Meson production at JLab 6&12GeV and EIC

Tanja Horn

THE
CATHOLIC UNIVERSITY
of AMERICA

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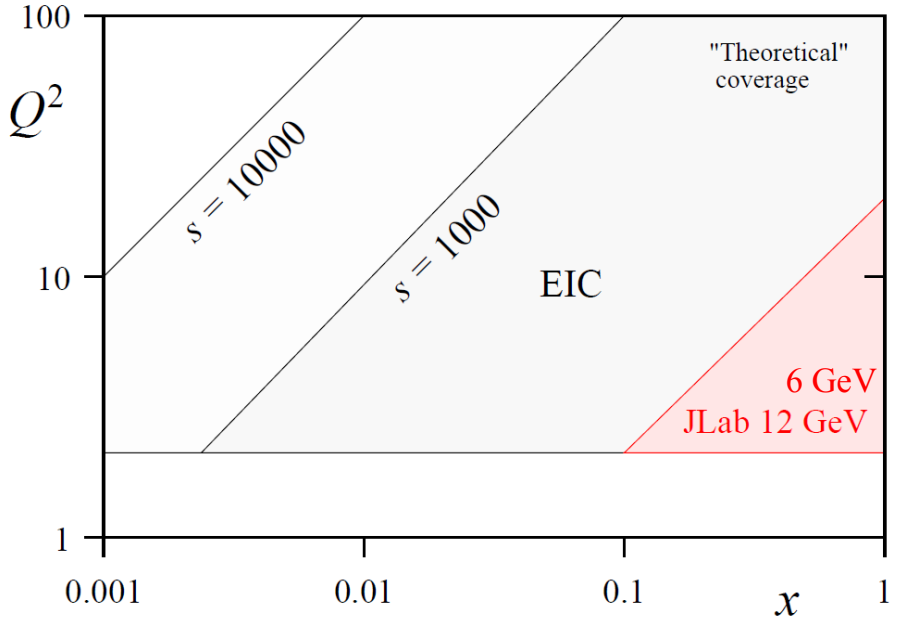
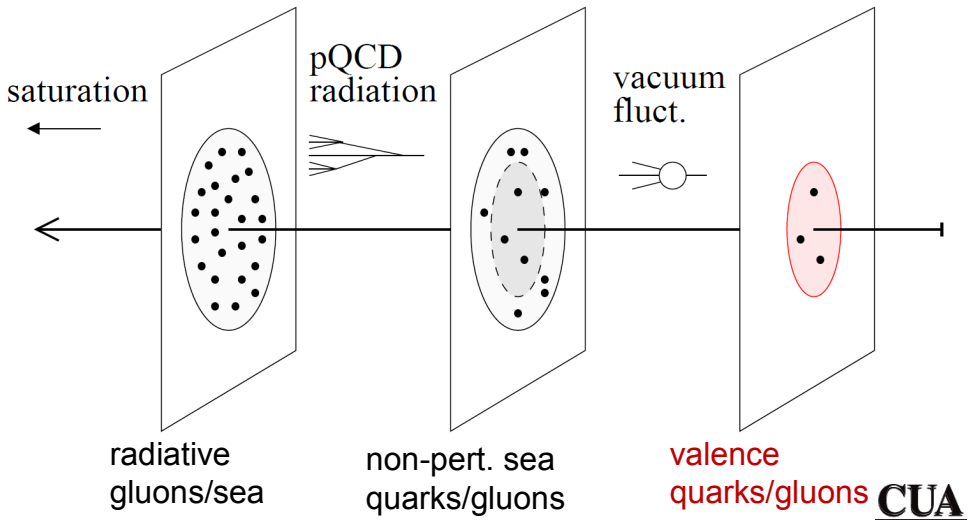
Nucleon Structure: landscape

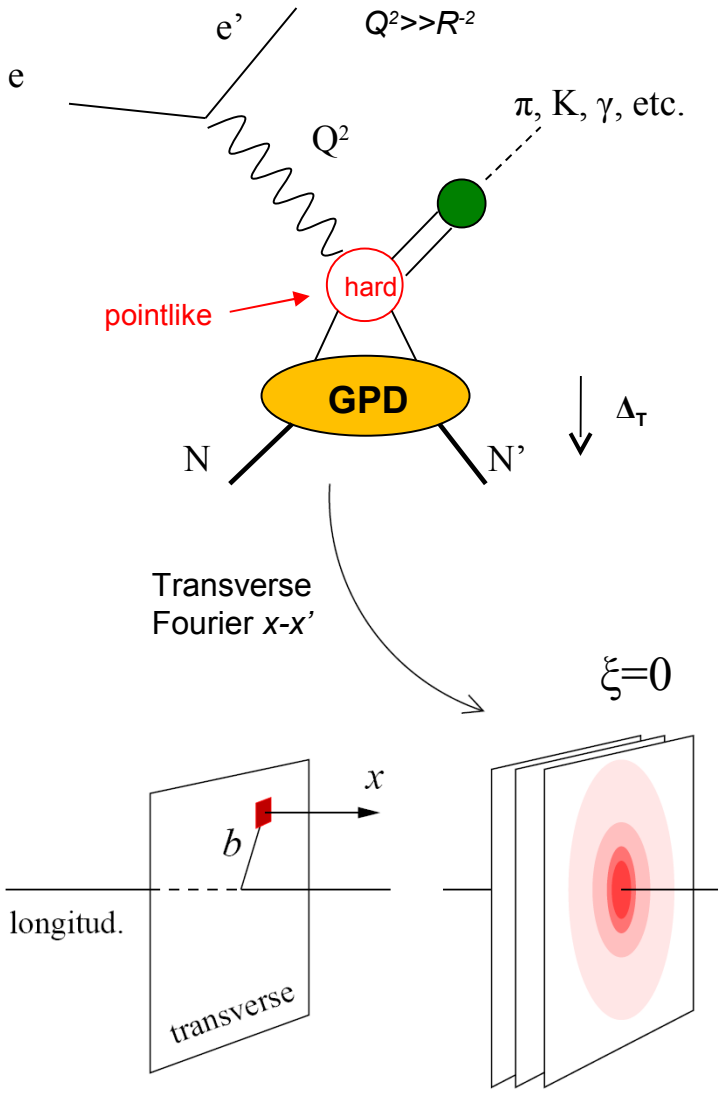
- Hadrons in QCD are relativistic many-body systems
  - Different components are probed in *e-p* scattering
- JLab 6&12 GeV: valence region
  - Quantum numbers: spin, flavor
  - Non-perturbative dynamics
  - "Source" of sea quarks and gluons
    - Vacuum structure, radiation
- Physical properties/measurements
  - Parton densities
  - Transverse spatial distributions:
    - GPDs and form factors
  - Tests of reaction mechanism
  - Orbital motion, correlations
- EIC: sea quarks, gluons





Nucleon Structure: exclusive processes

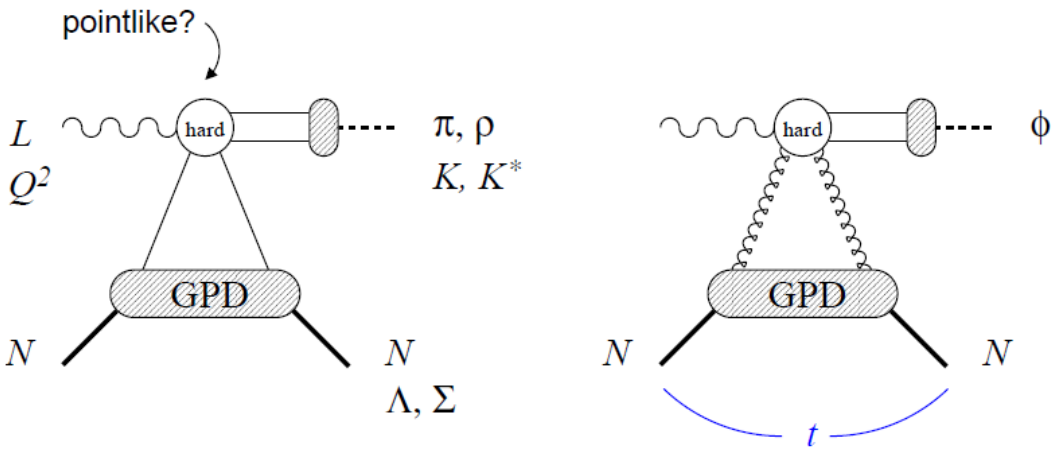
- Exclusive processes at sufficiently high Q^2 should be understandable in terms of the "handbag" diagram
  - The non-perturbative (soft) physics is represented by the GPDs
    - Shown to factorize from QCD perturbative processes for longitudinal photons *[Collins, Frankfurt, Strikman 97]*
- Physical interest in GPDs
  - **Transverse spatial distribution of partons with longitudinal momentum x:** transverse imaging of nucleon *[Burkhardt 00]*
  - Correlations in wave function
  - Moment x^{n-1} Form factor of local twist-2 spin-n operator: EM tensor, angular momentum *[Ji 96, Polyakov 02]*
- Tests of reaction mechanism
  - Model-independent features of small-size regime? Finite-size corrections?



Nucleon GPDs: spin-flavor

Deep Virtual Meson Production (DVMP)

Transverse spin/flavor distributions

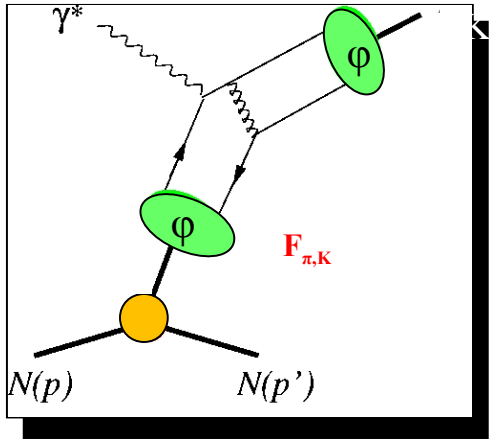


- Nucleon structure described by 4 GPDs: H, E (unpolarized), $\widetilde{H}$, $\widetilde{E}$ (polarized)
- *Quantum numbers* probe individual GPD components more selectively than DVCS
  - $\rho^o/\rho^+/K^*$ select H, E for u/d flavors
  - π,η,K select $\widetilde{H},\widetilde{E}$
- Need good understanding of *reaction mechanism*
  - *QCD factorization for mesons* is complex (additional interaction of the produced meson)

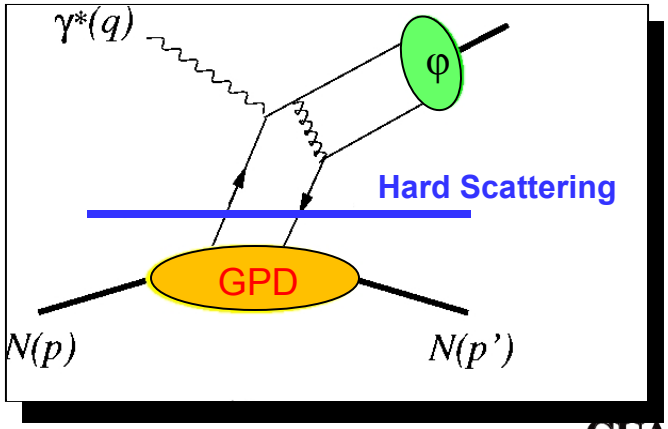
Transverse Spatial Distributions: Form Factors and GPDs

- 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

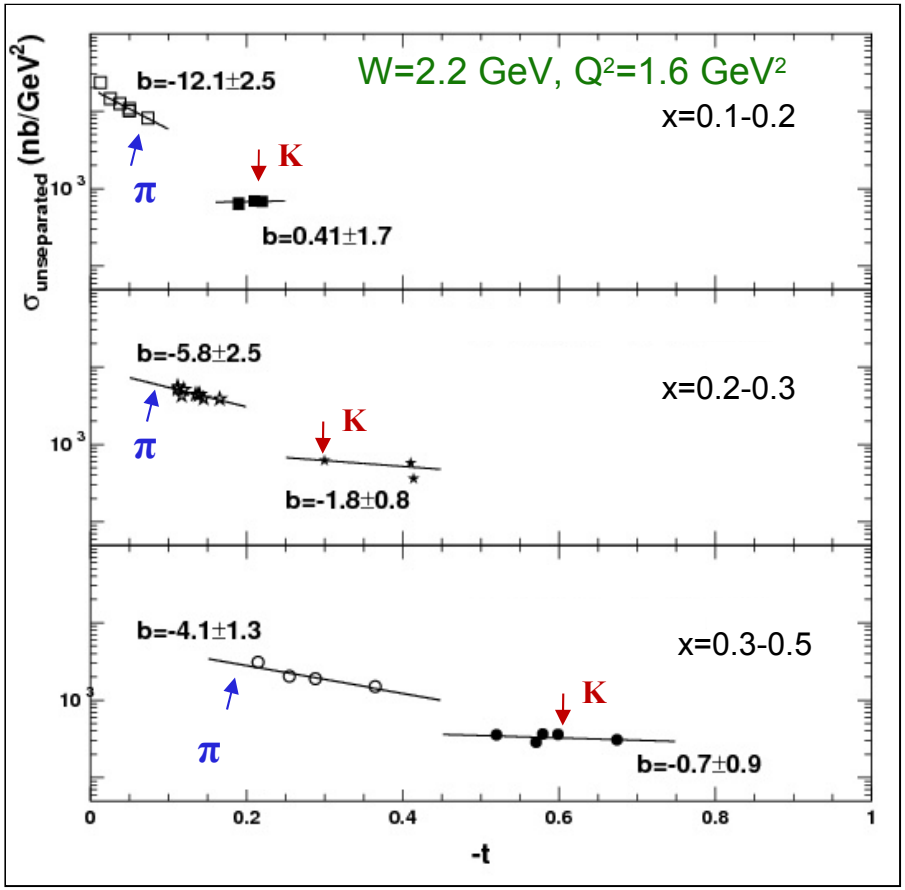


- A *comparison of pion and kaon* production data may shed further light on the reaction mechanism
  - quasi-model independent
  - more robust than calculations based on QCD factorization and present GPD models

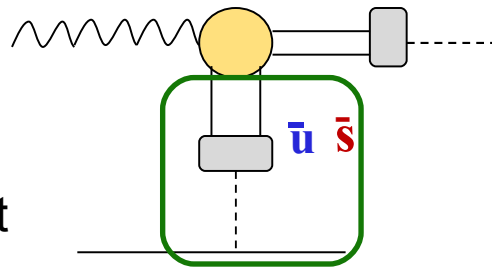


JLab 6 GeV: e^{-bt} scaling of σ_π and σ_K

Combines data from Cornell, DESY, and JLab 6 GeV

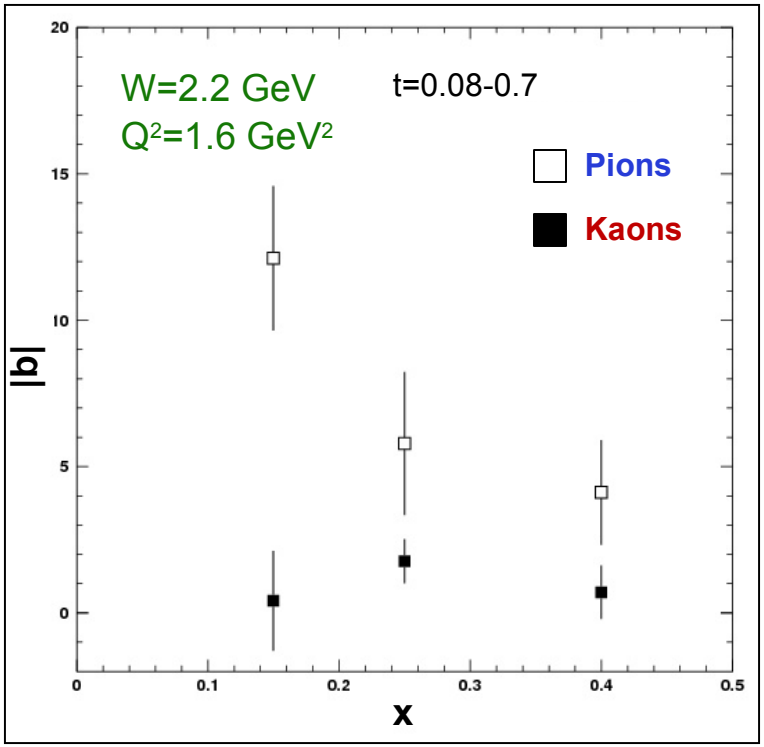


- Pion and kaon data follow an almost exponential t-dependence
  - Q^2 and t dependence does not factorize completely
- t-dependence flatter at larger x
- Pion t-dependence is steeper *at* low t than for kaons
  - pole factor $\left(m_{K,\pi}^2 - t\right)^{-1}$ gives less enhancement for kaons than pions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

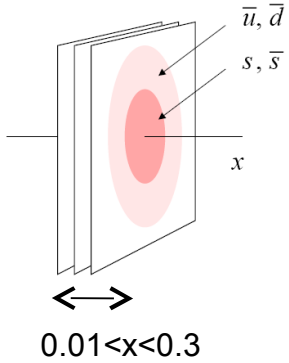


Pole factor enhances pion cross section – additional low t data would allow to interpret contribution for kaons

JLab 6 GeV: 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

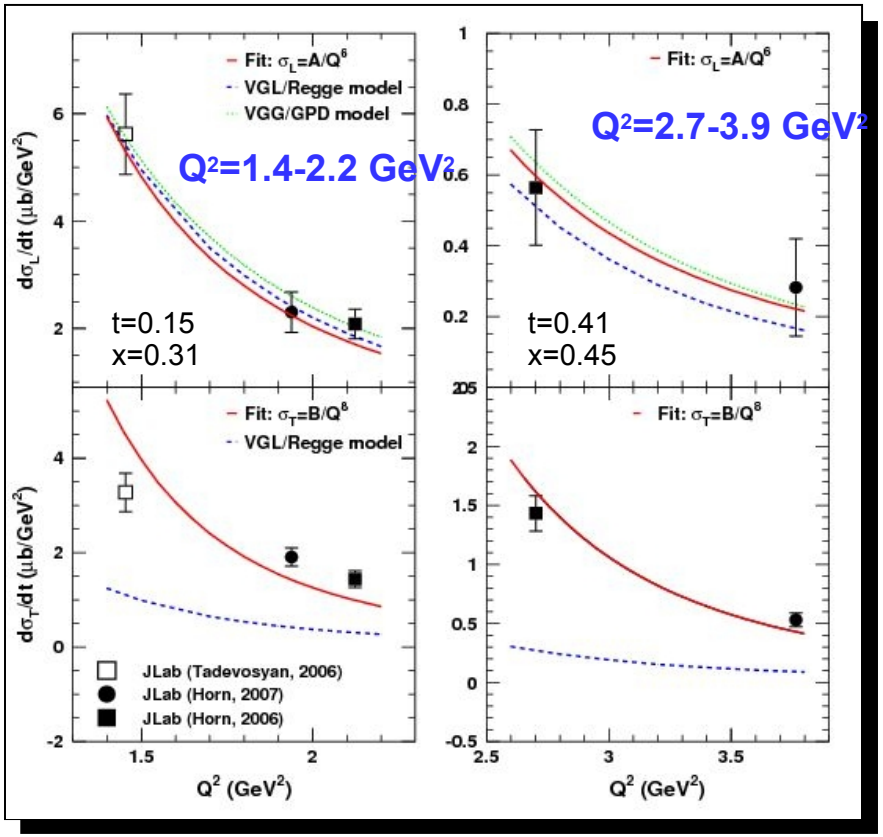


High quality *separated* data for both K and π in for $|t|<1\text{GeV}^2$ would allow for better constraining effective transverse sizes

JLab 6 GeV: Q^2 dependence of σ_L and σ_T

- Measurements of GPDs are limited to kinematics where *hard-soft factorization* applies
- A test is the Q^2 dependence of the polarized cross section:
  - $\sigma_L \sim Q^{-6}$
  - $\sigma_T \sim Q^{-8}$
  - For large Q^2: $\sigma_L >> \sigma_T$
- 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

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

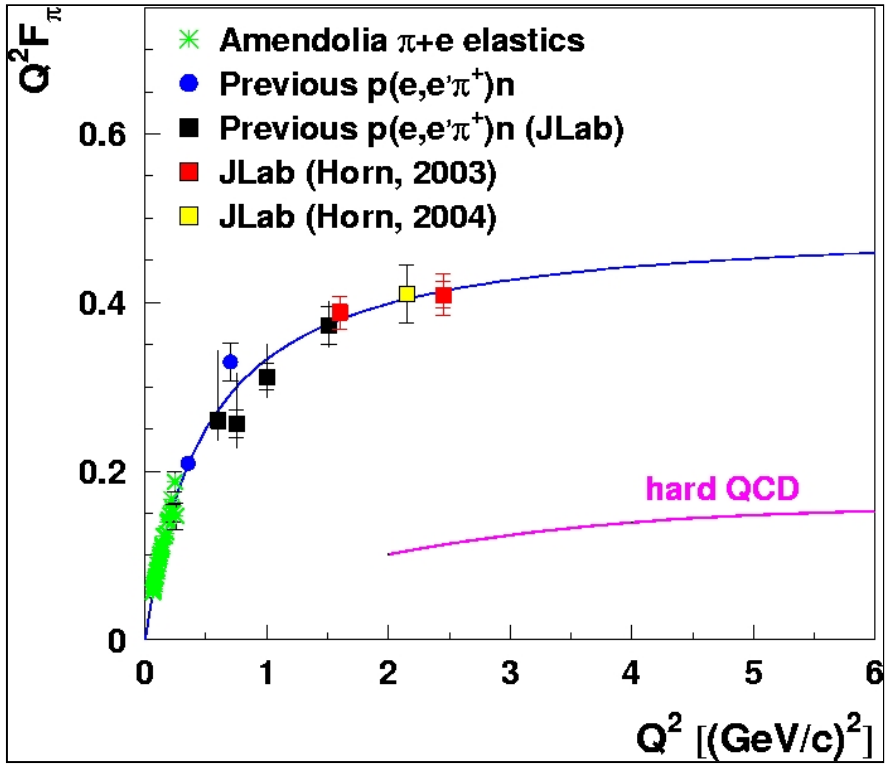


Full understanding of the onset of factorization requires an extension of the kinematic reach

JLab 6 GeV: Pion Form Factor – a similar puzzle?

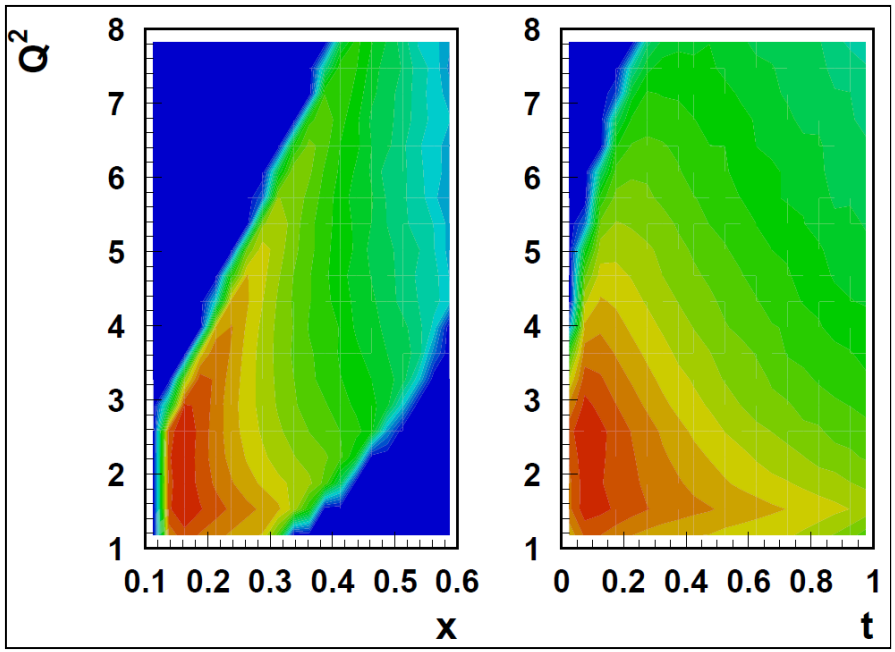
T. Horn et al., Phys. Rev. Lett. 97 (2006) 19200.
T. Horn et al., arXiv:0707.1794 (2007).

- Q^2 dependence of the pion form factor (F_π) follows prediction from perturbative QCD
  - Factorization condition seems to hold
- Different magnitudes imply that
  - Factorization condition does not hold
  - Or something else is missing in the calculation

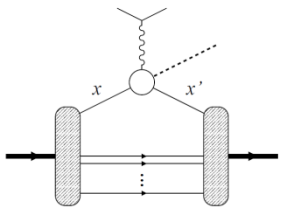


Further information on the pion puzzle through varying the system

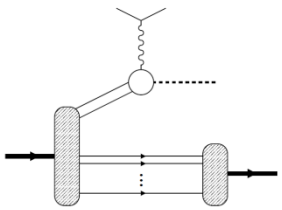
JLab 12 GeV: exclusive reactions



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



Scattering from q or $\bar{q}$



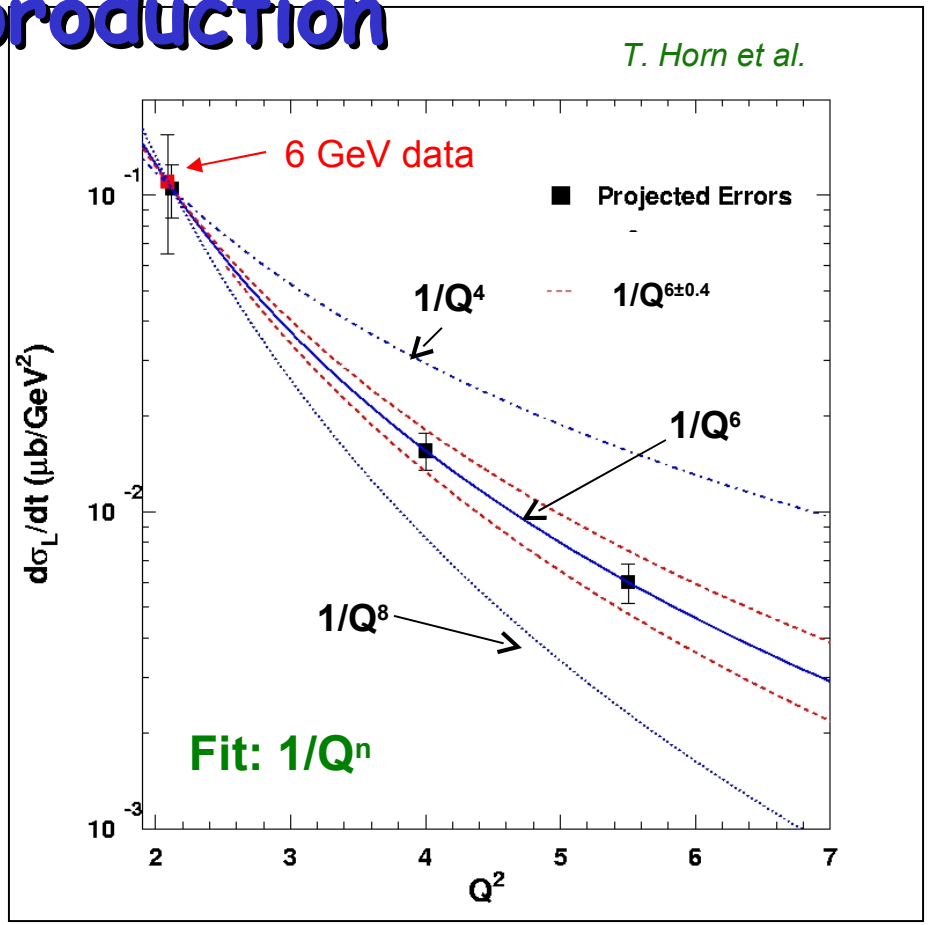
Knockout of $q\bar{q}$ pair

$s = 2E_e m_p$

- Unique features:
  - Center of mass energy, s=20.6 GeV² [minimum for MEIC is ~200 GeV²]
  - 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 $\gamma^* N \to \gamma + N$
  - Transverse charge densities from elastic form factors $\int dx\, \rho(x,b)$
  - **Transverse flavor/spin distributions from exclusive meson production** $\gamma^* N \to N + \pi, K, \rho, K^*, \phi$
- 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
- Factorization essential for reliable interpretation of results from the JLab GPD program at both 6 GeV and 12 GeV



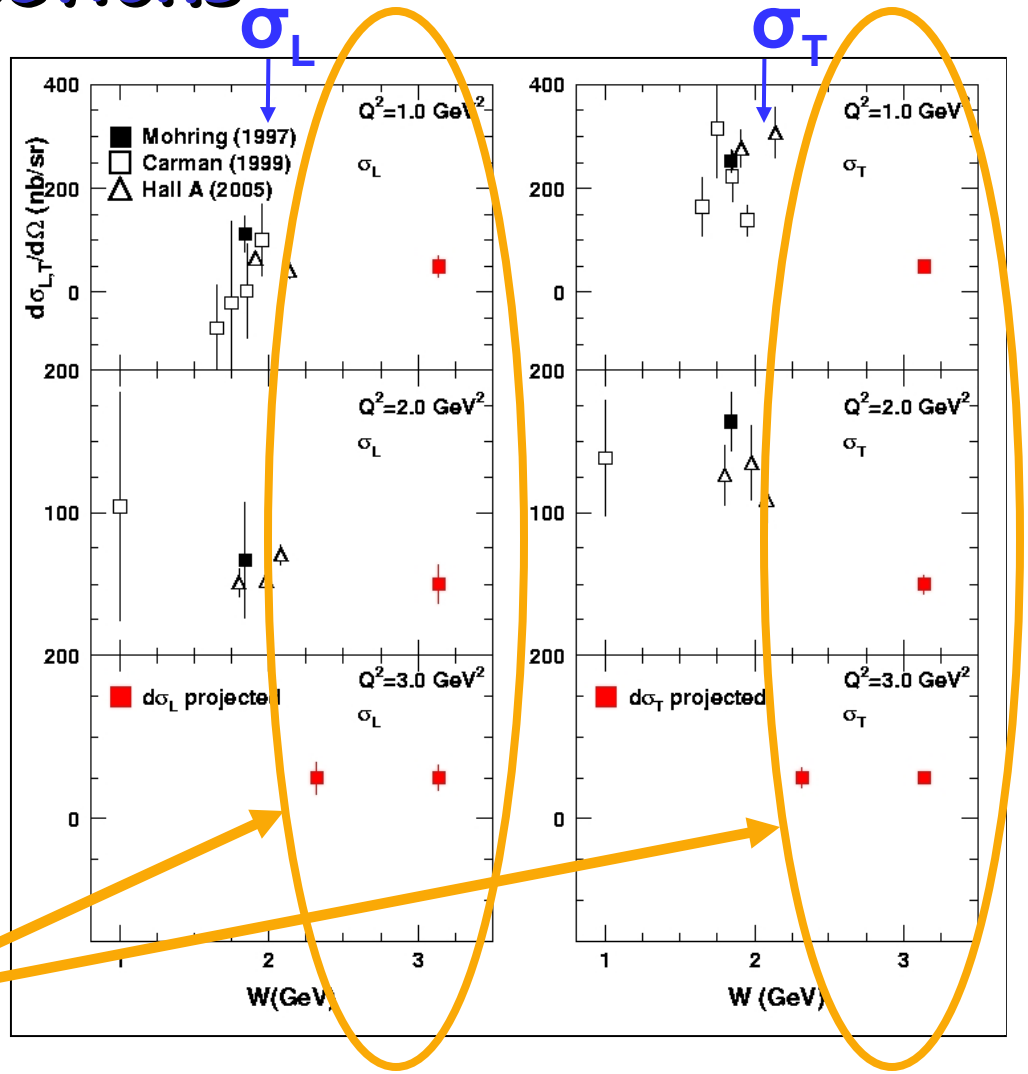
Is the partonic description applicable at JLab?

Can we extract GPDs from pion production?

JLab 12 GeV: L/T separated kaon cross sections

T. Horn et al.

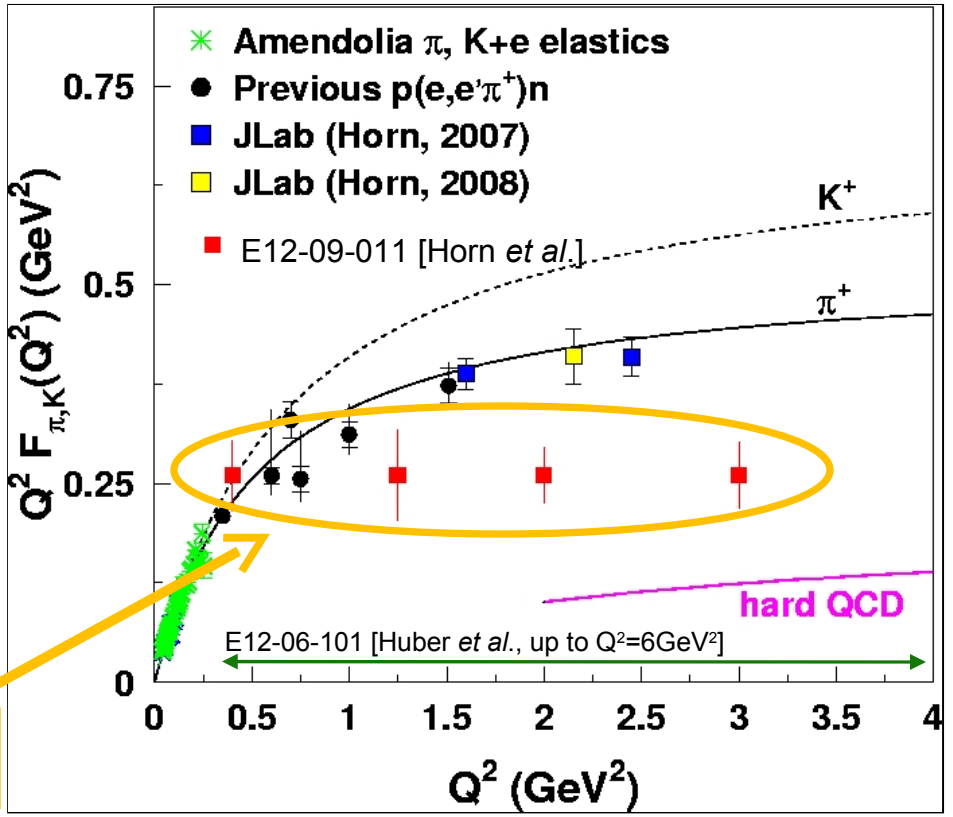
- Approved experiment E12-09-011 will provide first L/T separated **kaon** data above the resonance region
- Onset of factorization
- Understanding of hard exclusive reactions
  - QCD model building
  - Coupling constants



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

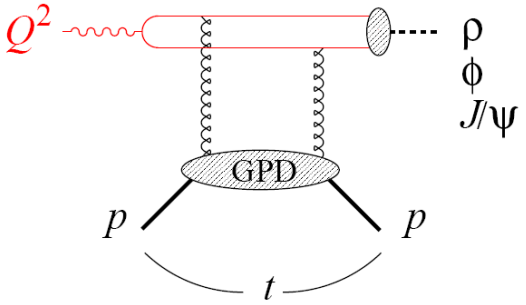
T. Horn et al., Phys. Rev. Lett. 97 (2006) 192001.

Is onset of scaling different for kaons than pions?

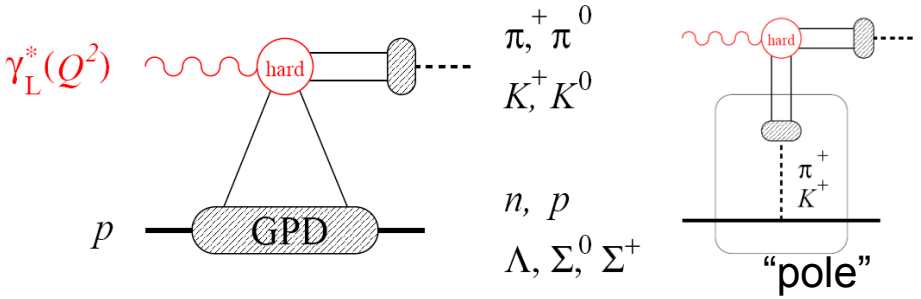
Kaons and pions together provide quasi model-independent study

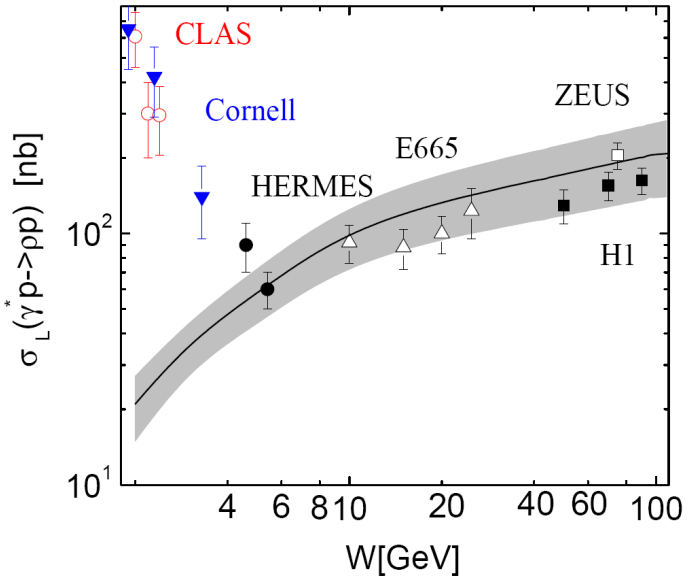
Valence Quark Imaging: JLab 12 GeV Mesons

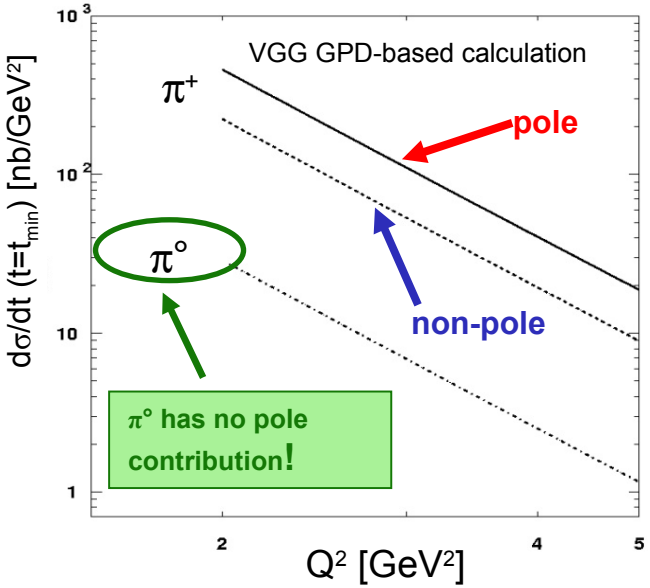
Vector Mesons



Pseudoscalar Mesons



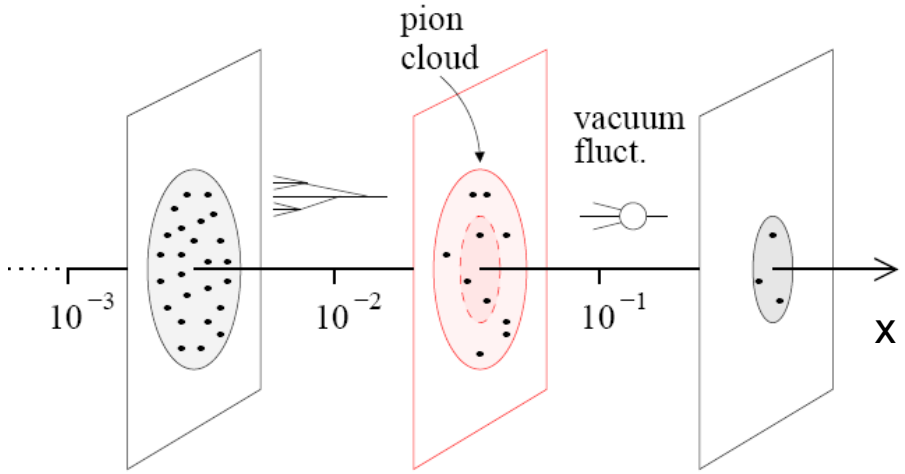




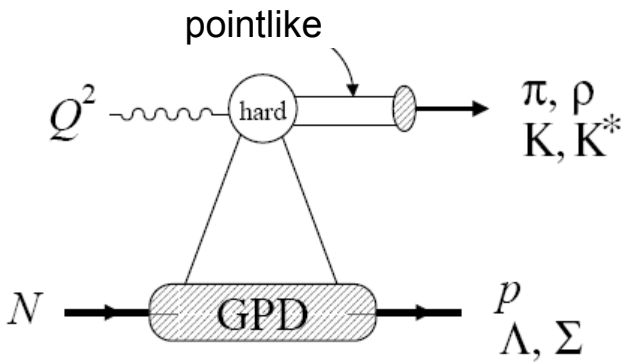
- Understanding of reaction mechanism
  - Role of qqbar pair knockout
  - Finite-size corrections

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

EIC: Quark Imaging through Meson Production



radiative sea | Non-perturbative sea quarks | valence quarks



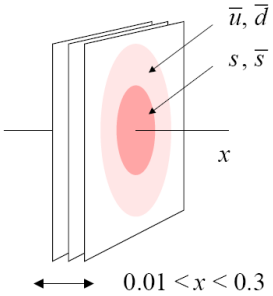
- Transverse distribution of non-perturbative sea quarks
- Flavor structure and longitudinal polarization
  - QCD vacuum structure
  - Chiral dynamics, "pion cloud"
- Exclusive meson production

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

  - Requires Q^2>10GeV^2 for dominance of "pointlike" configurations -> pQCD
  - Meson quantum numbers select spin/flavor component of GPD
  - Information about meson wavefunction: size flavor structure

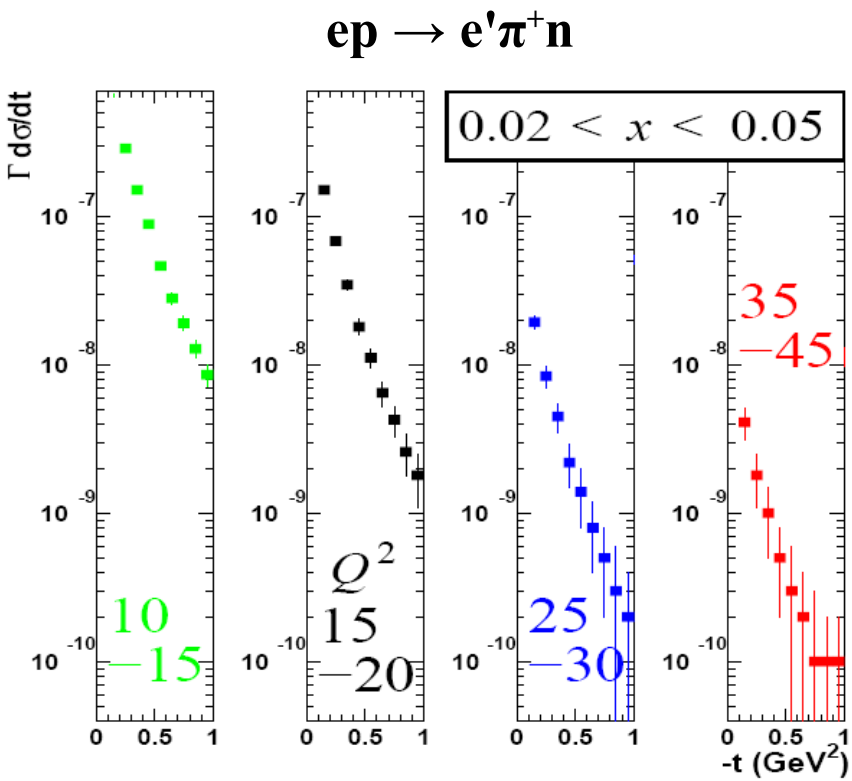
EIC: Transverse sea quark imaging

- New territory for collider!



- Spatial structure of *non-perturbative sea*
  - Closely related to Jlab 6/12 GeV
    - Quark spin/flavor separations
    - Nucleon/meson structure

- Simulation for π^+ production assuming 100 days at a luminosity of 10^{34} with 5 on 50 GeV (s=1000 GeV^2)
  - V. Guzey, C. Weiss: Regge model
  - T. Horn: empirical π^+ parameterization

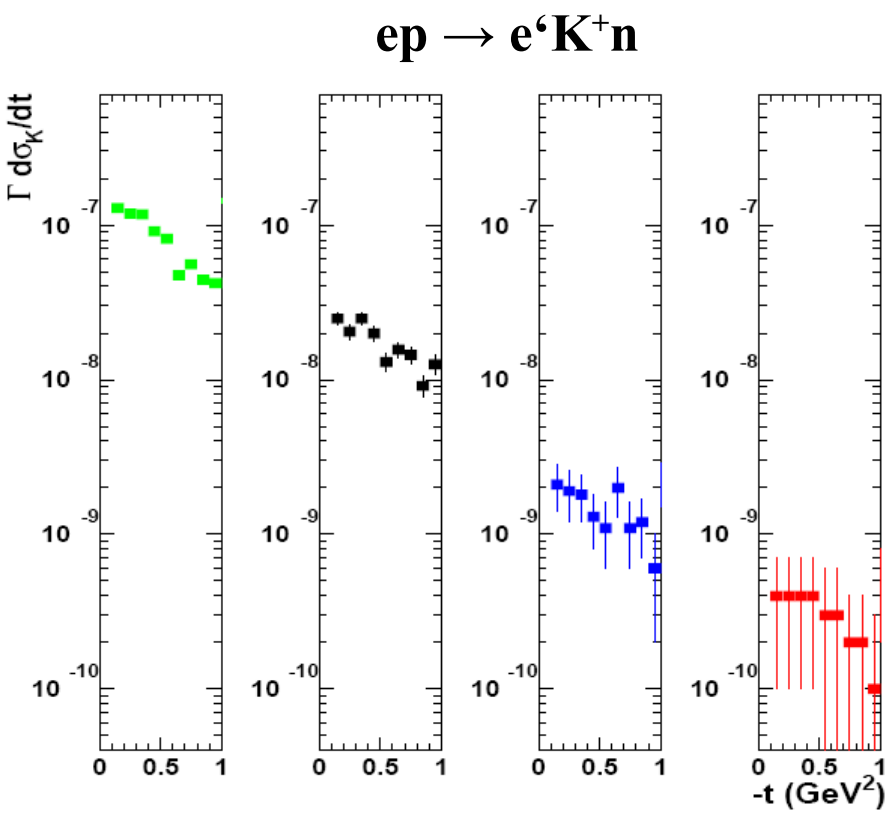


[Tanja Horn, Antje Bruell, Christian Weiss]

- Lower and more symmetric energies essential to ensure exclusivity

EIC: Transverse *strange* sea quark imaging

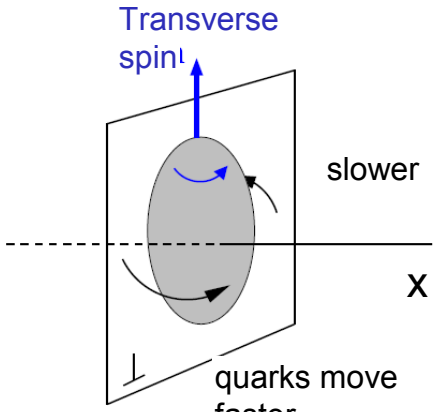
- Do strange and non-strange sea quarks have the same spatial distribution?
  - πN or $K\Lambda$ components in nucleon
  - QCD vacuum fluctuations
  - Nucleon/meson structure
- Rate estimate for $K\Lambda$ using an empirical fit to kaon electroproduction data from DESY and JLab assuming 100 days at a luminosity of 10^{34} with 5 on 50 GeV ($s=1000$ GeV^2)
  - Consistent with back-of-the-envelope scaling arguments
- Lower and more symmetric energies essential to ensure exclusivity

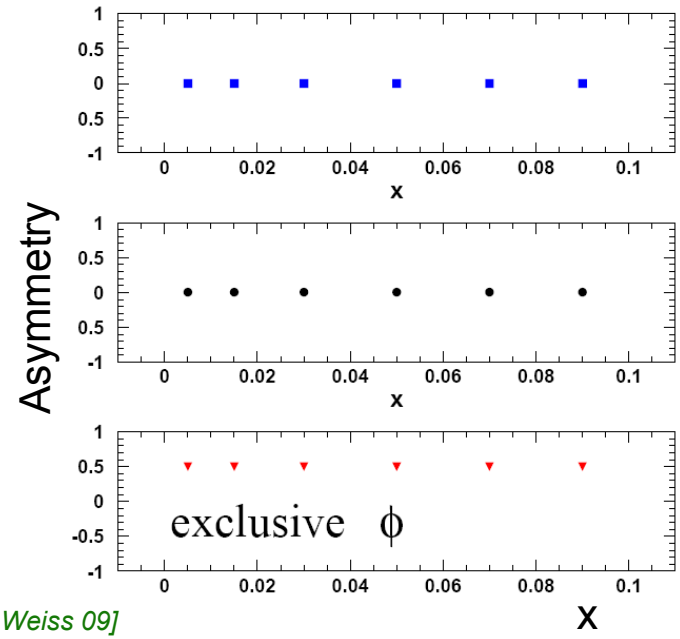


[Tanja Horn, David Cooper]

Pushes luminosity towards > 10^{34}, also at lower energy

Transverse polarization example





[Horn, Weiss 09]

- Deformation of transverse distribution by transverse polarization of nucleon
  - Helicity flip GPD *E*, cf. Pauli ff

    [M. Burkhardt]
- EIC: exclusive ρ and φ production with transversely polarized beam
  - Excellent statistics at $Q^2>10$ GeV^2
  - Transverse polarization natural for collider

$$\frac{\sigma\uparrow - \sigma\downarrow}{\sigma\uparrow + \sigma\downarrow} \propto \frac{\mathrm{Im}(\mathcal{H}\mathcal{E}^*)}{|\mathcal{H}|^2 + \mathrm{corr.}}$$

Beyond transverse imaging

- Longitudinal correlations in nucleon
  - GPDs at $x' \neq x$: correlated qqbar pairs in nucleon
    - QCD vacuum structure, relativistic nature of nucleon
  - EIC: reveal correlations through exclusive meson, γ at $x>0.1$, Q^2 dependence

…needs kinematic coverage beyond JLab 12 GeV

- Orbital motion of quarks/gluons
  - TMD and orbital motion from SIDIS
    - Major component of the EIC program
  - Connection with GPDs
    - Unintegrated distributions, Ji sum rule

…should be discussed together

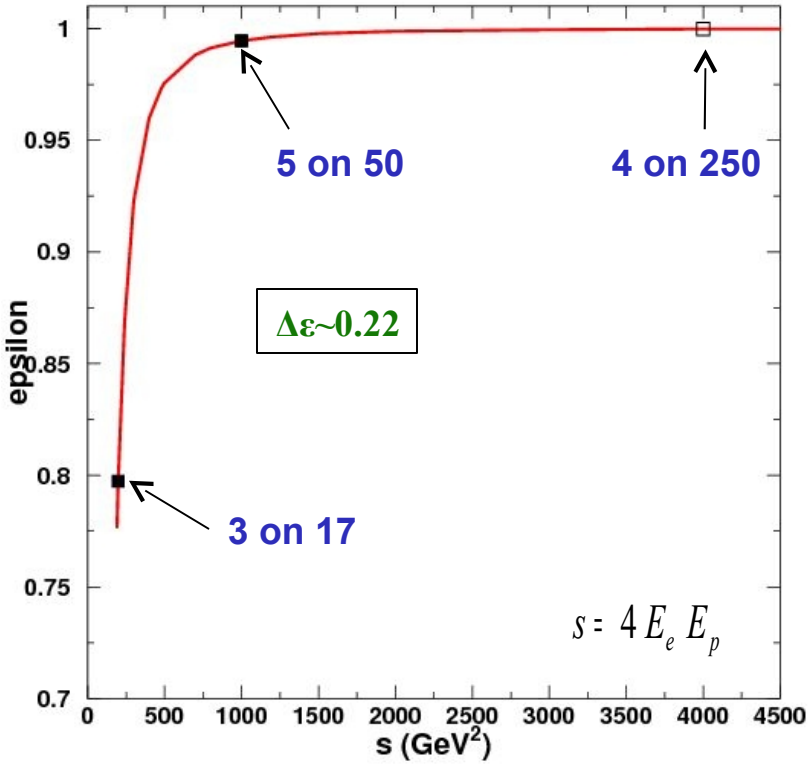
L/T separations in exclusive K^+/π^+ production

[Horn 08]

- L/T separated cross sections require:
  - Data taken at *different beam energies* (Rosenbluth)
  - *Sufficiently large Δε* (to avoid magnification of the systematic uncertainty in the separation)

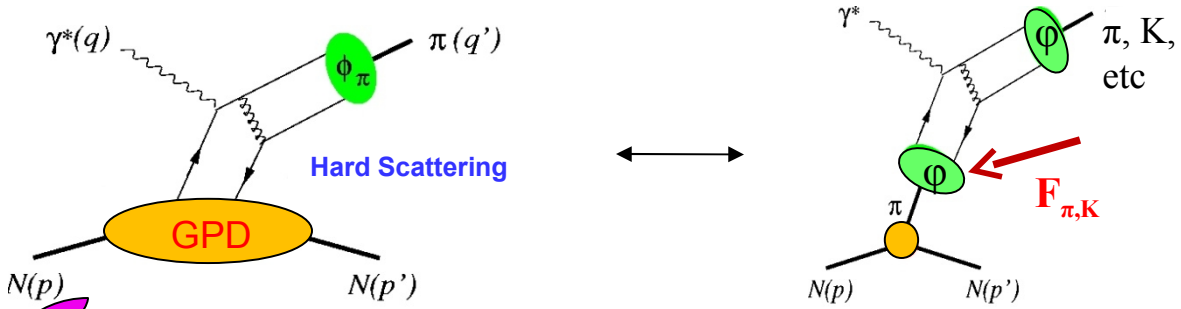
- Virtual photon polarization, ε, goes to unity at high √s

Q^2=10 GeV^2, x=0.1, -t=0.1



Requires special low energies for at least one ε point

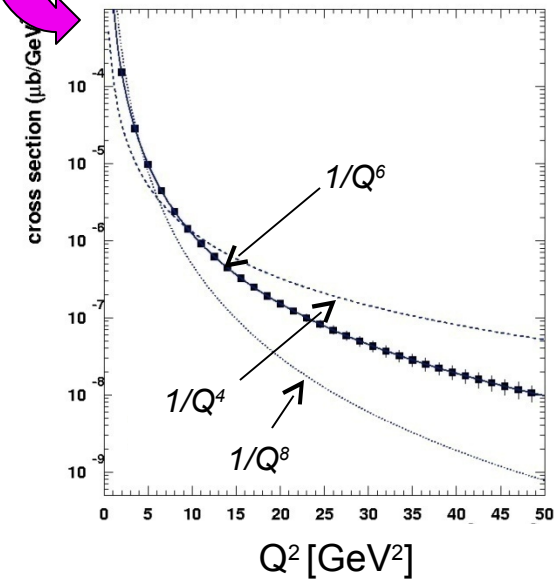
L/T separation examples



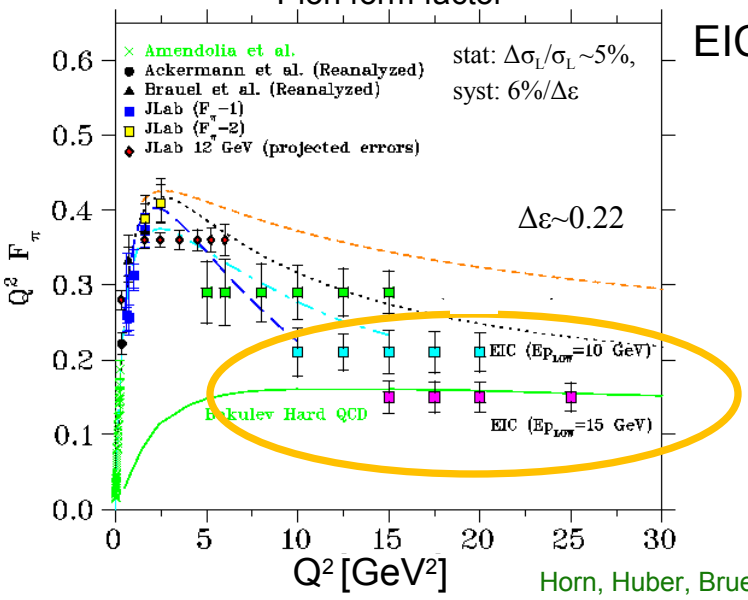
- In exclusive reactions we can study both nucleon GPDs *and* meson form factors

Pion factorization

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



Pion form factor



EIC: E_e=5 GeV, E_p=50 GeV

s=1000 GeV²

100 days

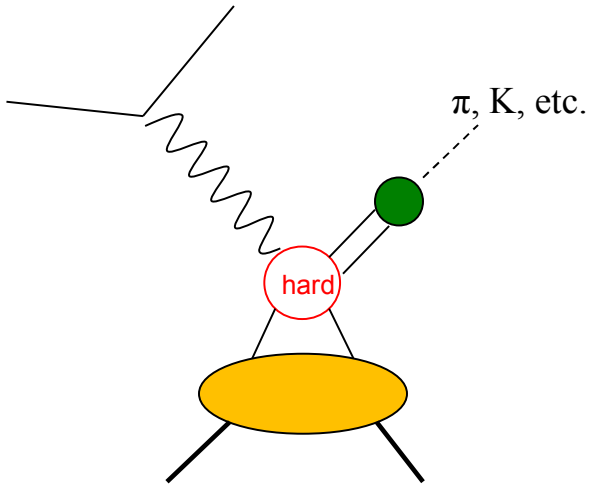
Luminosity 10^{34}

Horn, Huber, Bruell, Weiss [EICC 2008 HU]

Excellent potential to study the QCD transition nearly over the whole range from the strong QCD regime to the hard QCD regime.

Experimental Perspectives

- Exclusivity (channel selection)
- Particle identification
- Luminosity



⟹ Design of detector/Interaction Region (IR)

⟶ P. Nadel-Turonski talk

Deep Exclusive – meson kinematics

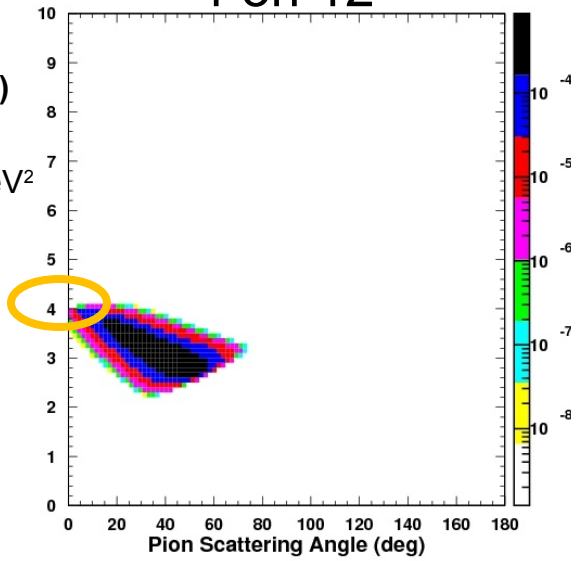
4 on 12

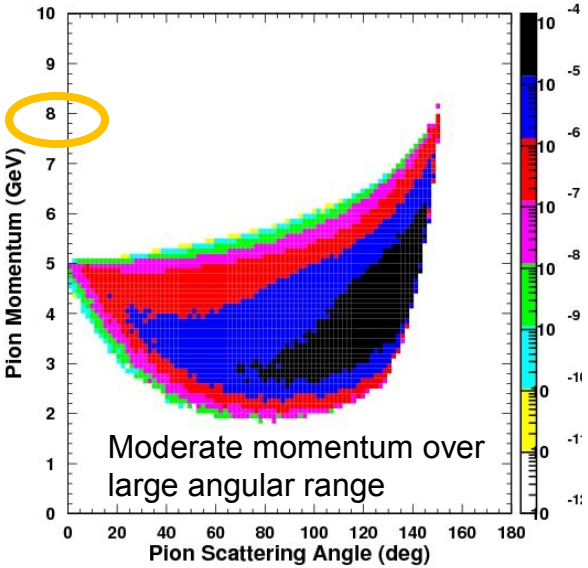
5 on 50

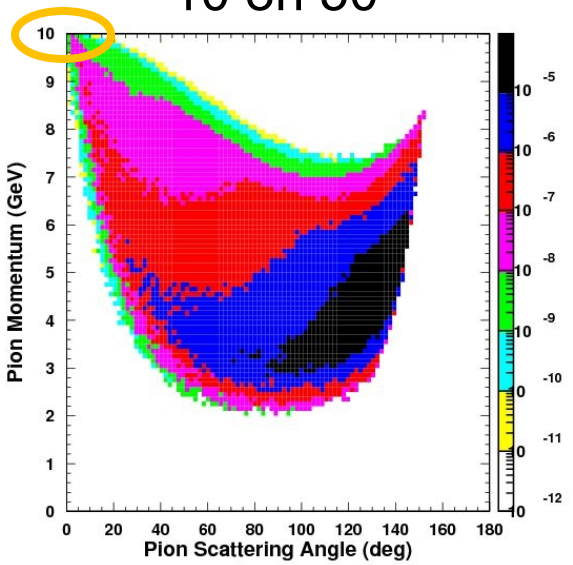
10 on 50

P (GeV/c)

$Q^2>10GeV^2$







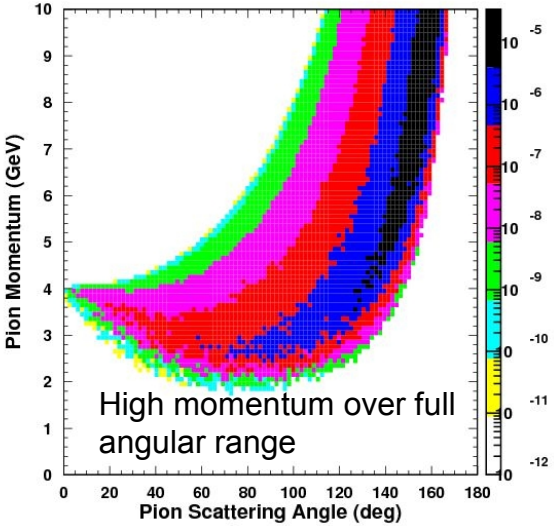
[Tanja Horn]

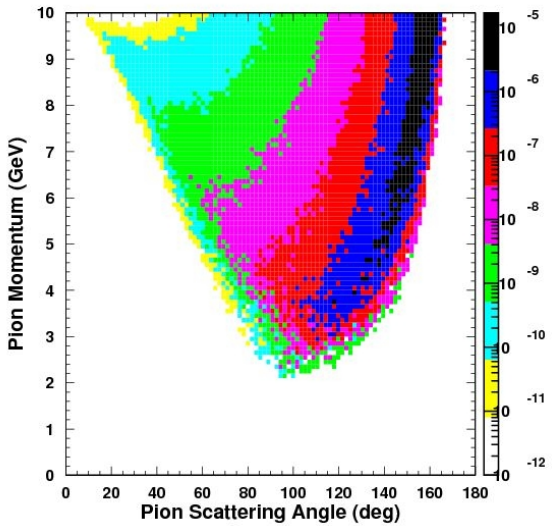
$ep \rightarrow e'\pi^+n$

4 on 250

10 on 250

P (GeV/c)

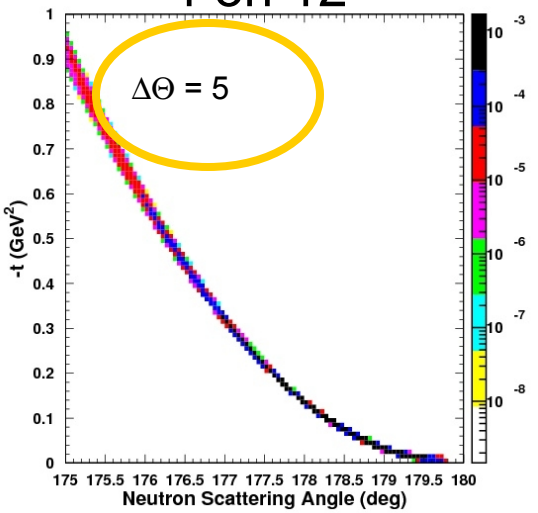




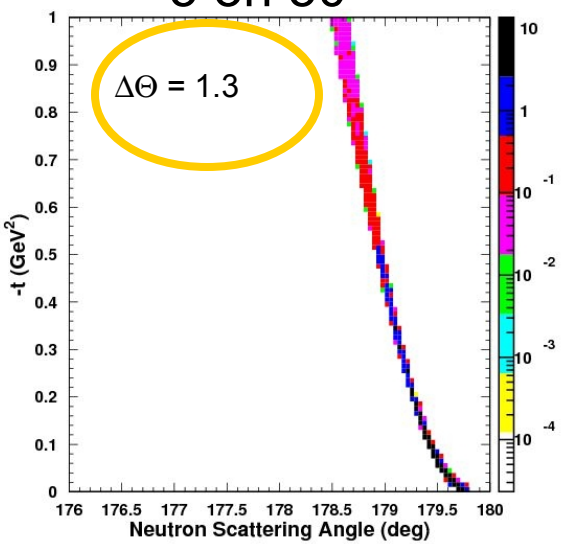
More symmetric kinematics improve detector *acceptance* (hermeticity), particle identification, and resolution (momentum and angular).

Deep Exclusive – recoil baryon kinematics

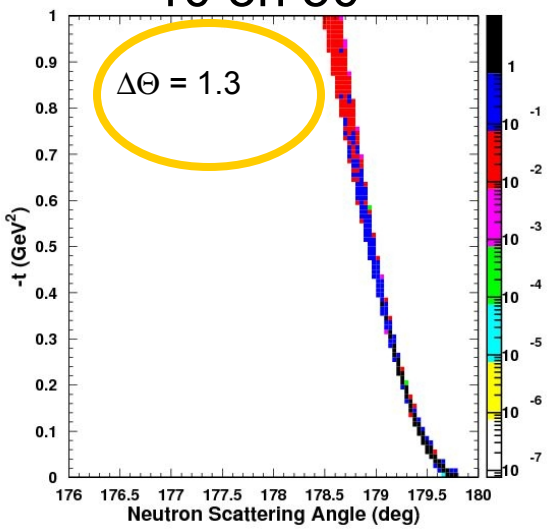
4 on 12



5 on 50



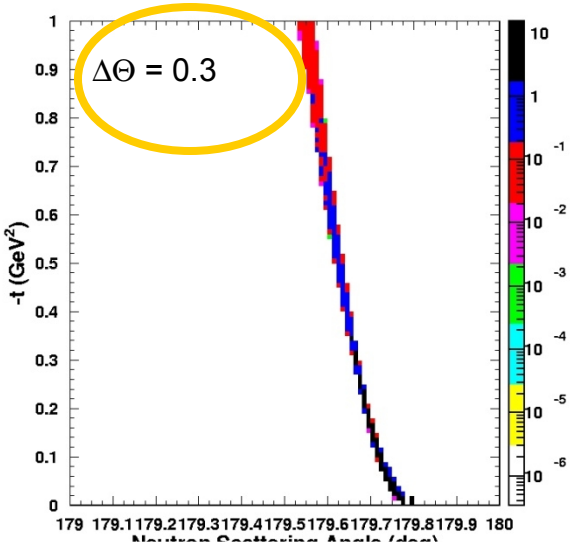
10 on 50



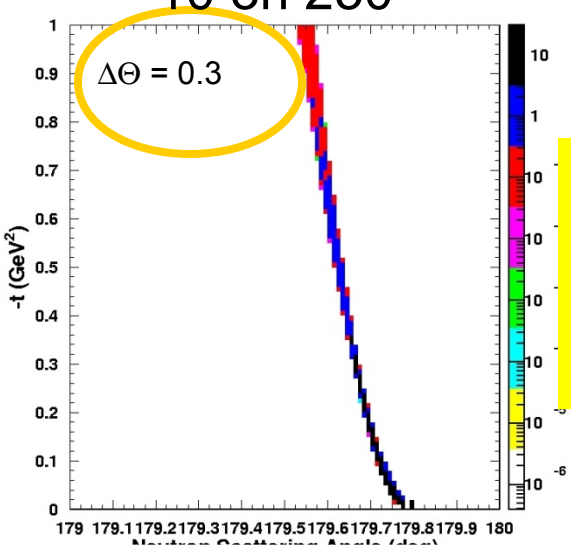
Want 0 < t < 1 GeV

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

4 on 250



10 on 250



$\delta t/t \sim t/E_p$
→ lower E_p better

[Tanja Horn]

Exclusive Meson Production Perspectives

- Energies
  - More symmetric energies favorable for exclusive meson production
  - Lower energies essential for ε range in pseudoscalar L/T separations (pion form factor)
- Kinematic reach
  - Need Q^2>10 GeV^2 (pointlike configurations)
  - *x* range between 0.001 and 0.1 overlapping with HERA and JLab12 GeV
  - *s*-range between *200 and 1000 GeV^2 (L/T separations)*
- Luminosity
  - Non-diffractive proceses (exclusive π and *K* production) require high luminosity for low rates, differential measurements in *x, t, Q^2*
  - Kaons push *luminosity >10^{34}*
- Detection
  - *Recoil detection* for exclusivity, should detect *down to 0.5 deg*

Summary

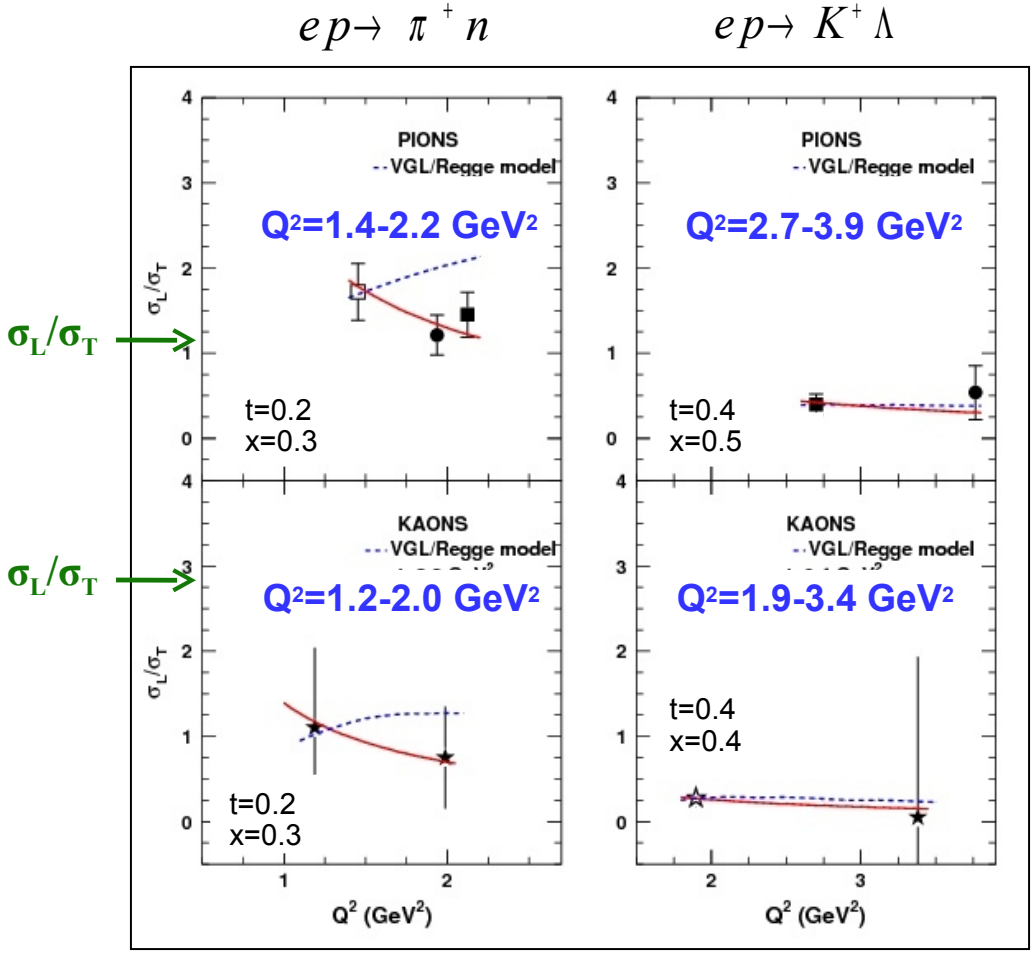
- The EIC is an excellent tool to access nucleon structure

- JLab 6&12 GeV: valence quarks
  - Main focus: valence quark imaging with DVCS
  - Also initial deep exclusive meson production studies

- EIC: gluon and sea quarks
  - Transverse gluon and sea quark imaging through deep exclusive meson production

JLab 6 GeV: Q^{-n} scaling of K and π σ_L/σ_T

- Difficult to draw a conclusion from current π^+, K^+ σ_L/σ_T ratios
  - Limited W and Q^2 coverage
  - Uncertainties from scaling in x, t



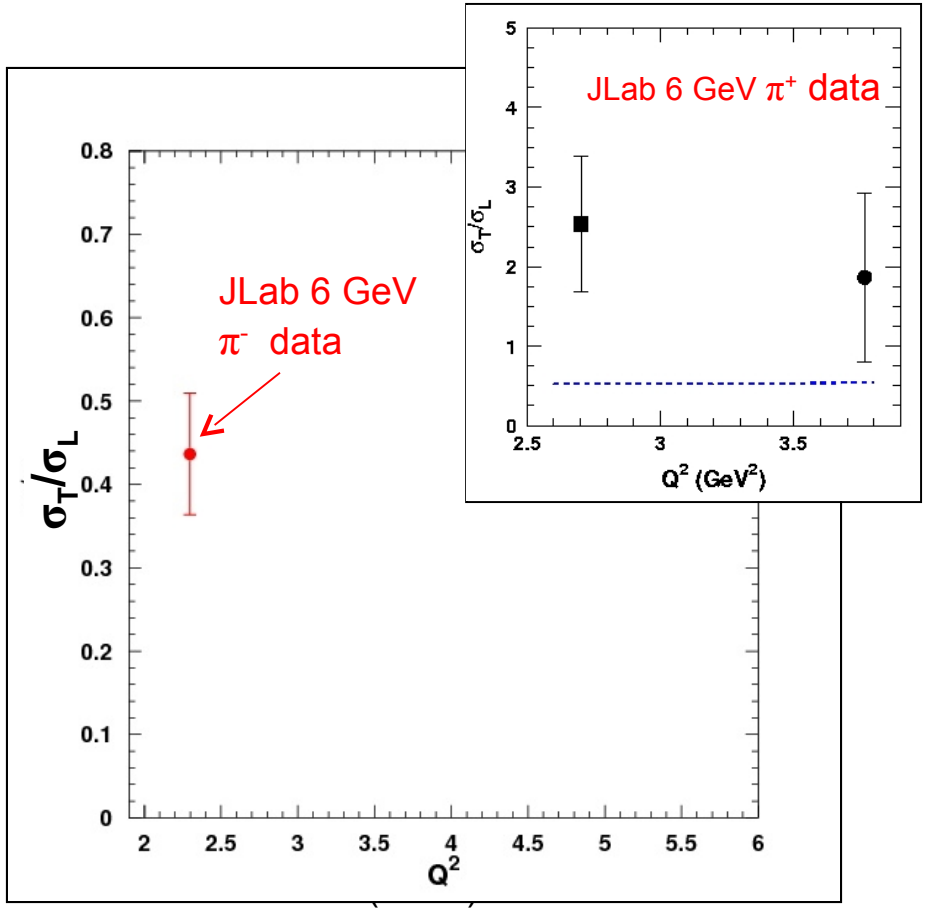
High quality σ_L and σ_T data for both kaon and pion would provide important information for understanding the meson reaction mechanism

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