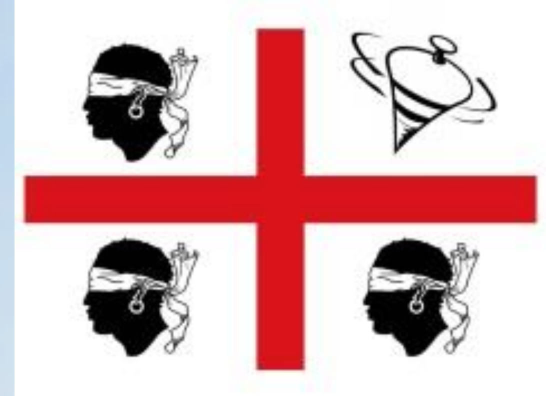


Exclusive Processes at Jefferson Lab at 6 GeV

for Transversity 2014

June 13th, 2014, Chia, Cagliari, Italy

Andrey Kim

University of Connecticut

UCONN | UNIVERSITY OF CONNECTICUT

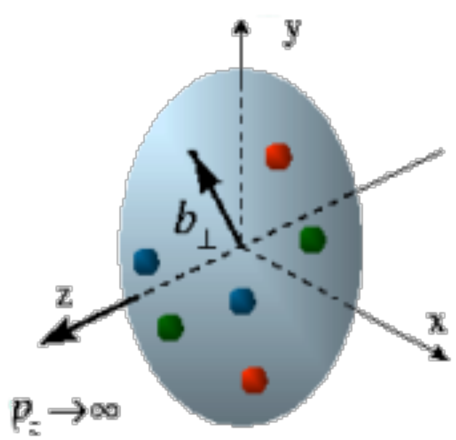
Jefferson Lab

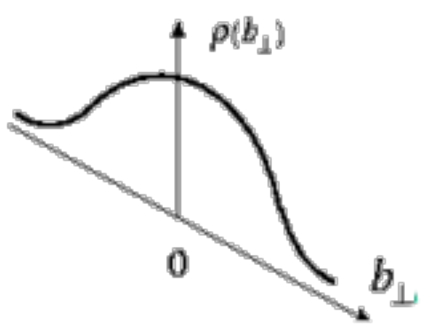
Generalized Parton Distributions

HARD EXCLUSIVE PROCESSES

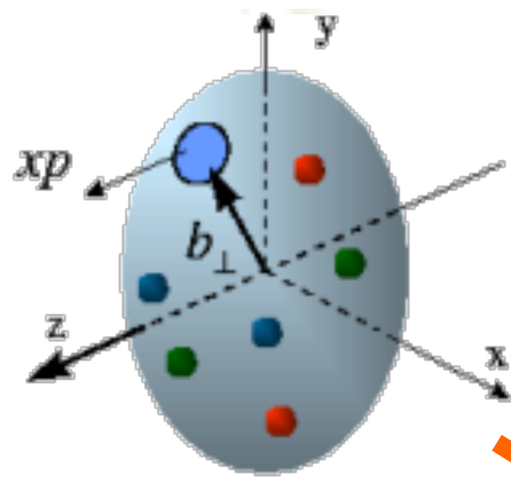
Elastic Scattering

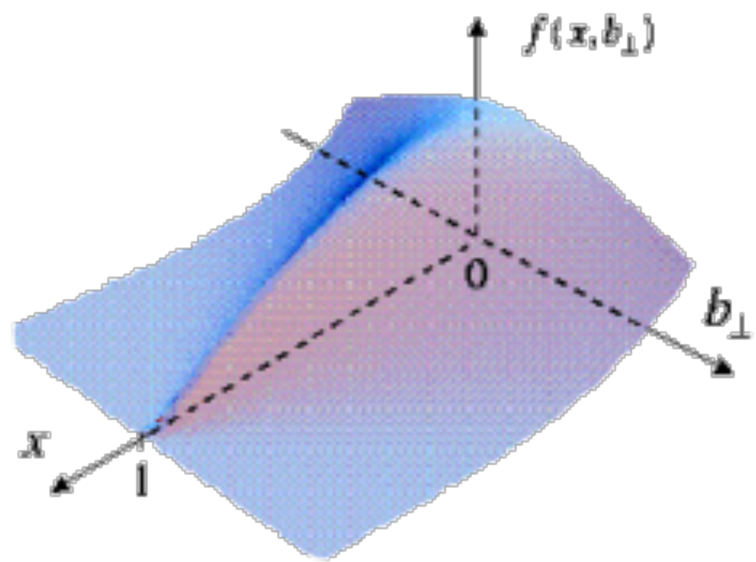
$$\int dx \sum_q H^q(x,\xi,t) = F_1(t)$$
$$\int dx \sum_q E^q(x,\xi,t) = F_2(t)$$
$$\int dx \tilde{H}^q(x,\xi,t) = G_A(t)$$
$$\int dx \tilde{E}^q(x,\xi,t) = G_P(t)$$





Form factors

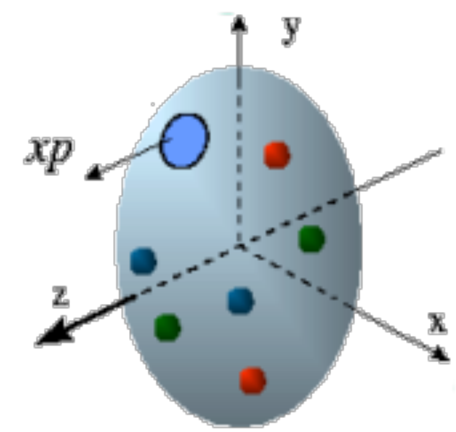


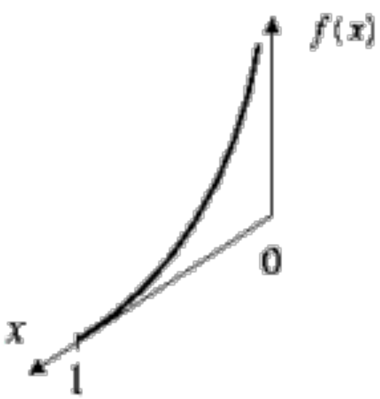


Correlation between quark longitudinal momentum and transverse spatial distributions

Deep Inelastic Scattering

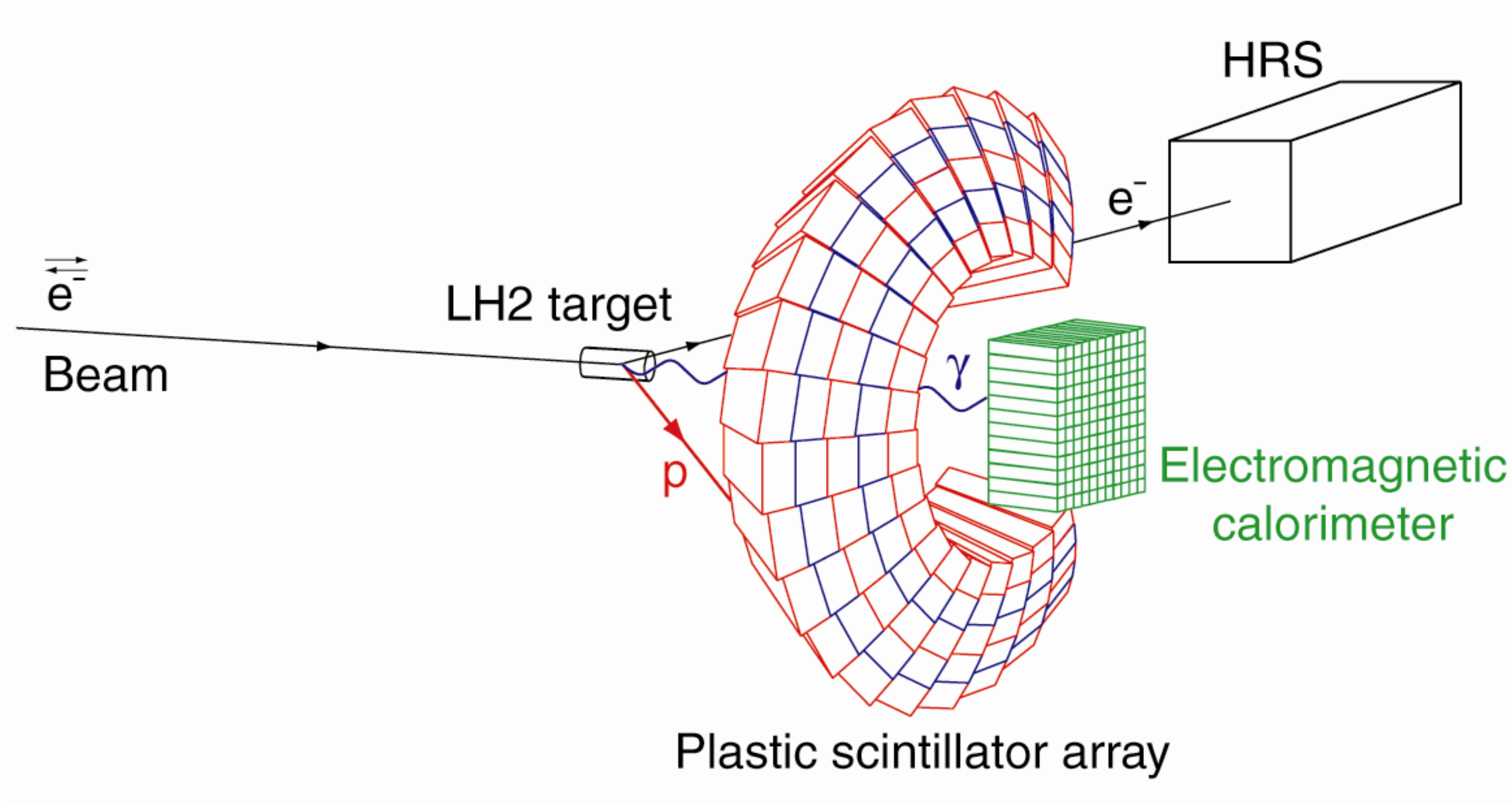
$$H^q(x, \xi = 0, t = 0) = q(x)$$
$$\tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x)$$



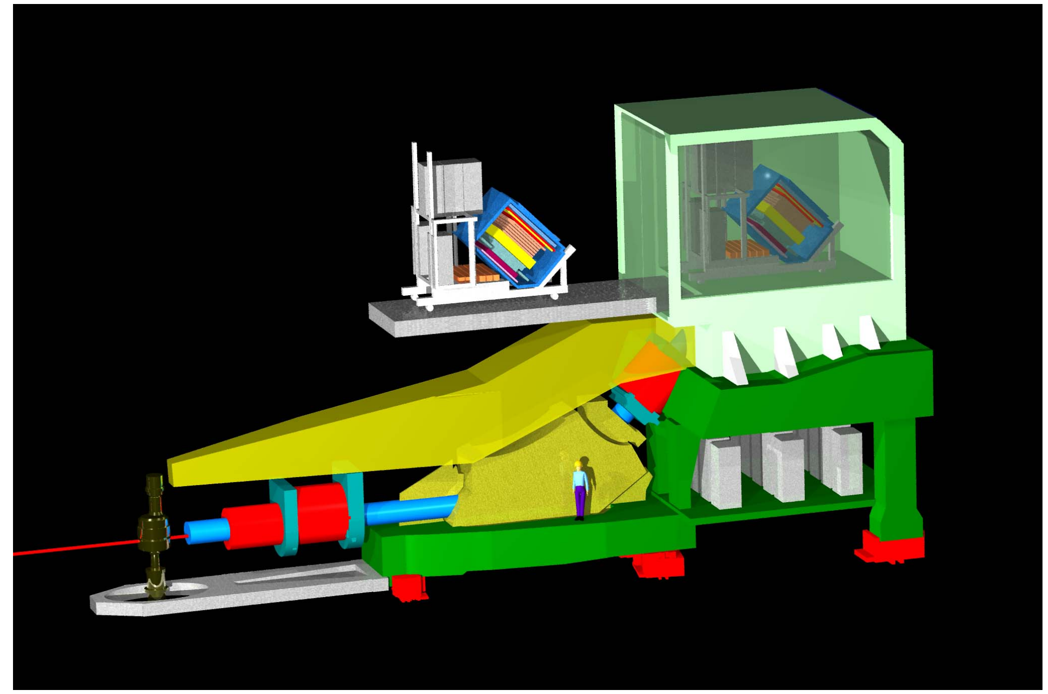


Parton distributions

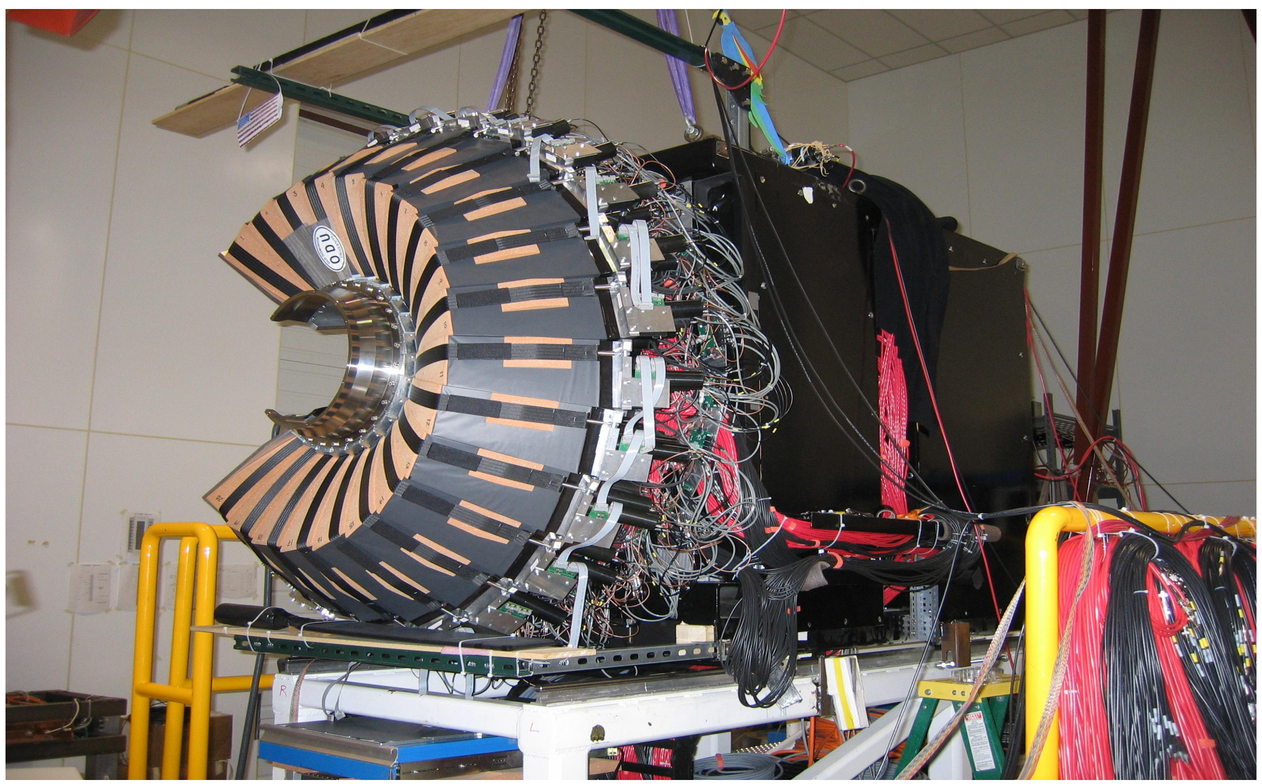
Hall A Experimental Setup at JLab



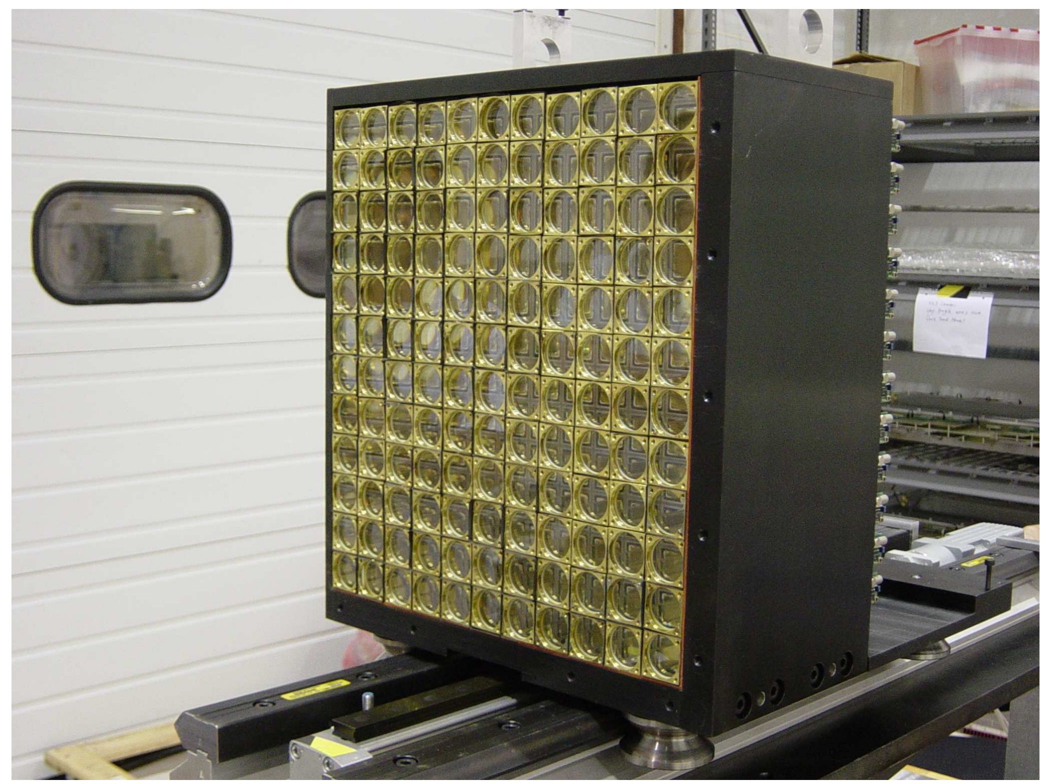
HIGH RESOLUTION SPECTROMETER



100-CHANNEL SCINTILLATOR ARRAY

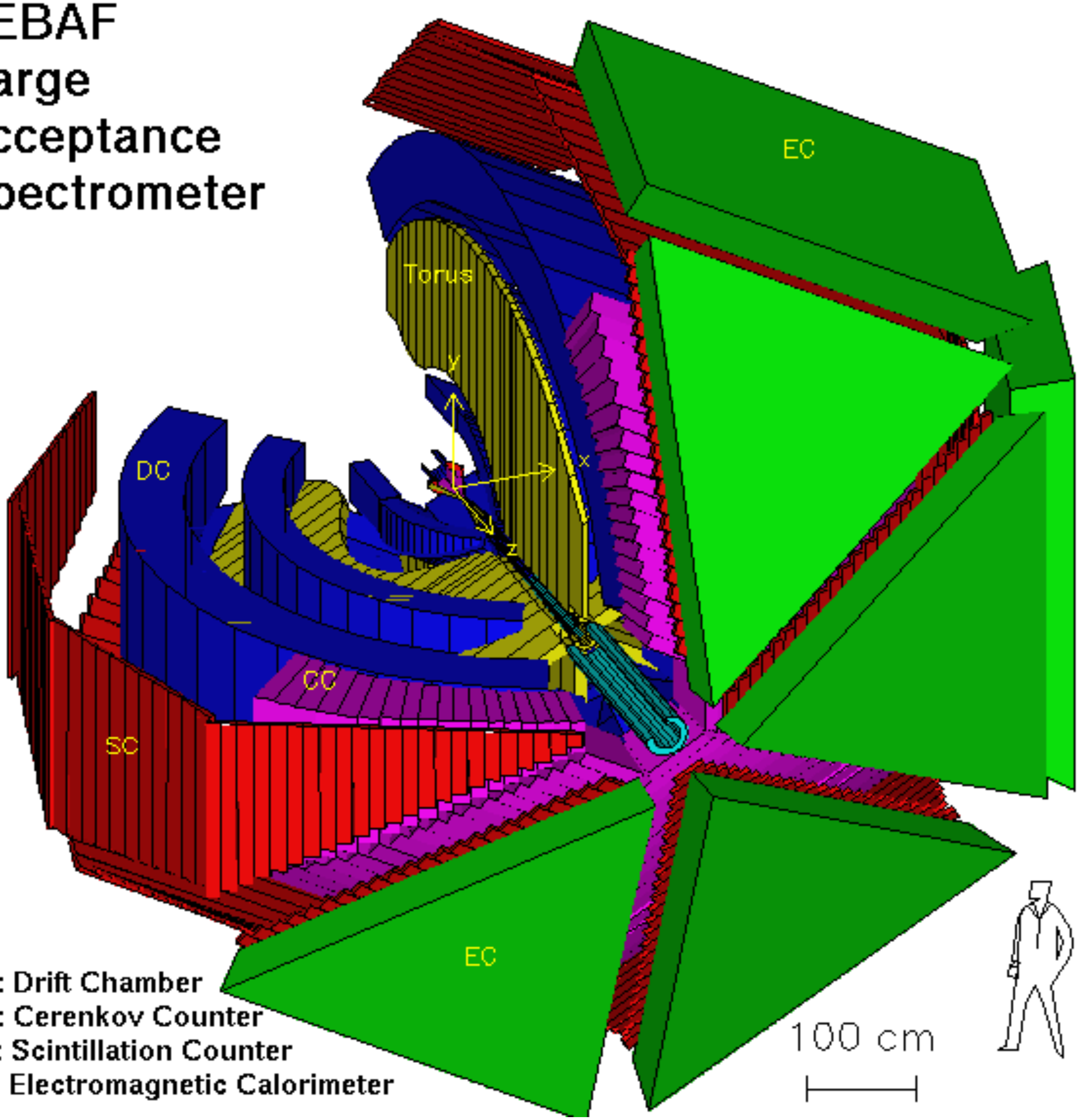


ELECTROMAGNETIC CALORIMETER



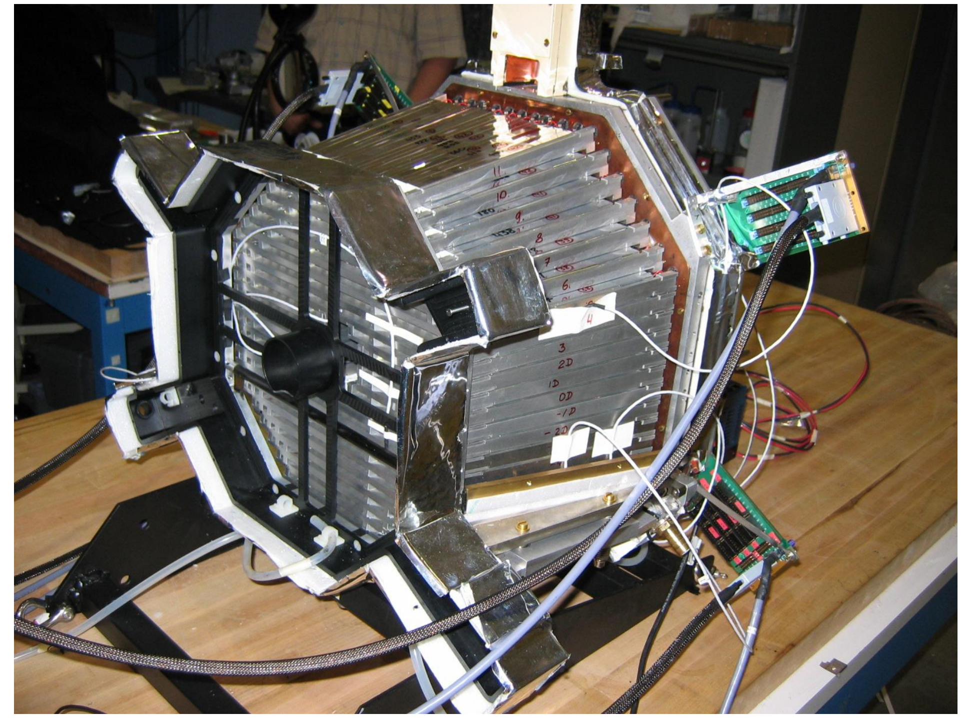
Hall B Experimental Setup at JLab

CEBAF
Large
Acceptance
Spectrometer



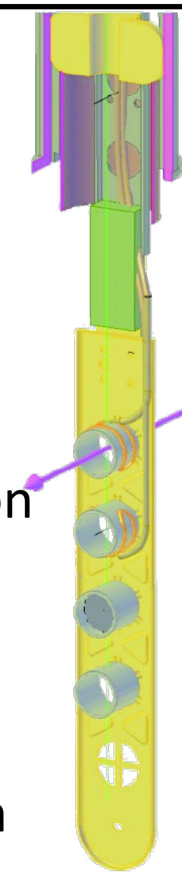
DC: Drift Chamber
CC: Cerenkov Counter
SC: Scintillation Counter
EC: Electromagnetic Calorimeter

IC: Inner Calorimeter



Longitudinally Polarized Target

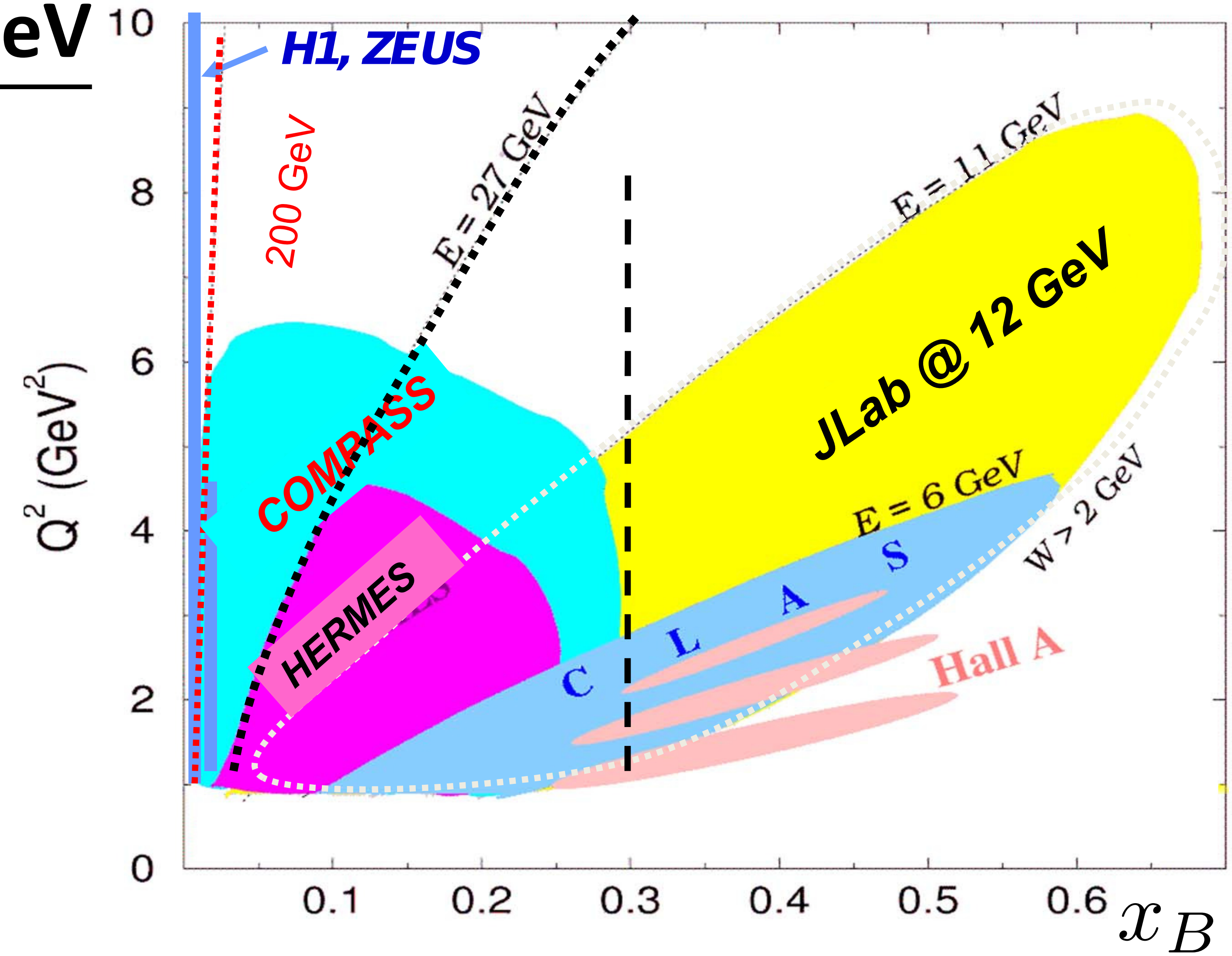
- Frozen ammonia as a target material
- polarized by Dynamic Nuclear Polarization in a 5 Tesla homogeneous magnetic field
- monitored using a Nuclear Magnetic Resonance system



Exclusive Processes at JLab at 6 GeV

✦ Hall A and Hall B (CLAS) at 6 GeV

- ✦ partially: complimentary, overlapping
- ✦ Hall A: high accuracy limited kinematics
- ✦ Hall B: wide kinematic range limited accuracy



✦ The roadmap:

- ✦ Early results (2001) from non-dedicated experiment (CLAS)
- ✦ First round of dedicated experiments in Halls A/B in 2004/2005
- ✦ Second round in 2008-2010
- ✦ Compeling exclusive program in Halls A/B at 12 GeV

DVCS Experimental Observables

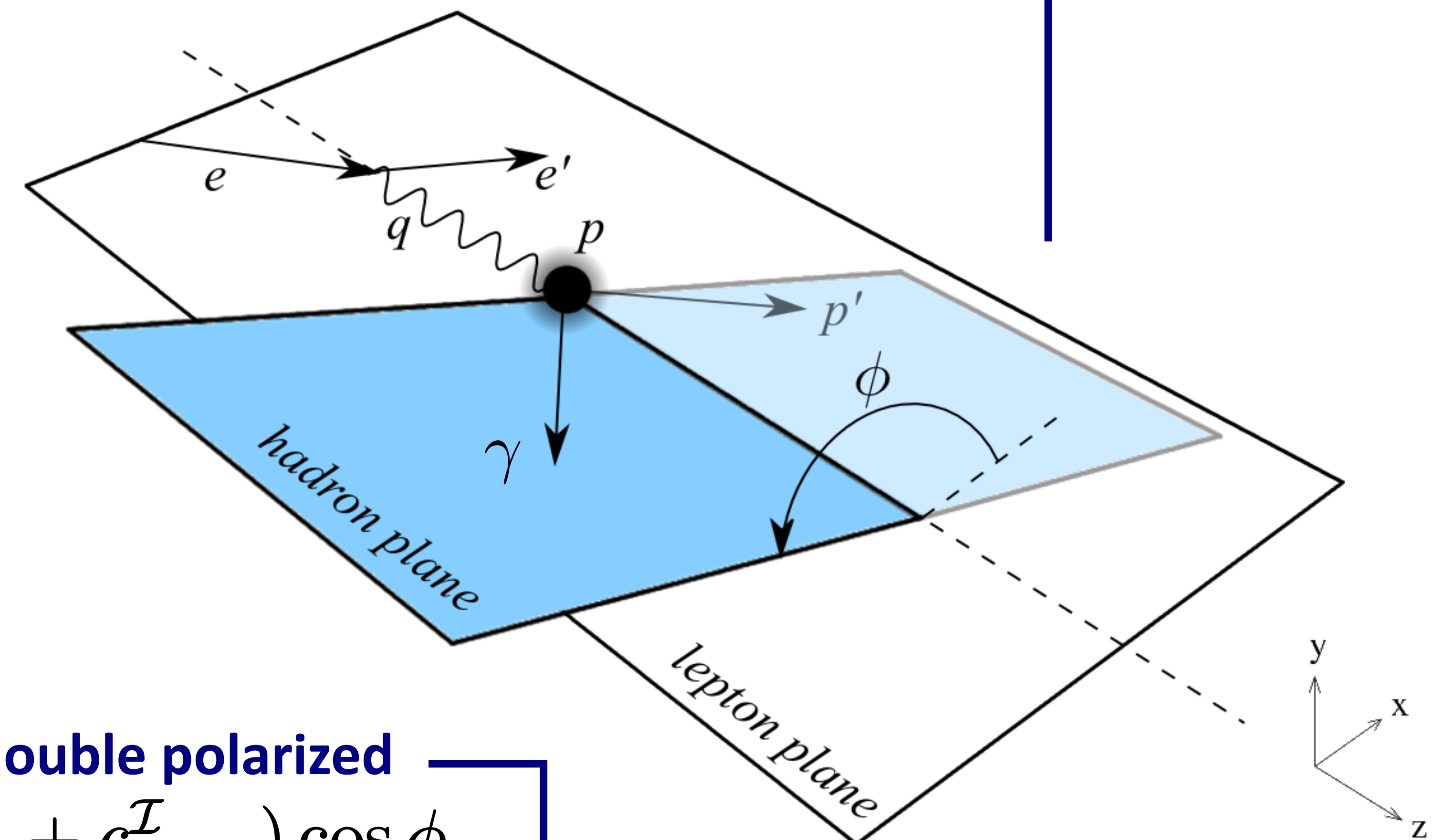
unpolarized terms

DVCS:

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} \propto c_0^{BH} + \sum_{n=1}^{2} c_n^{BH}\cos(n\phi) + s_1^{BH}\sin\phi$$

$$\propto c_0^{DVCS} + \sum_{n=1}^{2} [c_n^{DVCS}\cos(n\phi) + s_n^{DVCS}\sin(n\phi)]$$

$$\propto c_0^{\mathcal{I}} + \sum_{n=1}^{3} [c_n^{\mathcal{I}}\cos(n\phi) + s_n^{\mathcal{I}}\sin(n\phi)]$$



beam polarized

$$\propto s_{1,unp}^{\mathcal{I}}\sin\phi$$

target polarized

$$\propto s_{1,LP}^{\mathcal{I}}\sin\phi$$

double polarized

$$\propto c_{0,LP}^{BH} + c_{0,LP}^{\mathcal{I}} + (c_{1,LP}^{BH} + c_{1,LP}^{\mathcal{I}})\cos\phi$$

Deeply Virtual Compton Scattering

Unpolarized cross sections, unpolarized beam and target

$$\sigma_0 \sim \mathrm{Re}\{F_1 H - \frac{t}{4M^2} F_2 E - \xi^2 (F_1 + F_2)(H + E)\}$$

Polarized beam and Unpolarized target (BSA)

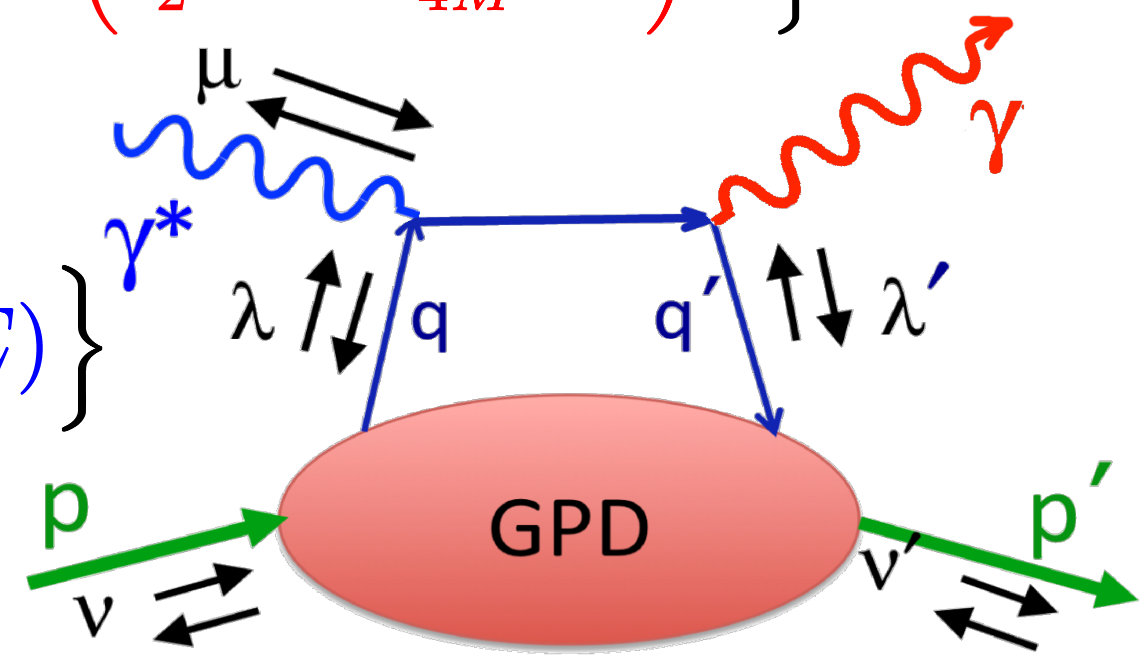
$$A_{LU} \sim \mathrm{Im}\left\{F_1 H + \xi(F_1 + F_2)\tilde{H} + \frac{t}{4M^2} F_2 E\right\}$$

Unpolarized beam and Polarized target (TSA)

$$A_{UL} \sim \mathrm{Im}\left\{F_1 \tilde{H} + \xi(F_1 + F_2)\left(H - \frac{x_B}{2} E\right) - \xi\left(\frac{x_B}{2} F_1 - \frac{t}{4M^2} F_2\right)\tilde{E}\right\}$$

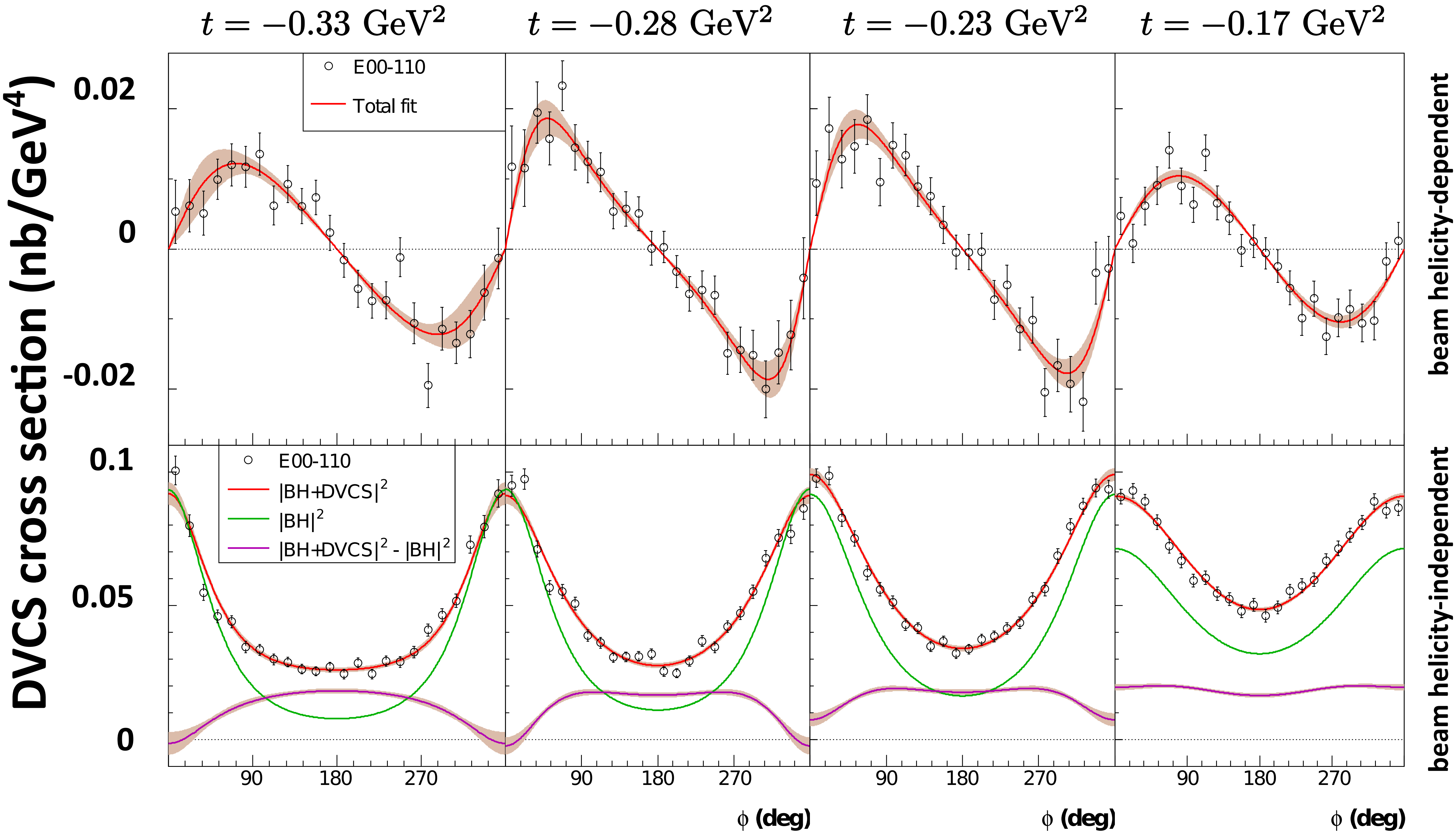
Polarized beam and Polarized target (DSA)

$$A_{LL} \sim \mathrm{Re}\left\{F_1 \tilde{H} + \xi(F_1 + F_2)(H + \frac{x_B}{2} E)\right\}$$



DVCS Cross Sections

First round experiment at Hall A: E00-110



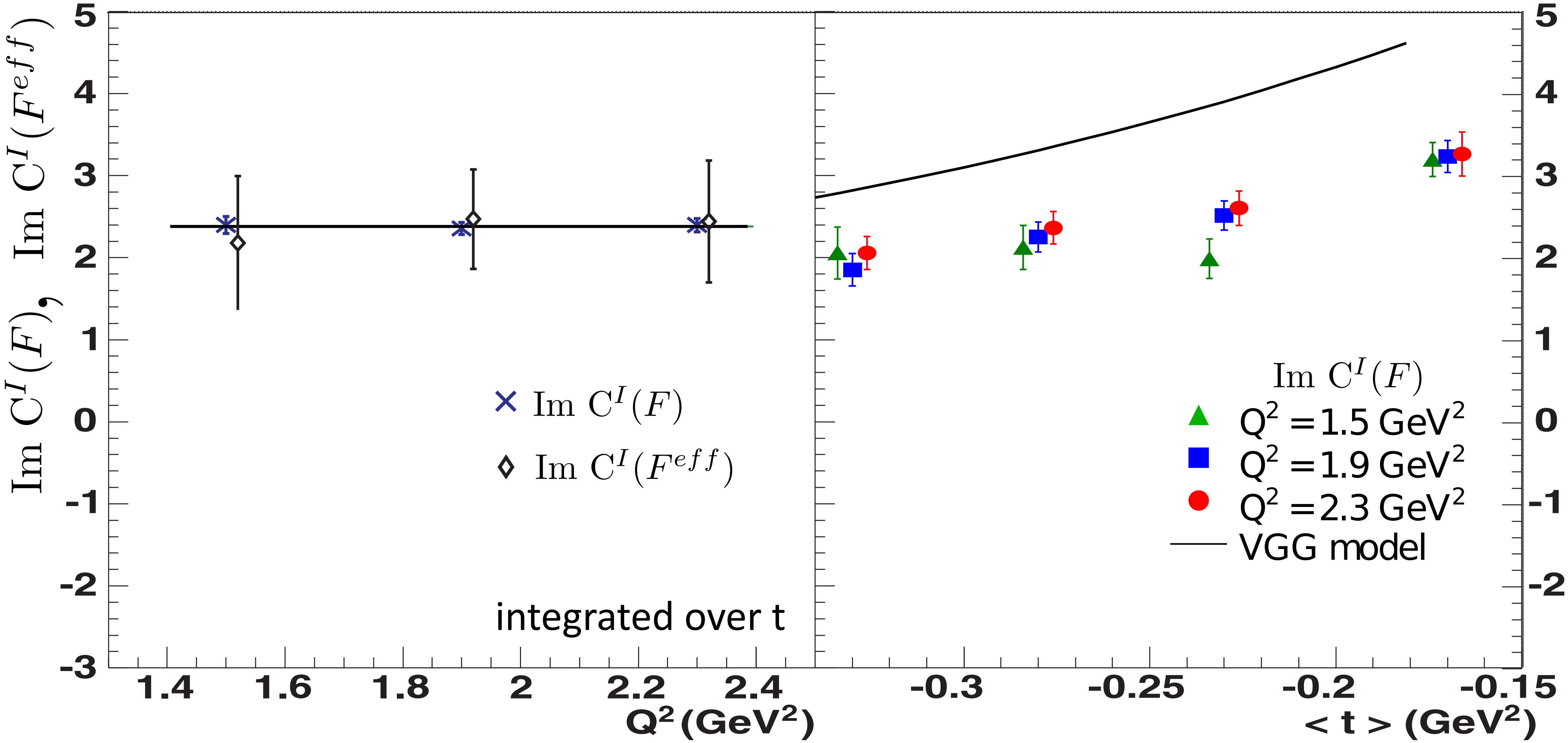
PRL**97**:262002 (2006), C. Munoz Camacho *et al.* (Hall A collaboration)

DVCS Scaling Test

First round experiment at Hall A: E00-110

- ✦ **Q^2 independence:**
  - ✦ Twist-2 dominance (GPDs)

curve is from VGG model calculations (Vanderhaeghen, Guichon, Guidal)

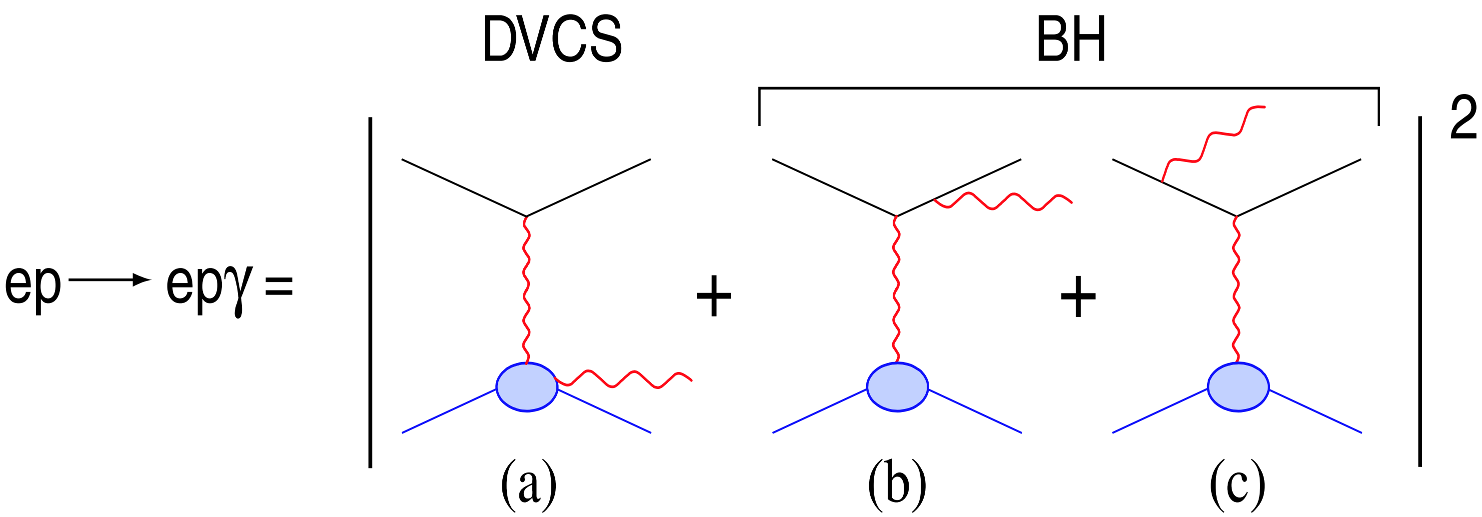


PRL**97**:262002 (2006), C. Munoz Camacho *et al.* (Hall A collaboration)

Separation of DVCS and Interference Terms

Second round experiment at Hall A: E07-007

$$\sigma(ep \to ep\gamma) = |BH|^2 + \underbrace{\mathcal{I}(BH \cdot DVCS)}_{\text{Linear combination of GPDs}} + \underbrace{|DVCS|^2}_{\text{Bilinear combination}}$$



Rosenbluth type separation

$$\sigma_1 = |BH|^2 + \Gamma_1 |DVCS|^2 + \Gamma_1' \mathcal{I}$$

$$\sigma_2 = |BH|^2 + \Gamma_2 |DVCS|^2 + \Gamma_2' \mathcal{I}$$

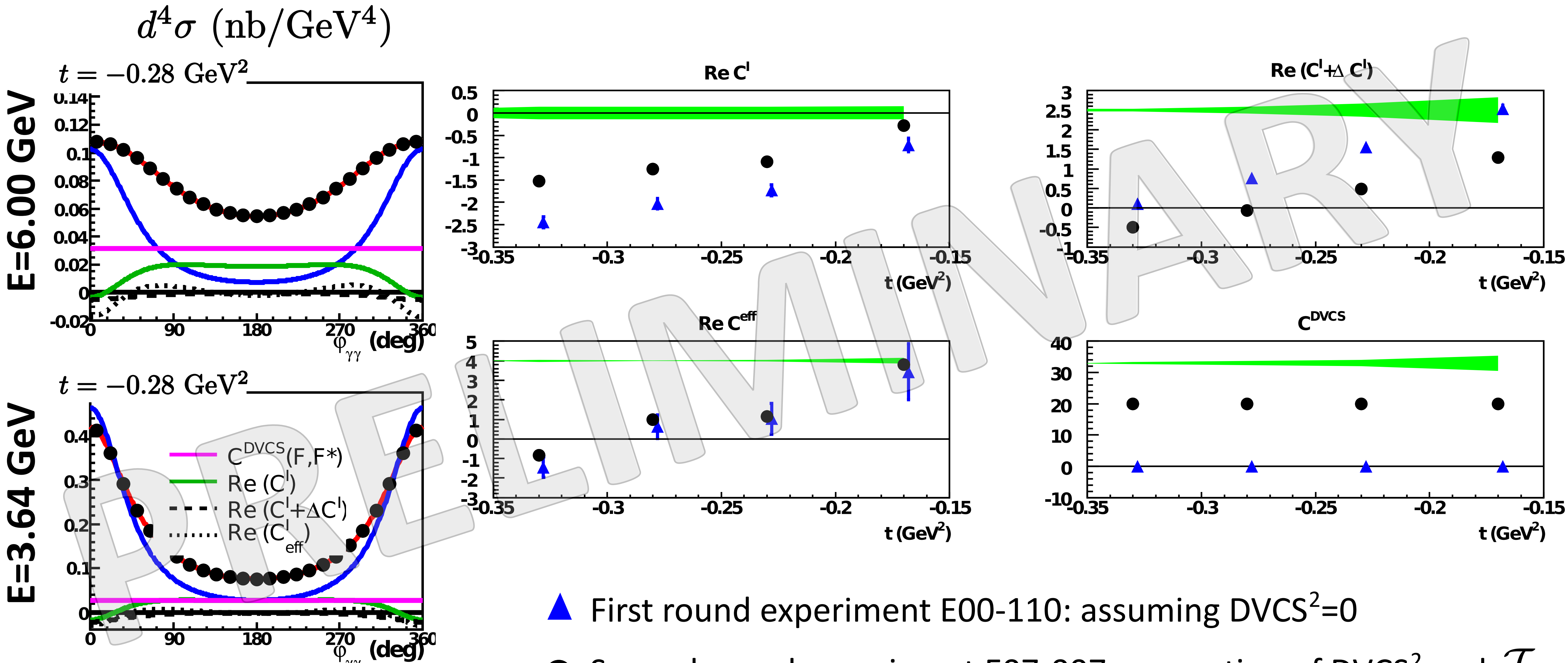
DVCS cross section has a very rich structure:

- ✦ Azimuthal analysis allows separation of different contributions
- ✦ Interference and DVCS terms mix in an azimuthal analysis
- ✦ The different energy dependence allows a full separation

Rosenbluth-like separation

Second round experiment at Hall A: E07-007

✦ Clean separation of BH-DVCS Interference term from pure DVCS^2

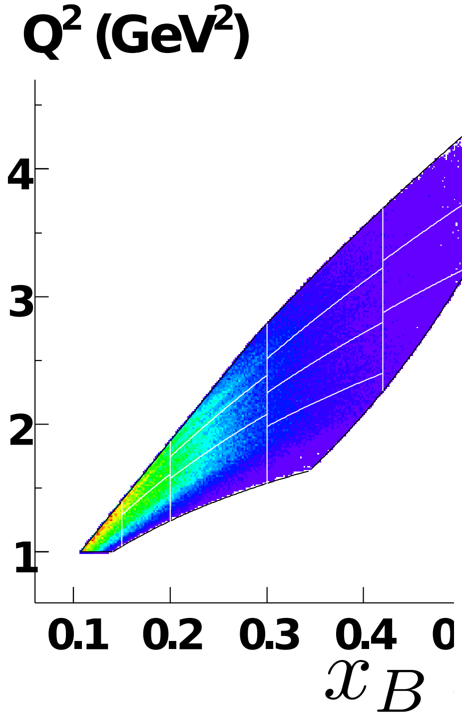


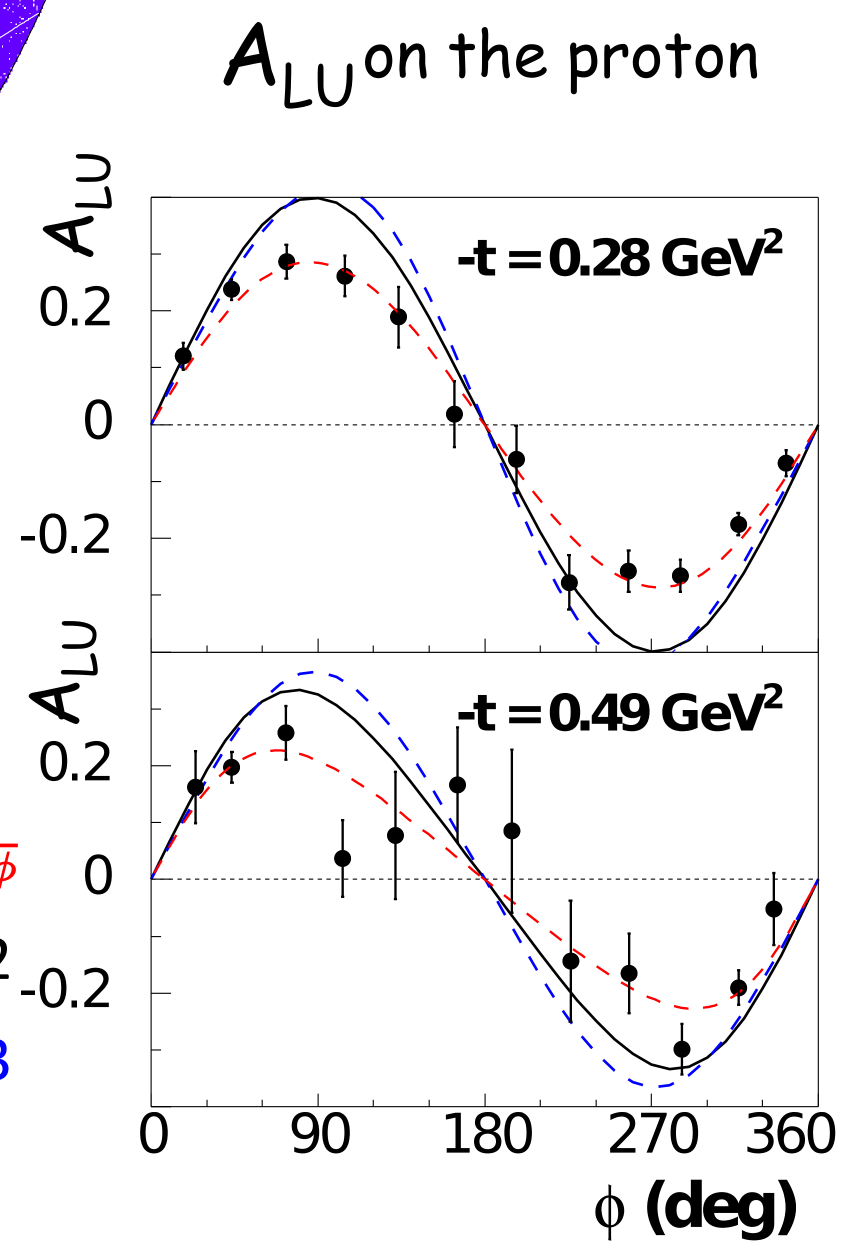
▲ First round experiment E00-110: assuming DVCS^2=0

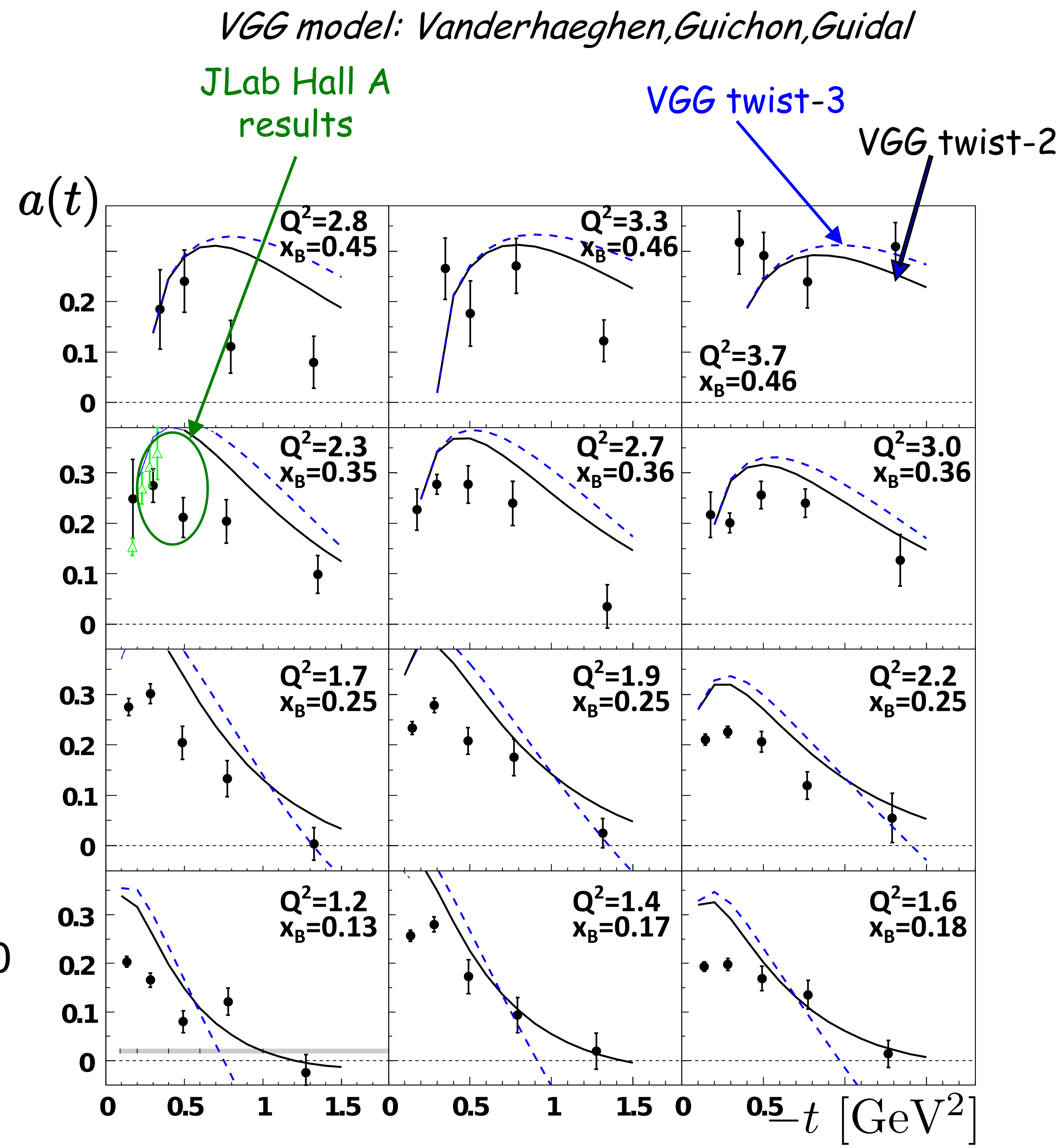
● Second round experiment E07-007: separation of DVCS^2 and $\mathcal{I}$

DVCS Beam Spin Asymmetries

First round experiment at Hall B: E01-113







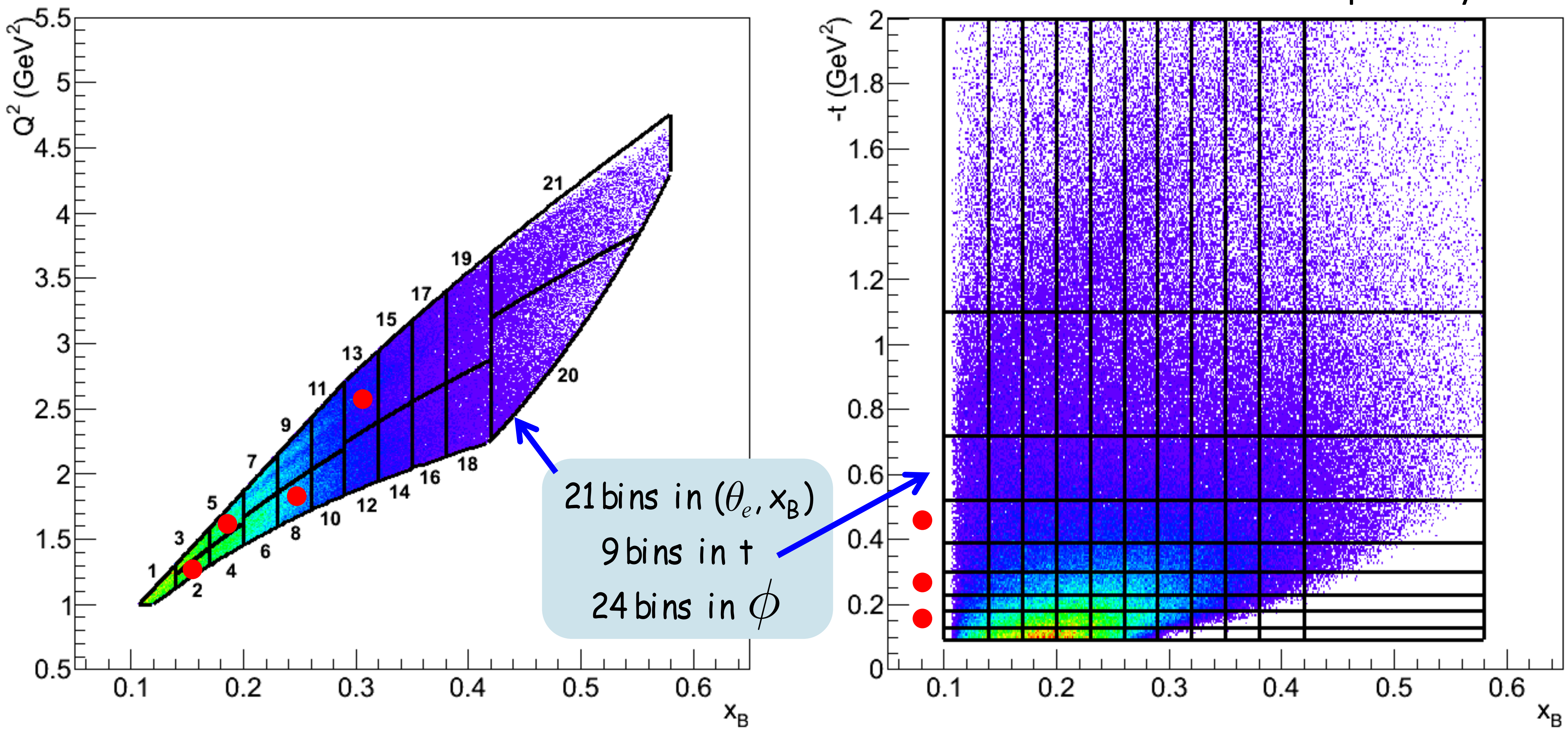
PRL**100**:162002 (2008) F.X. Girod *et al.* (CLAS collaboration)

DVCS Kinematic Coverage at CLAS

First round experiment at Hall B: E01-113

DVCS cross section measurements are underway

plots by H.S. Jo



Extraction of 4-fold cross sections

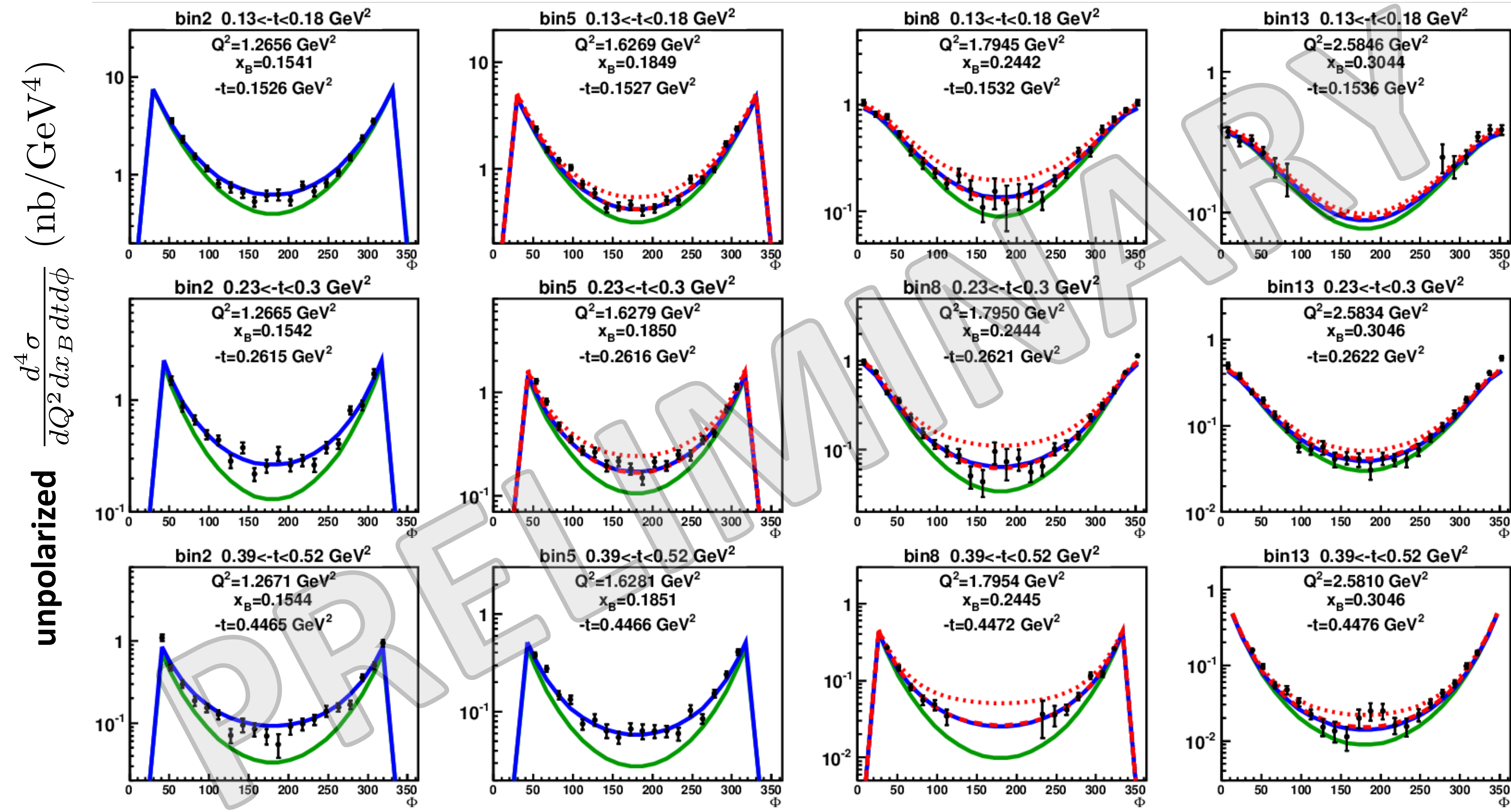
$$\frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi} \qquad \frac{1}{2}\left(\frac{d^4\overrightarrow{\sigma}_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi} - \frac{d^4\overleftarrow{\sigma}_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi}\right)$$

DVCS Cross Sections

plots by H.S. Jo

First round experiment at Hall B: E01-113

Measurements in a **LARGE** kinematic domain



clas
CEBAF Large Acceptance Spectrometer

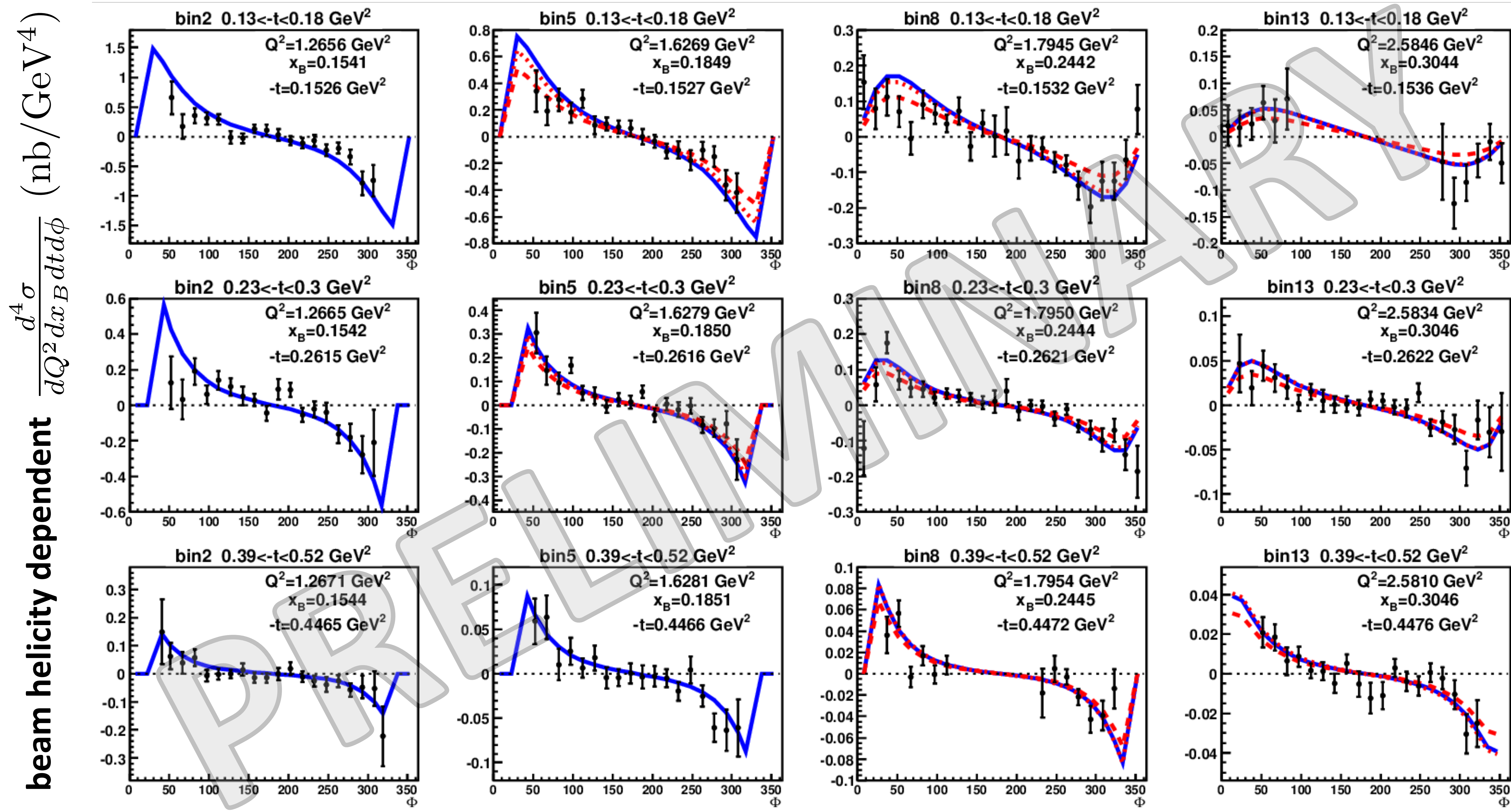
DVCS Cross Sections

plots by H.S. Jo

First round experiment at Hall B: E01-113

Measurements in a **LARGE** kinematic domain

- BH only
- VGG (H only)
- KM10 (Kumericki, Mueller)
- KM10a



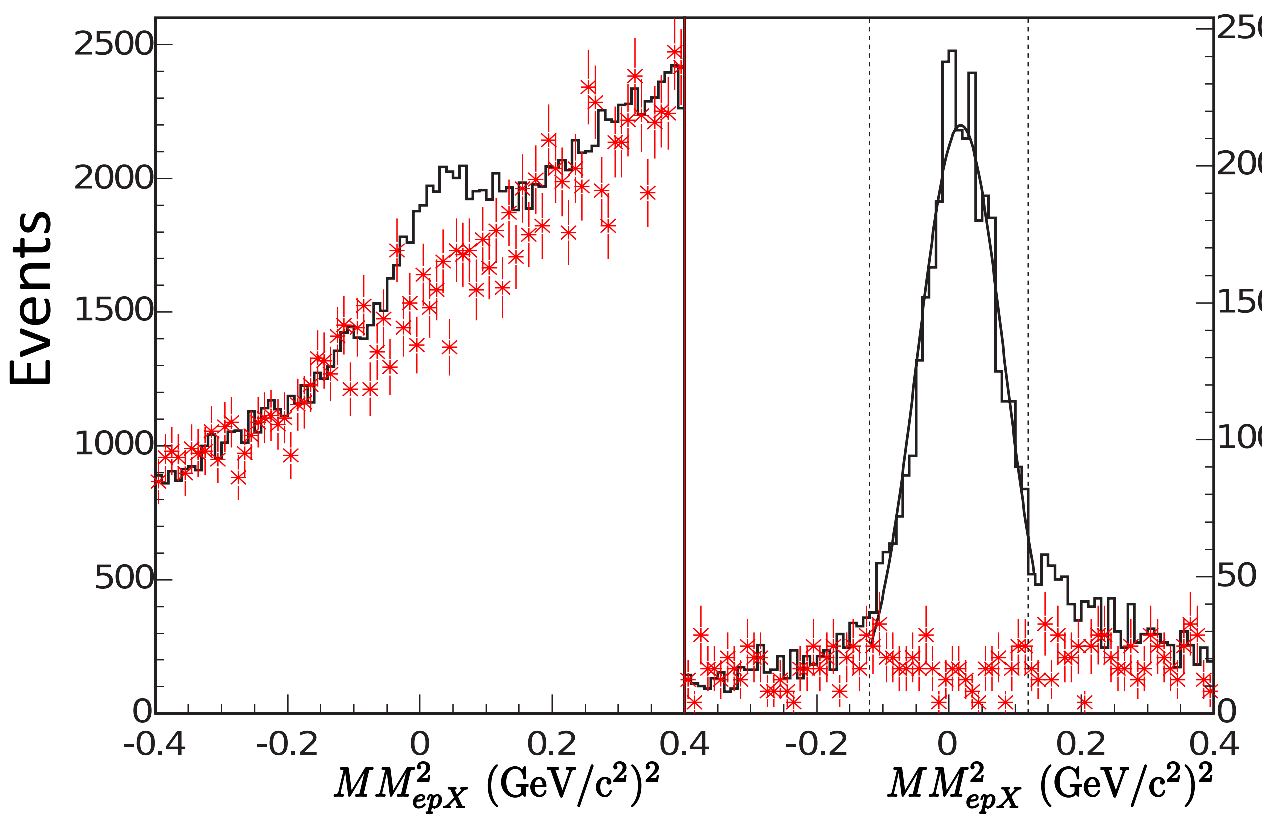
DVCS Target Spin Asymmetries

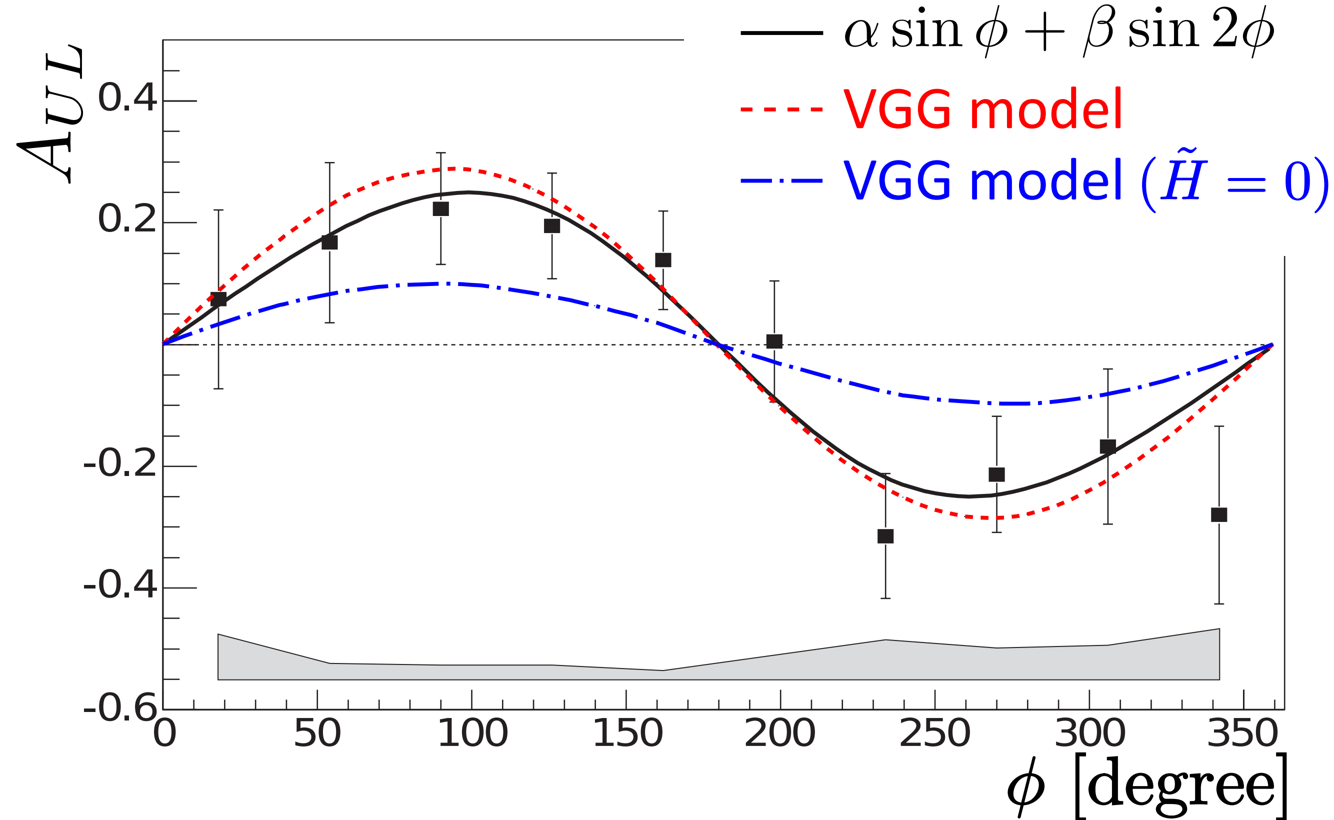
Non-dedicated experiment at Hall B (longitudinally polarized target)

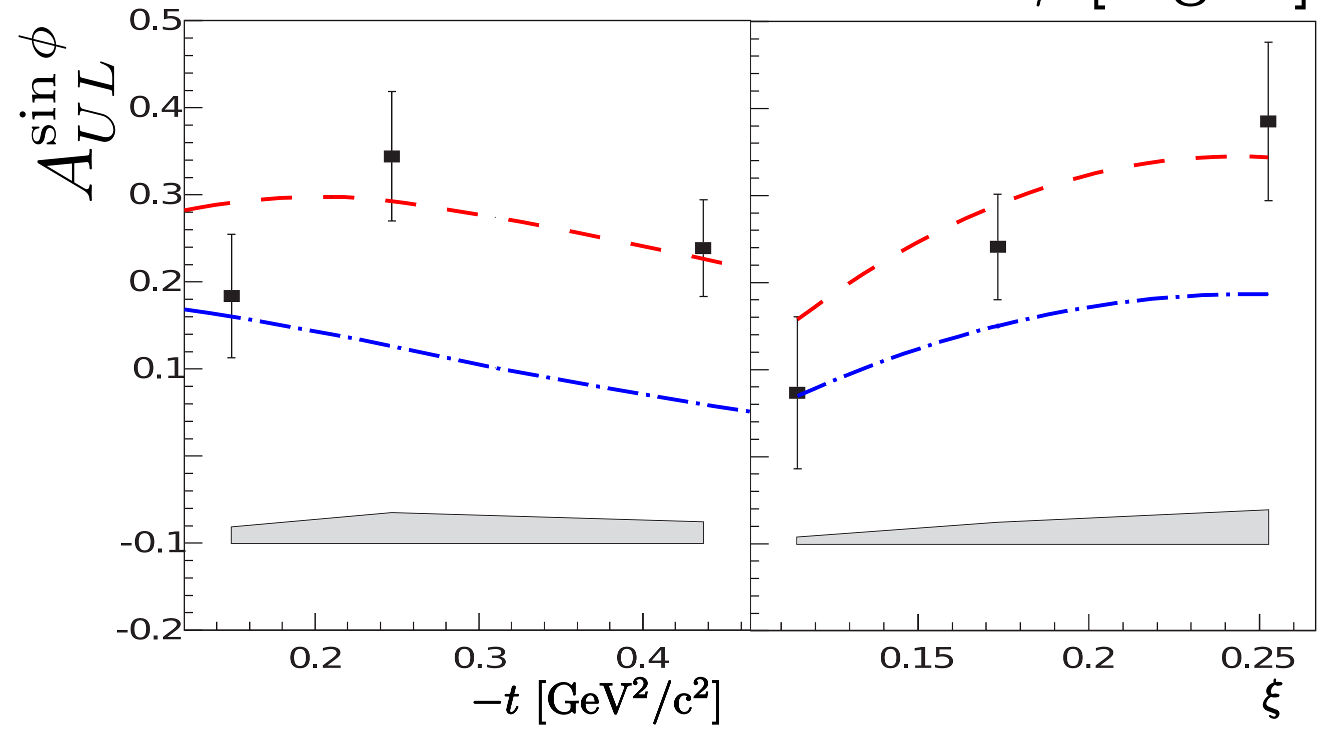
First measurements of DVCS target spin asymmetry:

- ✦ non-dedicated experiment
- ✦ no Inner Calorimeter

$H(e, e'\gamma p)$ exclusivity



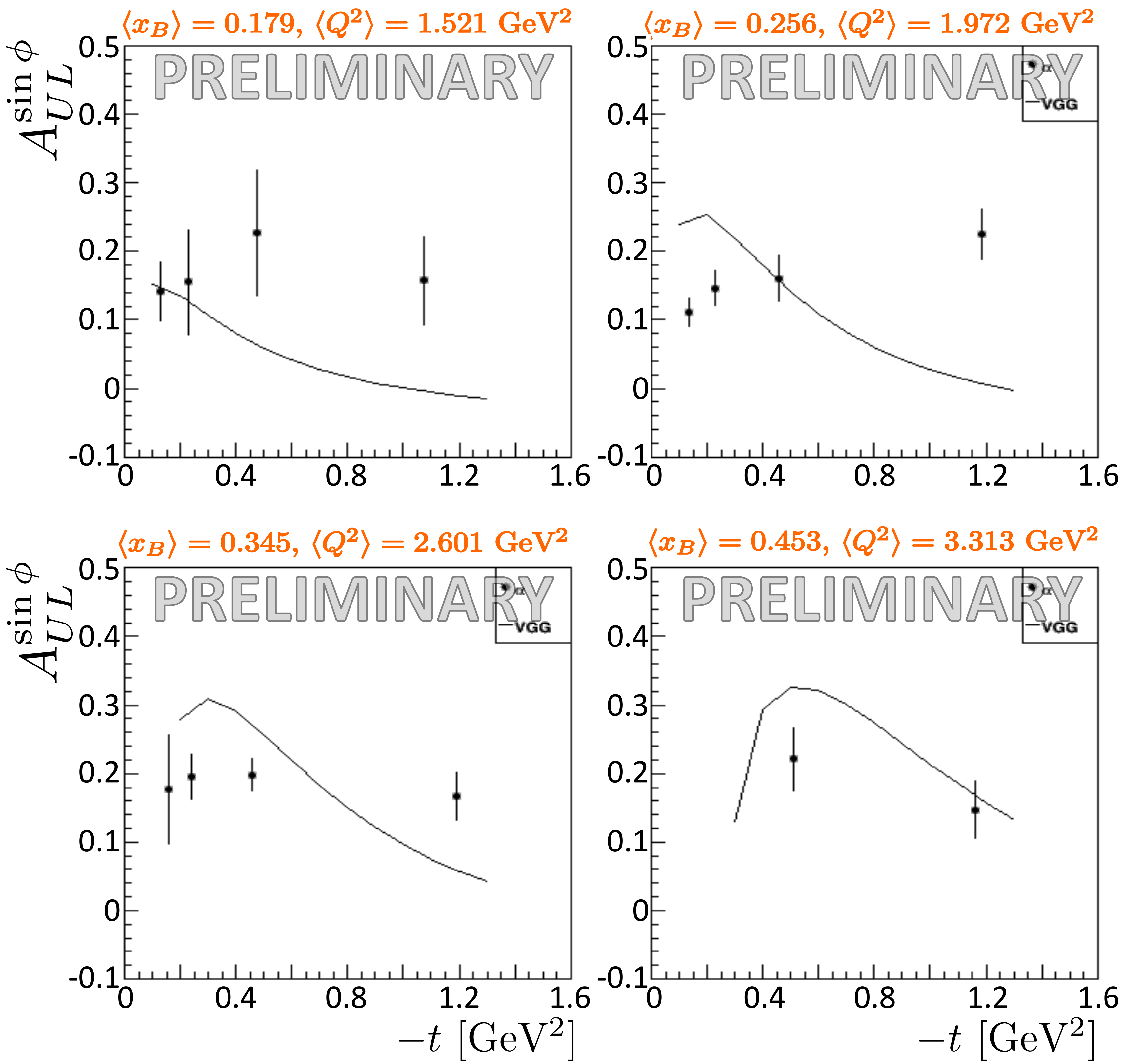




PRL**97**:072002 (2006) S. Chen *et al.* (CLAS collaboration)

DVCS Target Spin Asymmetries

Second round experiment at Hall B: E05-114 (longitudinally polarized target)



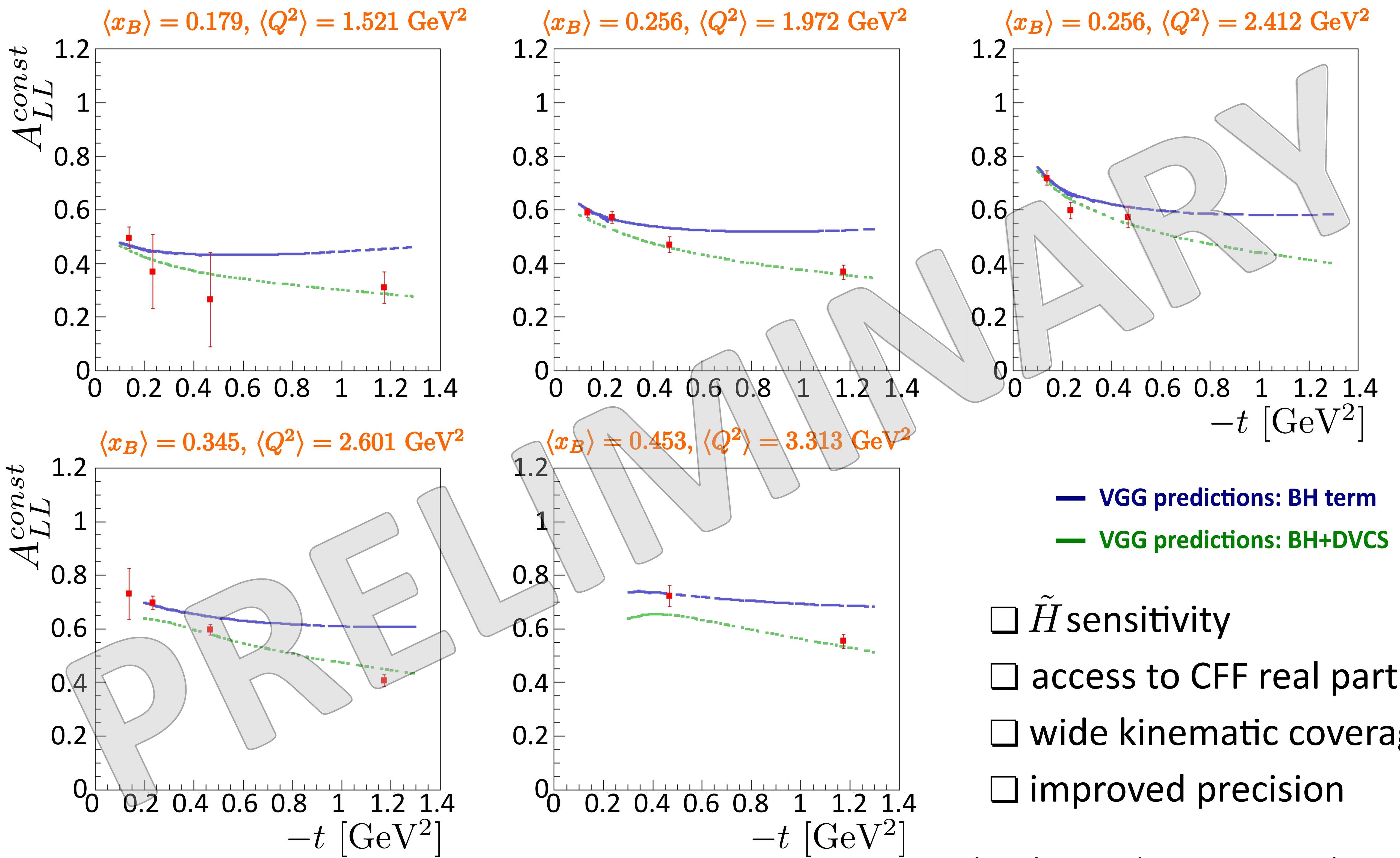
— **VGG predictions**

- ☐ $\tilde{H}$ sensitivity
- ☐ wide kinematic coverage
- ☐ improved precision

plots by eg1dvcs DVCS analysis group

DVCS Double Spin Asymmetries

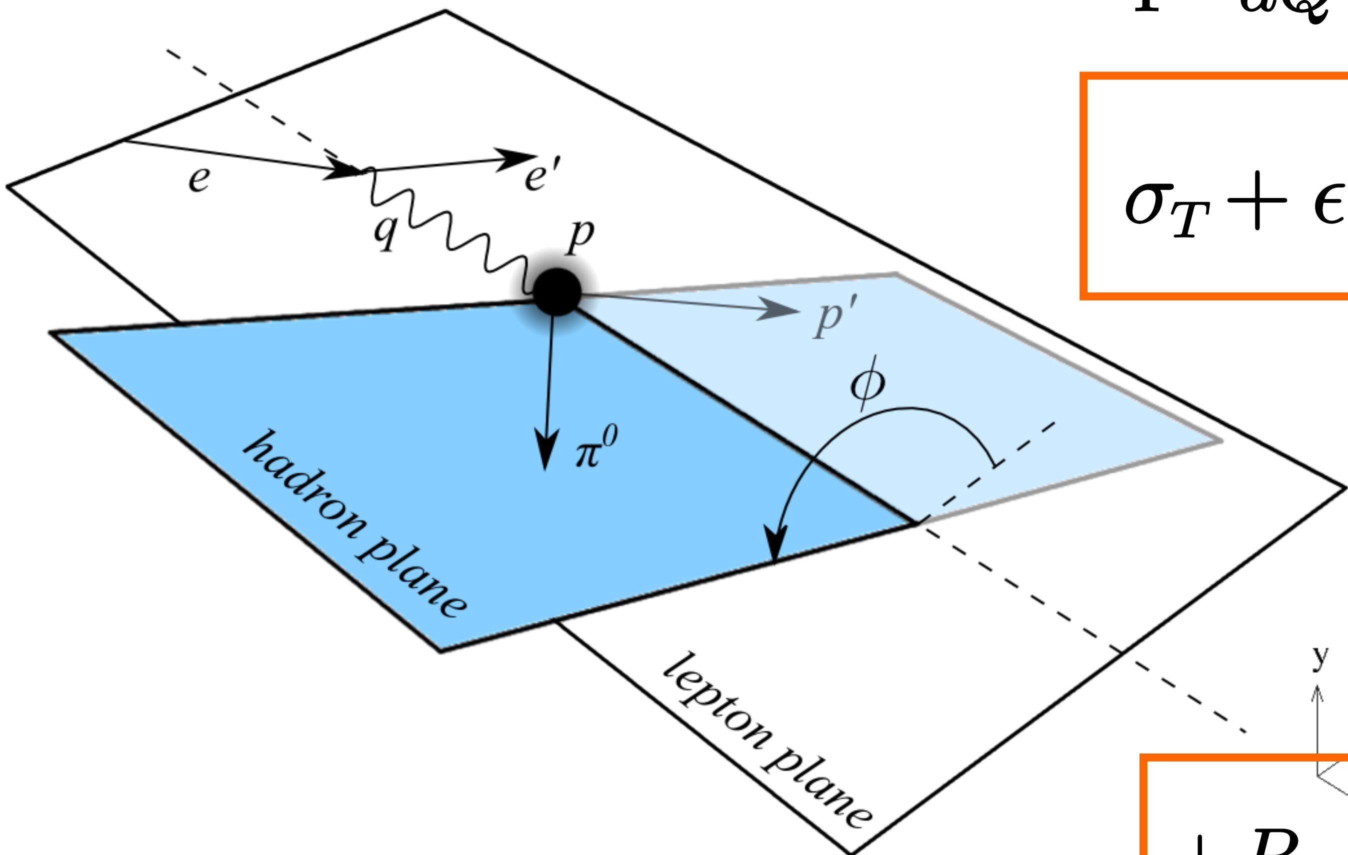
Second round experiment at Hall B: E05-114 (longitudinally polarized target)



- ❑ $\tilde{H}$ sensitivity
- ❑ access to CFF real parts
- ❑ wide kinematic coverage
- ❑ improved precision

plots by eg1dvcs DVCS analysis group

DVπ^0P Experimental Observables



$$\frac{2\pi}{\Gamma}\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} =$$

unpolarized terms

$$\sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}\cos 2\phi + \sqrt{\epsilon(1+\epsilon)}\,\sigma_{LT}\cos\phi$$

longitudinally polarized beam

$$+P_b\sqrt{\epsilon(1-\epsilon)}\,\sigma_{LT'}\sin\phi$$

$$+P_{tg}\left(\sqrt{\epsilon(1+\epsilon)}\,\sigma_{UL}^{\sin\phi}\sin\phi + \epsilon\sigma_{UL}^{\sin 2\phi}\sin 2\phi\right)$$

longitudinally polarized target

$$+P_b P_{tg}\left(\sqrt{1-\epsilon^2}\,\sigma_{LL} + \sqrt{\epsilon(1-\epsilon)}\,\sigma_{LL}^{\cos\phi}\cos\phi\right)$$

longitudinally polarized beam and longitudinally polarized target

Deeply Virtual π^0 Production

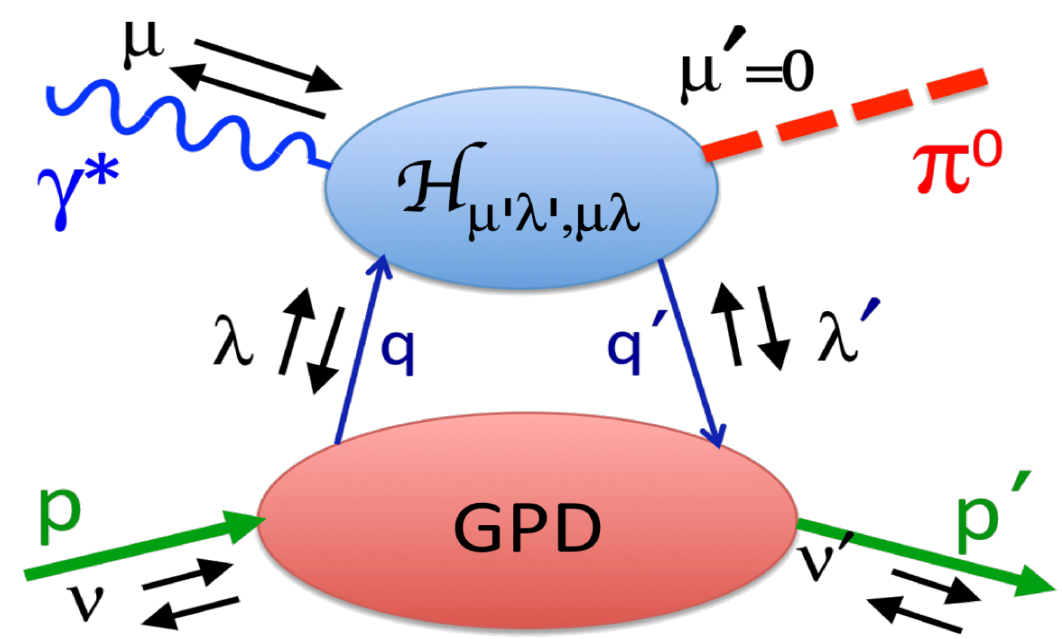
Phys.Rev., D84:034007, 2011: G. R. Goldstein, J. O. Gonzalez, S. Liuti.

Eur.Phys.J., A47:112, 2011: S.V. Goloskokov, P. Kroll.

$$\langle F \rangle = \sum_{\lambda} \int_{-1}^{1} dx \mathcal{H}_{0\lambda,\mu\lambda}(x,\xi,Q^2,t)F(x,\xi,t)$$

$$A_{UL}^{\sin\phi}\sigma_0 \sim \text{Im}\left[\langle \bar{E}_T\rangle^* \langle \tilde{H}\rangle + \xi \langle H_T\rangle^* \langle \tilde{E}\rangle\right]$$

$$A_{LU}^{\sin\phi}\sigma_0 \sim \text{Im}\left[\langle H_T\rangle^* \langle \tilde{E}\rangle\right]$$



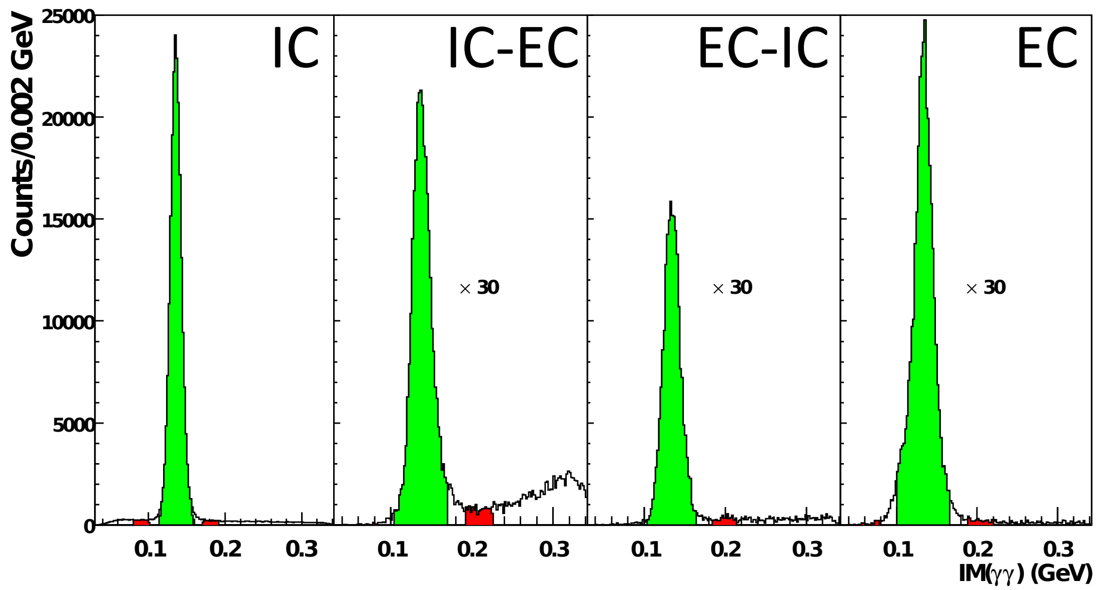
$$A_{LL}^{\cos 0\phi}\sigma_0 \sim |\langle H_T\rangle|^2$$

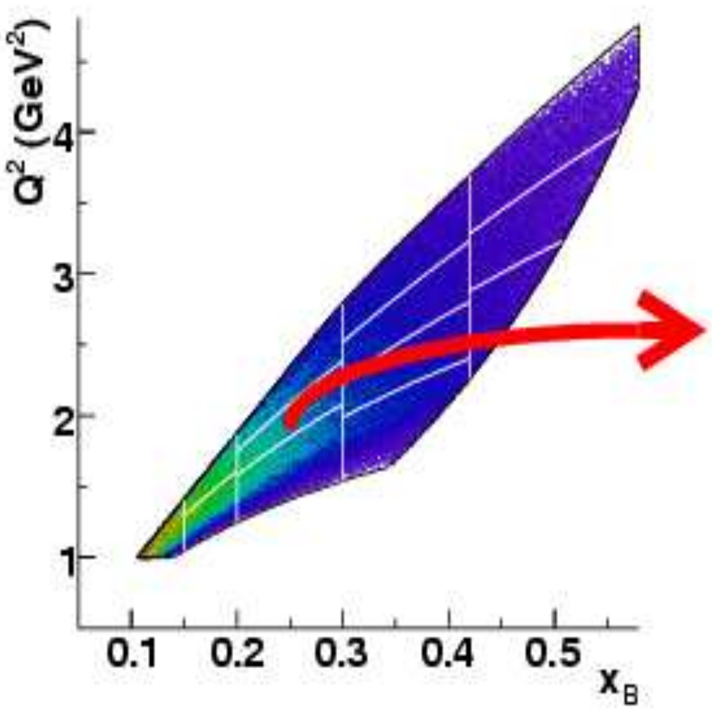
$$A_{LL}^{\cos\phi}\sigma_0 \sim \text{Re}\left[\langle \bar{E}_T\rangle^* \langle \tilde{H}\rangle + \xi \langle H_T\rangle^* \langle \tilde{E}\rangle\right]$$

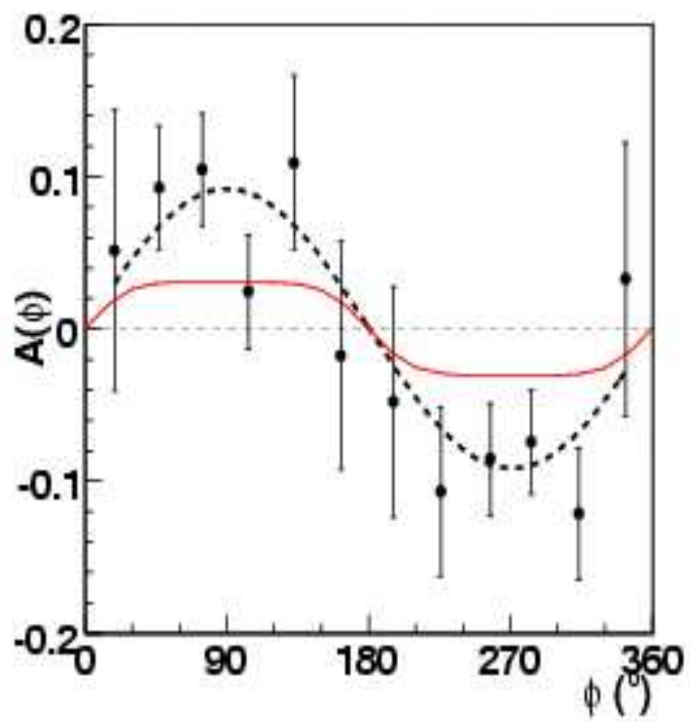
DVπ^0P Beam Spin Asymmetries

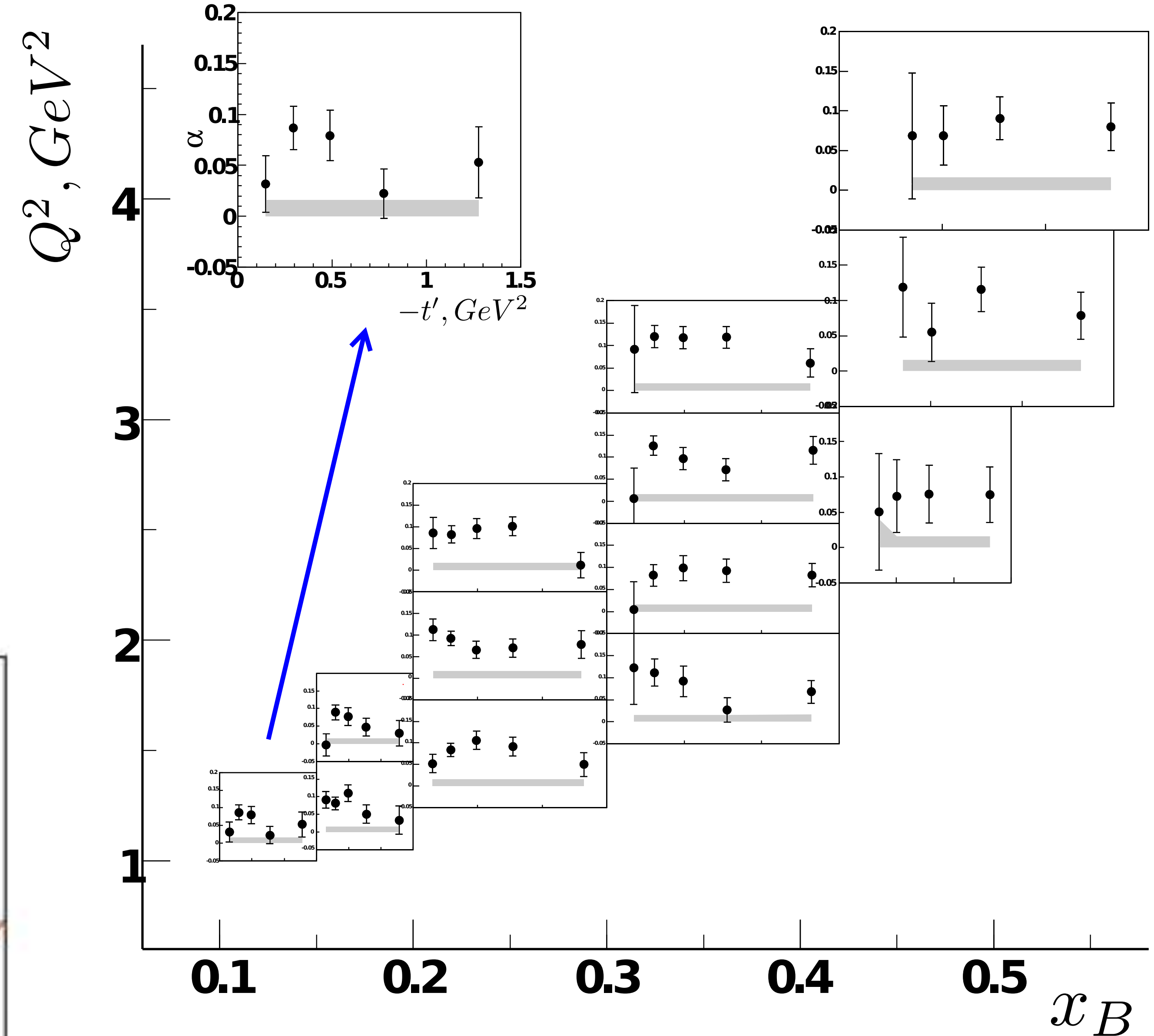
First round experiment at Hall B: E01-113

Two-photon invariant mass







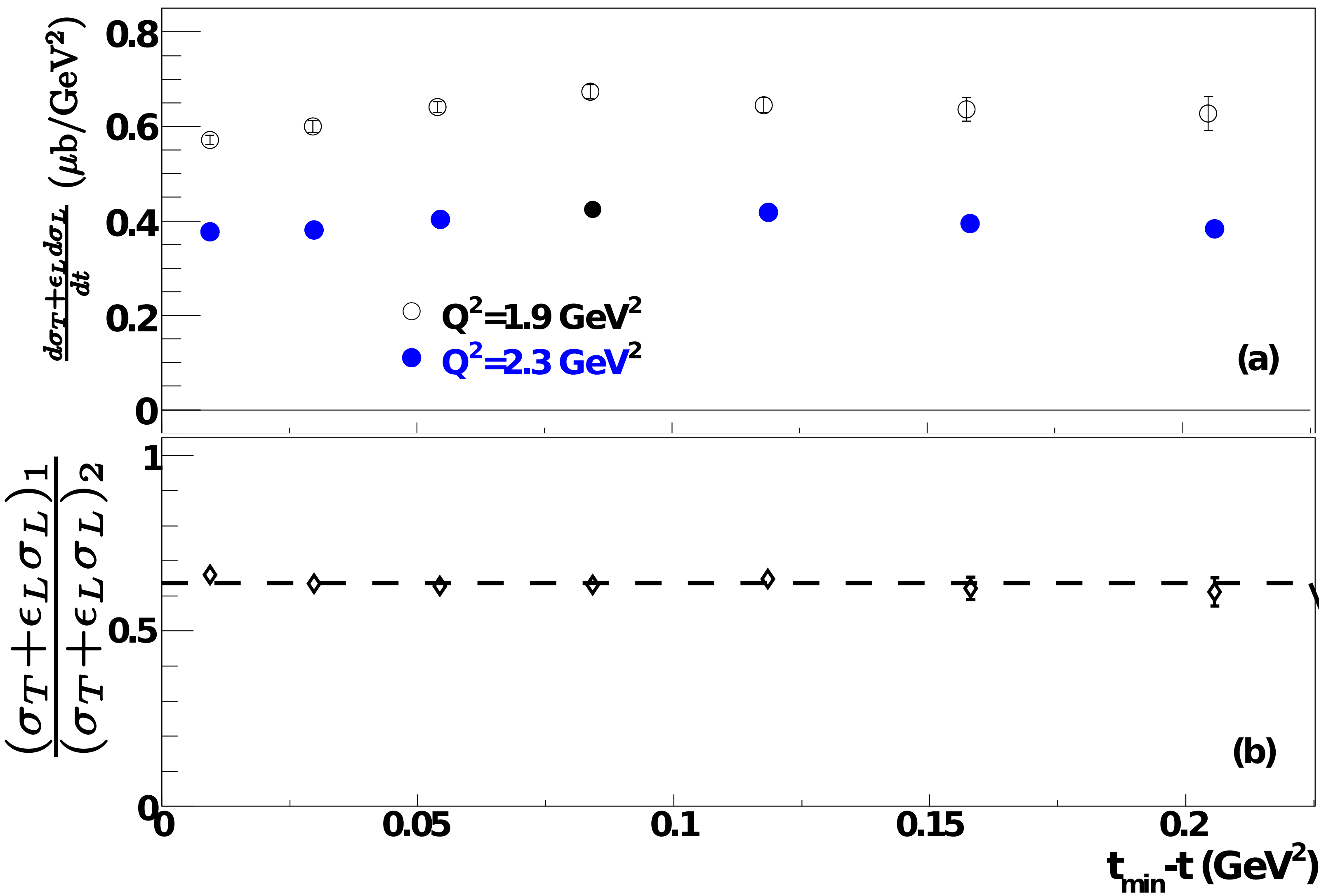


R. De Masi et al. Measurement of $ep\text{->}ep\pi^0$ **beam spin asymmetries above the resonance region. Phys.Rev., C77:042201, 2008.**

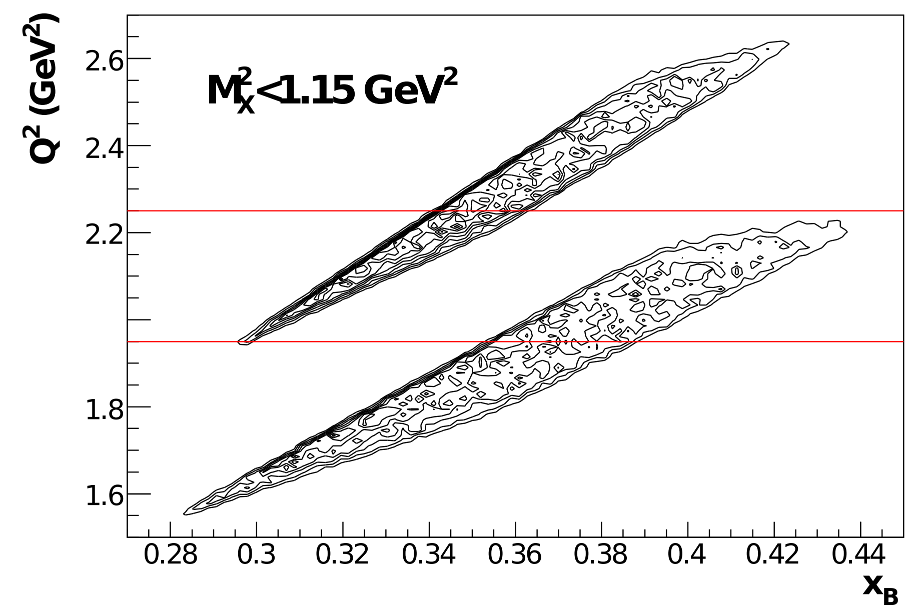
PRC**77**:042201 (2008), R. De Masi *et al.* (CLAS collaboration)

DVπ^0P Cross Sections

First round experiment at Hall A: E00-110



kinematic coverage



Leading twist predicts:

$$\sigma_L \sim Q^{-6}$$

but:

$$\sigma_T + \epsilon_L \sigma_L \sim Q^{-5}$$

σ_T is likely to dominate at these Q^2

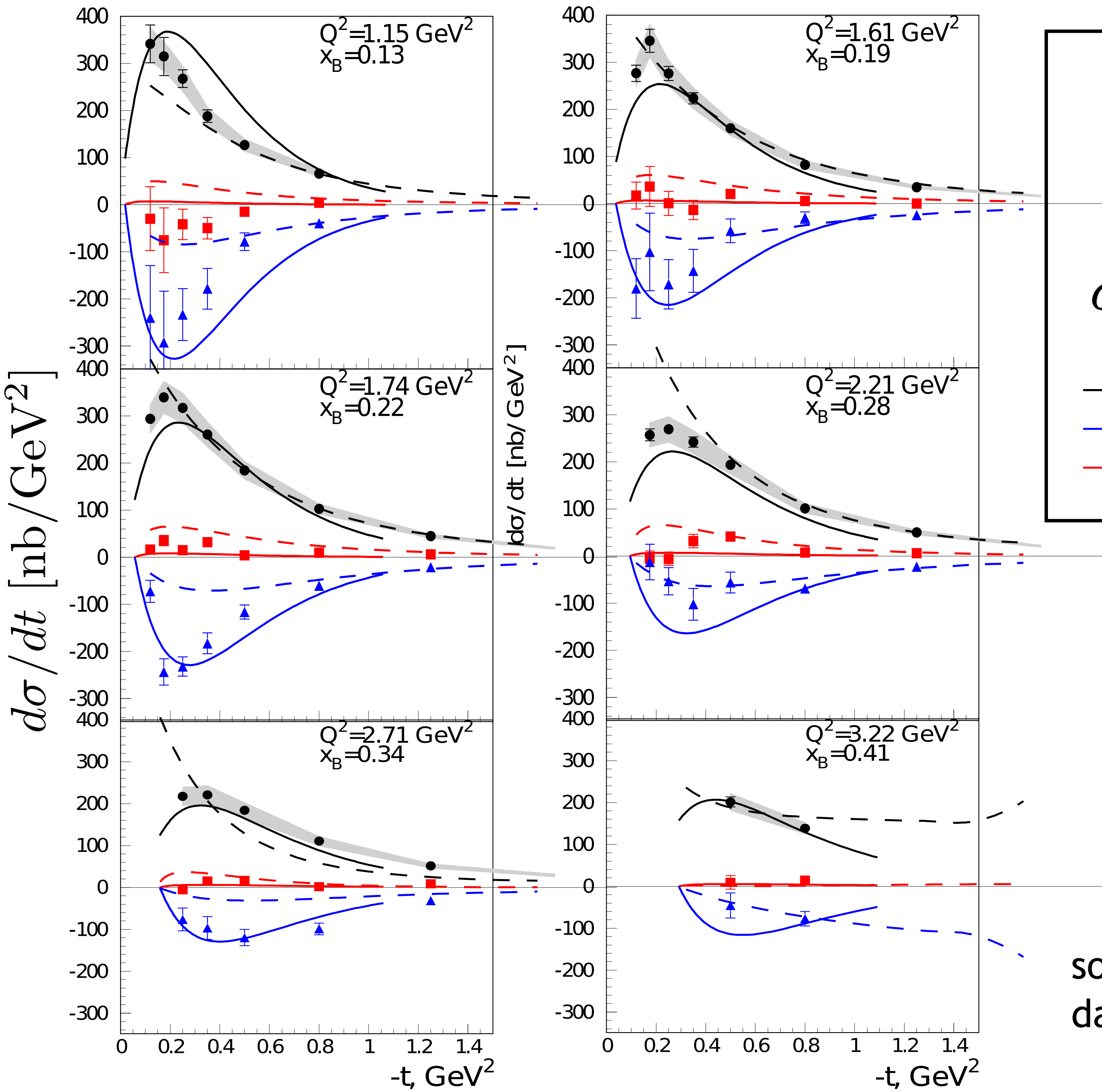
but L/T separation is necessary

PRC**83**:025125 (2011), E. Fuchey *et al.* (Hall A collaboration)

CLAS
CEBAF Large Acceptance Spectrometer

DVπ^0P Cross Sections

First round experiment at Hall B: E01-113



Inclusion of the Chiral-odd GPDs brings theoretical calculations into moderate agreement with the data.

$$\sigma_T \sim (1-\xi^2)|H_T|^2 - \frac{t'}{8m^2}|\bar{E}_T|^2$$

— $\sigma_0 = \sigma_T + \epsilon\sigma_L$
— σ_{TT}
— σ_{LT}

$$\sigma_{TT} \sim \frac{t'}{8m^2}|\bar{E}_T|^2$$

π^0 electroproduction
is uniquely sensitive process to access
transversity GPDs.

solid: P.Kroll & S.Goloskokov
dashed: G.R. Goldstein, J.O. Gonzalez & S.Liuti

PRL109:112001 (2012) I. Bedlinskiy et al. (CLAS collaboration)

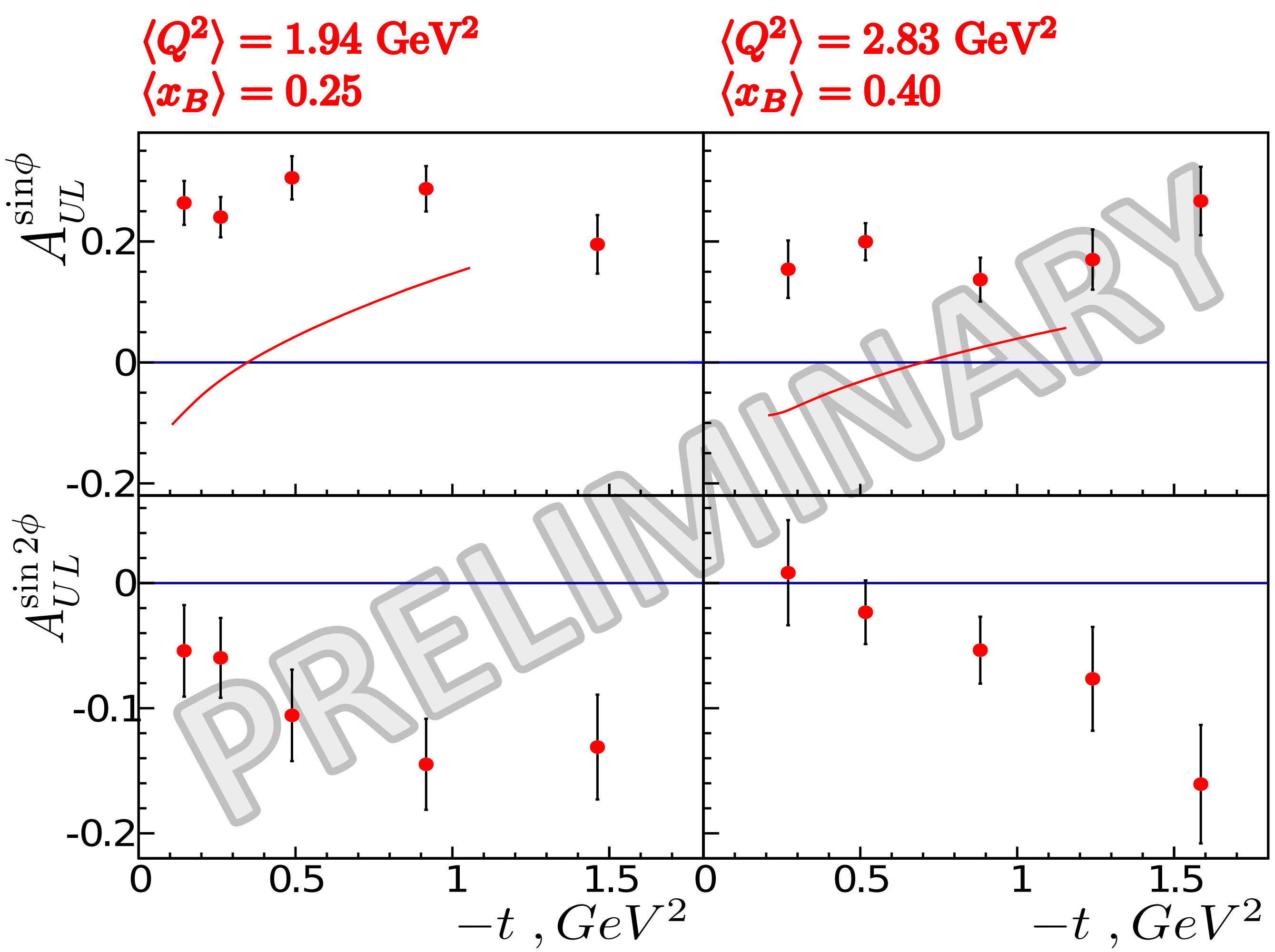
CEBAF Large Acceptance Spectrometer

DVπ^0P Spin Asymmetries

Second round experiment at Hall B: E05-114 (longitudinally polarized target)

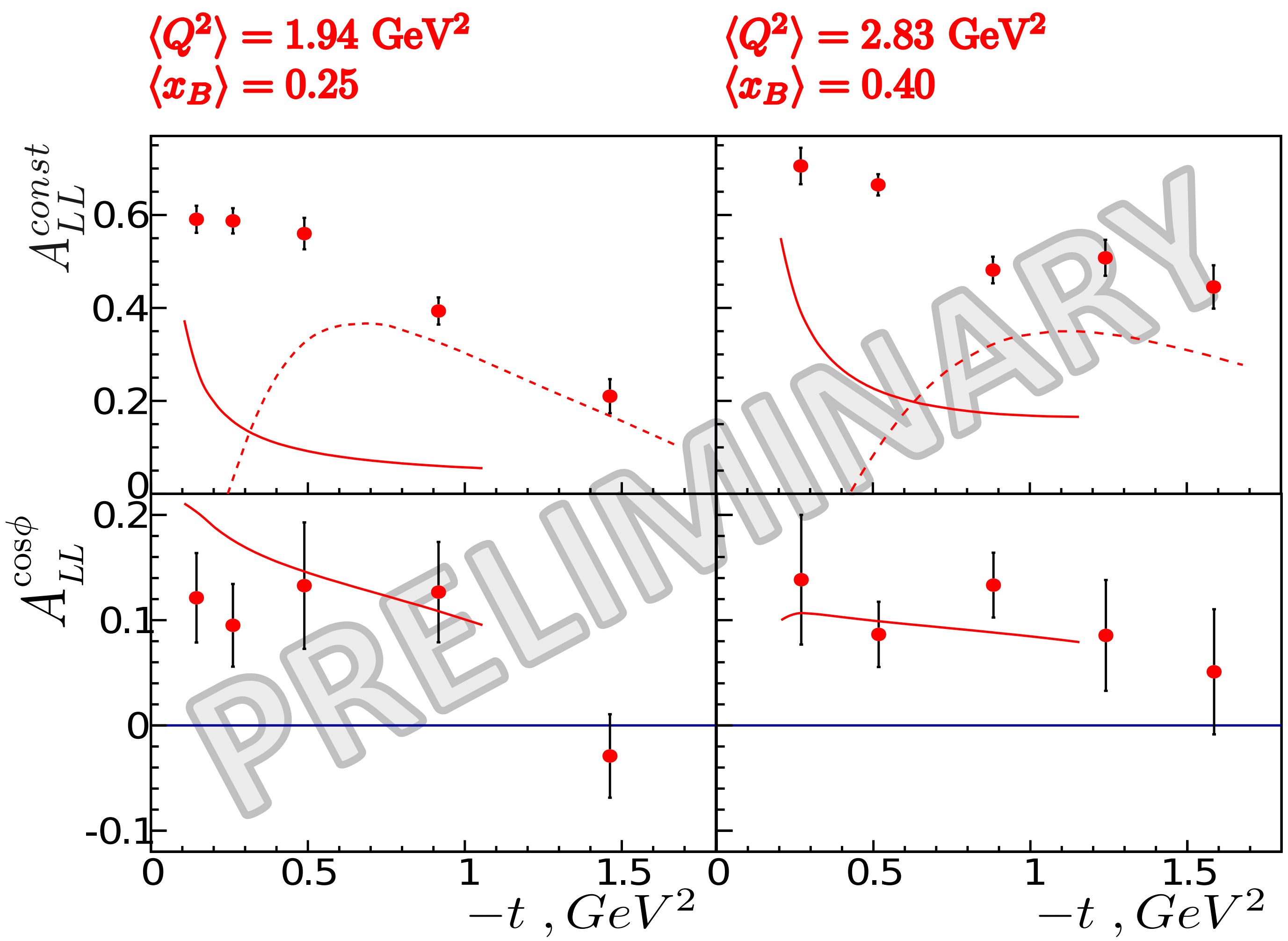
DVπ^0P single and double spin asymmetry measurements are underway

TARGET SPIN ASYMMETRY



$$A_{UL}^{\sin\phi}\sigma_0 \sim \mathrm{Im}\left[\langle \bar{E}_T\rangle^* \langle \tilde{H}\rangle + \xi \langle H_T\rangle^* \langle \tilde{E}\rangle\right]$$

DOUBLE SPIN ASYMMETRY



$$A_{LL}^{\cos 0\phi}\sigma_0 \sim |\langle H_T\rangle|^2$$

$$A_{LL}^{\cos\phi}\sigma_0 \sim \mathrm{Re}\left[\langle \bar{E}_T\rangle^* \langle \tilde{H}\rangle + \xi \langle H_T\rangle^* \langle \tilde{E}\rangle\right]$$

—— Goloskokov-Kroll

- - - Goldstein-Liuti

Summary

- ✦ Large data set (cross sections, single and double spin asymmetries) in the wide kinematic region is available
- ✦ DVCS and DVπ^0P provide access to the extensive set of chiral-even and chiral-odd GPDs
- ✦ DVCS reaction is a clean probe of the GPDs
- ✦ Combination of polarized and unpolarized observables provide constraints for *t* dependence on underlying GPDs and will help to establish the role of transversity of pion electroproduction
- ✦ Compeling GPD program in the future at JLab at 12 GeV...