Transverse Target Asymmetry in Exclusive π+ Production

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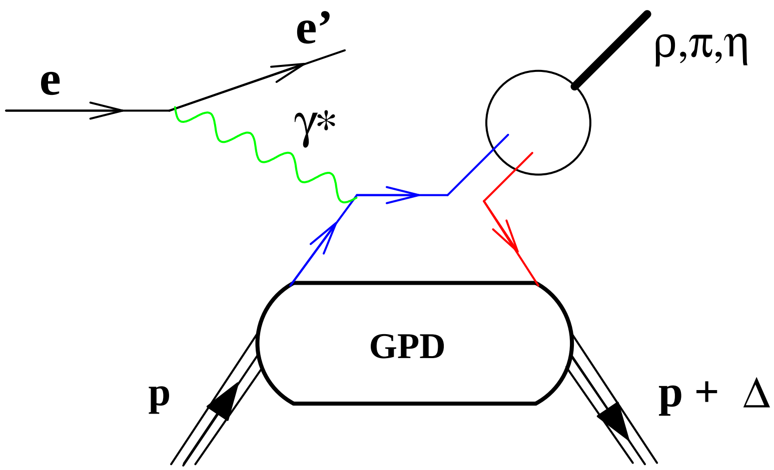
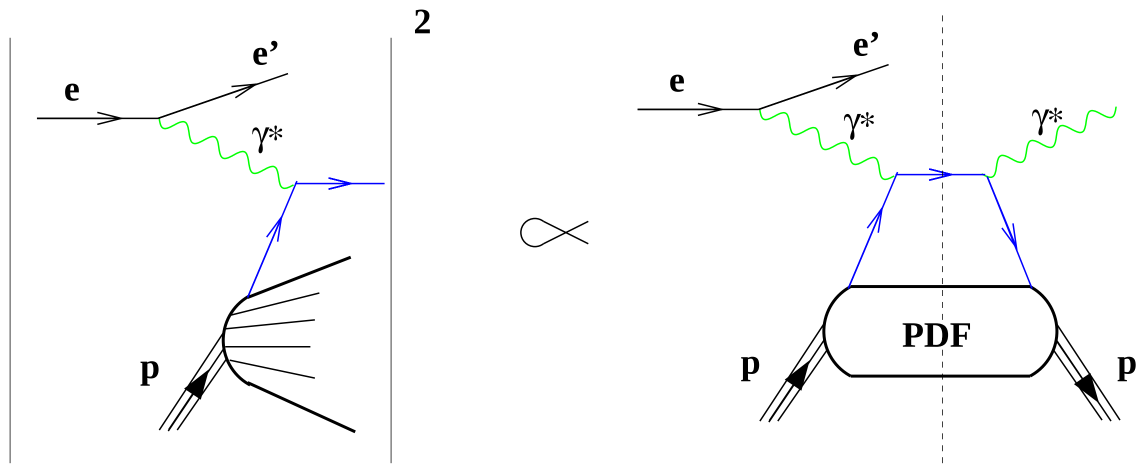


Outline

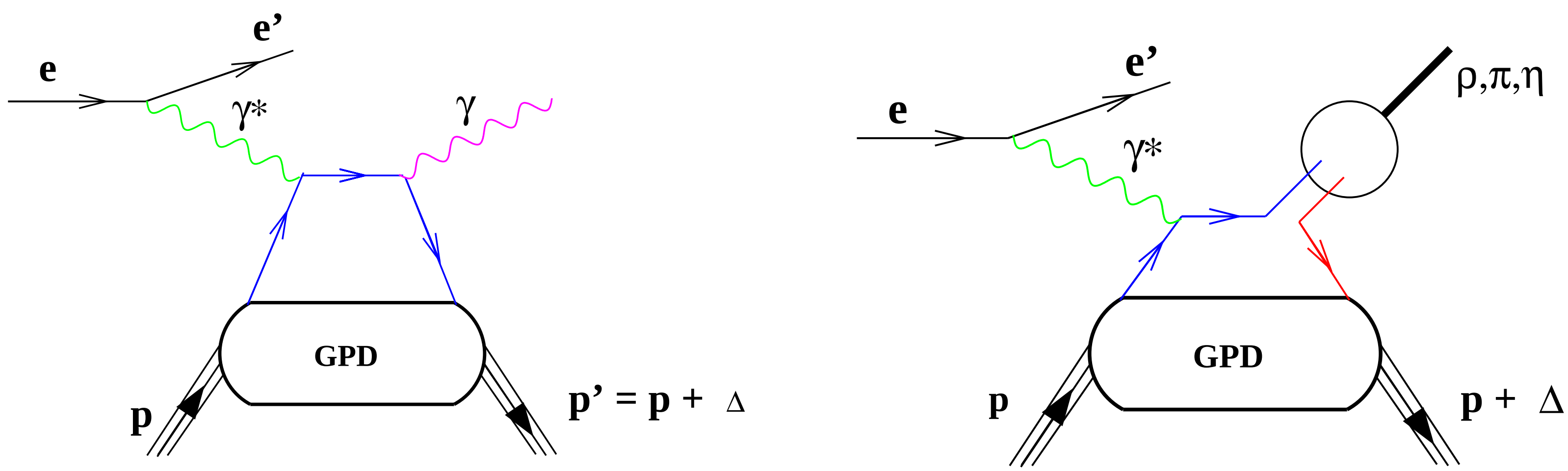
- Generalized Parton Distributions
  - Hard Exclusive Reactions and GPDs
  - New information from GPDs
  - Experimental Access to GPDs
- Hard Exclusive Pion Production in Hall C
  - Experimental requirements
  - Proposed measurement (A_{UT})

DIS and Parton Distribution Functions

- Factorization -> DIS can be described in terms of hard (perturbative) and soft (non-perturbative) processes
  - Hard scattering part is calculable
  - Non-perturbative part described by Parton Distribution Functions
- Forward Compton amplitude can be related to DIS cross section via optical theorem



Generalized Parton Distributions



- Off-forward kinematics -> final state momentum (or particle) differs from initial state
- Factorization has been proven for non-forward processes as well
- GPDs give information on correlations between partons of different momentum

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
  $\Delta^+ = -2\xi(p+\Delta/2)^+$

→ Longitudinal fraction of the momentum transfer, t
Parameterizes the skewedness

$H^{q,g}(x,\xi,t)$ 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

GPDs and DIS

$$H^q(x,0,0) = \begin{cases} q(x), & x > 0\,, \\ -\bar{q}(-x), & x < 0\,. \end{cases}$$

$$\tilde{H}^q(x,0,0) = \begin{cases} \Delta q(x), & x > 0\,, \\ \Delta\bar{q}(-x), & x < 0\,. \end{cases}$$

- In the limit of $\xi \to 0$ and $t \to 0$, H and $\tilde{H}$ reduce to ordinary parton distributions
- E and $\tilde{E}$ not accessible in DIS - parton helicity flip is forbidden

GPDs and Elastic Scattering

- First moments of GPDs yield usual elastic form factors
  - F_1,F_2 = Dirac and Pauli form factors
  - G_A, G_P = axial vector and pseudo scalar form factors
- Common formalism can describe DIS and elastic scattering

$$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$$

$$\int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t)$$

$$\int_{-1}^{1} dx \widetilde{H}^q(x,\xi,t) = G_A^q(t)$$

$$\int_{-1}^{1} dx \widetilde{E}^q(x,\xi,t) = G_P^q(t)$$

GPDs and Angular Momentum

- Intuitive link to total angular momentum when ξ=0 and $\Delta=\Delta_\perp$
- At ξ=0, $x=x_B$ and the probability interpretation is again valid
- $\Delta_\perp$ can be viewed as the Fourier transform of impact parameter, $b_\perp$
- GPDs describe probability to probe parton of momentum fraction x, at a transverse distance $b_\perp$
  - $\vec{L} = \vec{r} \times \vec{p}$

GPDs and Total Angular Momentum

- Second moments of GPDs at t=0 give expectation value of nucleon spin

X. Ji, PRL 78, 610

$$\int_{-1}^{1} dx x [H^{q,g}(x,\xi,t=0) + E^{q,g}(x,\xi,t=0)] = 2\hat{J}^{q,g}$$

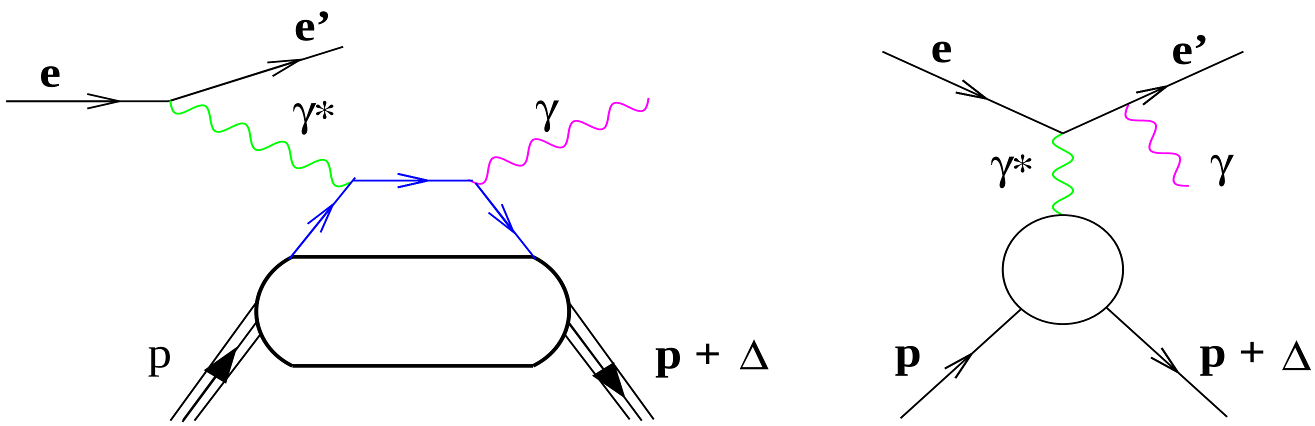
- Nucleon spin ⟶

$$\frac{1}{2} = \hat{J}_q + \hat{J}_g$$

$$\frac{1}{2} = \hat{L}_q + \frac{1}{2}\Sigma + \hat{J}_g$$

- $\hat{L}_q$ can be inferred from $\hat{J}_q$ (from GPDs) and $\frac{1}{2}\Sigma$ (from DIS)

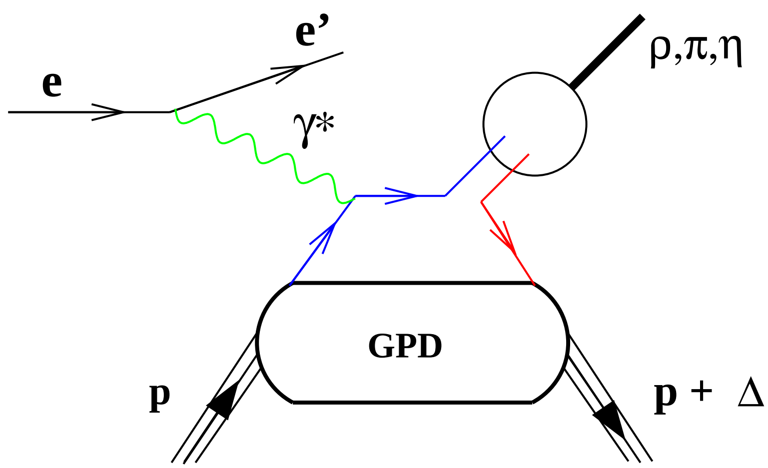
Experimental Access to GPDs
DVCS



- Deeply Virtual Compton Scattering sensitive to a combination of all 4 GPDs --> H,E,$\tilde{H}$,$\tilde{E}$
- Large background from Bethe-Heitler
- Azimuthal asymmetries can access DVCS and BH interference terms

$$d\sigma \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + (\mathcal{T}^*_{BH}\mathcal{T}_{DVCS} + \mathcal{T}^*_{DVCS}\mathcal{T}_{BH})$$

Experimental Access to GPDs
Exclusive Meson Production



- Vector mesons (ρ,ω,φ) sensitive to H and E
- Pseudo scalar mesons sensitive to $\tilde{H}$ and $\tilde{E}$
- Detection of final states easier – but interpretation complicated by convolution with meson DA
- Factorization only applies for longitudinal photons

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.

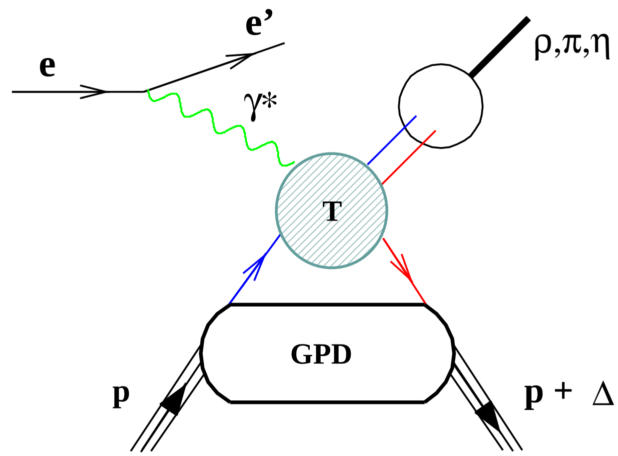
- To get new information from GPDs, we need a program that will measure …
  - a variety of exclusive processes (vector mesons, DVCS, pseudo scalar mesons)
  - a broad range of phase space (t, x_B)

GPD Program at JLab

- DVCS
  - Beam-spin asymmetry (Stepanyan et al, PRL 87, 182002, 2001)
  - E00-110, DVCS at 6 GeV (Hall A)
  - E01-113, DVCS at 6 GeV with CLAS
- Meson Production
  - E99-105, Deeply Virtual Electroproduction of Vector Mesons (CLAS)
- A major initiative for the 12 GeV upgrade is a program of Deep Exclusive Measurements to constrain GPDs

Observables in Hard Exclusive Reactions

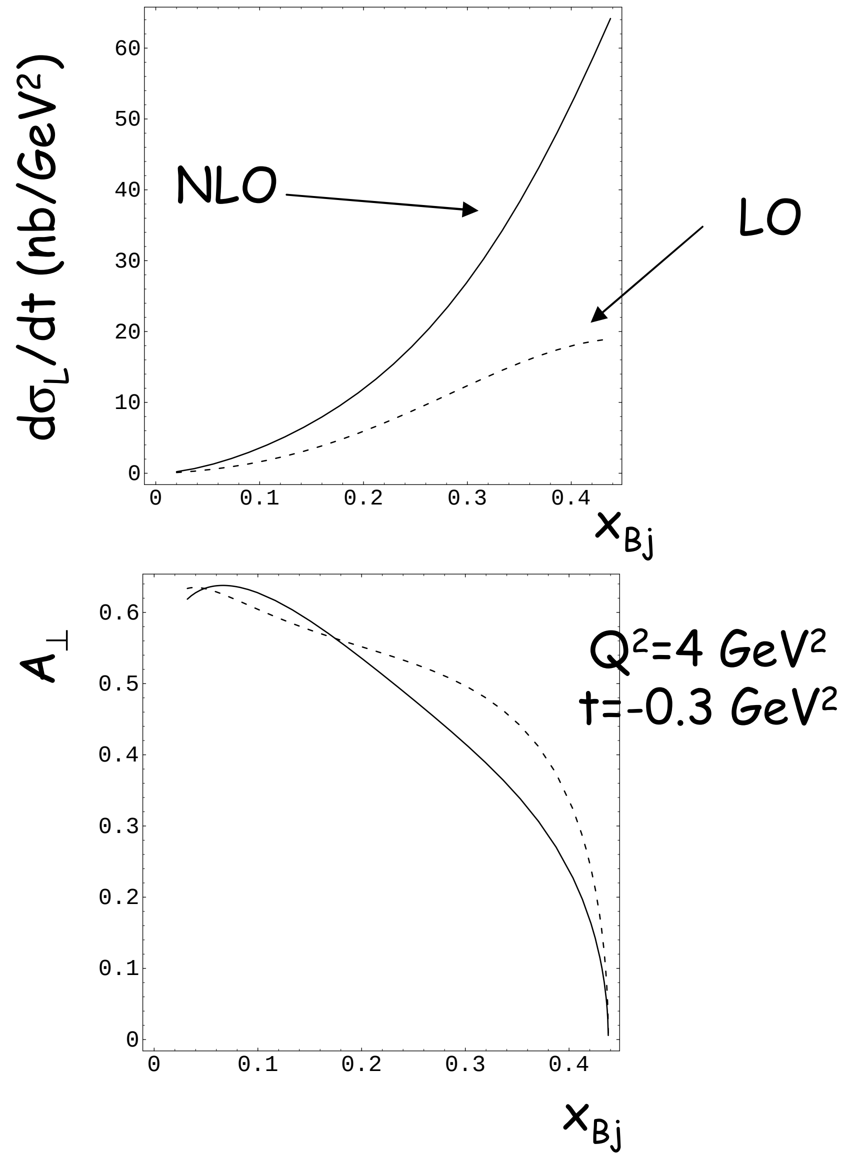
- To say anything about GPDs, we must be confident we are in a regime where soft-hard factorization applies (large Q^2)



- 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

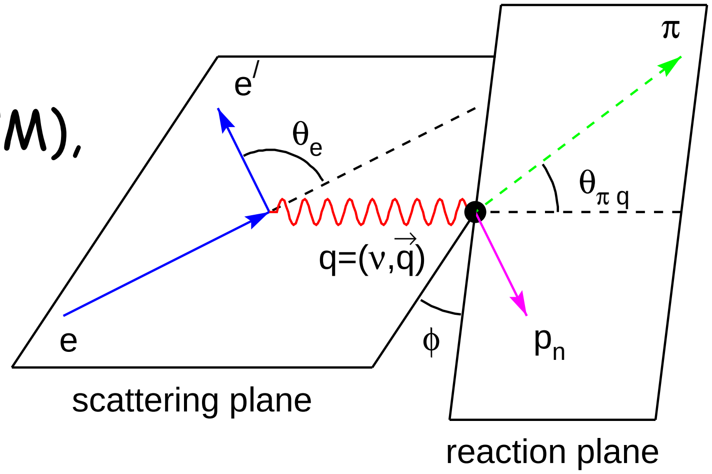
Exclusive π^+ Production at NLO

- Belitsky and Müller GPD based calc. of π^+ 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



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 ($d\sigma/d\Omega$)



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

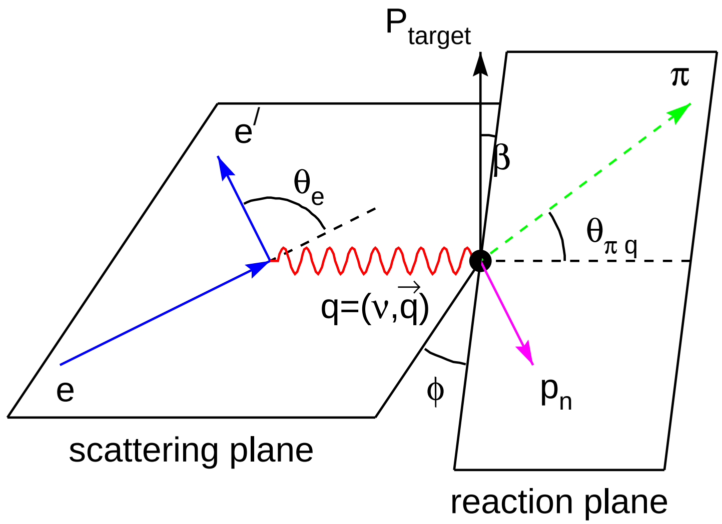
- Virtual photon cross section can be further broken down into contributions from longitudinal and transverse photons (formalism of Bartl and Majerotto)

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

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)]

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

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

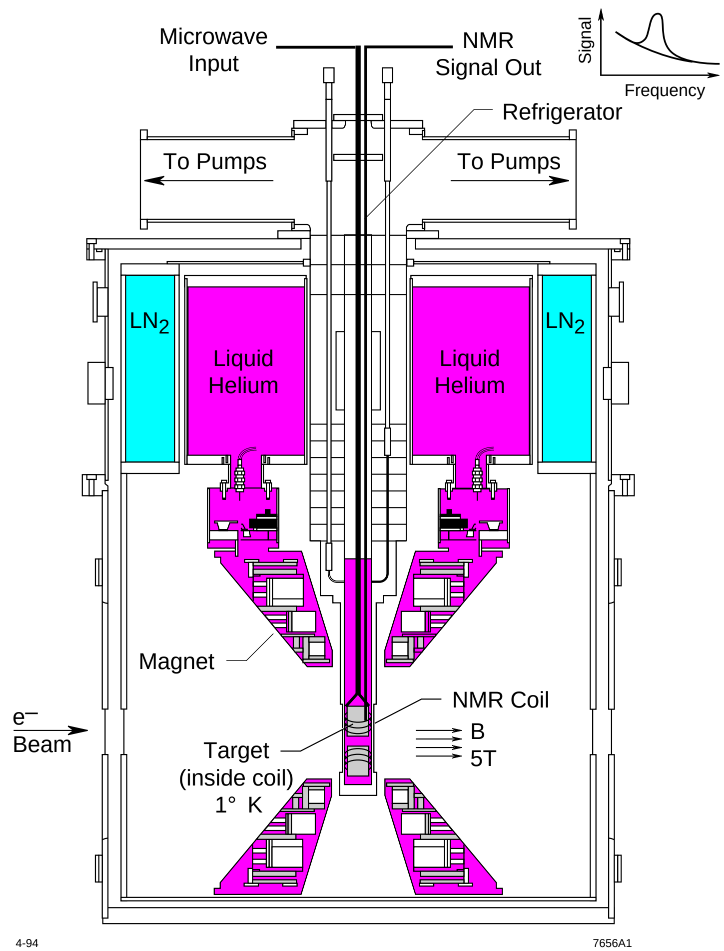
$$A_\perp = \frac{2}{\pi} \frac{2\sigma_L^y}{\sigma_L}$$

Measurement of $A_\perp$

- At JLab energies, we cannot ignore the contributions from transverse photons
- To cleanly extract $A_\perp$, we need
  - Proton target polarized transverse to virtual photon direction (not necessarily a normal target)
  - Large acceptance in π^+ azimuthal angle (i.e. ϕ and β)
  - Measurements at multiple beam energies and electron scattering angles -> ε dependence
- All of these available with UVa target and the Big Electron Telescope Array (BETA)

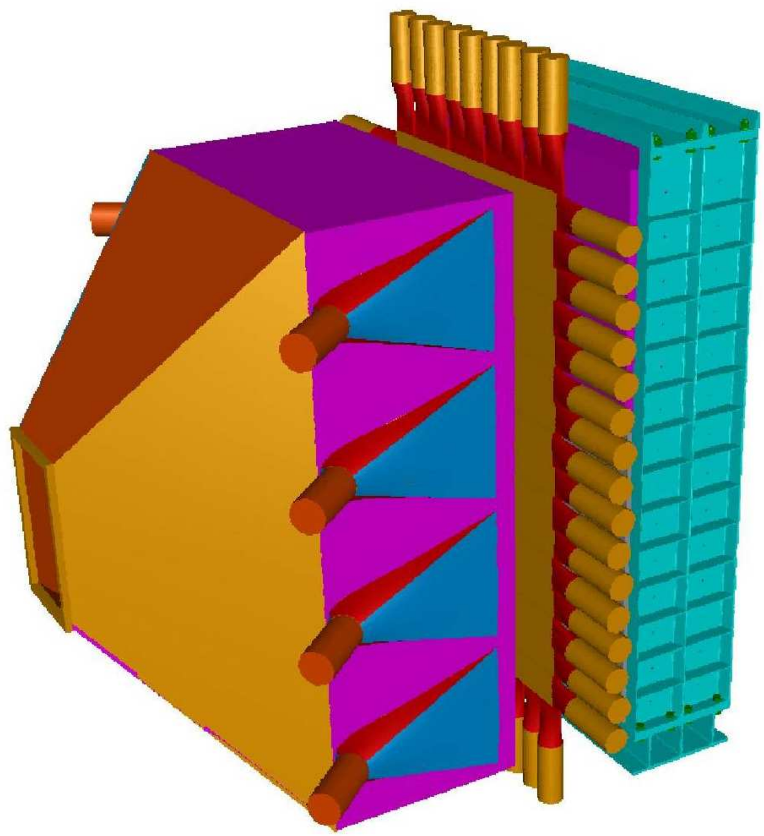
UVa Polarized Target

- $A_\perp$ measurement would use NH_3 polarized target
- Assume that average polarization ~80%
- Luminosity in uniform field region ~ 85 x 10^{33} cm^{-2} Hz
- Must be run at low currents – sufficient event rate can only be achieved with large acceptance detector



Big Electron Telescope Array

- Non-magnetic LARGE acceptance electron detector
- Components:
  - BigCal- fly's eye calorimeter to be used for G_E/G_M experiment
  - Gas Čerenkov
  - Lucite detector (?)
- PID not crucial for $A_\perp$ measurement, but helpful to reduce random backgrounds

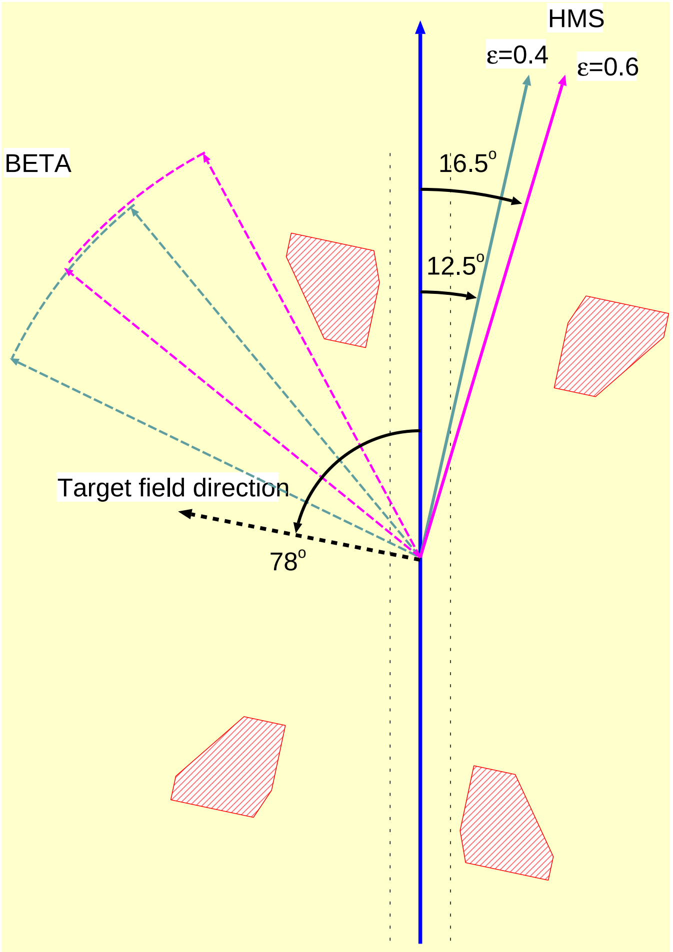


BETA Parameters

- Calorimeter front area = 218 cm (vertical) x 120 cm (horizontal)
  - Naïve solid angle: 219 msr at an effective distance of 3.45 m from target
  - Fiducial region solid angle: 194 msr
- Energy resolution = 5%/√E
- Position resolution at calorimeter = 4 mm -> angular resolution ~ 0.1 degrees

Hall C Configuration for $A_\perp$ Measurement

- Electrons will be detected in BETA, π^+s in the HMS
- Polarized target in perpendicular configuration
  - Target field pointing 78° beam left
- Target geometry allows for measurements at multiple values of ε



The Ideal $A_\perp$ Experiment

- The perfect $A_\perp$ experiment would include:
  - Large Q^2 (>3-5 GeV^2) and large W (>2 GeV)
  - Large $\Delta\varepsilon \sim 0.5$
  - Complete and uniform azimuthal angle acceptance (ϕ and β)
- A measurement in Hall C comes close to satisfying these requirements

$A_\perp$ Kinematics

- Kinematics limited by
  - HMS minimum angle -> assume 12.5° based on RSS experience
  - BETA minimum angle -> polarized target geometry requires central angle > 39°
- Potential kinematics

$Q^2 = 3\ GeV^2$
$W = 2\ GeV$
$x_B = 0.49$
$\Delta\varepsilon = 0.2$

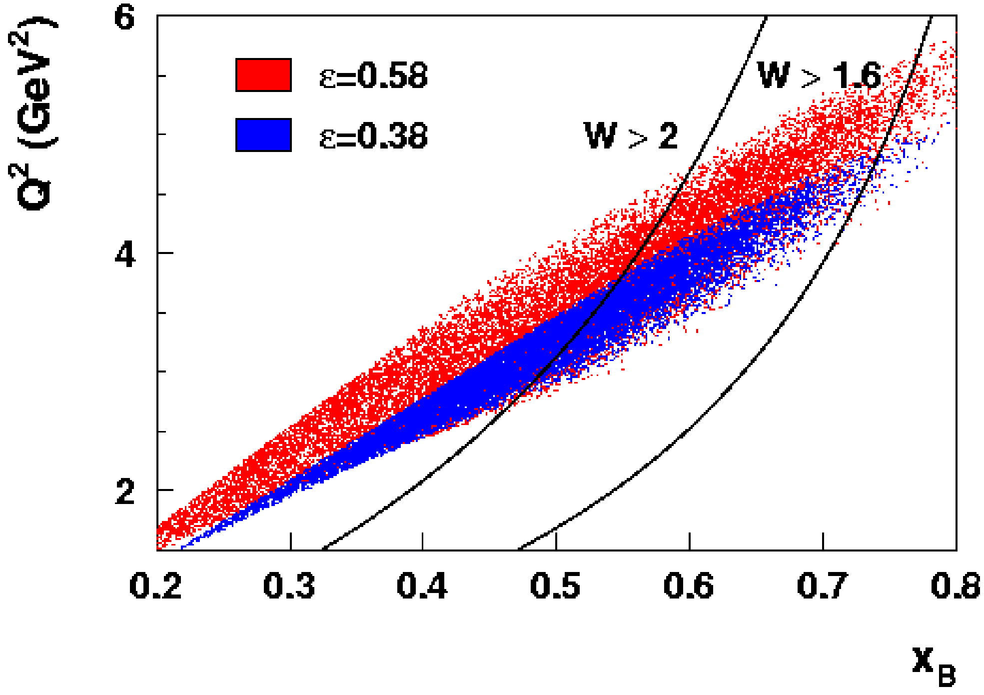
ε	E_{beam} (Gev)	θ_{BETA}	θ_{HMS}	P_{HMS} (GeV)
0.38	4.4	53°	12.5°	3.07
0.58	5.2	40°	16.0°	3.07

Simulation of Polarized Target and BETA

- Acceptance modeled using SIMC modified to include effects from polarized target field
- SIMC includes
  - Realistic optics model of HMS
  - Radiative effects, multiple scattering, energy loss
  - NOT a complete Monte Carlo a la GEANT, used mostly for acceptance and aperture checking
- Calorimeter model
  - No detector response, just geometry
  - Positions/energy at calorimeter smeared by Gaussian to approximate resolution effects
- Glen Warren's modifications for target-field (propagation and reconstruction) also included

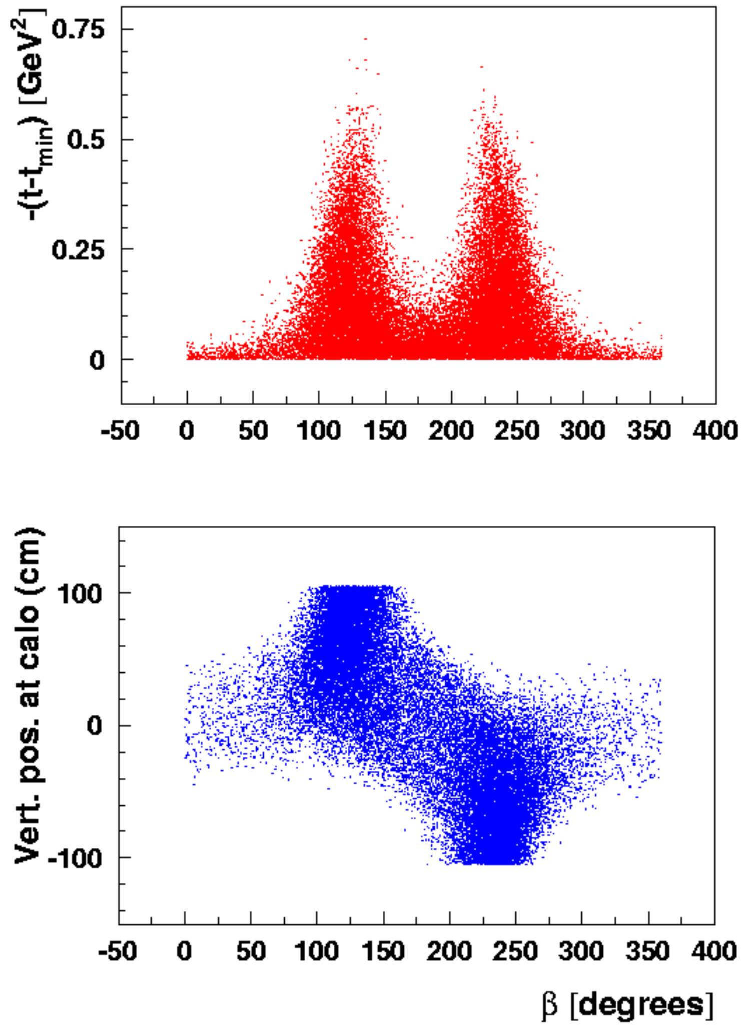
Kinematic Coverage - Electron

- Large Q^2, W acceptance -> can sample several x_B bins in one setting
- Not all of phase space at W > 2 GeV, but smaller W at larger Q^2
- Larger W requires smaller $\Delta\varepsilon$



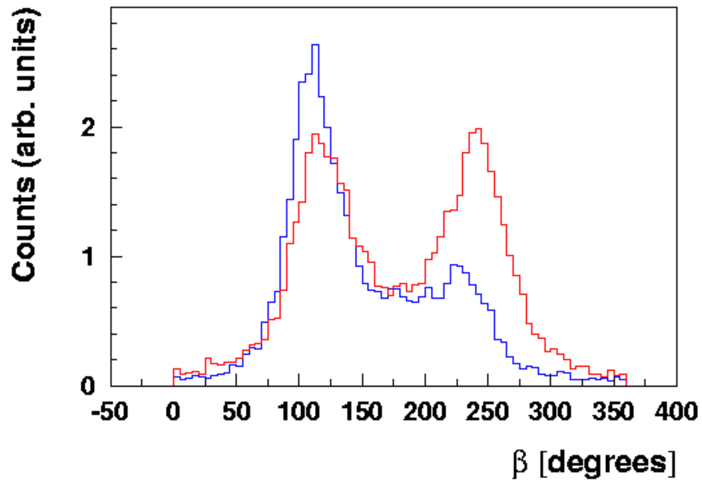
Kinematic Coverage - Pion

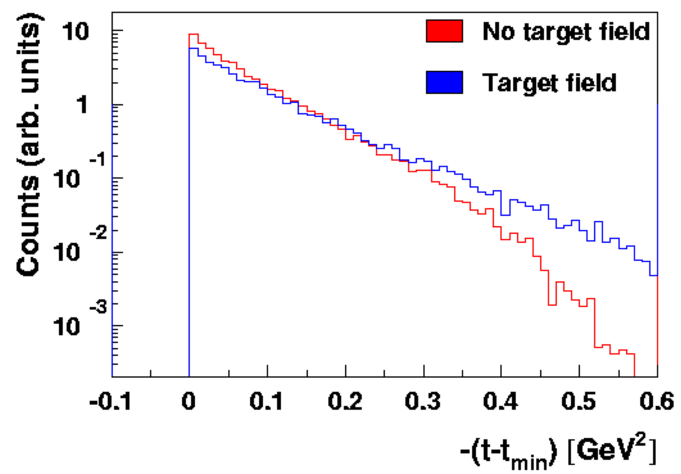
- At t=tmin (parallel kinematics) $A_\perp$ =0 - need significant $-t$ acceptance
- $A_\perp \sim \sin\beta$, failing complete β acceptance, sensitivity to region of large asymmetry
- Large vertical acceptance of BETA allows us to reach large $-t$ near β=90° and 270°



Effect of Polarized Target Field

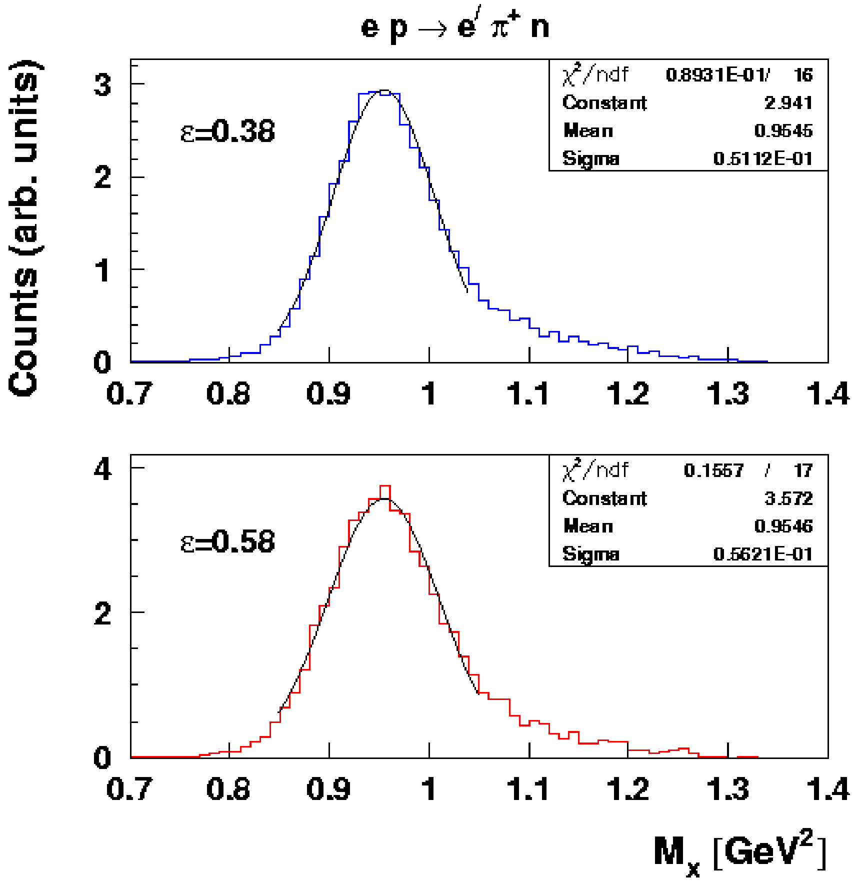
- Polarized target field biases HMS acceptance for π+ to "downward" going particles
- Lose symmetry in β acceptance
- -t is shifted to larger values (away from parallel kinematics)





Missing Mass Resolution

- Clean identification of exclusive final state requires good missing mass resolution
- M_x resolution dominated by calorimeter energy resolution
- $5\%/\sqrt{E}$ should be sufficient to suppress 2-pion and Δ contributions, but it can't be much worse
- Gain monitoring will be critical

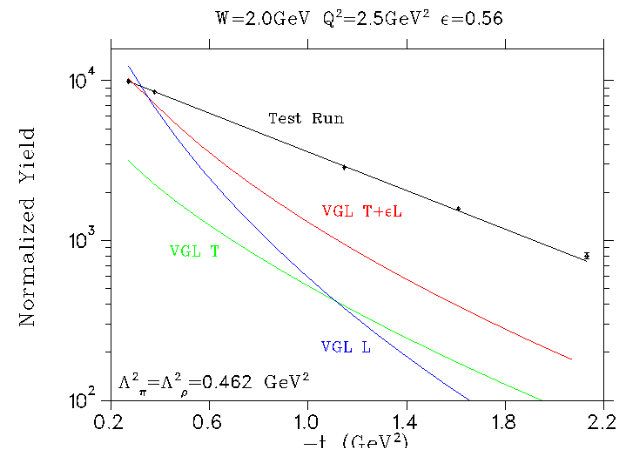


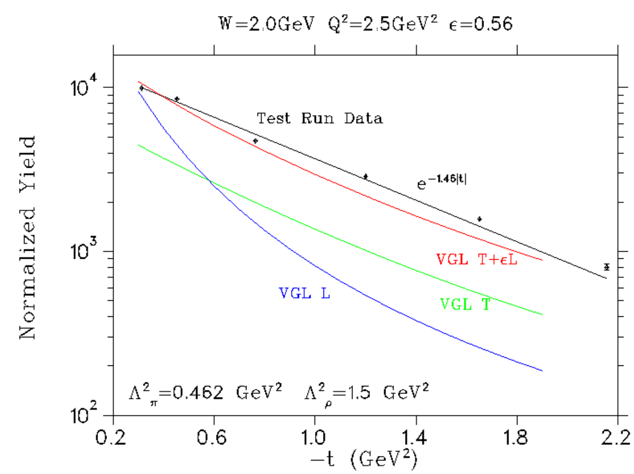
Rate Estimates

- Initial rate estimates (in LOI submitted in 2003) used Jochen Volmer's parameterization of F_{π}-I data
  - valid for Q^2 = 0.6 to 1.6 GeV^2
  - assumed extrapolation to higher Q^2 would be OK, but σ_T (σ_L) rises (drops) too quickly
- Newer rate estimates use VGL Regge model
  - Vanderhaeghen, Guidal, and Laget PRC 57, 1454
- VGL model reasonably consistent with F_{π}-I longitudinal cross sections (transverse slightly under predicted)

VGL Model at Q^2=2.5 GeV^2

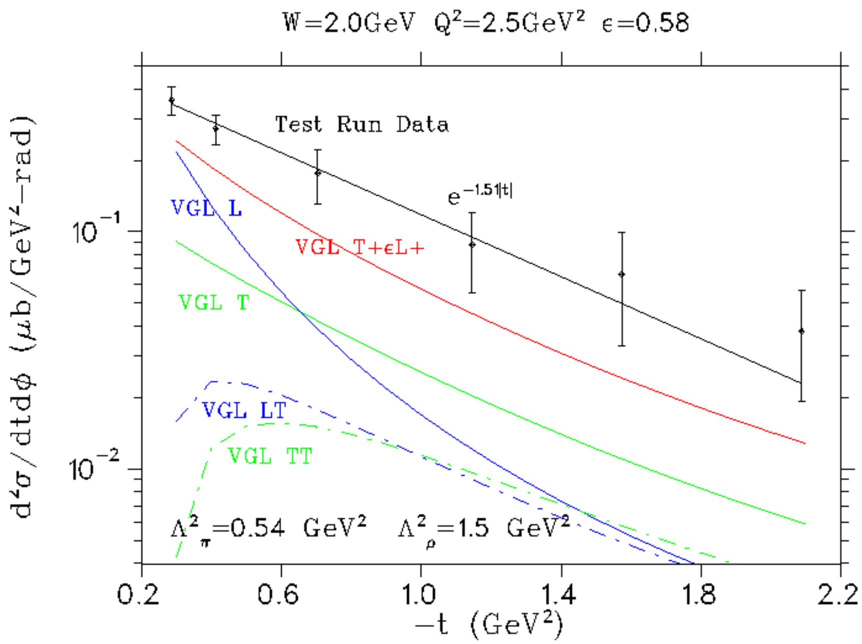
- Initial rate estimates with VGL model were extremely low!
- Garth Huber compared to large –t test data taken during F_π-II -> -t dependence was too steep
- By tweaking ρ trajectory cutoff parameter (Λ_ρ), found better agreement in –t dependence





Modified VGL Model

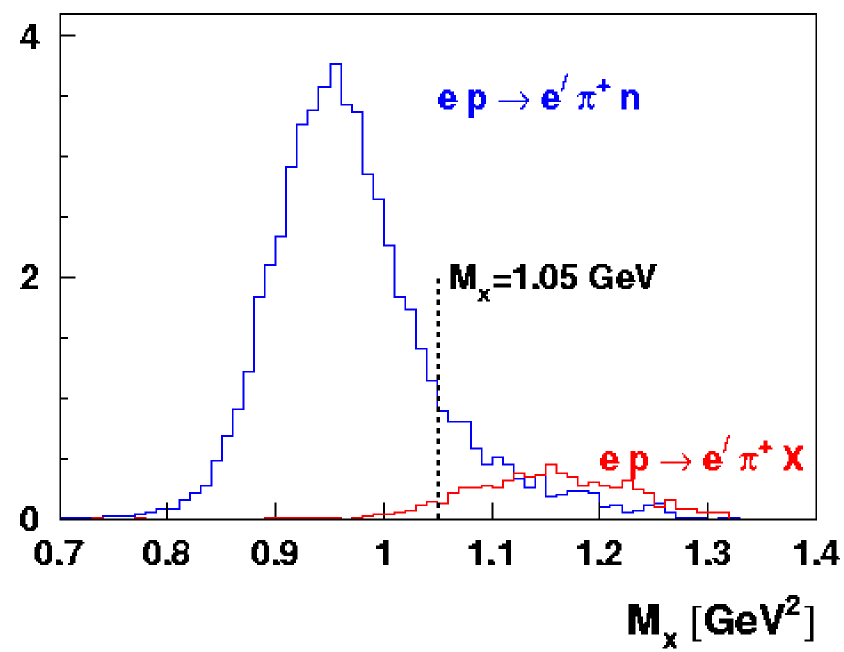
- Using modified VGL model, time for 10,000 counts from polarized H:
  - ε=0.38 - 883 hours (36 days)
  - ε=0.58 – 679 hours (28 days)
- Estimate includes Q^2-W matching cuts, calorimeter fiducial cuts, etc.
- BUT- even though –t dependence is better, still underpredicts cross section by ~ 40% !



- Model needs further investigation, so these estimates should be taken with a grain of salt!

Backgrounds from Semi-inclusive Pion Production

- Contribution from semi-inclusive π^+ production can nc longer be ignored with relatively poor missing mass resolution
- Model using CTEQ PDFs and fragmentation functions from e^+-e^- data (show fairly good agreement with Hall C Meson Duality experiment)
- For M_x<1.05 GeV cut, semi-inclusive yield is ~ 1% of exclusive yield

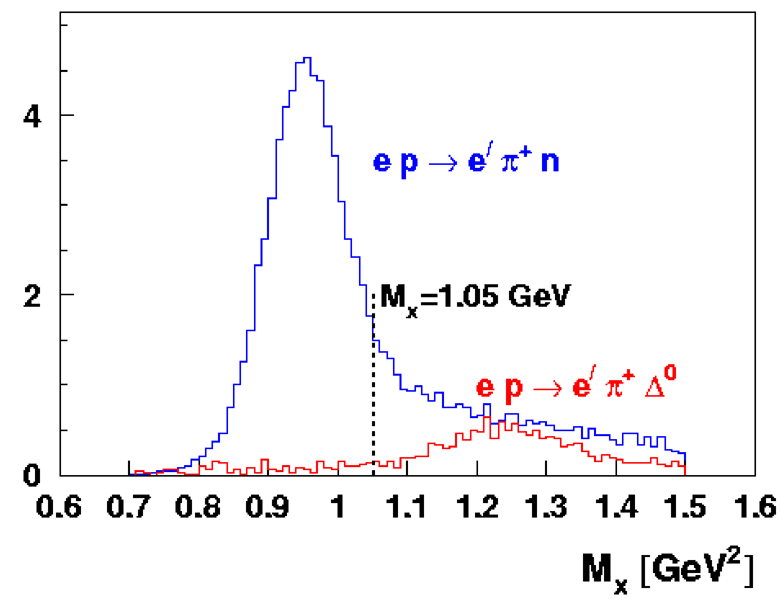


Associated Delta Production

- e p -> e' π+ Δ^0 also a potentially significant source of background
- GPD-based prediction of Frankfurt et al (PRL 84, 2589)

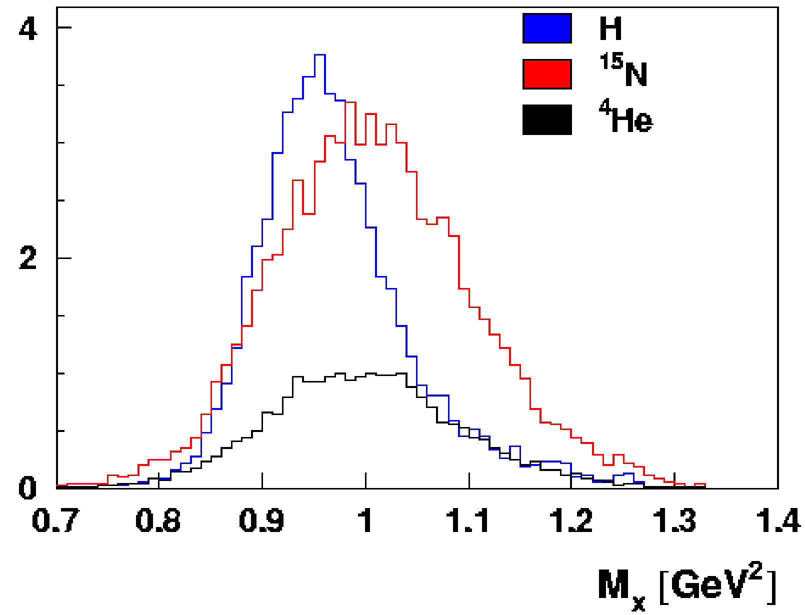
  $\sigma_L(\gamma^*p\text{->}\pi^+n)/\sigma_L(\gamma^*p\text{->}\pi^+\Delta^0) = 0.5$

- Using above simple assumption, Δ^0 production contributes ~ 3% to total yield for M_x < 1.05 GeV



Dilution Factor

- Large fraction of the detected rate comes from unpolarized materials in the target



- Model the dilution from ^{4}He, ^{15}N, and ^{12}C using a quasifree model of π^{+} electroproduction
- Define the dilution factor: $f = Y_H/(Y_H + Y_{He} + Y_N + Y_C) \approx 0.32$

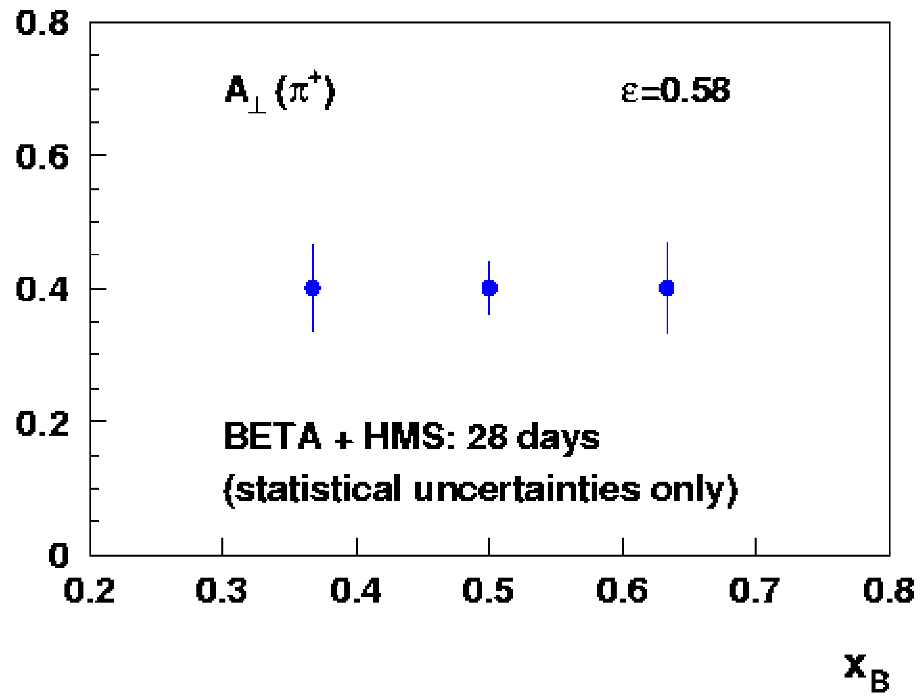
Unseparated Asymmetries

- Two ways to extract the asymmetry at each ε point
- Cross section fitting
  - Extract σ as a function of β and fit to:

    $\sigma = \sigma_U + \sigma_A \sin(\beta) + \text{(other terms??)}$
  - To cleanly extract $A_\perp = \sigma_y/\sigma_L$, we must do it this way
  - Requires detailed knowledge of acceptance
- Conventional asymmetry
  - $A(\beta) = (N(\beta) - N(\beta+\pi))/N_{tot}$
  - Ignores potential angular dependence in denominator
  - No way to cleanly de-convolute longitudinal and transverse contributions

Unseparated Asymmetry: Projected Uncertainties

- *Assuming*
  - P_{target} = 80% , <I> = 85 nA
- $\sigma = \sigma_U + \sigma_A \sin(\beta)$
- $A_\perp = \sigma_A/\sigma_U$
  - Assume $A_\perp = 0.4$
- $\delta A \approx$ 0.04-0.06 (stat)
- For L-T separation:
  - $\delta\, \sigma_A/\sigma_A$ = 10-18%
  - $\delta\, \sigma_U/\sigma_U$ = 1-2% (stat) but uncertainty in dilution factor will contribute another ~ 5%



Uncertainties - Separated Cross Sections

- For "separated" asymmetry, we need to do two L-T separations

  $\sigma_A = \sigma_T^{\perp} + \varepsilon\, \sigma_L^{\perp}$ $\qquad$ $\sigma_U = \sigma_T + \varepsilon\, \sigma_L$

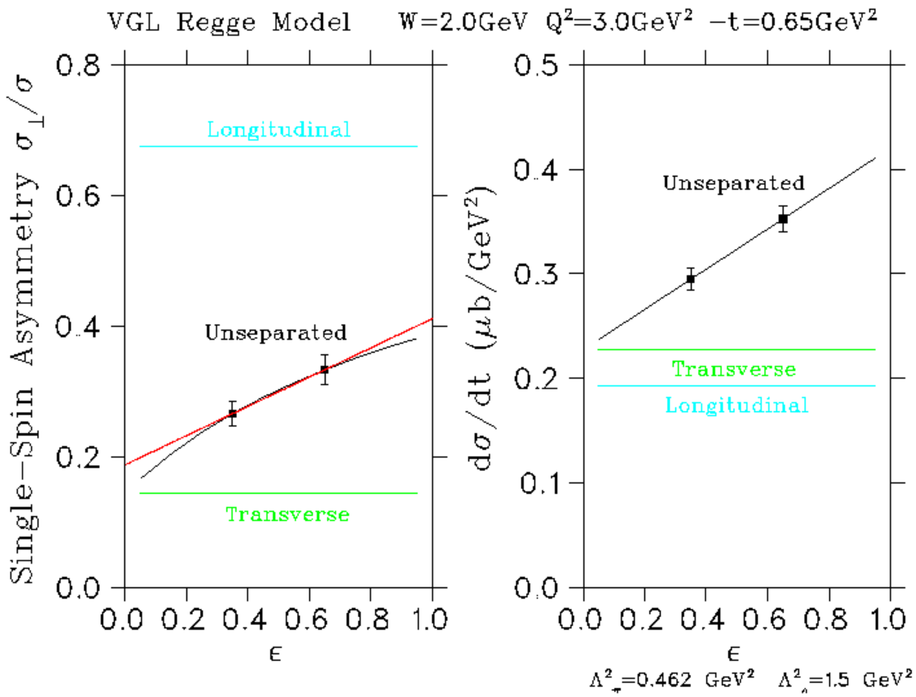
- Define $r = \sigma_T/\sigma_L$, uncertainty in longitudinal cross sections is

  $\Delta\sigma_L/\sigma_L = 1/(\varepsilon_1-\varepsilon_2)\ \Delta\sigma/\sigma\ [(r+\varepsilon_1)^2 + (r+\varepsilon_2)^2]^{1/2}$

- Unseparated asymmetries
  - δA ~ constant, independent of size of asymmetry
- Separated cross sections (and asymmetries):
  - $\delta A/A$ ~ constant

VGL Predictions for σ and $A_\perp$

- $A_\perp = (\sigma_T^\perp + \varepsilon\, \sigma_L^\perp)/(\sigma_T + \varepsilon\, \sigma_L)$
- In "modified" VGL model, the unseparated asymmetry is ~ 0.3-0.4
- While σ_L and σ_T are comparable, the transverse contribution to the asymmetry is small



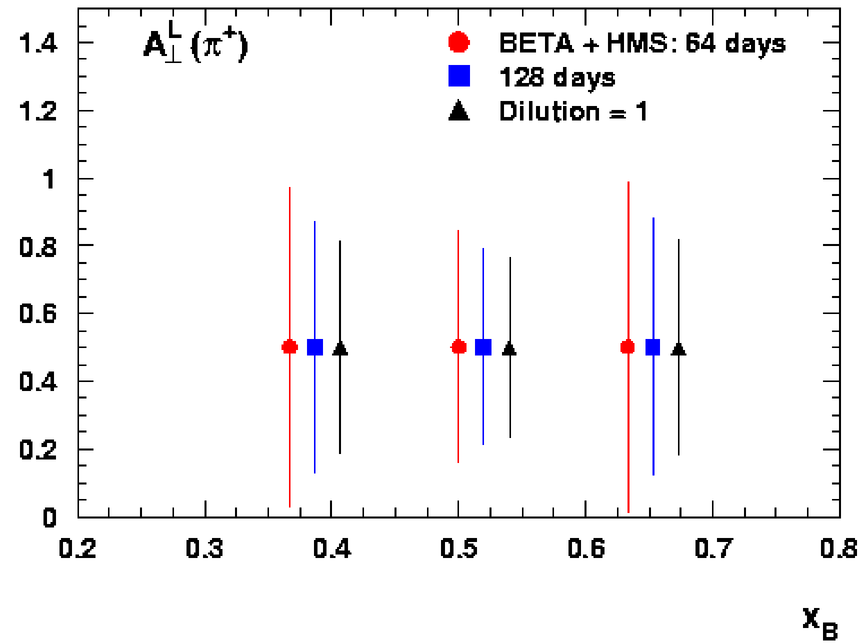
Projected Uncertainties for "Separated Asymmetry"

- Taking modified VGL model as guidance, assume
  - $\sigma_L/\sigma_T \approx 1$ and $(\sigma_L/\sigma_T)_\perp \approx 5$
  - $\sigma_\perp \approx 0.4\ \sigma$
- This gives $\delta\sigma_\perp/\sigma_\perp$ = 0.1 – 0.17

  $(\delta\sigma_\perp/\sigma_\perp)_L = 0.53 - 0.83$

  and

  $(\delta A_\perp/A_\perp)_L = 0.7 - 0.98$
- The only way to decrease these uncertainties is to:
  - Dramatically increase statistics
  - Decrease dilution factor
  - Increase $\Delta\varepsilon$



Ratio of full-blown L-T separations may not be the best way to go!

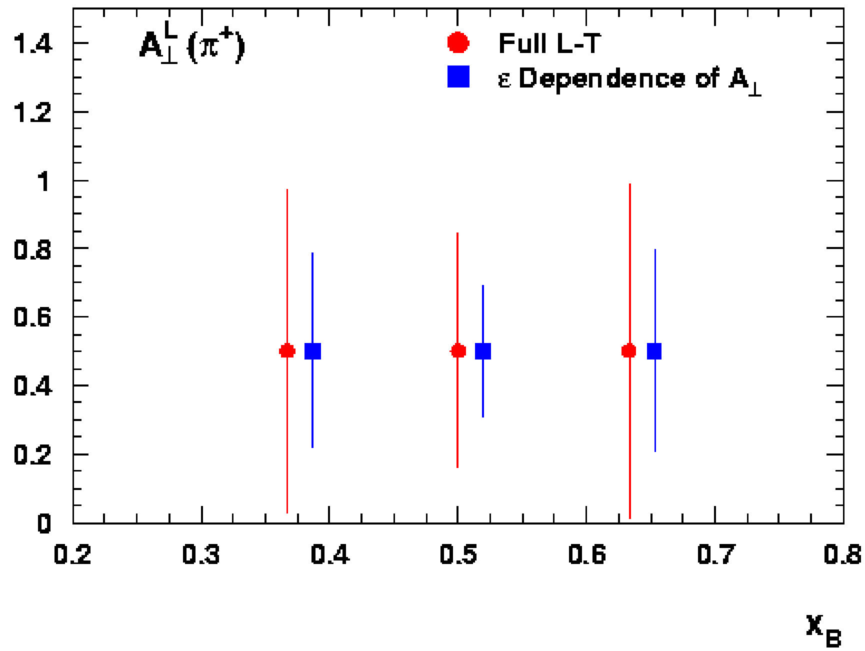
ε Dependence of $A_\perp$

- Two Rosenbluth separations and ratio of longitudinal cross sections

$$\sigma_A = \sigma_T^\perp + \varepsilon\, \sigma_L^\perp$$

$$\sigma_U = \sigma_T + \varepsilon\, \sigma_L$$

- 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 $A_{cor} = A x (r+\varepsilon)$



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

Systematic Uncertainties

- All discussion to this point has ignored systematic uncertainties
- In L-T separation, systematic uncertainties uncorrelated in ε are the big problem
- The usual suspects
  - Acceptance
  - Charge
  - Efficiencies
- All of the above will be more challenging than usual – we will have in addition:
  - Backgrounds changing vs. e
  - Missing mass resolution changing with e
- Typical Hall C L-T's -> uncorrelated uncertainty ~ 2.5%
- Since $\delta A/A$ ~ 8-10%, uncorrelated uncertainties could be larger

Options with a Normal Target

- With a target polarized out of plane, more flexibility in $A_\perp$ kinematics
  - BETA can move to smaller angle (~30°)
  - $\Delta\varepsilon$ range increases to 0.3 (still constrained at large ε by minimum HMS angle)
- Drawbacks
  - Can only sample one side of q-vector at small HMS angles -> for in-plane target, large vertical BETA acceptance allowed sampling of both sides of q
  - Rates are larger at smaller angle, but still rate limited at back angles

Other Measurements

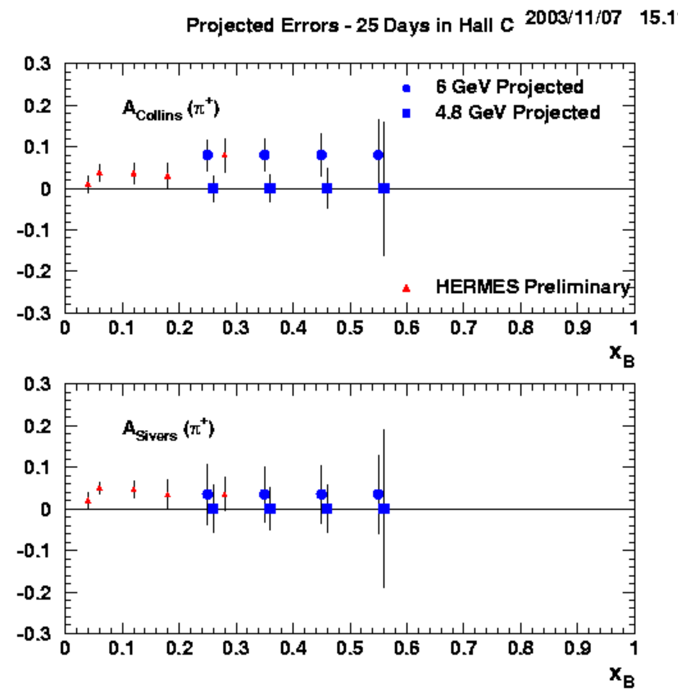
- LOI-03-002 in Hall B for a large program of transverse target measurements
  - Exclusive π^+ production mentioned as part of overall program
  - Even taking data continuously over a long period, the likely lower luminosity may not make a measurement feasible
  - No mention of L-T separation
  - Even extracting the ε dependence of the asymmetry requires good knowledge of the experimental acceptance
- HERMES currently carrying out a series of measurements on transversely polarized H target
  - Missing mass resolution not sufficient - exclusive π^+ measurement requires tricky (accurate?) background subtraction
  - L-T separations of any kind basically impossible

Transversity

- Transverse target asymmetry in semi-inclusive sector

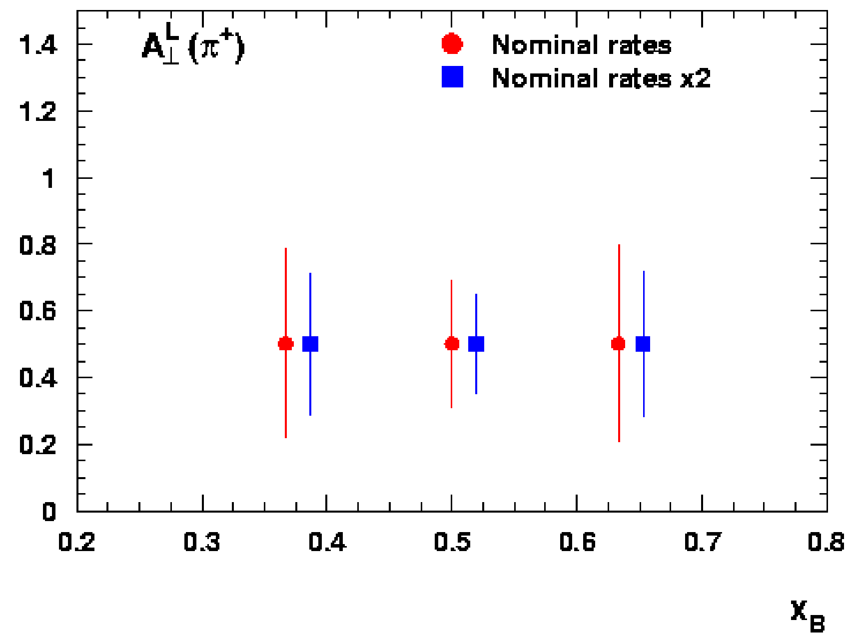
  p(e,e′ π⁺)X

- Sensitive to transversity distribution in the nucleon, $\delta q(x)$
- Transversity distribution can be related to the tensor charge of the nucleon
- A measurement at JLAB would access larger x than available at HERMES



Conclusions

- $A_\perp$ measurement feasible (although time consuming) in Hall C with BETA and UVa target
- Unseparated asymmetries can be measured to $\delta A \approx 0.06$
- Uncertainties on separated asymmetries significantly larger
- Lack of knowledge of exclusive π^+ cross section a big problem
  - "Modified" VGL model still underpredicts data
  - L-T ratio not well constrained



Perhaps best to choose kinematics where there is already high precision L-T separated cross section data -> overlap with F_π-II kinematics at Q^2= 2.5 GeV^2 ?