Exclusive Pseudoscalar Meson production

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Hall C Summer Workshop

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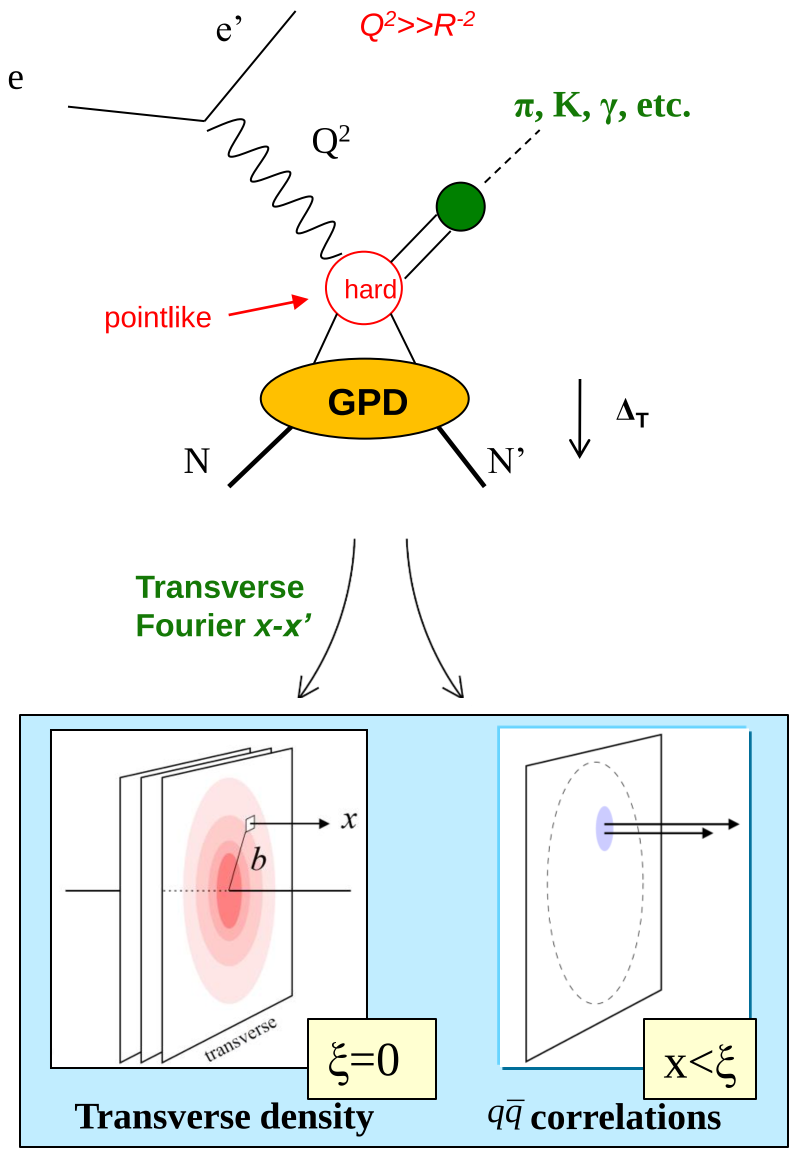
Nucleon Structure through Exclusive Processes

- Exclusive processes at sufficiently high Q^2 allow access to Generalized Parton Distributions (GPDs)
  - Factorization theorem: non-perturbative physics factorizes from perturbative QCD processes for longitudinal photons *[Collins , Frankfurt, Strikman 97]*

- GPDs are *a tool for transverse imaging of the nucleon*
  - **Encode information on correlations and distribution of partons in transverse space** *[Burkhardt 00]*
  - Moments, Form factor of local twist-2 spin-n operators: EM tensor, angular momentum *[Ji 96, Polyakov 02]*

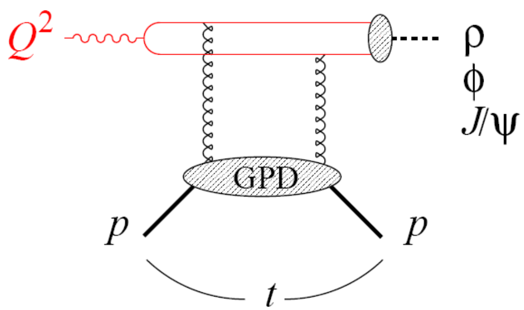
- Tests of reaction mechanism
  - Model-independent features of small-size regime
  - Finite-size corrections



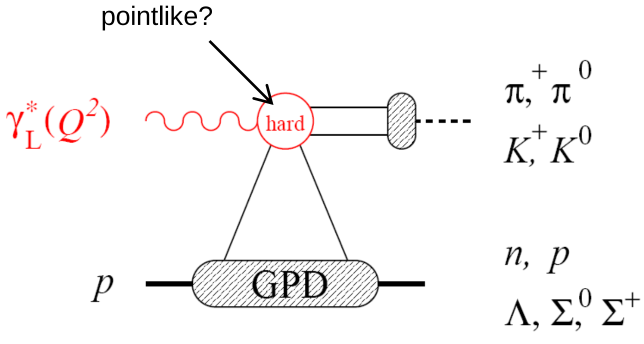
Nucleon structure: spin-flavor

Deep Virtual Meson Production (DVMP)

Exclusive Reactions: $\gamma^* N \rightarrow M + B$



Vector Mesons

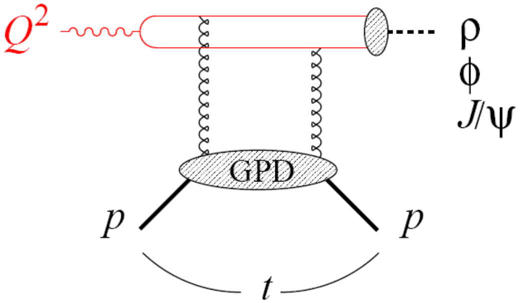


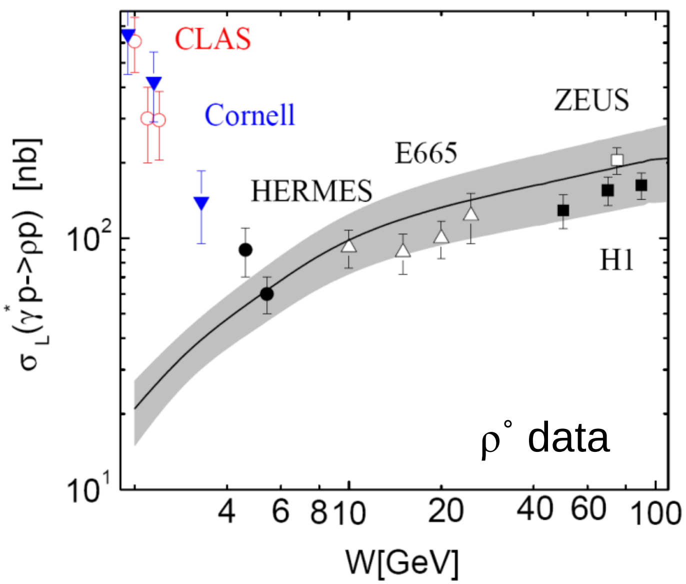
Pseudoscalar Mesons

- Nucleon structure described by 4 (helicity non-flip) GPDs:
  - *H, E* (unpolarized), $\tilde{H}, \tilde{E}$ (polarized)
- Quantum numbers in DVMP probe individual GPD components selectively
  - Vector : $\rho^o/\rho+/K^*$ select *H, E*
  - Pseudoscalar: π,η,K select the polarized GPDs, $\tilde{H}$ and $\tilde{E}$
- Need good understanding of reaction mechanism
  - QCD factorization for mesons is complex (additional interaction of the produced meson)

Meson Reaction Mechanism

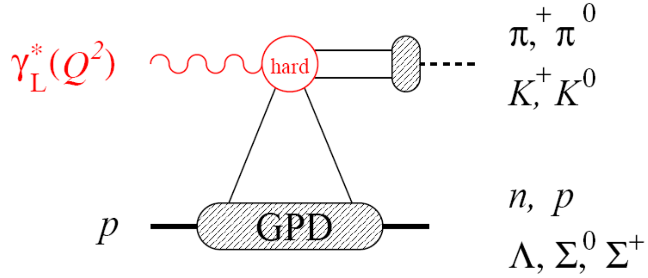
Vector Mesons

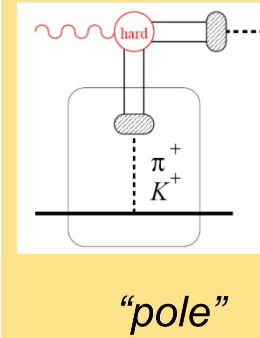


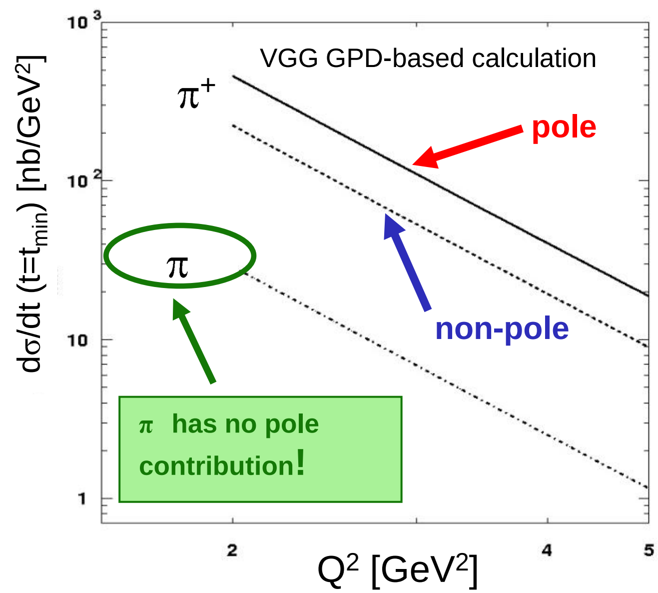


- Largest data set from CLAS (e1-6)
- Understand reaction mechanism
  - Role of qqbar pair knockout
  - Finite-size corrections

Pseudoscalar Mesons







- Feature: *pole term* in GPD
- Understand relative importance of "pole and "non-pole" contributions

Exclusive Pseudoscalar Data: Pions and Kaons

Evaluate data for phenomena signaling transition from non-perturbative to hard-scattering regime

$$e\,p \rightarrow \pi^+ n$$

- Cornell

  C.J. Bebek *et al*., Phys.Rev.D17 (1978) 1693.

- DESY

  P. Brauel *et al*., Z.Phys.C3 (1979) 101.

  A. Airapetian *et al*., Phys.Lett.B659 (2008) 486

- Jefferson Lab 6 GeV

  H.P. Blok, T. Horn *et al*., Phys.Rev.C78 (2008) 045202.

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

  K. Park *et al*., EPJ (2012).

$$e\,p \rightarrow K^+ \Lambda$$

- Cornell

  C.J. Bebek *et al.,* Phys.Rev.D15 (1977) 594.

- DESY

  P. Brauel *et al*., Z.Phys.C3 (1979) 101.

- Jefferson Lab 6 GeV

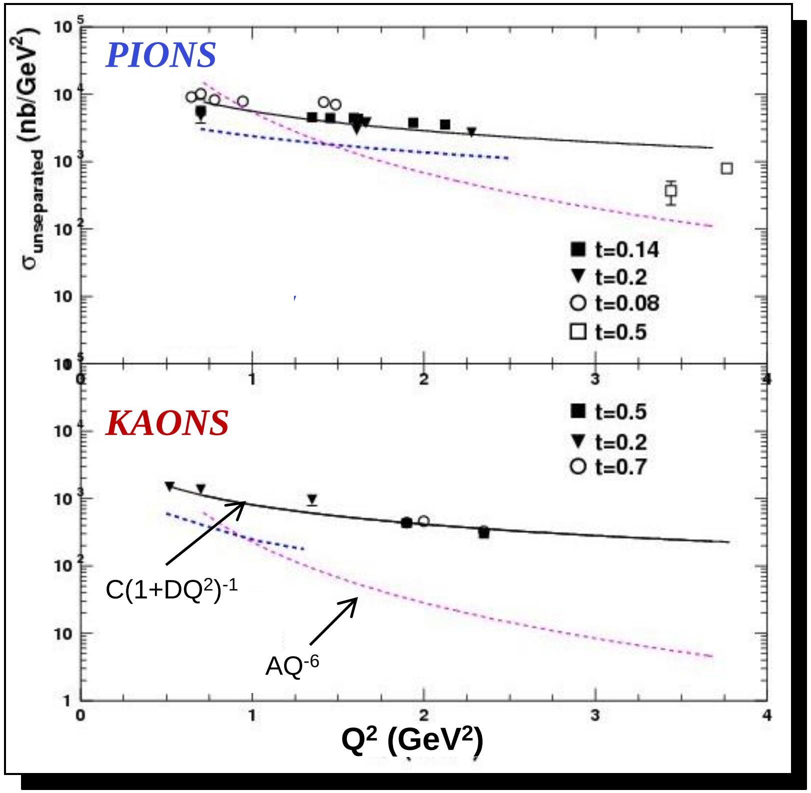
  M. Coman *et al*., arXiv:0911.3943.

  R. Mohring *et al*., Phys.Rev.C67 (2003) 055205

t-Dependence from Combined Data Sets

$ep \rightarrow K^+ \Lambda$

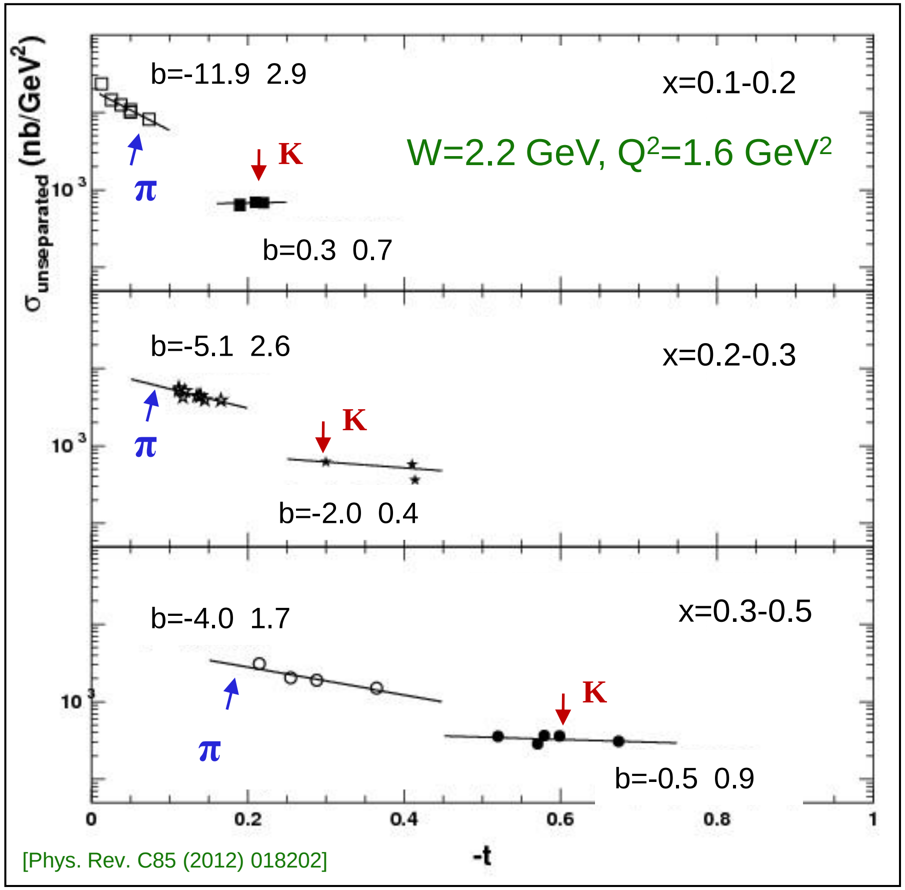
$ep \rightarrow \pi^+ n$



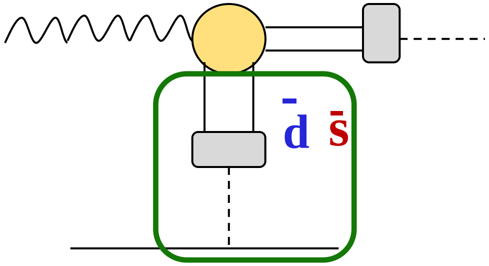
- Cross section depends on W, Q^2, t
- t-dependence can be obtained from the combined set by scaling in W and Q^2
- Scale cross section to common W value using empirical form $(W^2\text{-}M^2)^{-n}$
- Smooth Q^2 dependence allows to scale to common Q^2
  - Factor $C(1+DQ^2)^{-1}$ gives a good fit

e^{-bt} scaling of σ_π and σ_K

Combines data from Cornell, DESY, and JLab 6 GeV

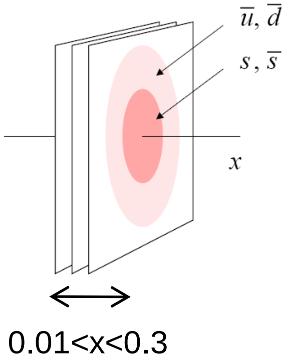


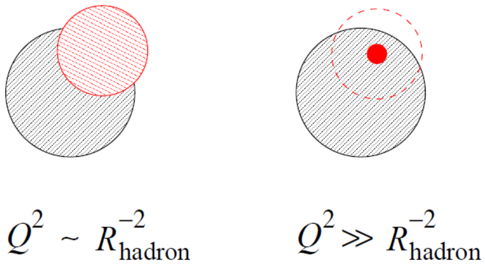
- Non-diffractive processes show exponential t-dependence
- t-dependence flatter at larger x
- Pion t-dependence is steeper *at* low *t* than for kaons
  - pole factor $(m^2_{K,\pi} - t)^{-1}$ gives less enhancement for kaons than pions
  - Different from u-quark exchange

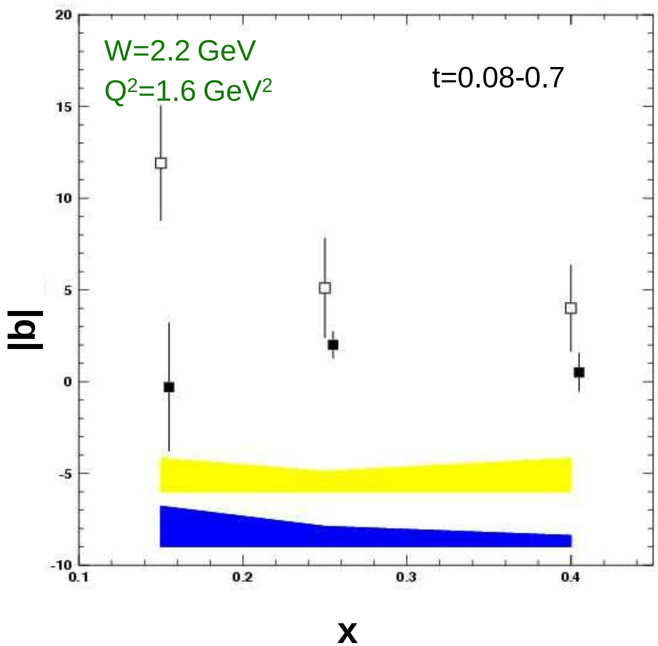


Pole factor enhances pion cross section – additional low t data would allow to interpret contribution for kaons

t-slopes of pions and kaons







- t-slope of cross section measures the transverse area of the interaction region
- t-slopes seem to become similar for π, K at x>0.2
- Current data not sufficient
  - Unseparated cross sections
  - Systematic uncertainties from scaling in W, Q^2, t

High quality *separated* data would allow for better constraining effective transverse sizes

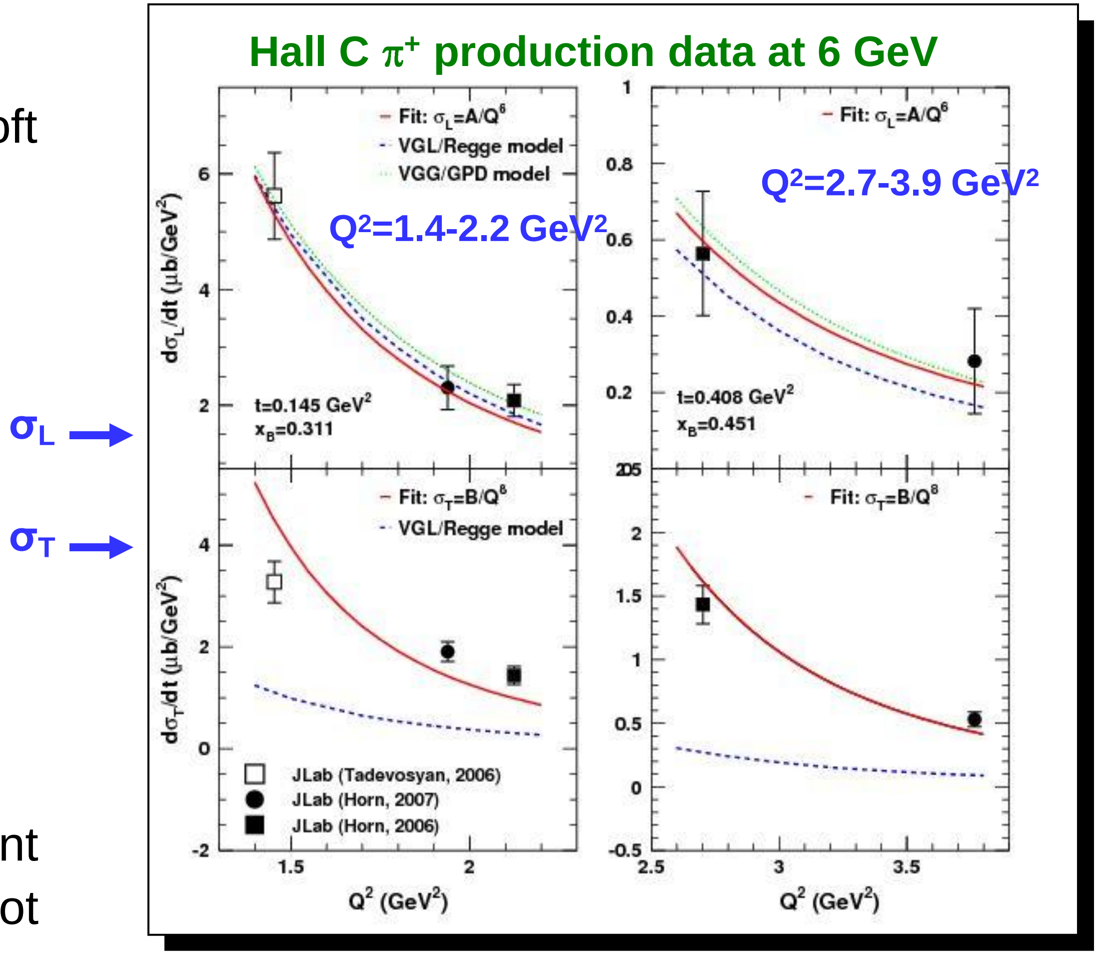
π^+ cross section: Q^{-n} scaling

$ep \rightarrow e'\pi^+ n$

- To access physics contained in GPDs, one is limited to the kinematic regime where hard-soft factorization applies

- A test is the Q^2 dependence of the cross section:
  - $\sigma_L \sim Q^{-6}$
  - $\sigma_T \sim Q^{-8}$
  - As Q^2 gets large: $\sigma_L >> \sigma_T$

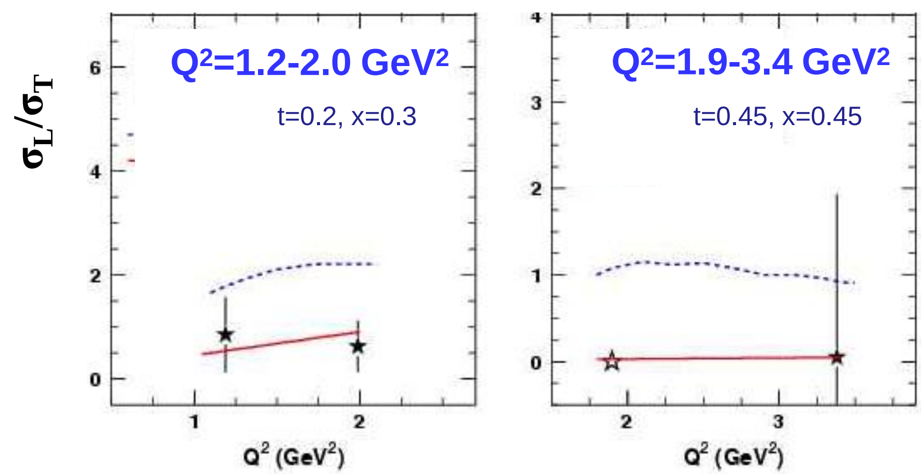
- The QCD scaling prediction is reasonably consistent with recent JLab π^+ σ_L data, *BUT* σ_T does not follow the scaling expectation



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

K^+ cross section: Q^{-n} scaling

Fit to hard scattering prediction: $\sigma_L/\sigma_T \sim Q^2$



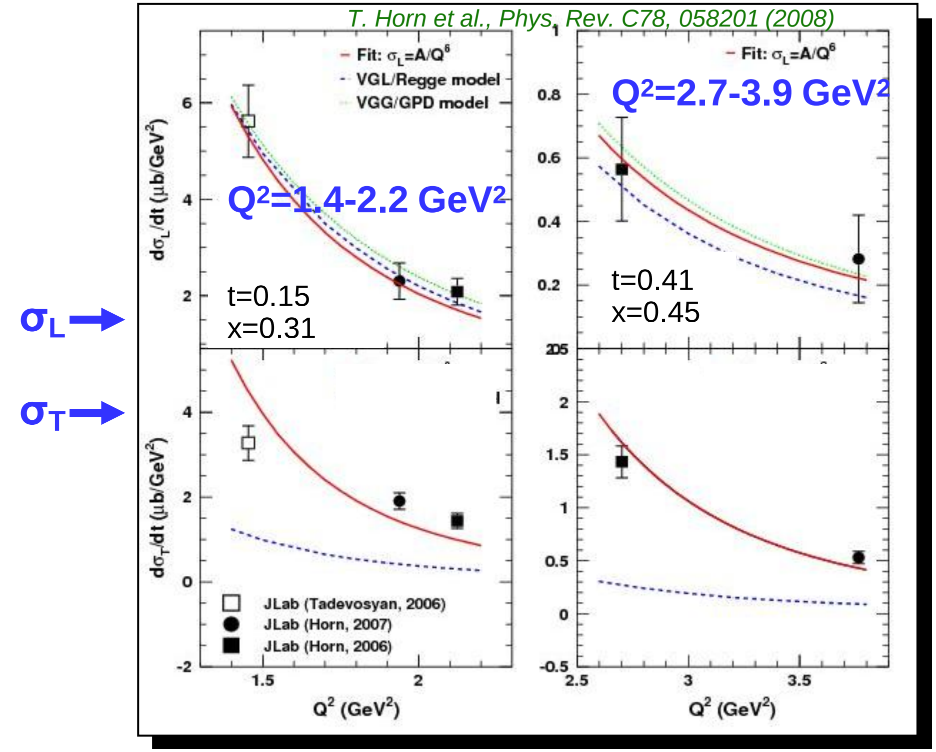
[Horn Phys. Rev. C85, 018202 (2012)]

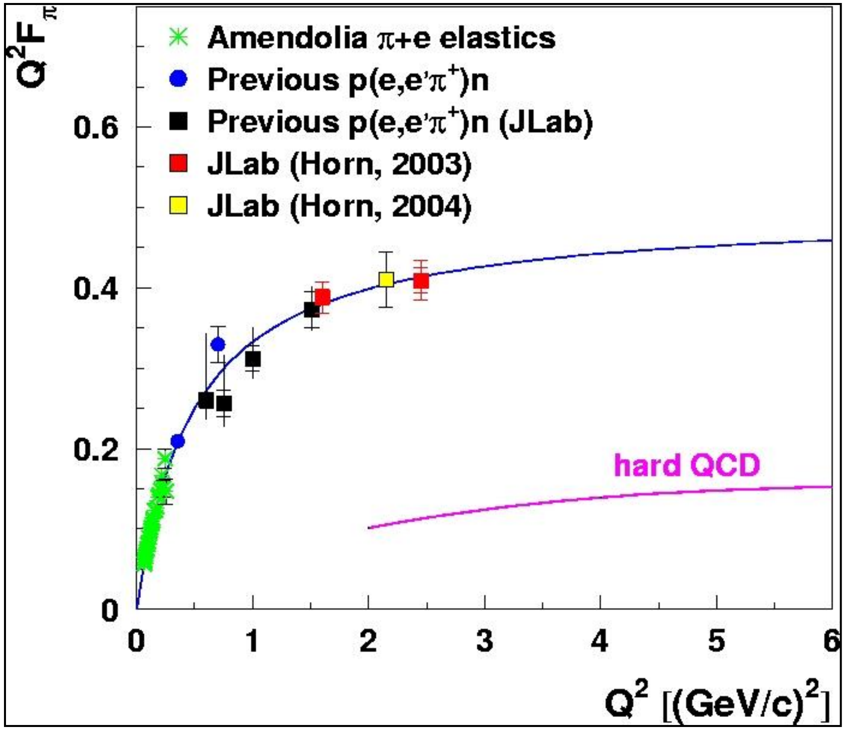
x_B	$-t$	$\sigma_L/\sigma_T \sim Q^{-n}$ n	$\sigma_L/\sigma_T \sim Q^2$ χ^2/ν (P)	$\sigma_L/\sigma_T \sim Q^{-2}$ χ^2/ν (P)
		Kaons		
0.3	0.2	1.48 ± 4.59	0.42(0.52)	0.01(0.91)
0.45	0.45	2.87 ± 15.2	0.04(0.84)	0.002(0.48)

Hard scattering

- QCD scaling prediction is reasonably consistent with K^+ cross section ratios
- Other fit forms for σ_L/σ_T also give a reasonable description
  - Using, e.g., DIS-Lund type description for σ_T *[Kaskulov 08]*
- Difficult to draw a conclusion from current K^+ σ_L/σ_T ratios
  - Limited W and Q^2 coverage
  - Uncertainties from scaling in x, t

Pion Form Factor – a puzzle?





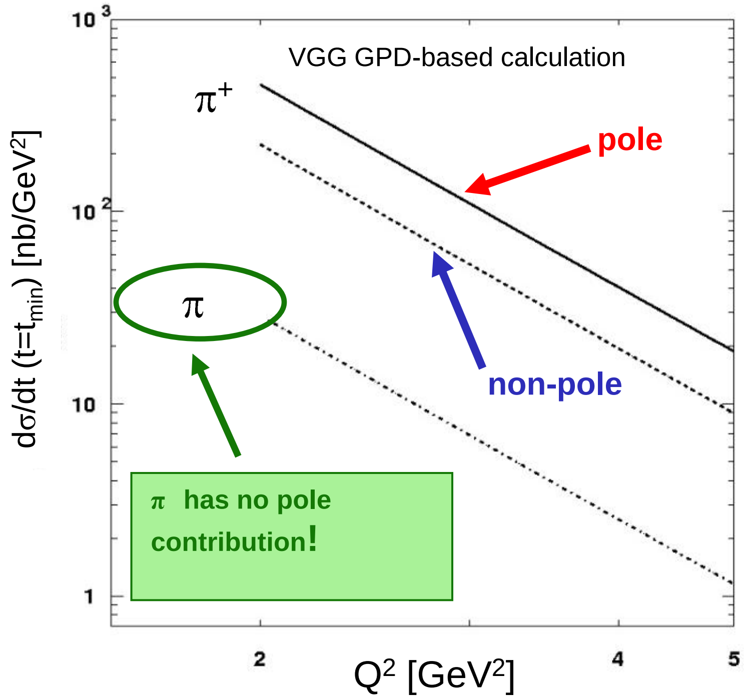
QCD scaling prediction is reasonably consistent with recent 6 GeV JLab π^+ σ_L data, *but* σ_T does not follow the scaling expectation

- Q^2 dependence of the pion form factor (F_π) follows prediction from perturbative QCD, 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

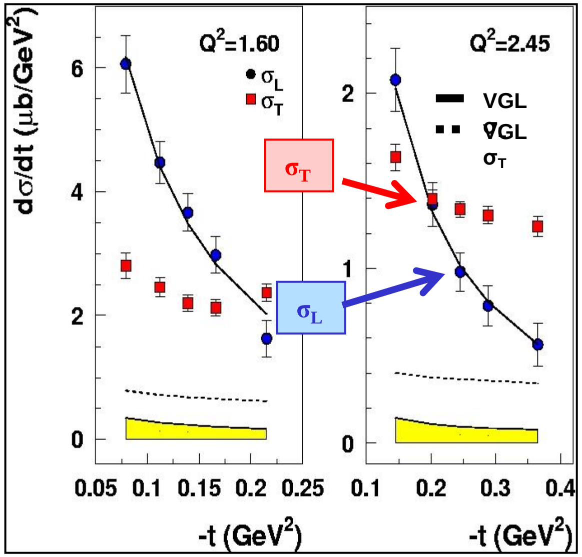
Pole and Non-pole contributions

- Production of π^+ and K^+ feature a meson exchange contribution in the t-channel (pole term), whose impact on factorization has to be understood
- In π° production the pole term is suppressed
  - The t-dependence at small t can thus be associated with the structure of the nucleon rather than its pion cloud
    - A large $R=\sigma_L/\sigma_T$ would imply the realization of the factorization theorem
  - A large response in σ_L may indicate non-pole contributions in π^+ production

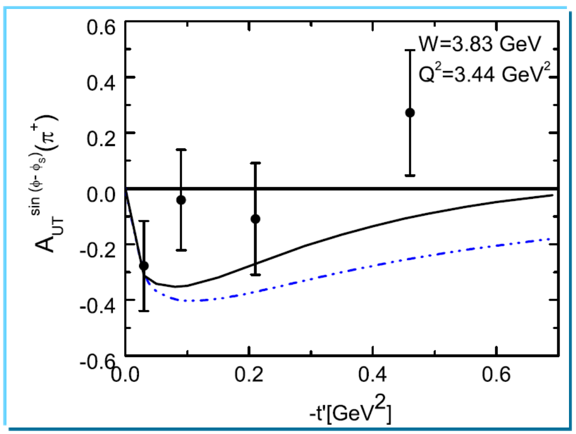


Comparison of R in π° and π^+ production important for understanding:
- Relative importance of pole and non-pole contributions in nucleon spin structure studies
- Non-pole contributions in F_π extraction

Transverse Contributions: π



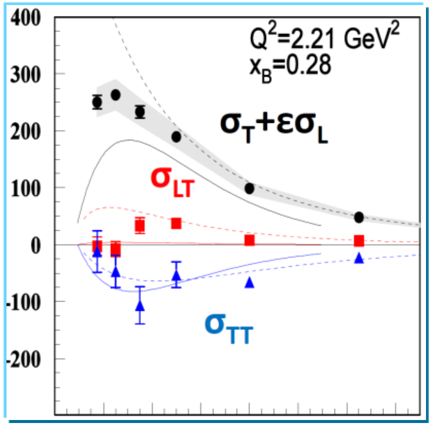
[Horn et al., 06]



[Airapetian et al, 10]

- Recent data suggest that transversely polarized photons play an important role in pion electroproduction
  - *Hall C π^+:* σ_T is larger than model predictions
  - HERMES π^+: sin ϕ modulation is large
  - CLAS: π^o substantial fraction of σ_{TT} in the *unseparated* cross section

[Kubarovsky10+]



- Recent theoretical developments suggest no strong suppression of σ_T at experimentally accessible values of Q^2 [GK 10; GK 11]
  - Large σ_T in π^o may allow access to helicity flip GPDs

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha_e}{2k}\frac{\mu_\pi^2}{Q^4}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\xi^2\left|\langle \bar{E}_T\rangle\right|^2\right]$$

$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha_e}{8k}\frac{\mu_\pi^2}{Q^4}\frac{t'}{4m^2}\xi^2\left|\langle \bar{E}_T\rangle\right|^2$$

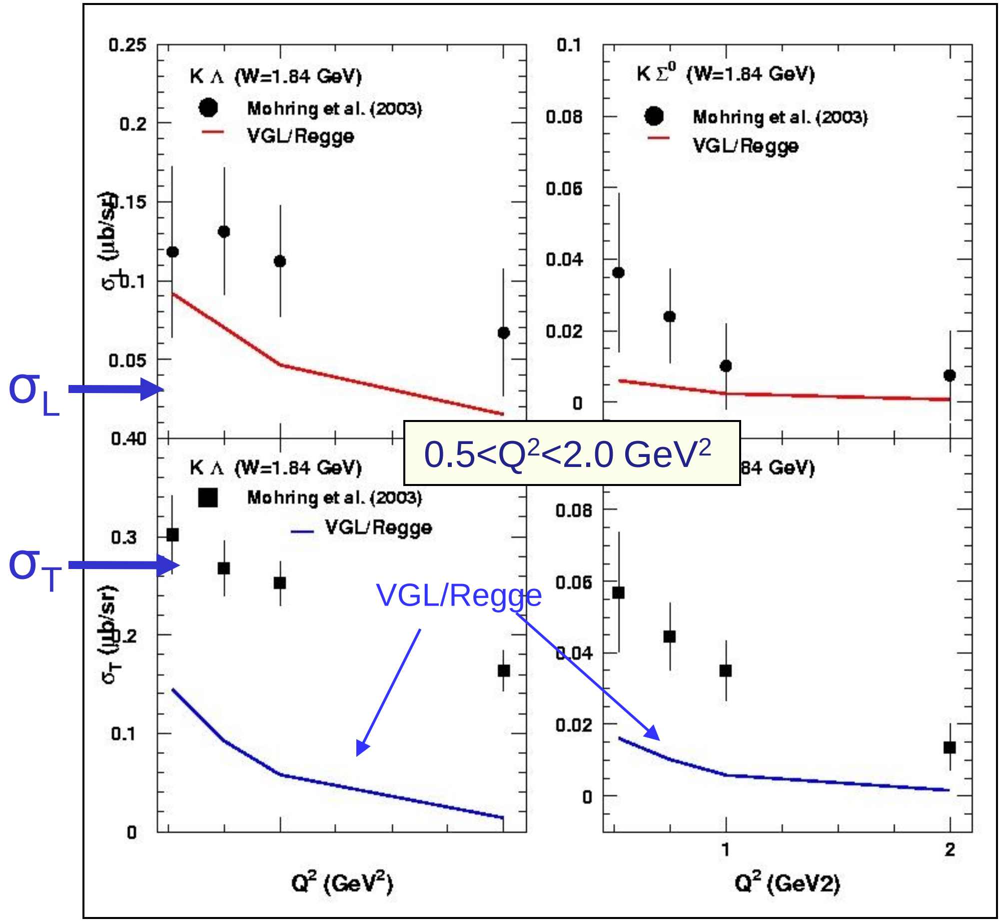
$$\bar{E}_T = 2\tilde{H}_T + E_T$$

Transverse Contributions: K^+

- For K^+ production in the *resonance region* σ_T is also not small at Q^2=2 GeV^2

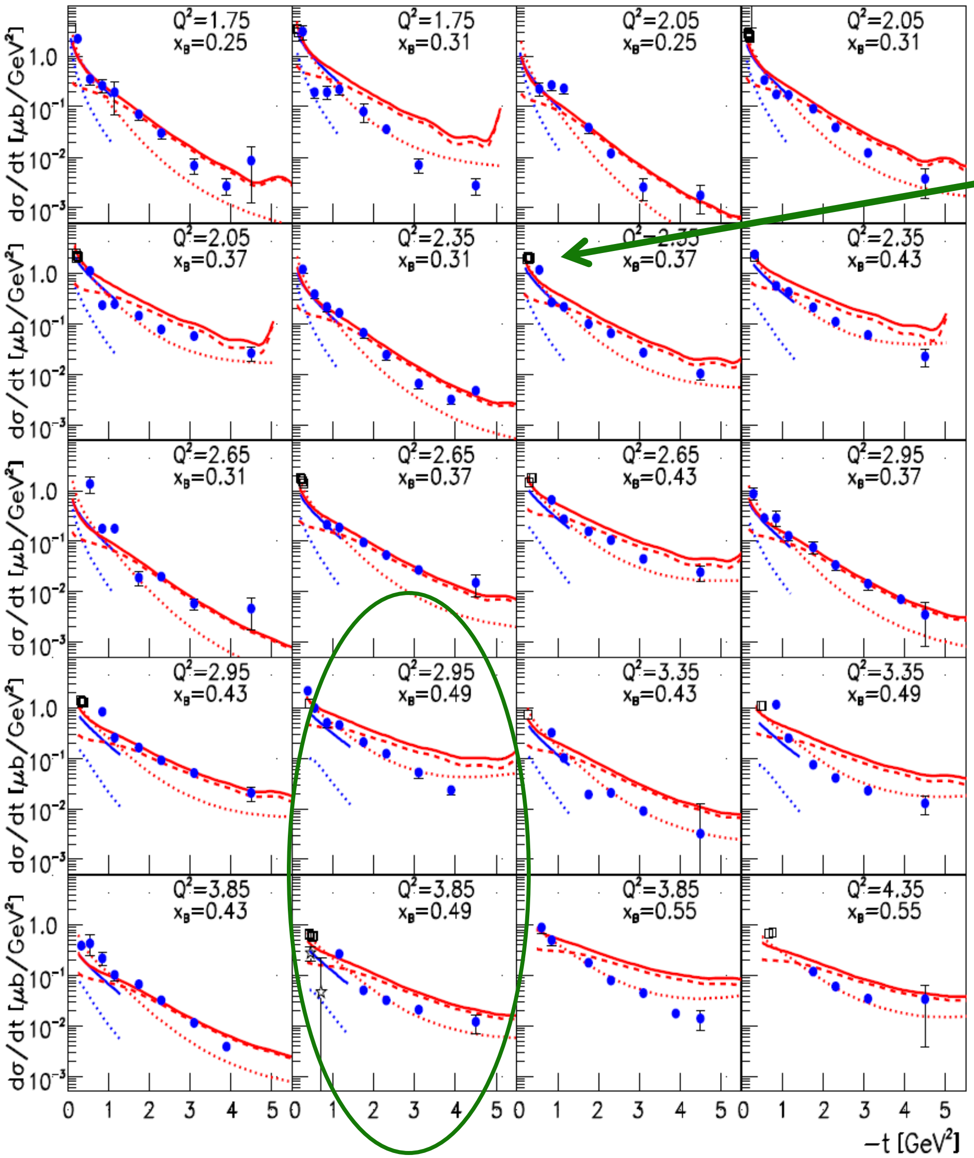
- Unfortunately, available kaon data are limited
  - No separated data above the resonance region
  - Limited W and Q^2 range
  - Significant uncertainty due to scaling in x_B and –t

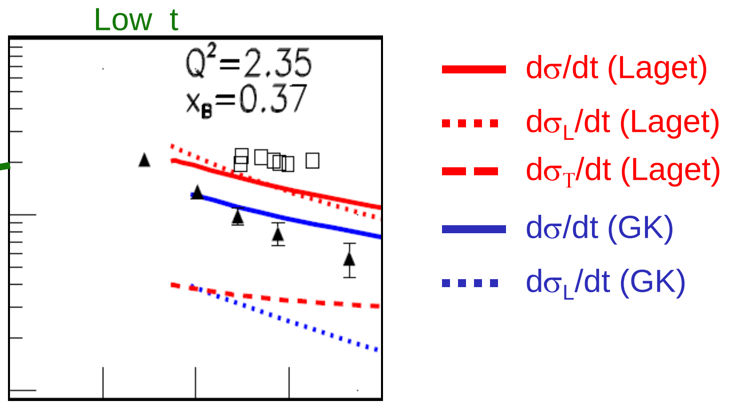
Hall C 6 GeV K^+ data (W=1.84 GeV)



[Mohring et al., Phys.Rev.C67:055205,2003]

π^+: Hadronic and Partonic models

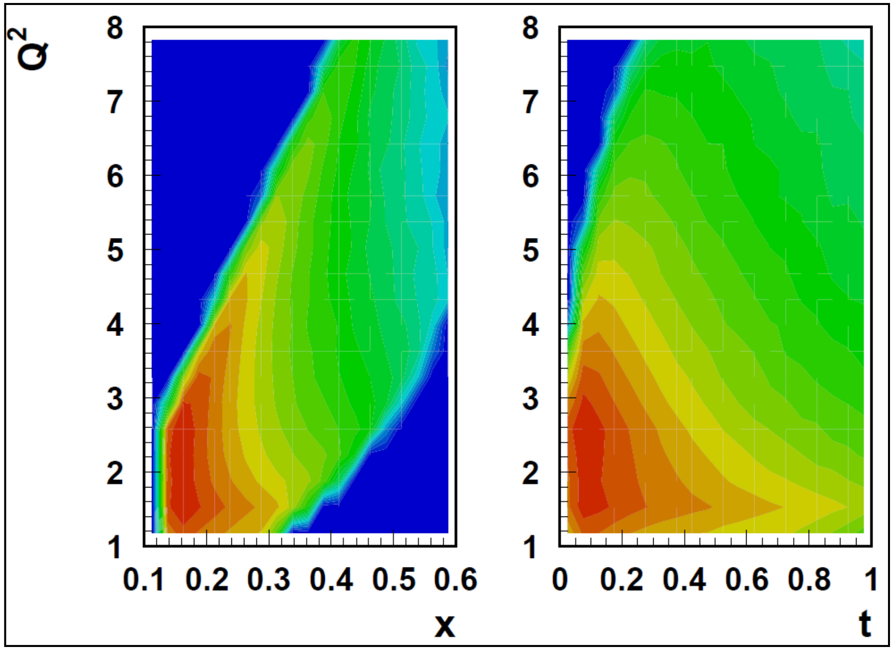




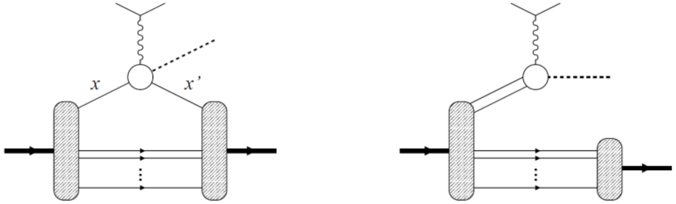
- CLAS: e1-6 data
- At large x hadronic and partonic models differ significantly in relative contribution of σ_L and σ_T
- Separated data will be important for understanding the reaction mechanism

JLab 12 GeV: exclusive reactions

$s = 2E_e m_p$



CLAS12 kinematic coverage $N(e,e'\gamma)N$



Scattering from q or $\bar{q}$ Knockout of $q\bar{q}$ pair

- Unique features:
  - Center of mass energy, *s*=20.6 GeV^2
  - Luminosity 10^{37} cm^{-2}s^{-1} (Hall A,C), 10^{35} (CLAS12) for valence region, differential measurements, spin asymmetries
  - CLAS12 and magnetic spectrometers in Hall A, C are complementary
- Transverse imaging in valence region:
  - GPDs from DVCS $\gamma^* N \rightarrow \gamma + N$
  - Transverse charge densities from elastic form factors $\int dx\, \rho(x,b)$
  - Transverse flavor/spin distributions from exclusive meson production

$$\gamma^* N \rightarrow N + \pi, K, \rho, K^*, \phi$$

Limited kinematic coverage:

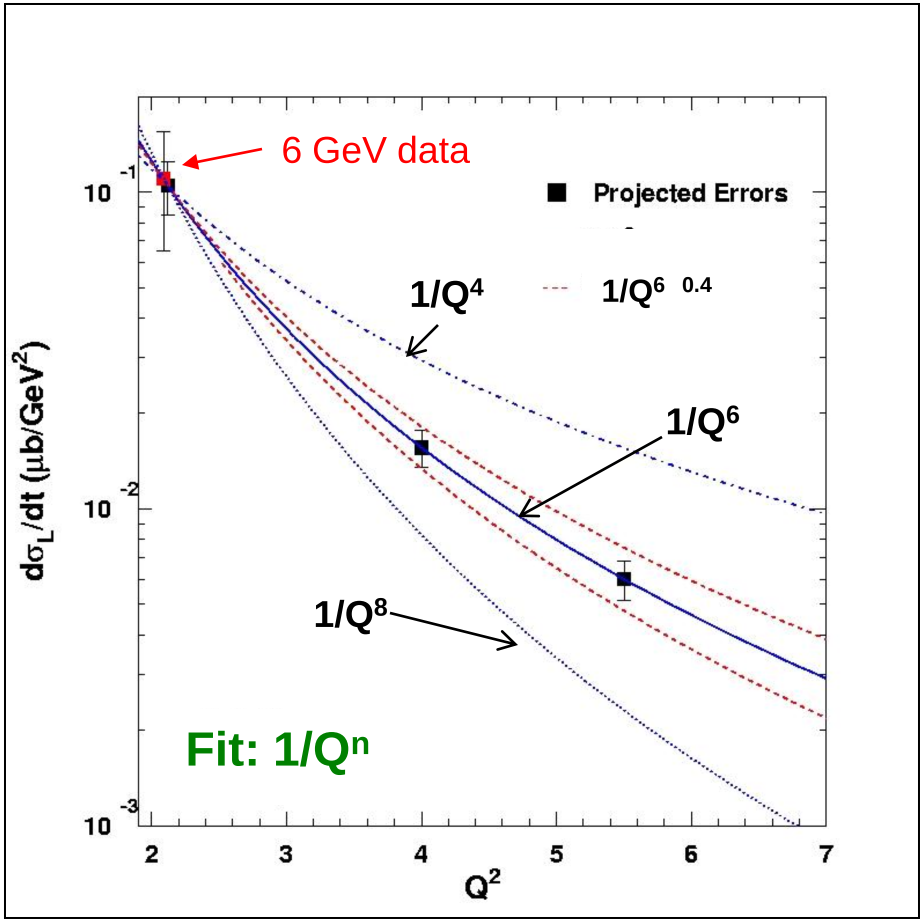
- **How to test the reaction mechanism?**

Factorization Tests in π^+ Electroproduction

- JLab experiment E12-07-105 will search for the onset of factorization

- Q^2 coverage is 2-3 times larger than at 6 GeV at smaller t

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

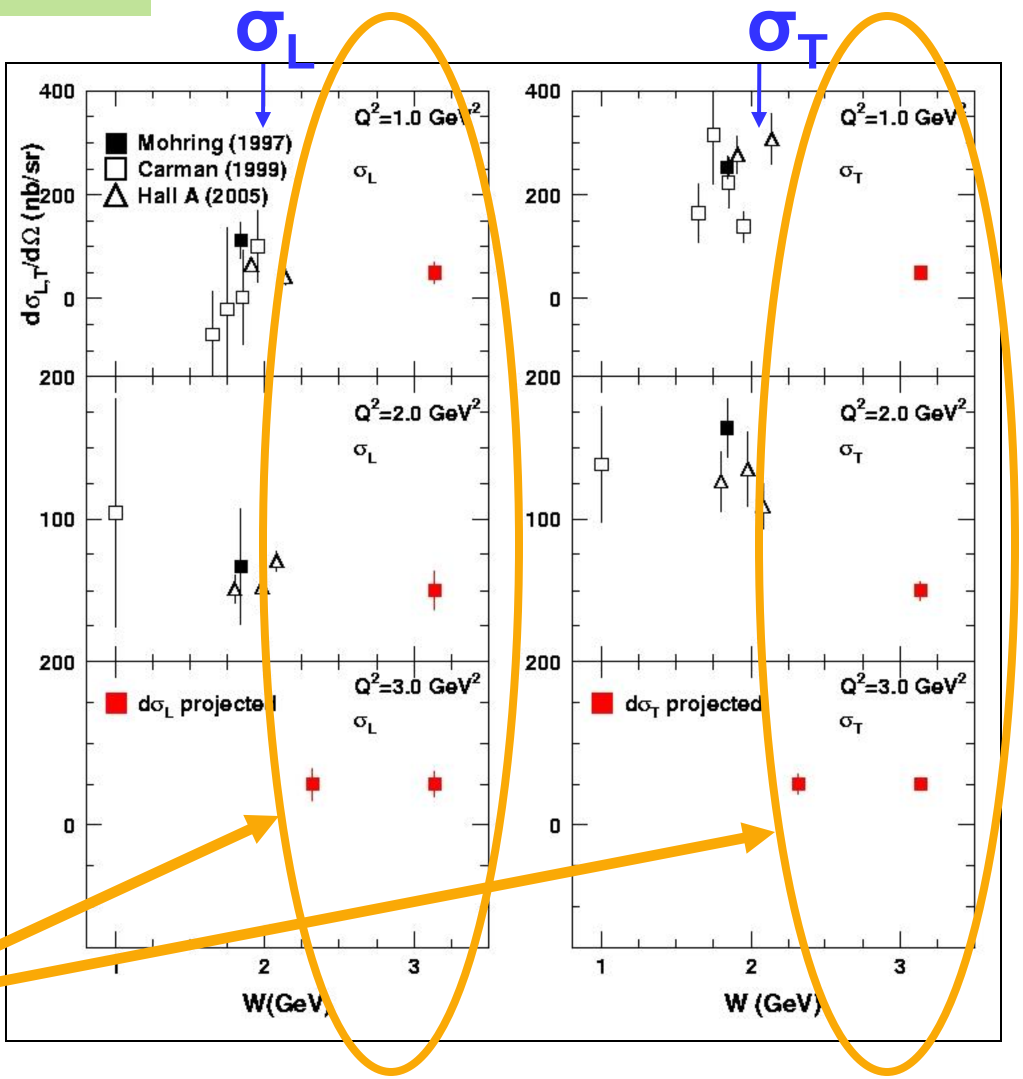


Is the partonic description applicable in practice?

Can we extract GPDs from pion production?

Kaon cross section: σ_L and σ_T

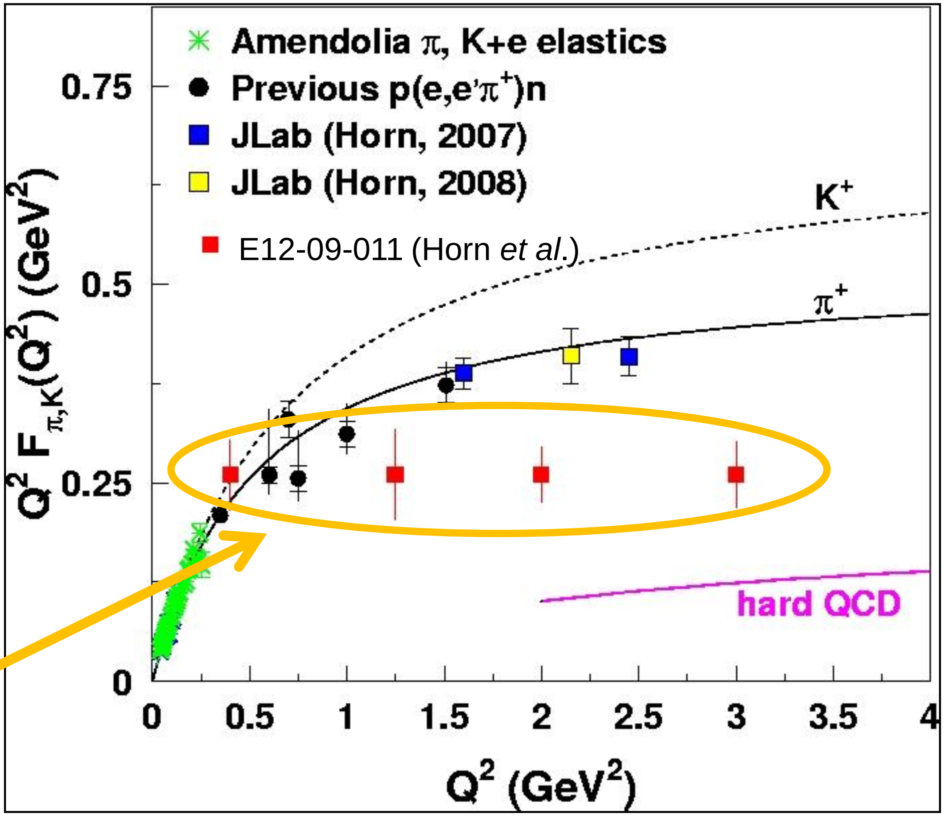
- Approved experiment E12-09-011 will provide first L/T separated **kaon** data above the resonance region
- Onset of factorization
- Understanding of hard exclusive reactions
  - QCD model building
  - Coupling constants



E12-09-011: Precision data for W > 2.5 GeV

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

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

Is onset of scaling different for kaons than pions?

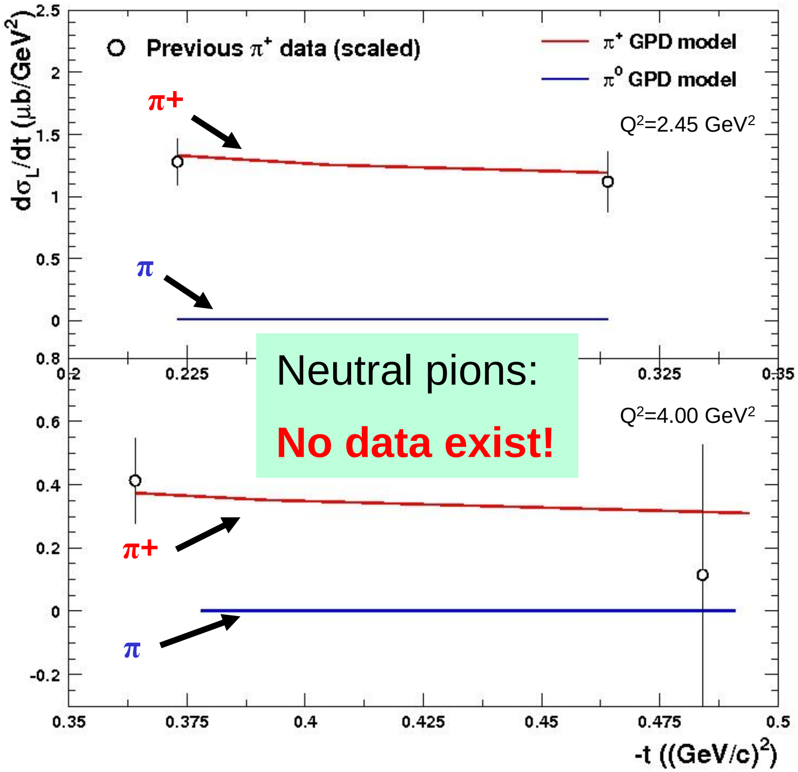
Kaons and pions together provide quasi model-independent study

Relative contribution of σ_L and σ_T in π^o production

Understand the relative contribution of σ_L in π production

- 12 GeV: Opportunity to compare to π^+ cross sections (E12-07-105)
- Significant response in σ_L in π^o could indicate non-pole contributions in π^+ production
  - If non-pole contributions smaller than anticipated may extract F_π to higher Q^2

Separated σ_L data and predictions



Summary

- Pseudoscalar meson production data play an important role in our understanding of nucleon structure

- JLab 12 GeV will allow for fundamental tests required for the interpretation of data from the GPD program and understanding pole/non-pole contributions in meson production
  - Extended kinematic reach
  - Studies of additional systems
  - Complementary precision L/T and surveys