JLab 12 GeV Program: Hard Exclusive and SIDIS Processes

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Physics Opportunities in Hall C at 12 GeV
August 4-5, 2008

Quark structure of the proton

Large database on unpolarized structures functions constrain parton distributions → $u(x)$, $d(x)$ …

Growing body of inclusive and semi-inclusive data constrain polarized pdfs → $\Delta u(x)$, $\Delta d(x)$,…

→JLab at 12 GeV can help put precision of polarized pdfs on par with unpolarized pdfs

Major facet of JLab 12 GeV program aimed at exploring proton structure beyond 1 dimension

→ TMD parton distributions which is linked to
→ Quark orbital angular momentum, and don't forget about …
→ Nucleon tomography

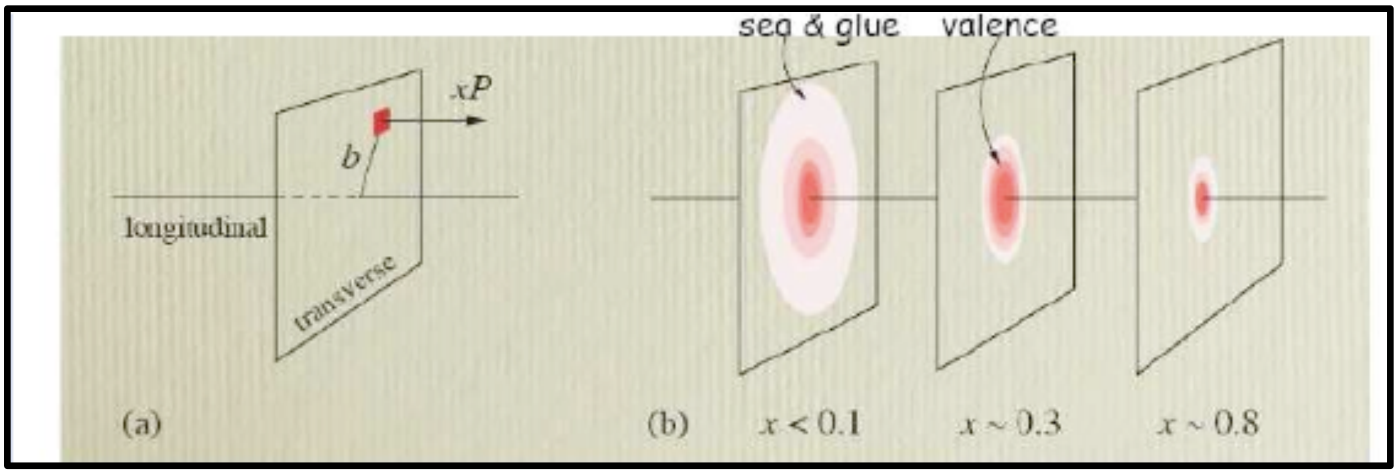
Generalized Parton Distributions

GPDs provide the common framework for connecting DIS to elastic scattering

More importantly, provide information on the angular momentum of the nucleon via the Ji sum rule

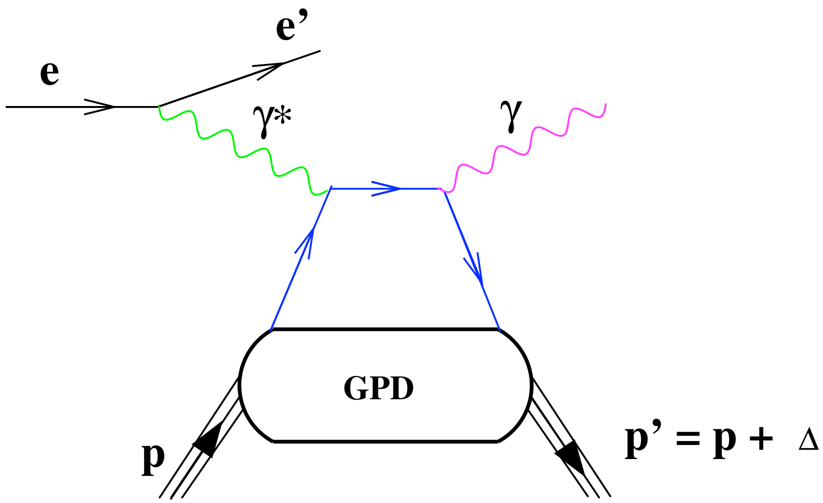
$$\int_{-1}^{1} dx x[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)] = 2J^q$$

Can also do fun things like proton tomography:



$$PDF(x,R_\perp) \equiv \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i(\Delta_\perp R_\perp)} GPD(x,t=-\Delta_\perp^2)$$

Hard Exclusive Reactions



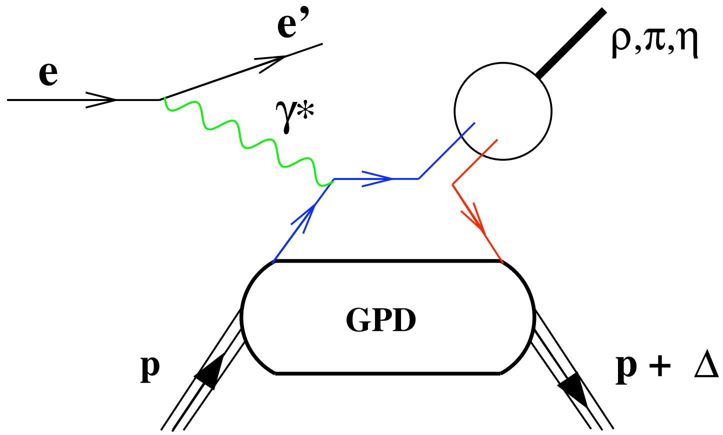
DVCS:

$$H, E, \tilde{H}, \tilde{E}$$

Beam-spin asymmetry → H

Long. target asymmetry → $H, \tilde{H}$

Trans. target asymmetry → E



Meson production:

pseudoscalar mesons (π,η):

$$\tilde{H}, \tilde{E}$$

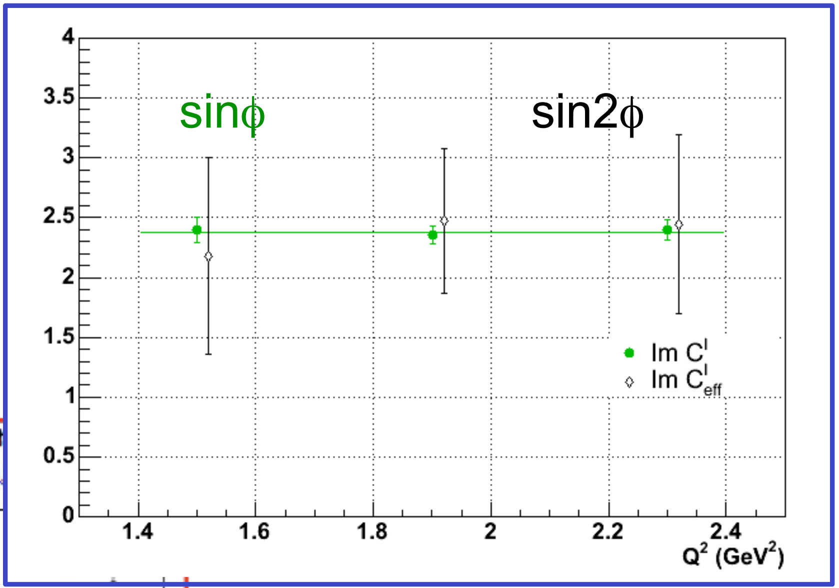
vector mesons (ρ,ω):

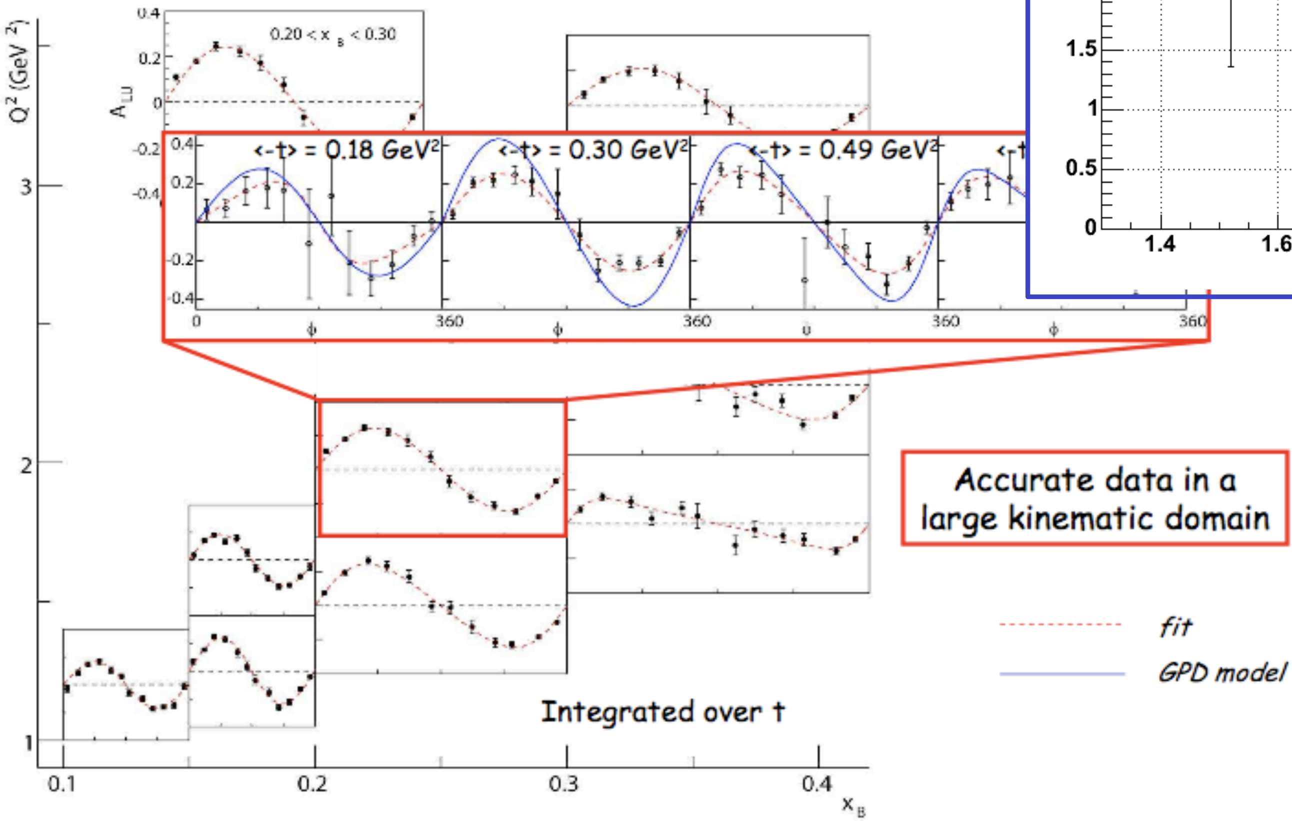
$$H, E$$

Note: need σ_L

6 GeV Highlights - DVCS

Hall A → Beam helicity dependent cross sections independent of Q^2





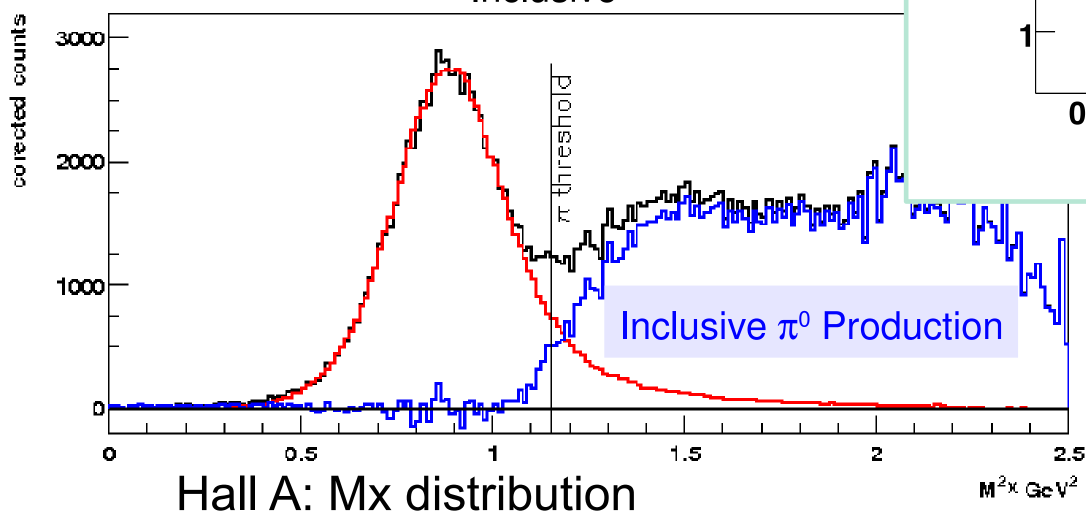
Hall B – Large phase space in one experiment

6 GeV Highlights – π^0

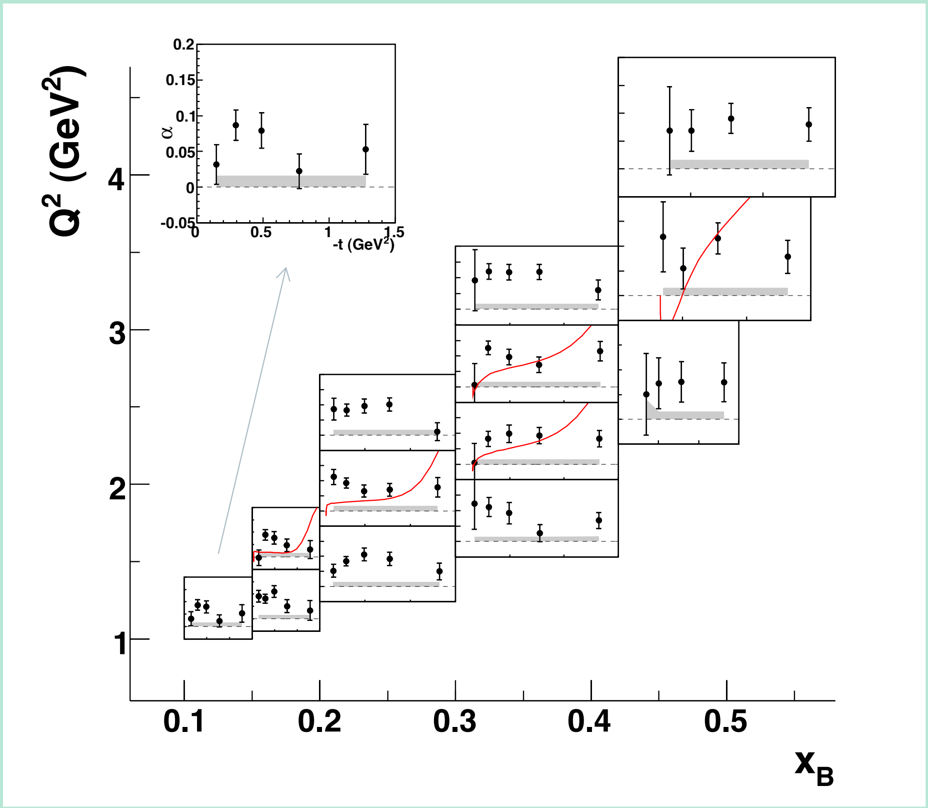
Initial results on π^0 cross sections and beam-spin asymmetries from Hall A and B suggest transverse photon contributions not zero

→ LT separation required

Inclusive

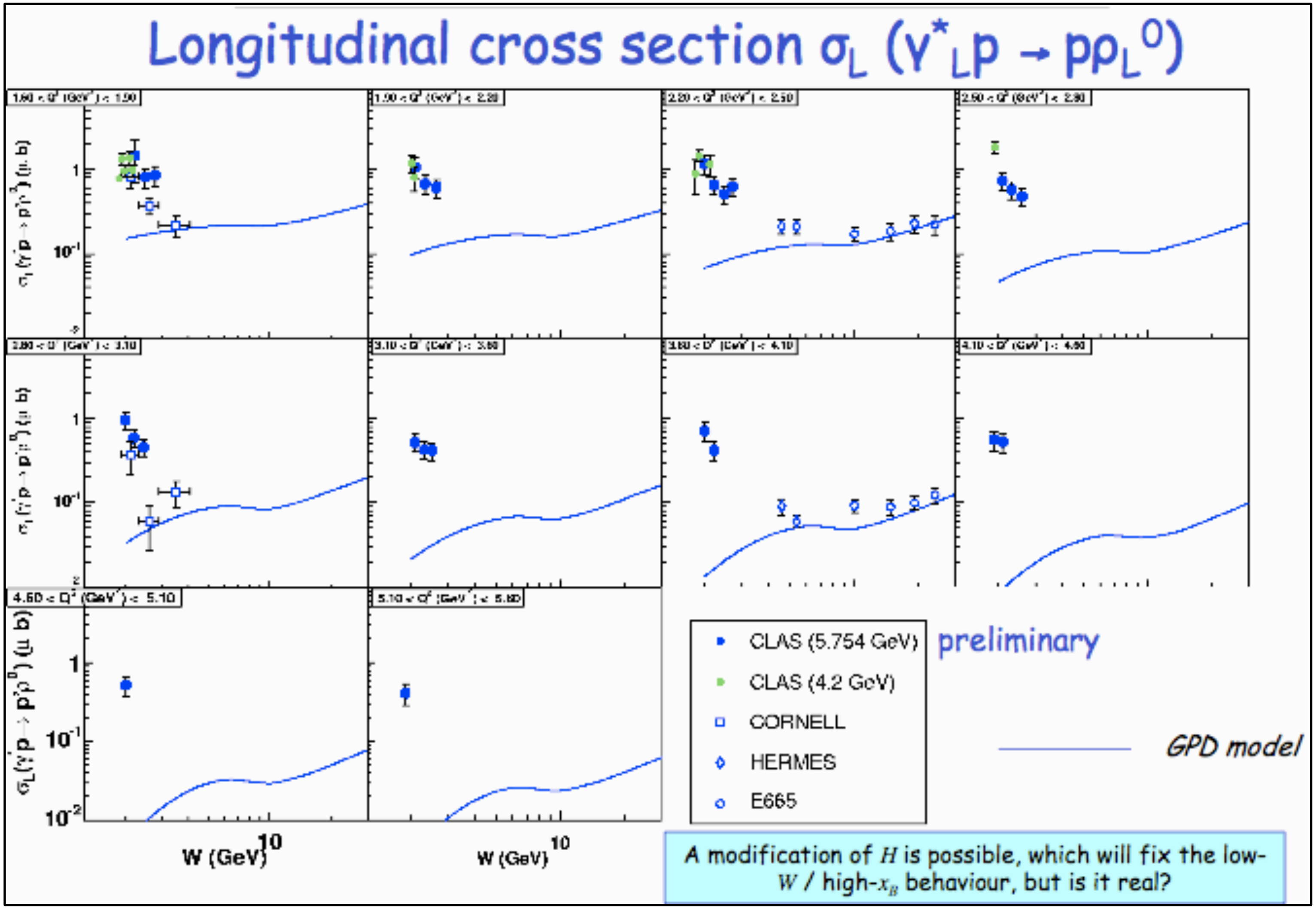


Hall A: Mx distribution



Hall B: $\sigma_{LT'}$

6 GeV Highlights – Vector Mesons



More to come at 6 GeV

Hall B:

1. DVCS beam spin asymmetry → double statistics
2. DVCS longitudinal target asymmetry
3. DVCS transverse target asymmetry (maybe using HD-ice target?)

Hall A:

→ "LT like" separation of terms in DVCS cross section
→ Same experiment will also attempt LT for π^0

Hard Exclusive Reactions at 12 GeV

Approved experiments (so far – PACS 30 and 32)

Deeply Virtual Compton Scattering with CLAS at 11 GeV (E12-06-119)

Measurements of the Electron Helicity Dependent Cross Sections of Deeply Virtual Compton Scattering with CEBAF at 12 GeV (E12-06-114)

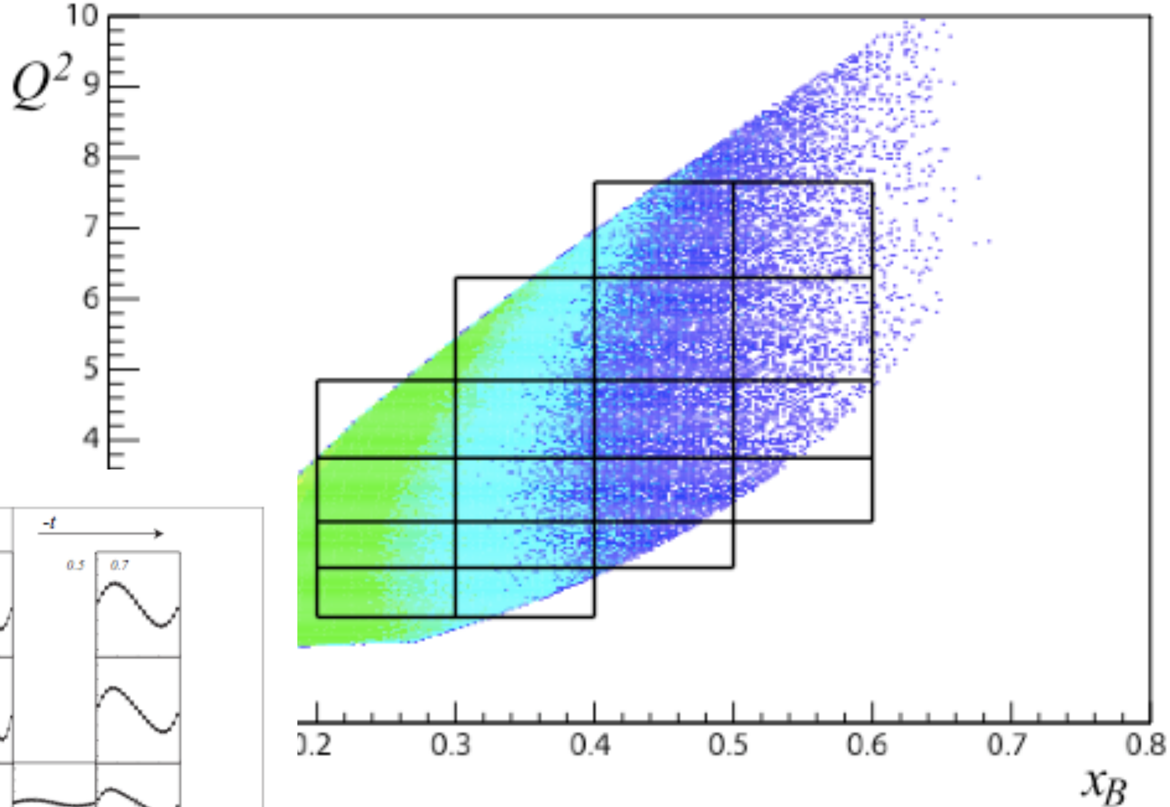
Hard Exclusive Electroproduction of π^0 and η with CLAS12 (E12-06-108)

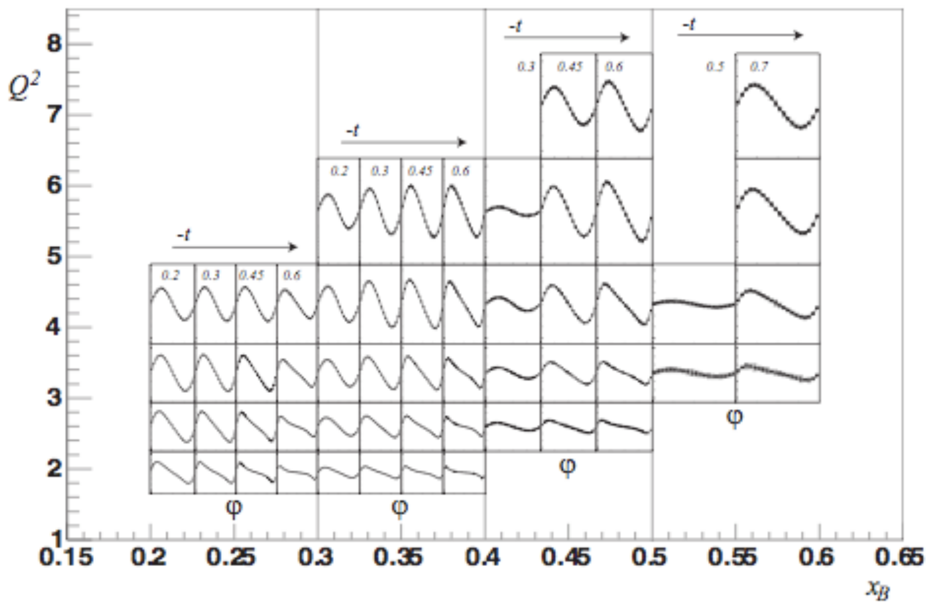
Scaling Study of the L-T Separated Pion Electroproduction Cross Section at 11 GeV (E12-7-105)

DVCS in Hall B

12 GeV Hall B experiment builds on 6 GeV experiment → expanded Q^2 and x range

Max Q^2: 4 GeV^2 → 6 GeV^2
Max x: 0.4 → 0.6

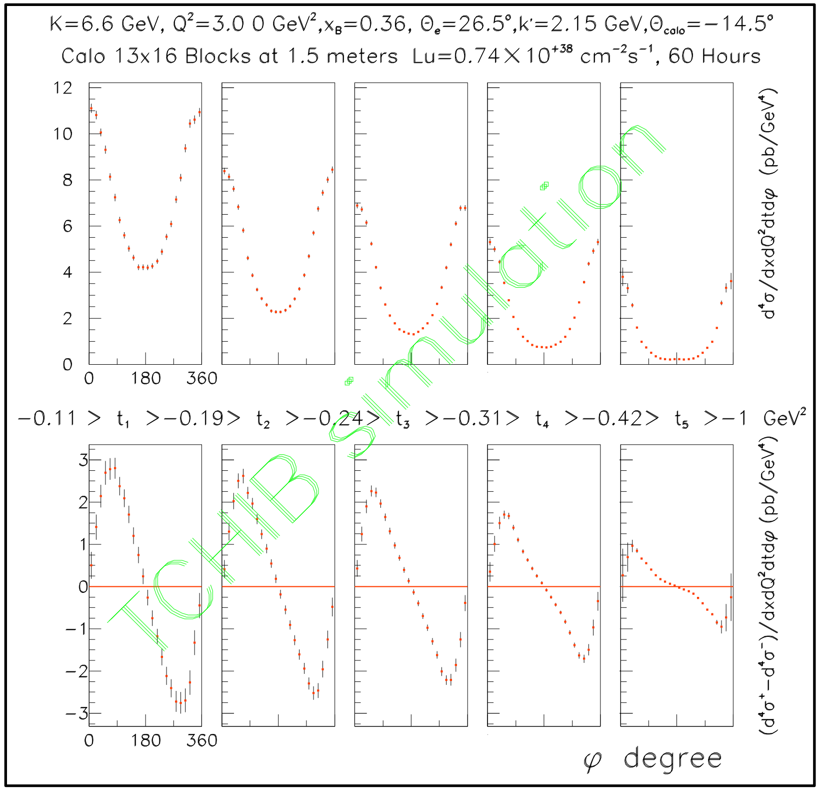


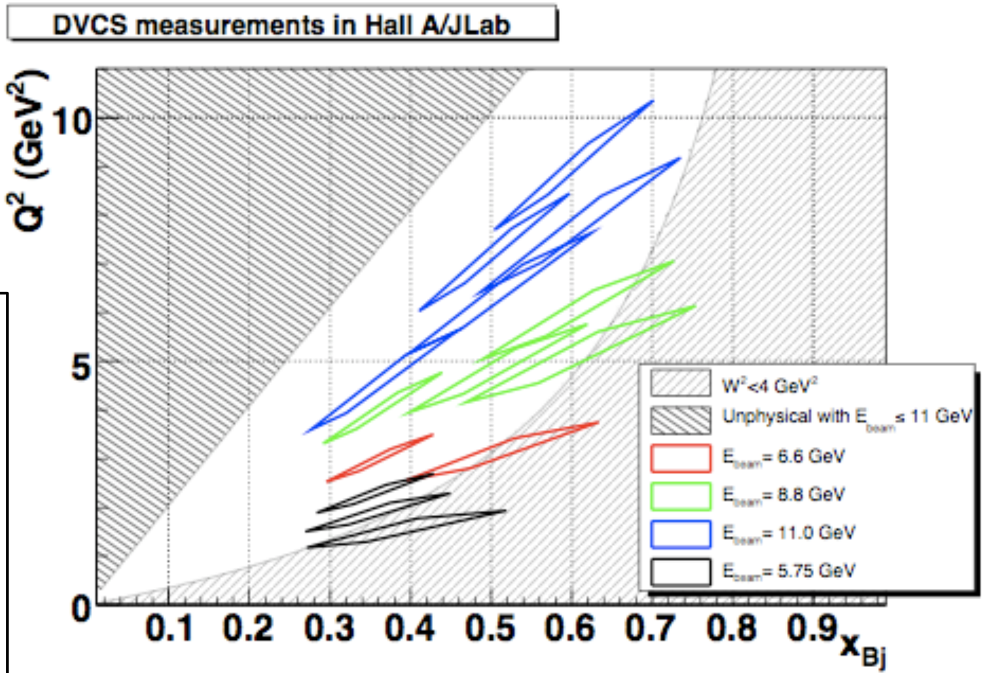


12 GeV proposal includes measurements with polarized target

DVCS in Hall A

12 GeV experiment features greatly expanded kinematic coverage



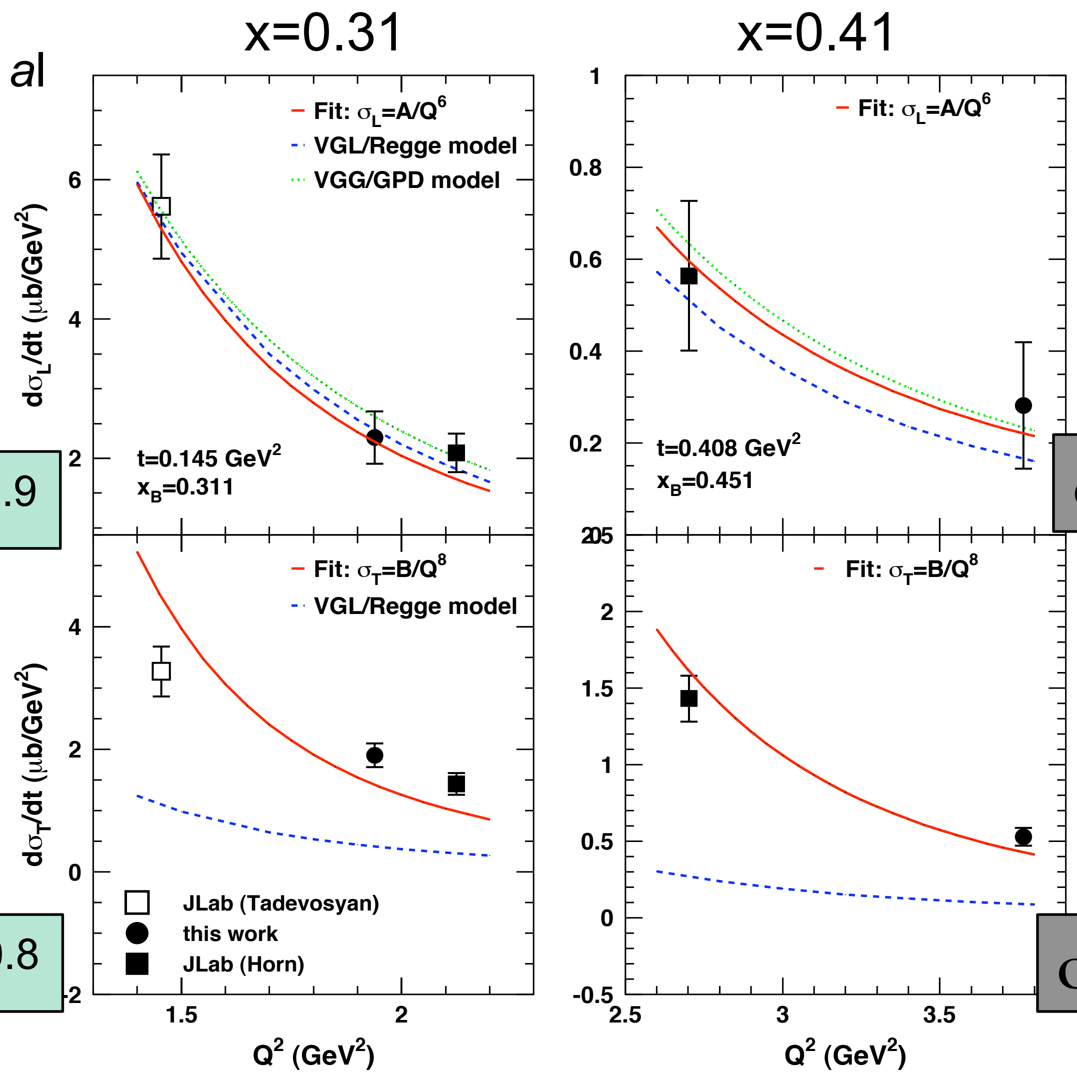


Extract twist-2 and twist-3 BH-DVCS interference terms

Extract π^0 cross sections → ***assume σ_L dominance in extracting GPDs***

Q^2 dependence of π^+ σ_L, σ_T

Hall C: Horn *et al*



$\sigma_L \sim 1/Q^{5.1+/-0.9}$

$\sigma_T \sim 1/Q^{4.2+/-0.8}$

$\sigma_L \sim 1/Q^{4.2+/-2.9}$

$\sigma_T \sim 1/Q^{6.0+/-0.9}$

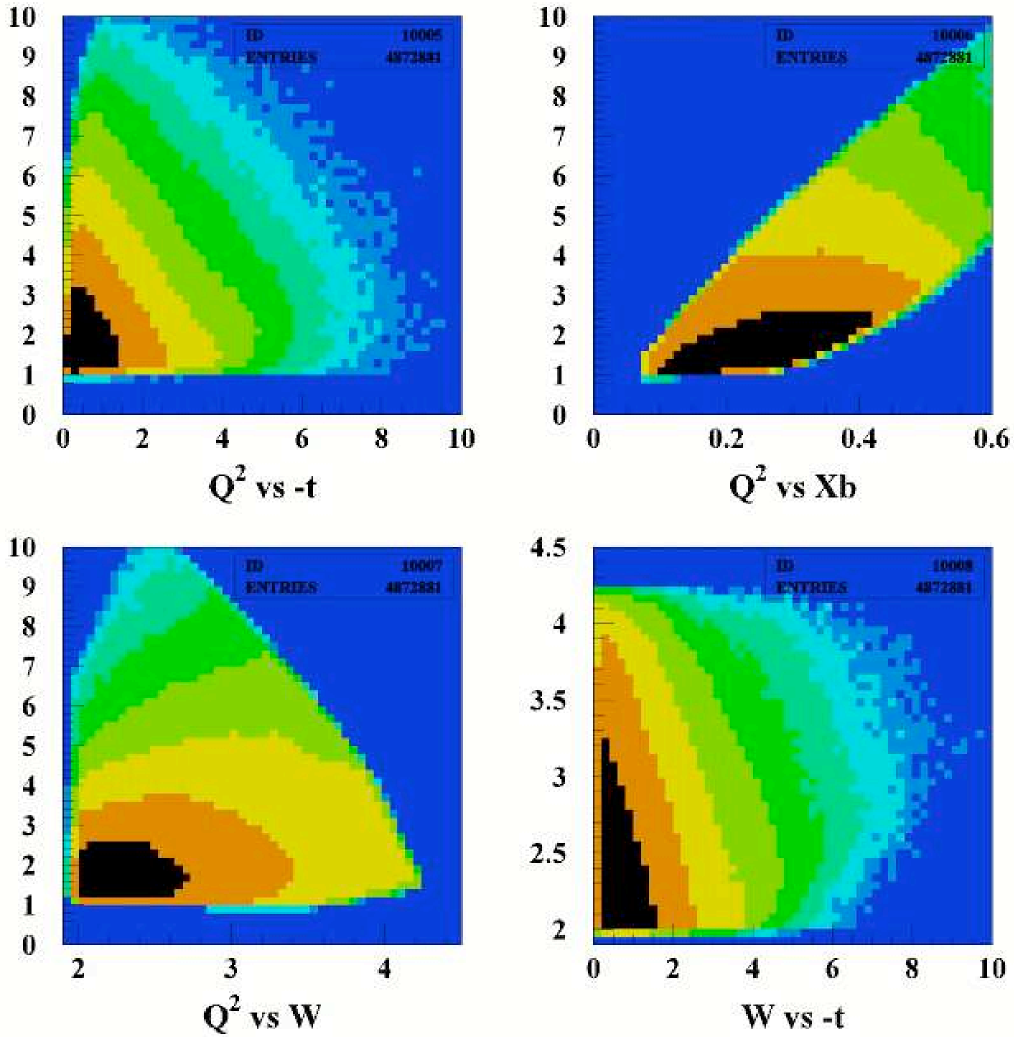
For π^+, σ_L is not even close to dominating at Q^2=4 GeV^2

Meson Production Hall B

Measure cross sections for π^0 and η electroproduction

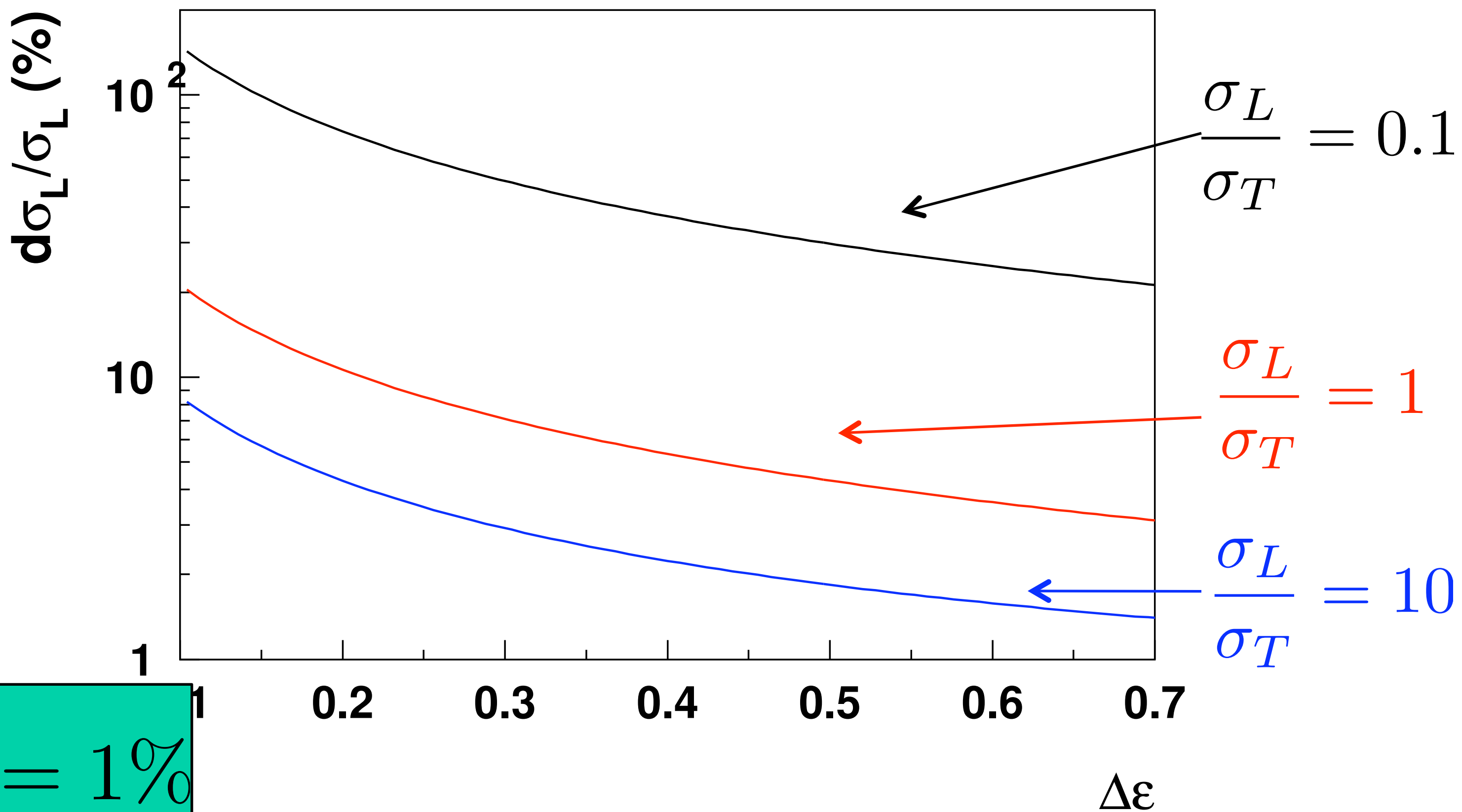
→$\sigma_T + \varepsilon\sigma_L$
→$\sigma_{L,}$ σ_T separation
→$\sigma_{TT,}$ $\sigma_{LT,}$ $\sigma_{LT'}$

Study Q^2 (at low $-t$) dependence of all to look for evidence of factorization



σ_L Uncertainties

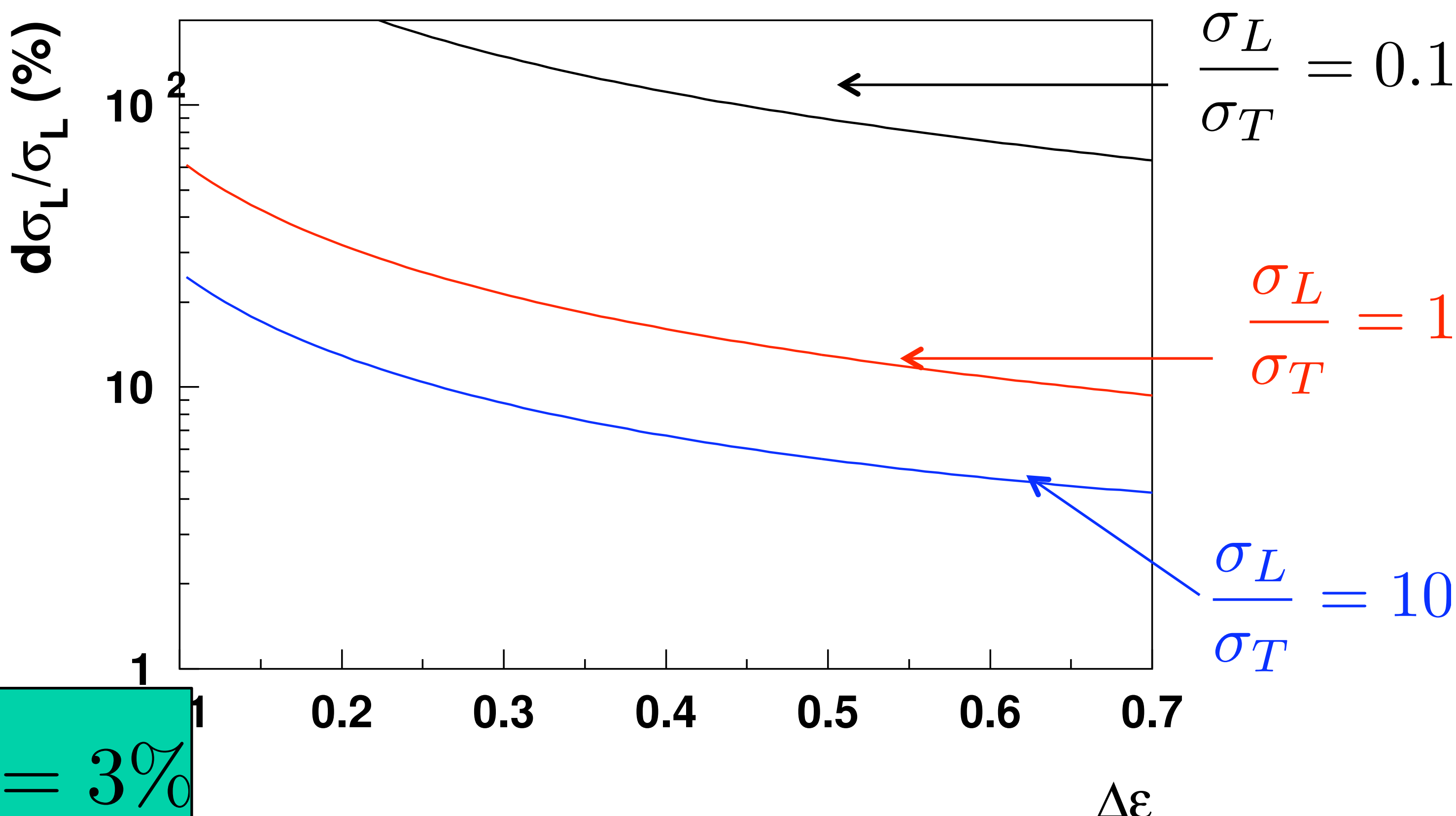
$$\frac{d\sigma_L}{\sigma_L} = \frac{d\sigma}{\sigma}\frac{1}{\epsilon_1 - \epsilon_2}\sqrt{(1/R+\epsilon_1)^2 + (1/R+\epsilon_2)^2}$$



$$\frac{d\sigma}{\sigma} = 1\%$$

σ_L Uncertainties

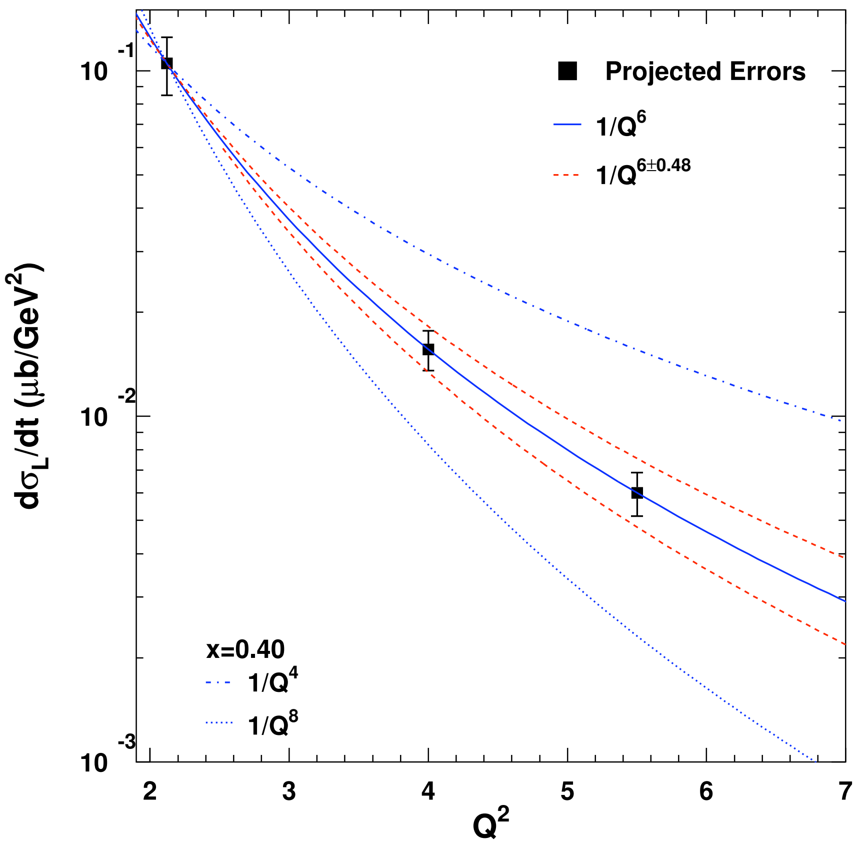
$$\frac{d\sigma_L}{\sigma_L} = \frac{d\sigma}{\sigma}\frac{1}{\epsilon_1 - \epsilon_2}\sqrt{(1/R+\epsilon_1)^2 + (1/R+\epsilon_2)^2}$$

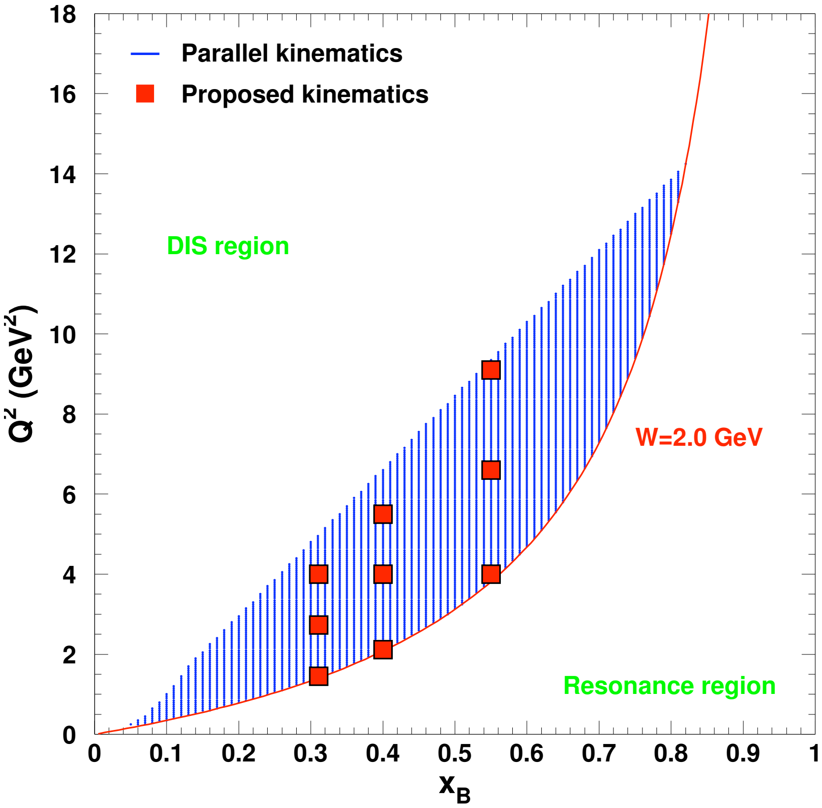


$$\frac{d\sigma}{\sigma} = 3\%$$

Charged Pion Production Hall C

Separated cross sections in π^+ production → examine Q^2 dependence at fixed *x,-t* to test $1/Q^6$ scaling





Additional test data for π^-, perhaps L-T ratio more favorable

Hard Exclusive Processes: what's missing?

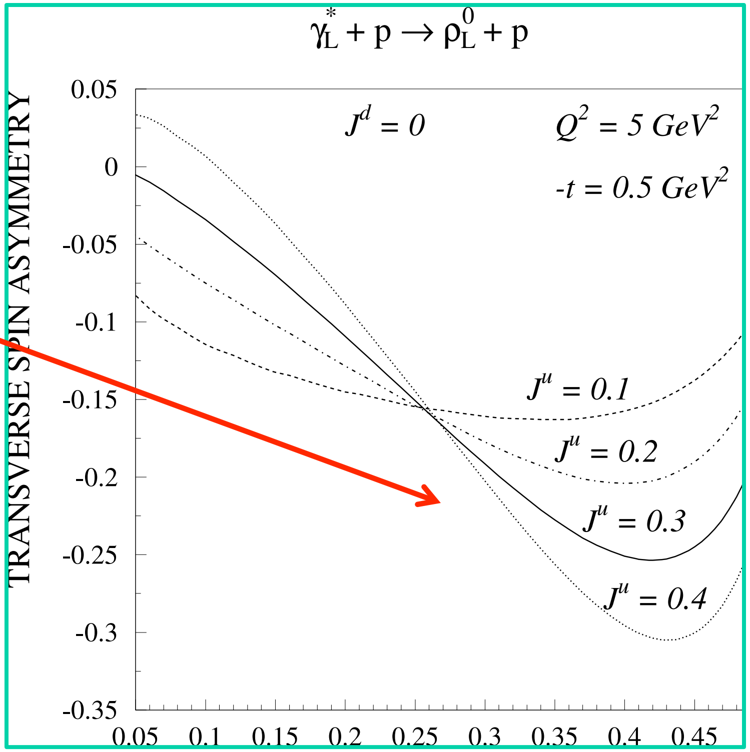
Transverse target asymmetries
→ DVCS → access to *E*
→ Pseudoscalar and vector meson production

Important for mesons in particular: factorization not expected to set in until very large Q^2

Need the ratio of 2 (longitudinal) observables to take advantage of "precocious" factorization

Vector mesons? → most straightforward way to get at Ji sum rule?

And what about strangeness? → kaons!



Semi-inclusive processes

Interest in semi-inclusive processes dominated originally by potential use in “flavor” tagging

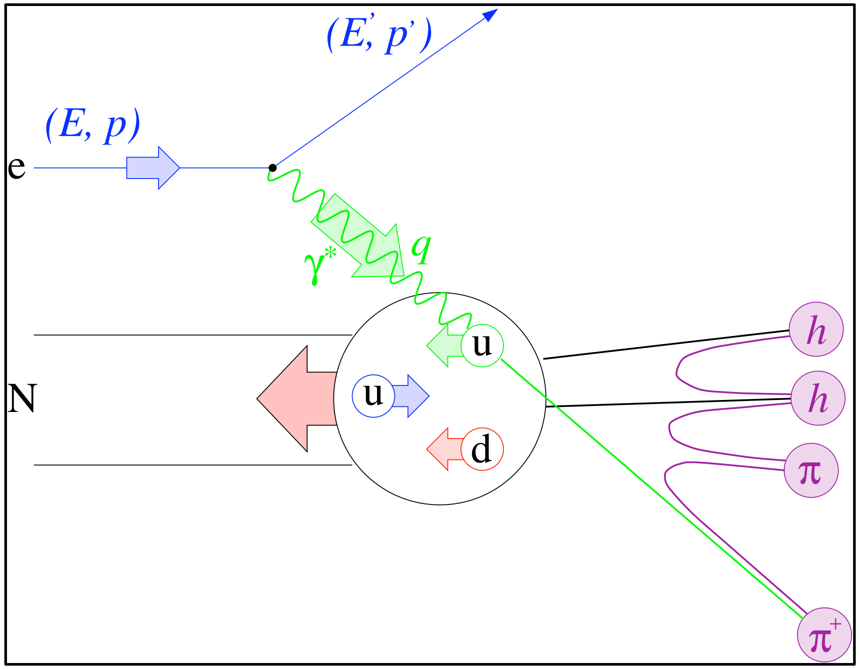
→ deconvolution of polarized PDFs

→ constraints on unpolarized sea

More recently, interest has grown in azimuthal asymmetries

→Transversity distribution

→ Transverse Momentum Distributions (TMDs)



$$\sigma \sim \sum_f e_f^2 q_f(x) D_f^h(z)$$

parton distribution

fragmentation function

Distribution Functions

N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	$h_1 \, h_{1T}^{\perp}$

quarks

nucleon

Diagonal elements = usual PDFs
Unpolarized nucleon → unpolarized quarks: u(x), d(x), …
Longitudinally polarized nucleon → long. pol. quark: Δu(x), Δd(x),..
Transversely polarized nucleon → trans. pol. quark: transversity distribution

Distribution Functions

N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	$\mathrm{h}_1 \, h_{1T}^{\perp}$

quarks

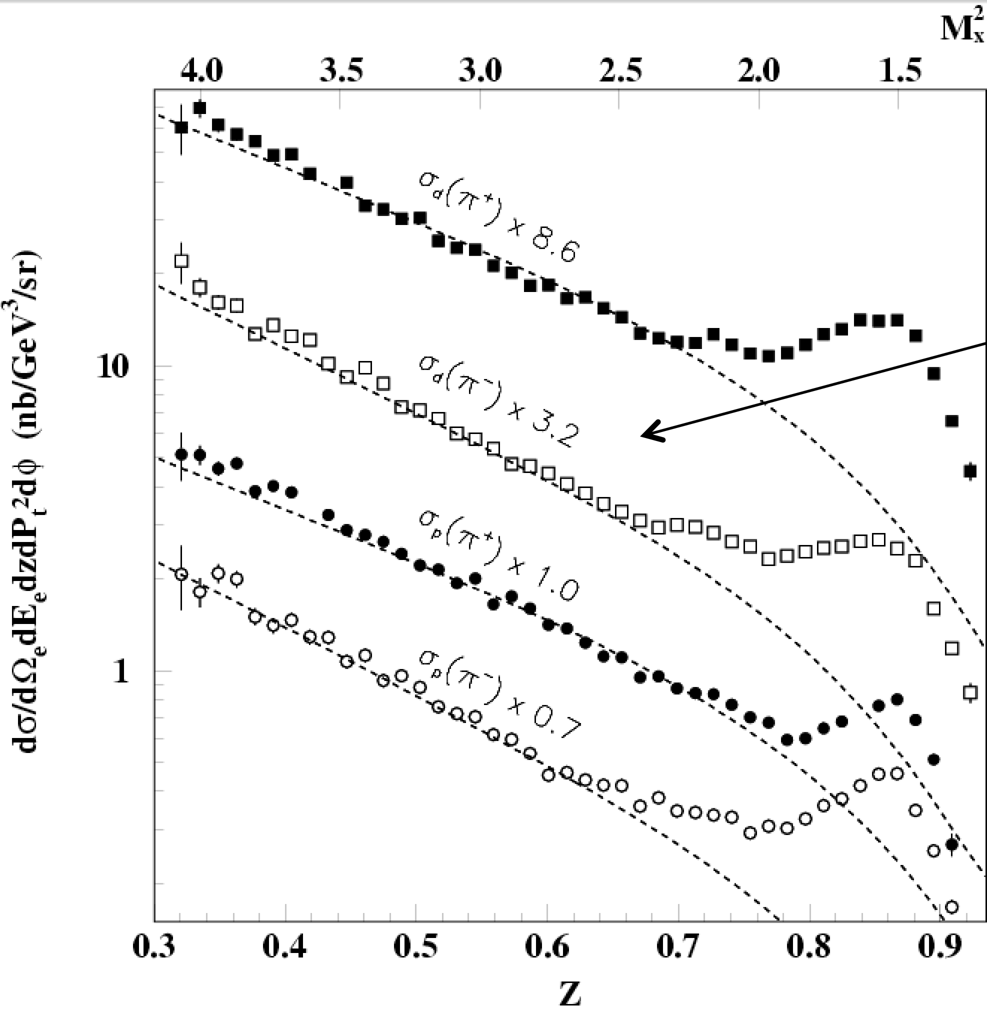
nucleon

Off-diagonal elements = transverse momentum distributions, require non-zero angular momentum

$f_{1T}^{\perp}$ → Sivers function, describes unpolarized quark in trans. pol. nucleon

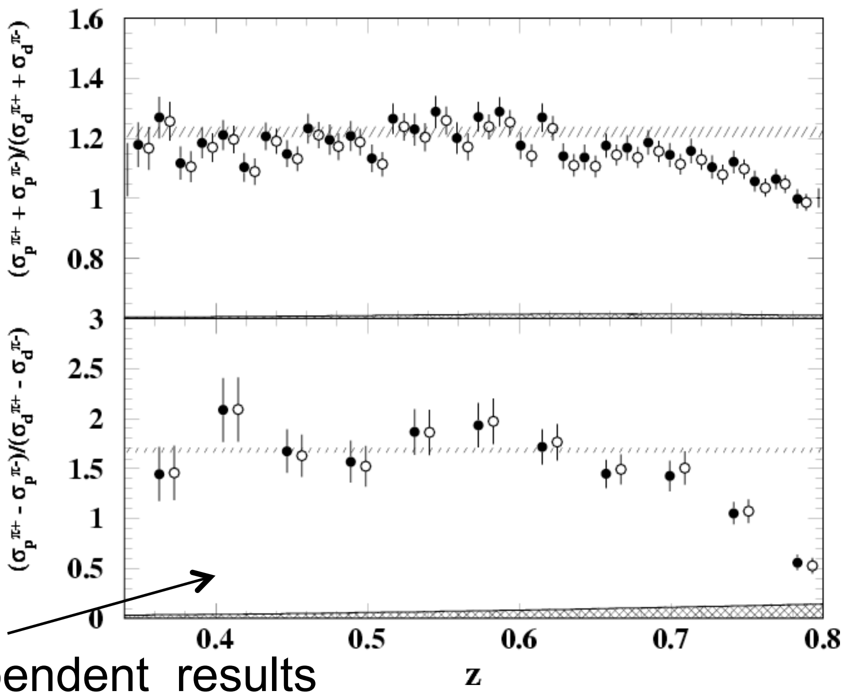
$h_1^{\perp}, h_{1L}^{\perp}, h_{1T}^{\perp}$ → Boer-Mulders functions describe transversely polarized quarks in un/long./trans./polarized nucleon

6 GeV Highlights – Meson Duality



ep,d→e'$\pi^{+/-}$X in Hall C

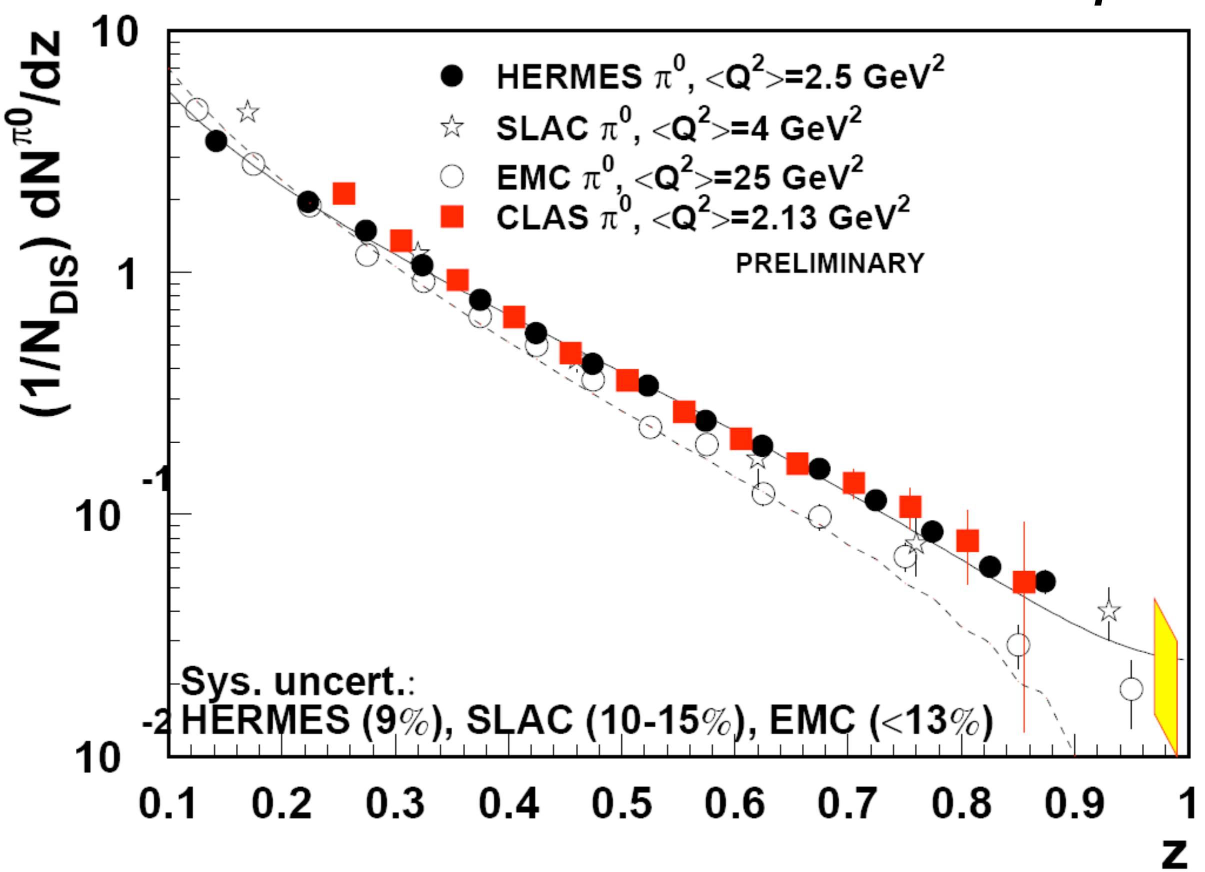
Low energy semi-inclusive cross sections consistent with calculation using high energy params. of frag. functions and cteq PDFs (z<0.7)



Combinations of D/p,π^+/π^- yields give z-independent results

6 GeV Highlights – Hall B Multiplicities

$ep \rightarrow e'\pi^0 X$

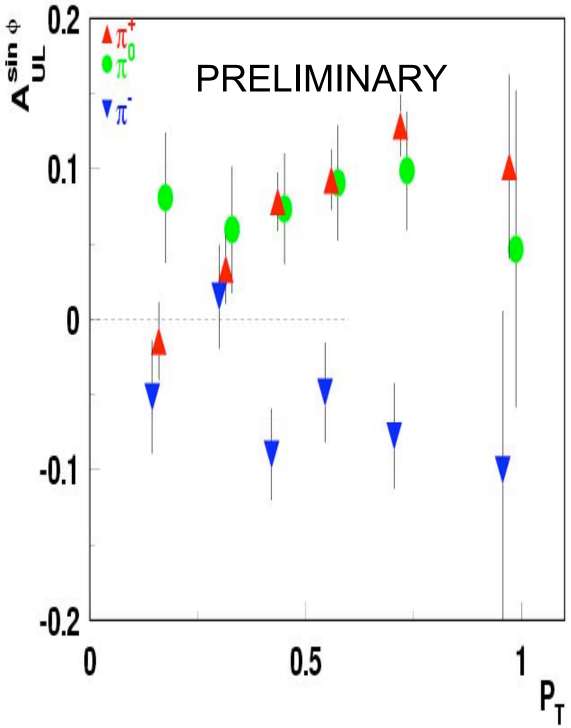


π^0 multiplicities in CLAS consistent with higher energy data

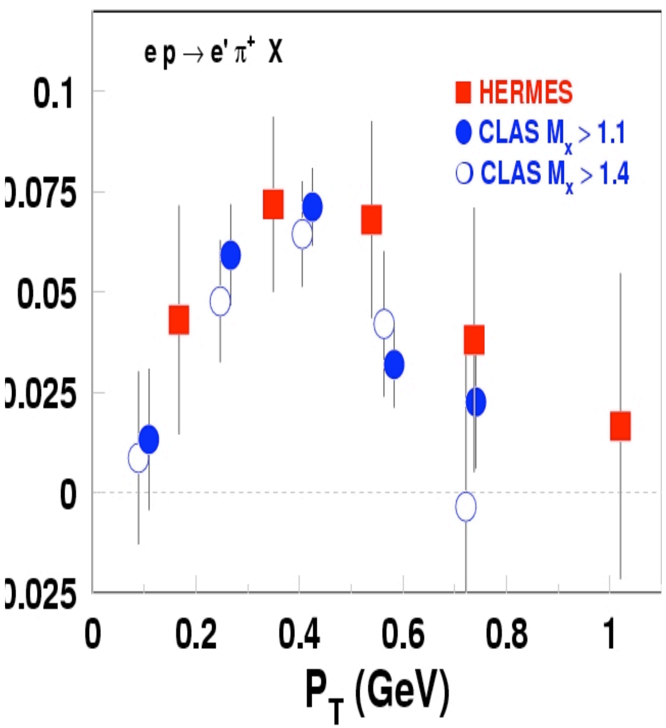
6 GeV Highlights – Hall B Azimuthal Asy.

$\sigma^{\sin\phi}_{LU(UL)} \sim F_{LU(UL)} \sim 1/Q$ (Twist-3)

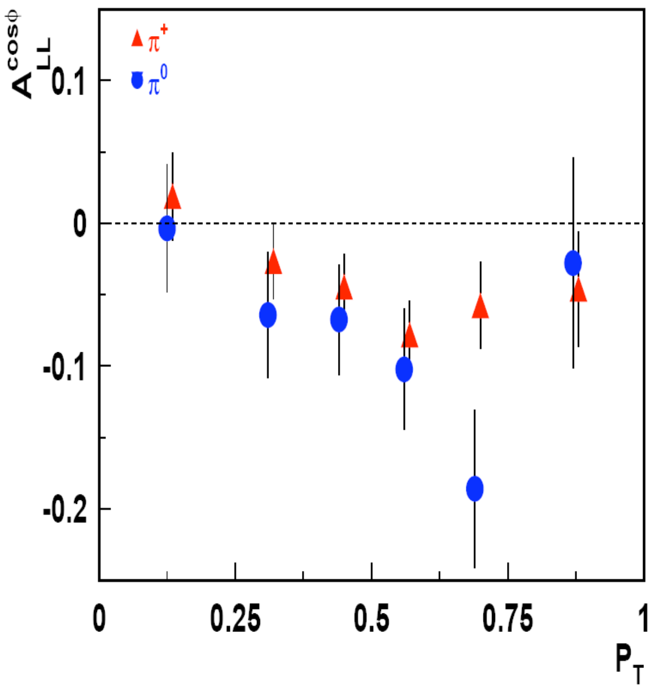
A_{UL} (CLAS @5.7 GeV)



A_{LU} CLAS @4.3 GeV



A_{LL} CLAS @5.7 GeV



$A^{\sin\phi}_{UL} \propto f_L^{\perp} D_1$ $\quad A^{\sin\phi}_{UL} \propto g^{\perp} D_1$ $\quad A^{\cos\phi}_{LL} \propto g_1 D_1$

More to come at 6 GeV

Hall A

1. Transversity in fall 2008 (polarized ^{3}He)
2. Flavor asymmetry in nucleon sea $\bar{d} - \bar{u}$ (conditionally approved – run before 12 GeV?)

Hall B

1. More data on longitudinally polarized targets (x10 stats)
2. Transversely polarized target (along w/DVCS – see earlier)

Hall C

1. Semi-sane – data from longitudinally polarized targets to constrain Δu, Δd…

→ *out of time before HKS/Q_{weak}, will take data parasitically during $g1_D$*

Semi-inclusive Reactions at 12 GeV

Approved experiments (so far – PACS 30 and 32)

Measurement of the Ratio $R=\sigma_L/\sigma_T$ in Semi-Inclusive Deep-Inelastic Scattering (E12-06-104)

Probing the Proton's Quark Dynamics in Semi-Inclusive Pion Production at 12 GeV (E12-06-112)

Studies of Spin-Orbit Correlations with Longitudinally Polarized Target (E12-07-107)

σ_L/σ_T in Semi-Inclusive Processes

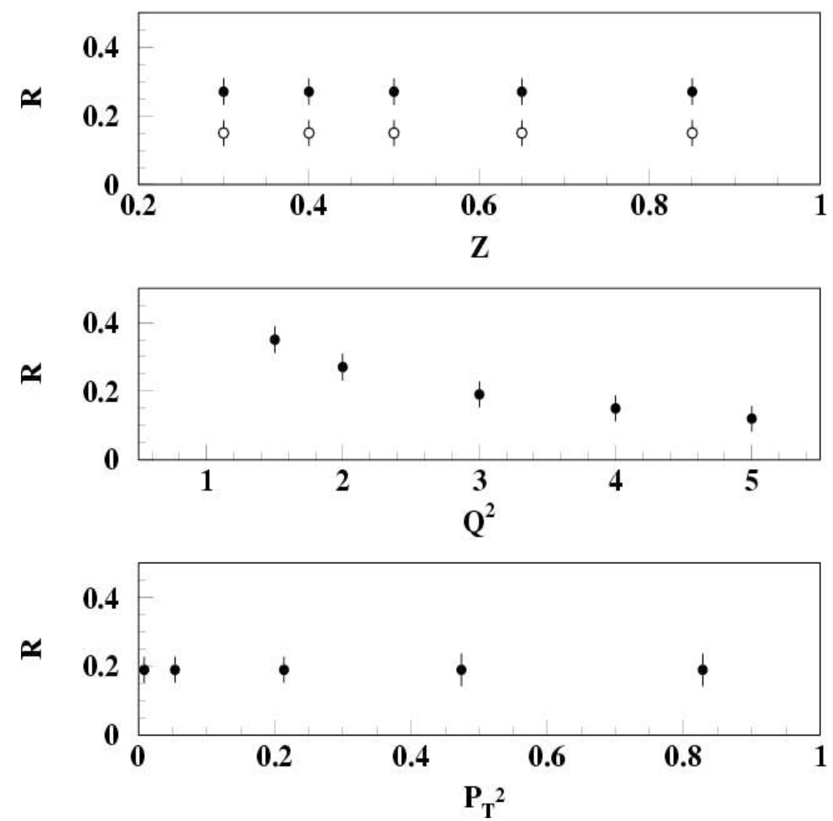
Analysis of semi-inclusive processes to extract polarized PDFs, etc., it is usually assumed that

$R=\sigma_L/\sigma_T$

for *semi-inclusive* similar to R for *inclusive* DIS

→No experimental verification that this assumption is true (except for low precision Cornell data)

Exclusive limit *(z=1)* : σ_L expected to dominate – how does this set in?



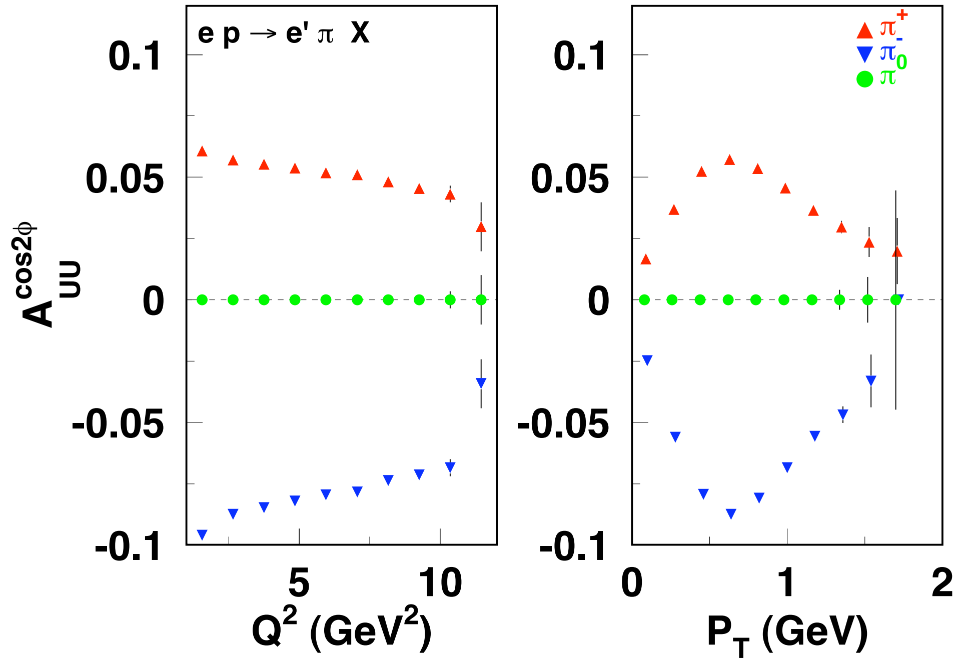
Unpolarized Azimuthal Moments in Hall B

cos2ϕ moment of semi-inclusive cross section from unpolarized target

$$\sigma_{UU}^{cos2\phi} \propto 2(1-y)cos2\phi \sum_{q,\bar{q}} e_q^2 x h_1^{\perp q}(x) H_1^{\perp q}(z)$$

Boer-Mulders function

Collins Fragmentation Function



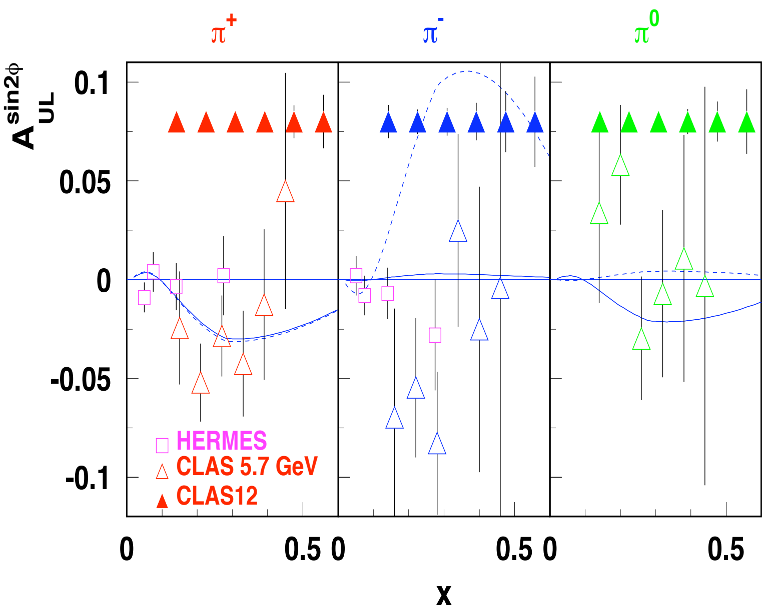
Contains information on Collins fragmentation function and TMD: related to interference of L=0 and L=1 wave functions

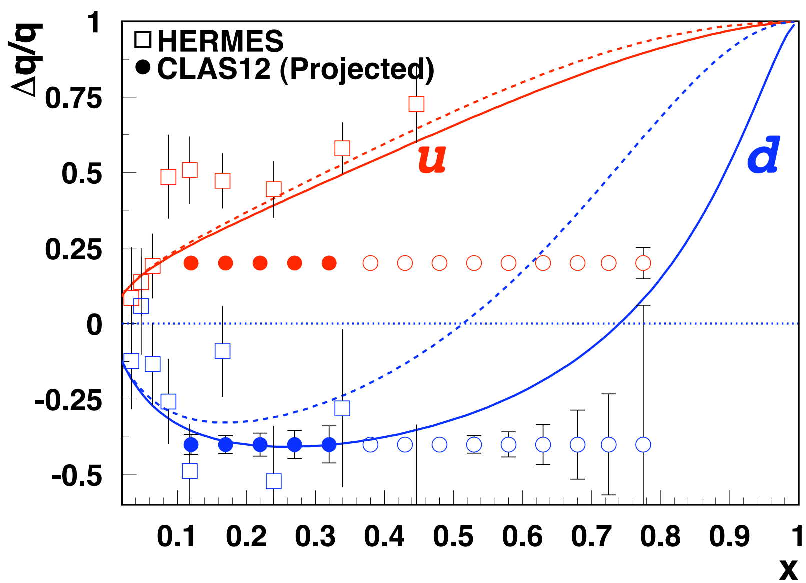
Polarized Target in Hall B

sin2ϕ moment of semi-inclusive cross section from long. pol. target

$$\sigma_{UL}^{sin2\phi} \propto S_L 2(1-y) sin2\phi \sum_{q,\bar{q}} e_q^2 x h_{1L}^{\perp q}(x) H_1^{\perp q}(z)$$

→Single spin asymmetry contains information on alternate Boer-Mulders function
→Double spin asymmetry yields polarized quark distributions





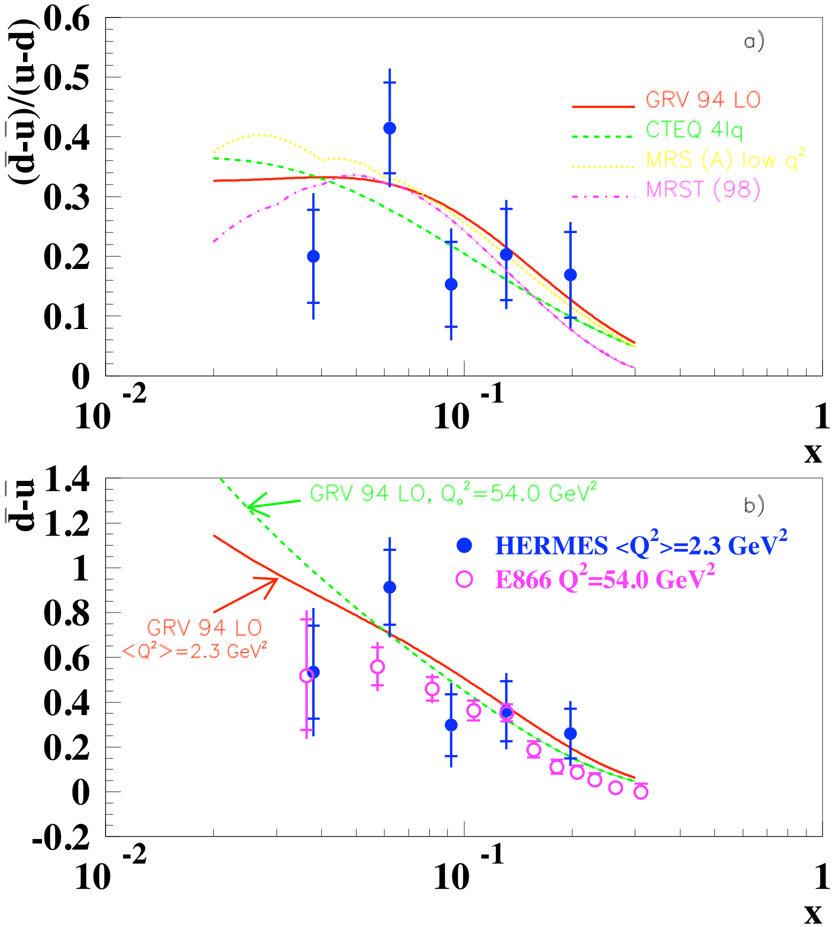
Factorization at JLab

Agreement of JLab 6 GeV data with higher energy measurements/ expectations suggests factorization should not be a problem at 12 GeV

Hall C semi-inclusive cross sections
→agree well with simple parameterization using CTEQ and high energy frag. functions

Hall B multiplicities, SSA's
→Agree with EMC, HERMES data

HERMES agreement with E866 measurement of sea asymmetry taken as evidence that factorization works at "modest" energies



Factorization at HERMES

Recent analyses from HERMES suggests that factorization may not be working as well as we thought!

→At x~0.3, good agreement with simple factorization picture is seen

Most JLab measurements so far are in this region or nearby

Maybe we are just “lucky” to see evidence of factorization at 6 GeV?

Must proceed cautiously, even at 12 GeV…

CENSORED

Semi-Inclusive Processes: what's missing?

Measurements with transverse targets

→ Obviously needed for transversity and Sivers effect measurements

Kaons

→ Most measurements so far emphasize pion production

→ Kaons needed for access to $\Delta s(x)$

Sea-asymmetry at 12 GeV? $\bar{d} - \bar{u}$

→ Proposal from PAC30 deferred based in part on questions about factorization (must be satisfied at very precise level)

This is exactly why we should do it! If it works and yields results consistent with E866/E906 Drell-Yan, gives us confidence in 12 GeV semi-inclusive program. If it yields "strange" results, gives information about where more study is needed.

Related Issues/Experiments Not Mentioned

Color transparency

2 experiments approved to study color transparency at 12 GeV

→ Exclusive ρ production in Hall B

→Exclusive π production and e,e'p in Hall C (conditional)

Important for GPD studies: Factorization not possible without the onset of Color Transparency (CT) *[M. Strikman, Nuc. Phys. A663,64 (2000)]*

Hadronization

2 experiments approved to study hadronization in nuclei

→Semi-inclusive production in Hall B

→Semi-inclusive production in Hall C

These experiments use the nucleus as a laboratory to understand how hadrons are formed in semi-inclusive processes (formation time, etc.)

→ Assumptions about factorization crucial as well as implicit assumption that the reaction mechanism is unchanged in nuclei

Conclusions

6 GeV program at JLab has provided first glimpse of physics we can do with hard exclusive, semi-inclusive processes

12 GeV program will provide data of great breadth and unparalleled precision

Our enthusiasm for the exciting physics we can do must be tempered by the knowledge that we must go out of our way to show that "factorization" is observed

→ What else can we do experimentally to convince ourselves and others that we are seeing factorization?
→ What about "precocious factorization"? Q^2 independence of ratios enough?