Meson Form Factors

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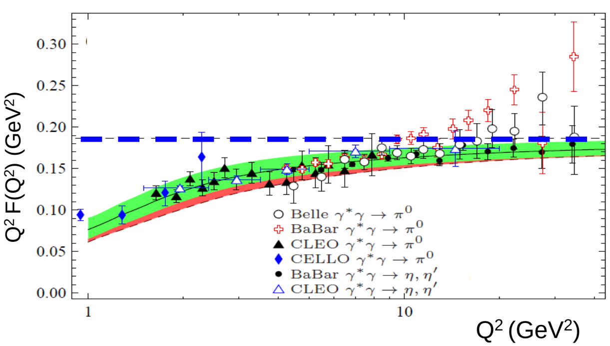
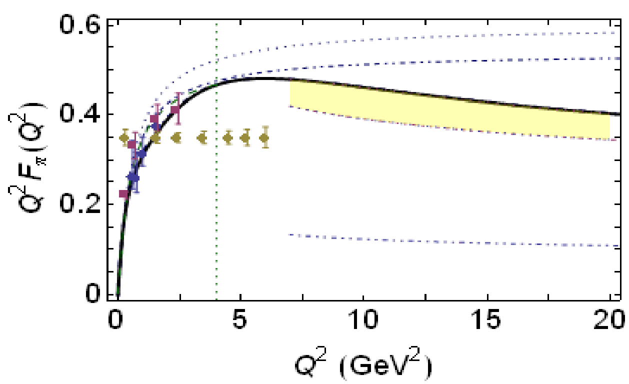
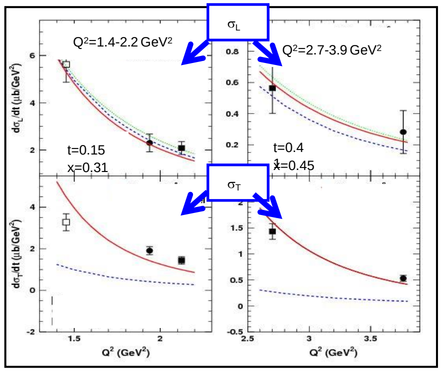






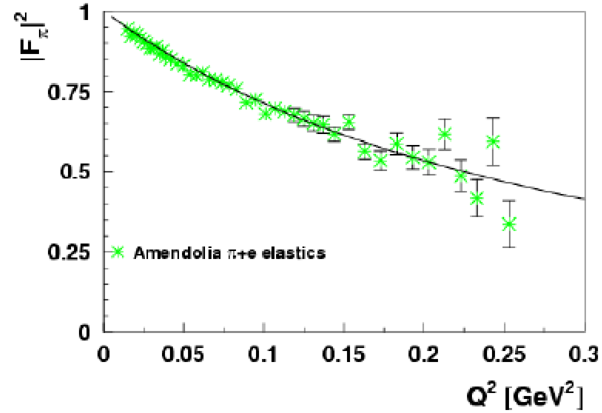
Overview

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

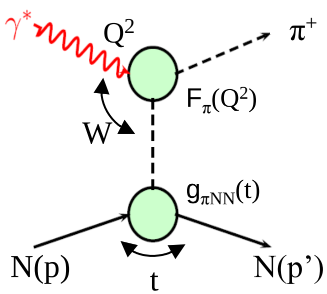
- Fundamental properties of meson form factors
  - Pion and kaon form factors are of special interest - connected to the Goldstone modes of dynamical chiral symmetry breaking
  - The pion is the lightest and one of the simplest QCD systems available for study – ***clearest test case for studies of the 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

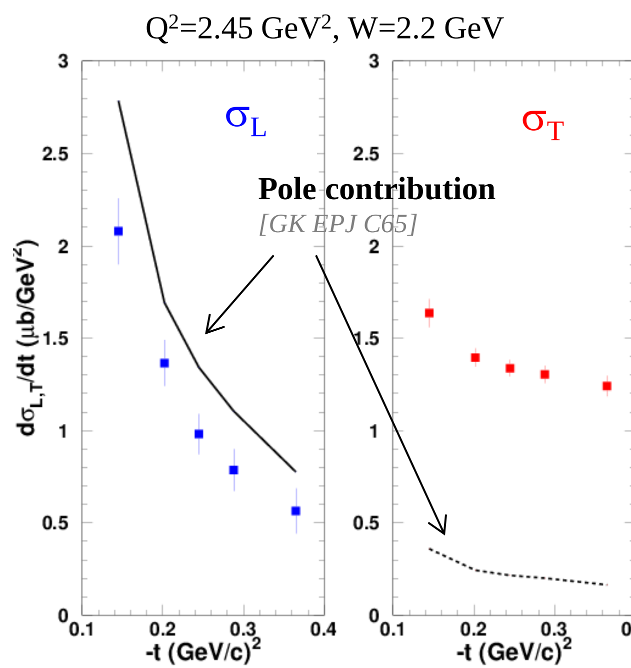


- At larger Q^2, $F_{\pi+}$ must be measured indirectly using the "pion cloud" of the proton in exclusive pion electroproduction: *$p(e,e'\pi^+)n$*
  - At small $-t$, the pion pole process dominates σ_L



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

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

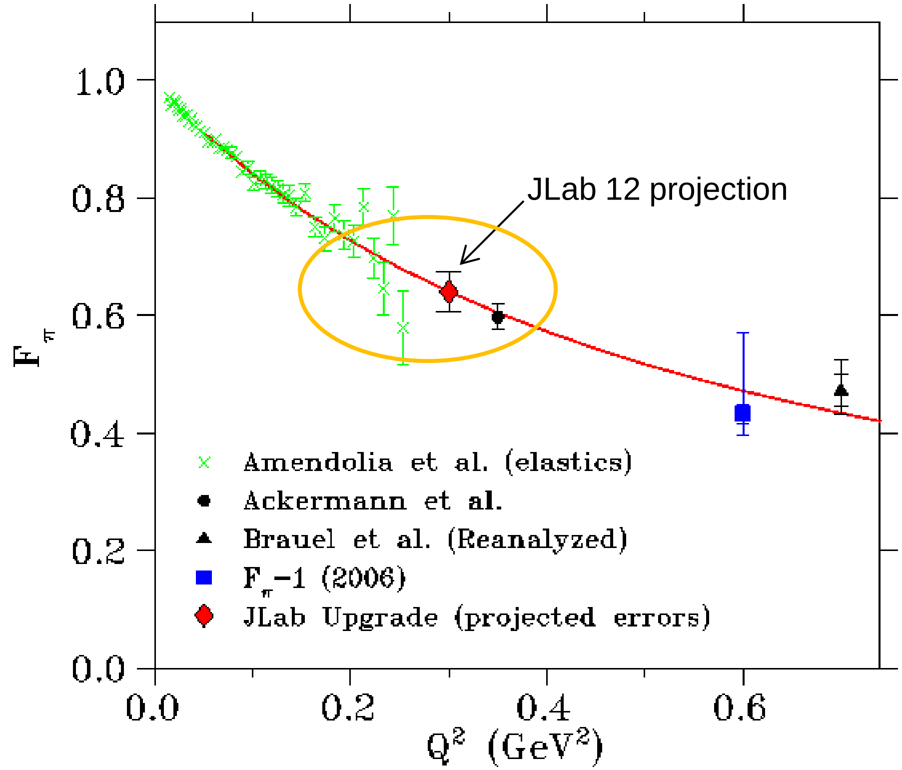


[T. Horn et al, Phys Rev. Lett.**97** (2006), 192001]

  - In the actual extraction, a model incorporating the π^+ production mechanism is used to extract F_π from σ_L

Precision data: 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. Ackerman 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

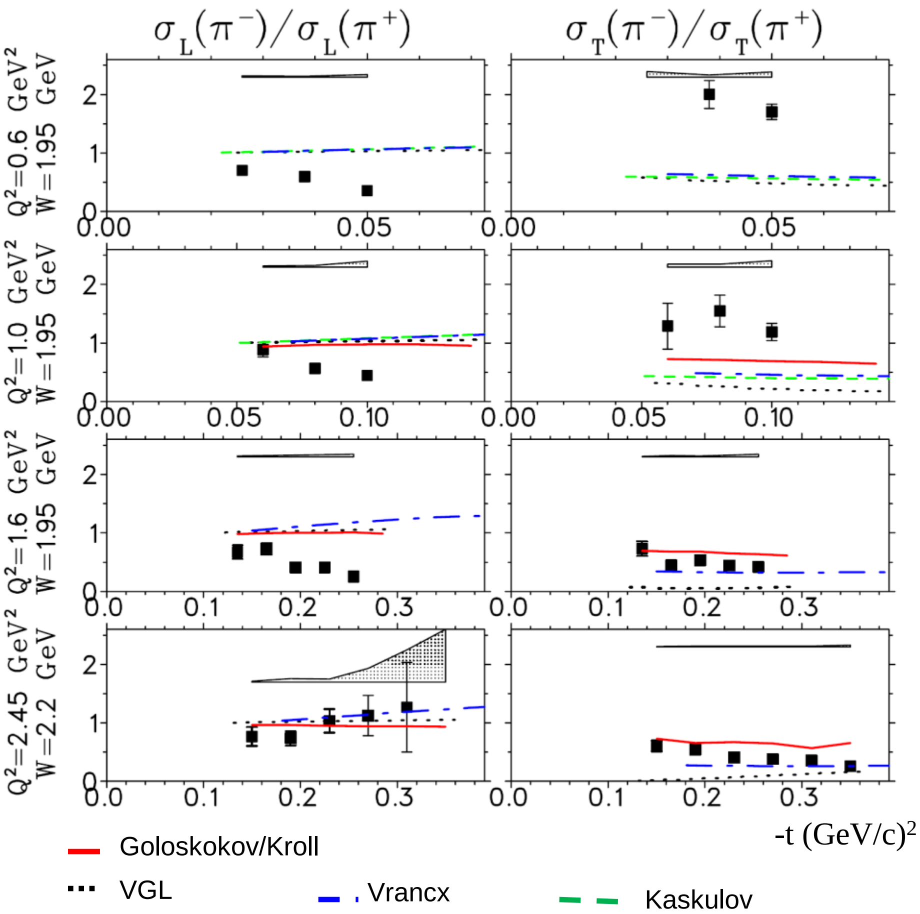
- **2014**: new results from ^{2}H target L/T separations
  *[Huber et al, PRL**112** (**2014**)182501]*

- 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

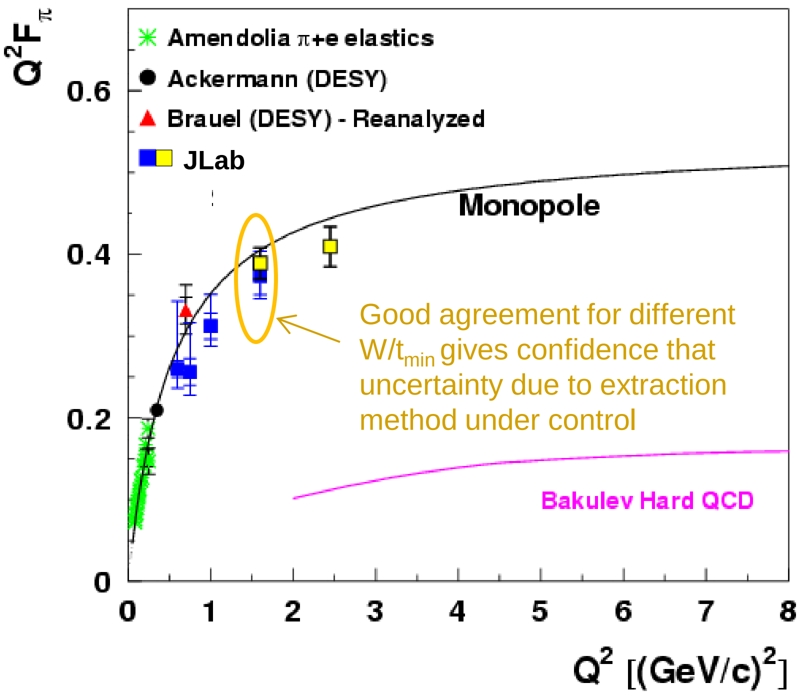
- With increasing t, R_T is expected to approach the ratio of quark charges
  [O. Nachtman, NP B115 (1976) 61]



R_L data consistent with pion-pole dominance

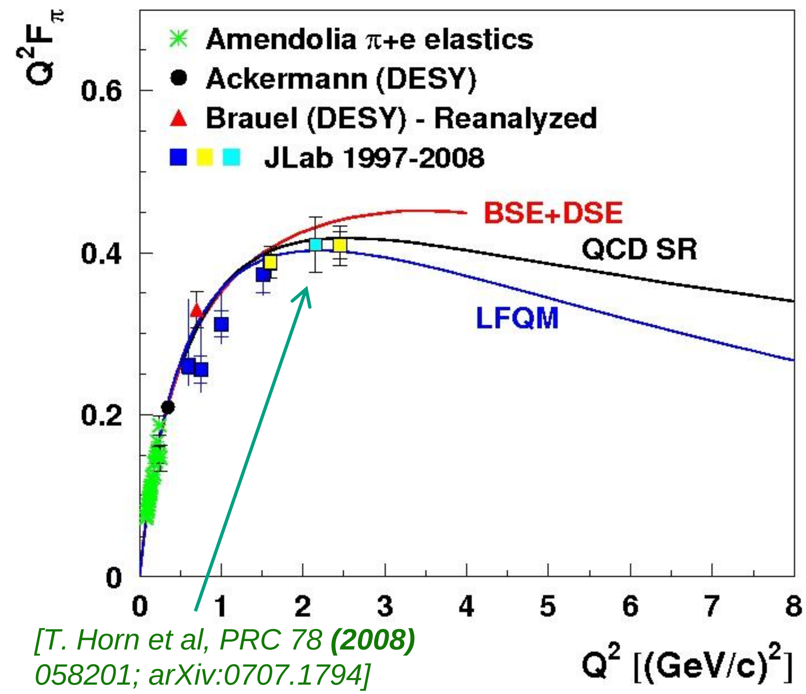
R_T data *t*-dependence shows rapid fall-off consistent with *s*-channel quark knockout

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



*[T. Horn et al, PRC 78 **(2008)** 058201; arXiv:0707.1794]*

- Several effective models do a good job describing the data

  Shown is a selection of models. Additional model comparison in:
  *Huber et al. Phys. Rev. C**78** 045203 **(2008)***

Experiments in Hall C have established the validity of the measurement technique in general

Require explanation for the "mismatch" between data and QCD predictions

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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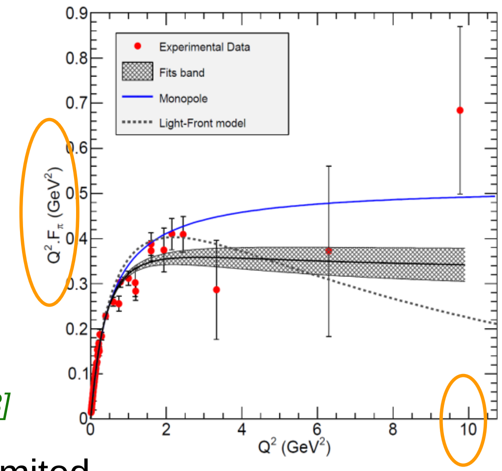
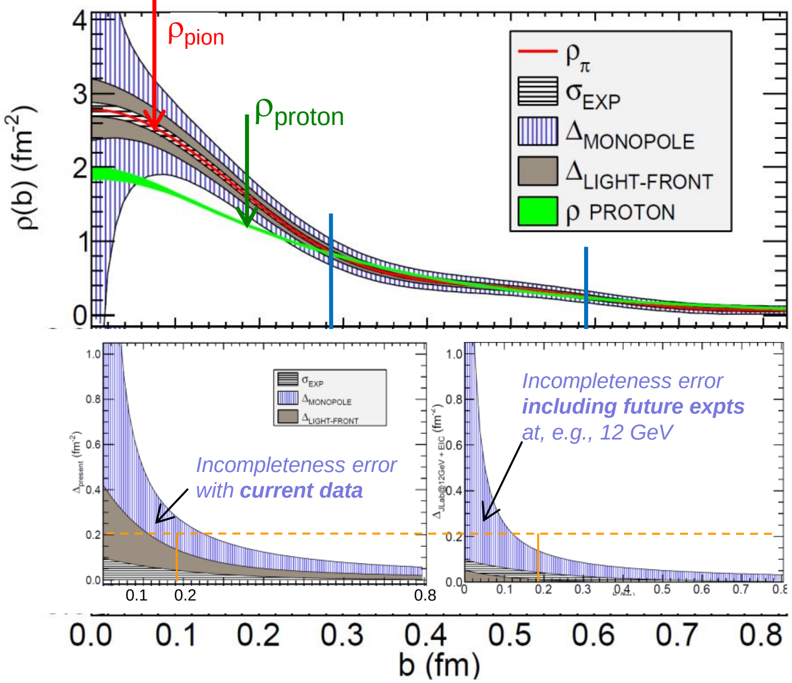


- Finite Radius Approximation
  *[S. Venkat et al., PRC **83 (2011)** 015203]*
- *Incompleteness error* due to limited data range– estimated using models
  - Upper bound: monopole
  - Lower bound: Light front model

2D Fourier Transform



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

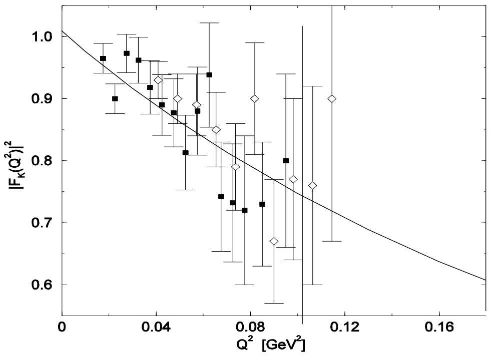
*[earlier analyses: G. Miller, PRC **79 (2009)** 055204); G. Miller, M. Strikman, C. Weiss, PRD **83 (2011)** 013006]*

- 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

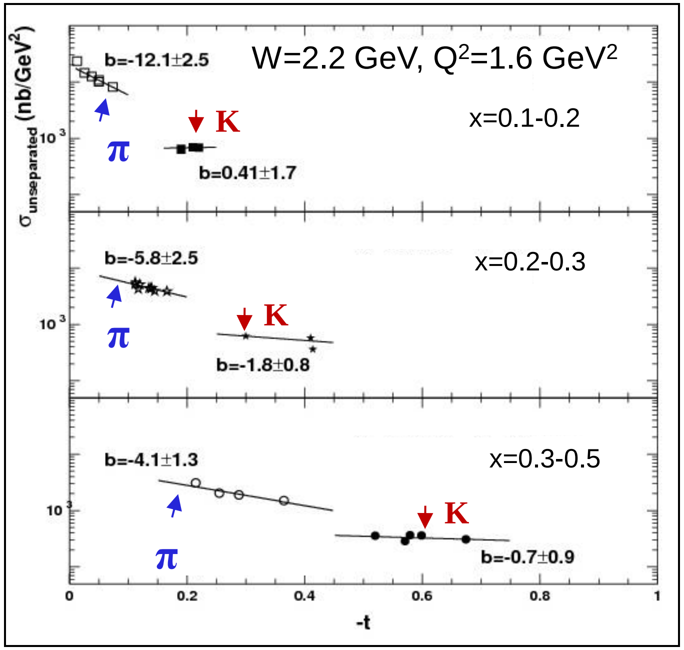
JLab 12 GeV data will allow further studies of a common transverse charge density – common confinement mechanism?

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]*

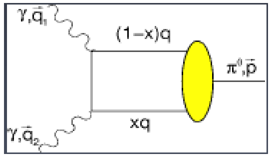
- <u>However</u>, the kaon pole is expected to be strong enough to produce a maximum in σ_L

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

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

New Pseudoscalar Meson Transition Form Factor Data

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

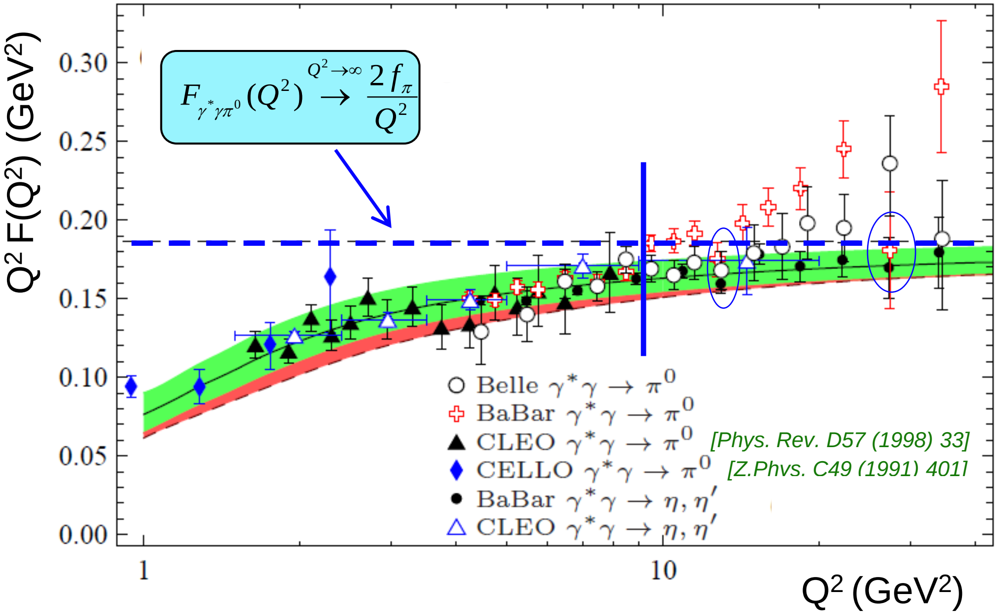


$$F^{\gamma^*\gamma\pi}(Q^2) = \frac{\sqrt{2} f_\pi}{4\pi^2 f_\pi^2 + Q^2}$$

- Simplest structure for pQCD analysis

- **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]*

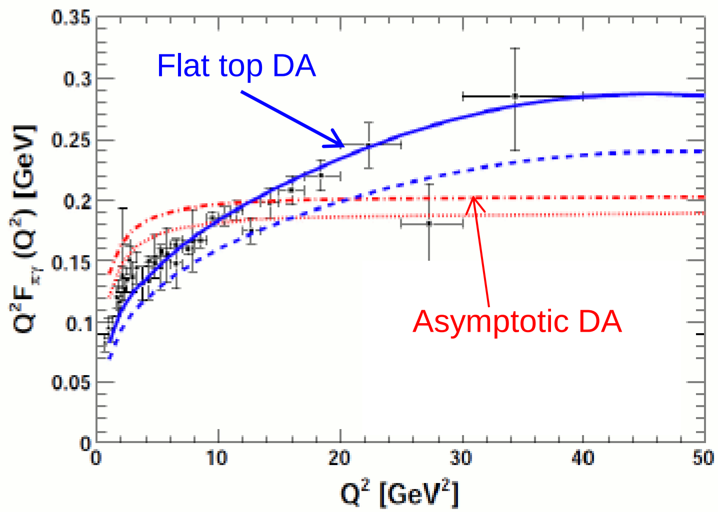
Opposing tendencies in the data cannot be reconciled until additional data on TFFs and other exclusive processes become available, but perhaps no crisis

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

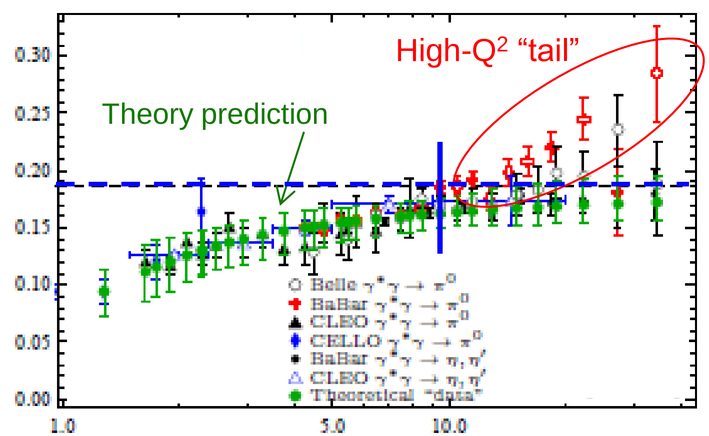
    [Li et al. PRD ***80 (2009)*** *074024]*



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

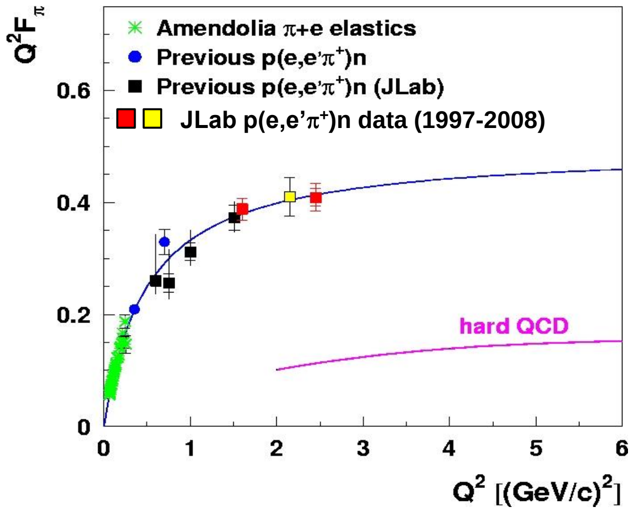
  [A. Bakulev et al., PL B578 (2004), 91; PR D73 (2006) 056002] *[Stefanis et al. PRD* ***87 (2013)*** *094025]*

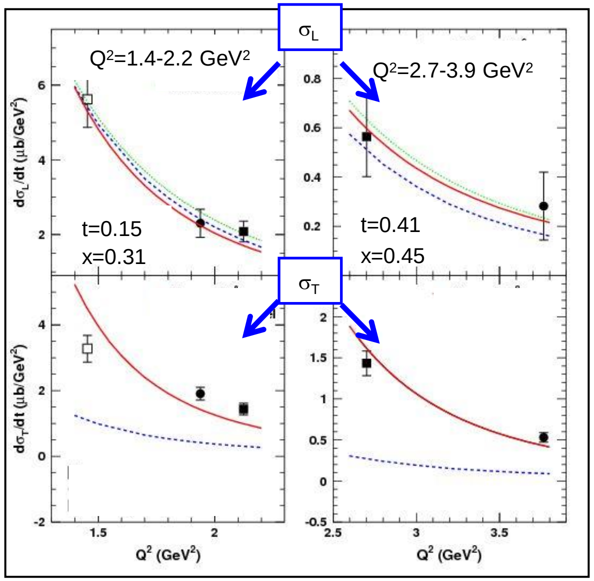
  - Consistent with basic features of the η TFFs implying *strong end point suppression*
  - However, cannot describe the high-Q^2 tail of the Babar data requiring *end point enhancement*



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

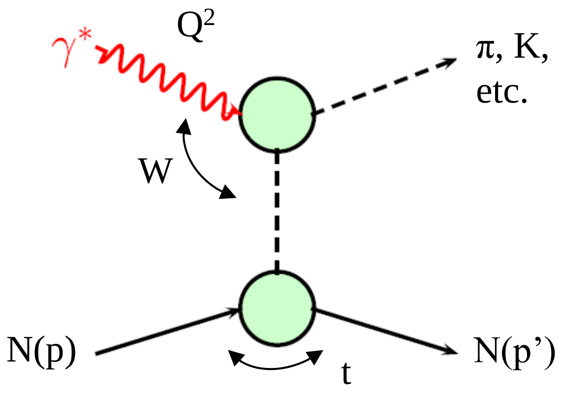
- ❑ Q^2 dependence of the pion cross section is an essential test of hard-soft factorization required for studies of the nucleon's transverse spatial structure

  - ➢ 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)**]*

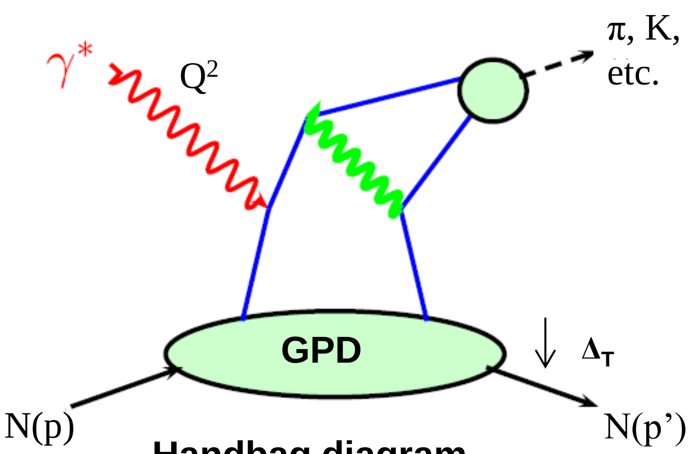
F_π and pion cross section data over a larger range in Q^2 at 12 GeV can provide essential information about the reaction mechanism – can we learn about nucleon structure using exclusive meson production?

From Long to Short Distances



t-channel process

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



Handbag diagram

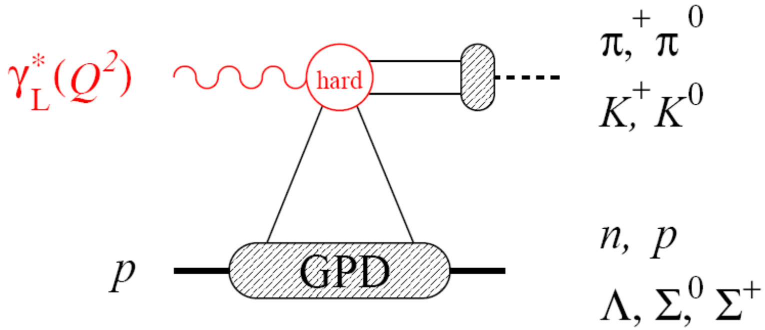
- At sufficiently high Q^2, the process should be understandable in terms of the "handbag"
  - The non-perturbative (soft) physics is represented by the GPDs
    - Shown to factorize from QCD perturbative processes for longitudinal photons *[Collins, Frankfurt, Strikman, 1997]*
  - In this limit only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

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

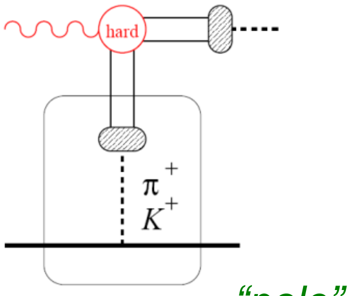
Exclusive meson production

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

- The quantum numbers of the produced meson determine spin, charge parity, and flavor and so allow to probe GPDs more selectively
  - Complementary to the information obtained by DVCS probing specific spin/flavor components
    - $\rho^o/\rho^+/K^*$ select H, E for u/d flavors
    - π,η,K select $\tilde{H},\tilde{E}$
  - 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



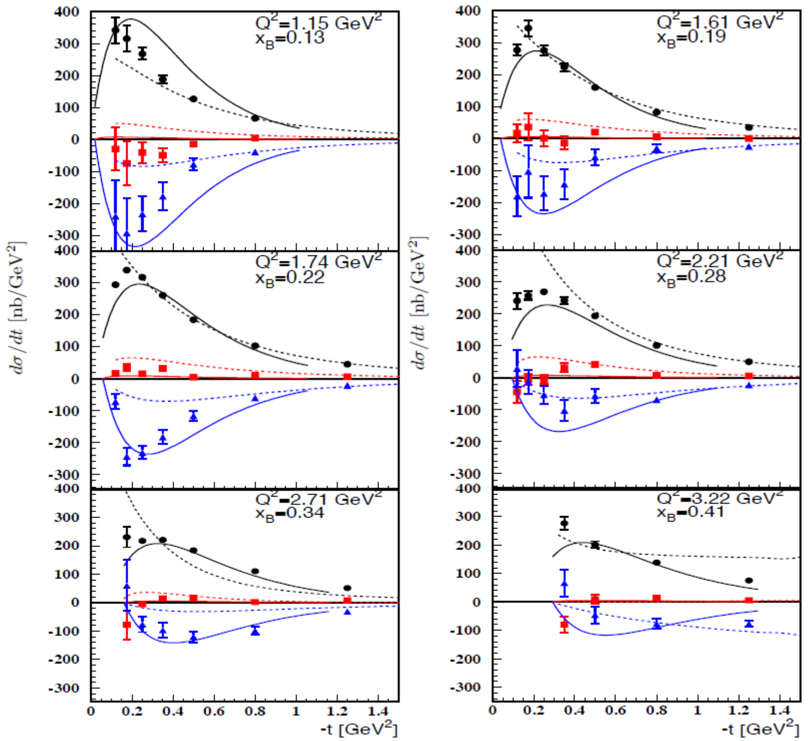
Hard exclusive meson production is an important tool in mapping nucleon GPDs and exploring other aspects of hadron structure

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]*

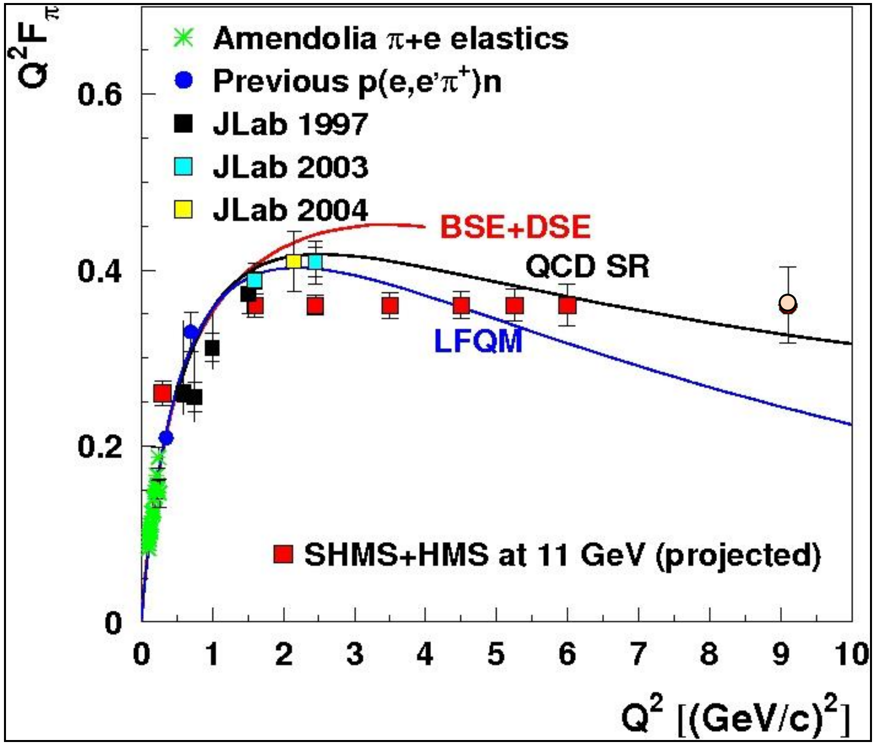
A large transverse cross section in π^0 production may allow for accessing helicity flip GPDs

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
- 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

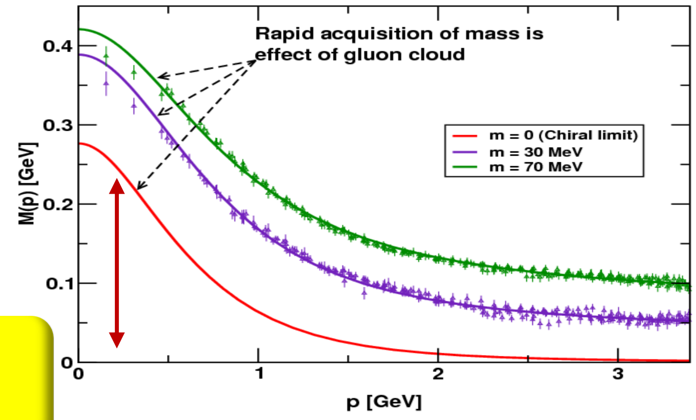
    *E12-**07**-105 spokespersons: T. Horn, G. Huber*



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

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

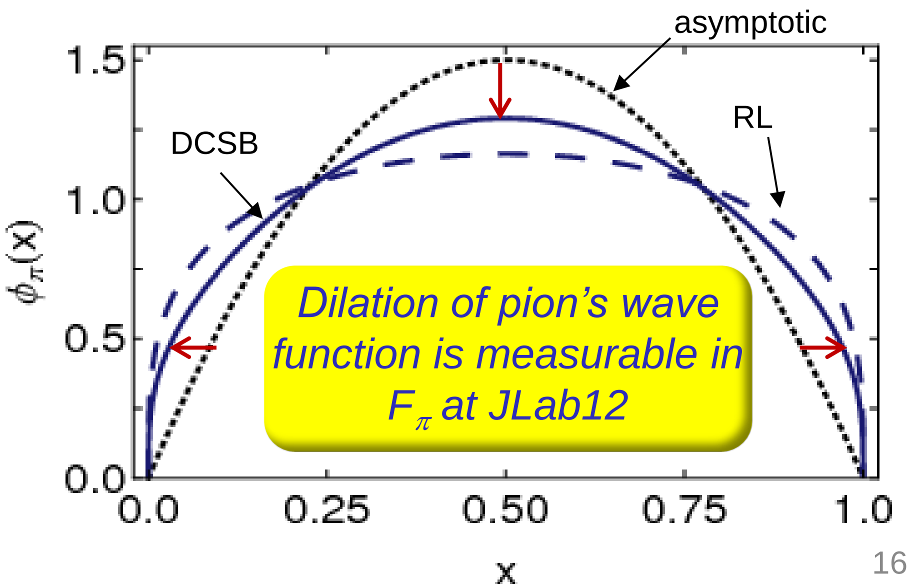
- There is a one-to-one connection between DCSB and the point-wise form of the pion's wave function.

*[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

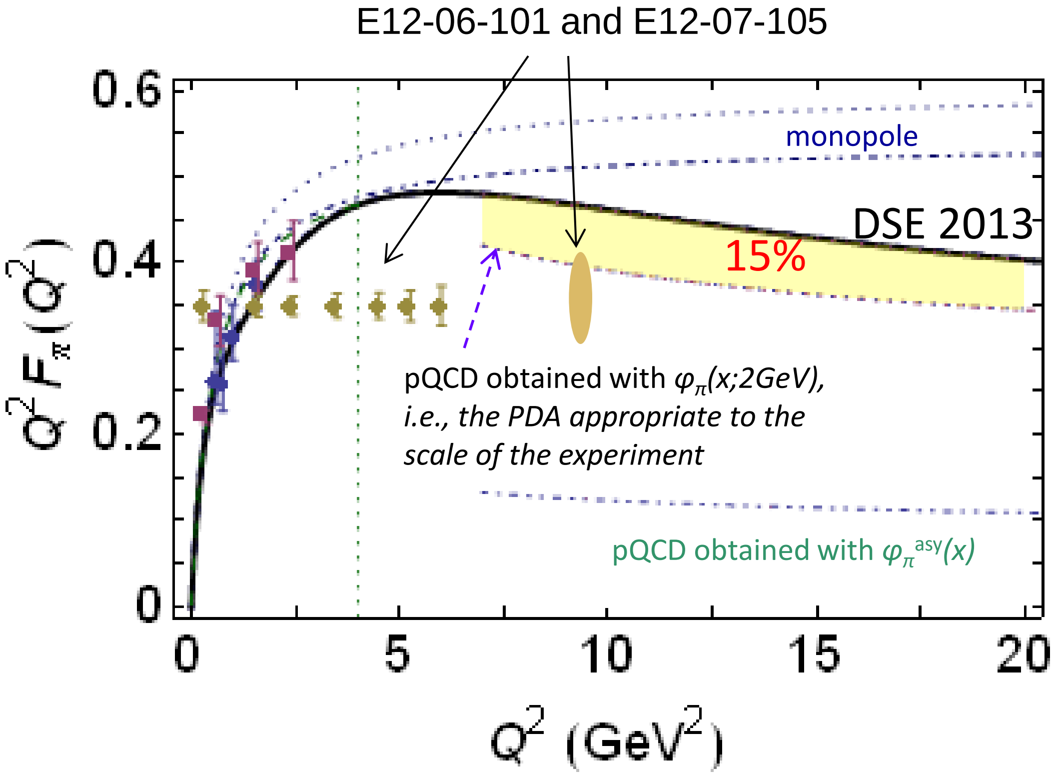


JLab 12 GeV F_π data and theory

- 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)

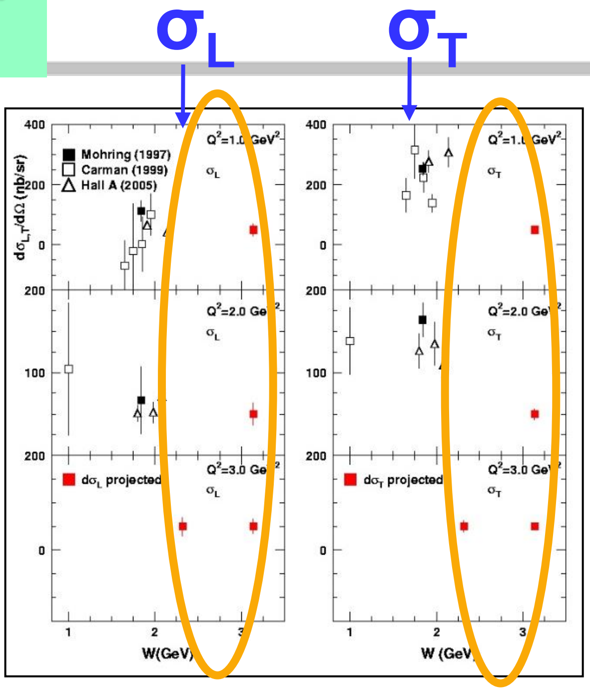
JLab: the only facility with capability for reliable Kaon measurements

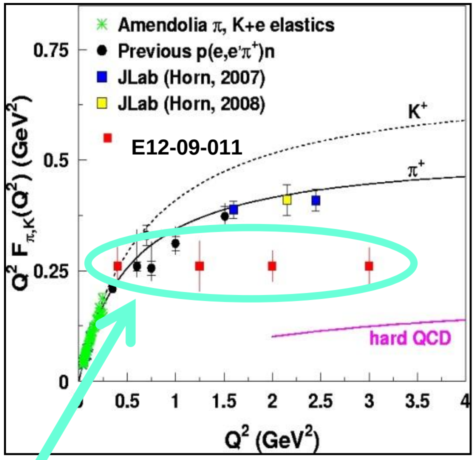
- CEBAF 11 GeV electron beam and SHMS small angle capability are essential for the first L/T separated **kaon** data above the resonance region

- **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^+ form factors

*[C. Shi, et al., arXiv:1406.3353 **(2014)**]*

*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

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 perhaps consistent with pQCD after all?

- 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

- There is a one-to-one connection between DCSB and the point-wise form of the pion's wave function – 12 GeV data can empirically check this

JLab 12 GeV will dramatically improve the π^+/π^0 precision data set, may allow for the first kaon form factor extractions, and provide the first detailed checks of factorization relevant for interpretation of nucleon GPDs with PS mesons