Exploring the Electromagnetic Structure of the Charged Pion and Kaon

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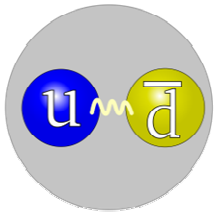
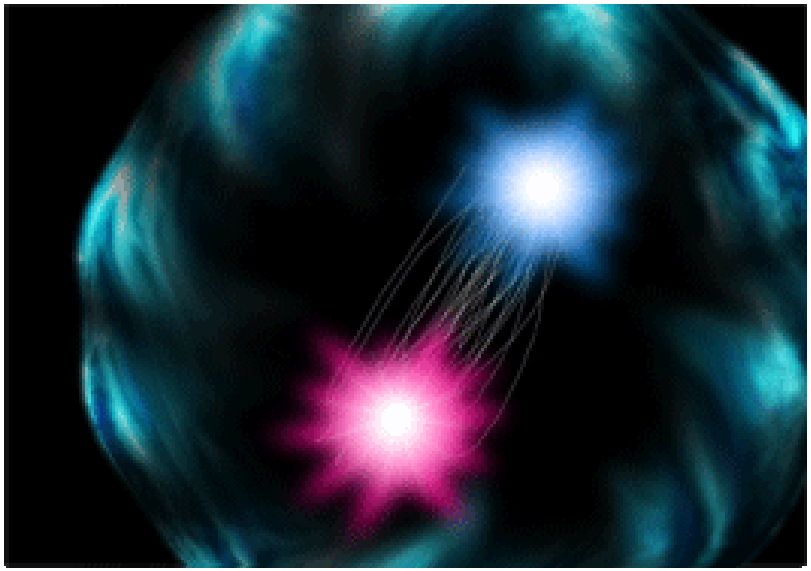
Charged Pion Form Factor

- **The pion is attractive as a QCD laboratory:**
- Simple, 2 quark system



- Electromagnetic form factor can be calculated exactly at very large momentum transfer (small distances).
- For moderate Q^2, it remains a theoretical challenge.
  - "the positronium atom of QCD"



Pion's structure is determined by two valence quarks, and the quark-gluon sea.

Downside for experimentalists:

- No "free" pion targets.
- Measurements at large momentum transfer difficult.

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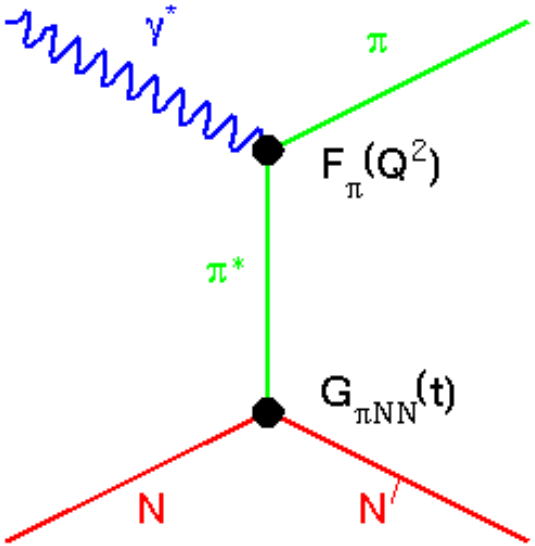
Measurement of F_π via Electroproduction

Above Q^2>0.3 GeV^2, F_π is 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, $F_\pi{}^2$ 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. The F_π values are in principle dependent upon the model used, but this dependence is expected to be reduced at sufficiently small $-t$.

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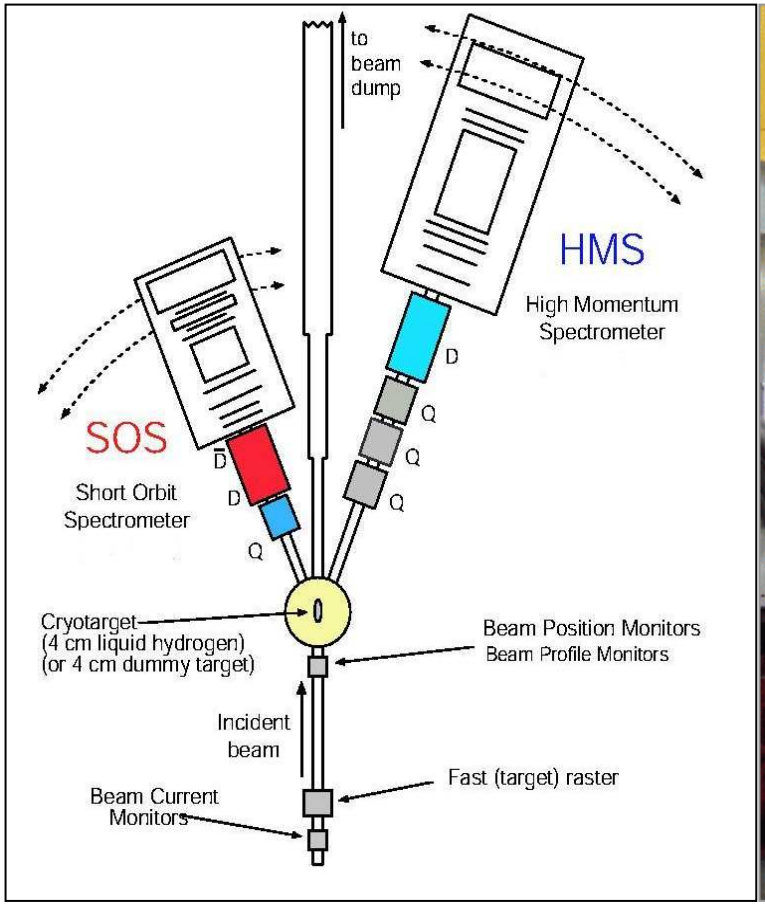
F_π Program at JLab Hall C



- 2 F_π experiments have been carried out at JLab
  (spokespersons H. Blok, G. Huber, D.Mack)
  - F_π-1: Q^2=*0.6-1.6* GeV^2 with 4 GeV beam, 1997-2001.
  - F_π-2: Q^2=*1.6, 2.45* GeV^2 with 6 GeV beam, 2003-2008.

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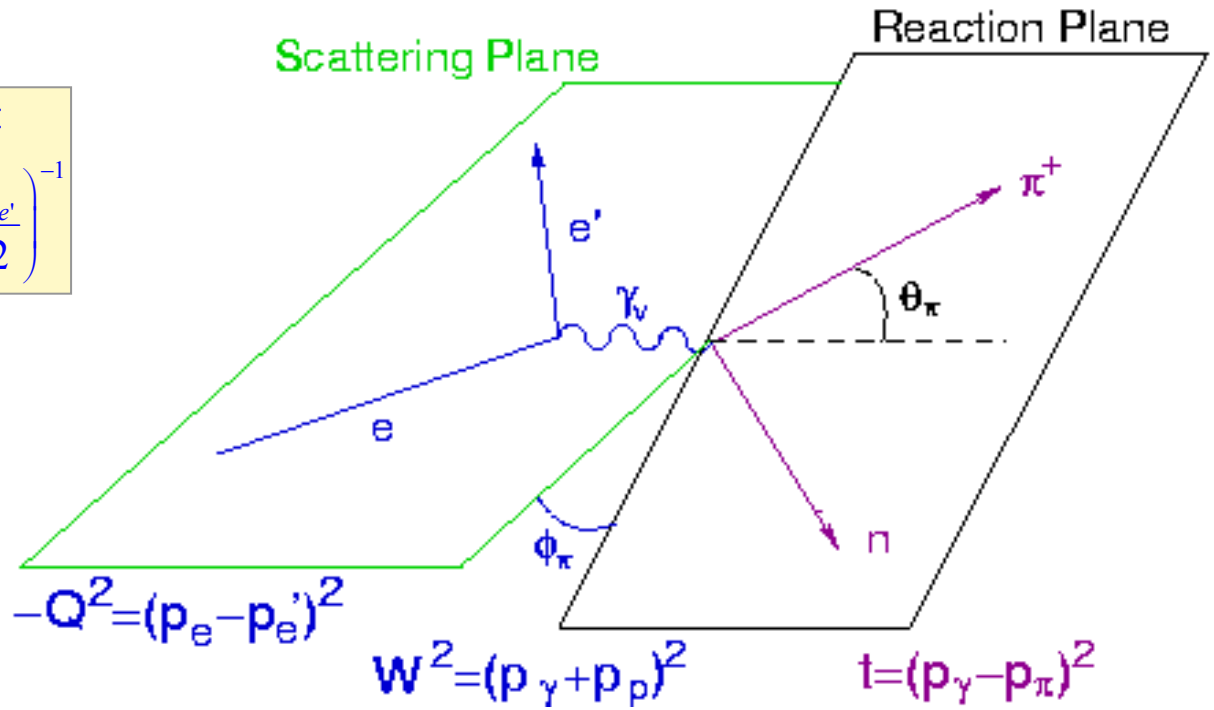
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

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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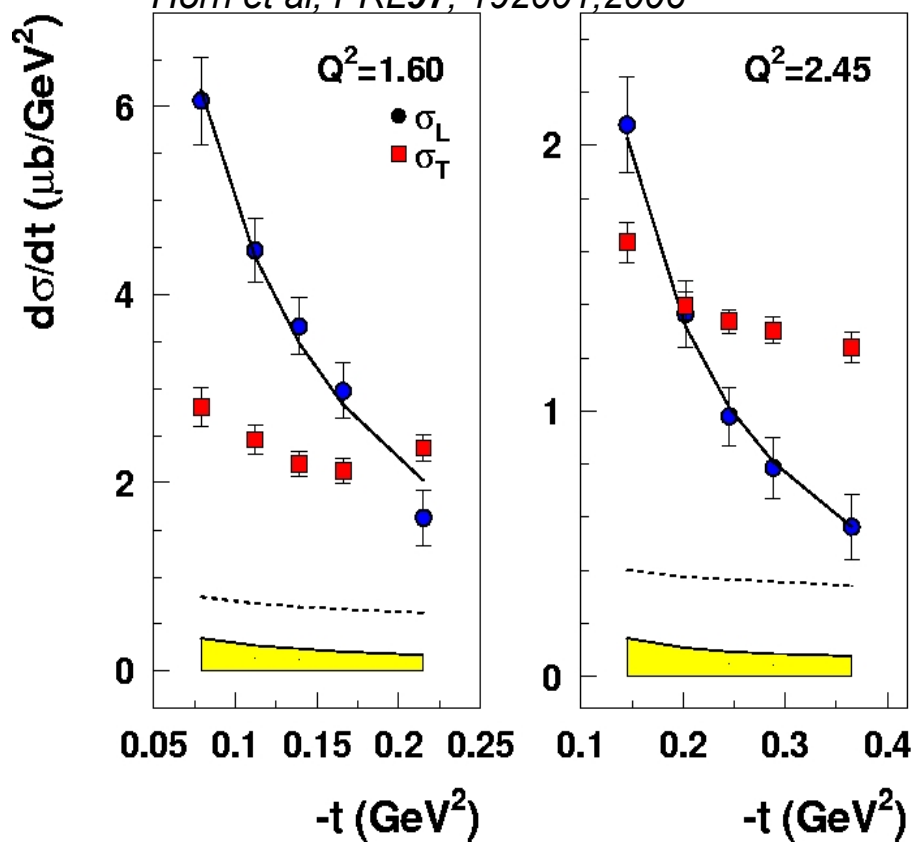
F_π Extraction from JLab data

- **Model is required to extract F_π from σ_L**
- **JLab F_π experiments used the VGL Regge model**
  [Vanderhaeghen, Guidal, Laget, PRC 57, 1454 (1998)]
  - Propagator replaced by π and ρ Regge trajectories
  - Most parameters fixed by photoproduction data
  - 2 free parameters: Λ_π, Λ_ρ
  - At small $-t$, σ_L only sensitive to Λ_π

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

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



The model of: T.K. Choi, K.J. Kong, B.G. Yu [arXiv: 1508.00969]
may soon become available as a second way to extract F_π from data.

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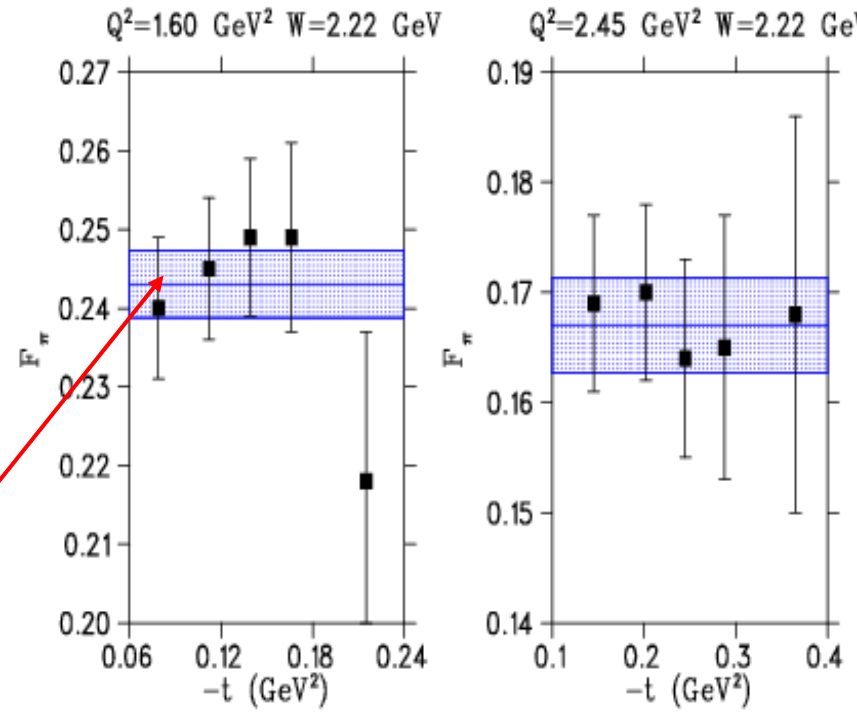
Fπ-2 VGL $p(e,e'\pi^+)n$ model check

- 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.



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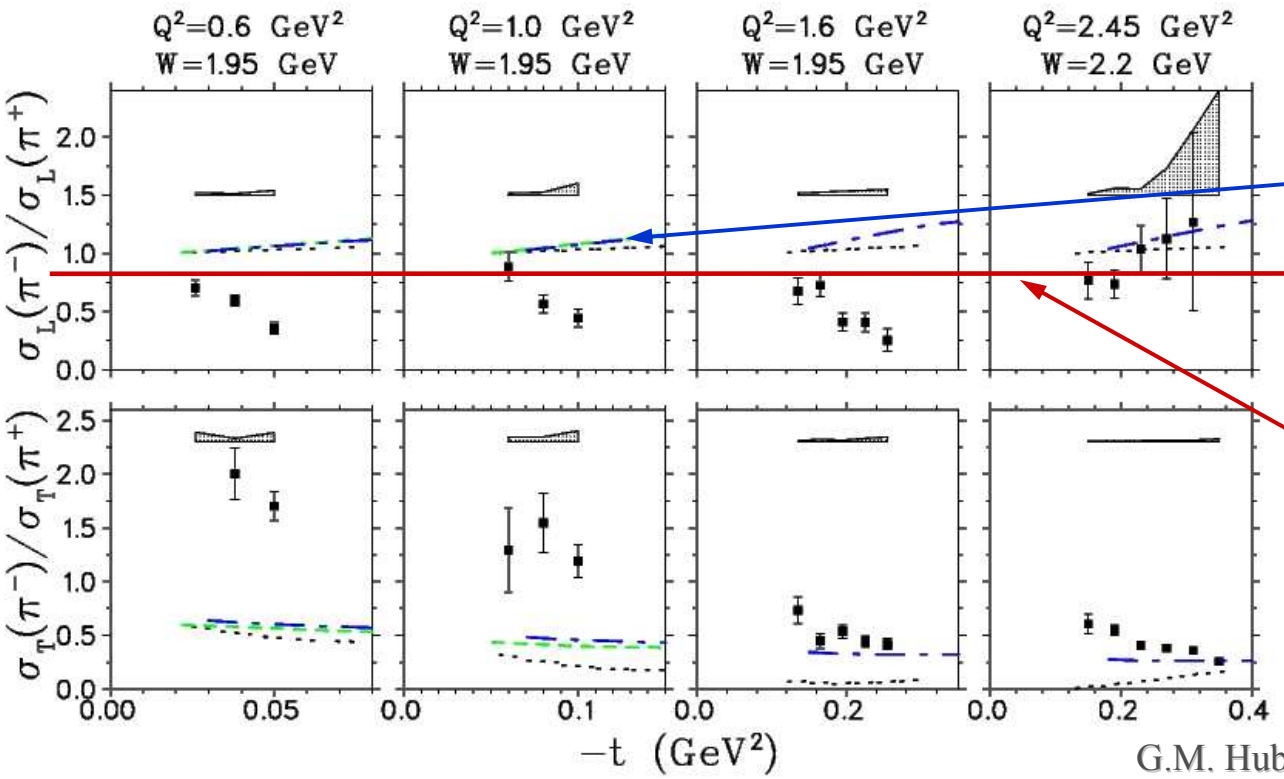
π^-/π^+ data to check *t*-channel dominance

- 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)

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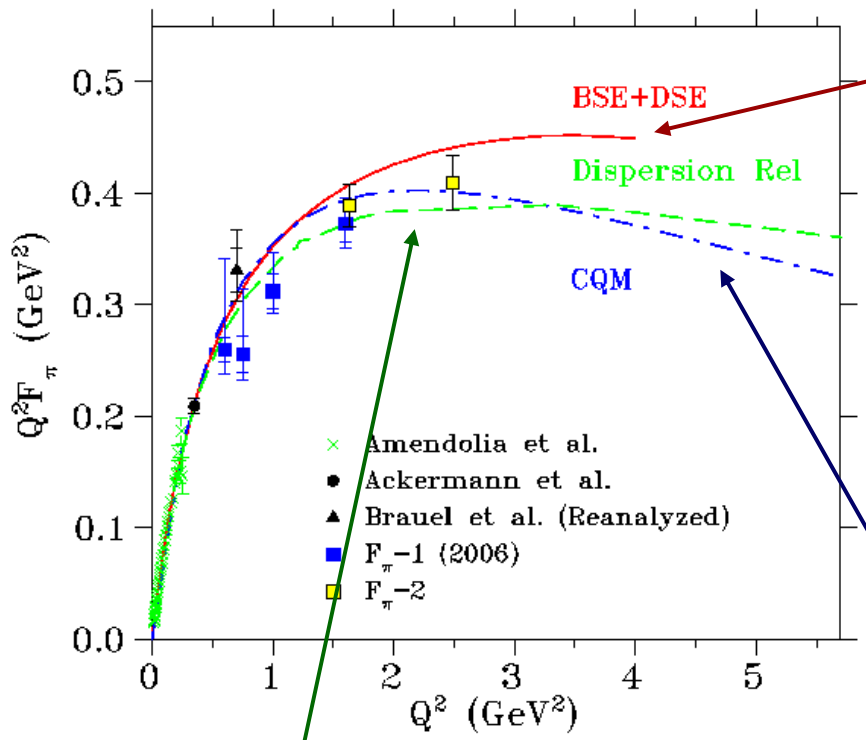
Current Experimental Status

JLab results in a region of Q^2 where model calculations begin to diverge.



Bethe-Salpeter/Dyson-Schwinger:
*[P. Maris and P. Tandy, Phys.Rev.C **62**(2000)055204]*

- B-S equation is conventional formalism for relativistic bound states.
- D-S expansion in terms of dressed quark propagators, consistent w/ confinement.
- Model parameters fixed from f_π and m_π, then r_π and F_π predicted.

Constituent Quark Model:
*[C-W. Hwang, Phys.Rev.D **64**(2001)034001]*

- Relativistic constituent quarks and effective interaction on the light front
- Consistent treatment of quark spins.
- Wave function parameters determined from f_π and $\pi^0 \rightarrow \gamma\gamma$ decay width, then charge and transition FF's and π^0 branching ratios predicted.

Disperson Relation with QCD Constraint:
*[B.V. Geshkenbein, Phys.Rev.D **61**(2000)033009]*

- Uses constraints posed by **causality** and **analyticity** to relate the timelike and spacelike domains of the pion form factor on the complex plane.
- Additional constraints, such as behavior of F_π in asymptotic region, imposed.

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

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12 GeV era – Hall C with SHMS and HMS

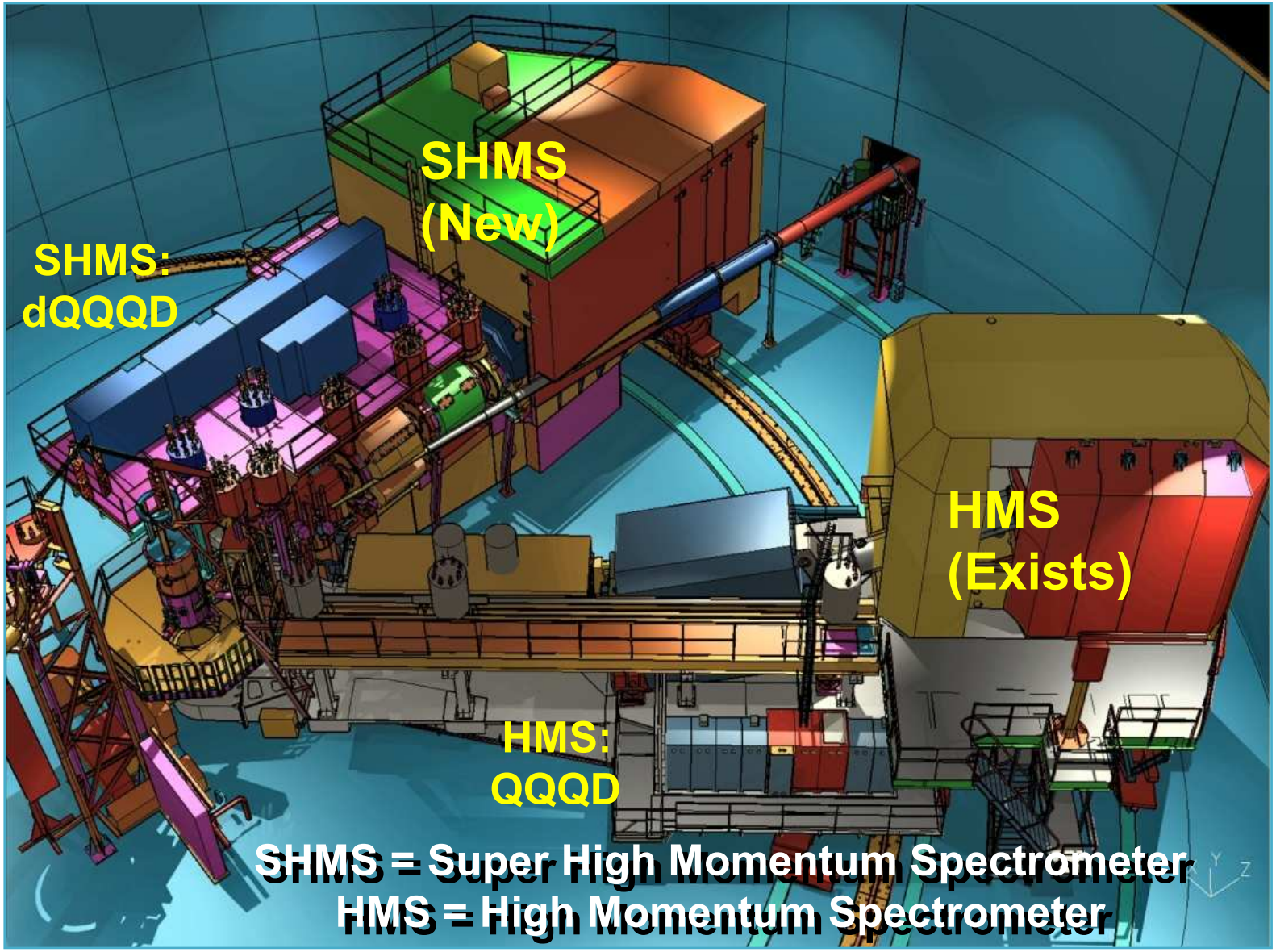
SHMS:
- 11 GeV/c Spectrometer
- Partner of existing 7 GeV/c **HMS**

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
- All derived from existing HMS/SOS detector designs

Well-Shielded Detector Enclosure

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



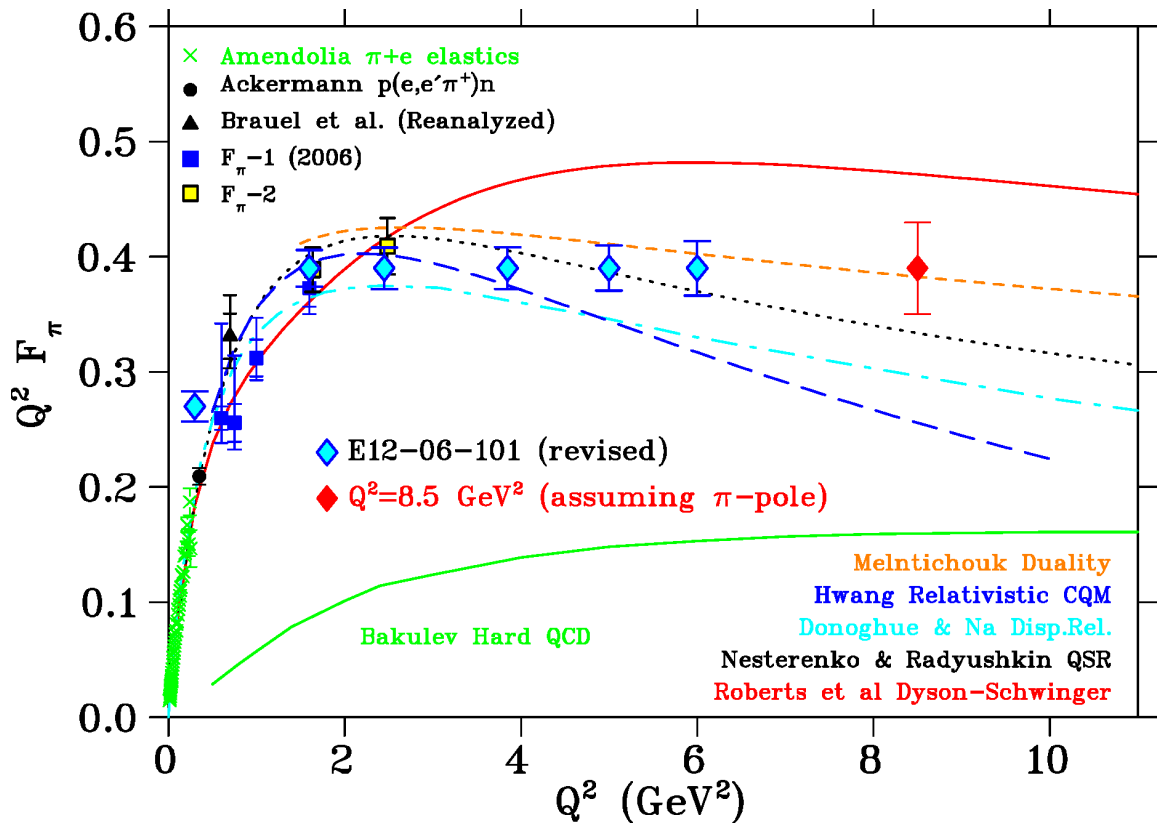
$F_\pi(Q^2)$ after JLab 12 GeV Upgrade

JLab 12 GeV upgrade will allow measurement of F_π up to $Q^2 = 6 \rightarrow 8.5\ GeV^2$

No other facility worldwide can perform this measurement.

New overlap point at $Q^2=1.6$ 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 π+e data.



Approved with "A" scientific rating and identified by JLab PAC41 as "high impact". (E12-06-101: GH, D. Gaskell, spokespersons)

Extension to Q^2=8.5 GeV^2 submitted to PAC44 (GH, D. Gaskell, T. Horn, spokespersons)

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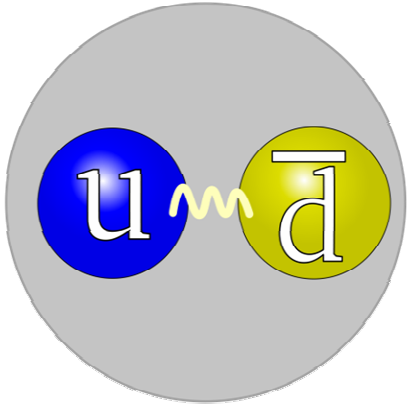
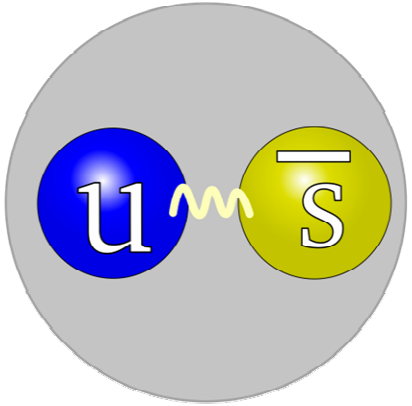
The Charged Kaon – a second QCD test case



π^+



K^+

- 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.

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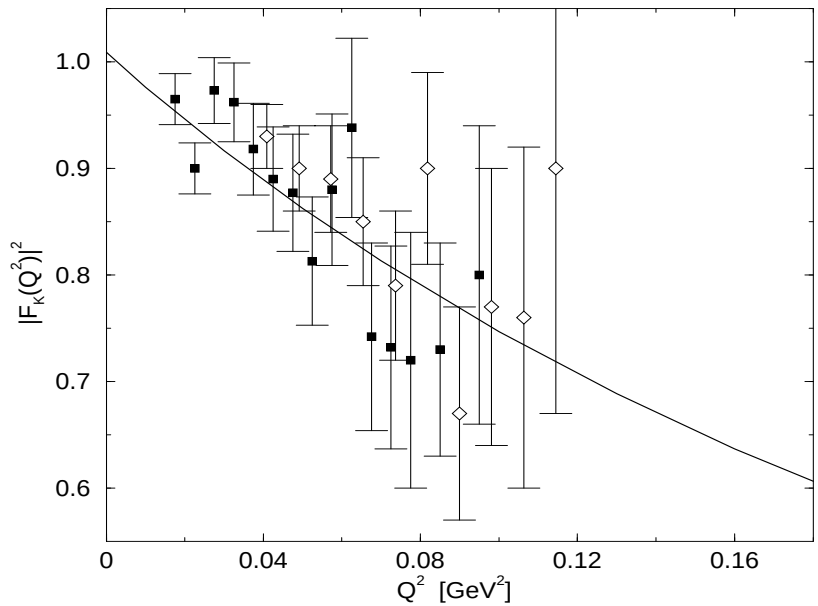
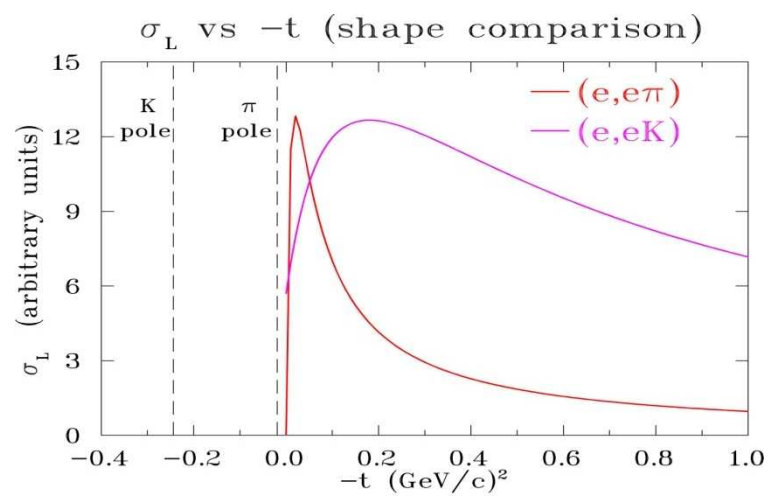
Measurement of K^+ Form Factor

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

  [Amendolia et al, PLB 178, 435 (1986)]

- 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.
- Can we demonstrate that the "pole" term dominates the reaction mechanism?





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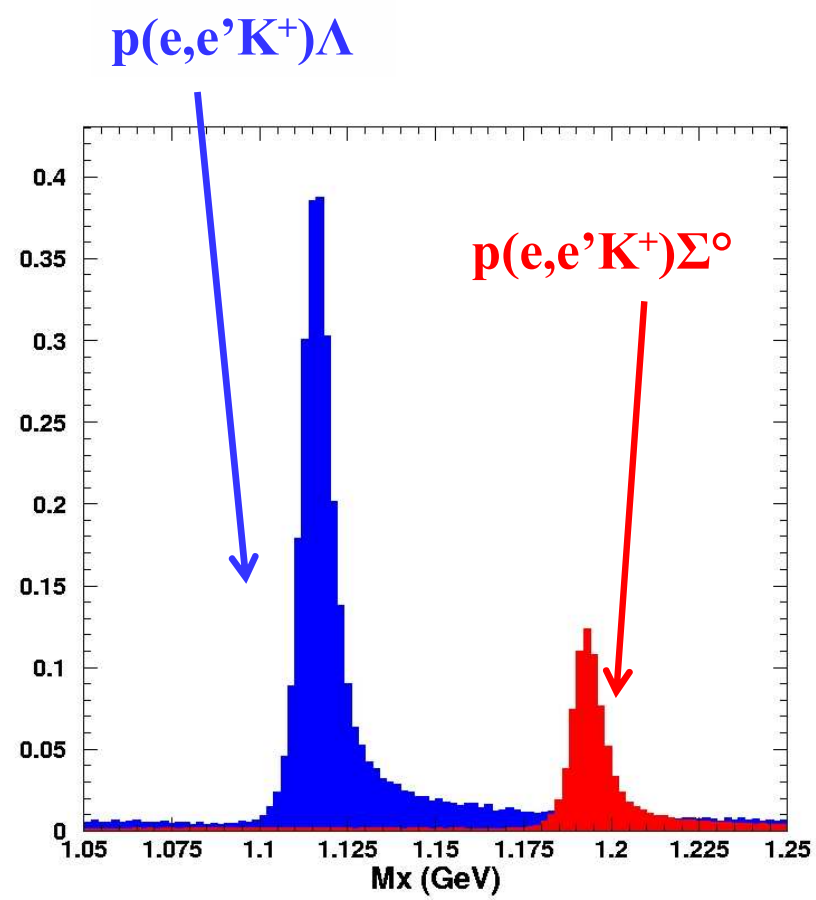
Isolate Exclusive Final States via Missing Mass

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

- SHMS+HMS missing mass resolution expected to be very good.
- 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.



Simulation at Q^2=2.0 GeV^2 , W=3.0 and high ε

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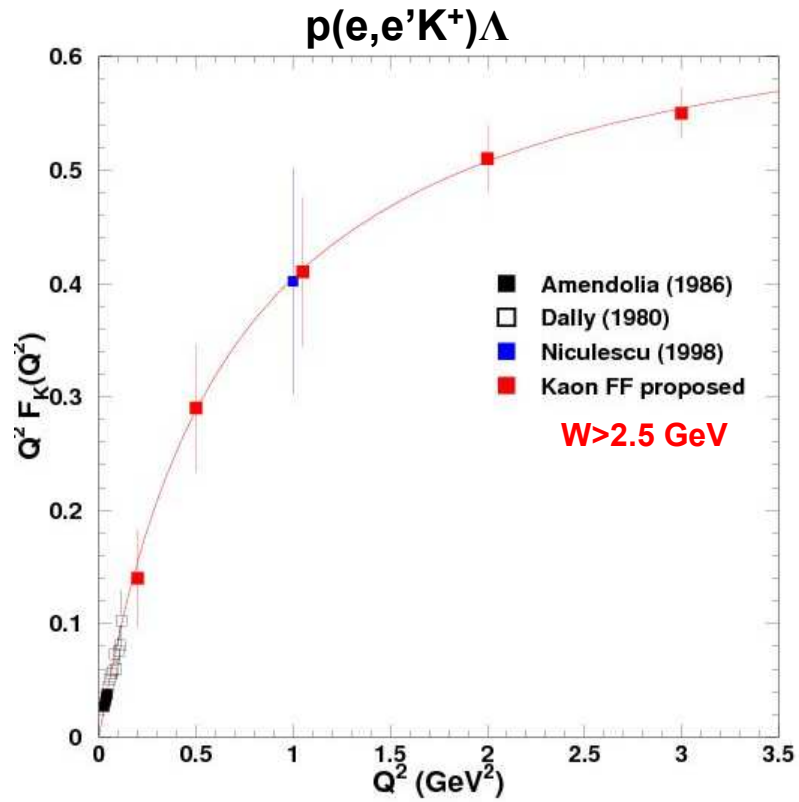
Projected Uncertainties for K^+ Form Factor

- 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 $q\bar{q}$ system for theoretical models, this time involving a strange quark.



For VGL/Regge calculation, assume Λ^2_K=0.67 GeV^2, and $\Lambda^2_{K^*}$=1.5 GeV^2,

Scheduled as an early SHMS commissioning experiment: LT-separation. (E12-09-011: T. Horn, G. Huber and P. Markowitz, spokespersons)

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Hall C Meson Form Factors Timeline

SHMS superconducting magnet installation and testing	Until Sept, 2016
SHMS front detector installation	July – Aug, 2016
Hall C Experimental Readiness Review	Aug 22 – 23, 2016
SHMS commissioning with beam	Dec 6 – 21, 2016
First physics-quality runs in Hall C	Feb 11 – May 7, 2017
First p(e,e'K+) run	May 31 – June 20, 2017

Data Reconstruction Software (hcana)

- Z. Ahmed (PDF), completed

SHMS Detector Checkout & Commissioning

- W. Li (Ph.D.), S. Basnet (M.Sc.), work underway

p(e,e'K^+)Λ Kaon Form Factor

- L/T commissioning experiment (2017 – 2018)

Pion Form Factor and π^+ QCD-Scaling Experiments

- Interleaved run-plans (2018 – 2020)

Regina Efforts

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