Meson Form Factors

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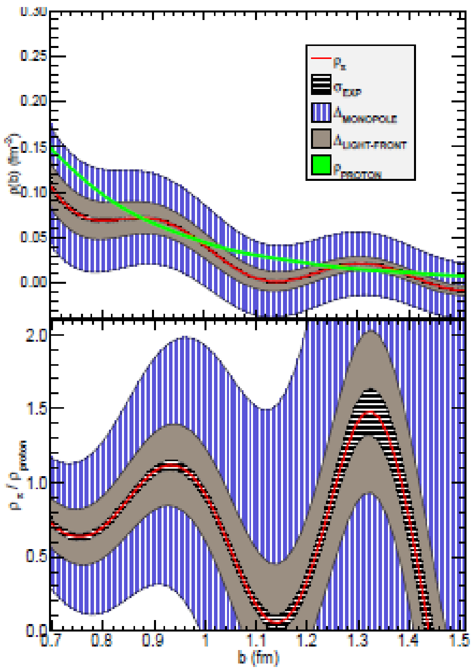
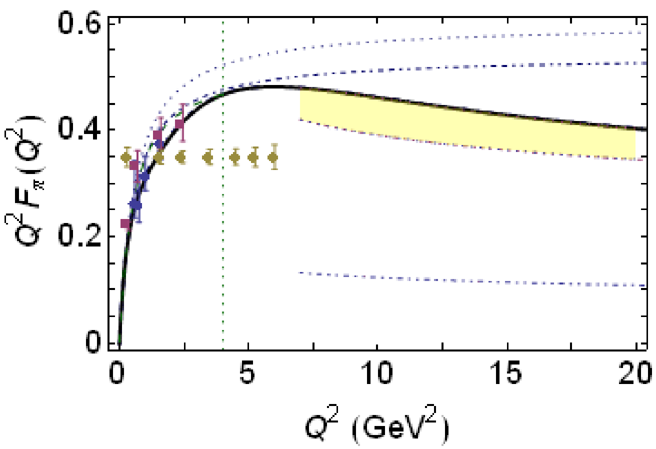
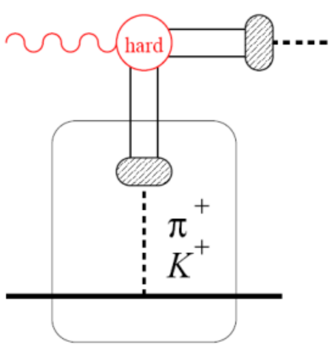






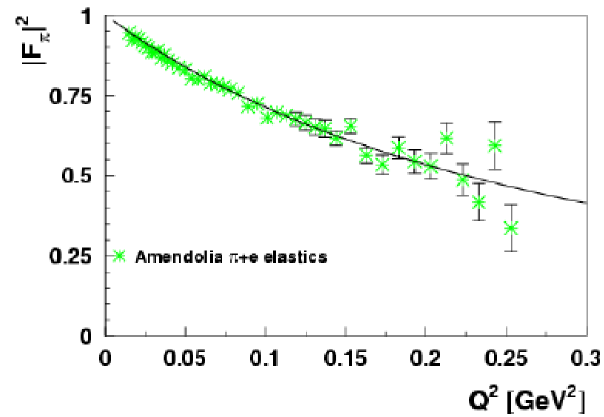
Overview

Form factors are essential for our understanding of internal hadron structure and the dynamics that bind the most basic elements of nuclear physics

- Fundamental properties of meson form factors
  - Pion and kaon form factors are of special interest - connected to the Goldstone modes of dynamical chiral symmetry breaking
  - The pion is the lightest and one of the simplest QCD systems available for study – ***clearest test case for studies of the transition between non-perturbative and perturbative regions***
- Recent advances in experiments: last 5-10 years
  - Dramatically improved precision in F_π measurements
  - New results on the pion transition form factor (TFF)
- Form factor data drive renewed activity on the theory side
  - Distribution amplitudes – signatures of dynamical chiral symmetry breaking
  - Contribution of transversely polarized photons to meson cross section

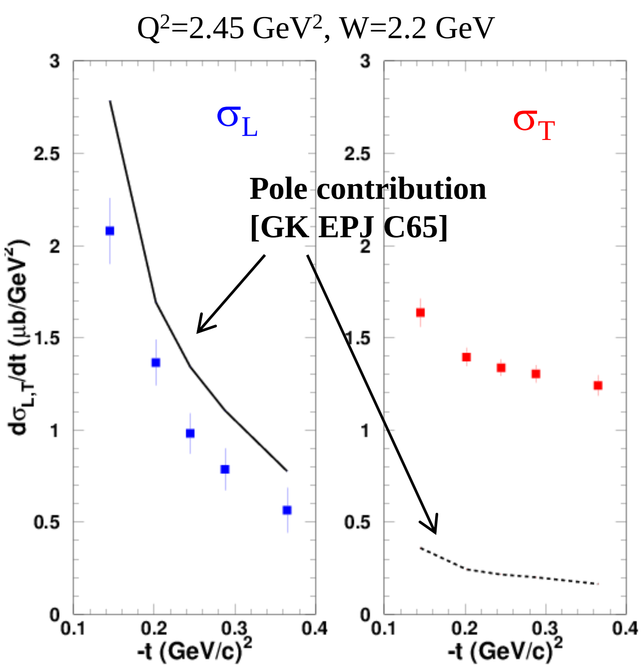
Measurement of π^+ Form Factor

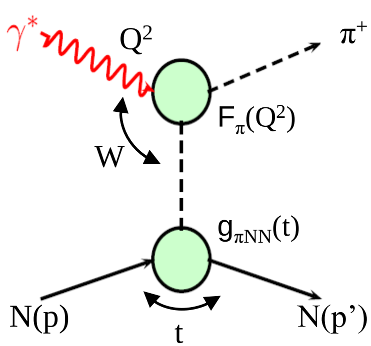
- At low Q^2, $F_{\pi+}$ can be measured directly via high energy elastic π^+ scattering from atomic electrons
  - CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV^2 *[Amendolia et al, NPB277,168 (1986)]*
  - These data used to constrain the pion charge radius: $r_\pi = 0.657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





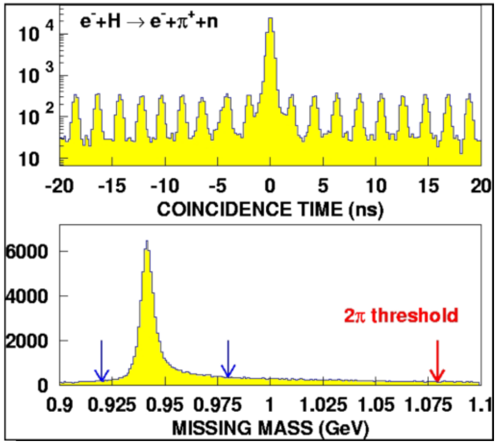
$$\frac{d\sigma_L}{dt} \propto \frac{-t}{(t-m_\pi^2)} g_{\pi NN}^2(t) Q^2 F_\pi^2(Q^2,t)$$

Extracting σ_L from exclusive π^+ data – some experimental points: L/T separation

- *Experiment:* detect scattered electron and pion and reconstruct the undetected neutron mass: $M_n^2 = \left(P_e^\mu - P_p^\mu - P_{e'}^\mu - P_\pi^\mu\right)^2$

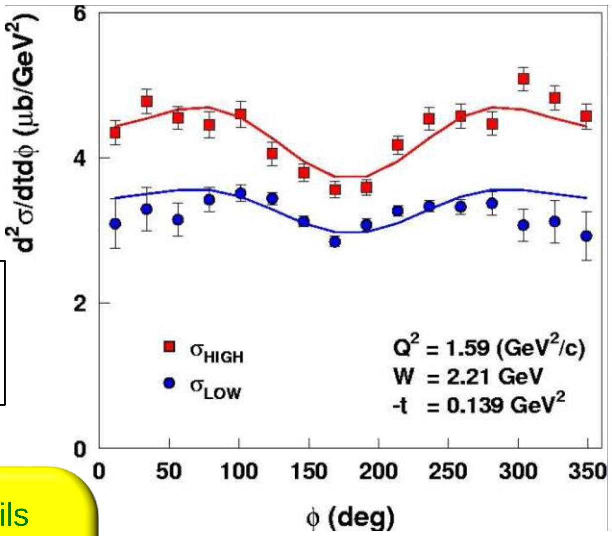
- *Analysis*: replicate the physical acceptance of the channel studied using a MC (spectrometer, rad. Effects, energy loss, multiple scattering, etc.)

Jlab 6 GeV: HMS+SOS



- *Analysis*: extract σ_L by simultaneous fit to the measured yields vs. azimuthal angle, ϕ, and virtual photon polarization, ε

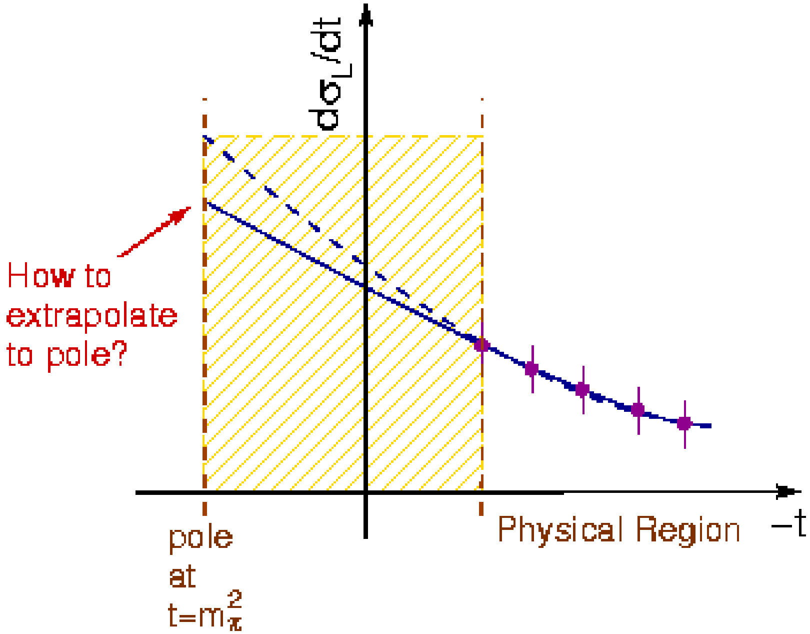
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(1+\varepsilon)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$



- Important points - L/T separation -> see D. Gaskell talk for details
  - Overlapping data at high and low ε
  - Azimuthal angle coverage between 0 and π for interference terms
  - ***Understanding of physical acceptance & control of uncertainties***

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

Preferred and currently used 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 $\alpha_\pi(t) = \alpha'_\pi(t - m_\pi^2)$

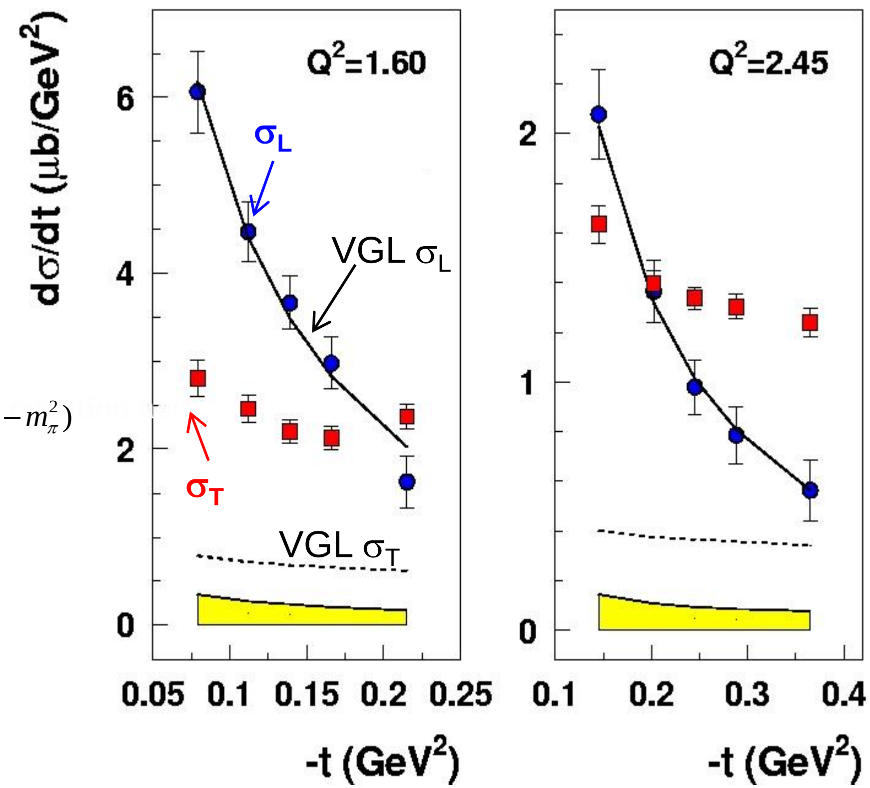
$$\left(t - m_\pi^2\right)^{-1} \Rightarrow \frac{\pi\alpha'_\pi}{2}\left(\alpha_\pi(t)+1\right)\frac{1+\exp[-i\pi\alpha_\pi(t)]}{\sin\pi\alpha_\pi(t)}\left(\frac{W}{W_0}\right)^{2\alpha_\pi(t)}$$

- 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]

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

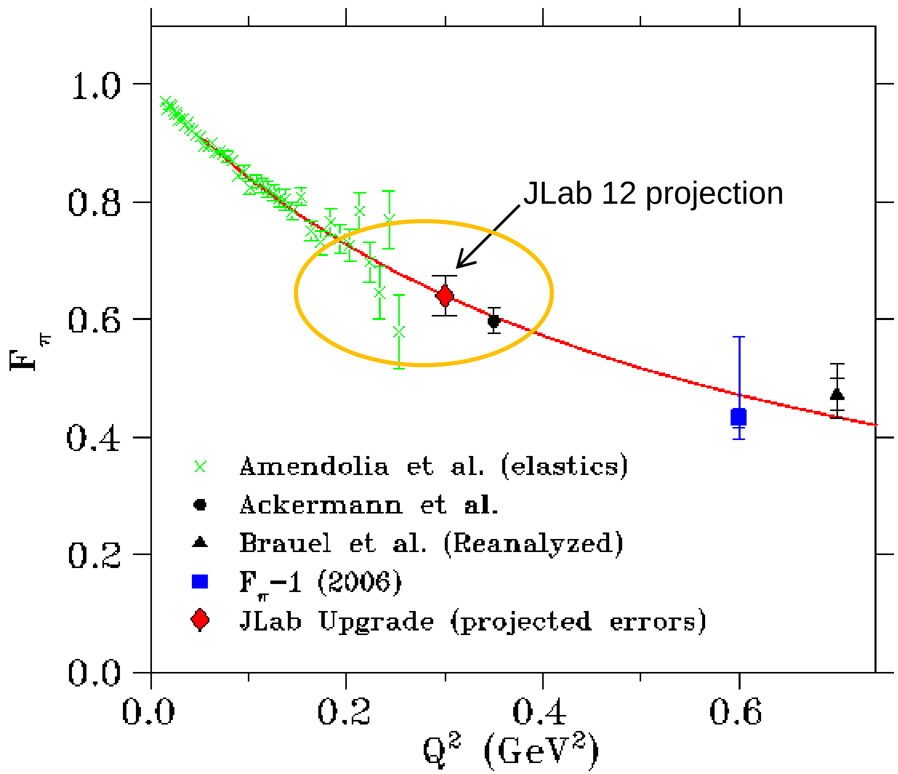
$$\Lambda_\rho^2 = 1.7\,GeV^2$$

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)

Precision data: check of t-channel dominance in σ_L with charged pion ratios in deuterium

- **2014**: new results from ^{2}H target L/T separations

  *[Huber et al, PRL**112** (**2014**)182501]*

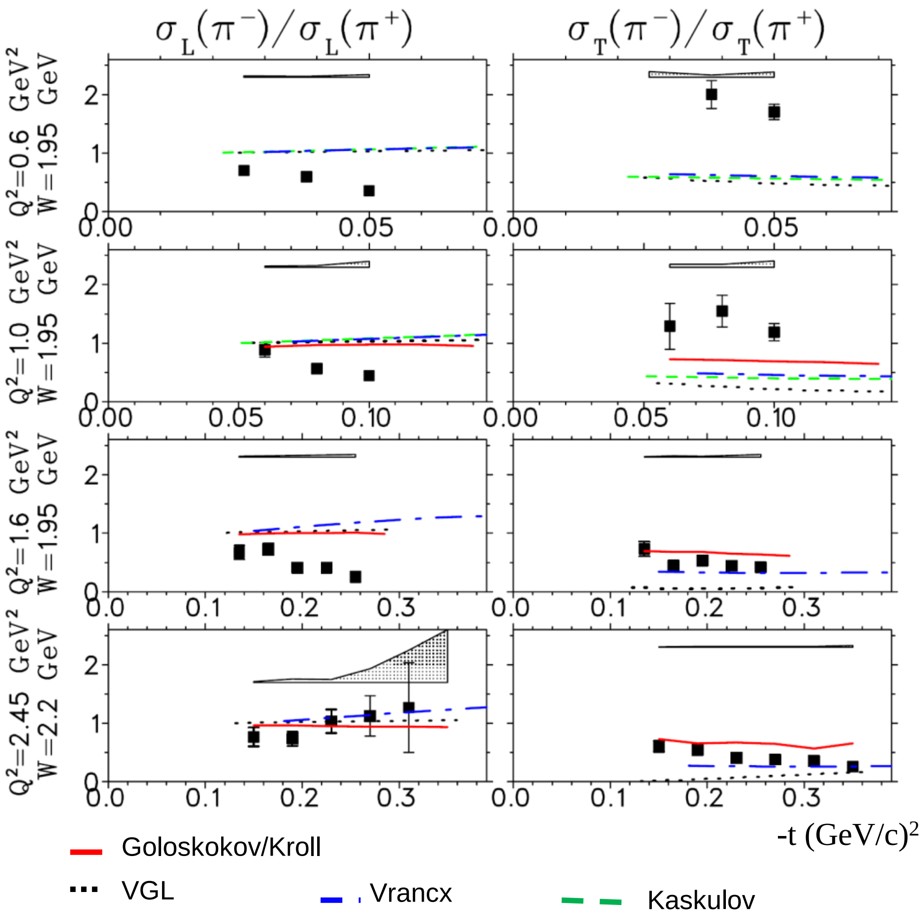
- π^+ *t*-channel diagram is pure isovector (G-parity conservation)

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

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

- With increasing t, R_T is expected to approach the ratio of quark charges

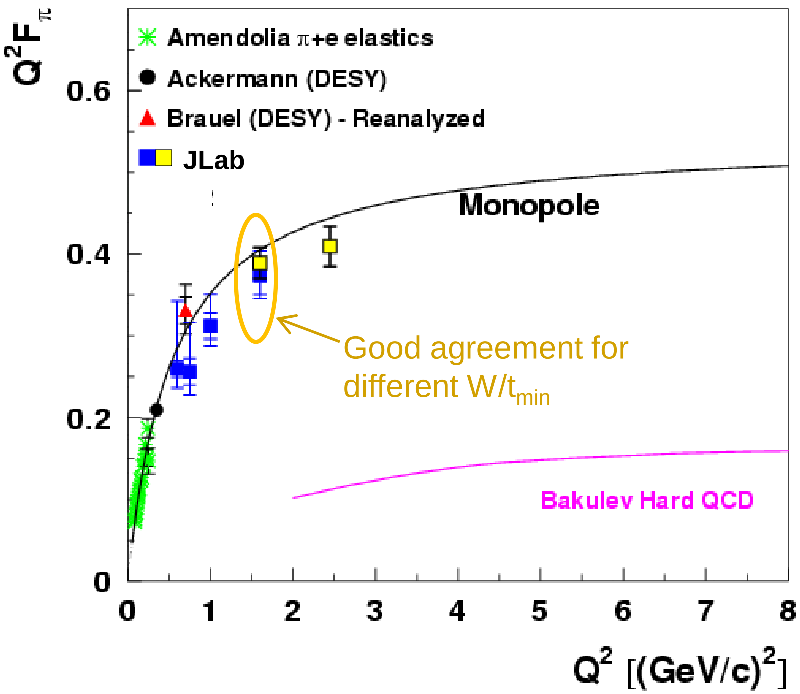
  [O. Nachtman, NP B115 (1976) 61]

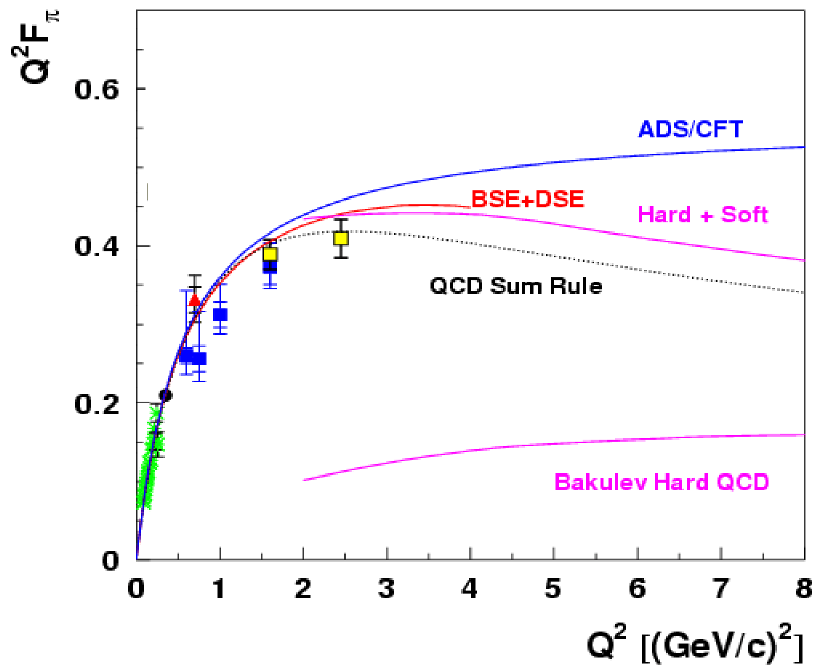


R_L data consistent with pion-pole dominance

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

$F_{\pi^+}(Q^2)$ in 2015





- 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)]*

Insight from data: Pion Transverse Charge Density and the edge of hadrons

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

- 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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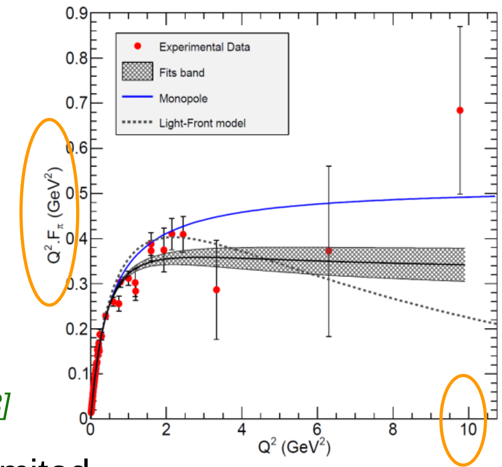
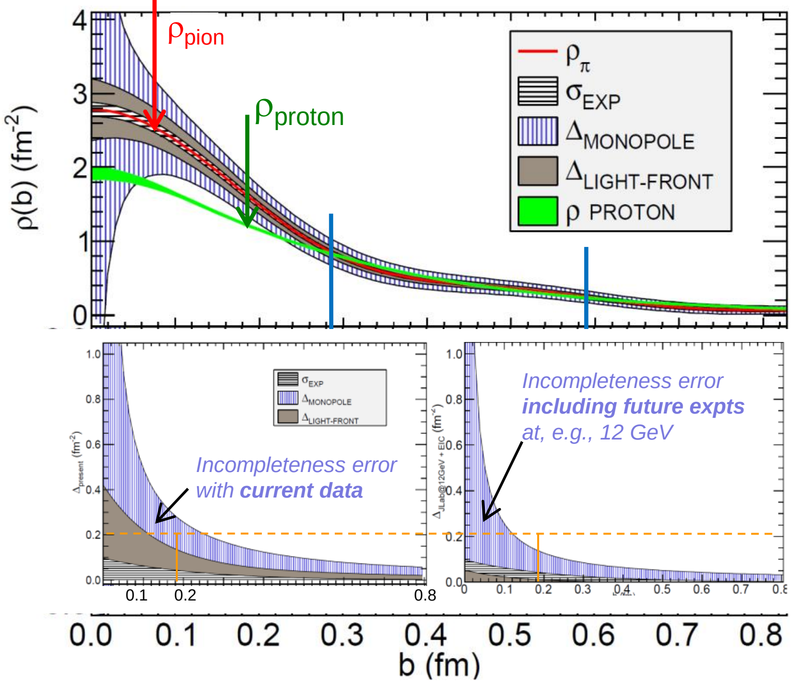


- Finite Radius Approximation

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

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

2D Fourier Transform



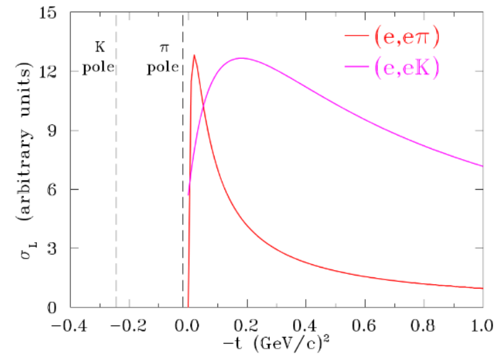
*[M. Carmignotto et al., Phys. Rev. C**90** 025211 **(2014)**]*

*[earlier analyses: G. Miller, PRC **79 (2009)** 055204); G. Miller, M. Strikman, C. Weiss, PRD **83 (2011)** 013006]*

- ρ_π is larger than ρ_p for b<0.3 fm - expected
- ρ_π and ρ_p coalesce for 0.3fm<b<0.6fm – *not* expected
  - Possible interpretation: proton consists of a core occupying most of the volume and a meson cloud dominating only at large impact parameter

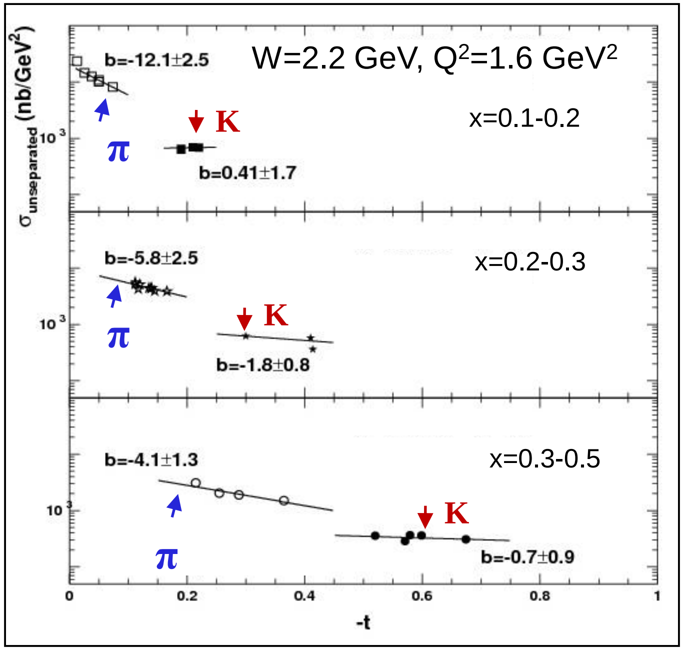
JLab 12 GeV data will allow further studies of a common transverse charge density – common confinement mechanism?

Extension to systems containing strangeness: the 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*



- Unseparated data: pion t-dependence is steeper *at* low *t* than for kaons

  *[T. Horn, Phys. Rev. C **85 (2012)** 018202]*

- <u>However</u>, the kaon pole is expected to be strong enough to produce a maximum in σ_L

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

JLab12 GeV essential for measurements at low *t*, which would allow for interpretation of the kaon pole contribution

Kaon Form Factor in 2015

- JLAB experiment E93-018 extracted $-t$ dependence of K^+ longitudinal cross section near $Q^2=1$ GeV^2

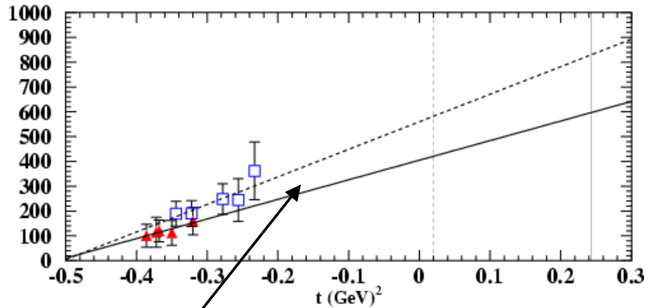
- A trial kaon form factor extraction was attempted using a simple Chew-Low extrapolation method

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

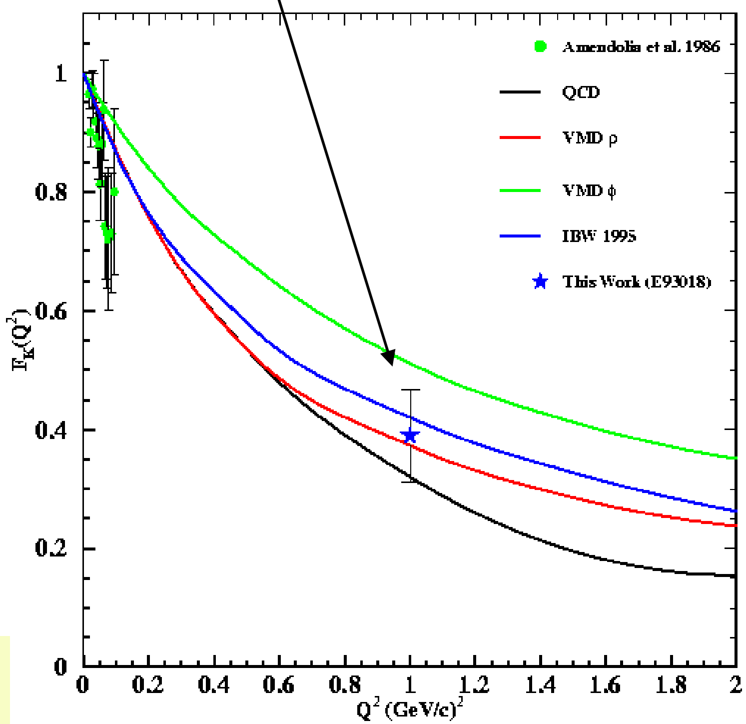
  - $g_{K\Lambda N}$ poorly known
    - Assume form factor follows monopole form
    - Use measurements at $Q^2=0.75$ and 1 GeV^2 to constrain $g_{K\Lambda N}$ and F_K simultaneously

- Extraction shows power of the data, but should probably not yet be interpreted 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.]

Kaons in JLab 6 GeV "pion" experiments

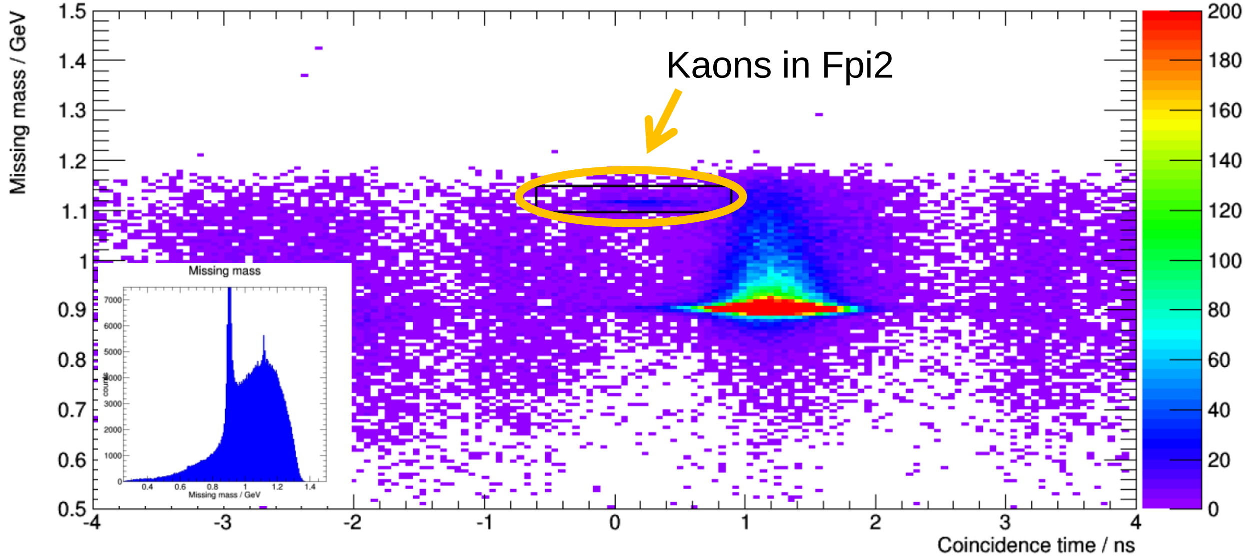
- 6 GeV pion experiments have kaons in their acceptance, e.g. FPI2, SIDIS

Figures from Marco Carmignotto

Runs 47358-47371:
- Ebeam = 5.2464 GeV

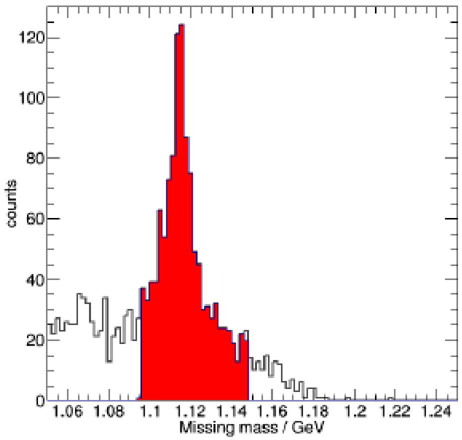
- e_Theta = 29.43 deg
- e_p = 1.7184 GeV/c

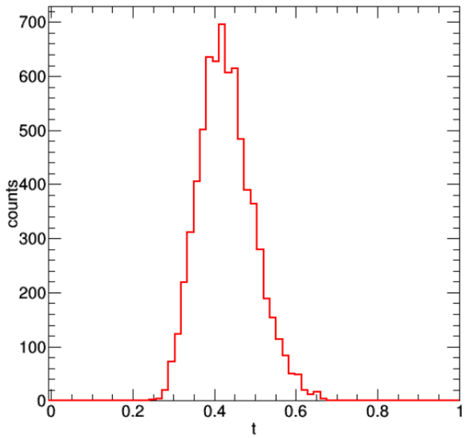
- h_Theta = 13.61 deg
- h_p = 3.3317 GeV/c



Cuts applied to all the plots:
* HMS acceptance:
  abs(hsdelta) < 8.5
  abs(hsxptar) < 0.09
  abs(hsyptar) < 0.055
* haero_su > 1.5
* ssshsum > 0.8 (SOS pion rejector)

After applying coincidence time cut:





Q^2=2.45 GeV^2

High ε=0.54 8000-9000 events

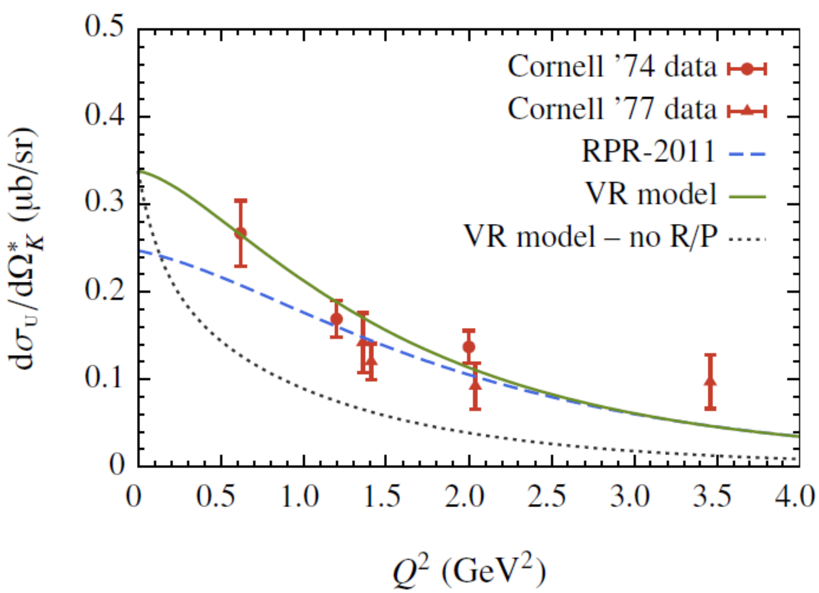
High ε=0.27 ~1200 events

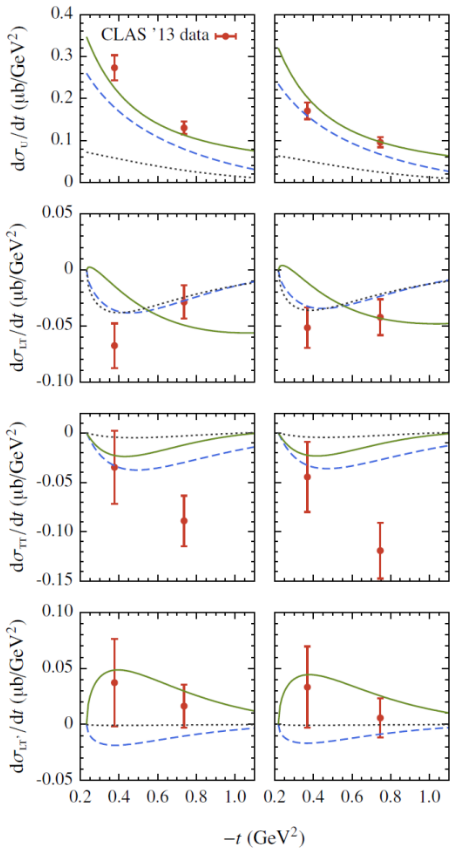
Parallel kinematics

Recent theory efforts to optimize the kaon VGL model: the "VR" model

- ❑ Extends the VGL Regge model by adding a hadronic model that includes DIS process, which dominates the transverse response at moderate and high Q^2
  - ➢ Residual effect of nucleon resonances in the proton EM TFF taken into account with a resonance-parton transition form factor *[T. Vrancx, J. Ryckebusch, J. Nys, Phys. Rev. C **89 (2014)** 065202]*

*[C.J. Bebek et al., Phys. Rev. Lett **32 (1974)** 21]*
*[C.J. Bebek et al., Phys. Rev. D **15 (1977)** 594]*





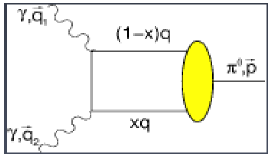
*[D. S. Carman et al., Phys. Rev. C **87 (2013)** 025204]*

- ❑ Good agreement with unseparated kaon data from Cornell and JLab Hall B

New Pseudoscalar Meson Transition Form Factor Data

…deepened the mystery on how QCD transitions from the soft to the hard regime

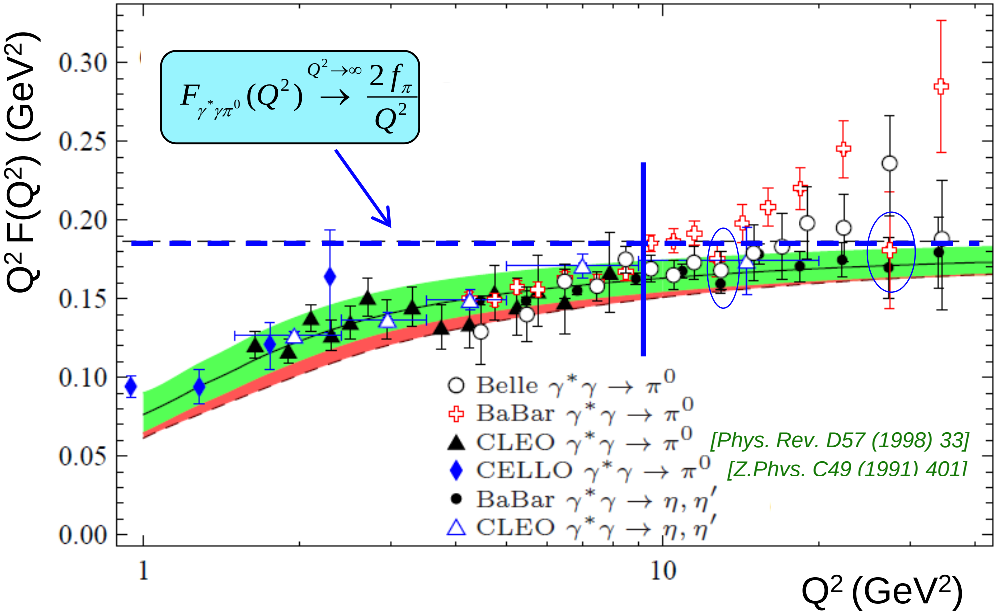
- Simplest structure for pQCD analysis



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

- **2009:** Babar data showed a continuous rise above the QCD asymptotic limit
  *[Phys. Rev. D **80 (2009)** 052002]*

- **2012:** BELLE measurements are fully consistent with η, η', η TFF and also with QCD scaling *[Phys. Rev. D **86 (2012)** 092007]*
  - 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 and Babar from one another *[Stefanis et al. PRD **87 (2013)** 094025]*

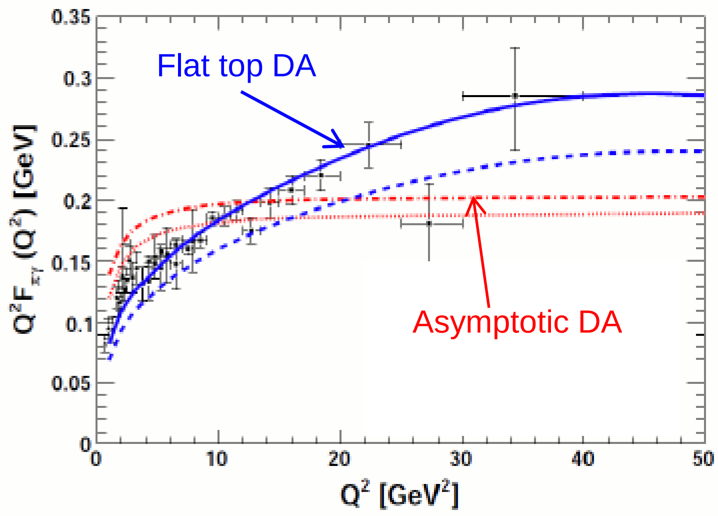
Opposing tendencies in the data cannot be reconciled until additional data on TFFs and other exclusive processes become available, but perhaps no crisis

Implications on the Pion Distribution Amplitude (DA)

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

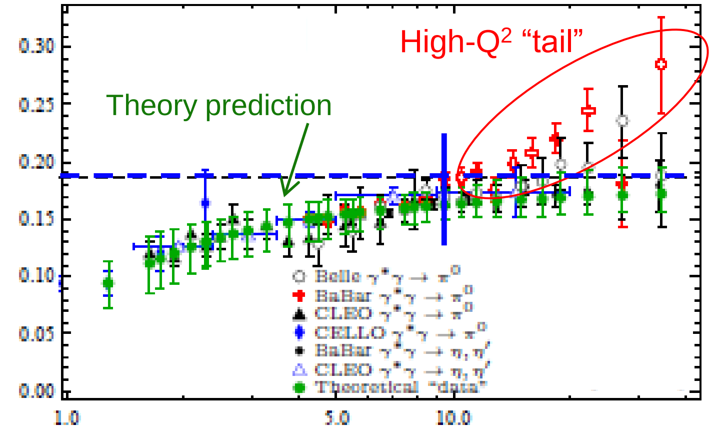
- Nonperturbative info about mesons is summarized in the DA - comparison with pQCD gives info on the shape, different trends in TFF due to DA endpoint character
  - Asymptotic distribution does not describe all the existing data
  - "Flat-top" DA best agreement with Babar but cannot be reconciled with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

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



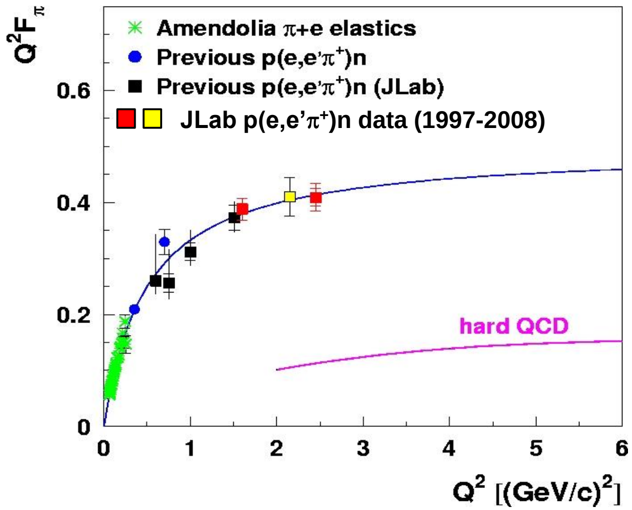
- Within standard QCD approach the BMS-like pion DA gives good agreement with global data

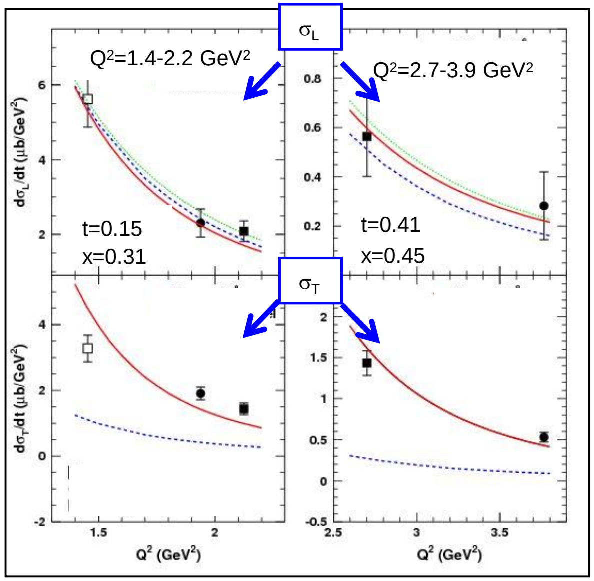
  [A. Bakulev et al., PL B578 (2004), 91; PR D73 (2006) 056002] *[Stefanis et al. PRD **87 (2013)** 094025]*
  - Consistent with basic features of the η TFFs implying *strong end point suppression*
  - However, cannot describe the high-Q^2 tail of the Babar data requiring *end point enhancement*



Additional pion data on components of the DA needed to understand the underlying mechanism of the large Q^2 enhancement

QCD factorization – important for both form factors and nucleon structure





- ❑ Q^2 dependence of F_π follows prediction from pQCD, suggests factorization holds, as perhaps in the TFF
- ❑ Different magnitudes imply that factorization does not hold or something is missing in the calculation
  - ➢ The form of the pion DA is also important for the calculation of the pQCD prediction
- ❑ Q^2 dependence of the pion cross section is an essential test of hard-soft factorization required for studies of the nucleon's transverse spatial structure
  - ➢ 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 ($\sigma_T \sim Q^{-8}$) and magnitude is large

*[T. Horn et al., Phys. Rev. C **78**, 058201 **(2008)**]*

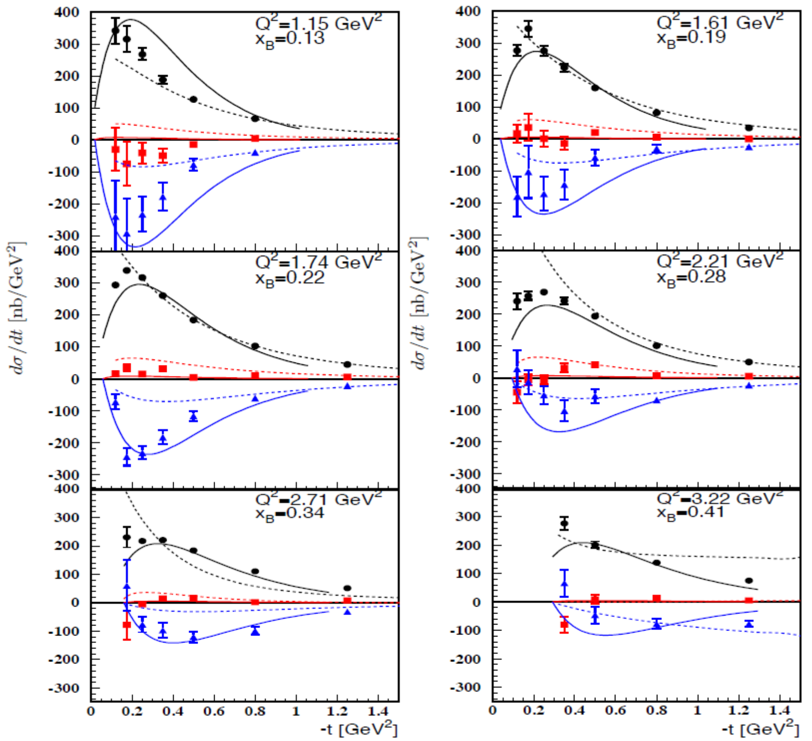
F_π and pion cross section data over a larger range in Q^2 at 12 GeV can provide essential information about the reaction mechanism – can we learn about nucleon structure using exclusive meson production?

Transverse Contributions may allow for probing a new set of GPDs

- 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, PRL**109**, ***(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

*E12-**07**-105 spokespersons: T. Horn, G. Huber*

*E12-**13**-010 spokespersons: C. Munoz-Camacho, T. Horn, C. Hyde, R. Paremuzyan, J. Roche; E12-**06**-101: K. Joo et al.*

- Considerable theoretical interest 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

*[Ahmad, Goldstein, Liuti, PRD **79 (2009)**]*

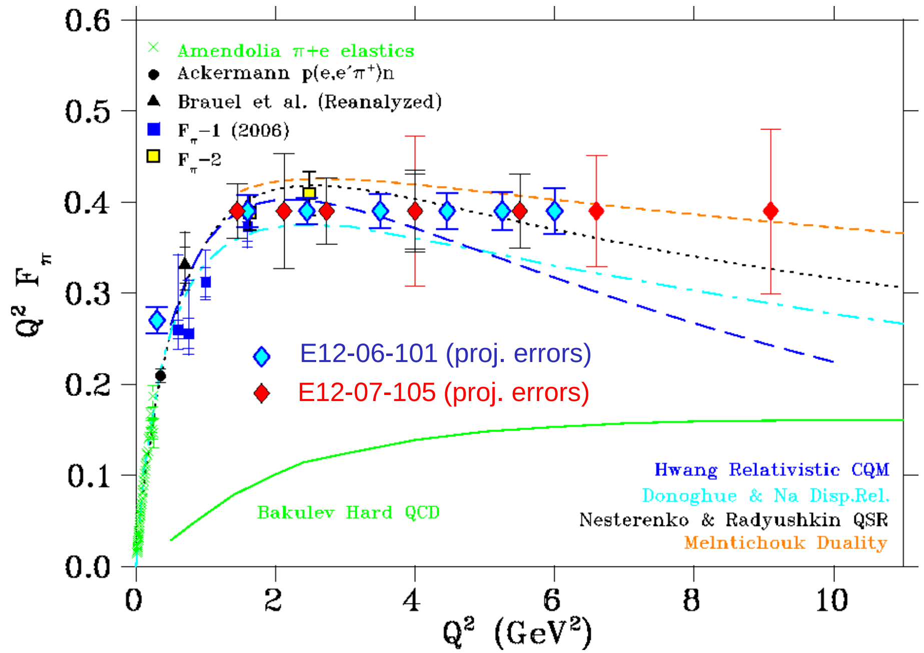
*[Goldstein, Gonzalez Hernandez, Liuti, J. Phys. G **39 (2012)** 115001]*

A large transverse cross section in π^0 production may allow for accessing helicity flip GPDs

JLab: the only facility with capability for reliable F_π measurements

- Experiments in Hall C have established the validity of the measurement technique
- CEBAF 10.9 GeV electron beam and SHMS small angle capability and controlled systematics are essential for extending precision measurements to higher Q^2

Figure from G. Huber



- The JLab 12 GeV π^+ experiments:
  - ***E12-06-101***: determine F_π up to Q^2=6 GeV^2 in a dedicated experiment
    - Require t_{min}<0.2 GeV^2 and $\Delta\varepsilon$>0.25 for L/T separation

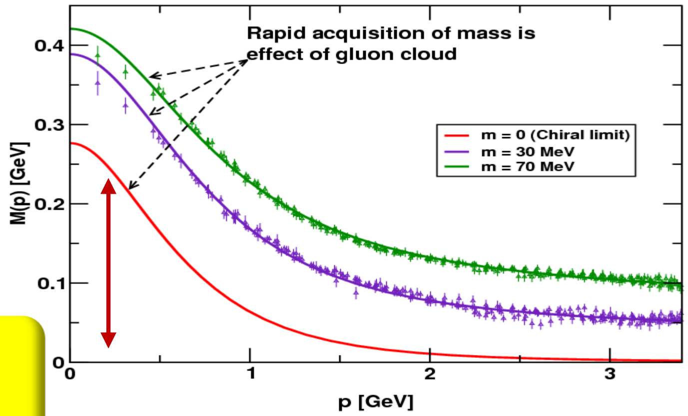
    *E12-**06**-101 spokespersons: G. Huber, D. Gaskell*
  - ***E12-07-105***: Primary goal L/T separated cross section data to highest possible Q^2~9 GeV^2 with SHMS/HMS to investigate hard-soft factorization
    - May allow for F_π extraction at Q^2~9 GeV^2

    *E12-**07**-105 spokespersons: T. Horn, G. Huber*

Higher Q^2 data will challenge QCD-based models in the most rigorous way and provide a real advance in our understanding of light quark systems

JLab 12 GeV F_π data and the Pion valence-quark DA

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



- Dynamical Chiral Symmetry Breaking (DCSB) is the most important mass generating mechanism for light-quark hadrons

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

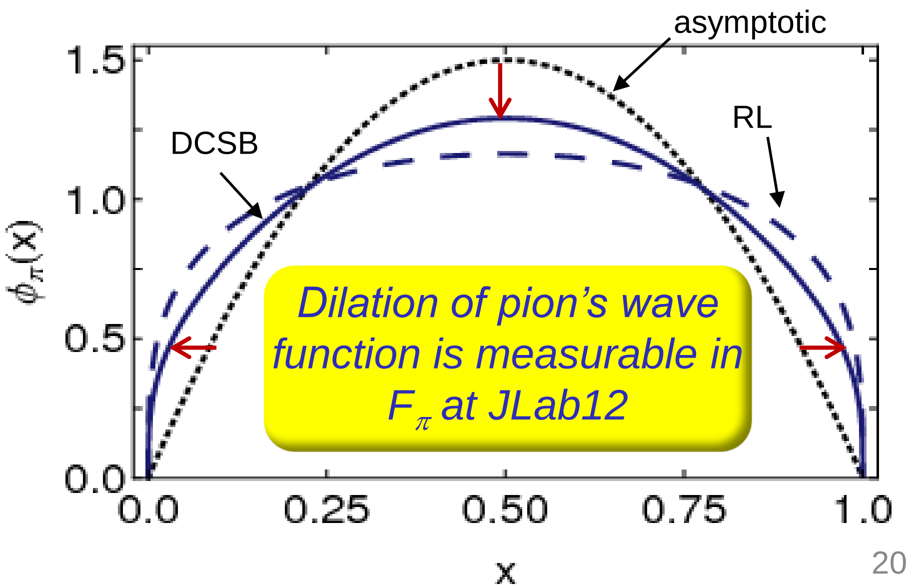
- There is a one-to-one connection between DCSB and the point-wise form of the pion's wave function.

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

[I. Cloet, et al., PRL ***111 (2013)*** *092001]*

- Dilation of the pion wave function measures the rate at which the dressed-quark approaches the asymptotic bare-parton limit – signature of DCSB

- Experiments at JLab12 can empirically verify the behavior of *M(p)*, and hence chart the IR limit of QCD

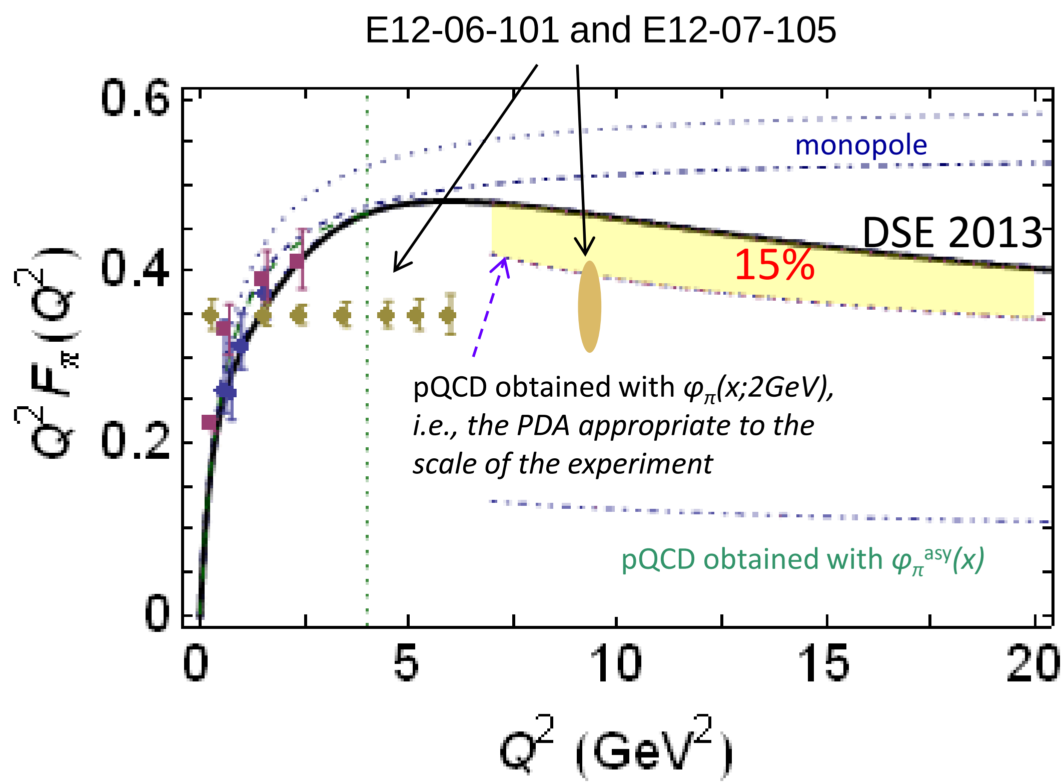


JLab 12 GeV F_π data and theory

- 2014:

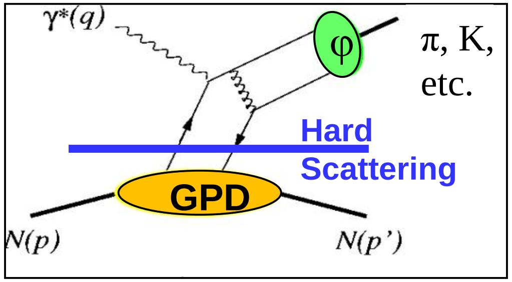
*[L. Chang, et al., PRL **111 (2013)** 141802; **PRL 110 (2013)** 1322001]*

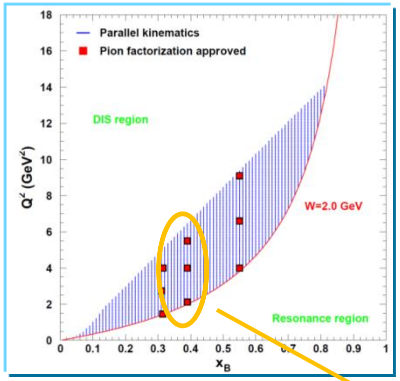
- When comparing the pQCD prediction the pion valence-quark DA has to have at form appropriate to the scale accessible in experiments - very different from the result obtained using the asymptotic DA
- Near agreement between the relevant pQCD and DSE-2013
- Monopole fit ~20% above DSE-2013 at Q^2~9 GeV^2



- JLab 12 GeV experiments will map out the kinematic regime where the hard contributions to F_π may begin to be dominant ($Q^2 > 8$ GeV^2)

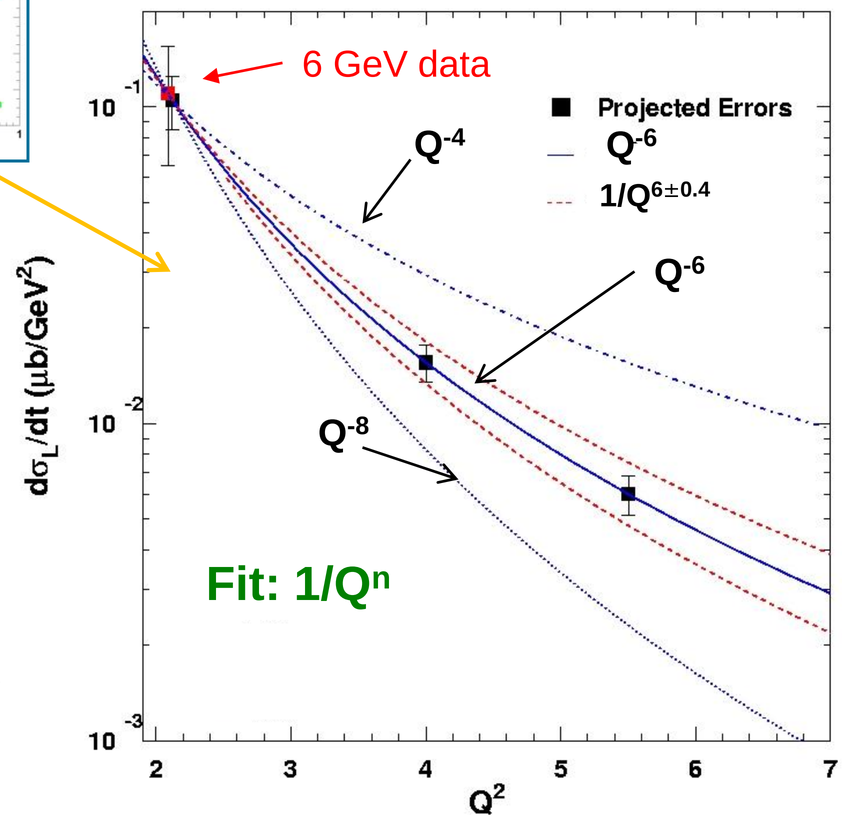
Factorization Tests in π^+ Electroproduction





- **E12-07-105**: primary goal: L/T separated π^+ cross sections to investigate hard-soft factorization
  - Highest Q^2 for any L/T separation in π^+ production

- Factorization essential for reliable interpretation of results from the JLab GPD program at both 6 GeV and 12 GeV



Is the partonic description applicable at JLab?
Can we extract GPDs from pion production?

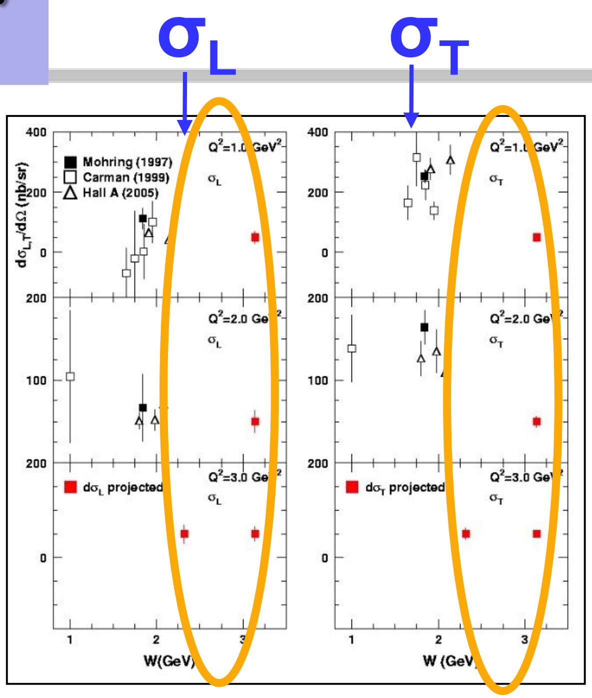
JLab: the only facility with capability for reliable Kaon measurements

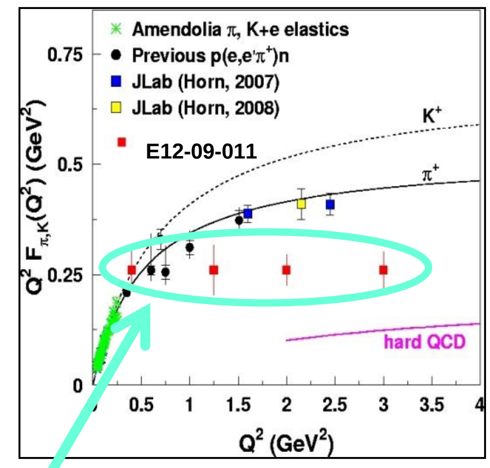
- CEBAF 11 GeV electron beam and SHMS small angle capability are essential for the first L/T separated **kaon** data above the resonance region

- **E12-09-011**: primary goal L/T separated kaon cross sections to investigate hard-soft factorization and non-pole contributions
  - New domain for GPD studies – system where strangeness is in play
  - 12 GeV data could allow for comparing the observed Q^2 dependence and magnitude of π^+ and K^+ FFs

    *[C. Shi, et al., arXiv:1406.3353 **(2014)**]*
  - Dedicated detector built

*E12-**09**-011spokespersons: T. Horn, G. Huber, P. Markowitz*

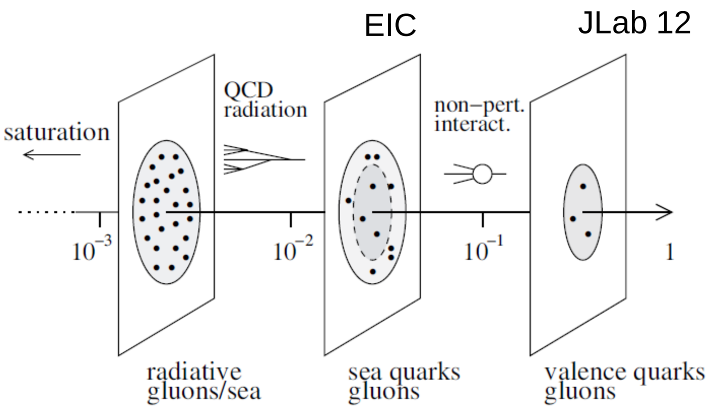


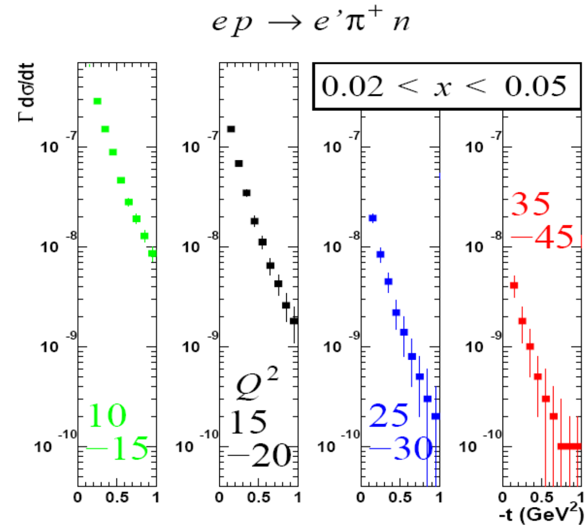


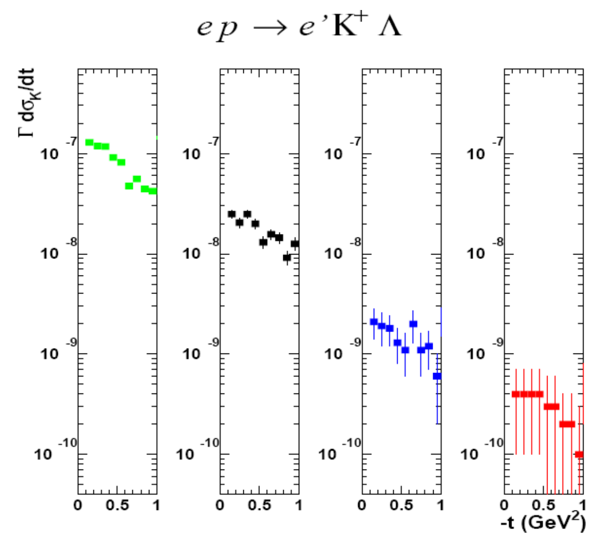
Projected uncertainties for kaon experiment at 12 GeV

Together with π^+ these data could make a substantial contribution towards understanding not only the K^+ production mechanism, but hard exclusive meson production in general

EIC: Plans for exclusive pion and kaon measurements







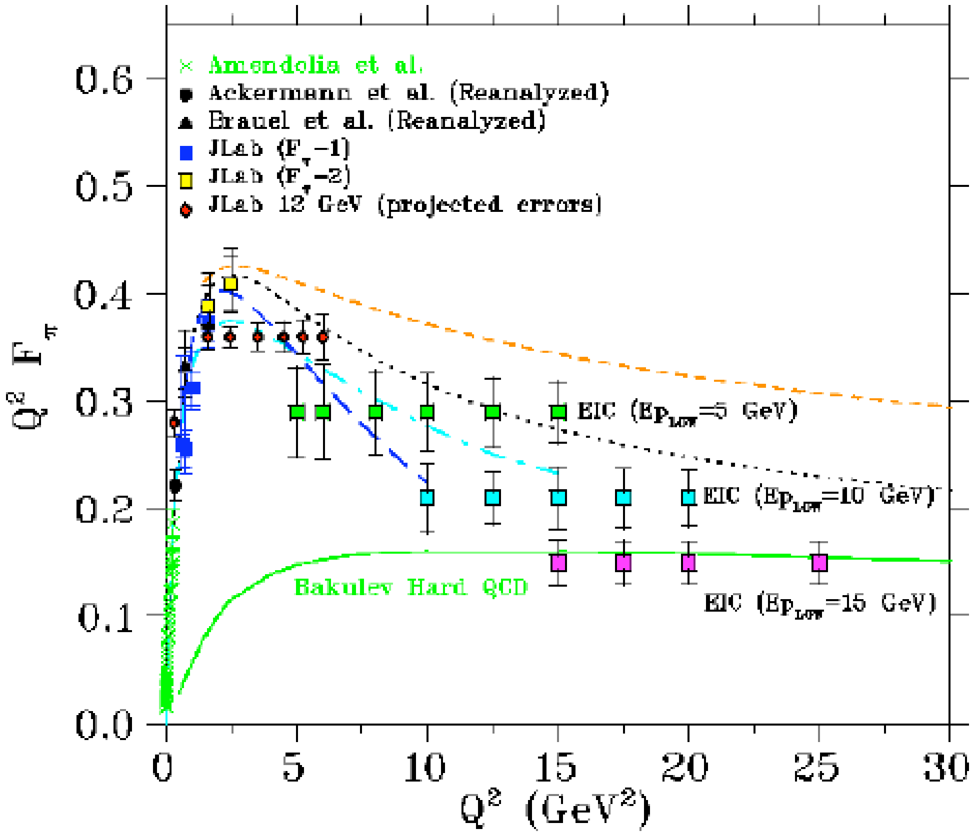
s=1000 GeV^2

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

- ❑ 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

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

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, may also allow for kaon form factor extractions, and may also have significant impact on nucleon structure studies