Meson Form Factors and Deep Exclusive Meson Production Experiments

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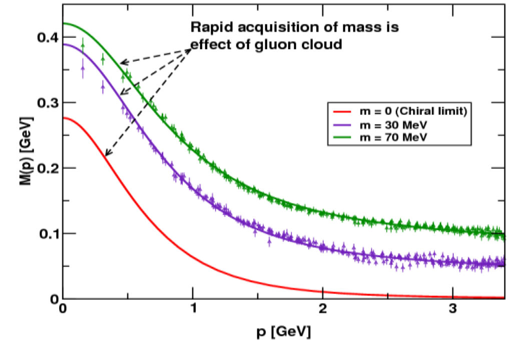
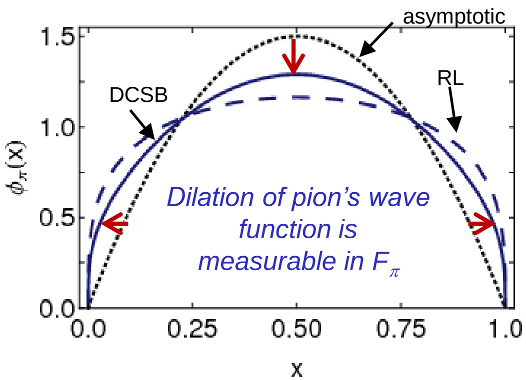
Overview

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

- Pion and kaon form factors are of special interest in hadron structure studies
  - The pion is the lightest QCD quark system and also has a central role in our understanding of the dynamic generation of mass.
  - The kaon is of interest as it replaces one light quark with a heavier strange quark.



- Recent advances in experiments: last 5-10 years
  - Dramatically improved precision in F_π measurements
  - Improved experimental understanding of the meson production/reaction mechanism

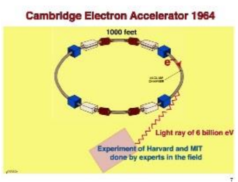


- Future approved measurements – JLab 12 GeV next 5-10 years
  - F_π and exclusive meson studies up to highest possible Q^2 – potential to reach the regime in which hard QCD's signatures will be quantitatively revealed
  - Exclusive kaon cross sections at low t and possible F_{K+} extraction

Meson Form Factor Data Evolution

Experiment

Capability to reliably access large Q^2 regime



JLab 6 GeV

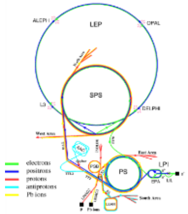
JLab 12 GeV

EIC

1959 1971 1976 1979 1981 1984 1986 1997 2003 2004 2017+ 2025+

Cornell University

Fermilab



Theory

- Accessing the form factor through electroproduction
- Extraction of meson form factor from data
- Electroproduction formalism

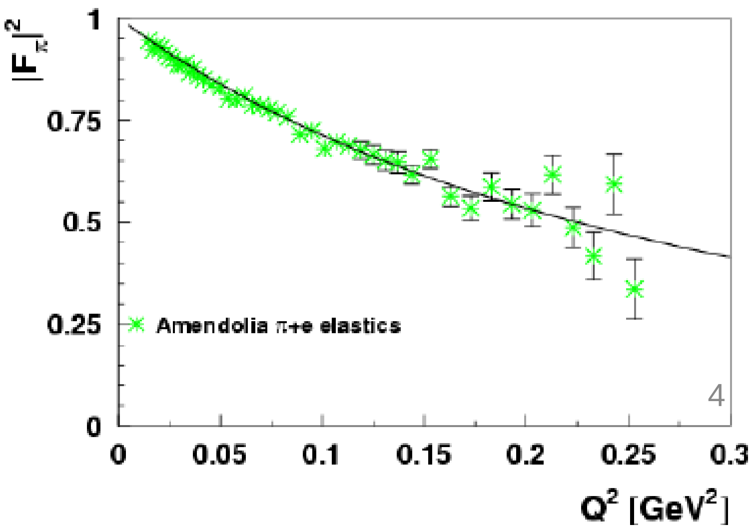
Theory

Major progress on large Q^2 behavior of meson form factor

Experimental Determination of the π^+ Form Factor

Through π-e elastic scattering

- 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



- The maximum accessible Q^2 is roughly proportional to the pion beam energy
  - $Q^2 = 1$ GeV^2 requires 1000 GeV pion beam

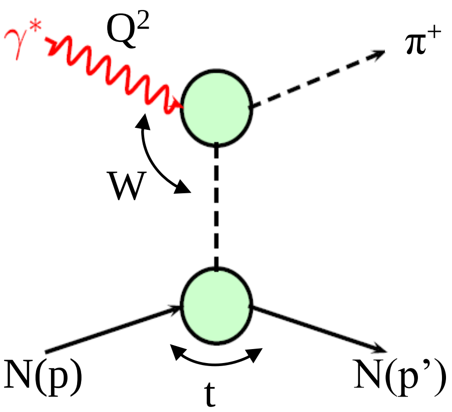
Experimental Determination of the π^+ Form Factor

Through pion electroproduction

- 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 the longitudinal cross section, σ_L
  - In the Born term model, F_π^2 appears as

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

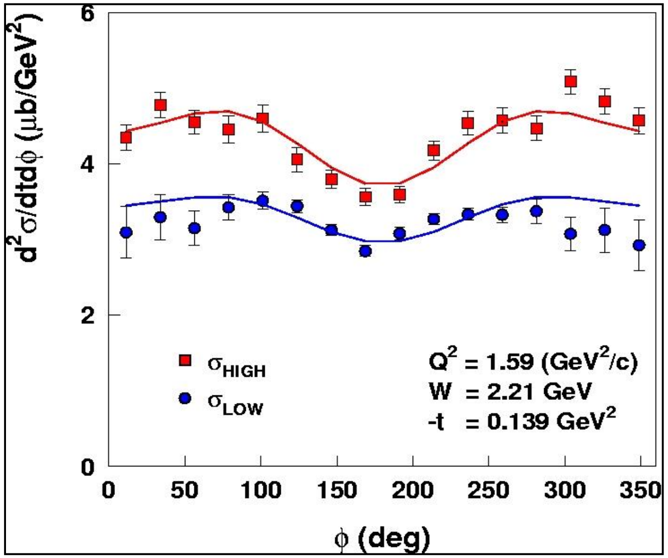
[In practice one uses a more sophisticated model]



- **Requirements:**
  - Full L/T separation of the cross section – isolation of σ_L
  - Selection of the pion pole process
  - Extraction of the form factor using a model
  - Validation of the technique - model dependent checks

L/T Separation Example

- σ_L is isolated using the Rosenbluth separation technique
  - Measure the cross section at two beam energies and fixed W, Q^2, -t
  - Simultaneous fit using the measured azimuthal angle (ϕ_π) allows for extracting L, T, LT, and TT



- Careful evaluation of the systematic uncertainties is important due to the $1/\varepsilon$ amplification in the σ_L extraction
  - Spectrometer acceptance, kinematics, and efficiencies

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

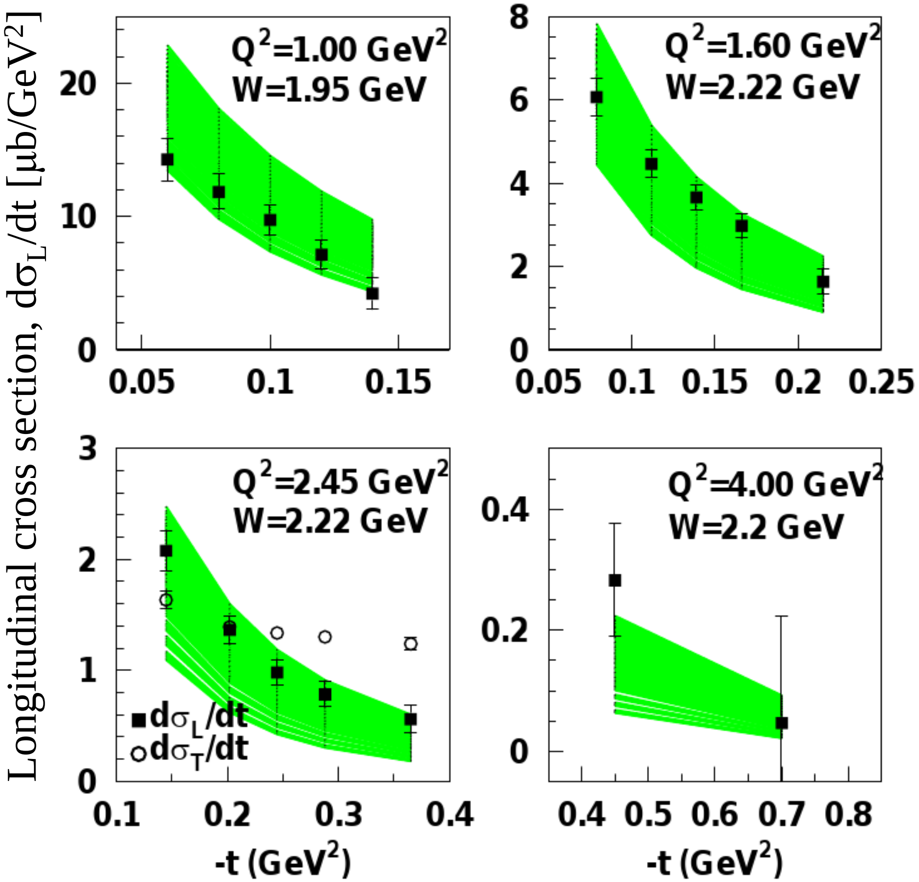
σ_L will give us F_π

Magnetic spectrometers a must for such precision cross section measurements

- This is only possible in Hall C at JLab

Pion pole process in pion electroproduction data at low *t*

L/T separated data from JLab 6 GeV (Hall C)



$$\frac{d\sigma^{pole}}{dt}\left(\gamma_L^* \to \pi^+\right) = \frac{1}{\kappa}\frac{-t}{\left(t - m_\pi^2\right)^2} Q^2 \rho_{\pi\pi}^2$$

$$\rho_{\pi\pi} = \sqrt{2} e_0 F_\pi(Q^2) g_{\pi NN} F_{\pi NN}(t)$$

$$F_{\pi NN} = \frac{\Lambda_N^2 - m_\pi^2}{\Lambda_N^2 - t} \qquad F_\pi = \frac{1}{1 + Q^2/\Lambda_\pi^2} \qquad [\Lambda_\pi^2 = 0.53\ \mathrm{GeV}^2]$$

Band indicates calculated range of values for:
Λ_N=0.4-0.6 GeV $g_{\pi NN}$=13.1-13.5

- Longitudinal cross section at W=2.2 GeV in good agreement with the pion pole calculation
- At W=1.95 GeV the pole calculation seems to predict a different Q^2 dependence than the data

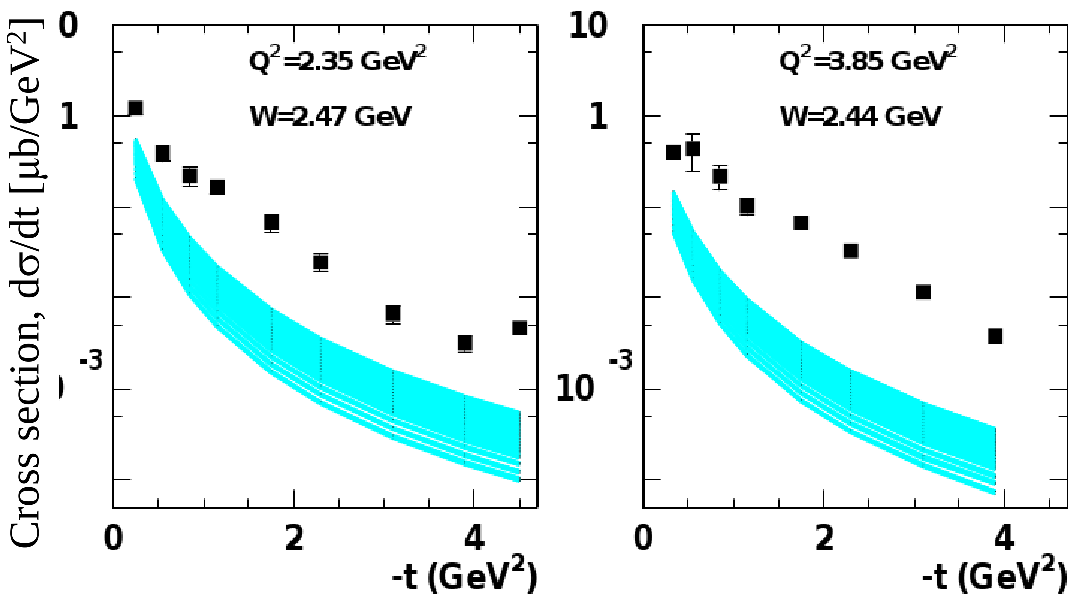
Note: the values of W and Q2 listed are the overall *central* values. Each t-bin has actually its own bin-centered W and Q2 values

*[L. Favart, M. Guidal, T. Horn, P. Kroll, Eur. Phys. J A **52** (2016) no.6, 158]*

Overall, σ_L data demonstrate the important contribution from the pion pole at small t

Pion pole process in pion electroproduction data at larger t

Unseparated data from JLab 6 GeV (CLAS) *[K. Park et al., EPJA **49** (2013)]*



Band indicates calculated range of values for:
Λ_N=0.4-0.6 GeV $g_{\pi NN}$=13.1-13.5

- ❑ At larger t the pole contribution does not give a good description of the data

*[L. Favart, M. Guidal, T. Horn, P. Kroll, Eur. Phys. J A **52** (2016) no.6, 158]*

- ❑ In the unseparated cross section one cannot quantify the contribution of longitudinal and transverse photons
  - ➢ For F_π extraction must fully separate cross section into longitudinal and transverse contributions

- ❑ Need to experimentally determine that F_π extraction does not depend on the t-value of the data

Extraction of F_π from σ_L Jlab data

- JLab 6 GeV 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

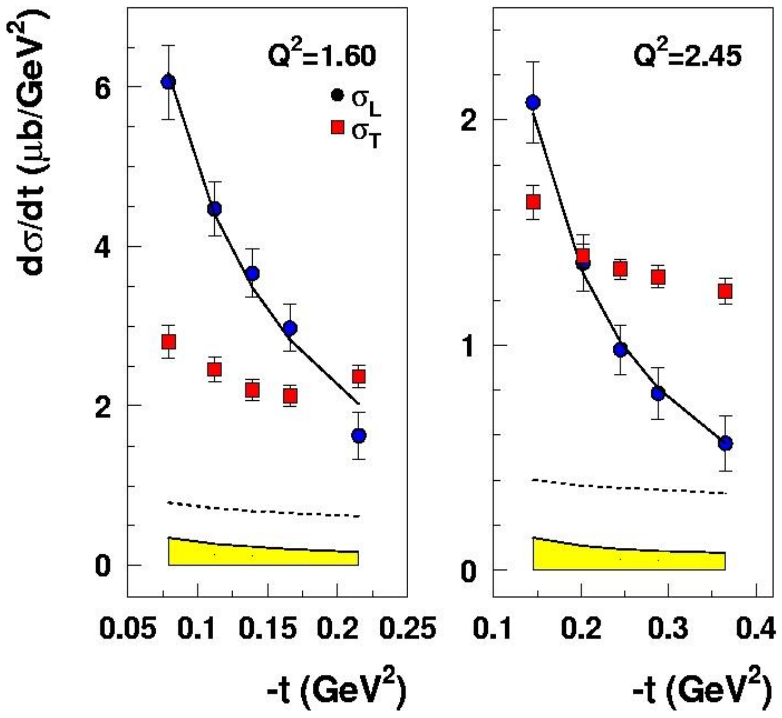
*[Vanderhaeghen, Guidal, Laget, PRC **57**, (1998) 1454]*

  - Feynman propagator replaced by π and ρ trajectories
  - Model parameters fixed by pion photoproduction data
  - Free parameters: $\Lambda_\pi^2, \Lambda_\rho^2$

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

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

*[Horn et al., PRL **97**, (2006) 192001]*



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

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

Validation: Check of non-pole backgrounds in σ_L with charged pion ratios in deuterium

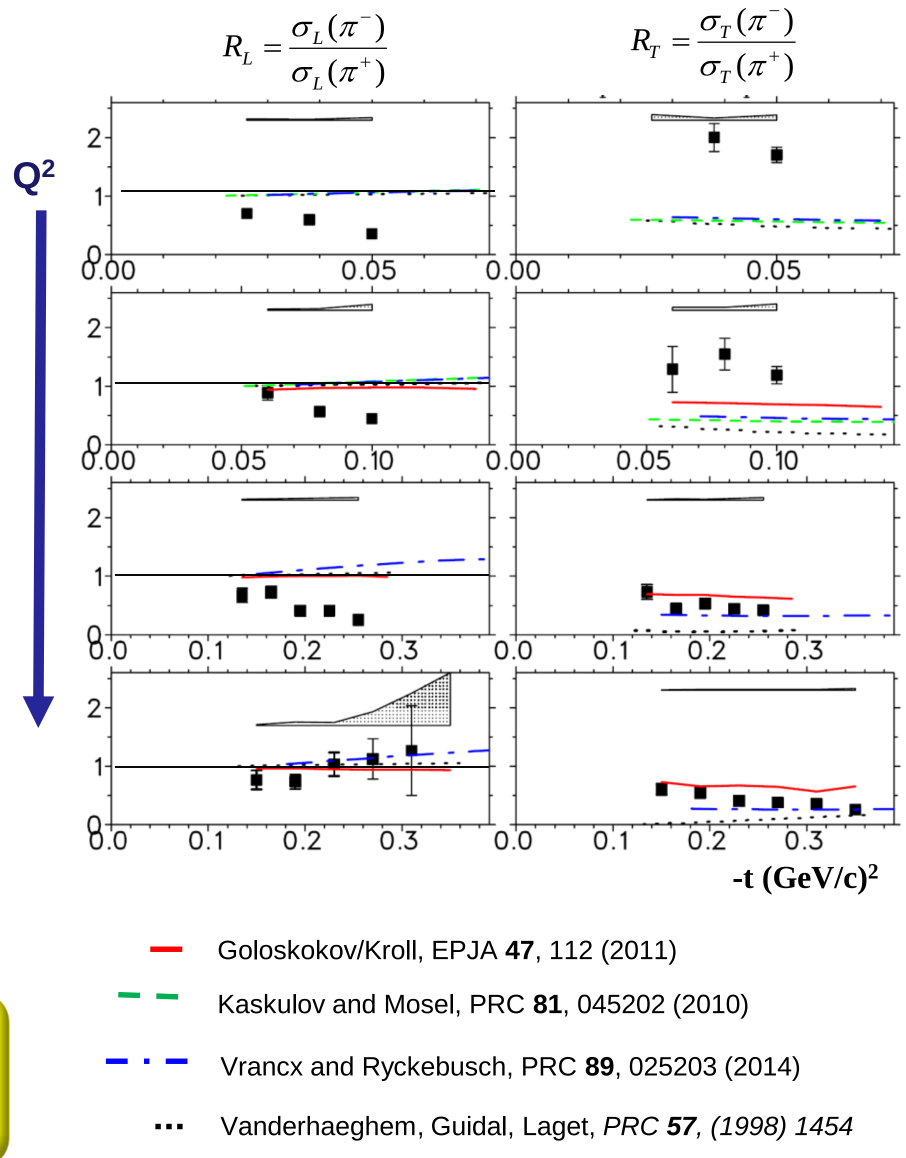
[Huber et al, PRL**112** (**2014**)182501]

- π^+ *t*-channel diagram is pure isovector (G-parity conservation)
- Measure (separated) π^-/π^+ *ratio to test pole dominance*

$$R_L = \frac{\sigma_L(\pi^-)}{\sigma_L(\pi^+)} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2}$$

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

- With increasing *t*, R_T is expected to approach the ratio of quark charges
  [O. Nachtman, NP B115 (1976) 61]



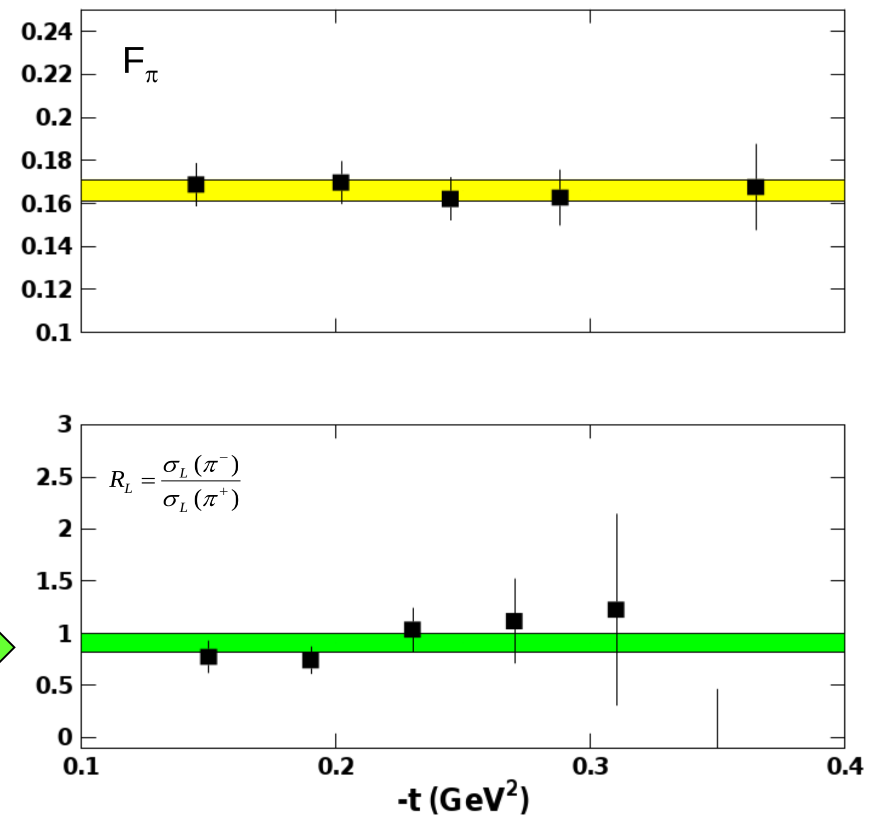
R_L approaches unity at large Q^2 - consistent with pion-pole dominance

Validation: experimental considerations

Experimental studies over the last decade have given *confidence* in the electroproduction method yielding the physical pion form factor

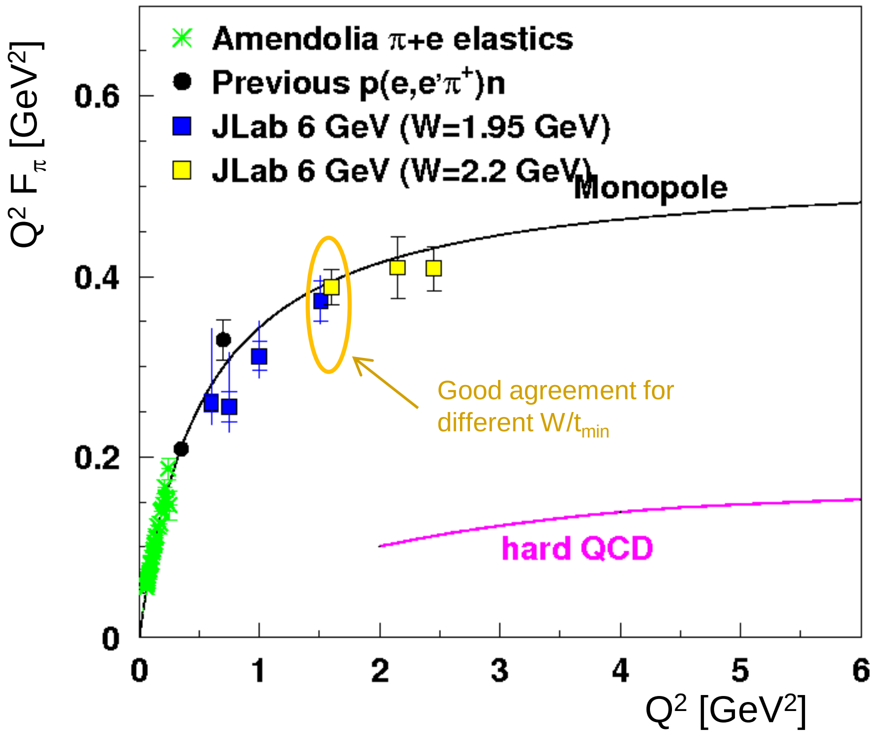
- Experimental studies include:
  - Check consistency of model with data
    - F_π values do not depend on the t-acceptance – confidence in applicability of model to the kinematic regime of the data
  - Verify that the pion pole diagram is the dominant contribution in the reaction mechanism
    - R_L approaches the pion charge ratio, consistent with pion pole dominance

    *[Huber et al, PRL**112** (**2014**)182501]*
  - Extract F_π at several values of t_{min} for fixed Q^2 (next slide)



*[T. Horn, C.D. Roberts, J. Phys. G**43** (2016) no.7, 073001]*

$F_{\pi^+}(Q^2)$ in 2016



- ❑ *Factor ~3* from hard QCD calculation evaluated with asymptotic wave function
  - Trend consistent with time like meson form factor data up to Q^2=18 GeV^2

    *[Seth et al, PRL **110** (2013) 022002]*

- ❑ Recent efforts:
  - Compare data with the QCD prediction calculated using the broad pion PDA predicted by modern analyses of continuum QCD

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

- ❑ Several effective models do a good job describing the data, e.g.,
  - *BSE+DSE: Maris and Tandy, Phys. Rev. **C62**, 055204 (2000)]*
  - *QCD SR: Nesterenko and Radyushkin, Phys. Lett. **B115**, 410(1982)*
  - *LFQM: C.-W.Hwang, PRD **64** (2001) 034011*
  - *Hard QCD: A.P. Bakulev et al, Phys. Rev. **D70** (2004)]*

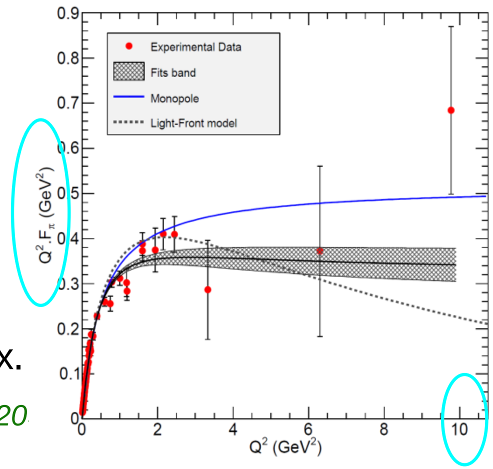
Insight from data: Pion Transverse Charge Density and the edge of hadrons

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

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

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

input

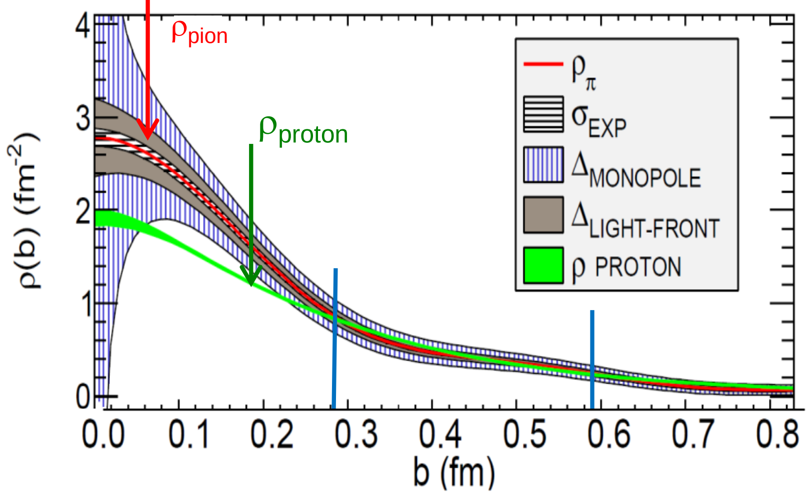


- Method: Finite Radius Approx.

*[S. Venkat et al., PRC **83 (2011)** 01520*

- Uncertainty dominated by *incompleteness error* due to limited data range– estimated using models

2D Fourier Transform



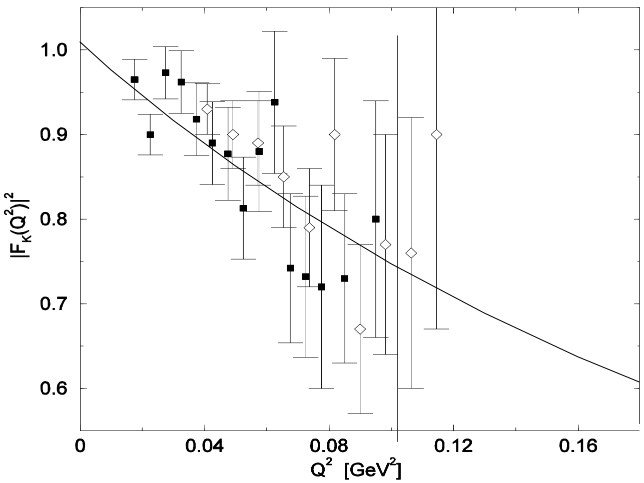
- ρ_π and ρ_p coalesce for 0.3 fm<b<0.6 fm
- Meson cloud only dominating at large impact parameter?

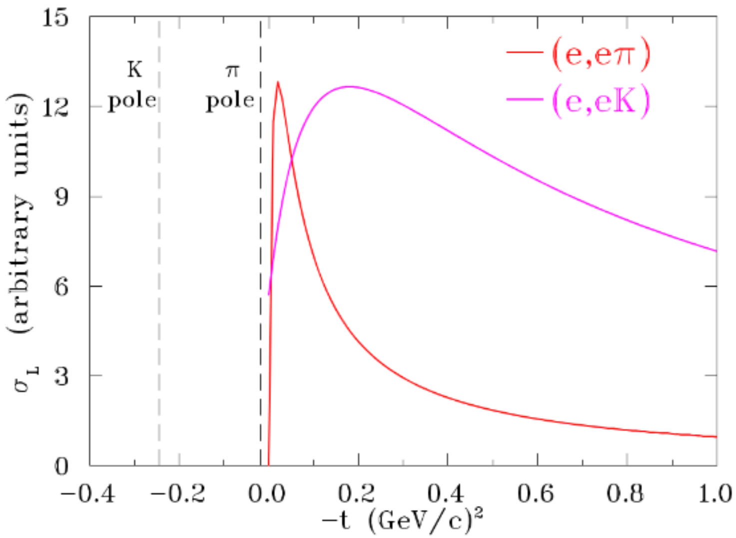
JLab 12 GeV data will allow further studies of transverse charge density and test for common confinement mechanism

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

Extension to systems containing strangeness: the K^+ Form Factor

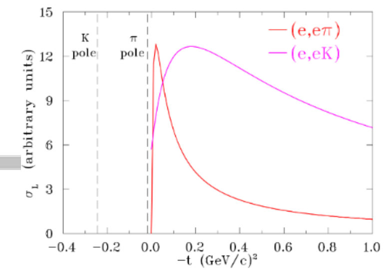
- Similar to π^+, elastic K^+ scattering from electrons used to measure charged kaon for factor at low Q^2
  - CERN SPS used 250 GeV kaons to measure form factor up to $Q^2 = 0.13$ GeV^2 *[Amendolia et al, PLB 178, 435 (1986)]*
  - These data used to constrain the kaon RMS radius: $r_K = 0.58 \pm 0.04$ fm



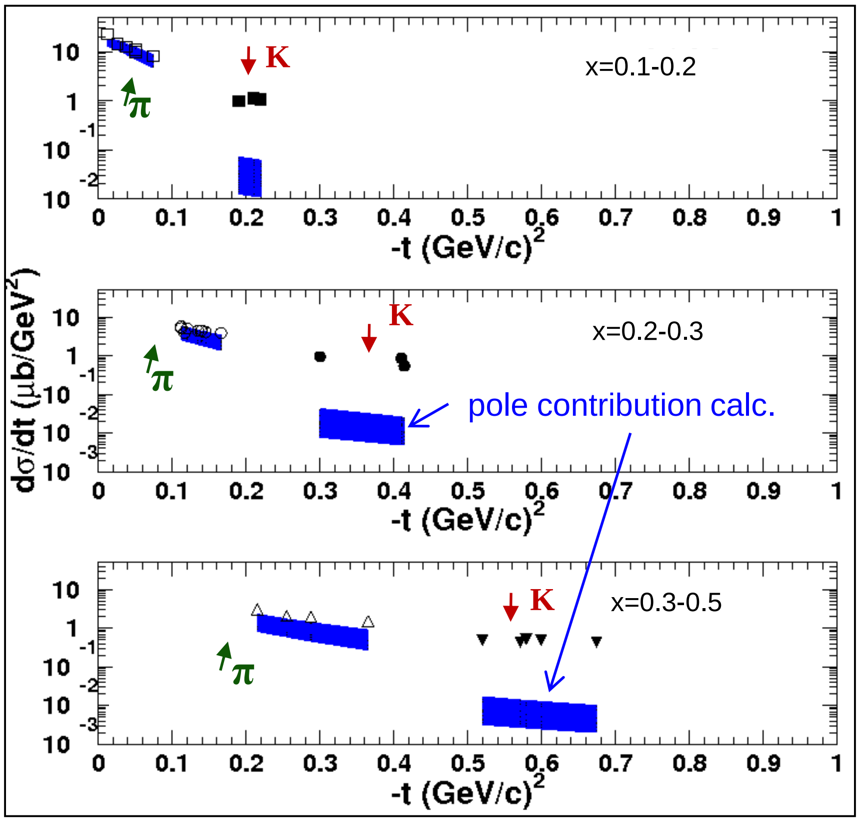


- Can "kaon cloud" of the proton be used in the same way as the pion to extract kaon form factor via ***p(e,e'K*$^+$*)*Λ?
  - *Need to quantify the role of the kaon pole*

Kaon pole process in kaon electroproduction



W=2.2 GeV, Q^2=1.6 GeV^2



*[L. Favart, M. Guidal, T. Horn, P. Kroll, Eur. Phys. J A**52** (2016) no.6, 158]*

❑ At large t:

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

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

- Due to experimental constraints most of existing kaon data fall into this category

Clearly, separated low-t data are needed in the deep inelastic regime

❑ At small t:

- Kaon pole is *expected* to be strong enough to produce a maximum in σ_L

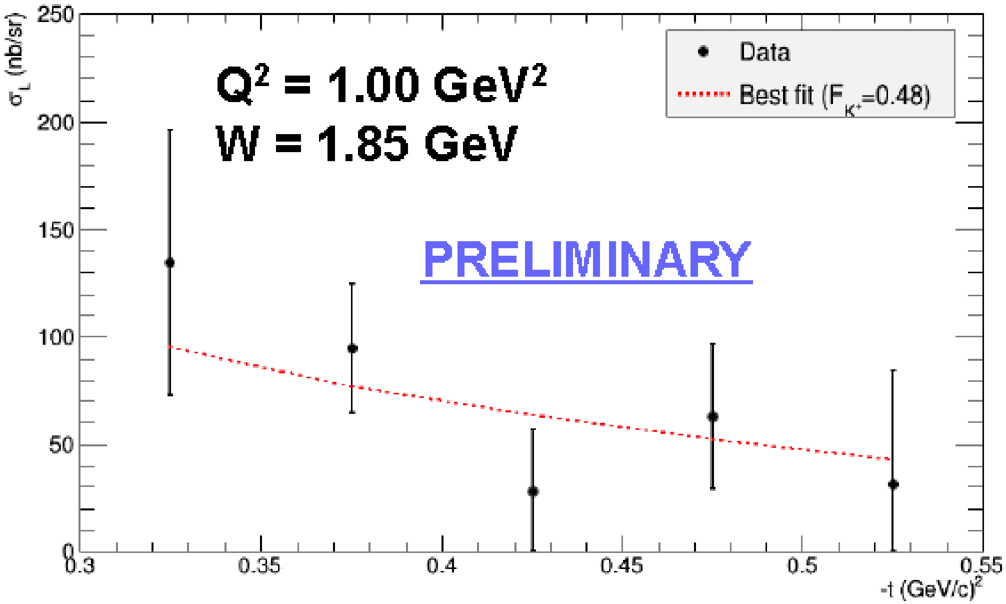
*[Kroll/Goloskokov EPJ A**47** (2011), 112]*

JLab 12 GeV will provide data to verify role of the kaon pole experimentally

JLab 6 GeV: F_{K+} extractions from *kaon* electroproduction data

- Analyze data with same techniques as used for pion analysis and extract F_{K+}
  - L/T separation
  - Extract form factor using the VGL Regge model

- The –*t* dependence of K^+ longitudinal cross section near $Q^2=1$ GeV^2 from experiment E93-018
  - Preliminary data analysis shows maybe some pole-like behavior
  - Data analysis ongoing – expect final results in a few months



[Analysis by Marco Carmignotto]

Kaon Transverse Charge Distribution

- Kaon space-like data sparse - evaluate transverse density based on a dispersion representation of the form factor

  [N. Mecholsky et al., 16+]

  - Dispersion relation uses ***time-like data***

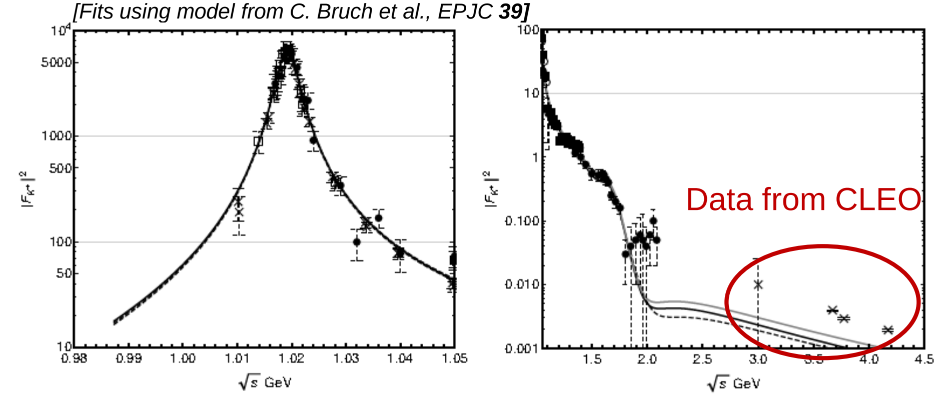
$$F_K(t) = \frac{1}{\pi} \int_{4m_K^2}^{\infty} dt' \frac{\operatorname{Im} F_K(t')}{t' - t + i\varepsilon}$$

  - Low t dominates except for very small values of b – use model for high t including recent data from CLEO

$$\rho(b) = \frac{1}{2\pi} \int_{4m_K^2}^{\infty} dt\, K_0(\sqrt{t}\, b) \frac{\operatorname{Im} F_K(t)}{\pi}$$

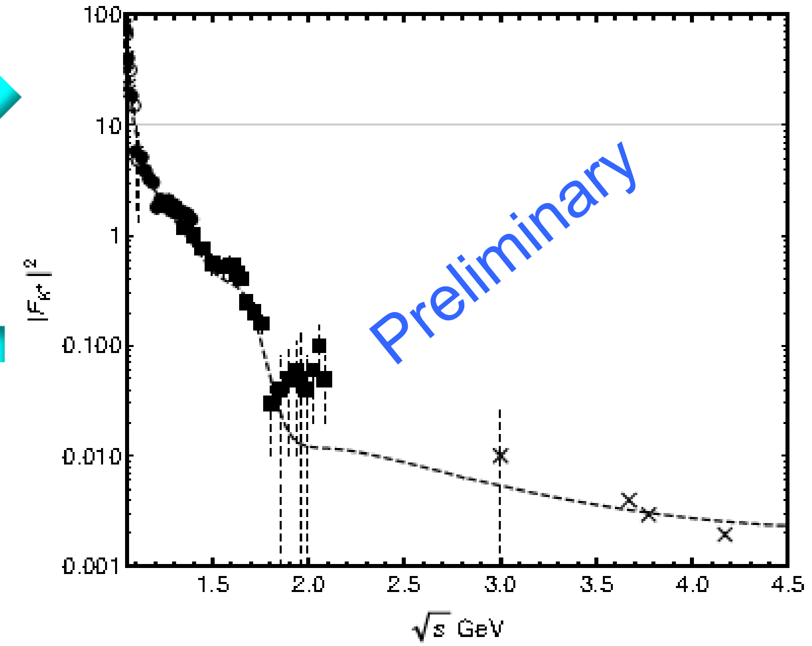
- Analytic continuation to spacelike region and studies of uncertainties ongoing

*[Fits using model from C. Bruch et al., EPJC **39**]*



*[T. Pedlar et al., PRL **95** (2005), 261803]*

*[K. Seth et al., PRL **110** (2013), 022002]*

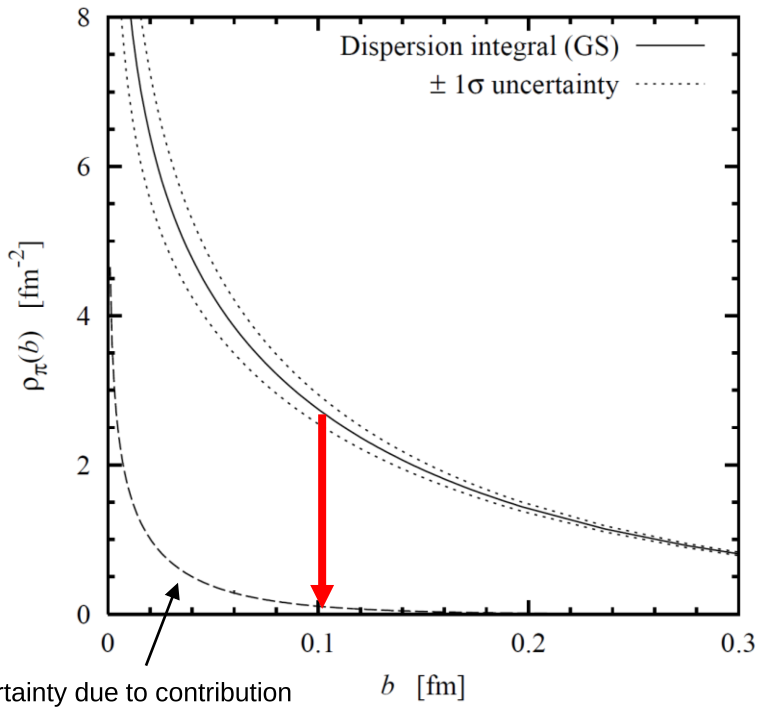


[New analysis: N. Mecholsky, J. Meija-Ott, M. Carmignotto, TH, I. Pegg, L. Resca, 16+]

Pion vs. Kaon Transverse Charge Density

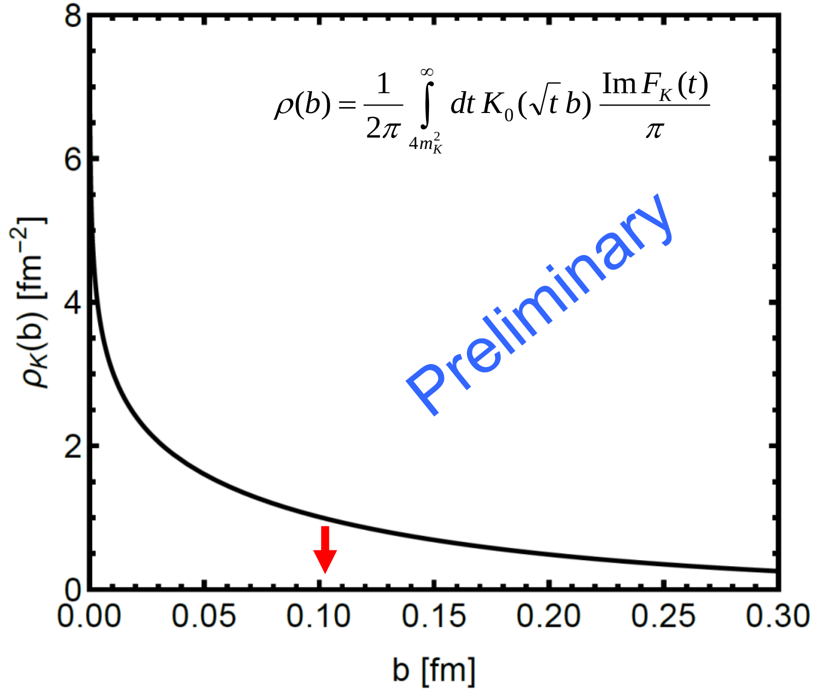
- Based on a dispersion representation of the form factors

Pion [G. Miller, M. Strikman, C. Weiss, PRD **83 (2011)** 013006]



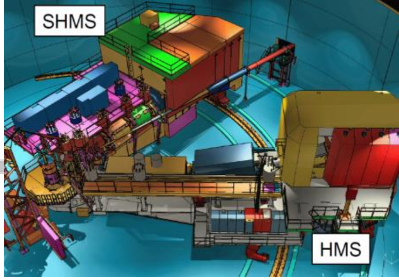
Uncertainty due to contribution of higher resonances

Kaon [N. Mecholsky et al., 16+]



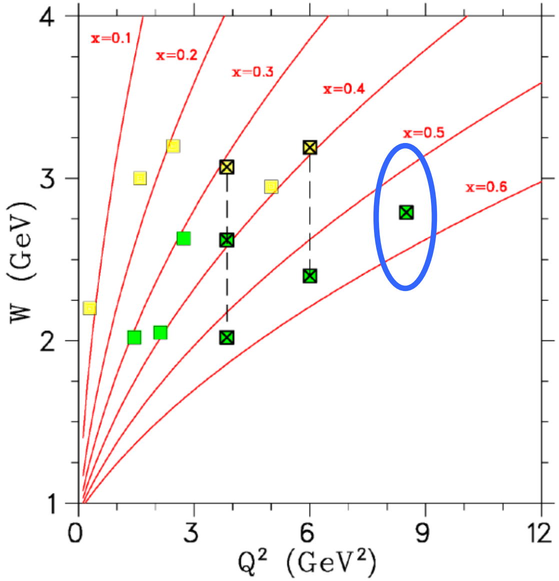
Perhaps pion and kaon transverse densities conform with expectation as the kaon is a heavier quark system

JLab12: F_π measurements



- CEBAF 10.9 GeV electron beam and SHMS small angle capability and controlled systematics are essential for extending precision measurements to higher Q^2

- The JLab 12 GeV π^+ experiments were optimized to extract F_π up to highest possible Q^2 value



  - ***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

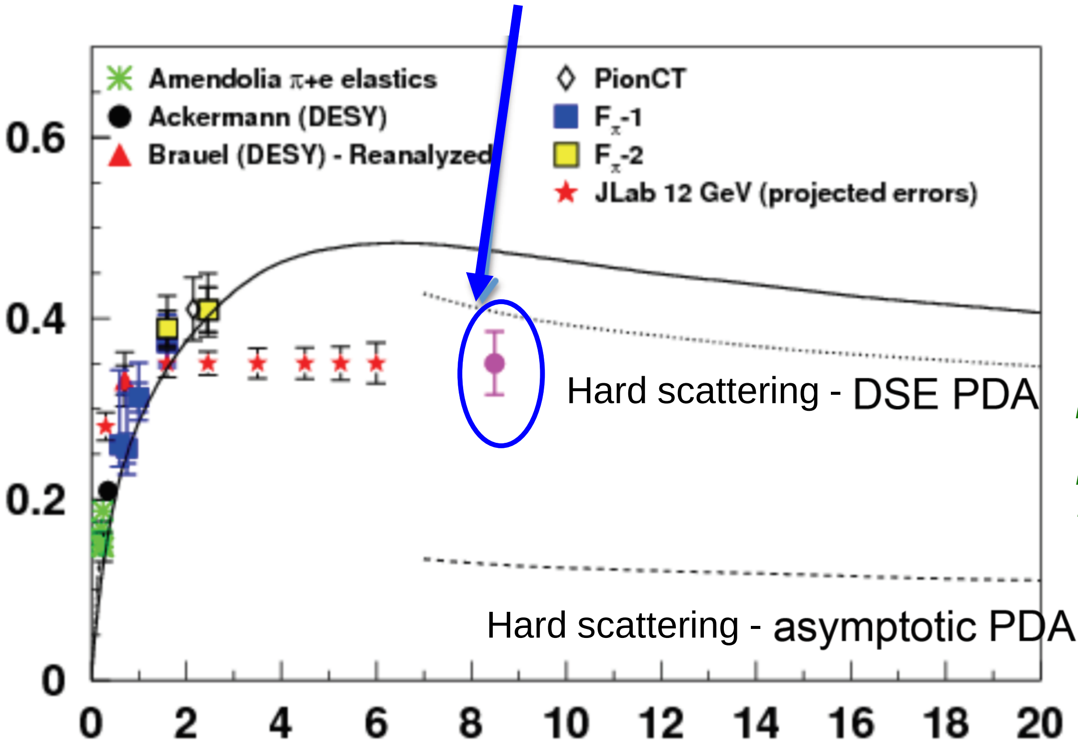
    *E12-**06**-101 spokespersons: G. Huber, D. Gaskell*

  - ***E12-07-105***: probe conditions for factorization of deep exclusive measurements in π^+ data to highest possible Q^2~9 GeV^2 with SHMS/HMS
    - Potential to extract F_π to the highest Q^2~9GeV^2 achievable at Jlab 12 GeV

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

JLab12: F_π kinematic reach

Measurement at Q^2=8.5 GeV^2 and t_{min}~0.5 GeV^2



- Reliable F_π extractions from existing data to the highest possible Q^2
- Validation of F_π extraction at highest Q^2

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

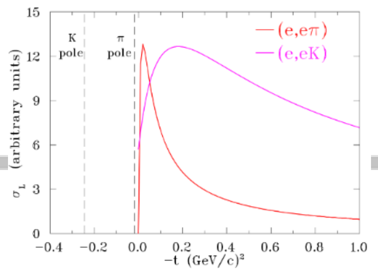
*[L. Chang, et al., PRL **111** (2013) 141802; PRL **110** (2013) 1322001]*

Projected precision using $R=\sigma_L/\sigma_T$ from VR model and assumes pole dominance – uncertainties are very sensitive to that value

JLab 12 GeV experiments have the potential to access the hard scattering scaling regime quantitatively for the first time – may also provide info on log corrections.

- These results would also have implications for nucleon structure interpretation.

JLab12: Kaon electroproduction and form factor measurements



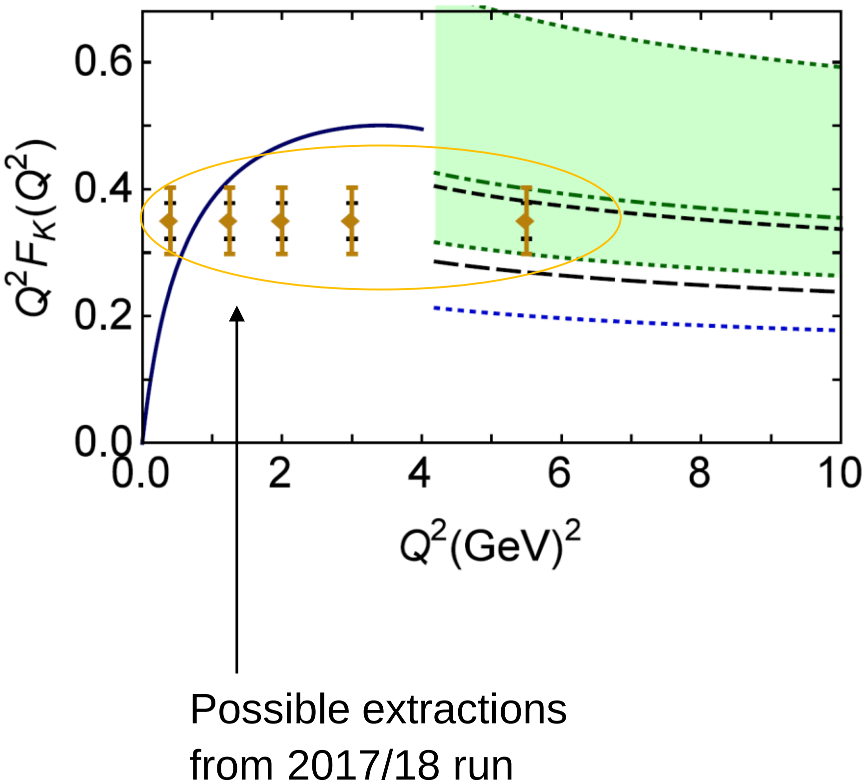
- **E12-09-011**: primary goal L/T separated kaon cross sections to investigate hard-soft factorization and non-pole contributions

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

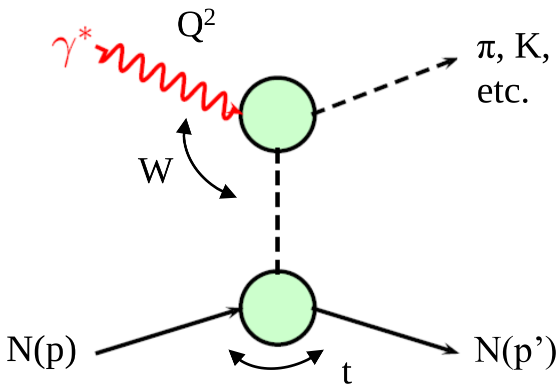
  - **scheduled to run in 2017/18**

- Possible kaon form factor extraction to highest possible Q^2 value achievable at JLab
  - Extraction like in the pion case by studying the model dependence at small t
  - Comparative extractions of F_π at small and larger t show only modest model dependence, where larger t data lie at a similar distance from pole as kaon data

*[T. Horn, C.D. Roberts, J. Phys. G**43** (2016) no.7, 073001]*

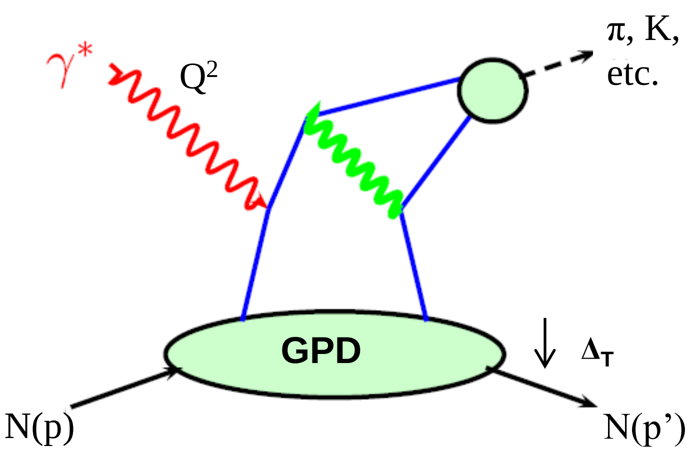


Transition to Deep Exclusive Meson Electroproduction



t-channel process

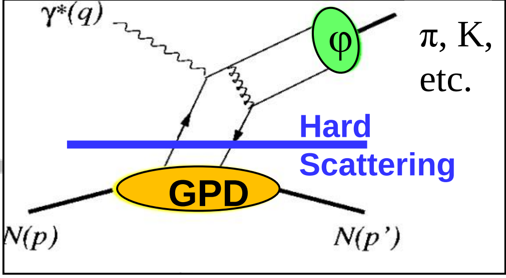
- In the limit of small $-t$, meson production can be described by the t-channel meson exchange (pole term)
  - Spatial distribution described by form factor



Handbag diagram

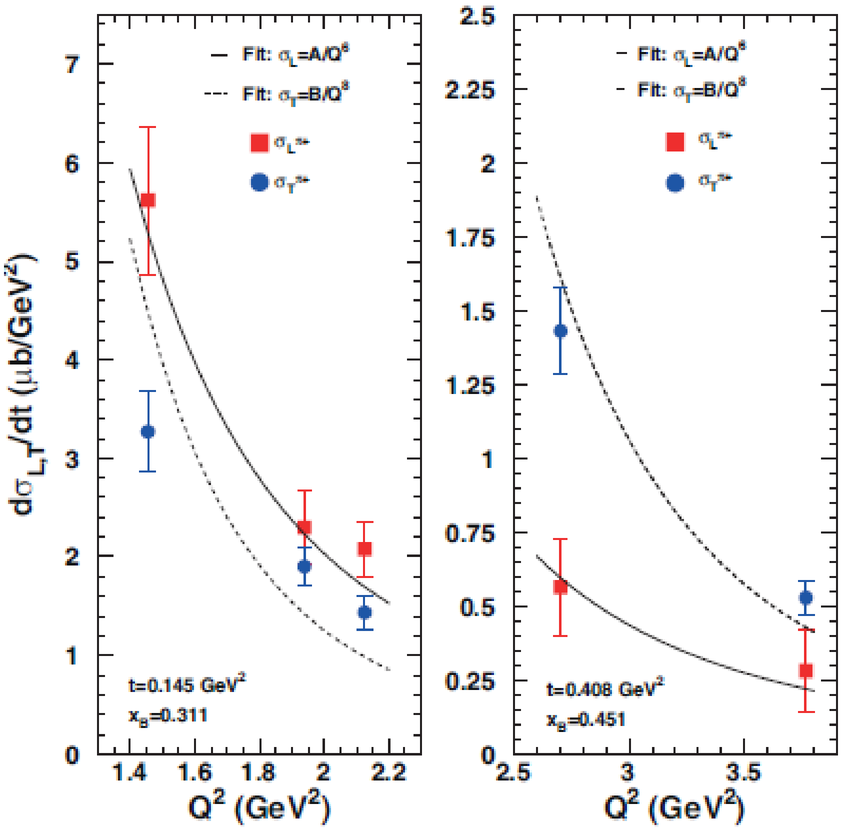
- At sufficiently high Q^2, the process should be understandable in terms of the "handbag" diagram – can be verified experimentally
  - The non-perturbative (soft) physics is represented by the GPDs
    - Shown to factorize from QCD perturbative processes for longitudinal photons *[Collins, Frankfurt, Strikman, 1997]*

JLab 12 GeV: Relative L/T contribution to the meson cross section



Important for nucleon structure studies

[L. Favart, M. Guidal, T. Horn, P. Kroll, Eur. Phys. J A 52 (2016) no.6, 158]



- ❑ Data from JLab 6 GeV demonstrated the technique of measuring the Q^2 dependence of L/T separated cross sections at fixed x/t

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

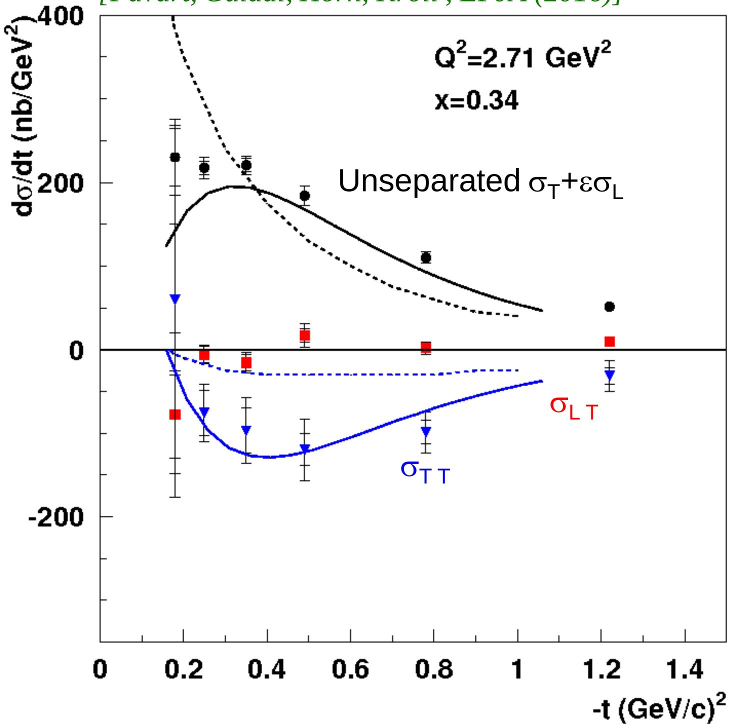
- ❑ Separated cross sections over a large range in Q^2 are essential for:
  - ➢ testing factorization required for studies of transverse spatial structure
  - ➢ understanding dynamical effects in both Q^2 and –t kinematics
  - ➢ interpretation of non-perturbative contributions in experimentally accessible kinematics

JLab 12 GeV provides separated (Hall C only) data up to Q^2 ~ 10 GeV^2 and 5 GeV^2 for π (E12-07-105) and K (E12-09-011), respectively

– Q^2 dependence of σ_L relevant towards an interpretation in a GPD-based framework

Transverse Contributions may allow for probing a new set of GPDs

[Favart, Guidal, Horn, Kroll , EPJA (2016)]



Goloskokov, Kroll, EPJ C65, 137 (2010); EPJ A45, 112 (2011)

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

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

- Recent data suggest that transversely polarized photons play an important role in charged and neutral pion electroproduction
  - Model predictions based on handbag in good agreement with data
- For pion and kaon production the relative contribution of longitudinal and transverse photons in JLab 12 GeV kinematics this has to be verified
- A large transverse cross section in meson production may allow for accessing helicity flip GPDs

JLab 12 GeV will provide relative σ_L and σ_T contributions to the π^0 cross section up Q^2~6 GeV^2

– Exclusive π^o data may also be helpful for constraining non-pole contributions in F_π extraction

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 at Q^2>~0.3 GeV^2
  - In general, require a model to extract the form factor at physical meson mass – experimental validation of the extraction is essential
  - K^+ requires experimental verification of pole dominance in σ_L
  - π^+ form factor: reliable measurements up to Q^2=2.45 GeV^2 from JLab 6 GeV

- JLab 12 GeV will dramatically improve the $\pi^+/K^+/\pi^0$ electroproduction data set
  - Pion and kaon form factor extractions up to high Q^2 possible (~9 and ~6 GeV^2)
  - Kaon experiment scheduled to run in 2017/18
  - L/T separated cross sections important for transverse nucleon structure studies – may allow for accessing new type of GPDs

- Beyond 12 GeV, EIC provides interesting opportunities to map pion and kaon structure functions over a large (x, Q^2) landscape – in progress…