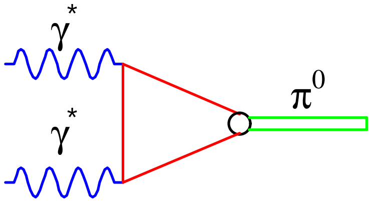
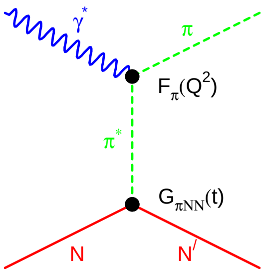


Meson Form Factors in the Space-Like Region



Dave Gaskell

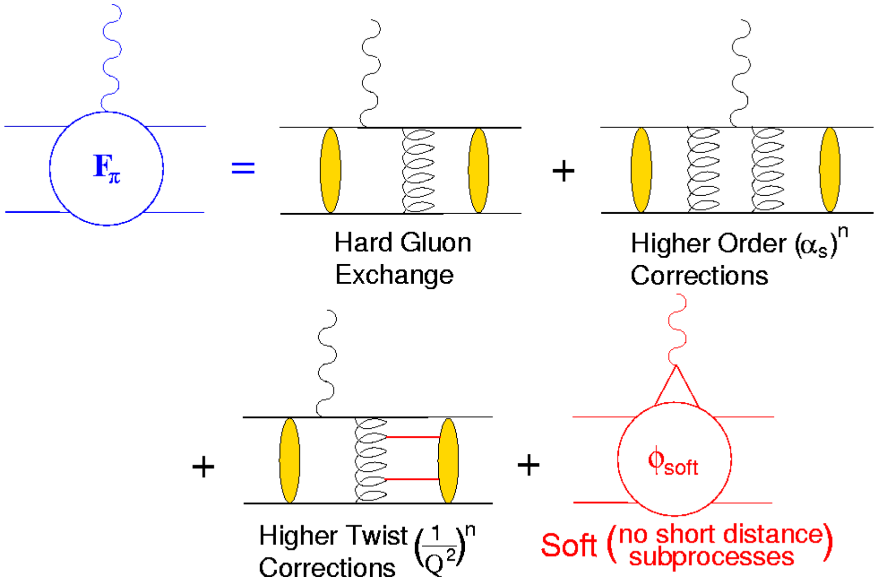
Jefferson Lab

Exclusive Reactions at High Momentum Transfer

May 23, 2007

Meson Form Factors and QCD

- The simple $q\bar{q}$ valence quark structure of mesons presents the ideal laboratory for testing our understanding of bound quark systems



- Asymptotic form factors can be calculated in pQCD – we know where we need to end up

- Excellent opportunity for studying the **transition** from effective degrees of freedom to quarks and gluons, i.e., from the soft to hard regime

QCD Hard Scattering Picture

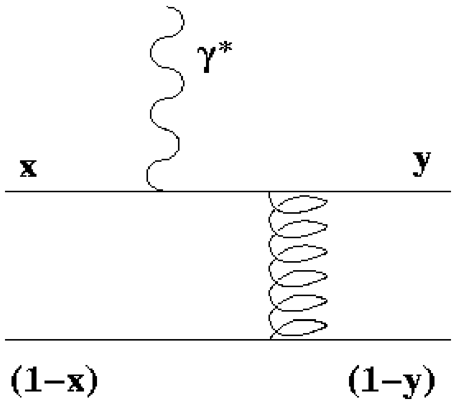
Example: π^+ form factor

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

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



and F_π takes the very simple form

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

where f^2_π=93 MeV is the $\pi^+ \to \mu^+ \nu$ decay constant.

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

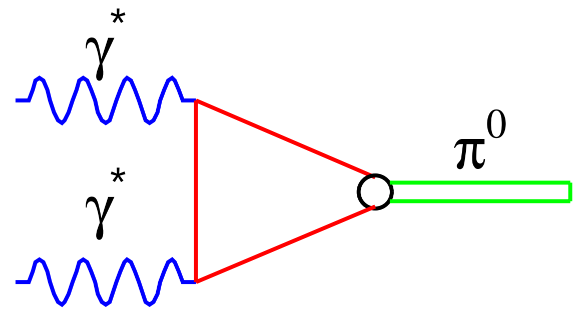
Meson Form Factor Experiments

- Theoretically, meson form factors present clean testing ground for our understanding of bound quark systems
- Due to lack of "meson targets", more challenging experimentally than hadron form factors
- Experiments to date have measured:
  - π^0 form factor - measured via $e^+e^- \rightarrow e^+e^-\pi^0$ up to Q^2= 8 GeV^2
  - π^+ form factor – measured via $\pi^+e^- \rightarrow \pi^+e^-$ and $p(e,e'\pi^+)n$ to Q^2=2.5 GeV^2
  - K+ form factor – measured via $K^+e^- \rightarrow K^+e^-$ up to Q^2=0.1 GeV^2

$\gamma^*\gamma \rightarrow \pi^0$ Form Factor Measurement

•At lowest order in hard scattering, $\gamma^*\gamma \rightarrow \pi^0$ **is a pure QED process**

•Good test of pion distribution amplitude



- Measured via $e^+e^- \rightarrow e^+e^-\gamma^*\gamma$ ⟶ $\gamma^*\gamma \rightarrow \pi^0$

pure QED *Form Factor*

- One electron scattered at large angle (detected) yielding virtual photon with large Q^2
- Second electron (undetected) scattered at small angle yielding “nearly real” photon

$F_{\gamma^*\gamma\pi^0}(Q^2)$ Results

1. Asymptotic pion distribution amplitude (DA)
2. Lowest order α_s

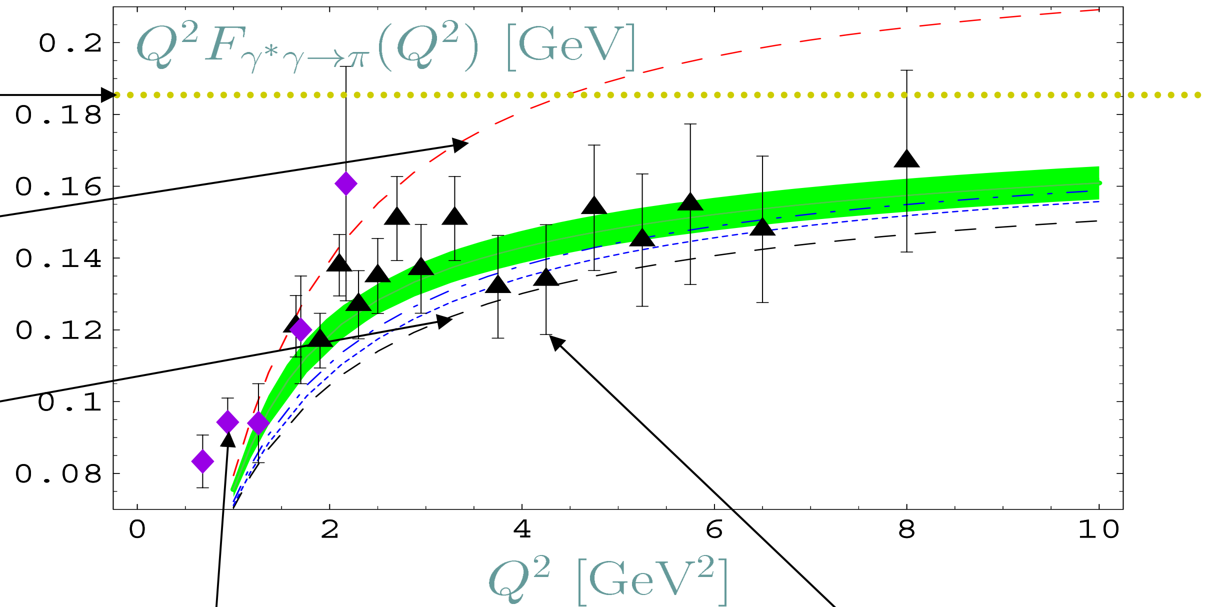
$$F_{\gamma^*\gamma\pi^0}(Q^2) \xrightarrow{Q^2\to\infty} \frac{2f_\pi}{Q^2}$$

Form factor approaches leading order pQCD results at $Q^2=8$ GeV^2

$Q^2 \to \infty$

CZ (QCD sum rule) DA

Asymptotic DA with appropriate Q^2 evolution



CELLO [Behrend et al, Z.Phys. ***C49****, 401(1991)]*

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

Pion Distribution Amplitude

- $F_{\gamma*\gamma\pi^0}$ (Q^2) results taken as evidence that asymptotic pion DA appropriate as low as Q^2=*1* GeV^2
- However, as will be seen, charged pion FF case is more complicated
- Interesting side note – modified QCD sum rule DA describes $F_{\gamma*\gamma\pi^0}$ (Q^2) results well

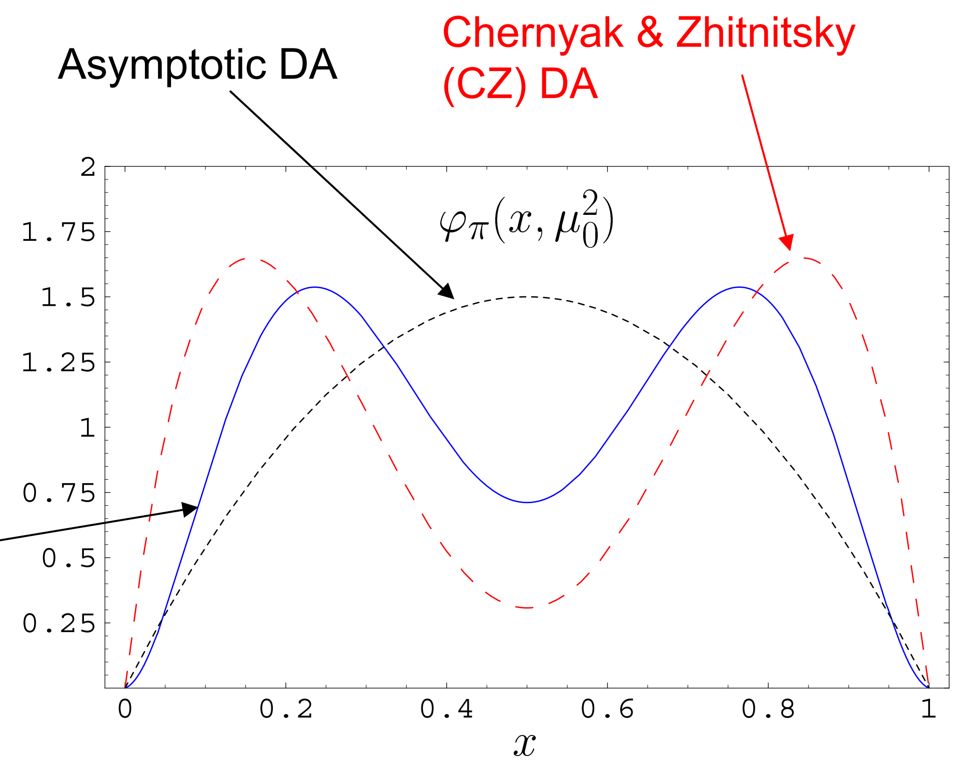
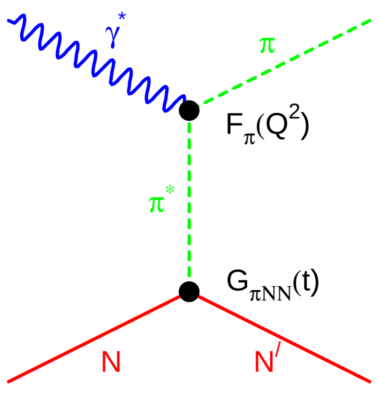


Figure from Bakulev et al, Phys. Rev. D70,033014

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

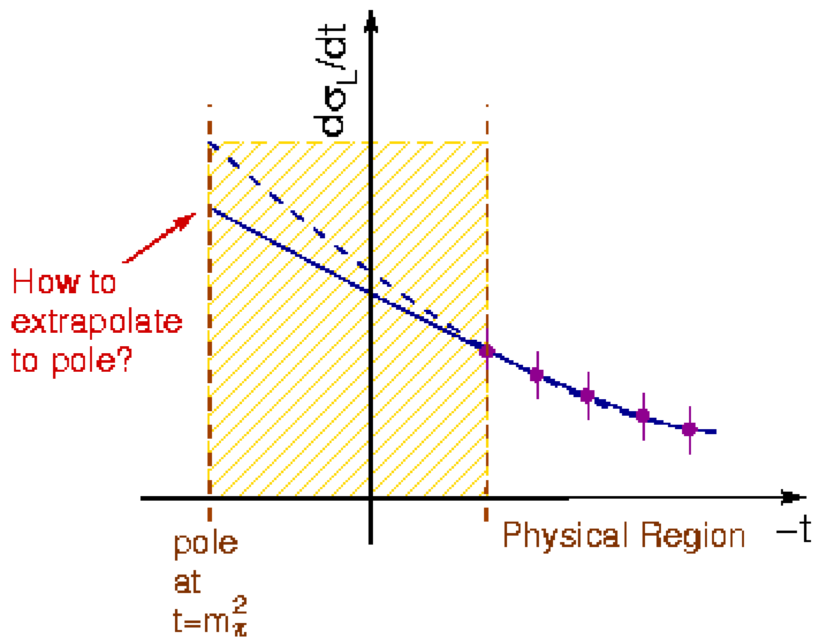
    $r_\pi = 0.657 \pm 0.012$ fm
- At larger Q^2, F_π must be measured indirectly using the "pion cloud" of the proton via $p(e,e'\pi^+)n$
  - At small $-t$, the pion pole process dominates σ_L
  - F_π^2 in Born term model



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

Extraction of π^+ Form Factor in *$p(e,e'\pi^+)n$*

- π^+ electroproduction can only access *t<0* (away from pole)
- Early experiments used "Chew-Low" technique
  - measured *–t* dependence
  - Extrapolate to physical pole
- This method is unreliable – different fit forms consistent with data yet yield very different FF

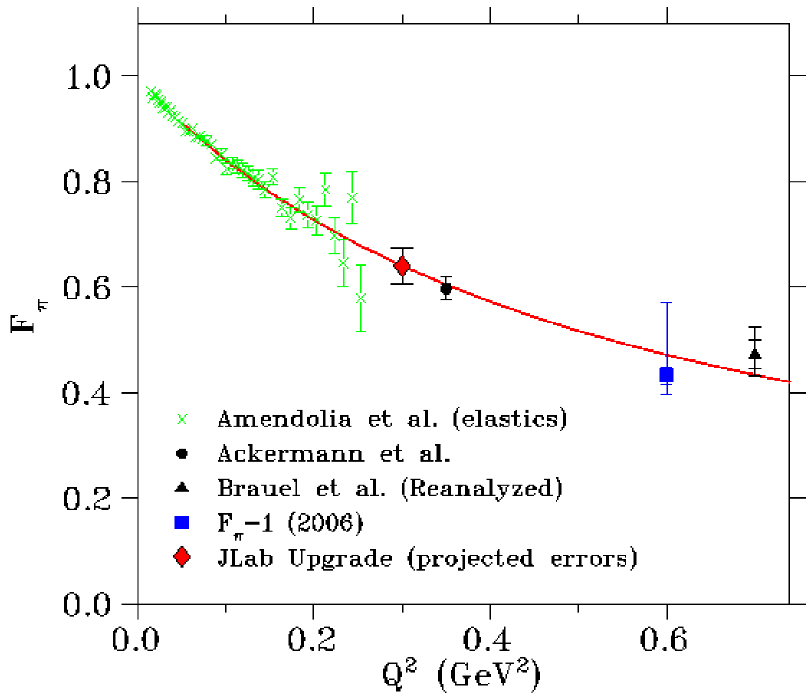


• Cross section model incorporating FF is required!

→ *t-pole* "extrapolation" is implicit, but one is only fitting data in physical region

Check of Pion Electroproduction Technique

- Does electroproduction really measure the physical form-factor since we are starting with an off-shell pion?
- This can be tested making $p(e,e'\pi^+)$ measurements at same kinematics as π+e elastics
- Looks good so far
  - Ackermann electroproduction data at $Q^2 = 0.35$ GeV^2 consistent with extrapolation of SPS elastic data



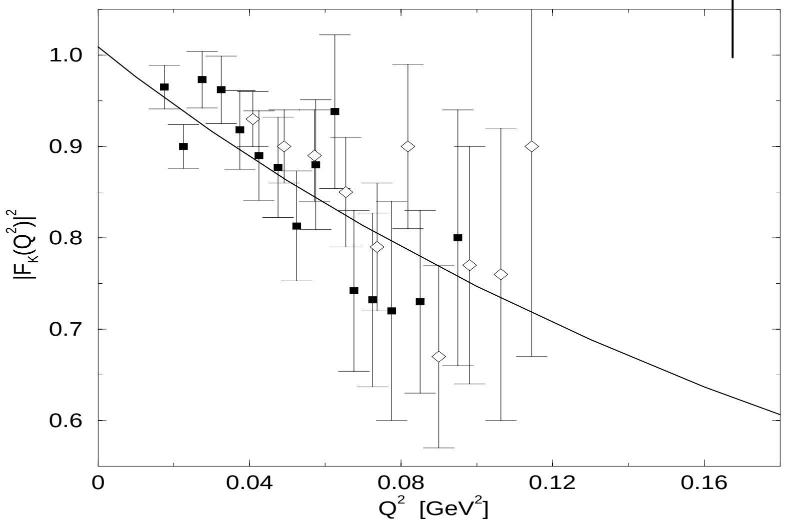
An improved test will be carried out after the JLAB 12 GeV upgrade

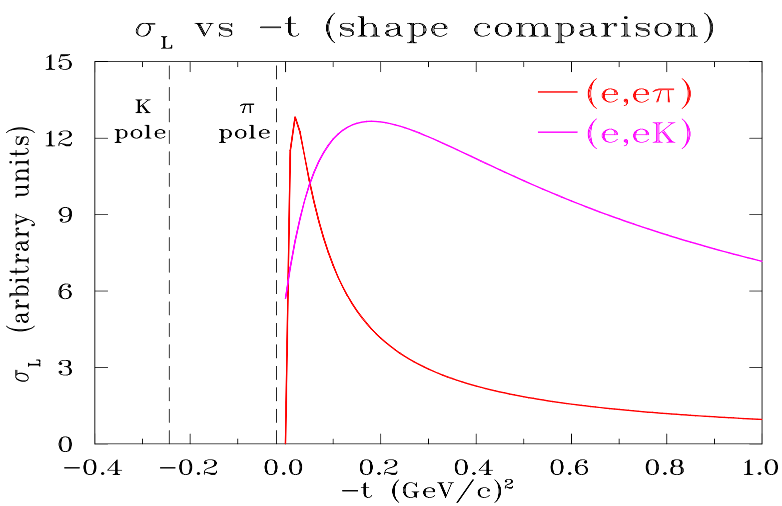
→**smaller *Q2 (=0.30* GeV^2)**

→***-t* closer to pole (=*0.005* GeV^2)**

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?





Kaon Form Factor at Large Q^2

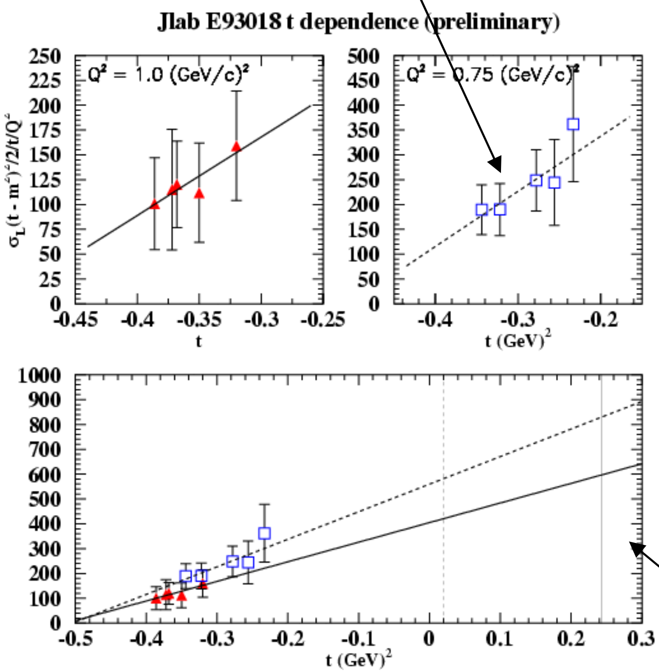
- JLAB experiment E93-018 extracted $-t$ dependence of K^+ longitudinal cross section near $Q^2=1$ GeV^2
- A trial Kaon FF extraction was attempted using a simple Chew-Low extrapolation technique

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

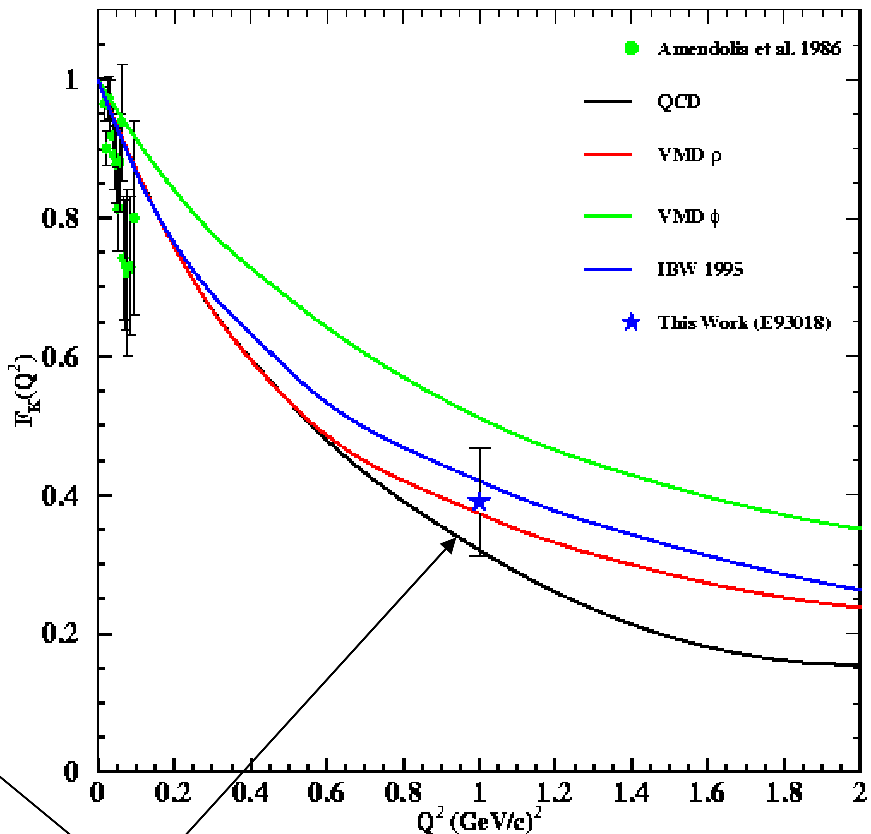
- $g_{K\Lambda N}$ poorly known
  - Assume form factor follows monopole form
  - Used measurements at $Q^2=0.75$ and 1 GeV^2 to constrain $g_{K\Lambda N}$ and F_K simultaneously
- Improved extraction possible using VGL model?

Test Extraction of K^+ Form Factor

-t dependence shows some "pole-like" behavior



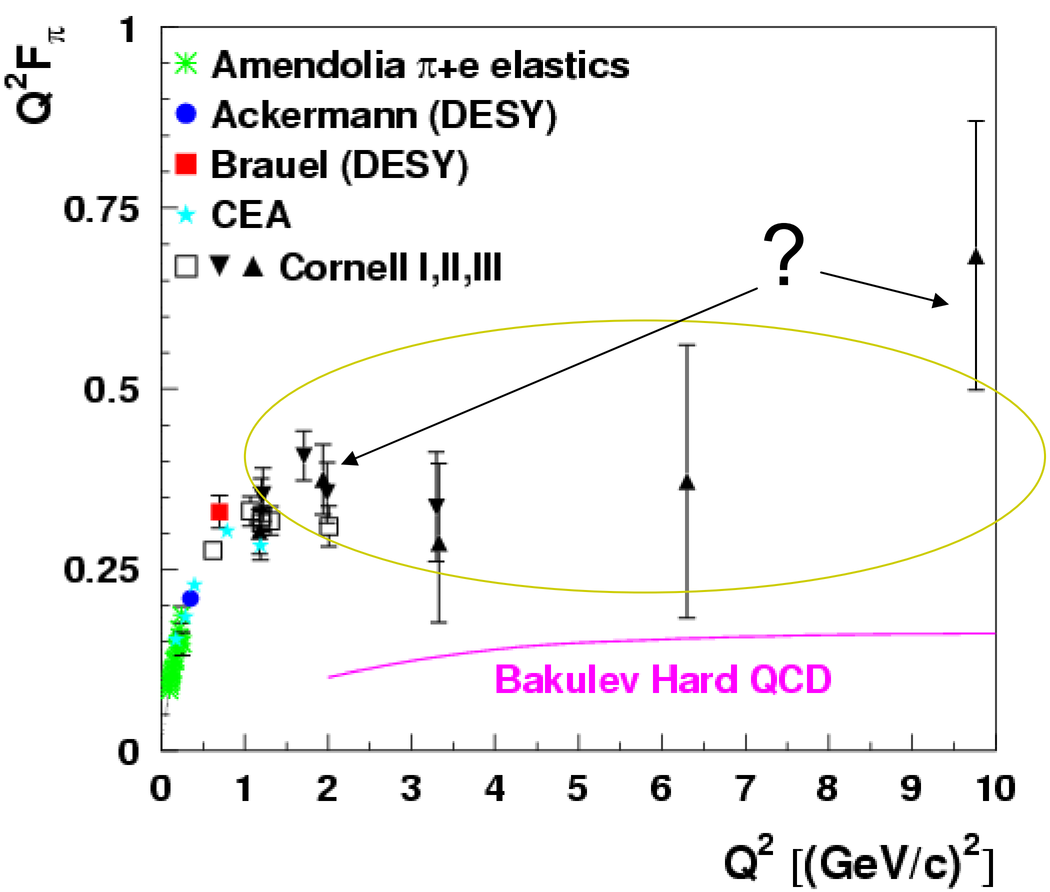
G. Niculescu, PhD. Thesis, Hampton U.



Extraction shows power of the data, but should not be interpreted (yet?) as real extraction of kaon FF!

"Chew-Low" type extraction

$F_{\pi^+}(Q^2)$ Measurements before 1997



- Older data at large Q^2 (> *1* GeV^2) extracted F_π from unseparated cross sections
- Used extrapolation of σ_T fit at low Q^2 to isolate σ_L
- Largest Q^2 points also taken at large $-t_{min}$

- Carlson and Milana *[PRL 65, 1717(1990)]* predict M_{pQCD}/M_{pole} grows dramatically for $-t_{min}>0.2$ GeV^2

- ***Pole term may not dominate!***

F_π Backgrounds

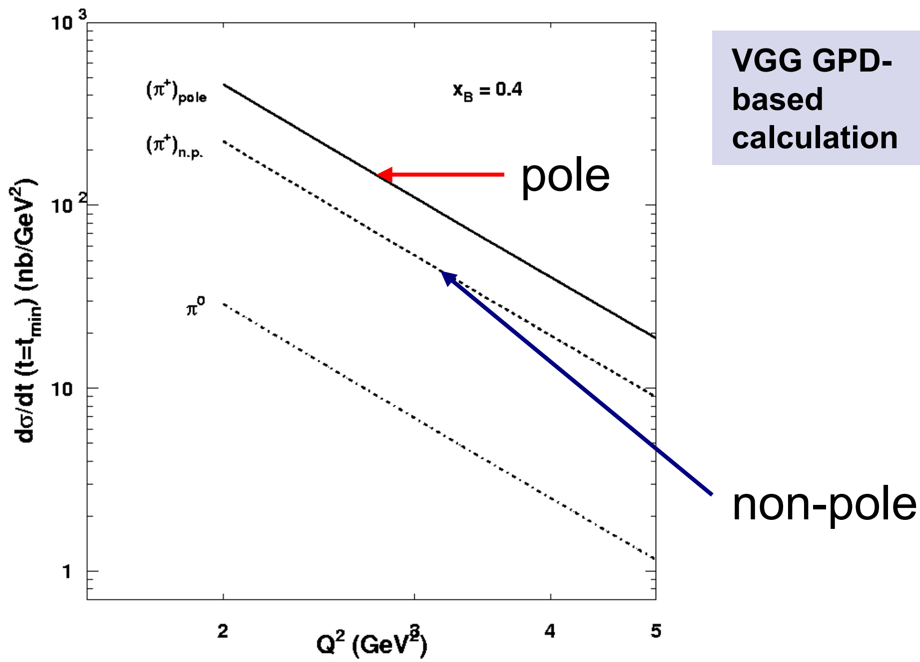
- Carlson and Milana prediction only real guidance as to size of non-pole backgrounds
- $-t_{min}$<0.2 GeV^2 constraint limits Q^2 reach of F_π measurements (for older data, 6 GeV JLab data, and future 12 GeV JLab measurements)
- Measurement of π^0 longitudinal cross section could help constrain pQCD backgrounds
- Example: in a GPD framework, π^+ and π^0 cross sections involve different combinations of same GPDs – ***but π^0 has no pole contribution***

π^0

$$A_{p\pi^o} \sim (e_u \tilde{H}^u - e_d \tilde{H}^d)$$
$$B_{p\pi^o} \sim (e_u \tilde{E}^u - e_d \tilde{E}^d)$$

π^+

$$A_{p\pi^+} \sim (\tilde{H}^u - \tilde{H}^d)(e_u + e_d)$$
$$B_{p\pi^+} \sim (\tilde{E}^u - \tilde{E}^d)(e_u + e_d)$$



VGG GPD-based calculation

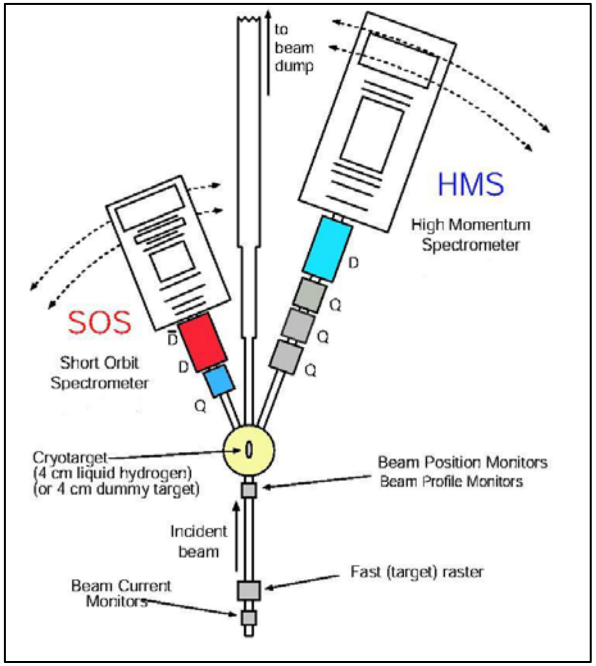
F_π Program at JLab

- 2 F_π experiments have been carried out at JLab *(spokespersons H.Blok, G. Huber, D.Mack)*
  - F_π-1: $Q2=0.6\text{-}1.6$ GeV^2
  - F_π-2: $Q2=1.6, 2.45$ GeV^2
- Second experiment took advantage of higher beam energy to access larger *W*, smaller *-t*

Expt	Q^2 (GeV^2)	W (GeV)	$\|t_{min}\|$ (Gev^2)	E_e (GeV)
F_π-1	0.6-1.6	1.95	0.03-0.150	2.445-4.045
F_π-2	1.6,2.45	2.22	0.093,0.189	3.779-5.246

- Full deconvolution of *L/T/TT/LT* terms in cross section
- Ancillary measurement of π^-/π^+ (separated) ratios to test reaction mechanism
- Both experiments ran in experimental Hall C: F_π-1 in 1997 and F_π-2 in 2003

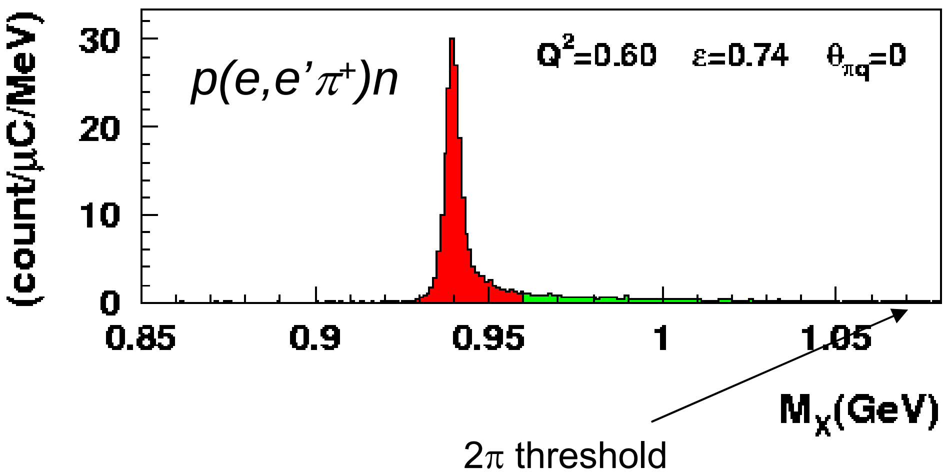
JLab F_π Experiment Details



- Short Orbit Spectrometer = e^-
- High Momentum Spectrometer = π^+
  - →Relatively small acceptance – easily understood
  - →"Pointing", kinematics well constrained
- Cryogenic targets, high currents yield relatively fast measurement

- Easy to isolate exclusive channel
  - →Excellent particle identification
  - →CW beam minimizes "accidental" coincidences
  - →Missing mass resolution easily excludes 2-pion contributions

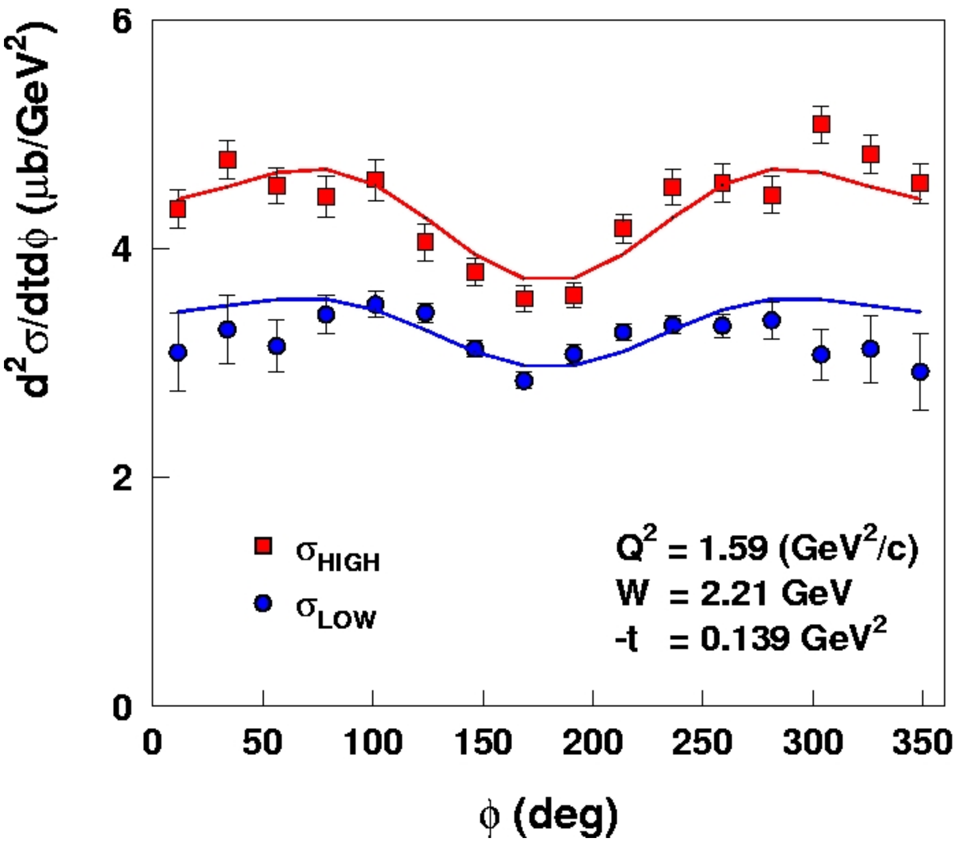
Fπ-1 missing mass distribution



Measuring σ_L

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

- 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/ε error amplification in σ_L
- Careful attention must be paid to spectrometer acceptance, kinematics, efficiencies, …



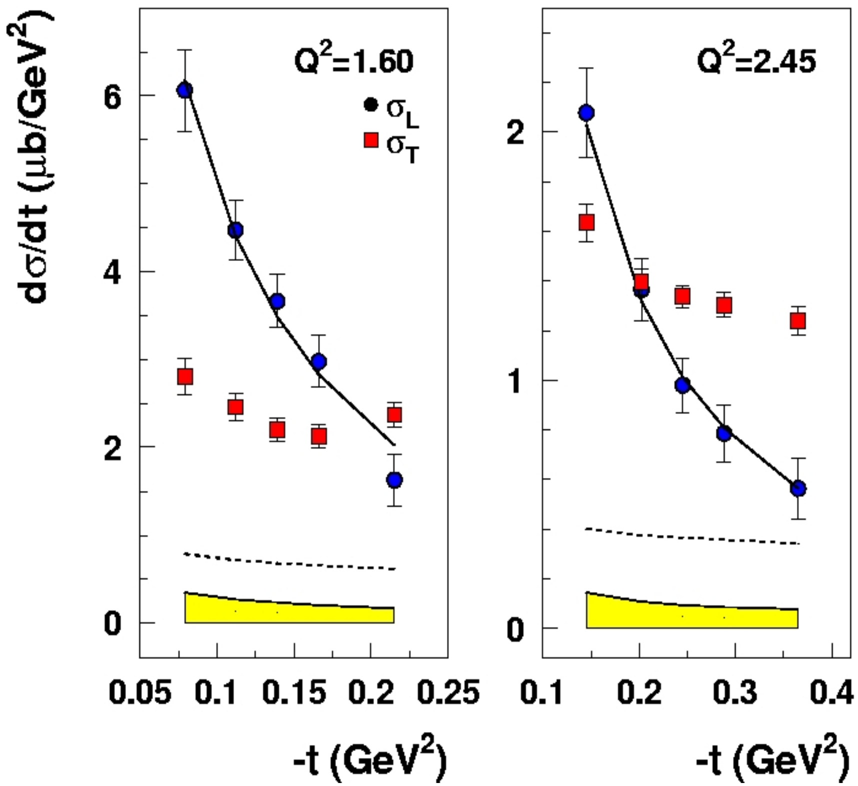
Horn et al, PRL97, 192001,2006

F_π Extraction from JLab data

- Model is required to extract F_π from σ_L

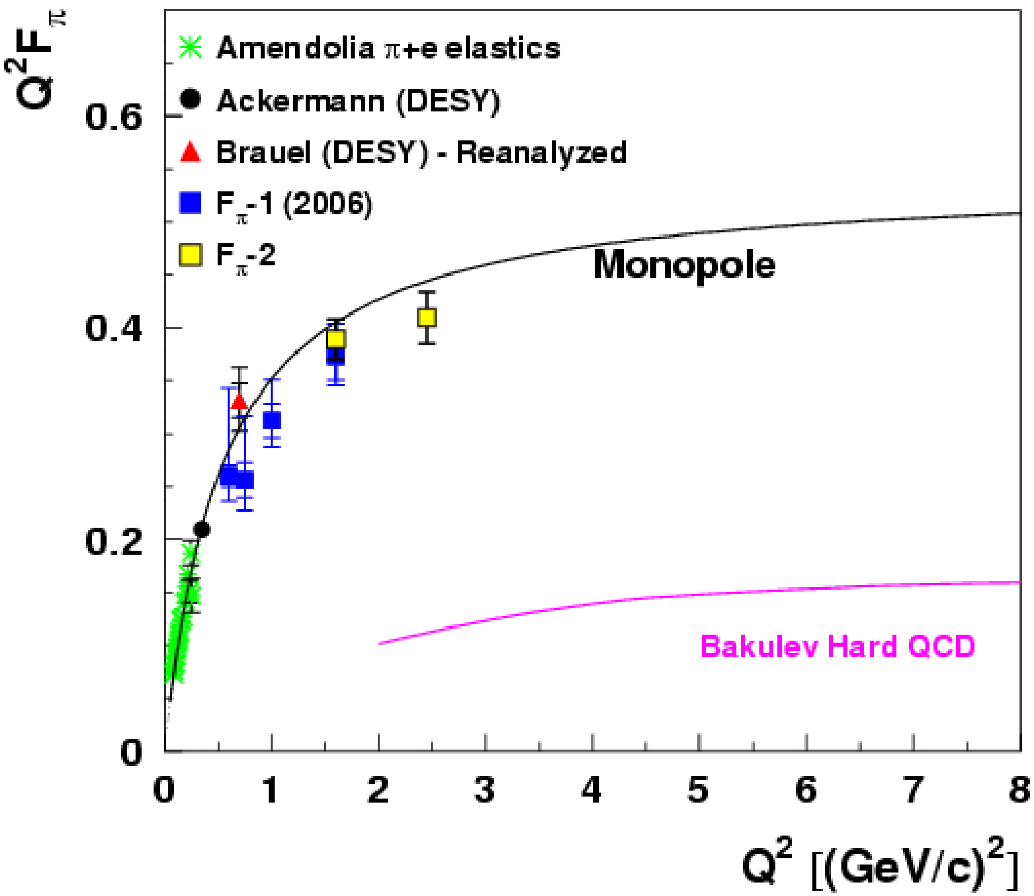
- JLab F_π experiments used the VGL Regge model
  [Vanderhaeghen, Guidal, Laget, PRC 57, 1454 (1998)]
  - Propagator replaced by π and ρ Regge trajectories
  - Most parameters fixed by photoproduction data
  - 2 free parameters: Λ_π, Λ_ρ
  - At small $-t$, σ_L only sensitive to Λ_π

Horn et al, PRL97, 192001,2006



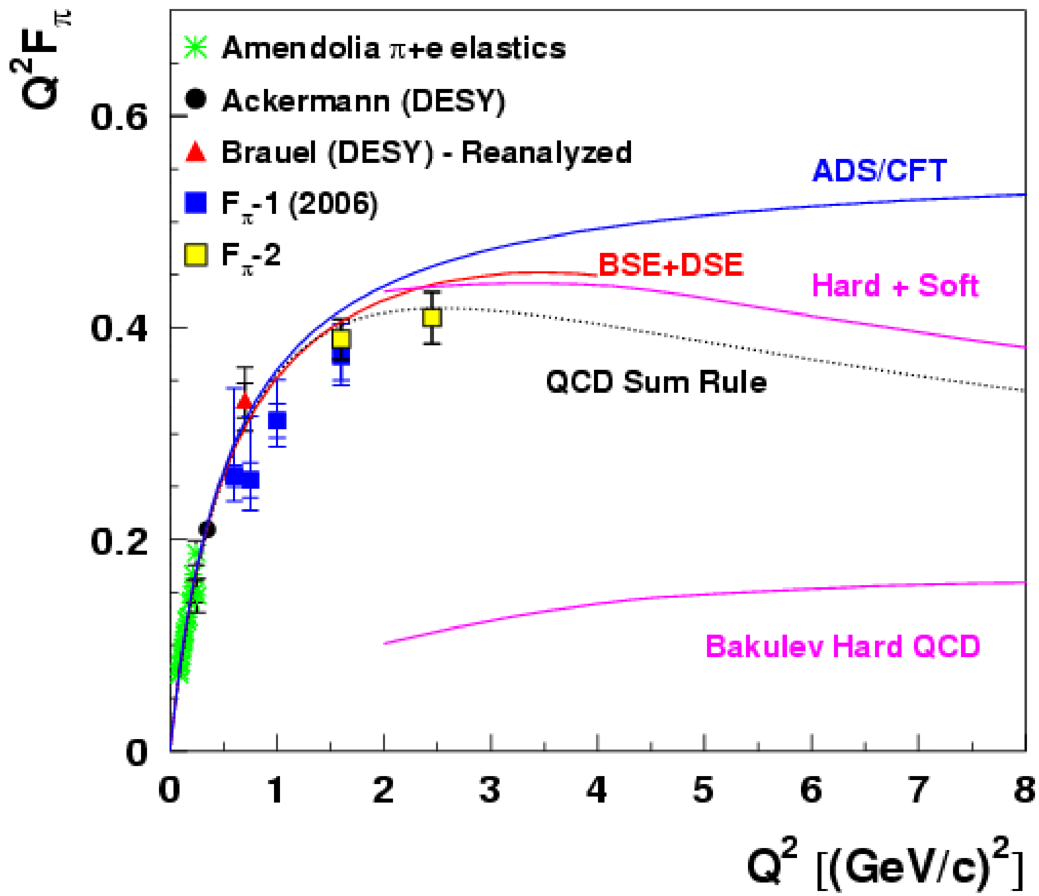
$$F_\pi(Q^2) = \frac{1}{1 + Q^2 / \Lambda_\pi^2}$$

$F_{\pi^+}(Q^2)$ in 2007



- Only true L-T separated data shown
- Trend suggested by extractions from unseparated cross sections still holds
  - Far from asymptotic limit
  - Inclusion of k_T effects has little impact
- Several effective models do a good job describing the data (QCD sum rules, constituent quark models, etc.)

$F_{\pi^+}(Q^2)$ in 2007



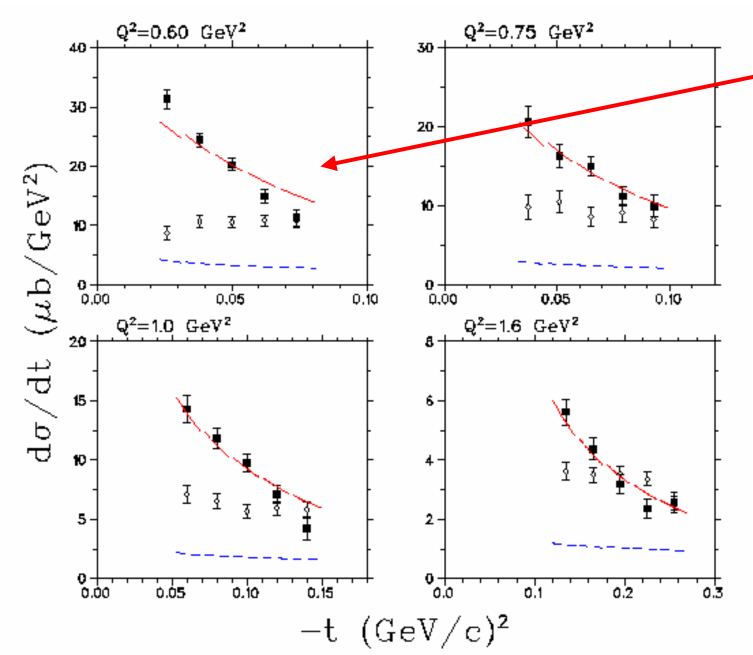
Maris and Tandy, Phys. Rev. ***C62****, 055204 (2000)*
`→ relativistic treatment of bound quarks (Bethe-Salpether equation + Dyson-Schwinger expansion)

Nesterenko and Radyushkin, Phys. Lett. ***B115****, 410(1982)*
→ Green's function analyticity used to extract form factor

A.P. Bakulev et al, Phys. Rev. ***D70*** *(2004)*
→Hard contribution to NLO with improved pion DA
→Soft contribution from local duality

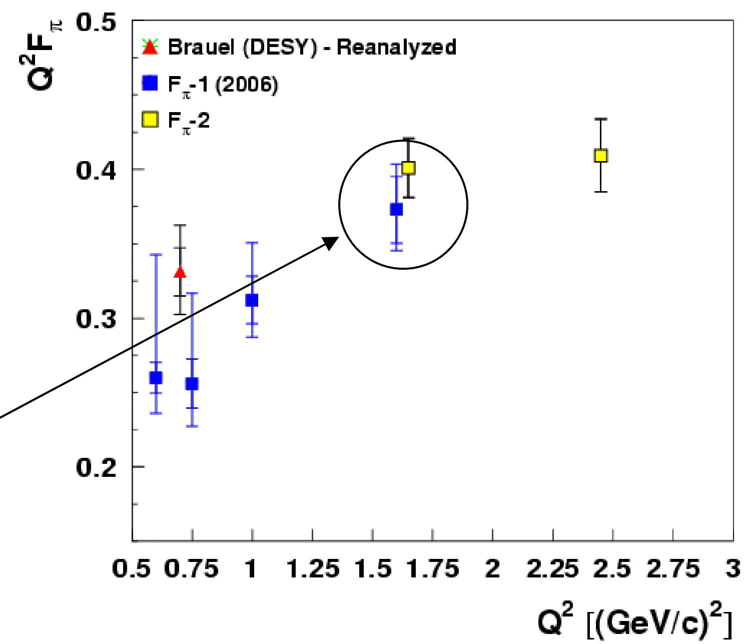
Brodsky and de Teramond, hep-th/0702205
→ Anti-de Sitter/Conformal Field Theory approach

Model/Intepretation Issues



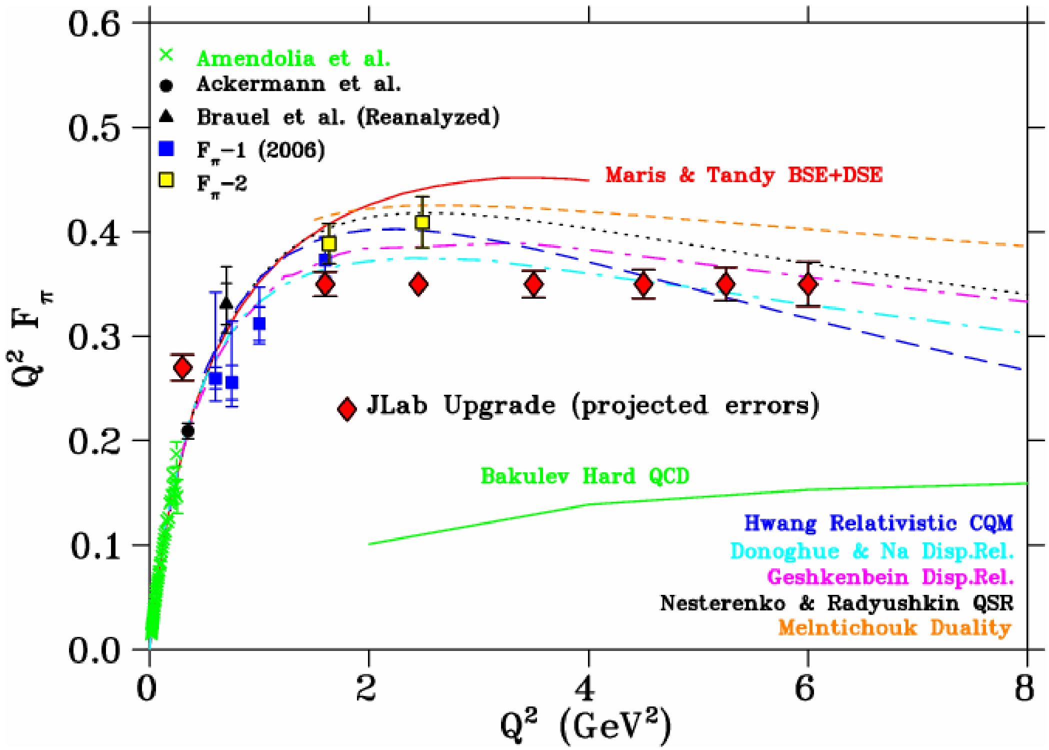
- VGL Regge model does not describe $-t$ dependence of F_π-1 σ_L at lowest Q^2
  - → Leads to large systematic errors for F_π
  - →Underscores the need for additional models

- Even if model describes data, does it give the “physical” form factor?
  - →Test by extracting FF at different distances from –t pole
  - →Ex: F_π-2, $-t_{min}=0.093$ GeV^2
    F_π-1, $-t_{min}=0.15$ GeV^2



$F_{\pi^+}(Q^2)$ after JLAB 12 GeV Upgrade

- JLab 12 GeV upgrade will allow measurement of F_π up to 6 GeV^2
  - Will we see the beginning of the transition to the perturbative regime?
- Additional point at $Q^2=1.6$ GeV^2 will be closer to pole: will provide another constraint on $-t_{min}$ dependence
- $Q^2=0.3$ GeV^2 point will be best direct test of agreement with elastic π+e data



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

Summary

- Access to meson form factors in space-like region experimentally difficult
  - π^0 measurements most direct
  - π^+ (K^+?) require model or extrapolation to extract FF at physical meson mass
- $F_{\gamma^*\gamma\pi^0}(Q^2)$ results suggest perturbative behavior at Q^2 as low as 1 GeV^2
- F_{π^+} results more complicated – at $Q^2=2.5$ GeV^2, data are still far from simple asymptotic picture
  - Soft processes seem to play a more important role for π^+
- Large Q2 K+ form factor measurements even more difficult
  - Large kaon mass means pole further from physically accessible region – interpretation less straightforward
  - F_{K+} accessible with refined models? With what uncertainty?
- JLab 12 GeV upgrade will dramatically improve π^+ data set
  - Will we begin to see the transition to perturbative regime?