

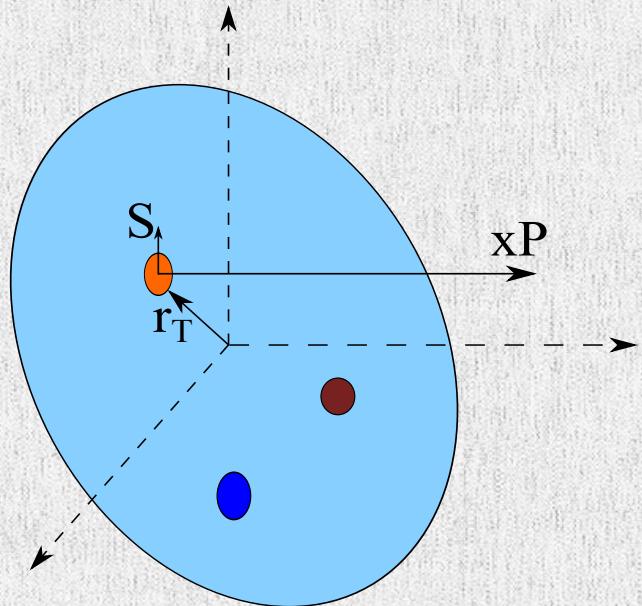
# Single and Double Spin Asymmetries from Deeply Virtual Exclusive $\pi^0$ Production on a Longitudinally Polarized Proton with CLAS

Andrey Kim<sup>1</sup> on behalf of the CLAS collaboration

<sup>1</sup> University of Connecticut



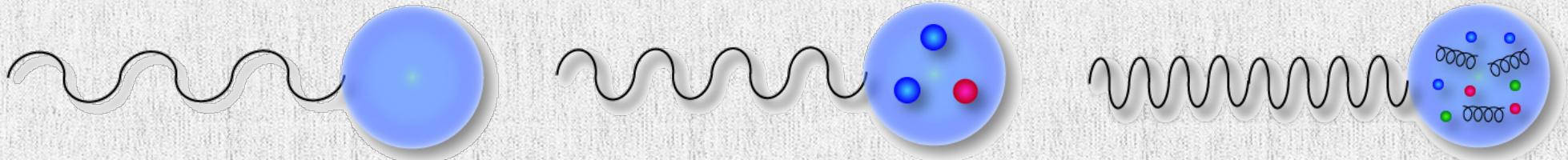
# INTRODUCTION



Deeply virtual exclusive reactions such as photon or  $\pi^0$  meson production with large gamma virtuality  $Q^2$  are key processes to probe the complex internal structure of nucleon and access information about quark position and angular momentum distributions from experimental observables.

Two main processes can be used to access this information experimentally:

**Deeply Virtual Compton Scattering** and **Deeply Virtual Meson Production**



# GENERALIZED PARTON DISTRIBUTIONS

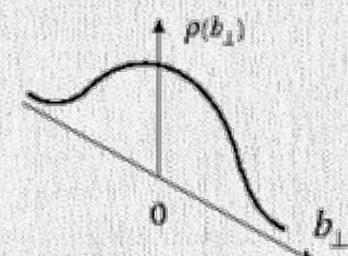
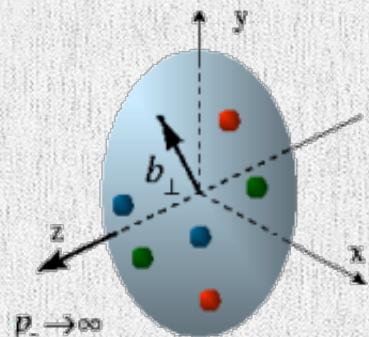
## Form factors

$$\int dx \sum_q H^q(x, \xi, t) = F_1(t)$$

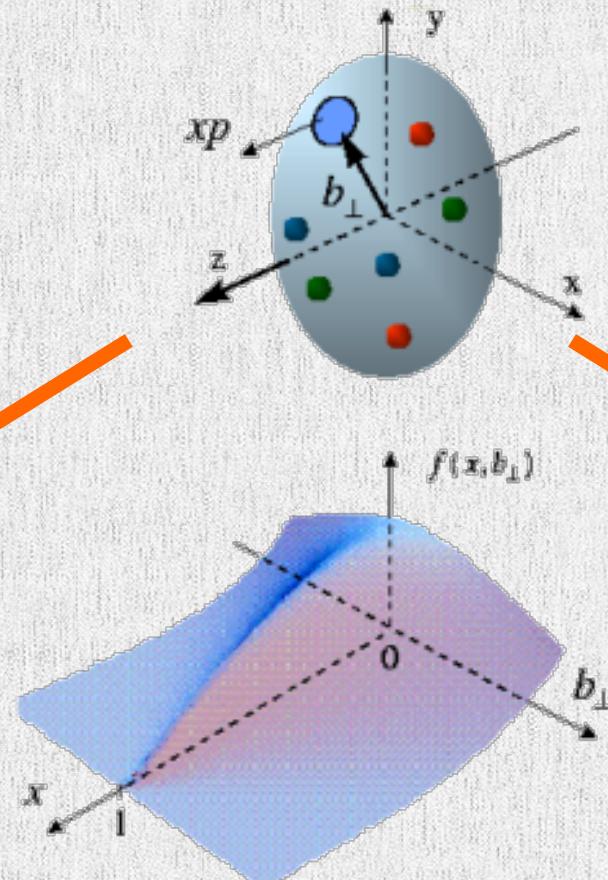
$$\int dx \sum_q E^q(x, \xi, t) = F_2(t)$$

$$\int dx \tilde{H}^q(x, \xi, t) = G_A(t)$$

$$\int dx \tilde{E}^q(x, \xi, t) = G_P(t)$$



D. Mueller, X. Ji, A. Radyushkin,  
A. Belitsky, M. Burkardt

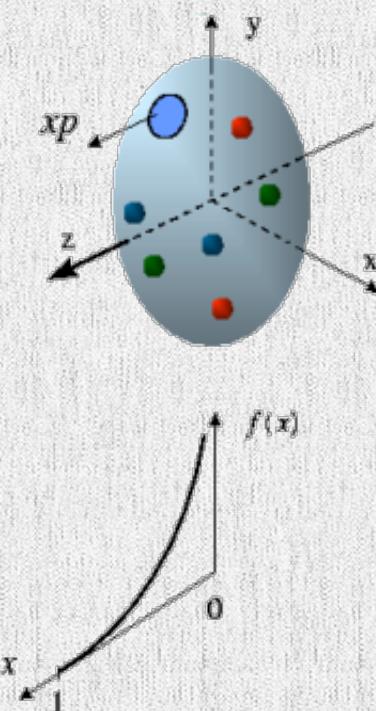


Correlation between quark longitudinal momentum and transverse spatial distributions

## Parton distributions

$$H^q(x, \xi = 0, t = 0) = q(x)$$

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



# GENERALIZED PARTON DISTRIBUTIONS

$H^q$	$\tilde{H}^q$	$E^q$	$\tilde{E}^q$	<b>parton helicity conserving (chiral-even) GPDs</b>
$H_T^q$	$\tilde{H}_T^q$	$E_T^q$	$\tilde{E}_T^q$	<b>parton helicity-flip (chiral-odd) GPDs</b>

For  $\pi^0$  electroproduction the GPDs appear in the flavor combinations:

$$F_i^{\pi^0} = (e_u F_i^u - e_d F_i^d) / \sqrt{2}$$

The GPDs depend on three kinematic variables,

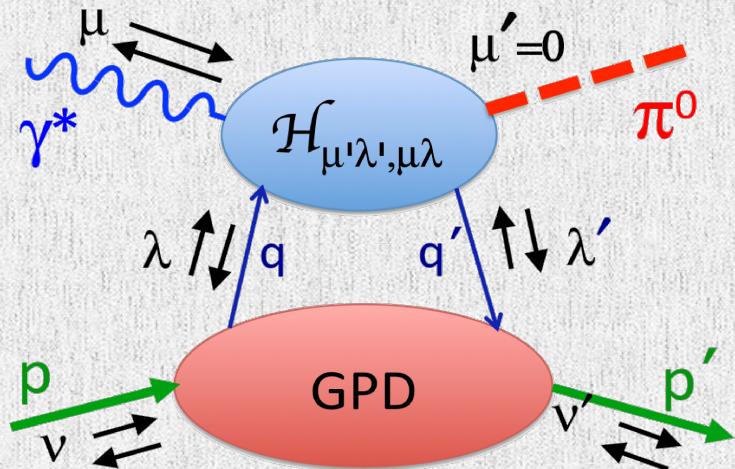
e.g.  $H^q(x, \xi, t)$

$x$  ←  
average parton  
momentum fraction

$\xi \simeq \frac{2x_B}{2-x_B}$   
(skewness) difference between  
the initial and final fractions of  
the longitudinal momentum  
carried by the struck parton

$t = (p - p')^2$   
momentum transfer  
between initial and  
final nucleons

# HELICITY AMPLITUDES



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

- ◆ Physical observables involve the convolution of GPDs
- ◆ Information on longitudinal fraction  $x$  is not accessible
- ◆ GPDs are functions of 3 variables

**Longitudinally polarized photons:**

$$M_{0+0+} \quad M_{0-0+}$$

**Transversely polarized photons:**

$$M_{0+++} \quad M_{0--+} \quad M_{0+-+} \quad M_{0-++}$$

$$M_{\mu'\pm,\mu+} = \sum_a [\langle H^a \rangle + \dots]$$



# GOLOSKOKOV-KROLL MODEL

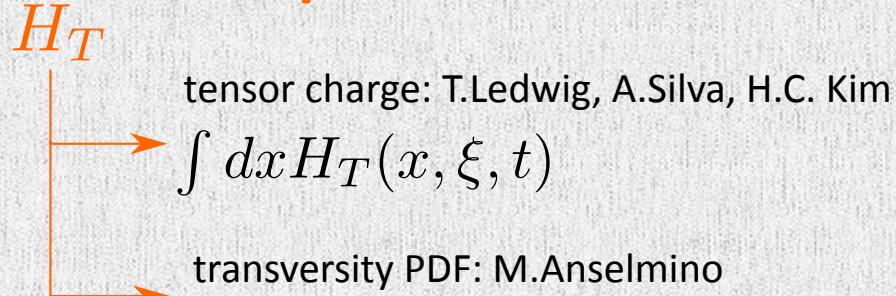
## Amplitude Hierarchy:

$$|M_{0--+}|, |M_{0+++}^U| \ll |M_{0-++}|, |M_{0+++}^N|$$

where  $M_{0+++}^N = \frac{1}{2}(M_{0+++} + M_{0-++})$

$$M_{0+++}^U = \frac{1}{2}(M_{0+++} - M_{0-++})$$

## GPDs parametrization:



$$\bar{E}_T = 2\tilde{H}_T + E_T$$

Lattice QCD: M.Gockeler  
 $\bar{E}_T$  moments

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THE EUROPEAN  
PHYSICAL JOURNAL A

Regular Article – Theoretical Physics

## Transversity in hard exclusive electroproduction of pseudoscalar mesons

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## UNPOLARIZED STRUCTURE FUNCTIONS:

$$\sigma_L \sim \left\{ (1 - \xi^2) \left| \langle \tilde{H} \rangle \right|^2 - 2\xi^2 \text{Re} \left[ \langle \tilde{H} \rangle^* \langle \tilde{E} \rangle \right] - \frac{t'}{4m^2} \xi^2 \left| \langle \tilde{E} \rangle \right|^2 \right\}$$

$$\sigma_T \sim \left[ (1 - \xi^2) |\langle H_T \rangle|^2 - \frac{t'}{8m^2} |\langle E_T \rangle|^2 \right]$$

$$\sigma_{TT} \sim |\langle \bar{E}_T \rangle|^2$$

## POLARIZED OBSERVABLES:

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

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

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

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

# GOLDSTEIN-LIUTI MODEL

PHYSICAL REVIEW D **84**, 034007 (2011)

## Chiral-even GPDs parametrization

recursive fit by imposing constraints from:



## Flexible parametrization of generalized parton distributions from deeply virtual Compton scattering observables

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(Received 16 February 2011; published 5 August 2011)

DIS experimental results → elastic form factors → DVCS data

## Evaluation of chiral-odd GPDs through the linear relations with

## chiral even GPDs within GL model:

$$\tilde{H}_T = -\frac{1}{F} \left( E - \frac{\zeta}{2} \tilde{E} \right)$$

$$E_T = \frac{(1 - \zeta/2)^2}{1 - \zeta} \left[ E - 2\tilde{H}_T - \left( \frac{\zeta/2}{1 - \zeta/2} \right)^2 \tilde{E} \right]$$

$$\tilde{E}_T = \frac{\zeta/2(1 - \zeta/2)}{1 - \zeta} \left[ E - 2\tilde{H}_T - \tilde{E} \right]$$

$$H_T = \frac{H + \tilde{H}}{2} - \frac{\zeta^2/4}{1 - \zeta} \frac{E + \tilde{E}}{2} - \frac{\zeta^2/4}{(1 - \zeta/2)(1 - \zeta)} E_T + \frac{\zeta/4(1 - \zeta/2)}{1 - \zeta} \tilde{E}_T - \frac{t_0 - t}{4M^2} \frac{1}{F} \left( E - \frac{\zeta}{2} \tilde{E} \right)$$

# DV $\pi^0$ P STRUCTURE FUNCTIONS

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

unpolarized terms

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

longitudinally  
polarized target

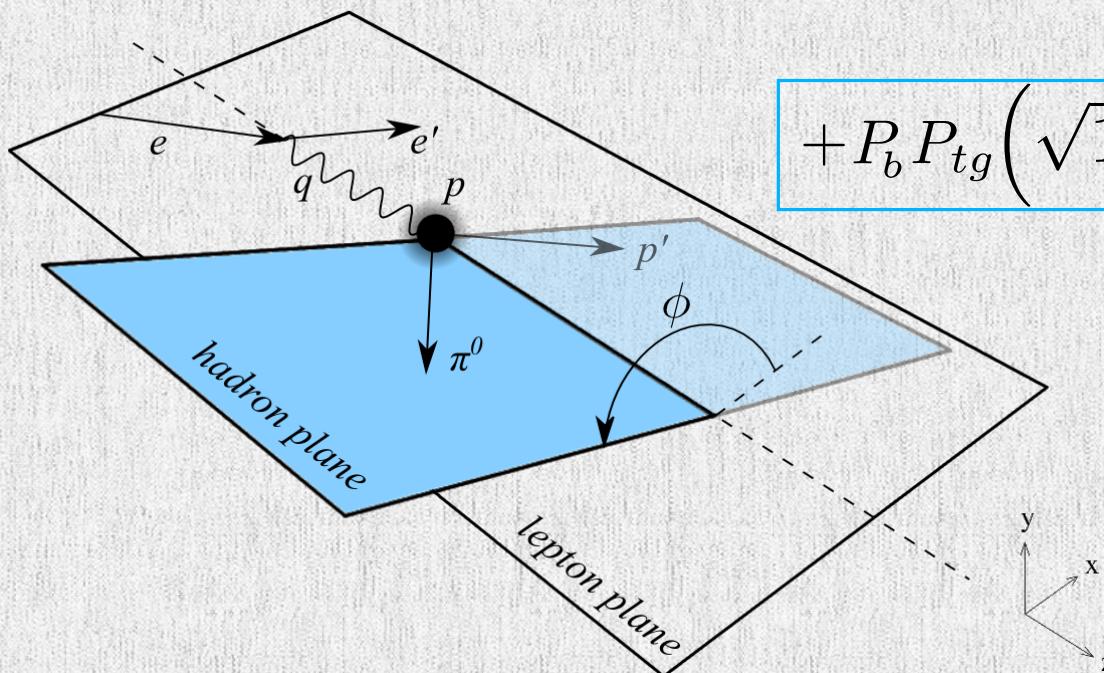
longitudinally  
polarized beam

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

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

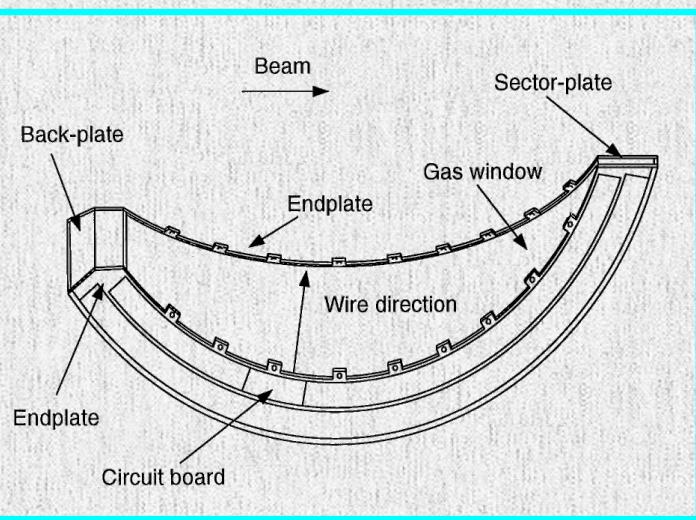
$$\rightarrow \boxed{+P_b P_{tg} \left( \sqrt{1-\epsilon^2}\sigma_{LL} + \sqrt{\epsilon(1-\epsilon)}\sigma_{LL}^{\cos \phi} \cos \phi \right)}$$

longitudinally polarized beam  
and  
longitudinally polarized target



# CEBAF LARGE ACCEPTANCE SPECTROMETER

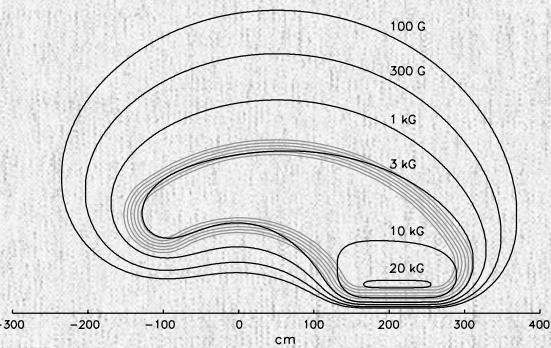
**DRIFT CHAMBER**



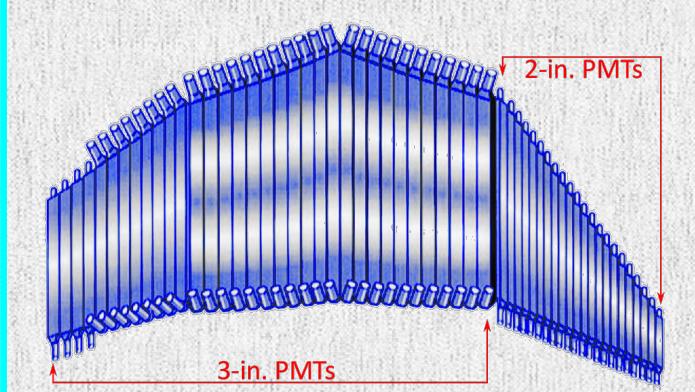
**ELECTROMAGNETIC CALORIMETER**



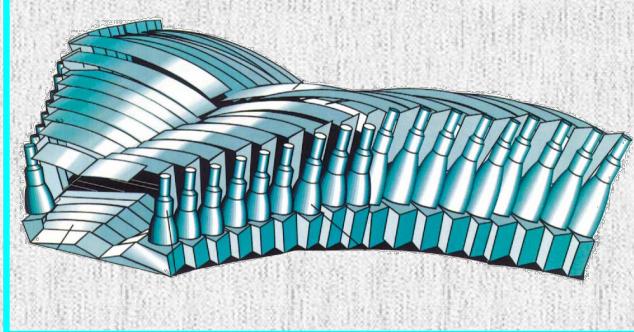
**MAGNETIC FIELD**



**SCINTILLATION COUNTERS**



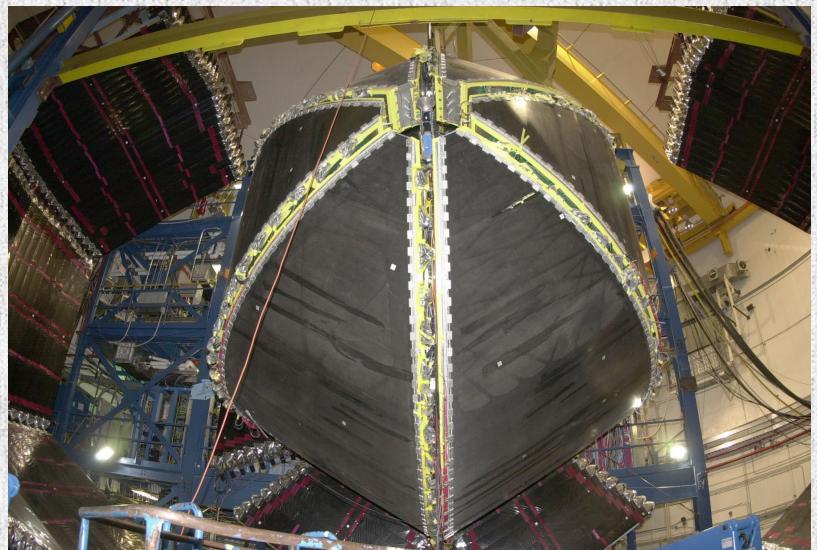
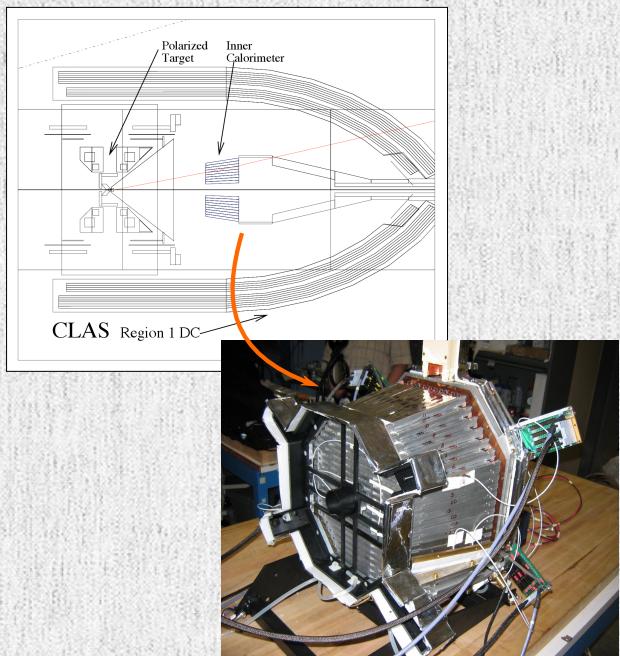
**CHERENKOV COUNTERS**



# EXPERIMENTAL SETUP

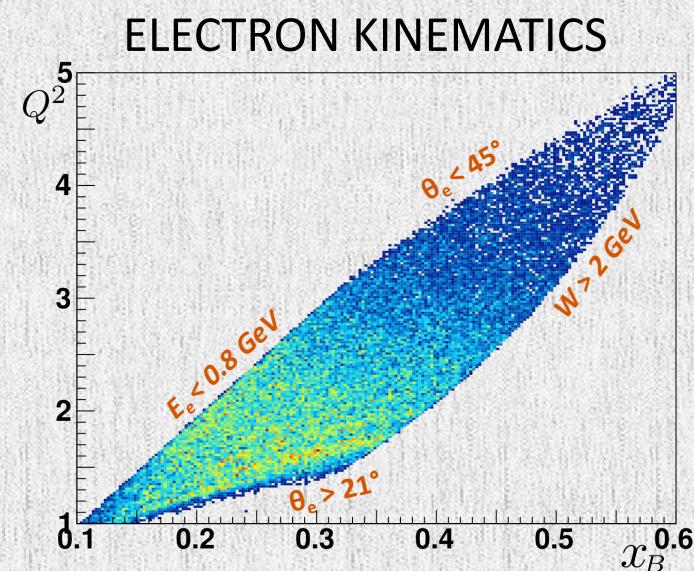
The presented experimental data were taken at Jefferson Lab:

- The data were collected between February and September 2009
- CEBAF provided a longitudinally polarized electron beam ( $>80\%$ )
- CEBAF Large Acceptance Spectrometer was used to detect outgoing particles
- The incident electron beam energy was approximately 6 GeV
- The integrated luminosity was  $75 \text{ fb}^{-1}$
- The target was longitudinally polarized  $^{14}\text{NH}_3$
- Inner Calorimeter was used to detect high energy photons at small angles



## The Inner Calorimeter (IC):

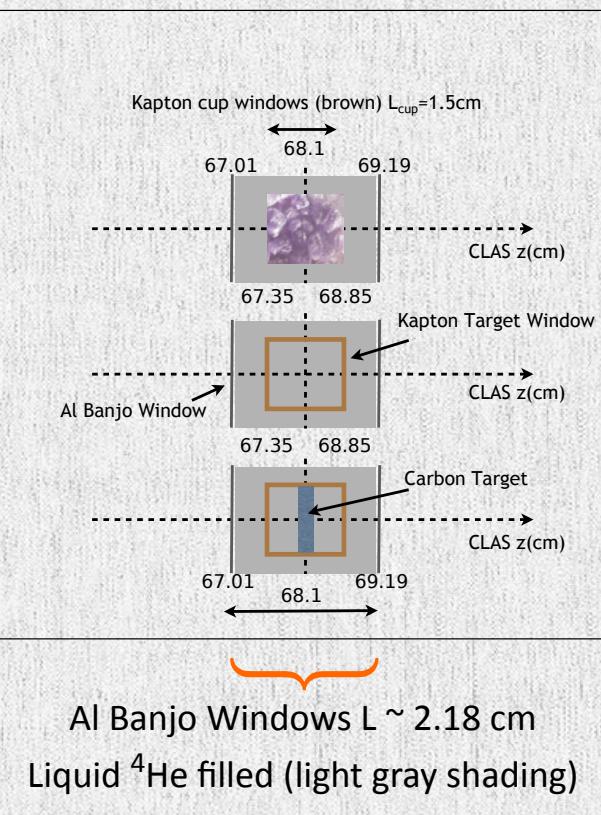
1. is an additional calorimeter inserted to the standard CLAS configuration downstream of the target.
2. detects photons from decay of the neutral pions in the forward direction and increase the detection of photons in the range from  $5^\circ$  up to  $16^\circ$ .
3. blocks charged particles permitting detection of the protons in angular range  $18^\circ$  to  $50^\circ$ , and electrons - from  $18^\circ$  to  $45^\circ$ .



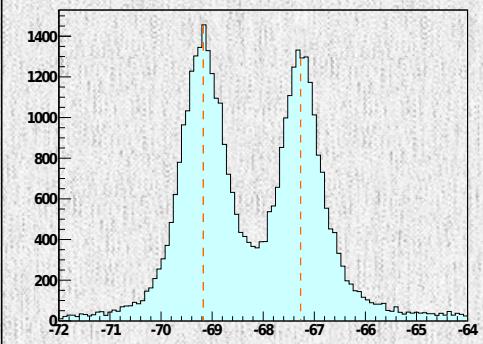
# LONGITUDINALLY POLARIZED TARGET

- ◆ Frozen ammonia was used as a target
- ◆ It was longitudinally polarized using Dynamic Nuclear Polarization (DNP) in a 5 Tesla homogeneous magnetic field
- ◆ The polarization was monitored using a Nuclear Magnetic Resonance (NMR) system

The side view of the target material in CLAS. Ammonia, empty and carbon (top to bottom) targets are shown here with a central nominal vertex.



Reconstructed electron vertex for run with empty target. Two peaks corresponds to the aluminum banjo windows



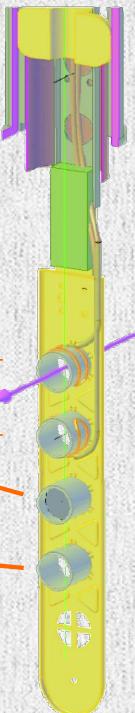
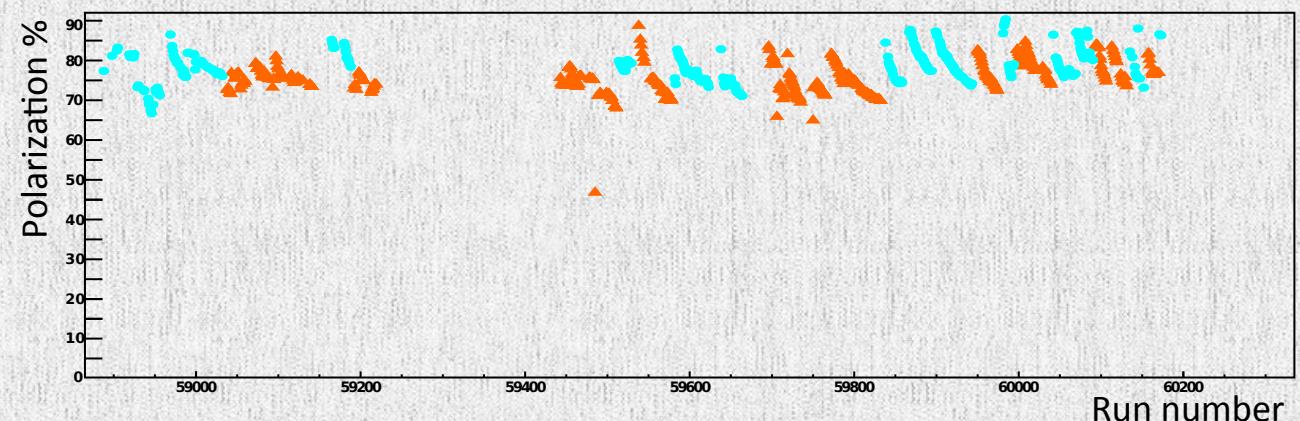
- Crushed beads of irradiated ammonia prepared at University of Virginia

- Disk of amorphous carbon

- Empty

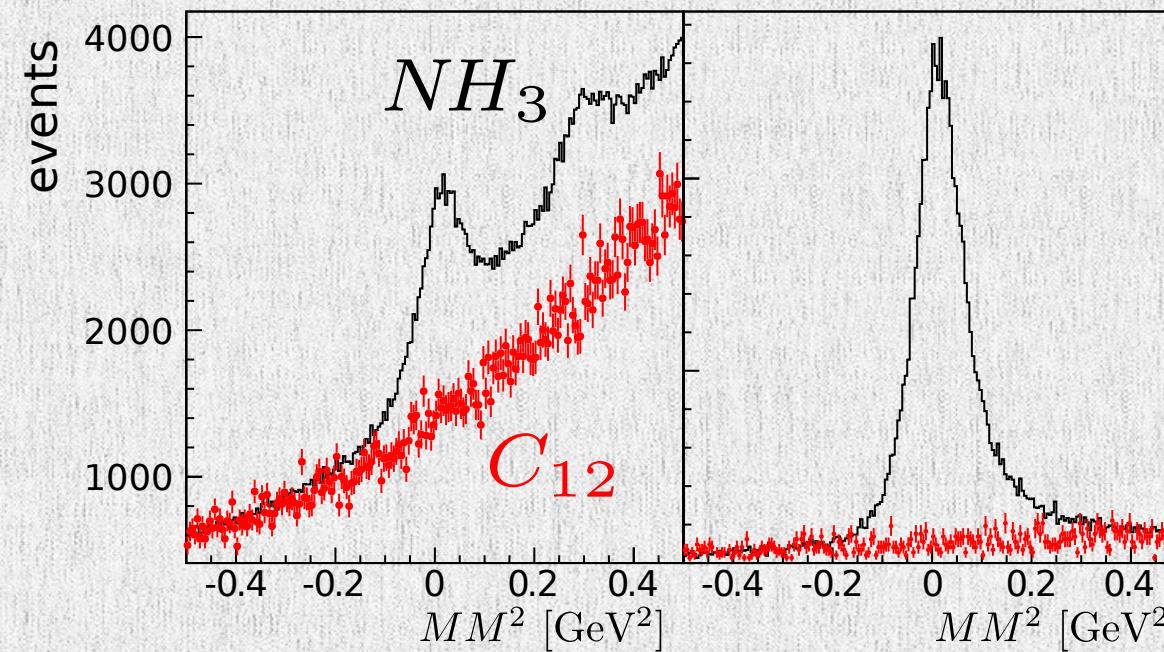
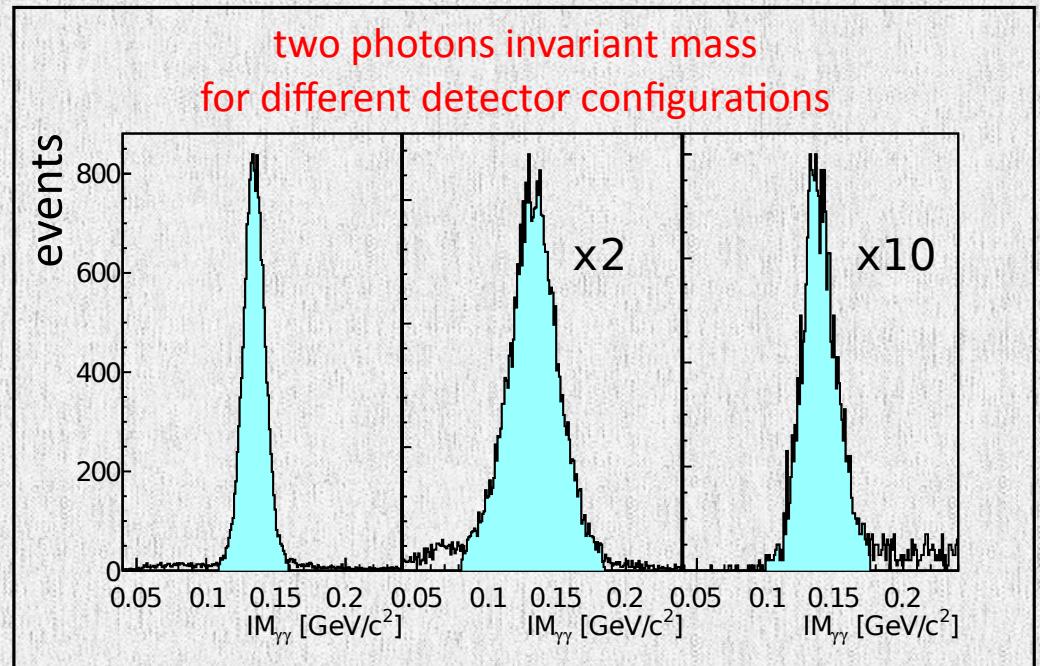
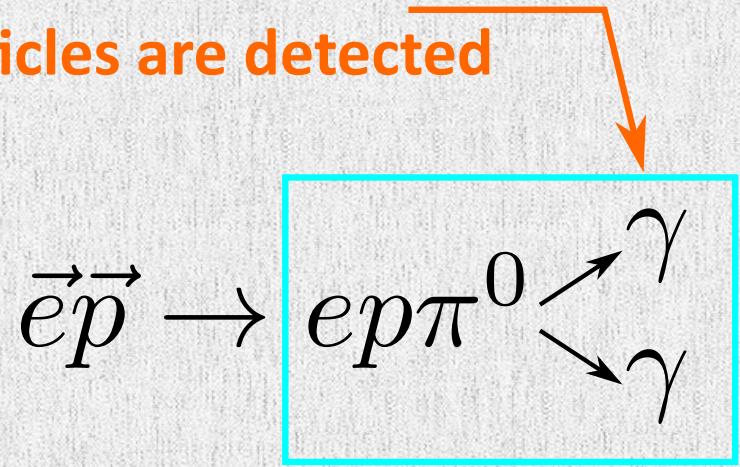
The last two cells are utilized for background studies.

NRM target polarization during eg1dvcs experiment



# EXCLUSIVE EVENTS

All four final-state particles are detected

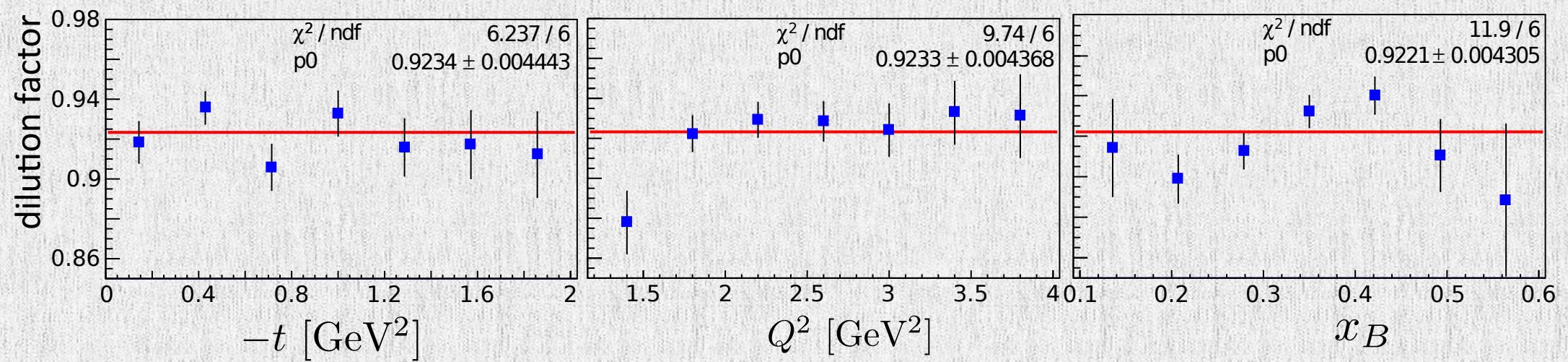
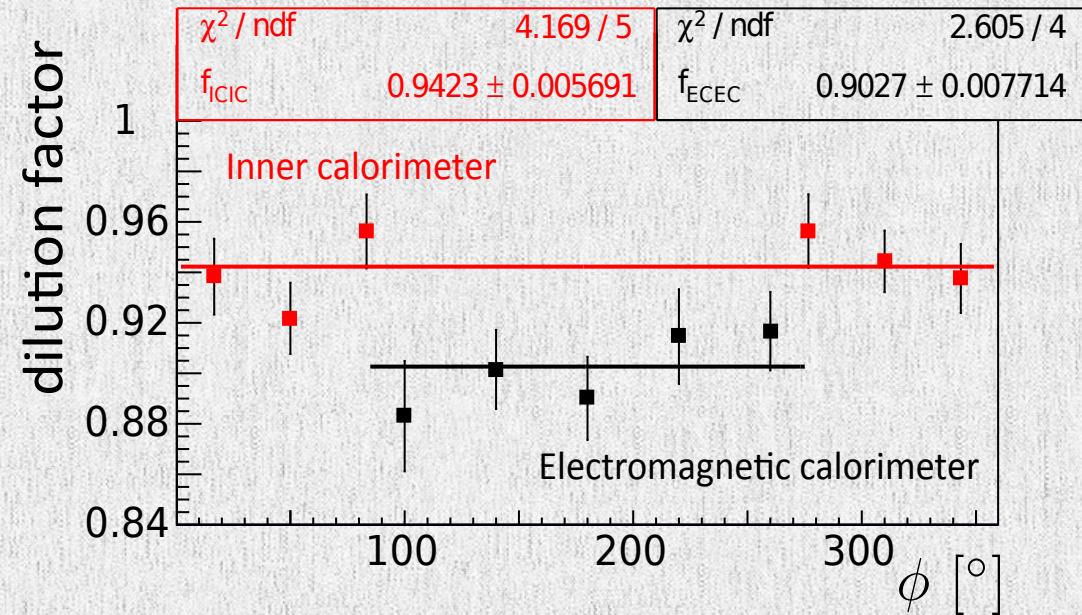


- ◆ Invariant Mass of two photons  $M_{\gamma\gamma}$
- ◆ Missing Mass Squared  $MM_{epX}$
- ◆ Angle between predicted and detected pions  $\theta_{X\pi^0}$
- ◆ Missing energy  $\Delta E_{ep\gamma\gamma}$

# DILUTION FACTOR

$$f = 1 - s \frac{N_{C_{12}}}{N_{NH_3}}$$

dilution factor  
 ↓  
 number of events from  $C_{12}$   
 ↓  
 $f = 1 - s \frac{N_{C_{12}}}{N_{NH_3}}$   
 ↑  
 C<sub>12</sub> to NH<sub>3</sub> normalization coefficient  
 ↓  
 number of events from NH<sub>3</sub>



# TARGET POLARIZATION MEASUREMENTS

$P_b P_t^+$	$P_b P_t^-$	$P_b^{Moller}$
$0.67 \pm 0.01$	$-0.63 \pm 0.01$	$0.836 \pm 0.006$

$$A_{exp} = \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$

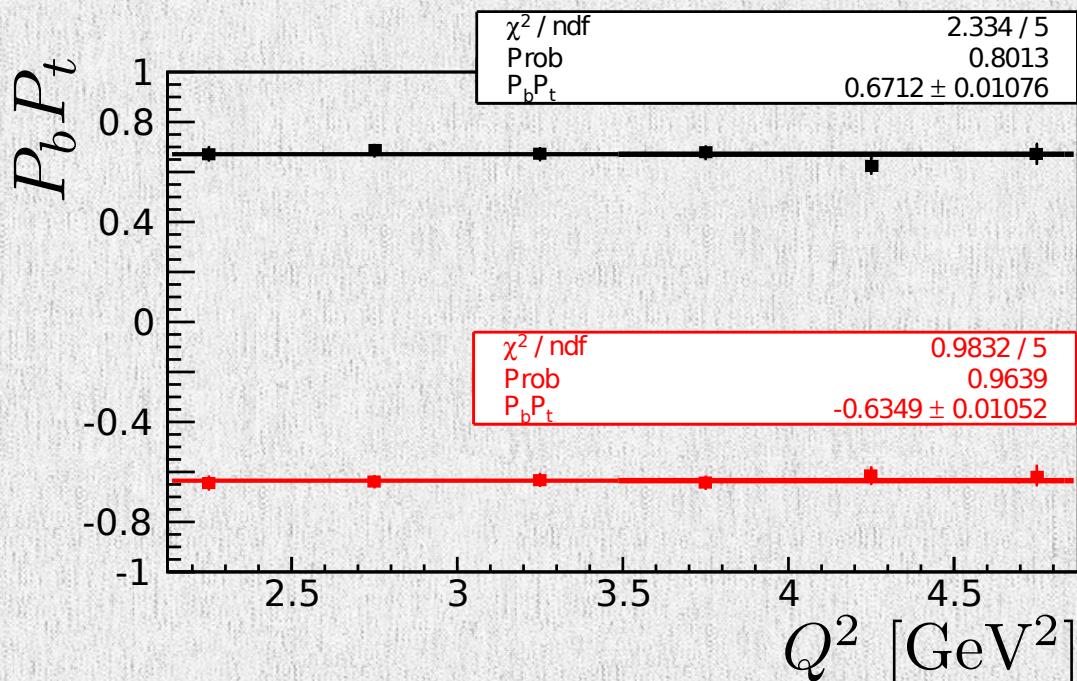
Experimental Asymmetry

$P_b P_t = \frac{A_{exp}}{A_{||}}$  The product of beam ( $\mathbf{P}_b$ ) and target polarizations ( $\mathbf{P}_t$ ) is extracted from elastic scattering:  $\vec{e}\vec{p} \rightarrow e\vec{p}$

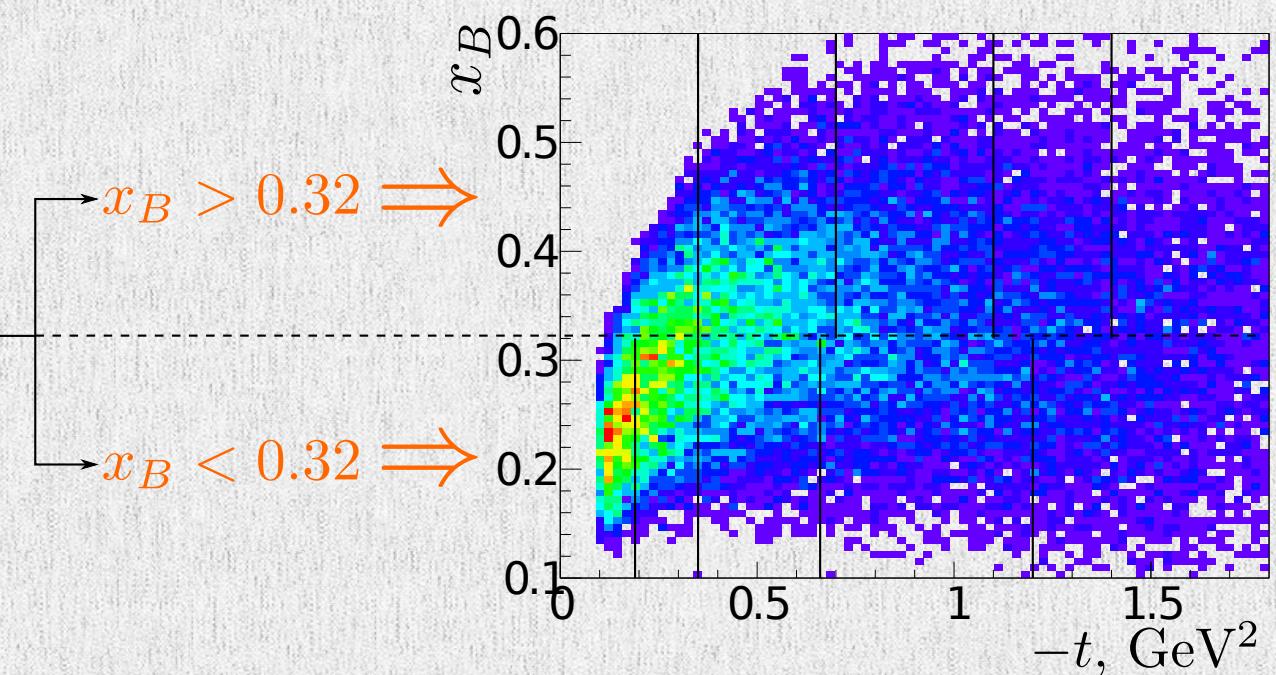
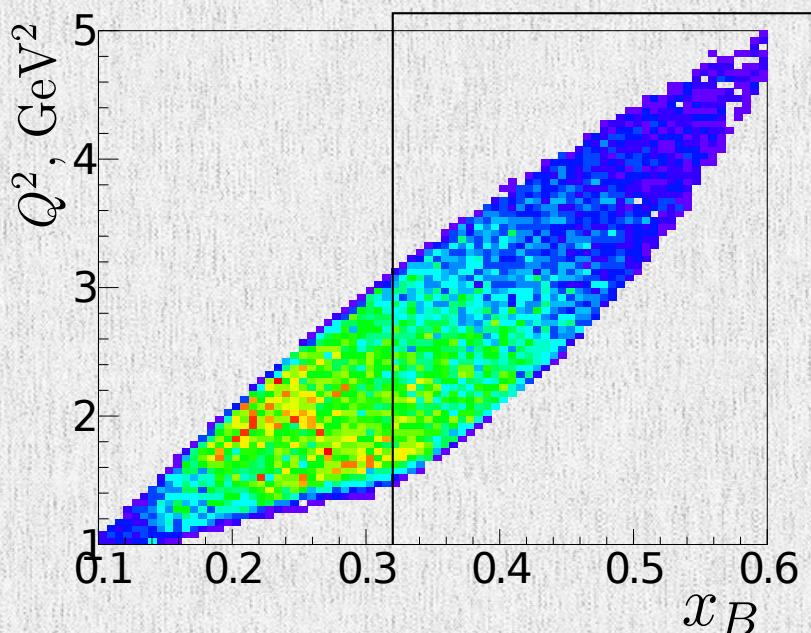
Theoretical Asymmetry

$$A_{||} = \frac{2\tau r \left[ \frac{M}{E} + r \left( \tau \frac{M}{E} + (1+\tau) \tan^2 \left( \frac{\theta}{2} \right) \right) \right]}{1 + \tau \frac{r^2}{\epsilon}}$$

where  $r = \frac{G_M}{G_E}$  - electric and magnetic form factors

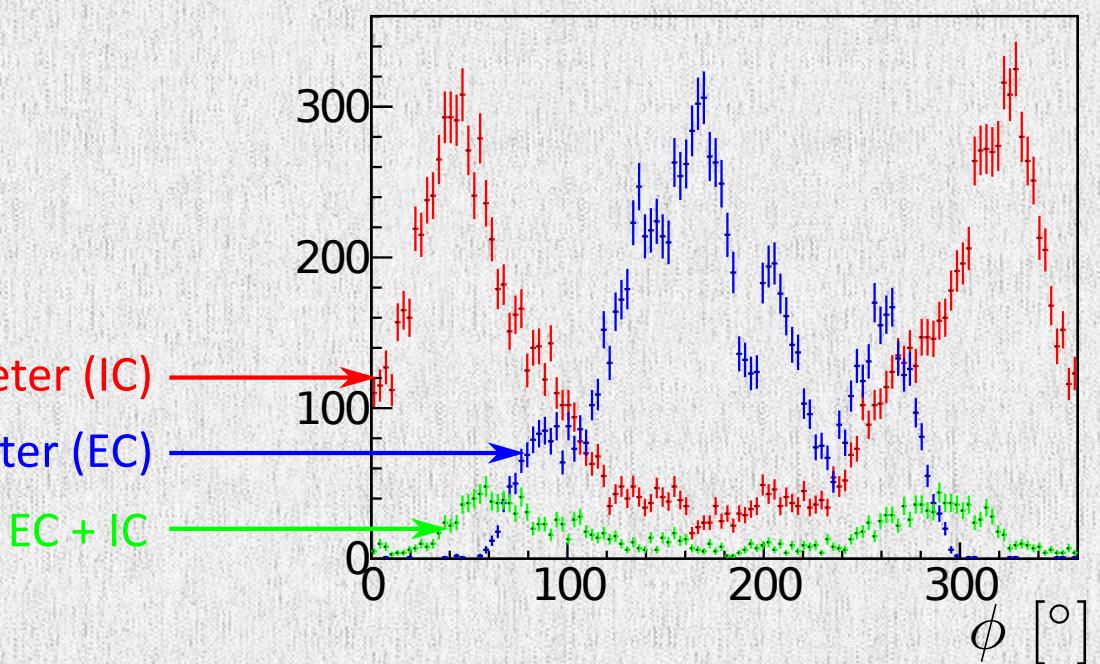


# KINEMATIC BINNING

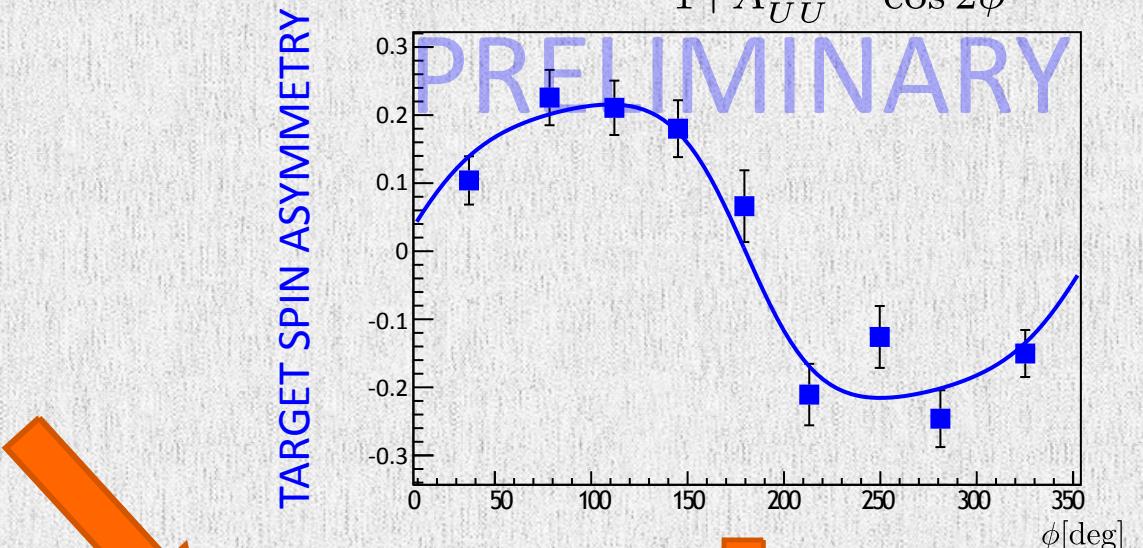
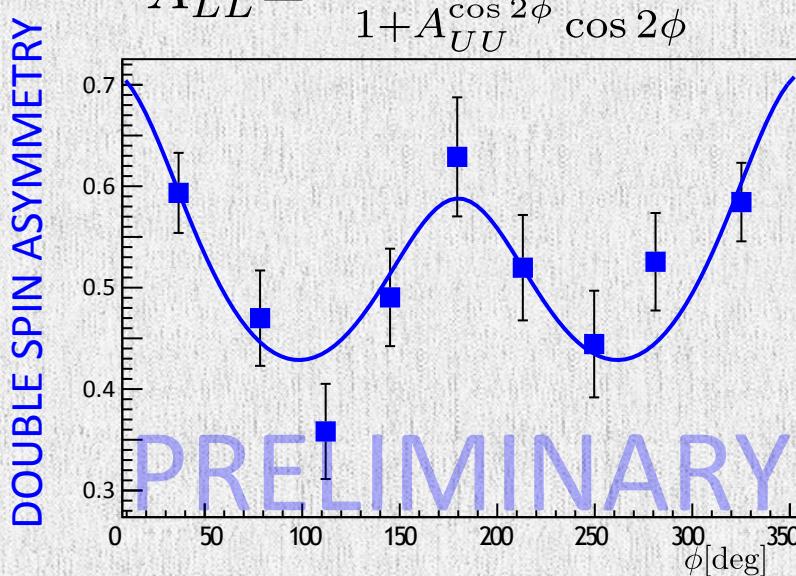
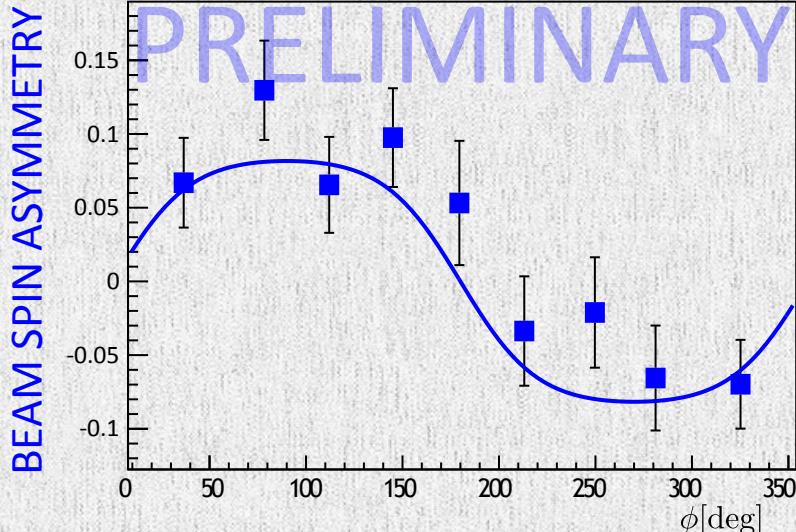


- ◆ 2 bin in  $\{Q^2, x_B\}$  plane
- ◆ 5 bins in  $t$
- ◆ 11 bins in  $\phi$

Inner calorimeter (IC)  
Electromagnetic calorimeter (EC)  
EC + IC



# DV $\pi^0$ P SPIN ASYMMETRIES



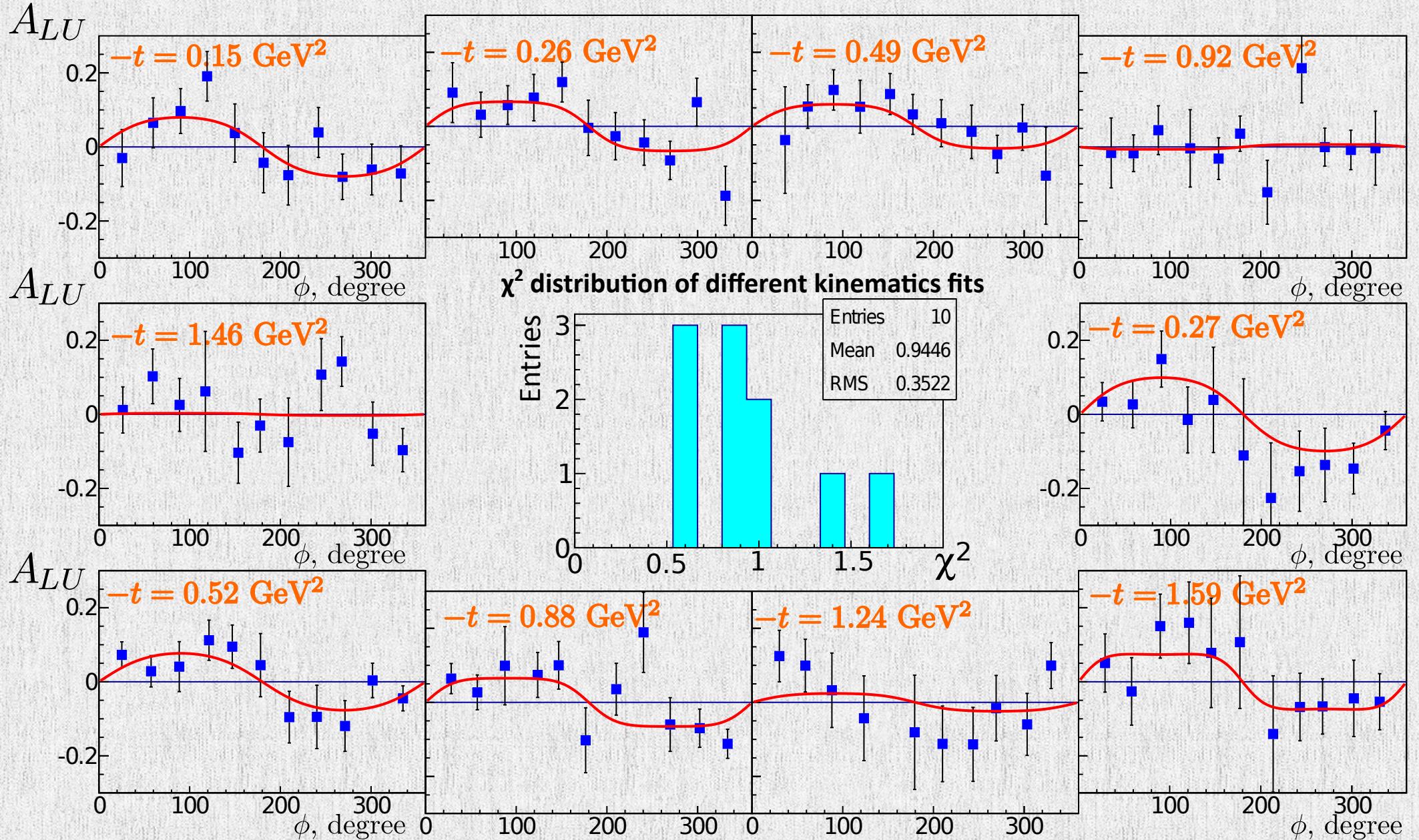
The data were **fitted simultaneously** with 6 parameters:

- 1.  $A_{UU}^{\cos 2\phi}$
- 2.  $A_{LU}^{\sin \phi}$
- 3.  $A_{UL}^{\sin \phi}$
- 4.  $A_{UL}^{\sin 2\phi}$
- 5.  $A_{LL}^{const}$
- 6.  $A_{LL}^{\cos \phi}$

The data were integrated over wide range of  $Q^2$ ,  $x_B$  and  $t'$

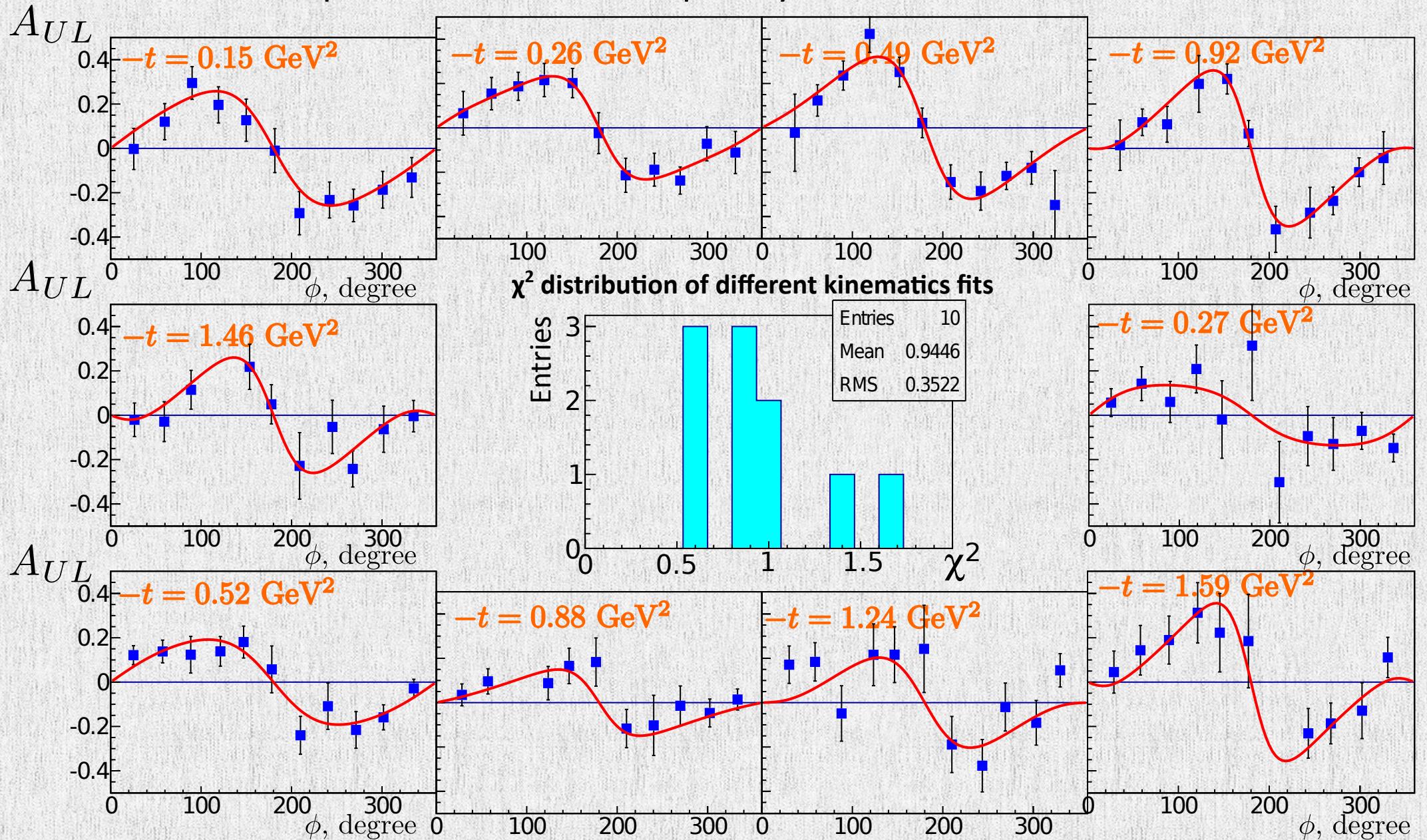
# DV $\pi^0$ P ASYMMETRIES

Azimuthal dependence of BEAM spin asymmetries in different kinematic bins



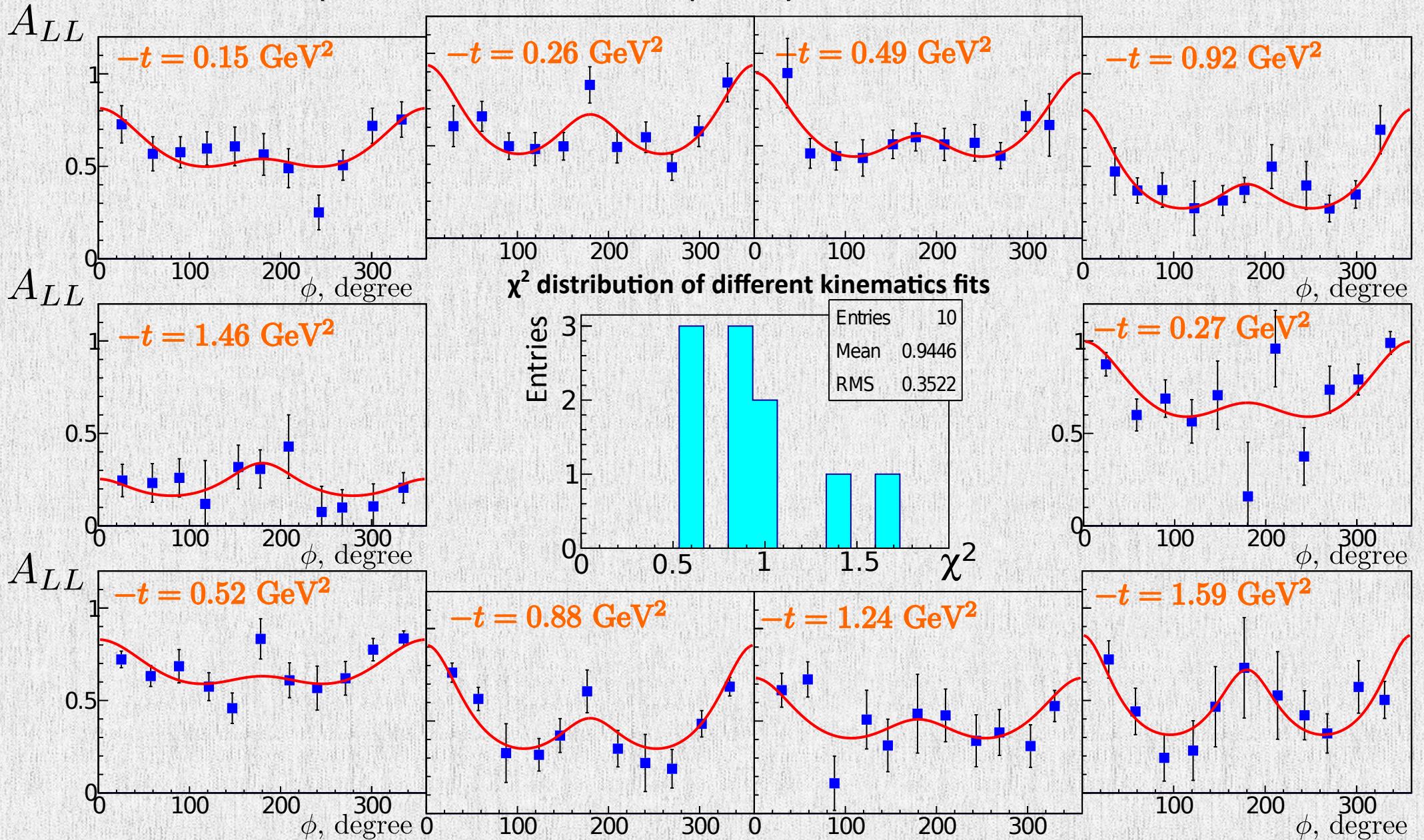
# DV $\pi^0$ P ASYMMETRIES

Azimuthal dependence of TARGET spin asymmetries in different kinematic bins



# DV $\pi^0$ P ASYMMETRIES

Azimuthal dependence of DOUBLE spin asymmetries in different kinematic bins

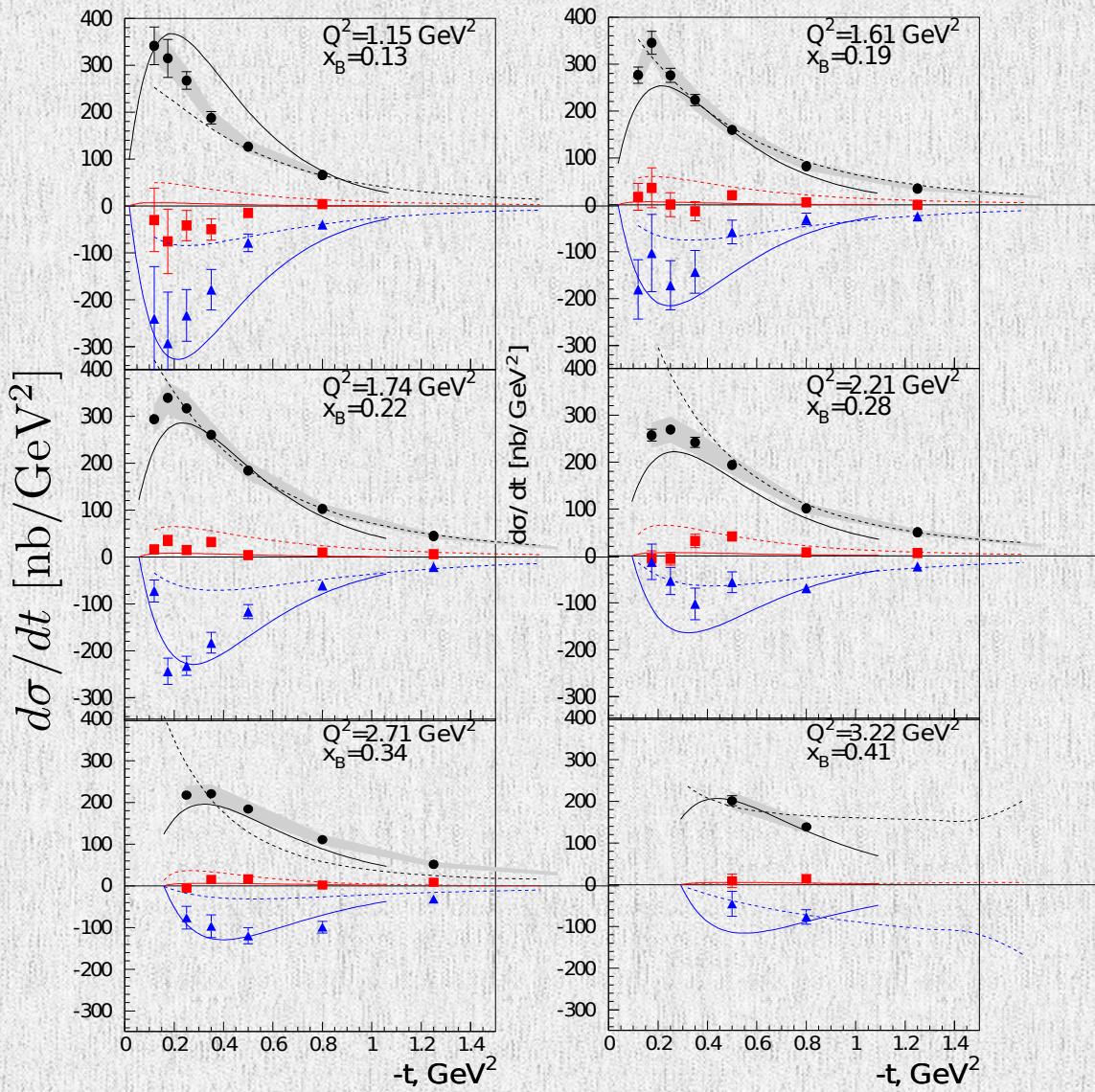


# UNPOLARIZED STRUCTURE FUNCTIONS

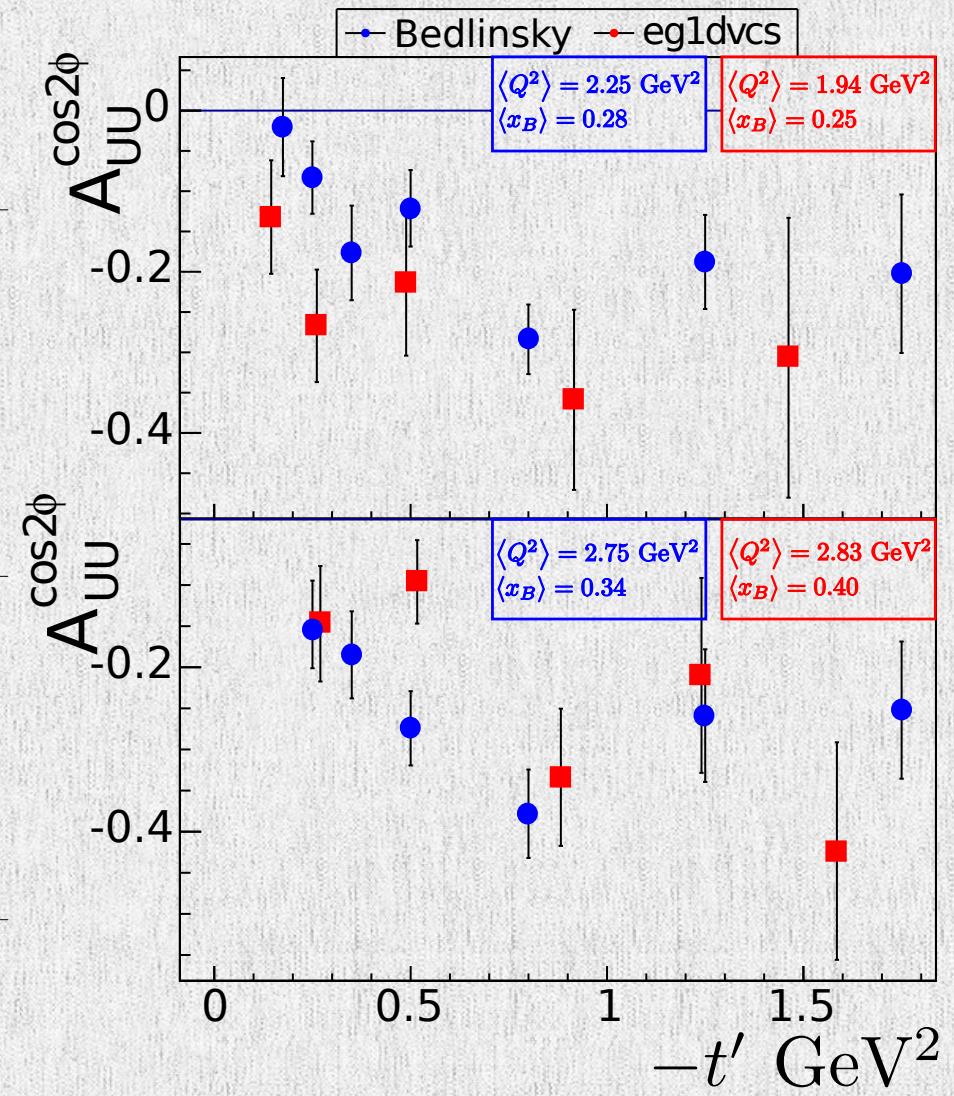
I. Bedlinsky *et al.* Measurement of Exclusive  $\pi^0$  Electroproduction Structure Functions and their Relationship to Transversity GPDs. 2012.

solid: P.Kroll & S.Goloskokov arXiv:1106.4897

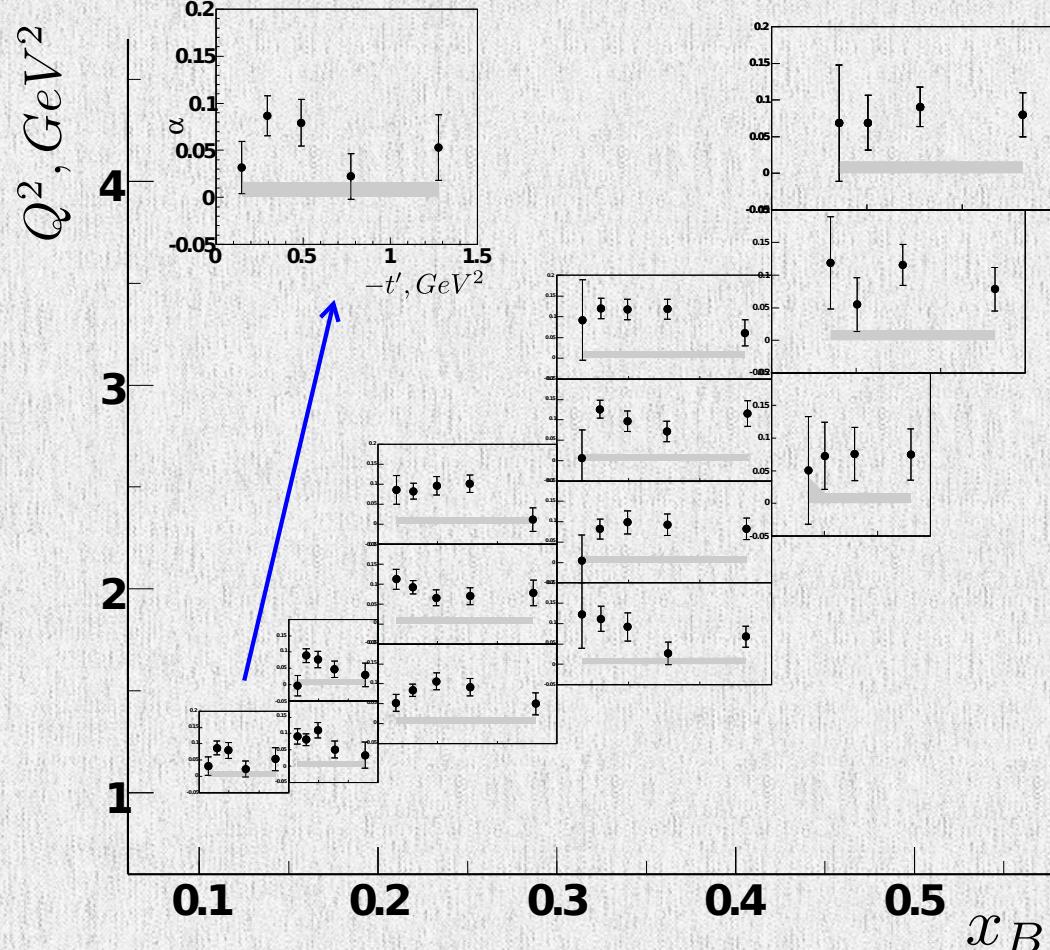
dashed: G.R. Goldstein, J.O. Gonzalez & S.Liuti arXiv:1012.3776



Comparison with previous measurements  
of unpolarized structure functions:



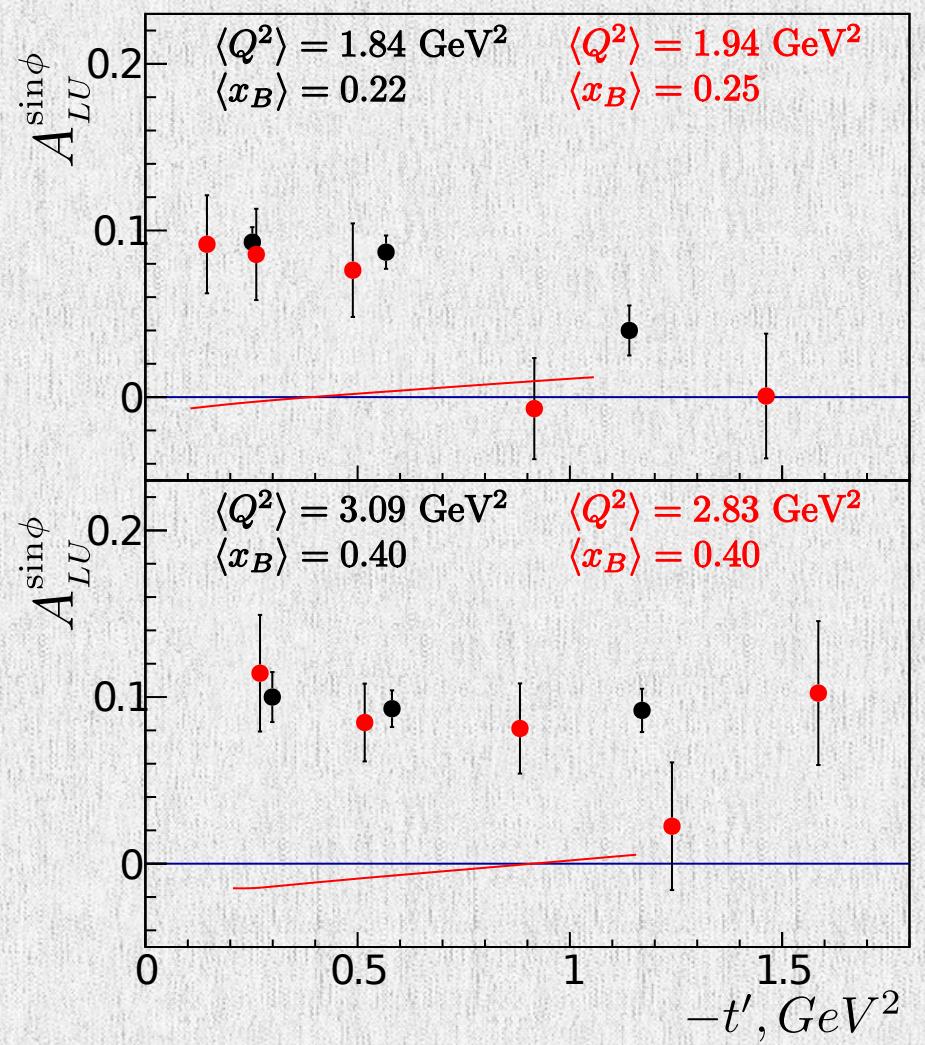
# BEAM SPIN ASYMMETRIES



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

● CLAS (eg1dvcs)  
● R. De Masi

The curves are from model  
of P.Kroll & S.Goloskokov



# TARGET SPIN ASYMMETRIES

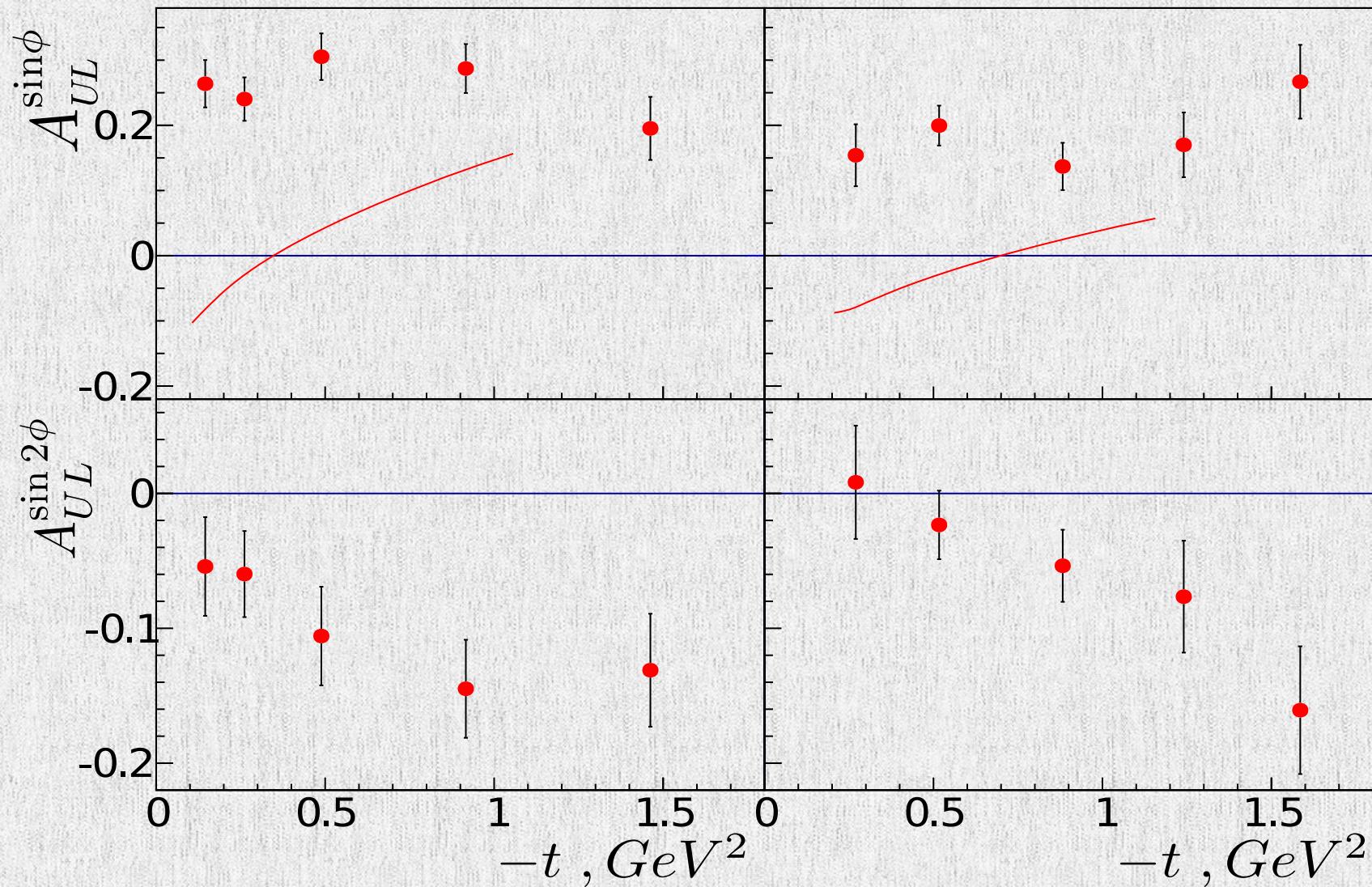
$$\langle Q^2 \rangle = 1.94 \text{ GeV}^2$$

$$\langle x_B \rangle = 0.25$$

$$\langle Q^2 \rangle = 2.83 \text{ GeV}^2$$

$$\langle x_B \rangle = 0.40$$

The curves are from model  
of P.Kroll & S.Goloskokov



# DOUBLE SPIN ASYMMETRIES

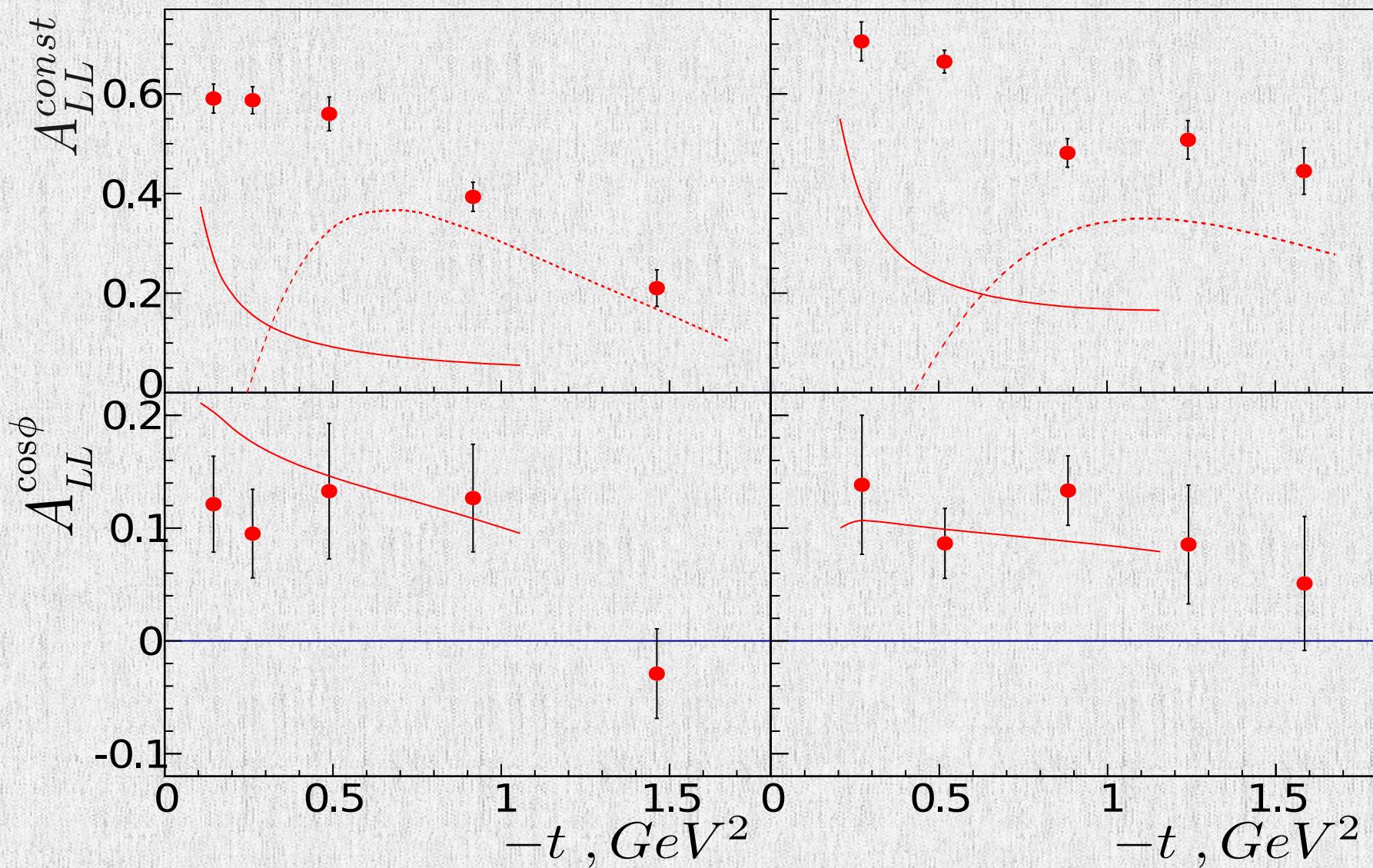
$$\langle Q^2 \rangle = 1.94 \text{ GeV}^2$$

$$\langle x_B \rangle = 0.25$$

$$\langle Q^2 \rangle = 2.83 \text{ GeV}^2$$

$$\langle x_B \rangle = 0.40$$

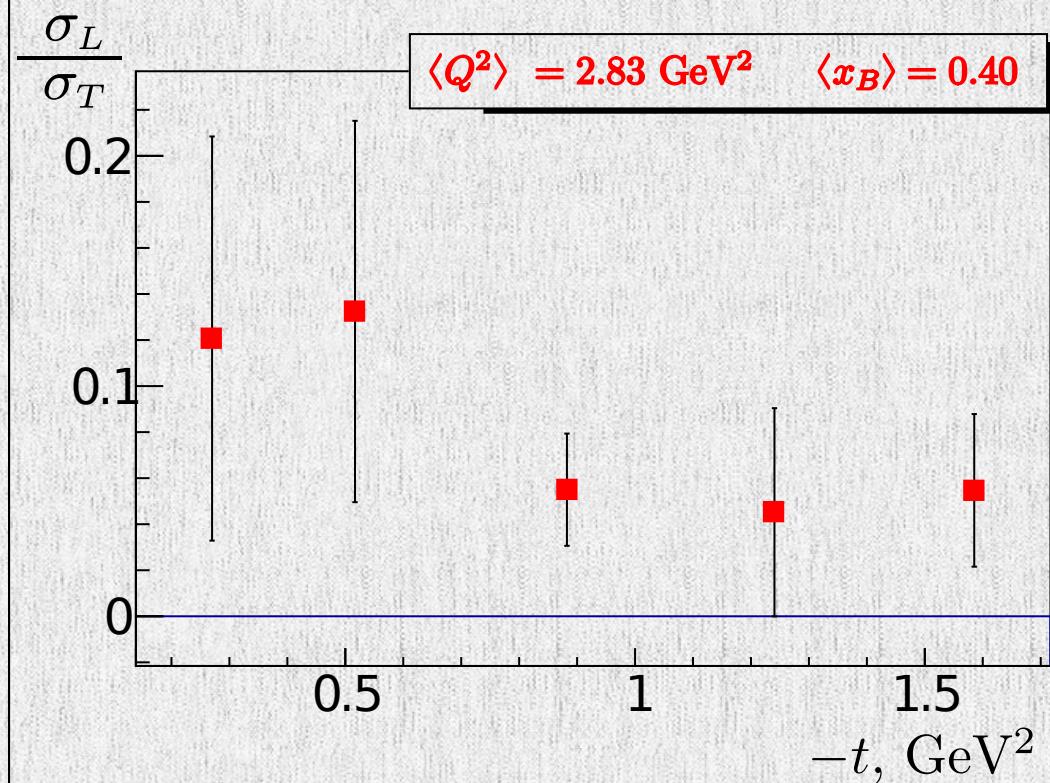
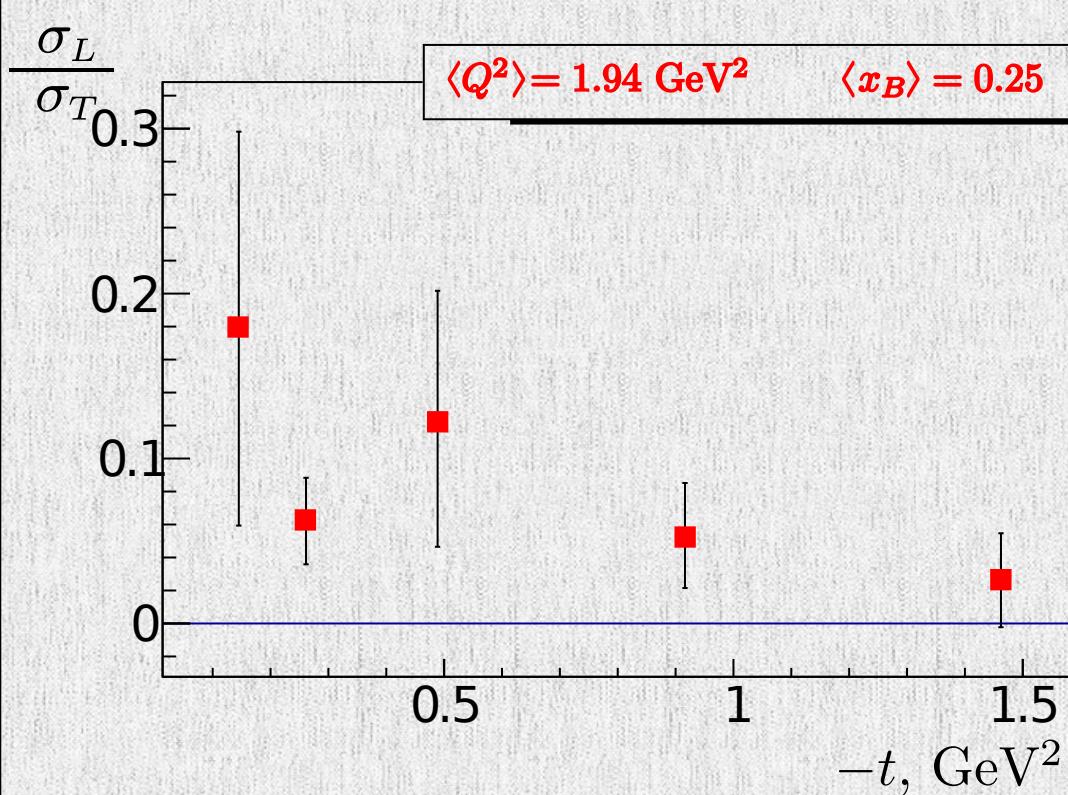
— Goloskokov-Kroll  
 - - - Goldstein-Liuti



# TRANSVERSE PHOTON AMPLITUDES

- ◆ The theoretical approaches were developed utilizing chiral odd GPDs in the calculation of pseudoscalar electroproduction
- ◆ The data confirm the expectation that  $\pi^0$  electroproduction is a uniquely sensitive process to access the transversity GPDs
- ◆ They lead to sizable transverse photon amplitudes, as *evidenced in the CLAS data*

Ratio of structure functions from unpolarized cross section



# SUMMARY

- ◆ The experiment provides the most extensive set of  $\pi^0$  electroproduction data with polarized proton target.
- ◆ The target and double spin asymmetries for exclusive neutral pion electroproduction in DIS region have been measured for the first time from CLAS (eg1dvcs) data.
- ◆ The current analysis adds new and sensitive information that will impact the extraction of GPDs from the data.
- ◆ Combination of polarized and unpolarized observables provide constraints for  $t$  dependence on underlying transverse GPDs and may help establish the role of transversity in pion electroproduction.