Hard Exclusive Pion Production at 12 GeV

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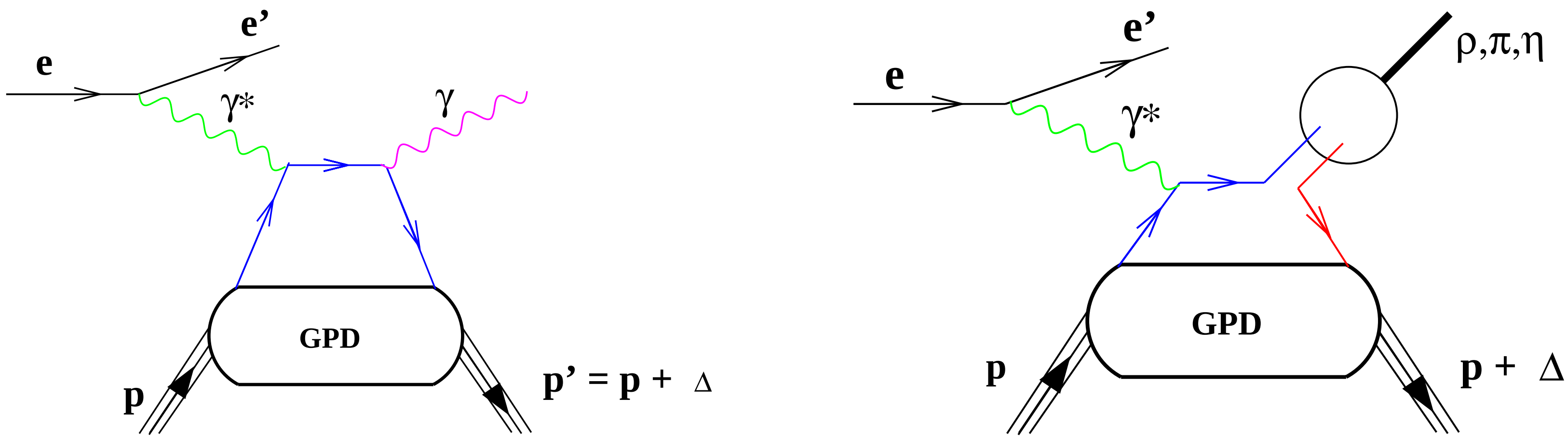
- Motivation: Soft-Hard Factorization, GPDs
- Factorization Studies
- Transverse Target Asymmetry
- Summary

Generalized Parton Distributions



- A major initiative for the 12 GeV upgrade is a program of Deep Exclusive Measurements to constrain GPDs
- GPDs may give us access to:
  - Orbital angular momentum in the nucleon
  - 3D pictures of the nucleon

Leading Twist GPDs

- At leading twist, 4 independent GPDs for each quark, gluon type
- x is the light cone momentum fraction of struck parton ($x \neq x_B$)
- $t=\Delta^2$, momentum transfer to nucleon
- ξ defined by
  $\Delta^+ = -2\xi(p+\Delta/2)^+$

$H^{q,g}(x,\xi,t)$ spin avg no hel. flip	$E^{q,g}(x,\xi,t)$ spin avg helicity flip
$\tilde{H}^{q,g}(x,\xi,t)$ spin diff no hel. flip	$\tilde{E}^{q,g}(x,\xi,t)$ spin diff helicity flip

Longitudinal fraction of the momentum transfer, t parameterizes the skewedness

GPD "Measurements"

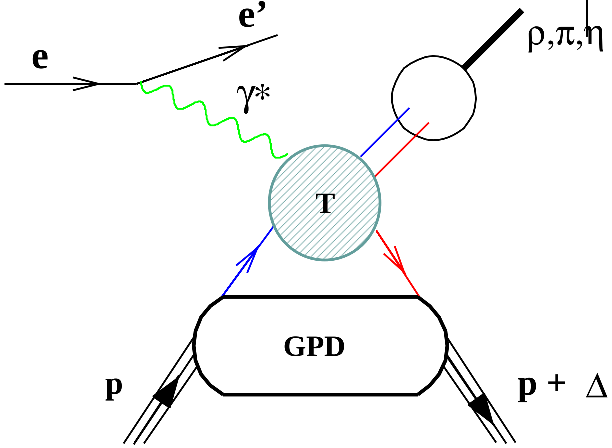
- GPDs are not observables – they are a framework that allows us to describe a wide variety of processes (DIS, elastic scattering, exclusive reactions)

- We already have constraints on GPDs from
  - DIS: $H(x,0,0) = q(x)$ and $\tilde{H}(x,0,0) = \Delta q(x)$
  - Elastic scattering: $\int dx\ x\ H(x,\xi,t) = F_1(t)$, etc.

- To get new information from GPDs, we need a program that will measure …
  - a variety of exclusive processes (vector mesons, DVCS, pseudo-scalar mesons)
  - a broad range of phase space (t, x_B)

Factorization in Hard Exclusive Reactions

- To say anything about GPDs, we must be confident we are in a regime where soft-hard factorization applies (large Q^2)



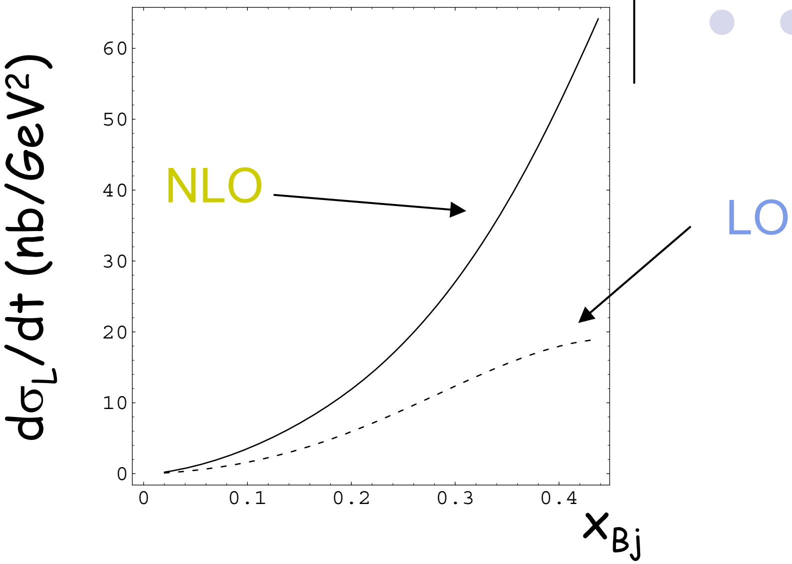
- Higher order corrections may be large for absolute cross sections for $Q^2 < 10$ GeV^2

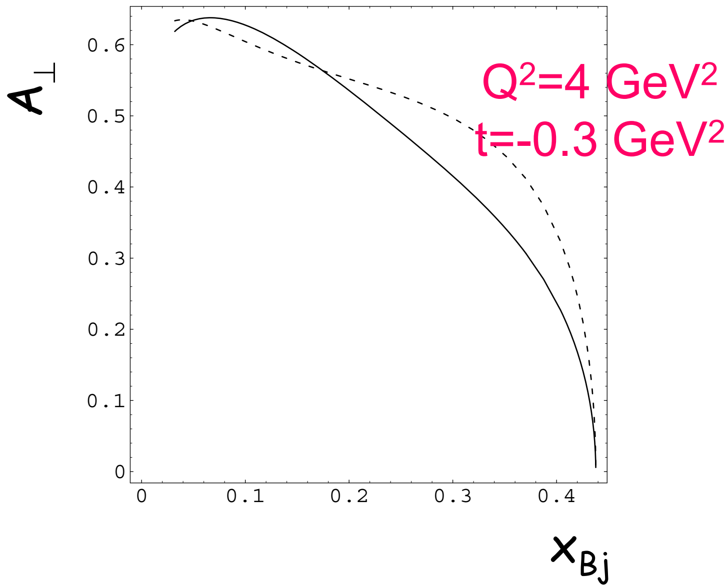
- Ratios have a better chance of exhibiting precocious factorization – higher order effects in numerator and denominator "cancel"

- Asymmetries (DVCS beam-spin and beam-charge asymmetry) and cross section ratios (σ_π/σ_η) are our best chance for being in the factorization regime at JLab energies

Exclusive π^+ Production at NLO

- Belitsky and Müller GPD based calc. of $\pi+$ production to NLO (Phys Lett B 513, 349)
  - Even at Q^2=10 GeV^2, NLO effects can be large, but cancel in the asymmetry, $A_\perp$
  - At Q^2=4, higher twist effects even larger in σ_L, but still cancel in asymmetry (CIPANP 2003)
- This cancellation of higher order effects known as precocious factorization





Deep Exclusive Reactions at 12 GeV

- JLab Program of Deep Exclusive Reactions must have 2 main components
  - Experiments aimed at optimal extraction of information about GPDs – asymmetries, cross section ratios, etc.
  - Experiments aimed at understanding the onset (or lack thereof) of Soft-Hard Factorization
    - This can, and must be included as part of the first sub-set of measurements (Q^2 dependence of asymmetries for example)
    - Absolute cross sections will yield a more sensitive test
      - Note that factorization only proven for longitudinal (transverse) meson (photon) production

- Experiments aimed at understanding or measuring the onset of factorization are not just a means of justifying GPD measurements, but are interesting in their own right

Test of Soft-Hard Factorization in Exclusive π^+ Production

- In the factorization regime pion electroproduction should scale like

$$\frac{d\sigma_L}{dt} \propto \frac{1}{Q^6}$$

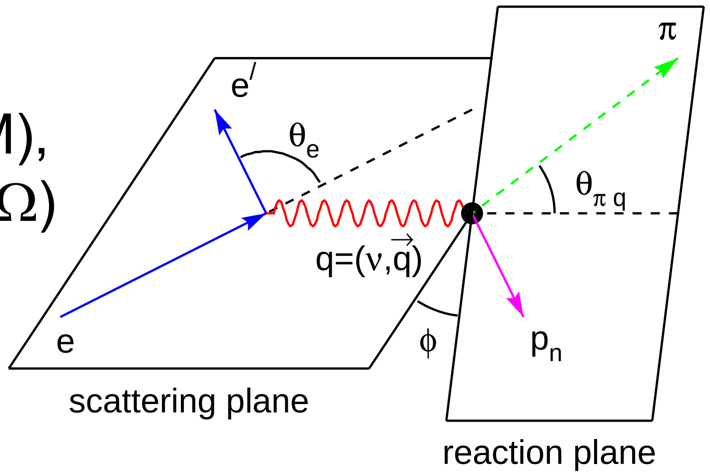
at fixed x and -t

- For vector mesons σ_L can be extracted via decay angular distributions (assuming s-channel helicity conservation)
  - Well suited to large acceptance device like CLAS
- Isolation of σ_L for charged pions requires a Rosenbluth Separation

Exclusive π^+ Production – Unpolarized Cross Section

- 5-fold lab cross section can be written in terms of virtual photon flux (Γ_V), Jacobian (virtual γ, target CM), and virtual photon cross section ($d\sigma/d\Omega$)

$$\frac{d\sigma}{dE\,d\Omega_e\,d\Omega_\pi} = \Gamma_V \mathcal{J} \frac{d\sigma}{d\Omega}$$



- Virtual photon cross section can be further broken down into contributions from longitudinal and transverse photons (formalism of Bartl and Majerotto)

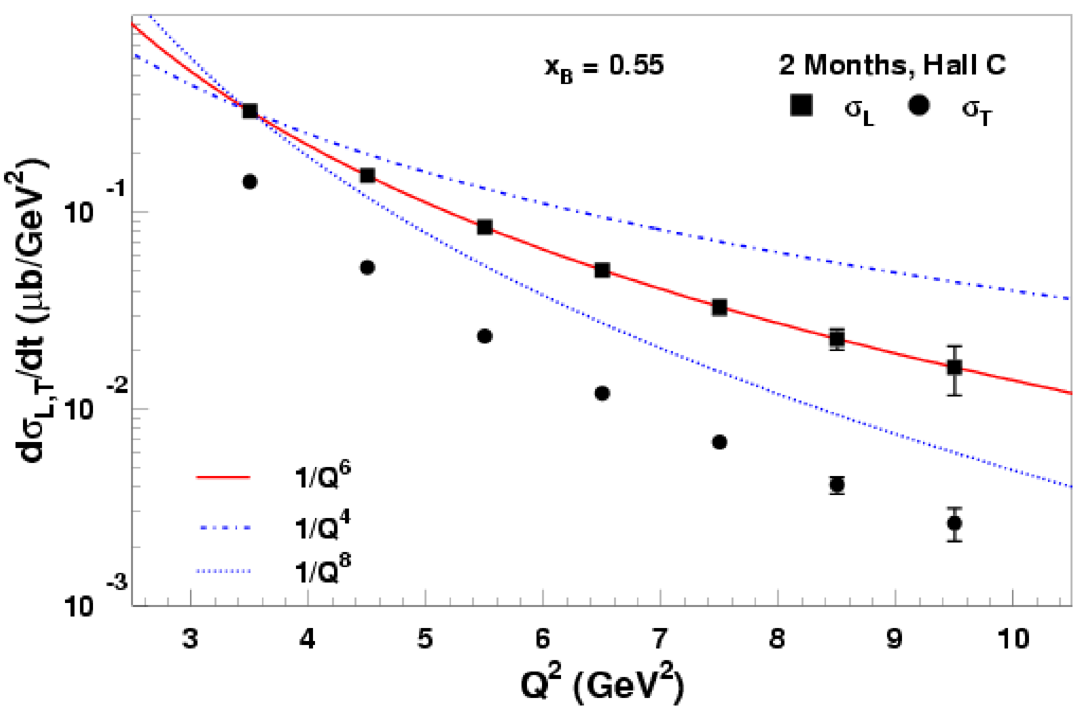
$$\frac{d\sigma}{d\Omega} = \sigma_T + \epsilon\sigma_L + \sqrt{\frac{1}{2}\epsilon(\epsilon+1)}\sigma_{LT}\cos\phi + \epsilon\sigma_{TT}\cos 2\phi$$

Q^2 Dependence of σ_L

- At fixed x= 0.55, -t = 0.5 GeV^2, we can measure Q^2 dependence of π^+ longitudinal cross section up to Q^2=9.5 GeV^2 in Hall C

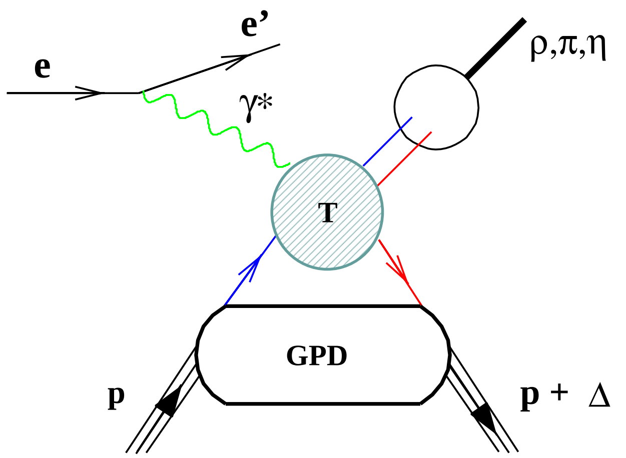
- Current estimates suggest we should expect scaling to set in at about Q^2=10 GeV^2

- Measuring deviations from scaling will help us understand how and if precocious scaling works



Factorization in Wide-Angle Processes

- Factorization has been proven for Deep Exclusive Reactions
  - Longitudinal cross sections only
  - Large Q^2, $-t << Q^2$



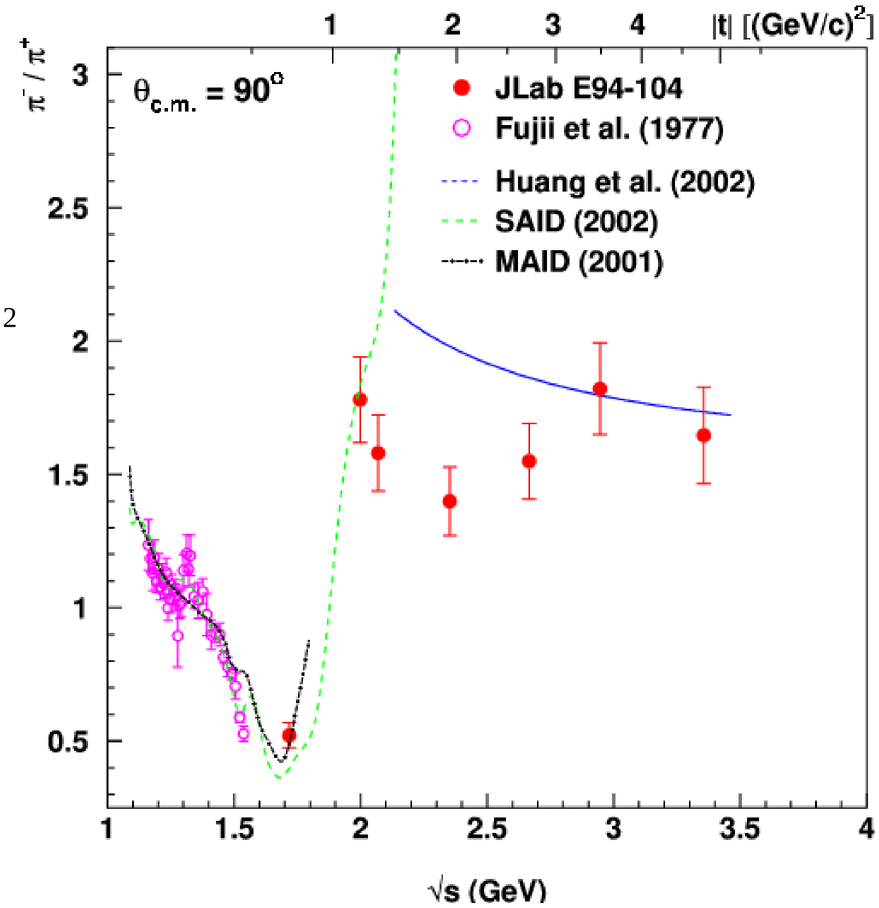
- Alternatively, factorization has also been shown to apply at small Q^2, large –t
  - Deep Exclusive Processes -> factorization holds to all orders
  - Wide-angle processes -> factorization proofs only hold to NLO (LO) for Compton scattering (meson production)
  - Longitudinal and transverse photons contribute to same twist – no factorization breakdown

Wide-angle Pion Photo-production

- One hard gluon exchange prediction for wide-angle charged pion photo-production

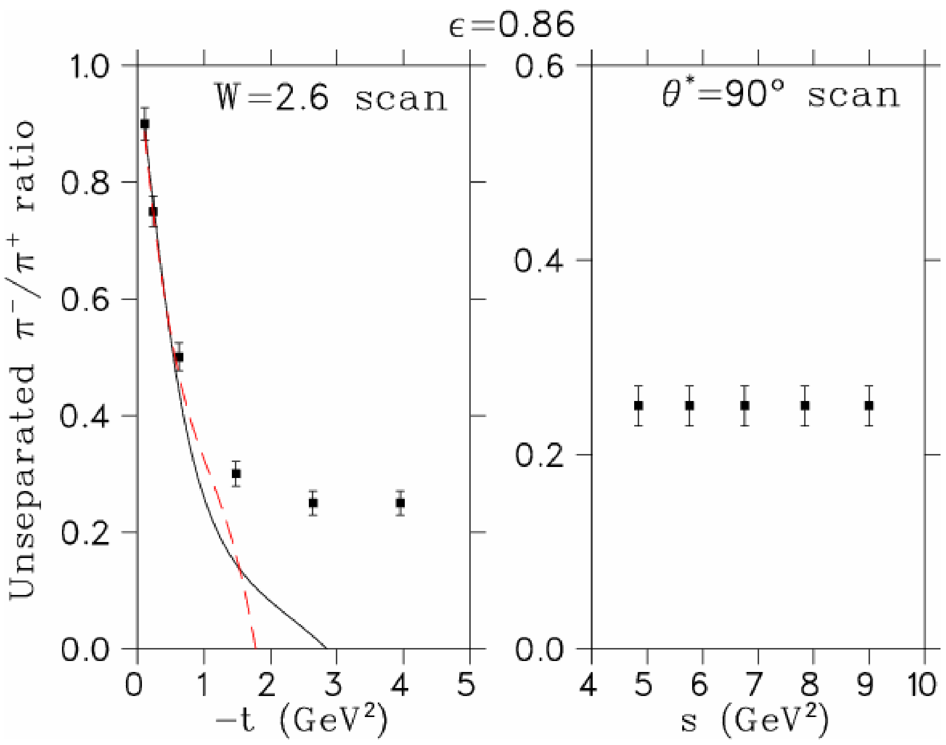
$$\frac{d\sigma(\gamma n \to \pi^- p)}{d\sigma(\gamma p \to \pi^+ n)} = \left[\frac{e_d(u-m_p^2)+e_u(s-m_p^2)}{e_u(u-m_p^2)+e_d(s-m_p^2)}\right]^2$$

- JLab E94104 results in agreement with this prediction
- Same model fails to describe absolute cross sections



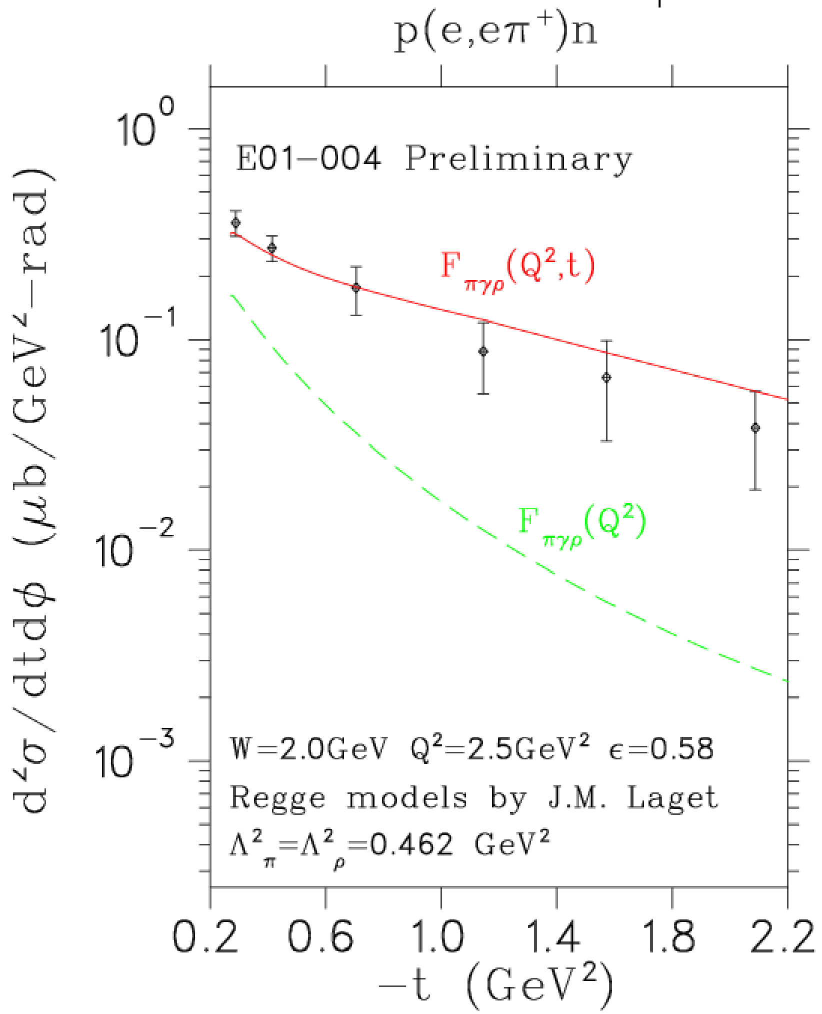
Wide-angle Pion Electroproduction

- Factorization calculations may be more accurate at Q^2=2-3 GeV^2
- With HMS-SHMS at 11 GeV, can measure –t dependence at fixed W and s dependence at fixed θ^*
- Measurements at multiple beam energies allow separation of longitudinal and transverse components



F_π-2 Test Data

- Test data taken during F_π-2 indicates that such a large –t measurement is practical with a two-spectrometer setup
- At large –t, ϕ coverage is incomplete
  - Models may help constrain values if we make good measurements at low –t
  - CLAS input may help



GPDs from Charged Pion Electroproduction

- The (longitudinal) pion electroproduction amplitude involves linear combination 2 contributions

$$A_{\pi^+ n} = -\int_{-1}^{1} dx \left(\tilde{H}^u - \tilde{H}^d \right) \left(\frac{e_u}{x - \xi + i\varepsilon} + \frac{e_d}{x + \xi - i\varepsilon} \right)$$

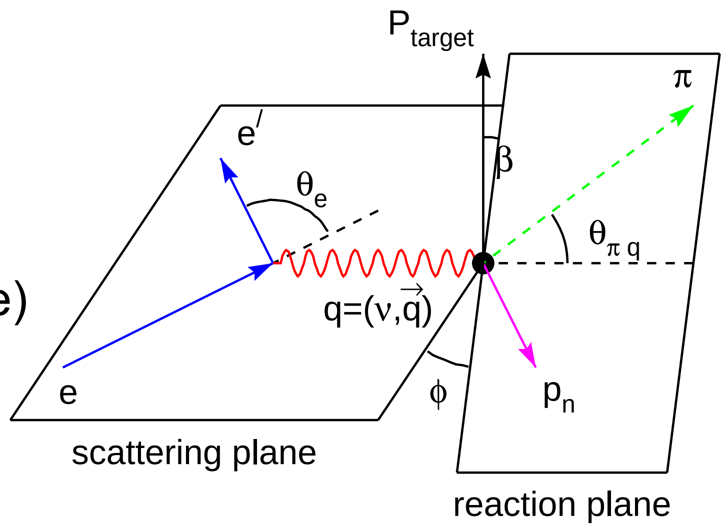
$$B_{\pi^+ n} = -\int_{-1}^{1} dx \left(\tilde{E}^u - \tilde{E}^d \right) \left(\frac{e_u}{x - \xi + i\varepsilon} + \frac{e_d}{x + \xi - i\varepsilon} \right)$$

- Two key observables
  - Longitudinal cross section: $\sigma_L \sim c_1 |A|^2 + c_2 |B|^2 + c_3 \,\mathrm{Re}(A^* B)$
  - Transverse target asymmetry: $A_\perp \sim \mathrm{Im}(A B^*)$

Exclusive π^+ Production with Target (or Recoil) Polarization

$$\sigma_t = P_x\left[-\sqrt{2\epsilon(1+\epsilon)}\sin\phi\,\sigma_{LT}^x - \epsilon\sin 2\phi\,\sigma_{TT}^x\right]$$
$$- P_y\left[\sigma_{TT}^y + \epsilon\cos 2\phi\,\sigma_{TT'}^y + 2\epsilon\,\sigma_L^y + \sqrt{2\epsilon(1+\epsilon)}\cos\phi\,\sigma_{LT}^y\right]$$
$$+ P_z\left[\epsilon\sin 2\phi\,\sigma_{TT}^z + \sqrt{2\epsilon(1+\epsilon)}\sin\phi\,\sigma_{LT}^z\right]$$

- Virtual photon cross section has additional contributions when target is polarized
- Target polarization components (P_x, P_y) are defined relative to the reaction plane
- β = azimuthal angle between (transverse) target polarization and reaction plane
- $P_x = P_\perp\cos\beta$ and $P_y = P_\perp\sin\beta$



π^+ Transverse Target Asymmetry

- Setting all transverse amplitudes to zero, the pion electroproduction cross section (with polarized target) is:

$$\sigma = \varepsilon\, \sigma_L - 2\, \varepsilon\, \sigma_L^y\, P_\perp \sin\beta \quad (P_y = P_\perp \sin\beta)$$

- The transverse target asymmetry is typically defined [Frankfurt et al, PRD 60, 014010 (1999)]

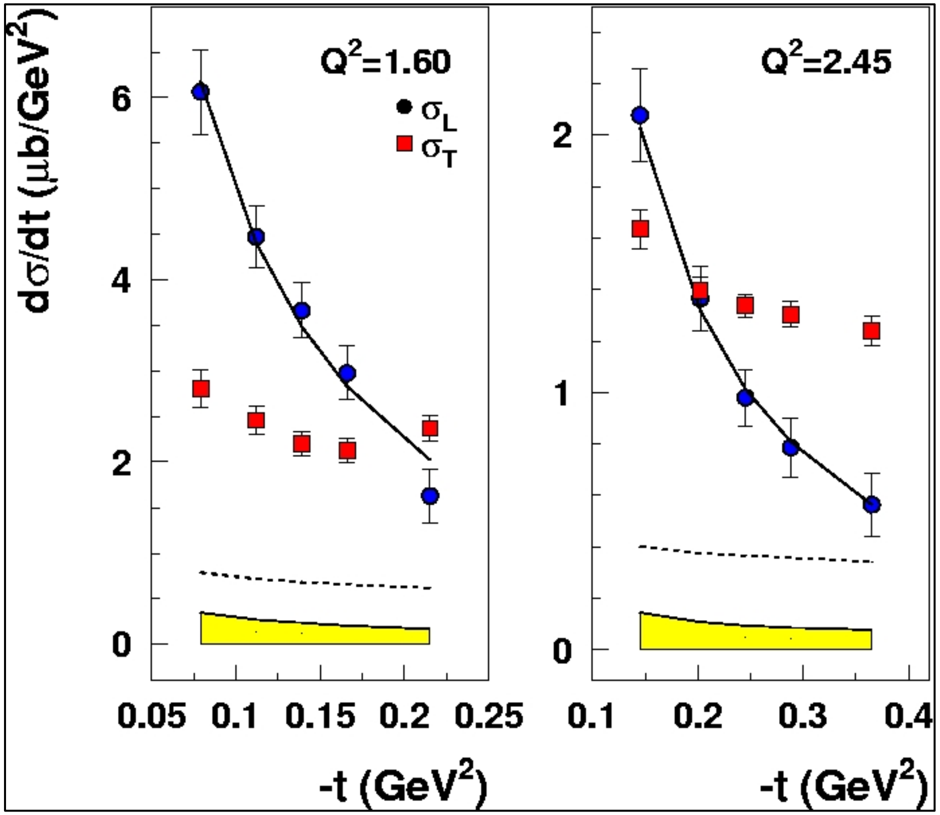
$$A_\perp = \frac{\int_0^\pi d\beta \frac{d\sigma}{d\beta} - \int_\pi^{2\pi} d\beta \frac{d\sigma}{d\beta}}{\int_0^{2\pi} d\beta \frac{d\sigma}{d\beta}}$$

- The transverse target asymmetry then involves the ratio of two longitudinal cross sections

$$A_\perp = \frac{2}{\pi} \frac{2\sigma_L^y}{\sigma_L}$$

Fπ-2 Cross Sections – Transverse Contributions

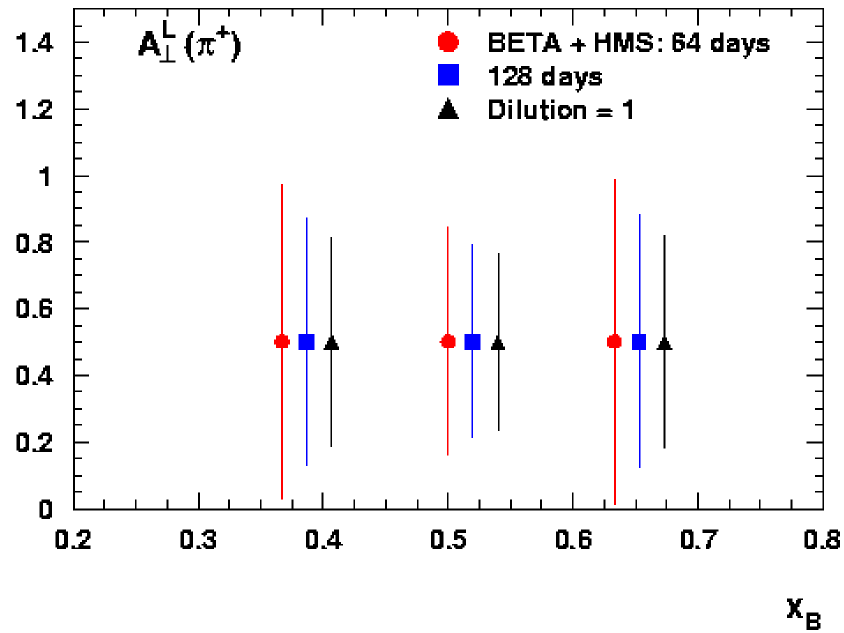
- Unpolarized cross sections from F_π-2 at W=2.2 GeV
- At Q^2=2.45 GeV^2, transverse contributions non-negligible
- Will need huge cancellations at these kinds of kinematics to extract meaningful transverse target ratio



$A_\perp$ Measurement at 6 GeV

- Potential for performing a measurement in Hall C w/UVa polarized target was investigated (6 GeV)
- Used BigCal to mitigate low luminosities
- Assumed it was necessary to extract σ_L and $\sigma_L{}^y$ simultaneously (2 full blown L-T separations from the same data set)
- In the end, limited by small $\Delta\varepsilon$ allowed by geometry of target

Double L-T Method



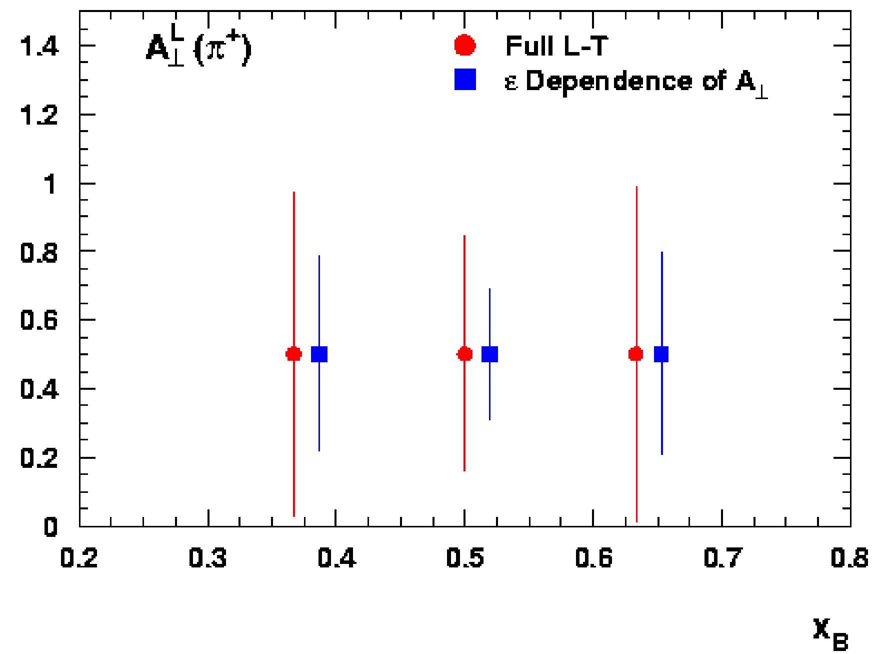
Q^2 = 2-5 GeV^2

W = 1.6-3 GeV

Alternative $A_\perp$ Measurement

- Two Rosenbluth separations and ratio of longitudinal cross sections
  - $\sigma_A = \sigma_T + \varepsilon\, \sigma_L$
  - $\sigma_U = \sigma_T + \varepsilon\, \sigma_L$
- Rosenbluth separation of asymmetry
  - $A = A_T + \varepsilon\, A_L$
  - At each ε, correct denominator (σ) by ratio $r=\sigma_T/\sigma_L$ -> $\sigma_L = \sigma/(r+\varepsilon)$ so $A_{cor} = A\,(r+\varepsilon)$

ε Dependence of Asymmetry



If we know r to 5% (from our data or other), then $(\delta A_\perp/A_\perp) = 0.33\text{-}0.52$

Measurement of $A_\perp$ at 11 GeV

- Relatively low luminosity available with UVa polarized target implies that $A_\perp$ measurement with spectrometers may be difficult
  - Large luminosity available with polarized ^{3}He target may make this more practical
    - Long cell length – L-T still practical?
  - Measurement at one or a few x_{Bj} values likely the most one would like to do
- Large acceptance device like CLAS may be better suited to measurement of the unseparated azimuthal asymmetries
  - Able to sample a large phase space all at once
  - Transverse components are likely not negligible
  - L-T separation of unpolarized cross sections required to get interpretable result
- Ideal program is likely a combined effort between CLAS12 with transverse target and Hall C

Summary

- JLab 12 GeV upgrade opens the door for a rich program using exclusive pion electroproduction
- GPD and factorization studies can be carried out using
  - Deep Exclusive Meson Production (large Q^2, low –t)
  - Wide-angle electroproduction
  - Transverse target asymmetries
- In most cases, the ability to isolate the longitudinal cross section is crucial
- Most efficient program involves close collaboration between Hall C (HMS-SHMS) and Hall B (CLAS12)