Transverse Meson Structure from Exclusive Measurements

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NSERC CRSNG

Pion and Kaon Structure at an EIC, Argonne National Lab, June 2, 2017.

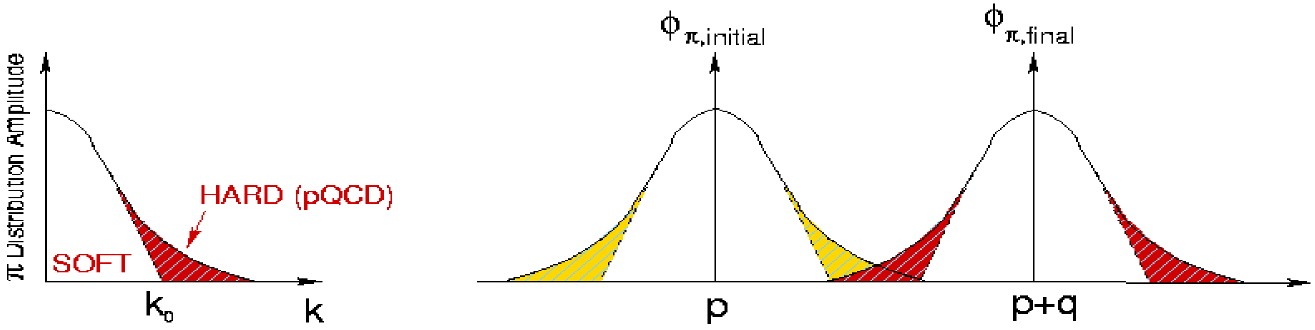
FRN: SAPIN-2016-00031

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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pQCD and the Charged Pion Form Factor

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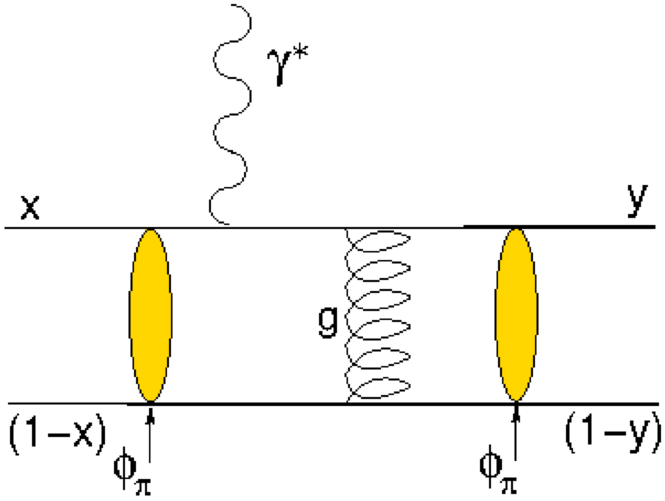
At large Q^2, perturbative QCD (pQCD) can be used

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

at asymptotically high Q^2, only the hardest portion of the wave function remains

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



and F_π takes the very simple form

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

where f_π=92.4 MeV is the $\pi^+\to\mu^+\nu$ decay constant.

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

Pion Form Factor at Finite Q^2

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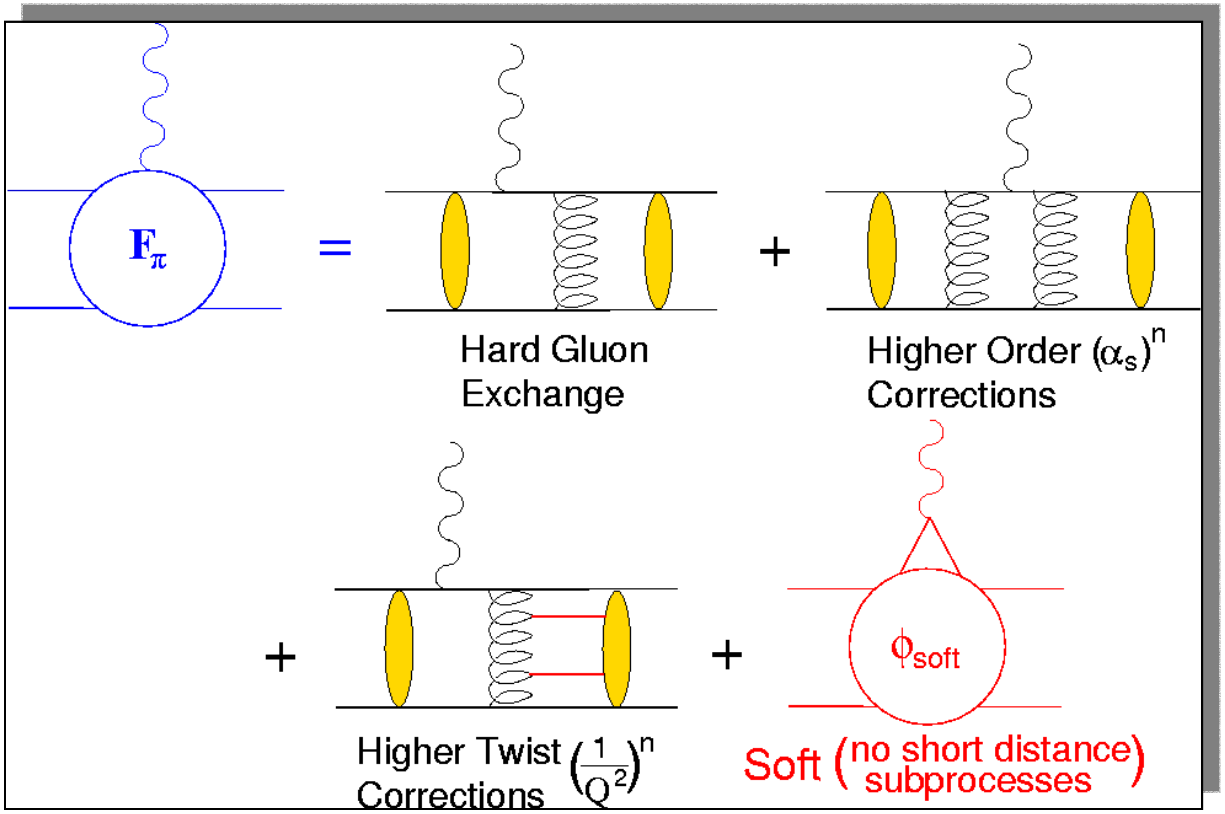
- At finite momentum transfer, higher order terms contribute.
- Calculation of higher order, “hard” (short distance) processes difficult, but tractable.



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.

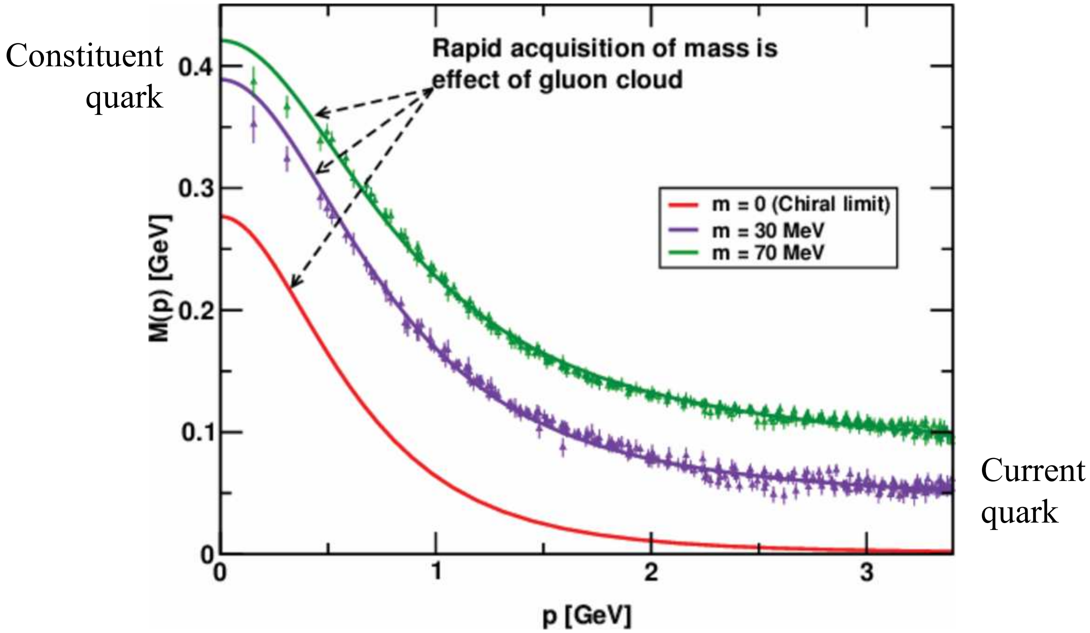
[A.V. Radyushkin, JINR 1977, arXiv:hep-ph/0410276]

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 limit.



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

Implications for Pion Structure

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."***

- For the pQCD derivation on slide #3, the normalization for F_π has been based on the conformal limit of the pion's twist-2 PDA.

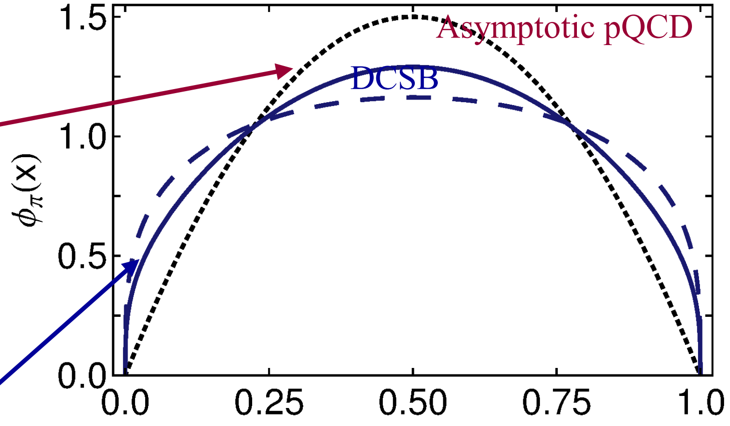
$$\phi_\pi^{cl}(x) = 6x(1-x)$$

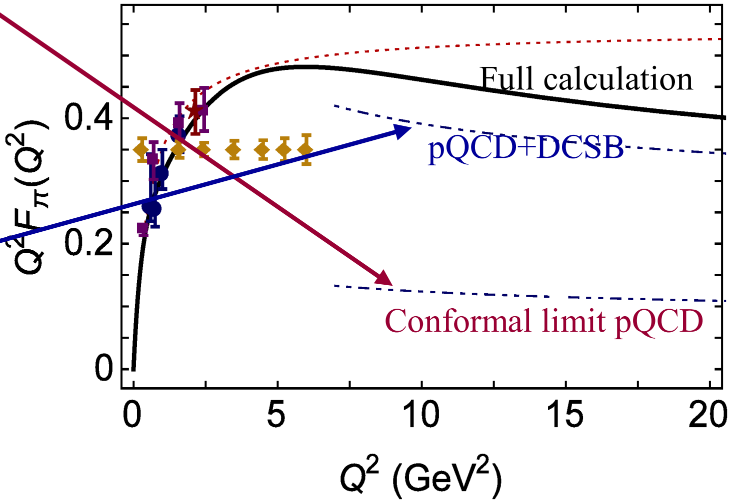
- This leads to "too small" F_π values in comparison with present & projected JLab data.

- 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 $Q^2 \geq 8$ GeV². Addresses issue raised in 1977.**



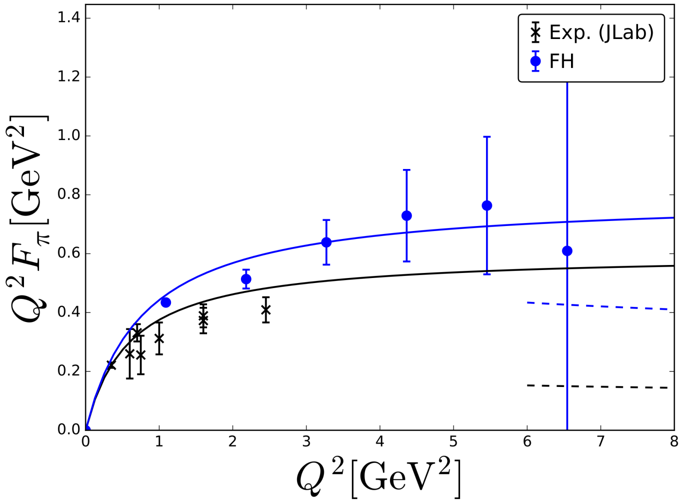


L. Chang, et al., PRL **110** (2013) 132001; **111** (2013) 141802.

New Lattice QCD at Higher Q^2

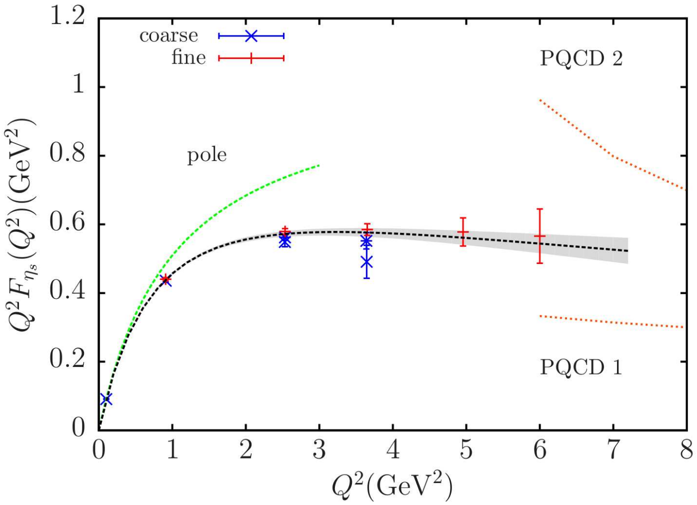
- **Lattice QCD calculations traditionally have difficulty predicting hadron structure at high-momentum transfer.**
- **Form factors drop rapidly with Q^2, so one is attempting to extract a much weaker signal from datasets with finite statistics.**

- **QCDSF/UKQCD/CSSM Collab. address with new technique relating matrix elements to energy shifts.**
- Simulate single set of u,d,s gauge configurations corresponding to $m_\pi \approx 470$ MeV.
- **Confident future LQCD will provide insight into transition of perturbative to non-perturbative QCD.**



Chambers et al., arXiv: 1702.01513

- **HPQCD Collab. study pseudoscalar η_s meson made of valence s quarks accurately tuned on full QCD ensembles of gluon field configurations.**
- Qualitatively similar to pion since $m_s < \Lambda_{QCD}$, but numerically much faster.
- F_π result flat for $2 < Q^2 < 6$ GeV^2, far above asymptotic QCD value.
- **Confident of future LQCD calcs. at higher Q^2.**



Koponen et al., arXiv: 1701.04250

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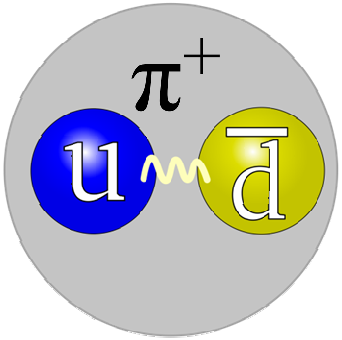
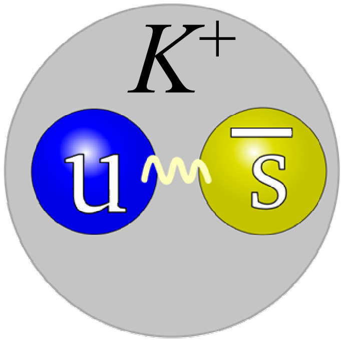
The Charged Kaon – a second QCD test case





- **The properties of the K^+ are also strongly influenced by DCSB.**
  - 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].
- **In the hard scattering limit, pQCD predicts that the π^+ and K^+ form factors will behave similarly:**

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

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

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

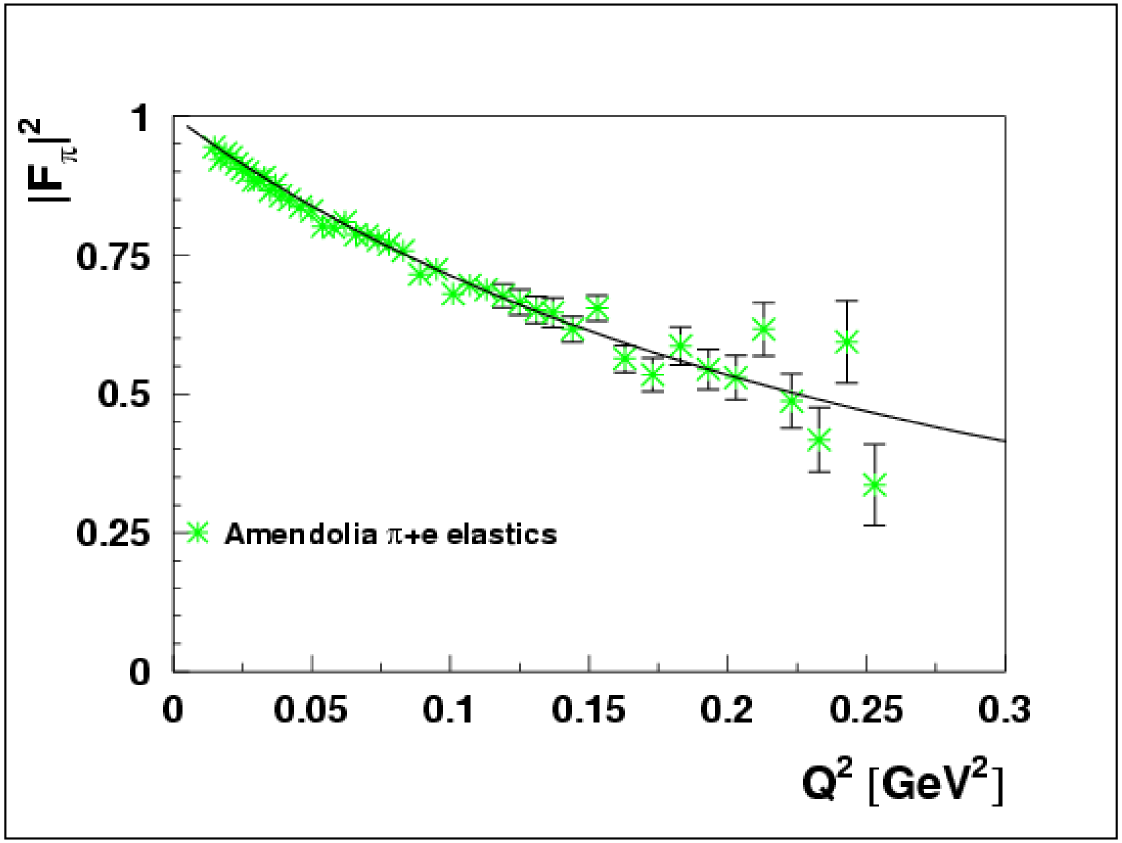
- CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV^2 *[Amendolia, et al, NP **B277**(1986)168]*

- 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



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

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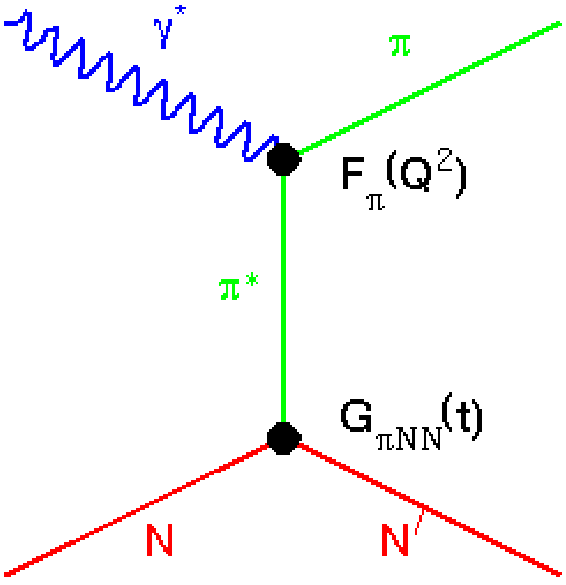
At larger Q^2, F_π must be measured indirectly using the “pion cloud” of the proton via pion electroproduction $p(e,e'\pi^+)n$

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

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

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



Drawbacks of this technique

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

Measurement of K^+ Form Factor

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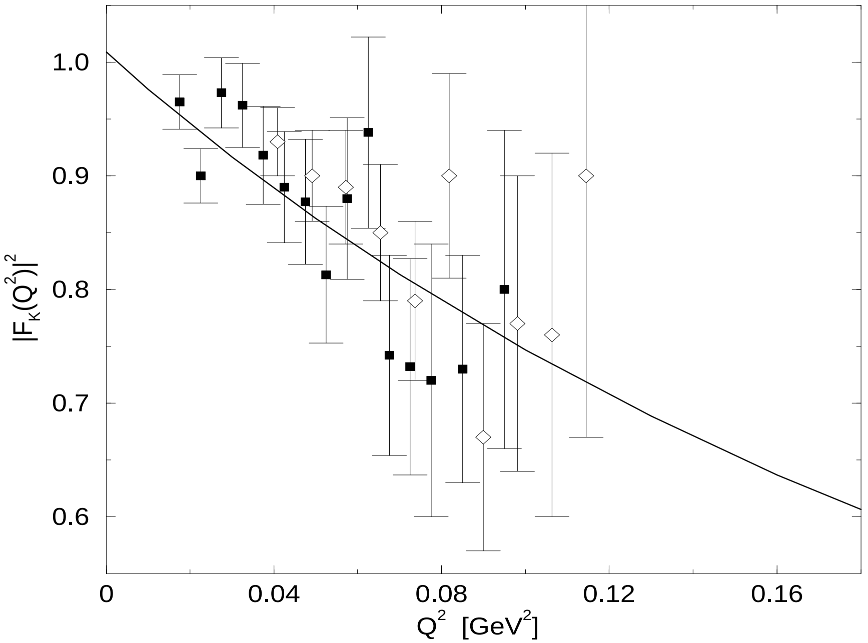
- Similar to π^+ form factor, elastic K^+ scattering from electrons used to measure charged kaon for factor at low Q^2

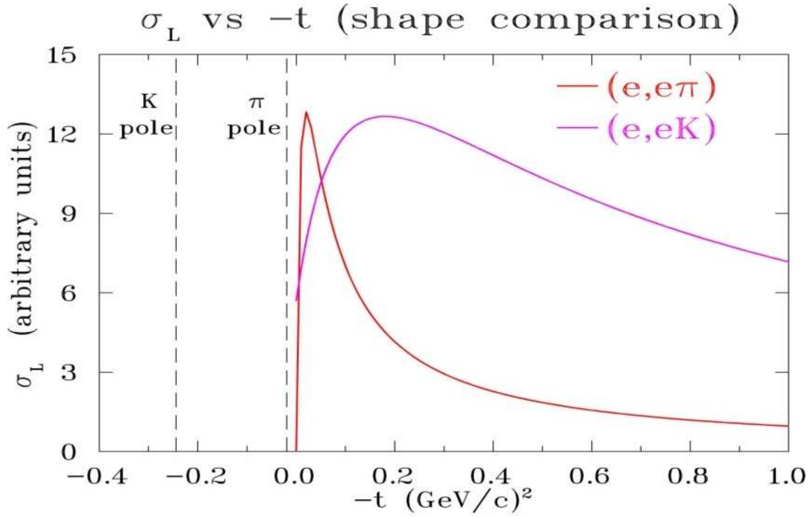
  [Amendolia, et al, PL **B178**(1986)435]

- 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.

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

- Many of these issues will be explored in JLab E12-09-11.

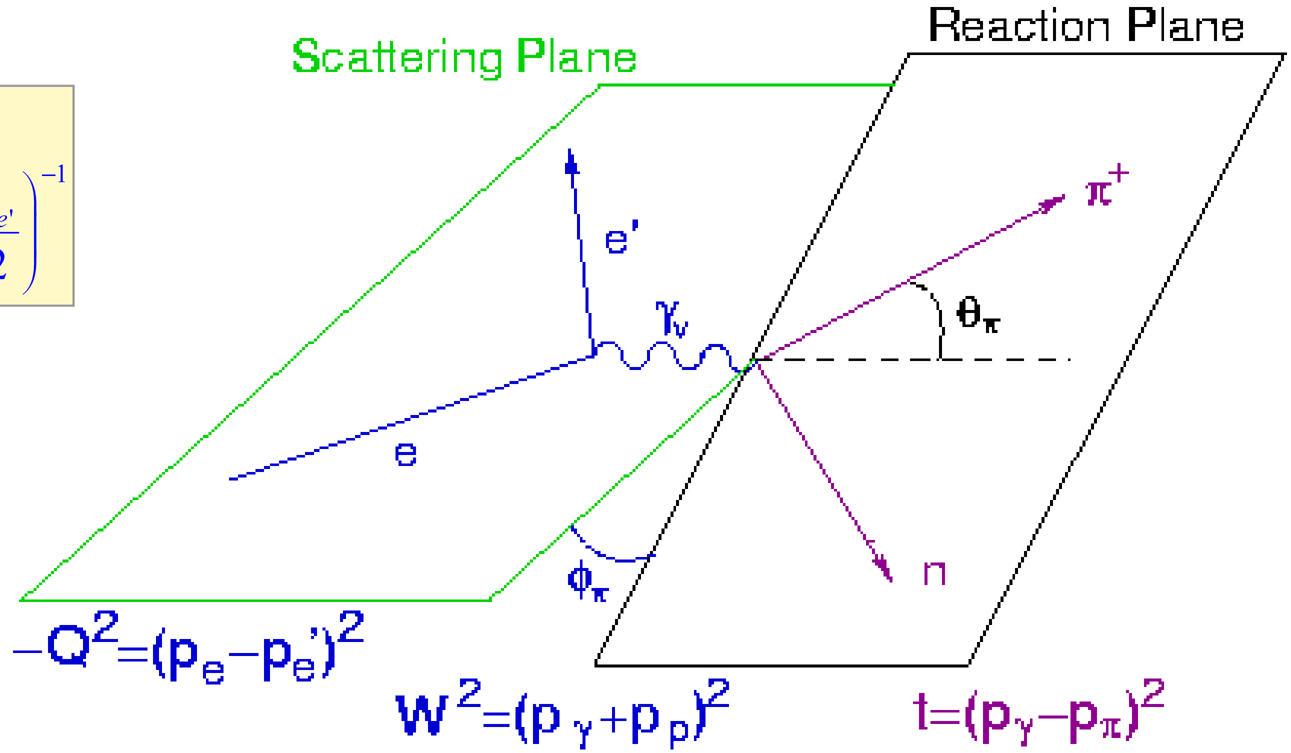




$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon\left(\varepsilon+1\right)}\,\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

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.**

Measuring $d\sigma_L/dt$ at JLab

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

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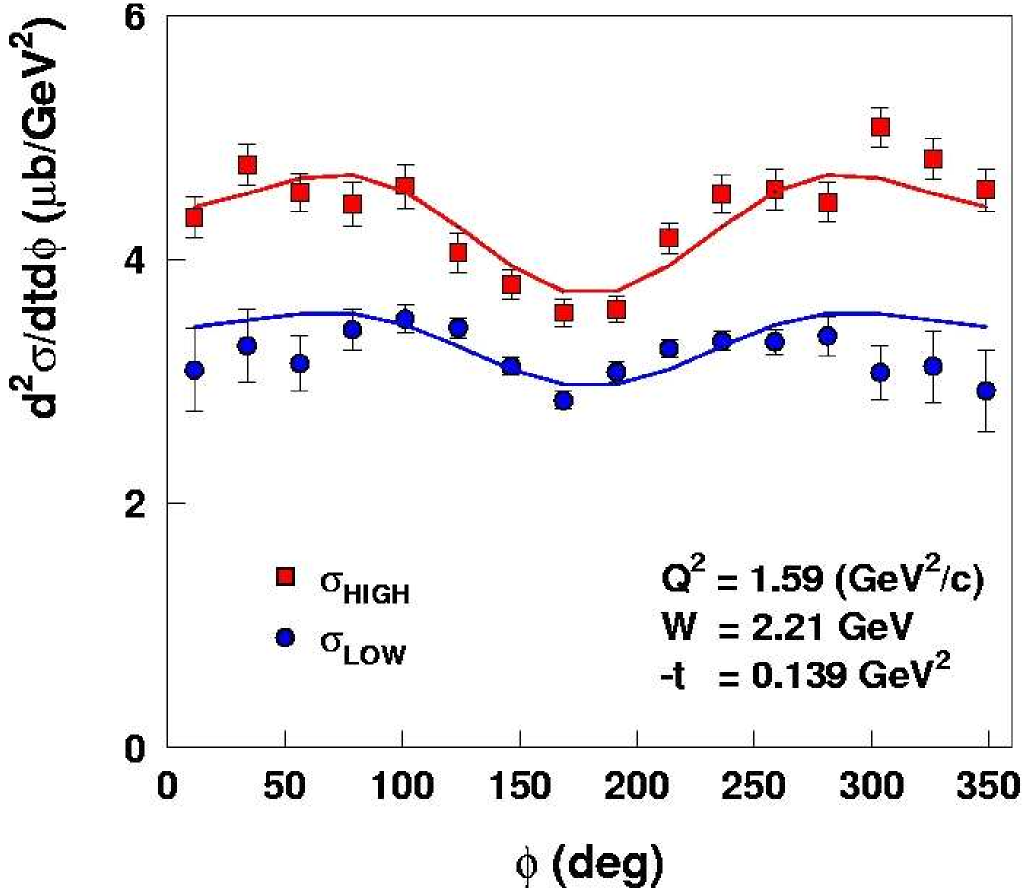
- Rosenbluth separation required to isolate σ_L
  - Measure cross section at fixed $(W, Q^2, -t)$ at 2 beam energies
  - Simultaneous fit at 2 ε values to determine σ_L, σ_T, and interference terms

- Control of point-to-point systematic uncertainties crucial due to $1/\Delta\varepsilon$ error amplification in σ_L
- Careful attention must be paid to spectrometer acceptance, kinematics, efficiencies, …



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

Chew–Low Method to determine Pion Form Factor

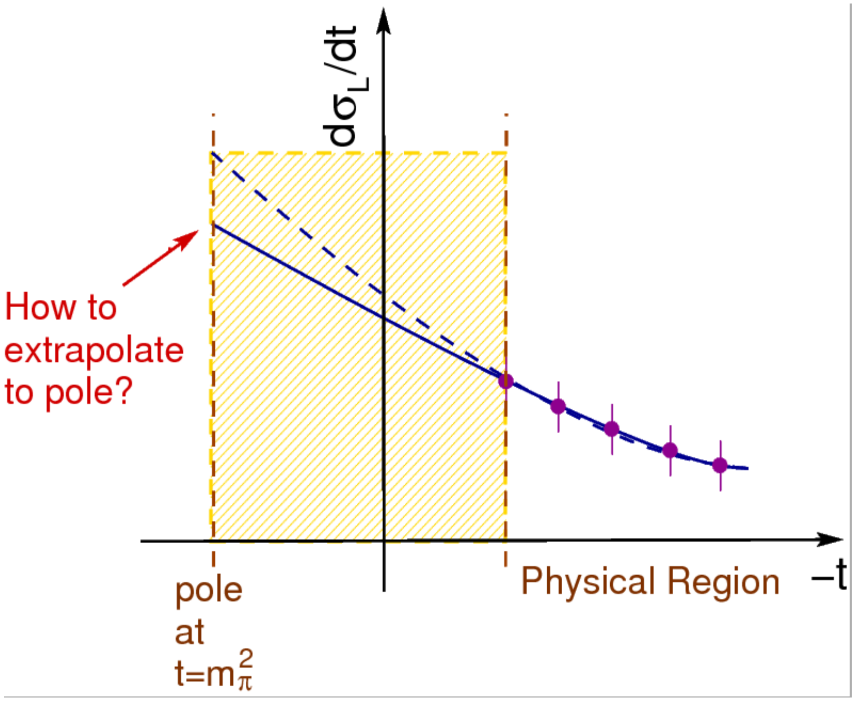
$p(e,e'\pi^+)n$ data are obtained some distance from the $t=m_\pi^2$ pole.

→ "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.

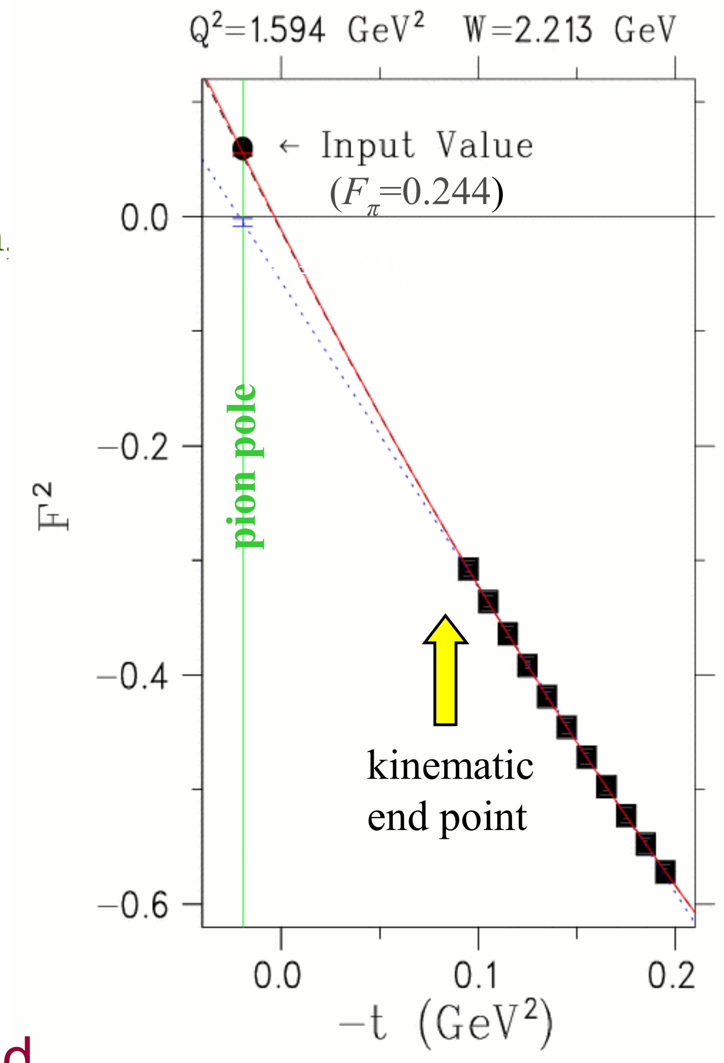
→ Different polynomial fits equally likely in physical region gave divergent form factor values when extrapolated to $t=m_\pi^2$.



The Chew-Low Method was subsequently abandoned.

Chew–Low Method Check with PseudoData

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



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

- 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 $(t\text{-}m_\pi)^2$ 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 σ_L data have only 4-6 *t*-bins and statistical and systematic uncertainties of 5-10%.
  - → Extrapolation with real data will be even more uncertain.

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 use 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. There has been considerable recent interest:
  - *T.K. Choi, K.J. Kong, B.G. Yu, arXiv: 1508.00969.*
  - *T. Vrancx, J. Ryckebusch, PRC **89**(2014)025203.*
  - *M.M. Kaskulov, U. Mosel, PRD **81**(2010)045202.*
  - *S.V. Goloskokov, P. Kroll, Eur.Phys.J. **C65**(2010)137.*

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

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

VGL Regge Model:

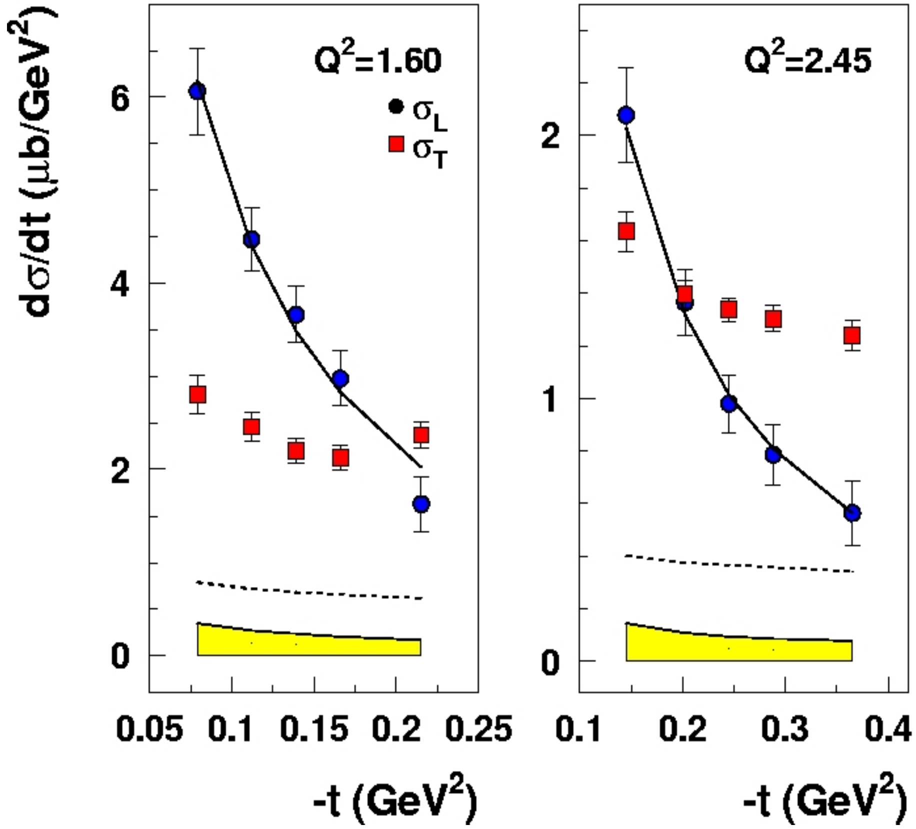
- Feynman propagator $\left(\frac{1}{t-m_\pi^{\ 2}}\right)$

  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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JLab Current and Projected Data

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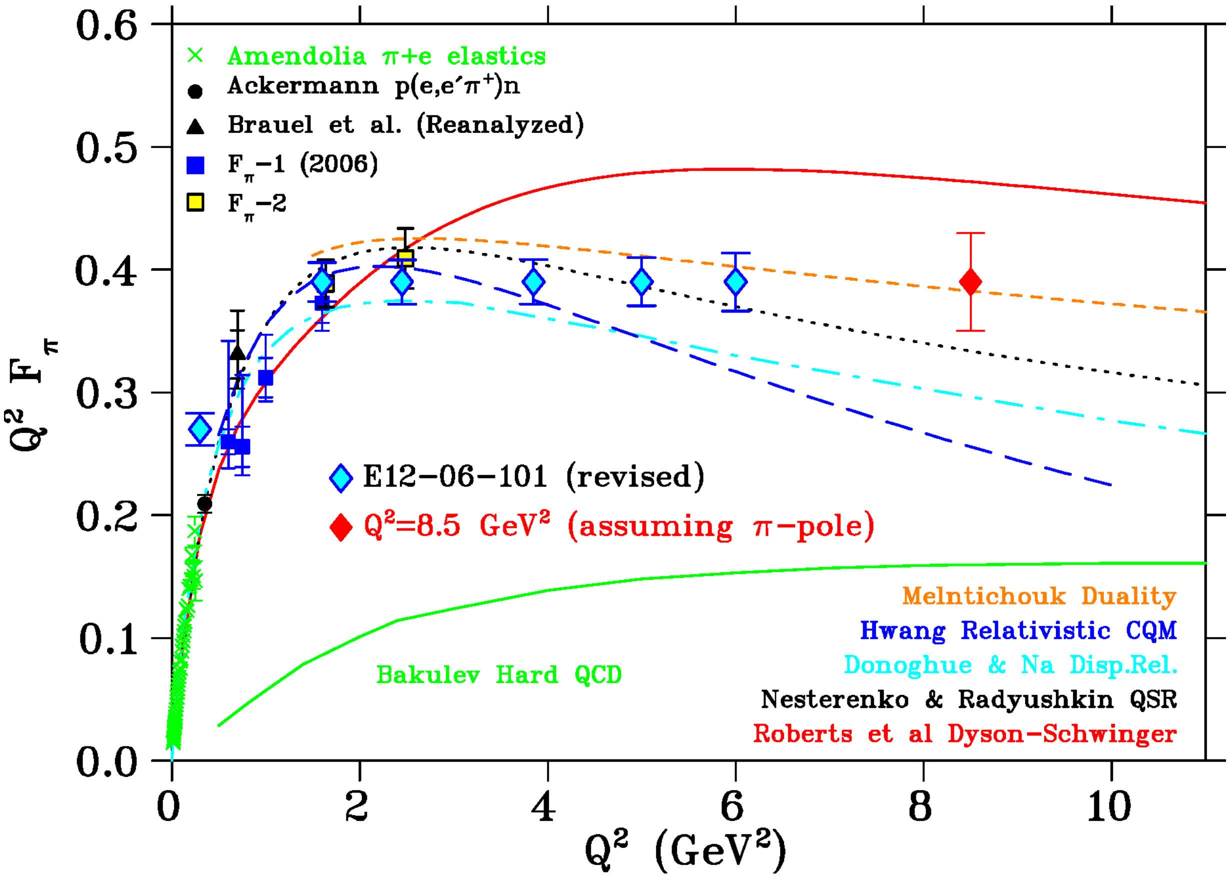
JLab 12 GeV upgrade will allow measurement of F_π to much higher Q^2.

No other facility worldwide can perform this measurement.

New overlap points at $Q^2=1.6, 2.45$ will be closer to pole to constrain- t_{min} dependence.

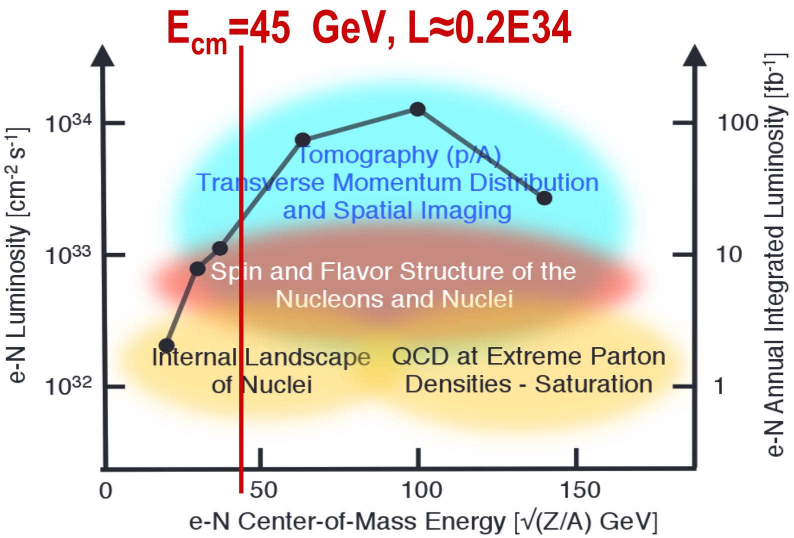
New low Q^2 point will provide best comparison of the electroproduction extraction of F_π vs. elastic $\pi+e$ data.



The ~10% measurement of F_π at Q^2=8.5 GeV^2 is at higher $-t_{min}$=0.45 GeV^2. Requires additional measurements (not yet approved) to verify π-pole dominance in σ_L.

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

- **ε>0.995 fairly straightforward.**
  - 5 GeV(e^-) x 100 GeV(p), allows access to a wide kinematic range.
- Lab cross sections in μb/sr²/GeV.
  - C. Weiss, V. Guzey (2008) extrapolation of soft model cross section to high Q^2, assuming QCD scaling behavior and $W^2 \gg Q^2$.


E_{cm}=45 GeV, L≈0.2E34

Q^2	W	$P_{e'}$	$\theta_{e'}$	P_π	θ_π	P_n	θ_n	$-t$	$d^3\sigma$
10.0	7.0	5.4	35.6	16.9	-10.6	83.7	-0.01	0.032	1.1
15.0	7.0	5.6	43.0	23.2	-9.4	77.2	-0.02	0.066	0.34
20.0	7.5	5.8	49.0	25.7	-9.8	74.4	-0.02	0.085	0.12
25.0	8.5	6.0	54.2	25.0	-11.2	74.9	-0.02	0.081	0.039
30.0	9.0	6.2	58.8	26.1	-11.7	73.6	-0.02	0.090	0.019
35.0	9.5	6.4	62.8	26.8	-12.3	72.7	-0.02	0.098	0.010

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High ε>0.995 Detector Requirements

- **Only way to assure exclusivity of the *p(e,e'π^+n)* reaction is by detecting the recoil neutron.**
  - Neutrons are emitted at small angle ($\theta<0.05^o$), momentum 73-84% of the proton beam. Resolution?
- **Scattered electron (5 GeV *e*$^-$ x 100 GeV *p*):**
  - Scattered electron angles of 35°-63° (wrt incident electron beam).
  - Resolution requirements modest ($\delta P/P \approx 5\times10^{-3}$, $\delta\theta \approx 1$mr)
  - Kinematics were chosen to avoid regions where cross sections drop rapidly, needing high resolution for small systematic errors.
- **17-26 GeV/c π^+ detected at forward angle** (9.5°-12.5°)
  - Will need reliable PID. e.g. ePHENIX concept in White Paper has Aerogel & RICH up to ~40°.
- **Requirements appear to be compatible with both eRHIC and JLEIC detector conceptual designs.**

→The critical issue is identification of the exclusive events.

5x100 Exclusive $p(e,e'\pi^+n)$ Kinematics

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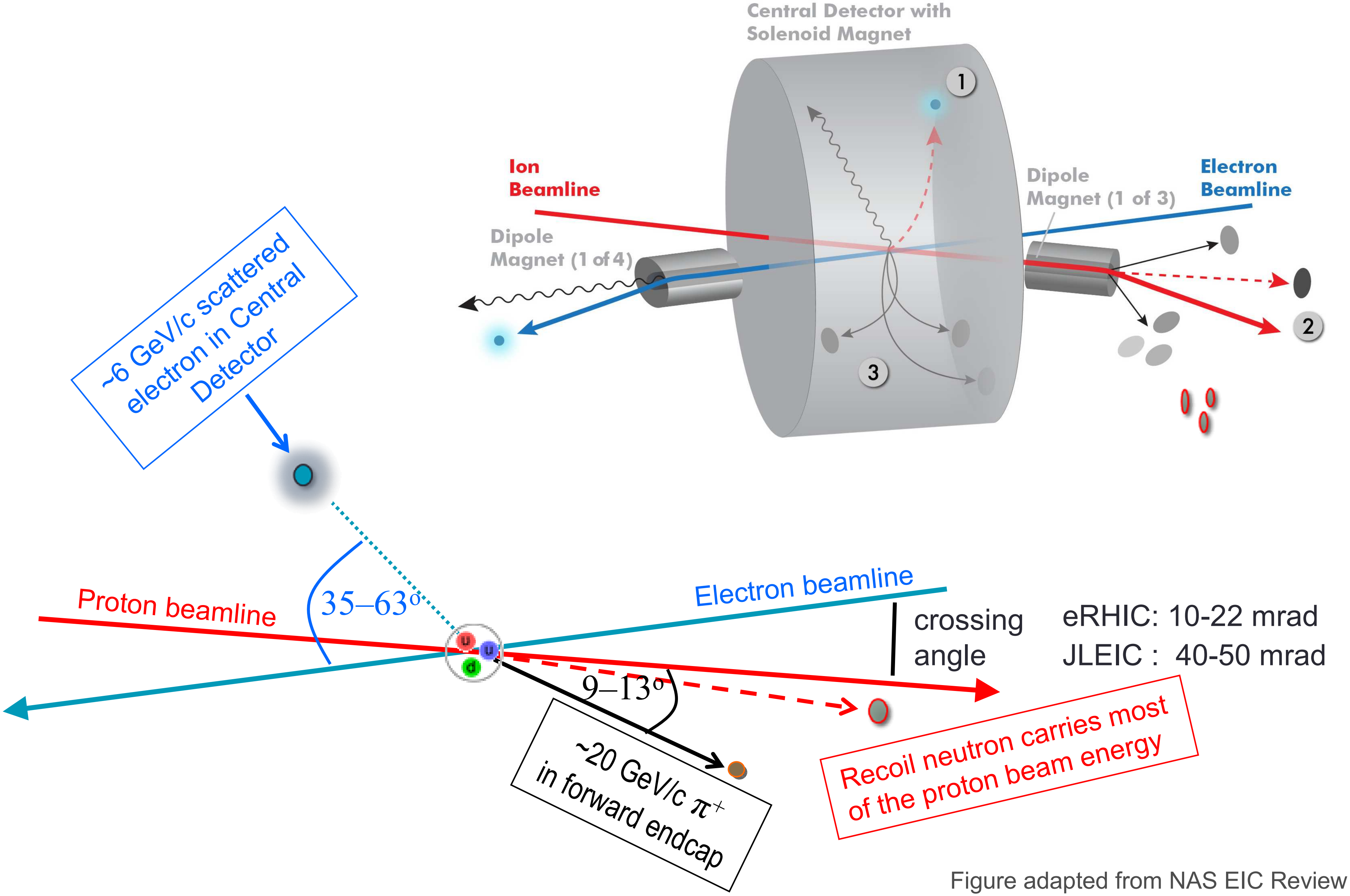


~6 GeV/c scattered electron in Central Detector

~20 GeV/c π^+ in forward endcap

Recoil neutron carries most of the proton beam energy

crossing angle

eRHIC: 10-22 mrad

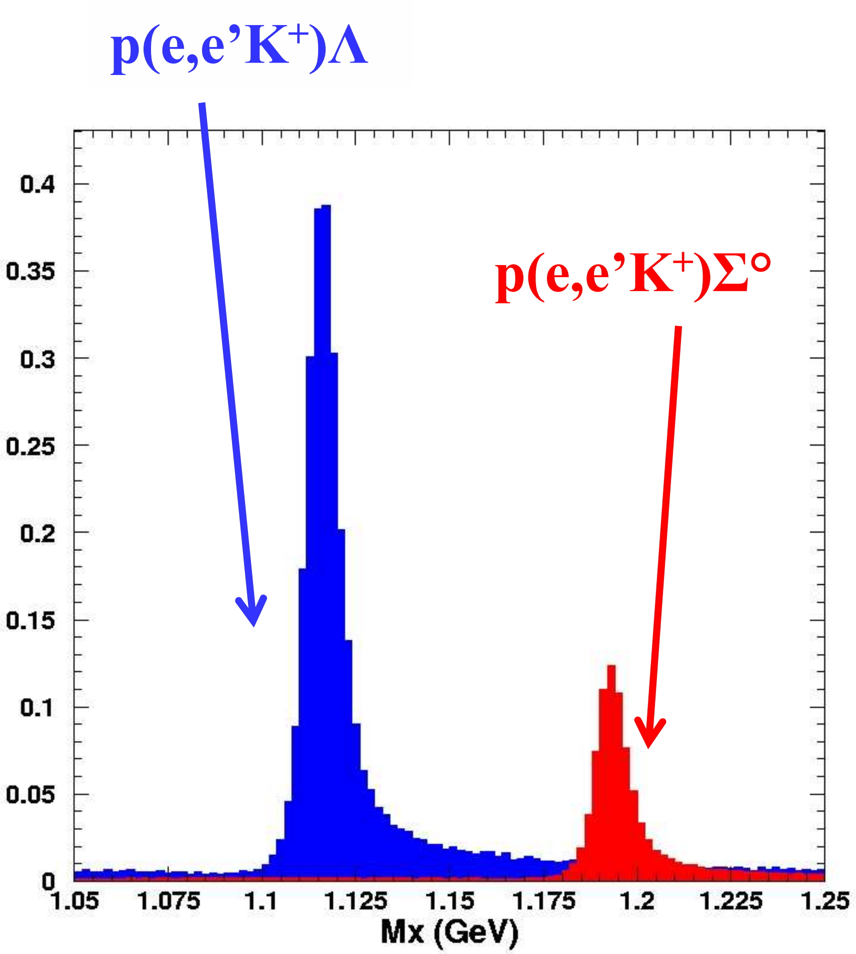
JLEIC : 40-50 mrad

Figure adapted from NAS EIC Review draft by A. Deshpande, March 2017

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

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

- At EIC CM energies, exclusive π, K cross sections are likely more comparable, statistics likely to be less of an issue than at JLab.
- **Assuring exclusivity poses many challenges.**
  - $\Lambda\Sigma$ final states are closer together in missing mass than n, n+π.
  - Λ $c\tau$=7.89 cm.
  - Planned vertex detectors cover central rapidity range, while in these kinematics Λ is at very small angle to proton beamline.
- Would need $\Lambda\rightarrow\pi^-p$ simulation. Requirements similar to EIC K^+ structure function measurement.



JLab Hall C simulation at Q^2=2.0 GeV^2, W=3.0 GeV and high ε

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How to separate σ_L from σ_T in e–p Collider

$$\varepsilon = \frac{2(1-y)}{1+(1-y)^2} \quad \text{where the fractional energy loss} \quad y = \frac{Q^2}{x(s_{tot} - M_N{}^2)}$$

- Systematic uncertainties in σ_L are magnified by $1/\Delta\varepsilon$.
  - Desire $\Delta\varepsilon>0.2$.
- **To access $\varepsilon<0.8$, one needs $y>0.5$.**
  - This can only be accessed with small s_{tot},

    i.e. low proton collider energies (5–15 GeV), where luminosities are too small for a practical measurement.
- **A conventional L-T separation is impractical, need some other way to identify σ_L.**

σ_L via Beam and Target Polarization

Although the technique has not been tested for this reaction, it is in principle possible to extract $R=\sigma_L/\sigma_T$ using polarization degrees of freedom

For parallel kinematics (outgoing meson along $\vec{q}$) in proton rest frame

$$R=\frac{\sigma_L}{\sigma_T}=\frac{1}{\varepsilon_L}\left(\frac{1}{\chi_z}-1\right)$$

Longitudinal polarization of virtual photon

$$\varepsilon_L=\left(Q^2/\omega_{cm}^2\right)\varepsilon$$

z-component of proton "reduced" polarization in exclusive pseudoscalar meson production

$$\chi_z=\frac{1}{2P_eP_p\sqrt{1-\varepsilon^2}}A_z$$

A_z = double-spin asymmetry

Schmieden, Tiator Eur.Phys.J. A **8**(2000)15–17.

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Polarization Technique Considerations

- **A point in favor of this technique is that P_p (component of proton polarization parallel to $\vec{q}$) should be readily optimizable at EIC.**
- **Need to keep in mind that the $R=\sigma_L/\sigma_T$ polarization relation only strictly applies in parallel kinematics.**
  - The detector geometry enforces very tight constraints, as recoil neutron angle is very sensitive to θ_{CM}.

$$\boxed{\sigma_L \propto P_e P_p \sqrt{1-\varepsilon^2}\, A_z}$$

- **Figure of merit for this technique vanishes for ε≈1.0.**
- ε≈0.95 gives $\sqrt{1-\varepsilon^2} \approx 0.31$
- Requires E_{CM}<20 GeV, e.g. 3x25. Luminosity low.
- **At best, this could be used as a spot-check only in specific kinematics. Generally not feasible.**

Isolate σ_L using a Model

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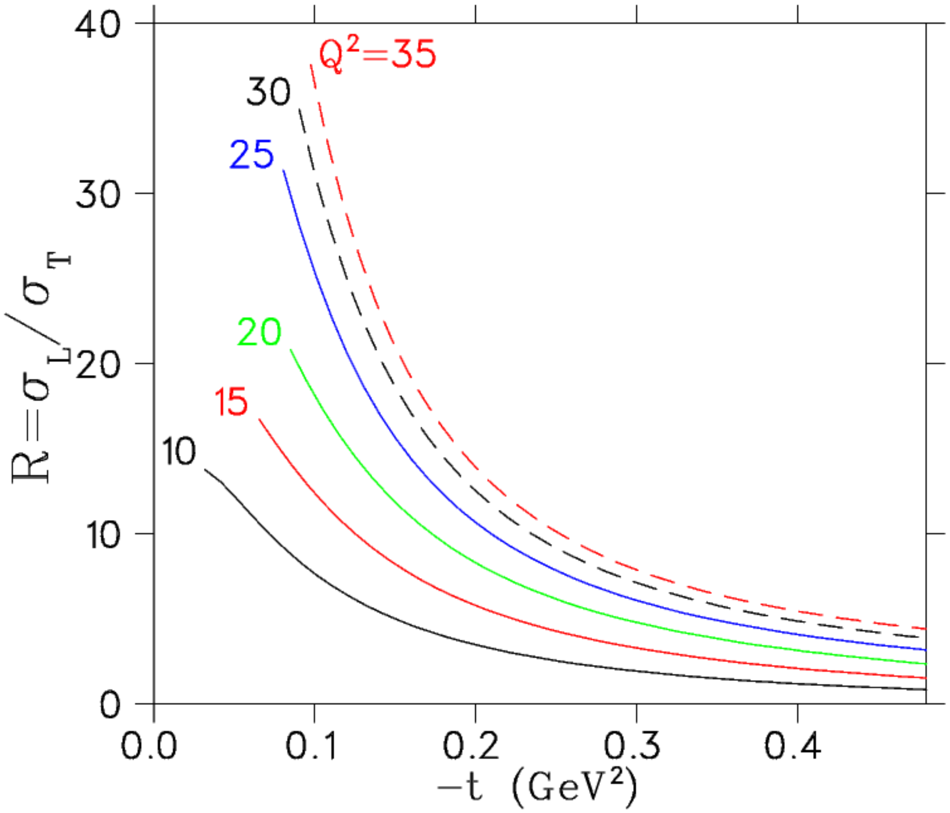
- In the hard scattering regime, QCD scaling predicts $\sigma_L \propto Q^{-6}$ and $\sigma_T \propto Q^{-8}$.
- At high Q^2, W accessible at EIC, phenomenological models predict $\sigma_L \gg \sigma_T$ at small $-t$.
- The most practical choice might be to use a model to isolate dominant $d\sigma_L/dt$ from measured $d\sigma_{UNS}/dt$.
- **In this case, it is very important to confirm the validity of the model used.**



- T. Vrancx, J. Ryckebusch, PRC **89**(2014)025203.
- Predictions are for ε>0.995 Q^2, W kinematics shown earlier.

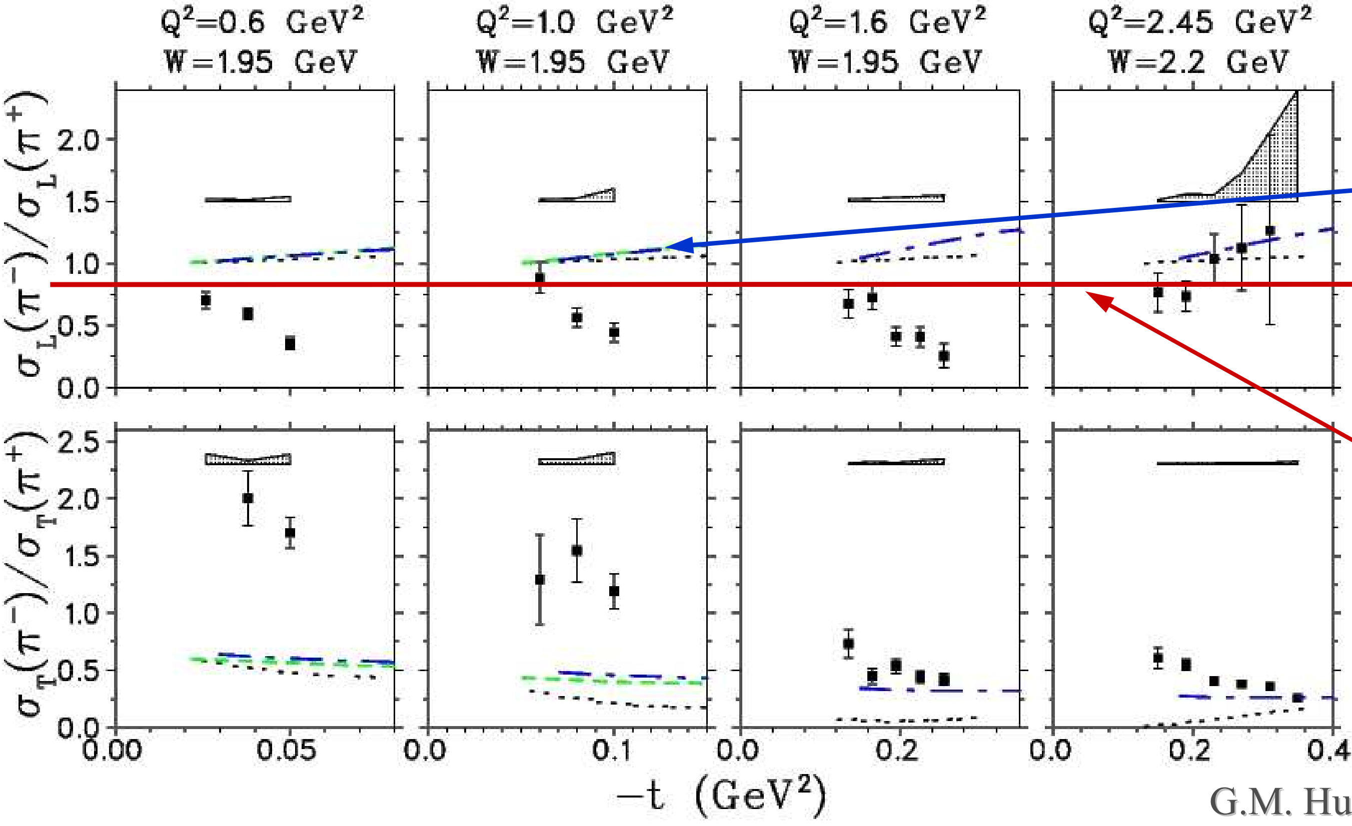
π^-/π^+ data to check *t*-channel dominance

- 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 (such as $b_1(1235)$ contributions to *t*-channel) will dilute ratio.

- **Qualitatively in agreement with our F_π-1 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 no evidence for this contribution at W=2.2 GeV.



Vrancx-Ryckebusch Model:

- VR extend VGL with hard DIS process of virtual photons off nucleons.

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

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

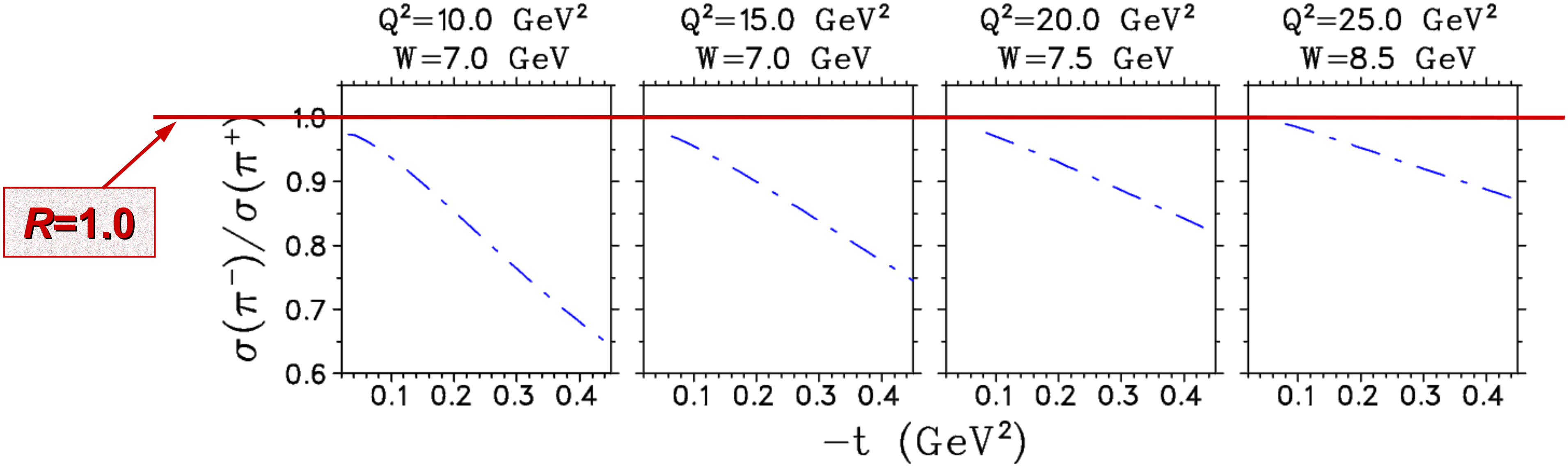
G.M. Huber, et al., PRL **112**, 182501 (2014)

Similar approach to confirm $\sigma_L \gg \sigma_T$ at EIC

- Exclusive $^{2}H(e,e'\pi^{+}n)n$ and $^{2}H(e,e'\pi^{-}p)p$ in same kinematics as $p(e,e'\pi^{+}n)$
- π *t*–channel diagram is purely isovector (G-parity conservation).

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

- **The π^-/π^+ ratio will be diluted if σ_T is not small, or if there are significant non-pole contributions to σ_L.**
- **Compare measured π^-/π^+ ratio to model expectations.**



T. Vrancx, J. Ryckebusch, PRC **89**(2014)025203.

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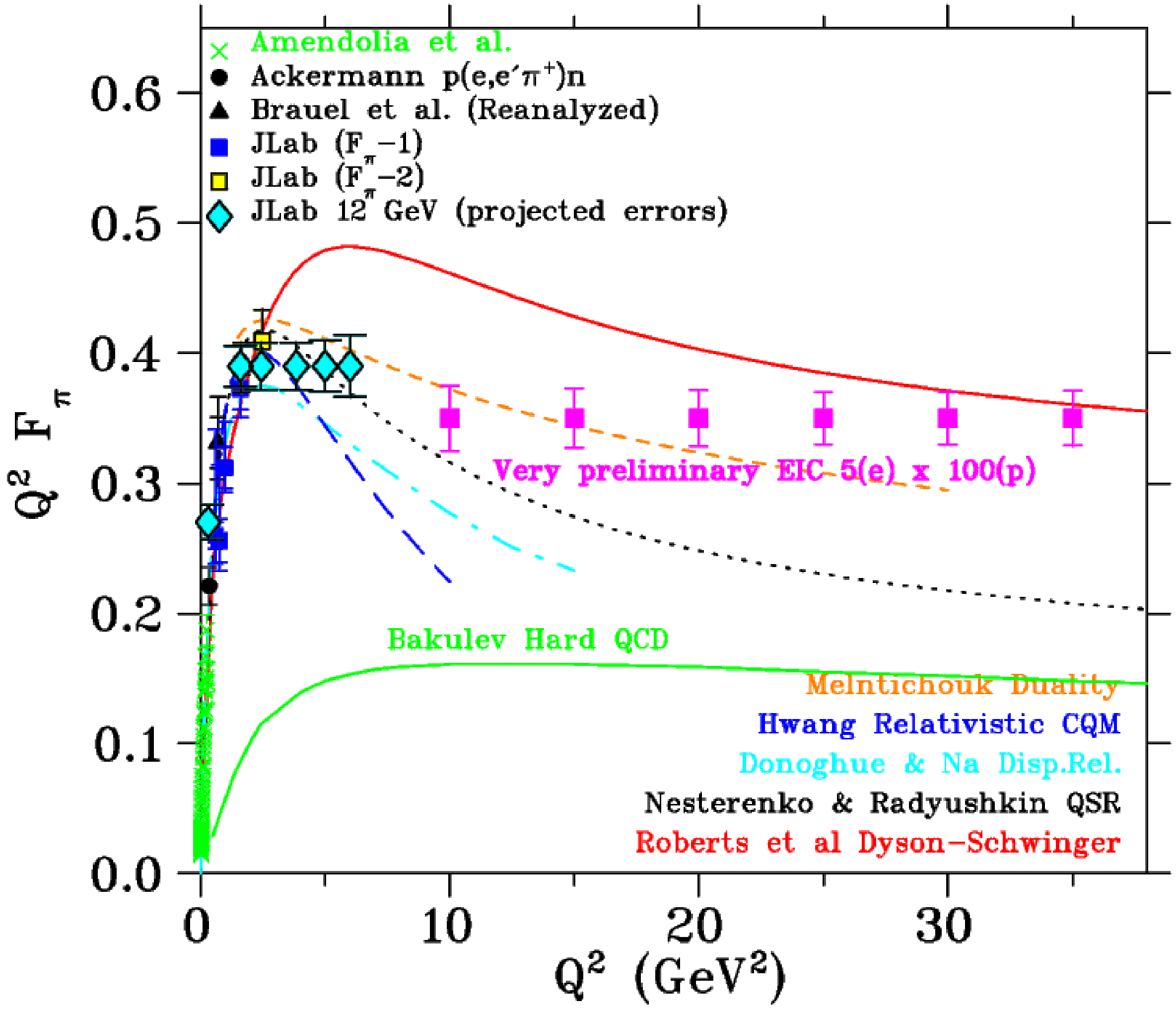
EIC Kinematic Reach (Very Tentative)



Assumptions:

- 5(e^-) x 100(p).
- Integrated L=20 fb^{-1}/yr.
- Identification of exclusive $p(e,e'\pi^+n)$ events.
- 10% exp. syst. unc.
- $R=\sigma_L/\sigma_T$ from VR model, and π pole dominance at small $-t$ confirmed in ^{2}H π^-/π^+ ratios.
- 100% syst. unc. in model subtraction to isolate σ_L.

Much more study needed to confirm assumptions.

Summary

- 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.
- Measurement of F_π at EIC involves significant challenges.
  - Need good identification of $p(e,e'\pi^+n)$ triple coincidences.
  - Conventional L-T separation not possible due to low proton ring energies required to access $\varepsilon<0.8$.
  - Use of polarization degrees of freedom with $\varepsilon \approx 0.95$ seems very difficult due to low E_{CM} required.
  - As $\sigma_L \gg \sigma_T$ expected, most likely possibility is to use model to extract σ_L from $d\sigma_{UNS}/dt$ → Used also for $Q^2=10$ GeV^2 Cornell expt (1978).
  - Best to use exclusive π^-/π^+ ratio in e+d collisions to validate model.
  - **Looks promising, but more studies are needed.**

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