Measurement of the Charged Pion Form Factor to High Q^2 at JLab

University of Regina

Garth Huber

(on behalf of the PionLT Collaboration)

Precision tests of fundamental physics with light mesons
ECT* Workshop, Trento, Italy
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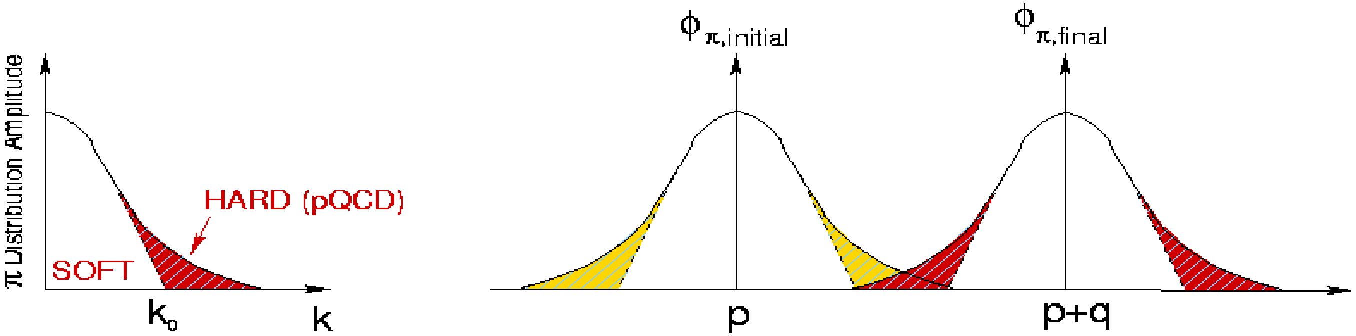
Charged Meson Form Factors

Simple $q\bar{q}$ valence structure of mesons presents the ideal testing ground for our understanding of bound quark systems.

In quantum field theory, the form factor is the overlap integral:

$$F_\pi(Q^2) = \int \phi_\pi^*(p)\phi_\pi(p+q)dp$$



The meson wave function can be separated into φ_π^{soft} with only low momentum contributions ($k<k_0$) and a hard tail φ_π^{hard}.

While φ_π^{hard} can be treated in pQCD, φ_π^{soft} cannot.

From a theoretical standpoint, the study of the Q^2–dependence of the form factor focuses on finding a description for the hard and soft contributions of the meson wave-function.

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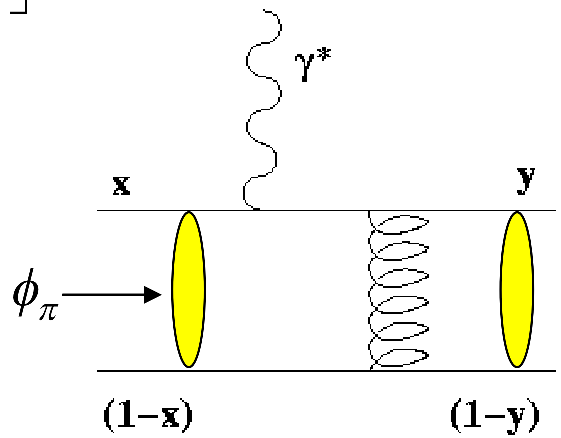
The Pion in perturbative QCD

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, only hardest portion of pion distribution amplitude contributes

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



and F_π takes the very simple form

$$Q^2 F_\pi(Q^2) \underset{Q^2\to\infty}{\longrightarrow} 16\pi\alpha_s(Q^2) f_\pi^2$$

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

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

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]

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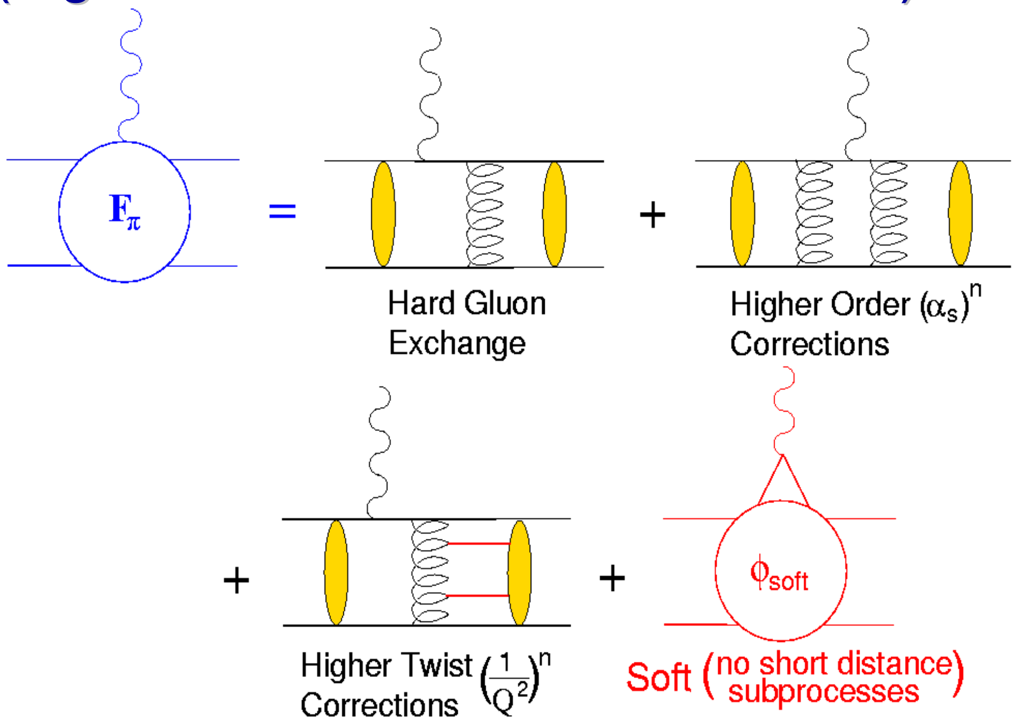
Pion Form Factor at Intermediate Q^2

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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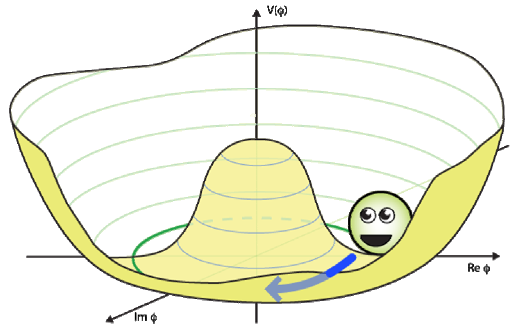
The Pion as a Goldstone Boson

- A remarkable feature of QCD is Dynamical Chiral Symmetry Breaking (DCSB) because it cannot be derived directly from the Lagrangian and is related to nontrivial nature of QCD vacuum.
  - Explicit symmetry breaking, which is put in "by hand" through finite quark masses, is quite different.
- DCSB is now understood to be one of the most important emergent phenomena in the Standard Model, responsible for generation of >98% baryonic mass.



- **Two important consequences of DCSB:**
  1. Valence quarks acquire a dynamical or constituent quark mass through their interactions with the QCD vacuum.
  2. The pion is the spin-0 boson that arises when Chiral Symmetry is broken, similar to how Higgs boson arises from Electroweak Symmetry Breaking.

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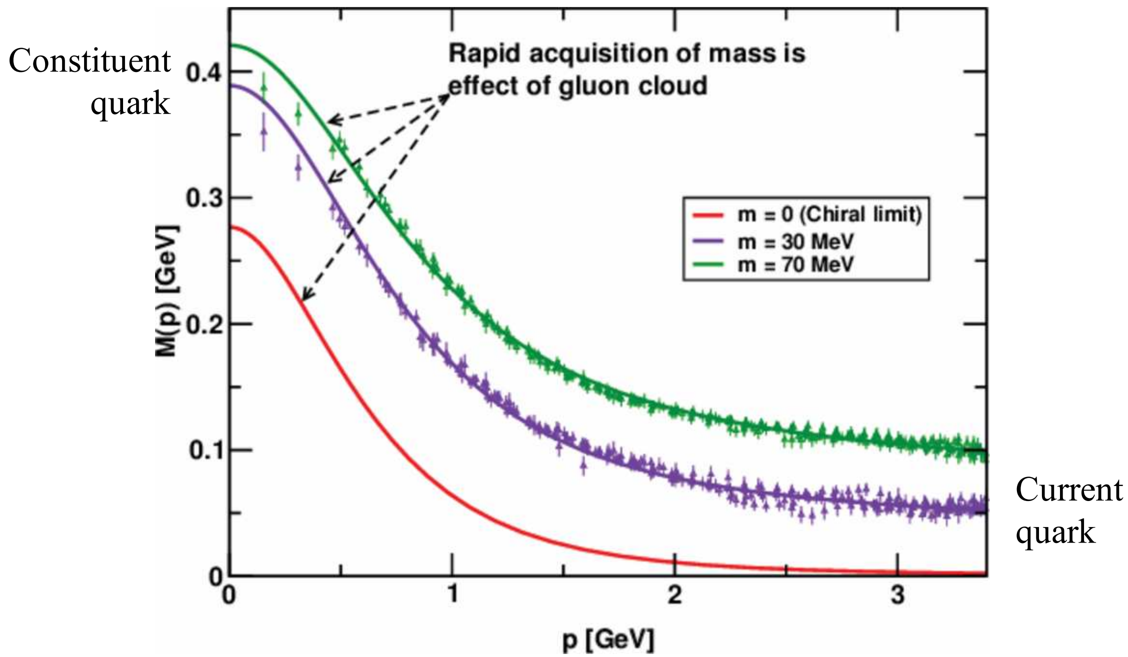
Recent Theoretical Advances

Amazing progress in the last few years.

- **We now have a much better understanding how Dynamical Chiral Symmetry Breaking (DCSB) generates hadron mass.**
- Quenched lattice–QCD data on the dressed–quark wave function were analyzed in a Bethe–Salpeter Equation framework by Bhagwat, et al.
- For the first time, the evolution of the current–quark of pQCD into constituent quark was observed as its momentum becomes smaller.

- The constituent–quark mass arises from a cloud of low–momentum gluons attaching themselves to the current quark.
- **This is DCSB:** an essentially non-perturbative effect that generates a quark *mass from nothing*: namely, it occurs even in the chiral (m=0) limit.



M.S. Bhagwat, et al., PRC **68** (2003) 015203.
L. Chang, et al., Chin.J.Phys. **49** (2011) 955.

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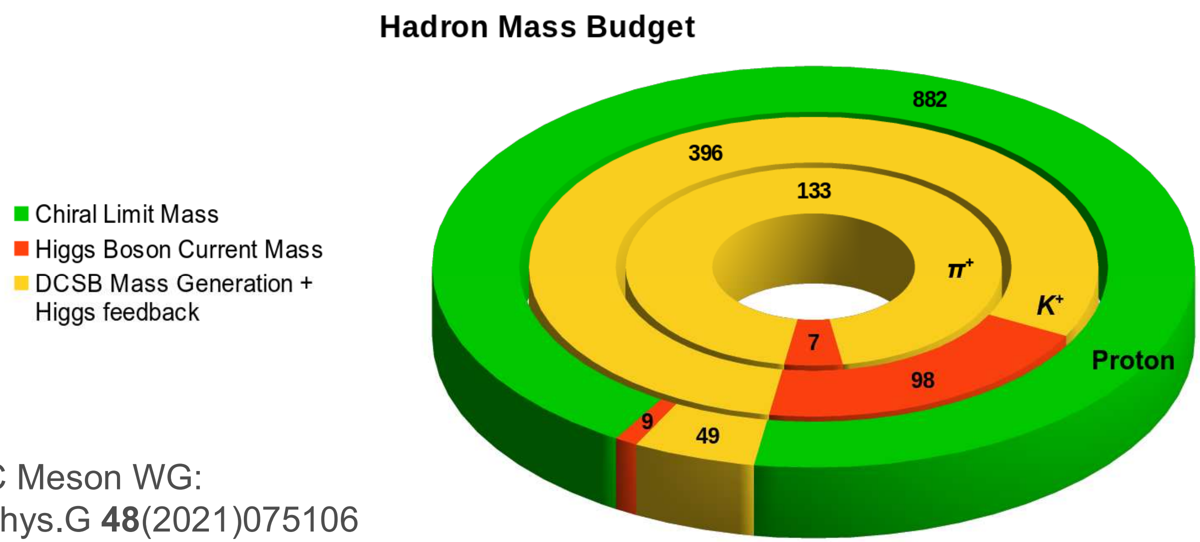
Contrasts in Hadron Mass Budgets



EIC Meson WG:
J.Phys.G **48**(2021)075106

Stark Differences between proton, K$^+$, π^+ mass budgets

- Due to Emergent Hadronic Mass (EHM), Proton mass large in absence of quark couplings to Higgs boson (chiral limit).
- Conversely, and yet still due to EHM and DCSB, *K* and π are massless in chiral limit (i.e. they are Goldstone bosons).
- The mass budgets of these crucially important particles demand interpretation.
- Equations of QCD stress that any explanation of the proton's mass is incomplete, unless it simultaneously explains the light masses of QCD's Goldstone bosons, the π and *K*.

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Synergy: Emergent Mass and π^+ Form Factor

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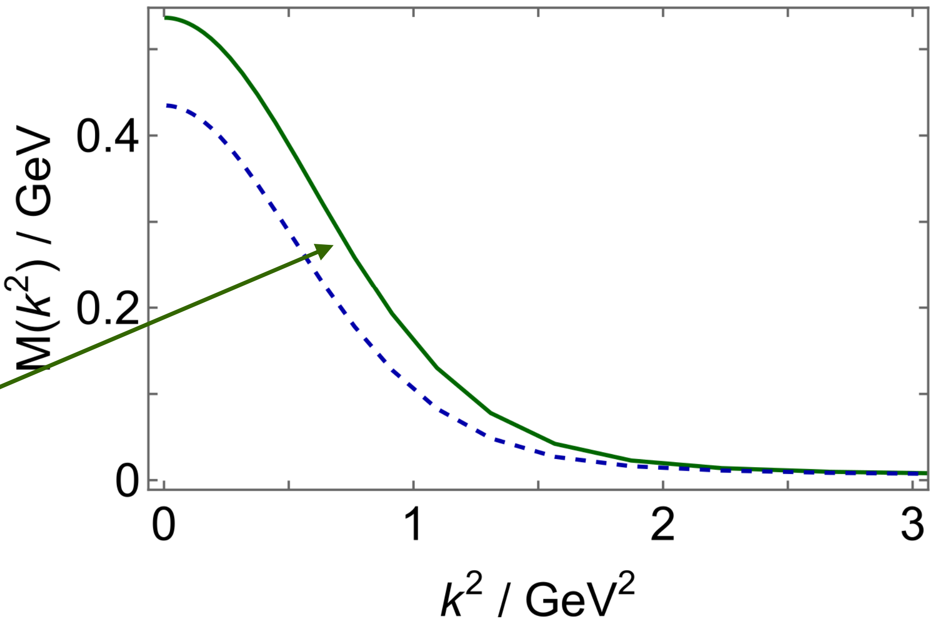
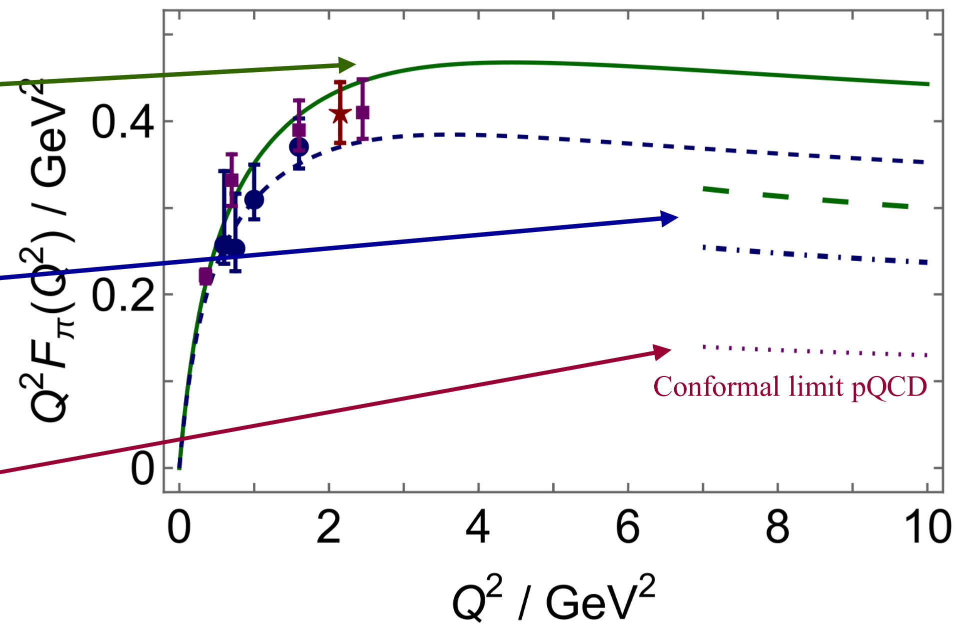
At empirically accessible energy scales, π^+ form factor is sensitive to emergent mass scale in QCD

- **Two dressed–quark mass functions distinguished by amount of DCSB**
  - DCSB emergent mass generation is 20% stronger in system characterized by solid green curve, <u>which is more realistic case</u>



- **$F_\pi(Q^2)$ obtained with these mass functions**
  - r_π=0.66 fm with solid green curve
  - r_π=0.73 fm with solid dashed blue curve
- **$F_\pi(Q^2)$ predictions from QCD hard scattering formula (slide #3), obtained with related, computed pion PDAs**
- **QCD hard scattering formula, using conformal limit of pion's twist–2 PDA**

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



Chen, et al., PRD **98**(2018)091505(R); Aguilar et al, EPJA **55**(2019)190

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

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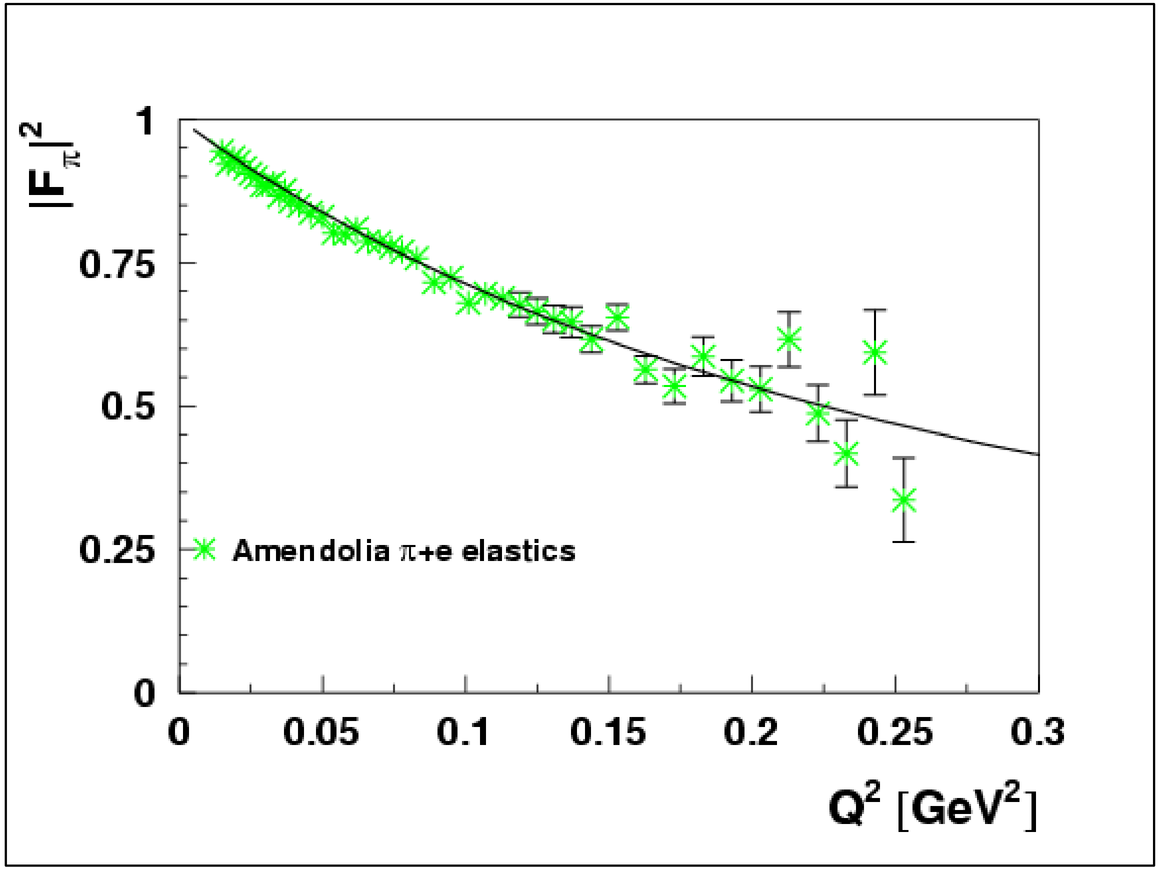
At low Q^2, F_π can be measured model–independently via high energy elastic π^- scattering from atomic electrons in Hydrogen

- CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV^2 *[Amendolia, et al., NPB **277**(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 – Higher Q^2

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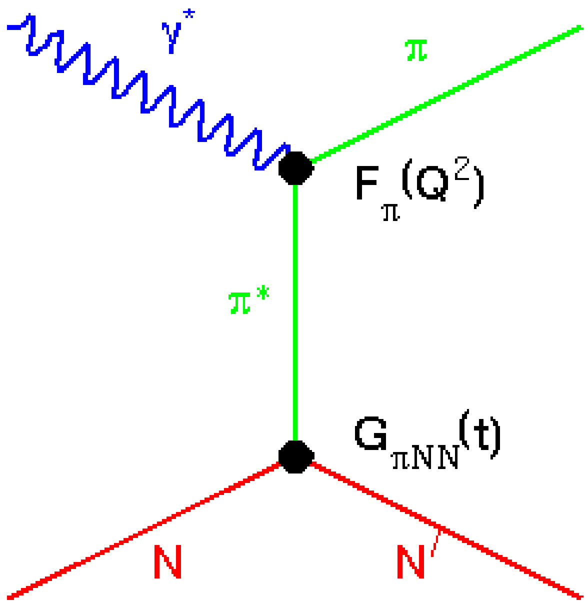
At larger Q^2, F_π must be measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e,e'\pi^+)n$

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

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

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



Drawbacks of this technique

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

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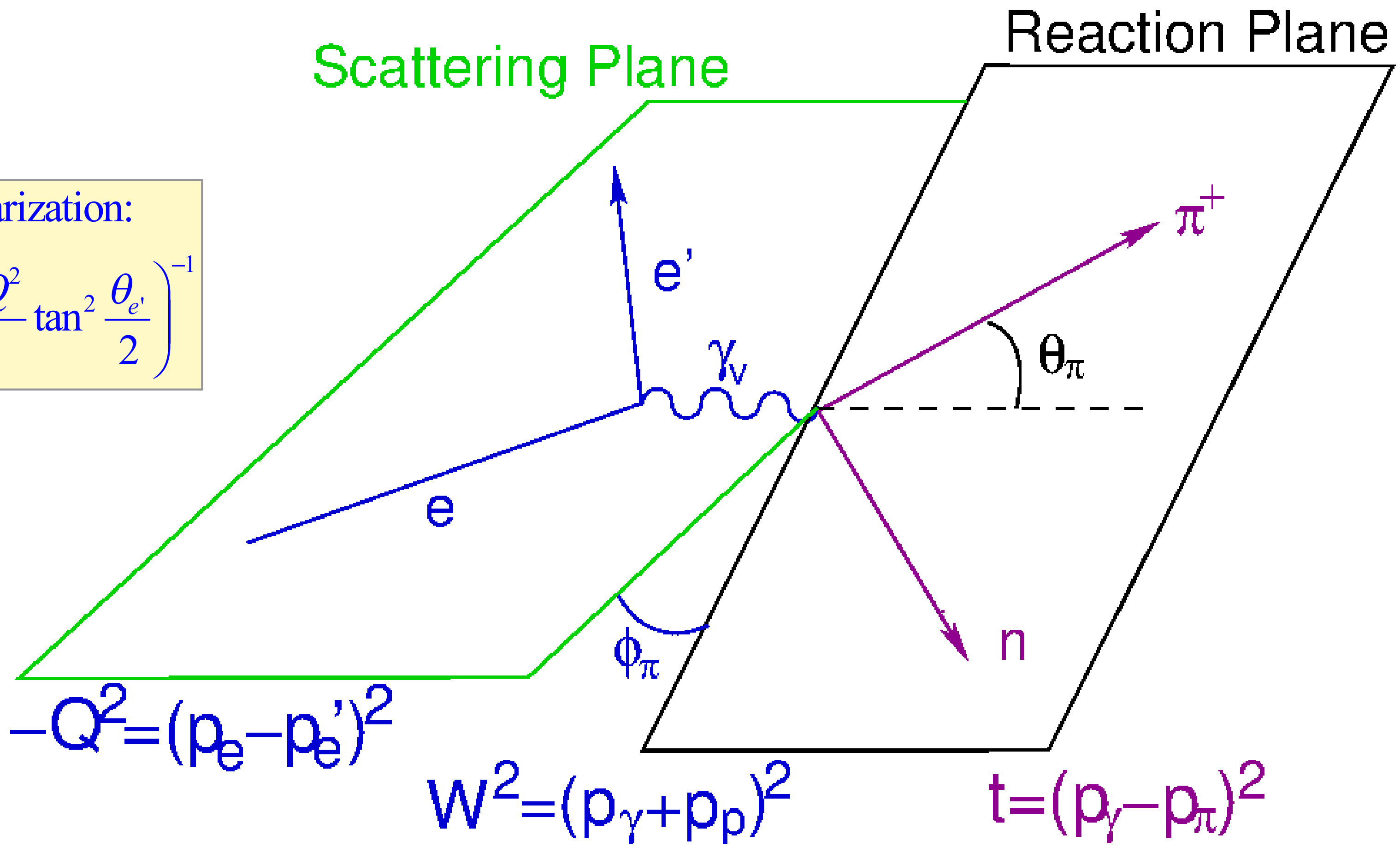
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

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.
- Need to take data at smallest available $-t$, so σ_L has maximum contribution from the π^+ pole.

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L/T–separation error propagation

Error in $d\sigma_L/dt$ is magnified by $1/\Delta\varepsilon$

→ To keep magnification factor <5x, need Δε>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 $\Delta\varepsilon$

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

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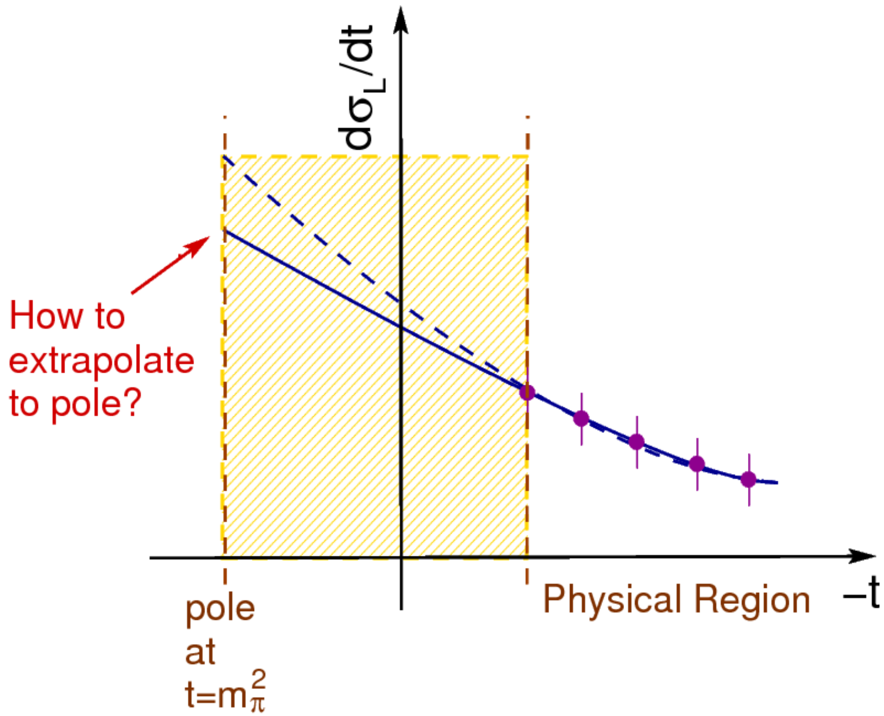
p(e,e'π^+)n **data are obtained some distance from the** ***t=m_π^2*** **pole.**

→ "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_π^2*



The Chew–Low Method was subsequently abandoned

Only reliable approach is to use a model incorporating the π^+ production mechanism and the `spectator' nucleon to **extract** F_π from σ_L

- JLab F_π experiments have used the Vanderhaeghen-Guidal-Laget (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]*

- **More models would allow a better understanding of the model dependence of the F_π result.**
- Some recent model developments, more are welcome!
  - *R.J. Perry, A. Kizilersu, A.W. Thomas, PLB* ***807****(2020)135581*
  - *T.K. Choi, K.J. Kong, B.G. Yu, J.Kor.Phy.Soc.* ***67****(2015) L1089; arXiv: 1508.00969*
  - *T. Vrancx, J. Ryckebusch, PRC* ***89****(2014)025203*

Our philosophy remains to publish our experimentally measured $d\sigma_L/dt$, so that updated values of $F_\pi(Q^2)$ can be extracted as better models become available.

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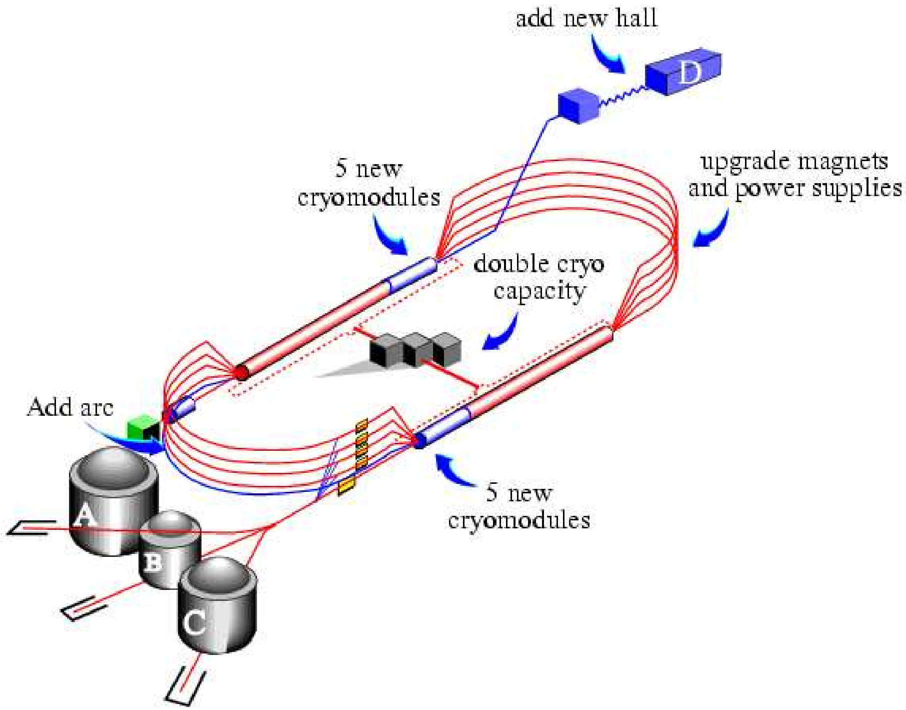


Two 1.5 GHz Superconducting Linear Accelerators provide electron beam for Nucleon & Nuclear structure studies.

- **Beam energy E → 12 GeV.**
- **Beam current >100 μA.**
- **Duty factor 100%, 85% polarization.**
- Experiments in all 4 Halls can receive beam simultaneously.

JLab Hall C – 12 GeV Upgrade

SHMS:
- 11 GeV/c Spectrometer
- Partner of existing 7 GeV/c **HMS**

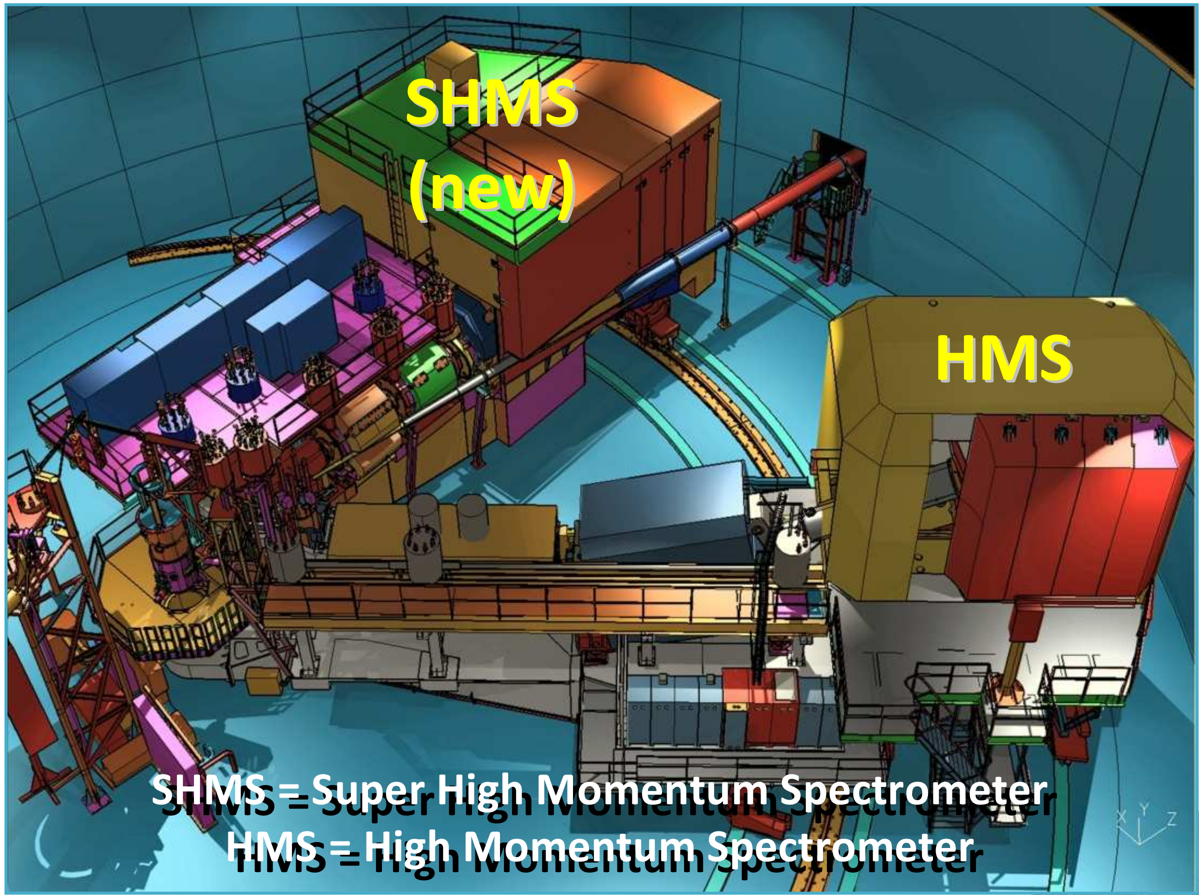
MAGNETIC OPTICS:
- Point-to Point QQQD for easy calibration and wide acceptance.
- Horizontal bend magnet allows acceptance at forward angles (5.5°)

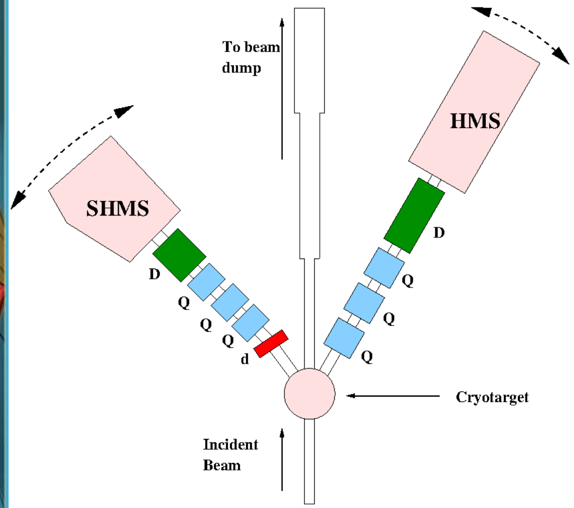
Detector Package:
- Drift Chambers
- Hodoscopes
- Cerenkovs
- Calorimeter

Well-Shielded Detector Enclosure

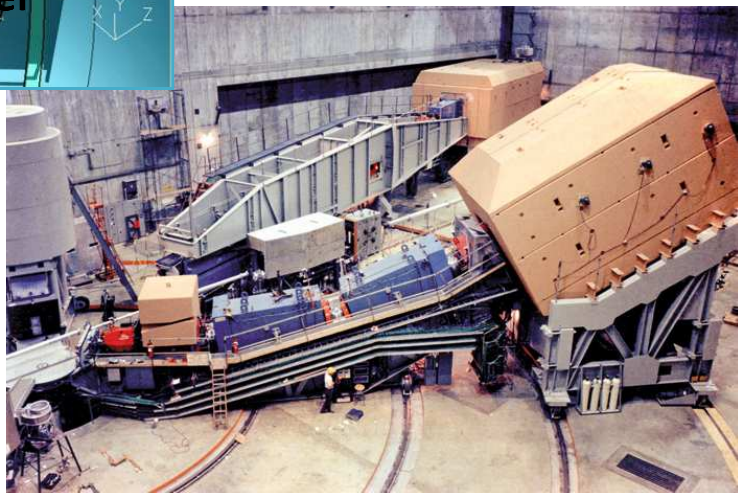
Rigid Support Structure
- Rapid & Remote Rotation
- Provides Pointing Accuracy & Reproducibility demonstrated in HMS

Luminosity
- ~4x10^{38} cm^{-2} s^{-1}



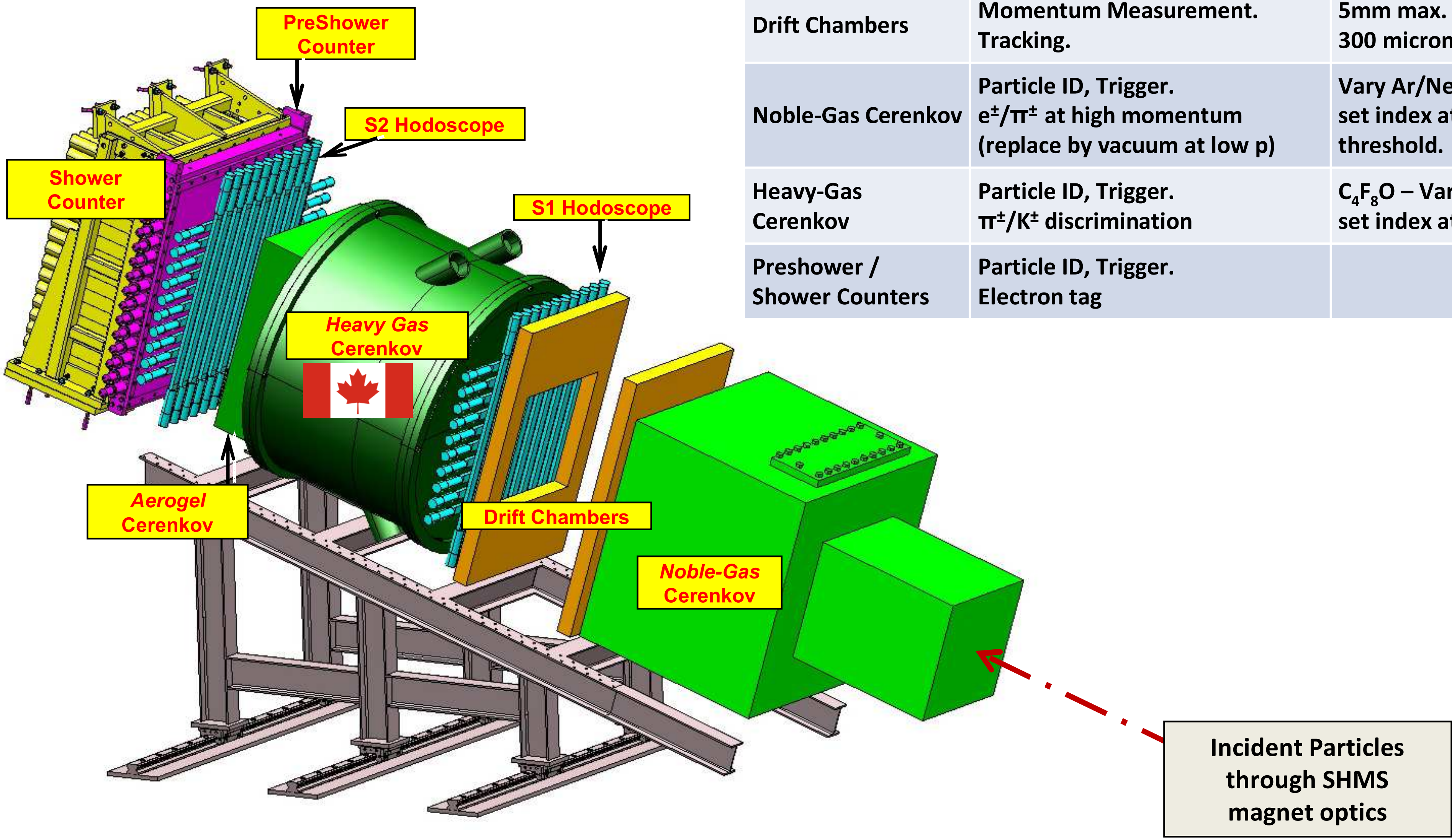


Upgraded Hall C has some similarity to SLAC End Station A, where the quark substructure of proton was discovered in 1968.



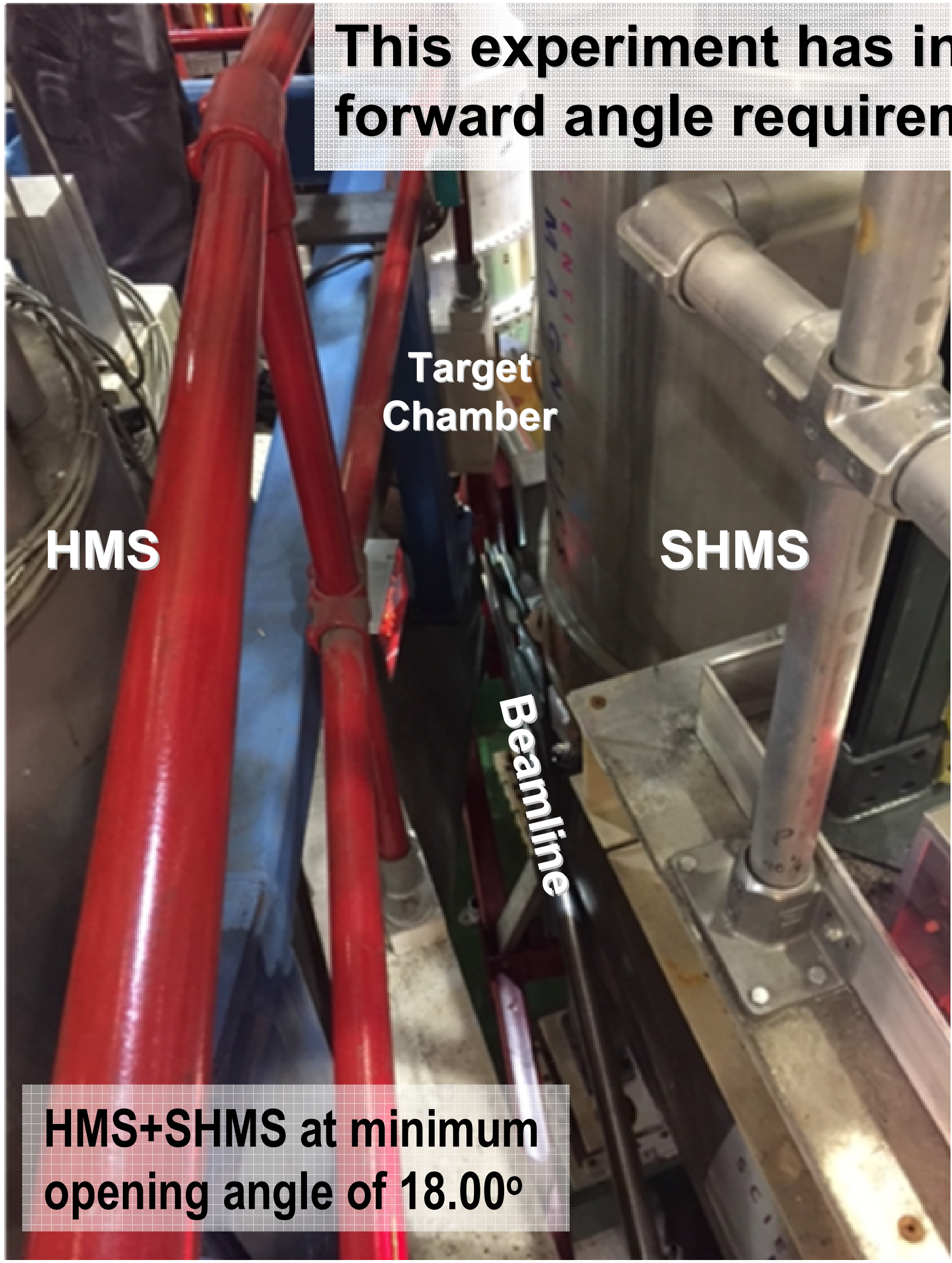
SHMS Focal Plane Detector System

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	



HMS and SHMS during Data Taking

This experiment has in large part driven the forward angle requirements of the SHMS+HMS



HMS+SHMS at minimum opening angle of 18.00^{o}

SHMS at 5.69^{o}

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

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Coincidence measurement between charged pions in SHMS and electrons in HMS.

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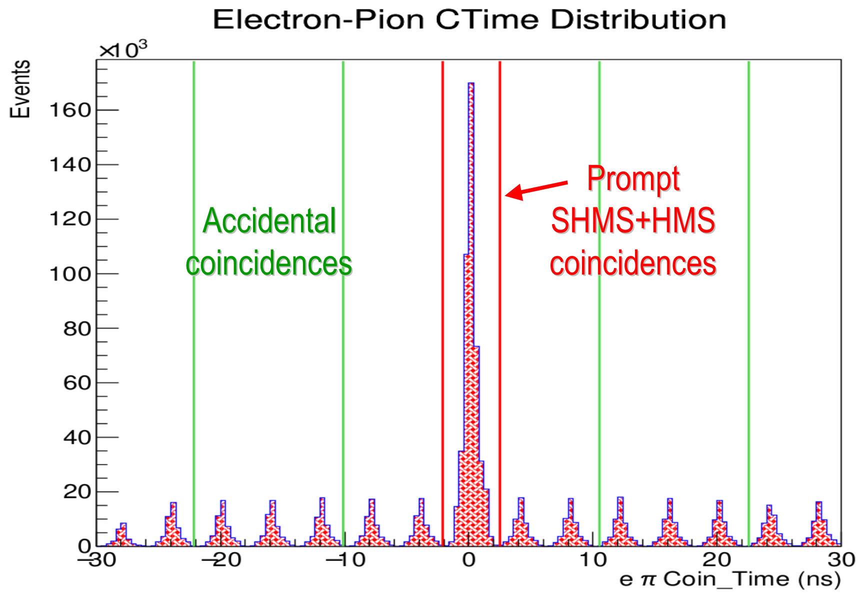
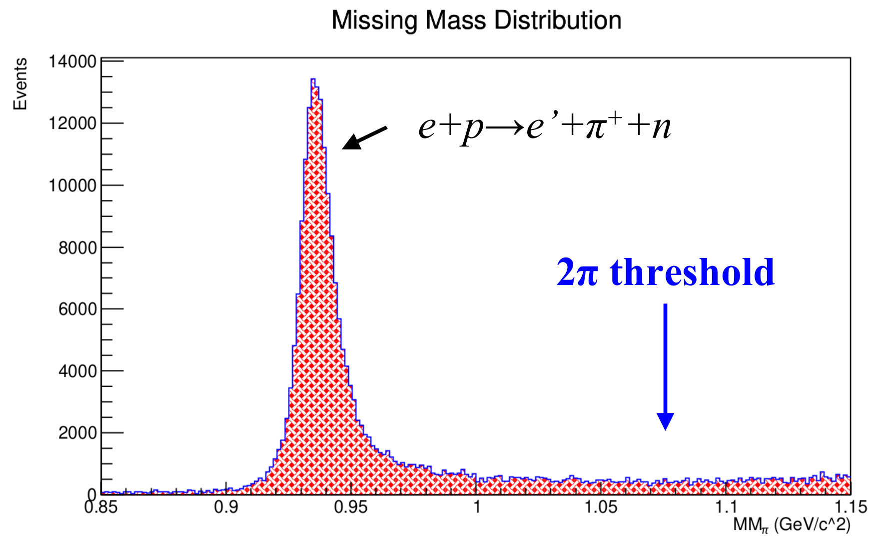
Easy to isolate exclusive channel

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





PionLT experiment E12–19–006 Data

Q^2=1.60, W=3.08, x= 0.157, ε=0.685

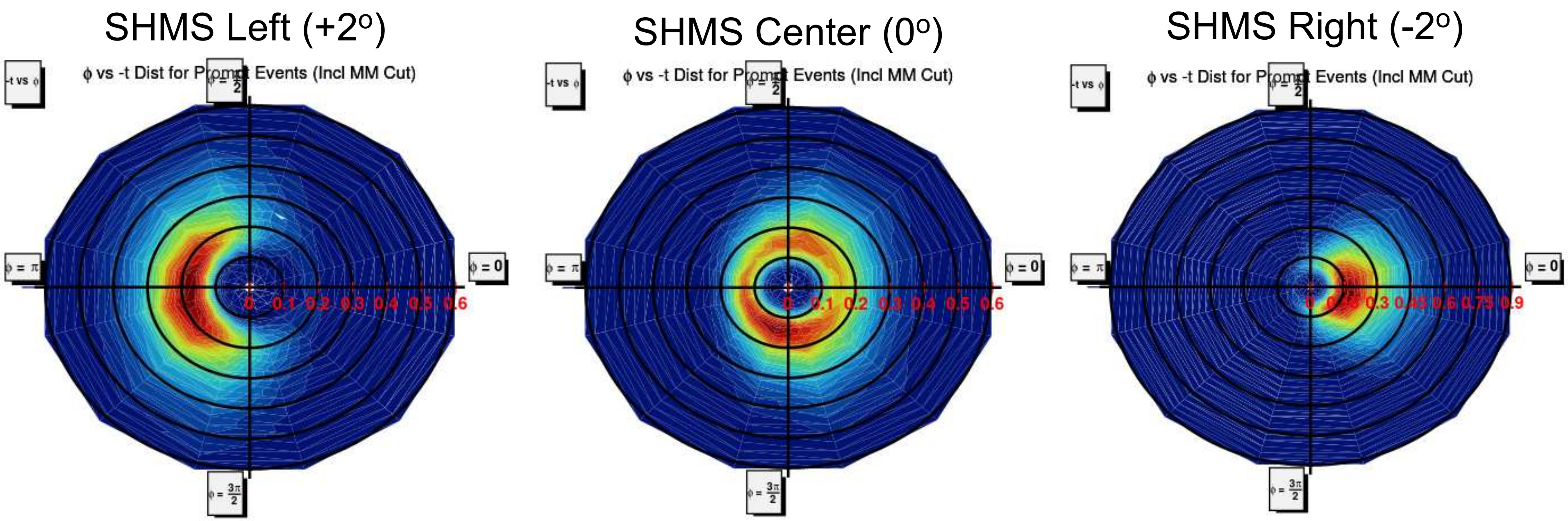
E_{beam}=9.177 GeV, P_{SHMS}=+5.422 GeV/c, θ_{SHMS}= 10.26° (left)

Plots by Muhammad Junaid (Regina PhD student)

PionLT (E12–19–006) t–φ Coverage

- Measure σ_{LT}, σ_{TT} by taking data at three pion spectrometer (SHMS) angles, +2°, 0°, -2°, with respect to *q*–vector

Example t–φ plots from: Q^2=3.85, W=3.07, High ε



Plots by Nathan Heinrich (Regina PhD student)

- To control systematics, an excellent understanding of spectrometer acceptances is required
  - Over–constrained *p(e,e'p)* reaction, and inelastic e+^{12}C, used to calibrated spectrometer acceptances, momenta, kinematic offsets, efficiencies.
  - Control of point–to–point systematic uncertainties crucial due to 1/Δε error amplification in σ_L

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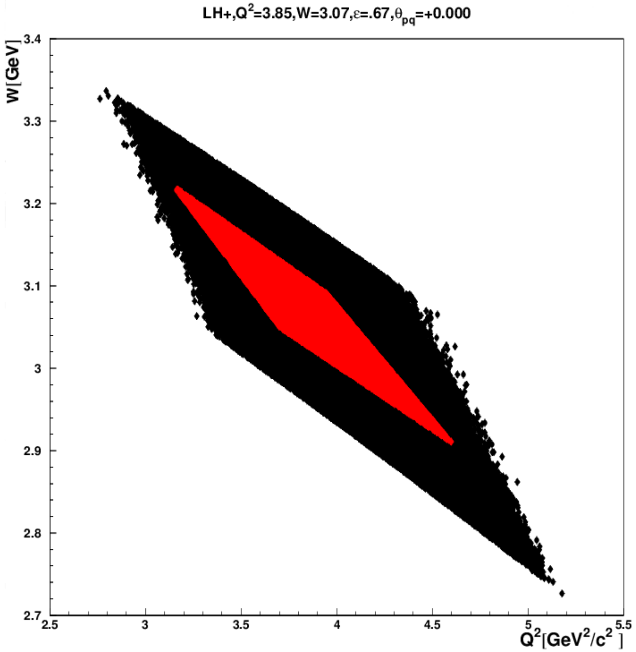
The different pion arm (SHMS) settings are combined to yield φ-distributions for each *t*-bin

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

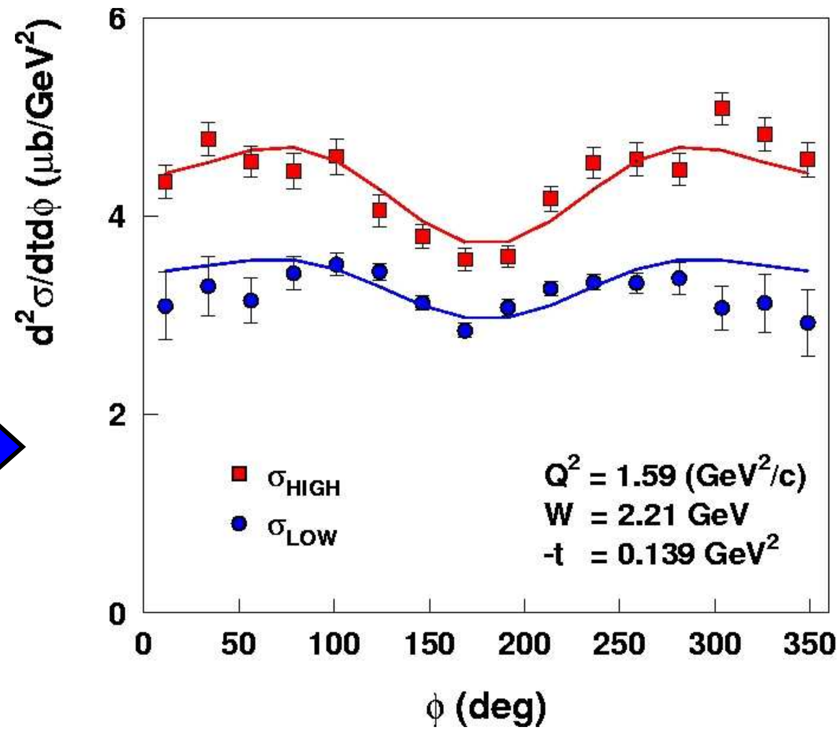


Diamond cuts define common (W,Q^2) coverage at both ε

Simulated SHMS+HMS acceptance at Q^2=3.85, W=3.07

■ High ε=0.67 ■ Low ε=0.30

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



Fπ-2 data: T. Horn, *et al*, PRL **97** (2006)192001

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Extract $F_\pi(Q^2)$ from JLab σ_L data

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Model incorporates π^+ production mechanism and spectator neutron effects:

VGL Regge Model:

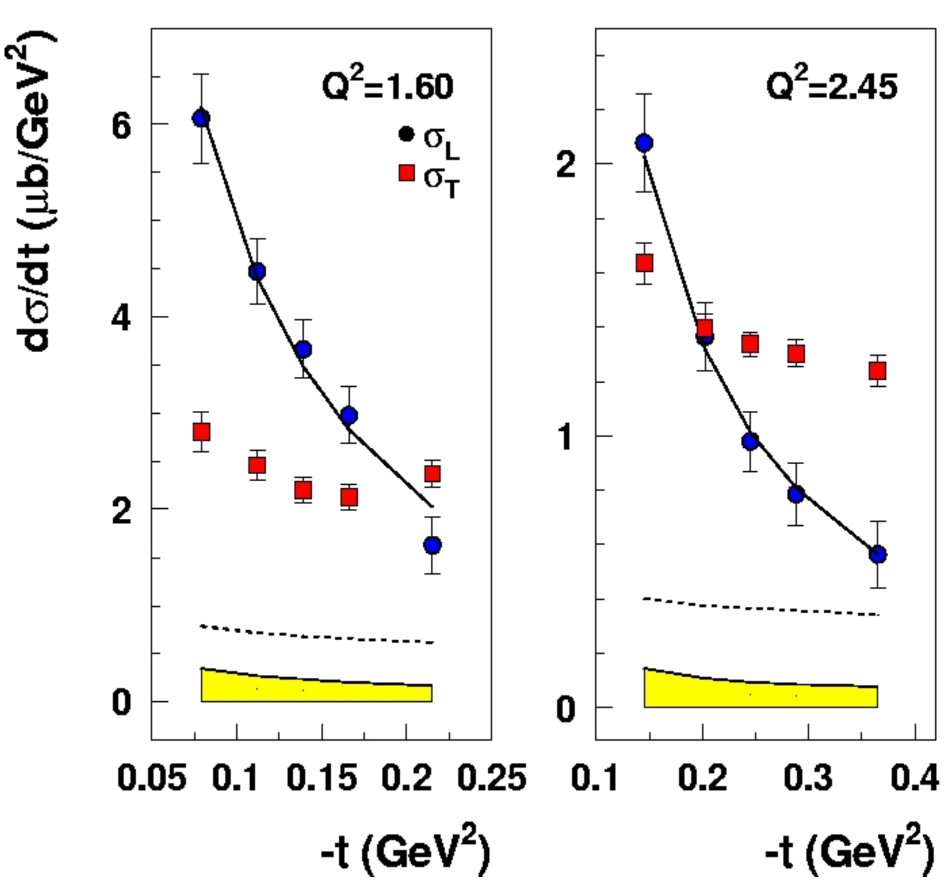
- Feynman propagator $\left(\frac{1}{t - m_\pi^2}\right)$

  replaced by π and ρ Regge propagators.
  - Represents the exchange of a series of particles, compared to a single particle.
- Free parameters: Λ_π, Λ_ρ (trajectory cutoff).

  [Vanderhaeghen, Guidal, Laget, PRC **57**(1998)1454]
- At small $-t$, σ_L only sensitive to F_π

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

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



Fπ-2 data: T. Horn et al., PRL **97**(2006)192001.

Error bars indicate statistical and random (pt-pt) systematic uncertainties in quadrature.
Yellow band indicates the correlated (scale) and partly correlated (t-corr) systematic uncertainties.

Λ_π^2=0.513, 0.491 GeV^2, Λ_ρ^2=1.7 GeV^2.

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Current Experimental Status

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pQCD LO+NLO Calculation:

Analytic perturbation theory at the parton amplitude level.

*A.P. Bakulev, K. Passek-Kumericki, W. Schroers, & N.G. Stefanis, PRD **70** (2004) 033014.*

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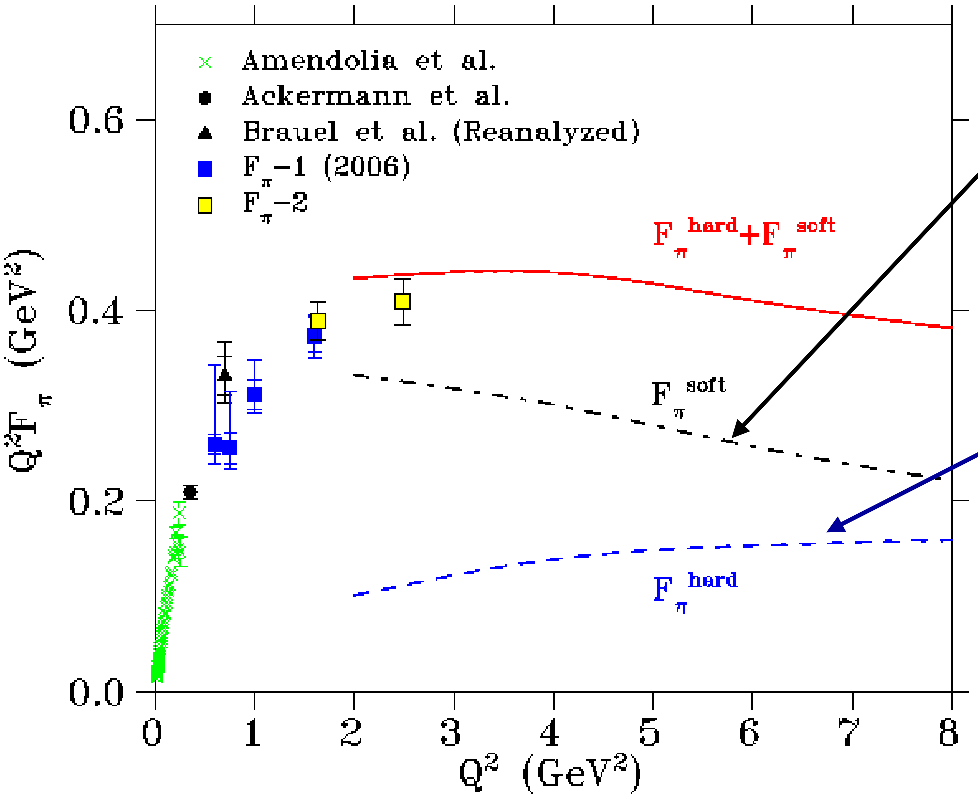

For details: G.M. Huber et al., PRC **78** (2008) 045203.

SOFT QCD:
- Extra piece needed to describe data.
- Estimated from local quark-hadron duality model.
- Consistent with DCSB expectations.

HARD QCD: pQCD LO+NLO

- JLab 6 GeV F_π results are far from the values predicted by pQCD.
- At the distance scales probed by the experiment (0.15<r<0.30 fm), the π^+ structure is not governed by the two valence quarks.
- Virtual quarks and gluons dominate.

Model / Intepretation Issues

- A common criticism of the electroproduction technique is the difficulty to be certain one is measuring the "physical" form factor.

> "What is at best measured in electroproduction is the transition amplitude between a mesonic state with an effective space-like mass $m^2=t<0$ and the physical pion. It is theoretically possible that the off-shell form factor $F_\pi(Q^2,t)$ is significantly larger than the physical form factor because of its bias towards more point-like $q\bar{q}$ valence configurations within its Fock state structure." --S.J. Brodsky, Handbook of QCD, 2001.

- What tests/studies can we do to give confidence in the result?
  - 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 π^+e elastic scattering at same Q^2.

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Check of Pion Electroproduction Technique

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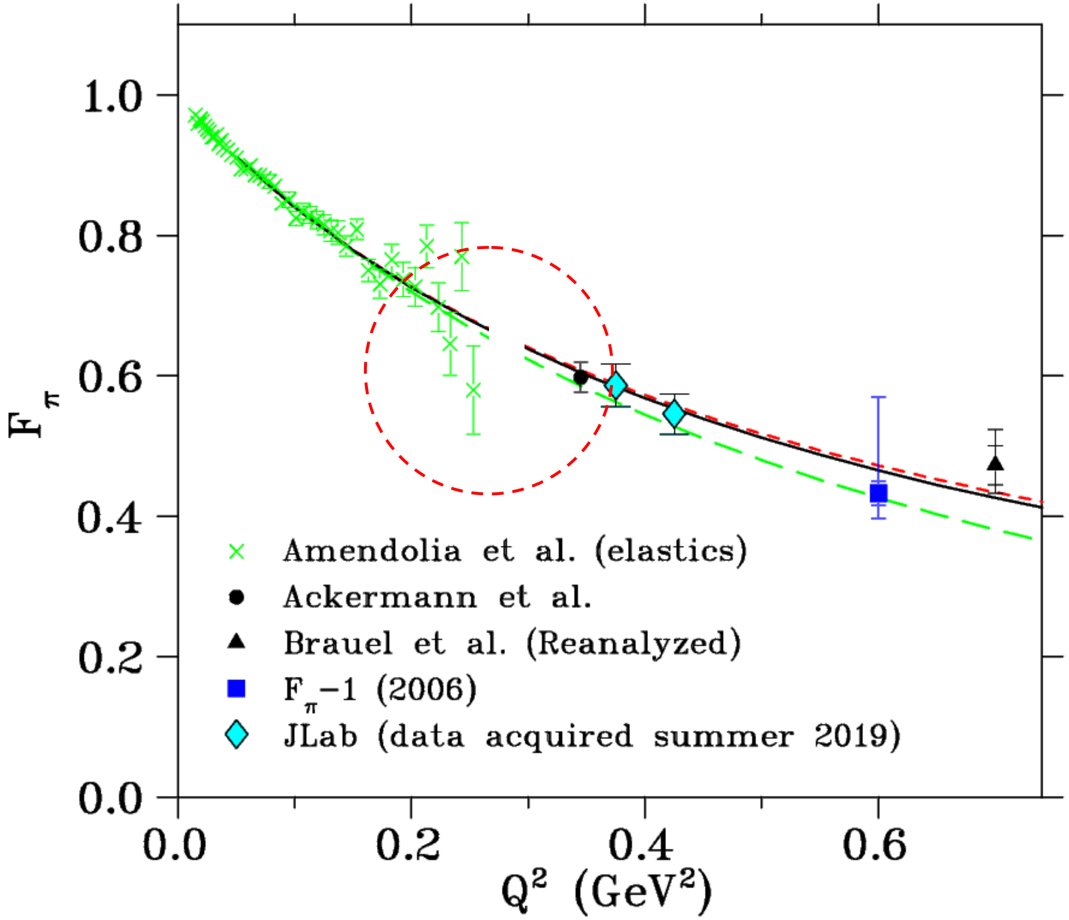
- Does electroproduction really measure the on–shell form–factor?
- Test by making $p(e,e'\pi^+)n$ measurements at same kinematics as π^+e elastics.
- ***Can't quite reach the same Q^2, but electro–production appears consistent with extrapolated elastic data.***



Data for new test acquired in Summer 2019:

- **small Q^2 (0.375, 0.425) competitive with DESY Q^2=0.35**
- **$-t$ closer to pole (=*0.008* GeV^2) vs. DESY 0.013**

A similar test for K^+ form factor is part of Kaon–LT

Verify that σ_L is dominated by t-channel process

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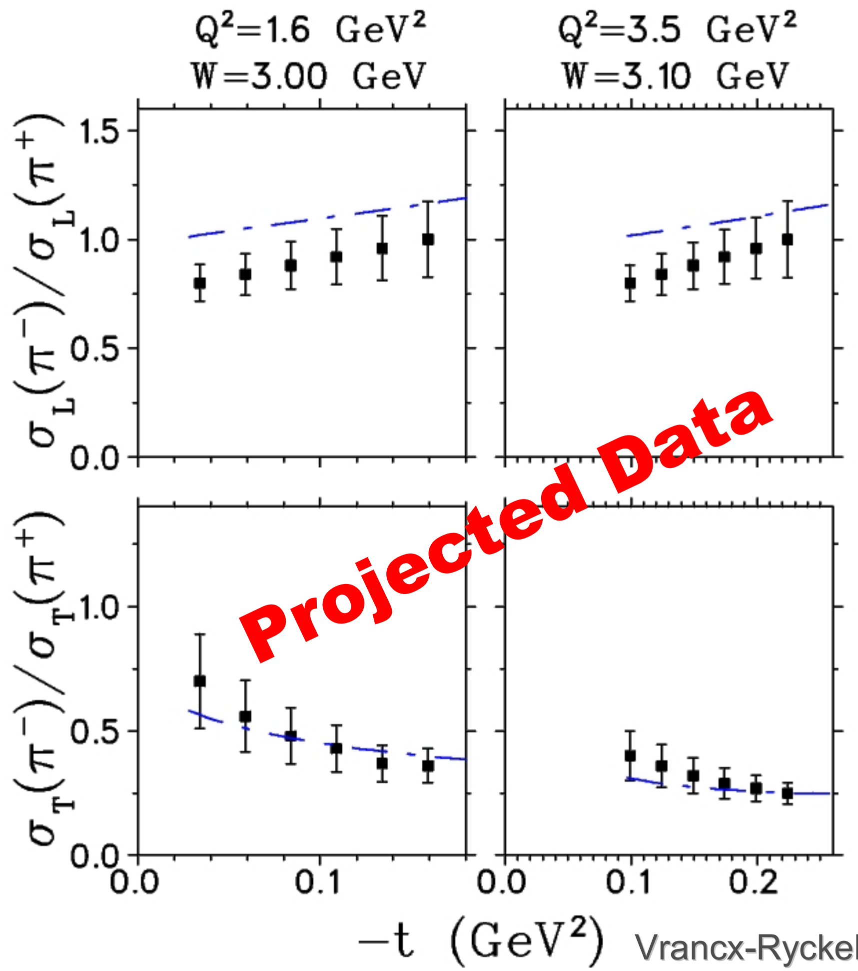
- π^+ t-channel diagram is purely isovector.
- Measure

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

using a deuterium target.

- Isoscalar backgrounds (such as $b_1(1235)$ contributions to the t-channel) will dilute the ratio.
- We will do the same tests at Q^2=1.60, 3.85, 6.0 GeV^2.



Vrancx-Ryckebusch Regge+DIS Model
[PRC **89**(2014)025203]

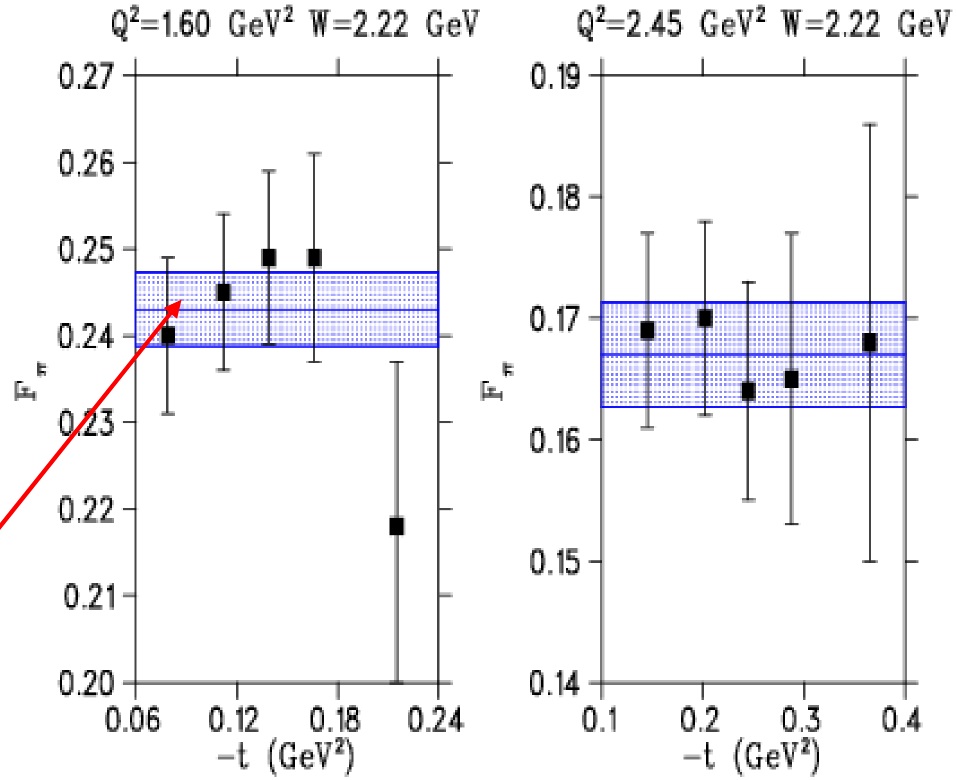
Because one of the many problems encountered by the historical data was isoscalar contamination, this test will increase the confidence in the extraction of $F_\pi(Q^2)$ from our σ_L data.

Fπ–2 VGL $p(e,e'\pi^+)n$ model check

- To check whether VGL Regge model properly accounts for:
  - π^+ production mechanism.
  - spectator nucleon.
  - other off–shell (*t*–dependent) effects.

  extract F_π values for each *t*–bin separately, instead of one value from fit to all *t*–bins.

Error band based on fit to all *t*-bins.



Fπ-2 data: G.M. Huber, et al., PRC **78** (2008) 045203

Only statistical and t–uncorrelated systematic uncertainties shown

- Deficiencies in model may show up as *t*–dependence in extracted $F_\pi(Q^2)$ values.
- Resulting F_π values are insensitive (<2%) to *t*–bin used.
- Lends confidence in applicability of VGL model to the kinematical regime of the JLab data, and the validity of the extracted $F_\pi(Q^2)$ values.

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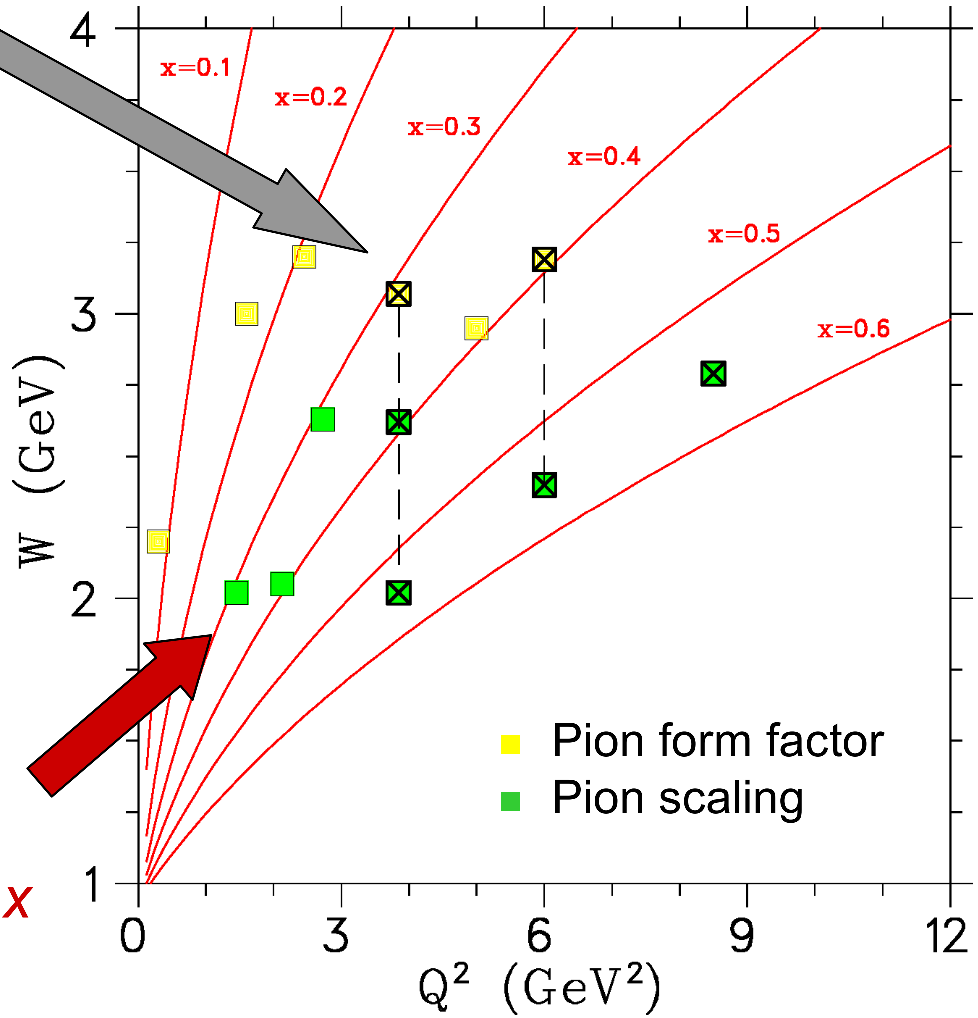
E12–19–006 Optimized Run Plan

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

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



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

For more details, visit Pion-LT RedMine: https://redmine.jlab.org/projects/hall-c/wiki/

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Current and Projected F_π Data

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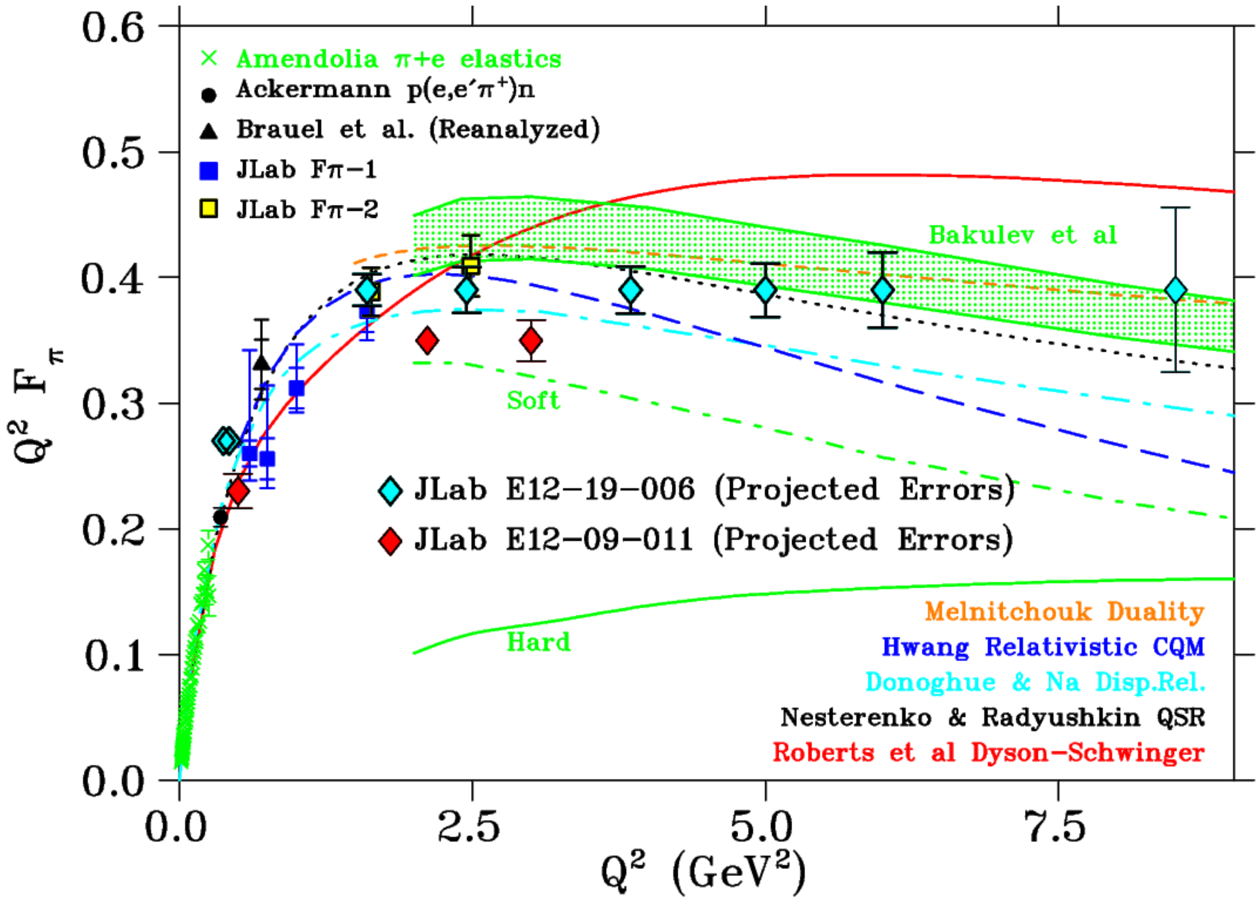
SHMS+HMS will allow measurement of F_π to much higher Q^2

No other facility worldwide can perform this measurement

Data taking completed September 2022 (E12–19–006: G. Huber, 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.

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Summary

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- Higher Q^2 data on the pion form factor are vital to our better understanding of hadronic physics
  - Pion properties are intimately connected with dynamical chiral symmetry breaking (DCSB), which explains the origin of more than 98% of the mass of visible matter in the universe
  - F_π is our best hope to directly observe QCD's transition from confinement-dominated physics at large length–scales to perturbative QCD at short length-scales
- New experimental capabilities:
  - PionLT (E19–12–006) has for the first time, since the pioneering measurements at Cornell in 1970's, acquired the high quality data needed to test these theoretical developments with authority
  - Expect first results in ~2 years

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BACKUP SLIDES

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Implications for Pion Structure

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Craig Roberts (2016): ***"No understanding of confinement within the Standard Model is practically relevant unless it also explains the connection between confinement and DCSB, and therefore the existence and role of pions."***

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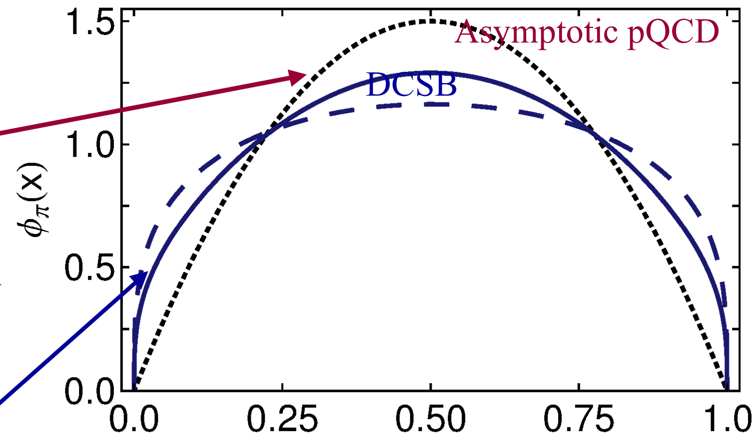
- For the pCQD derivation on slide #13, the normalization for F_π has been based on the conformal limit of the pion's twist–2 PDA.

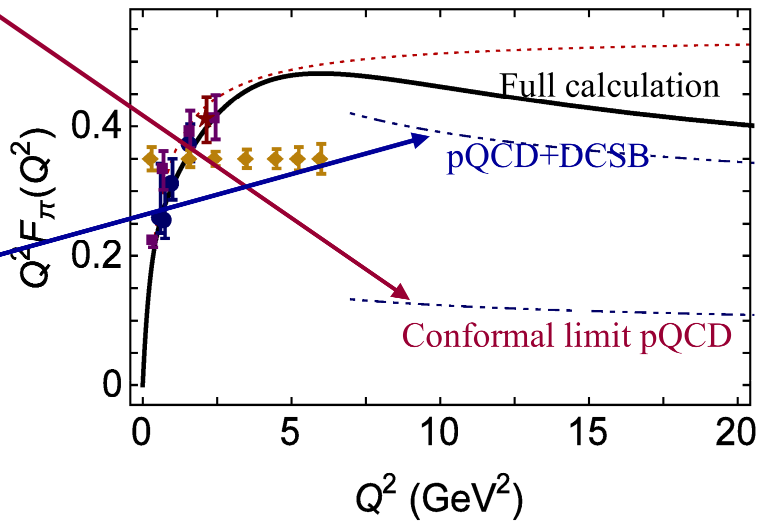
$$\phi_\pi^{cl}(x) = 6x(1-x)$$

- This leads to "too small" F_π values in comparison with present & projected JLab data.
- Recent works incorporating DCSB effects indicate that at experimentally accessible energy scales the actual pion PDA is broader, concave function, close to

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

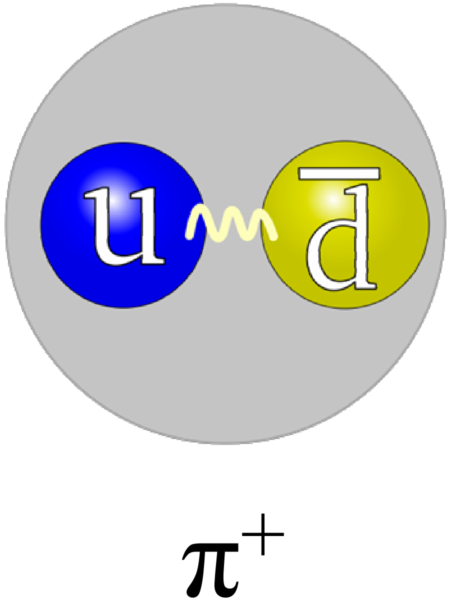
- Simply inputting this $\varphi_\pi(x)$ into the pQCD expression for F_π brings the calculation much closer to the data.
- **Underestimates full computation by ~15% for $Q^2 \geq 8$ GeV^2. Addresses issue raised in 1977.**

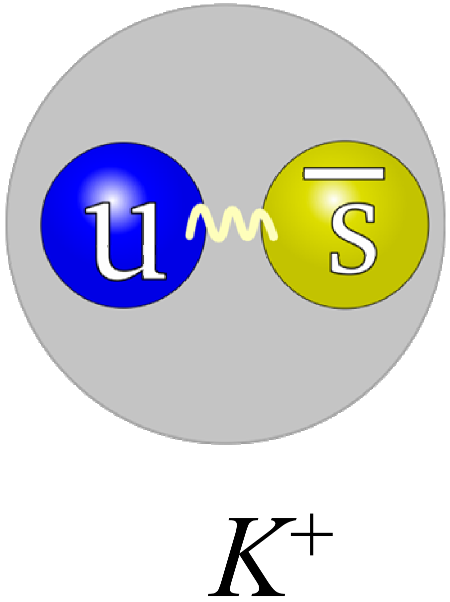




L. Chang, et al., PRL **110** (2013) 132001; **111** (2013) 141802.

The Charged Kaon – a 2nd QCD test case





- In the hard scattering limit, pQCD predicts that the π^+ and K^+ form factors will behave similarly

$$\frac{F_K(Q^2)}{F_\pi(Q^2)} \underset{Q^2\to\infty}{\longrightarrow} \frac{f_K^2}{f_\pi^{\ 2}}$$

- It is important to compare the magnitudes and Q^2–dependences of both form factors.

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K^+ properties also strongly influenced by DCSB

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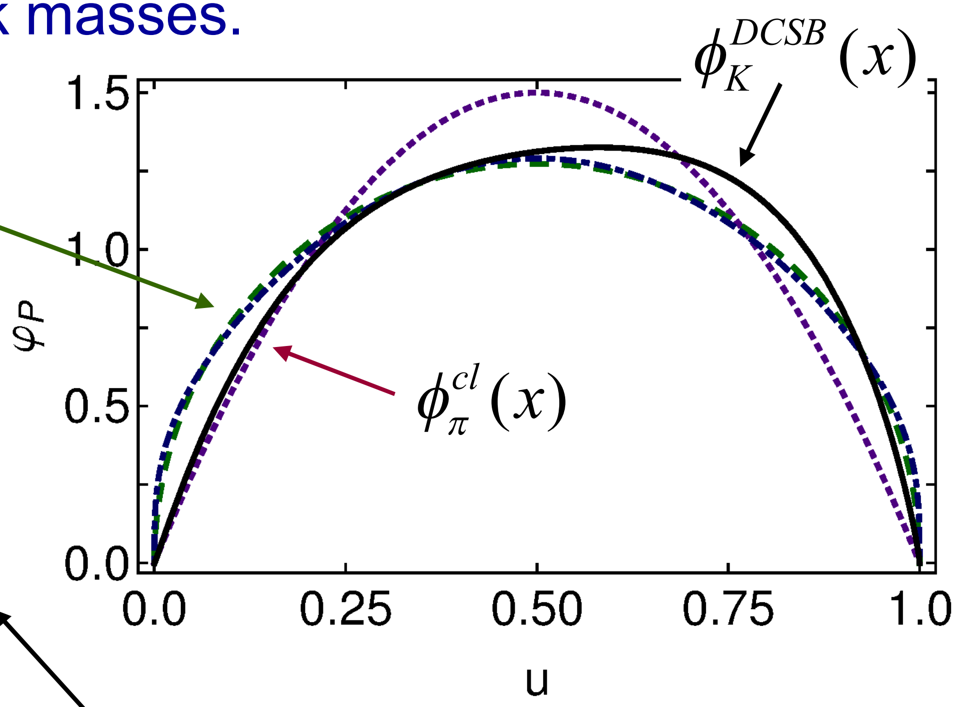
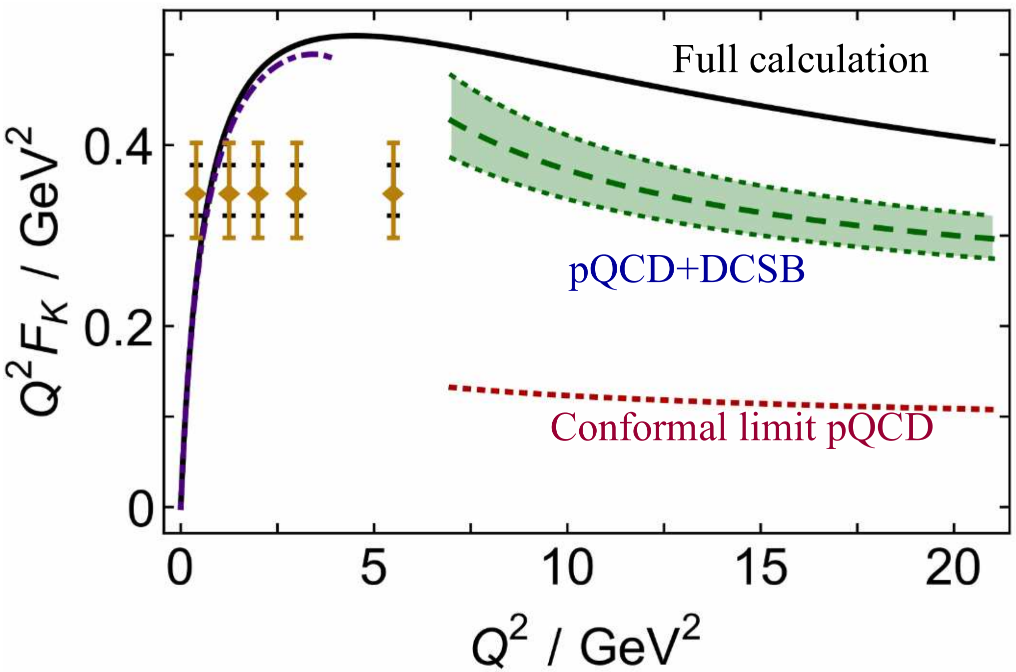
- ***K⁺* PDA also is broad, concave and asymmetric.**
- While the heavier s quark carries more bound state momentum than the u quark, the shift is markedly less than one might naively expect based on the difference of u, s current quark masses.
  [C. Shi, et al., PRD **92** (2015) 014035].





- ***F_K* DCSB model prediction for JLab kinematics**
  [F. Guo, et al., arXiv: 1703.04875].

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The pion is the "positronium atom" of QCD, its form factor is a test case for most model calculations

- **What is the structure of the π^+ at all Q^2?**
  - at what value of Q^2 will the pQCD contributions dominate?
- A difficult question to answer, as both "hard" and "soft" components (such as gluonic effects) must be taken into account.
  - non–perturbative hard components of higher twist strongly cancel soft components, even at modest Q^2.
    [Braun et al., PRD ***61****(2000)073004]*
  - the situation for nucleon form factors is even more complicated.
- **Many model calculations exist, but ultimately...**
  - **Reliable $F_\pi(Q^2)$ data are needed to delineate the role of hard versus soft contributions at intermediate Q^2.**
- **A program of study unique to Jefferson Lab** (until the completion of the EIC)

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Chew–Low Method Check with PseudoData

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Plot $$F^2 = \frac{N}{4\hbar c(eg_{\pi NN})^2}\frac{(t-m_\pi^2)^2}{-Q^2 m_\pi^2}\frac{d\sigma_L}{dt}$$ **vs. –*t***

- Pure pole cross section gives straight line through origin, with value $F_\pi^2(Q^2)$ at pole.
- **Other contributions introduce non–linearities since don't contain $(t-m_\pi)^2$ factor, but don't influence F^2 value at pole**

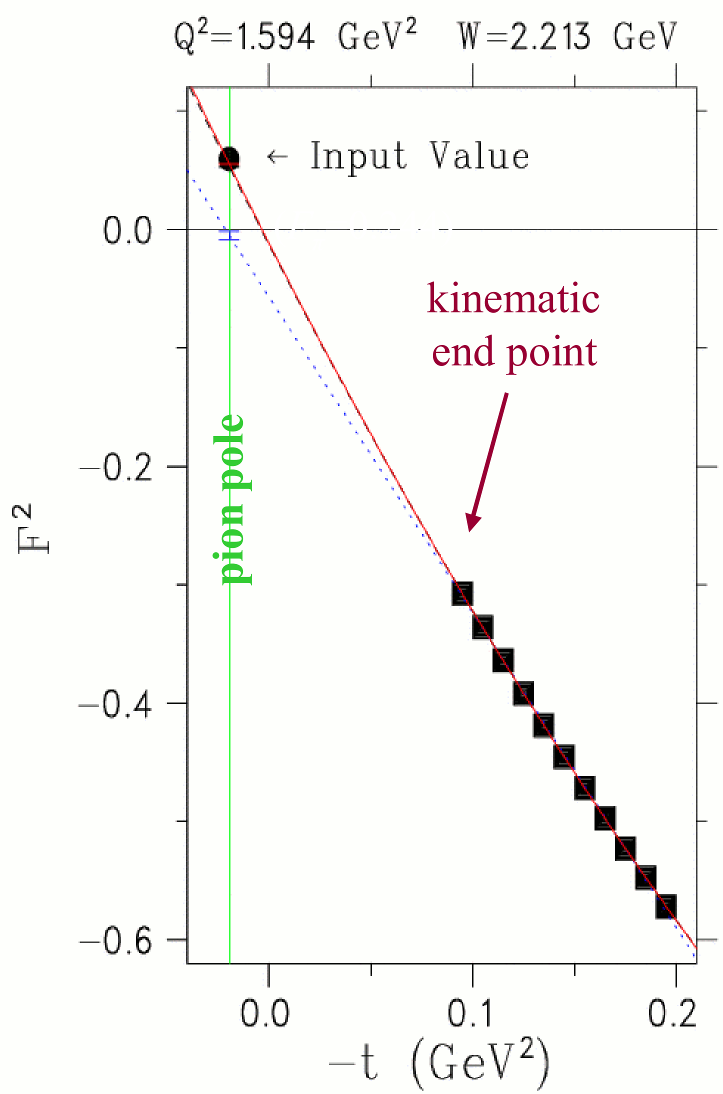
  → Do not know if behavior of F^2 with $-t$ is linear, quadratic, or higher order

All fits missed the input F_π

→ no consistent trend on order of polynomial best able to reproduce input value (6-15% deviation, Q^2=0.6–2.45 GeV^2)

- Experimental data have only 4–6 *t*-bins and statistical and systematic uncertainties of 5–10%

  → Extrapolation with real data will be even more uncertain



For details see: G.M. Huber et al., PRC 78(2008)045203.

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Magnetic Spectrometer Calibrations

- **Similarly to Fπ-2, we use the over-constrained *p(e,e'p)* reaction and inelastic $e+^{12}C$ in the DIS region to calibrate spectrometer acceptances, momenta, offsets, etc.**
  - Fπ-2 beam energy and spectrometer momenta determined to <0.1%.
  - Spectrometer angles <0.5 mr.
  - Fπ-2 agreement with published $p+e$ elastics cross sections <2%.

Uncertainties from F_π Proposal (E12–06–101)

Projected Systematic Uncertainty Source	Pt-Pt ε-random t-random	ε-uncorrelated common to all t-bins	Scale ε-global t-global
Spectrometer Acceptance	0.4%	0.4%	1.0%
Target Thickness		0.2%	0.8%
Beam Charge	-	0.2%	0.5%
HMS+SHMS Tracking	0.1%	0.4%	1.5%
Coincidence Blocking		0.2%	
PID		0.4%	
Pion Decay Correction	0.03%	-	0.5%
Pion Absorption Correction	-	0.1%	1.5%
MC Model Dependence	0.2%	1.0%	0.5%
Radiative Corrections	0.1%	0.4%	2.0%
Kinematic Offsets	0.4%	1.0%	-

- Uncorrelated uncertainties in σ_{UNS} are amplified by $1/\Delta\varepsilon$ in L/T separation.
- Scale uncertainty propagates directly into separated cross section.

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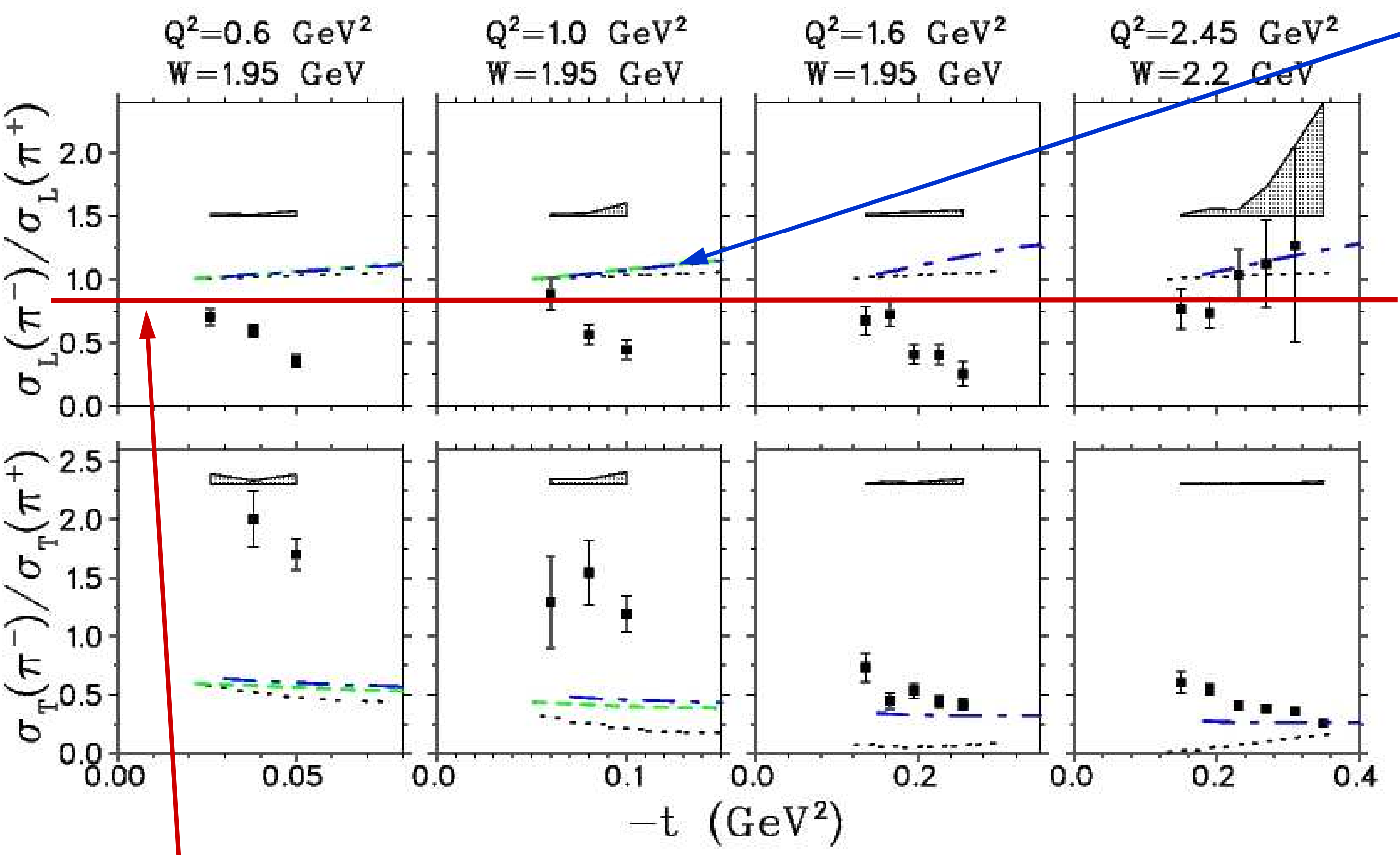
Relevance to Pion Form Factor Extraction



Vrancx–Ryckebusch Regge+DIS Model:

- VGL Regge Model underpredicts σ_T by large factor.
- VR extend Regge model with hard DIS process of virtual photons off nucleons.
- W=1.95 GeV, higher –t data described poorly.

[PRC **89**(2014)025203]

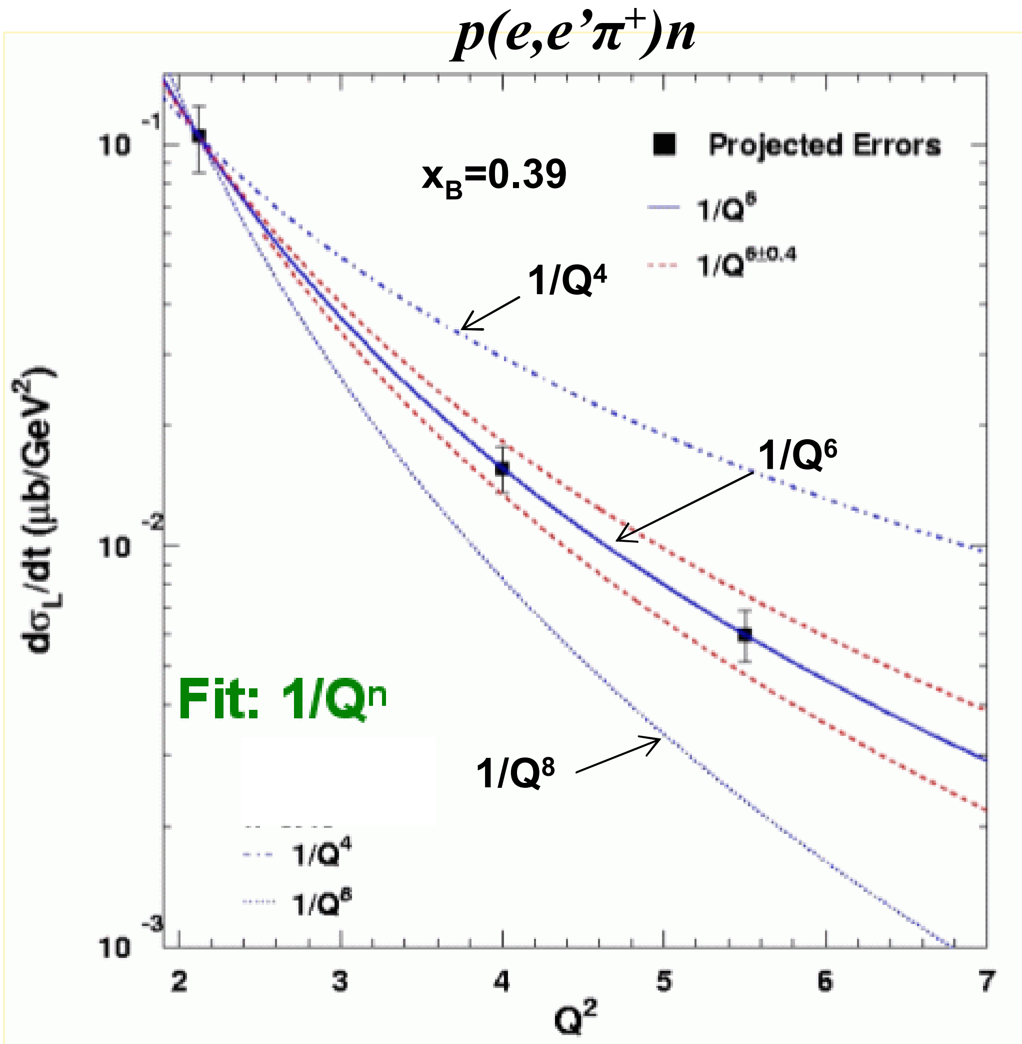
R_L=0.8 consistent with $|A_S/A_V|$<6%.

- **Qualitatively in agreement with our analysis:**
  - We found evidence for small additional contribution to σ_L at *W*=1.95 GeV not taken into account by the VGL model.
- We found little evidence for this contribution in data analysis at *W*=2.2 GeV.

$p(e,e'\pi^+)n$ Q^{-n} Hard–Soft Factorization Test

- QCD counting rules predict the Q^{-n} dependence of $p(e,e'\pi^+)n$ cross sections in Hard Scattering Regime:
  - σ_L scales to leading order as Q^{-6}.
  - σ_T scales as Q^{-8}.
  - As Q^2 becomes large: $\sigma_L >> \sigma_T$.

x	Q^2 (GeV^2)	W (GeV)	$-t_{min}$ (GeV/c)^2
0.31	1.45–3.65	2.02–3.07	0.12
0.39	2.12–6.0	2.05–3.19	0.21
0.55	3.85–8.5	2.02–2.79	0.55



- **Experimental validation of onset of hard scattering regime is essential for reliable interpretation of JLab GPD program results.**
  - If σ_L becomes large, it would allow leading twist GPDs to be studied.
  - If σ_T remains large, it could allow for transversity GPD studies.

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π^-/π^+ Hard–Soft Factorization Test

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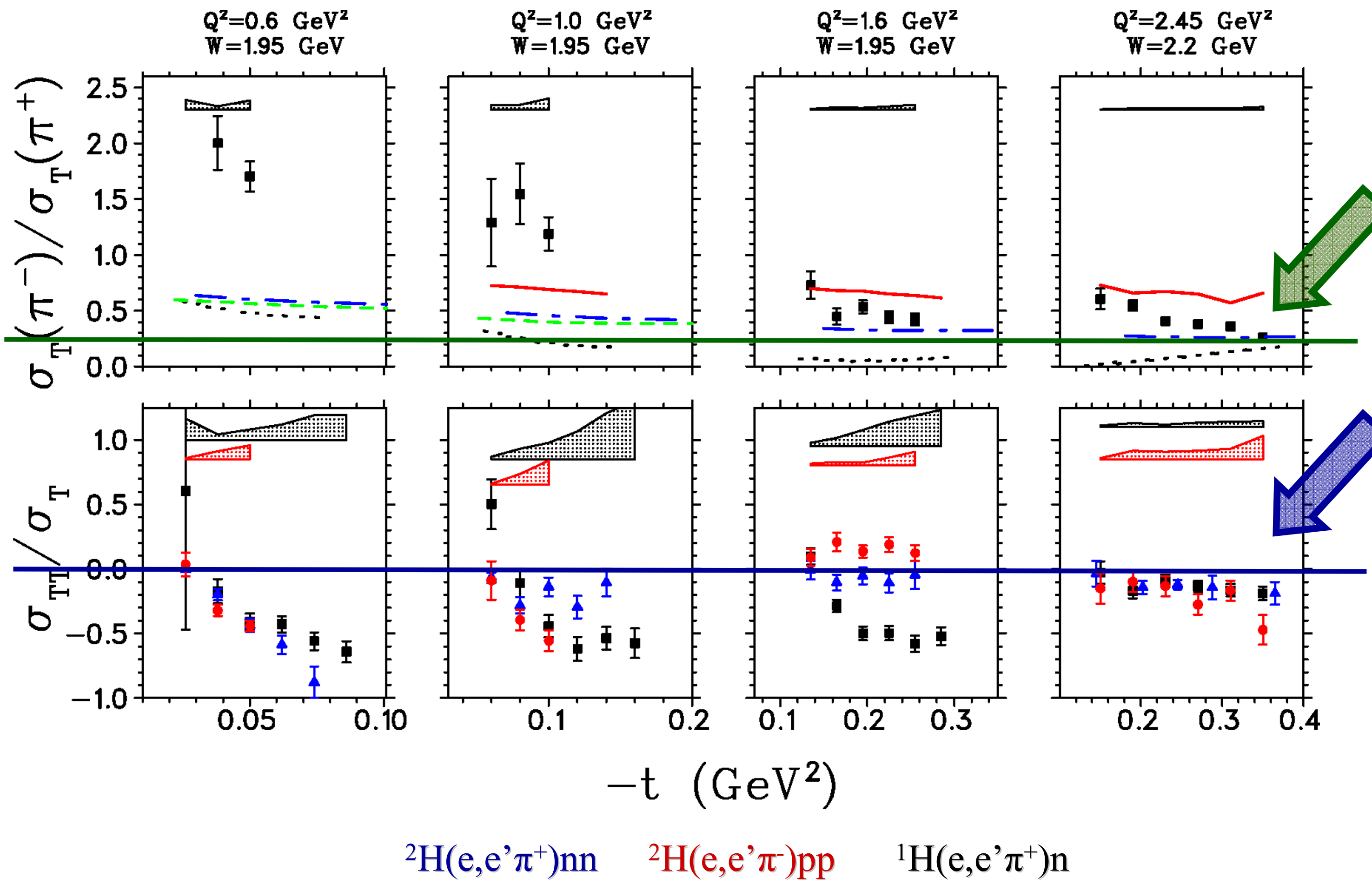
- **Transverse Ratios tend to ¼ as –*t* increases:**
  - **→ Is this an indication of Nachtmann's quark charge scaling?**
- **–*t*=0.3 GeV^2 seems too low for this to apply. Might indicate the partial cancellation of soft QCD contributions in the formation of the ratio.**

A. Nachtmann, Nucl.Phys.**B115** (1976) 61.



$$R_T \rightarrow \frac{2Q_d^2}{2Q_u^2} = \frac{1}{4}$$

- Another prediction of quark–parton mechanism is the suppression of σ_{TT}/σ_T due to *s*-channel helicity conservation.
- Data qualitatively consistent with this, since σ_{TT} decreases more rapidly than σ_T with increasing Q^2.

G.M. Huber, et al., PRC **92** (2015) 015202

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Measurement of K^+ Form Factor

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- Similar to π^+ form factor, elastic K^+ scattering from electrons used to measure charged kaon form factor at low Q^2

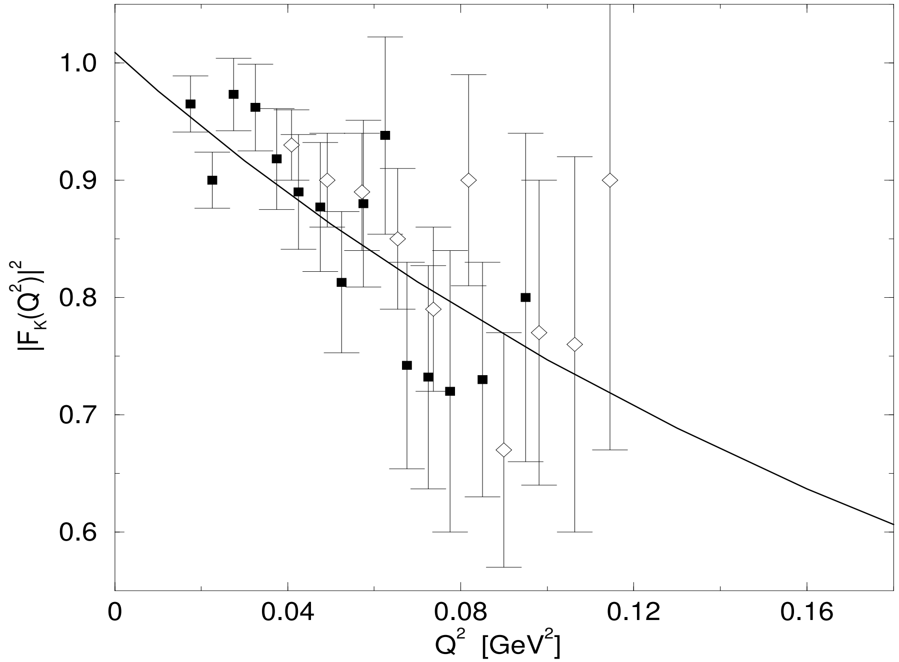
  [Amendolia, et al., PL **B178** (1986) 435]

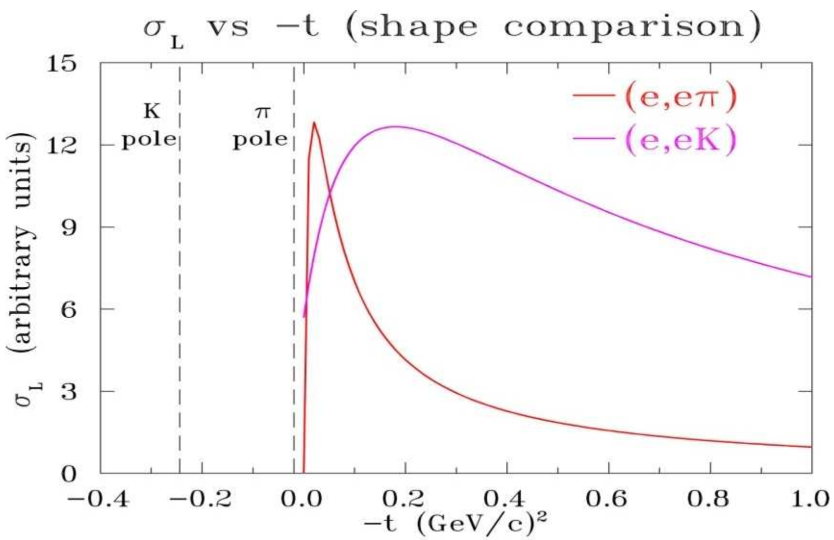
- Can "kaon cloud" of the proton be used in the same way as the pion to extract kaon form factor via ***p(e,e'K⁺)***Λ ?

- Kaon pole further from kinematically allowed region

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

- Many of these issues are being explored in JLab E12–09–011





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

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Isolate Exclusive Final States via Missing Mass

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

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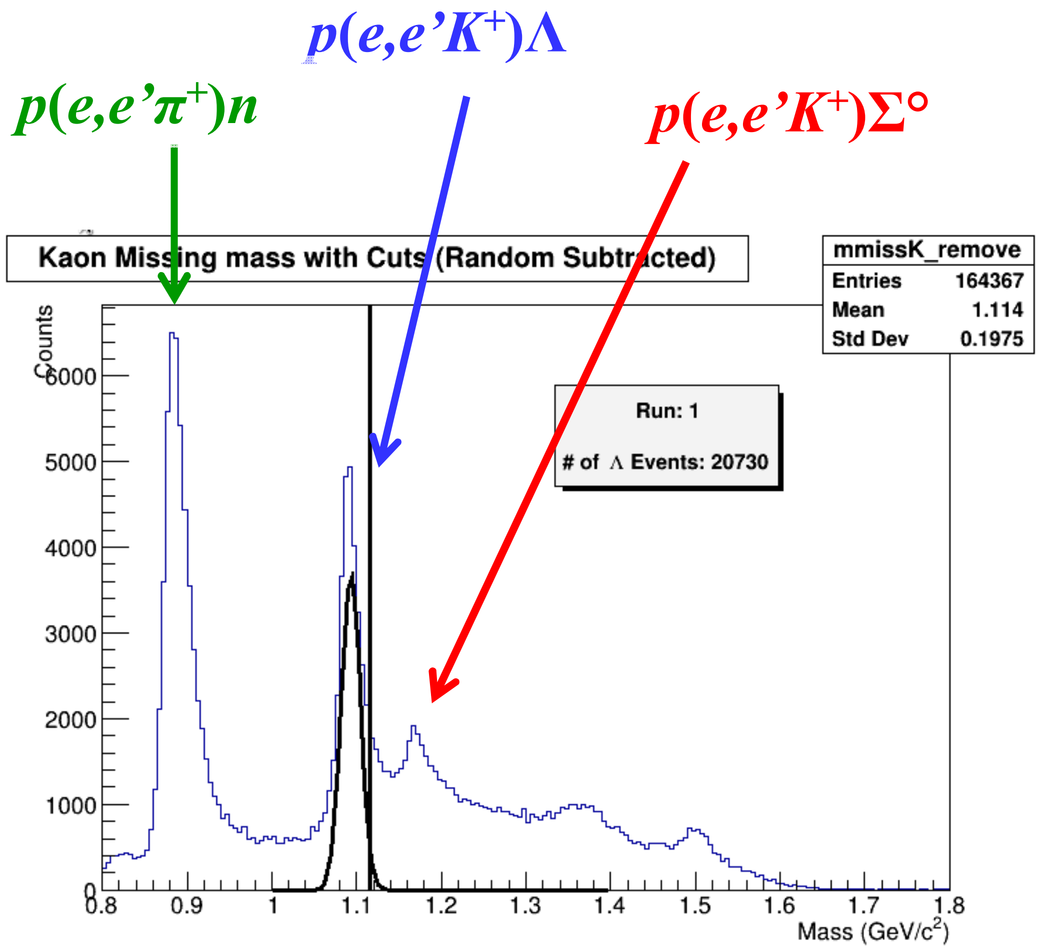
- Spectrometer coincidence acceptance allows for simultaneous studies of Λ and Σ° channels.

- Kaon-pole dominance test through

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

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



Online: Q^2=3.0 GeV^2 , W=2.32, high ε, θ_{Kq}=+3.0

Kaon Form Factor Experiment Goals

- **Measure the –t dependence of the $p(e,e'K^+)\Lambda,\Sigma^\circ$ 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
- **If warranted by the data, extract the Q^2 dependence of the kaon form factor to shed new light on QCD's transition to quark–gluon degrees of freedom.**

- **Even if we cannot extract the kaon form factor, 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

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Projected Uncertainties for K^+ Form Factor

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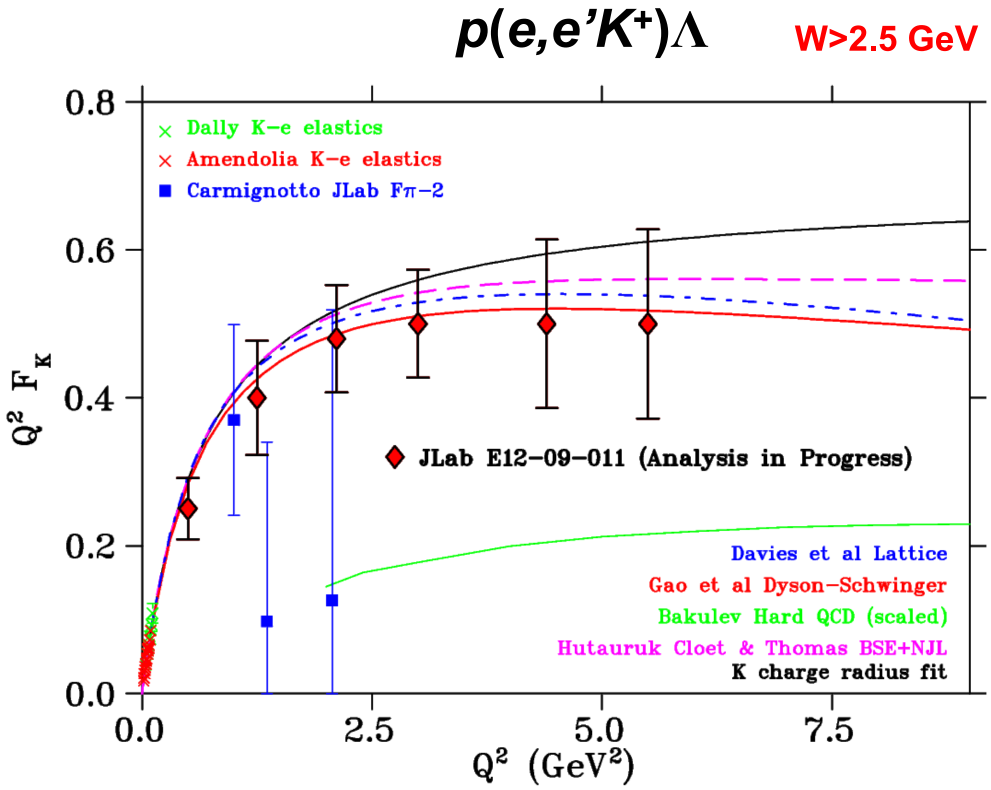
- First measurement of F_K well above the resonance region.
- Measure form factor to Q^2=3 GeV^2 with good overlap with elastic scattering data.
  - Limited by $-t$<0.2 GeV^2 requirement to minimize non–pole contributions.
- Data will provide an important second $q\bar{q}$ system for theoretical models,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

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Importance of JLab–22 F_π in EIC Era

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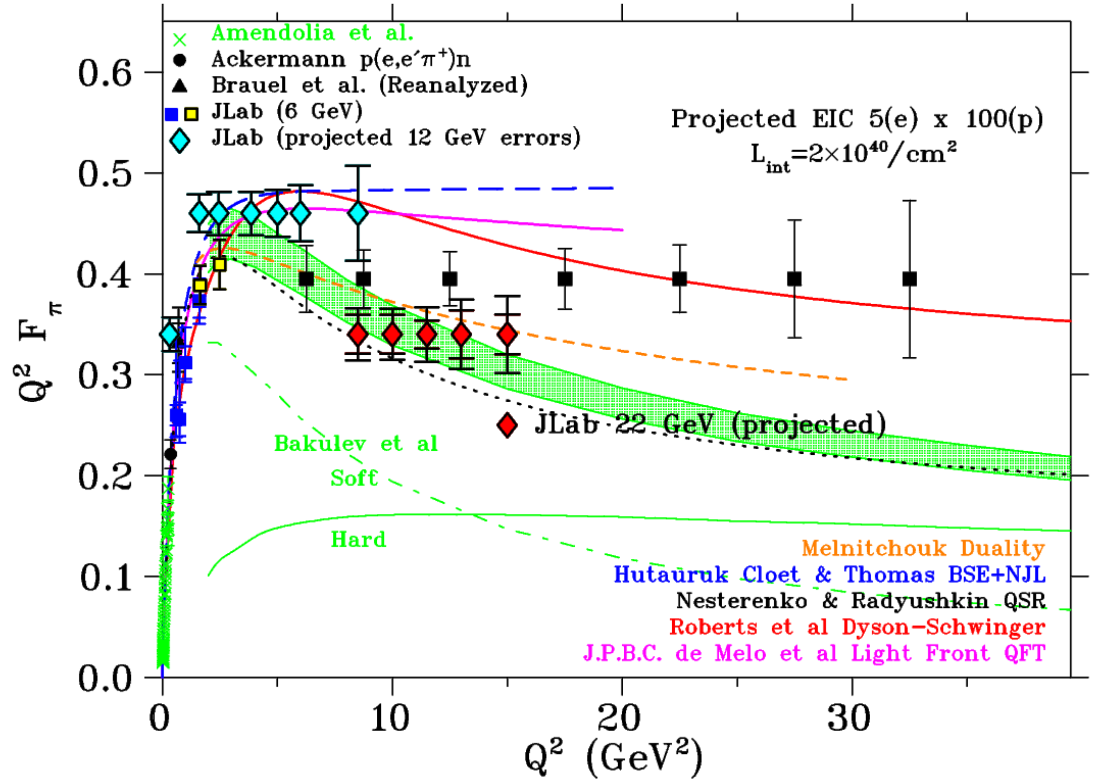

- Quality L/T–separations impossible at EIC (can't access ε<0.95)
- JLab will remain ONLY source of quality L–T separated data!
- **Phase 2: 22 GeV beam with upgraded VHMS**
  - Extends region of high quality F_π values to $Q^2=13\ GeV^2$
  - Somewhat larger errors to $Q^2=15\ GeV^2$
- Provides MUCH improved overlap of F_π data set between JLab and EIC!

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EIC Kinematic Reach (projection)

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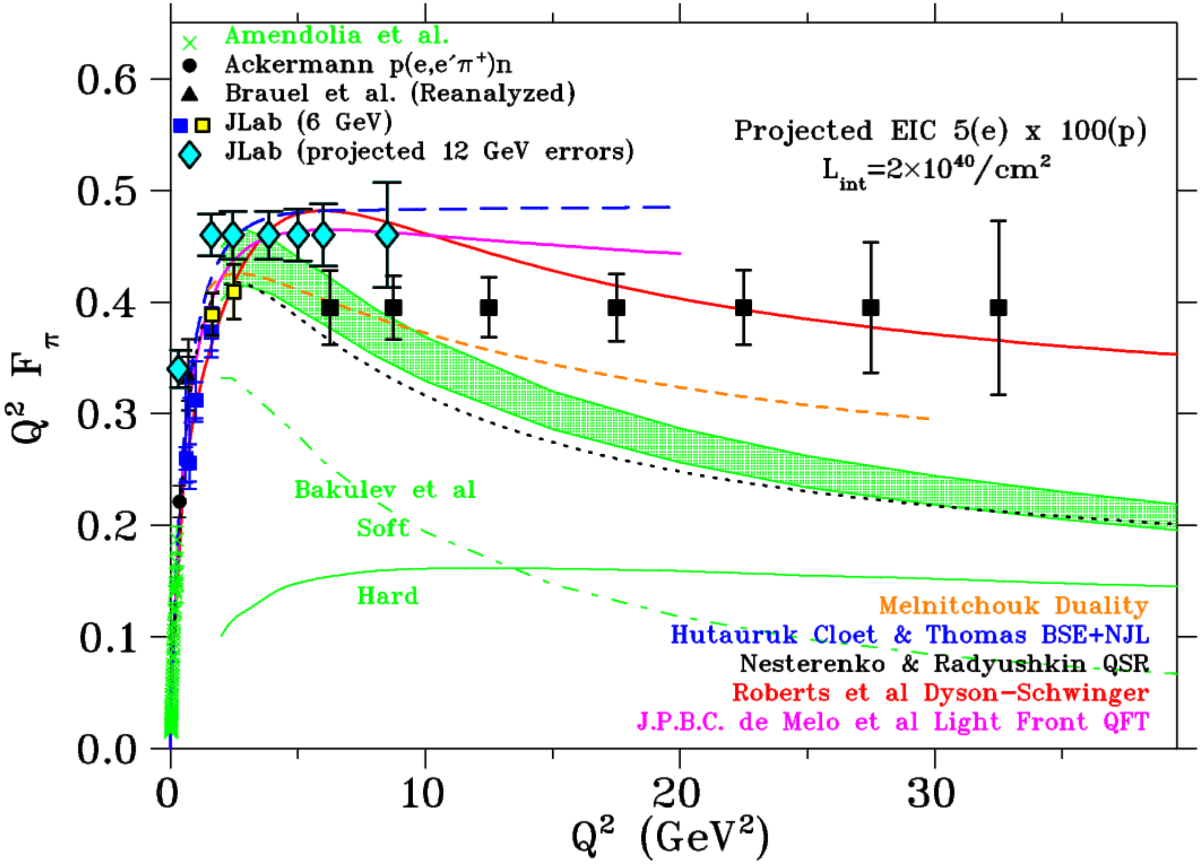

Assumptions:

- $5(e^-)$ x $100(p)$.
- Integrated L=20 fb^{-1}/yr.
- Clean identification of exclusive $p(e,e'\pi^+n)$ events.
- Syst. Unc: 2.5% pt–pt and 12% scale.
- $R=\sigma_L/\sigma_T$ =0.013–0.14 at lowest $-t$ from VR model, and $\delta R=R$ syst. unc. in model subtraction to isolate σ_L.
- π pole dominance at small $-t$ confirmed in ^{2}H π^-/π^+ ratios.

Results look very promising, but more study needed to confirm assumptions.

Endorsement in USA Long Range Plan

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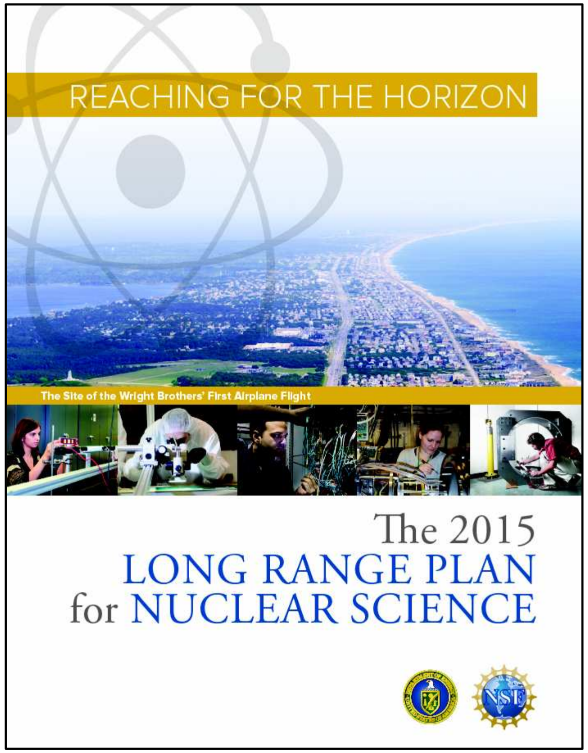
Section 2.1.1: The Quark Structure of Hadrons

- The pion plays a unique role in nature. It is the lightest quark system… It is also the particle responsible for the long range character of the strong interaction that binds the atomic nucleus together.
- If [chiral symmetry] were completely true, the pion would have no mass.
- The pion is seen as key to confirm the mechanisms that dynamically generate nearly all of the mass of hadrons and central to the effort to understand hadron structure.



- **With such strong theoretical motivation, the study of the pion form factor is one of the flagship goals of the JLab 12-GeV Upgrade.**
- **The SHMS (in Hall C) will nearly quadruple the momentum transfer over which the pion form factor is known.**
- **These measurements will probe a broad regime in which the phenomenology of QCD begins to transition from large- to small-distance-scale behavior.**

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Strong Endorsement in many Reviews

University of Regina

Report to PAC18, 12 GeV Session:

Measuring F_π at Higher Q^2

G.M. Huber, H.P. Blok, D.J. Mack

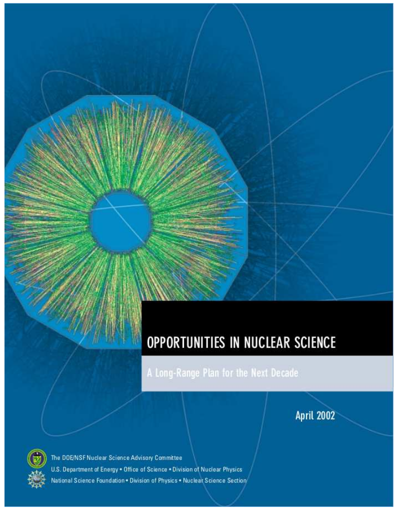
on behalf of the Exclusive Reactions Working Group

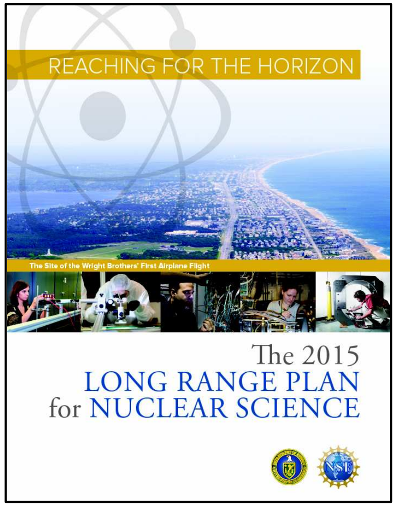
July 6, 2000

F_π first proposed to JLab PAC in 2000!

F_π Rated "Early High Impact" by PAC35 in 2010

F_π endorsed by NSAC in 2002, as one of the key motivations for the JLab 12 GeV Upgrade.





F_π endorsed again by NSAC in 2015, *"as one of the flagship goals of the JLab 12 GeV Upgrade".*

PAC47 (2019) Theory Report:
"Since the proposals were originally reviewed, the physics motivations have only increased."
→ Top "A" rating reaffirmed by PAC

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