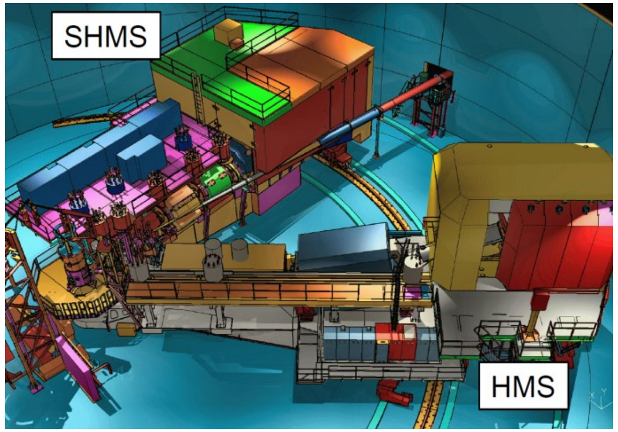
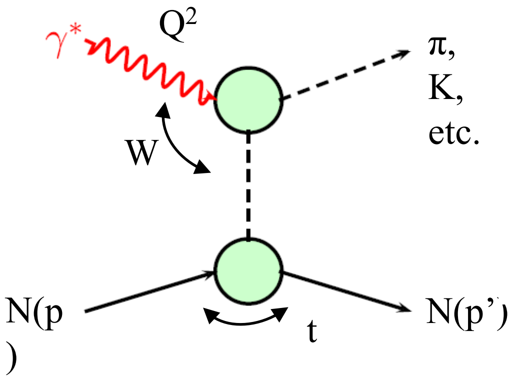
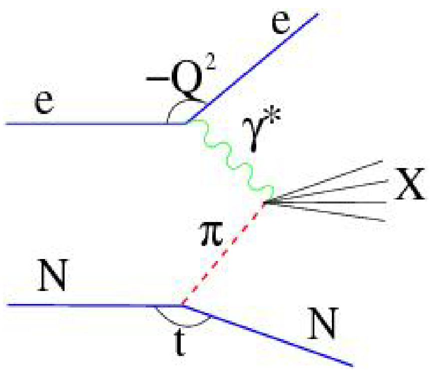
Studies of Meson Structure in Hall C







Tanja Horn

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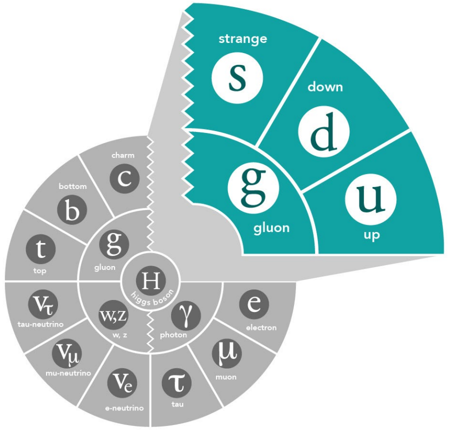
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Supported in part by NSF grants PHY2309976 and PHY2012430

JLUO24 Jefferson Lab User Organization Annual Meeting

Jefferson Lab, June 10-12, 2024

The Incomplete Hadron: Mass puzzle

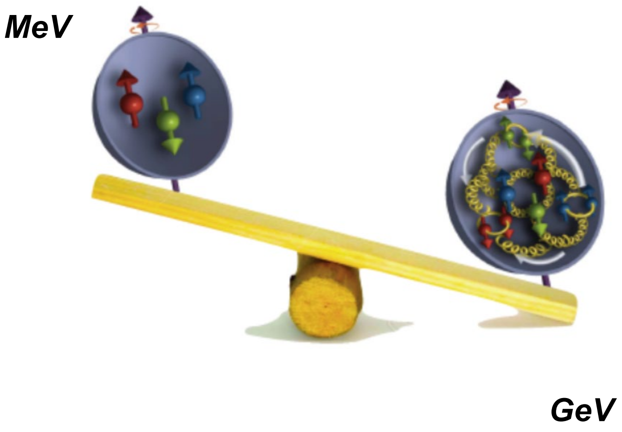


Proton: Mass ~ 940 MeV (~1 GeV)
Most of mass generated by dynamics

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!"

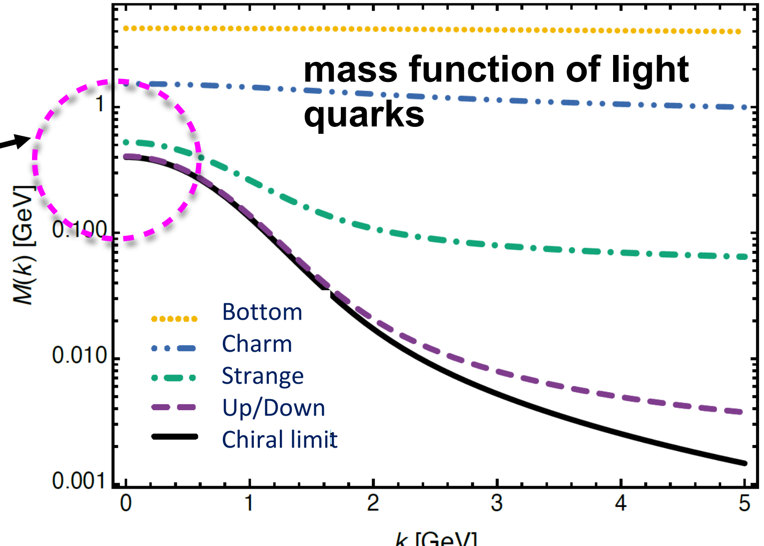


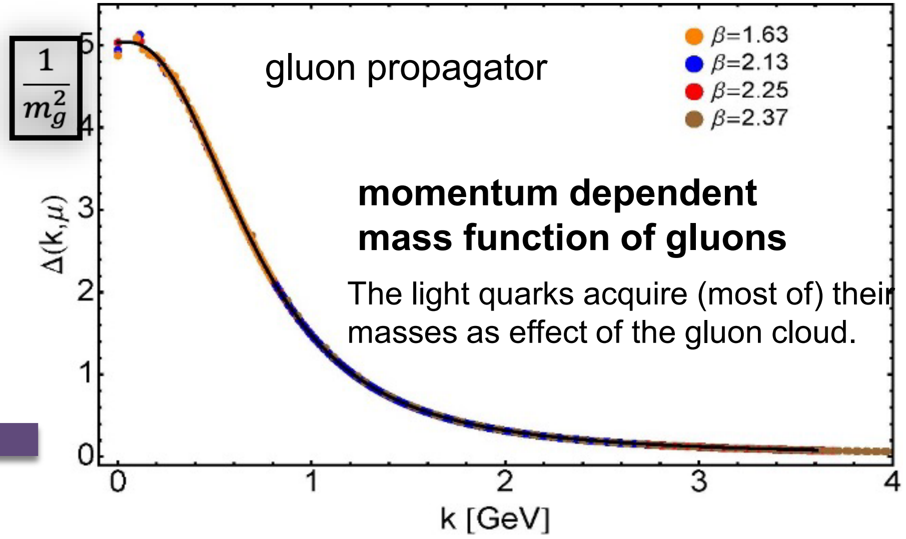
Visible world: mainly made of light quarks – its mass emerges from quark-gluon interactions.

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*


mass function of light quarks


gluon propagator

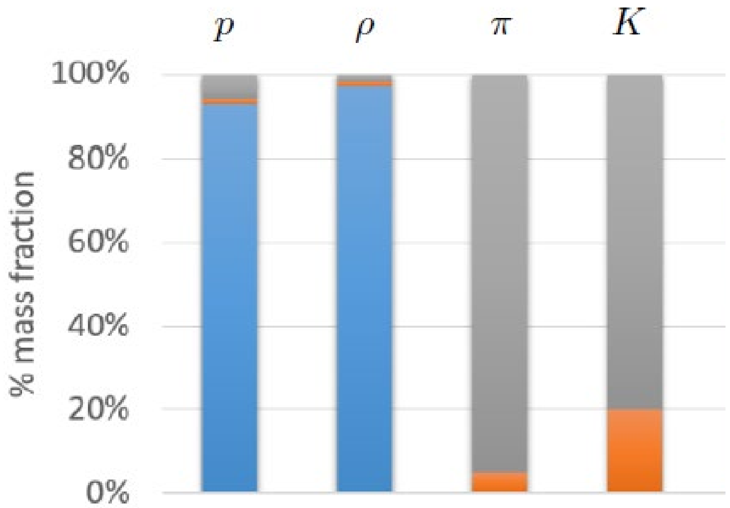
momentum dependent mass function of gluons

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

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**)*

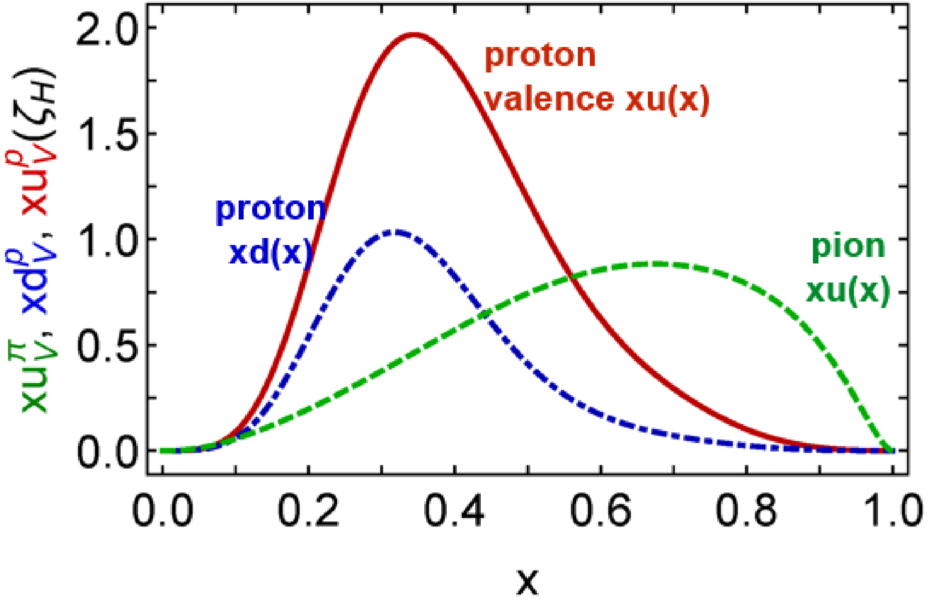


❑ Emergent hadron mass (EHM)
❑ Interference of emergent hadron mass & Higgs mechanism
❑ Higgs mechanism

Mass budget for nucleons and mesons are vastly different

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

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



Valence quark distribution of proton/pion are also very different

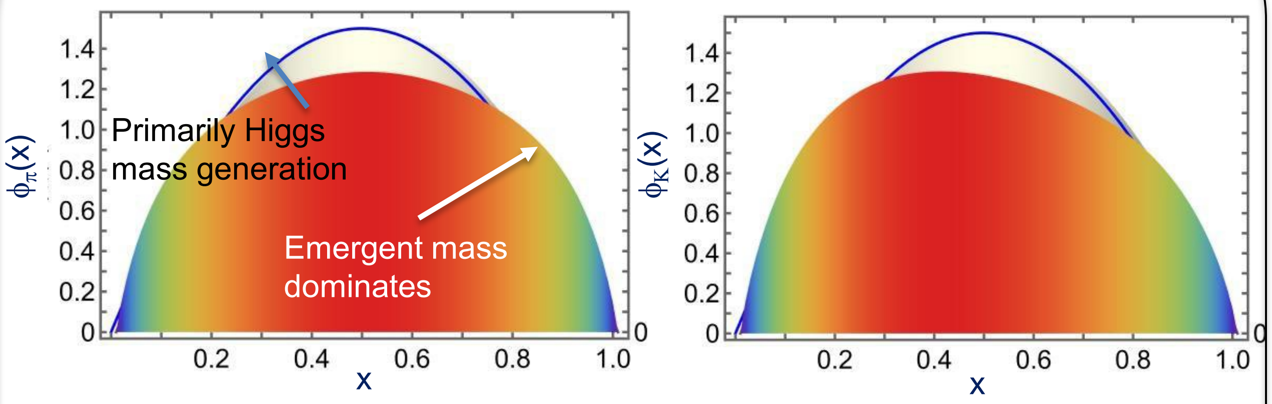
→ **Difference between meson PDFs: direct information on emergent hadron mass (EHM)**

Light Mesons and EHM

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

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

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*



Primarily Higgs mass generation

Emergent mass dominates

☐ 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.

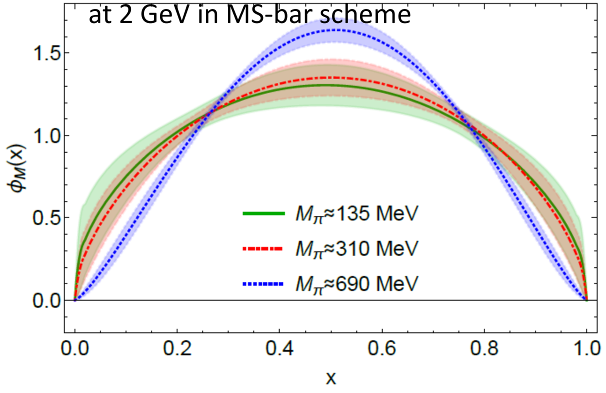
☐ The DA for the light-quark pion is a broad, concave function, a feature of emergent mass generation.

☐ Kaon DA is asymmetric around the midpoint – signature of constructive interference between EHM and HB mass-generating mechanism

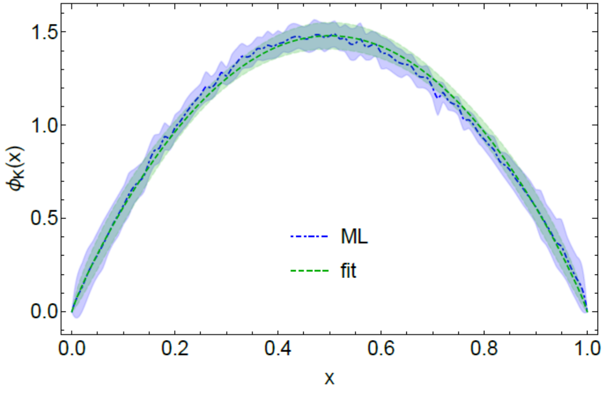
Strong synergy with lattice QCD

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

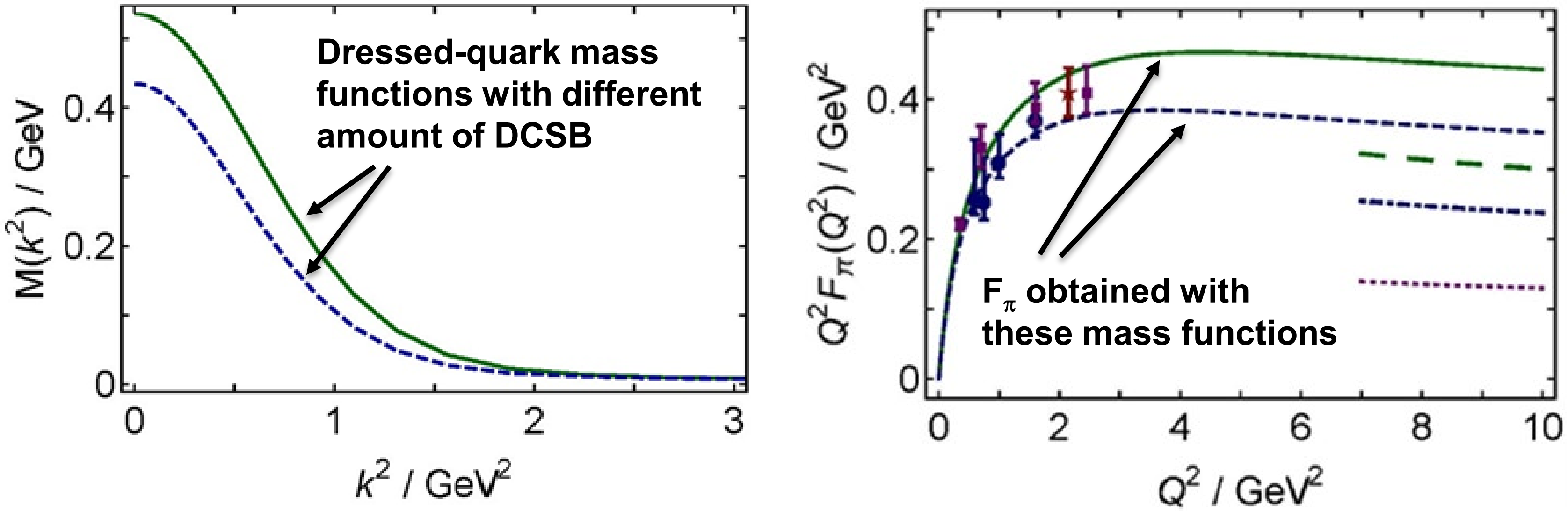


Fit to lattice data for kaon, and using machine learning approach

- ➢ 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)



Dressed-quark mass functions with different amount of DCSB

F_π obtained with these mass functions

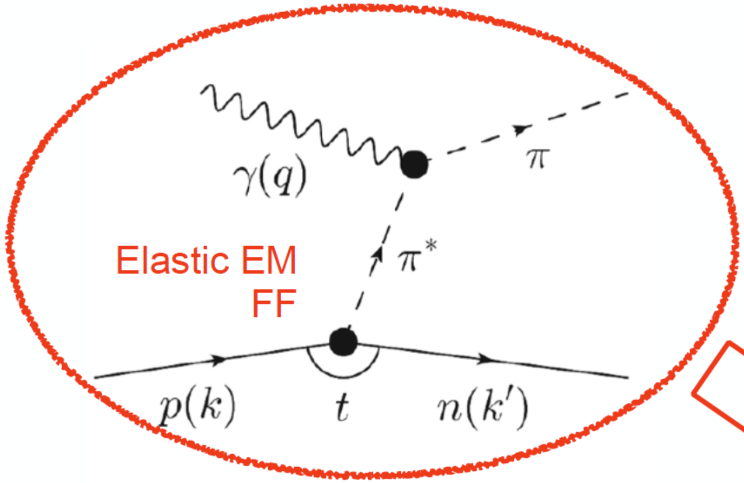
A.C. Aguilar et al., Eur. Phys. J. A ***55*** *(**2019**) 10, 190*

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_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, $\phi(x)=6x(1-x)$.

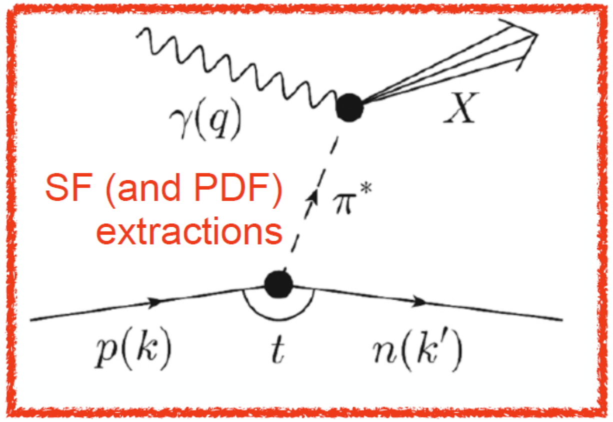
Accessing Pion/Kaon Structure Information

Sullivan

Hard scattering from virtual meson cloud of nucleon



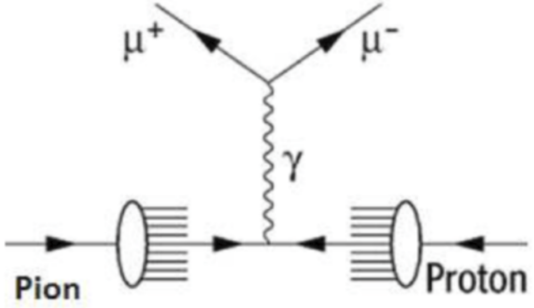
Elastic EM FF



SF (and PDF) extractions

Drell-Yan

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



☐ **Pion/Kaon elastic EM Form Factor**

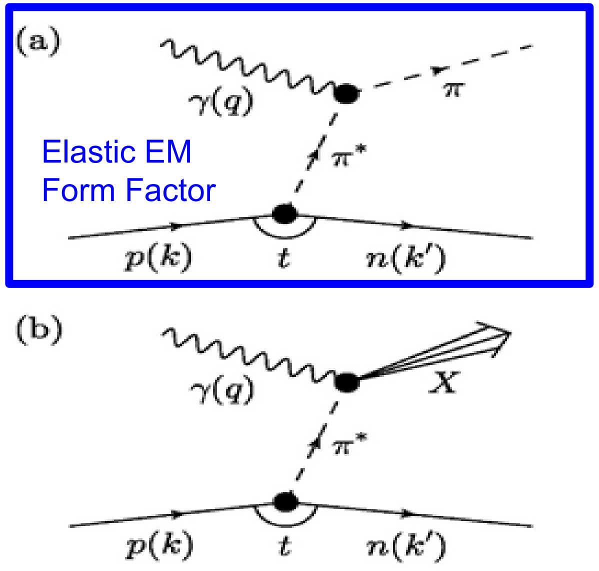
- Informs how EHM manifests in the wave function
- Decades of precision F_π studies at JLab and recently completed measurement in Hall C for F_π and also F_K
- EIC offers exciting kinematic landscape for FF extractions

☐ **Pion/Kaon Structure Functions**

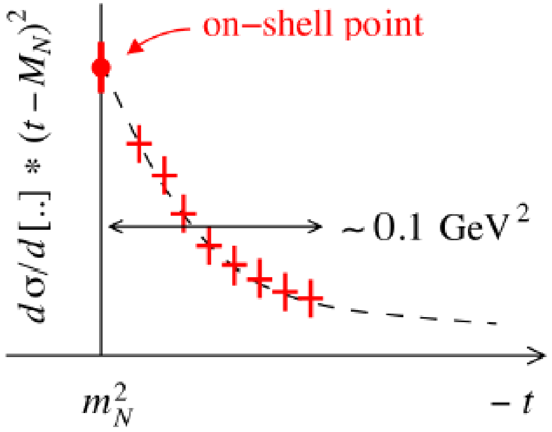
- Informs about the quark-gluon momentum fractions

Accessing meson structure through the Sullivan Process

- 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*



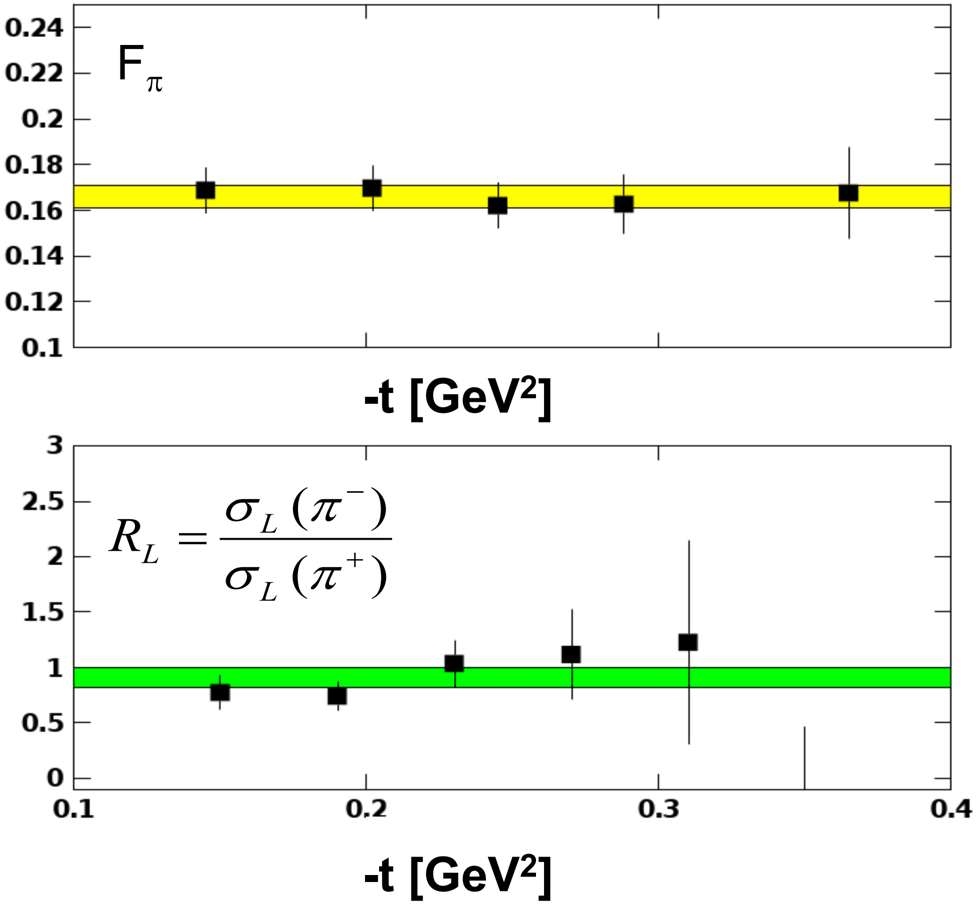
- To **check these conditions** are satisfied empirically, one can **take data covering a range in *t*** and compare with phenomenological and theoretical expectations.

- **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*

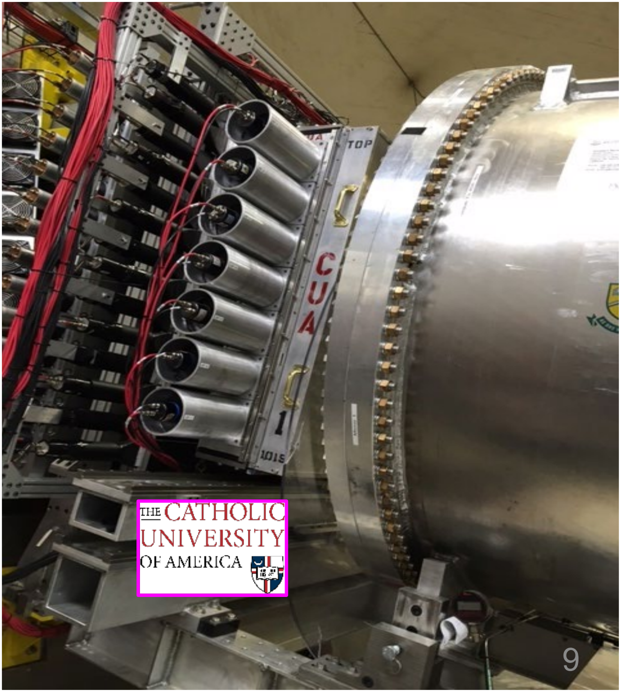
*G. Huber et al, PRL**112** (**2014**)182501*

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

Exclusive Meson Experiments in Hall C @ 12 GeV JLab

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

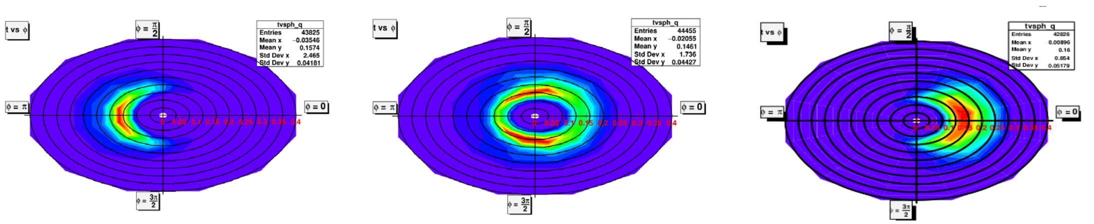
- ❑ CEBAF 10.9 GeV electron beam and SHMS small angle capability and controlled systematics are essential for precision measurements to higher Q^2
- ❑ Focusing spectrometers fulfill the L/T separation requirements
- ❑ Dedicated key SHMS Particle Identification detectors for the experiments
  - Aerogel 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

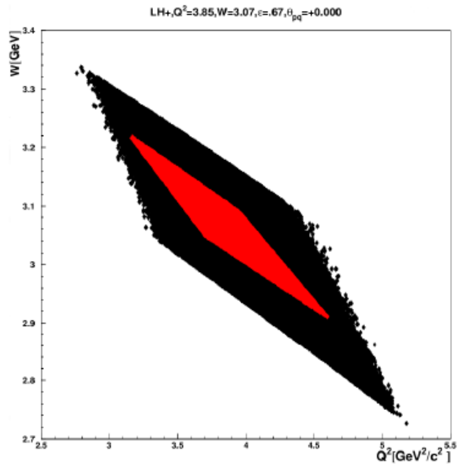
LT Separation Example

Three SHMS angles



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

Two/three beam energies



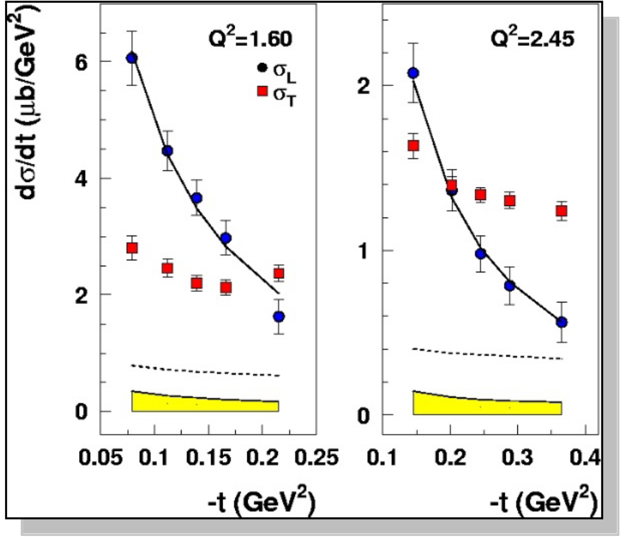
Define common (W, Q^2) coverage at all beam energies (ε)

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

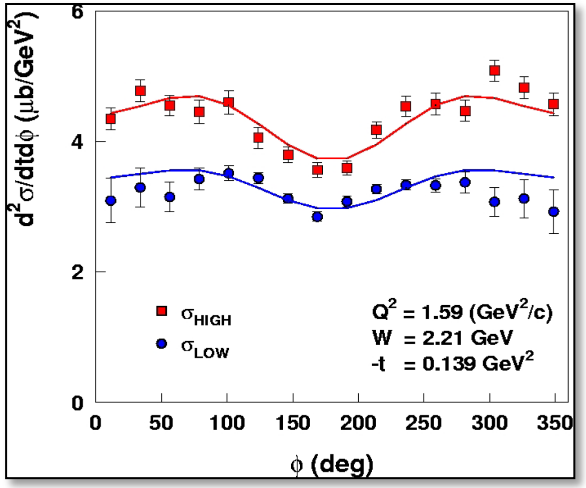
LT Separated Cross Section

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

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



Unseparated Cross Section



Physics Cross Section

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

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

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

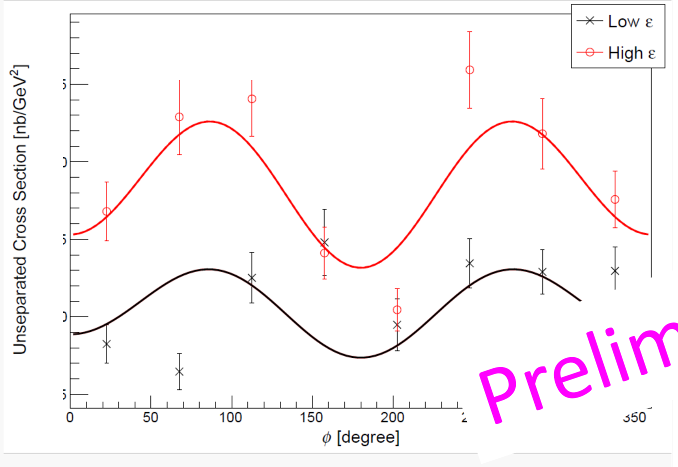
Grad. Students: Vijay Kumar (URegina), Richard Trotta (CUA), Ali Usman (URegina), A. Postuma (URegina)

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

KaonLT experiment (completed in 2018/19):

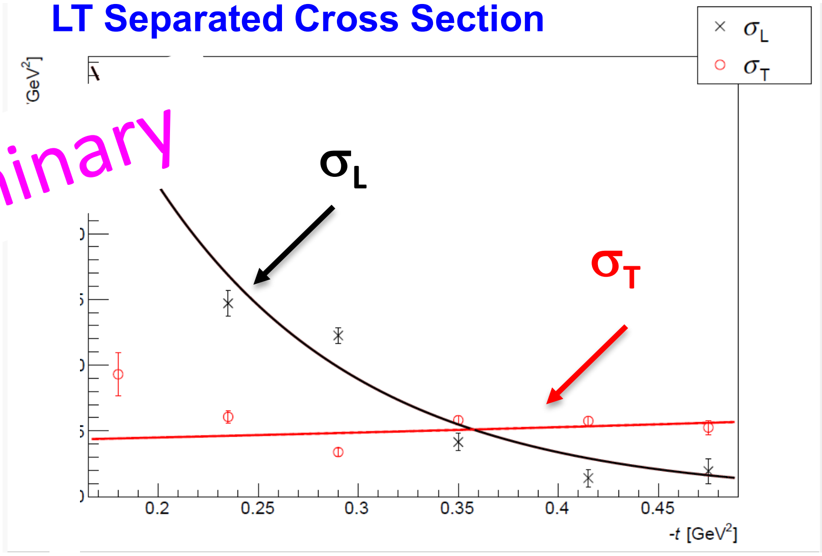
- Highest Q^2 for L/T separated kaon electroproduction cross section
- First separated kaon cross section measurement above W=2.2 GeV
- Separated cross sections have been extracted – anticipate publication as soon as later this year; KaonFF will follow if warranted by data

Unseparated Cross Section

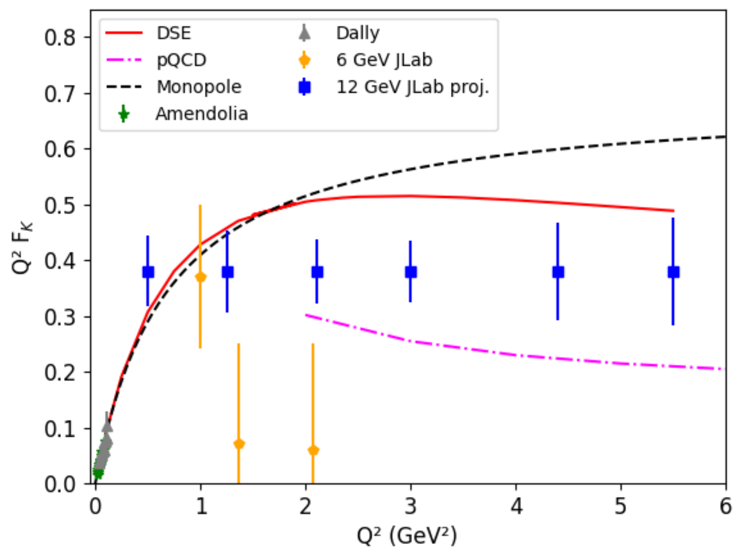


First look at the unseparated and separated cross sections at Q^2=3 GeV^2, W=3.14 GeV

LT Separated Cross Section



Projected Uncertainties for F_K



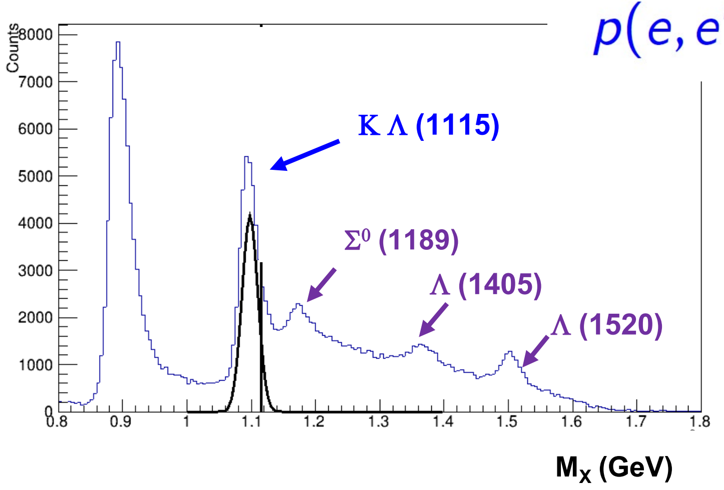
$$2\pi\frac{d^2\sigma}{dt\,d\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

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

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

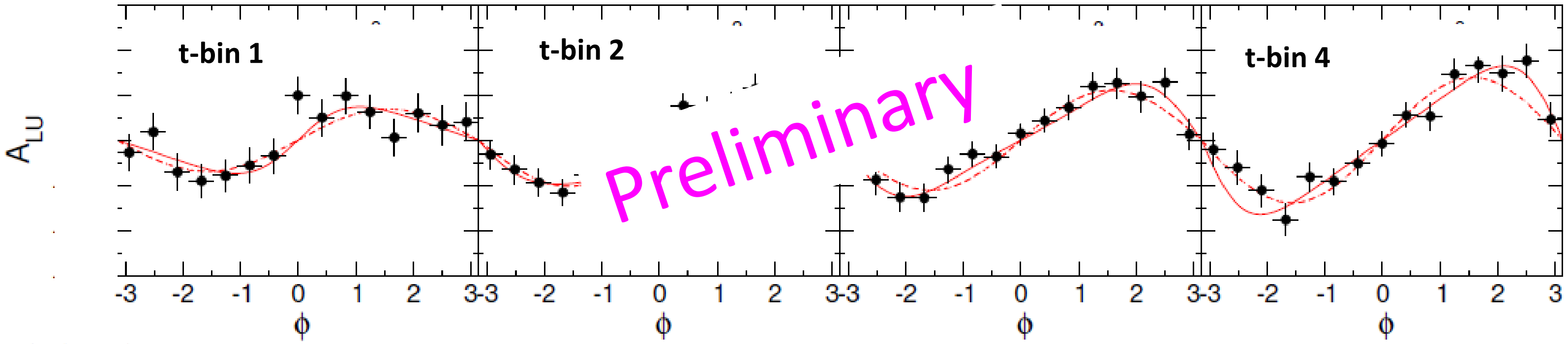
Grad. Students: Vijay Kumar (URegina), Richard Trotta (CUA), Ali Usman (URegina), A. Postuma (URegina)

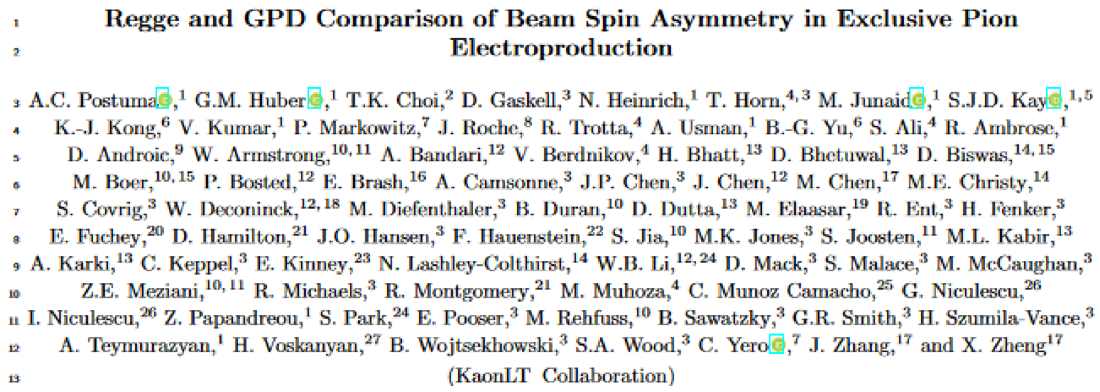
Additional Physics Channels/Topics



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

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

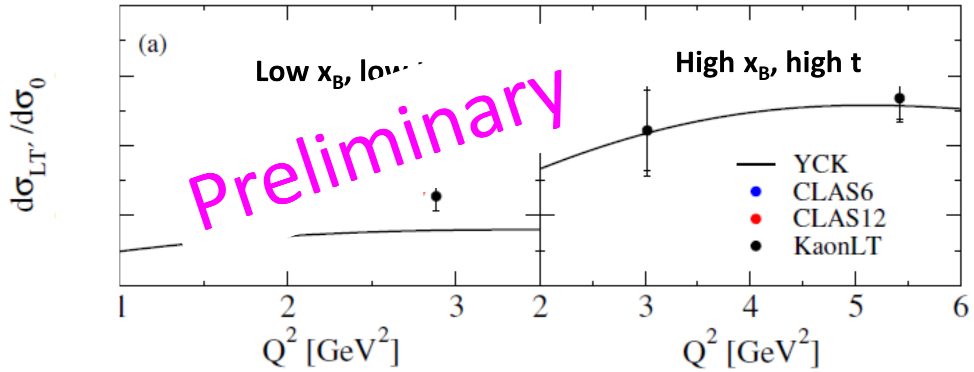




Regge and GPD Comparison of Beam Spin Asymmetry in Exclusive Pion Electroproduction

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

(KaonLT Collaboration)



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

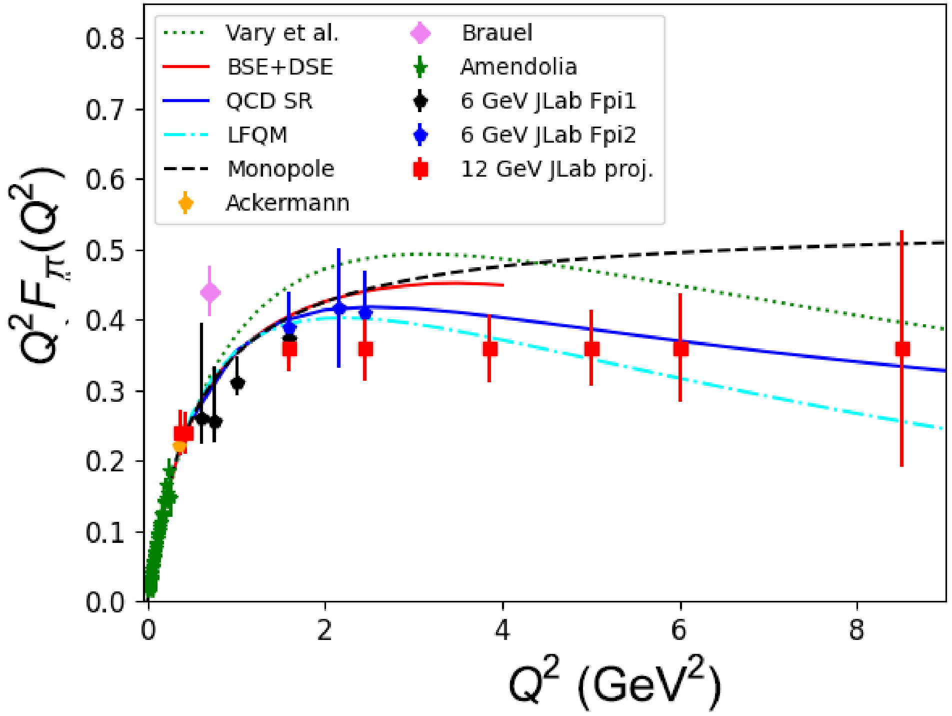
Spokespersons: Dave Gaskell (JLab), Tanja Horn (CUA), Garth Huber (URegina)

Grad. Students: Nathan Heinrich (URegina), M. Junaid (URegina)

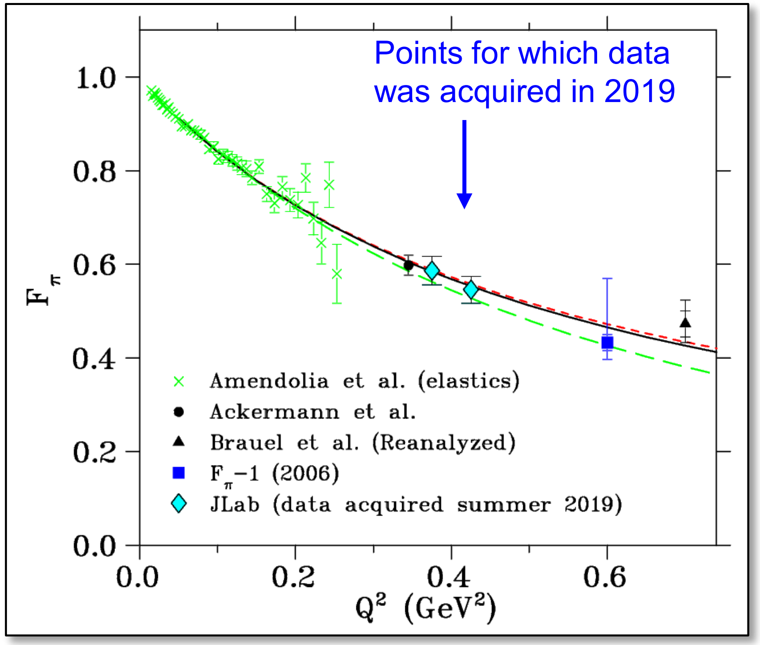
PionLT experiment (<u>completed in 2022</u>):

- 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 low t up to Q^2 = 6 GeV^2
- Pion form factor at Q^2 values up to 8.5 GeV^2
- Calibrations are ongoing

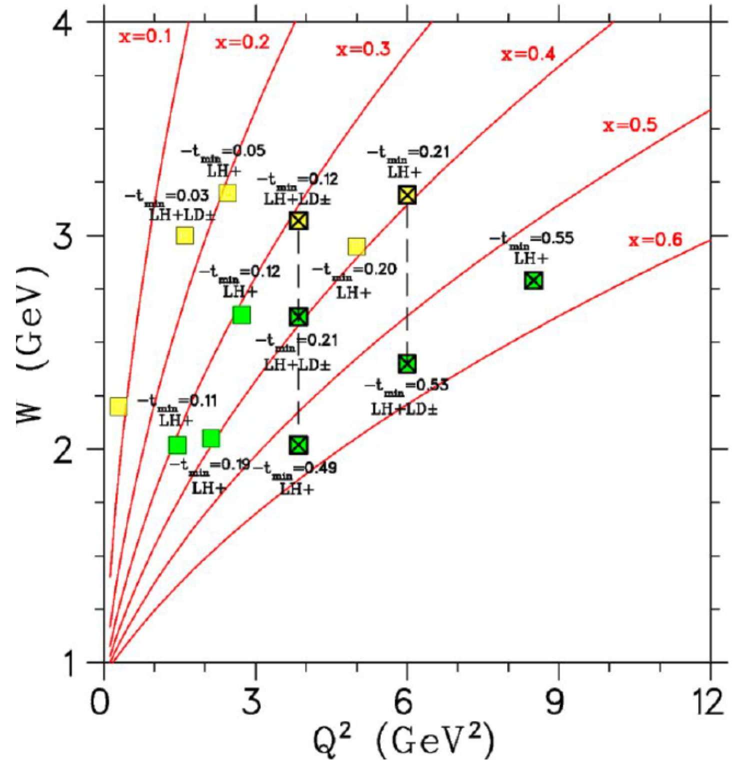
Projected Uncertainties for F_π



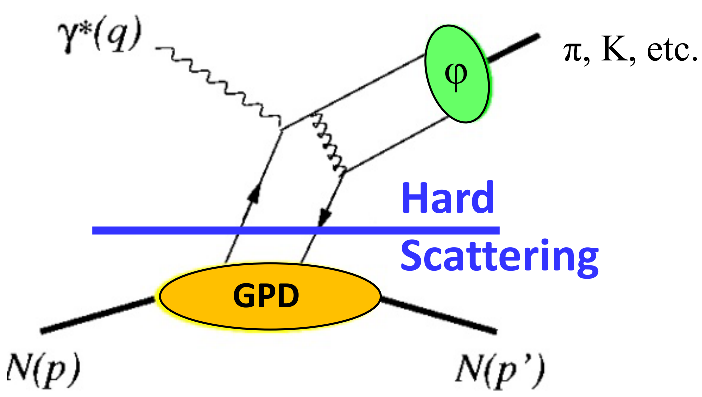
Zoom in at low Q^2 range of the projected Uncertainties for F_π

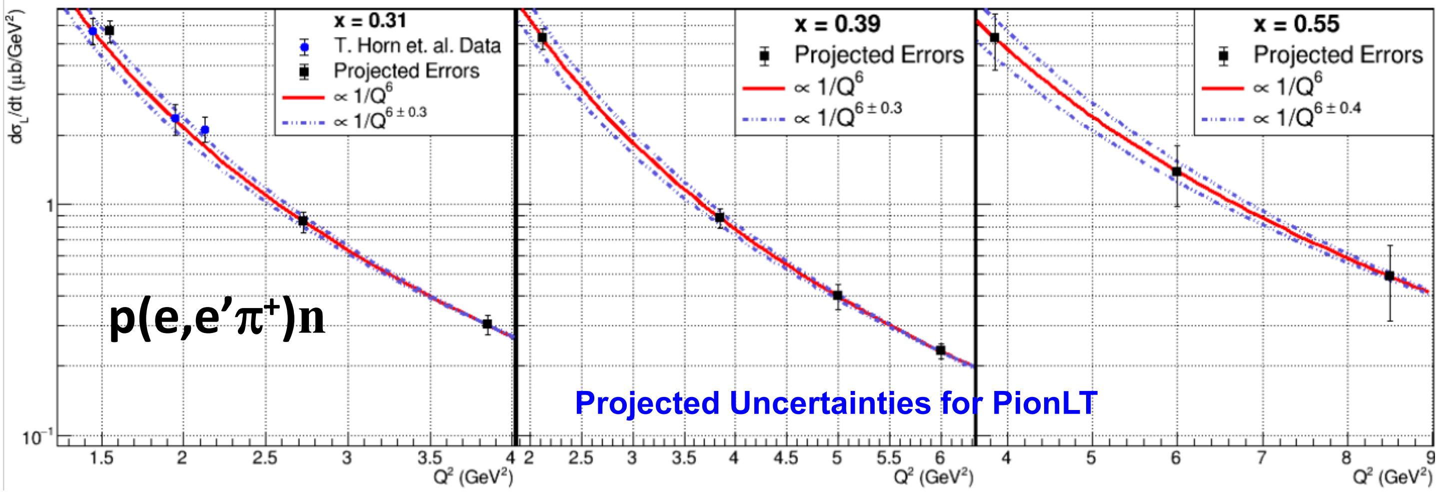


Data acquired in PionLT



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

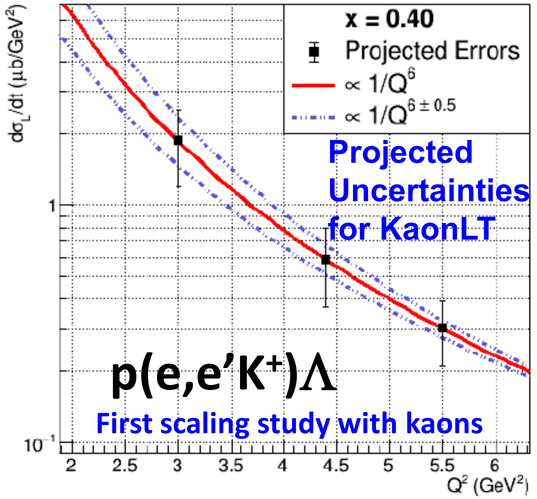




- ☐ One of the most stringent tests of the reaction mechanism is the Q^2 dependence of cross section
  - –σ_L scales to leading order as Q^{-6}
  - –σ_T does not

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

Fit: $1/Q^n$



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

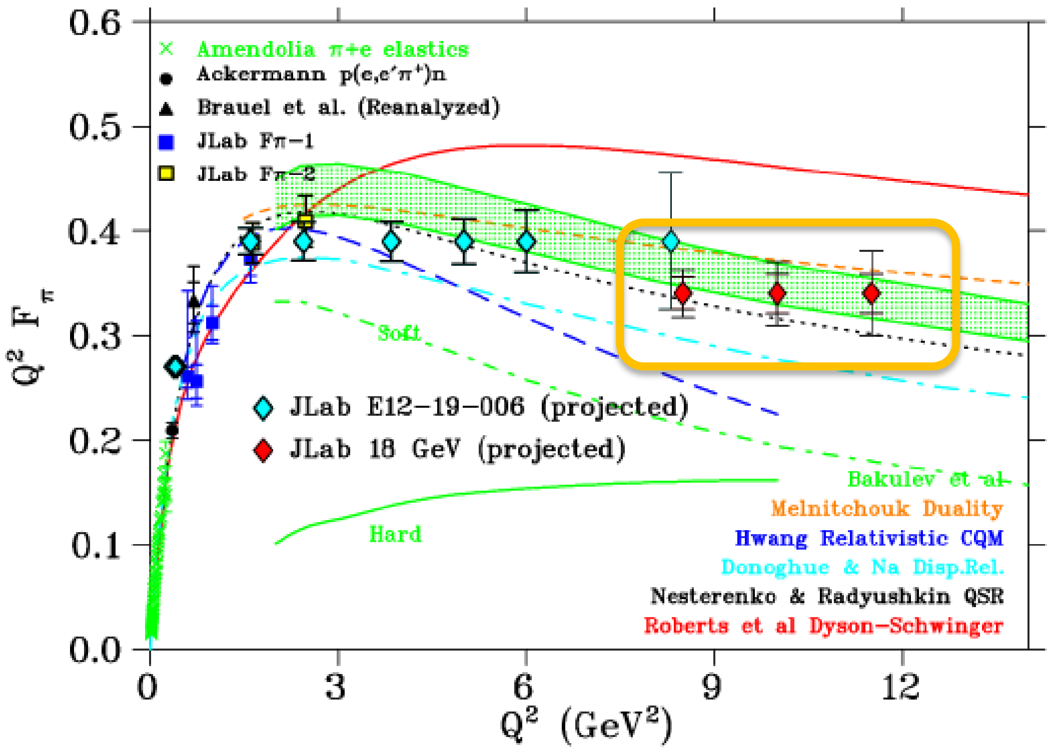
Q^{-n} scaling test range doubles with 18 GeV beam and HMS+SHMS

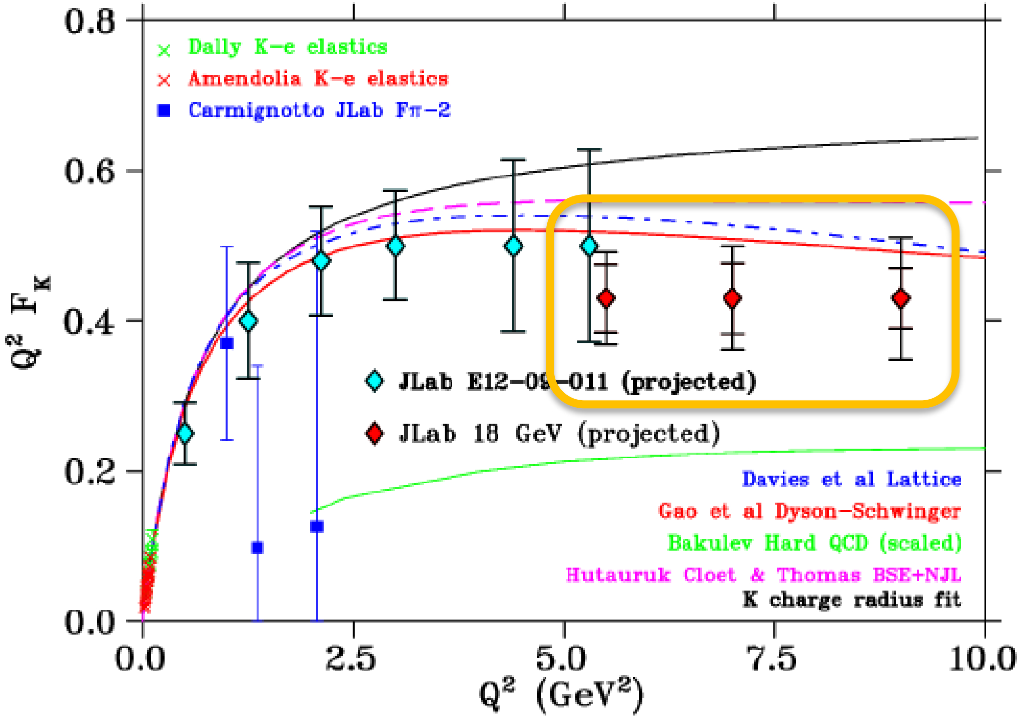
JLab 22 GeV: Opportunities for π, K form factors

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

Projections based on 50 days of beam time

A. Accardi, et al., "Strong Interaction Physics at the Luminosity Frontier with 22 GeV electrons at Jefferson Lab", **arXiv:2306.09360**, EPJA (in press)i



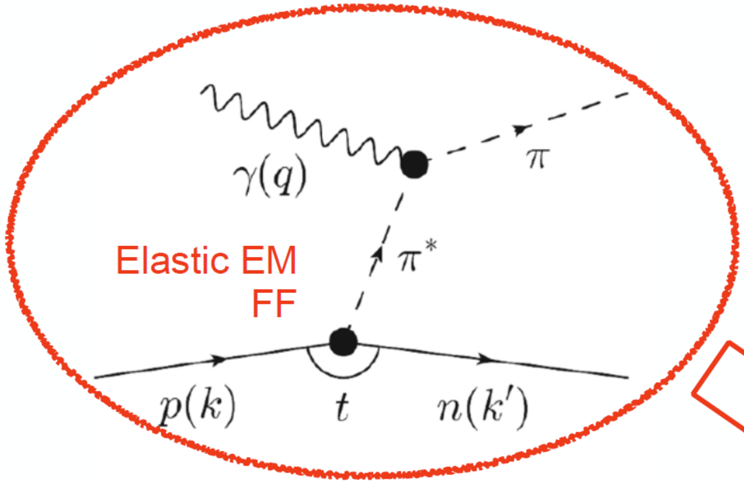


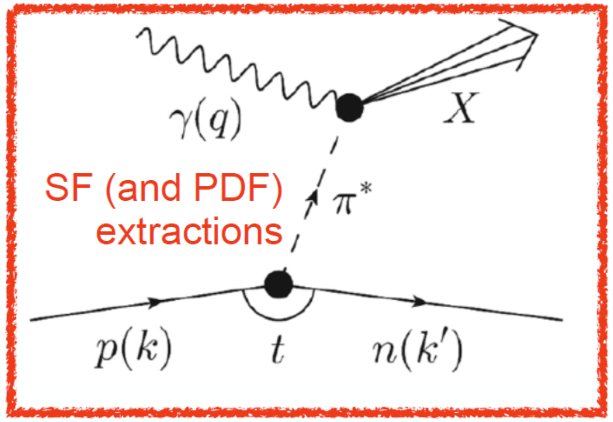
- Assume a staged energy upgrade with Phase 1 at 18 GeV and minor updates of SHMS, HMS PID, tracking, and DAQ
- Enables a significant increase in Q^2 reach of quality LT separations for DVMP – only possible in Hall C
- Interpretation of future data, e.g., EIC, depend on the extrapolation of LT data –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

Accessing Pion/Kaon Structure Information

Sullivan

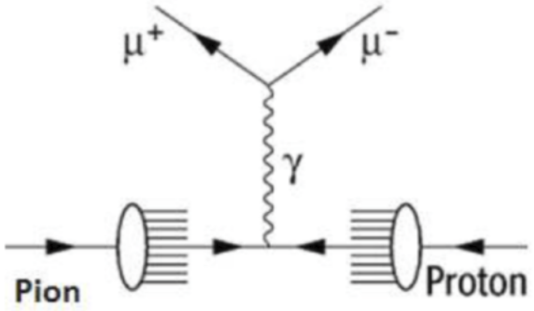
Hard scattering from virtual meson cloud of nucleon





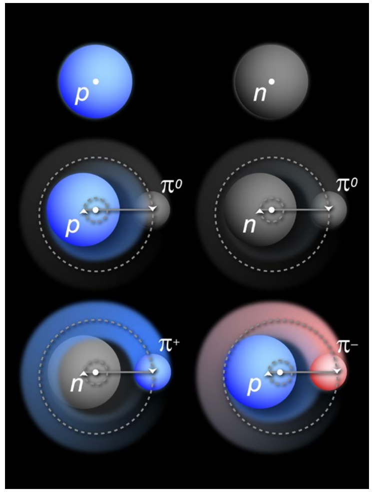
Drell-Yan

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



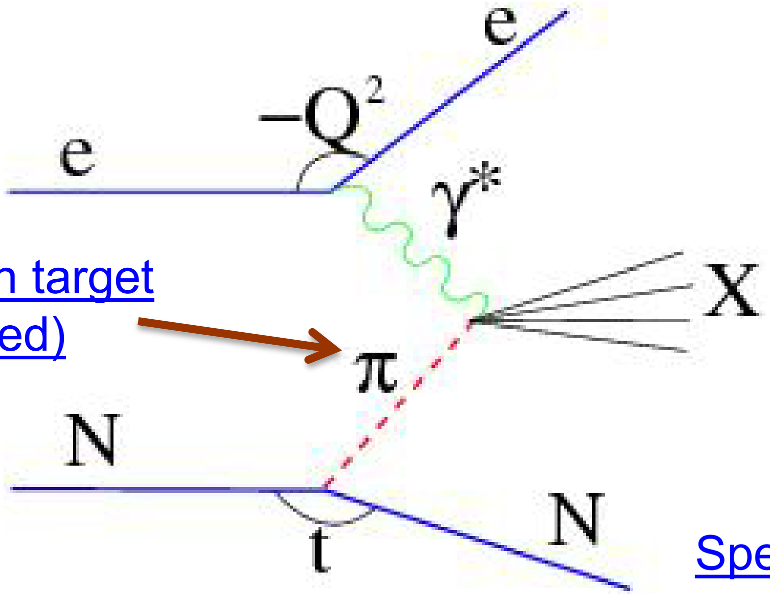
- ❑ **Pion/Kaon elastic EM Form Factor**
  - Informs how EHM manifests in the wave function
  - Decades of precision F_π studies at JLab and recently completed measurement in Hall C for F_π and also F_K
  - EIC offers exciting kinematic landscape for FF extractions
- ❑ **Pion/Kaon Structure Functions**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

Physics Objects for Pion/Kaon Structure Studies



Sullivan process:
scattering from nucleon-meson fluctuations

Detect scattered electron



Pion/Kaon target (undetected)

DIS event – undetected recoiling hadronic system

Spectator “tagged” neutron/lambda

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

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

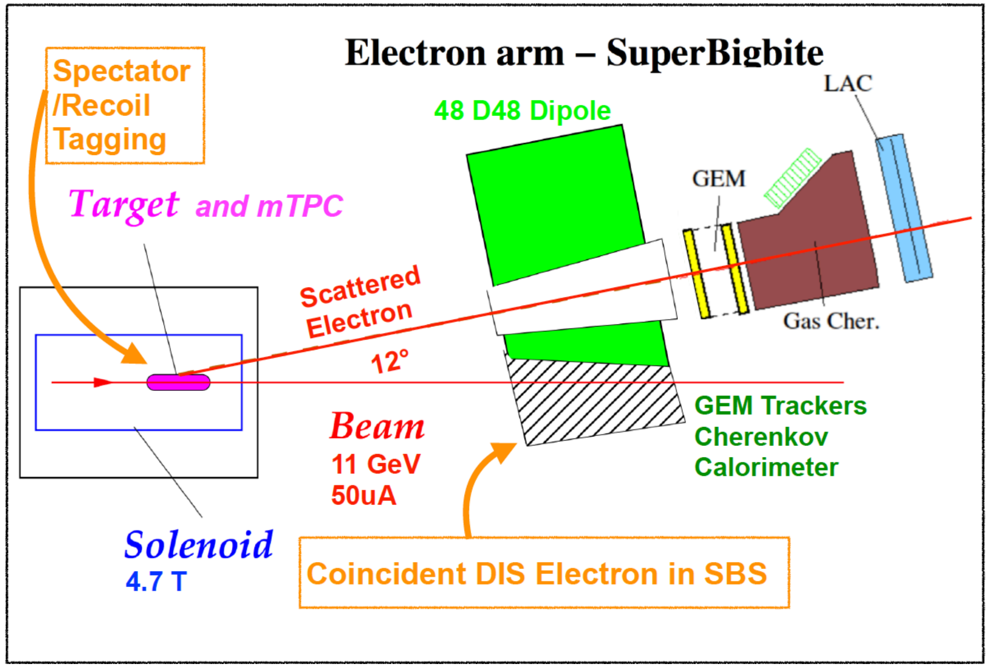
Tagged structure function
a direct measure of the mesonic content of nucleons

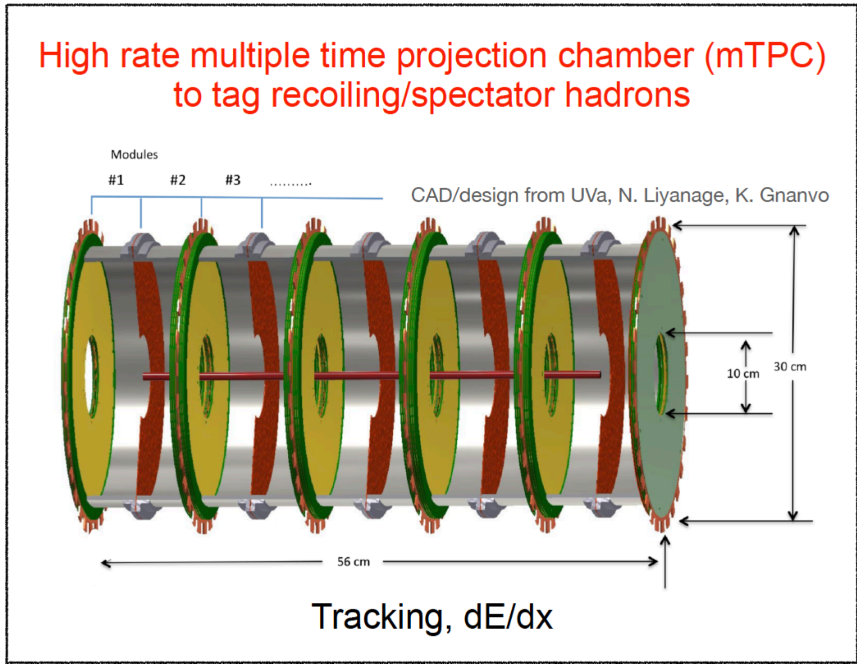
$$F_2^T(x,Q^2,z,t) = \frac{R^T}{\Delta z\Delta t}F_2^p(x,Q^2).$$

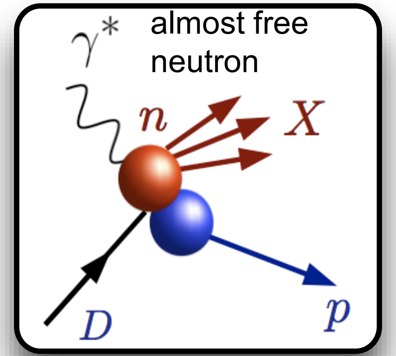
Tagged DIS can be used to tag the “meson cloud”

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

Projected JLab TDIS Results for π, K Structure Functions

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

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

TDIS with SBS:

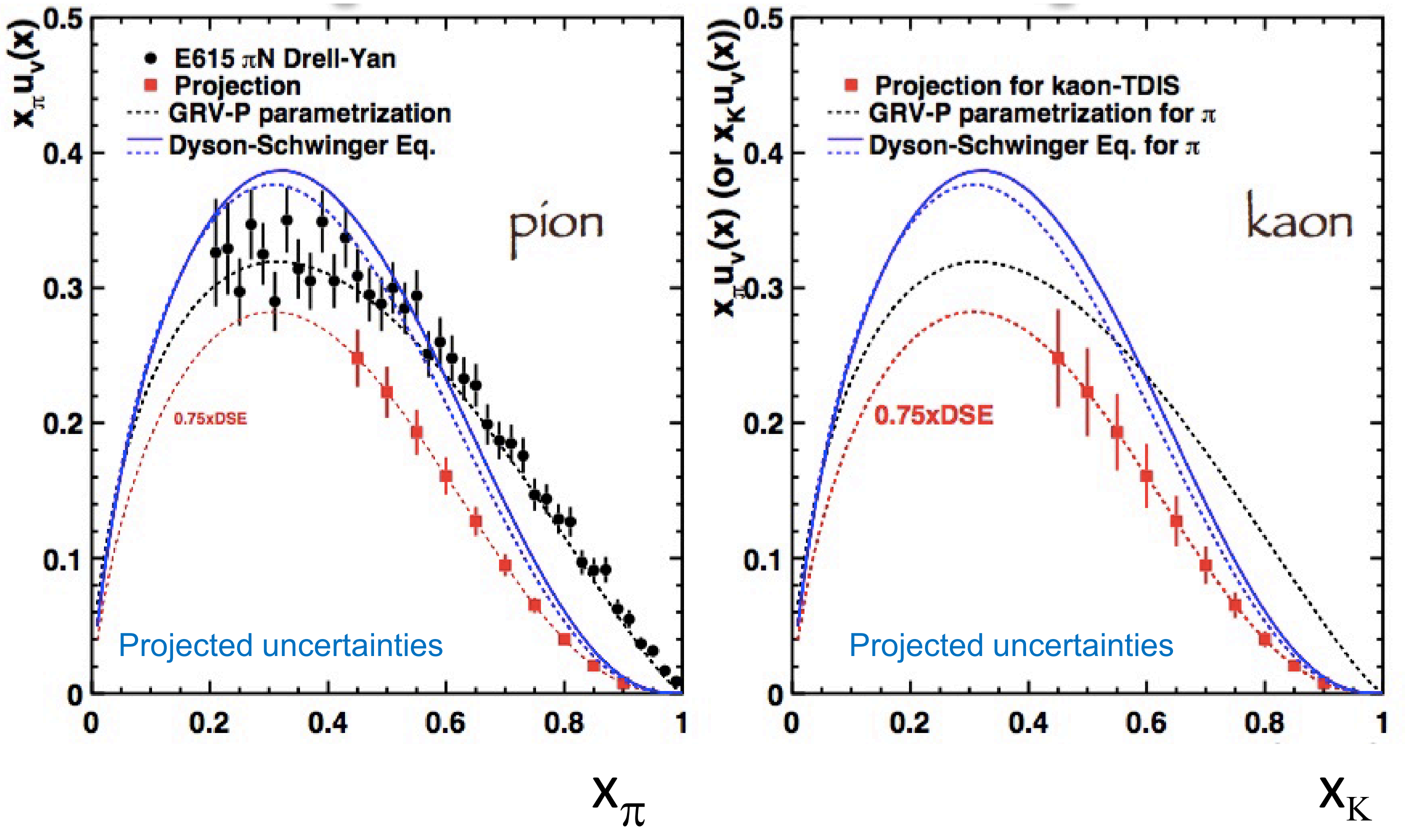
✓High luminosity,
50 μAmp,
$\mathcal{L} = 3\text{x}10^{36}/\text{cm}^2\ \text{s}$

✓Large acceptance
~70 msr

Important for small cross sections

Pion and Kaon F2 SF extractions in valence regime

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

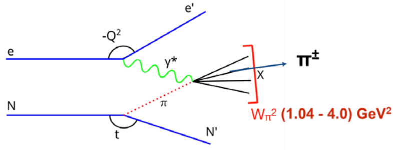


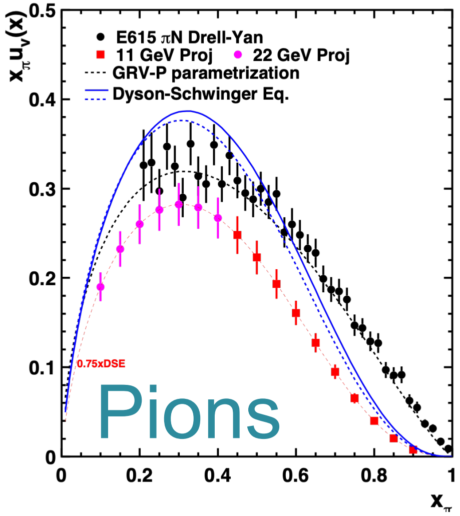
Projections based on phenomenological pion cloud model
T.J. Hobbs, Few Body Syst. 56 (2015) 6-9
J.R. McKenney et al., Phys. Rev. DD 93 (2016) 05011

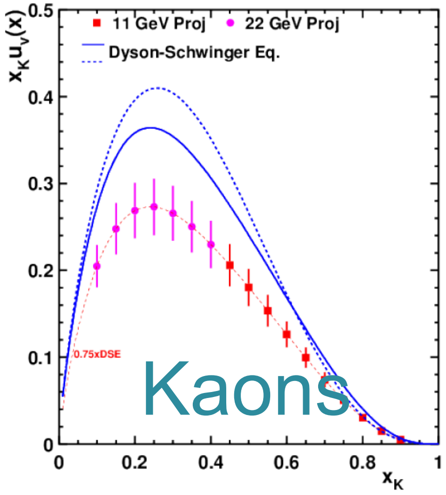
Essentially no kaon data currently

JLab 22 GeV: Opportunities for TDIS π, K Structure

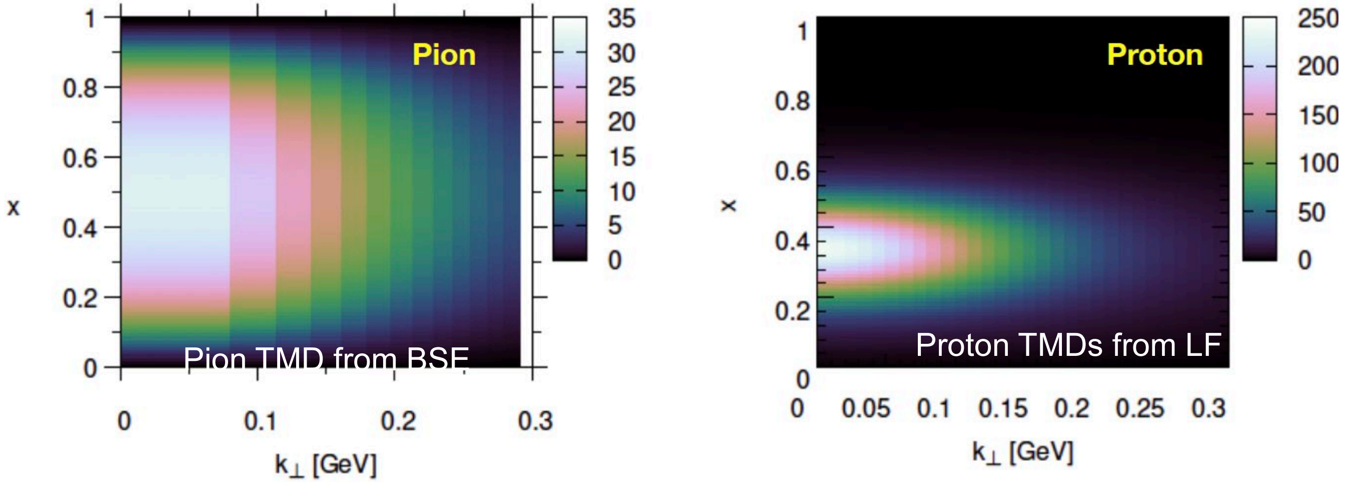
Tagged DIS in the JLab era study group: Dipangkar Dutta (MSU), Carlos Ayerbe-Gayoso, Rachel Montgomery (U. Glasgow), Tanja Horn (CUA), Thia Keppel (JLab), Paul King (OU), Rolf Ent (JLab), Patrick Barry (JLab)







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



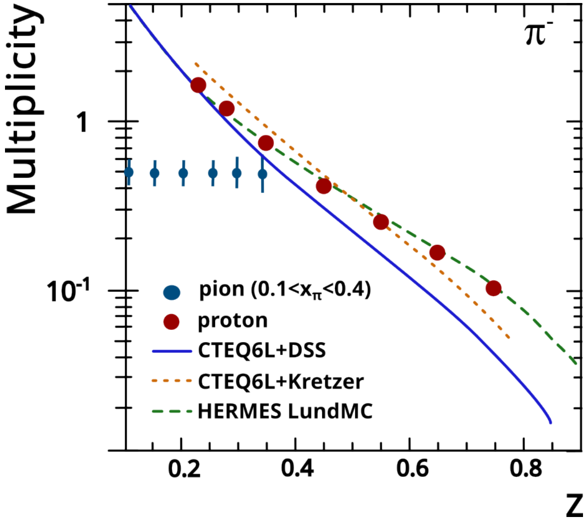
Significant x-broadening of Pion TMDs compared to proton TMDs

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

- The low-W² region was not measured at HERA – strength of resonances is unknown
- Wide kinematic coverage in TDIS to measure the resonance region

☐ 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)



Summary

- ☐ Meson structure is essential for understanding EHM and our visible Universe
  - ○ Meson structure is non-trivial and experimental data for pion and kaon structure functions is extremely sparse

- ☐ JLab 12 GeV will dramatically improve the $\pi^+/K^+/\pi^0$ electroproduction data set
  - ○ Pion and kaon form factor extractions up to high Q^2 possible (~9 and ~6 GeV^2)
  - ○ L/T separated cross sections important for transverse nucleon structure studies – may allow for accessing new type of GPDs
- ☐ 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 landscape 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