Low Q^2 Results from the PionLT and KaonLT experiments at Jefferson Lab

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On behalf of the PionLT and KaonLT Collaborations

Supported by:

Center for Frontiers in Nuclear Science

NSERC CRSNG

SAPIN-2021-00026

APS Spring Meeting, Denver CO, March 18, 2026

PionLT/KaonLT Motivation

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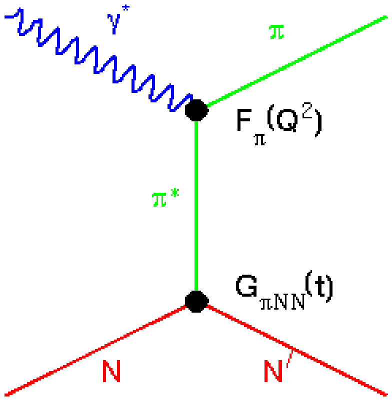
1) Determine the Pion Form Factor at Q^2>0.3 GeV^2:



- Indirectly measure F_π using the "pion cloud" of the proton via p(e,e'π^+)n

$$|p\rangle = |p\rangle_0 + |n\pi^+\rangle + \ldots$$

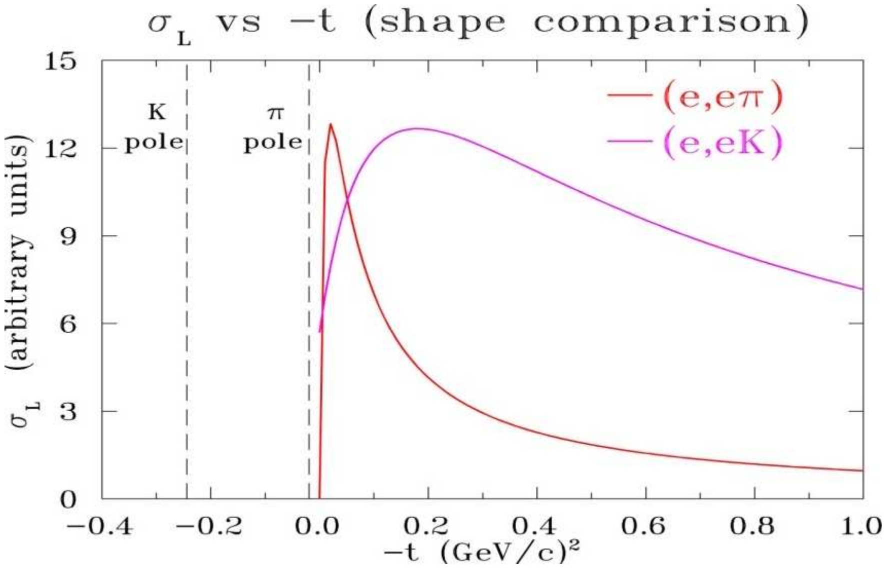
  - Pion pole process dominates σ_L in forward kinematics
  - Determining σ_L requires a Rosenbluth L/T-separation, which is experimentally challenging

2) Can a similar method be used for K^+ Form Factor?

- Can the "kaon cloud" of the proton be used in the same way as the pion to extract K^+ elastic form factor via ***p(e,e'K⁺)Λ*** ?
- Kaon pole further from kinematically allowed region

$$\boxed{\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_K^2)} g^2_{K\Lambda N}(t) F_K^2(Q^2,t)}$$

Born Term Model pole equation to illustrate link between σ_L and elastic form factor



Meson Form Factors require a Model

- **Meson elastic form factors determined via the electroproduction technique are in principle model–dependent, although this dependence is reduced if σ_L data are taken at sufficiently low *-t***
- Our JLab 6 GeV studies indicate the method is reliable for low $-t < 0.4$ GeV^2 $p(e,e'\pi^+)n$ data [GMH et al., PRC 78 (2008) 045203]
  - A goal of KaonLT is to determine if the same holds for $p(e,e'K^+)\Lambda$
- **It is sometimes asked if the electroproduction technique is measuring the "physical" pion or kaon form factor**
- **The PionLT/KaonLT experiments have adopted a data-driven approach to address this concern to the greatest extent possible:**
  - Check consistency of model with data
  - Extract form factor at several values of $-t_{min}$ for fixed Q^2
  - Test that the pole diagram is really the dominant contribution to the reaction mechanism
  - **Verify that electroproduction technique yields results consistent with p-e elastic scattering at same Q^2**

Low Q^2 Check of Electroproduction Technique

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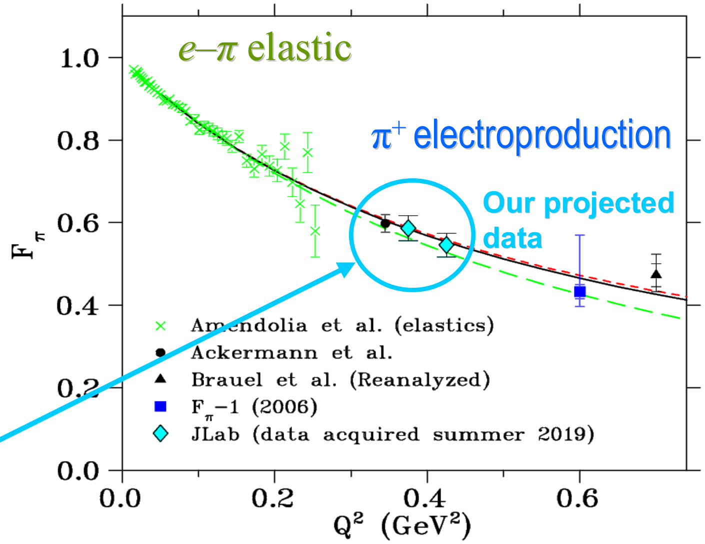
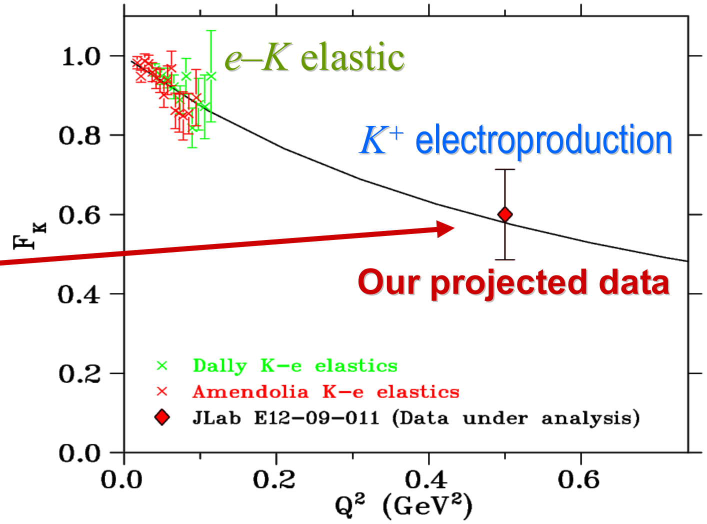
Directly compare $F_\pi(Q^2)$ values extracted from very low $-t$ electroproduction with values measured in elastic e-π scattering

- Q^2=0.35 GeV^2 data from DESY consistent with limit of elastic scattering data within uncertainties.
  [H. Ackermann, et al., NP **B137**(1978)294]

- **PionLT acquired p(e,e'π^+)n data for a test at Q^2=0.375, 0.425 GeV^2 with much lower statistical and systematic uncertainties**

- **KaonLT data at Q^2=0.50 permits a test using $p(e,e'K^+)\Lambda$**

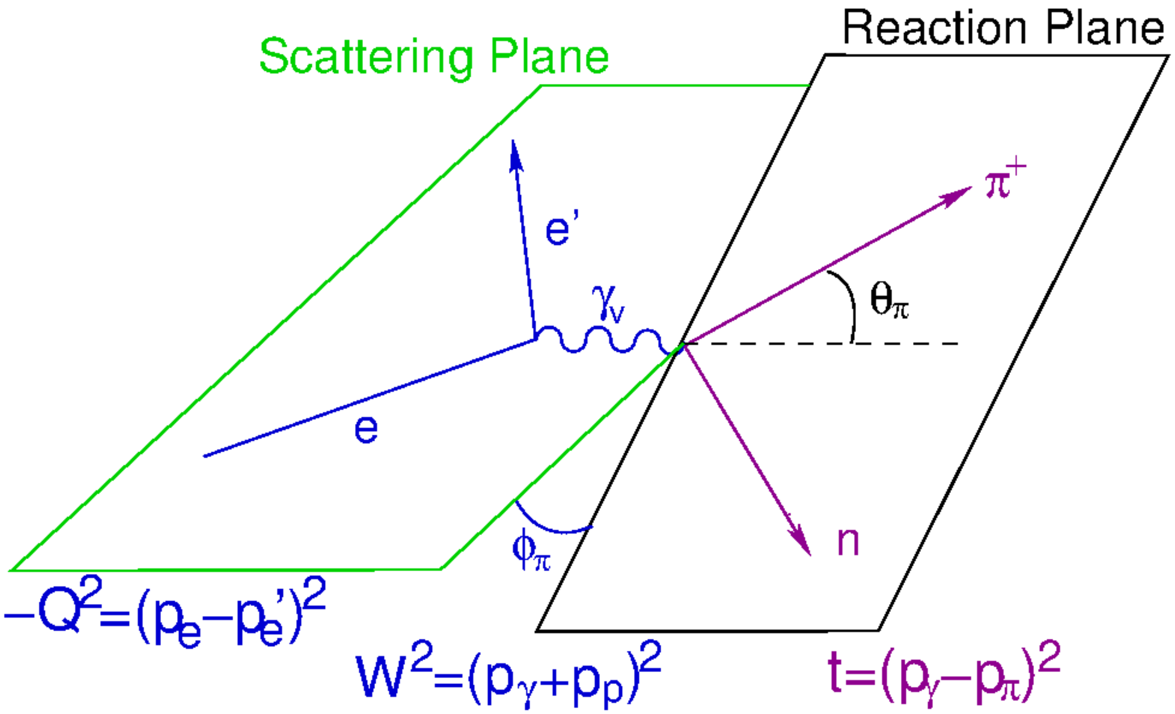




$$2\pi\frac{d^2\sigma}{dt\,d\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Virtual-photon polarization:

$$\varepsilon=\left(1+2\frac{(E_e-E_{e'})^2+Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$



- L-T separation required to separate σ_L from σ_T
- Data for at least 2 ε are required, preferably more
    - Uncertainty in $\sigma_L \sim 1/\Delta\varepsilon$, where $\Delta\varepsilon=\varepsilon_{HI}-\varepsilon_{LO}$
    - Need $\Delta\varepsilon > 0.2$ to avoid >500% statistical error magnification
- Need to take data at smallest available $-t$, so σ_L has maximum contribution from the π^+ pole
- Need to measure t–dependence of σ_L at fixed Q^2,W

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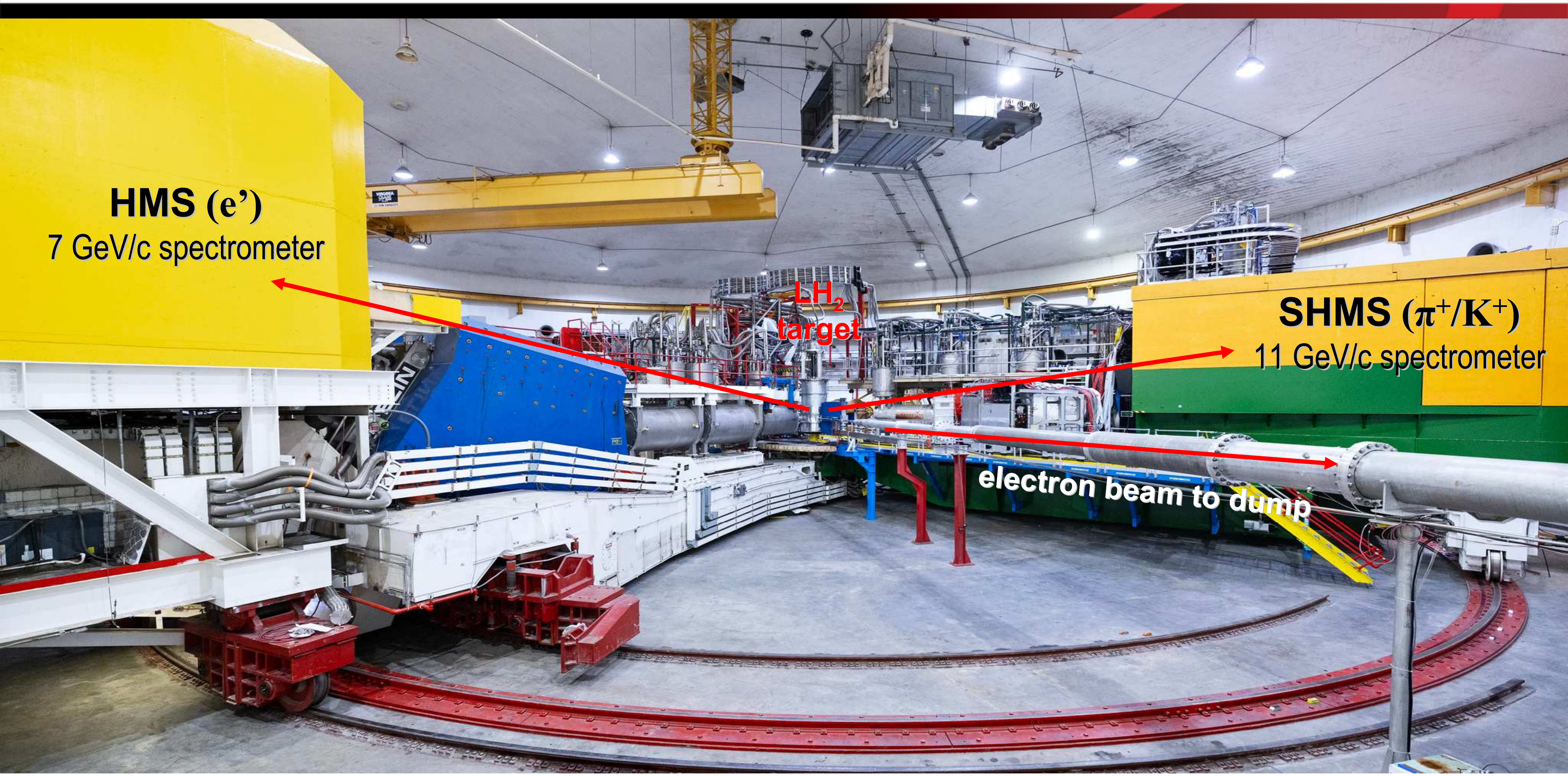
Jefferson Lab Hall C



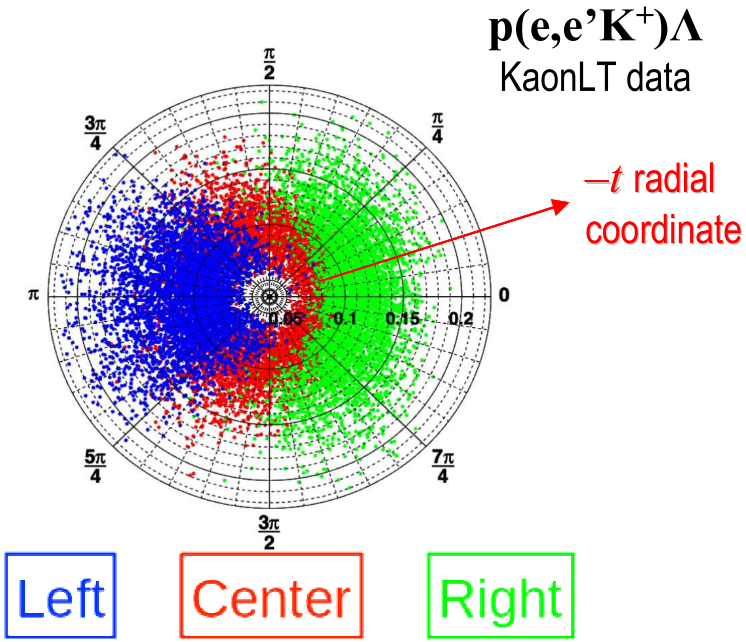
- •**HMS and SHMS MAGNETIC OPTICS:**
  - – Point-to Point QQQD for easy calibration of magnetic optics acceptance and event reconstruction
  - – SHMS Horizontal bend magnet allows spectrometer rotation to forward angles (5.5°); the HMS can rotate to a minimum of 10.5°
- •**Rigid Support Structure and Connection to Pivot:** Provide Rapid & Remote Rotation, Pointing Accuracy & Reproducibility
- •**Spectrometer Detector Packages:** Drift Chambers, Hodoscopes, Cherenkovs, PbG Calorimeter
- •**Well-Shielded Detector Enclosures permit measurements at Very High Luminosity:** ~4×10^{38} cm^{-2} s^{-1}

PionLT/KaonLT Low Q^2 Kinematics

- 3 ε acquired for PionLT high quality L/T-separation, 2 ε for KaonLT
- Multiple SHMS angles needed for full φ (azimuthal) coverage

PionLT: p(e,e'π^+)n

SHMS Azimuthal angle	**Low ε** =0.29 (2.7 GeV)	**Mid ε** =0.63 (3.6 GeV)	**High ε** =0.78 (4.5 GeV)
Q^2=0.375 GeV^2 W=2.2 GeV x_B=0.09			
Center ($\theta_{\pi q}$=0)	▲	▲	▲
Left1 ($\theta_{\pi q}$=+2^0)	▲	▲	▲
Left2 ($\theta_{\pi q}$=+4^0)	▲	▲	▲
Right1 ($\theta_{\pi q}$=–2^0)	X	▲	▲
Right2 ($\theta_{\pi q}$=–4^0)	X	▲	X
Q^2=0.425 GeV^2 W=2.2 GeV x_B=0.09			
Center ($\theta_{\pi q}$=0)	▲	▲	▲
Left1 ($\theta_{\pi q}$=+2^0)	▲	▲	▲
Left2 ($\theta_{\pi q}$=+4^0)	▲	▲	▲
Right1 ($\theta_{\pi q}$=–2^0)	X	X	▲
Right2 ($\theta_{\theta q}$=–4^0)	X	X	▲


p(e,e'K^+)Λ
KaonLT data

KaonLT: p(e,e'K^+)Λ/Σ^0

SHMS Azimuthal angle	**Low ε** =0.45 (3.8 GeV)	**High ε** =0.69 (4.9 GeV)
Q^2=0.5 GeV^2 W=2.4 GeV x_B=0.09		
Center (θ_{Kq}=0)	▲	▲
Left (θ_{Kq}=+3^0)	▲	▲
Right (θ_{Kq}=–3^0)	X	▲

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

Coincidence measurement between π^+ in SHMS and electrons in HMS

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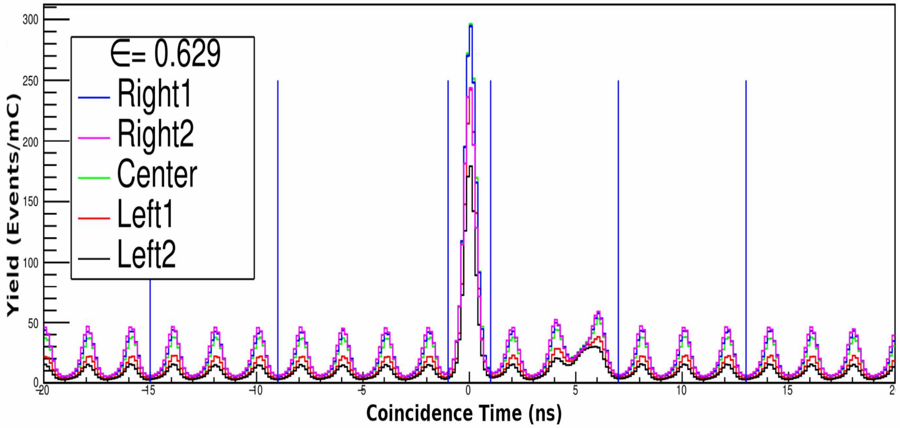
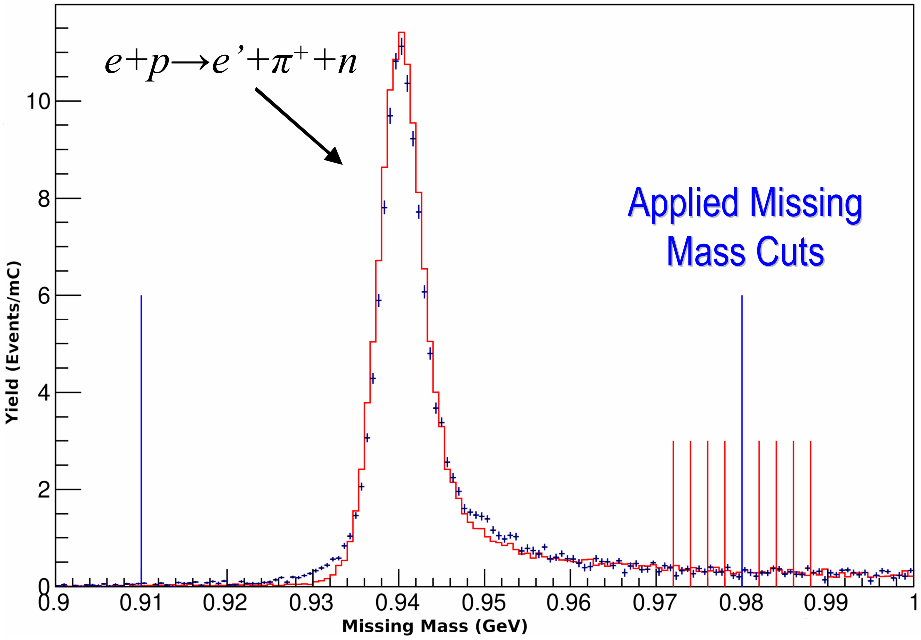
Easy to isolate exclusive channel

- Excellent particle identification
- CW beam minimizes “accidental” coincidences
- Missing mass resolution easily excludes 2–pion contributions

$$M_X = \sqrt{(E_{\det} - E_{init})^2 - (p_{\det} - p_{init})^2}$$

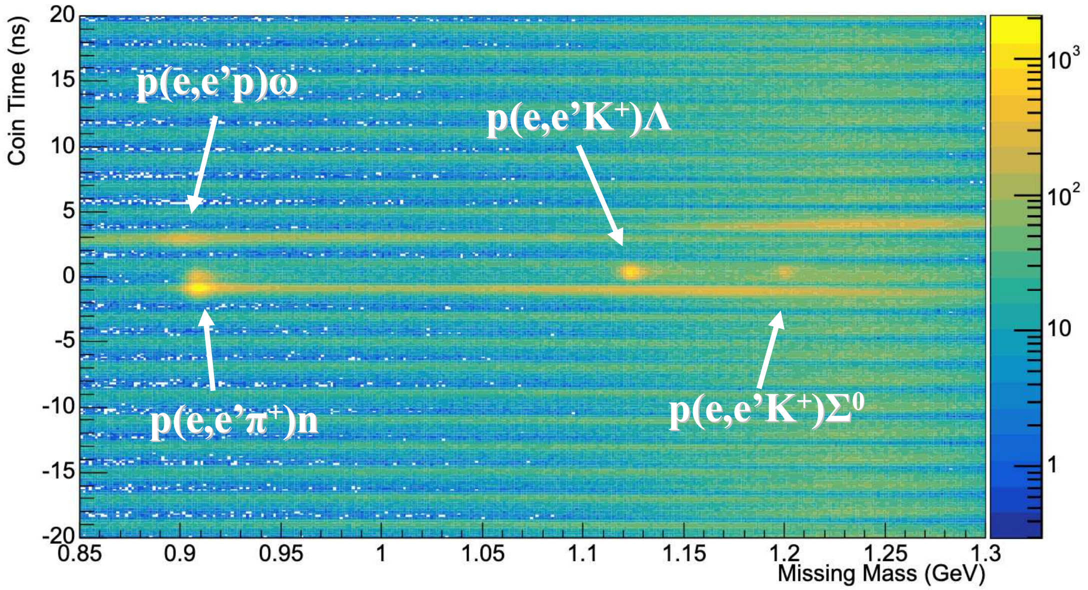




PionLT data: Q^2=0.375 Mid ε SHMS Center Setting

$p(e,e'K^+)\Lambda$ Event Selection

Clean K^+ identification is more work, due to high π^+/K^+ ratio

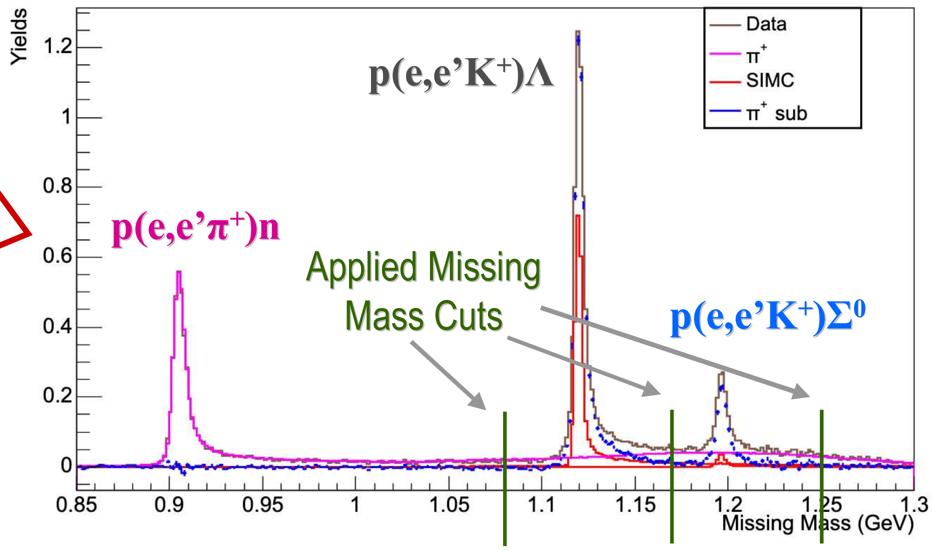


With the lower SHMS momenta used for Low Q^2 measurements

$$CoincidenceTime = t_{HMS} - t_{SHMS}$$

corrected for particle type using time of flight for electrons (HMS) and kaons (SHMS) is effective to distinguish different reaction types

- Some π^+ background remains after time cuts
- A separate sample of pure $p(e,e'\pi^+)X$ events is obtained with alternate cuts, normalized and subtracted from the $p(e,e'K^+)X$ data
- The subtracted Λ/Σ^0 peak shapes agree well with MC simulation



KaonLT data: Q^2=0.35 Low ε SHMS Center Setting

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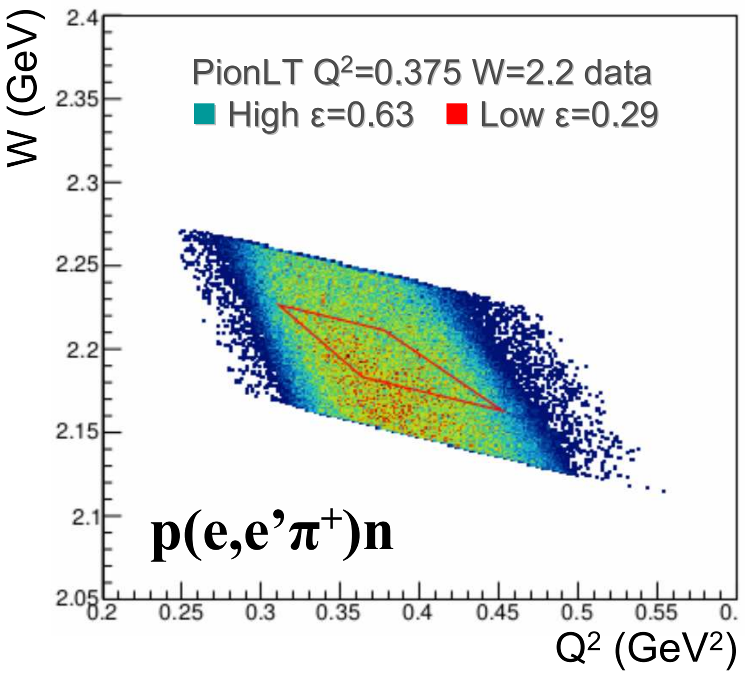
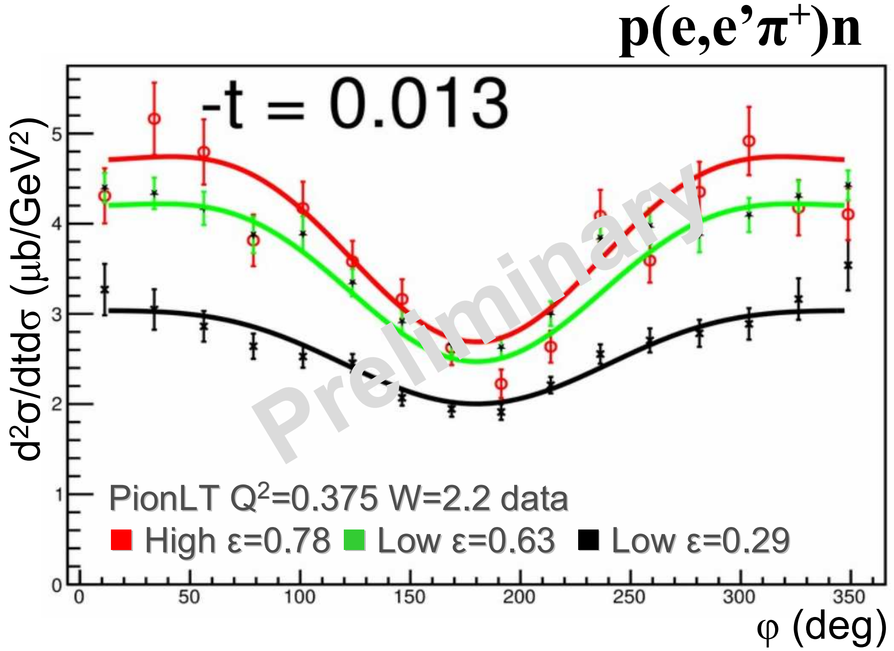
The different meson arm (SHMS) settings are combined to yield φ-distributions for each *t*-bin

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



Diamond cuts define common (W,Q^2) acceptance at both ε

- Extract σ_L by simultaneous fit of Rosenbluth formula using measured azimuthal angle (φ_π) and knowledge of virtual photon polarization (ε)



Preliminary L/T-separated results

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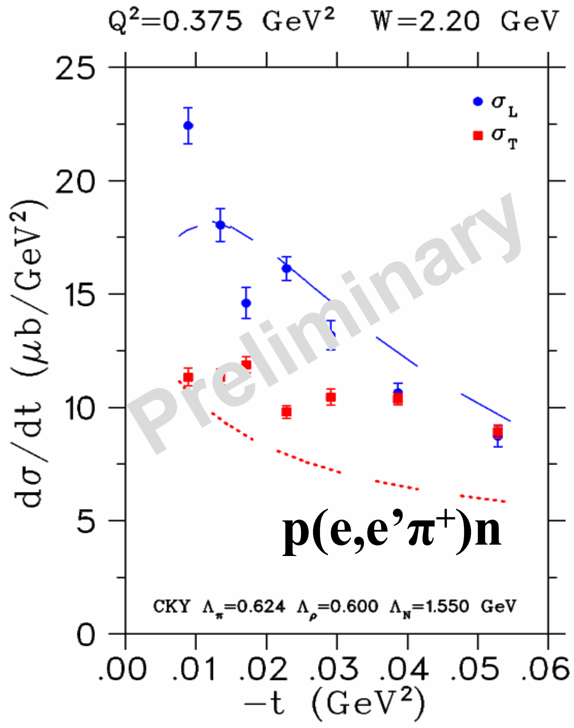
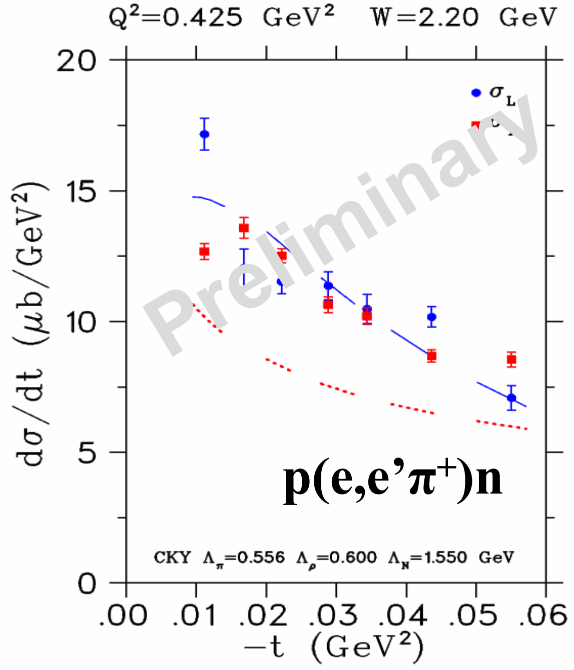


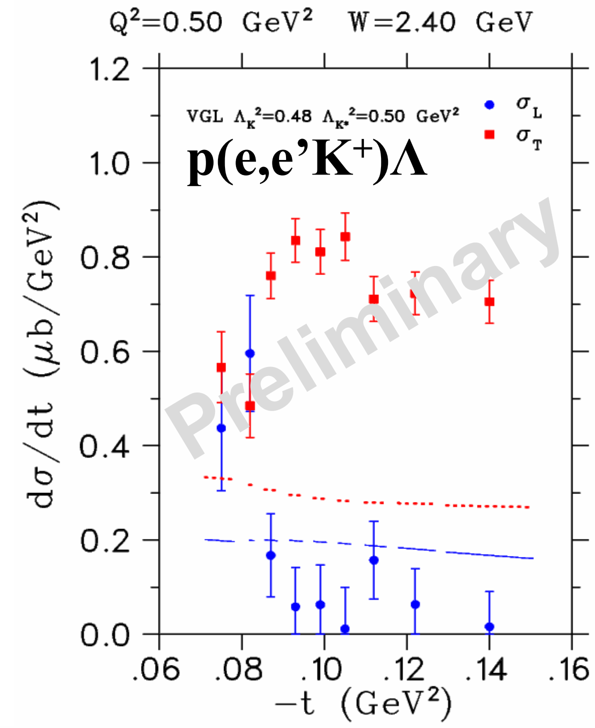


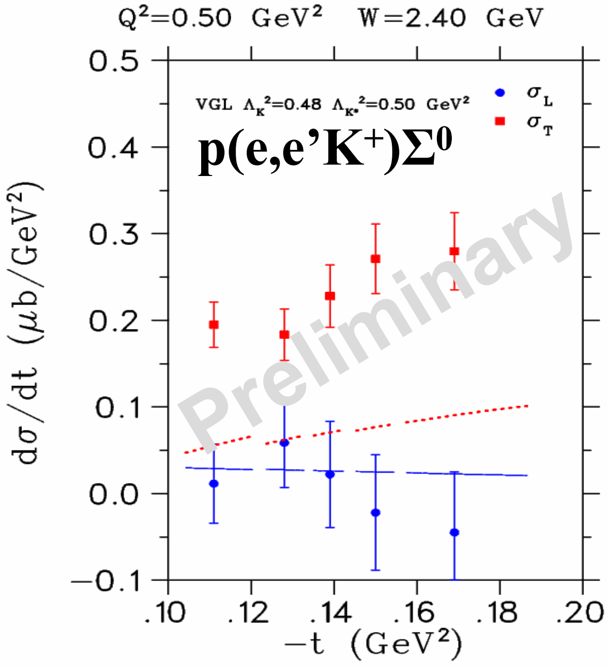
p(e,e'π^+)n

- σ_L shows rise at low $-t$ characteristic of π pole dominance
- T/L is significantly larger than expected from old Ackermann data [NP B137 (1978) 294]
  - Our large σ_T is readily apparent in large ε=0.29 cross section
- Curves are CKY Regge Model prediction [J Korea PhysSoc 67 (2015)L1089]

p(e,e'K$^+$)Λ/Σ^0

- As expected, T/L ratio is much larger than π^+ and rise in σ_L at low $-t$ is less
- Σ^0/Λ ratio is small
- Curves are VGL Regge model prediction [PRC 61 (2000) 025204]





Next steps

- **The end result of PionLT/KaonLT will be an order of magnitude increase in the world data set for exclusive pion and kaon reactions and form factors over a wide kinematic range ($0.4<Q^2<8.5$ GeV^2, $2.0<W<3.3$ GeV)**
  - We hope this will encourage model development for $p(e,e'\pi^+)n$, $p(e,e'K^+)\Lambda/\Sigma^0$ reactions, so we can glean maximum new hadron structure information from these data
- **Expecting papers on Low Q^2 L/T/LT/TT separated results for $p(e,e'\pi^+)n$, $p(e,e'K^+)\Lambda$ and $p(e,e'K+)\Sigma^0$ by end of year**
  - Low Q^2 experimental systematic uncertainty studies not yet completed
- **Much work remains to understand $d\sigma_L/dt$ model fit systematic uncertainties before we can release meson form factor results**
  - Plan to compare VGL, CKY and PKT model fits to data to better understand model dependence in form factor results
  - It will be interesting to see whether Low Q^2 F_π F_K results are consistent (within uncertainties) to π^+ and K^+ charge radius results from meson-electron elastic scattering method

PionLT/KaonLT Collaboration

Experiment Leadership and Data Analysis Working Group:
Garth Huber, Dave Gaskell, Tanja Horn, Pete Markowitz, Julie Roche, Stephen Kay, Richard Trotta, Abdennacer Hamdi, Nathan Heinrich, Muhammad Junaid, Vijay Kumar, Alicia Postuma, Nermin Sadoun, Ali Usman, Chi Kin Tam, Sameer Jain, Gabriel Niculescu, Ioana Niculescu, Kathleen Ramage, Rachel Montgomery

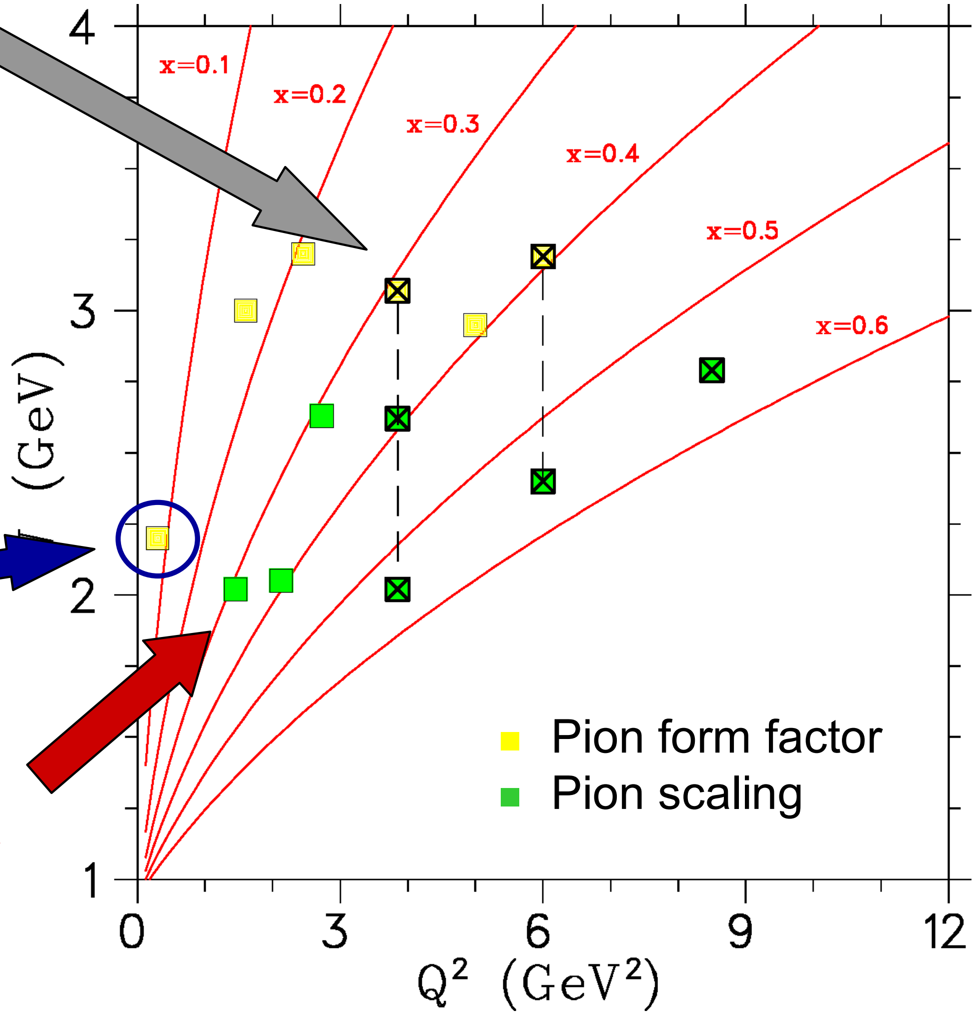
PionLT Kinematic Coverage

Points along vertical lines allow F_π values at different distances from pion pole, to check model properly accounts for:

- π^+ production mechanism
- spectator nucleon
- off-shell (t–dependent) effects

Low Q^2 data presented today

Points along red curves allow $1/Q^n$ scaling tests at fixed x_B



KaonLT is similar in idea, but smaller in scope due to reduced cross section

L/T–separation error propagation

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Error in $d\sigma_L/dt$ is magnified by $1/\Delta\varepsilon$, where $\Delta\varepsilon=(\varepsilon_{Hi}-\varepsilon_{Low})$

→ To keep magnification factor <5x, need $\Delta\varepsilon>0.2$, preferably more!

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

$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{(\varepsilon_1-\varepsilon_2)}\left(\frac{\Delta\sigma}{\sigma}\right)\sqrt{(R+\varepsilon_1)^2+(R+\varepsilon_2)^2} \qquad \text{where } R=\frac{\sigma_T}{\sigma_L}$$

$$\frac{\Delta\sigma_T}{\sigma_T} = \frac{1}{(\varepsilon_1-\varepsilon_2)}\left(\frac{\Delta\sigma}{\sigma}\right)\sqrt{\varepsilon_1^2\left(1+\frac{\varepsilon_2}{R}\right)^2+\varepsilon_2^2\left(1+\frac{\varepsilon_1}{R}\right)^2}$$

The relevant quantities for F_π extraction are R and $\Delta\varepsilon$

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

Measurement of π^+ Form Factor – Low Q^2

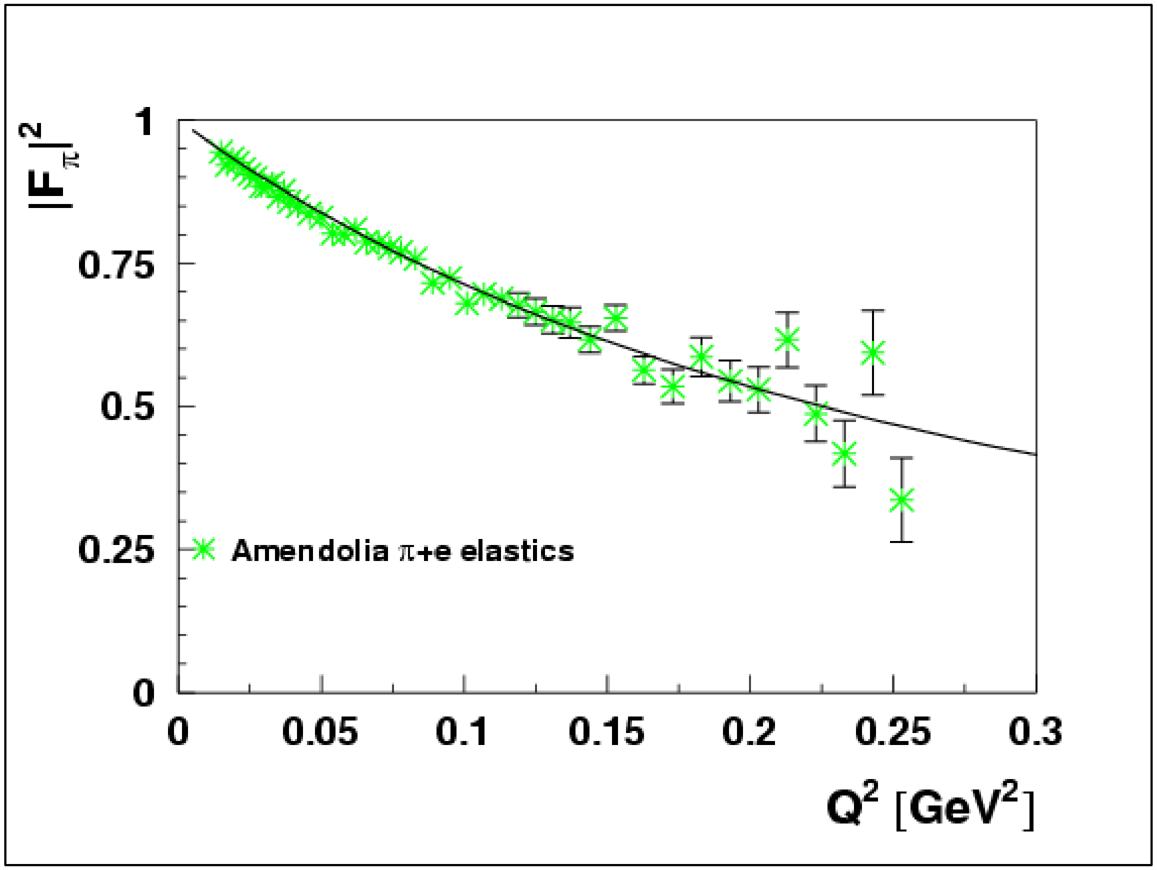
At low Q^2, F_π can be measured model-independently via high energy elastic π^- scattering from atomic electrons in Hydrogen

- CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV^2 *[Amendolia, et al., NP **B277** (1986) 168]*

- Data used to extract pion charge radius
  $r_\pi = 0.657 \pm 0.012$ fm

Maximum accessible Q^2 roughly proportional to pion beam energy

Q^2=1 GeV^2 requires 1 TeV pion beam



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Measurement of π^+ Form Factor – Larger Q^2

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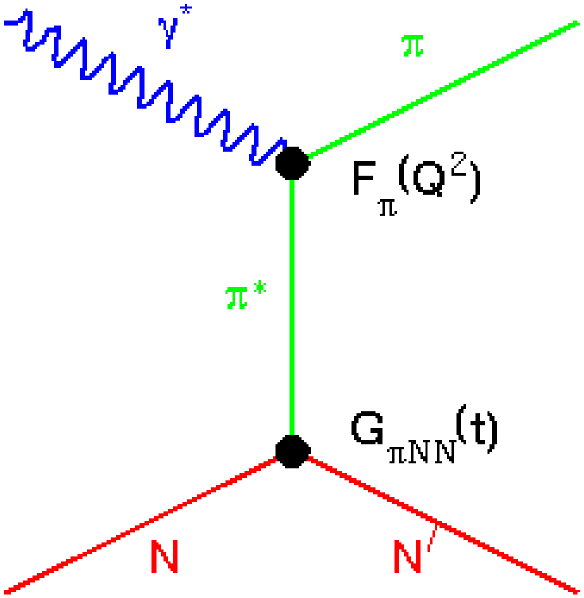
At larger Q^2, F_π must be measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e,e'\pi^+)n$

$$|p\rangle = |p\rangle_0 + |n\pi^+\rangle + \ldots$$

- At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L
- In Born term model, F_π^2 appears as,

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



Drawbacks of this technique

1. Isolating σ_L experimentally challenging
2. Theoretical uncertainty in form factor extraction.

K^+ pole is further in the unphysical region, uncertainties will be larger

Chew–Low Method to determine Pion Form Factor

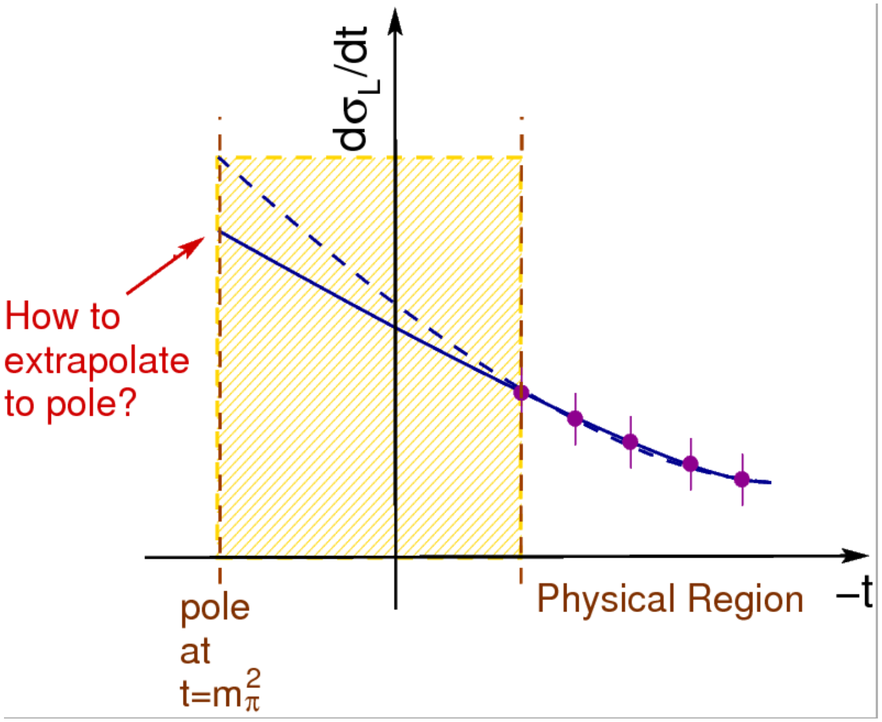
***$p(e,e'\pi^+)n$* data are obtained some distance from the $t=m_\pi^2$ pole.**

→ "Chew Low" extrapolation method requires knowing the analytic dependence of $d\sigma_L/dt$ through the unphysical region.

Extrapolation method last used in 1972 by Devenish & Lyth

- Very large systematic uncertainties.
- Failed to produce reliable result.

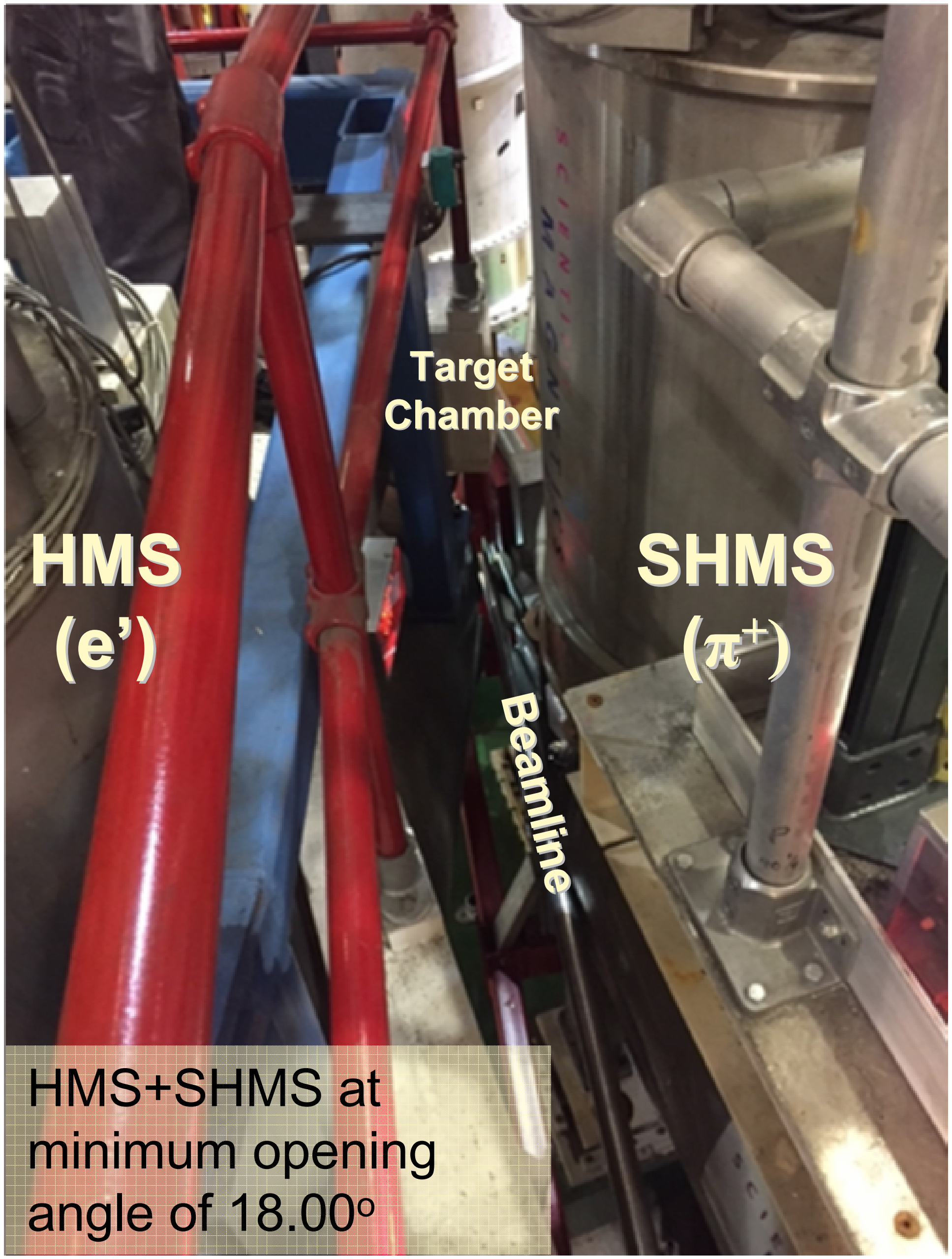
→ Different polynomial fits equally likely in physical region gave divergent form factor values when extrapolated to $t=m_\pi^2$



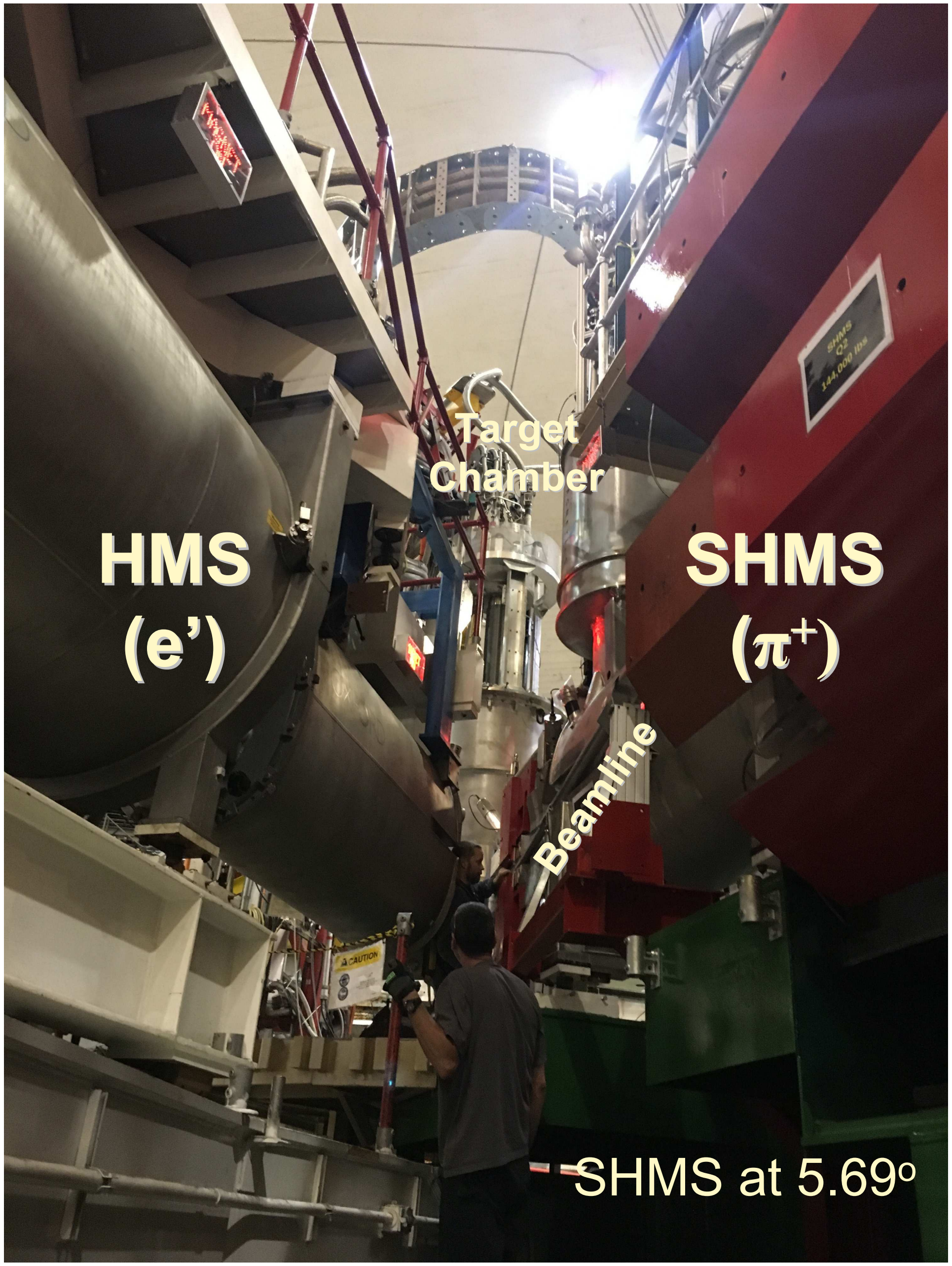
The Chew–Low Method was subsequently abandoned

Hall C during Data Taking

π^+/K^+ FF experiments have challenging forward angle requirements

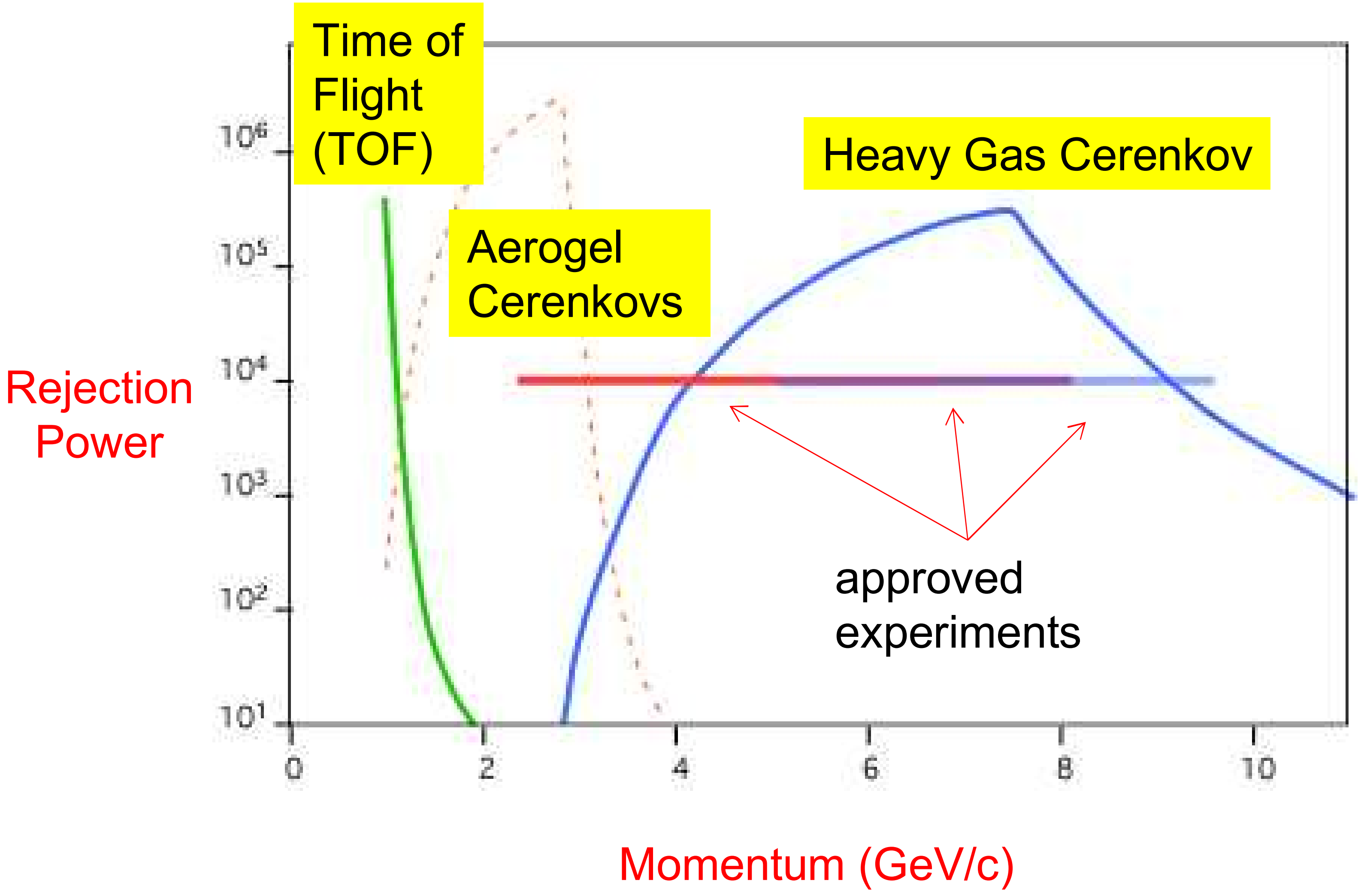


HMS+SHMS at minimum opening angle of 18.00°

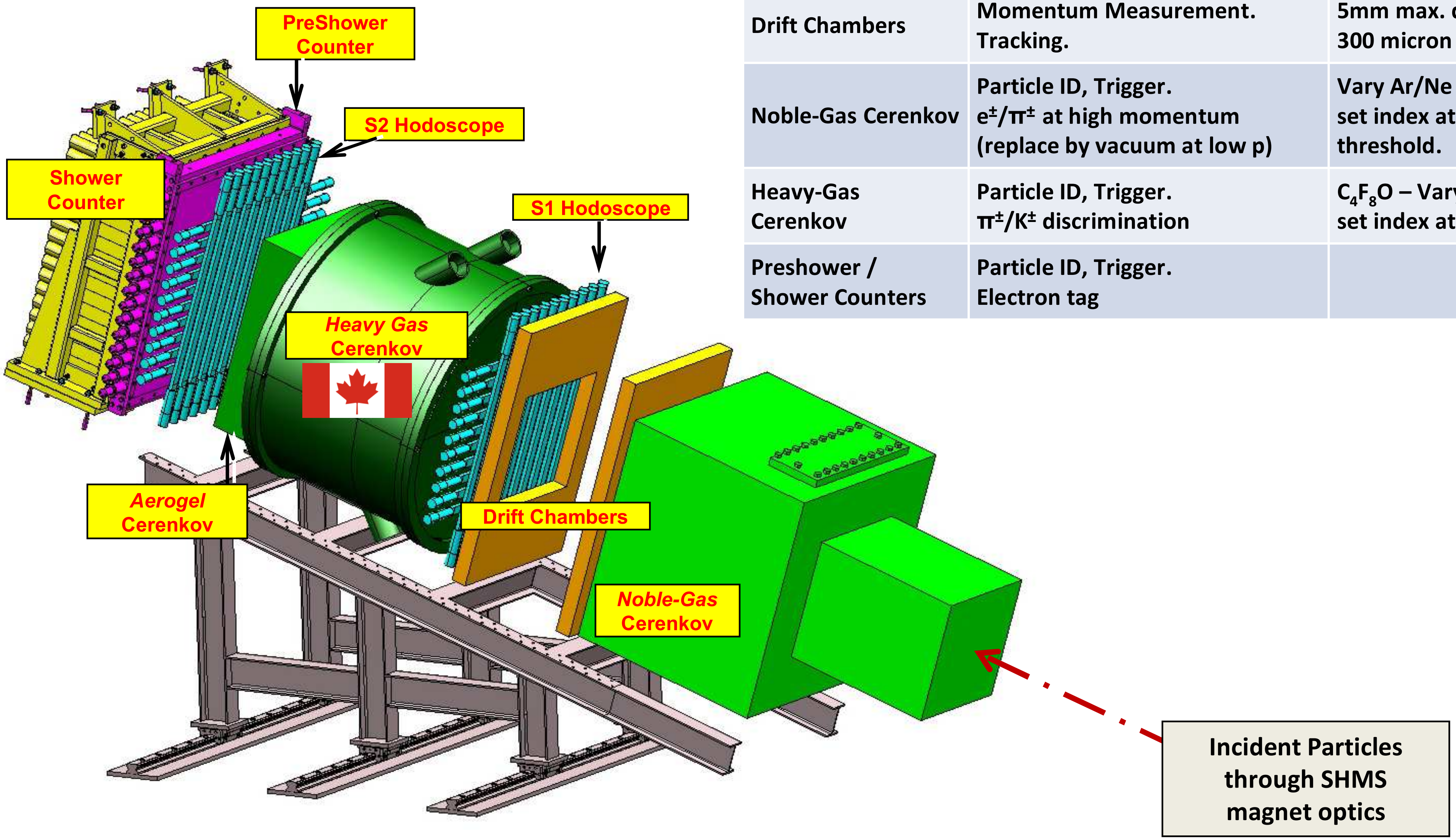


SHMS at 5.69°

SHMS Particle Identification: +Hadrons



SHMS Detector System



DETECTOR	PURPOSE	NOTES
S1XY, S2XY Hodoscopes	Lowest-level Trigger. Time reference	
Drift Chambers	Momentum Measurement. Tracking.	5mm max. drift 300 micron resolution
Noble-Gas Cerenkov	Particle ID, Trigger. $e^{\pm}/\pi^{\pm}$ at high momentum (replace by vacuum at low p)	Vary Ar/Ne mixture to set index at $\pi^{\pm}$ threshold.
Heavy-Gas Cerenkov	Particle ID, Trigger. $\pi^{\pm}/K^{\pm}$ discrimination	C_4F_8O – Vary pressure to set index at $K^{\pm}$ threshold
Preshower / Shower Counters	Particle ID, Trigger. Electron tag	

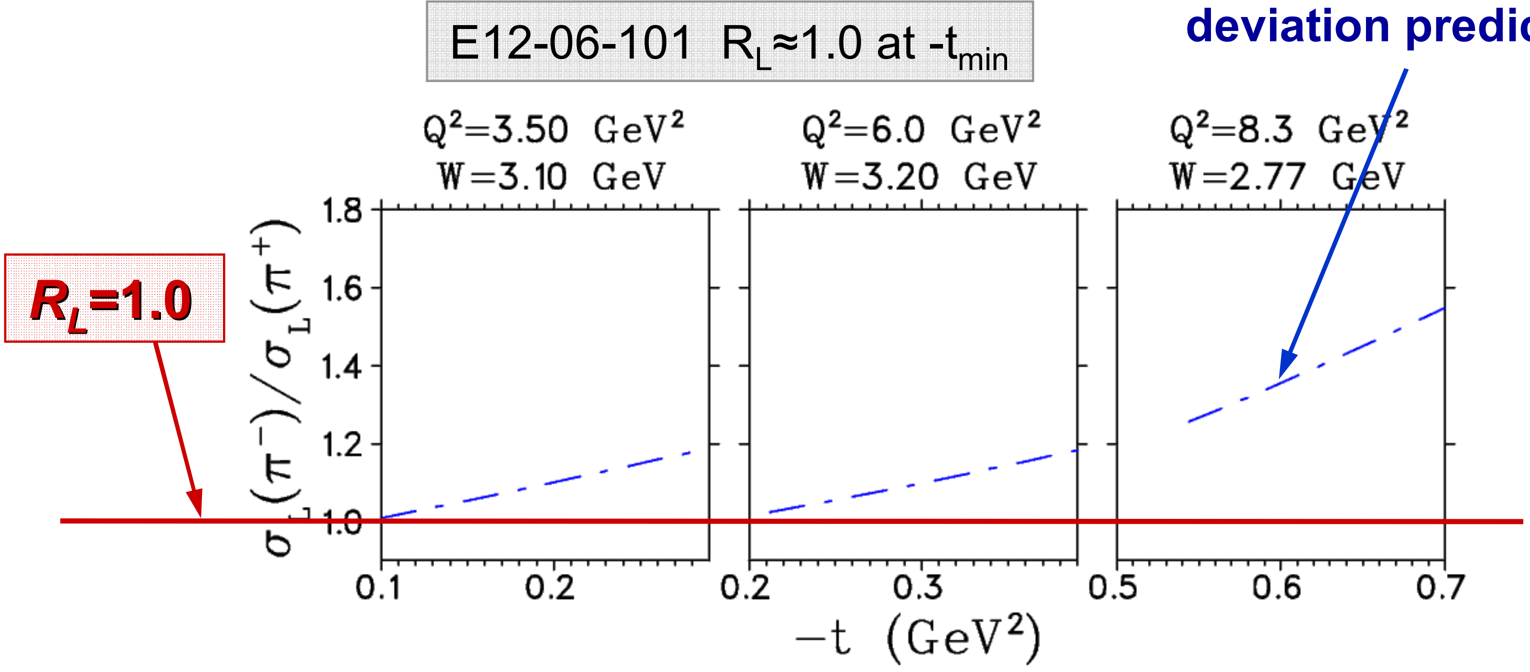
One way to understand non-pole to σ_L

Data–driven approach to better understand non–pole backgrounds at higher –*t*.

- Exclusive ^{2}H(e,e'π^+)nn and ^{2}H(e,e'π^-)pp L/T-separations.
- π^+ *t*–channel diagram is purely isovector (G-parity conservation).

$$R_L = \frac{\sigma_L[n(e,e'\pi^-)p]}{\sigma_L[p(e,e'\pi^+)n]} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2}$$

- Isoscalar backgrounds would distort ratio (e.g. $b_1(1235)$ in *t*–channel).



Significant R_L deviation predicted

Deviation of data from R$_L$=1.0 could confirm large non-pole contributions estimated by model.

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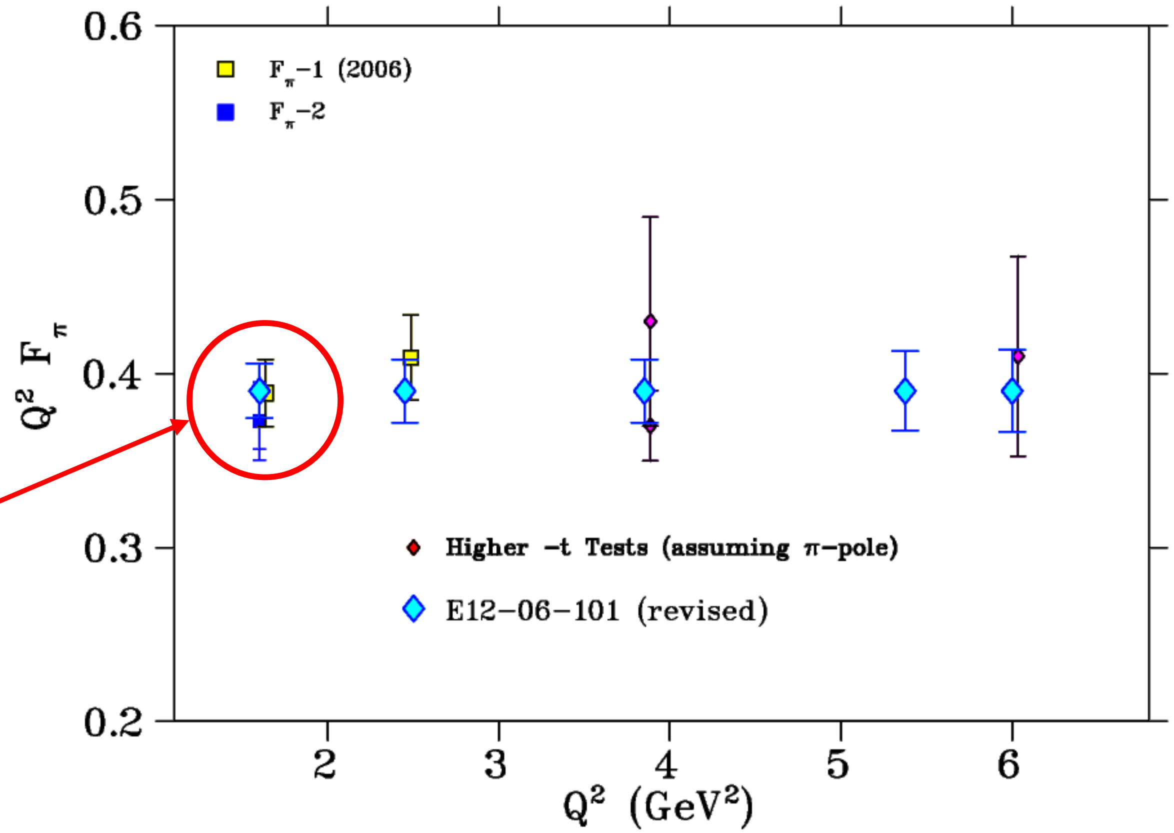
Another way to understand non-pole to σ_L

Test by extracting F_π at different distances from pole.

Expt: F_π-2, $-t_{min}=0.093$ GeV^2
$W=2.22$ GeV.
F_π-1, $-t_{min}=0.15$ GeV^2
$W=1.95$ GeV.

***W=2.22* point 30% closer to pole.**

→ Agreement ~4%.



We have taken 12 GeV data for further tests:

Q^2=1.6 GeV^2	$-t_{min}$=0.029 GeV^2	W=3.00 GeV
Q^2=2.45 GeV^2	$-t_{min}$=0.048 GeV^2	W=3.20 GeV
Q^2=3.85 GeV^2	$-t_{min}$=0.12, 0.21, 0.49 GeV^2	W=3.07, 2.62, 2.02 GeV
Q^2=6.0 GeV^2	$-t_{min}$=0.21, 0.53 GeV^2	W=3.19, 2.40 GeV

3rd Check of Electroproduction Technique

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

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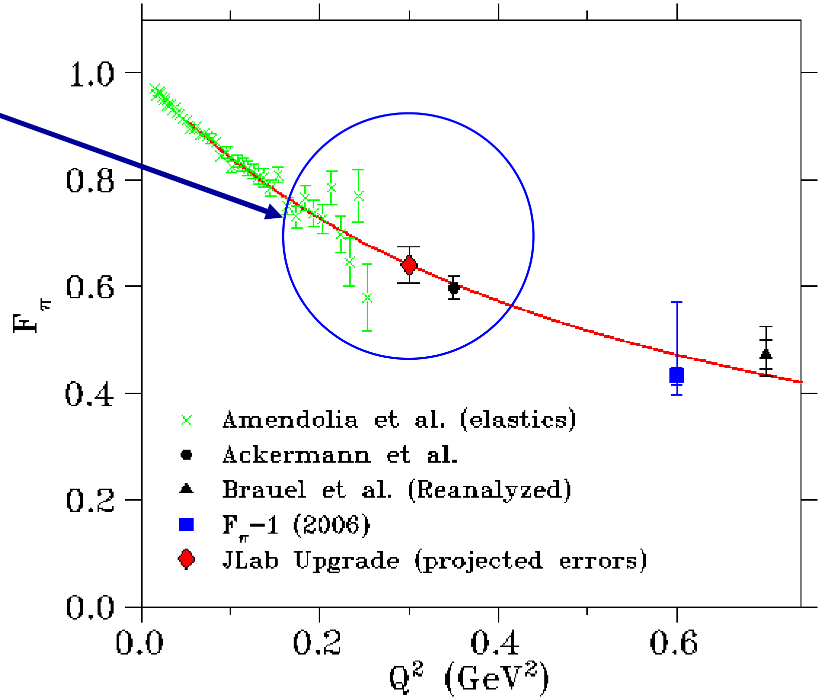
METHOD PASSES CHECKS:

- Q^2=0.35 GeV^2 data from DESY consistent with limit of elastic scattering data within uncertainties.
  *[H. Ackermann, et al., NP **B137**(1978)294]*
- **We have data for a better test at Q^2=0.375, 0.425 GeV^2 with much lower statistical and systematic uncertainties**



Data analysis in progress by V. Kumar (U.Regina)

Current and Projected F_π Data

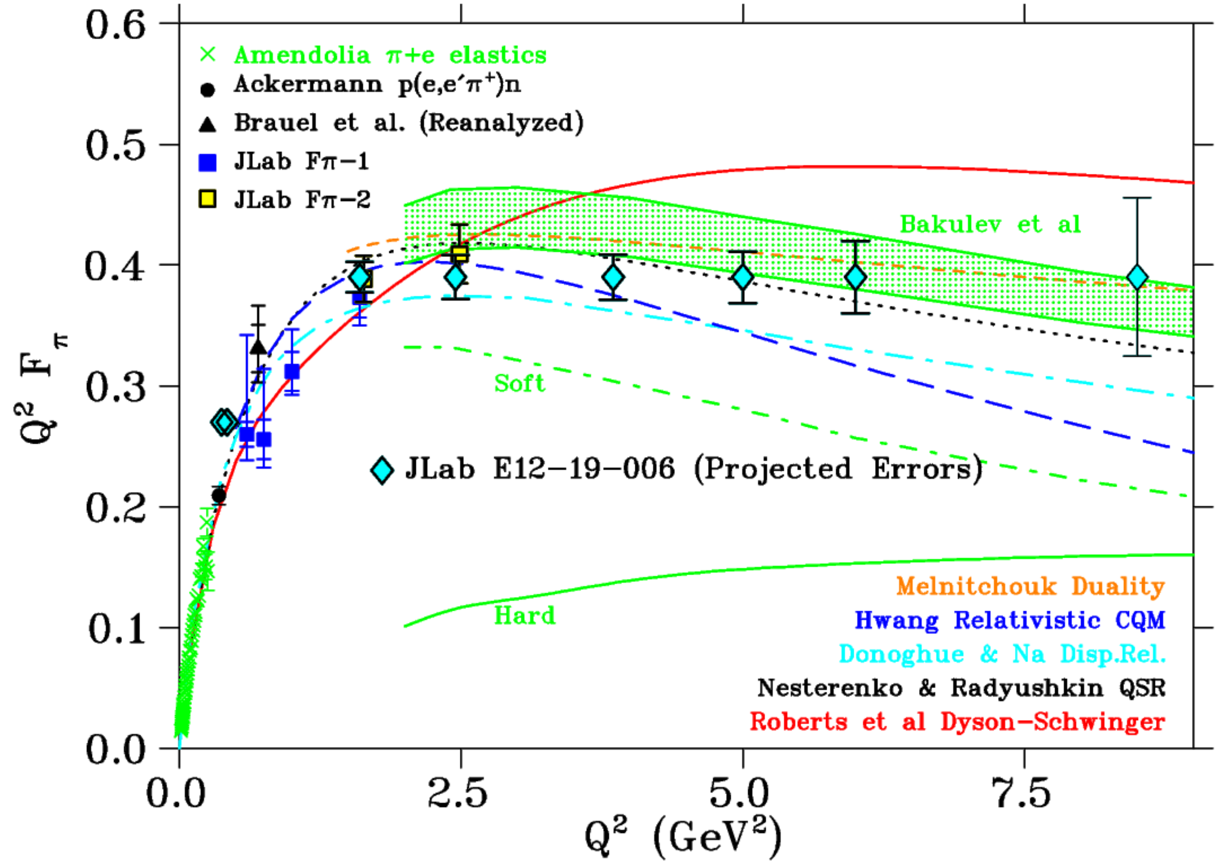
SHMS+HMS will allow measurement of F_π to much higher Q^2

No other facility worldwide can perform this measurement

Data taking completed September 2022 (E12–19–006: GMH, D. Gaskell and T. Horn, spokespersons)

y–positions of projected points are arbitrary

Error bars are calculated from obtained statistics and projected systematic uncertainties



The ~10% measurement of F_π at Q^2=8.5 GeV^2 is at higher $-t_{min}$=0.45 GeV^2

The pion form factor is the clearest test case for studies of QCD's transition from non–perturbative to perturbative regions

$p(e,e'K^+)\Lambda(\Sigma^0)$ Experiment

Isolate Exclusive Final States via Missing Mass

$$M_X = \sqrt{(E_{\det} - E_{init})^2 - (p_{\det} - p_{init})^2}$$

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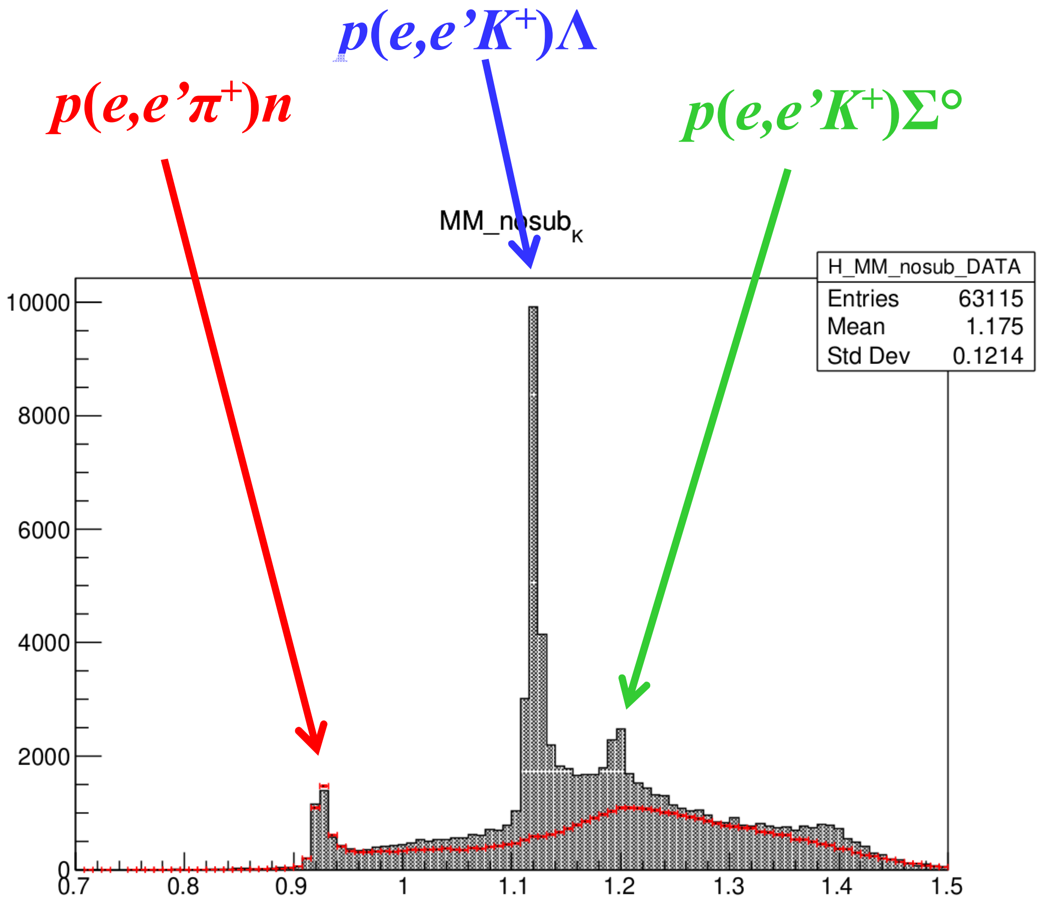
- Spectrometer coincidence acceptance allows for simultaneous studies of Λ and $\Sigma°$ channels.
- Kaon-pole dominance test through

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

- Should be similar to ratio of $g^2_{pK\Lambda}/g^2_{pK\Sigma}$ coupling constants if t-channel exchange dominates.



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

Plot by Richard Trotta (CUA/Virginia)

Kaon Form Factor Experiment Goals

- **Measure the –t dependence of the *p(e,e'K$^+$)Λ,Σ°* cross section at fixed Q^2 and W>2.5 GeV to search for evidence of K$^+$ pole dominance in σ_L**
  - Separate the cross section components: L, T, LT, TT
  - First L/T measurement above the resonance region in K$^+$ production
- **<u>If warranted by the data</u>, extract the Q^2 dependence of the kaon form factor to shed new light on QCD's transition to quark-gluon degrees of freedom.**

- **<u>Even if we cannot extract the kaon form factor</u>, the measurements are important.**
  - $K^+\Lambda$ and $K^+\Sigma^\circ$ reaction mechanisms provide valuable information in our study of hadron structure
  - Flavor degrees of freedom provide important information for QCD model building and understanding of basic coupling constants

Σ^0/Λ Ratio

- Following the first exclusive measurements on p(e,e'K^+)Λ and p(e,e'K^+)Σ^0 at Cornell [Bebek et al. PRL 32(1974)21], Otto Nachtmann constructed a simple parton model in attempt to explain the surprisingly large drop in the Σ^0/Λ Ratio with Q^2 [NP B74(1974)422]
  - i.e. even by 1974 it was understood that the Ratio drops from ~0.6 at Q^2=0 (photoproduction) to ~0.025 by Q^2=2 GeV^2
- He found that the Σ^0/Λ Ratio is related to the decrease of the $F_1^{\gamma^*n}/F_1^{\gamma^*p}$ ratio as Q^2 increases, where $F_1^{\gamma^*N}$ are the usual structure functions for electron-nucleon DIS
- His prediction only applies to σ_T, the scarcity of prior L/T-separated cross sections in the Q^2=0.5-2.0 region means that KaonLT is the first opportunity to reliably test his prediction

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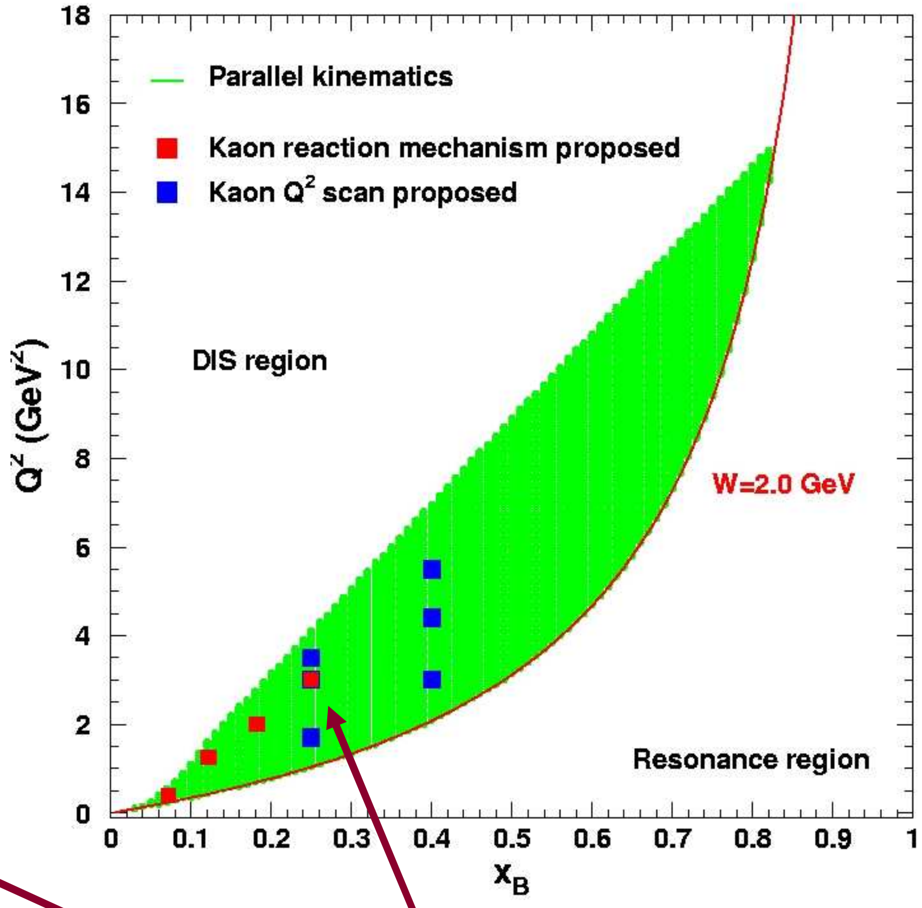
$p(e,e'K^+)\Lambda(\Sigma^0)$ Experiment Overview

- Measure the separated cross sections at varying $-t$ and x_B
  - If K^+ pole dominates σ_L allows for extraction of the kaon ff (W>2.5 GeV)
- Measure separated cross sections for the $p(e,e'K^+)\Lambda(\Sigma^\circ)$ reaction at two fixed values of –t and x_B
  - Q^2 coverage is a factor of 2-3 larger compared to 6 GeV at much smaller $-t$
  - Facilitates tests of Q^2 dependence even if L/T ratio less favorable than predicted

x	Q^2 (GeV^2)	W (GeV)	-t (GeV/c)^2
0.1-0.2	0.4-3.0	2.5-3.1	0.06-0.2
0.25	1.7-3.5	2.5-3.4	0.2
0.40	3.0-5.5	2.3-3.0	0.5



Q^2=3.0 GeV^2 was optimized to be used for both t-channel and Q^{-n} scaling tests

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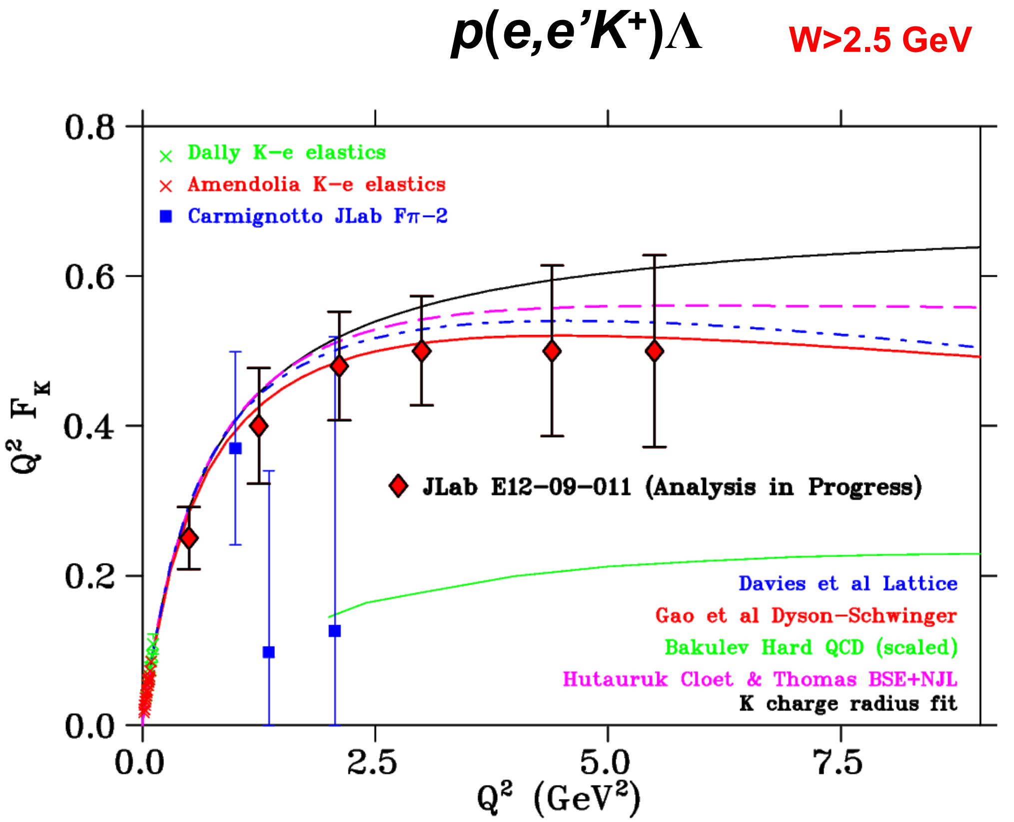
Projected Uncertainties for K^+ Form Factor

- First measurement of F_K well above the resonance region.
- Measure form factor to Q^2=3 GeV^2 with good overlap with elastic scattering data.
    - Limited by $-t$<0.2 GeV^2 requirement to minimize non–pole contributions.
- Data will provide an important second $q\overline{q}$ system for theoretical models, this time involving a strange quark.



Extraction of F_K from Q^2>4 GeV^2 data is more uncertain, due to higher $-t_{min}$

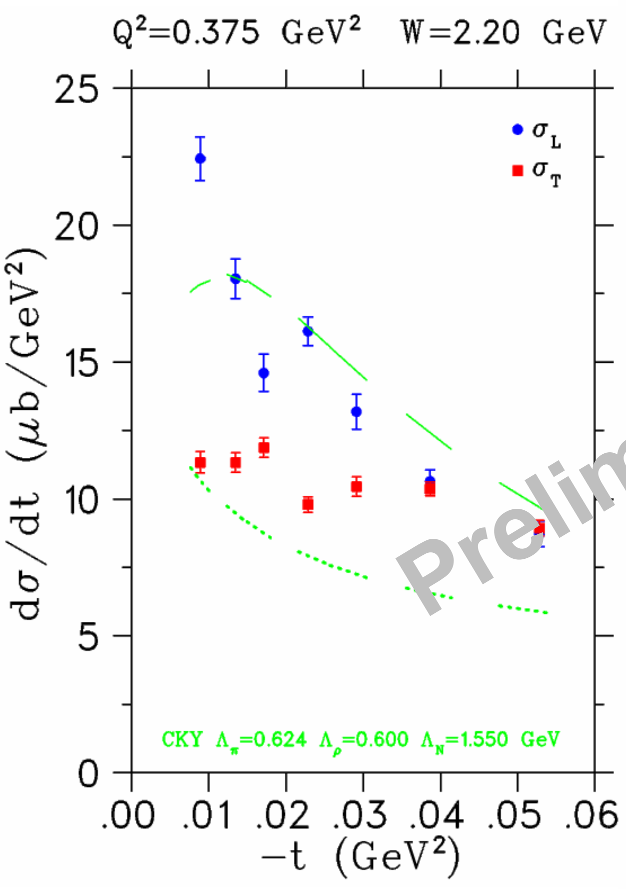
- ***Partially completed as an early SHMS commissioning experiment: LT–separation (E12–09–011: T. Horn, G. Huber and P. Markowitz, spokespersons)***
- ***Data under analysis, expecting final results next year***

— R. Trotta (CUA/Virginia)

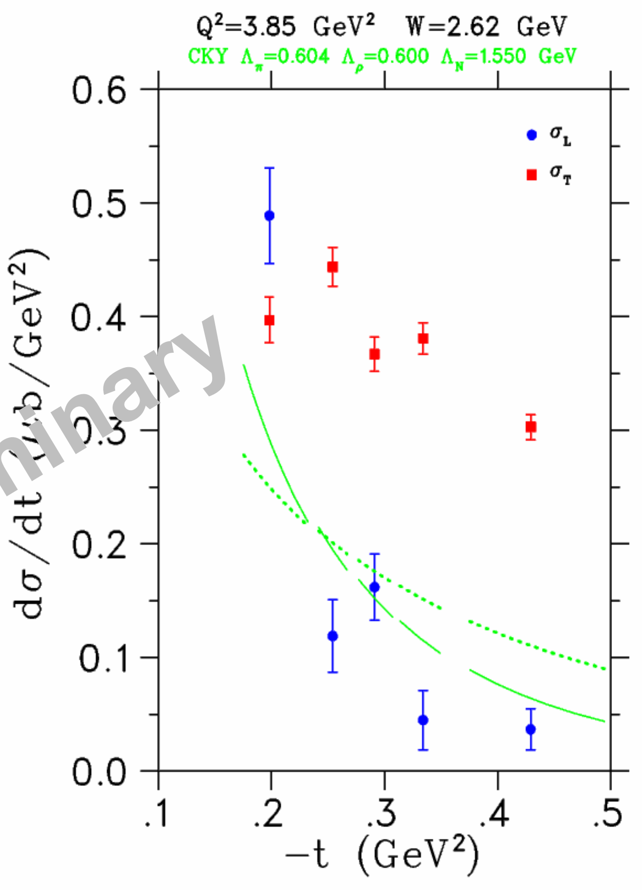
F_π Extraction from JLab data

- **A model is required to extract F_π from $d\sigma_L/dt$**
  - Fit of model to σ_L gives F_π at each Q^2

- **JLab 6 GeV F_p expts used VGL Regge model** [Vanderhaeghen, Guidal, Laget, PRC 57(1998)1454]
  - Most parameters fixed by photoproduction data
  - At small $-t$, σ_L only sensitive to π Regge trajectory cutoff Λ_π
- **Choi, Kong, Yu Regge model allows 2nd way to extract F_π from σ_L data** [JKorPhysSoc 67(2015)L1089, arXiv: 1508.00969]
- **Perry, Kizilersu, Thomas model also being considered** [PLB 807(2020)135581]



V.Kumar et al, publication in process



M. Junaid et al, publication in process

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Comparison with π VGL Regge Model

Phys Rev C 57(1998)1454

- The first model written for our data
- As the t-channel π exchange diagram is by itself not gauge invariant, the s-channel (for π^+ production) or u-channel (for π^- production) nucleon exchange diagram was also Reggeized, to ensure gauge invariance of their sum
- Two model parameters: σ_L sensitive to Λ_π^2, much less sensitive to Λ_ρ^2

F_π–1,2 used VGL Model to extract F_π from σ_L

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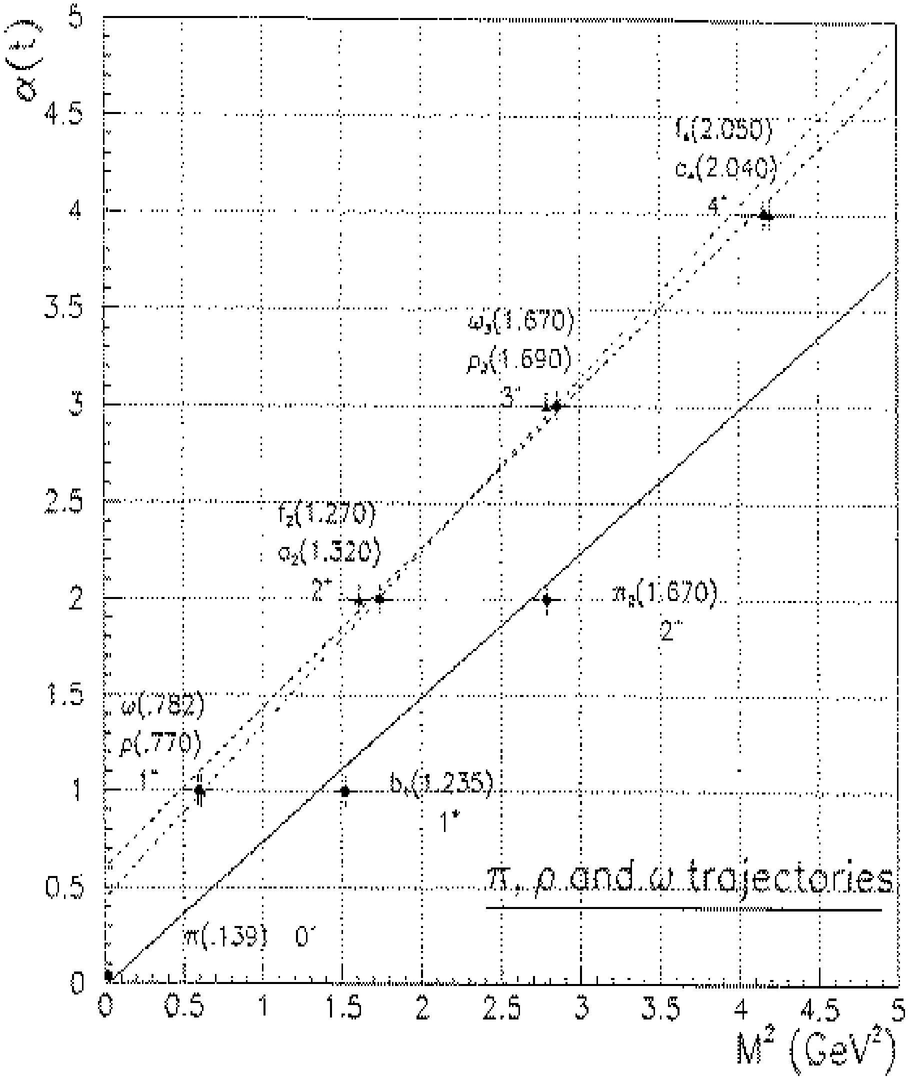
- Feynman propagator $\left(\frac{1}{t-m_\pi^2}\right)$

  replaced by π and ρ Regge propagators.
  - Represents the exchange of a series of particles, compared to a single particle.
- Model parameters fixed from pion photoproduction.
- Free parameters: $\Lambda_{\square}$, Λ_ρ (trajectory cutoffs).
- ρ exchange does not significantly influence σ_L at small $-t$.
- Pion form factor is a free parameter in the model, parameterized as:

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



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

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Comparison with π CKY Regge Model

J Korea PhysSoc 67(2015)L1089

- The fact that VGL dramatically underestimates σ_T while doing a much better job on σ_L led to new model development, with the goal of increasing σ_T without degrading σ_L description
- The Kaskulov-Mosel and Vrancx-Ryckebusch models include intermediate (DIS-like) processes on the recoil nucleon, leading to the same final state. The CKY model is an extension of this work
- Third model parameter, Λ_N, for proton exchange in s-channel, is added to restore gauge invariance and plays a role in σ_T

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Comparison with *K* VGL Regge Model

Phys Rev C 61(2000)025204

- An original and essential feature of this model is the way gauge invariance is restored for the *K* t-channel exchanges by proper ‘‘Reggeization’’ of the s-channel nucleon pole contribution. In our model they are Reggeized in the same way and multiplied by the same electromagnetic form factor. This approach clearly differs from traditional ones…
- Two model parameters: Λ_K^2, Λ_{K*}^2
- Carmignotto et al. [PRC 97(2018)205204] varied Λ_K^2, keeping $\Lambda_{K*}^{2} \approx \Lambda_K^2$

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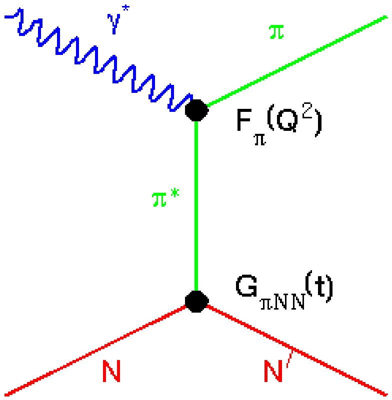
Comparison with *K* CKY Regge Model

Private communication (2023)

- The charge form factor of kaon, $F_K(Q^2)$, which gives the leading contribution to the longitudinal cross section σ_L, can be treated as gauge invariant by including the nucleon pole in the s-channel with charge form factor $F_1(Q^2)$
- Four model parameters: Λ_K Λ_{K*} Λ_{N1} Λ_{N2}

DEMP Motivation

1) Determine the Pion Form Factor at Q^2>0.3 GeV^2:



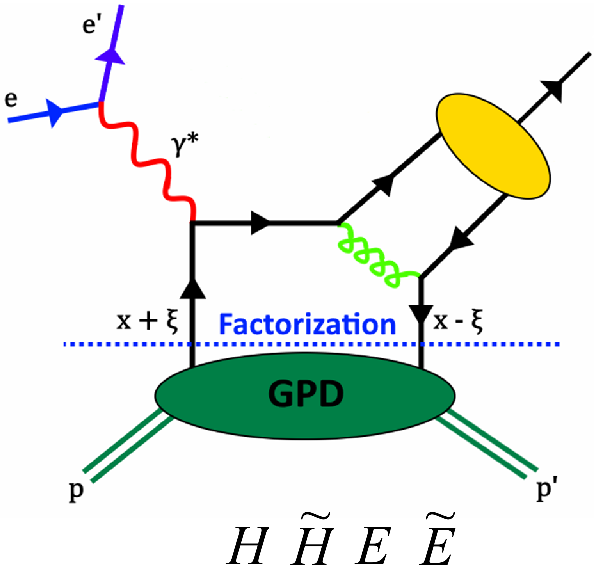
- Indirectly measure F_π using the "pion cloud" of the proton via p(e,e'π^+)n

$$\left|p\right\rangle = \left|p\right\rangle_0 + \left|n\pi^+\right\rangle + \ldots$$

  - Pion pole process dominates σ_L in forward kinematics.
  - Can a similar method be used to determine the kaon form factor?

2) Study the Hard-Soft Factorization Regime:

Implications for GPD studies, as they can only be extracted from hard exclusive data where hard-soft factorization applies.



- Investigate if p(e,e'π^+)n and p(e,e'K$^+$)Λ cross sections at fixed *x* behave according to the Q^{-n} scaling expectations of hard QCD.
- Form $\dfrac{\sigma_T[n(e,e'\pi^-)p]}{\sigma_T[p(e,e'\pi^+)n]}$ ratios where soft contributions may cancel, yielding insight to factorization at modest Q^2.

The Pion in perturbative QCD

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At very large Q^2, pion form factor (F_π) can be calculated using pQCD

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

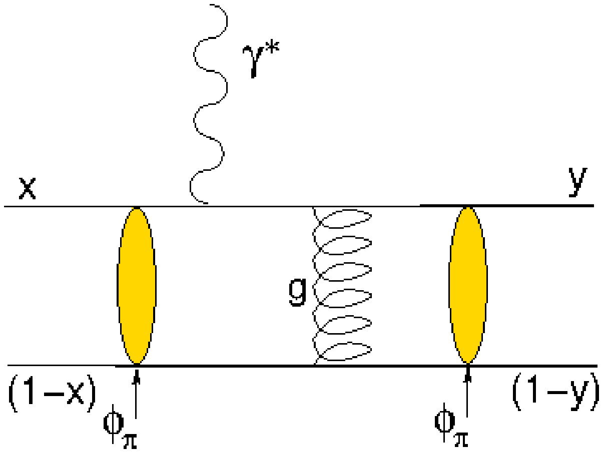
at asymptotically high Q^2, the pion distribution amplitude becomes

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

and F_π takes the very simple form

$$Q^2 F_\pi(Q^2) \xrightarrow[Q^2\to\infty]{} 16\pi\alpha_s(Q^2) f_\pi^2$$

G.P. Lepage, S.J. Brodsky, Phys.Lett. **87B**(1979)359.



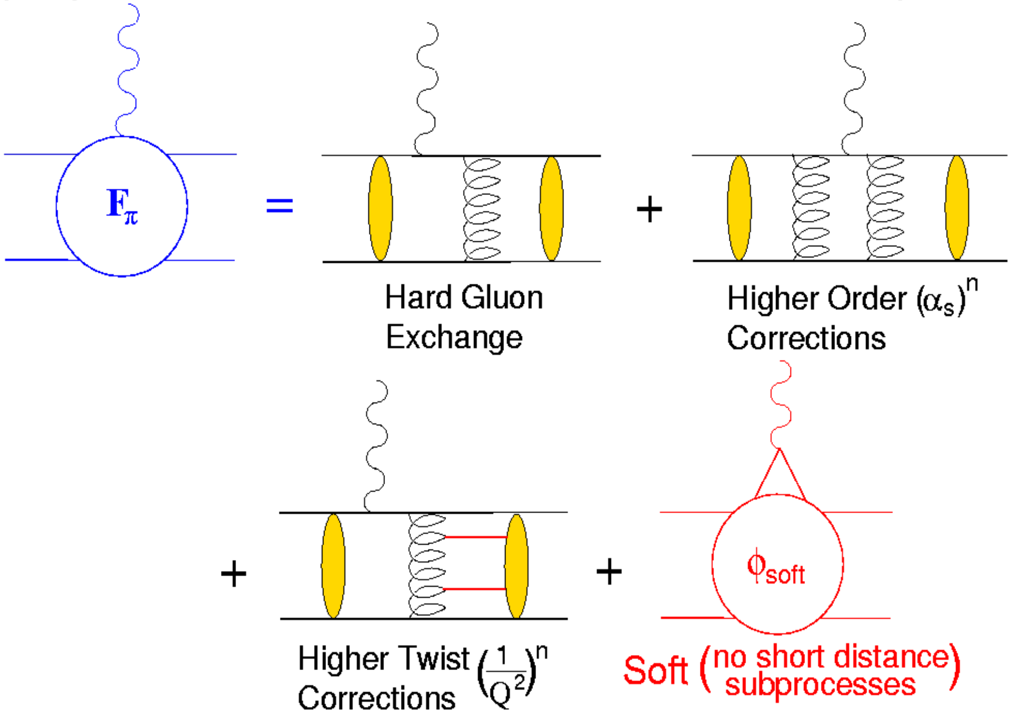
f_π=93 MeV is the $\pi^+ \to \mu^+ \nu$ decay constant.

This only relies on asymptotic freedom in QCD, *i.e.* $(\partial\alpha_S/\partial\mu)<0$ as $\mu\to\infty$.

Q^2F_π should behave like $\alpha_s(Q^2)$ even for moderately large Q^2.
→ Pion form factor seems to be best tool for experimental study of nature of the quark-gluon coupling constant renormalization.
[A.V. Radyushkin, JINR 1977, arXiv:hep–ph/0410276]

Pion Form Factor at Intermediate Q^2

At experimentally–accessible Q^2, both the "hard" and "soft" components (e.g. transverse momentum effects) contribute.



- **The interplay of hard and soft contributions is poorly understood.**
  - → Different theoretical viewpoints on whether higher–twist mechanisms dominate until very large momentum transfer or not.

- **The pion elastic and transition form factors experimentally accessible over a wide kinematic range.**
  - → A laboratory to study the **transition** from the soft to hard regime.

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