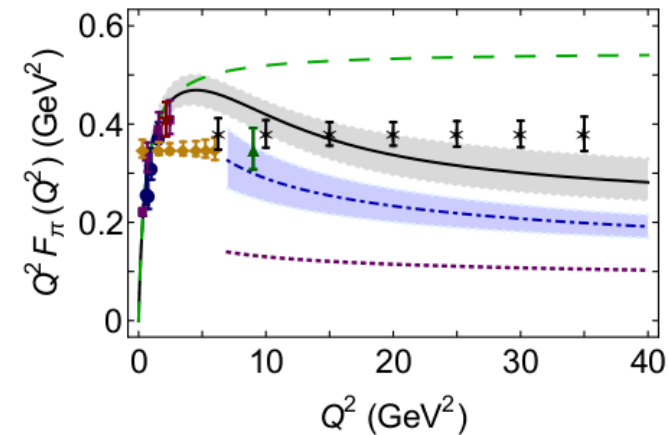
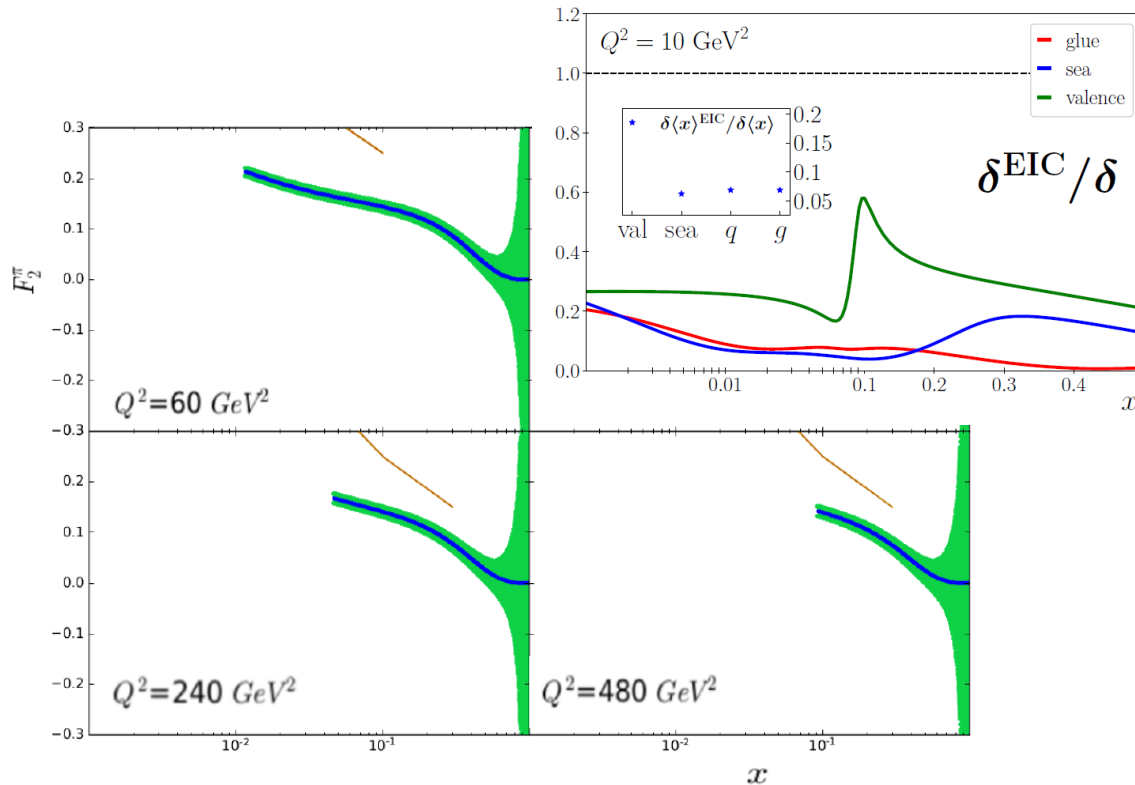
and kaon

PR12-15-006



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 measurements play an important role in our understanding of the structure and interactions of hadrons based on the principles of QCD
- Meson form factors can be accessed through the Sullivan process
 - Technique validated experimentally – also theoretical calculations
 - JLab: Pion and kaon form factor extractions up to high Q^2 (~ 9 and ~ 6 GeV^2)
- Opportunities to map meson structure functions through the Sullivan process
 - JLab TDIS experiments – resolve large x issues
 - EIC: mapping pion and kaon structure functions over a large (x, Q^2) landscape

Off-shellness considerations

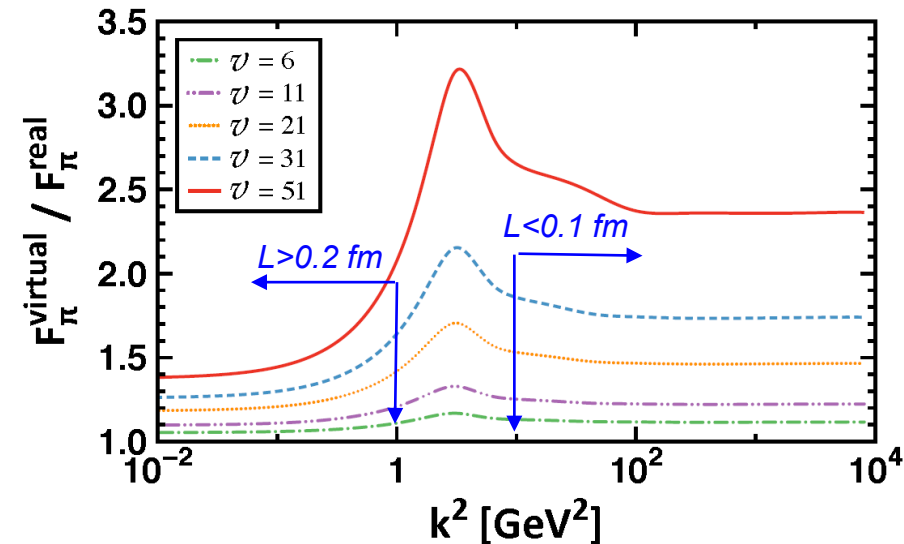
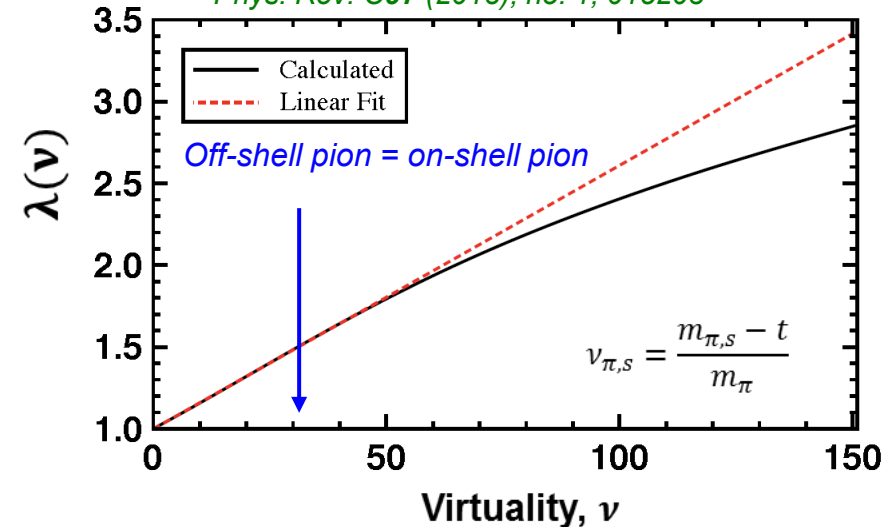
In the Sullivan process, the mesons in the nucleon cloud are virtual (off-shell) particles

- Recent calculations estimate the effect in the BSE/DSE framework – **as long as $\lambda(v)$ is linear in v the meson pole dominates**
 - Within the linearity domain, alterations of the meson internal structure can be analyzed through the amplitude ratio

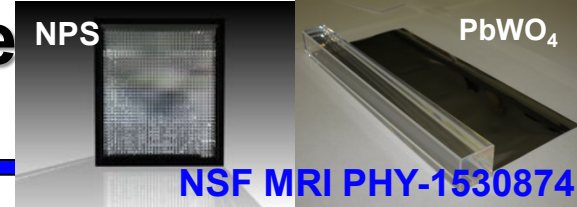
- **Off-shell meson = On-shell meson for $t < 0.6 \text{ GeV}^2$ ($v \approx 30$) for pions and $t < 0.9 \text{ GeV}^2$ ($v_s \sim 3$) for kaons**

This means that pion and kaon structure can be accessed through the Sullivan process

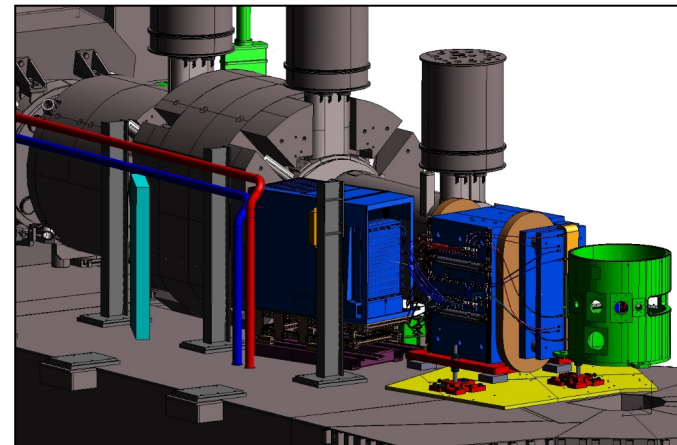
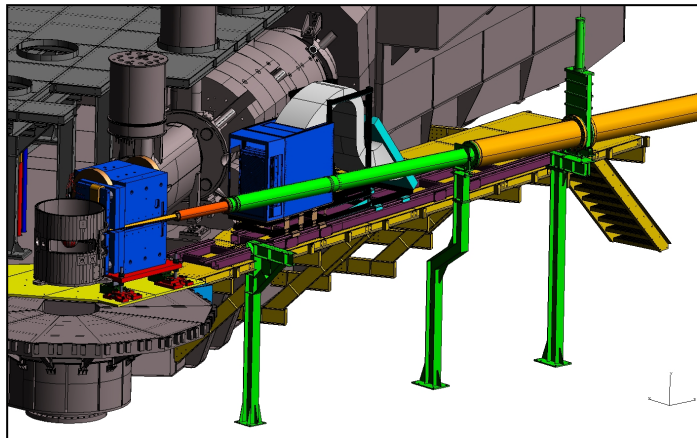
S-X Qin, C. Chen, C. Mezrag, C.D. Roberts,
Phys. Rev. C97 (2018), no. 1, 015203



Opportunities with the Neutral Particle Spectrometer (NPS) in Hall C

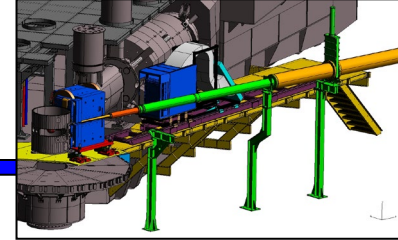


- ❑ The NPS is a facility in Hall C, utilizing the well-understood HMS and the SHMS infrastructure, to allow for precision (coincidence) cross section measurements of neutral particles (γ and π^0).



- ❑ Approved experiments to date
 - E12-13-010 – Exclusive Deeply Virtual Compton and π^0 Cross Section Measurements in Hall C
 - E12-13-007 - Measurement of Semi-inclusive π^0 production as Validation of Factorization
 - E12-14-003 – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies
 - E12-14-005 – Wide Angle Exclusive Photoproduction of π^0 Mesons
 - E12-17-008 – Polarization Observables in Wide-Angle Compton Scattering
- ❑ Conditionally approved experiments: TCS with transverse target

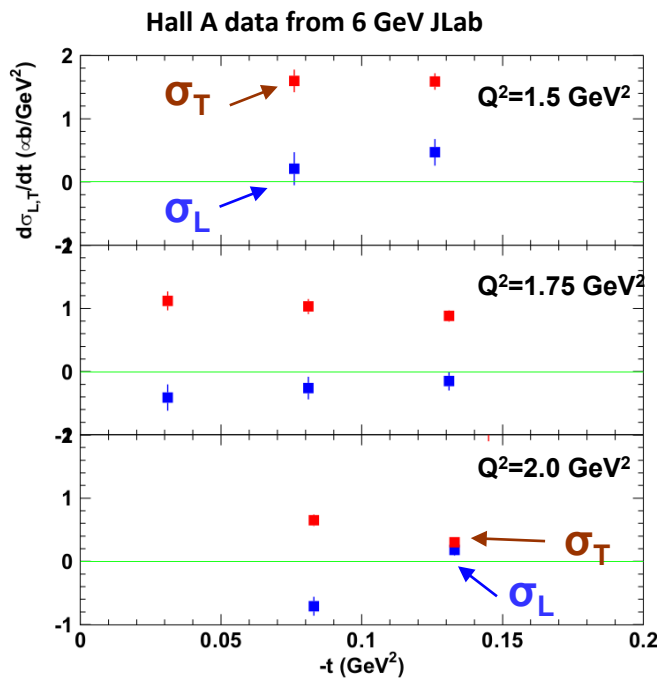
NPS/E12-13-010: Exclusive π^0 cross section



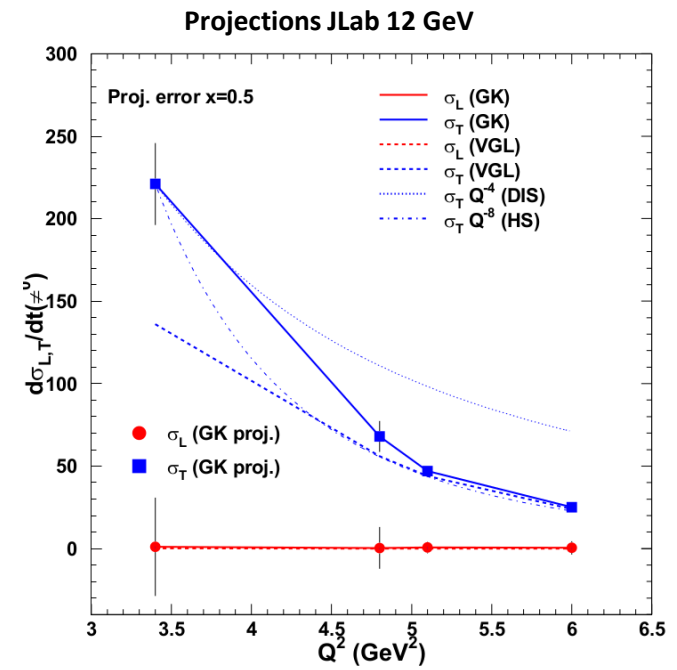
- Results from Hall A suggest that σ_L in π^0 production is non-zero up to $Q^2=2 \text{ GeV}^2$

E12-13-010 spokespersons: C. Munoz-Camacho, T. Horn, C. Hyde, R. Paremuzyan, J. Roche

- Need to understand Q^2/t dependence for final conclusion on dominance of σ_T
 - If σ_T large: access to transversity GPDs



E12-13-010 projections



M. Defurne et al, PRL 117 (2016) no.26, 262001

E12-13-010 will provide relative σ_L and σ_T contributions to the π^0 cross section up $Q^2 \sim 6 \text{ GeV}^2$ to verify reaction mechanism

EIC Detector Nomenclature

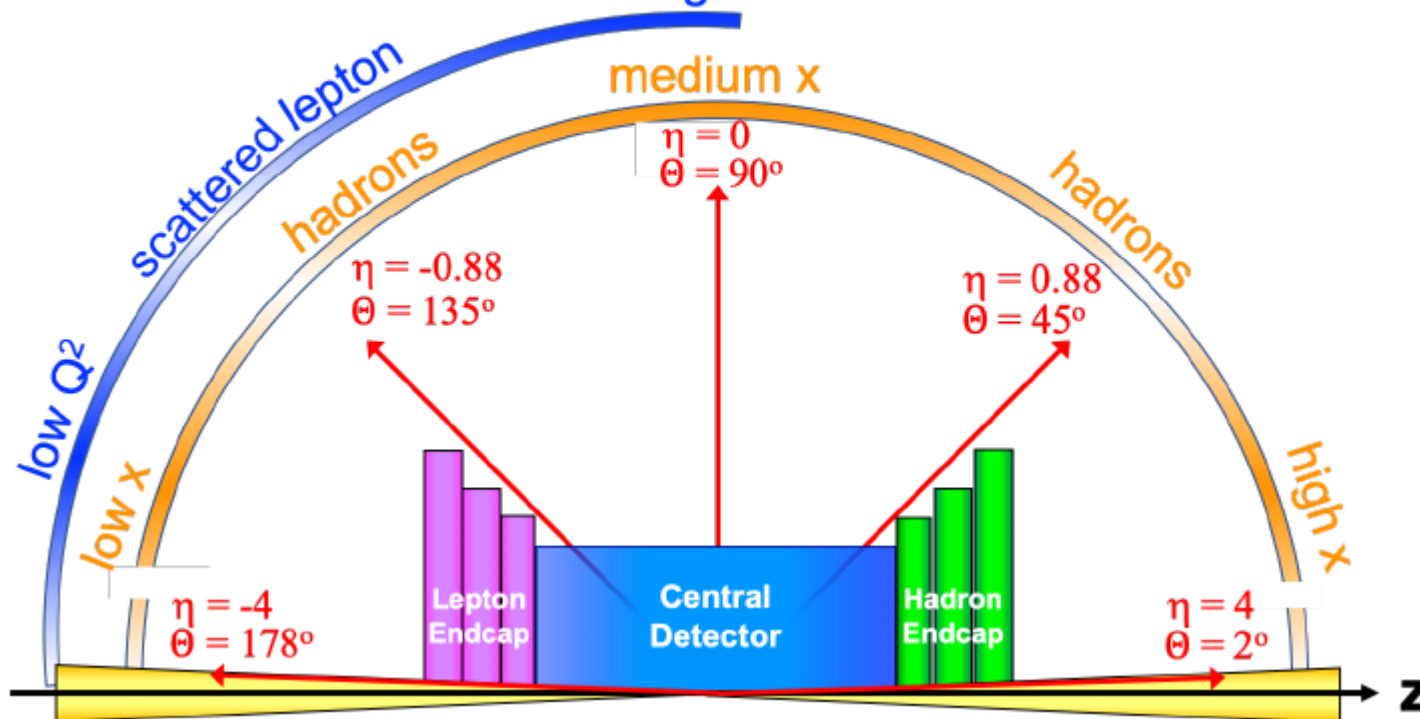
p: 41 GeV, 100 to 275 GeV

p/A beam

electron beam

e: 5 GeV to 18 GeV

high Q^2



low Q^2 scattered electrons
Bethe-Heitler photons
for luminosity

Backward

Main detector =
Barrel +
Lepton Endcap +
Hadron Endcap

particles from nuclear
breakup, i.e. neutrons,
scattered protons, and ions
from diffractive reactions

Forward