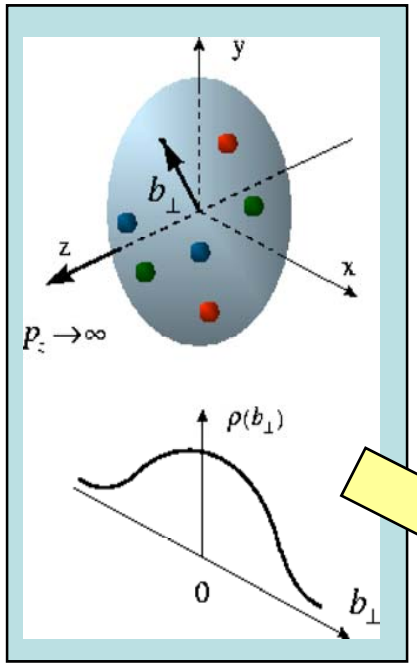
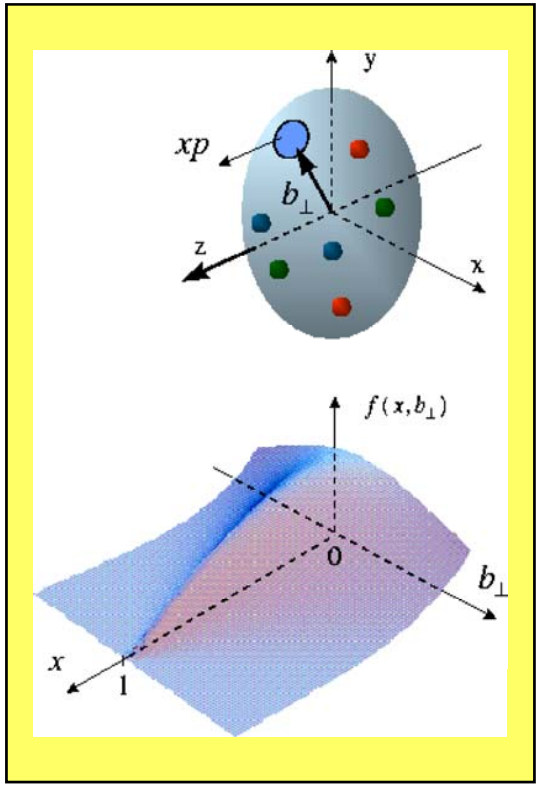
# Deep Exclusive Processes

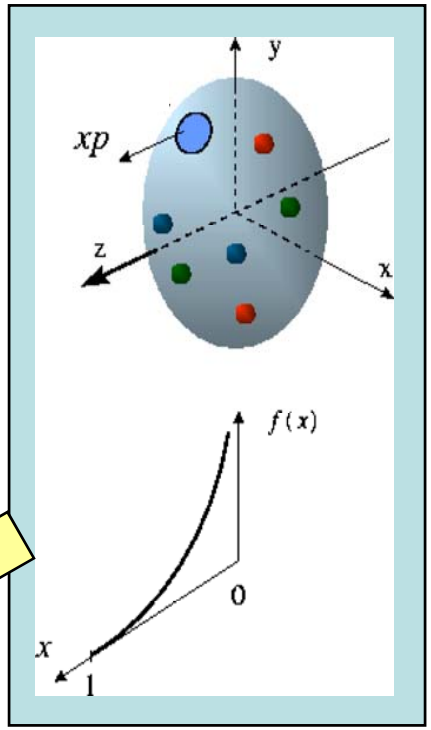
*Latifa Elouadrhiri*
*Office: CC B121*
*Phone: X7303*
*E-mail: latifa@jlab.org*
**Jefferson Lab**

# How are the proton's charge/current densities related to its quark momentum/spin distribution?

D. Mueller, X. Ji, A. Radyushkin, …1994 -1997
M. Burkardt, A. Belitsky… Interpretation in impact parameter space



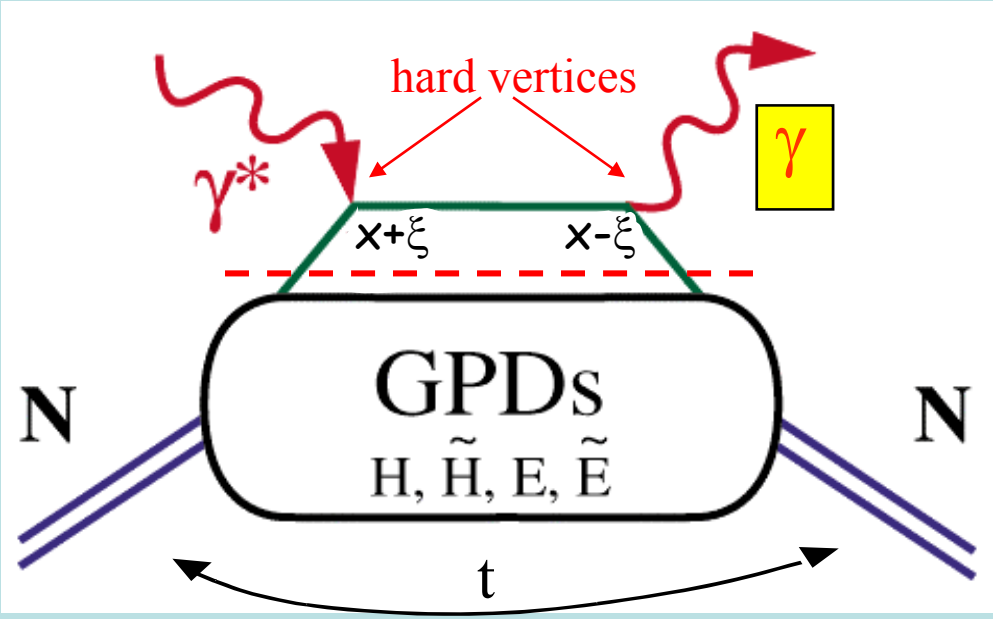

Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & spin distributions

# Basic Process – Handbag Mechanism

## Deeply Virtual Compton Scattering (DVCS)




x - longitudinal quark momentum fraction

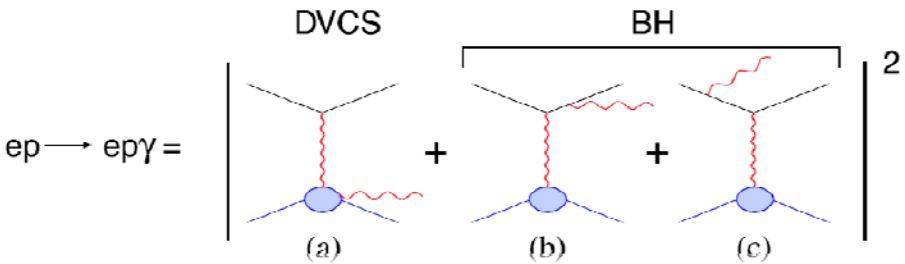
2ξ - longitudinal momentum transfer

$\sqrt{-t}$ - Fourier conjugate to transverse impact parameter

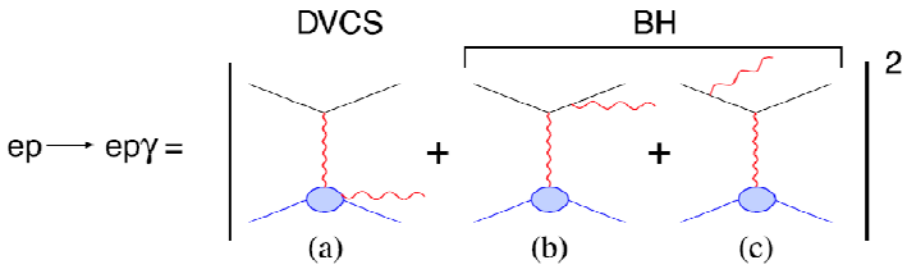
GPDs depend on 3 variables, e.g. $H(x, \xi, t)$. They probe the quark structure at the amplitude level.

$$\xi = \frac{x_B}{2-x_B}$$

# DVCS experimentally: interference with Bethe-Heitler (BH)



# DVCS experimentally: interference with Bethe-Heitler (BH)




At leading twist:

$$d^5\overrightarrow{\sigma} - d^5\overleftarrow{\sigma} = \Im m\,(T^{BH}\cdot T^{DVCS})$$

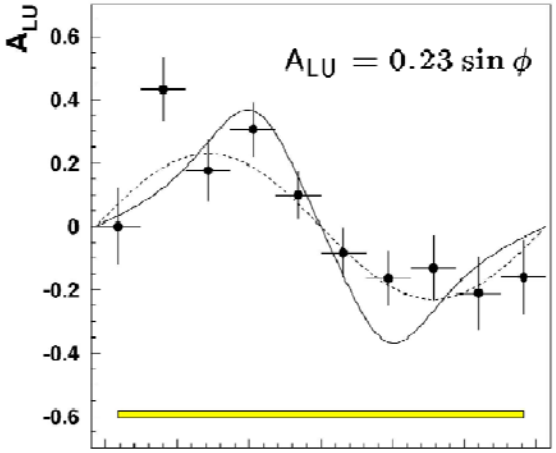
$$d^5\overrightarrow{\sigma} + d^5\overleftarrow{\sigma} = |BH|^2 + \Re e\,(T^{BH}\cdot T^{DVCS}) + |DVCS|^2$$

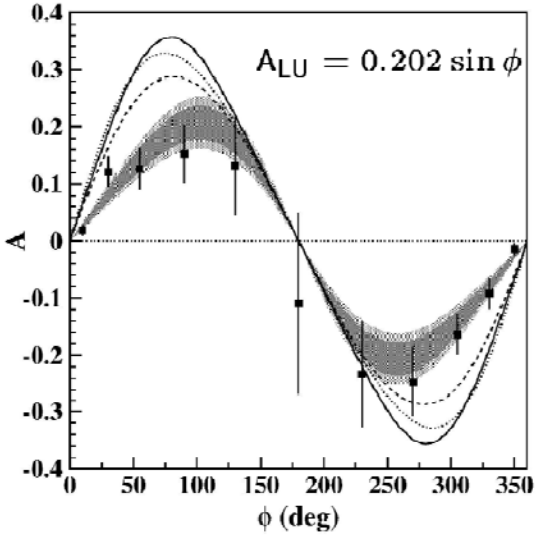
$$\mathcal{T}^{DVCS} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\epsilon} + \cdots =$$

$$\underbrace{\mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}}_{\text{Access in helicity-independent cross section}} - \underbrace{i\pi\, H(x=\xi,\xi,t)}_{\text{Access in helicity-dependent cross-section}} + \ldots$$

# Non-dedicated DVCS observations

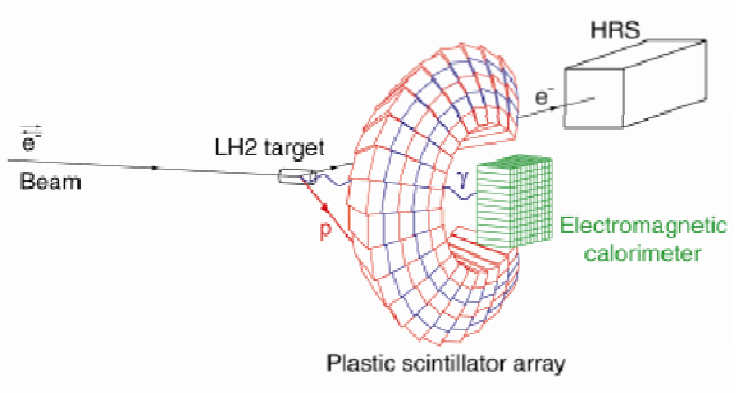
| Experiment | Observable |
|---|---|
| H1 | $\sigma$ |
| ZEUS | $\sigma$ |
| HERMES | BSA/$A_{LU}$ |
| | BCA |
| | TSA/$A_{UL}$ & $A_{UT}$ |
| CLAS | BSA/$A_{LU}$ |
| | TSA/$A_{UL}$ |



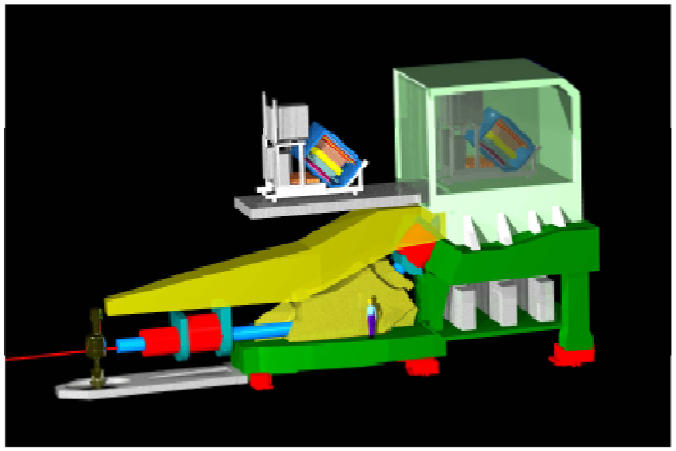




HERMES and CLAS : first observations $A_{LU} \sim \sin\phi$

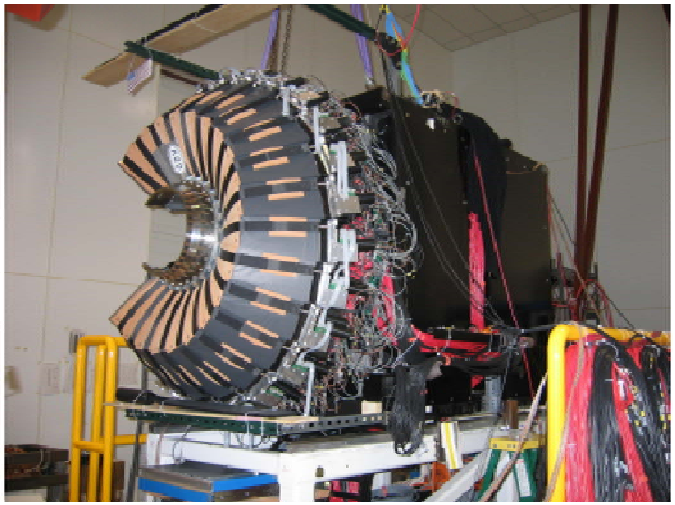
# Hall A experimental setup



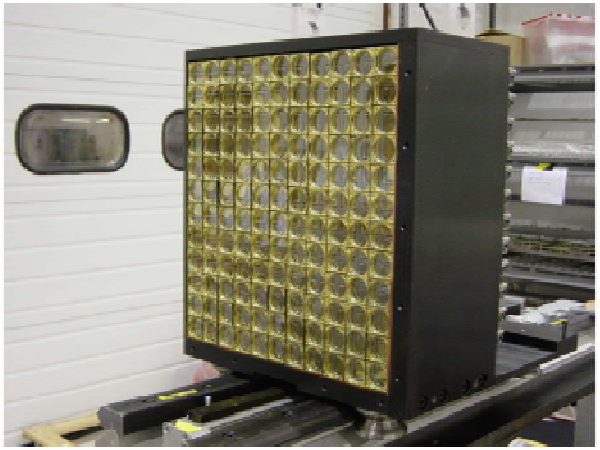

High Resolution Spectrometer



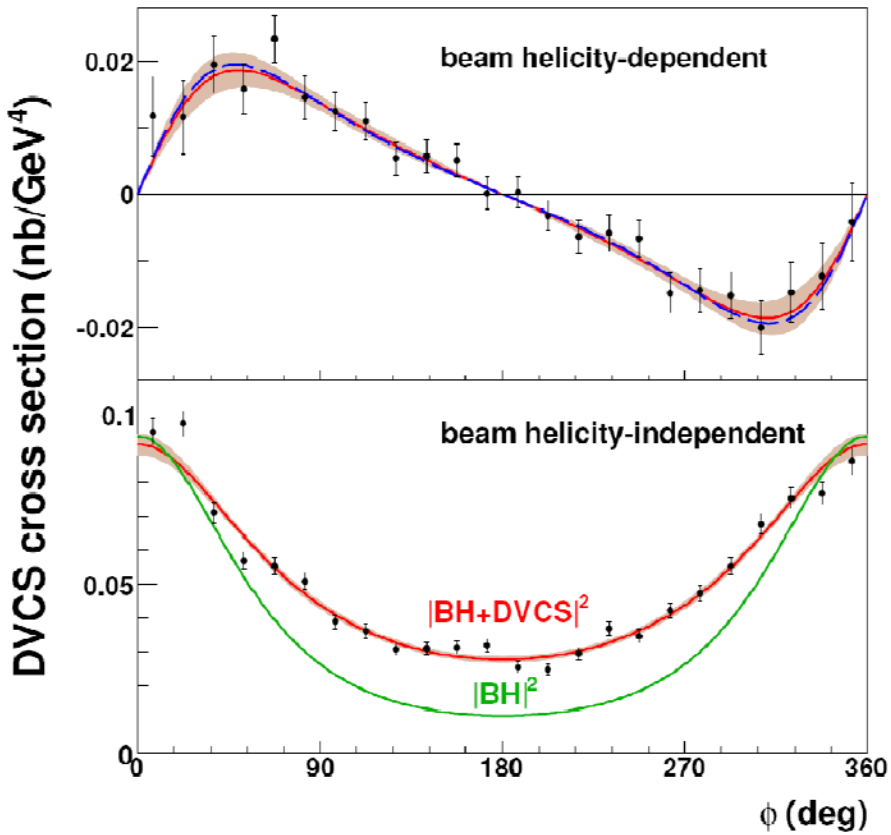
100-channel scintillator array



132-block $PbF_2$ electromagnetic calorimeter



# E00-110 cross section results




- $Q^2 = 2.3\,\mathrm{GeV}^2$
- $\langle t \rangle = -0.28\,\mathrm{GeV}^2$
- $x_{\mathrm{Bj}} = 0.36$

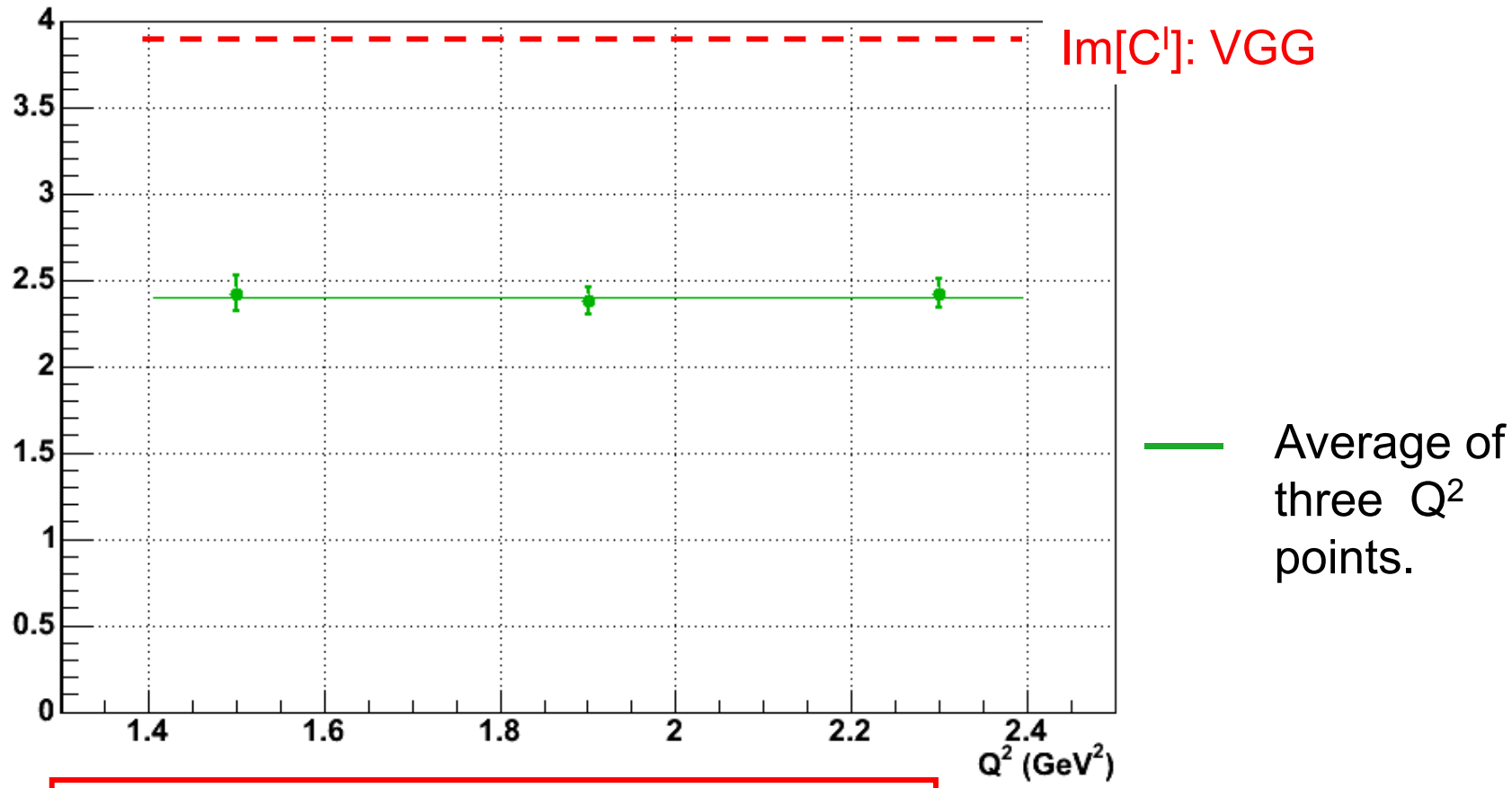
Twist-2 dominant contribution

Contributions from $\mathrm{BH}^2$, $\mathrm{DVCS}^2$ and BH-DVCS interference

C.M.C. *et al.*, Phys. Rev. Lett. **97**, 262002 (2006)
Physics Today, March 2007

# $Q^2$-dependence: averaged over t: <t>=-0.23 $GeV^2$

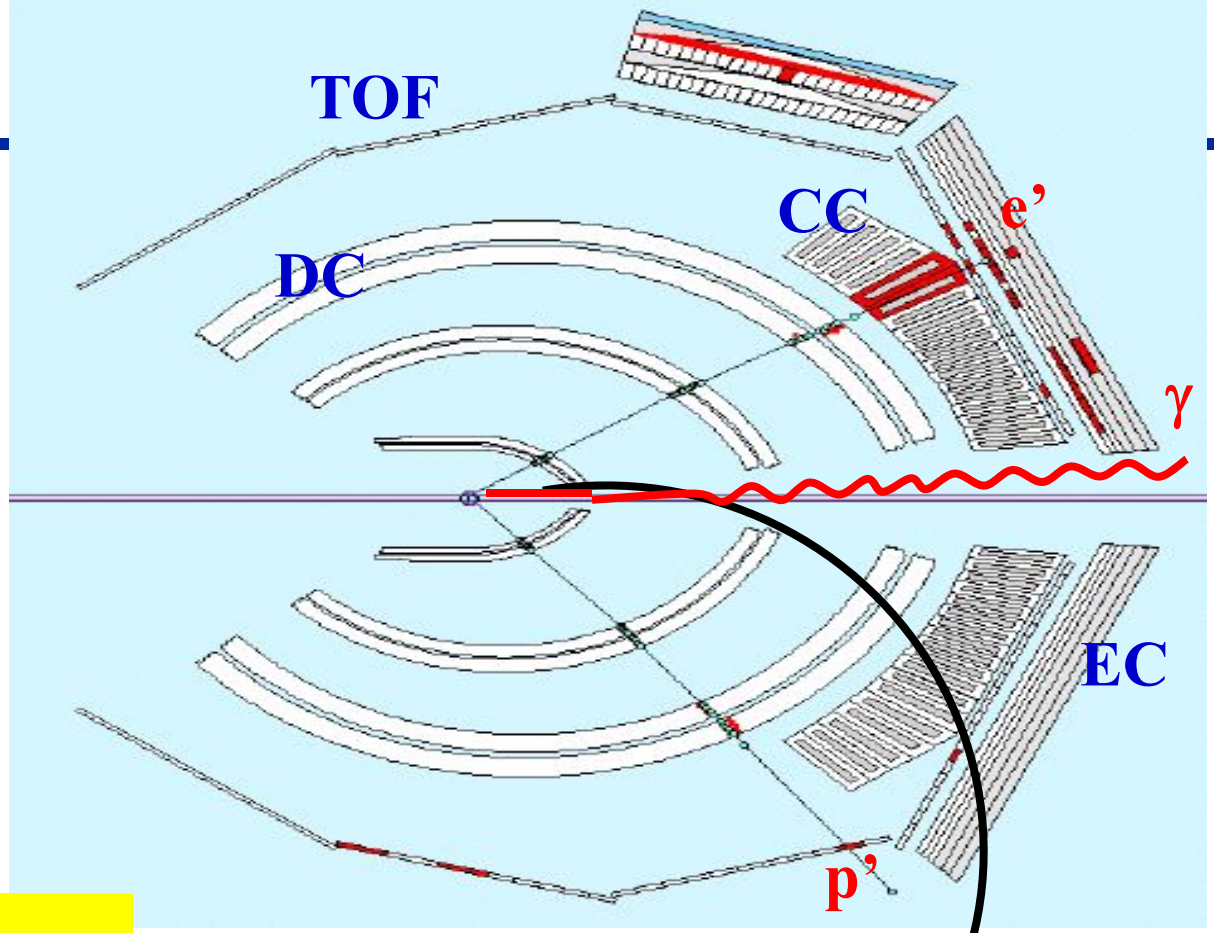
$Im[C^I(\mathcal{F})]$: 'sinφ term'

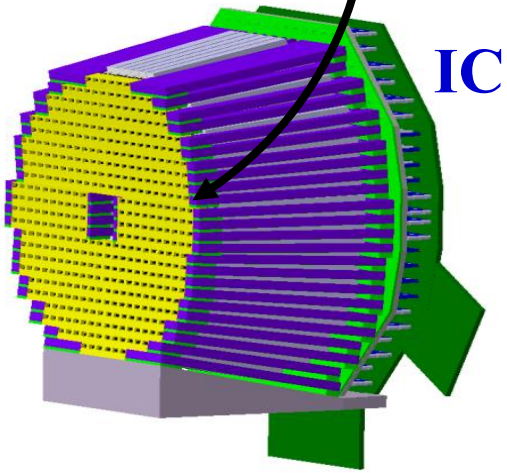



No $Q^2$ dependence: strong indication for scaling behavior and handbag dominance

# ep→e'p'γ in CLAS

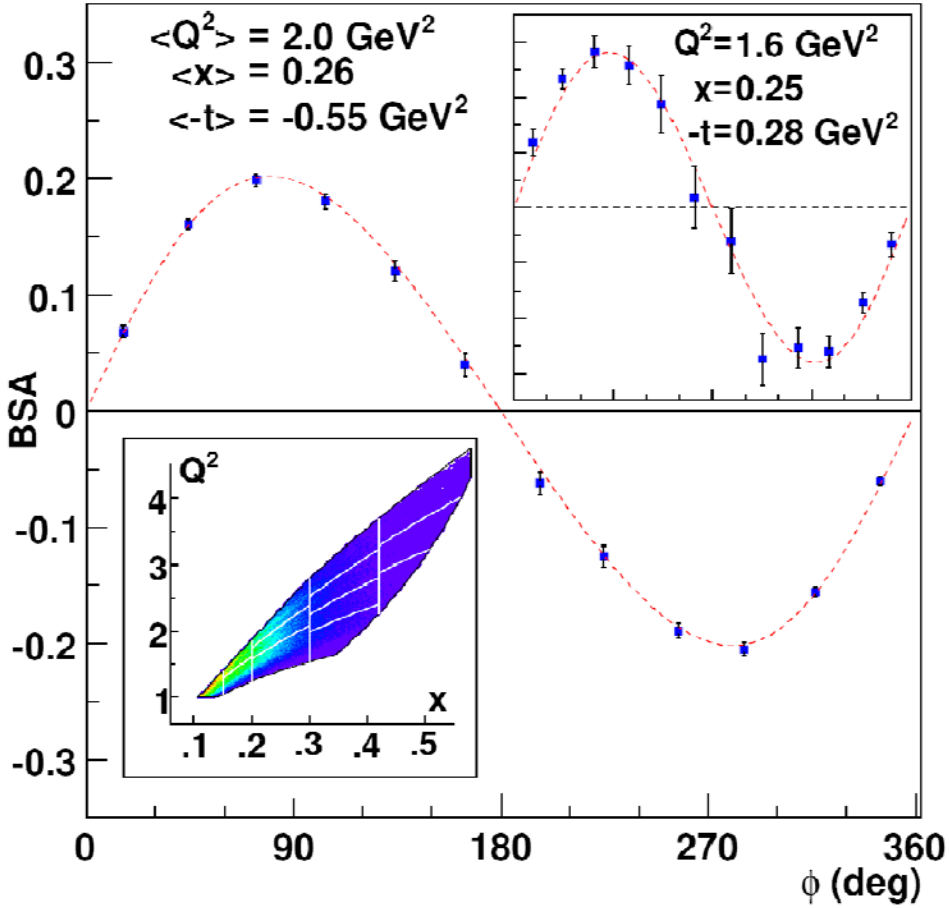
All 3 particles are detected



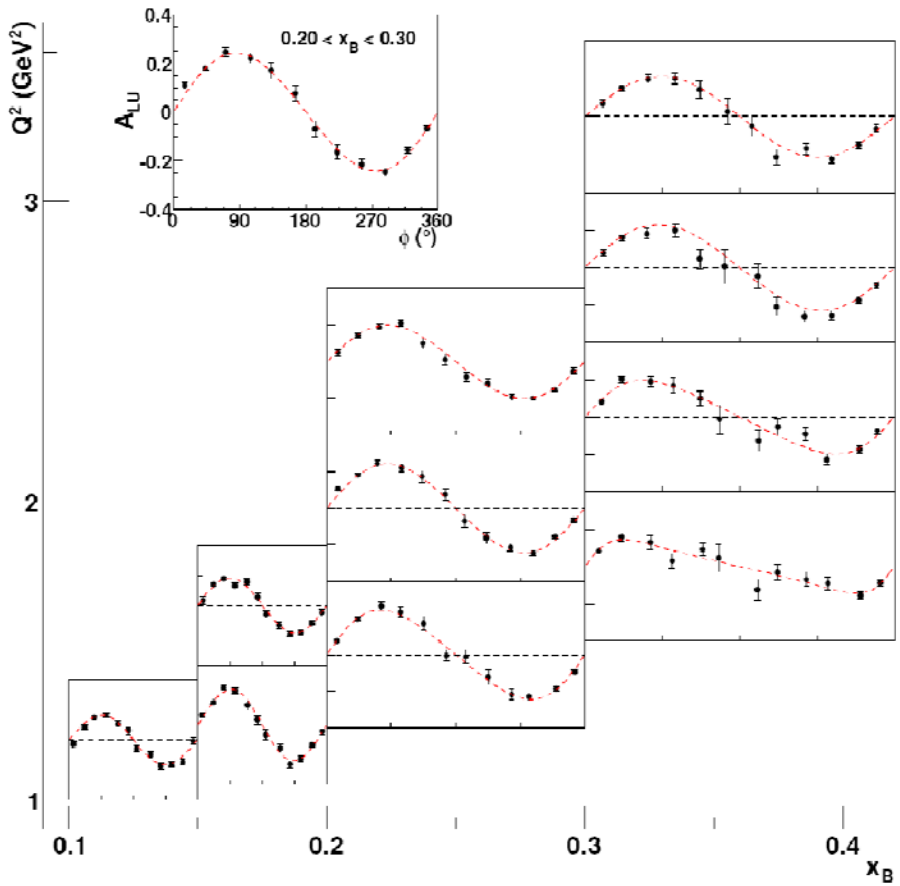




- **electron ID**:
  - EC, CC, DC and TOF
- **proton ID**:
  - DC and TOF
- **photon ID**:
  - IC or EC

# Asymmetries as a function of $\phi$ integrated over $(x_B, Q^2, t)$



# Asymmetries as a function of $\phi$ integrated over $t$




$$A_{\mathrm{LU}} = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}}$$

Results integrated on all range $0.09 < -t < 1.8$ GeV$^2$

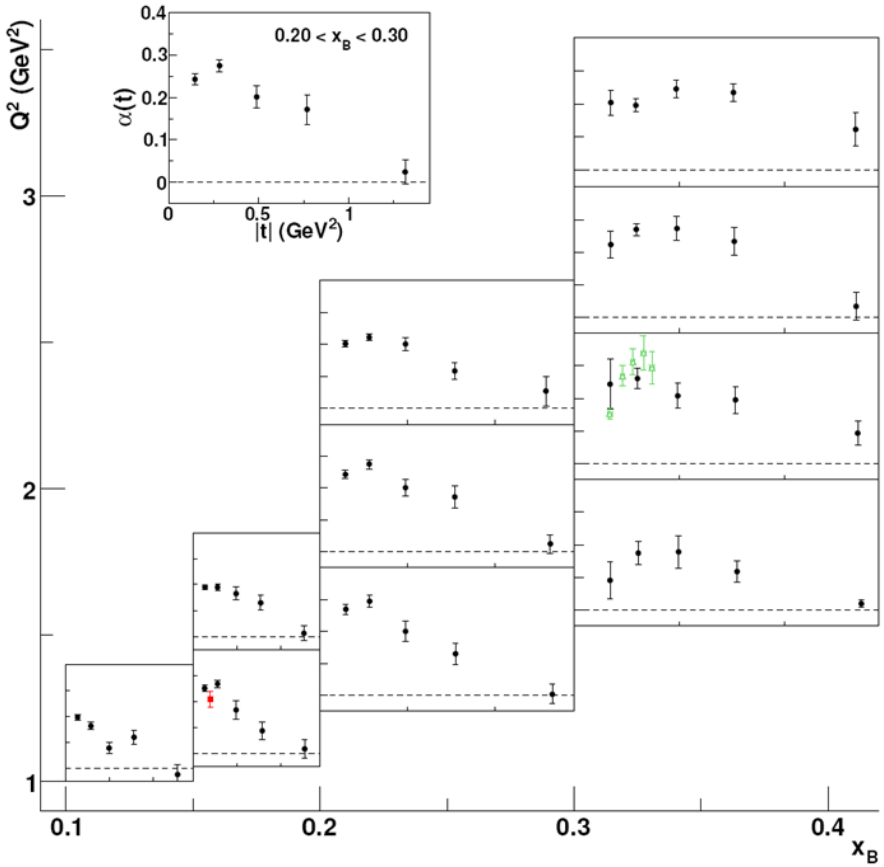
Fitted with parameterization :

$$A_{\mathrm{LU}} = \frac{\alpha \sin\phi}{1 + \beta \cos\phi}$$

describing well the observed shapes

Errors dominated by statistics

# Asymmetries at 90° as function of $t \Leftrightarrow \alpha(t)$



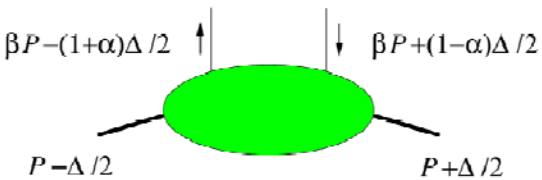

Slope $d\alpha/d|t|$ decreases with $x_B/Q^2$

First constraints
for a global fit of GPDs
on a wide kinematical domain

Results compatible with previous CLAS
and Hall-A

# Description : VGG model

## Doubles Distributions and Regge phenomenology




Analytical constraints automatically satisfied.

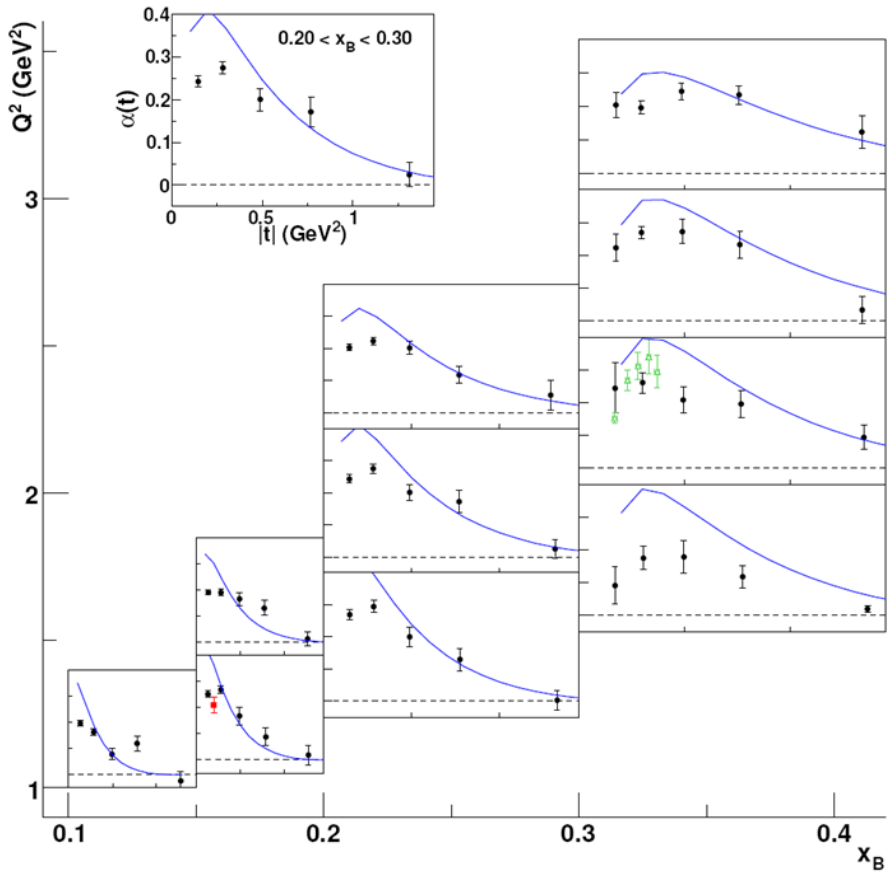
Phenomenological constraints (FFs & PDFs) naturally implemented.

$$H^q(x,\xi,t) = \int_{-1}^{1} \mathrm{d}\beta \int_{-1+|\beta|}^{1-|\beta|} \mathrm{d}\alpha\, \delta(x-\beta-\xi\alpha)\mathfrak{h}_V^q(\beta,\alpha,t) + \theta(1-\frac{x^2}{\xi^2})D^q\left(\frac{x}{\xi},t\right)$$

$$\begin{aligned}
\mathfrak{h}_V^q(\beta,\alpha,t=0) &= q(\beta)\pi_b(\beta,\alpha) \\
\mathfrak{h}_V^q(\beta,\alpha,t) &= \mathfrak{h}_V^q(\beta,\alpha,t=0)\beta^{-\alpha_1'(1-\beta)t} \\
D^q\left(\frac{x}{\xi},t\right) & \quad \text{Calculated in the } \chi\text{QSM model}
\end{aligned}$$

# Confrontation with data

$t$ dependancy




Model with $D$-tern without GPD $E$

Excellent qualitative agreement

Good quantitative agreement

Overshoot at moderate $|t|$

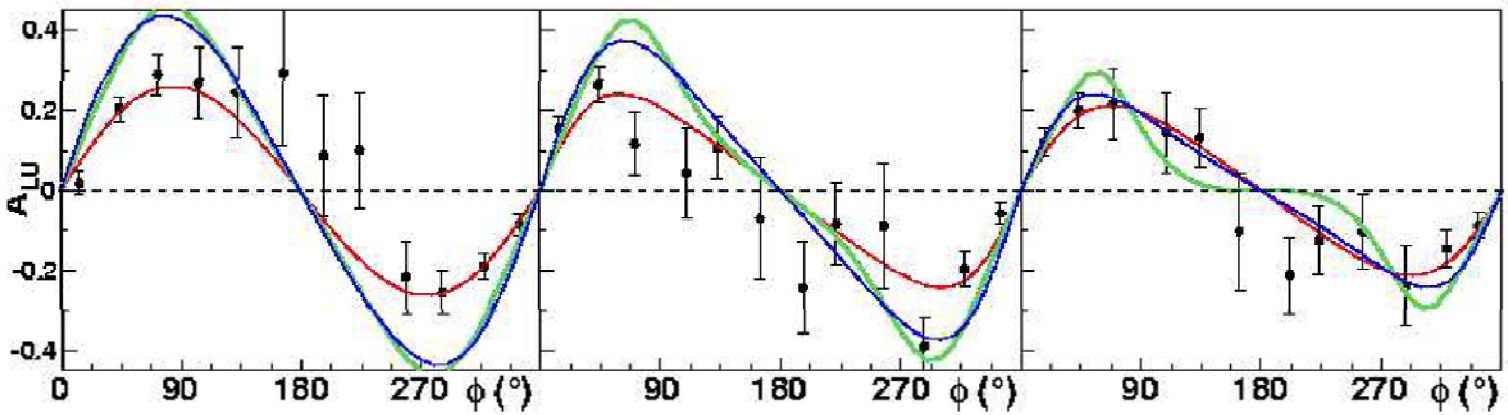
$\phi$ dependancy for twist-3 in WW "approximation"

$x_B = 0.35$ and $Q^2 = 2.4$ GeV$^2$ fixed

Fit to data

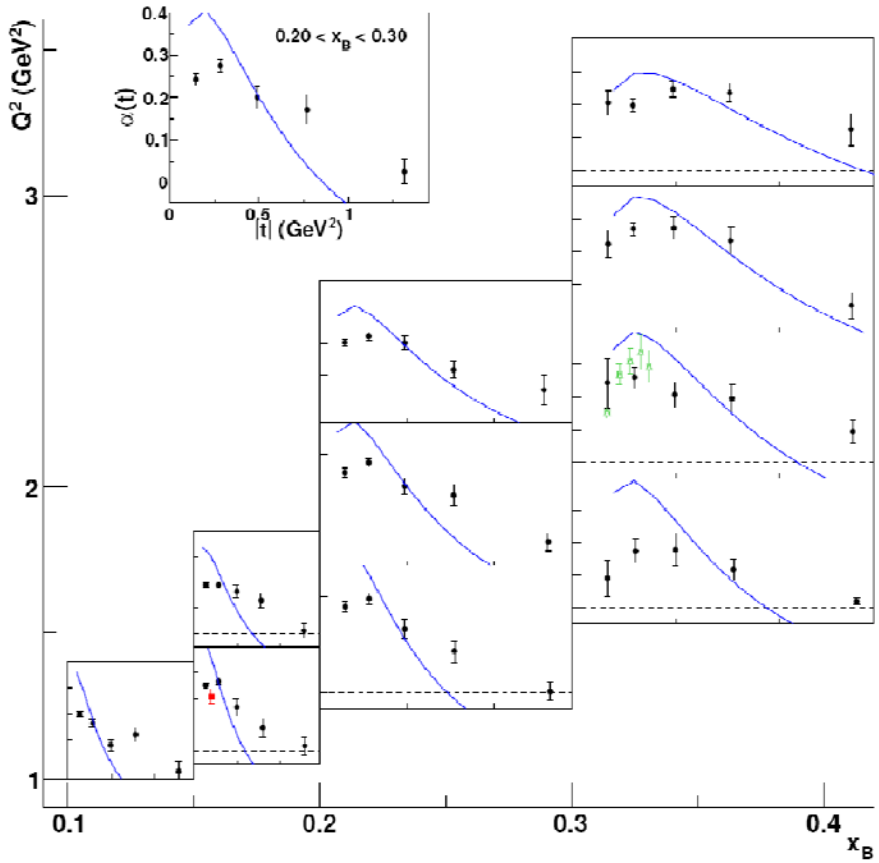
VGG model twist-2

VGG model twist-3 WW




$0.2 < -t < 0.4$ $0.4 < -t < 0.6$ $0.6 < -t < 1.$ GeV$^2$

# $t$ dependancy for twist-3 in WW "approximation"




Qualitative disagreement with $\phi$ shape

Quantitative disagreement in $t$ slope

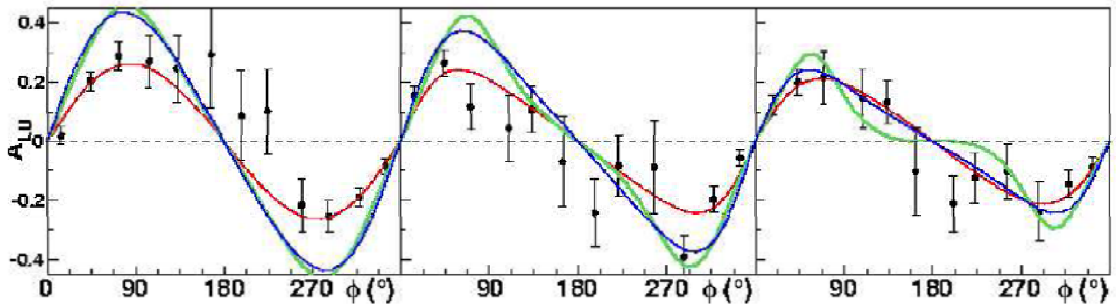
## $\phi$ dependancy for twist-3 in WW "approximation"

$x_B = 0.35$ and $Q^2 = 2.4$ GeV$^2$ fixed

Fit to data

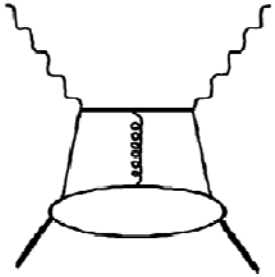
VGG model twist-2

VGG model twist-3 WW

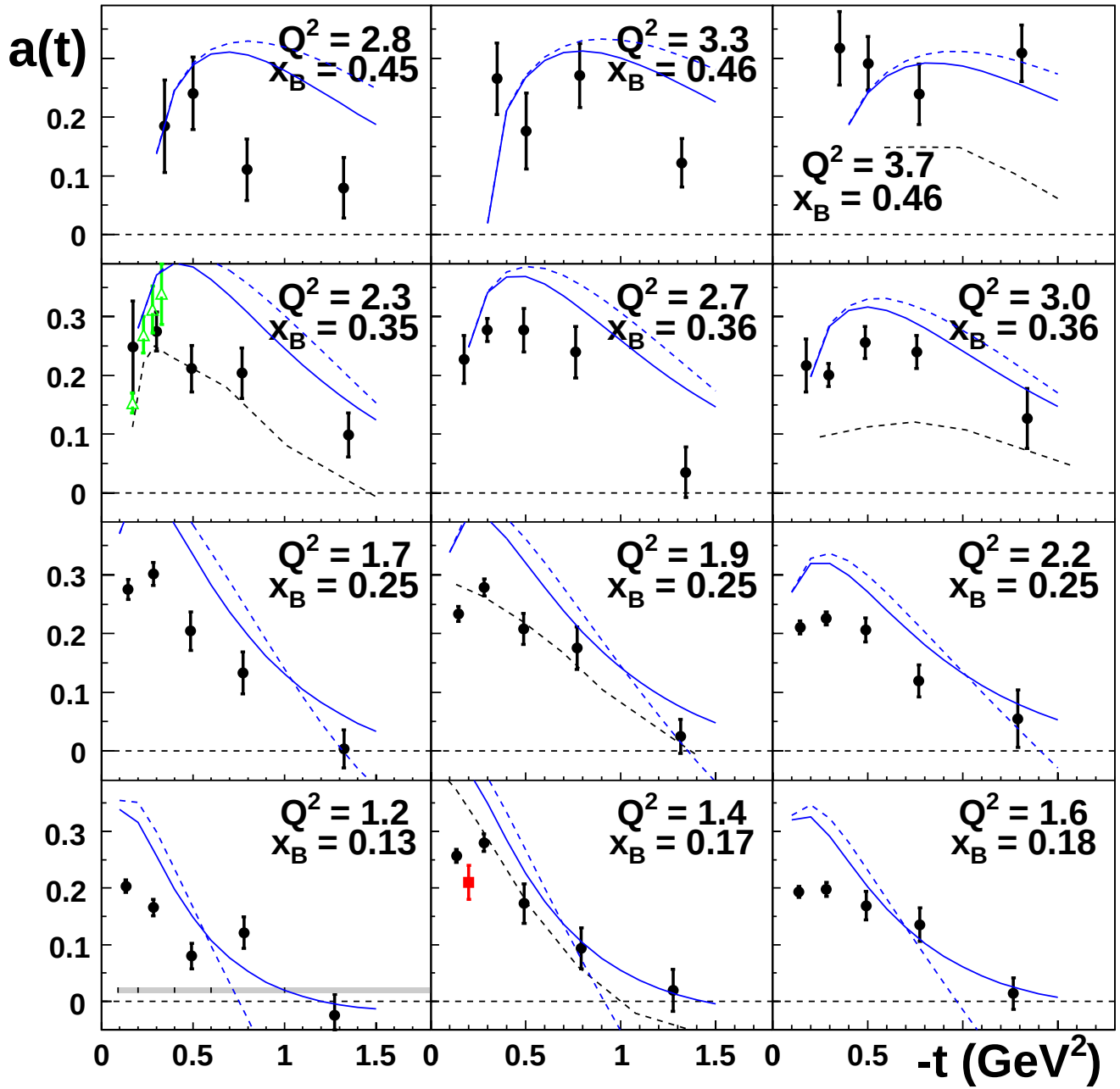



$0.2 < -t < 0.4$ $0.4 < -t < 0.6$ $0.6 < -t < 1.$ GeV$^2$

WW approximation for twist-3 :
needs improvement
*IF* true disagreement : $\bar{q}Gq$ correlations ?
Large $|t|$ measurements are important



# BSA: a vs. t




- CLAS e1-dvcs
- Hall A
- CLAS @ 4.3 $GeV^2$
- VGG(*) twist-2 (DD)
- VGG(*) twist-2 and 3
- Regge model (**)

(*) Guidal, Polyakov, Radyushkin, Vanderhaegen, PRD 72 (2005)

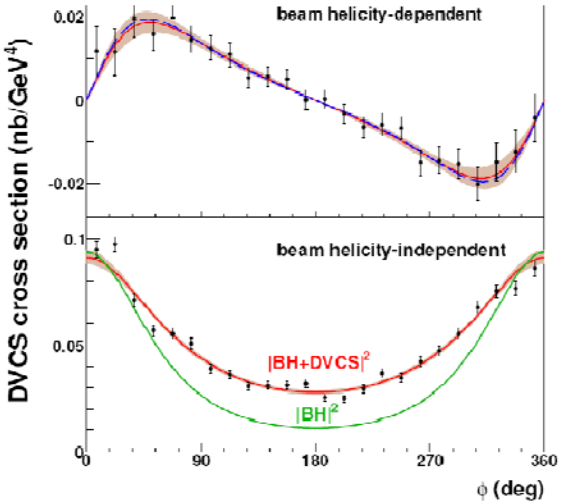
(**) Cano and Laget, PL B551 (2003)

**GPD model overestimates the data**

**arXiv: 0711.4805 [hep-ex]**
**Submitted to PRL**

## What we learned in E00-110:

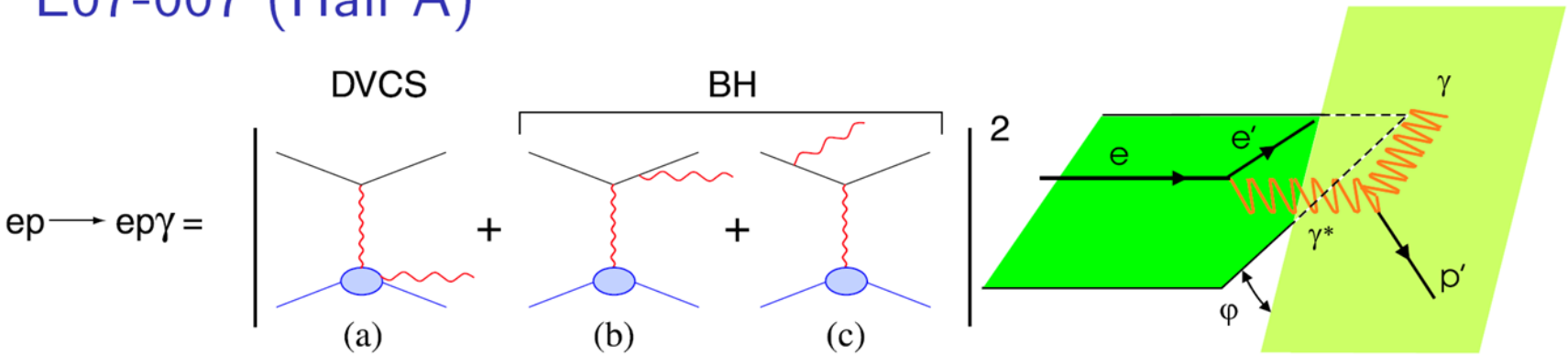
- DVCS helicity-independent cross section at one $Q^2$ point *only*:
  - BH only a small part of the total cross section
    $\Rightarrow$ both BH-DVCS interference and DVCS$^2$ are significant
    $\Rightarrow$ Need to separate these two contributions to extract a clean measurement of GPDs integrals




$$\sigma(ep \to ep\gamma) = \underbrace{|BH|^2}_{\text{Known to } \sim 1\%} + \underbrace{\mathcal{I}(BH \cdot DVCS)}_{\text{Linear combination of GPDs}} + \underbrace{|DVCS|^2}_{\text{Bilinear combination of GPDs}}$$

- $Q^2$–dependence of the helicity-independent cross section: stringent test of factorization

# E07-007 (Hall A)



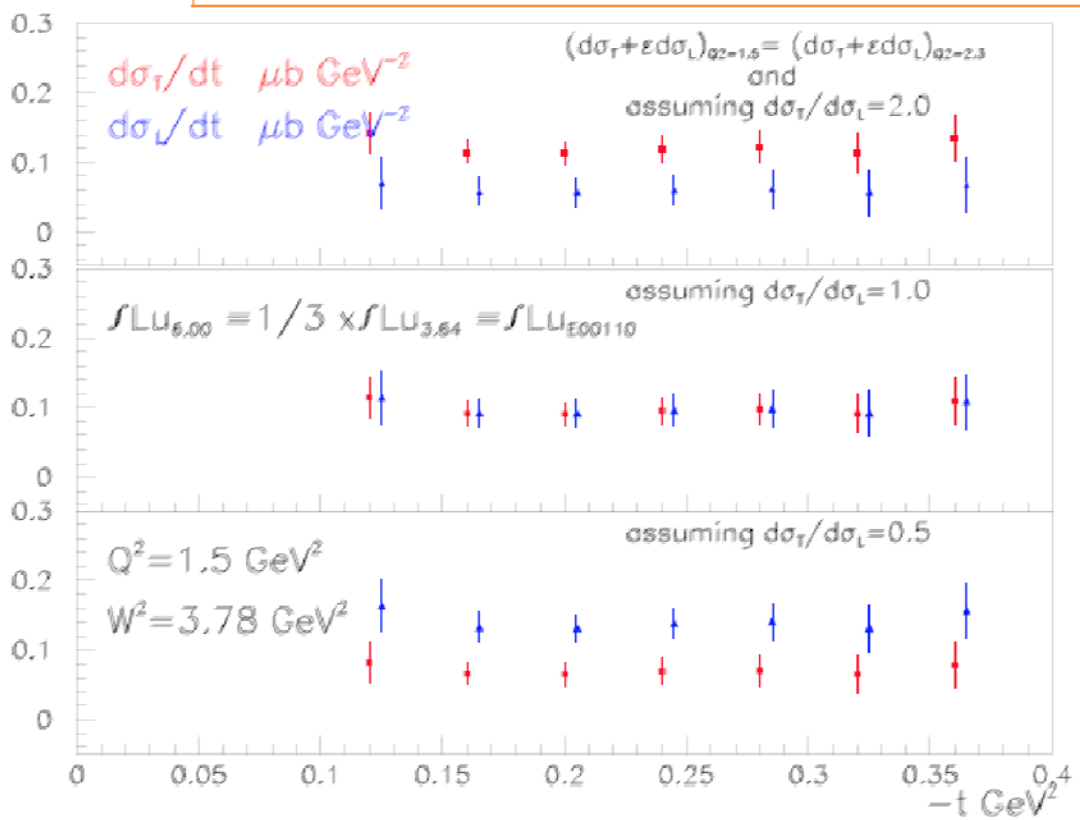

$$\sigma(ep \to ep\gamma) = \underbrace{|BH|^2}_{\text{Known to } \sim 1\%} + \underbrace{\mathcal{I}(BH \cdot DVCS)}_{\text{Linear combination of GPDs}} + \underbrace{|DVCS|^2}_{\text{Bilinear combination of GPDs}}$$

DVCS cross section has a very rich azimuthal structure:

- Azimuthal analysis allows the separation of the different contributions to $\mathcal{I}$ if DVCS$^2$ is negligeble.
- If DVCS$^2$ is important, $\mathcal{I}$ and DVCS$^2$ terms **MIX** in an azimuthal analysis.
- The **different energy dependence** of $\mathcal{I}$ and DVCS$^2$ allow a full separation.

# E07-007: $\sigma_L$ Rosenbluth separation ($Q^2 = 1.5$ GeV$^2$)

$\sigma_L$ **with statistical accuracy** $\ll \sigma_T + \epsilon\sigma_L$



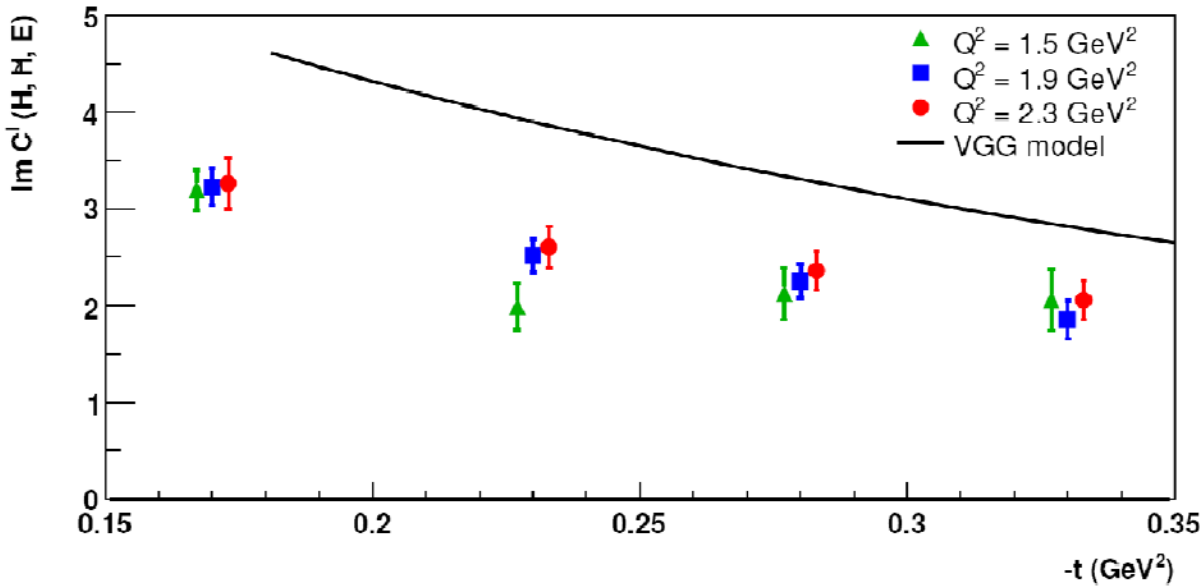

$$\frac{\sigma_T}{\sigma_L} = 2.0$$

$$\frac{\sigma_T}{\sigma_L} = 1.0$$

$$\frac{\sigma_T}{\sigma_L} = 0.5$$

# GPD linear combinations and integrals

**First linear combination of GPDs extracted from DVCS data**




$t-$dependence: spatial size of the distribution of quarks at $x_B = 0.36$

# Measuring GPDs through polarization

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$$

Kinematically suppressed

$\Rightarrow$ $H(\xi,t)$

$\xi \approx x_B/(2-x_B)$

$k = t/4M^2$

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi\{F_1\tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E) - ..\}d\phi$$

Kinematically suppressed

$\Rightarrow$ $\tilde{H}(\xi,t),\ H(\xi,t)$

Unpolarized beam, transverse target:

$$\Delta\sigma_{UT} \sim \sin\phi\{k(F_2 H - F_1 E) + .....\}d\phi$$

Kinematically suppressed

$\Rightarrow$ $H(\xi,t),\ E(\xi,t)$

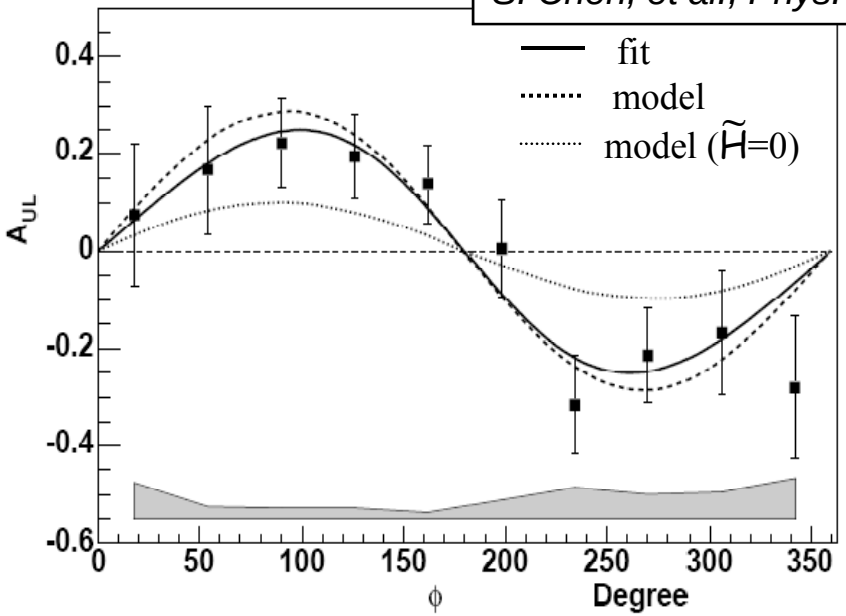
# First DVCS measurement with spin-aligned target

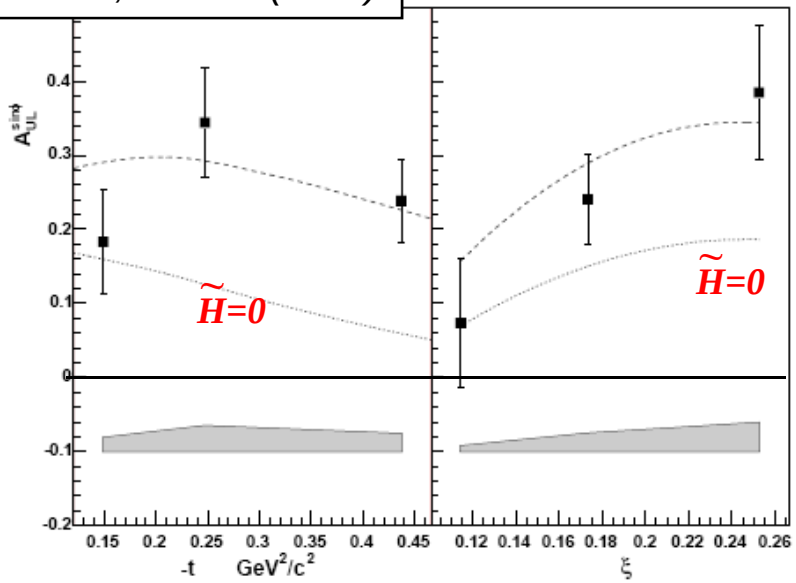
Unpolarized beam, longitudinally spin-aligned target:

$$\Delta\sigma_{UL} \sim \sin\phi \, \mathrm{Im}\{F_1 \tilde{H} + \xi(F_1+F_2) H + \ldots\} d\phi$$

$A_{UL}$ is dominated by $H$ and $\tilde{H}$

*S. Chen, et al., Phys. Rev. Lett 97, 072002 (2006)*



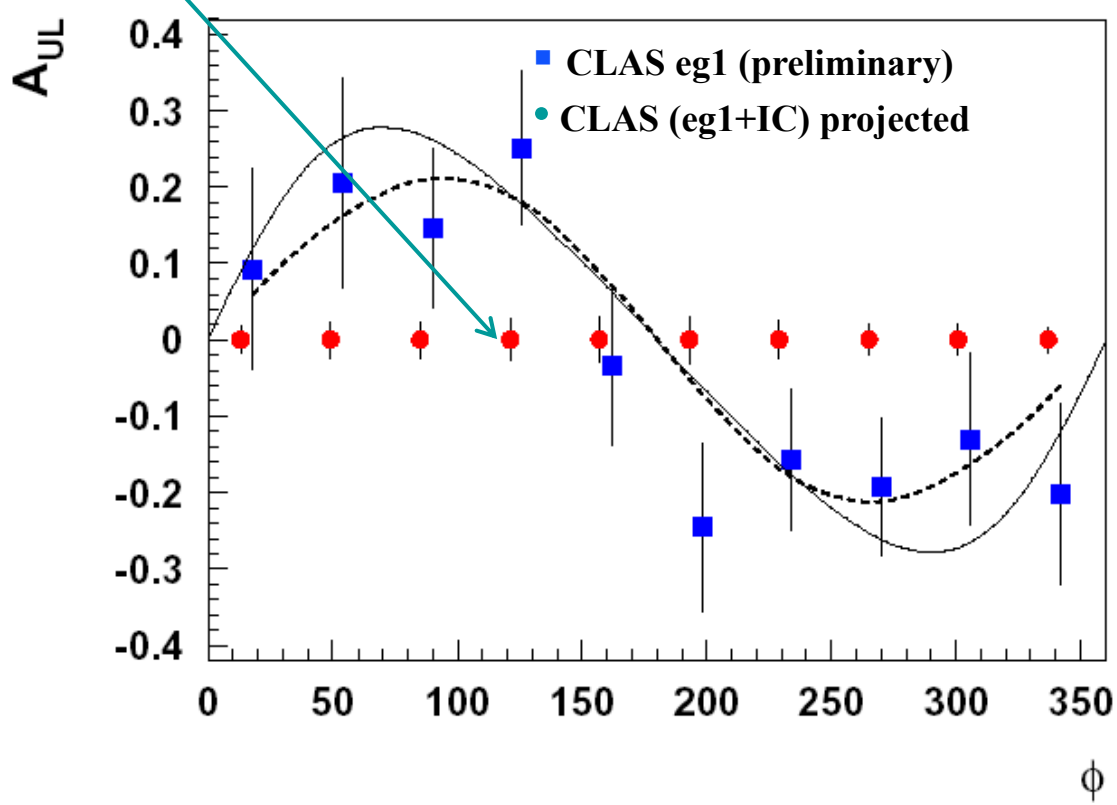




$\alpha$ = 0.252 ± 0.042
$\beta$ = -0.022 ± 0.045

Planned experiment in 2008 will improve accuracy dramatically.

# Target Spin Asymmetry: $\phi$ Dependence

**6 GeV run with $NH_3$ longitudinally polarized target (CLAS + IC) 60 days of beam time**




**A dedicated CLAS experiment with longitudinally polarized target will provide a statistically significant measurement of the kinematical dependences of the DVCS target SSA**

# Measuring GPDs through polarization

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$$

Kinematically suppressed

$H(\xi,t)$

$\xi \approx x_B/(2-x_B)$

$k = t/4M^2$

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi\{F_1\tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E) - ..\ \}d\phi$$

Kinematically suppressed

$\tilde{H}(\xi,t),\ H(\xi,t)$

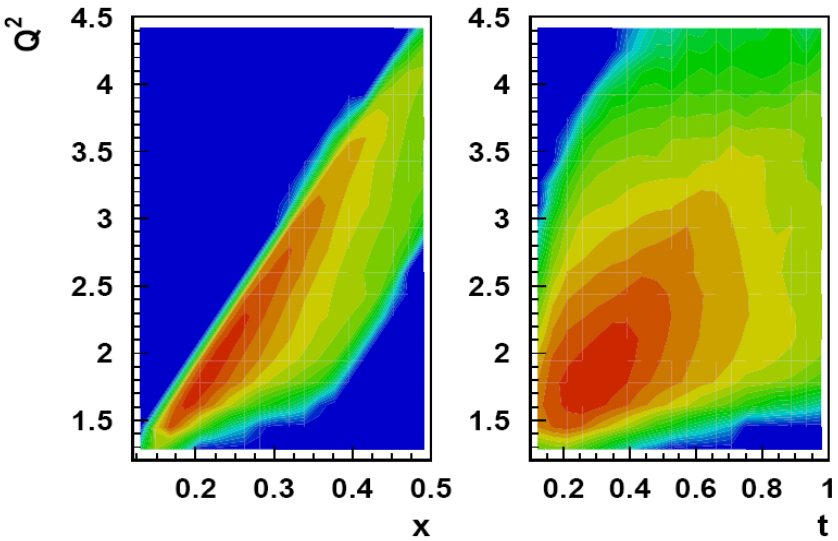
Unpolarized beam, transverse target:

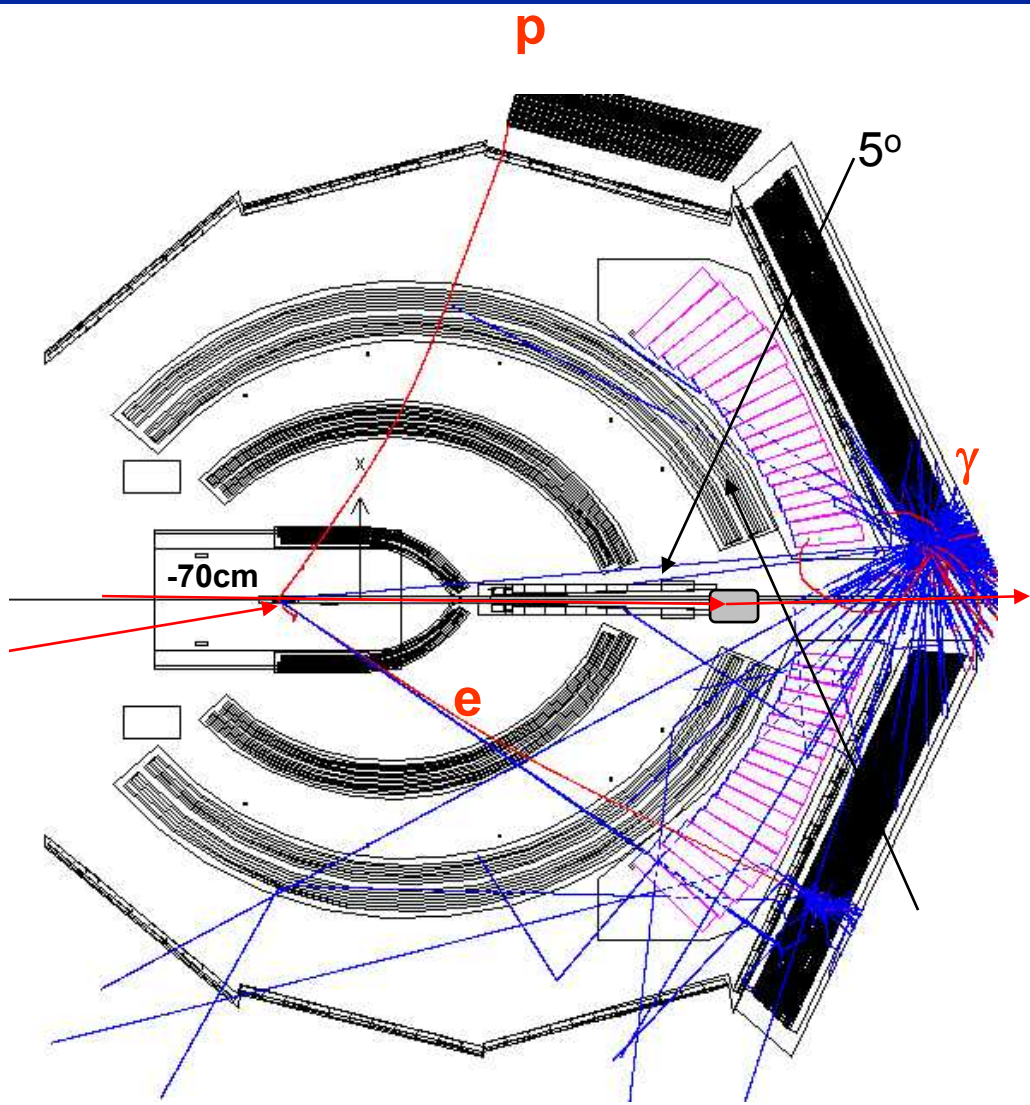
$$\Delta\sigma_{UT} \sim \sin\phi\{k(F_2 H - F_1 E) + \ .....\}d\phi$$

Kinematically suppressed

$H(\xi,t),\ E(\xi,t)$

# Operating CLAS with transverse target



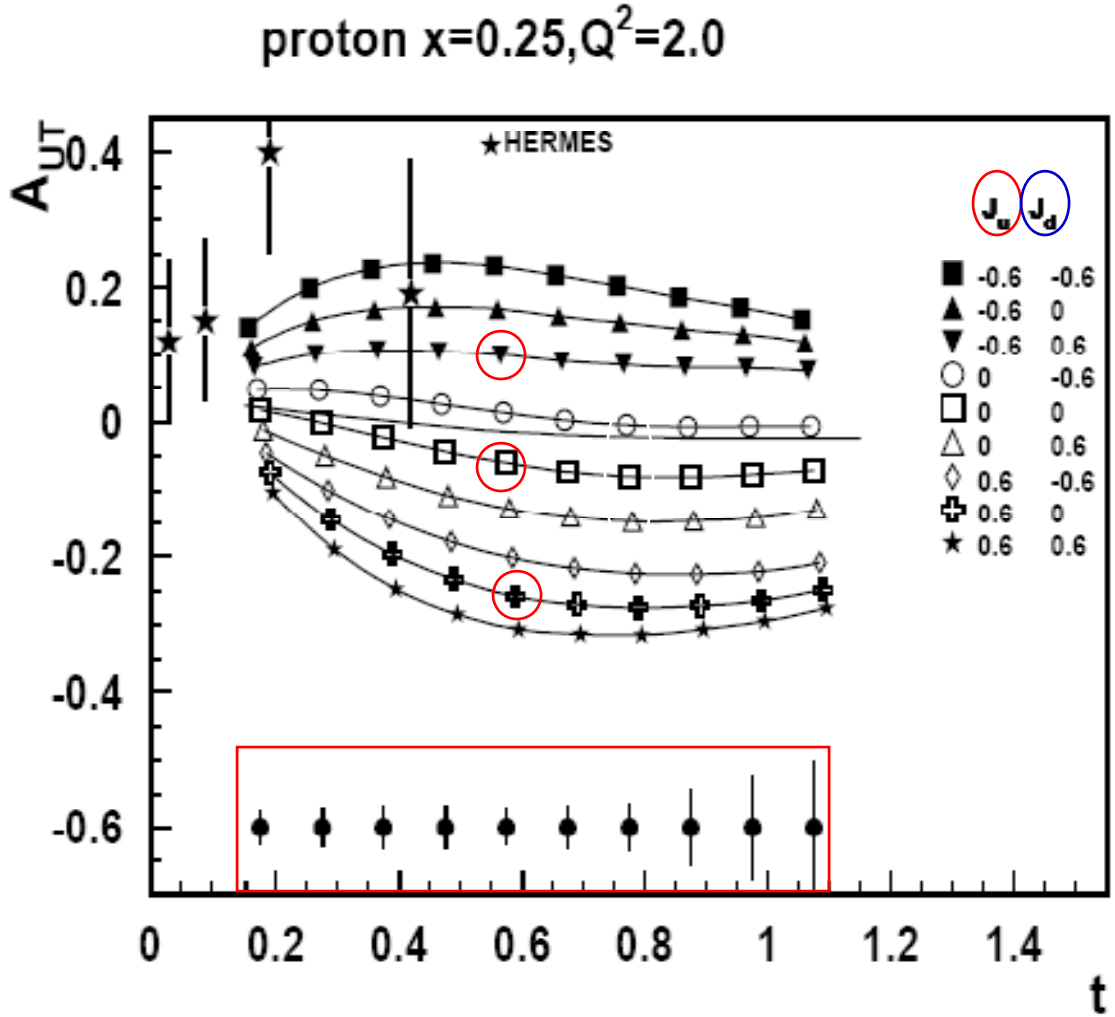



# Sensitivity of $A_{UT}$ to GPD $E$ on proton

## Main result:

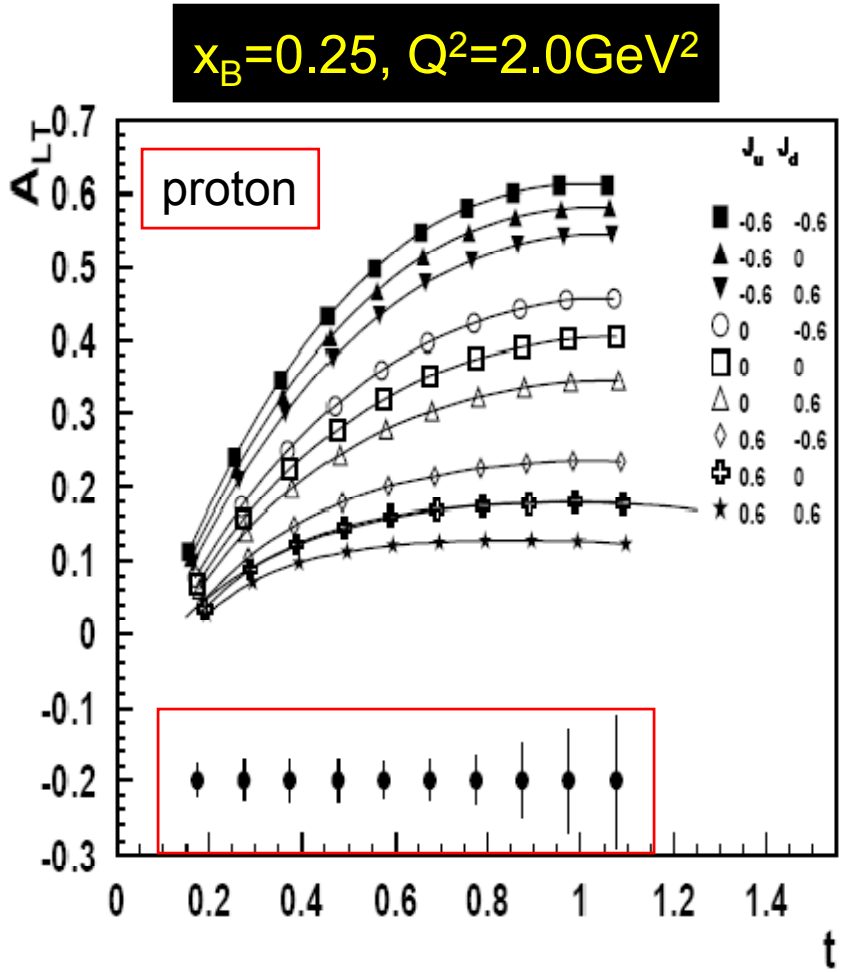
Error bars assume no knowledge of final state kinematics and include full subtraction of background events measured with $H_2$ and with $D_2$ target samples.

all final state particles are detected in CLAS




Transverse asymmetry is large and has strong sensitivity to GPD-$E$

# Double Polarization Asymmetry $A_{LT}$ and GPD $E$




Double spin asymmetry also sensitive to GPD-$E$

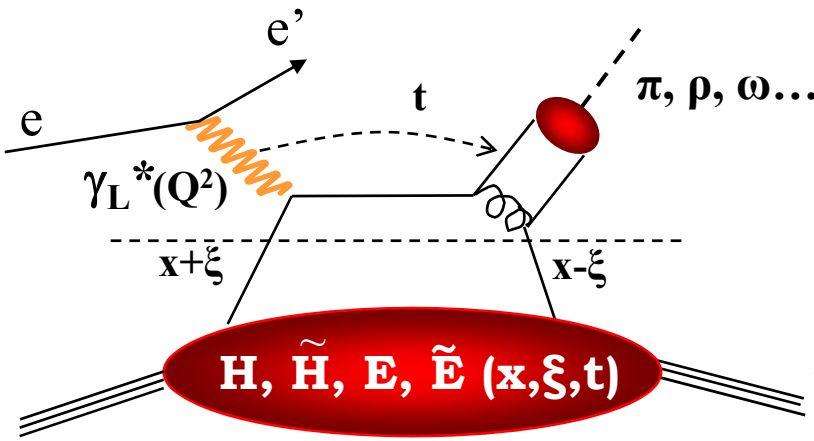
# Transverse target Future experiment in Hall B

- Measurement of azimuthal moments in DVCS with transversely polarized hydrogen (and deuterium) targets are highly sensitive to the GPD-$E$ and the quark contributions to the angular momentum of the proton.

- Precision measurements of single (and double) spin asymmetries with CLAS with transversely polarized target

  - Stringent constraints on GPD-$E(x=\xi,\xi,t)$
  - Quark distributions in transverse impact parameter space
  - First information on polarized neutron asymmetries

# Hard exclusive meson production and GPDs




4 **G**eneralized **P**arton **D**istributions (**GPD**s)

$H$, $E$ → Vector mesons ($\rho$, $\omega$, $\phi$)

$\tilde{H}$, $\tilde{E}$ → Pseudoscalar mesons ($\pi$, $\eta$)

| | |
|---|---|
| $\pi^0$ | $2\Delta u+\Delta d$ |
| $\eta$ | $2\Delta u-\Delta d$ |

| | |
|---|---|
| $\rho^0$ | $2u+d$ |
| $\omega$ | $2u-d$ |
| $\rho^+$ | $u-d$ |

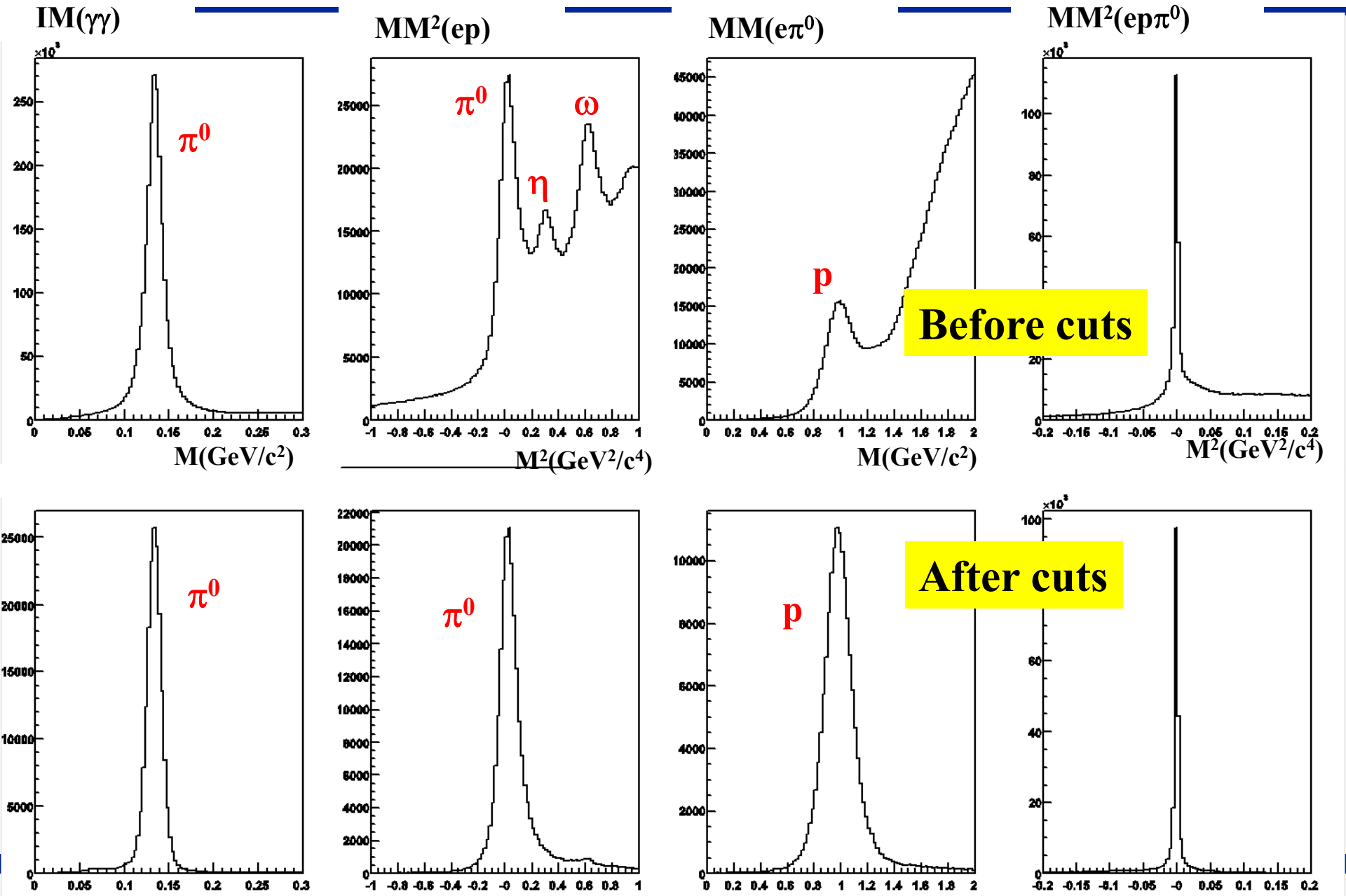
Factorization proven only for **longitudinally polarized** virtual photons and valid at **high $Q^2$** and **small t**

**quark flavor decomposition accessible via meson production**

$$\sigma(\pi^0) \sim \left| \int dx\, \tilde{H}(x,\xi,t) \right|^2$$

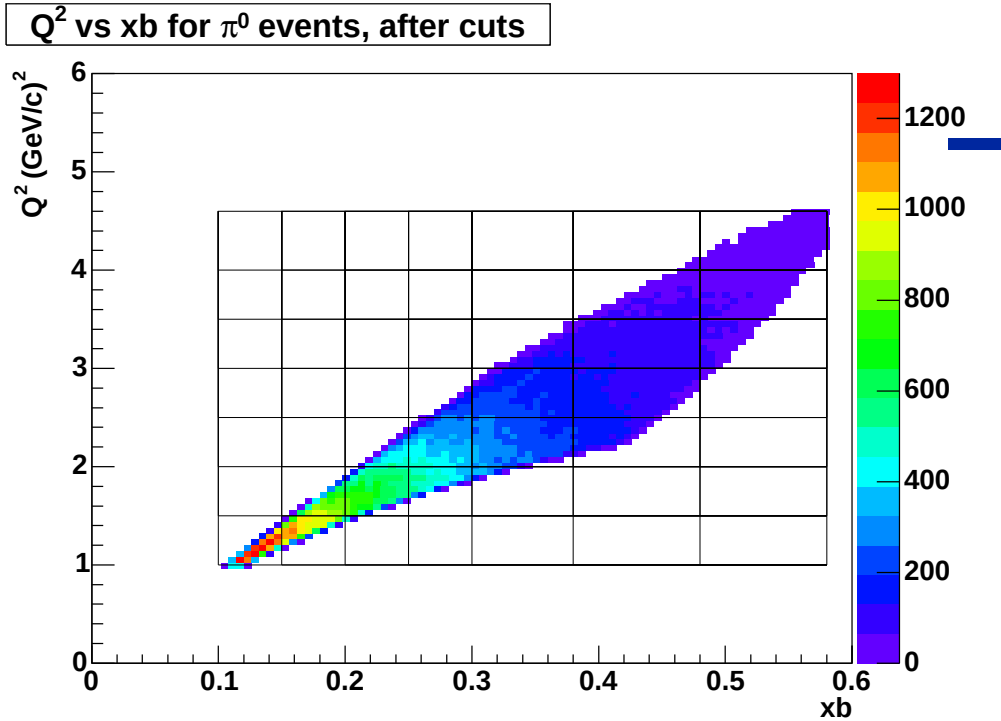

Office of Science U.S. DEPARTMENT OF ENERGY

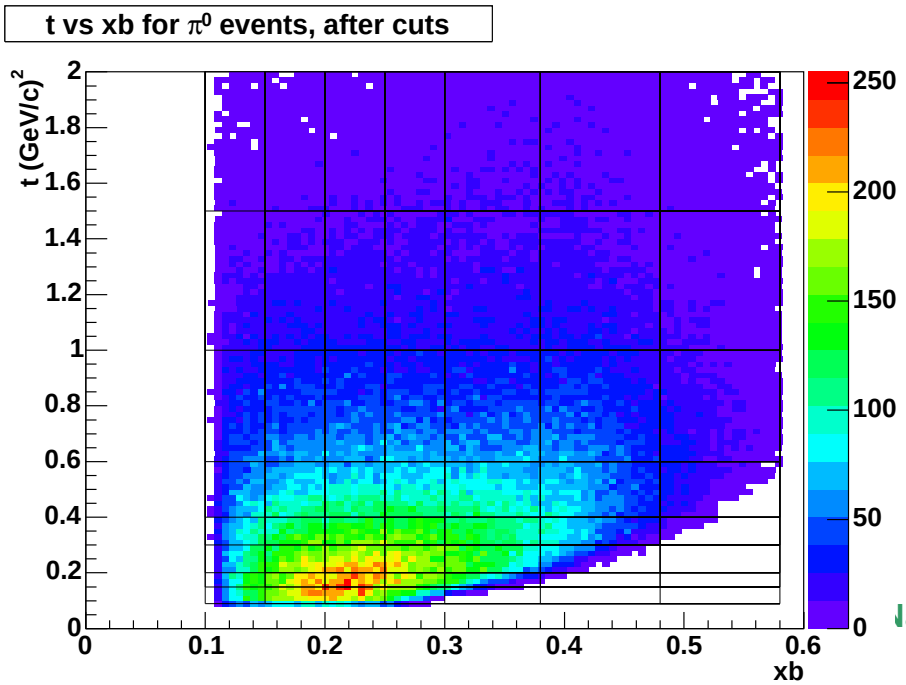
# $ep \rightarrow ep\pi^0$ in CLAS: channel selection

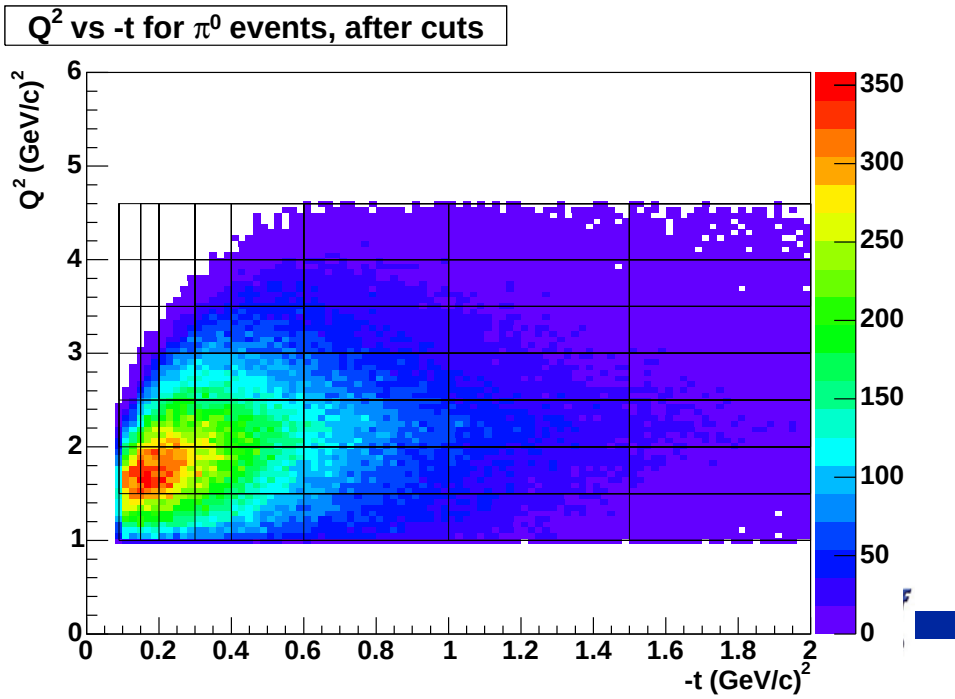


# $ep \rightarrow ep\pi^0$: Kinematical coverage and binning

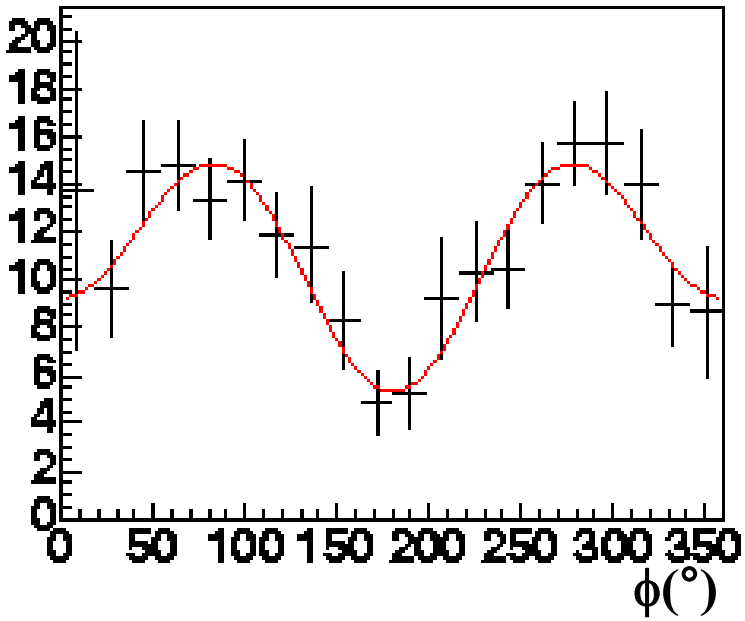
- $W > 2$ GeV/$c^2$
- 7 $Q^2$ bins (1 - 4.6 GeV$^2$/$c^2$)
- 7 $x_B$ bins (0.1 – 0.55)
- 8 -t bins (0.09 – 2 GeV$^2$/$c^2$)
- 20 $\phi$ bins

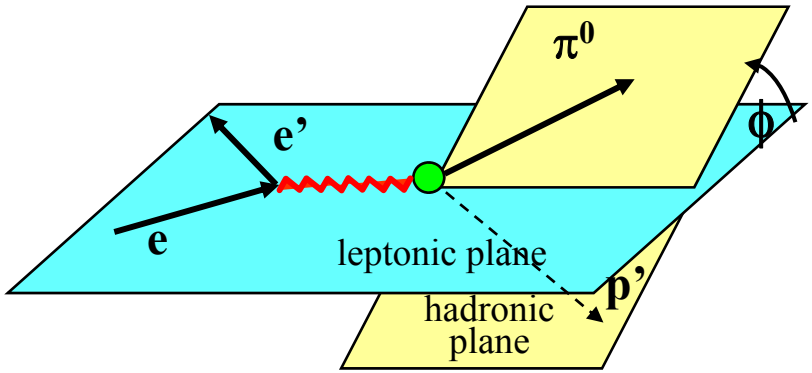


# $ep \rightarrow ep\pi^0$: reduced cross sections




$$\frac{d^4\sigma}{dQ^2 dx_B d\phi dt} = \Gamma(Q^2, x_B)\frac{d^2\sigma}{d\phi dt}$$

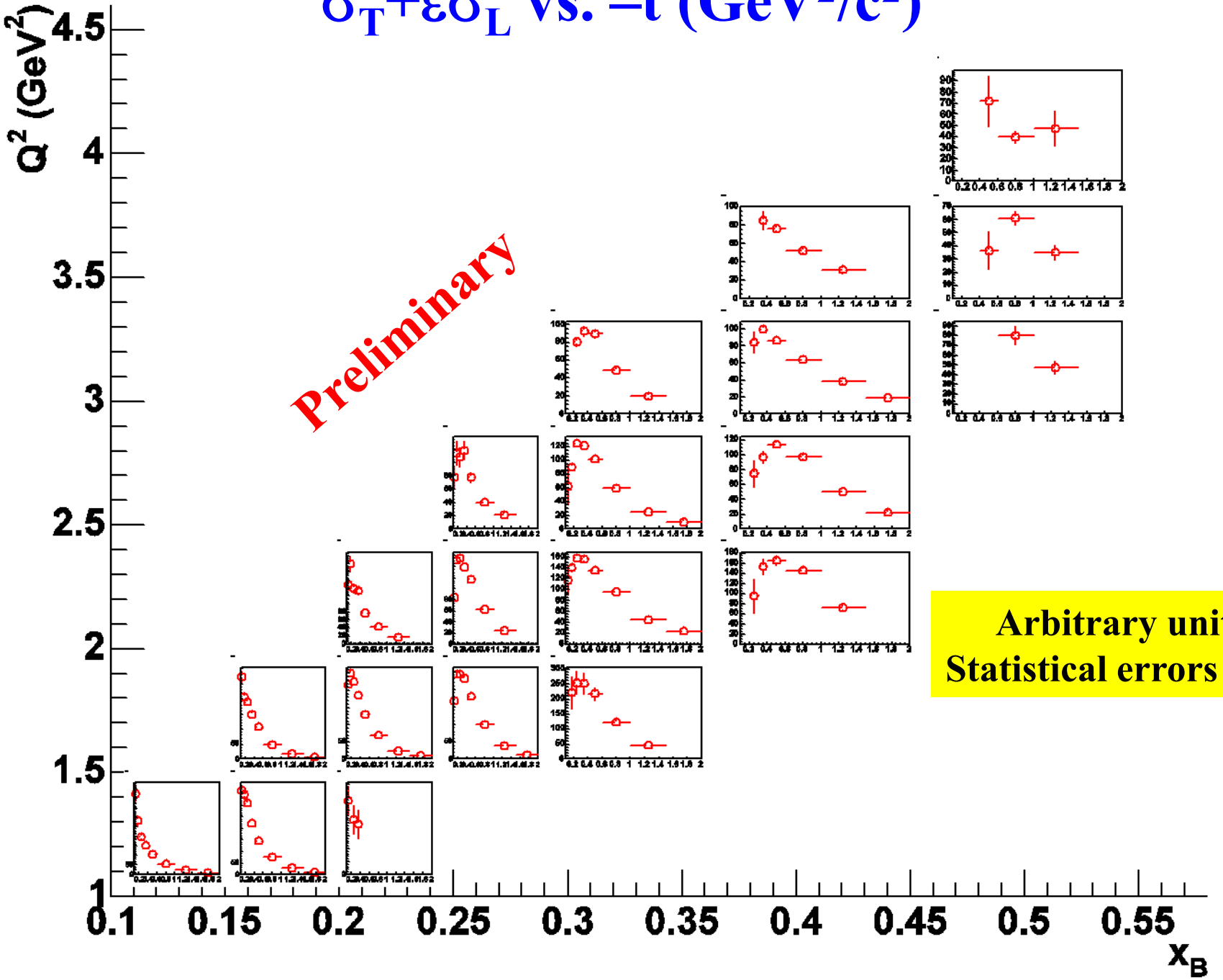
$$\frac{d\sigma}{d\phi dt} = \frac{1}{2\pi}\left(\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi\right)$$

**NO $\sigma_T/\sigma_L$ separation**

**Each $Q^2$-$x_B$-t bin is fitted with the function:**

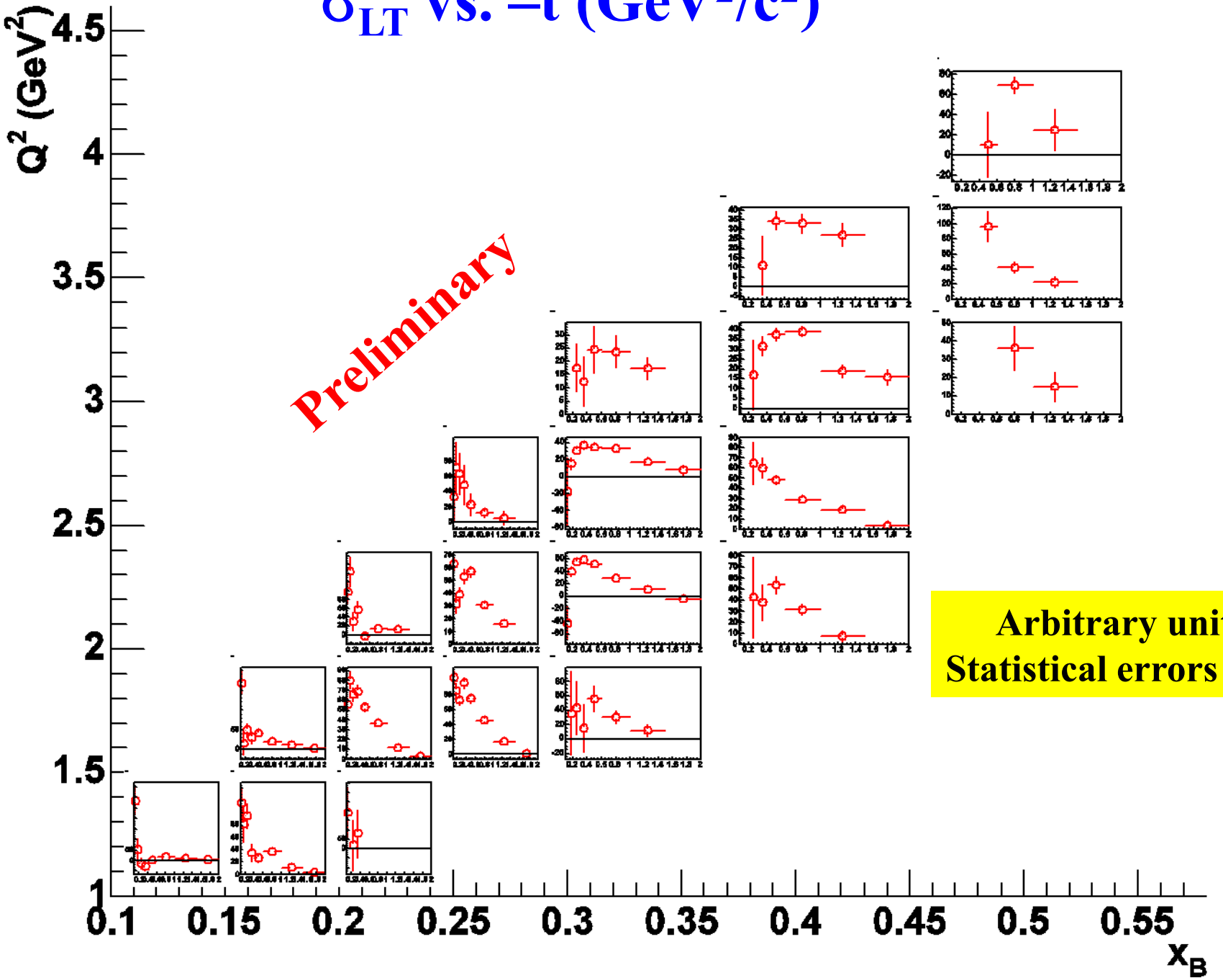
$$A + B\sqrt{2\varepsilon(\varepsilon+1)}\cos\phi + C\varepsilon\cos 2\phi$$

# $\sigma_T+\varepsilon\sigma_L$ vs. $-t$ ($GeV^2/c^2$)



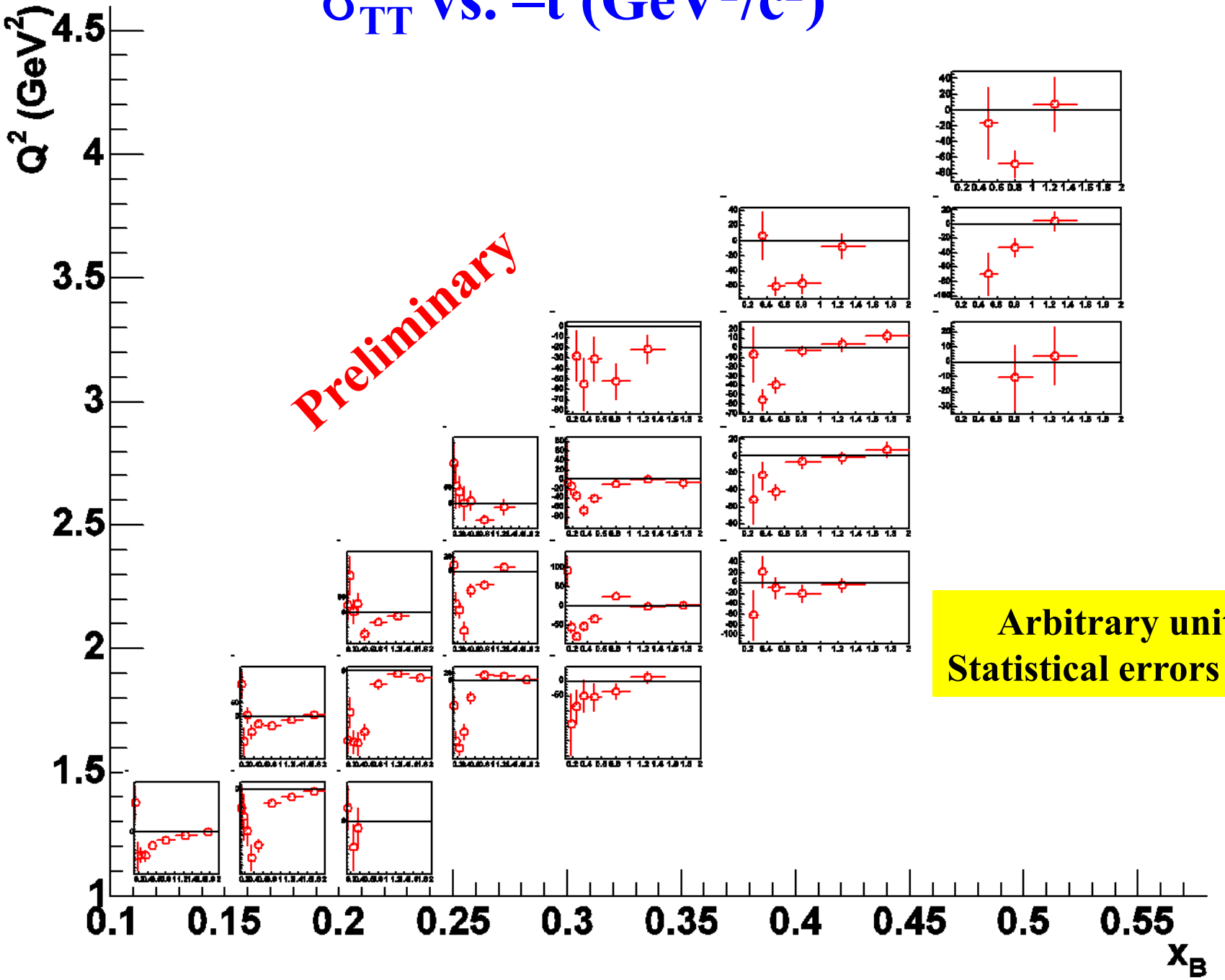

**Arbitrary units**
**Statistical errors only**

# $\sigma_{LT}$ vs. $-t$ ($GeV^2/c^2$)




**Arbitrary units**
**Statistical errors only**

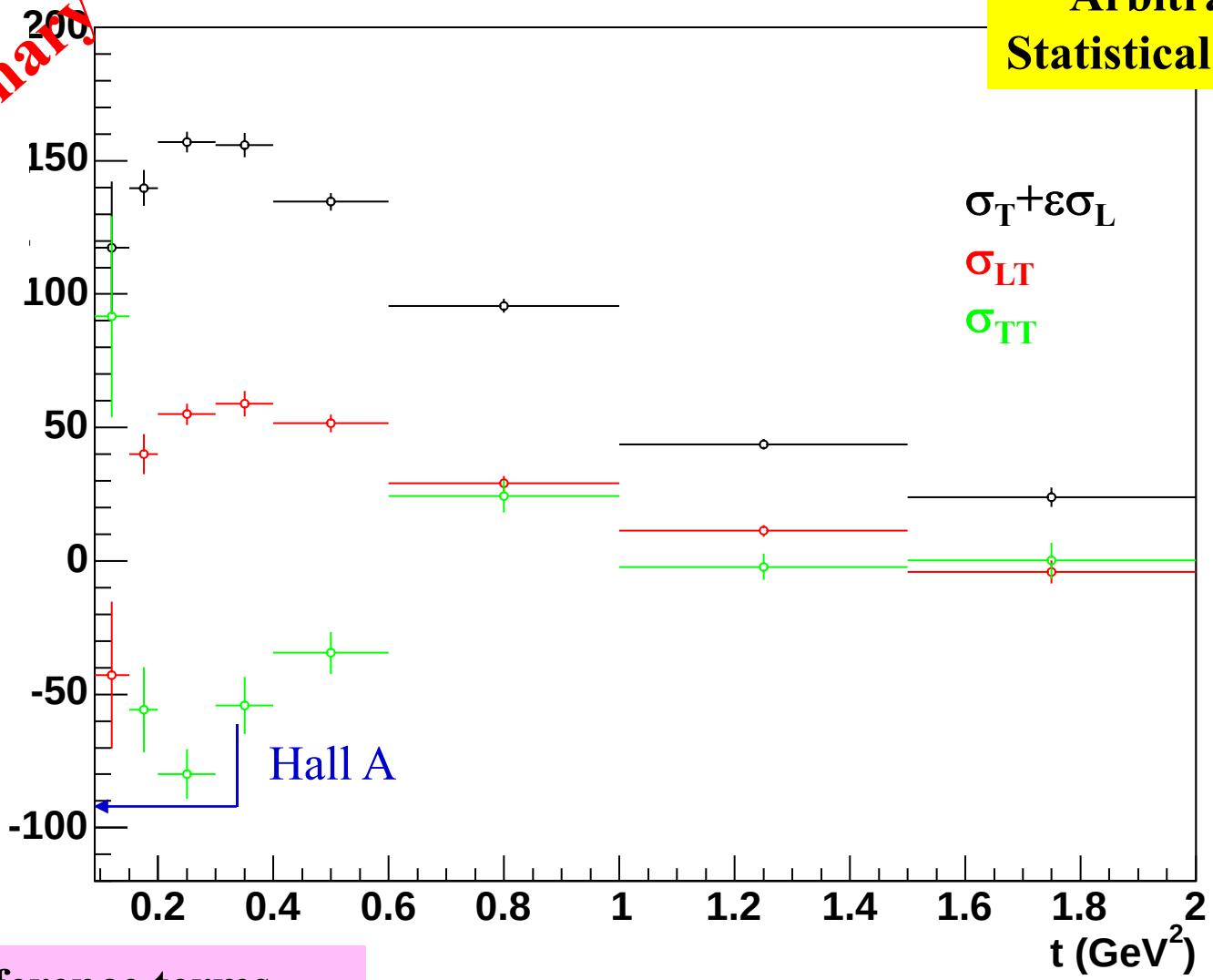
# $\sigma_{TT}$ vs. $-t$ ($GeV^2/c^2$)




**Arbitrary units**
**Statistical errors only**

Preliminary

**Arbitrary units**
**Statistical errors only**



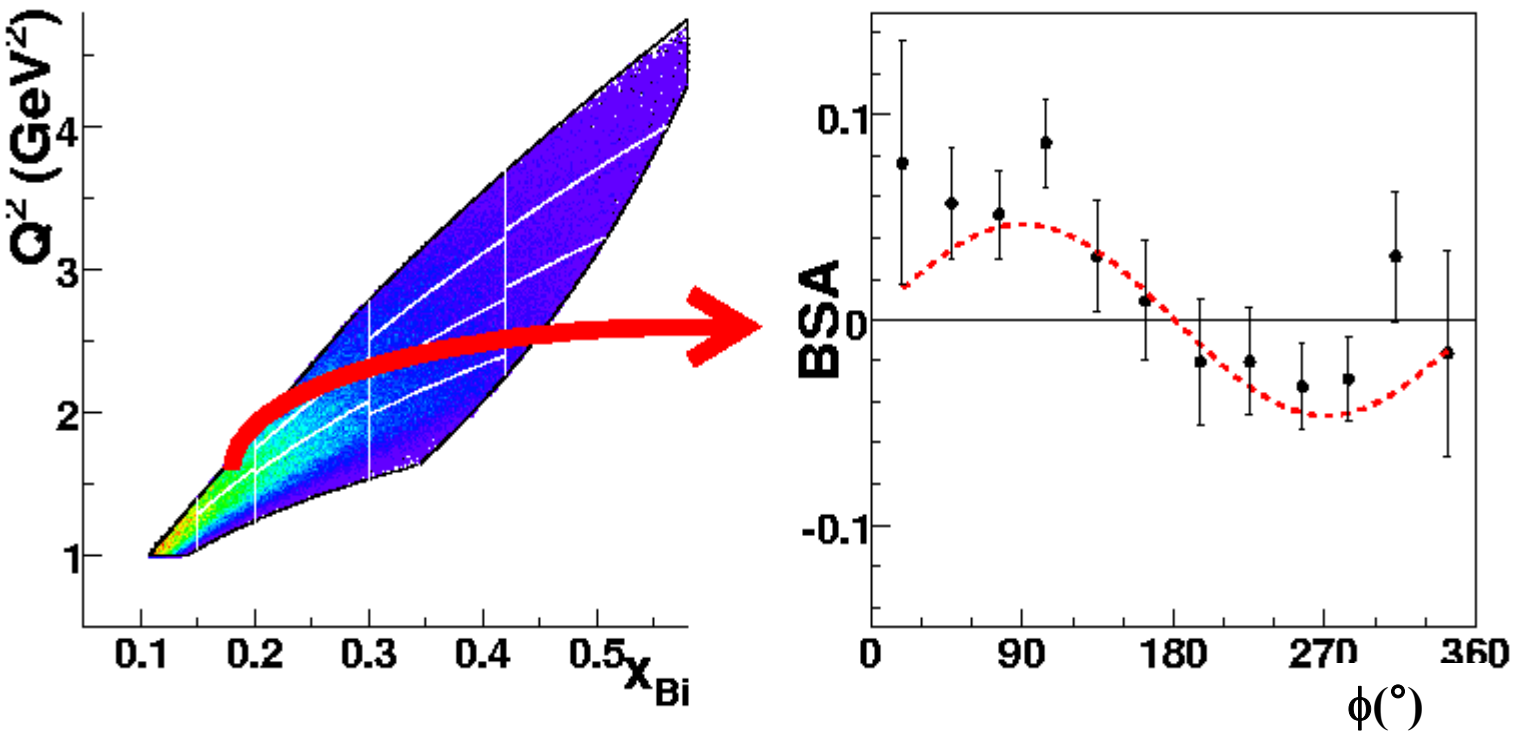

**Interference terms different from zero: transverse and longitudinal contributions**

$Q^2 = 2.25\ (GeV/c)^2$ , $x_B = 0.34$



Office of Science
U.S. DEPARTMENT OF ENERGY

# Beam-spin asymmetry

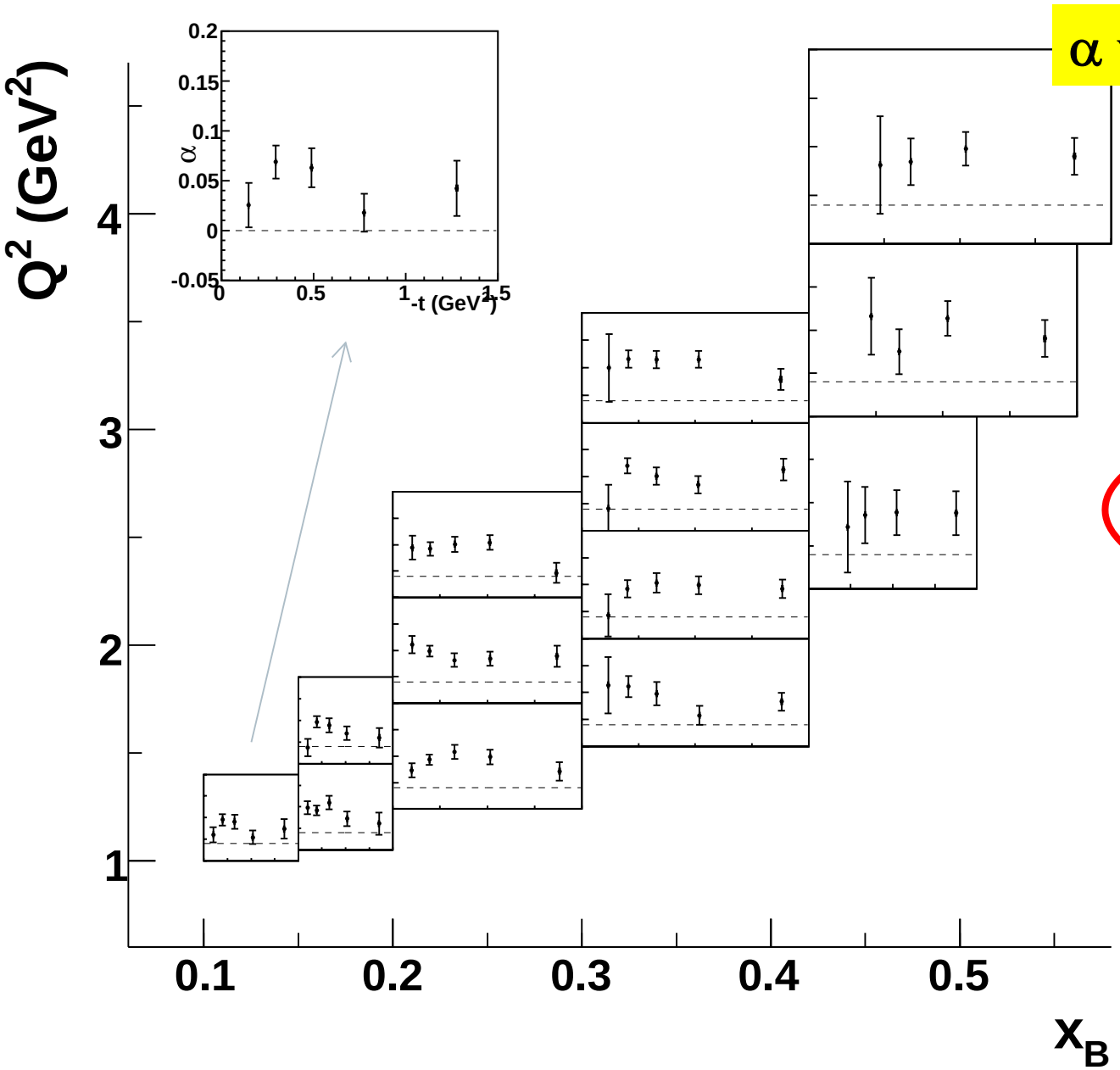



**BSA fit: αsinϕ**

$$\frac{d\sigma}{d\phi dt} = \frac{1}{2\pi}\left(\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi + h\sqrt{2\varepsilon(\varepsilon-1)}\,\frac{d\sigma_{L'T}}{dt}\sin\phi\right)$$

**Rita De Masi's & Bo Zhao's analysis**

# Beam-spin asymmetry




$\alpha \approx 0.08$

$\frac{d\sigma_{L'T}}{dt}$ non zero

Rita De Masi's
&
Bo Zhao's
analysis

Science
U.S. DEPARTMENT OF ENERGY

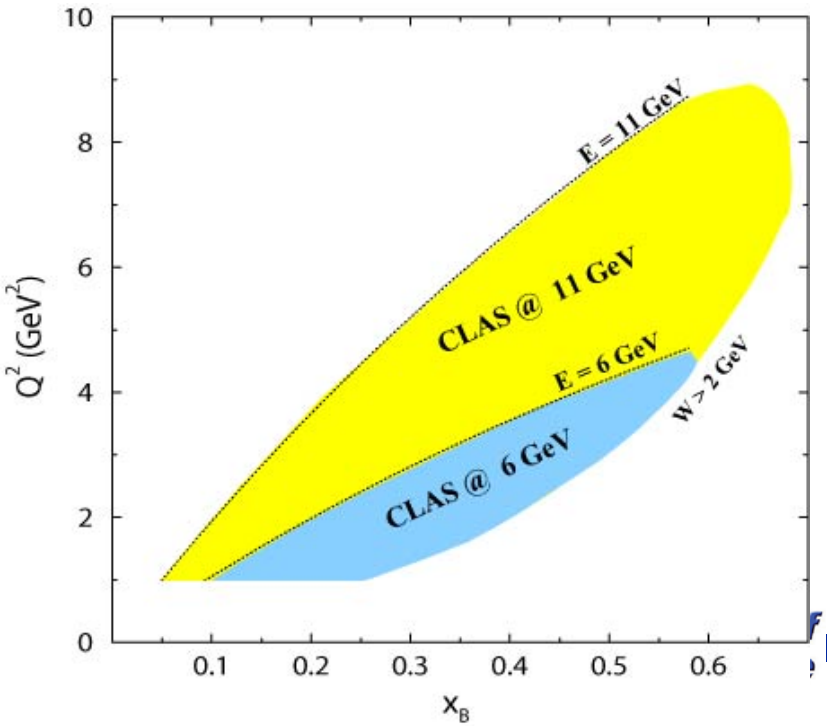
# Summary

- DVCS is the **cleanest reaction** giving access to **GPDs**
- First pioneering experiments and dedicated Hall A experiment gave **evidence for handbag dominance** at modest $Q^2$
- The e1-dvcs experiment at CLAS allowed for the first time to extract **BSA** and **polarized and unpolarized cross sections** (still preliminary) for DVCS over **the widest phase space** ever covered → **strong constraint for GPD models**
- **DVMP cross sections** (and asymmetries) analyses are underway using e1-dvcs data, aiming to **flavor decomposition** of GPDs: $ep\pi^0$, $ep\eta$, $ep\rho^+$
- **ΔVCS** asymmetry under study, to study N→Δ transition GPDs

# Outlook

➢ Next year at CLAS: new DVCS experiment with **longitudinally polarized target**

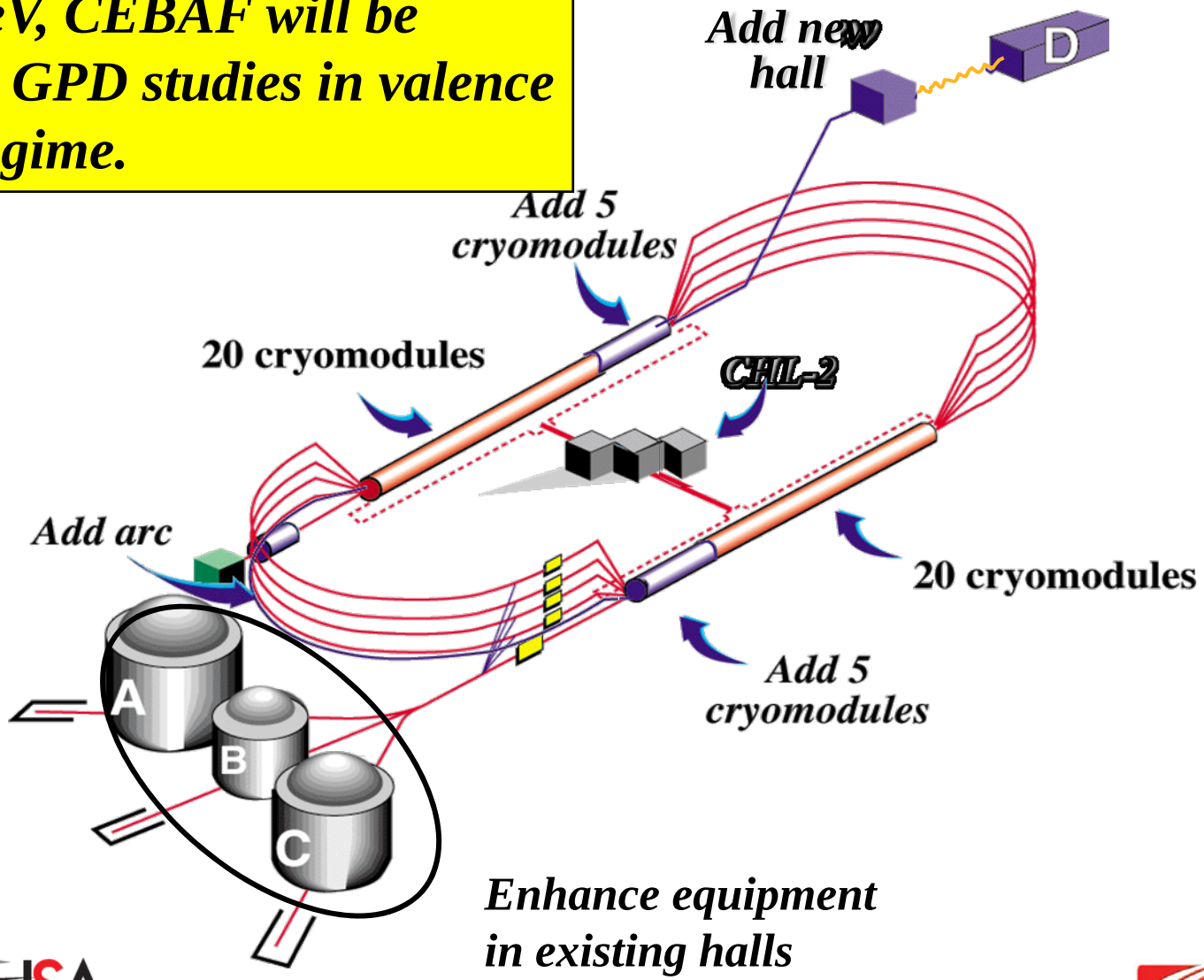
➢ **CLAS@12 GeV** will explore DVCS and DVMP for $Q^2$ up to 9 $GeV^2$ and $x_B$ up to 0.7



In the past few years, we were able to glimpse some of the new physics that is accessible through GPDs. However, much more experimental and theoretical work is needed to efficiently unravel the complex *structure* of the proton.

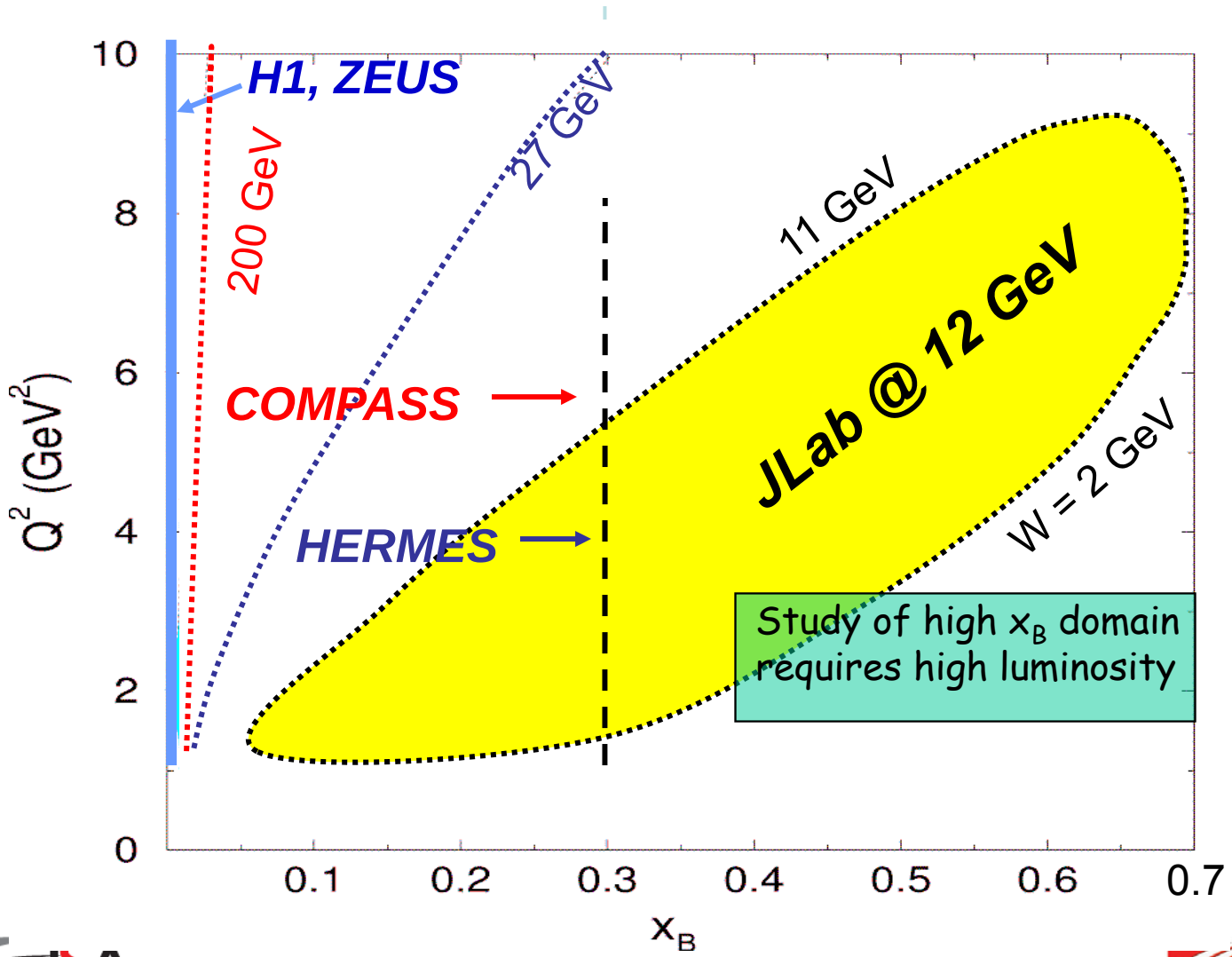
# JLab Upgrade to 12 GeV

***At 12 GeV, CEBAF will be ideal for GPD studies in valence quark regime.***




***Enhance equipment in existing halls***

# Deeply Virtual Exclusive Processes - Kinematics Coverage of the 12 GeV Upgrade



# Hall B Overview

- Hall B currently houses the **CLAS** detector. **CLAS** is a large acceptance detector and will be modified and upgraded to ***CLAS12,*** which will be worldwide the only large acceptance, multi-purpose detector for fixed target electron scattering experiments.

- ***CLAS12*** is expected to operate with an upgraded luminosity of $L=10^{35}cm^{-2}s^{-1}$, more than an order of magnitude increase over **CLAS**, and with improved particle identification.

- With these capabilities ***CLAS12*** will support a broad experimental program in fundamental nuclear physics.

# Present-day CLAS

# *CLAS12* - Initial 12 GeV Physics Program

- **GPD's** and **3D-Imaging of the Nucleon**
  - Deeply Virtual Compton Scattering - DVCS
  - Deeply Virtual Meson Production at low/high t
- **Valence Quark Distributions**
  - u- and d-Quark Spin Distributions in Proton and Neutron
  - Neutron Structure Function $F_{2n}(x,Q^2)$ , d/u
  - TMD Quark Distribution Functions in SIDIS
- **Form Factors and Resonance Excitations**
  - The Magnetic Structure of the Neutron – $G_{Mn}$
  - N* Transition Form Factors at high $Q^2$
- **Hadrons in the Nuclear Medium**
  - Space-Time Characteristics of Quark Hadronization
  - Color Transparency
  - Short Distance Dynamics of Light Nuclei
- **Spectroscopy of Strange Baryons**

# *CLAS12* - PAC approved proposals

| Proposal | Physics | Experiment days |
|---|---|---|
| E12-06-119a | DVCS with polarized beam | 80 |
| E12-06-112 | $ep \rightarrow e\pi^{+/-/0} X$ | 60 |
| E12-06-108 | DVMP in $\pi^0$,$\eta$ production and L/T separation | 120 |
| E12-06-119b | DVCS on polarized target | 120 |
| E12-06- 109 | Nucleon Spin Structure Functions | 80 |
| E12-07-107 | Single Spin Asymmetries | 103 |
| E12-06-106 | Color Transparency $\rho^0$ | 40 |
| E12-06-117 | Quark Hadronization | 60 |
| E12-07-104 | Neutron magnetic form factor | 56 |
| Total | | 719 |

# *CLAS12* – Upgrade Goals

Capabilities to measure exclusive processes at 12 GeV

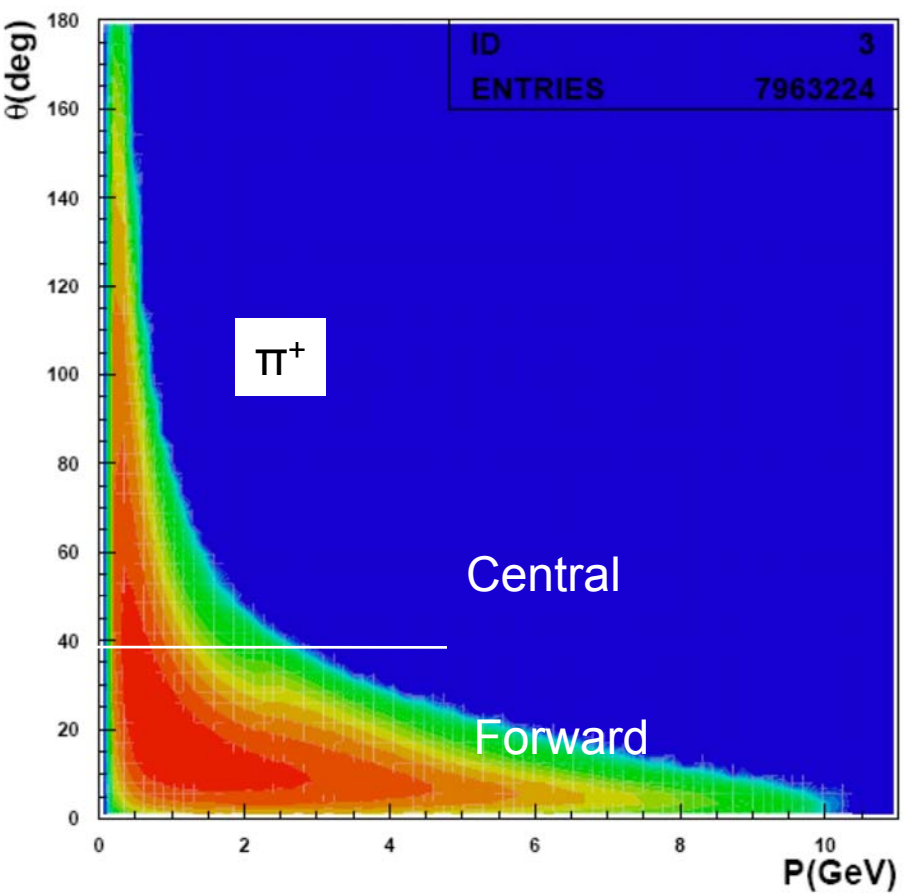
- Operating luminosity up to $10^{35}$ $cm^{-2}sec^{-1}$
- Particle ID to higher momentum ($e^-/\pi^-$, $\pi$/K-p, $\gamma/\pi^o$)
- Momentum & angle resolution for use of missing mass techniques
- Coverage of large range in polar and azimuth angle
- Identify detached vertices

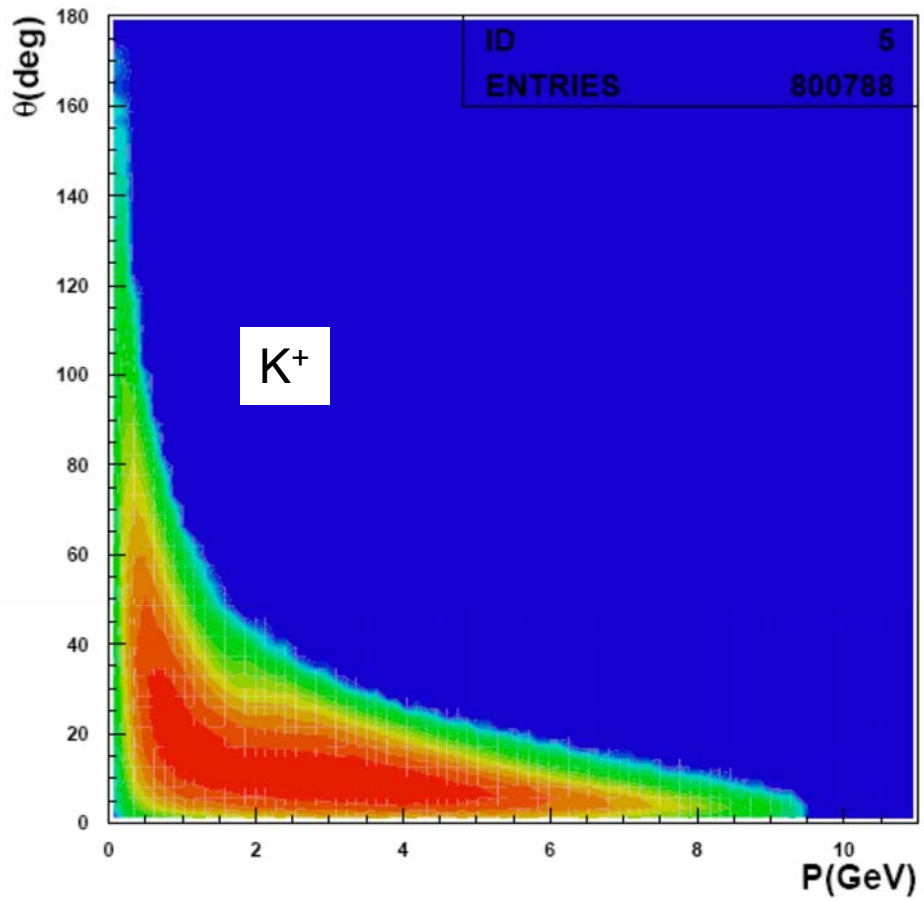
**Solution:**

- Reduce DC occupancies to reach higher luminosities
  - Move DC's further downstream reducing solid angle seen by each cell
  - Improved magnetic shielding for Møller background electrons
- Upgrade the forward PID system
  - Additional threshold Cherenkov detector
  - Timing resolution of the Time-of-Flight detectors
  - Calorimeter granularity for $\pi^o/\gamma$ separation
  - Add tracking capabilities for improved vertex resolution
- Complement the forward detection system with central detector
  - Tracking and magnetic analysis at large angles
  - Particle identification capabilities
  - Operation of a dynamically polarized target

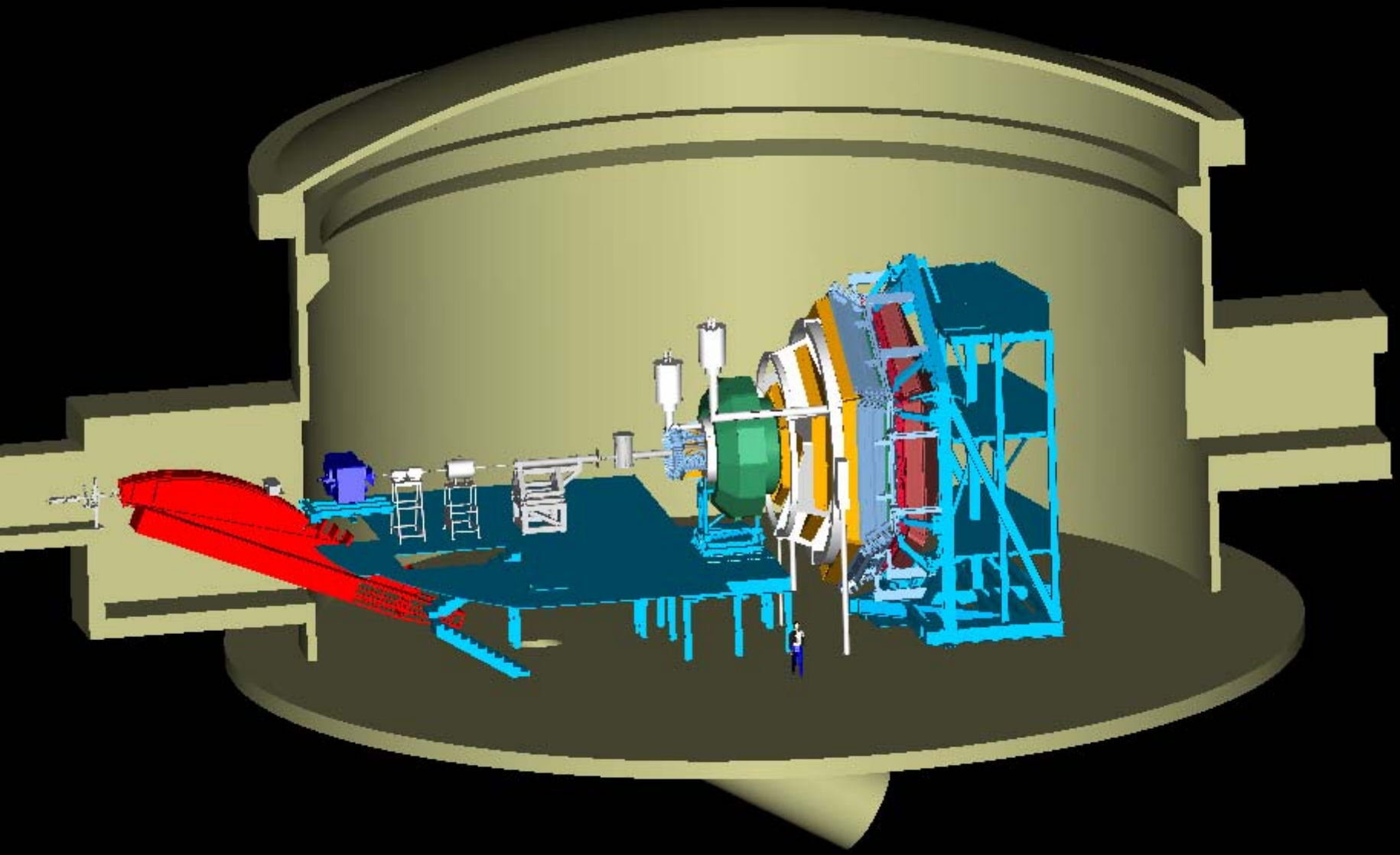
# Distribution of $\pi^+$, $K^+$ in DIS Kinematics

$$e^-p \rightarrow e^-hX,\ h=\pi^+, K^+$$



# CLAS12 in Hall B

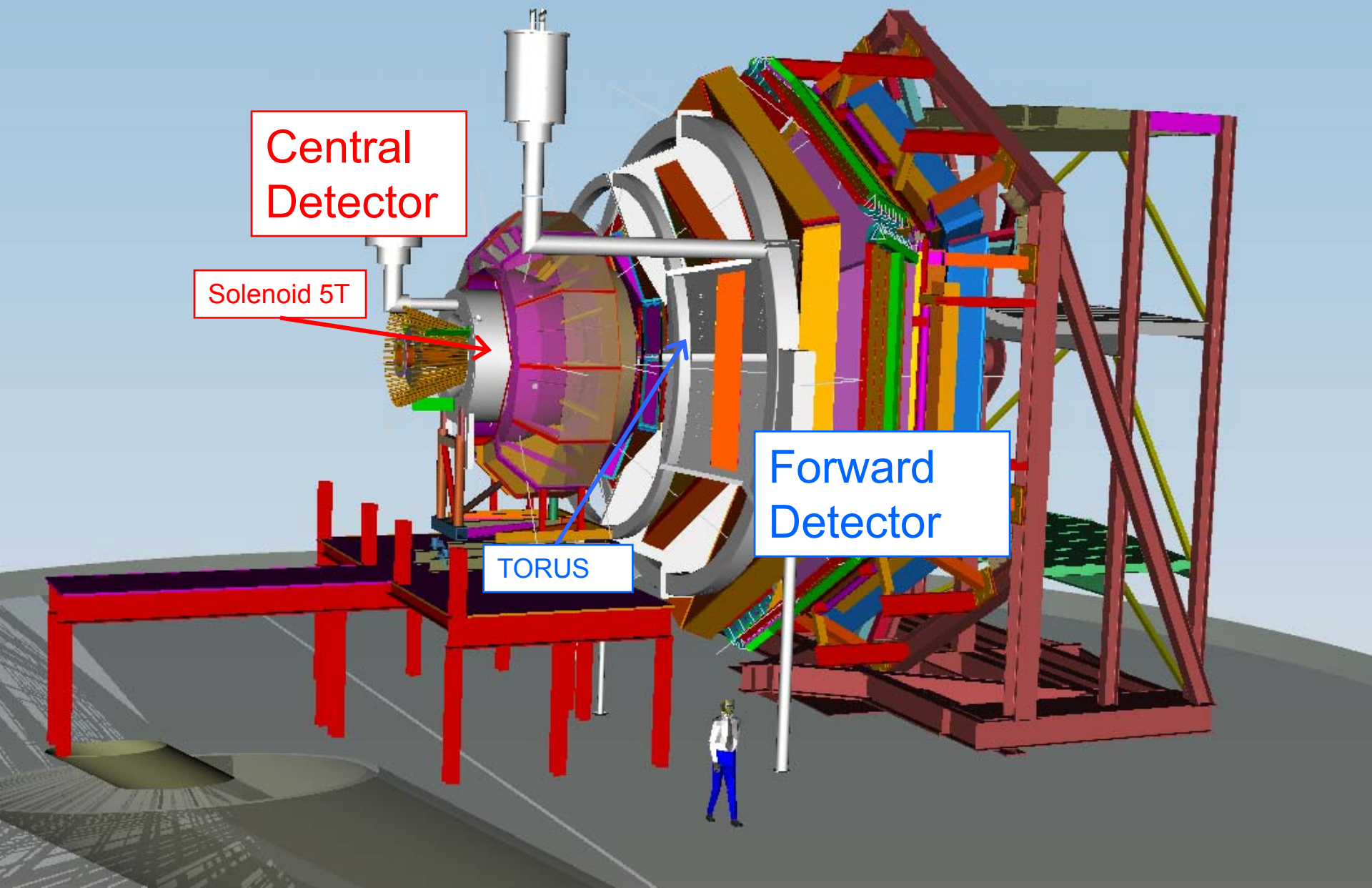


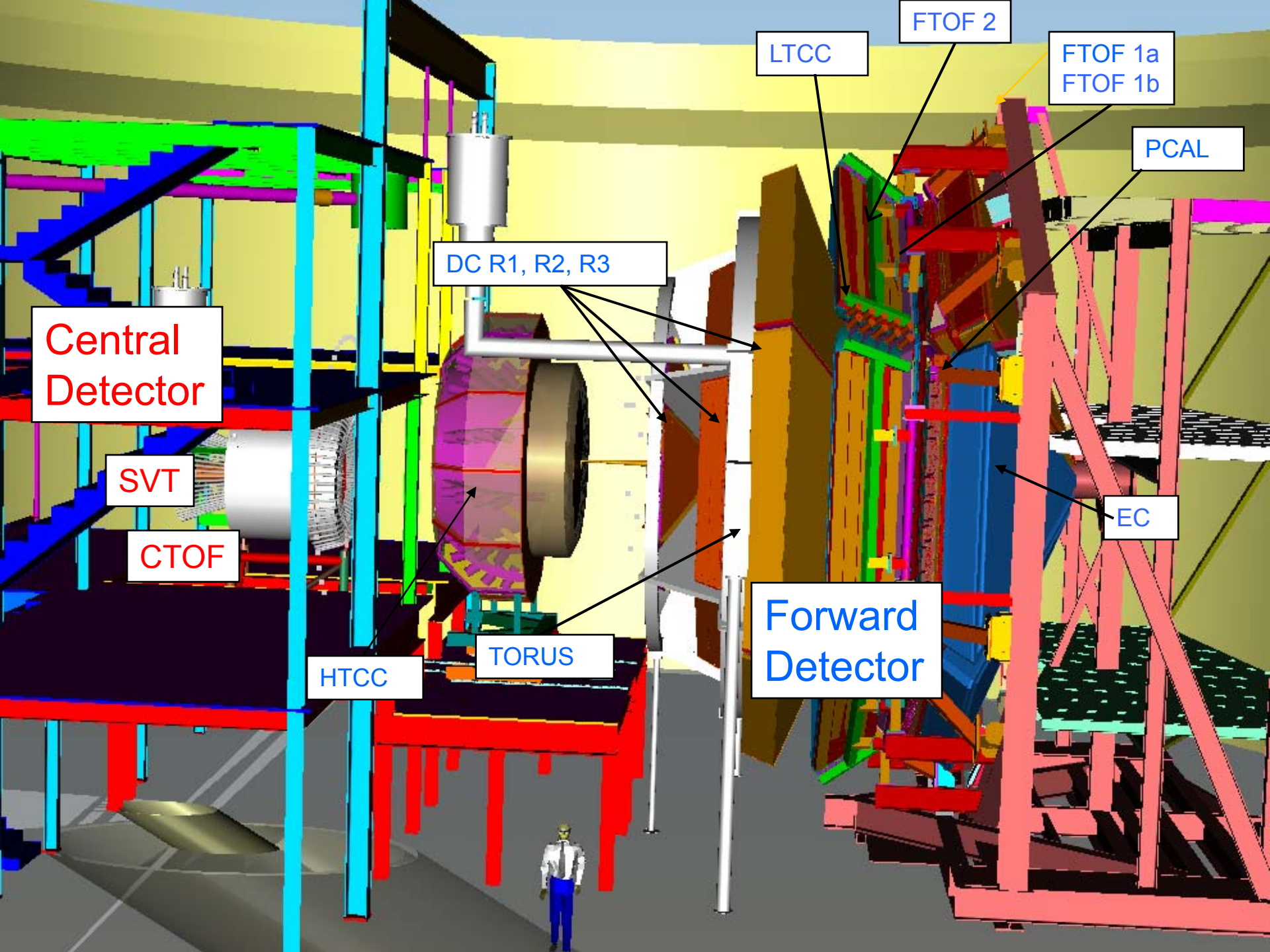
# Utilization of existing Hall B Equipment

- Re-use existing CLAS detector components
  - Forward electromagnetic calorimeters
  - Low threshold gas Cherenkov counters
  - Time-of-flight scintillators
  - Drift chamber electronics and gas system
  - Inner $PbW0_4$ small-angle calorimeter
  - DAQ and readout electronics

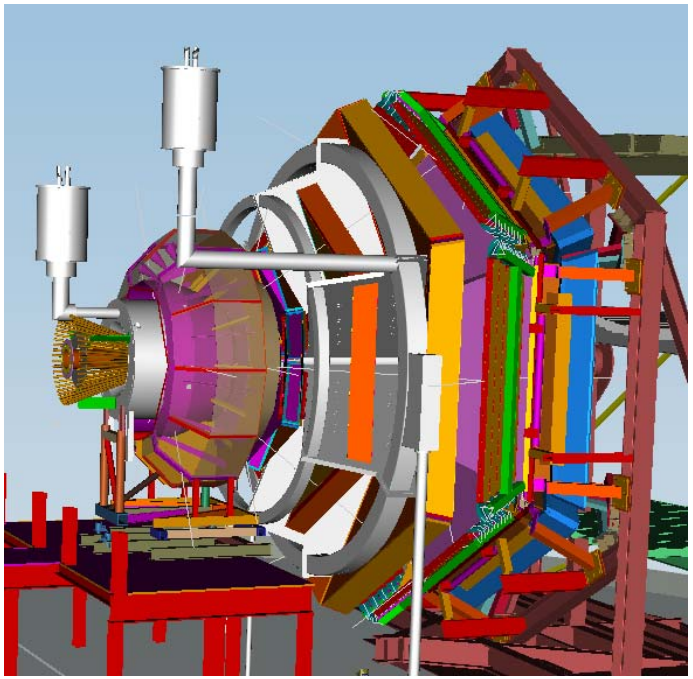
- Re-use other Hall B components
  - Cryogenic targets
  - Møller polarimeter
  - Raster magnets & power supplies
  - Faraday cup
  - Beam diagnostics
  - Photon energy tagging system
  - Coherent bremsstrahlung/goniometer
  - Frozen spin polarized target
  - Pair spectrometer magnet & power supplies
  - Utility distribution & space frames

# CLAS12 - Detector




FTOF 2
LTCC
FTOF 1a
FTOF 1b
PCAL
DC R1, R2, R3
Central Detector
SVT
CTOF
EC
Forward Detector
TORUS
HTCC

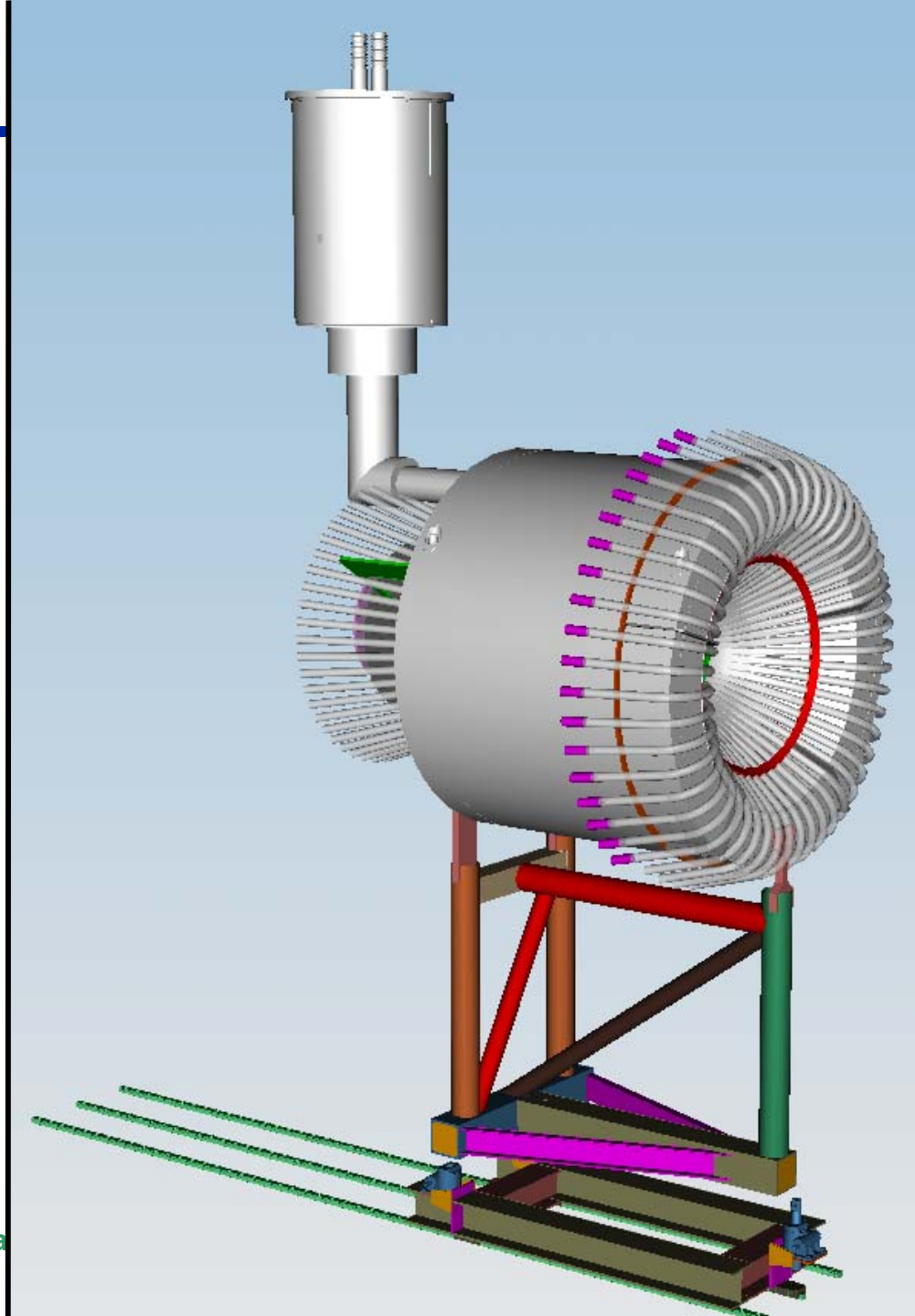
# *CLAS12* – Design Parameters



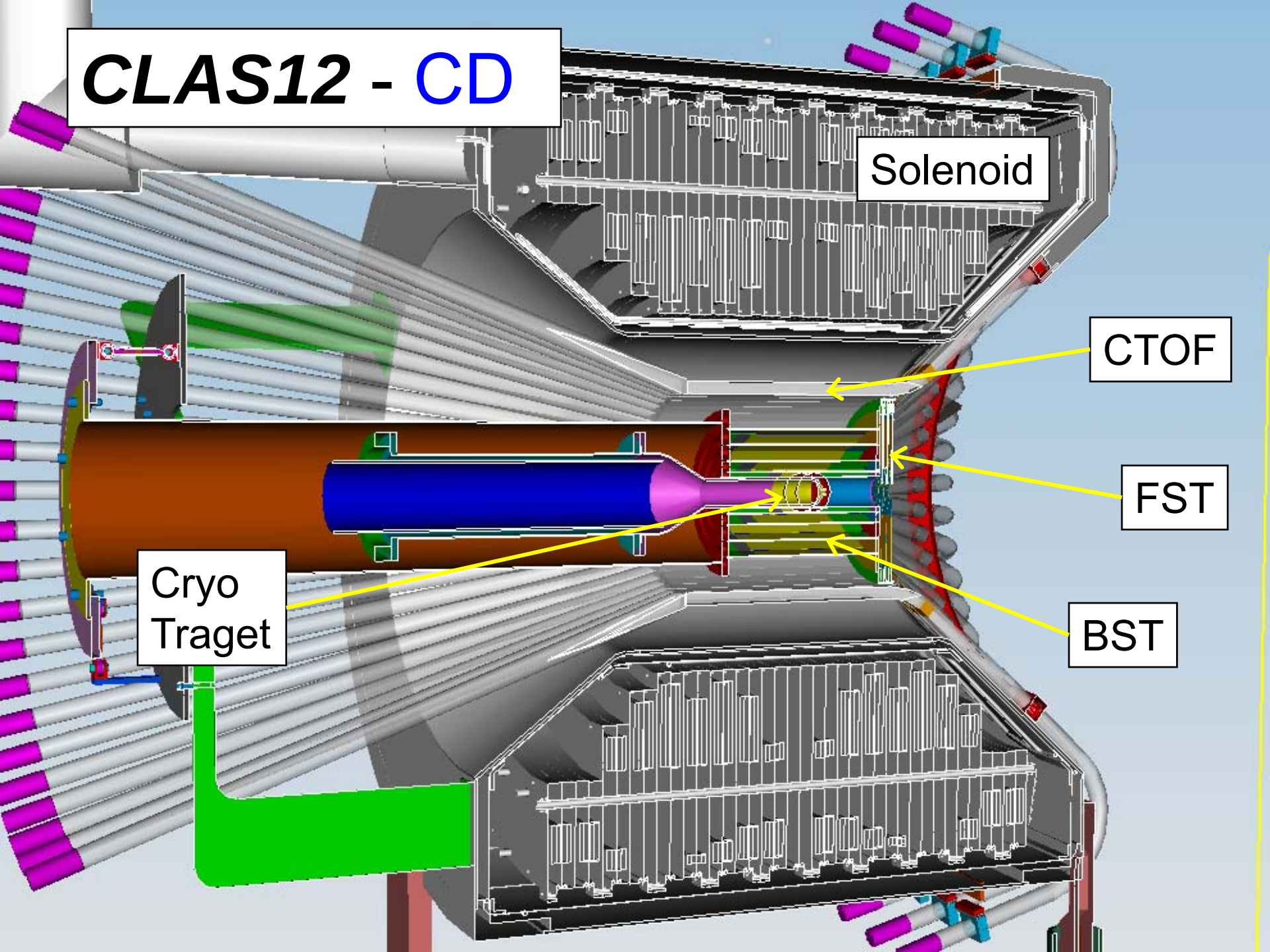
| | Forward Detector | Central Detector |
|---|---|---|
| **Angular range** | | |
| Tracks | $5^0 – 40^0$ | $35^0 – 125^0$ |
| Photons | $3^0 – 40^0$ | n.a. |
| **Resolution** | | |
| $\delta p/p$ (%) | < 1 @ 5 GeV/c | < 5 @ 1.5 GeV/c |
| $\delta\theta$ (mr) | < 1 | < 10 - 20 |
| $\Delta\phi$ (mr) | < 3 | < 5 |
| **Photon detection** | | |
| Energy (MeV) | >150 | n.a. |
| $\delta\theta$ (mr) | 4 @ 1 GeV | n.a. |
| **Neutron detection** | | |
| $N_{eff}$ | < 0.7 (EC+PCAL) | n.a. |
| **Particle ID** | | |
| $e/\pi$ | Full range | n.a. |
| $\pi/p$ | Full range | < 1.25 GeV/c |
| $\pi/K$ | Full range | < 0.65 GeV/c |
| $K/p$ | < 4 GeV/c | < 1.0 GeV/c |
| $\pi^0 \rightarrow \gamma\gamma$ | Full range | n.a. |
| $\eta \rightarrow \gamma\gamma$ | Full range | n.a. |

# *CLAS12* Central Detector

- Superconducting 5T Solenoid Magnet, w/ 78cm ø warm bore.
- Central scintillator array (CTOF).
- Silicon Vertex Tracker, barrel part (BST), forward part (FST).
- Space for cryogenic target.



# CLAS12 - CD

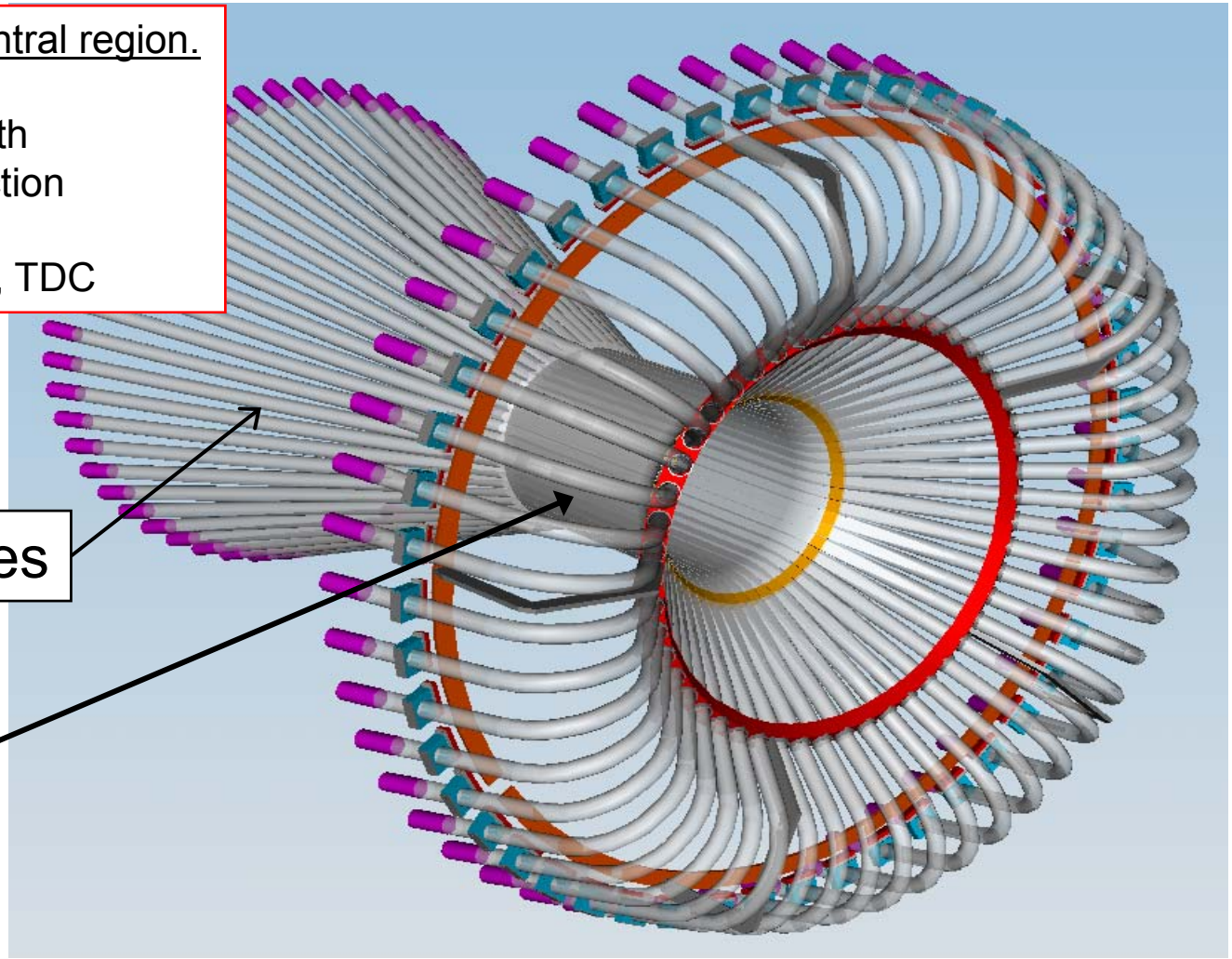


# *CLAS12* - Central Time-of-Flight Counter

Charged Particle ID in central region.

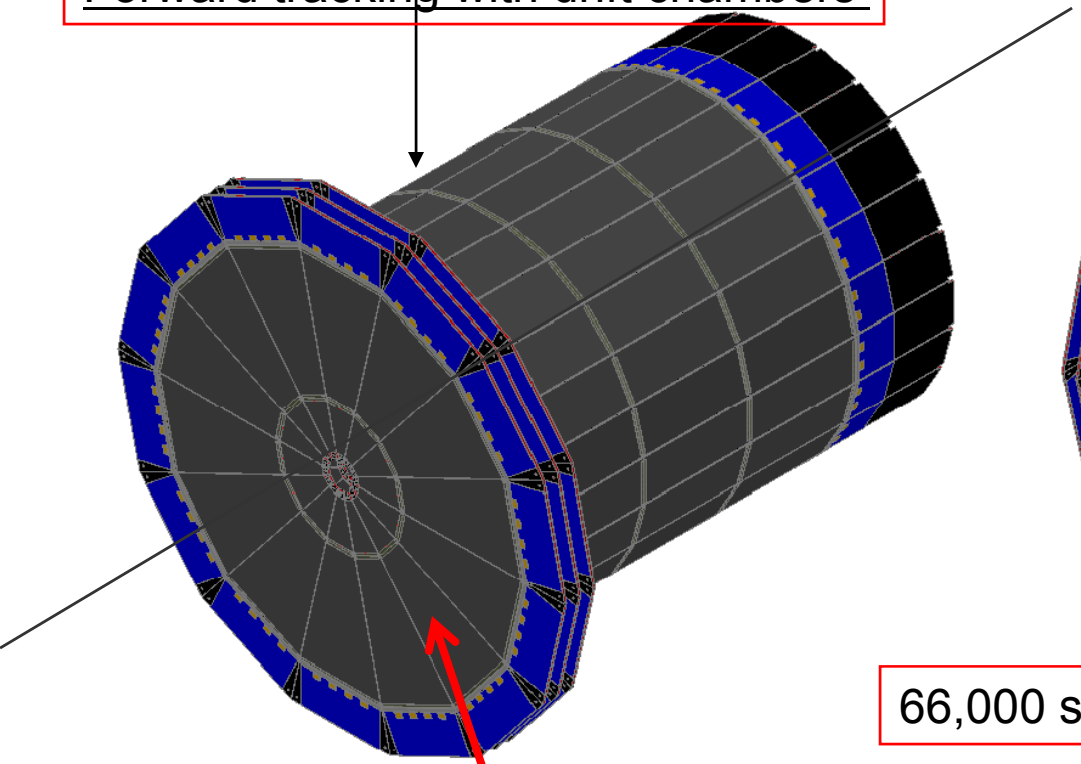
50 plastic scintillators with trapezoidal cross section

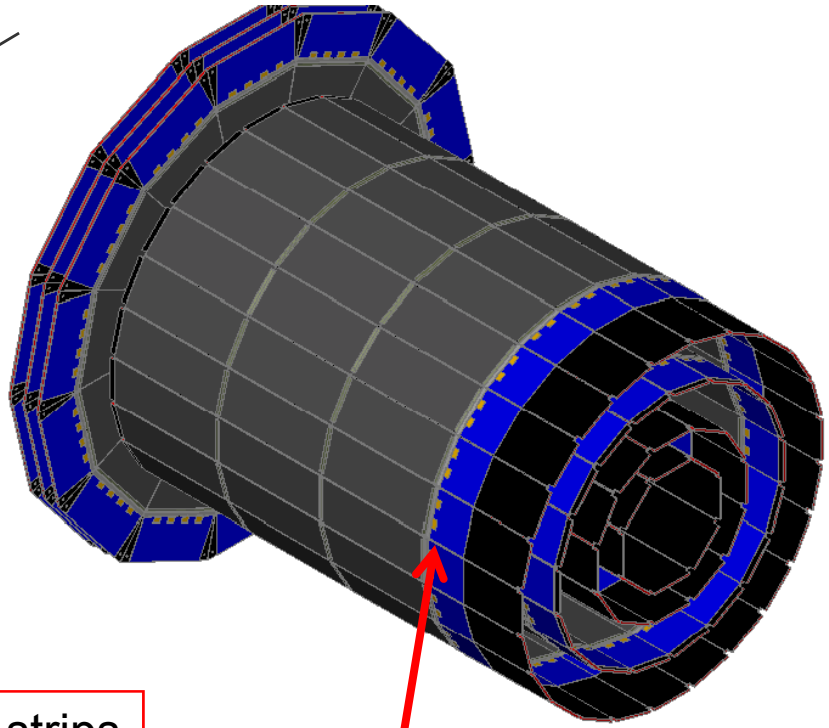
100 channels PMT, fADC, TDC



# *CLAS12* – Silicon Vertex Tracker

Central tracking in solenoid magnet
Forward tracking with drift chambers



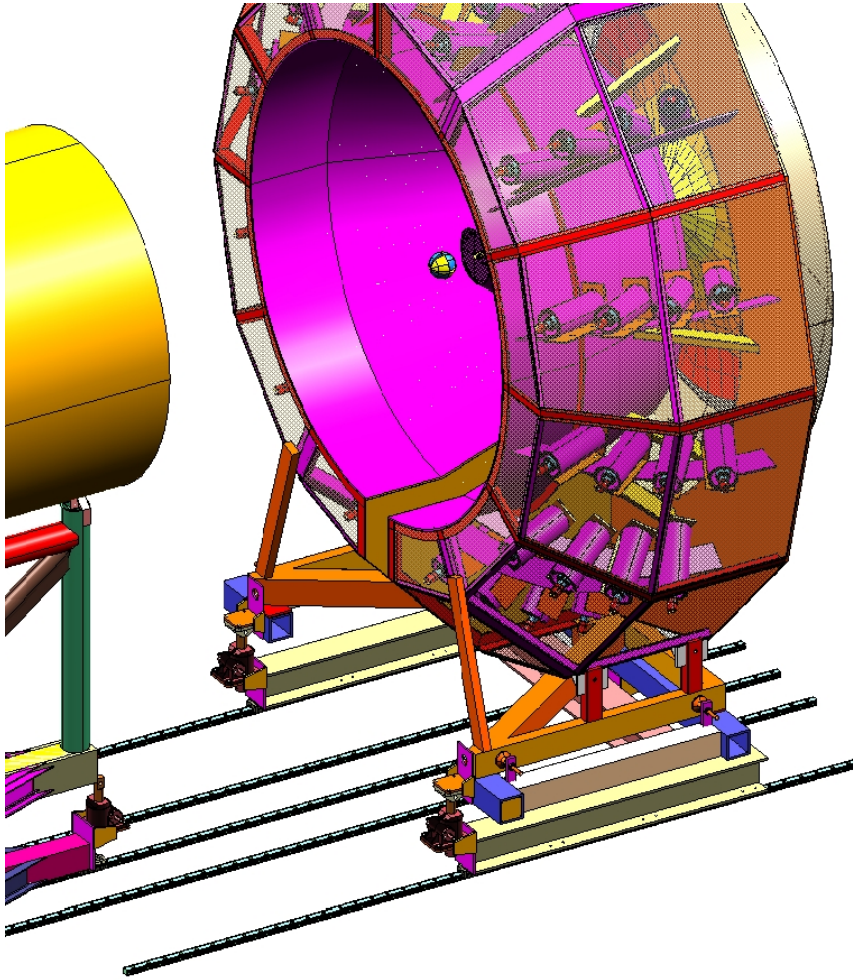


66,000 strips

Forward part, 6 stereo layers ±12°
With forward DC systems provide vertex

Barrel part, 8 stereo layers w/ 3°
Standalone Tracking in 5T magnetic field

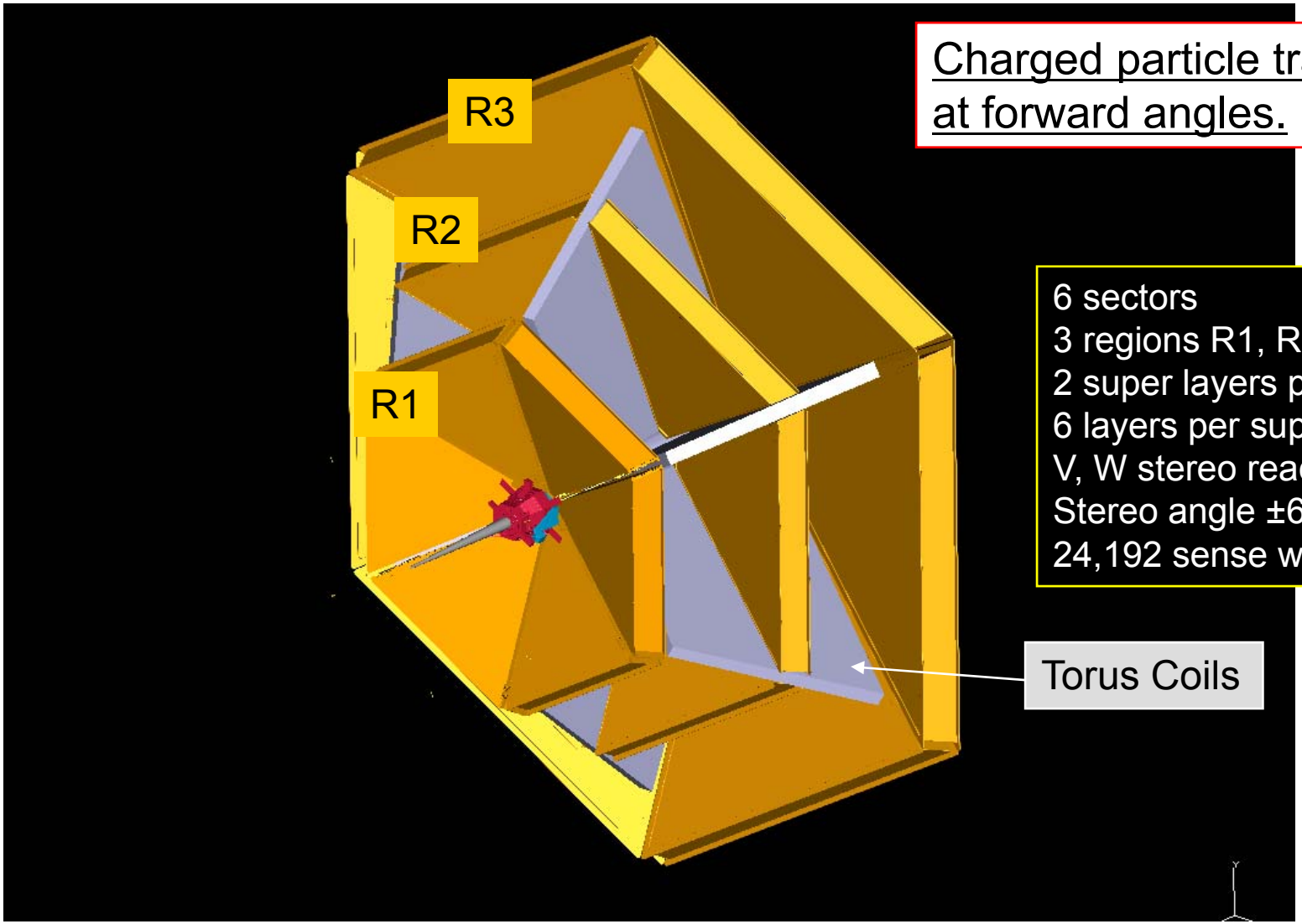
# *CLAS12* - High Threshold Cerenkov Counter (HTCC)



Electron identification up to 5GeV/c
π/K.p separation > 5 GeV/c
Level 1 Trigger

| | |
|---|---|
| Radiator gas: | $CO_2$ @ 1 atm |
| π threshold: | 4.9 GeV/c |
| π rejection: | 200 |
| # of PMTs (5”): | 48 |
| # sectors: | 12 |
| Mirror weight: | < 200mg/cm$^2$ |

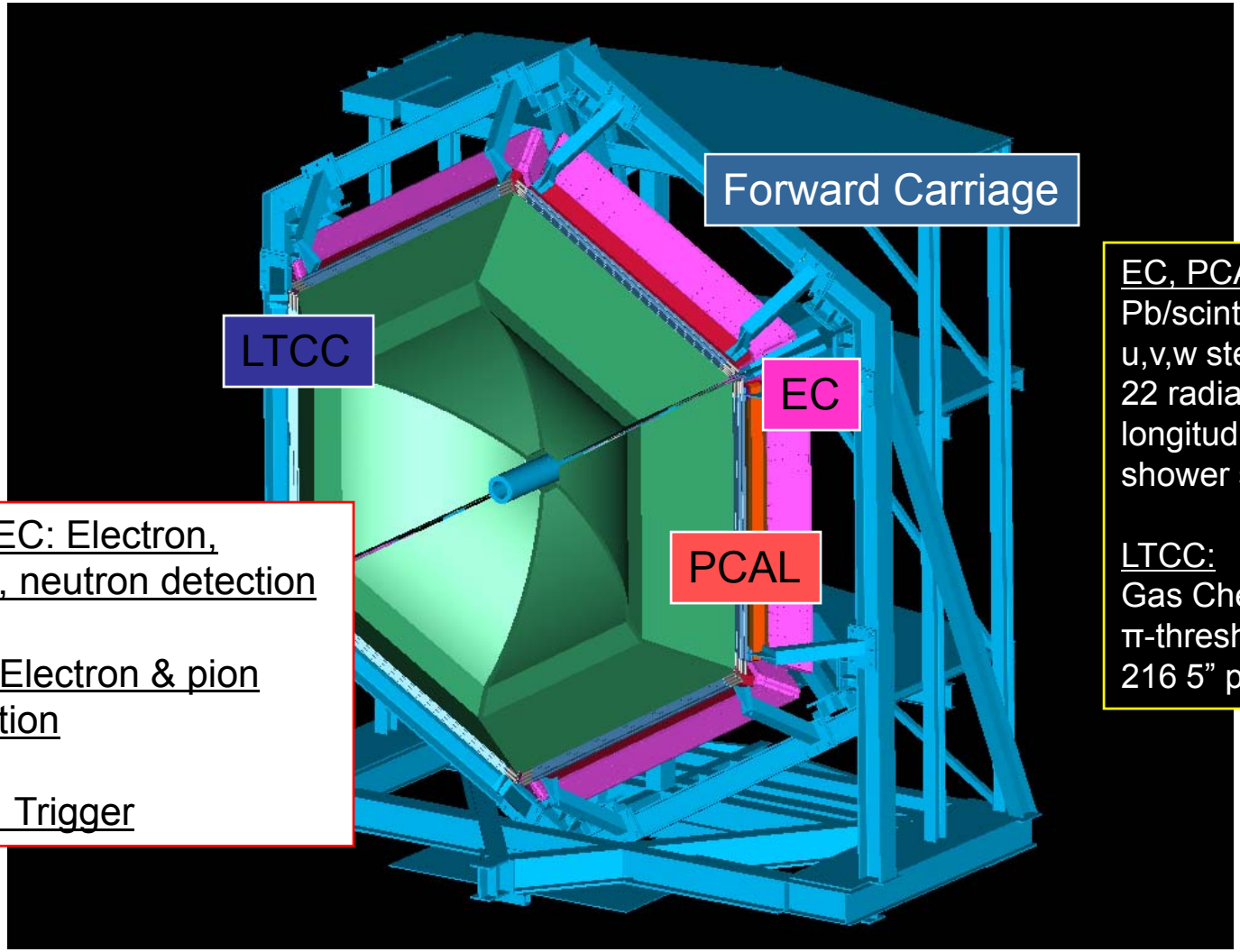
# *CLAS12* - Forward Drift Chambers




Charged particle tracking at forward angles.

6 sectors
3 regions R1, R2, R3
2 super layers per region
6 layers per super layer
V, W stereo readout
Stereo angle ±6 degrees
24,192 sense wires

# *CLAS12* - Forward Carriage




PCAL/EC: Electron, photon, neutron detection

LTCC: Electron & pion separation

Level 1 Trigger

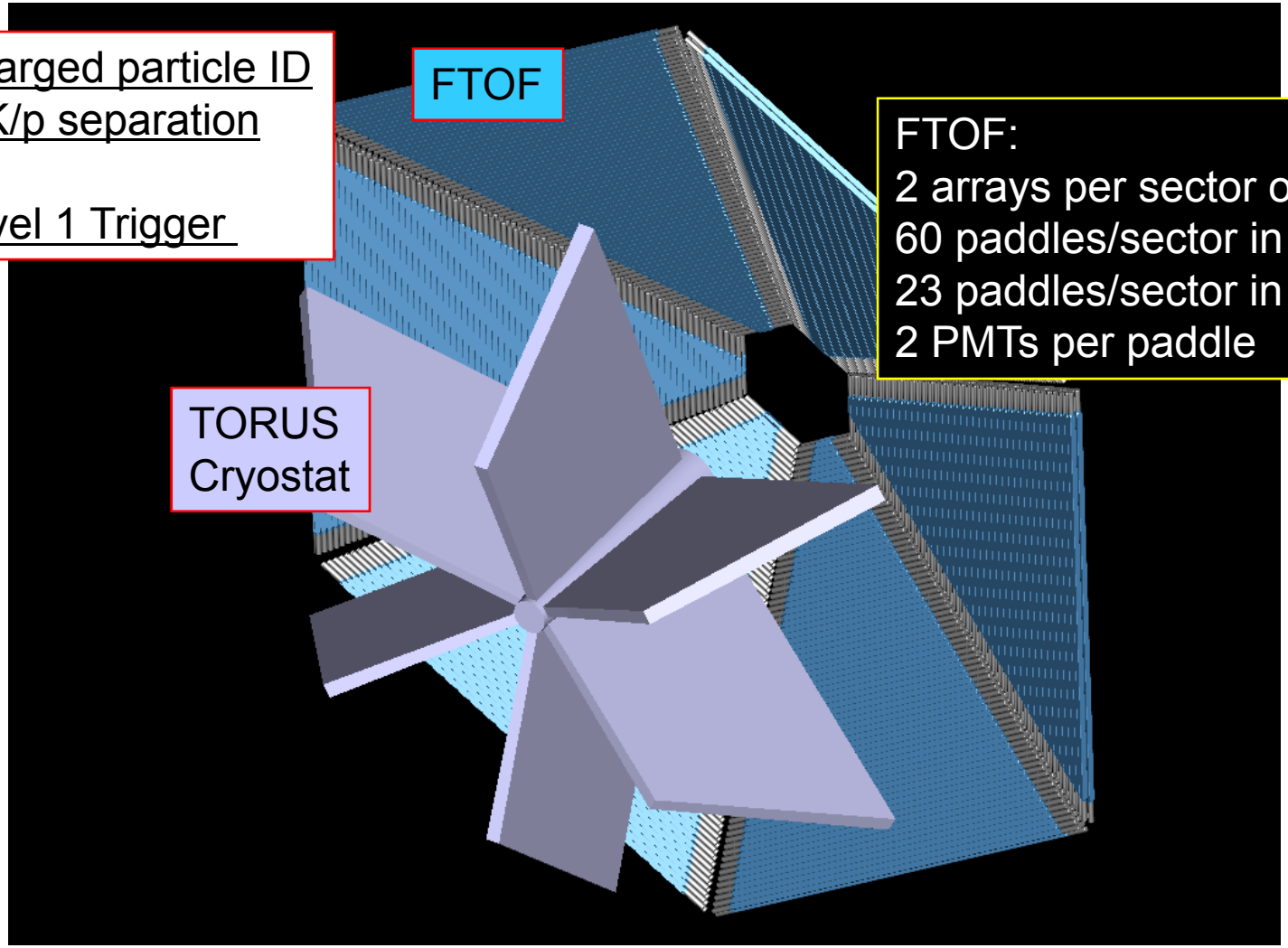
EC, PCAL:
Pb/scintillators sandwich
u,v,w stereo readout
22 radiation lengths
longitudinal/transverse shower sampling

LTCC:
Gas Cherenkov counter
π-threshold: 2.7 GeV/c
216 5” photomultipliers

# *CLAS12* - Forward TOF Counters

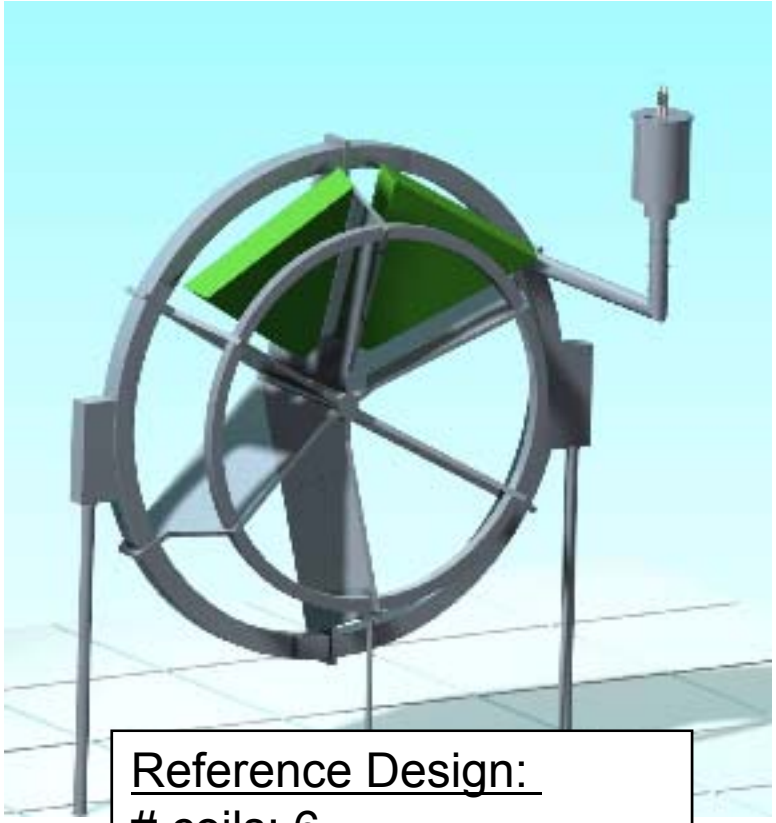
Charged particle ID
π/K/p separation

Level 1 Trigger

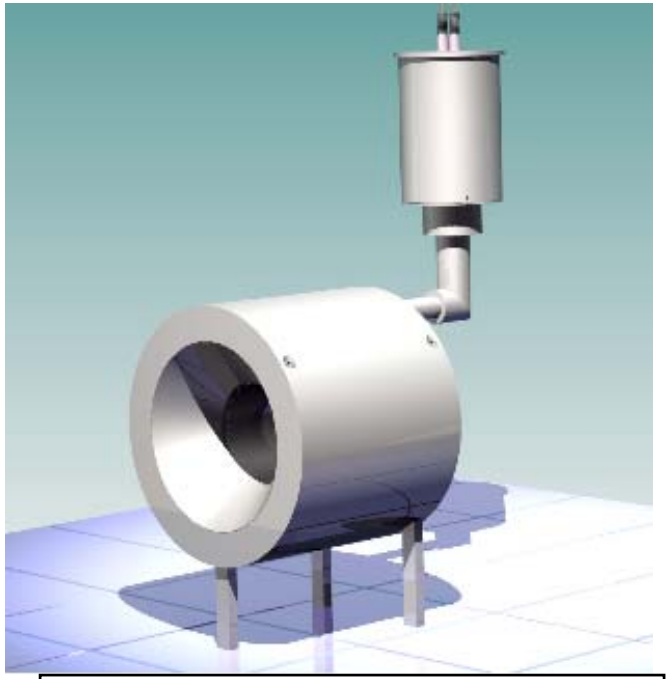



FTOF:
2 arrays per sector of scintillators
60 paddles/sector in array 1b (new)
23 paddles/sector in array 1a (existin
2 PMTs per paddle

# Torus and Solenoid Magnets

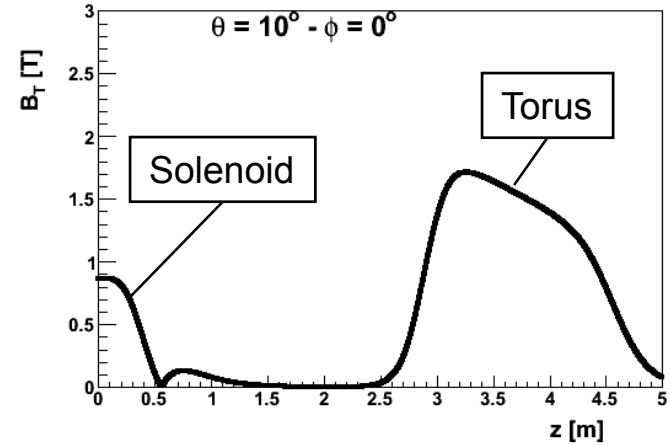


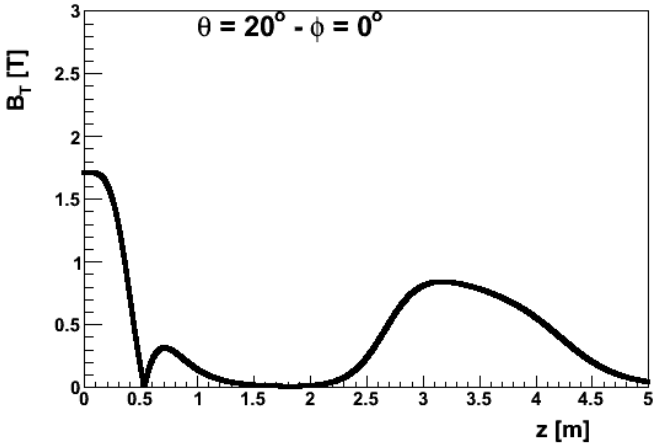
Reference Design:
# coils: 6
Radial thickness: 294mm
Width: 100mm
Stored energy: 14MJ

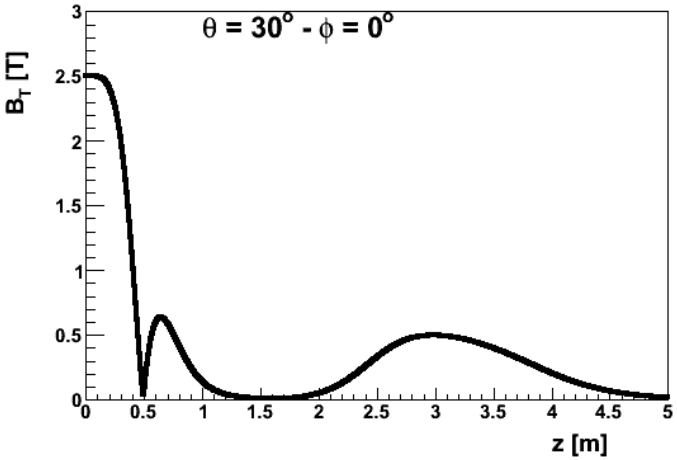


Reference Design:
Max. field: B=5 Tesla
Homogeneity: $\Delta B/B<10^{-4}$
Main coil windings: 4000
Shielding coil: 1880
Stored energy: 25 MJ

# *CLAS12* - Magnetic Field




The Torus *transverse* field becomes weaker with increasing angle while the Solenoid *transverse* field component increases in strength.

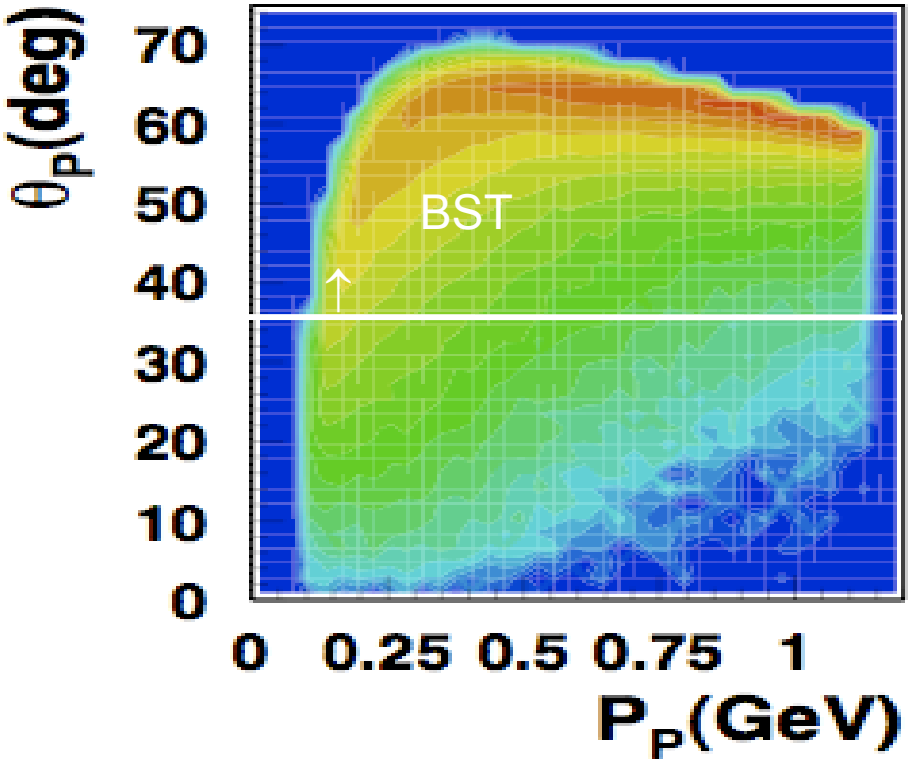
# Examples of Physics Reactions

- Deeply Virtual Compton Scattering
- Excited nucleon states
- Cascade spectroscopy
- Use of missing mass techniques

# *CLAS12* - DVCS protons in BST

$ep \rightarrow ep\gamma$

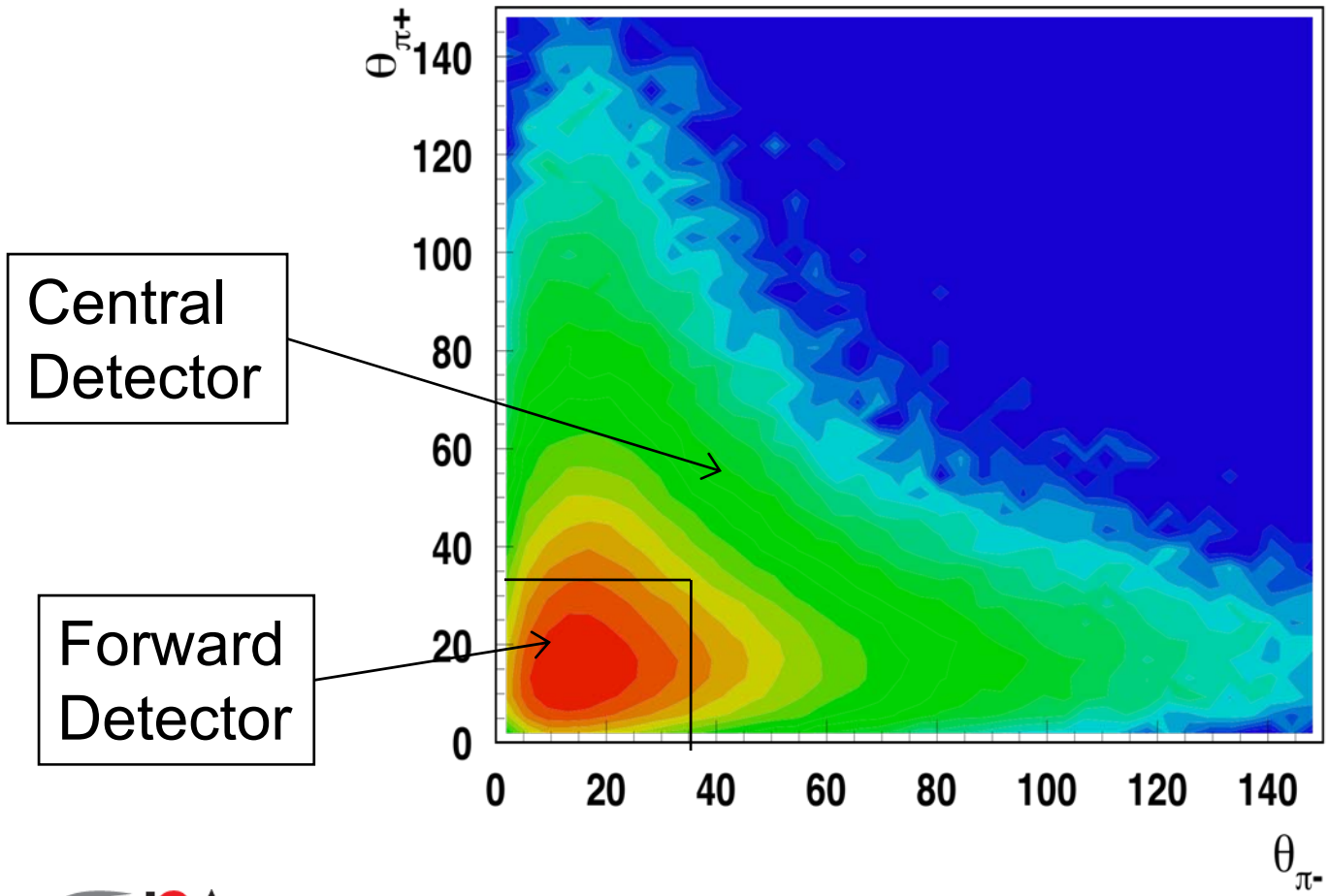
Measurement of Generalized Parton Distributions




Critical for tracking of recoil protons that occupy phase space at Lab angles greater than 35 degrees.

# Kinematics for $ep \rightarrow eN^*(N^* \rightarrow p\pi^+\pi^-)$

Measurement in full angular range needed for N* spectroscopy and partial wave analysis of final state hadrons.

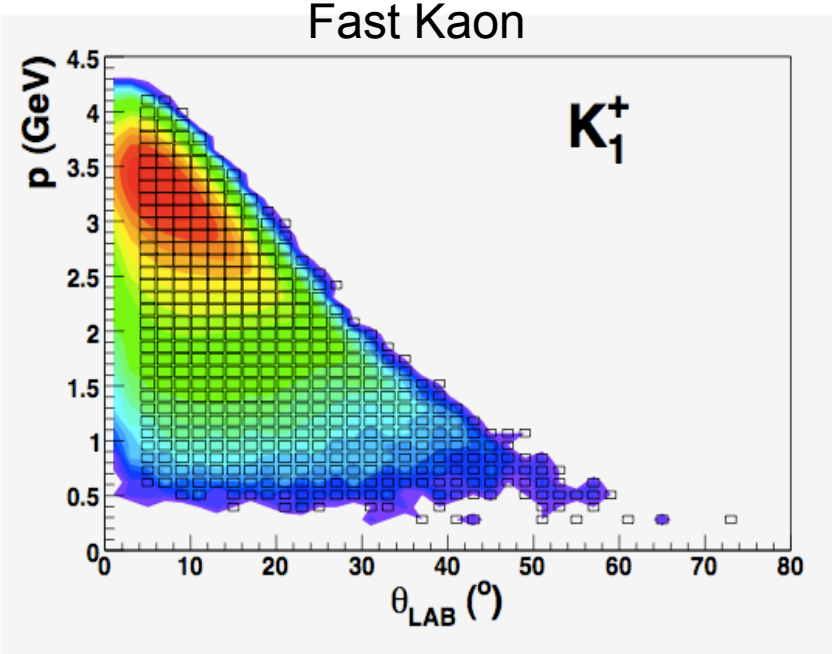


# Kinematics for $\gamma p \rightarrow K_1^+ K_2^+ \Xi^{-*}$

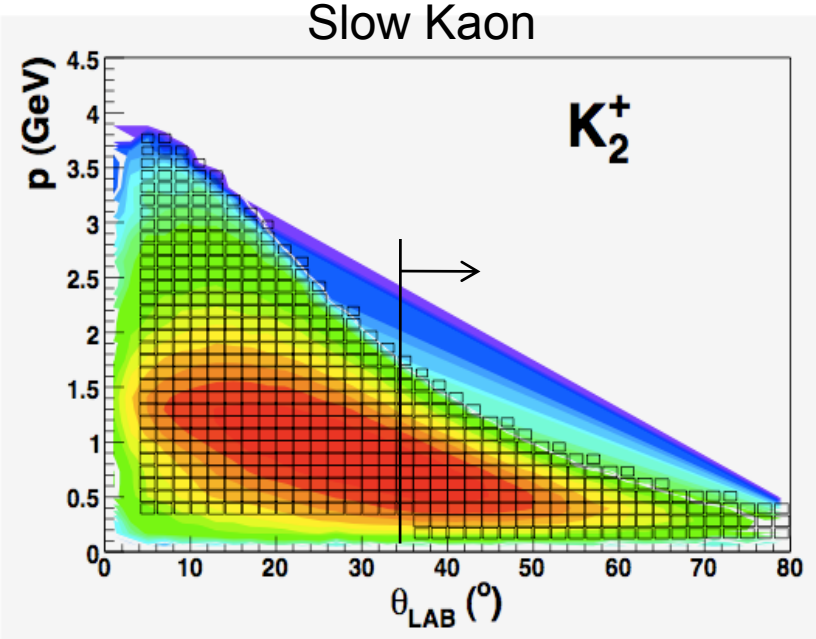
## $(\Xi^{-*} \rightarrow \Lambda\pi^-,\ \Lambda \rightarrow p\pi^-)$

Strange baryon spectroscopy – Search for cascade states

Fast Kaon



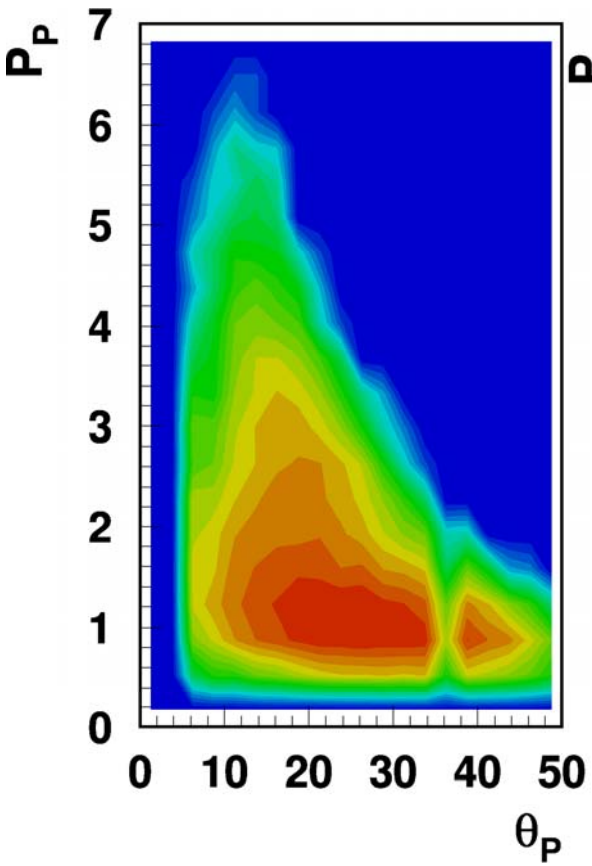

Slow Kaon

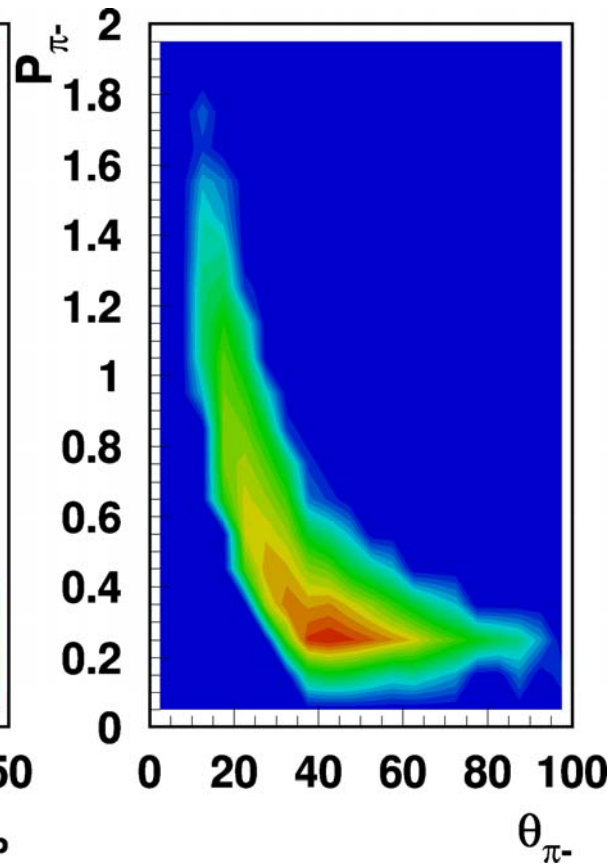


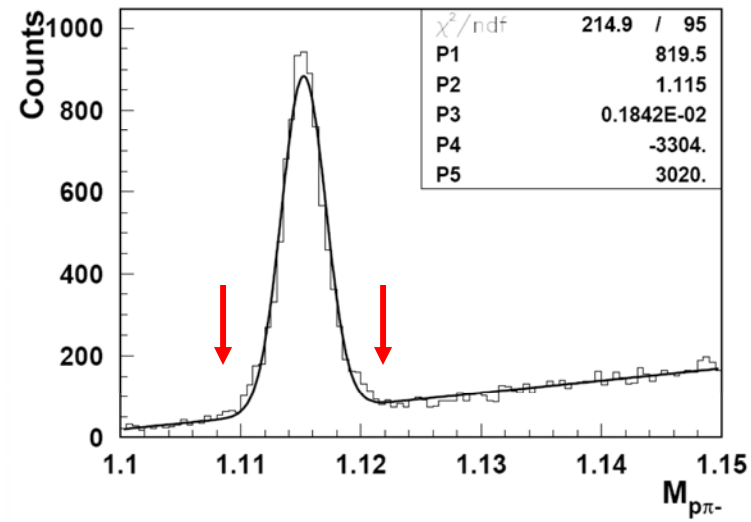

Direct reconstruction of $\Xi^{+*}$ with tracking in FST/BST of detached vertices, e.g $\Xi^{-*} \rightarrow \Lambda\pi^-,\ \Lambda \rightarrow p\pi^-$

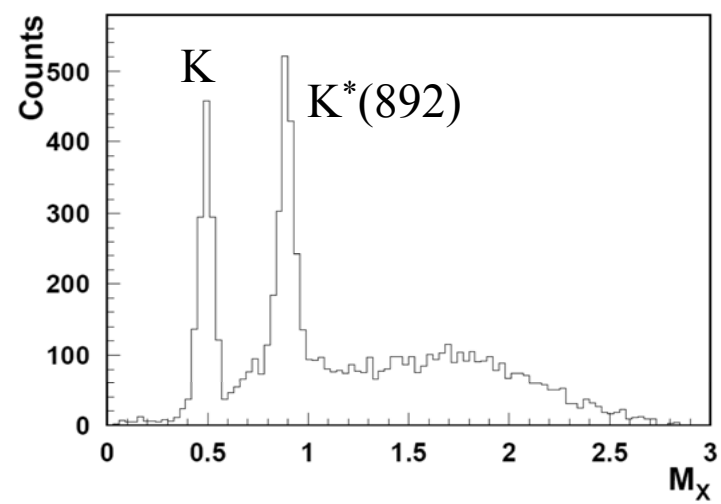
# *CLAS12* - Missing Mass Techniques

$$ep \rightarrow e\Lambda(p\pi^-)X$$



# Rates & Background

# *CLAS12* - Electromagnetic Background

Low energy electromagnetic processes, especially Møller scattering of beam electrons off atomic electrons are the main contributor to the background load in an open large acceptance spectrometer such as ***CLAS12***.

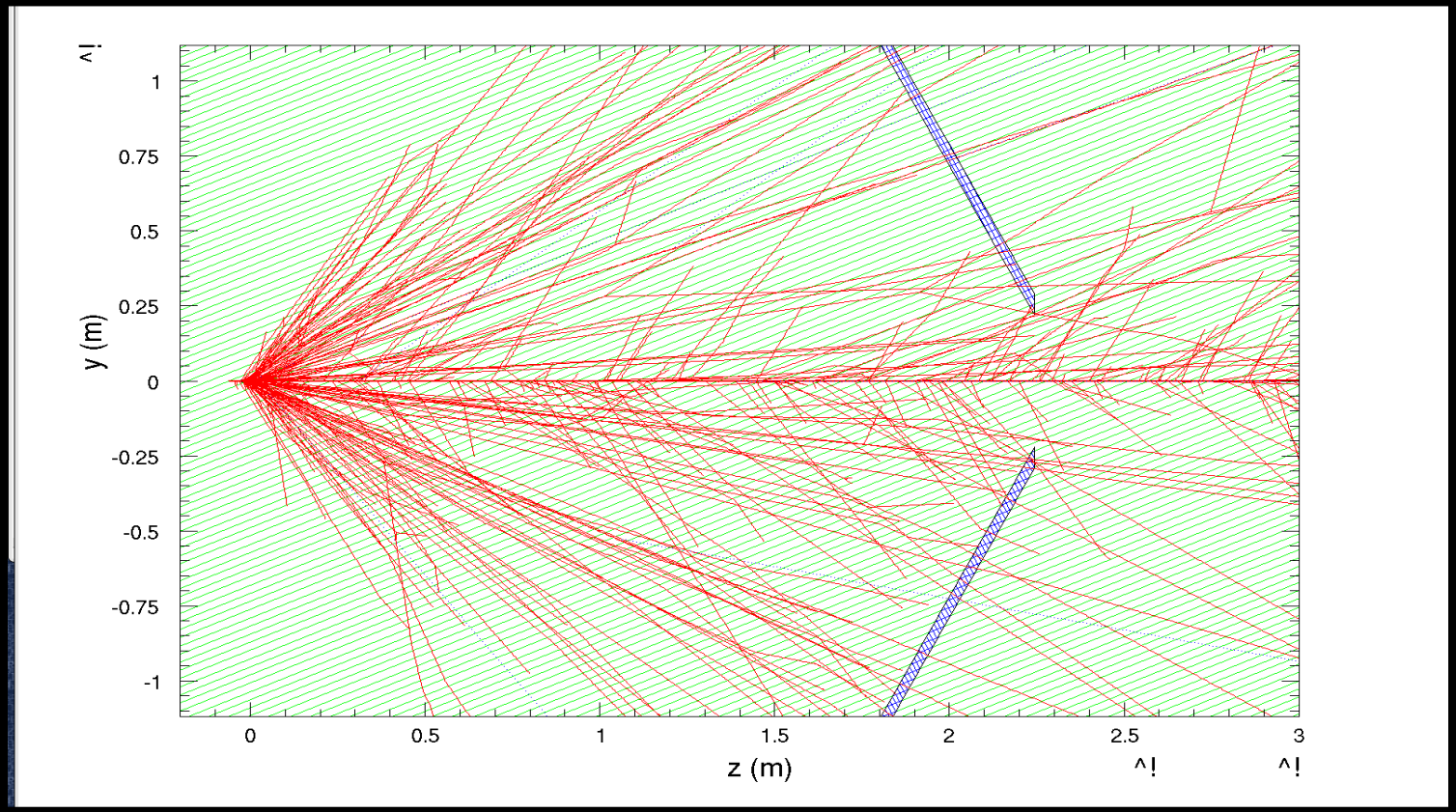
The full event and background load has been measured with CLAS, e.g. for DVCS process at 5.7 GeV. The GEANT simulation reproduces hit occupancy on tracking chambers.

We used the calibrated simulation code to extrapolate to 11 GeV and simulate the same process at higher luminosity for CLAS12 situation.

This background was also studied in a full Geant4 simulation.

# CLAS12

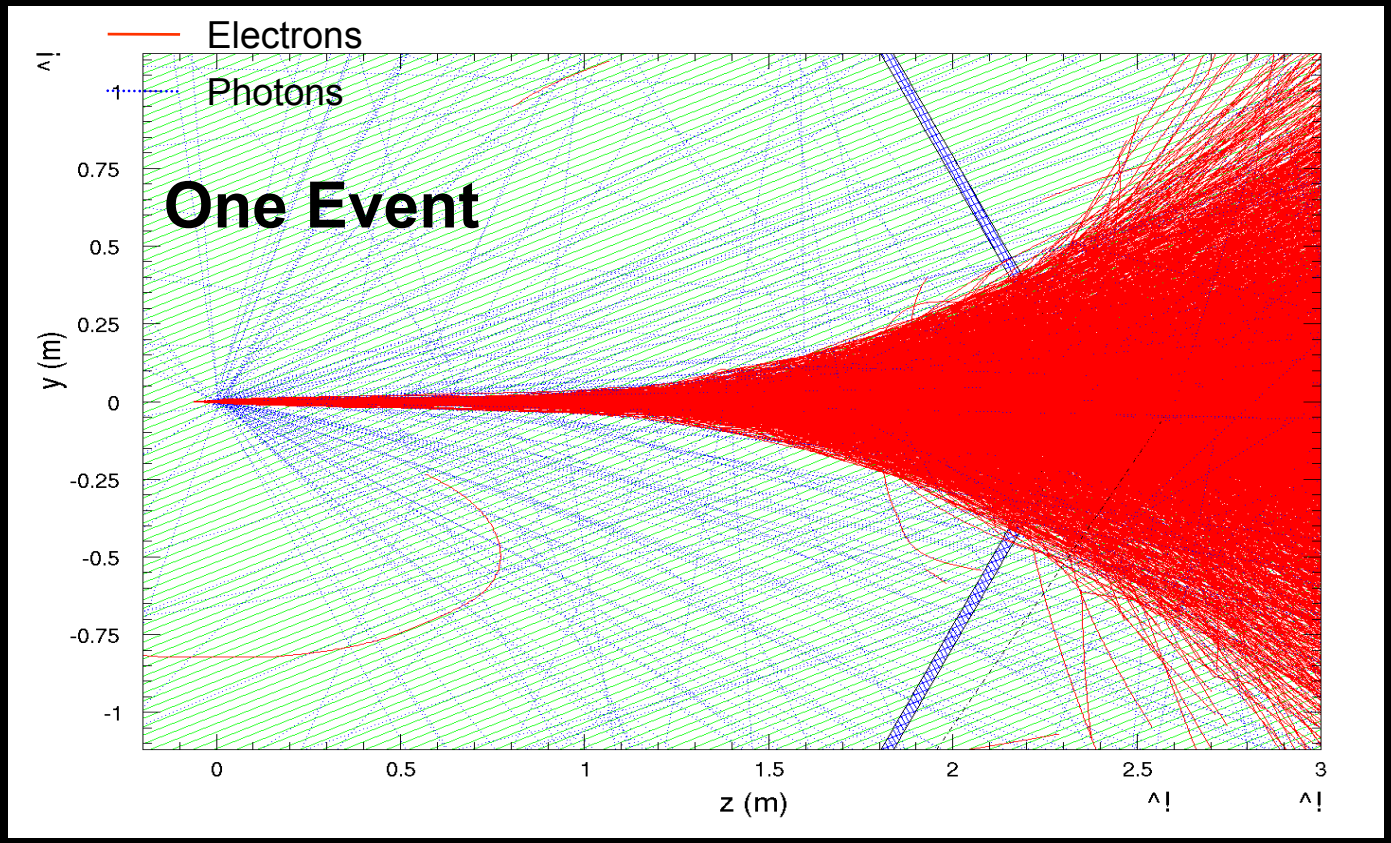
## Background at $L=10^{32}cm^{-2}s^{-1}$, $\Delta T$ = 150ns




No magnetic field

# CLAS12

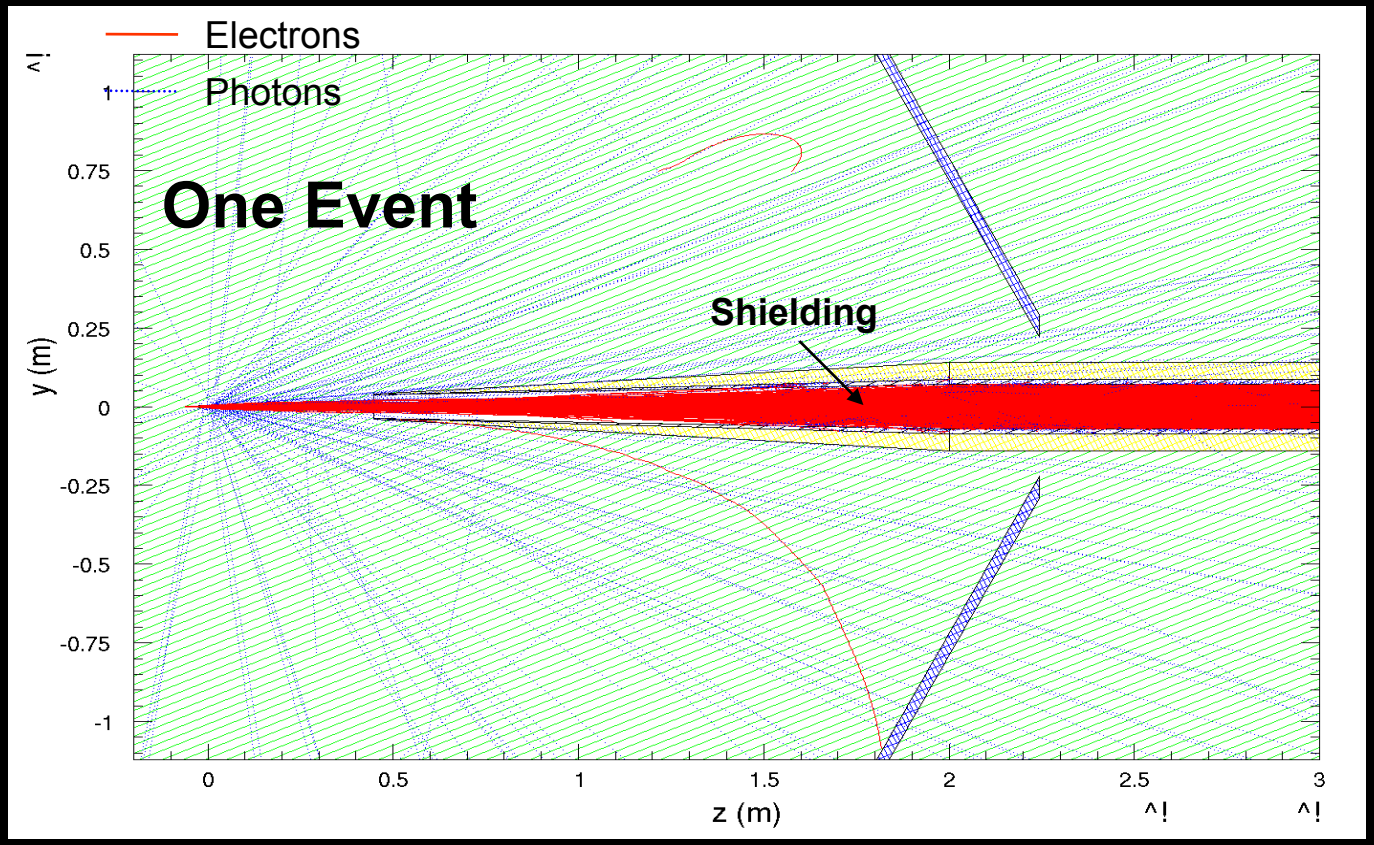
## Background at $L=10^{35}cm^{-2}s^{-1}$, $\Delta T$ = 150ns




5 T Magnetic Field

# CLAS12

## Background at $L=10^{35}cm^{-2}s^{-1}$, $\Delta T$ = 150ns




5 T Magnetic Field and Shielding

# *CLAS12* – Expected Rates in DC R1

| | CLAS | CLAS12 |
|---|---|---|
| **Energy** | **5.75** | **11** |
| **Luminosity ($cm^{-2}s^{-1}$)** | **$2x10^{34}$** | **$10^{35}$** |
| Total rate | 5.94 | 5.76 |
| **Electrons from γ's** | **0.74** | **1.7** |
| **Scattered electrons** | **4.65** | **1.0** |
| **Hadrons** | **0.55** | **3.06** |

# *CLAS12* - Event rates & multiplicities

- Simulations show that typical deep inelastic events contain
  - 3.5 charged particles per event at $\theta < 35^o$ (Forward Detector)
  - 0.75 charged particles at $\theta > 35^o$ (Central Detector)
- The total hadronic interaction rate is ~$5 \times 10^6$ $sec^{-1}$
- Expected level 1 trigger rate is up to 10KHz (inclusive electron rate ~4KHz, non-electron triggers ~5KHz), (talk by Boiarinov)
- Expected data rate is 50-80Mb$sec^{-1}$ for beam energies from 6.6 to 11 GeV.

# *CLAS12* - Event reconstruction

- **A full event reconstruction is available for CLAS detectors that has been used to aid the R&D and design effort for** *CLAS12.*

- **The collaboration is developing new simulation and reconstruction software packages making use of modern tools.**

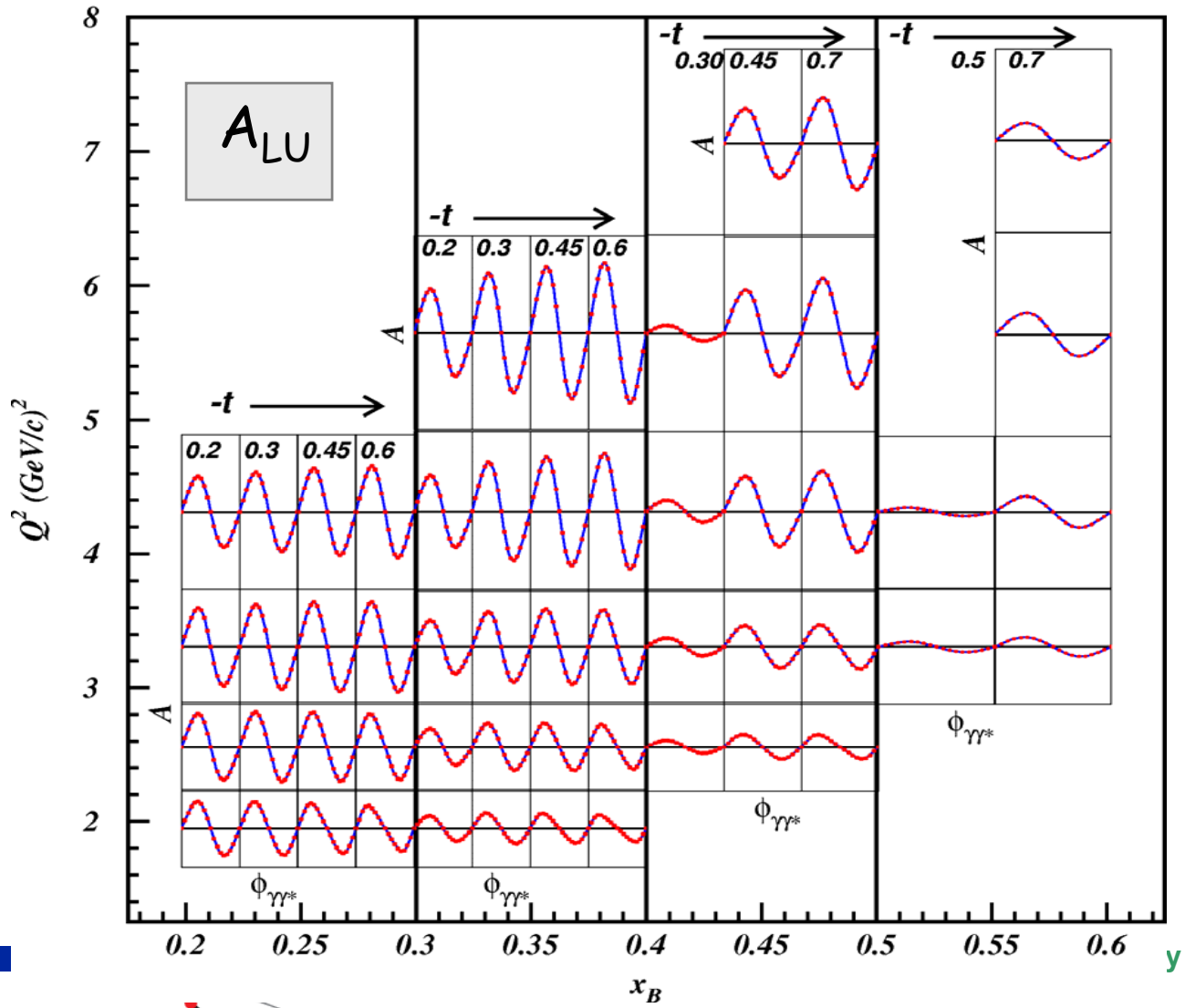
- **The current effort is focused on Geant4 as simulation package (talk by Ungaro), and track reconstruction using the Kalman Filter approach (talk by Procureur).**

# Hall B Upgrade Summary

- **The physics program allows to firmly establish requirements for the *CLAS12* performance in terms of rate capability, particle ID, and resolution.**
- **At 12 GeV typical events contain high momentum tracks at forward angles. The toroidal magnetic field of *CLAS12* and the forward tracking system provide excellent angle and momentum reconstruction.**
- **Essential parts of the physics program require tracking of low momentum at large angles. This is achieved by the Silicon Tracker.**
- **The increase in luminosity is achieved by improved background shielding and high rate capability of the tracking devices.**
- **The new Cerenkov and Scintillation counters in *CLAS12* are designed to improve particle separation at higher momentum.**
- **An experienced team is in place that built, installed, commissioned and operates CLAS, and collaboration members have taken on responsibilities for the construction of new detector components, and for state-of-the art event simulation and reconstruction.**

# DVCS/BH- Beam Asymmetry

$E_e = 11$ GeV




With large acceptance, measure large $Q^2$, $x_B$, t ranges simultaneously.

$A(Q^2,x_B,t)$
$\Delta\sigma(Q^2,x_B,t)$
$\sigma\ (Q^2,x_B,t)$

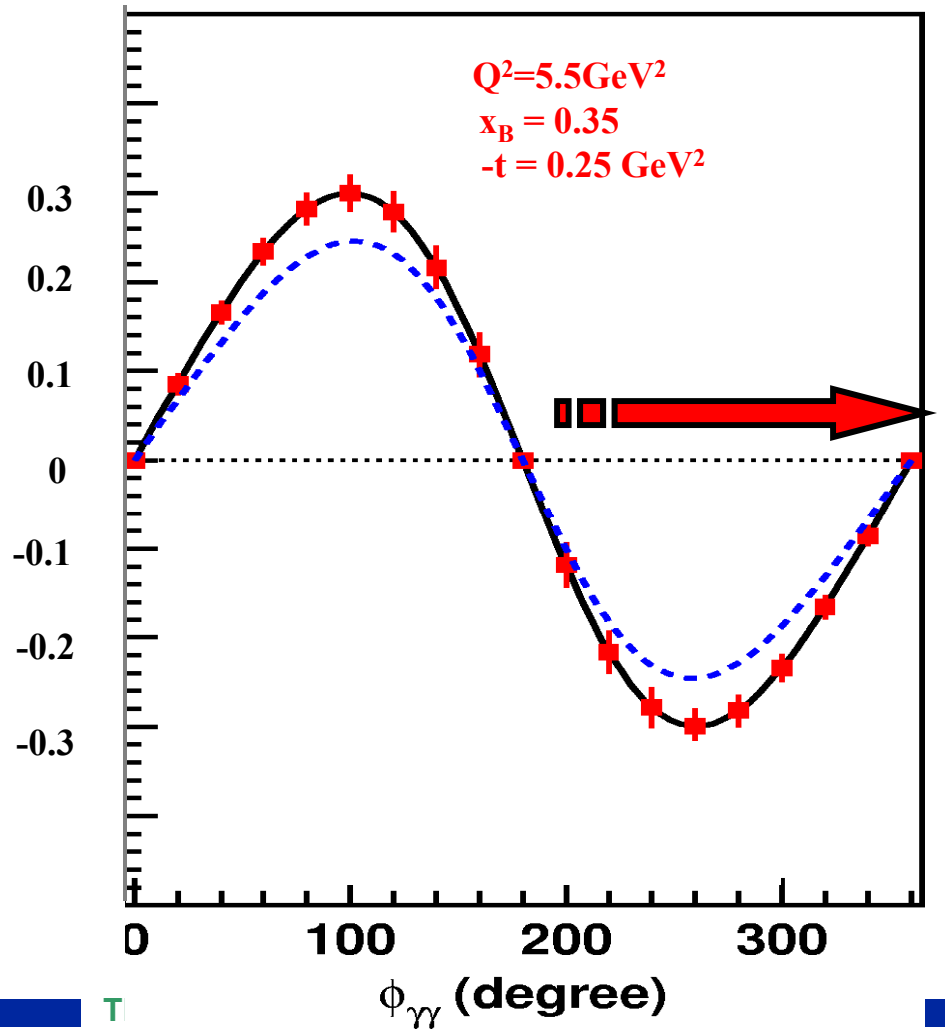


Office of Science
U.S. DEPARTMENT OF ENERGY

# CLAS12 - DVCS/BH- Beam Asymmetry

*Luminosity = 720fb$^{-1}$*

*$E_e$ = 11 GeV*



# CLAS12 - DVCS/BH Beam Asymmetry

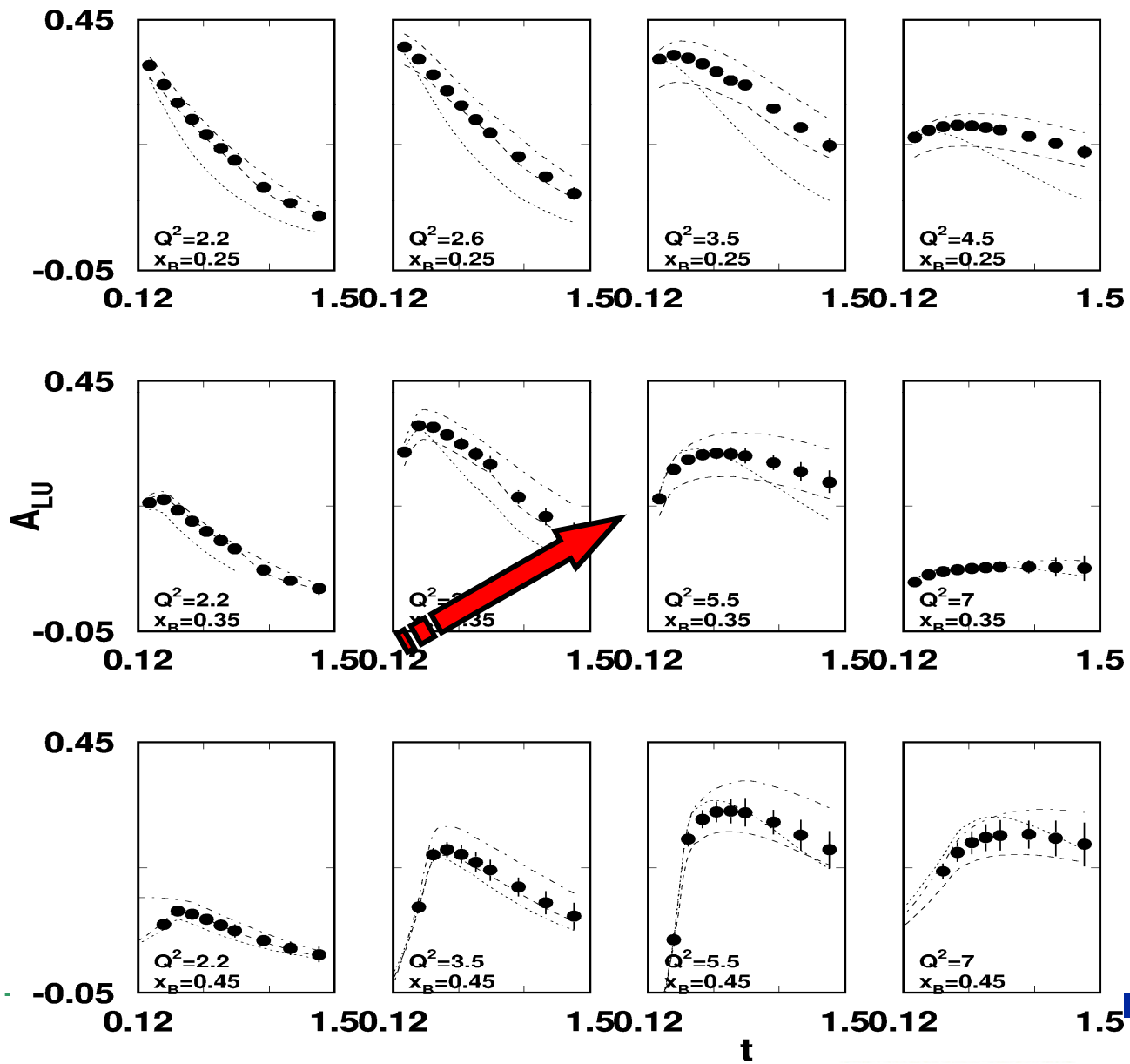
$\vec{e}\,p \longrightarrow ep\gamma$

***E = 11 GeV***

$\Delta\sigma_{LU} \sim \sin\phi\, \mathrm{Im}\{F_1 \mathcal{H} + ..\}d\phi$

Selected Kinematics

$L = 1\times10^{35}$
$T = 2000$ hrs
$\Delta Q^2 = 1\ GeV^2$
$\Delta x = 0.05$



# CLAS12 - DVCS/BH Target Asymmetry

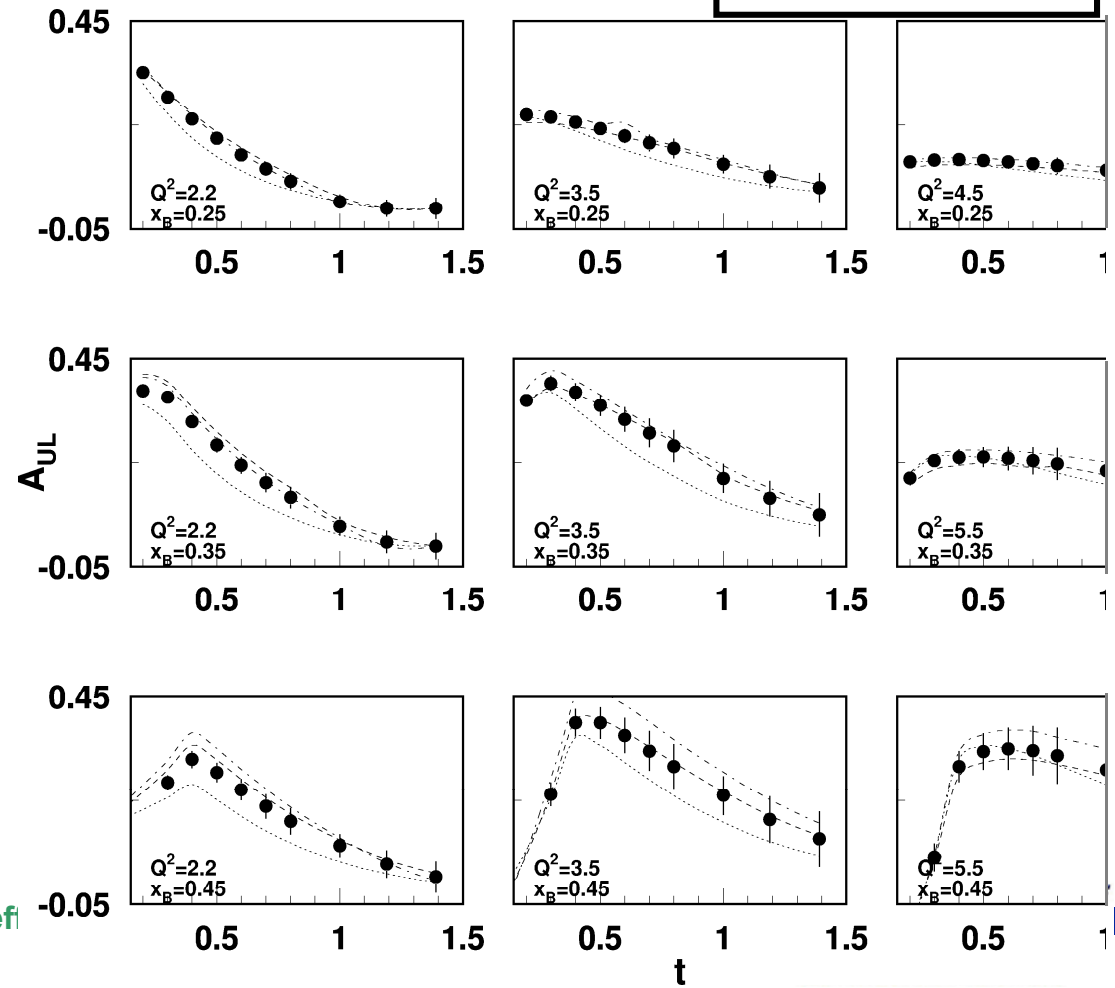
$$e\,\vec{p} \longrightarrow e p \gamma$$

Longitudinally polarized target

$$\Delta\sigma \sim \sin\phi\, \mathrm{Im}\{F_1 \widetilde{H} + \xi(F_1+F_2)H \ldots\} d\phi$$

**E = 11 GeV**

L = $2\times10^{35}$ cm$^{-2}$s$^{-1}$
T = 1000 hrs
$\Delta Q^2$ = 1GeV$^2$
$\Delta x$ = 0.05



# CLAS12 - DVCS/BH Target Asymmetry

$e\,p^{\uparrow} \longrightarrow e p \gamma$

*E = 11 GeV*

Sample kinematics

$Q^2$=2.2 GeV$^2$, $x_B$ = 0.25, -t = 0.5GeV$^2$

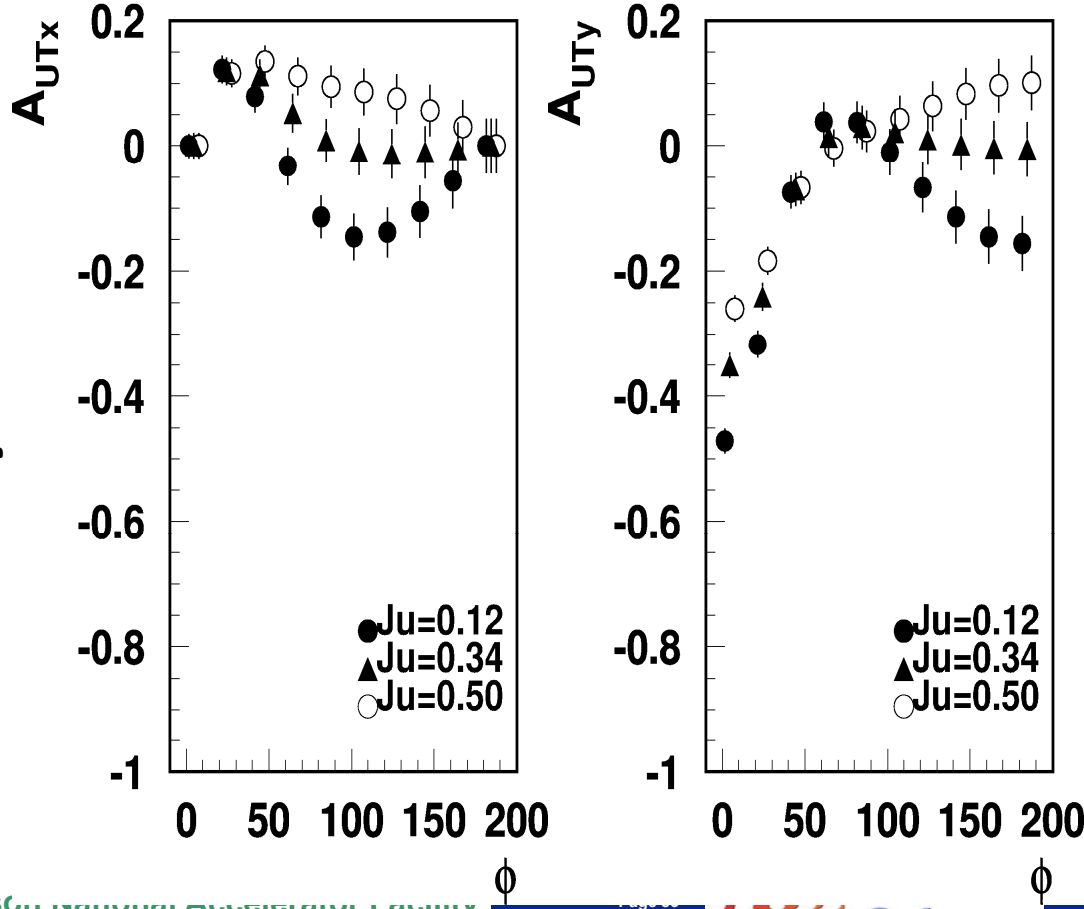
Transverse polarized target

$$\Delta\sigma \sim \sin\phi\, \mathrm{Im}\{k_1(F_2 H - F_1 E) + \ldots\} d\phi$$

$A_{UTx}$ Target polarization in the scattering plane

$A_{UTy}$ Target polarized perpendicular to the scattering plane

- Asymmetries are highly sensitive to the u-quark contributions to the proton spin.

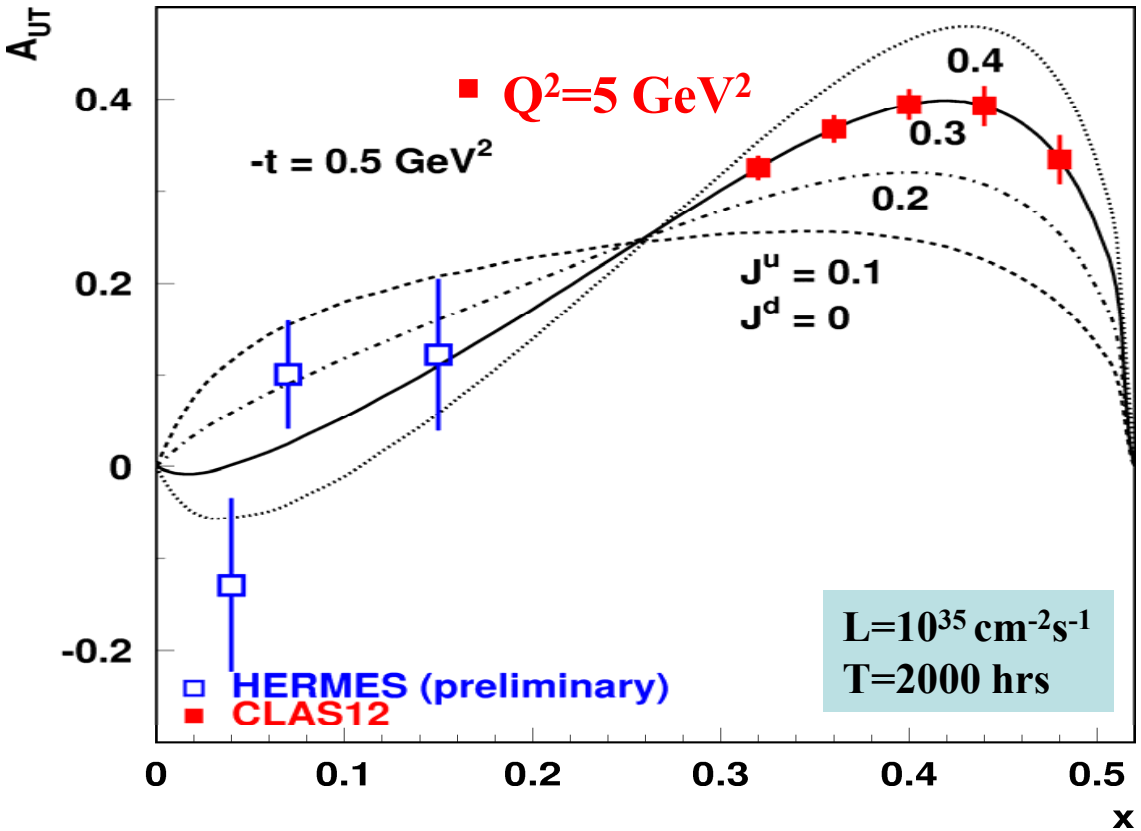


# CLAS12: $ep^{\uparrow} \to ep\rho^0$

$$A_{UT} = -\frac{2\Delta_{\perp}(\mathrm{Im}(AB^*))/\pi}{|A|^2(1-\xi^2) - |B|^2(\xi^2+t/4m^2) - \mathrm{Re}(AB^*)2\xi^2}$$

$\rho^0$

$$A \sim (2H^u + H^d)$$
$$B \sim (2E^u + E^d)$$




**Asymmetry depends on the GPD E, necessary for Ji's sum rule**

**Goeke, Polyakov, Vanderhaegen (2001)**

***…and CLAS12 will allow us to measure also DVCS polarized and unpolarized cross sections, nDVCS, vector and pseudo-scalar meson electroproduction…***

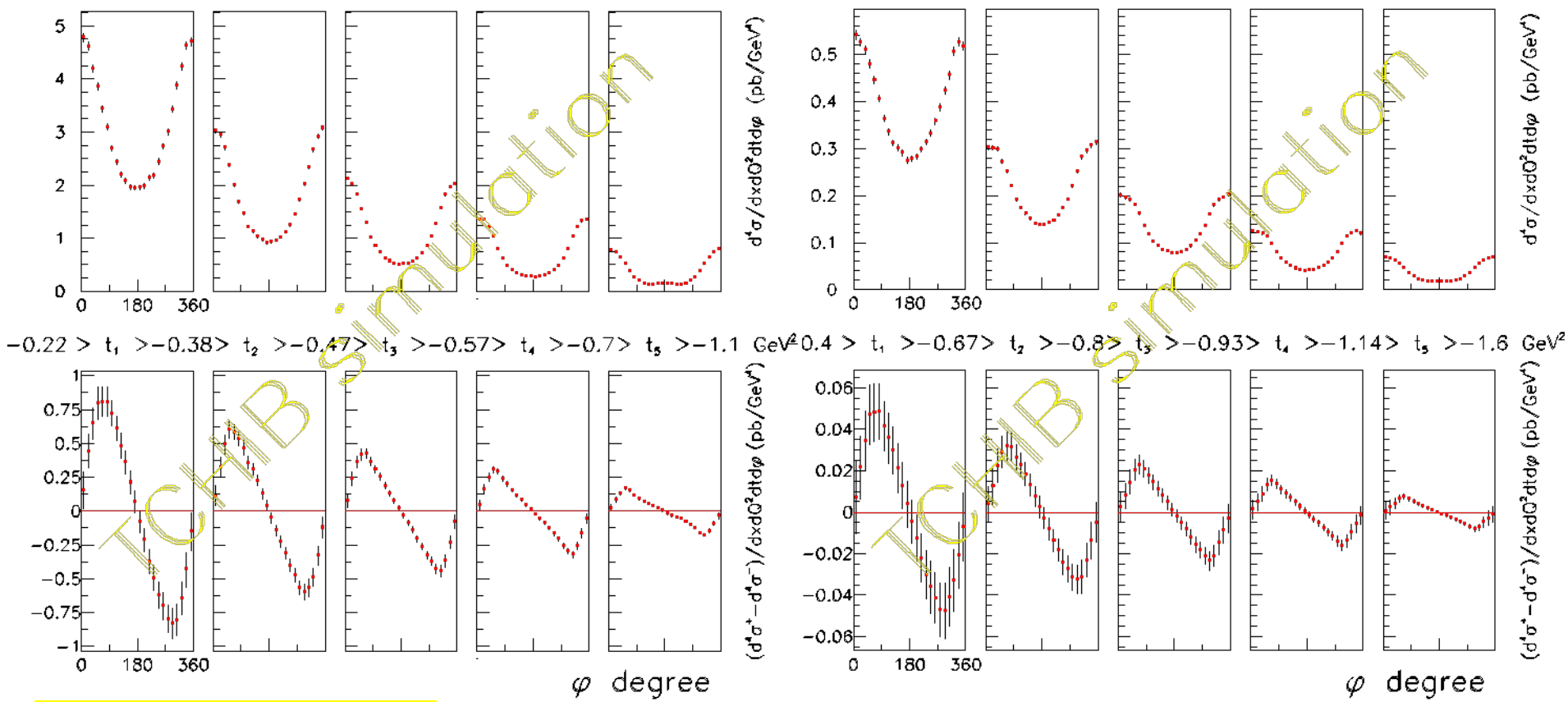
# JLab12: projected results for DVCS in Hall A

**Unpolarized cross sections (pb/GeV$^4$)**

**400 hours**

$E_e$=8.8 GeV, $Q^2$ = 4.8 GeV$^2$, $x_B$=0.5

$E_e$=11 GeV, $Q^2$ = 9 GeV$^2$, $x_B$=0.6




**…and exclusive $\pi^0$ electroproduction will also be measured**

**Polarized cross section differences (pb/GeV$^4$)**

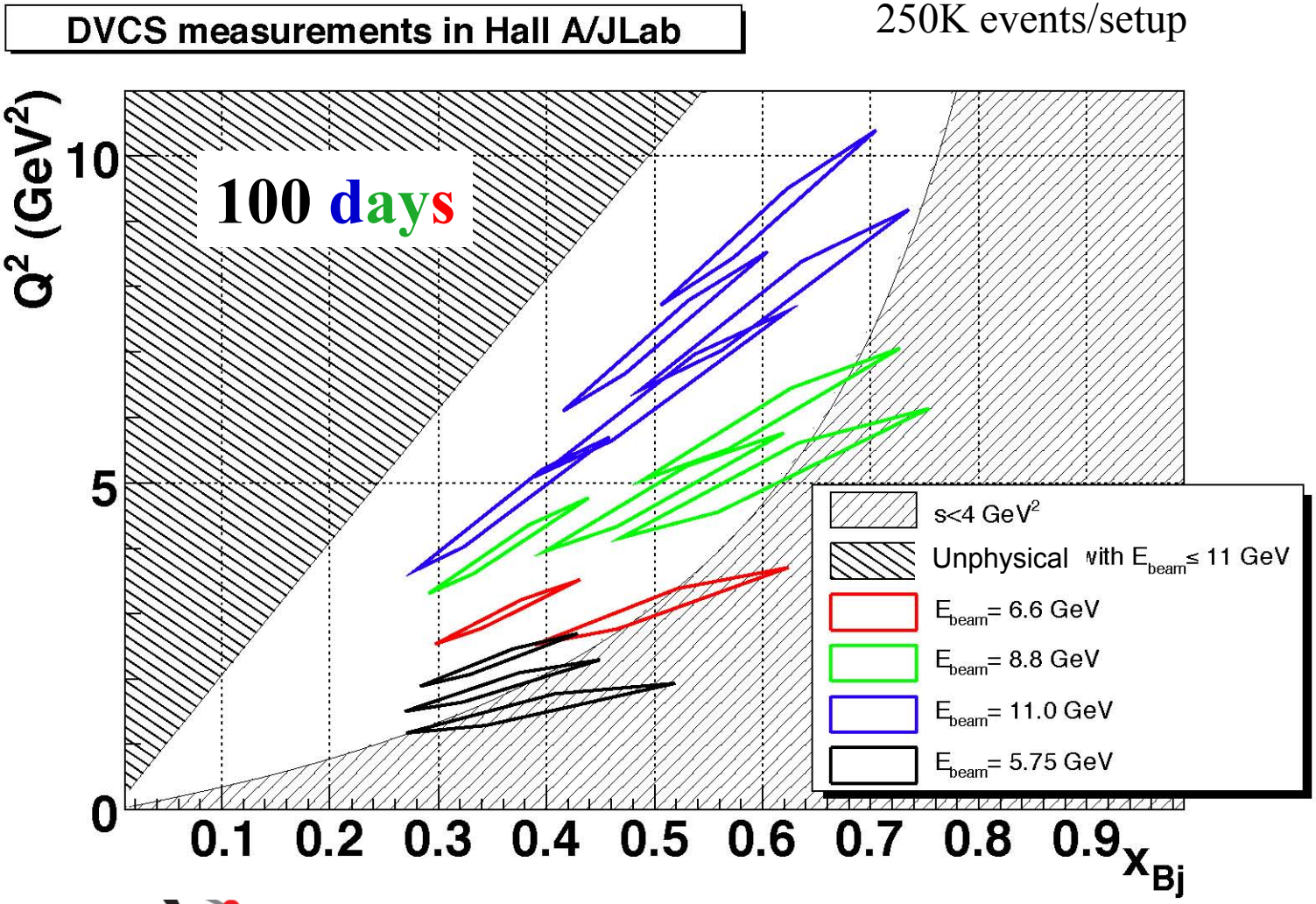


C. Hyde-Wright et al., arXiv:nucl-ex/0609015

# JLab12: Hall A with 3, 4, 5 pass beam

**H(e,e'γ)p**

**High luminosity → high accuracy**
Absolute measurements: $d\sigma(\lambda_e=\pm 1)$
250K events/setup




**Twist 2 & Twist 3 separation**

Im{DVCS*BH} $+\varepsilon$DVCS$^2$

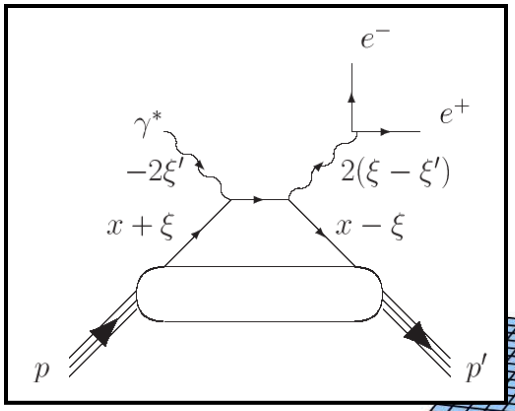
Re{DVCS*BH} $+\varepsilon'$DVCS$^2$

Office of Science
U.S. DEPARTMENT OF ENERGY

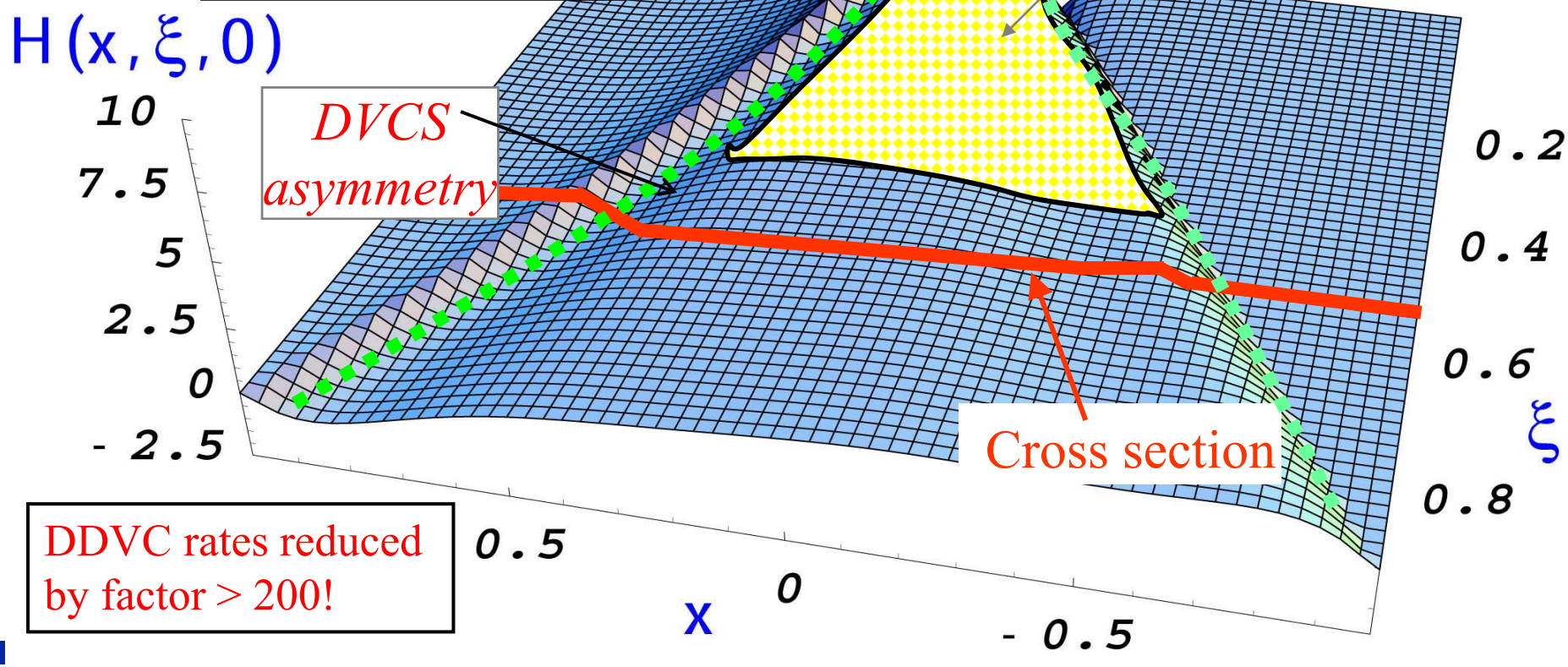
# Conclusions

- **Deeply virtual exclusive processes have been shown to reveal novel information on the *structure* of nucleons.**
- **First results on *DVCS* (and DVMP) show the feasibility of the measurements, and seem consistent with the handbag approximation.**
- **First dedicated DVCS high precision experiments at JLab have either been completed, are underway, or planned for 2007/2008. They will give precise *direct* information on several GPDs in limited kinematics**
- **The JLab 12 GeV energy upgrade with new instrumentation (CLAS12) will provide ideal conditions for an extensive program to measure deeply virtual exclusive processes in a broad kinematics regime.**

# Double DVCS (DDVCS)



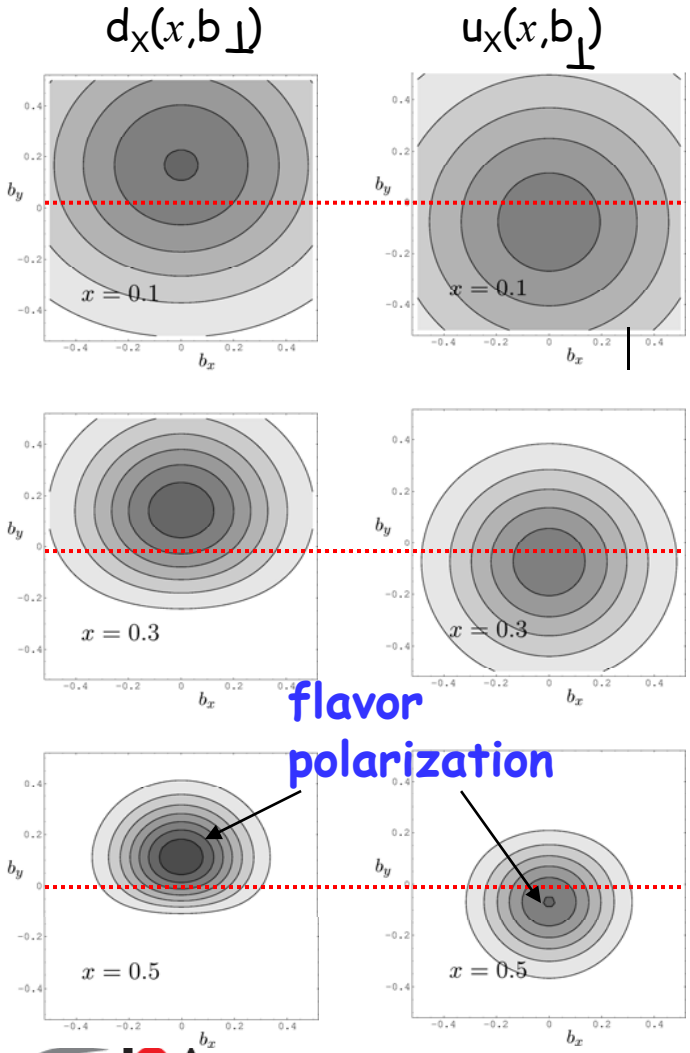

$e^-p \rightarrow e^-pe^+e^-$




DDVC rates reduced by factor > 200!

# Tomographic Images of the Proton

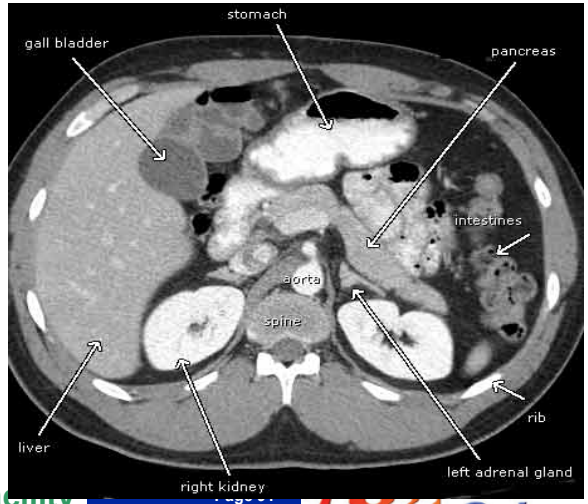
Target polarization




$$q(x,\mathbf{b}_\perp) = \int \frac{d^2t}{(2\pi)^2}\, e^{-i\cdot t\cdot \mathbf{b}_\perp} E(x,0,t)$$

M. Burkardt

CAT scan slice
of human abdomen

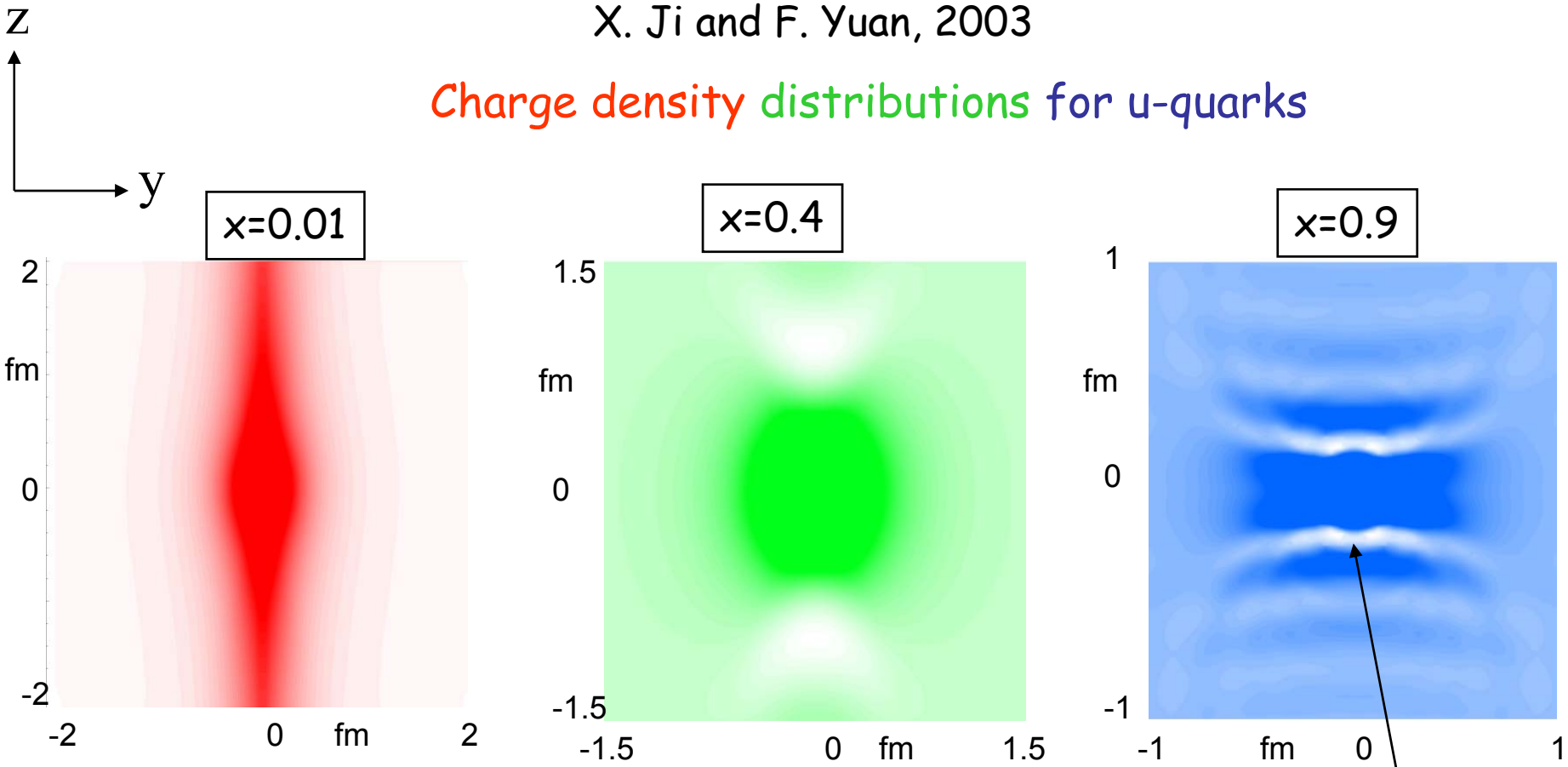



$E^d(x,t)$ $E^u(x,t)$

# Tomographic Images of the Proton

X. Ji and F. Yuan, 2003

Charge density distributions for u-quarks




3D image obtained by rotation around the z-axis

# Conclusions

- We have come a long way in studying the structure of the proton since Hofstadter's pioneering experiments more than 50 years ago.
- With QCD as the theoretical framework, and the handbag mechanism and GPDs as tools the proton (and neutron) structure can be accessed systematically.
- First experiments demonstrate the applicability of the basic "handbag" mechanism at moderate (Jlab) energies.
- The JLab energy upgrade and new equipment provide the means to explore the complex proton structure in the full valence quark regime.

# Conclusions

- **Deeply virtual exclusive processes have been shown to reveal novel information on the *structure* of nucleons.**
- **First results on *DVCS* (and DVMP) show the feasibility of the measurements, and seem consistent with the handbag approximation.**
- **First dedicated DVCS high precision experiments at JLab have either been completed, are underway, or planned for 2007/2008. They will give precise *direct* information on several GPDs in limited kinematics**
- **The JLab 12 GeV energy upgrade with new instrumentation (CLAS12) will provide ideal conditions for an extensive program to measure deeply virtual exclusive processes in a broad kinematics regime.**