Pion and Kaon Structure analysis and future plans

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Jefferson Lab
Thomas Jefferson National Accelerator Facility

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Hall A/C User Group Meeting

Jefferson Lab, June 17 – 18, 2026

Insights into Hadron Structure and Mass through Mesons

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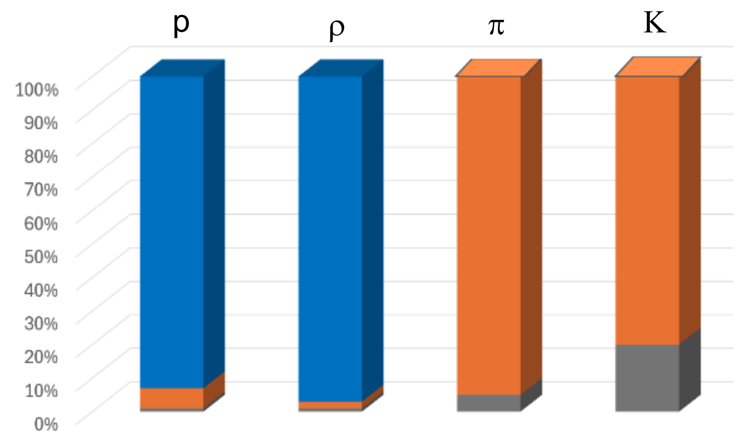
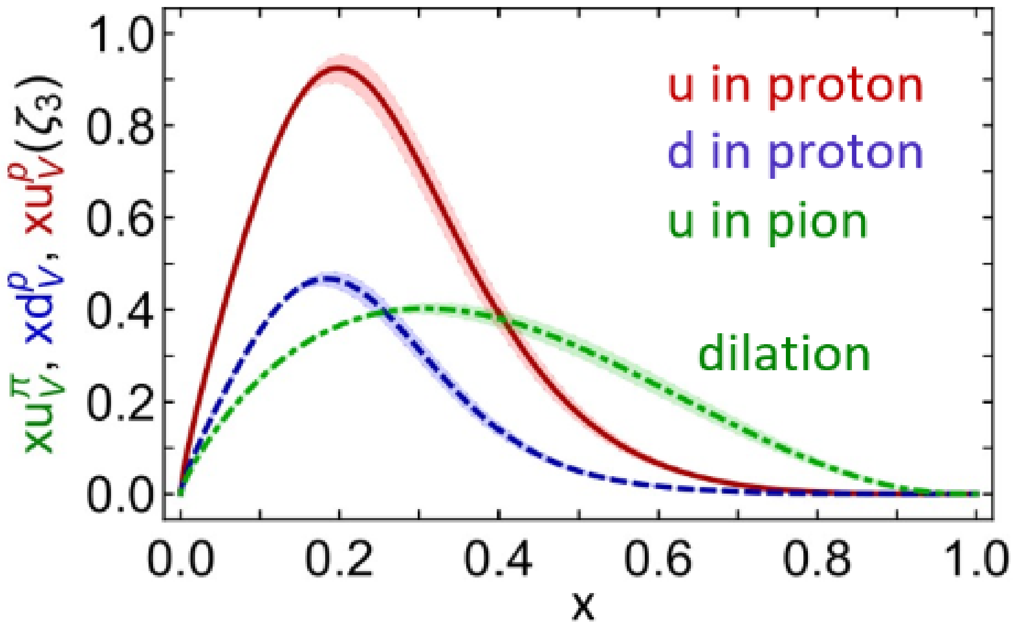


*K. Raya, A. Bashir, D. Binosi, C.D. Roberts, J. Rodriguez-Quintero, Few Body Sust. **65** (**2024**) 2, 60*
*D. Binosi, C.D. Roberts, Z.-Q. Yao, PoS QCHCC24 (**2025**) 001*



Mass budget for nucleons and mesons are vastly different

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

Valence quark distribution of proton/pion are also very different

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

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

Meson Form Factors and Emergent Hadron Mass

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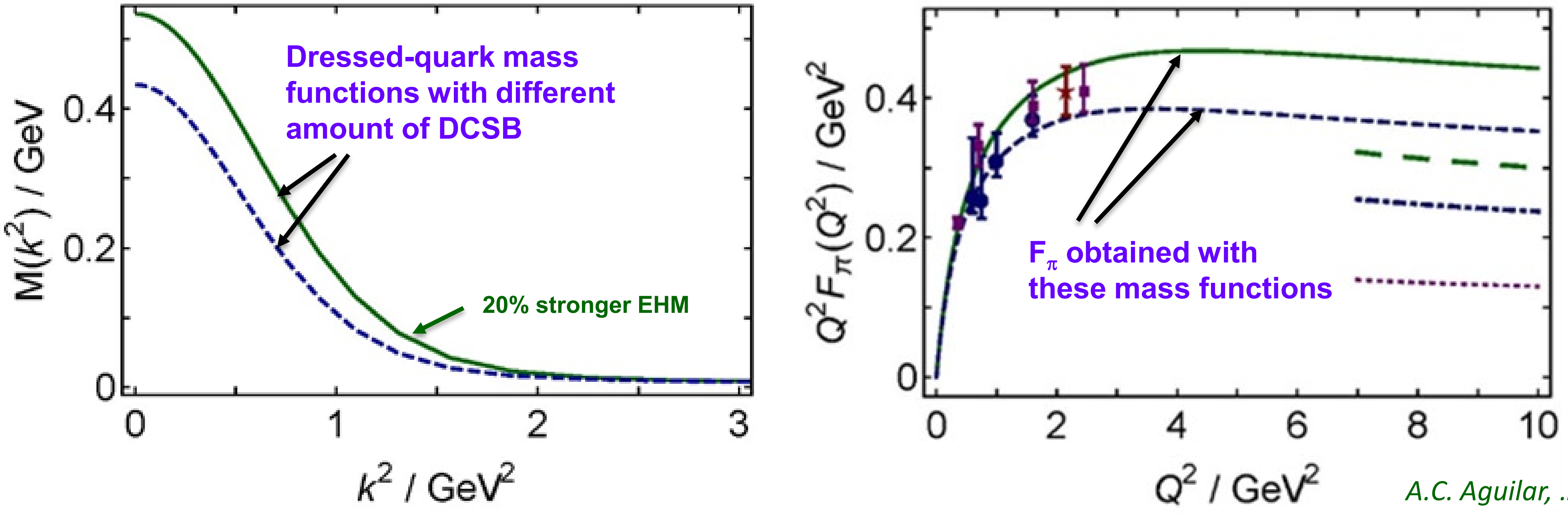
There are several measurement observables (e.g., hadron elastic/transition form factors)



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

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

Experimental Pion/Kaon Structure from JLab to EIC

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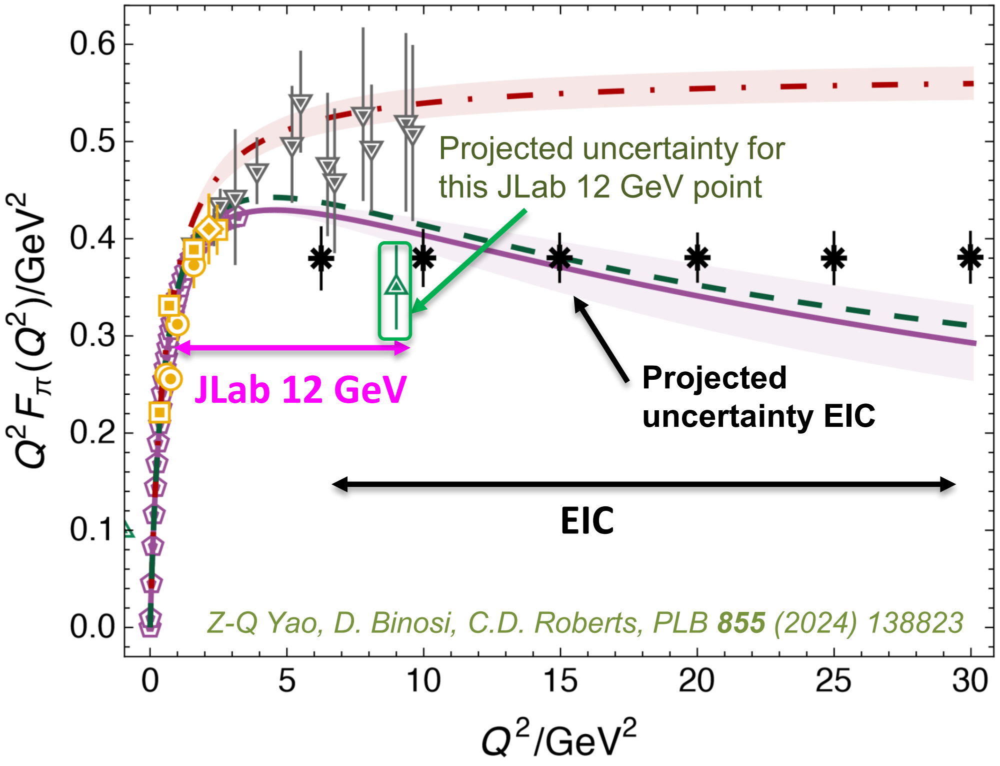
Pion and kaon form factors are of special interest in hadron structure studies

- Hall C experiments have established JLab's capability for reliable F_π measurements and are among the top-cited works from JLab

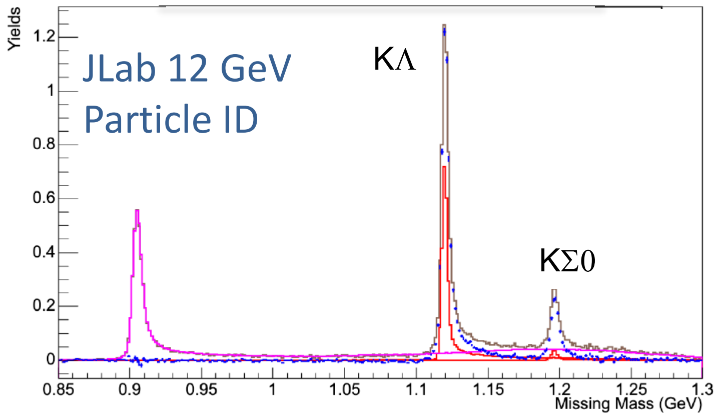
Pion

New higher Q^2 data would challenge QCD-based models in the most rigorous way and provide a real advance in our understanding of light quark systems – EHM in the wavefunction

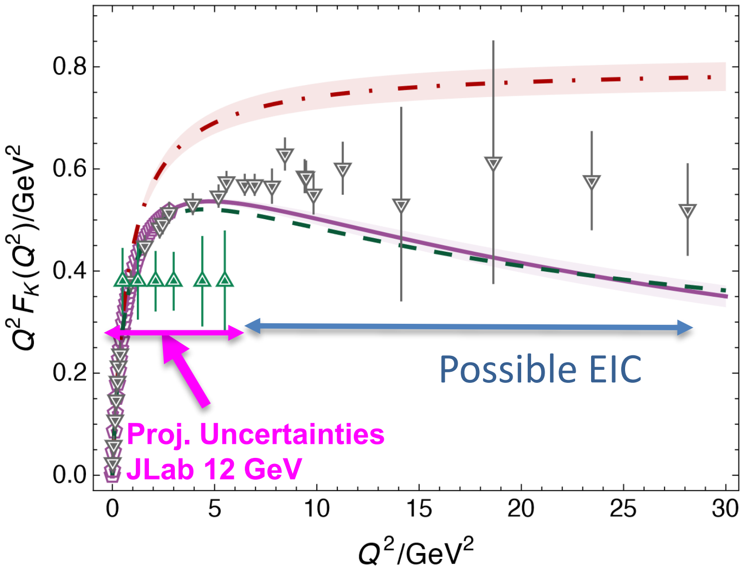


Kaon

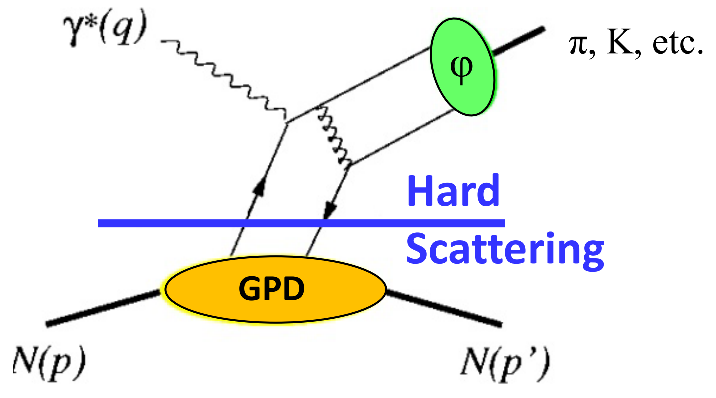
- $K^+\Lambda/K^+\Sigma^0$ cross sections will be the foundation for determining the conditions under which a clean separation of these channels may be possible at the EIC

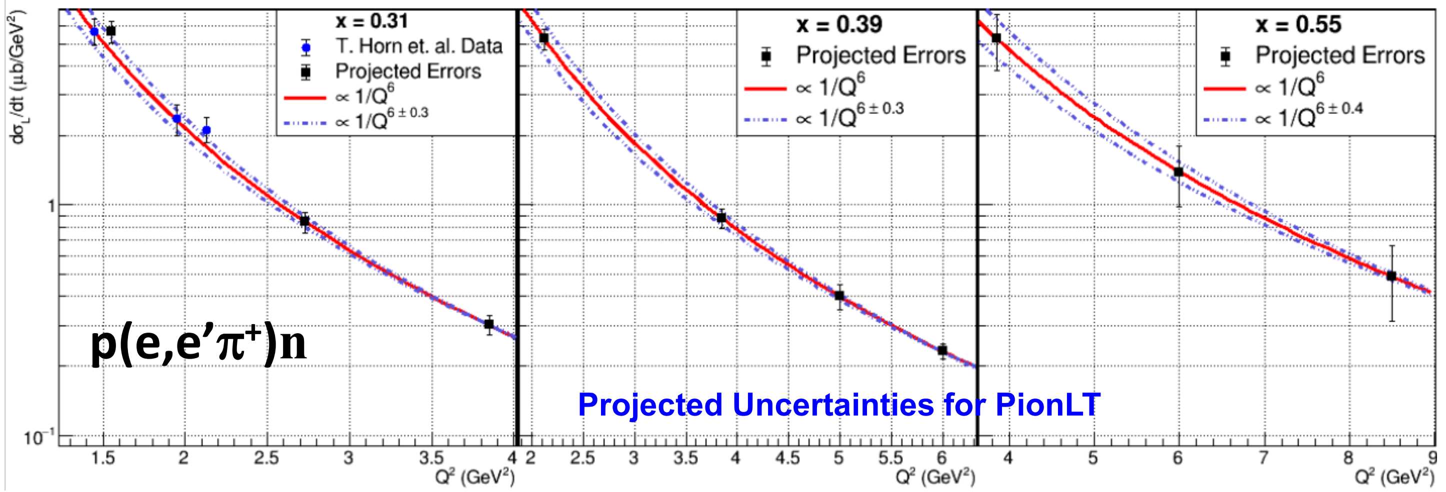


- Precise $F_K(Q^2)$ data for a material domain above Q^2 ~5 GeV^2, could deliver insights into the size and range of nonperturbative EHM–HB interference effects in hard exclusive processes



L/T Separated π^+/K^+ Cross Sections – towards Femtography





For reliable interpretation of the GPD program need to validate the reaction mechanism – key are precision L/T separated data over a range of Q^2 at fixed x/t

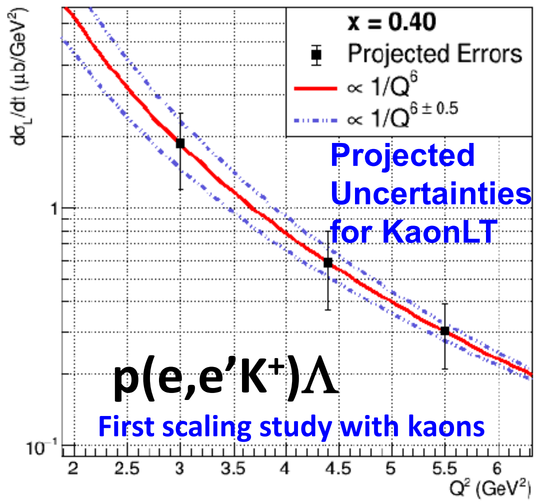
- If σ_T is confirmed to be large, it could allow for detailed investigations of transversity GPDs.
- If, on the other hand, σ_L is measured to be large, this would allow for probing the usual GPDs

- 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

- JLab 12 GeV provides π^+/K^+ L/T separated cross sections to investigate the reaction mechanism towards 3D imaging studies

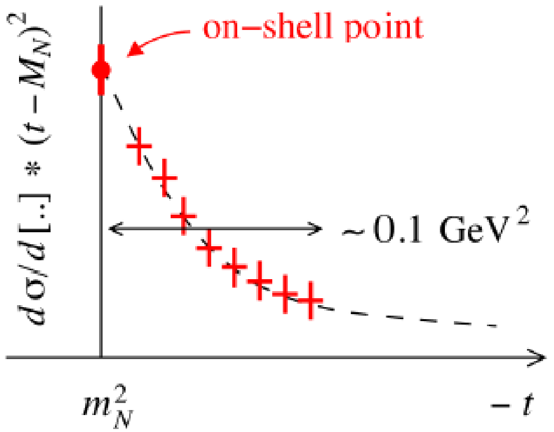


PionLT π^+: to Q^2~9 GeV^2
KaonLT K^+: to Q^2~6 GeV^2

Accessing meson structure through the Sullivan Process

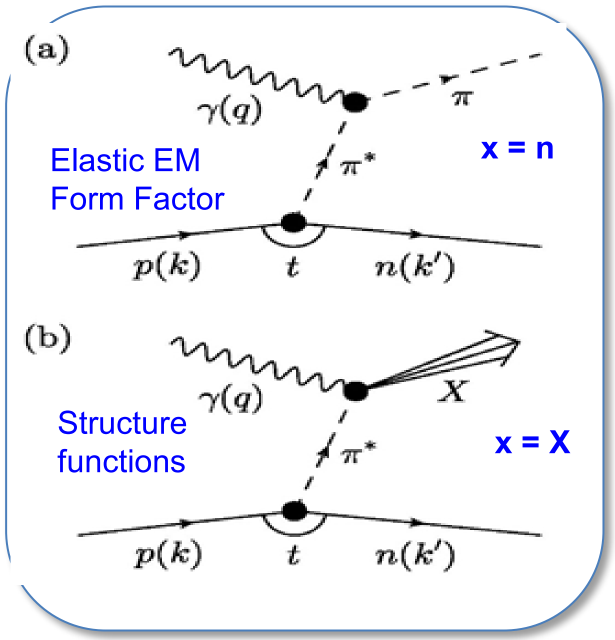
- The **Sullivan process can provide reliable access to a meson target** as t becomes space-like if the pole associated with the ground-state meson is the dominant feature of the process and the structure of the (off-shell) meson evolves slowly and smoothly with virtuality.

*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.

Sullivan Process



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

- Also **progress with elastic form factors – experimental validation (next page)**

Experimental Validation (Pion Form Factor example)

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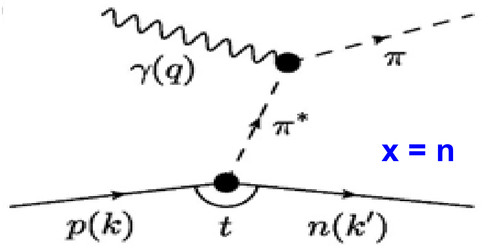
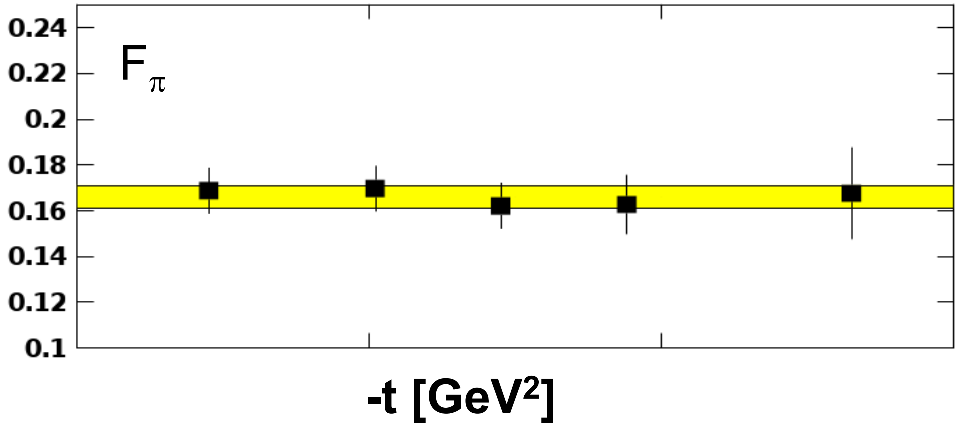
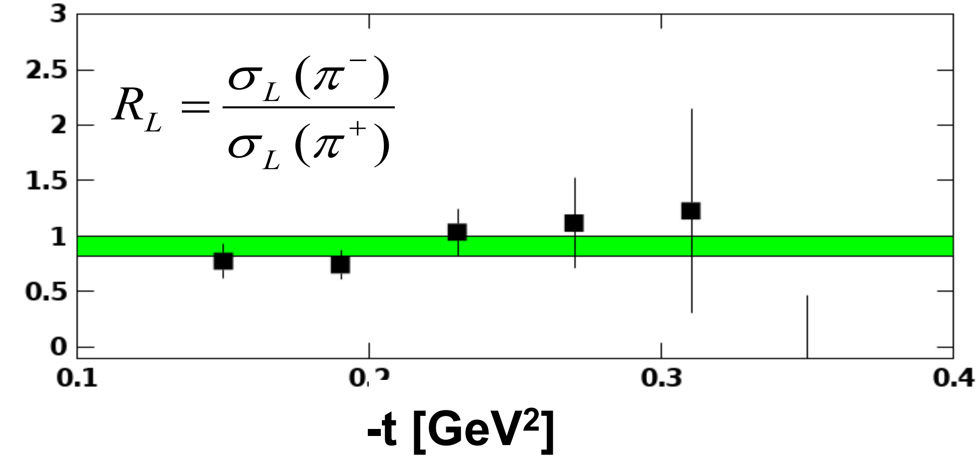
Experimental studies over the last decade have given ***confidence*** in the electroproduction method yielding the physical pion form factor







Experimental studies include:

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

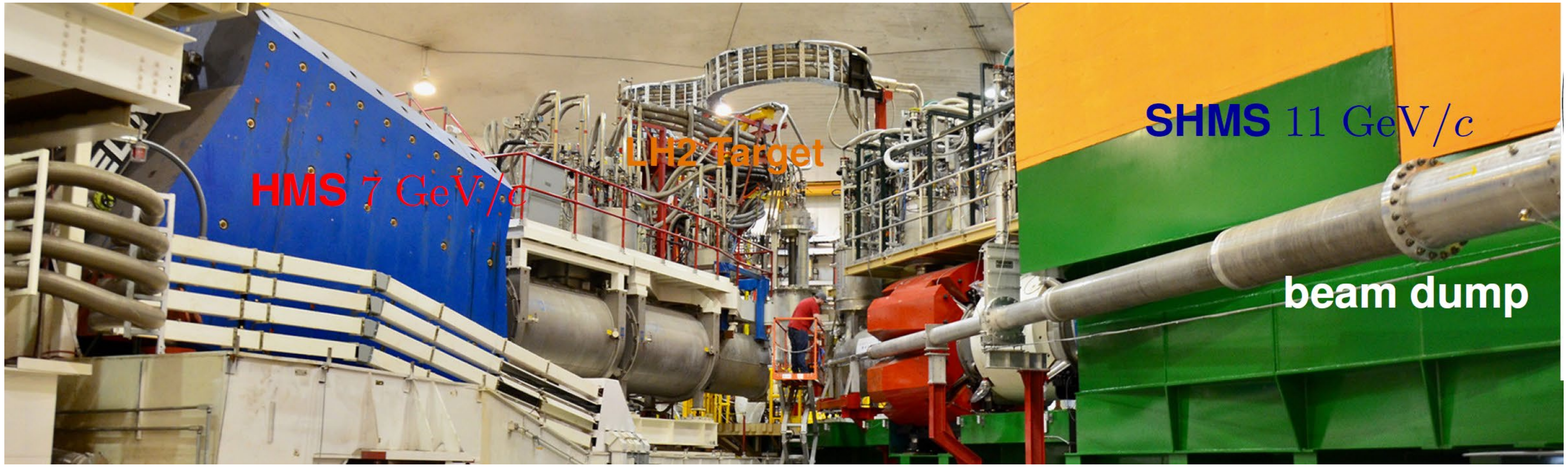
*T. Horn, C.D. Roberts, J.Phys.G **43 (2016)** 7, 073001*

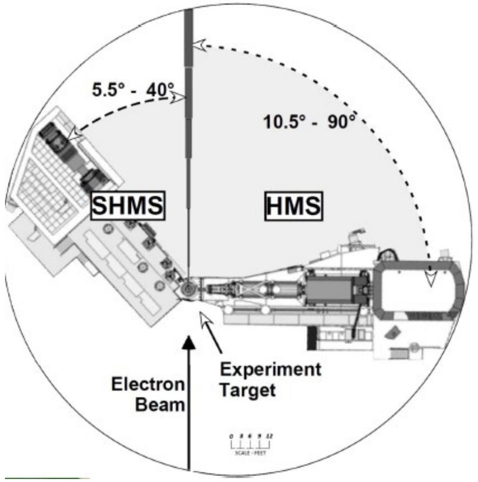
*G. Huber, …, T. Horn, et al, PRL**112 (2014)**182501*

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

Hall C: Precision Experiments with HMS + SHMS

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





S. Ali et al. Nucl.Instrum.Meth.A **1083** (**2026**) 171070

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

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

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

Our Team and Opportunities

Spokespersons (PionLT/KaonLT): Tanja Horn (CUA), Garth Huber (U. Regina), Dave Gaskell (JLab), Pete Markowitz (FIU)

Postdocs: Chi Kin Tam (CUA), Abdennacer Hamdi (U. Regina)
Former postdocs: Vladimir Berdnikov (now at JLab), Stephen Kay (now at U. of York)

PionLT and KaonLT collaborators from PAC proposals

Graduate Students:

KaonLT(E12-09-011)	PionLT (E12-19-006)
Richard Trotta (CUA, PhD 2024, now at UVA)	Nathan Heinrich (U. Regina)
Ali Usman (U. Regina, PhD 2024)	Muhammad Junaid (U. Regina)
Vijay Kumar (U. Regina, PhD 2025)	Kathleen Ramage (U. of Glasgow)
Alicia Postuma (U. Regina)	Sameer Jain (CUA)
	Nermin Sadoun (U. Regina)

Example of non-student driven Analyses: Gabriel Niculescu (JMU), Ioana Niculescu (JMU)

KaonLT	$p(e,e'K^+)\Sigma/p(e,e'K^+)\Lambda$ separated cross section ratios	Q^2=0.5, 2.115, 3.0, 4.4, 5.5	$g_{K N \Lambda}/g_{K N \Sigma}$ coupling constant ratio versus t. This is listed as one of our K^+-pole tests.	Requires extraction of Σ L/T/LT/TT cross sections from calibrated K^+ data.

Many analysis opportunities! Please contact one of the spokespeople if interested!

Link to full list of physics topics

Join the mailing list!

Publication in preparation

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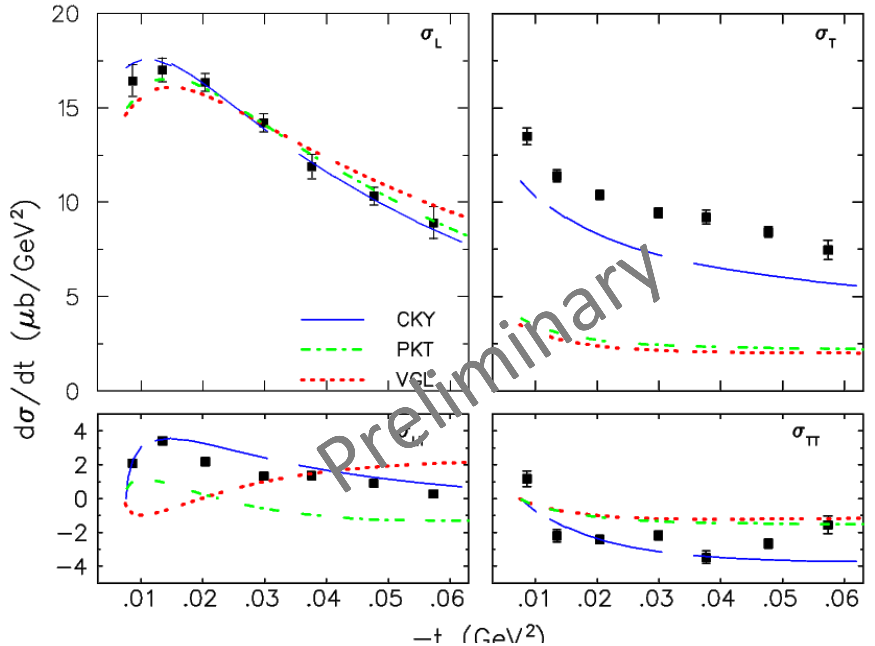
Results from PionLT: Low Q^2

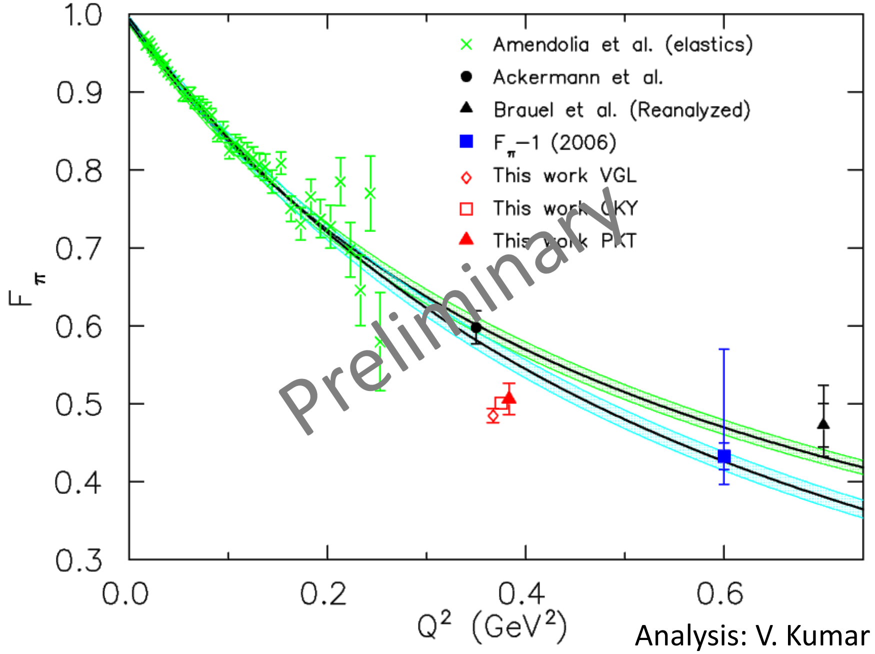
- **Goal:** further validation of the pion electroproduction method for F_π extractions
  - check the extracted F_π values using the electroproduction method against those obtained from elastic π^+e^- scattering at the CERN SPS
  - At smaller –*t* than previous measurements

Q^2 (GeV^2)	W (GeV)	-t (GeV^2)
0.375	2.20	0.008
0.425	2.20	0.010

- The π^+ form factor was extracted from σ_L using three Regge models (VGL, CKY, and PKT).
- The results are consistent with the elastic fits of Amendolia et al. - ~one standard deviation below

VGL: M. Vanderhaeghen, M. Guidal, J.M. Laget, PRC ***57*** *(1998) 1454; Nucl. Phys. A****627*** *(1997) 645*
CKY: T.K. Choi, K.J. Kong, B.G. Yu, Kor. Phys. Soc. ***67*** *(2015) L1089*
PKT: R. J. Perry et al., PLB ***807*** *(2020) 135581*





Analysis: V. Kumar

Results from PionLT: Higher Q^2

Analysis towards F_π Q^2 dep ongoing

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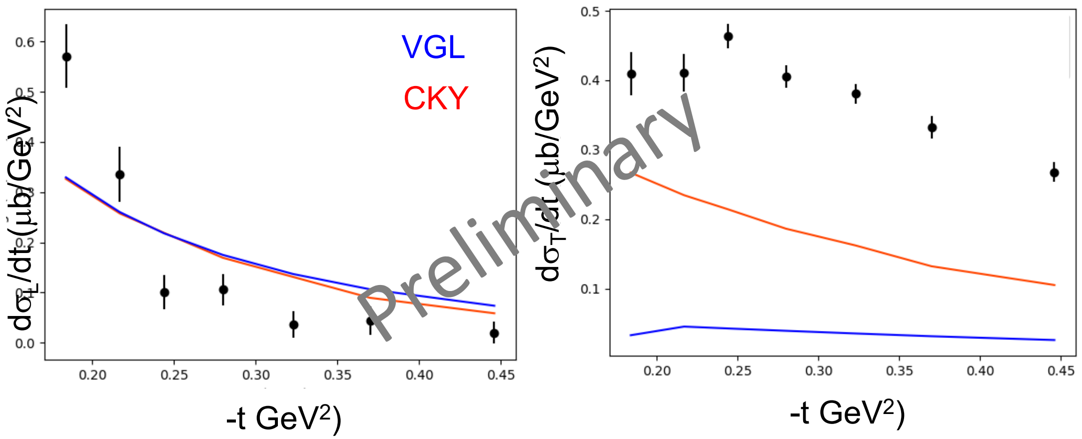
Goals

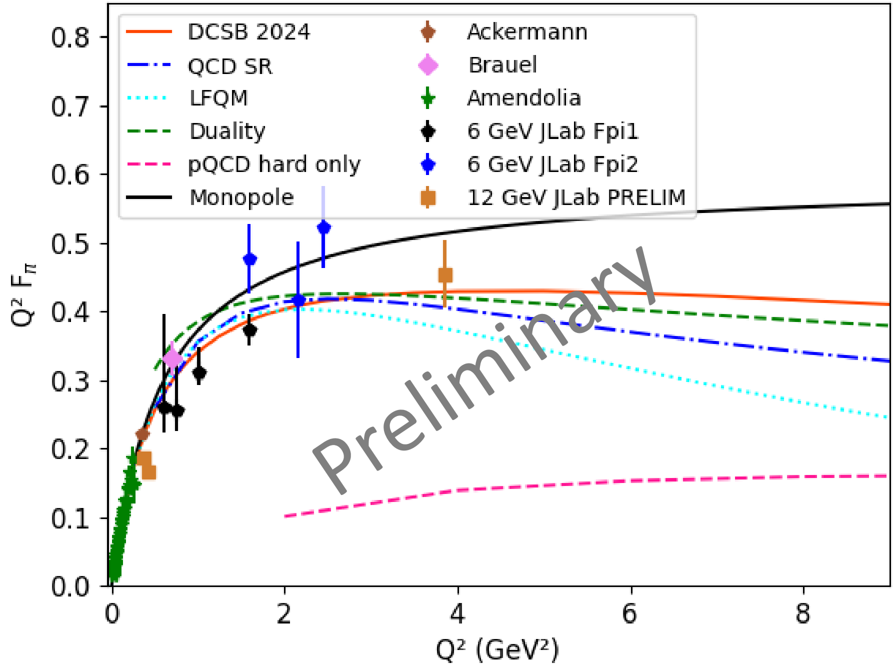
- L/T separated cross sections as a function of Q^2 at fixed x=0.3, 0.4, 0.55 to investigate the reaction mechanism towards 3D imaging studies
- Reliable pion form factor extractions up to the largest Q^2 accessible until the EIC

Data

Q^2 (GeV^2)	W (GeV)	-t (GeV^2)	x_B
1.45	2.02	0.11	0.31
1.60	3.08	0.03	
2.12	2.05	0.19	0.39
2.45	3.20	0.05	
2.73	2.63	0.12	0.31
3.85	2.02, 2.62, 3.07	0.12	0.55 0.39, 0.31
5.0	2.95	0.20	
6.0	2.40, 3.19	0.21	0.55, 0.39
8.5	2.79	0.55	0.55

Q^2=3.85 GeV^2, W=2.62 GeV





Analysis: M. Junaid

Results from PionLT: deuterium data

Analysis ongoing

Goals

- ❑ Pion pole dominance test using R_L (= $\sigma_L(\pi^-)/\sigma_L(\pi^+)$), which approaches the pion charge ratio if consistent with pion pole dominance

Data

Q^2 (GeV^2)	W (GeV)	-t (GeV^2)
1.60	3.08	0.03
2.45	3.20	0.05
3.85	2.62, 3.07	0.12
6.0	2.40	0.21

Status

- ❑ Event selection and PID – complete
- ❑ Background subtractions - complete
- ❑ Detection efficiencies – complete
- ❑ Luminosity studies - ongoing

Detecting Pions

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

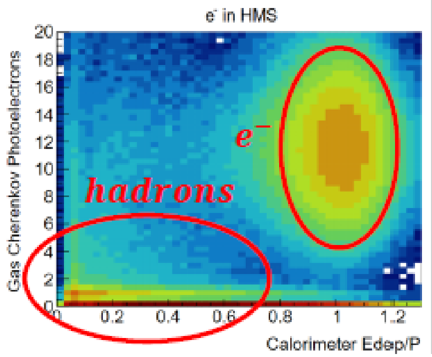
E_{beam}	Q^2	W	$-t_{min}$	x_B
6.40	1.60	3.08	0.03	0.17

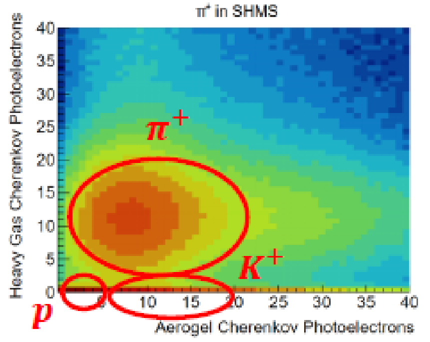
HMS - Calorimeter
- Gas Cherenkov

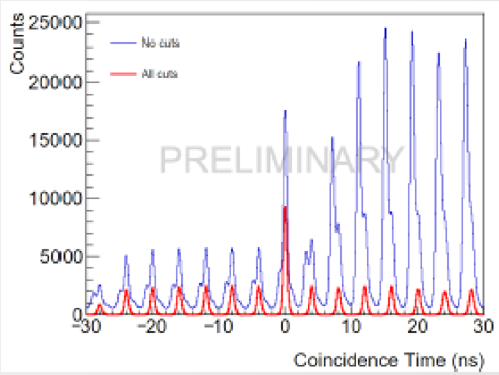
SHMS - Aerogel
- RF Time

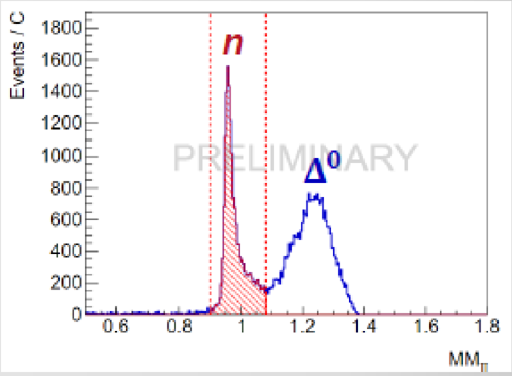
Timing - Coincidence time

Particle Identification (PID)









Analysis: K. Ramage, N. Sadoun

Results from KaonLT (Phase 1): Low Q^2

Publication in preparation

Goals:

- ❑ Obtain information on the role of the K and K* exchanges (in the t-channel)
- ❑ Check the overall normalization of the form factor

Measurements/Analysis:

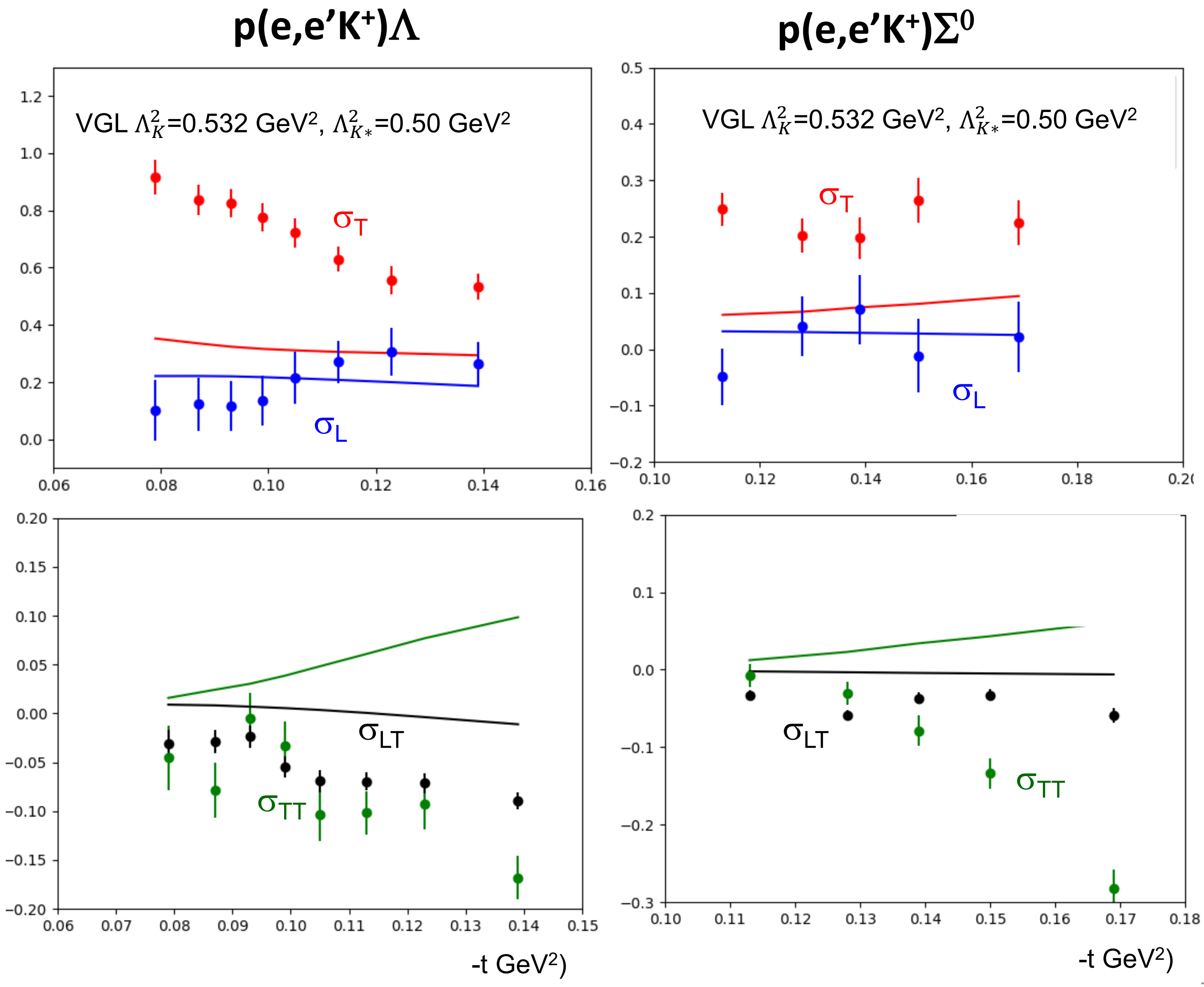
- ❑ Scan the –t dependence of the L/T separated data to determine σ_L and σ_T contributions to Λ and Σ^0 final states
- ❑ Full deconvolution of all response functions

Q^2 (GeV^2)	W (GeV)	-t (GeV^2)
0.5	2.40	0.07

Results:

- ❑ σ_L is not dominant in either channel
- ❑ Data consistent with dominance of Λ over Σ^0 channel. $\sigma_L(\Sigma^0/\Lambda)$ may have small t-dep., $\sigma_T(\Sigma^0/\Lambda)$~0.37 is independent of –t
- ❑ With Phase2 KaonLT: Q^2 dependence of Σ^0/Λ to test O. Nachtmann prediction

O. Nachtmann, NP B 74 (1978) 422



Analysis: A. Hamdi

Results from KaonLT (Phase 1): Low Q^2

Publication in preparation

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Q^2 (GeV^2)	W (GeV)	-t (GeV^2)
0.5	2.40	0.07

Compare data to Regge Models (VGL, CKY):

- ❑CKY gives a better description of σ_T
- ❑Description of σ_L is similar

Parameters: mass scale for the EM form factor:

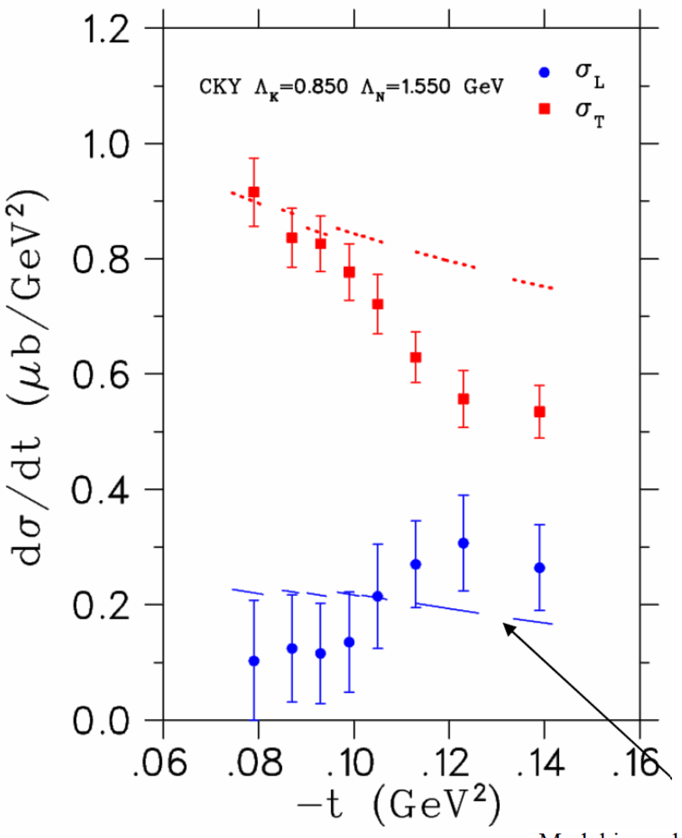
- ❑Compatible with the kaon charge radius
- ❑Models give a largely passable description of the t-dependence

VGL Λ_K^2=0.532 GeV^2, Λ_{K*}^2=0.50 GeV^2 $\rightarrow$ $\Lambda_K^2 \sim \Lambda_{K*}^2$

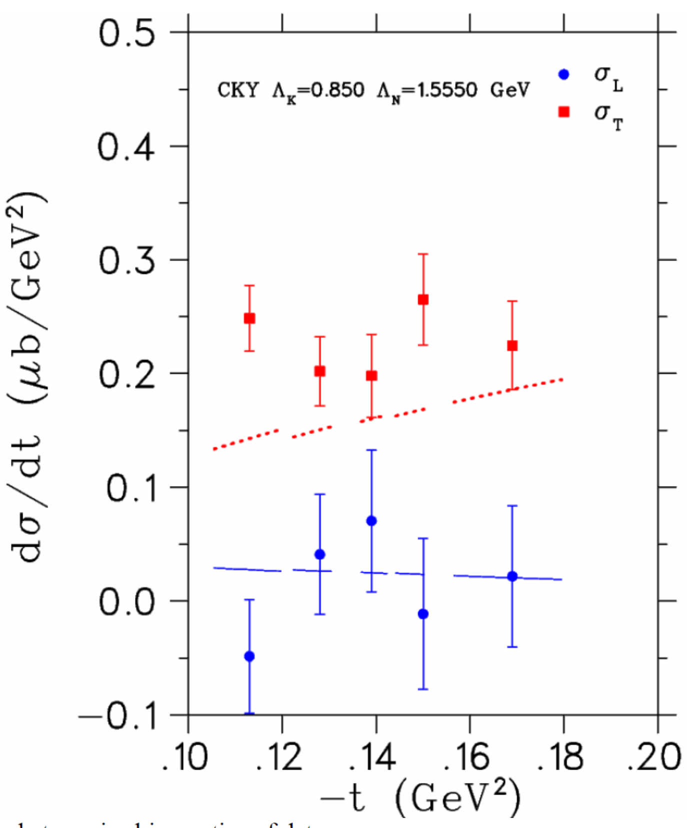
CKY Λ_K=0.850 GeV, Λ_N =1.55 GeV

- ❑Best fit of the K trajectory is consistent with the value measured by direct scattering of kaons on atomic electrons

p(e,e'K$^+$)Λ



p(e,e'K$^+$)Σ^0



Model is evaluated at precise kinematics of data.
Discontinuities indicate change in (Q^2,W) for each t-bin.

Analysis: A. Hamdi, G. Huber

Results from KaonLT (Phase 1): Higher Q^2

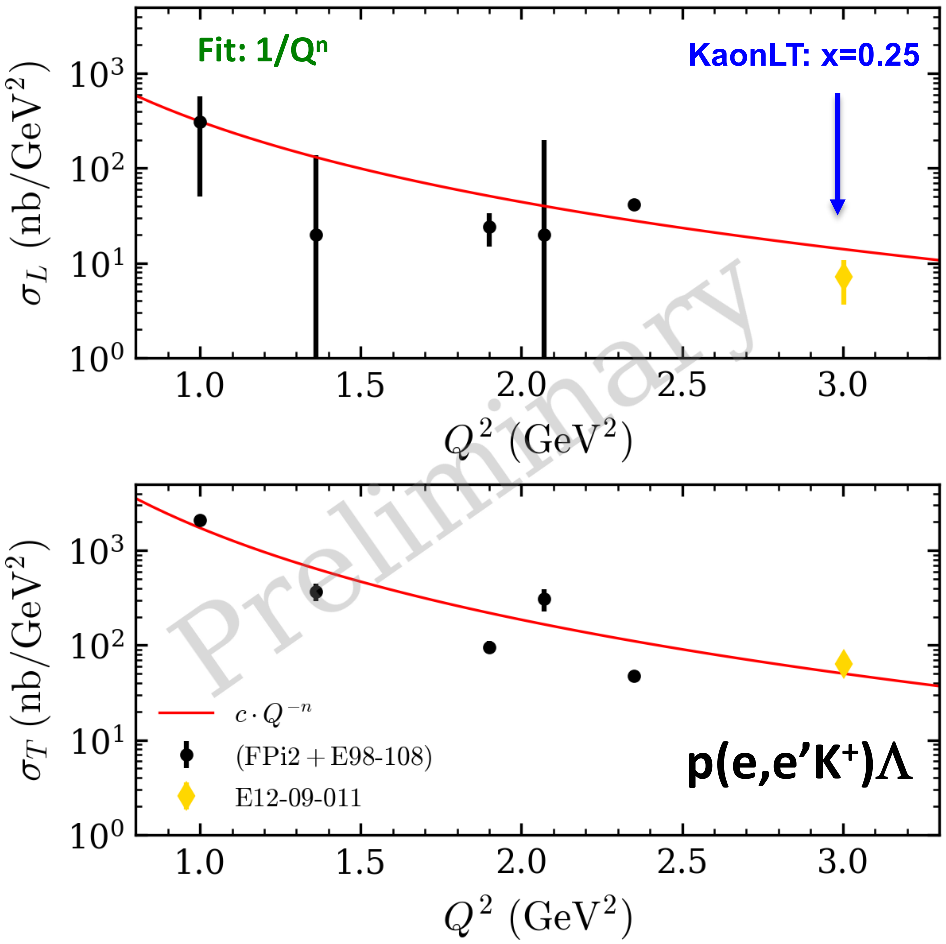
Goals

- L/T separated cross sections as a function of Q^2 at fixed x=0.25, 0.4 to investigate the reaction mechanism with strangeness towards 3D imaging studies
- L/T separated cross sections as a function of t up to the largest Q^2 to investigate the reaction mechanism towards kaon form factor extractions

Q^2 (GeV^2)	W (GeV)	-t (GeV^2)	x_B
2.115	2.95	0.008	0.21
3.00	3.14	0.010	0.25
3.0	2.32	0.531	0.40
4.4	2.74	0.507	0.40
5.5	3.02	0.503	0.40

- Results for σ_L consistent with QCD scaling, but *only one* point $\rightarrow$ others will be taken in KaonLT Phase 2 (see later slides)
- σ_T is large at Q^2=3 GeV^2

First JLab 12 GeV scaling results with kaons



Publication in preparation

Analysis: C-K Tam

Results from KaonLT (Phase 1): Higher Q^2

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p(e,e'K⁺)Λ

Goals

- ❑ L/T separated cross sections as a function of Q^2 at fixed x=0.25, 0.4 to investigate the reaction mechanism with strangeness towards 3D imaging studies
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Data

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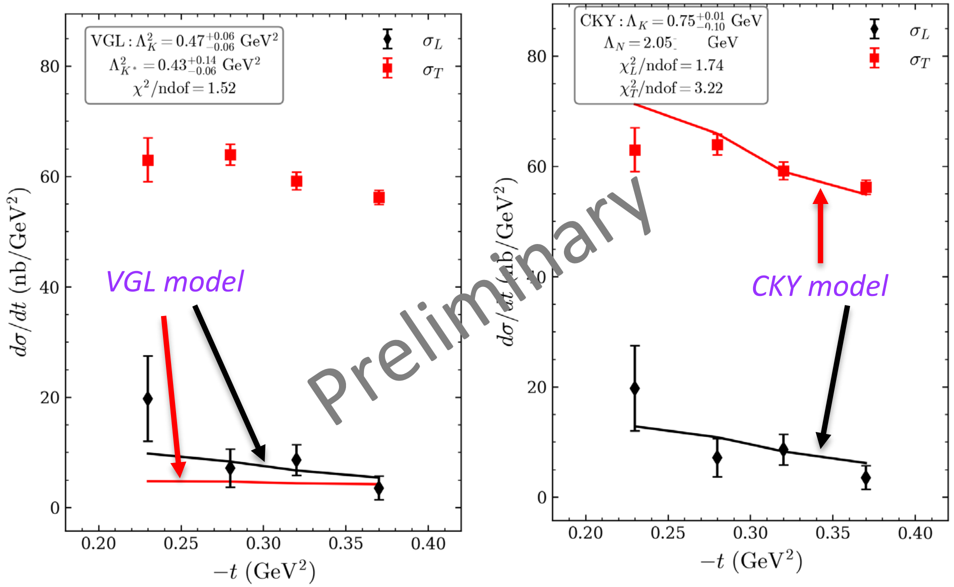
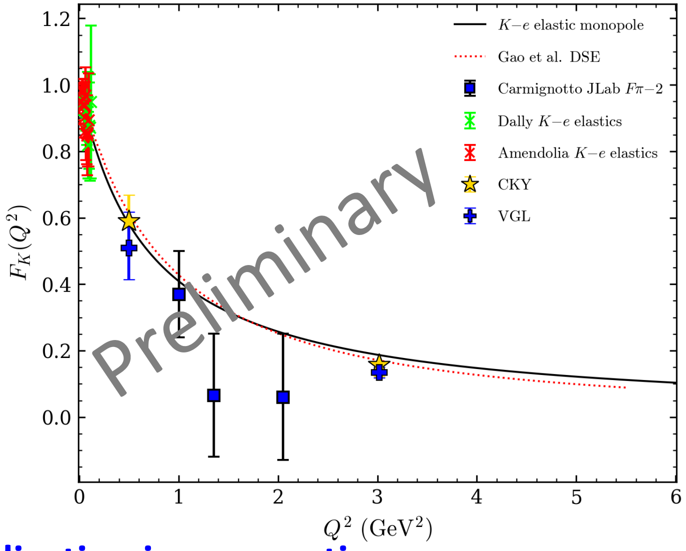




Publication in preparation

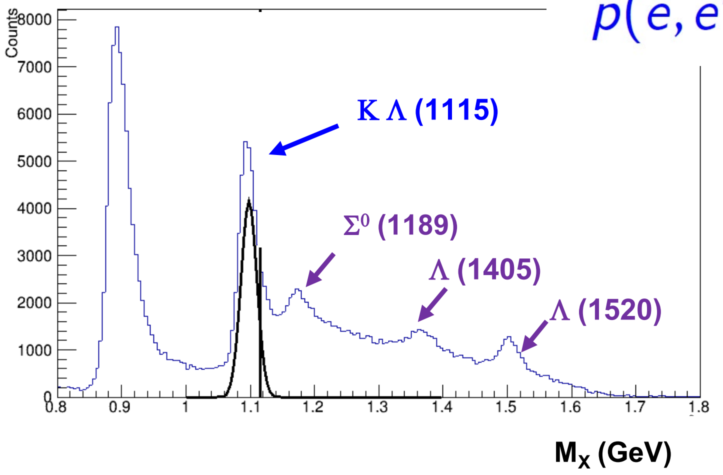
- ❑ Higher Q^2 cross sections have been extracted and compared to the two Regge models (VGL, CKY) – σ_T better described by CKY, VGL: $\Lambda_K^2 \sim \Lambda_{K*}^2$
- ❑ Preliminary FF results consistent with elastic data by Amendolia et al.

Analysis: C-K Tam

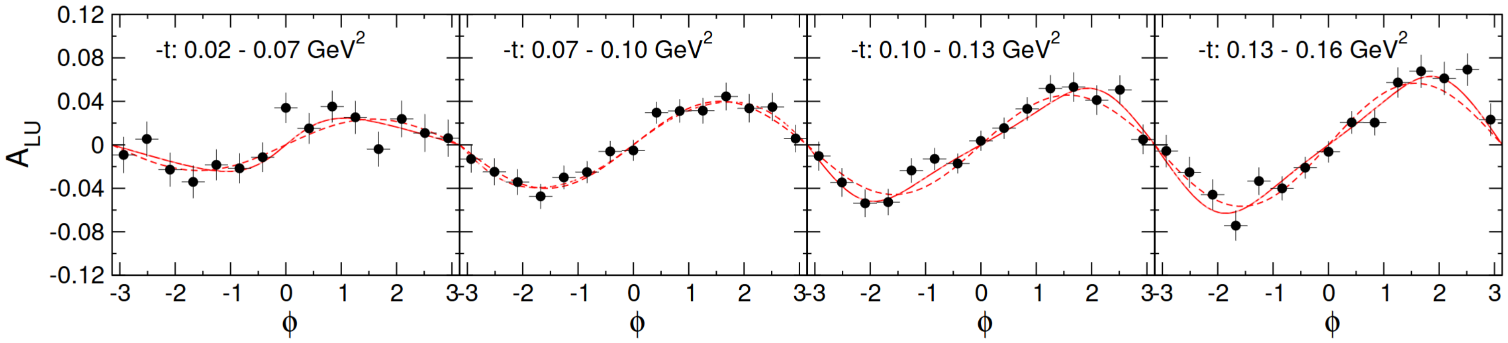
Results from KaonLT (Phase 1) – π^+ BSA

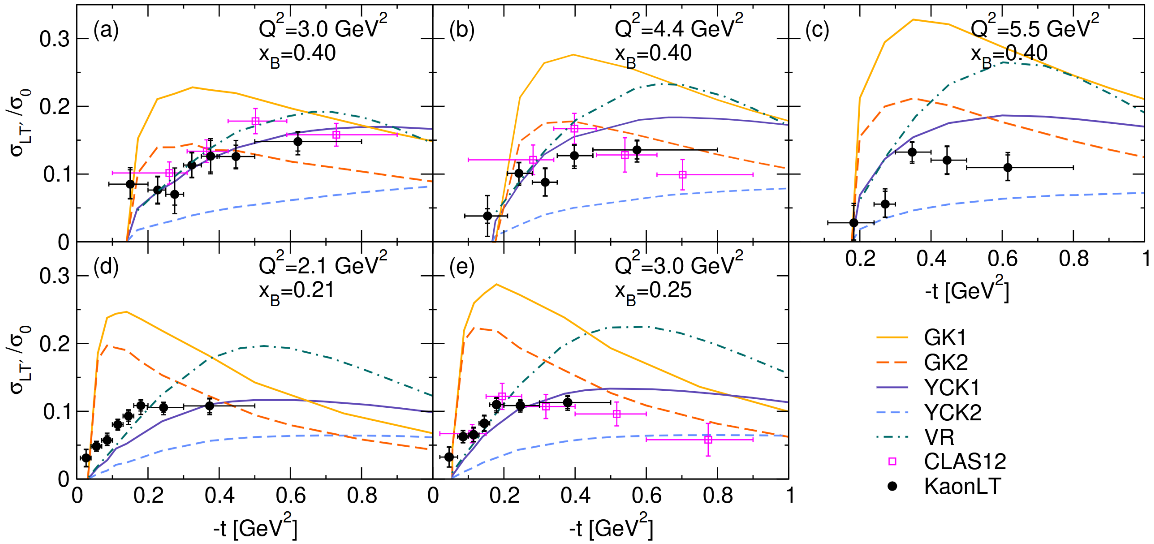
Additional Physics Channels/Topics

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



First publication from KaonLT: *A. Postuma, et al., Phys.Lett.B* **872** (**2026**) 140094





- KaonLT measured the beam spin asymmetry (JLab news release 2026)
- Finer binned at lower –t data (compared to CLAS12) suggest that have not yet reached hard/soft factorization
- Extraction of GPDs from these data should be delayed until a model-independent test can be performed, e.g., a Q^{-n} scaling study at fixed x_B for Rosenbluth separated cross-sections

Analysis: A. Postuma

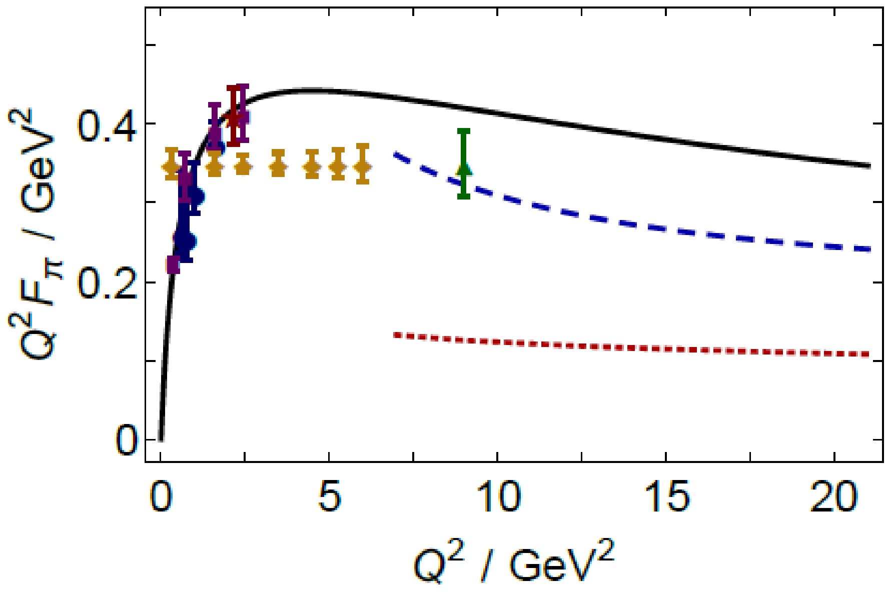
PionLT (E12-19-006) - Outlook

[Link to full list of physics topics]

PionLT data: F_π extractions and cross section (BSA) studies

- ❑ Complete higher Q^2 analyses and additional topics
  - ○ Pion pole dominance test
  - ○ Extract F_π to Q^2=8.5 GeV^2
- ❑ Global studies of pion and kaon cross sections providing information for future experiments, e.g., EIC
- ❑ Physics from p-channels

Many analysis opportunities! Contact us if interested!



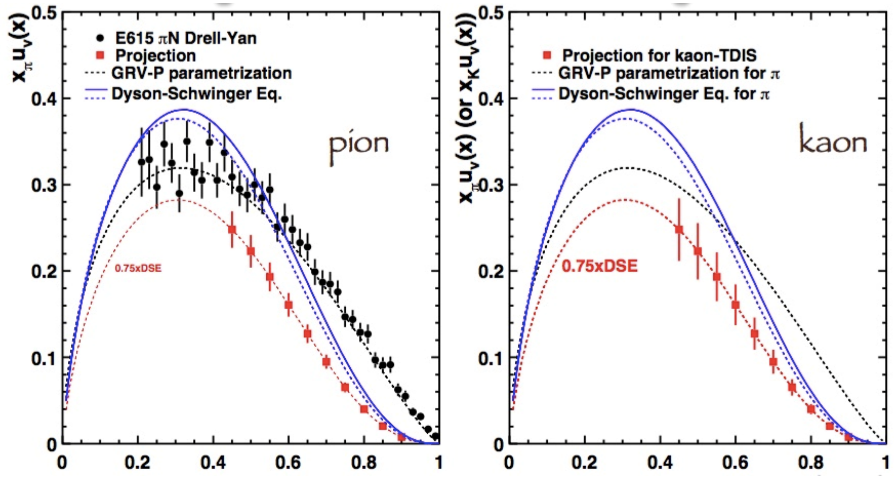
Examples of related studies:

E12-13-010/007: L/T separated exclusive and SIDIS π^0 cross sections

- ❑ Factorization test, additional information for FF
- ❑ data taking completed 2024

C12-15-006/006A: Pion and kaon SF studies through TDIS

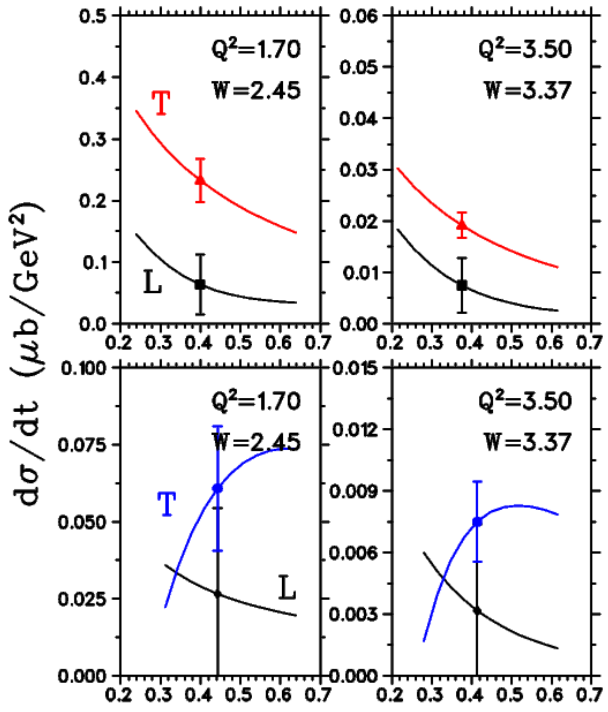
- ❑ Measure tagged SFs in the valence region to measure the mesonic content of nucleons: charged pion SF and kaon SF

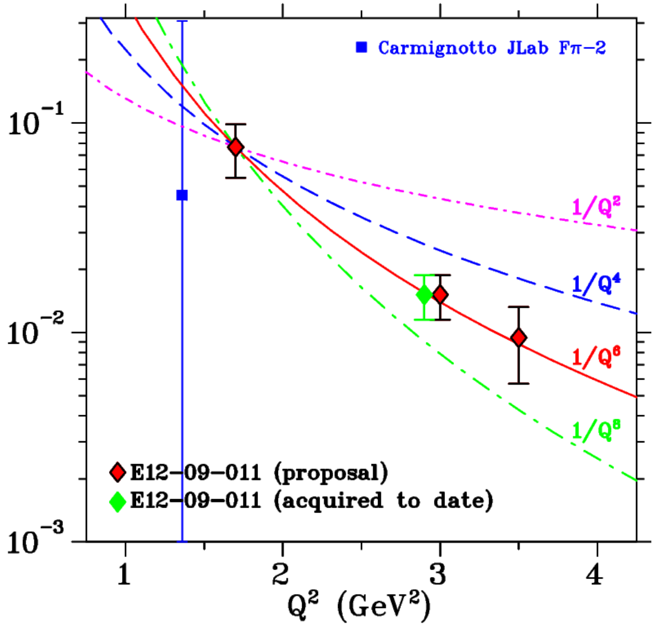


KaonLT (E12-09-011) Outlook

- **KaonLT Phase 1** data**:** Complete higher Q^2 analysis and additional topics
- **Run KaonLT Phase 2:** establish a high-precision data base of $K^+\Lambda$, $K^+\Sigma^0$ cross sections
    - Shed light on the reaction mechanism
    - Establish validation technique for possible kaon form factor measurements at the EIC
- **KaonLT Phase 2 allows for**:
    - performing L/T separations for the Q^2 scan at x_B=0.25 to validate the hard-soft reaction mechanism (possible GPD access)

      PAC34: "…it is compulsory to first test that the regime of validity has been reached, and this can be done by comparing the Q^2 variation of the cross section against the prediction of QCD. This is a solid physics case…."
    - improving the uncertainties of possible 12 GeV kaon form factor extractions
- **KaonLT Phase 2 expected to run as soon as March 2027**





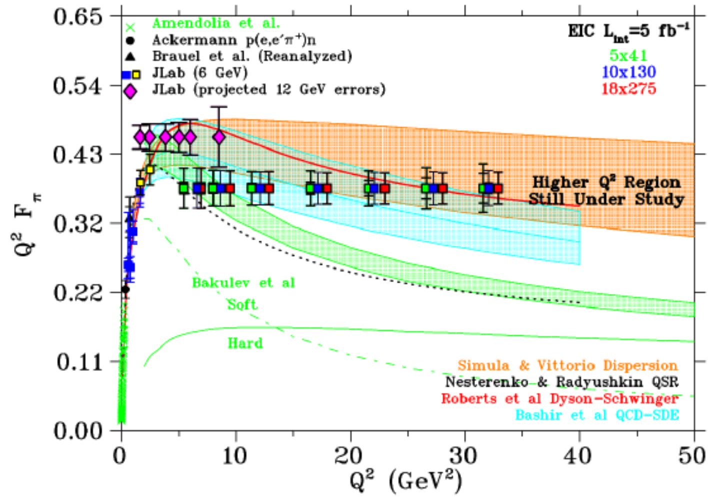
EIC Early Science Examples

Meson SF Working group members:

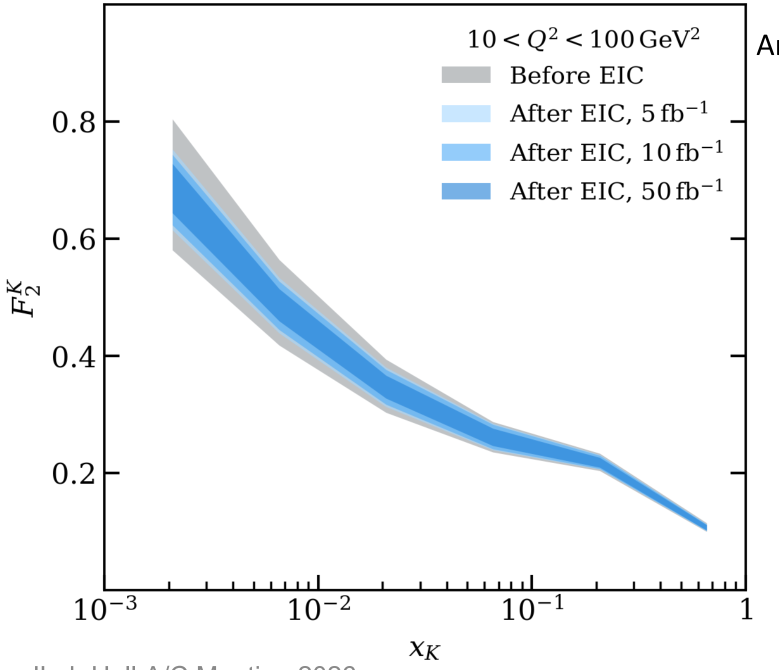
Far-forward region at EIC opens up the high Q^2 regime for F_π/F_K and SF via Sullivan process

Pion Form Factor and Structure Function

- F_π looks promising even with the modest integrated luminosity in the early science program. How high in Q^2 will be possible?
- Pion SF reduce uncertainties in global PDF fits



Analysis: S. Kay



Analysis: B. Fraisse

Kaon Form Factor and Structure Function

- Measurements more complicated as need to measure Λ momenta and Λ difficult to measure (it decays!)
- Baptiste Fraisse (CUA) developed a new Λ recon algorithm searching for triple coincidences with several calorimeters – reasonable recon efficiency and high purity.
- Projections for Kaon SF look promising
- F_K projections ongoing for EIC

Summary

THE CATHOLIC UNIVERSITY OF AMERICA

- ❑ Meson structure is essential for understanding EHM and our visible Universe
- ❑ The JLab 12 GeV era is going strong – **PionLT and KaonLT Phase 1 complete**
  - First publication from KaonLT Phase 1 in 2026 – two more in preparation, e.g. low Q^2 F_K
  - First publication from PionLT on low Q^2 F_π in preparation
- ❑ Ongoing analysis of PionLT and KaonLT Phase 1 will produce
  - Pion and kaon form factor extractions up to high Q^2 possible (~9 and ~6 GeV^2) – preliminary results becoming available
  - L/T separated cross sections important for transverse nucleon structure studies – may allow for accessing new type of GPDs
- ❑ **KaonLT Phase 2 expected to run as soon as 2027**
  - performing L/T separations for the Q^2 scan at x_B=0.25 to validate the hard-soft reaction mechanism (possible GPD access)
  - improving the uncertainties of possible 12 GeV kaon form factor extractions
- ❑ There are very **exciting imminent opportunities to collect additional data for light mesons**
  - TDIS experiments provide data for resolving and cross-checking pion PDF issues at high-x and provides kaon SF extraction in an almost empty kaon structure world data set
- ❑ **Beyond JLab: π^+/K^+ structure is a Far Forward processes with major EIC Science and Detector Emphasis**

Our Collaboration remains extremely active in charged pion and kaon measurements

Curious or have ideas? – join us in PionLT/KaonLT or Meson SF spaces!