Exclusive Meson Production at high Q^2 and Factorization

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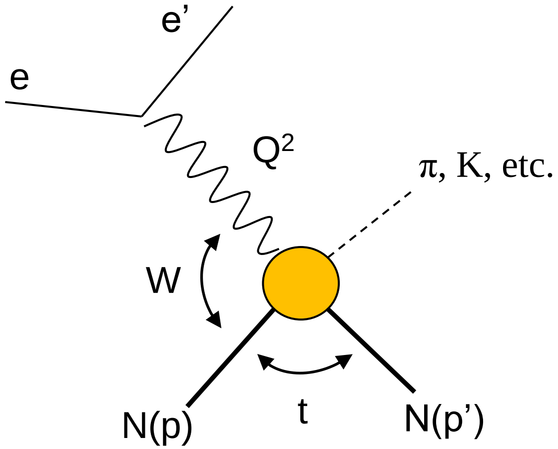
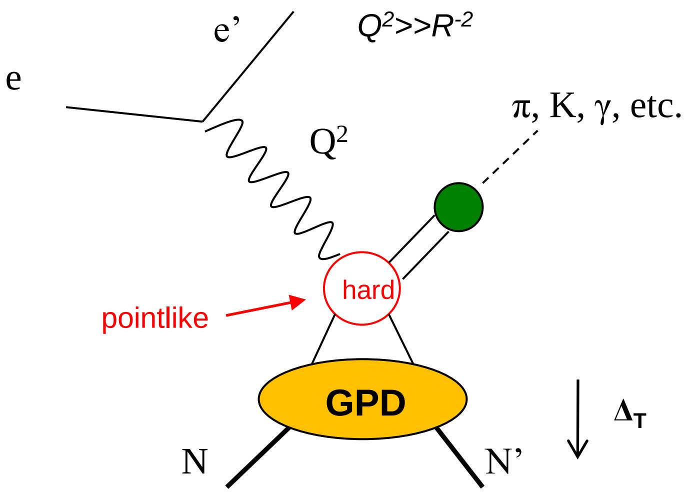
Meson Reaction Dynamics



t-channel process

- Meson production can be described by the t-channel exchange meson pole term in the limit of small –t and large W
  - Pole term is dominated by longitudinally polarized photons
  - Spatial distribution described by form factor



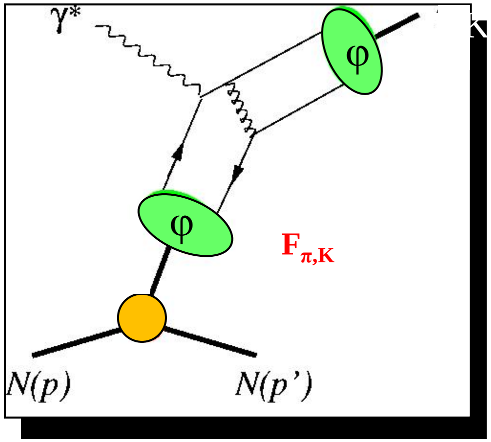
handbag

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

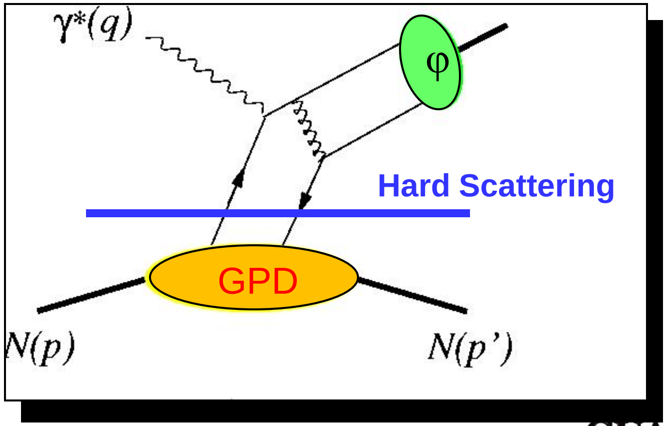
Transverse Spatial Distributions: Form Factors and GPDs

- Meson form factors and nucleon GPDs are essential to understand the structure of hadrons

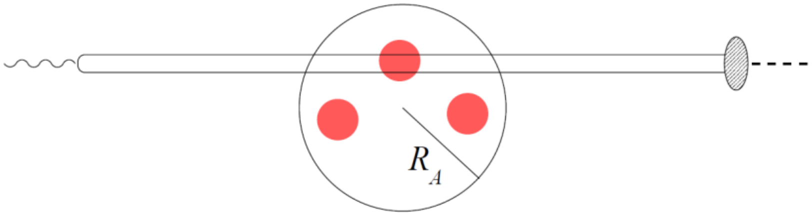
- But measurements of form factors and GPDs have certain prerequisites:
  - For form factors, must make sure that σ_L is dominated by the meson pole term at low -t
  - For GPDs, must demonstrate that factorization applies ($\sigma_L \sim Q^{-6}$ to leading order)



- A *comparison of pion and kaon* production data may shed further light on the reaction mechanism
  - quasi-model independent
  - more robust than calculations based on QCD factorization and present GPD models



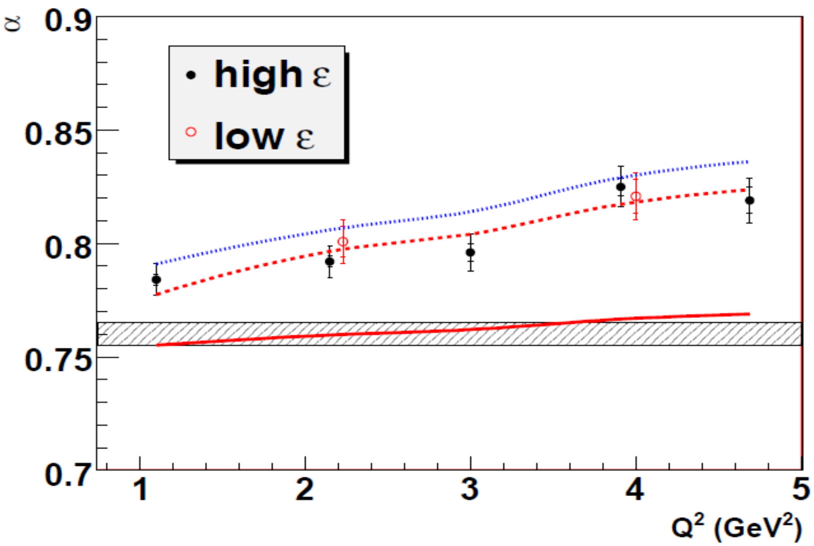
Factorization and Color Transparency



$l_{coh}, l_{form} >> R_A$

$\sigma(A) = \sigma_0 A^{\alpha}$

$\therefore T = A^{\alpha-1}$

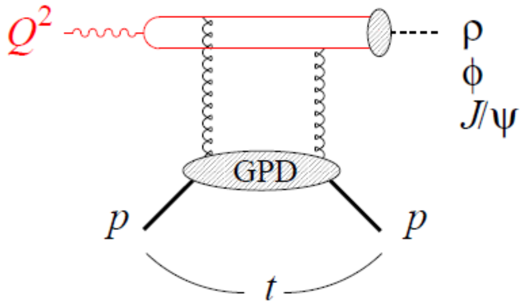


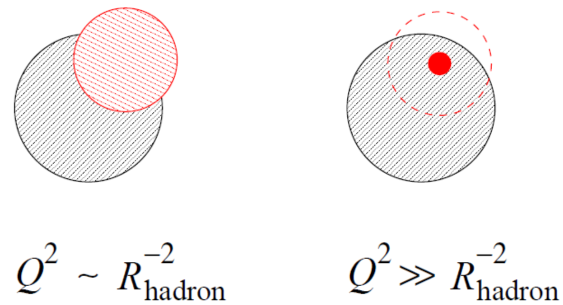
Consistently larger than 0.76 found from π-N scattering cross sections

- Color transparency (CT) is a phenomenon predicted by QCD in which hadrons produced at large Q^2 can pass through nuclear matter with little or no interaction *[A.H.Mueller, Proc. 17th rec. de Moriond, Moriond, p13 (1982), S.J.Brodsky, Proc. 13th intl. Symp. on Multip. Dyn., p963 (1982)]*
  - At high Q^2, hadron can be created with a small transverse size (PLC)
  - Hadron can propagate through the nucleus before assuming its equilibrium size
- CT is a signature of the approach of the factorization regime

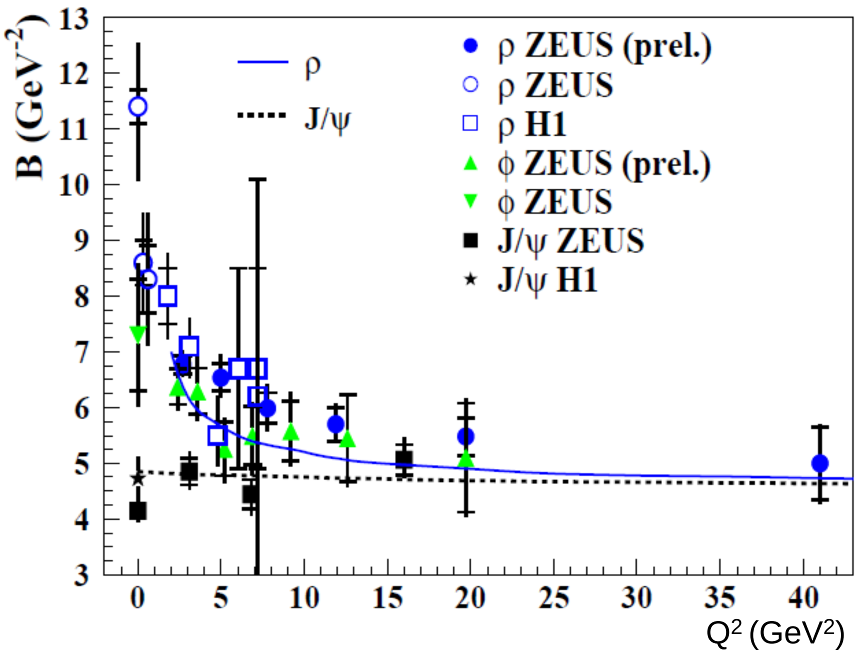
Recent CT results are suggestive but not conclusive for mesons

Vector Mesons and the Small Size Regime





HERA Vector Meson Data



- t-slope of cross section measures the transverse area of the interaction region
  - Reflects size of target and that of dominant configurations of produced meson
- t-slope decreases with increasing Q^2 and stabilizes when small-size configurations dominate
- In small size regime t-slope can be associated with t-dependence of GPD

Data show that factorization sets in, but precision in mapping its onset is not sufficient for the needs of JLab experiments

Exclusive Pseudoscalar Data: Pions and Kaons

- Data used in this analysis
  - Used separated cross sections where possible

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

- 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.**

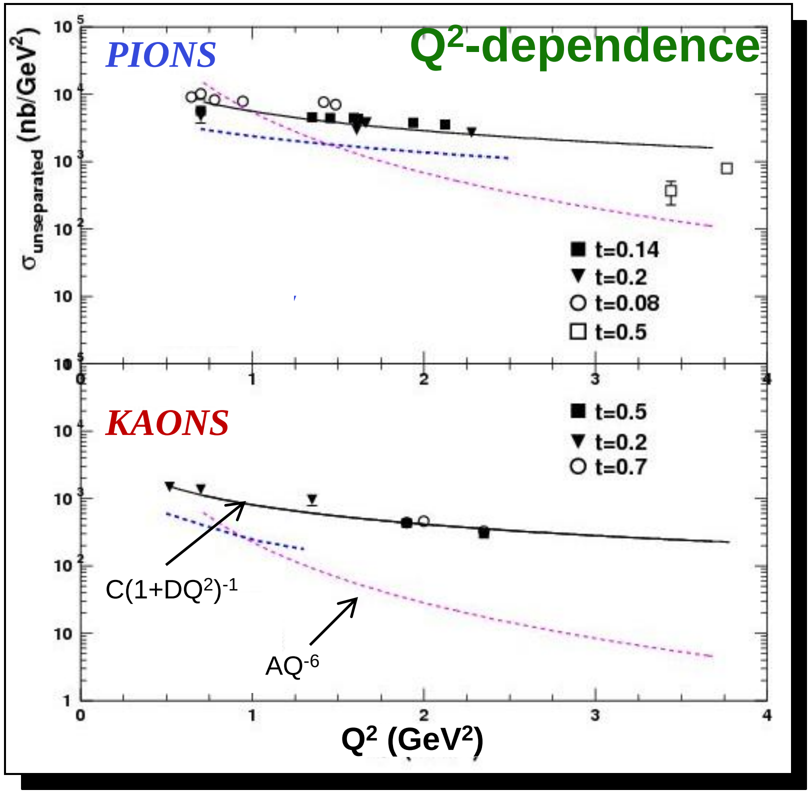
$$ep \rightarrow K^+ \Lambda$$

- 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

$ep \rightarrow K^+ \Lambda$

$ep \rightarrow \pi^+ n$

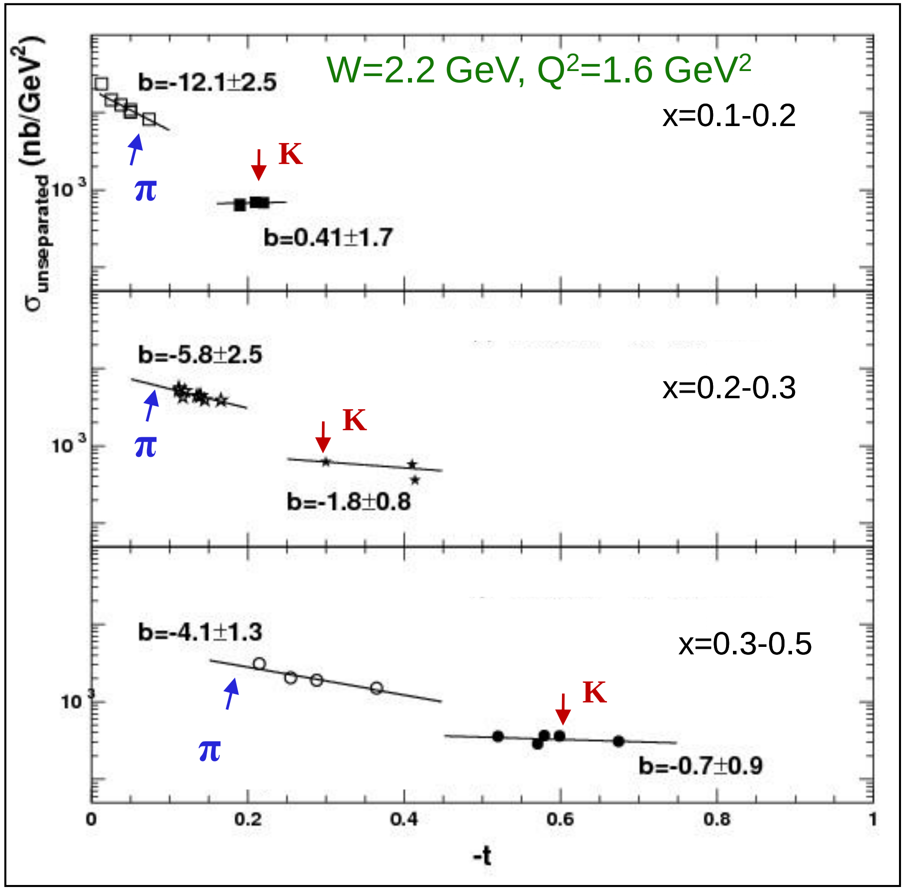


- Cross section depends on W, Q^2, t
- t-dependence can be obtained from the combined set by scaling in W and Q^2
- Scale cross section to common W value using empirical form $(W^2\text{-}M^2)^{-2}$
- Smooth Q^2 dependence allows to scale to common Q^2
  - Factor $C(1+DQ^2)^{-1}$ gives a good fit
  - Scaling prediction Q^{-6} does not fit well

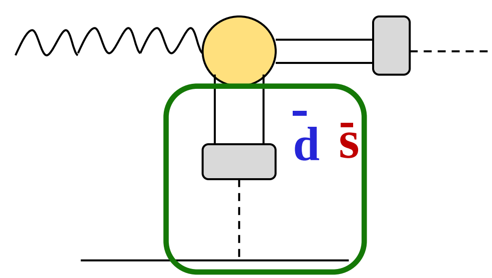
Scaled cross section to a common W and Q^2 value – now what about t?

Low Q^2: e^{-bt} scaling of σ_π and σ_K

Combines data from Cornell, DESY, and JLab 6 GeV

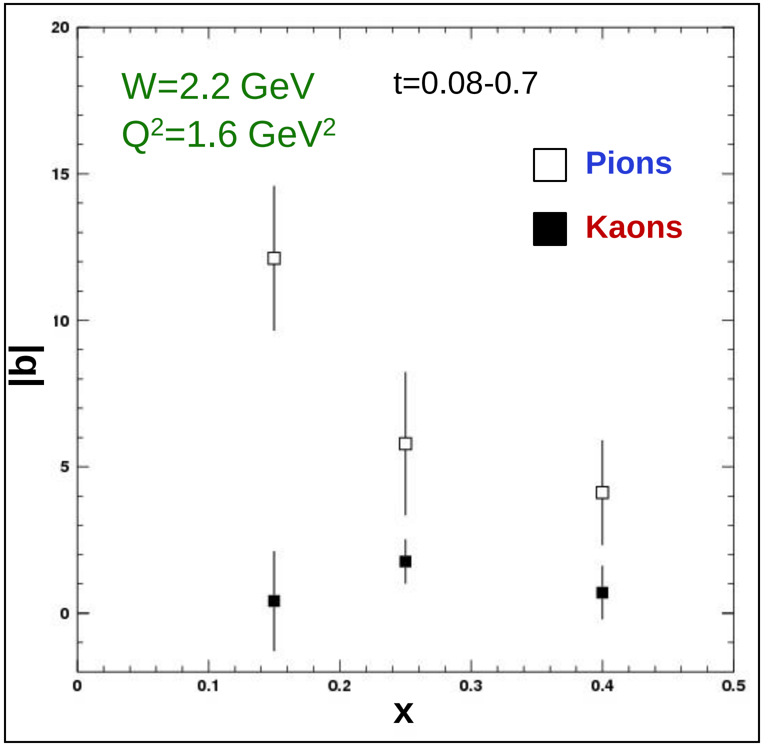


- Pion and kaon data follow an almost exponential t-dependence
  - Q^2 and t dependence does not factorize completely
- t-dependence flatter at larger x
- Pion t-dependence is steeper *at* low *t* than for kaons
  - pole factor $(m^2_{K,\pi} - t)^{-1}$ gives less enhancement for kaons than pions
  - Different from u-quark exchange

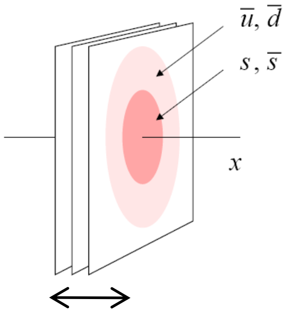


Pole factor enhances pion cross section – additional low t data would allow to interpret contribution for kaons

t-slopes of pions and kaons



- t-slope measures the overall size 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



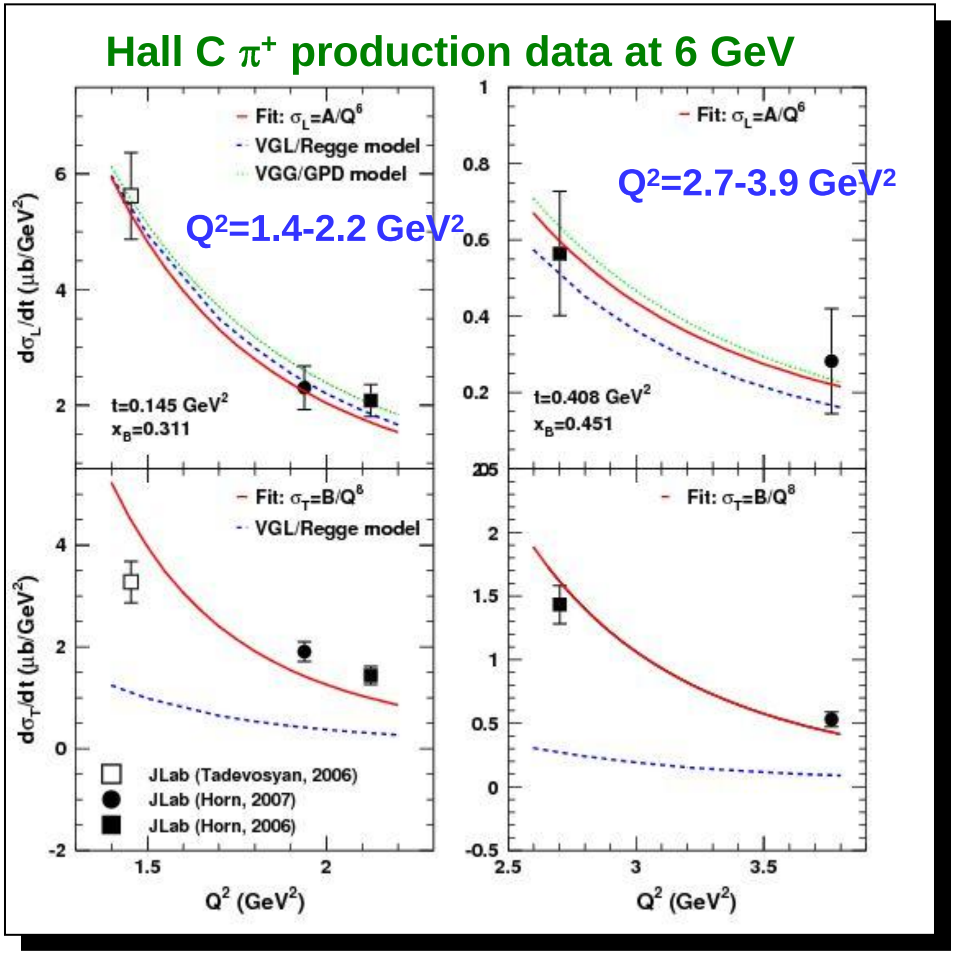
High quality *separated* data for both K and π in for |t|<1GeV^2 would allow for better understanding of onset of factorization, and constraining effective transverse sizes

High Q^2: Q^{-n} scaling of σ_L and σ_T

- 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

σ_L →

σ_T →



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

Kaon production data would allow for a quasi model-independent comparison that is more robust than calculations based on QCD factorization and present GPD models

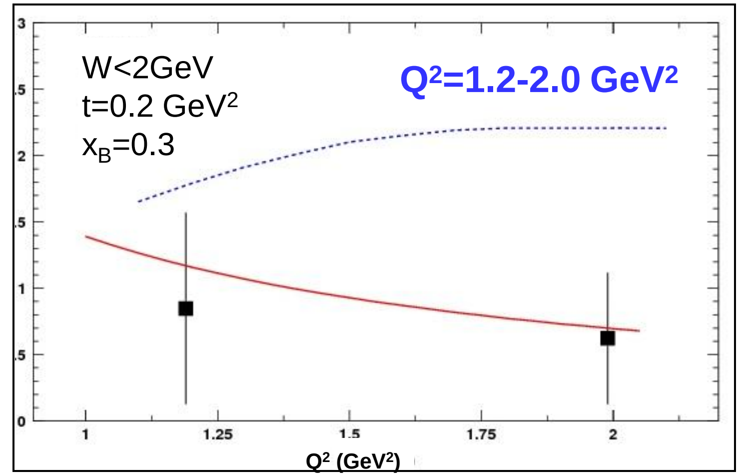
Kaons: Q^{-n} scaling of σ_L/σ_T in the resonance region

$ep \rightarrow e'K^+n$

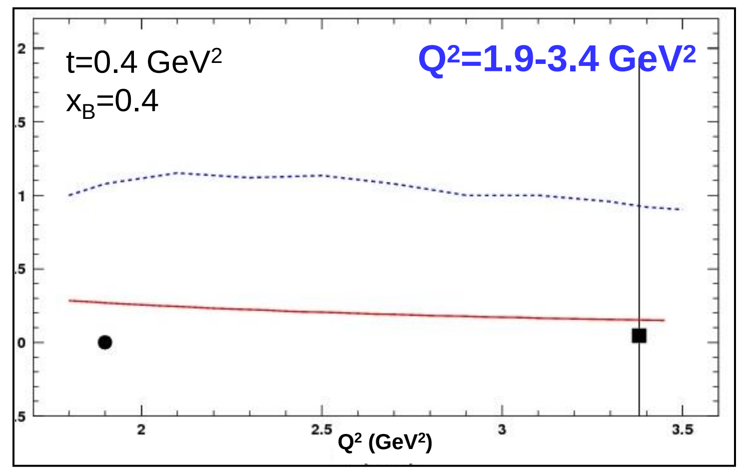
- Q^{-n} scaling trough $R=\sigma_L/\sigma_T$ is not as rigorous as the scaling test of the individual cross sections
- Current knowledge of σ_L and σ_T *above* the resonance region is insufficient
- Current models not sufficient for understanding reaction mechanism
- Difficult to draw a conclusion from current K^+ σ_L/σ_T ratios
  - Limited W and Q^2 coverage
  - Uncertainties from scaling in x, t

Cornell and JLab/Hall A data

$R=\sigma_L/\sigma_T$ →



$R=\sigma_L/\sigma_T$ →



High quality σ_L and σ_T data for both kaon and pion would provide important information for understanding the meson reaction mechanism

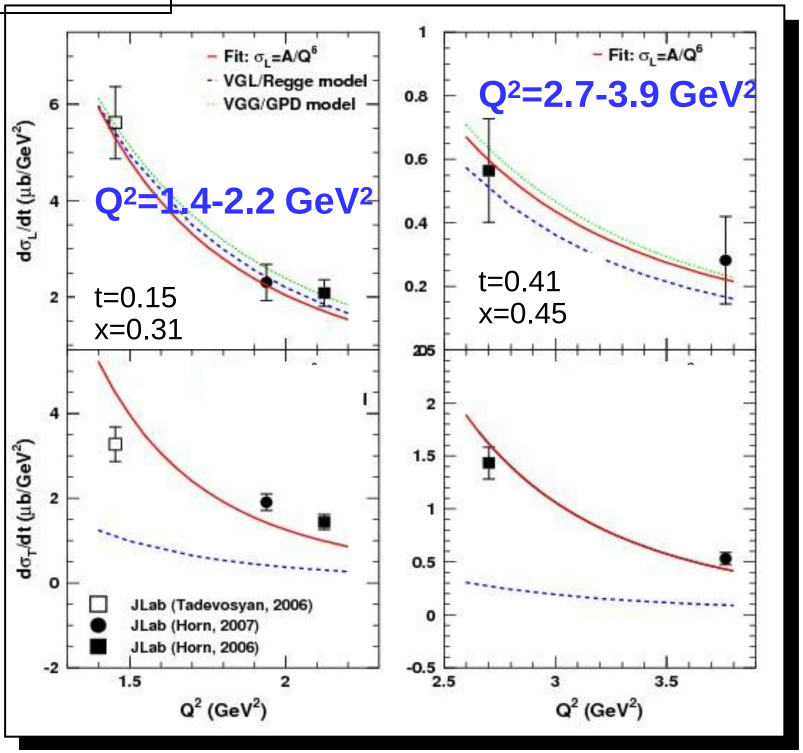
Pion Form Factor – a puzzle?

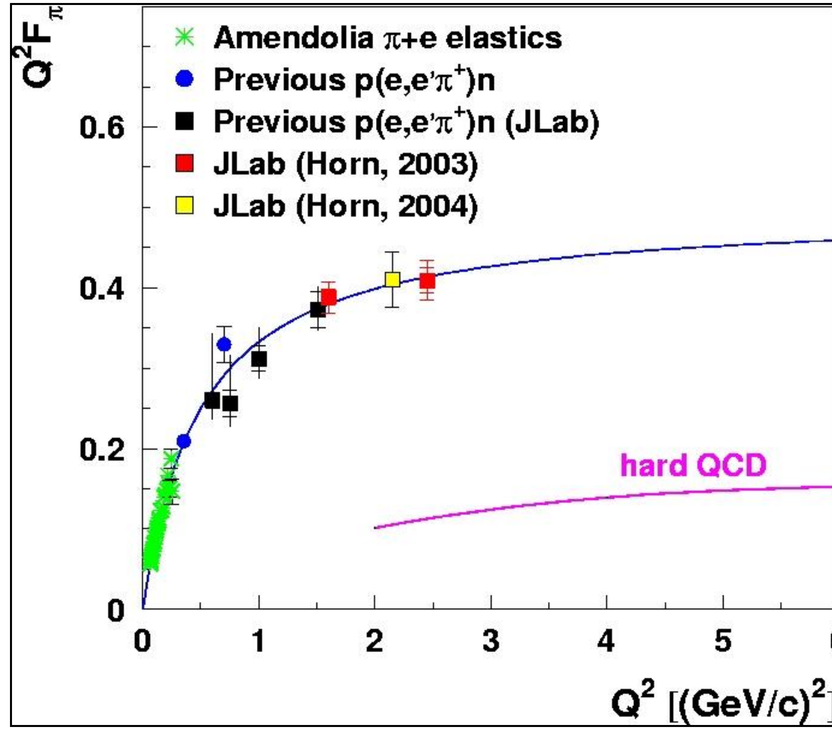
$ep \rightarrow e'\pi^+ n$

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

$\sigma_L \rightarrow$

$\sigma_T \rightarrow$



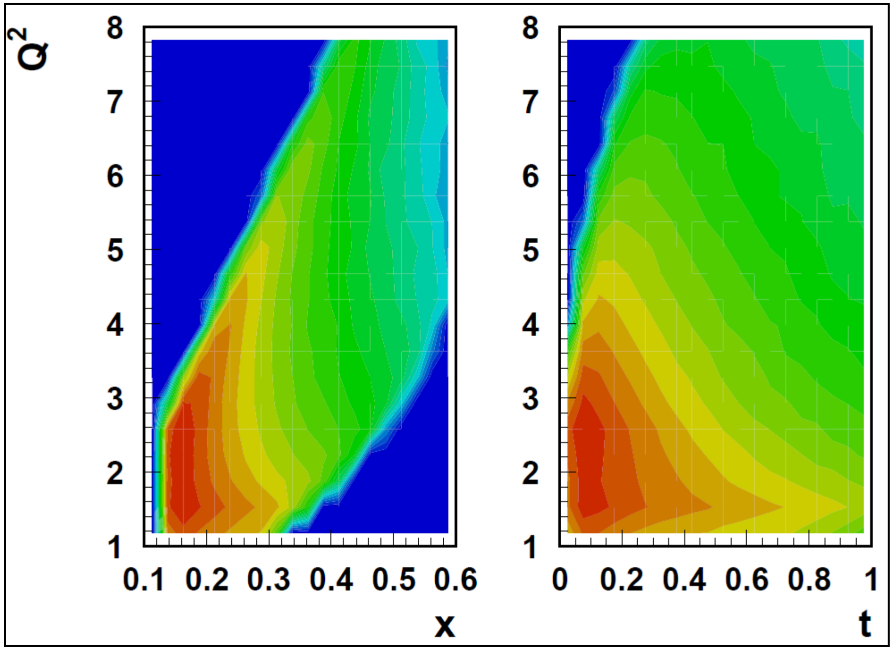


- The QCD scaling prediction is reasonably consistent with recent 6 GeV JLab π^+ σ_L data, *but* σ_T does not follow the scaling expectation

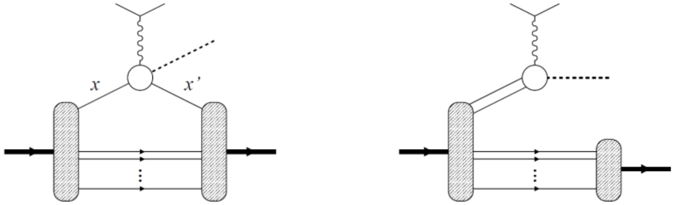
- Q^2 dependence of the pion form factor (F_π) follows prediction from perturbative QCD, suggests factorization holds
- Different magnitudes imply that factorization does not hold or something is missing in calculation

Further information on the pion puzzle through varying the system

JLab 12 GeV: exclusive reactions



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

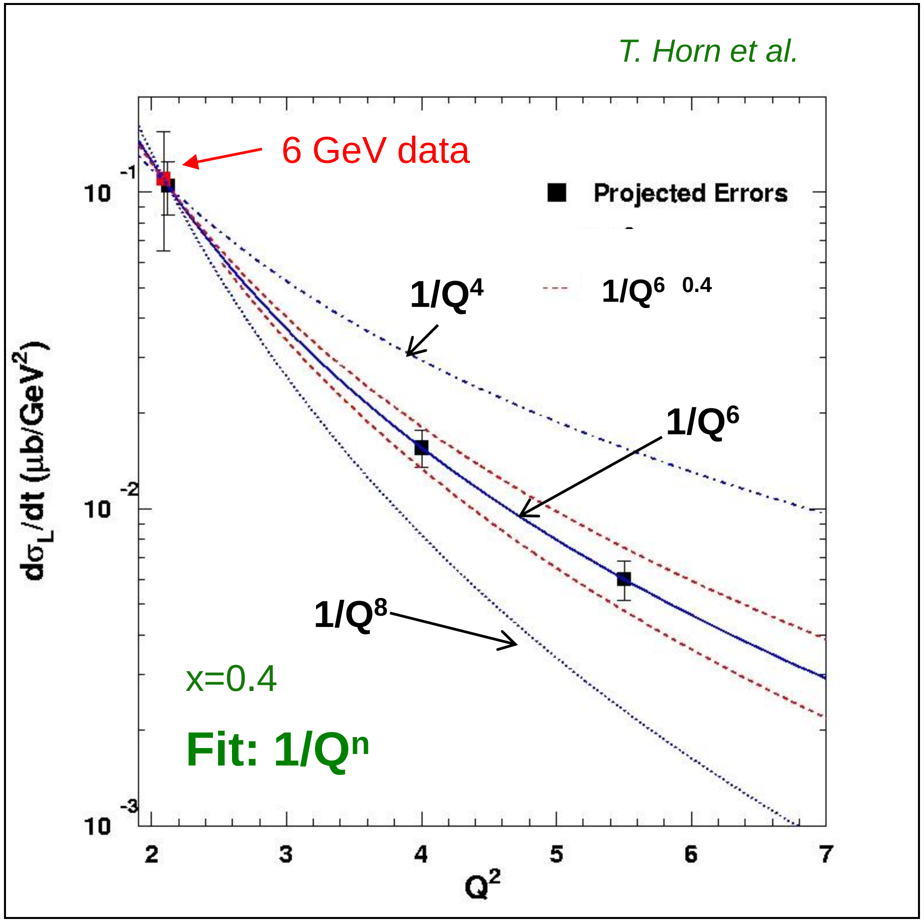


$s = 2E_e m_p$

- Unique features:
  - Center of mass energy, s=20.6 GeV^2 [minimum for MEIC is ~200 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?

JLab 12 GeV: 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
  - x=0.3, 0.4, 0.5
- 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?

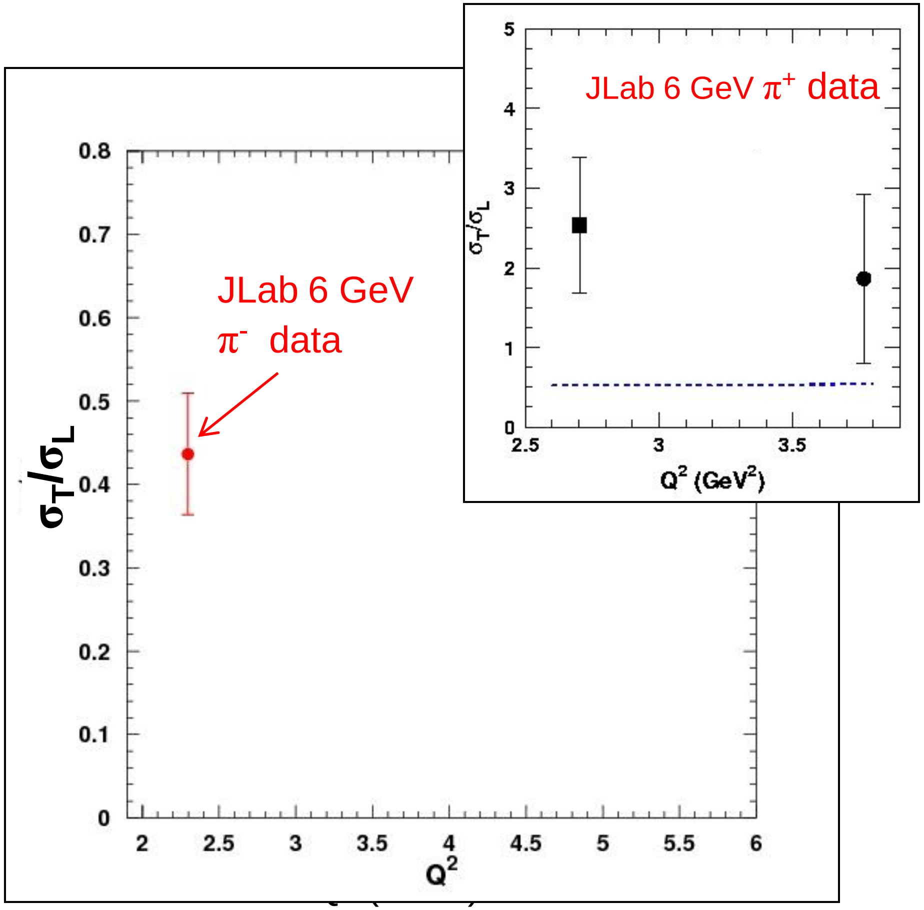
Can we extract GPDs from pion production?

σ_L without explicit L/T?

- If σ_L is small, GPD flavor studies may be limited to focusing spectrometers
  - L/T separations required

- But data suggest that σ_L is larger for π^- than for π^+ production
  - If this holds, one can extract σ_L from unseparated cross sections

$$\sigma = \sigma_T + \varepsilon\sigma_L \xrightarrow{\sigma_T \to 0} \varepsilon\sigma_L$$



E12-07-105 will compare π^+ and π^- production to check possibilities of extracting GPDs without explicit L/T

JLab 12 GeV: L/T separated kaon cross sections

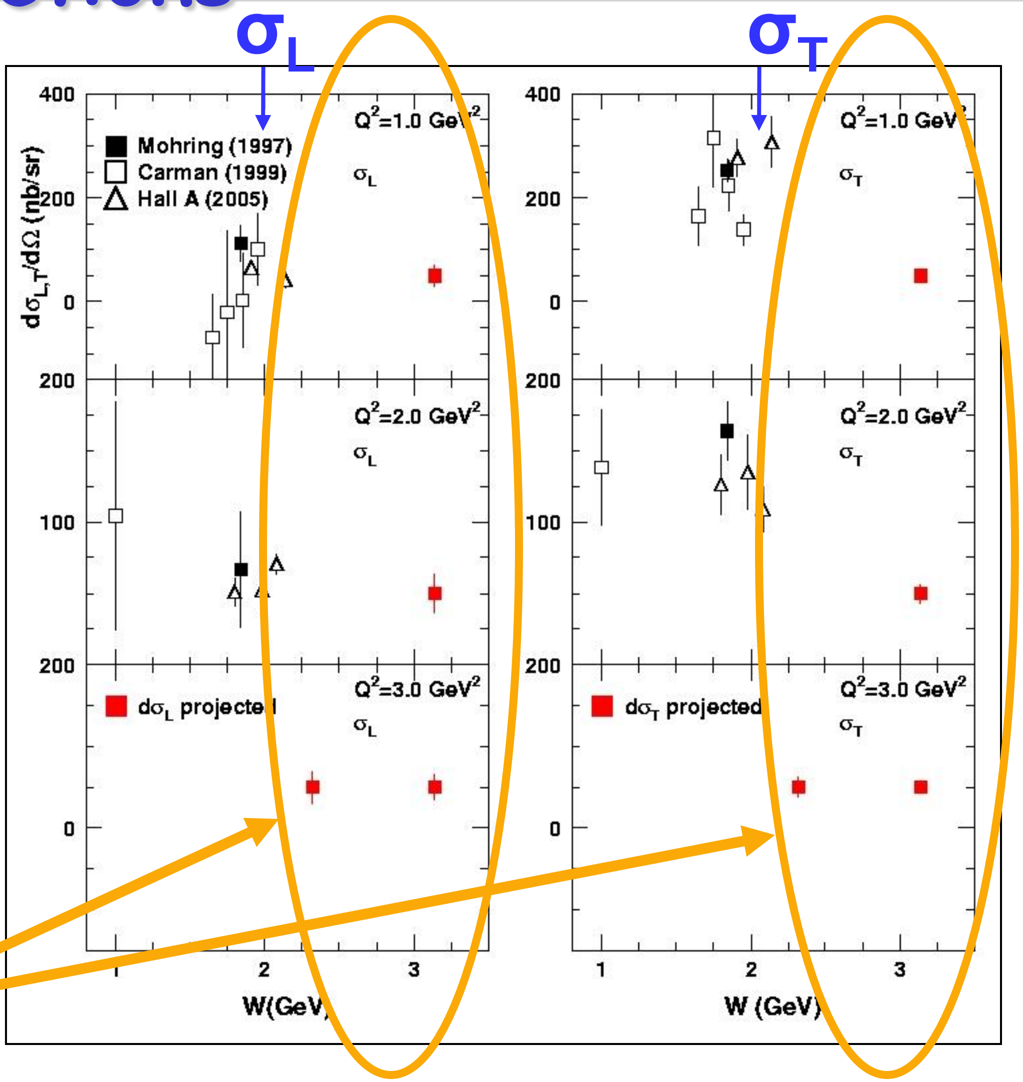
T. Horn et al.

- Approved experiment E12-09-011 will provide first L/T separated **kaon** data above the resonance region

- Onset of factorization

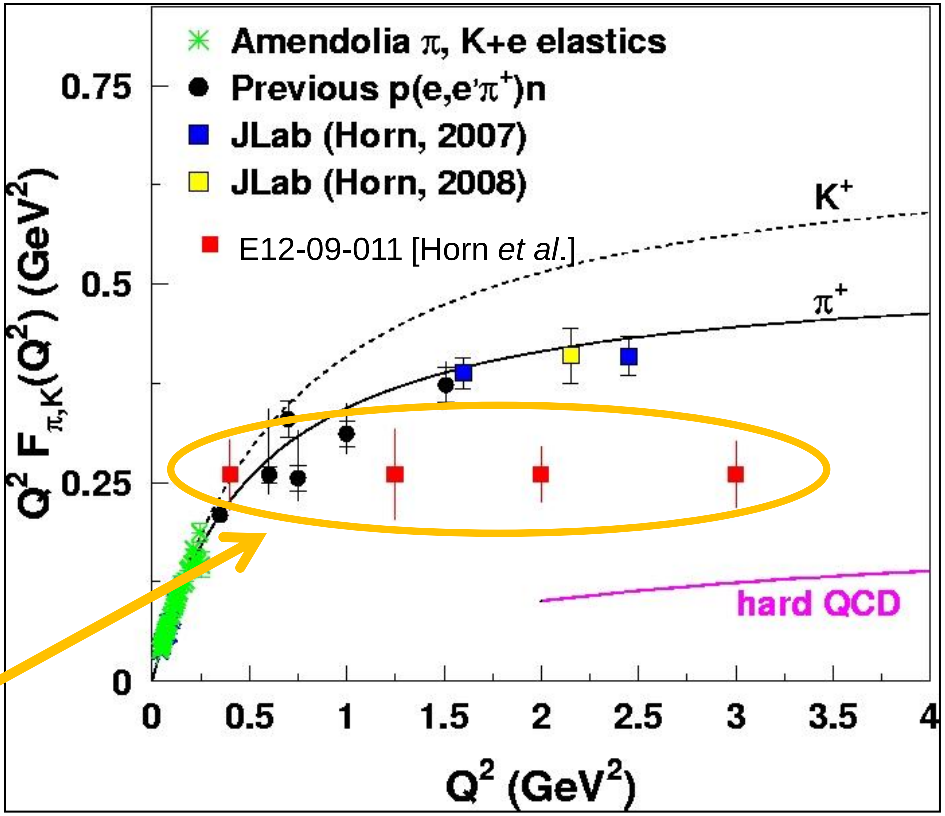
- Understanding of hard exclusive reactions
  - QCD model building
  - Coupling constants

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



JLab 12 GeV: $F_{\pi, K}$ – can kaons shed light on the 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?



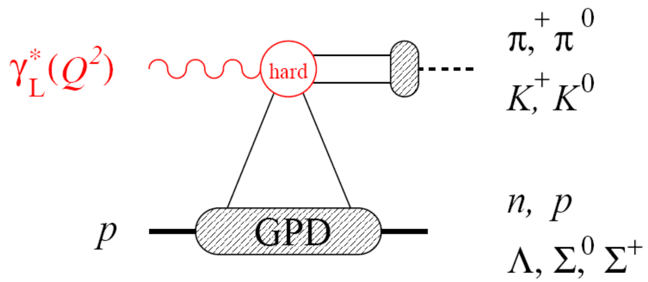
Projected uncertainties for kaon experiment at 12 GeV

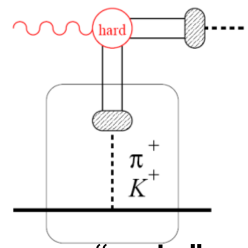
T. Horn et al., Phys. Rev. Lett. 97 (2006) 192001.

Is onset of scaling different for kaons than pions?

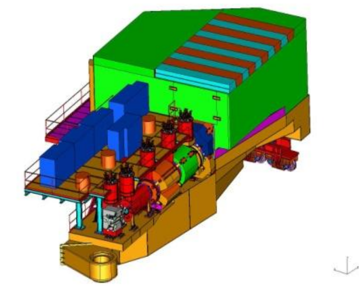
Kaons and pions together provide quasi model-independent study

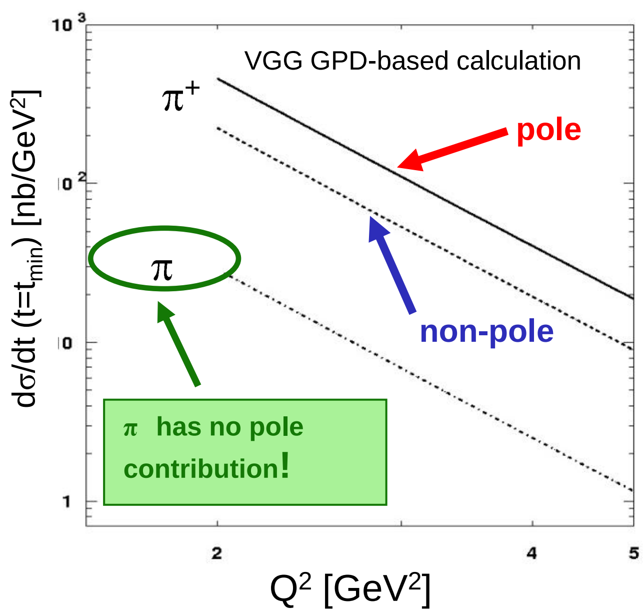
JLab 12 GeV: Non-pole Contributions and nucleon spin structure





"pole"





- Feature: pole term in GPD in pseudo-scalar meson production
- Jlab 12 GeV provides understanding of relative importance of "pole and "non-pole" contributions, which is needed to access nucleon spin structure GPD ($\tilde{H}$)

Summary

- Meson production plays an important role in our understanding of hadron structure

- JLab 12 GeV will allow rigorous tests of factorization in meson production
  - Extended kinematic reach and studies of additional systems
  - Essential prerequisite for studies of valence quark spin/flavor/spatial distributions

- Beyond JLab 12 GeV: meson production at an electron-ion collider allows for imaging of sea quarks and gluons
  - Consistent description of kinematic dependencies of all channels?