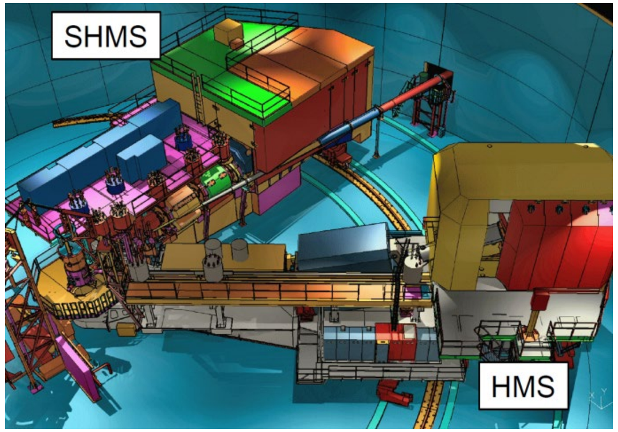
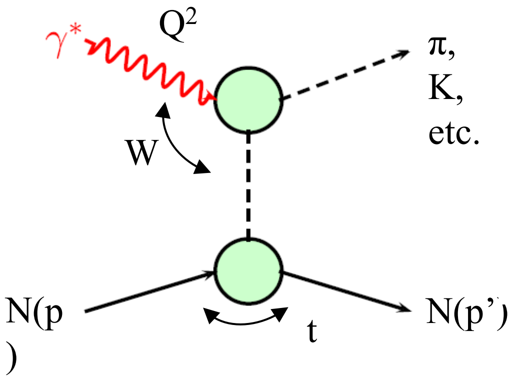
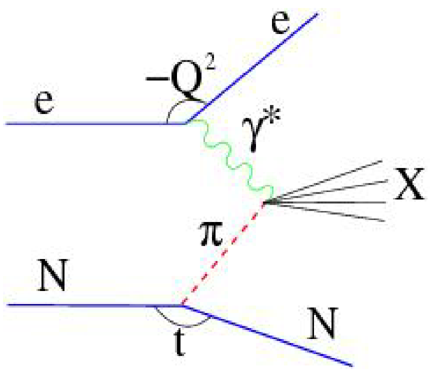
PionLT/KaonLT – first separated cross sections from JLab 12 GeV data



Dave Gaskell, [Tanja Horn](), Garth Huber, Pete Markowitz

On behalf of the PionLT/KaonLT Collaborations





THE CATHOLIC UNIVERSITY OF AMERICA

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Supported in part by NSF grants PHY2309976 and PHY2012430

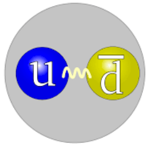
JLUO25 Jefferson Lab User Organization Annual Meeting

Jefferson Lab, June 24-26, 2025

Experiments Overview

PionLT (E12-19-006)

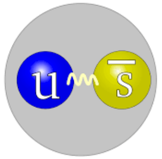
Spokespersons: D. Gaskell (JLab), T. Horn (CUA), G.Huber (URegina)



- L/T separated cross sections as a function of Q^2 at fixed x=0.3, 0.4, 0.55 to validate the reaction mechanism towards 3D imaging studies
- Reliable pion form factor extractions to the highest possible Q^2
- Validation of pion form factor extractions at the highest Q^2

KaonLT (E12-09-011)

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



- 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 and precision $K^+\Lambda$, $K^+\Sigma^0$ cross sections as a function of t up to the largest Q^2 to investigate the reaction mechanism towards kaon form factor extractions

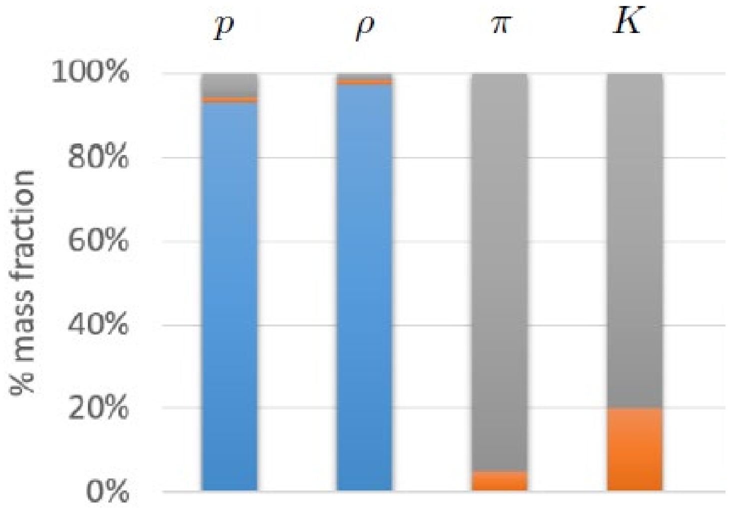
Pion and Kaon Experiments Motivation

- Pion and Kaon structure has an important place in studies of the transition from the nonperturbative to perturbative region
- Need to validate the hard-exclusive reaction mechanism – key are precision longitudinal-transverse (L/T) separated data over a range of Q^2 at fixed x/t
- EIC YR: comparison of F_π and F_K over a wide range in Q^2 will provide "*unique information relevant to understanding the generation of hadronic mass*" *R. Abdul Khalek, …, T. Horn, et al., Nucl. Phys. A **1026** (2022) 122447*
- Need L/T separated and precision cross section data for tests of the reaction mechanism (in particular $K^+\Lambda$, $K^+\Sigma^0$) - not possible at EIC - JLab is the only source for this towards hadron structure at EIC

Insights into Hadron Structure and Mass through Mesons

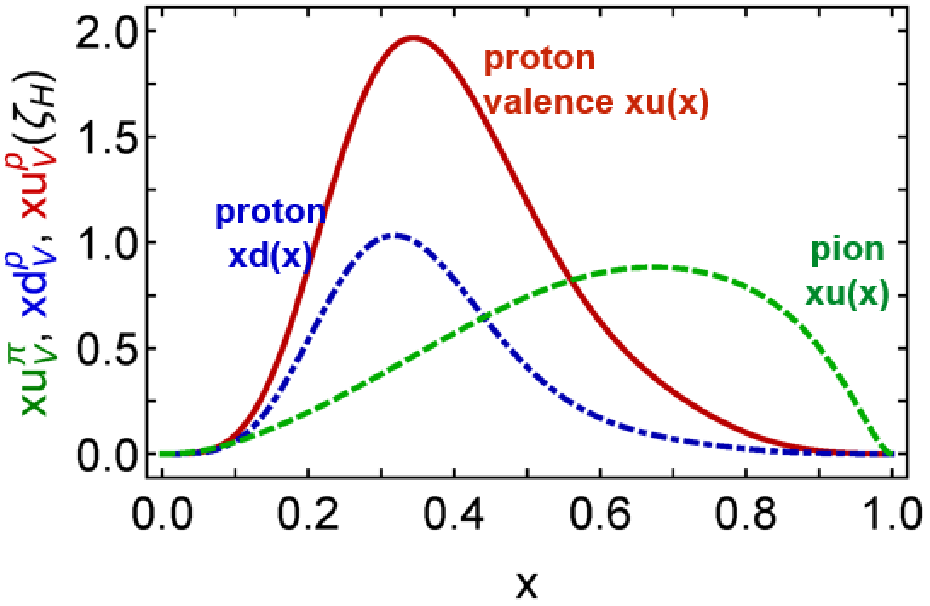
Understanding pion/kaon is vital to understand the **dynamic** generation of hadron mass and offers unique insight into EHM and the role of the Higgs mechanism

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



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

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



Mass budget for 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

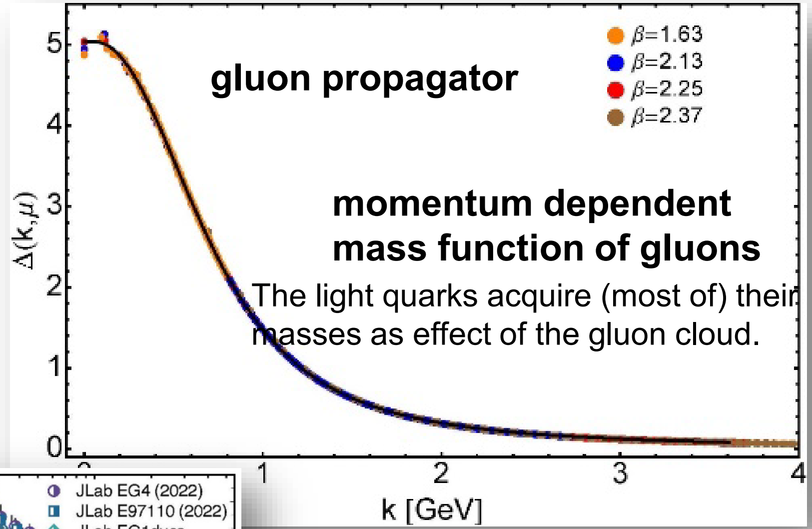
Valence quark distribution of proton/pion are also very different

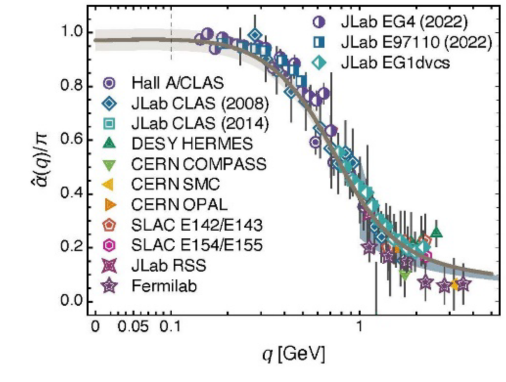
→ Difference between meson PDFs: direct information on emergent hadron mass (EHM)

Emergence of Hadron Mass (EHM)

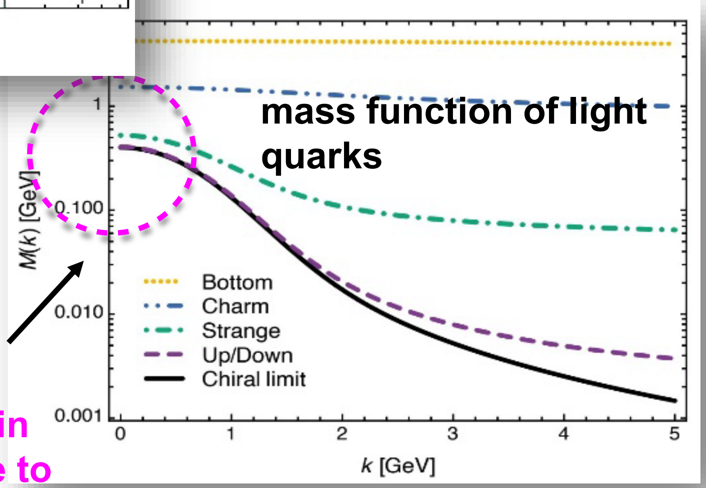
Adapted from C.D. Roberts at PAW24, Geneva, Switzerland, Mar 18-20, 2024

- Absent Higgs boson couplings, QCD Lagrangian is scale invariant
- Yet …
  - Massless gluons become massive
  - A momentum-dependent charge is produced
  - Massless quarks become massive
- EHM is expressed in
  EVERY strong interaction observable
- Challenge to Theory:
  Elucidate all observable consequences of these phenomena and highlight the paths to measuring them
- **Challenge to Experiment:**
  Test the theory predictions so that the boundaries of the Standard Model can finally be drawn





THREE PILLARS OF EHM



Rapid increase in mass due to gluon cloud

"Mass without mass!"

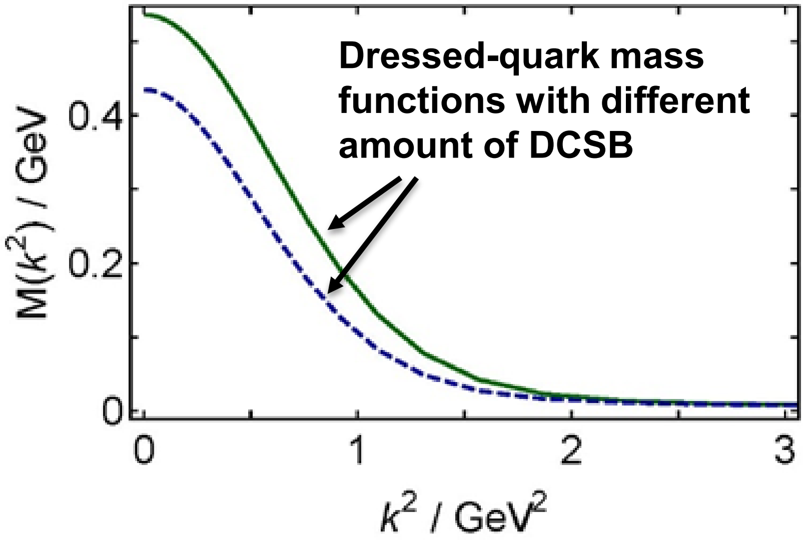
- ✓ *Process independent strong running coupling*
  Daniele Binosi *et al.*, arXiv:1612.04835 [nucl-th] Phys. Rev. D 96 (2017) 054026/1-7
- ✓ *Experimental determination of the QCD effective charge $\alpha_{g1}(Q)$.*
  A. Deur; V. Burkert; J.-P. Chen; W. Korsch, Particles 5 (2022) 171
- ✓ *QCD Running Couplings and Effective Charges*, Alexandre Deur, Stanley J. Brodsky and Craig Roberts, e-Print: 2303.00723 [hep-ph], Prog. Part. Nucl. Phys. **134** (2024) 104081

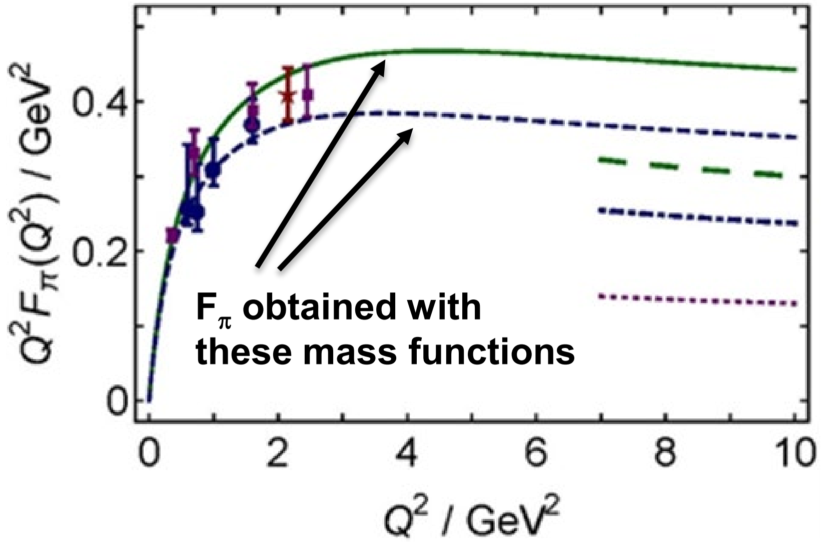
See also C. D. Roberts, D. Richards, T. Horn, L. Chang, Prog.Part.Nucl.Phys. ***120 (2021)*** *103883*

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

Meson Form Factors and Emergent Mass

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





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

- ❑ Two dressed quark mass functions distinguished by the amount of DSCB
  - ○ Emergent mass generation is 20% stronger in the system characterized by the solid green curve, which is the more realistic case

- ❑ Fpi obtained using these mass functions
  - ❑ r_π=0.66 fm (solid green)
  - ❑ r_π = 0.73 fm (solid dashed blue)
- ❑ F_π predictions from QCD hard scattering form, obtained with the related, computed π DAs
- ❑ QCD hard scattering formula using conformal limit of pion's twist-2 PDA

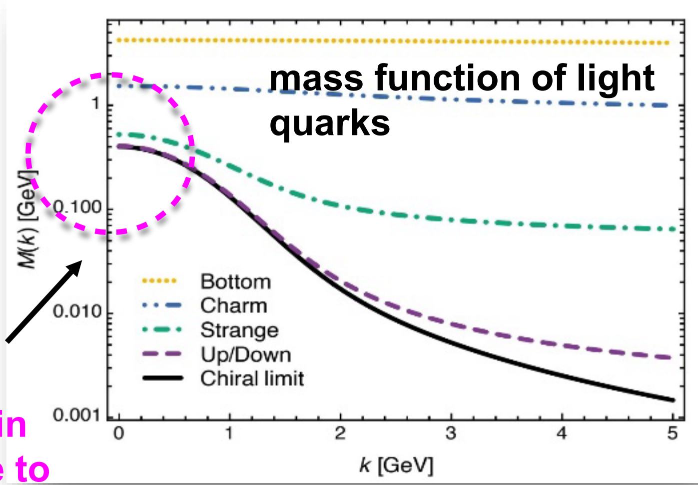
At experimentally accessible energy scales, the pion form factor is sensitive to EHM scale in QCD

Review Scientific Motivation: Form Factors

$$\frac{F_K(Q^2)}{F_\pi(Q^2)} \xrightarrow[Q^2\to\infty]{} \frac{f_K^2}{f_\pi^{\,2}}$$

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

- ***Pion and kaon form factors*** are of special interest in hadron structure studies
  - pions and kaons are not point like; their internal structure is more complex than is usually imagined
  - precise $F_K(Q^2)$ data $>Q^2$ ~5 GeV^2, could deliver insights into the size and range of nonperturbative EHM–HB interference effects in hard exclusive processes

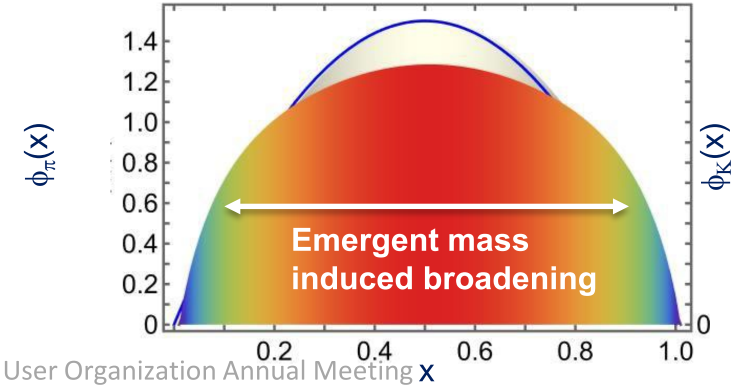


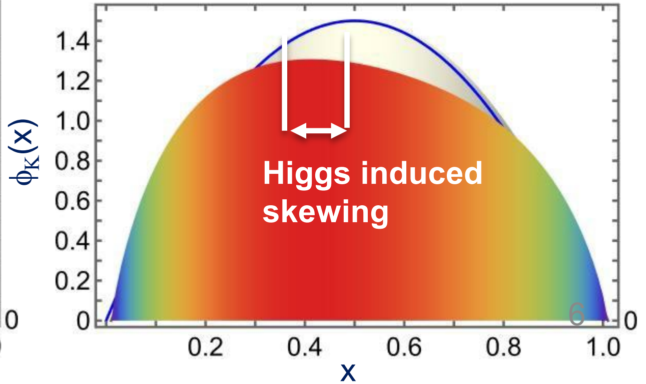
Rapid increase in mass due to gluon cloud

- Recent advances and future prospects in experiments
  - Completed Hall C experiments have established JLab's capability for reliable F_π measurements using the π^-/π^+ validation methods
  - $K^+\Lambda/K^+\Sigma^0$ cross sections can play a similar role. These data will be the foundation for determining the conditions under which a clean separation of these channels may be possible at the EIC

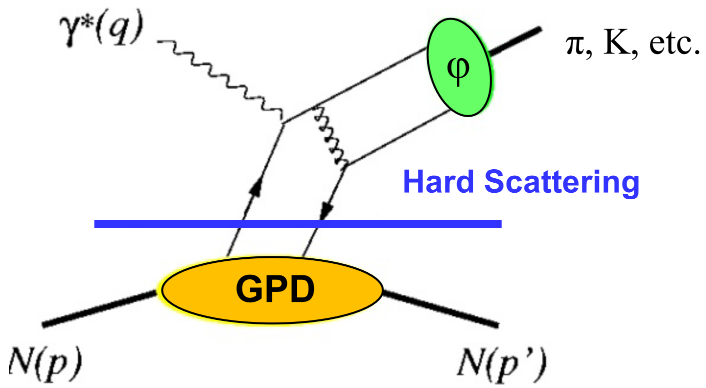
C.D. Roberts, D.G. Richards, T. Horn, L. Chang, Prog. Part. Nucl. Phys. ***120*** *(****2021****) 103883/1-65*

- Experimental development has been matched by theoretical and computational advances
  - QCD calculations within DSE framework describe how quarks acquire momentum-dependent mass
  - Increasingly precise calculations of PDFs and distribution amplitudes through continuum calculations and on the lattice

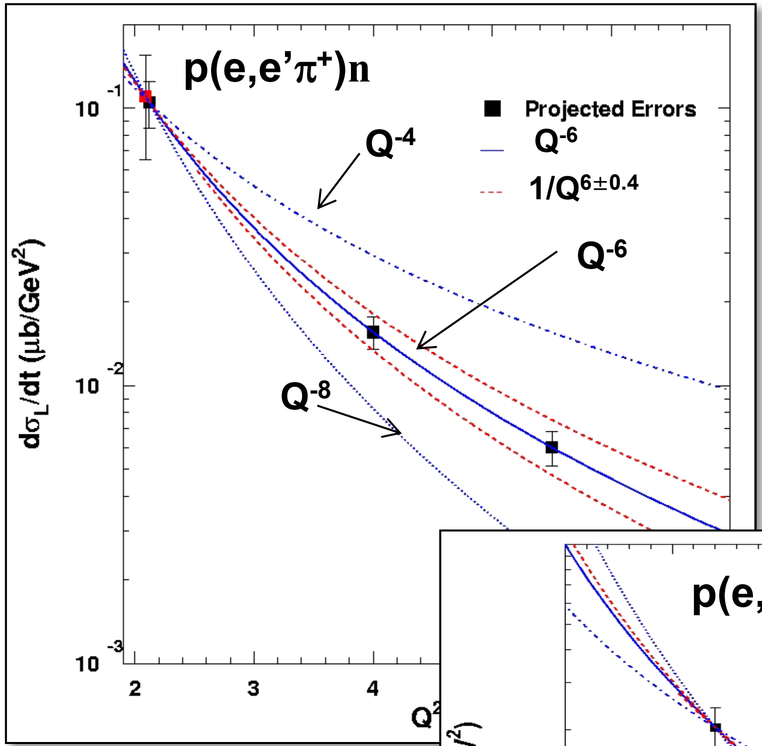




Review Scientific Motivation: Reaction Mechanism

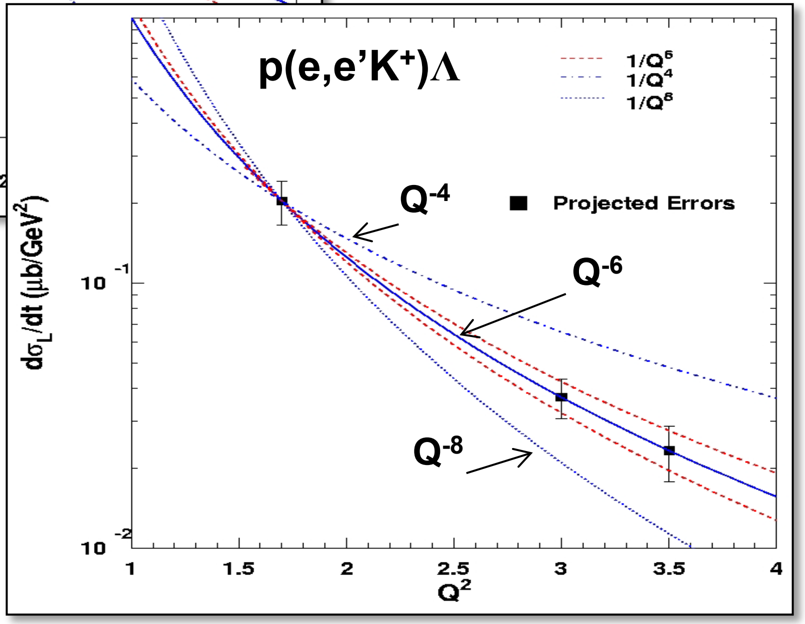


- One of the most stringent tests of the reaction mechanism is the Q^2 dependence of the π and K electroproduction cross section
  - σ_L scales to leading order as Q^{-6}
  - σ_T does not
- Experimental validation of reaction mechanism is essential for reliable interpretation of results from the JLab GPD program at 12 GeV for meson electroproduction
- **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^2~9 GeV^2
K^+: to Q^2~6 GeV^2

Fit: Q^{-n}



PionLT Publications – based on two 6 GeV pion experiments

~2000

- J. Volmer, et al., Phys. Rev. Lett. **86** (2001) 1713 – **383 citations**
  - Precision F_π results between Q^2=0.60 and 1.60 GeV^2
- T. Horn, D. Gaskell, G. Huber, et al., Phys. Rev. Lett. **97** (2006) 192001 – **334 citations**
  - Precision F_π results at Q^2=1.60 and 2.45 GeV^2
- V. Tadevosyan, et al., Phys. Rev. C**75** (2007) 055205 – **262 citations**
- G. Huber, T. Horn, D. Gaskell, et al., Phys. Rev. C**78** (2008) 045203 – **294 citations**
  - Archival paper of precision F_π measurements at JLab 6 GeV
- H. P. Blok, T. Horn, G. Huber, et al., Phys. Rev. C**78** (2008) 045202 – **156 citations**
  - Archival paper of precision LT separated pion cross sections at JLab 6 GeV
- T. Horn, D. Gaskell, G. Huber, et al., Phys. Rev. C**78** (2008) 058201 – **104 citations**
  - L/T cross sections and F_π at Q^2=2.15 GeV^2 ,exploratory at Q^2~4.0 GeV^2

6 GeV Pion Experiments:
1997 (phase 1)
2003 (phase 2)

Plus, several spin-off papers on, e.g. L/T separations in π^- and ω production, high-t, transverse charge density (2012-present)

- Topical/Invited papers including Pion/Kaon results with outlook to 12 GeV results and beyond
  - T. Horn, C.D. Roberts, J. Phys. G **43** (2016) 7, 073001 – **173 citations**
  - A. Aguilar, …. T. Horn, …, G. Huber, et al., Eur. Phys. J A **55** (2019) 10, 190 – **174 citations**
  - C.D. Roberts, D. Richards, T. Horn, L. Chang, Prog.Part.Nucl.Phys. **120** (2021) 103883 – **161 citations**
  - J. Arrington, …, T. Horn, …, G. Huber, et al., J.Phys.G **48** (2021) 7, 075106 – **101 citations**

2025

PionLT Publications – based on two 6 GeV pion experiments

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  - ➢ Precision F_π results between Q^2=0.60 and 1.60 GeV^2
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- ❑ G. Huber, T. Horn, D. Gaskell, et ... 5203 – **294 citations**
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2025

6 GeV Pion Experiments:
1997 (phase 1)
2003 (phase 2)

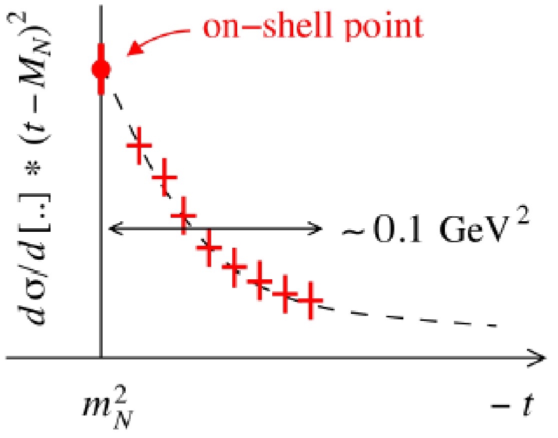
Plus several spin-off papers on, e.g. L/T separations in π^- and ω production, high-t, transverse charge density (2012-present)

A lot of interest in Pion (and Kaon!) LT data!

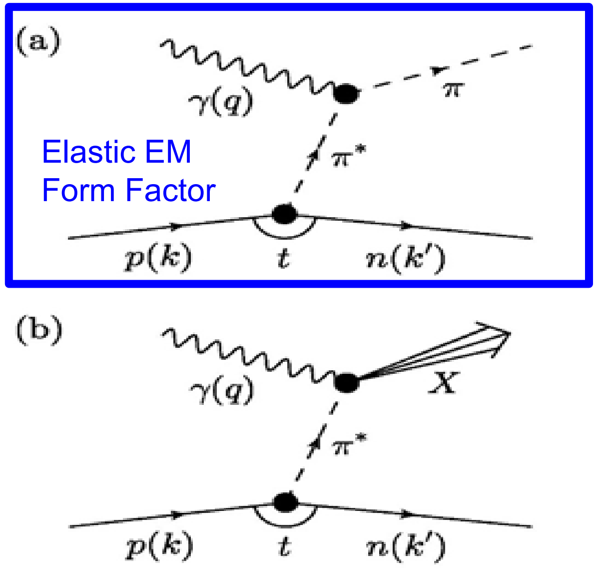
Accessing meson structure through the Sullivan Process

- 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) 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.

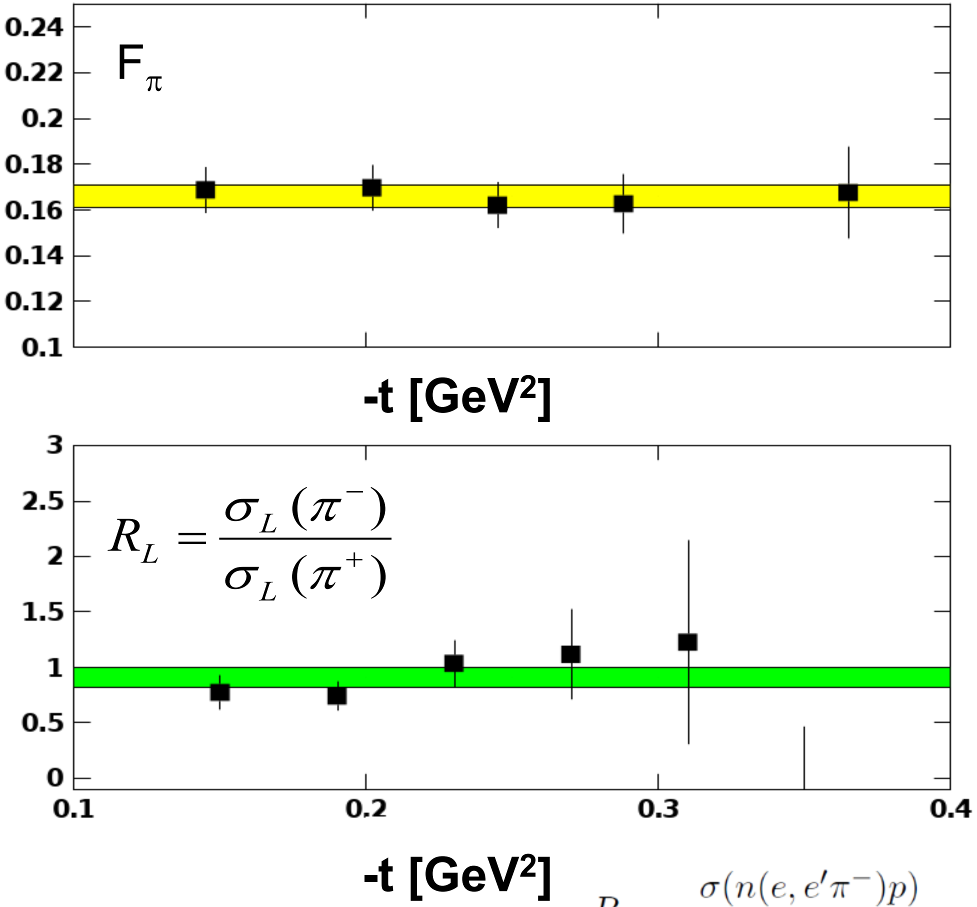
Experimental Validation (Pion Form Factor example)

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

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*



$$R_L = \frac{\sigma(n(e,e'\pi^-)p)}{\sigma(p(e,e'\pi^+)n))} = \frac{|A_v - A_s|^2}{|A_v + A_s|^2}$$

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

For the kaon need the ratio of L/T separated longitudinal $K^+\Lambda$ and $K^+\Sigma^0$ cross sections

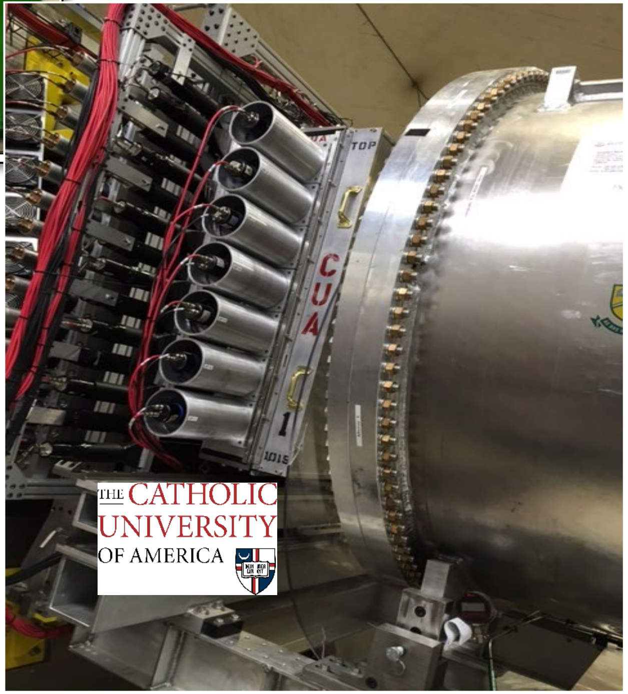
$$\frac{\sigma_L(\gamma^* p \to K^+\Sigma^0)}{\sigma_L(\gamma^* p \to K^+\Lambda^0)}$$

Hall C Deep Exclusive Charged Meson Experiments

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

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

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

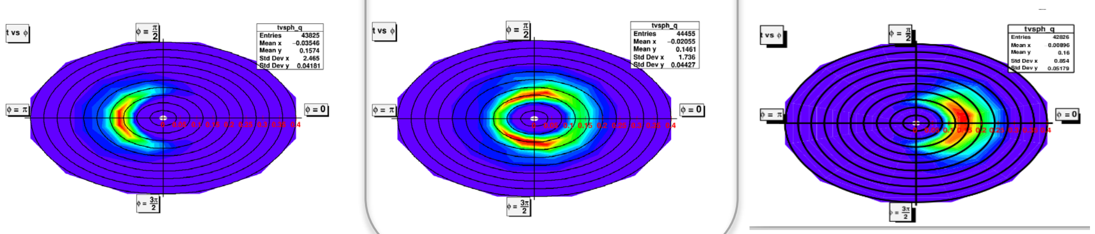


- CEBAF 10.9 GeV electron beam and SHMS small angle capability and controlled systematics are essential for precision measurements to higher Q^2
- Focusing spectrometers fulfill the L/T separation requirements
- Dedicated key SHMS Charged Particle Identification detectors
  - Aerogel Cherenkov – funded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

LT Separation Example

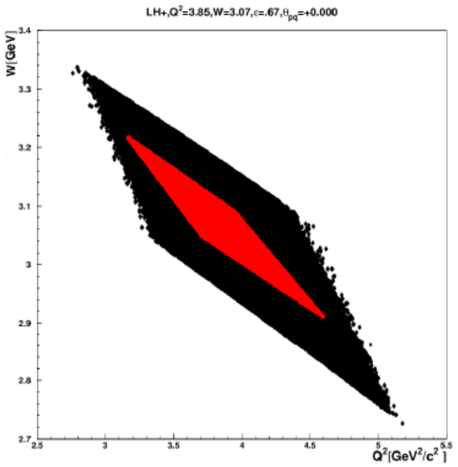
Three SHMS angles

“central” angle



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

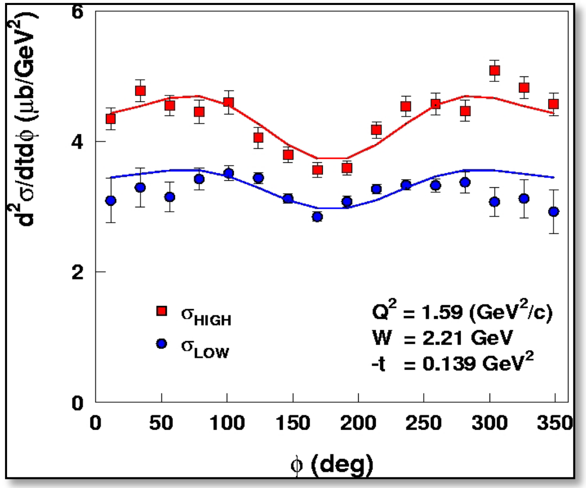
Two/three beam energies



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)

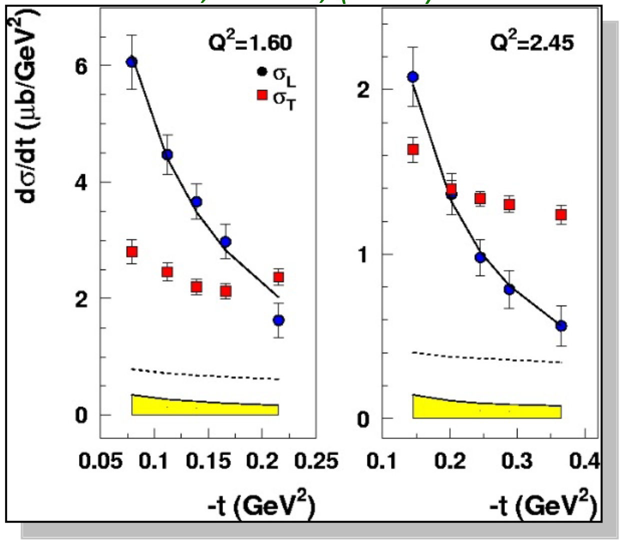
Unseparated Cross Section



LT Separated Cross Section

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

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



Physics Cross Section

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

σ_L gives F_π and F_K

Extraction of F_π from σ_L 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

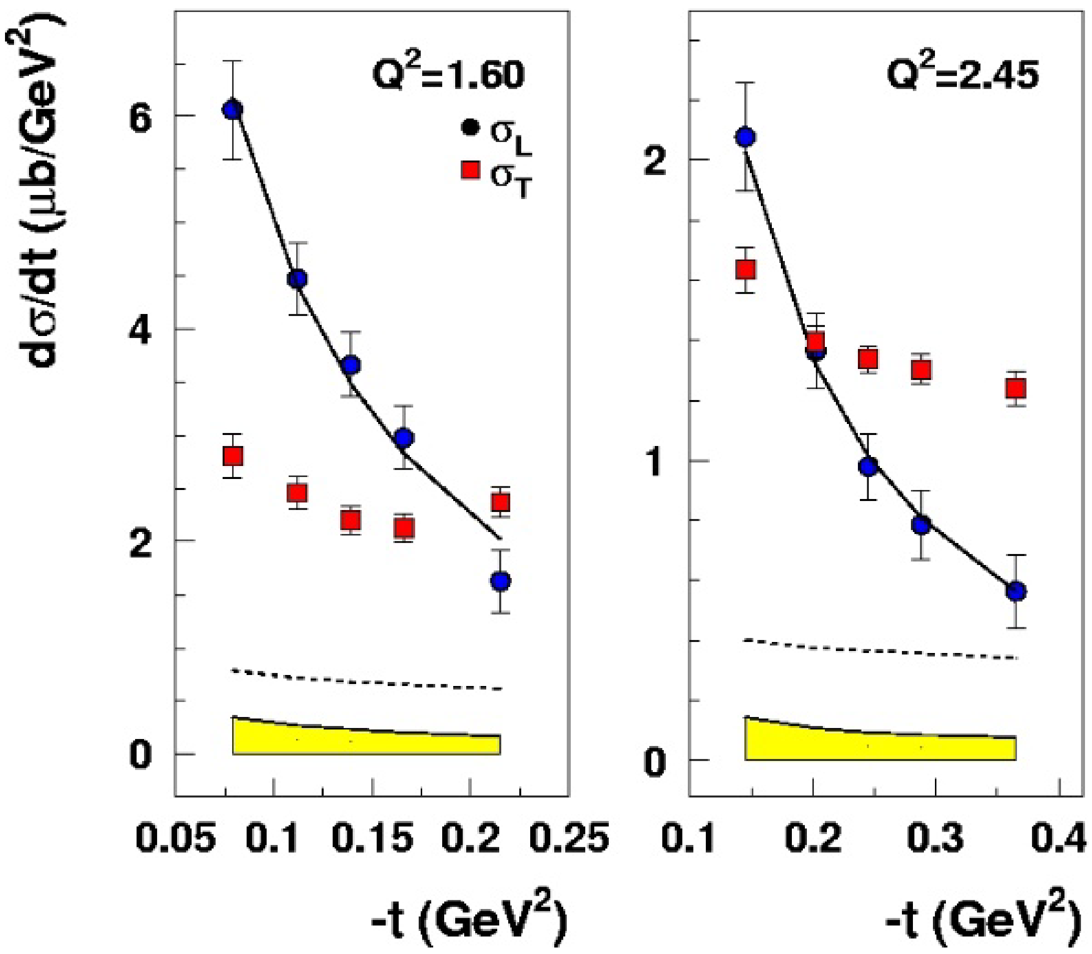
  *[Vanderhaeghen, Guidal, Laget, PRC **57**, (1998) 1454]*

  - Feynman propagator replaced by π and ρ trajectories
  - Model parameters fixed by pion photoproduction data
  - Free parameters: $\Lambda_\pi^2, \Lambda_\rho^2$

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

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

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



$$\Lambda_\pi^2 = 0.513,\ 0.491\ GeV^2$$

$$\Lambda_\rho^2 = 1.7\ GeV^2$$

PionLT/KaonLT – Data Collection Status

[Link to all data and topics available]

PionLT experiment (completed in 2022):

- The experiment complete fraction is 100%

Q^2 (GeV^2)	x_B	-t (GeV^2)	W (GeV)	Plan
8.5	0.55	0.55	2.8	Q^{-n}/FF
6.0	0.55/0.39	0.53/0.21	2.4/3.2	Q^{-n}/FF
5.0	0.39	0.20	2.95	Q^{-n}/FF
3.85	0.55/0.39/ 0.31	0.49/0.2/ 0.1	2.0/2.6/ 3.1	Q^{-n}/FF
2.73	0.31	0.12	2.6	Q^{-n}
2.45		0.05	3.2	FF
2.12	0.39	0.19	2.0	Q^{-n}
1.60	0.15	0.11	3.1	FF
1.45	0.31	0.11	2.0	Q^{-n}
0.375	0.087		2.2	FF
0.425	0.097		2.2	FF

KaonLT experiment (data collection in 2018/19):

- The experiment complete fraction is 80% (32 days out of 40 approved PAC days at PAC38)
- The remaining beam time to establish a high precision data base of $K^+\Lambda$, $K^+\Sigma^0$ cross sections was approved at PAC49

Q^2 (GeV^2)	x_B	-t (GeV^2)	W (GeV)	Plan	Comment
5.5	0.40	0.503	3.02	Q^{-n}	Low stat
4.4	0.40	0.507	2.74	Q^{-n}	Low stat
3.0	0.40	0.531	2.32	Q^{-n}	Low stat
3.0	0.25	0.219	3.14	Q^{-n}/FF	No Q^{-n}
2.115	0.21	0.166	2.95	FF	No Q^{-n}
0.5	0.09	0.081	2.40	FF	Done
1.25			3.14	FF	No data
1.70	0.25		2.45	Q^{-n}	No data
3.50	0.25		3.37	Q^{-n}	No data

Data taken in 2018/19 – some settings with low statistics only

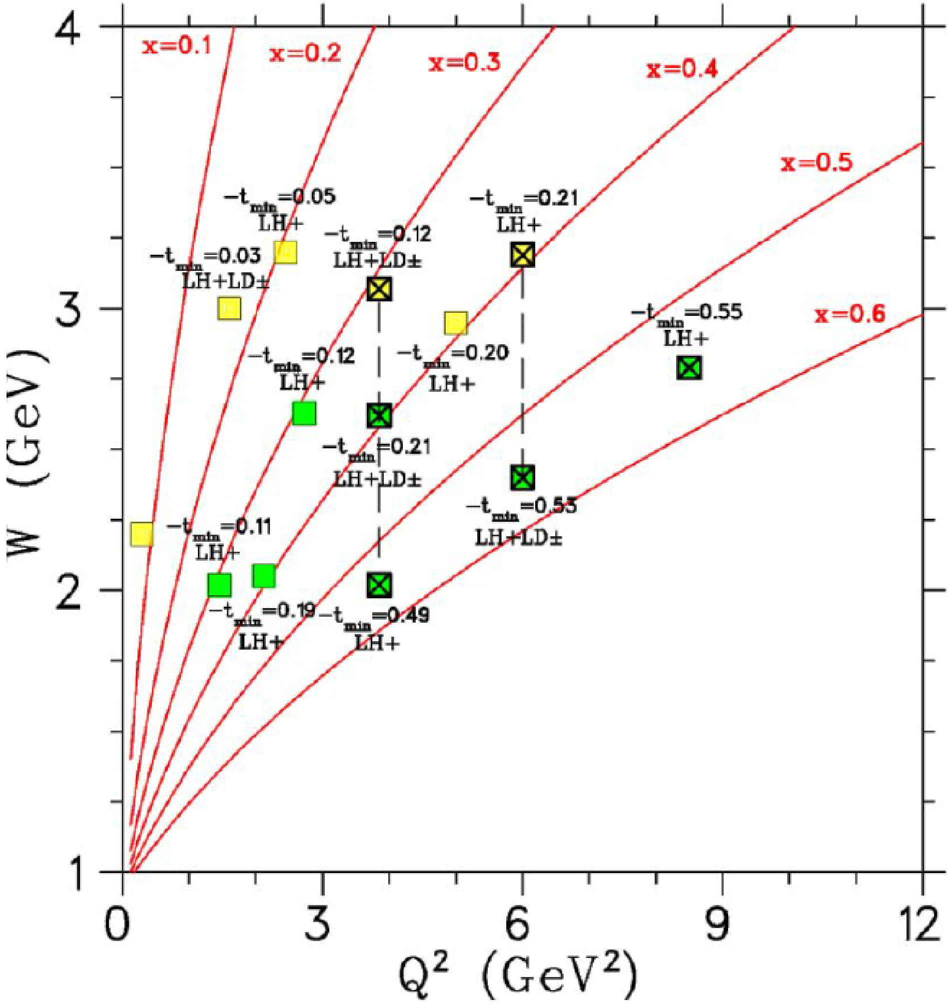
L/T-separated data, from which the contributions of σ_L and σ_T to Λ and Σ^0 final states can be determined

PionLT/KaonLT – Data Collection Status

[Link to all data and topics available]

PionLT experiment (completed in 2022):

- The experiment complete fraction is 100%



KaonLT experiment (data collection in 2018/19):

- The experiment complete fraction is 80% (32 days out of 40 approved PAC days at PAC38)
- The remaining beam time to establish a high precision data base of $K^+\Lambda$, $K^+\Sigma^0$ cross sections was approved at PAC49

Q^2 (GeV^2)	x_B	-t (GeV^2)	W (GeV)	Plan	Comment
5.5	0.40	0.503	3.02	Q^{-n}	Low stat
4.4	0.40	0.507	2.74	Q^{-n}	Low stat
3.0	0.40	0.531	2.32	Q^{-n}	Low stat
3.0	0.25	0.219	3.14	Q^{-n}/FF	No Q^{-n}
2.115	0.21	0.166	2.95	FF	No Q^{-n}
0.5	0.09	0.081	2.40	FF	Done
1.25			3.14	FF	No data
1.70	0.25		2.45	Q^{-n}	No data
3.50	0.25		3.37	Q^{-n}	No data

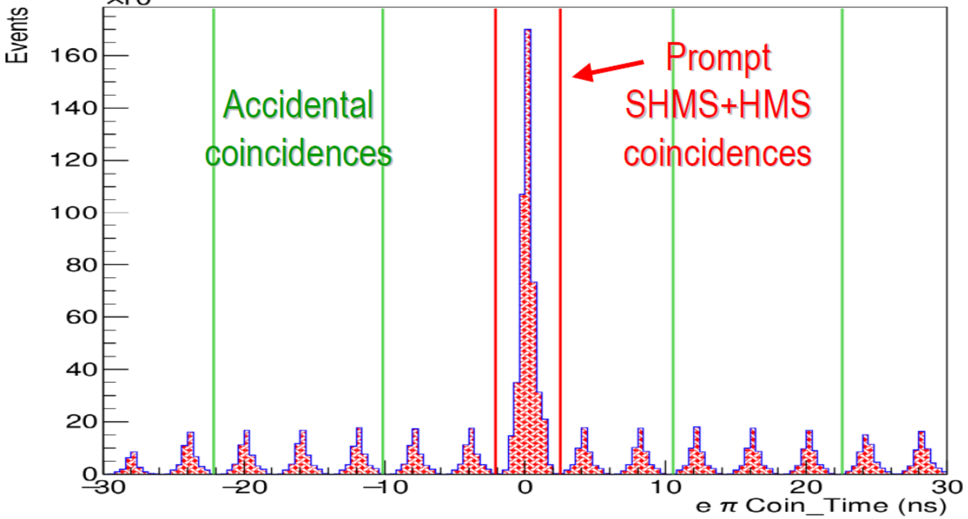
Data taken in 2018/19 – some settings with low statistics only

L/T-separated data, from which the contributions of σ_L and σ_T to Λ and Σ^0 final states can be determined

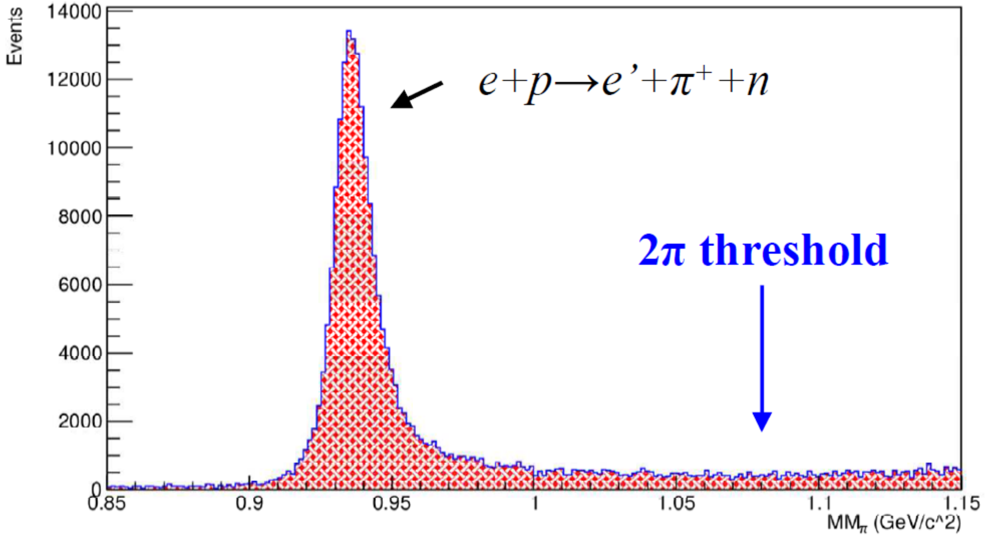
PionLT – Analysis Results

[Link to all data and topics available]

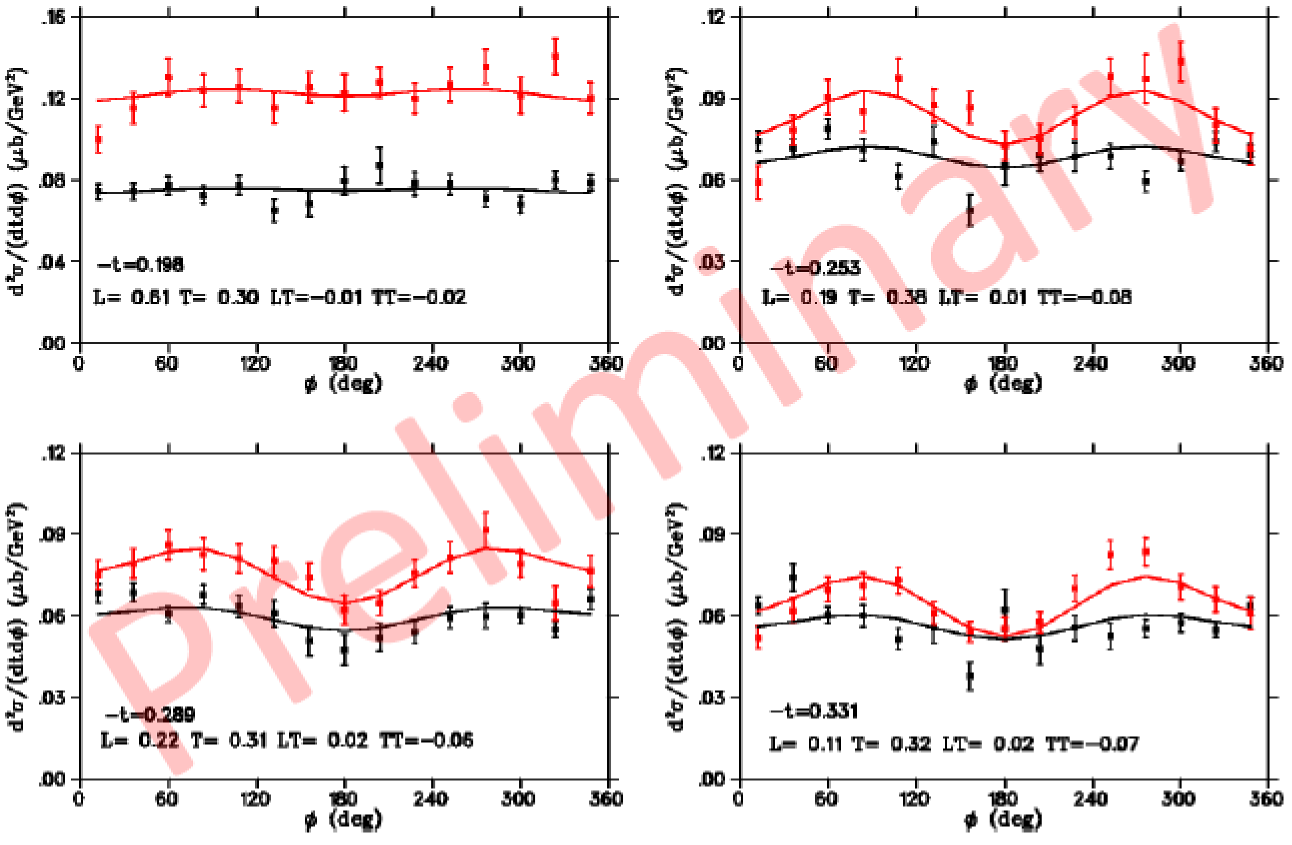
Event selection



Isolating the exclusive channel



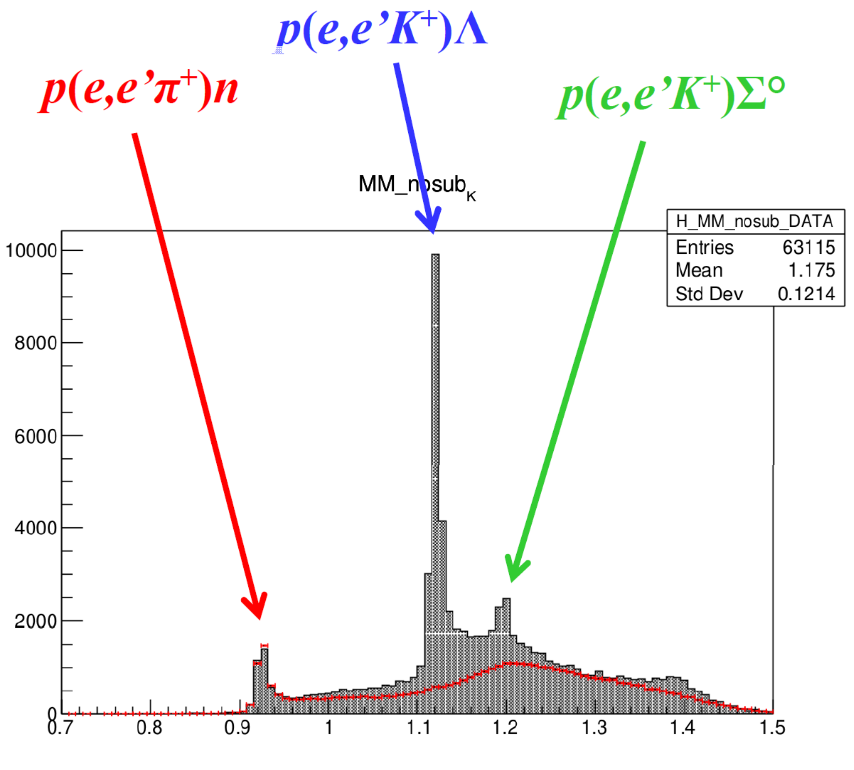
Q^2=3.85 Gev^2, W=2.62 GeV, t=0.21 GeV^2



PionLT unseparated cross sections (Analysis by M. Junaid)

KaonLT – Analysis Results

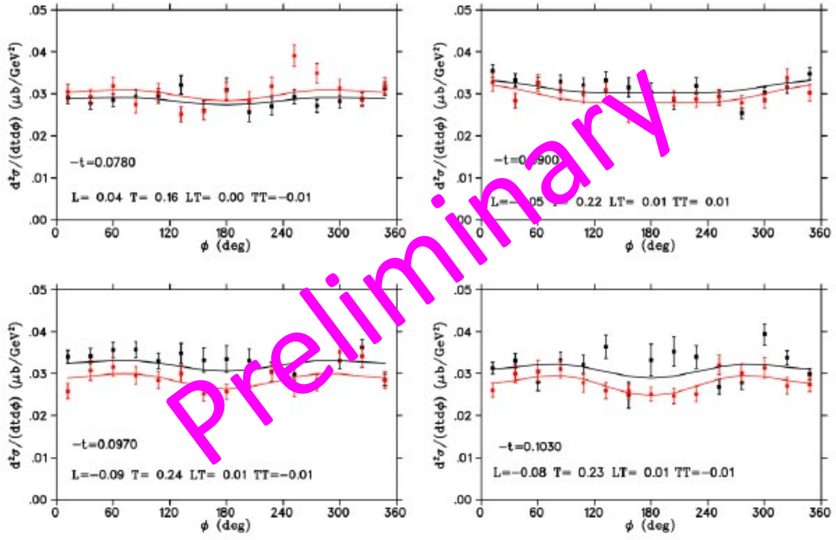
[Link to all data and topics available]



Q^2=3.0 GeV^2 , W=3.14, low ε, θ_{Kq}=+0.0

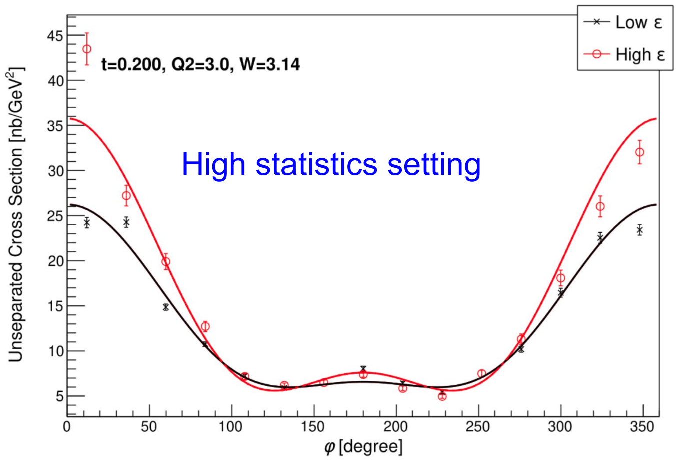
- Isolate exclusive final states through missing mass
- Spectrometer coincidence acceptance allows for simultaneous studies of Λ and Σ^0 channels

Q^2=0.5 GeV^2, W=2.4 GeV, x=0.09

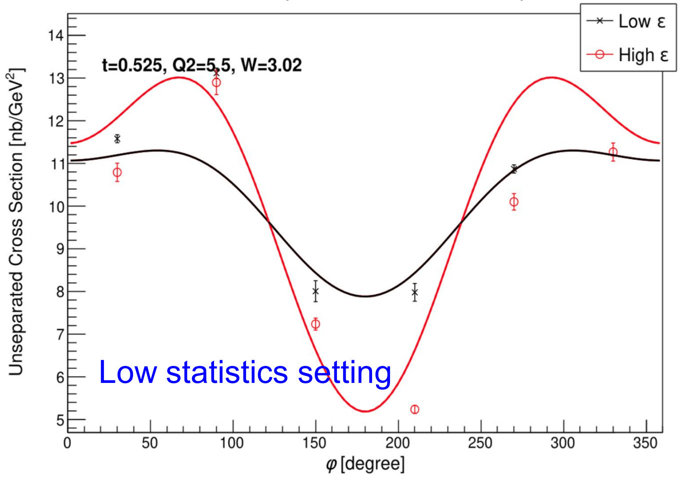


KaonLT unseparated cross sections at low Q^2 (Analysis by A. Hamdi)

Q^2=3.0 GeV^2, W=3.14 GeV, x=0.25



Q^2=5.5 GeV^2, W=3.02 GeV, x=0.40

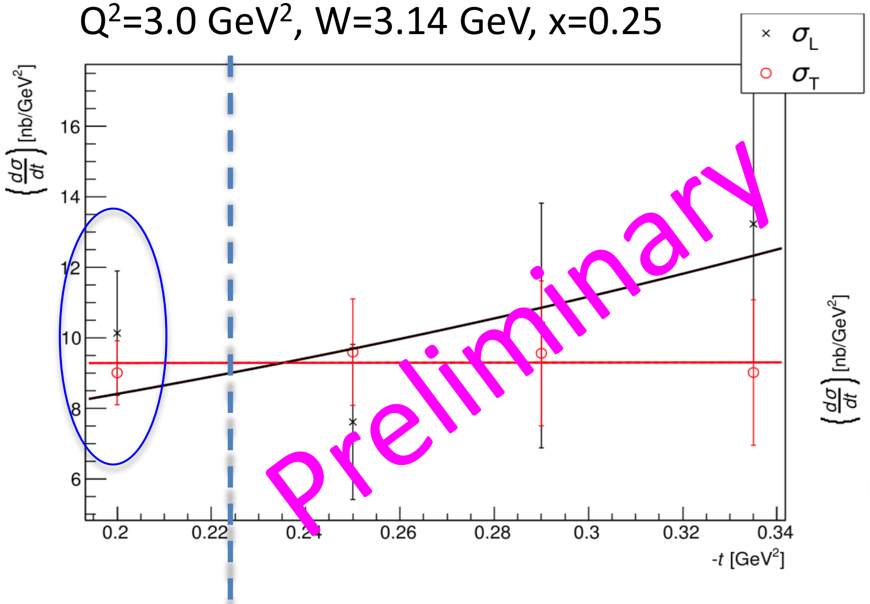


KaonLT unseparated cross sections at higher Q^2 (Analysis by R. Trotta)

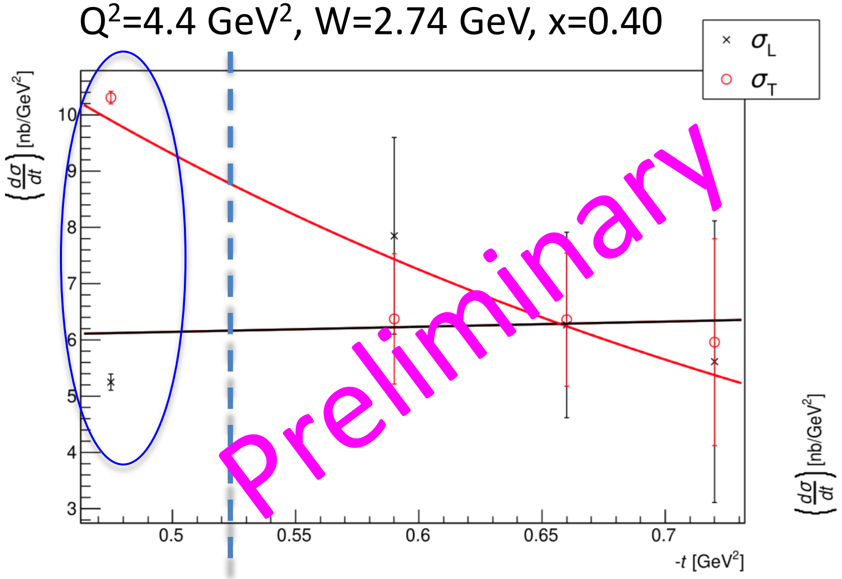
KaonLT – Analysis Results

[Link to all data and topics available]()

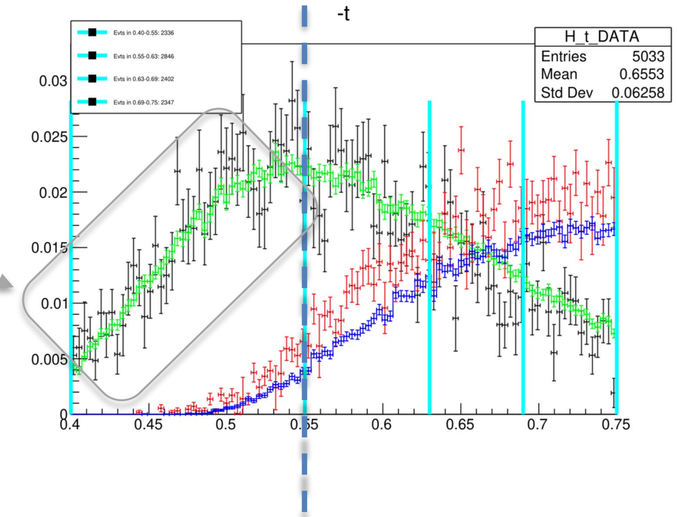
Q^2=3.0 GeV^2, W=3.14 GeV, x=0.25



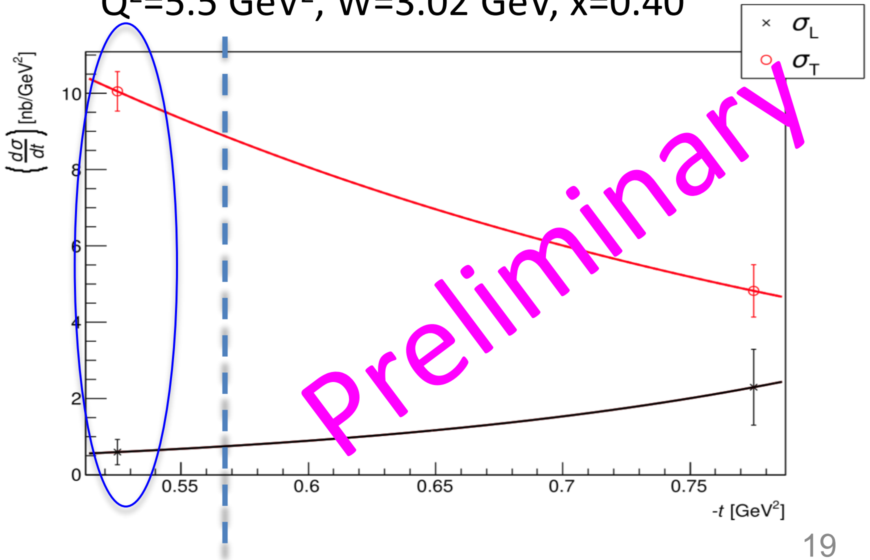
Q^2=4.4 GeV^2, W=2.74 GeV, x=0.40



Bins closest to t_{min} (left of the dashed line) are dominated by data taken at the "central" spectrometer angle



Q^2=5.5 GeV^2, W=3.02 GeV, x=0.40



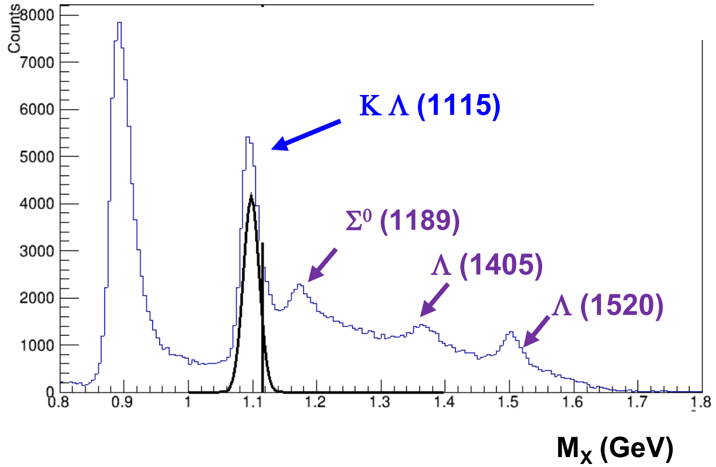
- The dominant systematic uncertainty is the HGCer PID. Shown here is a global uncertainty of 3.6%
- σ_L decreases rapidly with increasing Q^2
- σ_T also decreases with Q^2, but much slower
- Analysis ongoing: systematics, reaction model tests

KaonLT separated cross sections at higher Q^2 (Analysis by R. Trotta)

KaonLT – Additional Channels/Topics

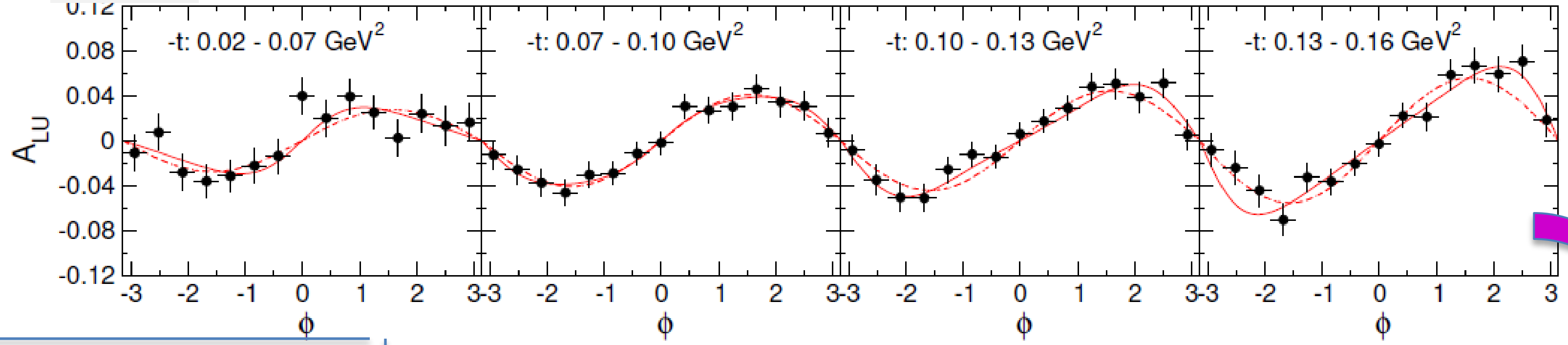
[Link to all data and topics available]

Beam Spin Asymmetries for π^+n and $\pi^+\Delta^0$



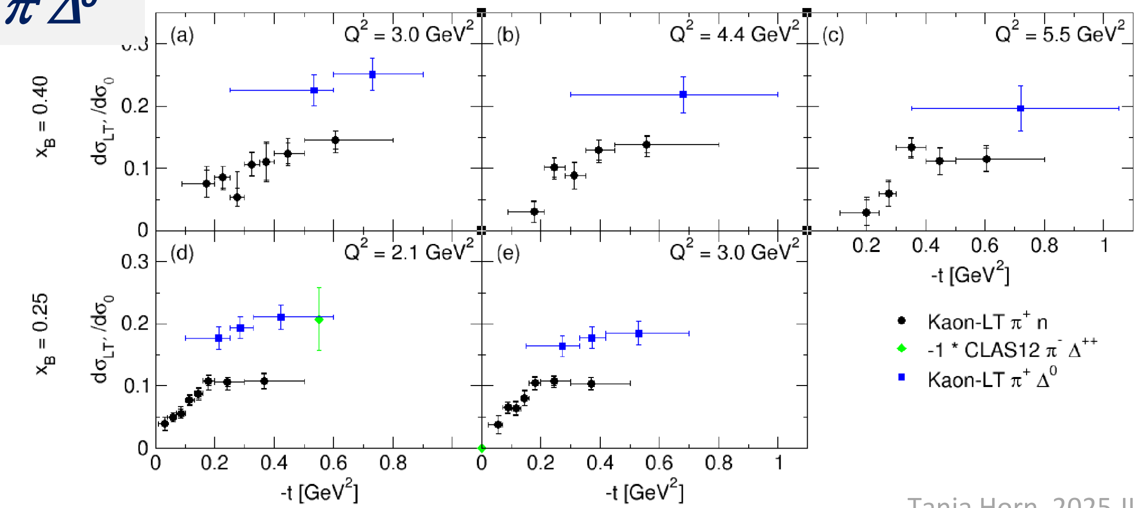
- KaonLT allowed for measuring the BSAs for these channels
- The t-dependence of $\sigma_{LT'}/\sigma_0$ was determined at fixed Q^2 and x_B was extracted from the BSA – also the Q^2 dependence of $\sigma_{LT'}/\sigma_0$
- Manuscript for $p(e,e'\pi^+)n$ has been submitted for publication

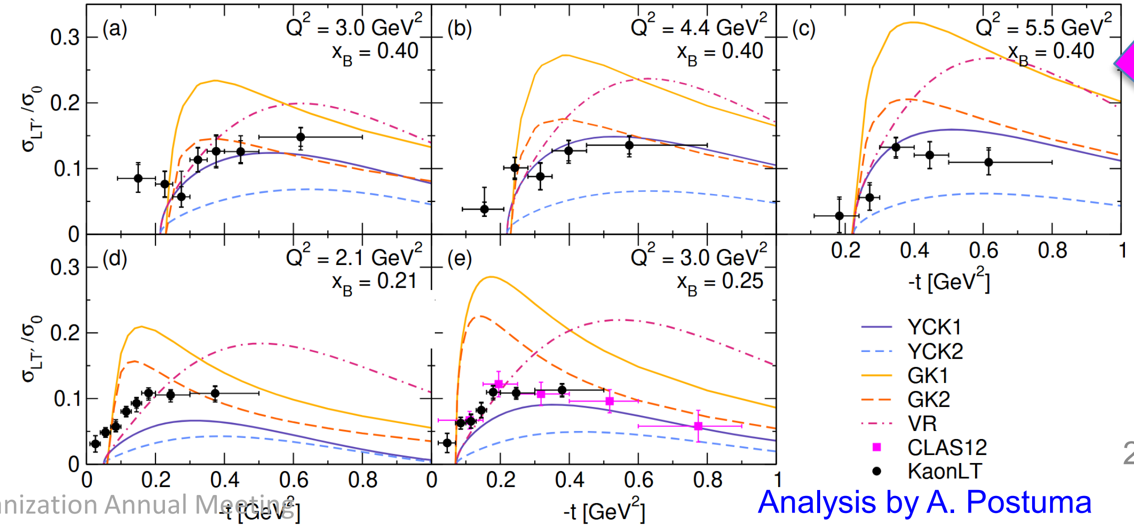
π^+n



Analysis by A. Usman

$\pi^+\Delta^0$



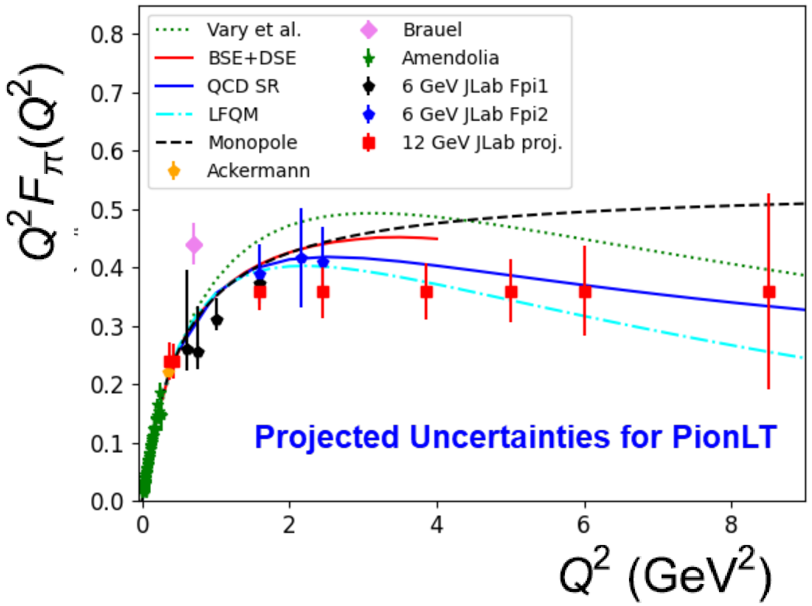


Analysis by A. Postuma

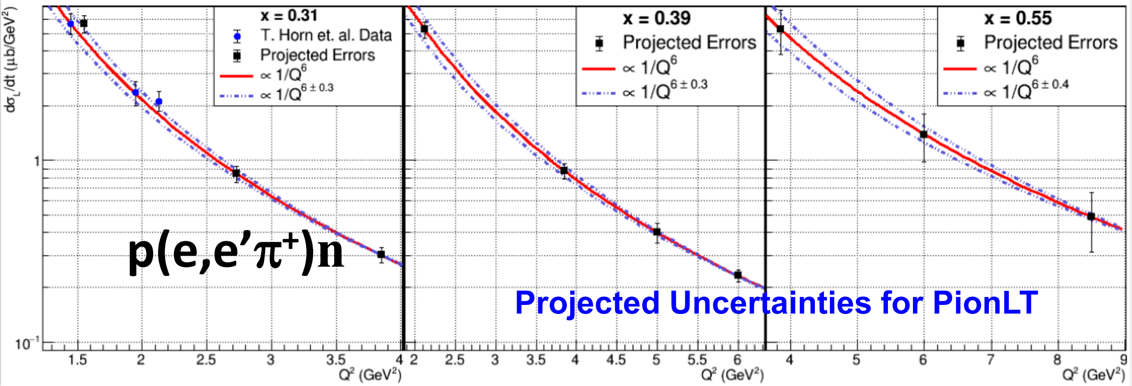
PionLT/KaonLT – Projected Uncertainties

[Link to all data and topics available]

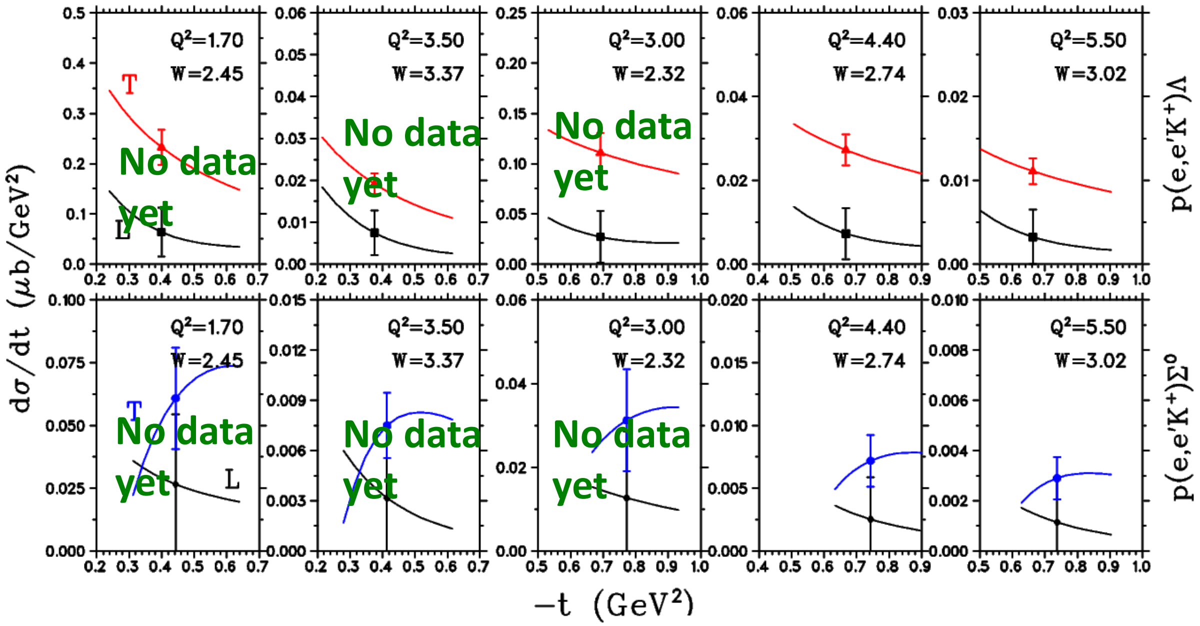
PionLT experiment (completed in 2022):



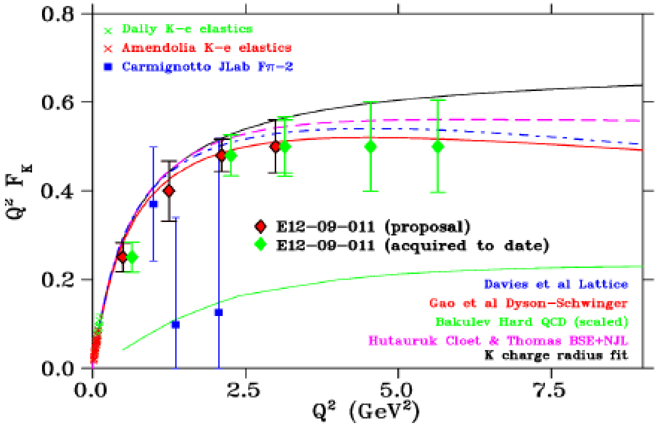
Grad. Students: N. Heinrich (URegina), M. Junaid (URegina)

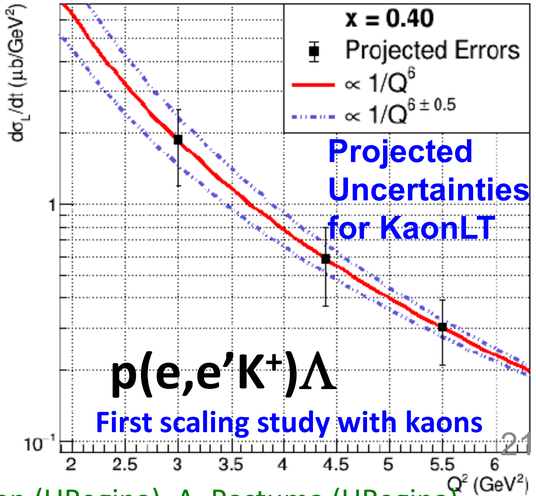


KaonLT experiment (data collection in 2018/19):



Projected Uncertainties for KaonLT





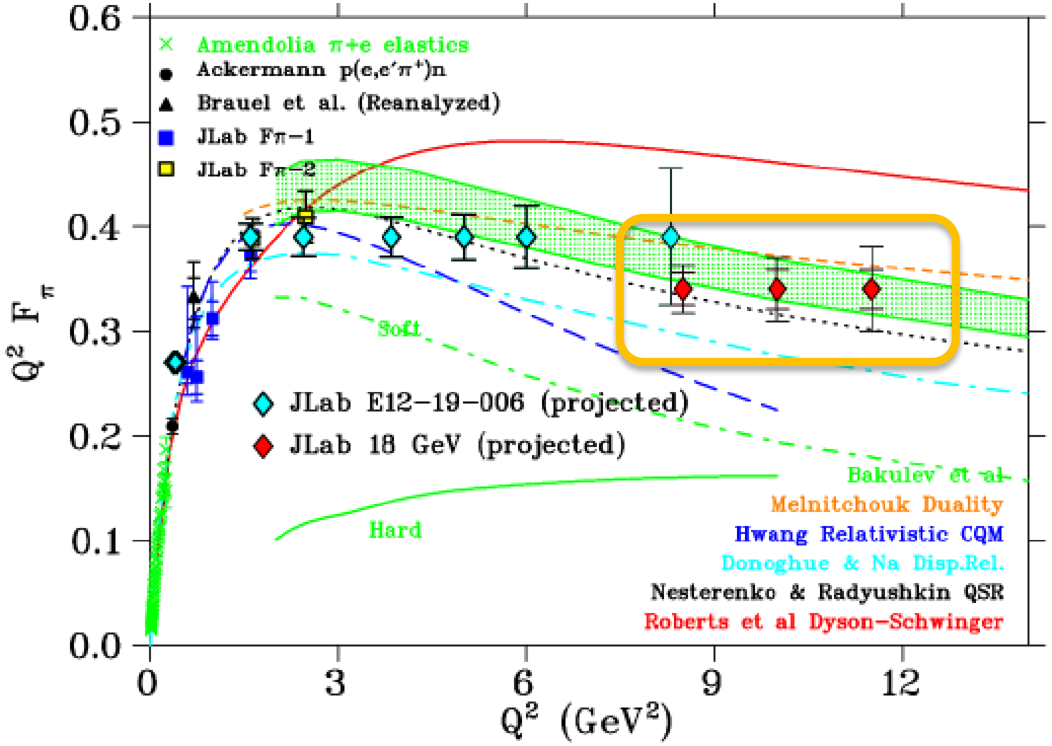
Grad. Students: V. Kumar (URegina), R. Trotta (CUA), A.Usman (URegina), A. Postuma (URegina)

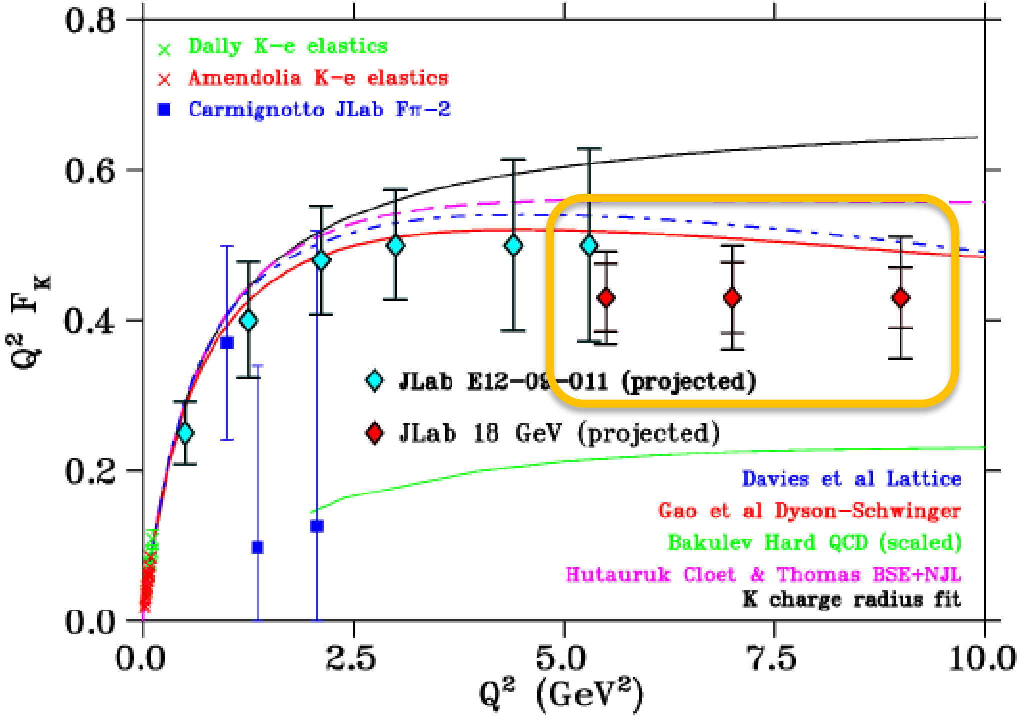
JLab 22 GeV: Opportunities for π, K form factors

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

Projections based the same statistics per setting as PionLT

A. Accardi, et al., "Strong Interaction Physics at the Luminosity Frontier with 22 GeV electrons at Jefferson Lab", Eur. Phys. J A **60** (2024) 9, 173





- ❑ 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

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
  - Higher Q^2 data on π^+ and K^+ form factors play a vital role in the understanding of hadronic physics – inform on how Emergent Hadron Mass manifests in the wave function
- PionLT/KaonLT will dramatically improve the π^+/K^+electroproduction data set
  - The only source of L/T separated cross sections towards hadron structure at colliders
  - JLab L/T separated data will be crucial for interpretation of EIC data for decades to come
- PionLT/KaonLT will provide precision cross sections for tests of the reaction mechanisms
  - Q^2 scans at fixed x_B will allow for validation of hard-soft factorization for transverse nucleon structure studies – may allow for accessing new type of GPDs
  - t- scans will allow for improving the uncertainties in possible form factor extractions
- PionLT was completed in 2022 and KaonLT has a complete fraction of 80% (expected to be completed as soon as FY27)
  - First separated cross sections are available from KaonLT
  - BSA results have been submitted for publication, results on cross sections expected later this year
  - Link to all data and topics available – still many opportunities, new collaborators welcome!