Meson Form Factors

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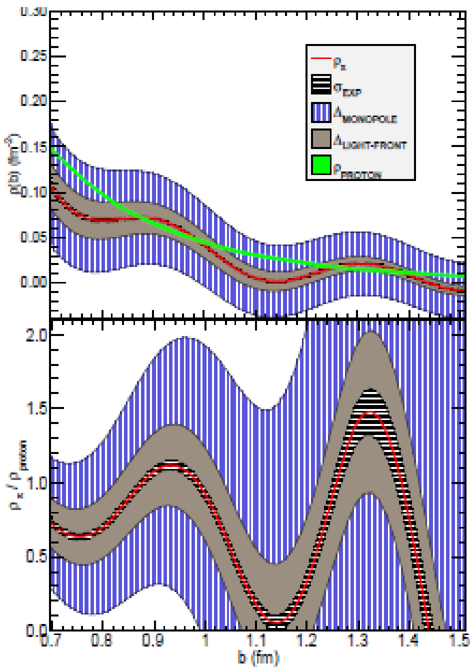
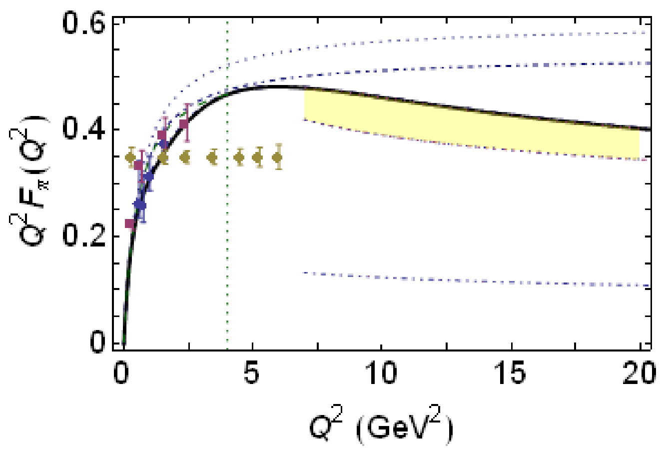
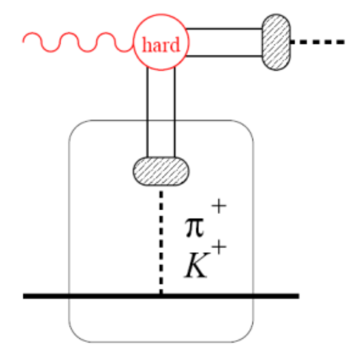


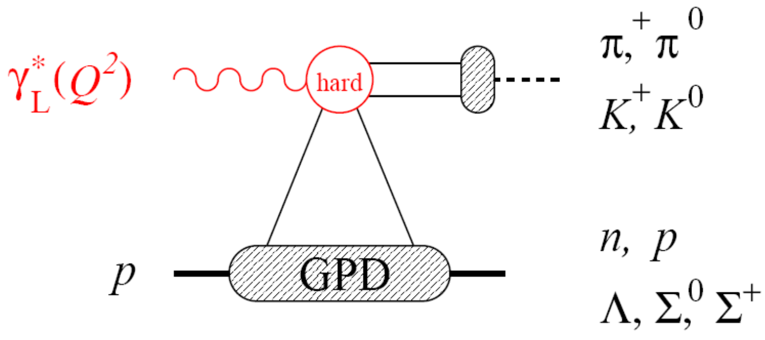




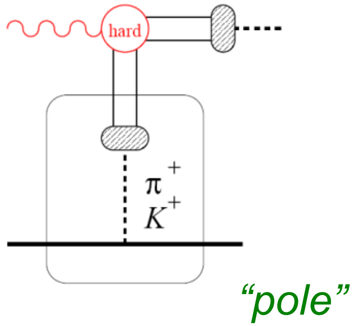
Exclusive Meson Production

$\gamma^* N \rightarrow M + B$

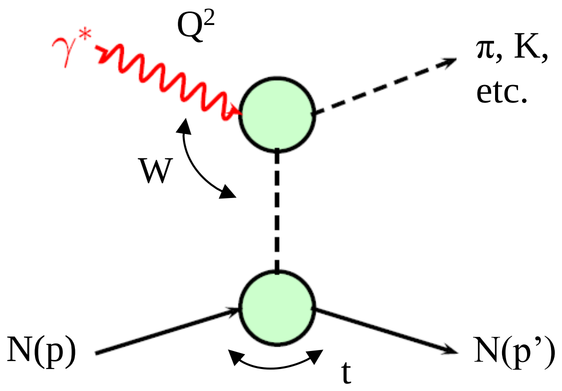
- Hard exclusive meson production is an important tool in mapping nucleon GPDs and exploring other aspects of hadron structure
  - Complementary to the information obtained by DVCS probing specific spin/flavor components
  - Information about meson wave function: size, flavor structure



- Pseudoscalar mesons: π^+, K^+, π^0, η
  - Reaction mechanism tests
  - Pole and non-pole contributions
  - Meson form factor extraction
  - Transverse charge densities from elastic form factors $\int dx\, \rho(x,b)$
  - Quark transversity

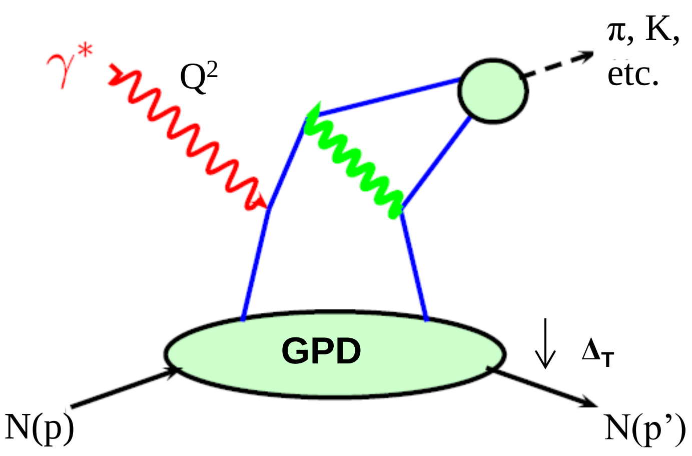


Form Factors and GPDs



t-channel process

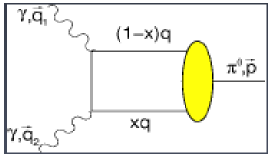
- In the limit of small $-t$, meson production can be described by the t-channel meson exchange (pole term)
  - Spatial distribution described by form factor
  - The Q^2 dependence of the form factor allows for finding a description of hard (pQCD) and soft contributions of the meson wave function



Handbag diagram

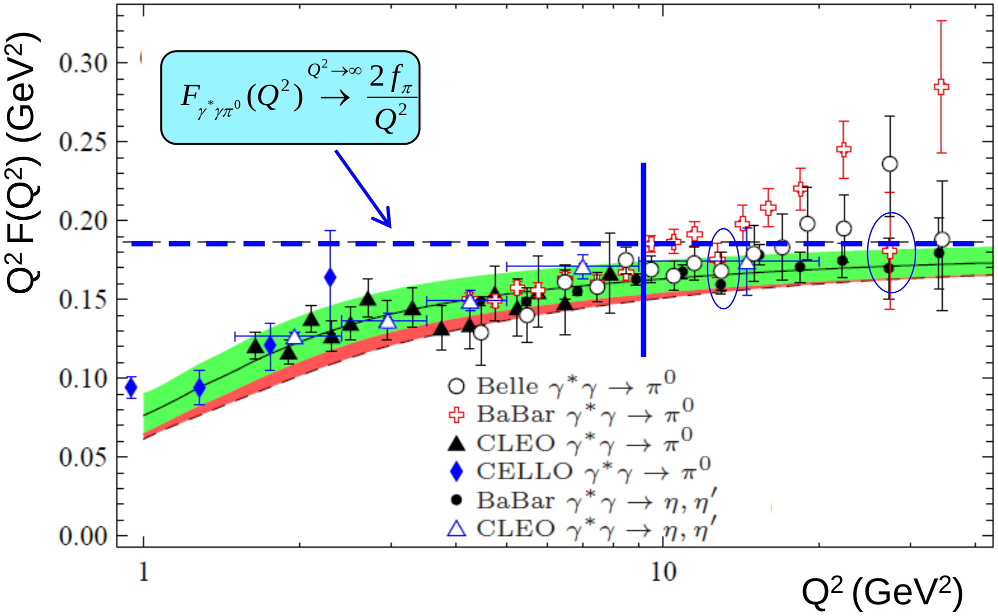
- At sufficiently high Q^2, the process should be understandable in terms of the "handbag" diagram
  - The non-perturbative (soft) physics is represented by the GPDs
    - Shown to factorize from QCD perturbative processes for longitudinal photons *[Collins, Frankfurt, Strikman, 1997]*
    - In this limit only the hardest part of the meson wave function remains

Pseudoscalar Meson Transition Form Factor Data



$$F^{\gamma^*\gamma\pi}(Q^2) = \frac{\sqrt{2} f_\pi}{4\pi^2 f_\pi^2 + Q^2}$$

- ❑ Simplest structure for pQCD analysis
- ❑ Babar data on the $\pi^0 \to \gamma^* \gamma$ TFF showed a continuous rise above the QCD asymptotic limit
- ❑ BELLE measurements are fully consistent with η, η', η TFF and also with QCD scaling
  - Results also agree with BaBar data for Q^2<~9 GeV^2 *[Balakireva, Lucha et al., 12+]*



- ❑ Statistical analysis shows that one cannot predict the trends observed at Belle/Babar from one another *[Stefanis et al. PRD 87 (2013) 094025]*

CELLO [Z.Phys. C49 (1991) 401]

CLEO [Phys. Rev. D57 (1998) 33]

BABAR [Phys. Rev. D80 (2009) 052002]

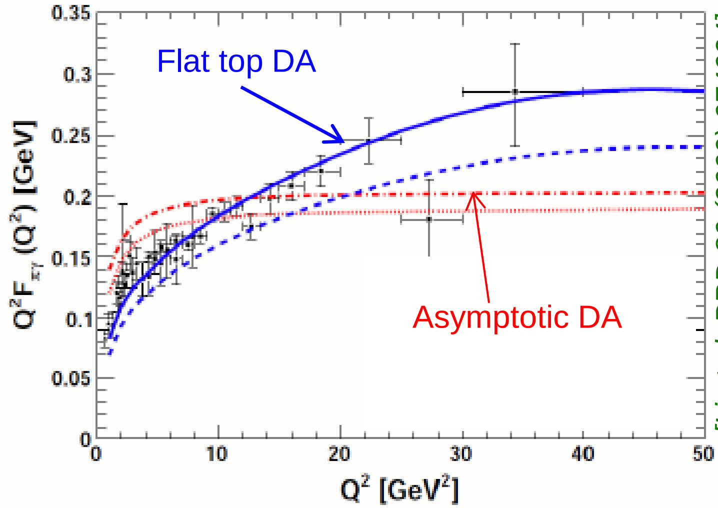
BELLE [Phys. Rev. D86 (2012) 092007]

Opposing tendencies in the data cannot be reconciled until additional data on TFFs and other exclusive processes become available

Transition Form Factor and Pion Distribution Amplitude (DA)

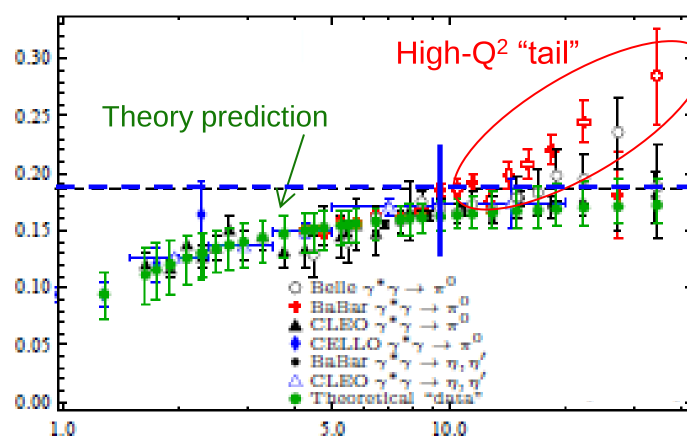
$\pi^0 \to \gamma^* \gamma$

- Nonperturbative info about mesons is summarized in the DA - comparison with pQCD gives info on the shape, different trends in TFF due to DA endpoint character
  - Asymptotic distribution does not describe all the existing data
  - "Flat-top" DA best agreement with Babar but cannot be reconciled with standard QCD framework based on collinear factorization



[Li et al. PRD 80 (2009) 074024]

- Within standard QCD approach the BMS-like pion DA gives good agreement with global data
  [A. Bakulev et al., PL B578 (2004), 91; PR D73 (2006) 056002]
  - Consistent with basic features of the η TFFs implying *strong end point suppression*
  - However, cannot describe the high-Q^2 tail of the Babar data requiring *end point enhancement*

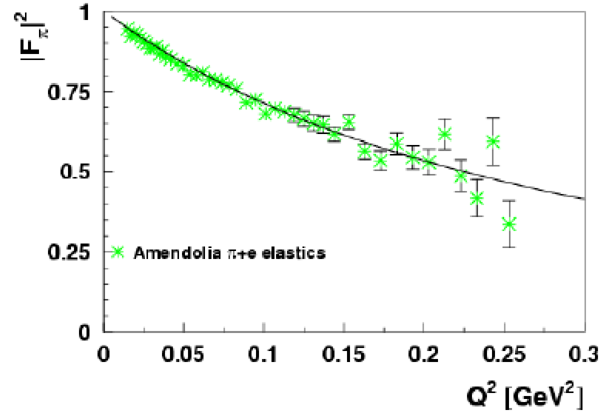


[Stefanis et al. PRD 87 (2013) 094025]

Additional pion data on components of the DA could help understanding the underlying mechanism of the large Q^2 enhancement

Measurement of π^+ Form Factor

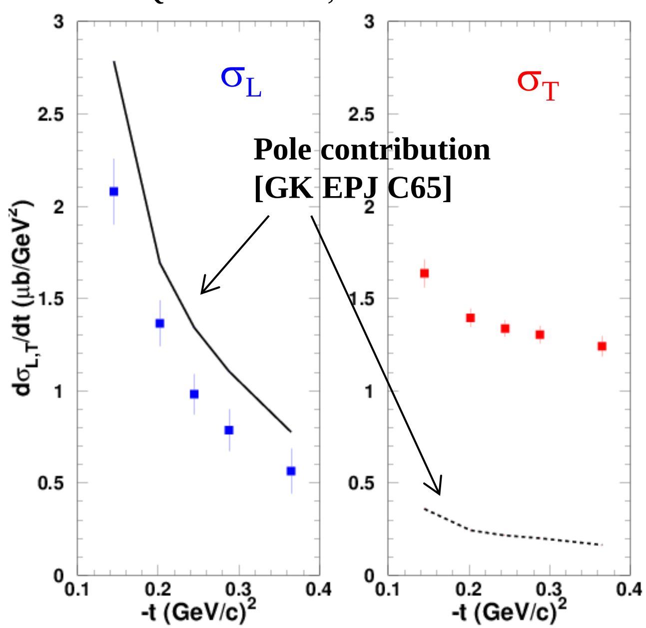
- At low Q^2, $F_{\pi+}$ can be measured directly via high energy elastic π^+ scattering from atomic electrons
  - CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV^2 *[Amendolia et al, NPB277,168 (1986)]*
  - These data used to constrain the pion charge radius: $r_\pi = 0.657 \pm 0.012$ fm

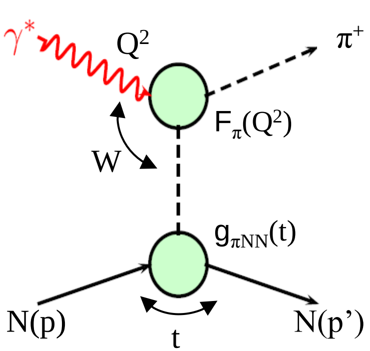


- At larger Q^2, $F_{\pi+}$ must be measured indirectly using the "pion cloud" of the proton via the *$p(e,e'\pi^+)n$ process*
  - At small $-t$, the pion pole process dominates σ_L

[Kroll/Goloskokov EPJ C65 (2010), 137]

Q^2=2.45 GeV^2, W=2.2 GeV

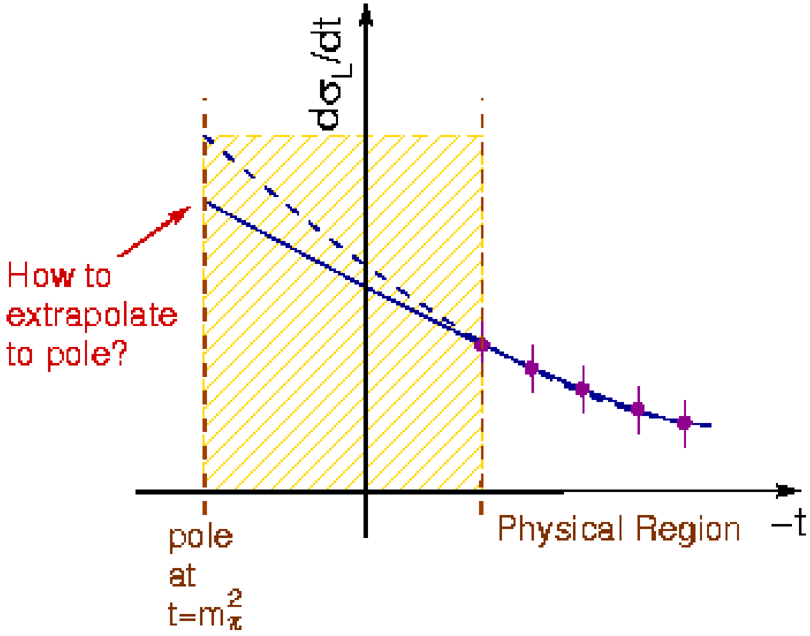




$$\frac{d\sigma_L}{dt} \propto \frac{-t}{(t-m_\pi^2)} g_{\pi NN}^2(t) Q^2 F_\pi^2(Q^2,t)$$

Determine F_π from data: Chew-Low Extrapolation Method

- *p(e,e'π^+)n* data are obtained a distance away from the $t = m_\pi^2$ pole
  - "*Chew-Low*" extrapolation method requires knowing the analytical dependence of $d\sigma_L/dt$ through the unphysical region



- Extrapolation method last used in 1972 by Devnish & Lyth *[PRD 5, 47]*
  - Very large systematic uncertainties
  - Fails to produce reliable results – different polynomial fits equally likely in physical region give divergent form factor values when extrapolated to $t = m_\pi^2$

Chew-Low method is not used in F_π extractions anymore

Only reliable method is to use a model incorporating the π^+ mechanism and the spectator nucleon to extract F_π from σ_L

F_π from σ_L data using VGL/Regge model

JLab F_π experiments used the VGL Regge model as it has proven to give a reliable description of σ_L across a wide kinematic domain

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

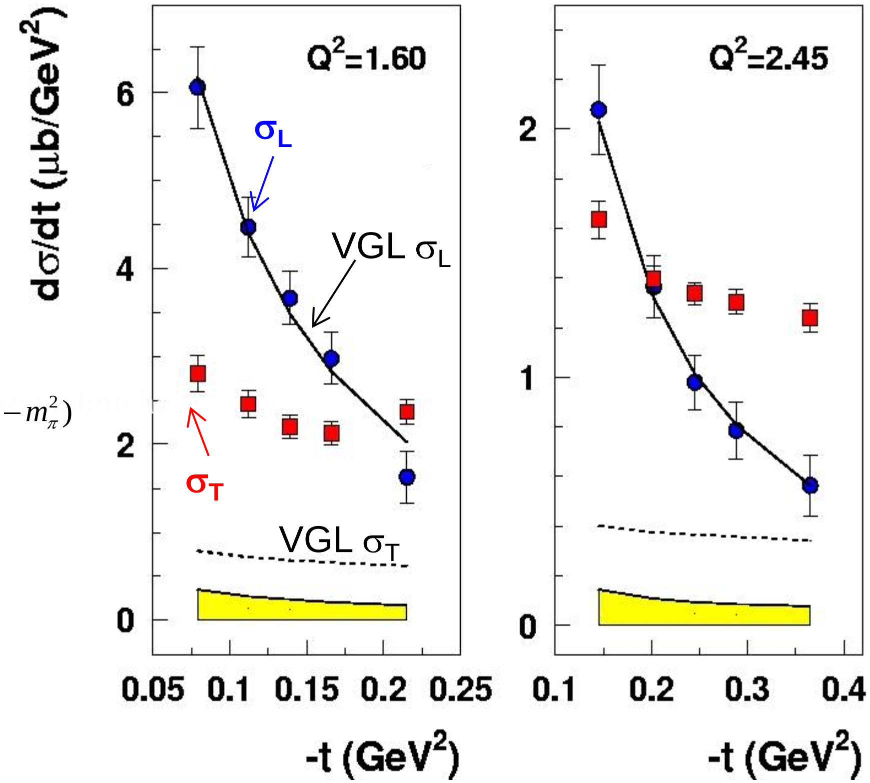
- Feynman Propagator replaced by π and ρ Regge trajectories $\alpha_\pi(t) = \alpha'_\pi(t - m_\pi^2)$

$$\left(t - m_\pi^2\right)^{-1} \Rightarrow \frac{\pi\alpha'_\pi}{2}\left(\alpha_\pi(t)+1\right)\frac{1+\exp[-i\pi\alpha_\pi(t)]}{\sin \pi\alpha_\pi(t)}\left(\frac{W}{W_0}\right)^{2\alpha_\pi(t)}$$

- Model parameters fixed by pion photoproduction data
- Free parameters (trajectory cutoff): Λ_π, Λ_ρ

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

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



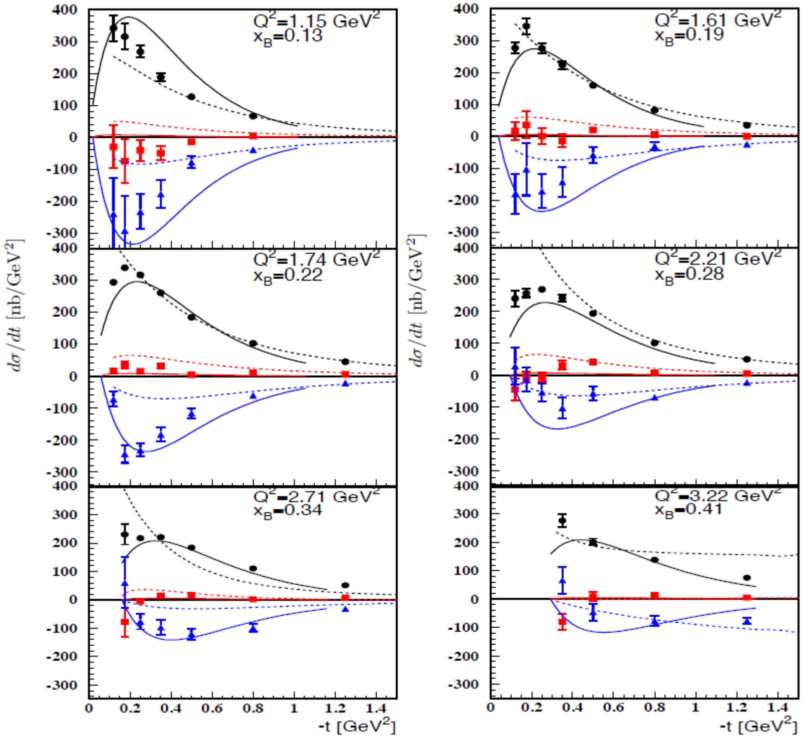
[Horn et al, PRL97, 192001,2006]

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

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

Transverse Contributions

- Recent data suggest that transversely polarized photons play an important role in charged and neutral pion electroproduction
  - *HALL C π^+:* σ_T magnitude is large even at Q^2=2.5 GeV^2
  - HERMES π^+: sin ϕ_s modulation is large
    [Airapetian et al, Phys. Lett. B 682, 345 (2010)]
  - CLAS: π^0 data show substantial fraction of σ_{TT} in the *unseparated* cross section



[Bedlinskiy et al, PRL109, (2012) 109; *arXiv:1405.0988 (2014)]*

- Measurements of relative σ_L and σ_T contributions to the π cross section to higher Q^2 planned for JLab 12 may shed light on this

- Considerable theoretical interest also related to extraction of GPDs
  - Goloskokov, Kroll, EPJ C65, 137 (2010); EPJ A45, 112 (2011)
  - Kaskulov, Mosel, PRD 81 (2010) 045202
  - Bechler, Mueller, arXiV:0906.2571 (2009)
  - Faessler, Gutsche, Lyubovitskij, Obukhovsky, PRC 76 (2007) 025213

- More models would allow to better understand model dependence of F_π

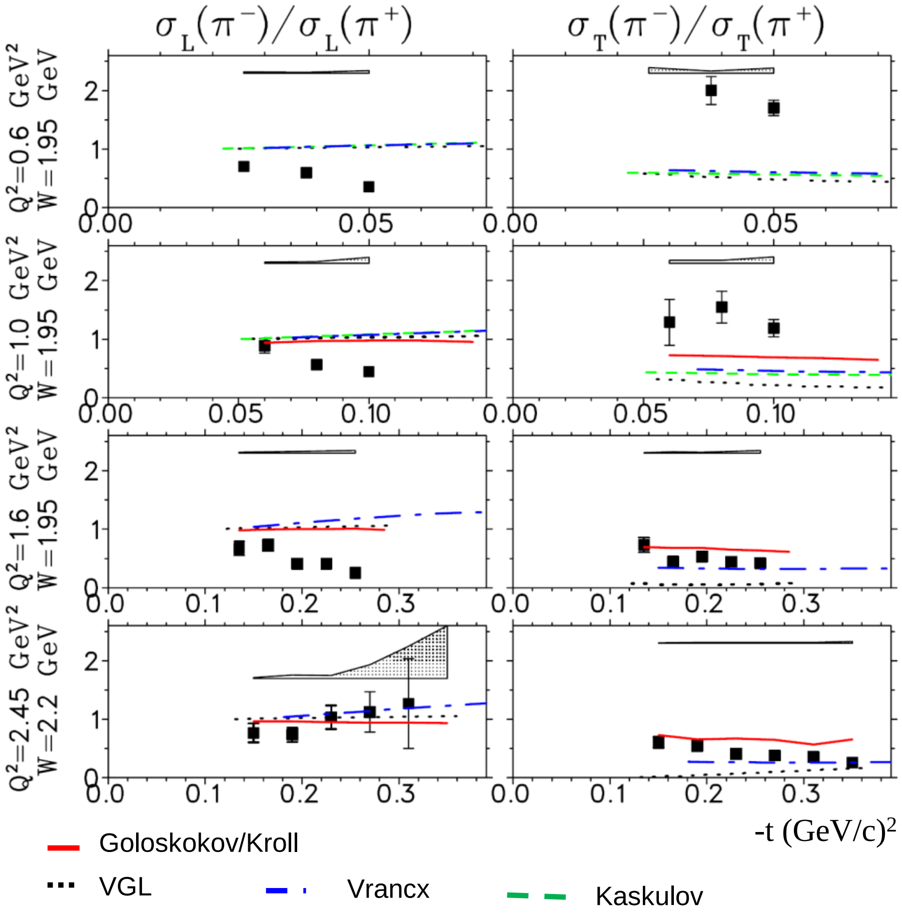
Experimental check of t-channel dominance in σ_L

- 2H target L/T separations
  - JLab 6 GeV data

- π^+ *t*-channel diagram is pure isovector (G-parity conservation)

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

- Isoscalar backgrounds like $b_1(1235)$ contributions to *t*-channel will dilute the ratio



[Huber et al, PRL112 (2014)182501]

R_L data consistent with pion-pole dominance

R_T data *t*-dependence shows rapid fall-off consistent with *s*-channel quark knockout

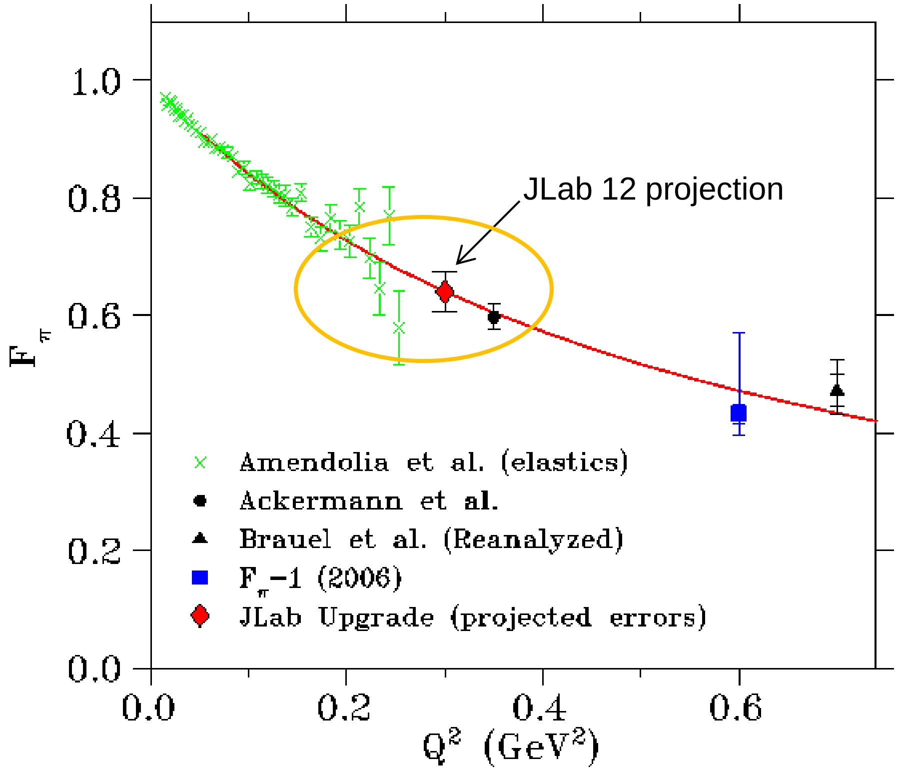
Electroproduction method consistency check

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

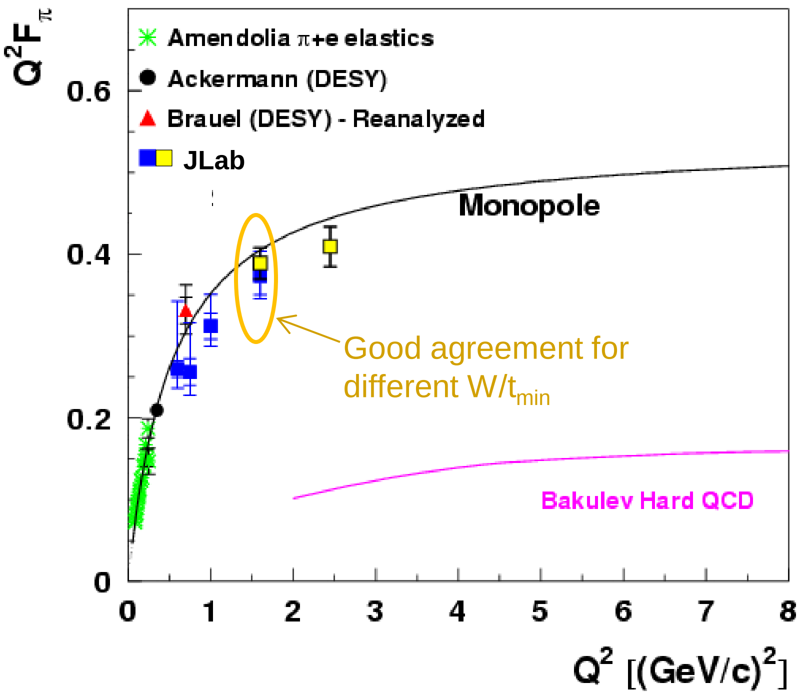
- Method passes check: Q^2=0.35 GeV^2 data from DESY consistent with limit of elastic data within uncertainties

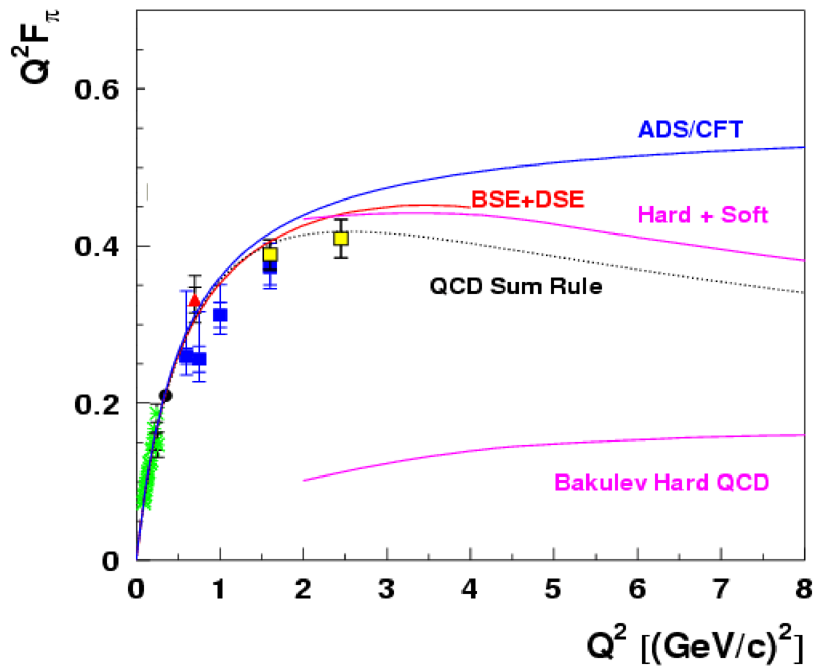
[H. Ackernman et al., NP B137 (1978) 294]

- More detailed tests planned with future 12 GeV experiment taking data at 50% lower –*t* (0.005 GeV^2)



$F_{\pi+}(Q^2)$ in 2014





- Far from asymptotic limit
  - Consistent with timelike meson form factor data which show no asymptotic behavior up to Q^2=18 GeV^2 *[Seth et al, PRL,110 (2013) 022002]*
- Best described by a combination of monopole ***and*** dipole forms

- Several effective models do a good job describing the data

[Brodsky and de Teramond, PRD 77 (2008) 056007]

*[Maris and Tandy, Phys. Rev. **C62**, 055204 (2000)]*

*[Nesterenko and Radyushkin, Phys. Lett. **B115**, 410(1982)]*

*[A.P. Bakulev et al, Phys. Rev. **D70** (2004)]*

Pion Transverse Charge Density

$$F_\pi(Q^2) = A \cdot \frac{1}{(1+B\cdot Q^2)} + (1-A)\cdot\frac{1}{(1+C\cdot Q^2)^2}$$

- Provides an interpretation of EM form factors in terms of physical charge and magnetization densities

$$\rho_\pi(b) = \frac{1}{\pi R^2}\sum_{n=1}^{\infty} F_\pi(Q_n^2)\frac{J_0(X_n \frac{b}{R})}{[J_1(X_n)]^2}$$

$$Q_n \equiv \frac{X_n}{R}$$

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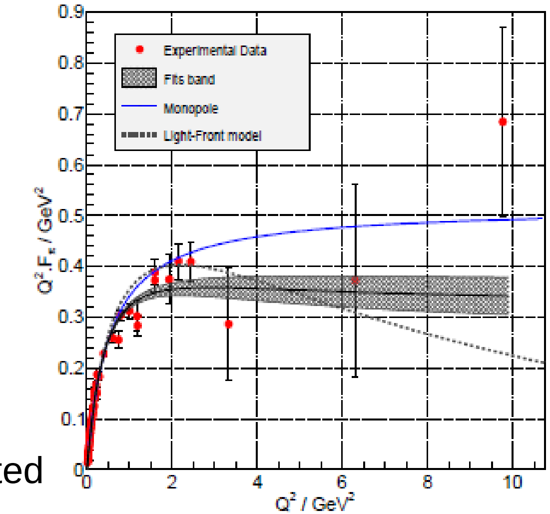
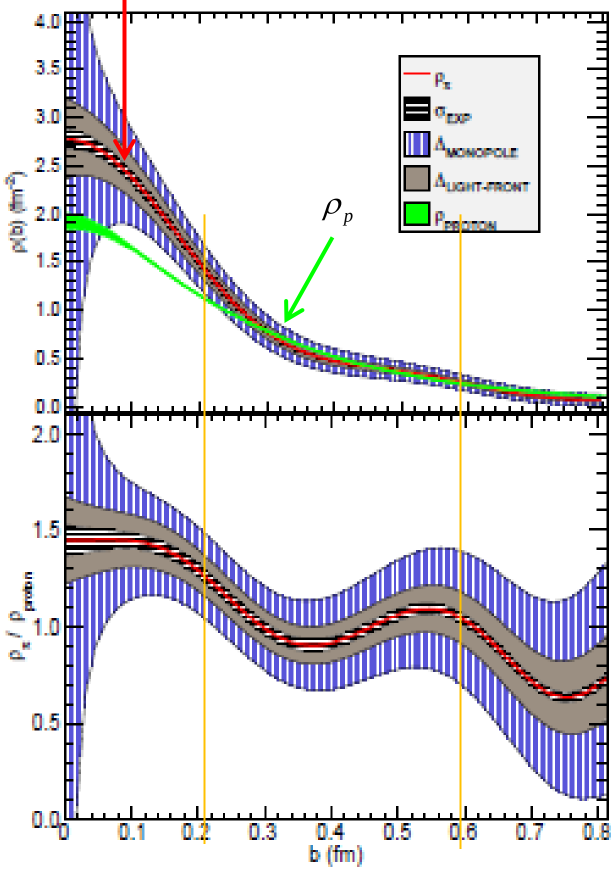


- Finite Radius Approximation

[S. Venkat et al., PRC 83 (2011) 015203]

- *Incompleteness error* due to limited data – estimate using models
  - Upper bound: monopole
  - Lower bound: Light front model

2D Fourier Transform

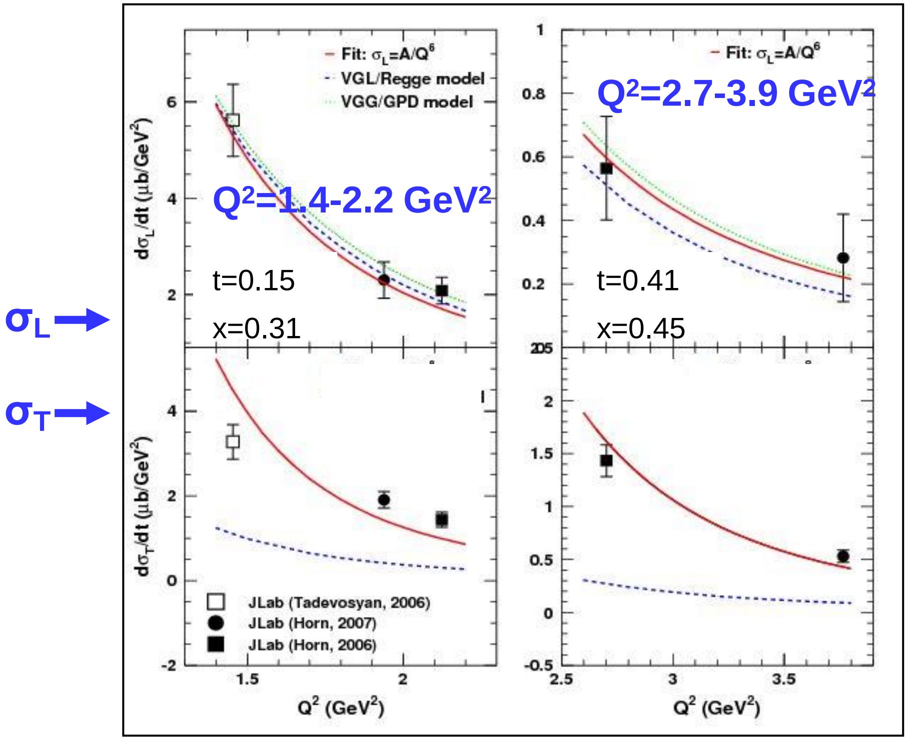


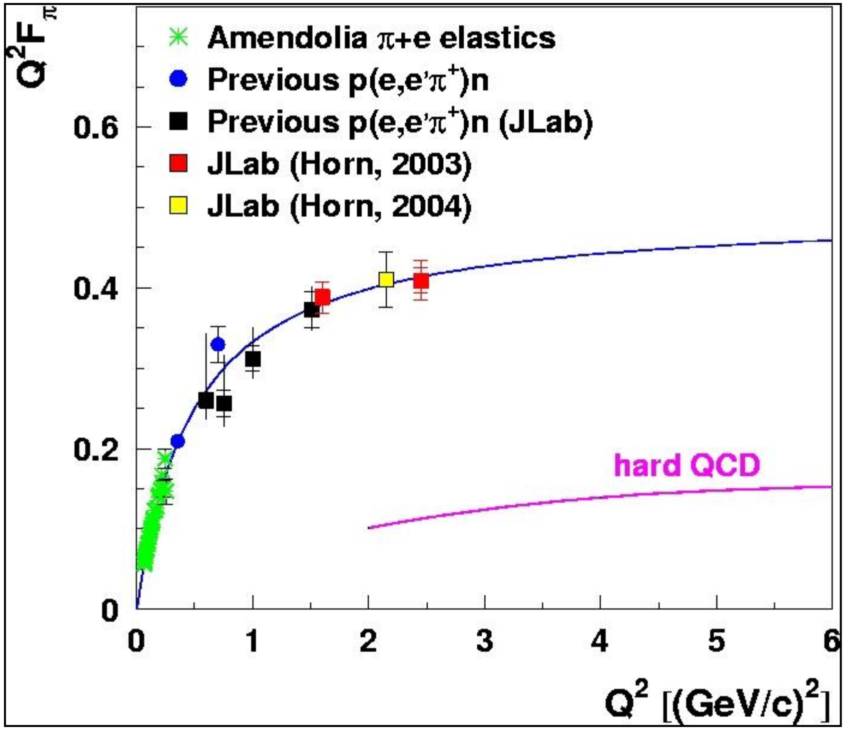
[M. Carmignotto et al., arXiv.1404.1539 (2014)]

- Pion charge density is larger than proton for b<0.2 fm - expected
- Pion and proton densities coalesce for 0.3 fm < b < 0.6 fm – *not* expected

Pion Form Factor – a QCD factorization puzzle?

[T. Horn et al., Phys. Rev. C78, 058201 (2008)]





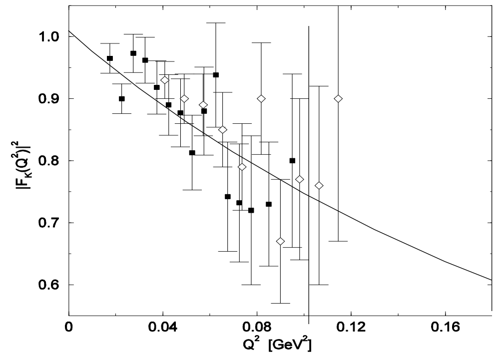
- The QCD scaling prediction ($\sigma_L \sim Q^{-6}$) is reasonably consistent with recent 6 GeV JLab π^+ σ_L data, *but* σ_T does not follow the scaling expectation ($\sigma_T \sim Q^{-8}$)

- Q^2 dependence of F_π follows prediction from pQCD, suggests factorization holds
- Different magnitudes imply that factorization does not hold or something is missing in calculation

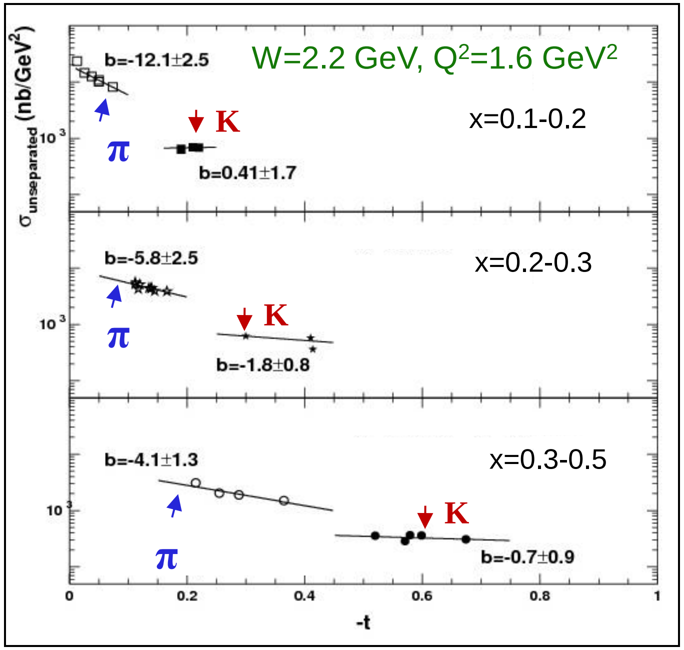
Further information on the pion puzzle through varying the system

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***? – *need to quantify the role of the kaon pole*



[T. Horn, Phys. Rev. C85 (2012) 018202]

- Unseparated data: pion t-dependence is steeper *at* low *t* than for kaons
  - pole factor $(m_{K,\pi}^2 - t)^{-1}$ gives less enhancement for kaons
- However, the kaon pole is expected to be strong enough to produce a maximum in σ_L

[Kroll/Goloskokov EPJ A47 (2011), 112]

Additional low t data would allow to interpret pole contribution for kaons

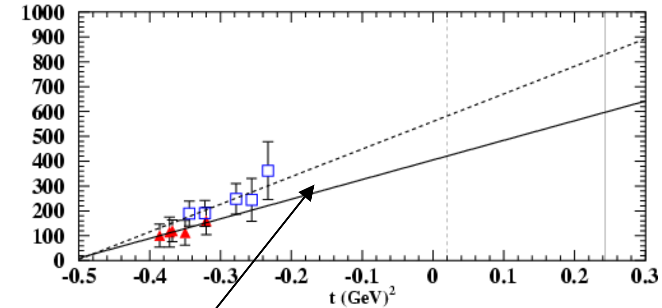
Kaon Form Factor in 2014

- JLAB experiment E93-018 extracted –*t* dependence of K^+ longitudinal cross section near $Q^2=1$ GeV^2
- A trial kaon form factor extraction was attempted using a simple Chew-Low extrapolation method

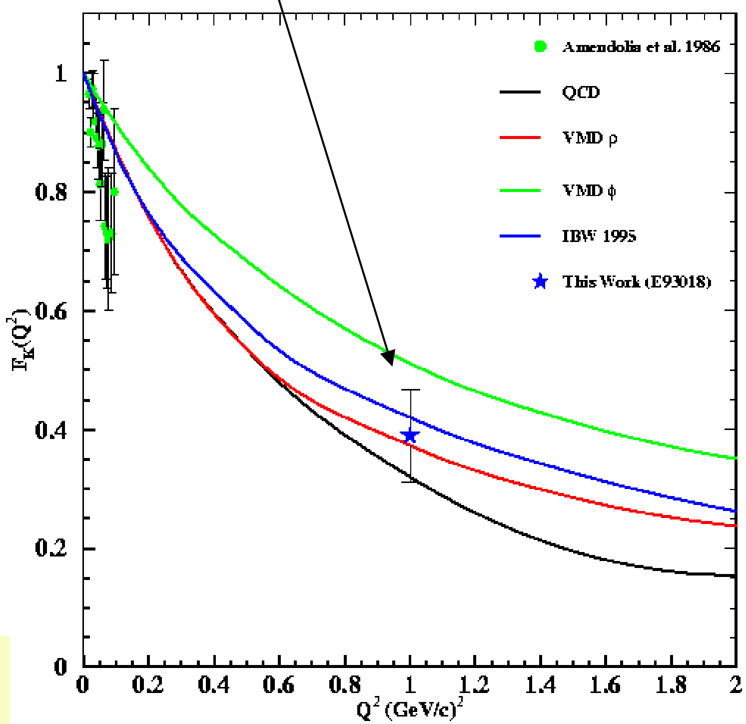
$$\sigma_L \approx \frac{-2tQ^2}{(t-m_K^2)^2} k(eg_{K\Lambda N})^2 F_K^2(Q^2)$$

  - $g_{K\Lambda N}$ poorly known
    - Assume form factor follows monopole form
    - Use measurements at $Q^2=0.75$ and 1 GeV^2 to constrain $g_{K\Lambda N}$ and F_K simultaneously
- Extraction shows power of the data, but should not be interpreted (yet?) as real extraction of kaon FF

Work on improved extraction ongoing using a model like in pion case [M. Carmignotto]



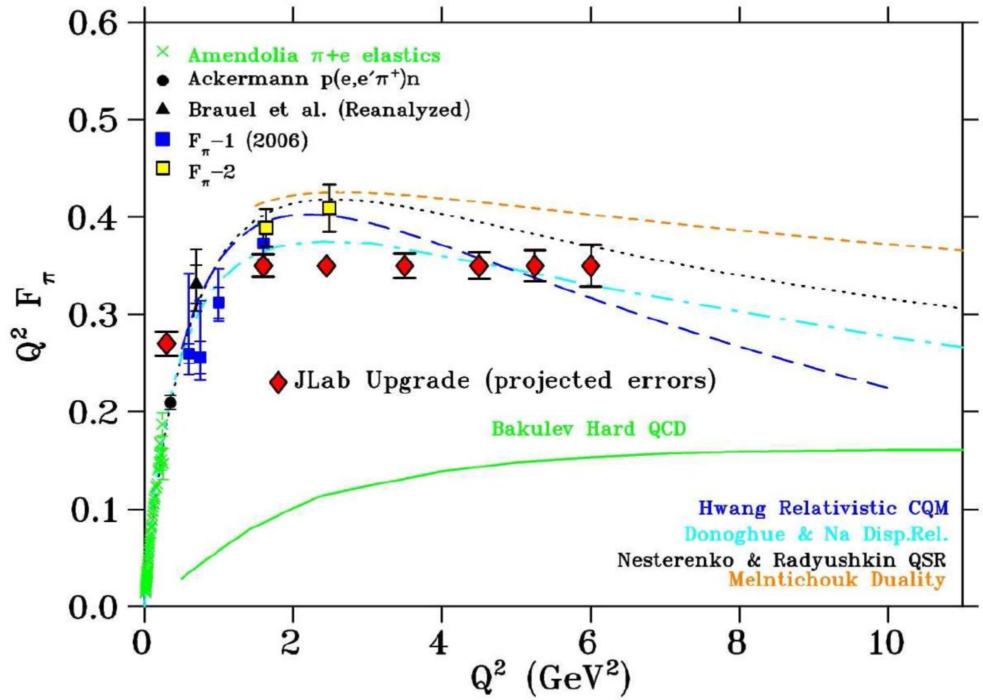
“Chew-Low” type extraction



[G. Niculescu, PhD. Thesis, Hampton U.]

JLab 12 GeV: Pion Electroproduction Experiments

- ❑ ***E12-06-101***: CEBAF 10.9 GeV electron beam and SHMS small angle capability allow for determining F_π up to Q^2=6 GeV^2 in a dedicated experiment
  - Require t_{min}<0.21 GeV^2 and $\Delta\varepsilon$>0.25 for L/T separation
  - Approved with A priority in 2010



E12-06-101 spokespersons: G. Huber, D. Gaskell

- ❑ ***E12-07-105***: Primary goal L/T separated cross section data to highest possible Q^2~9 GeV^2 with SHMS/HMS to investigate hard-soft factorization
  - Approved with A- priority in 2011

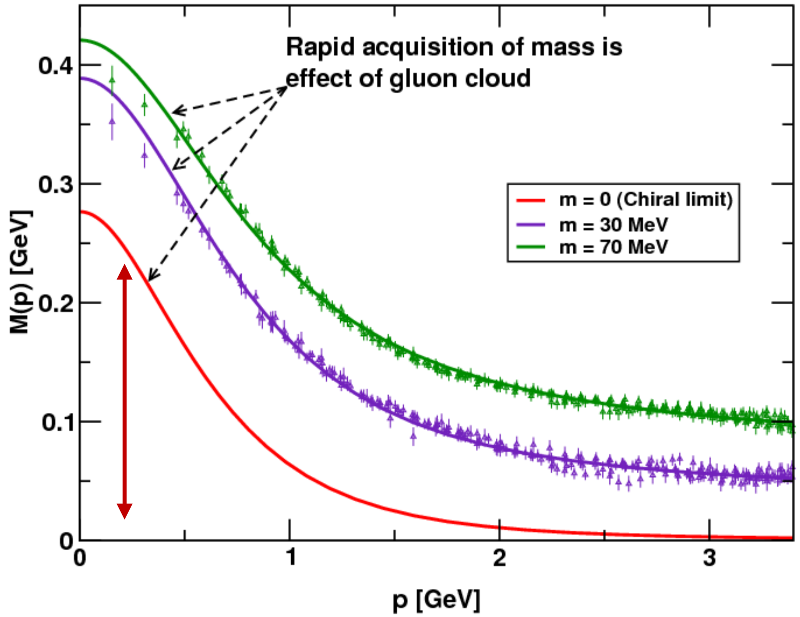
Interesting prospect: Pion valence-quark Distribution Amplitude

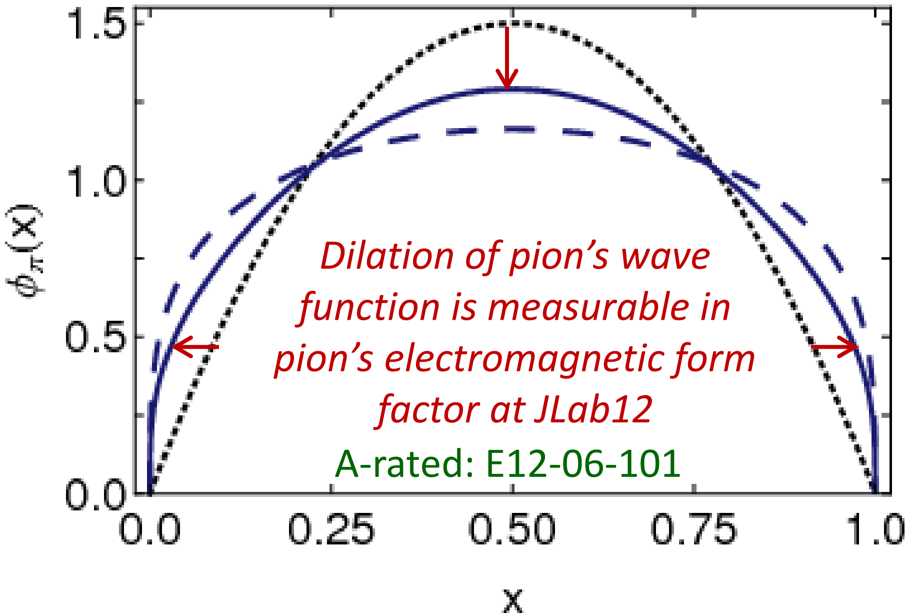
C.D. Roberts, [Prog. Part. Nucl. Phys. 61 (2008) 50]

Slides based on C.D. Roberts, BARYONS 2013

[Lei Chang, et al., PRL 111 (2013) 141802; PRL 110 (2013) 1322001]

$$S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}$$





- one-to-one connection between Dynamical Chiral Symmetry Breaking and the point-wise form of the pion's wave function.
- Dilation measures the rate at which dressed-quark approaches the asymptotic bare-parton limit
- Experiments at JLab12 can empirically verify the behavior of *M(p)*, and hence chart the IR limit of QCD

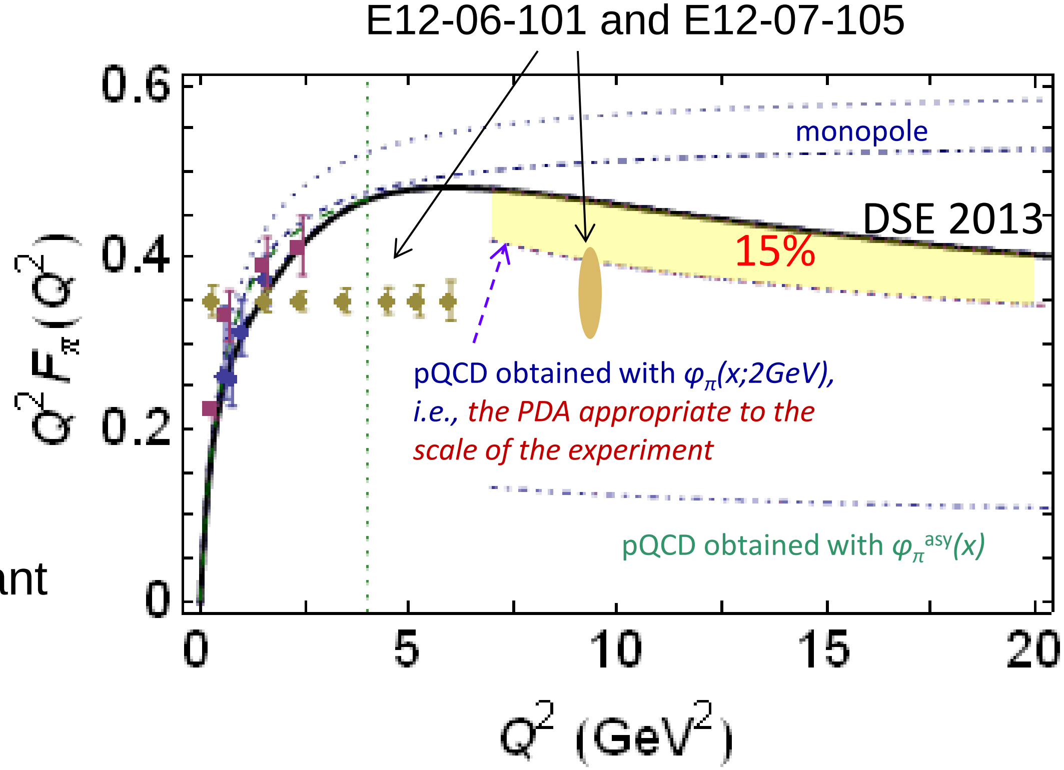
Interesting prospect: Pion Form Factor

Slides based on C.D. Roberts, BARYONS 2013

[Lei Chang, et al., PRL 111 (2013) 141802; PRL 110 (2013) 1322001]

- Prediction of pQCD obtained when the pion valence-quark DA has the form appropriate to the scale accessible in modern experiments is very different from the result obtained using the asymptotic DA

- Near agreement between the relevant pQCD prediction and DSE-2013 prediction is interesting

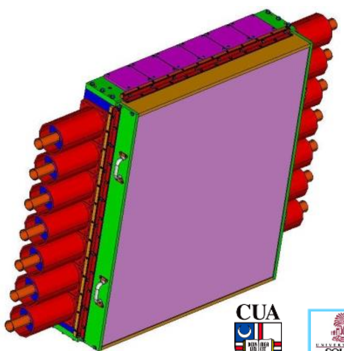


- Expect dominance of hard contributions to the pion form factor for $Q^2 > 8$ GeV^2
  - Kinematic regime covered by JLab 12 experiments E12-06-101 and E12-07-105

JLab 12 GeV: Plans for kaon experiments

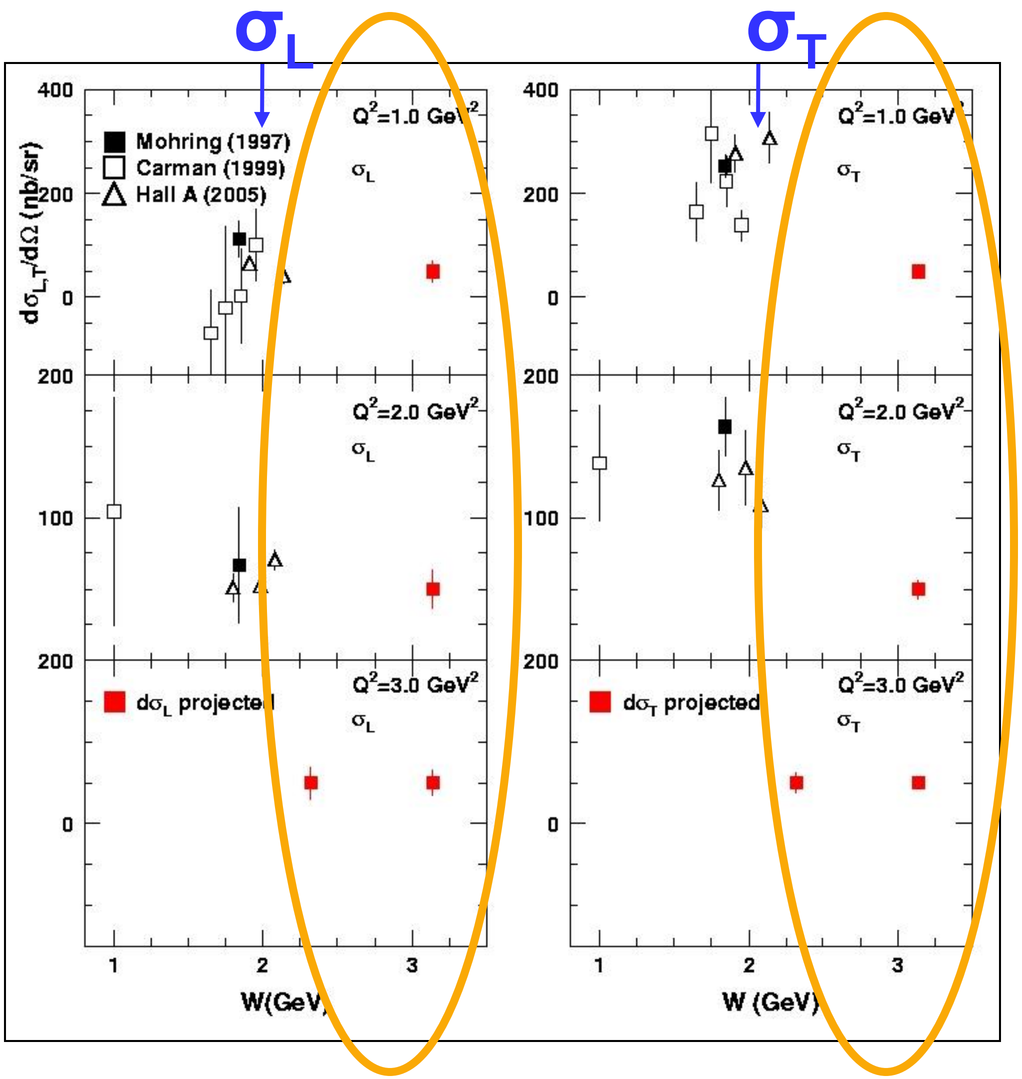
- **E12-09-011**: will provide first L/T separated **kaon** data above the resonance region (*W* > 2.5 GeV)
  - Onset of factorization
  - Understanding of hard exclusive reactions
    - QCD model building
    - Coupling constants

- New aerogel detector constructed for kaon/proton separation



[NSF-MRI: PHY-1039446]

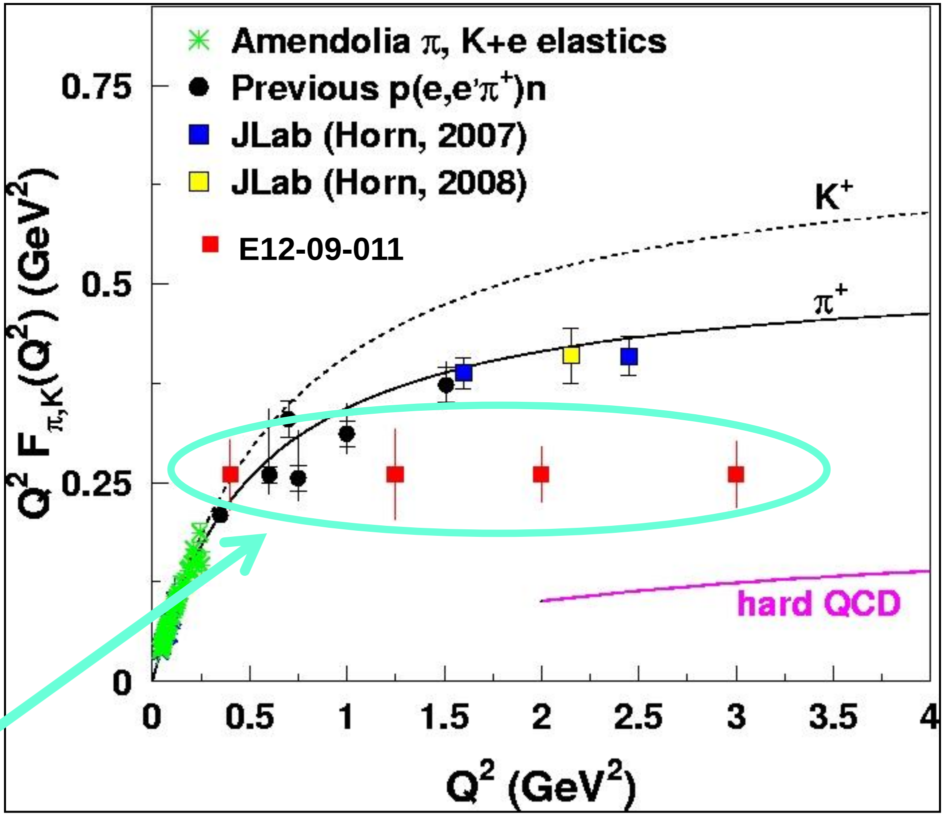
Testing of the completed aerogel detector at JLab



$F_{\pi, K}$ – can kaons shed light on the puzzle?

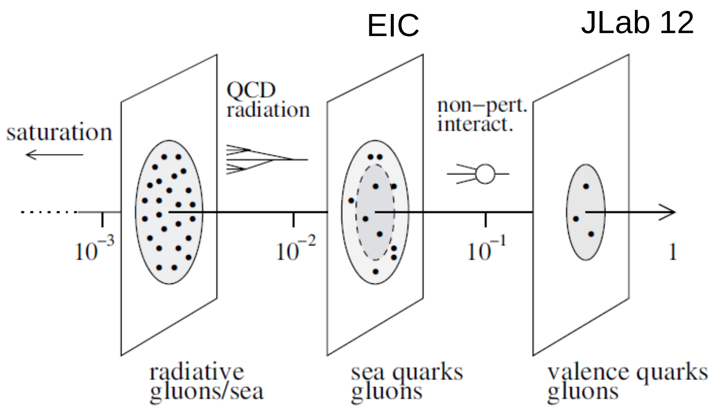
- Compare the observed Q^2 dependence and magnitude of π^+ and K^+ form factors

- Will the analogy between pion cross section and form factor also manifest itself for kaons?

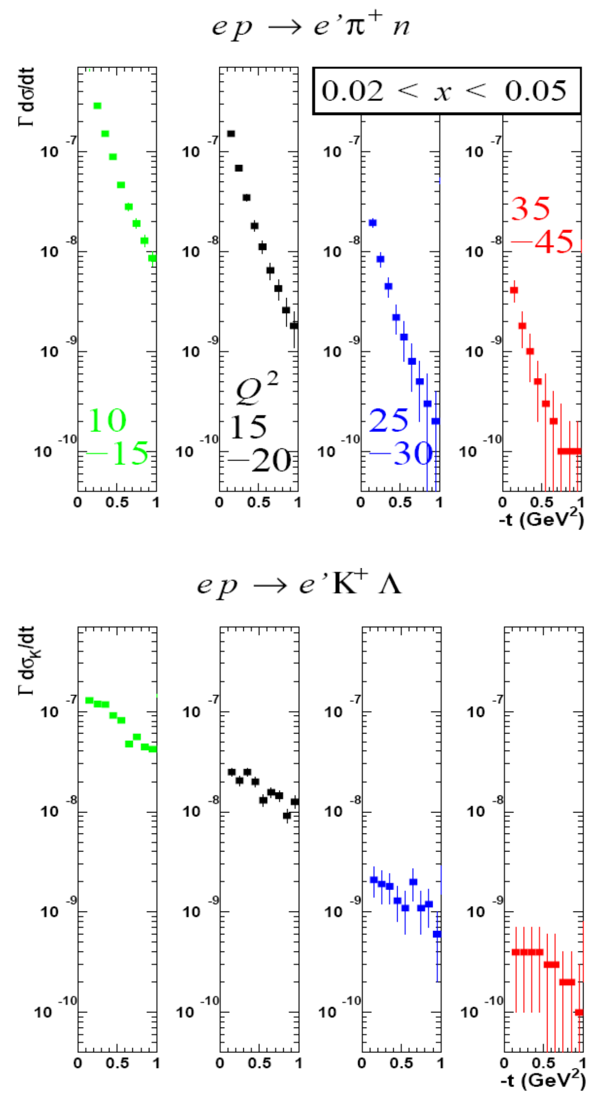


Projected uncertainties for kaon experiment at 12 GeV

EIC: Plans for exclusive pion and kaon measurements



- ❑ Spatial structure of *non-perturbative sea*
  - – Closely related to JLab 6/12 GeV
    - ○ Quark spin/flavor separations
    - ○ Nucleon/meson structure
- ❑ One of the key measurements in the EIC WP

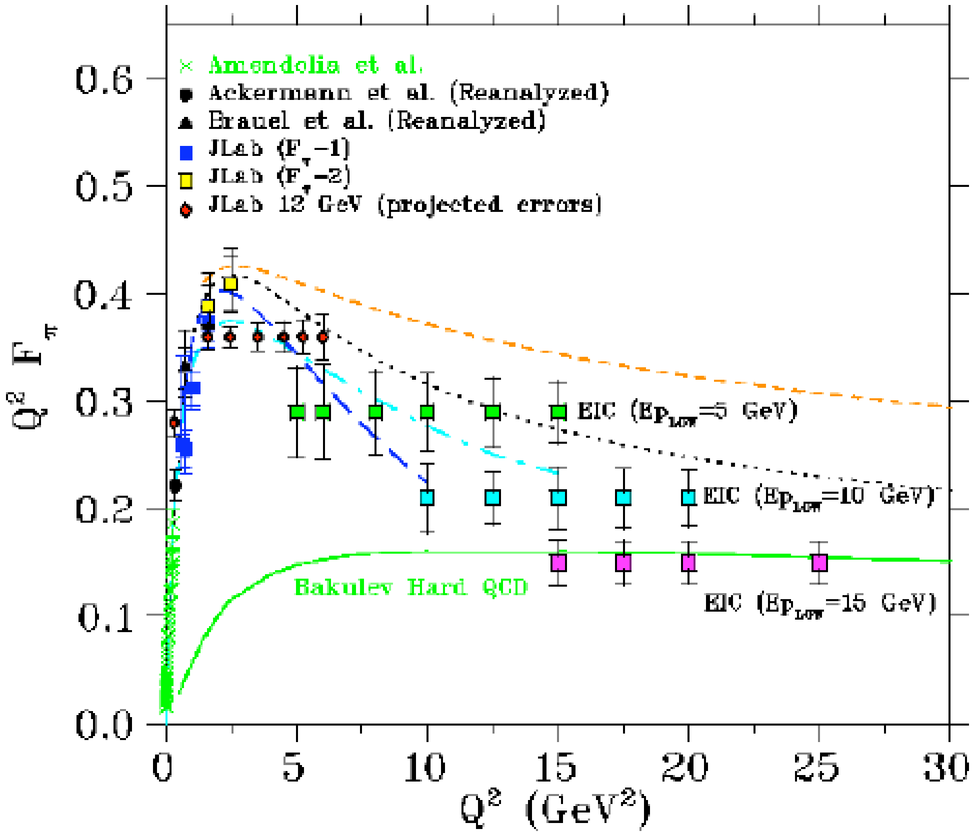


s=1000 GeV^2

$\mathcal{L}$=10^{34} cm^2 s^{-1}

EIC: kinematic reach of F_π

Projections by G. Huber, 2010



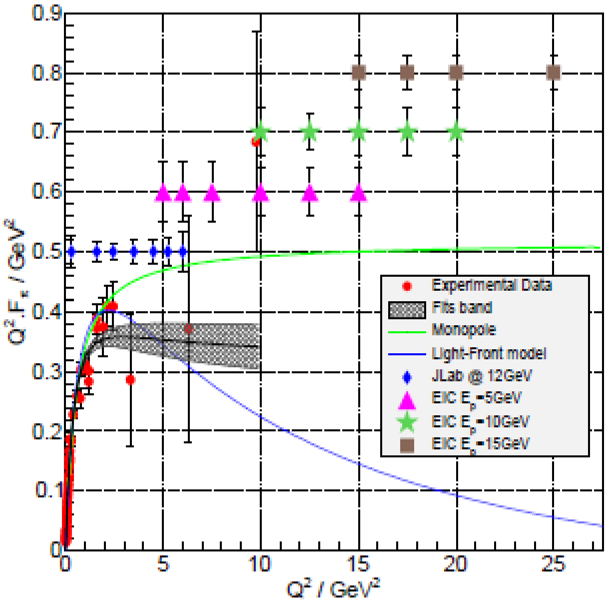
Assumptions:

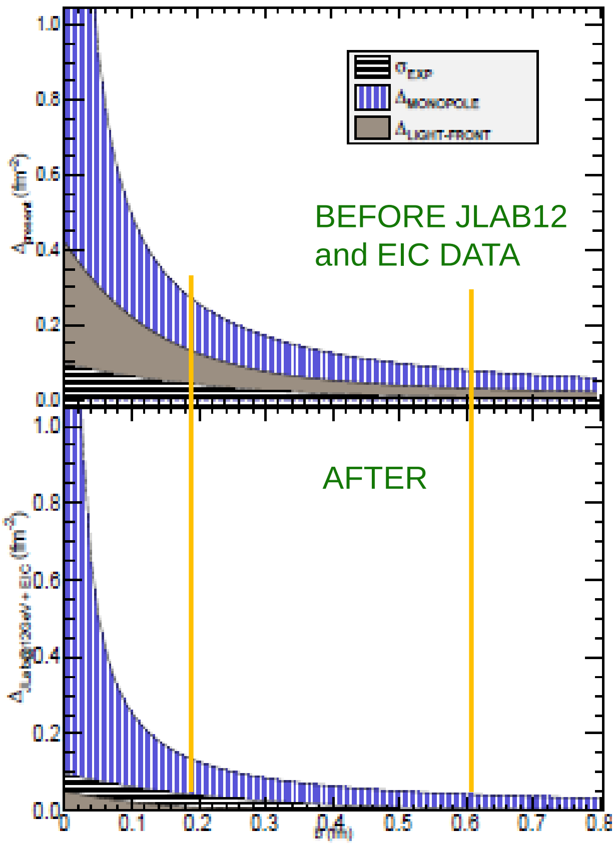
- **High ε:** 5(e^-) on 50(p).
- **Low ε** proton energies as noted.
- Δε~0.22.
- Scattered electron detection over 4π.
- **Recoil neutrons detected at θ<0.35° with high efficiency.**
- Statistical unc: $\Delta\sigma_L/\sigma_L$~5%
- Systematic unc: 6%/Δε.
- **Approximately one year at L=10^{34}.**

Excellent potential to study the *QCD transition* nearly over the whole range from the *strong QCD* regime to the *hard QCD* regime

Impact of future experiments on Pion Transverse Density

- Projected uncertainties give sufficient precision to distinguish between theoretical models for $Q^2>3$ GeV^2, thus narrow down selection of models for estimating the incompleteness error





- Improvement of the extraction of the pion transverse charge density
  - Precision would be better than 20% for b>0.1 fm - interesting for studies of the hadron "edge"

Summary

- Meson form factor measurements play an important role in our understanding of the structure and interactions of hadrons based on the principles of QCD

- Meson form factor measurements in the space-like region
  - π^0 most direct
  - π^+ requires a model to extract the form factor at physical meson mass
  - K^+ requires experimental verification of pole dominance in σ_L

- π^0 transition form factor data show opposing trends in particular at high Q^2 inconsistent with perturbative QCD
  - Essential to probe additional channels for a consistent and global understanding

- π^+ form factor results in both space- and timelike regions seem to indicate scaling with Q^2 but are in magnitude far from the perturbative prediction

- JLab 12 GeV will dramatically improve the π^+/π^0 data set and may also allow for kaon form factor extractions