# Generalized Parton Distributions Studies with CLAS and CLAS12

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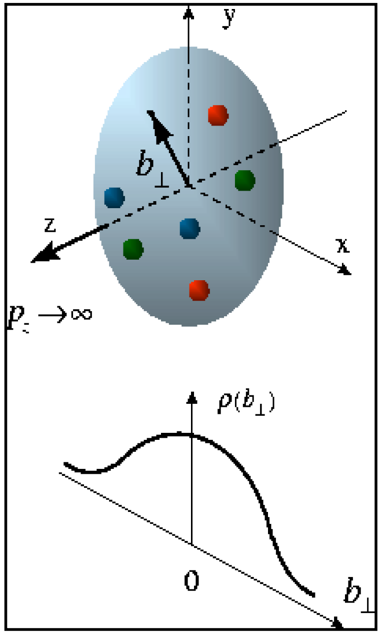
Jefferson Lab

# Outline

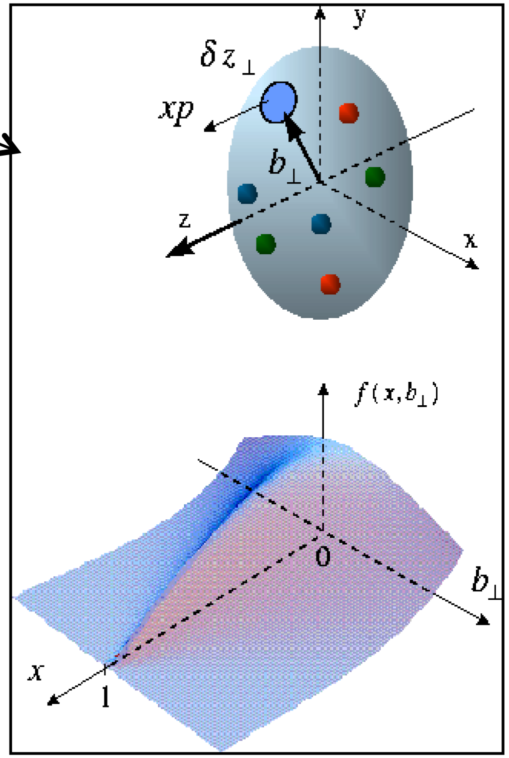
- Generalized Parton Distributions - a unifying framework of hadron structure
- Experiments to access GPDs
- 12 GeV Upgrade project
- Summary

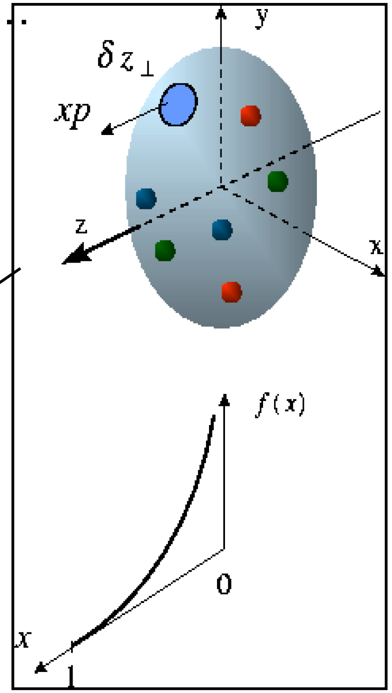
# Generalized Parton Distributions (GPDs)




D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, …

**GPDs** connect the charge and parton distribution



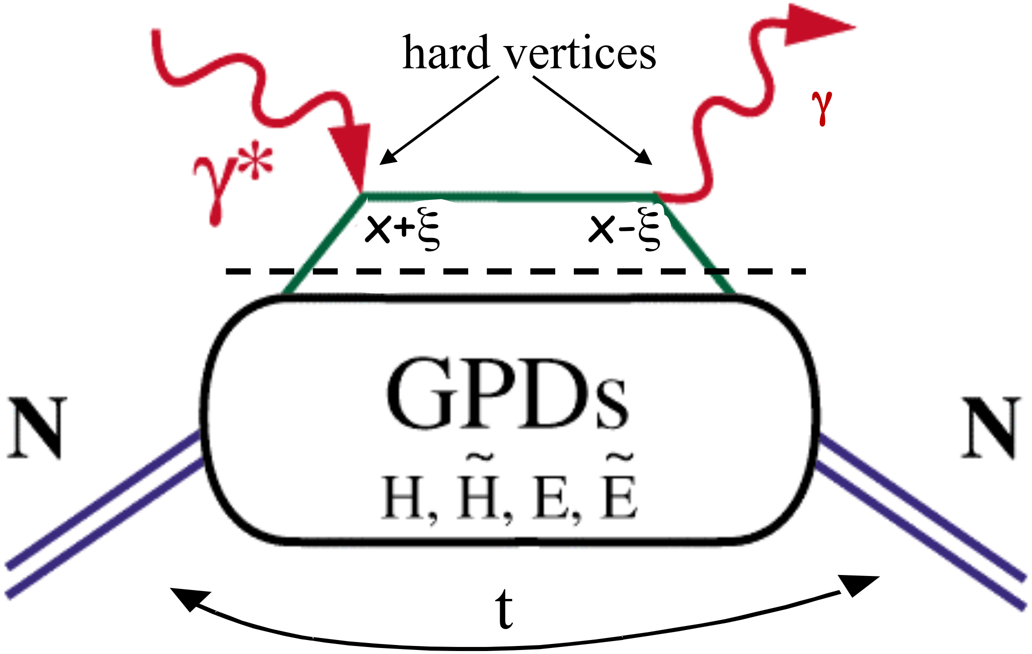

The size and structure of proton.
Proton form factors, **transverse** charge and current distributions
Nobel prize 1961- R. Hofstadter

Internal constituents of the nucleon
Quark **longitudinal** momentum and helicity distributions
Nobel prize 1990 - J. Friedman, H. Kendall, R. Taylor

Extend longitudinal quark momentum & helicity distributions
to transverse momentum distributions - TMDs

# 3 dimensional imaging of the nucleon

## 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 describe the internal nucleon dynamics.

# Link to DIS and Elastic Form Factors

Form factors (sum rules)

$$\int_{-1}^{1} dx \sum_q \left[ H^q(x,\xi,t) \right] = F_1(t) \quad \text{Dirac f.f.}$$

$$\int_{-1}^{1} dx \sum_q \left[ E^q(x,\xi,t) \right] = F_2(t) \quad \text{Pauli f.f.}$$

$$\int_{-1}^{1} dx\, \tilde{H}^q(x,\xi,t) = G_{A,q}(t), \quad \int_{-1}^{1} dx\, \tilde{E}^q(x,\xi,t) = G_{P,q}(t)$$

DIS at $\xi = t = 0$

$$H^q(x,0,0) = q(x)$$

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

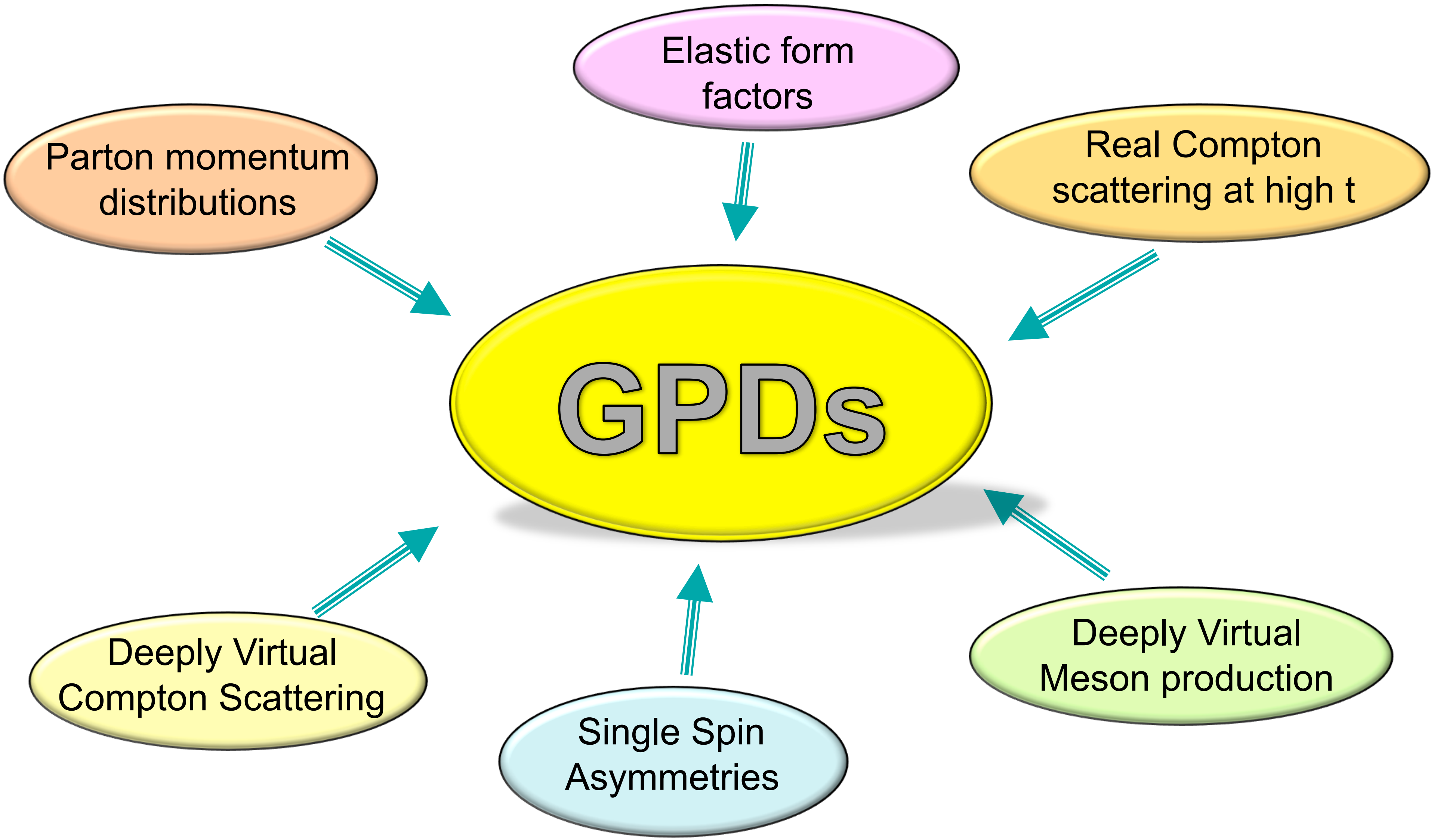
$$H^q, E^q, \tilde{H}^q, \tilde{E}^q(x,\xi,t)$$

*Angular Momentum Sum Rule*

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

X. Ji, Phy.Rev.Lett.78,610(1997)

# Universality of GPDs



# How can we determine the GPDs?

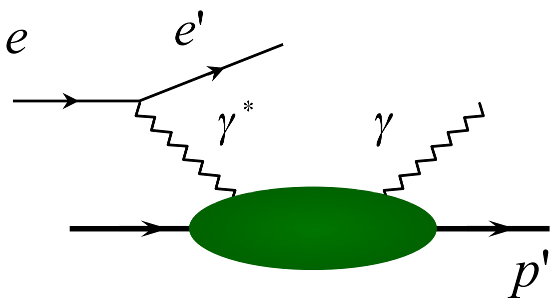
# Accessing GPDs in Exclusive Processes

- Deeply virtual Compton scattering (clean probe, flavor blind)

$ep \to e' p' \gamma$ — *Sensitive to all GPDs.*

$ep \to e' p' L^+ L^-$ — *Insensitive to quark flavor*

…



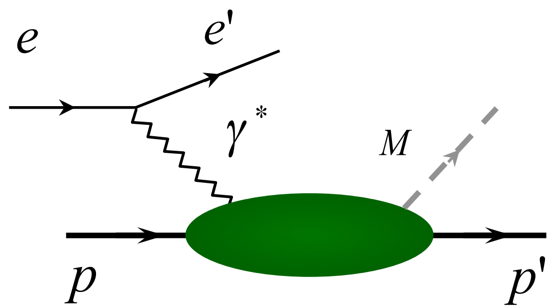

- Hard exclusive meson production (quark flavor filter)

$ep \to e' p' \pi$ — *Sensitive to $\tilde{H}$, $\tilde{E}$*

$ep \to e' p' \rho$ } *Sensitive to H, E*

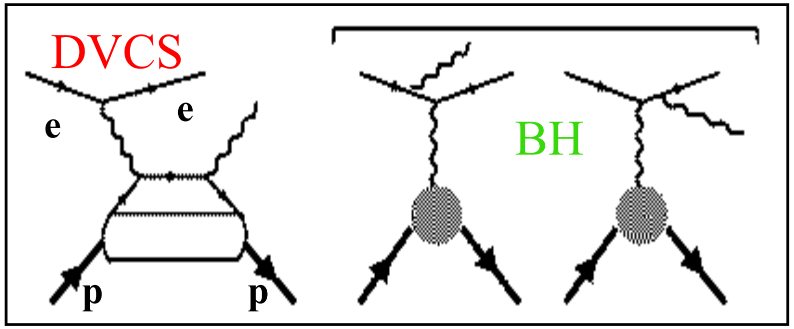
$ep \to e' p' \omega$

…




- 4 GPDs in leading order, 2 flavors (u, d) → 8 measurements

# Accessing GPDs through DVCS

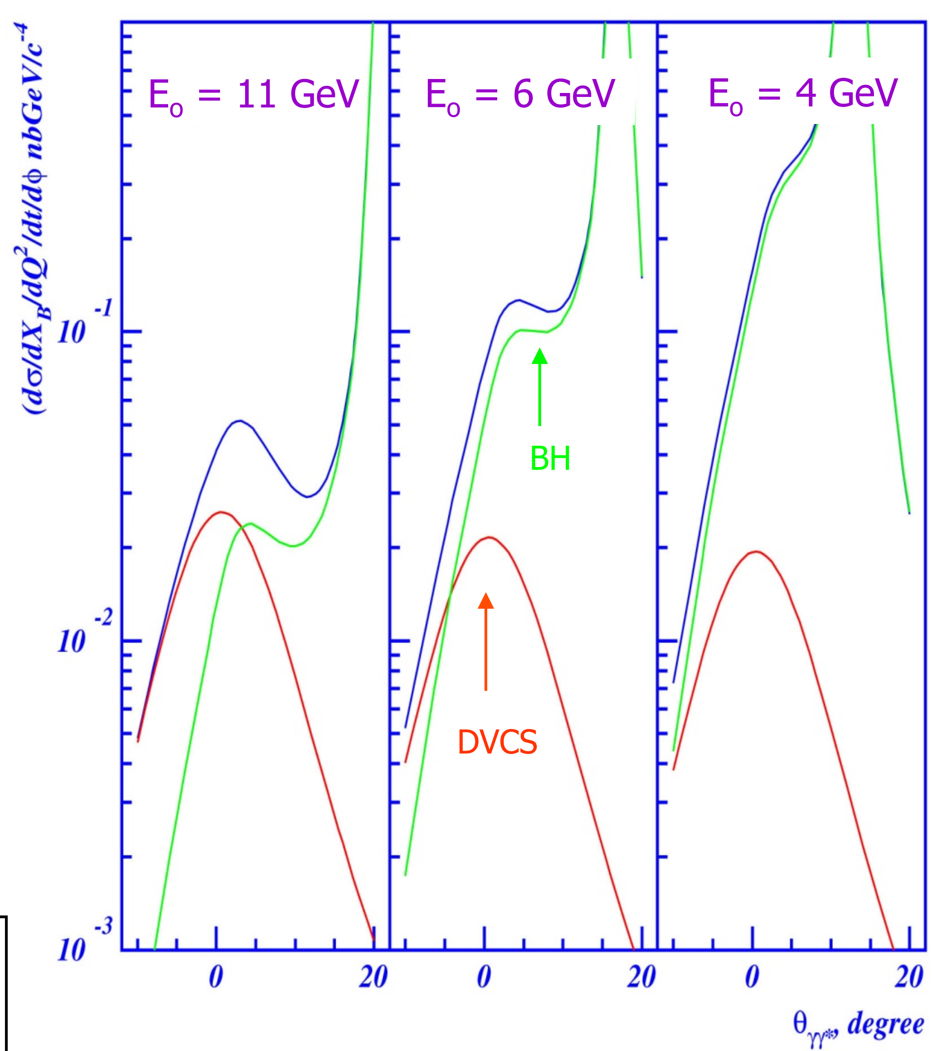



$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |T^{DVCS} + T^{BH}|^2$$

$T^{BH}$: given by elastic form factors $F_1$, $F_2$
$T^{DVCS}$: determined by GPDs

$$I \sim (T^{BH}) Im(T^{DVCS})$$

Cross section of $ep \rightarrow ep\gamma$ at $Q^2$=2 GeV/c$^2$ and $X_B$=0.35




BH-DVCS interference generates *beam and target polarization asymmetries* that carry the proton structure information.

# Measuring GPDs through polarization

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

Polarized beam, unpolarized target:

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

Kinematically suppressed

⇒ $H$

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

$k = t/4M^2$

Unpolarized beam, longitudinal target:

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

Kinematically suppressed

⇒ $\widetilde{H}$

Unpolarized beam, transverse target:

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

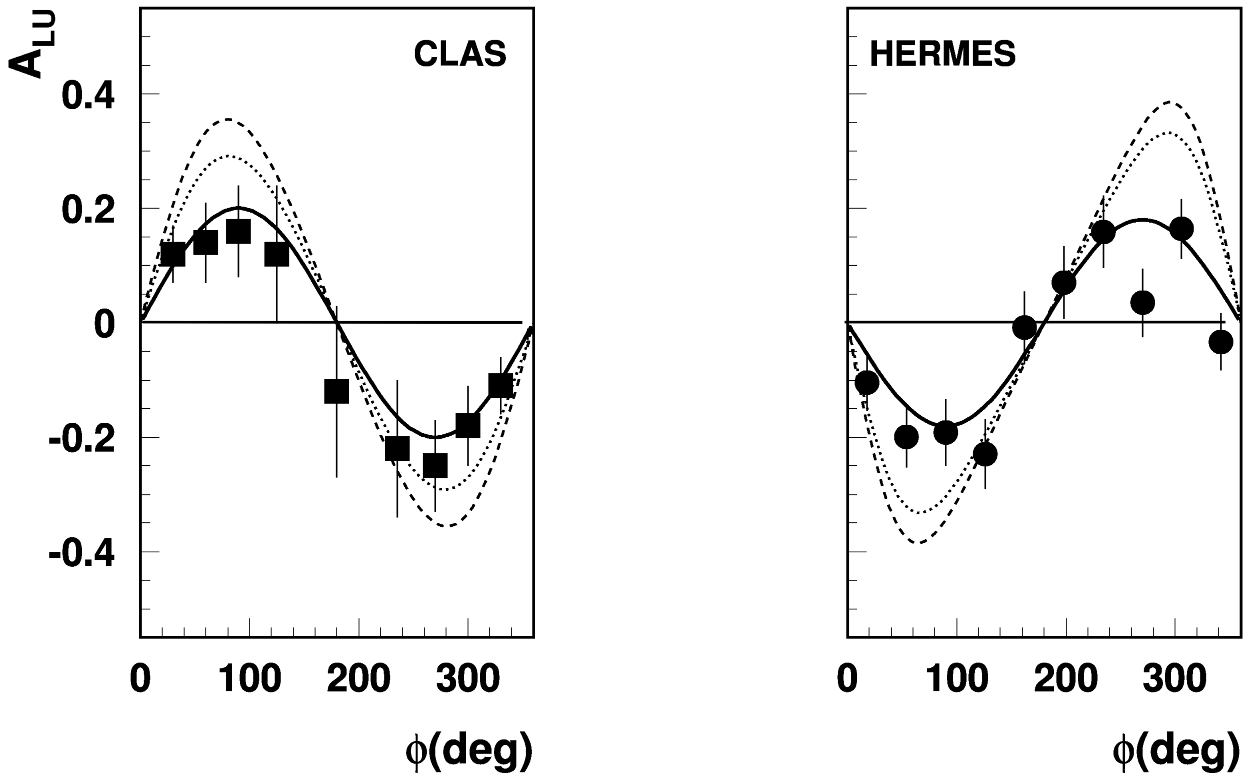
Kinematically suppressed

⇒ $H$, $E$

# Pioneering Experiments Observe Interference

2001

$\vec{e}^- p \to e^- p\gamma$




$\vec{e}^+ p \to e^+ p\gamma$

$A_{UL} = \alpha \sin\phi + \beta \sin 2\phi$

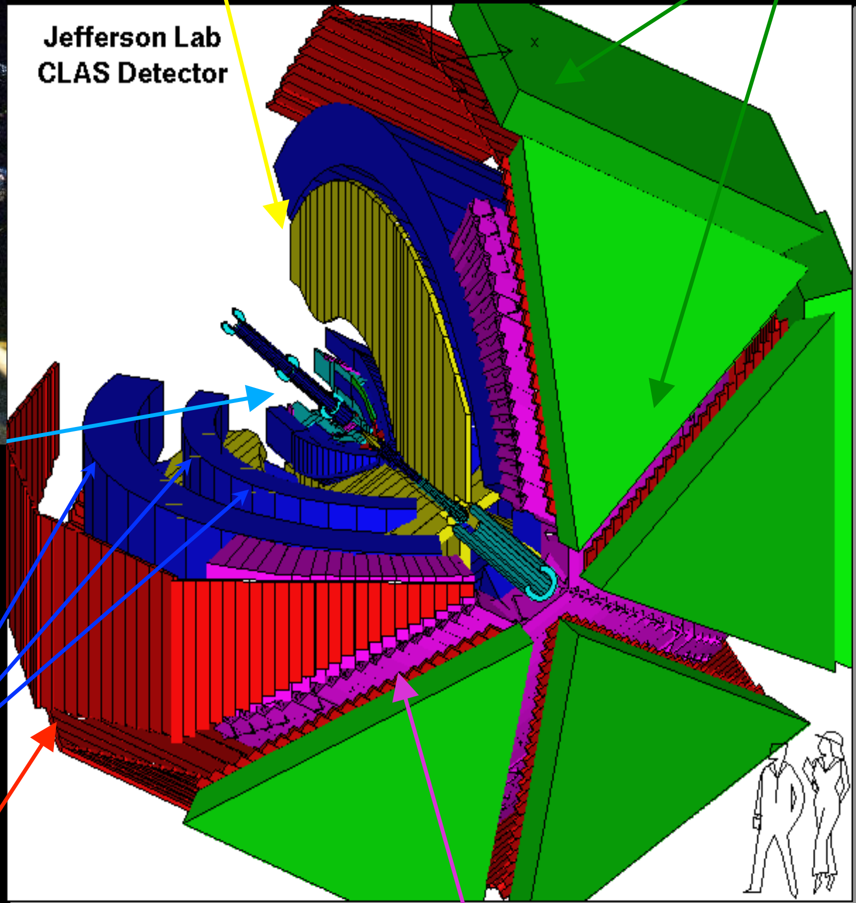
twist-2 (α) twist-3 (β)

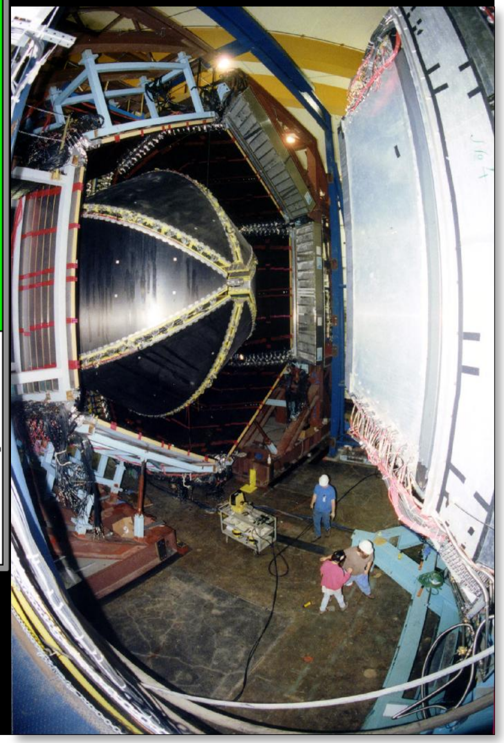
**First GPD** analyses of HERA/CLAS/HERMES data in LO/NLO consistent with **$\alpha \sim 0.20$.**
A. Freund (2003), A. Belitsky et al. (2003)

# CEBAF Large Acceptance Spectrometer

Torus Magnet
6 Superconductive Coils

Electromagnetic Calorimeter
lead/plastic scintillator, 1296 PMTs



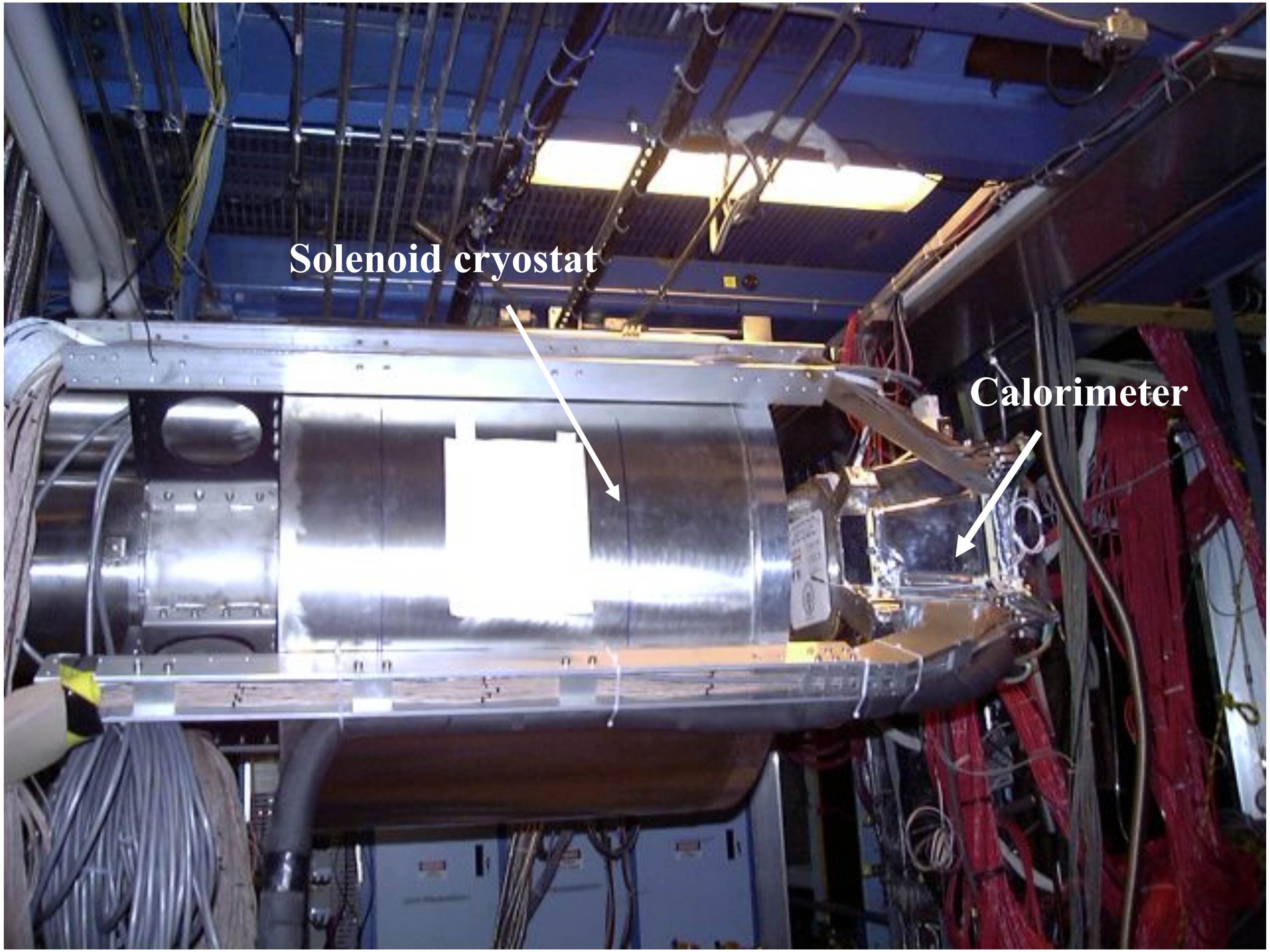
Target + $\gamma$
start counter
e mini-torus

Drift Chamber
35,000 cells

Time of Flight
Plastic Scintillator,
684 PMTs

Cherenkov Counter
e/$\pi$ separation, 256 PMTs

# Hall B - DVCS Solenoid and Calorimeter



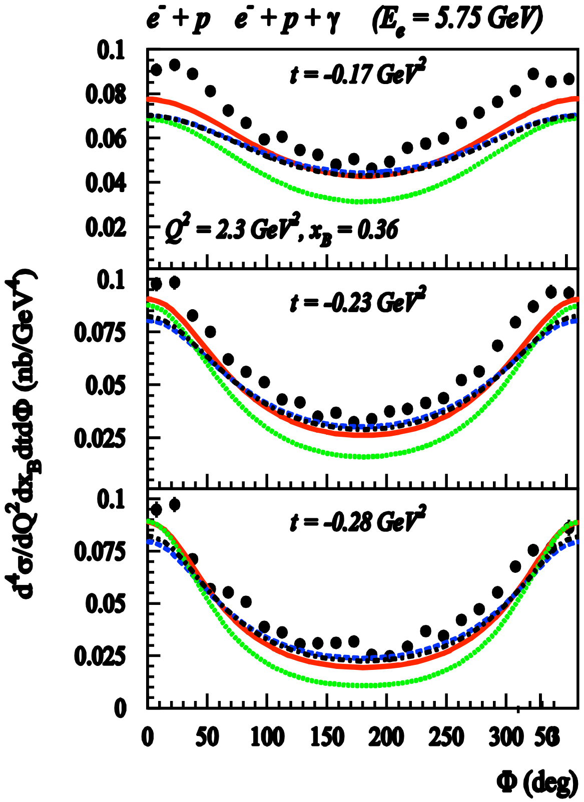



Jefferson Lab

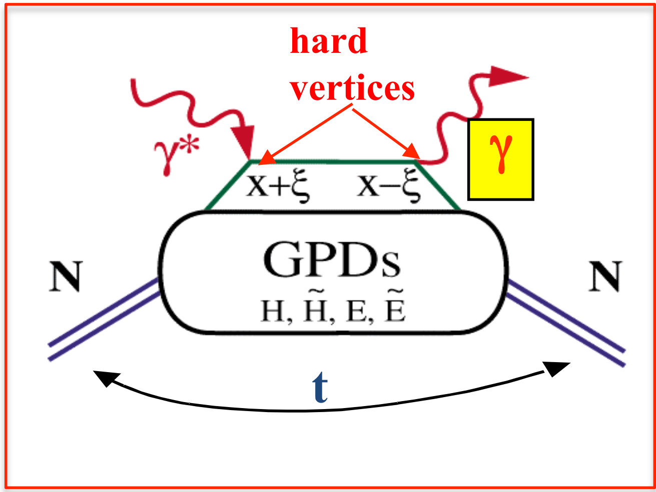
# Deeply Virtual Compton Scattering & GPDs

**Unprecedented set of Deeply Virtual Compton Scattering data accumulated in Hall A and with *CLAS***

**Hall A**




*Phys.Rev.Lett.97:262002,2006*



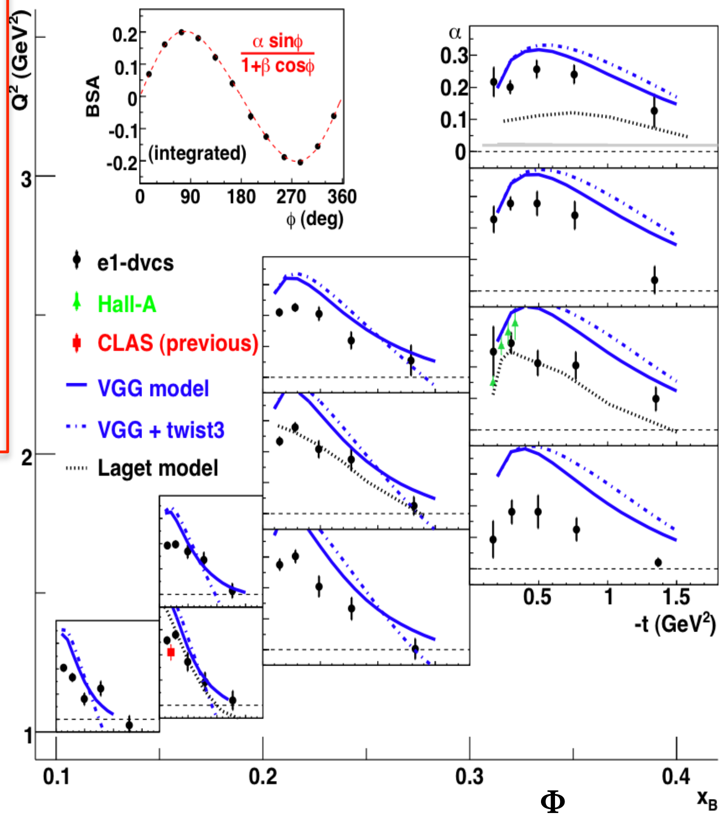

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma_{LU}}{2\sigma}$$

Polarized beam, unpolarized target:

Kinematically suppressed

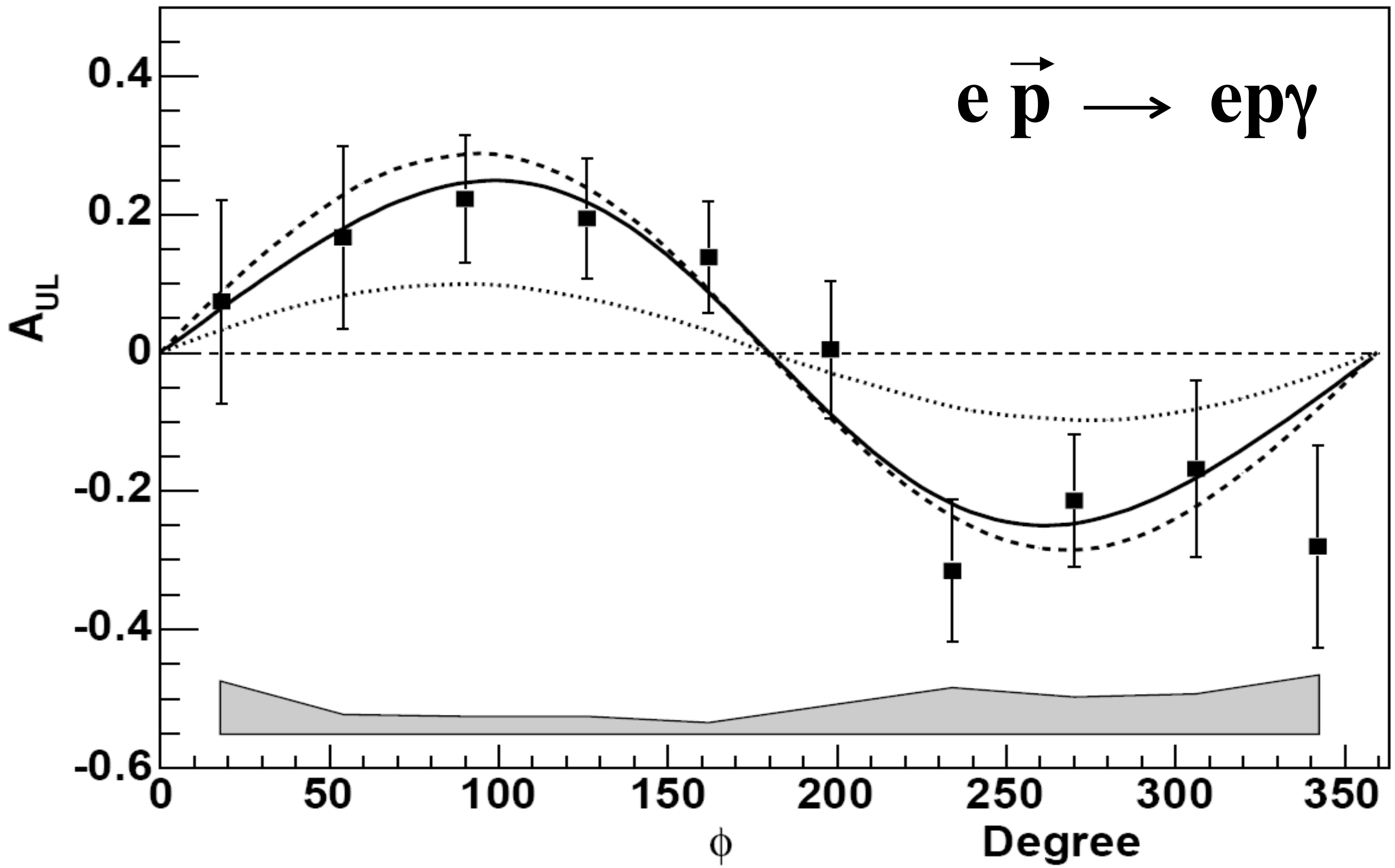
$$\Delta\sigma_{LU} \sim \sin\phi\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$$

***CLAS***




*Phys.Rev.Lett.100:162002,2008*

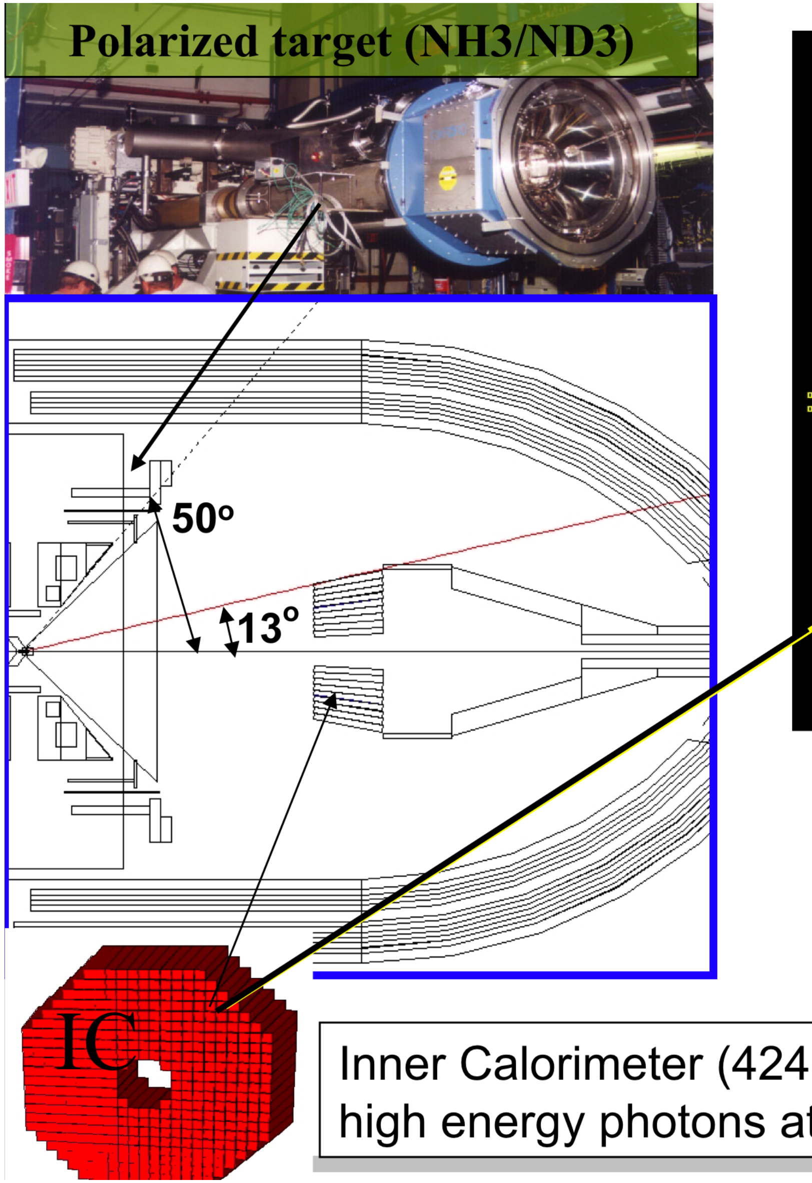
# First measurement with CLAS

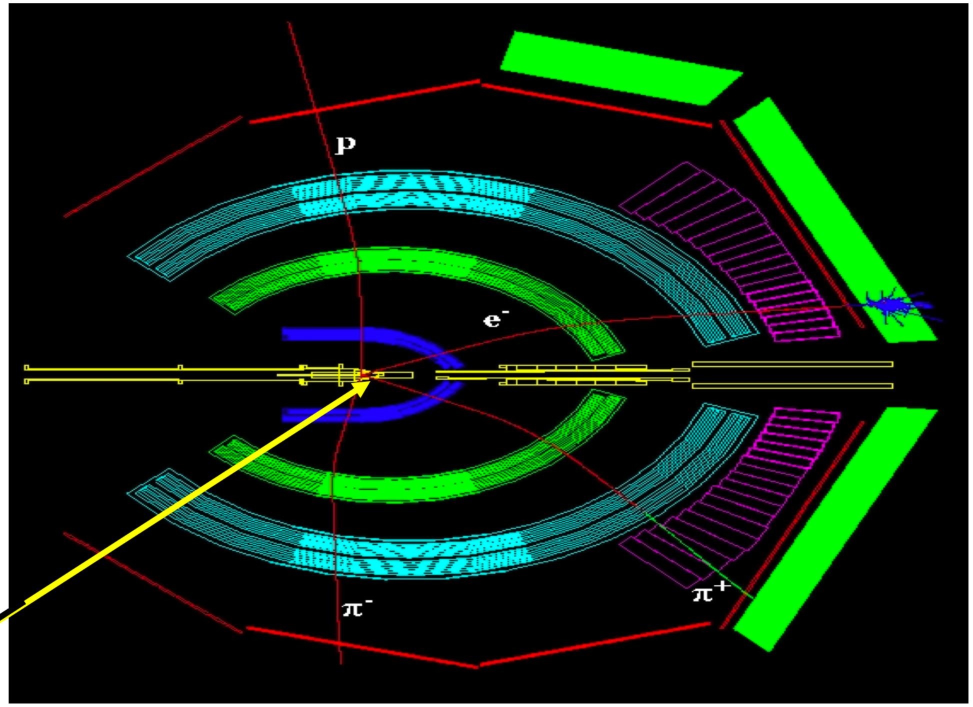



**S.Chen et al. Phys.Rev.Lett.97:072002,2006**

# eg1-dvcs setup



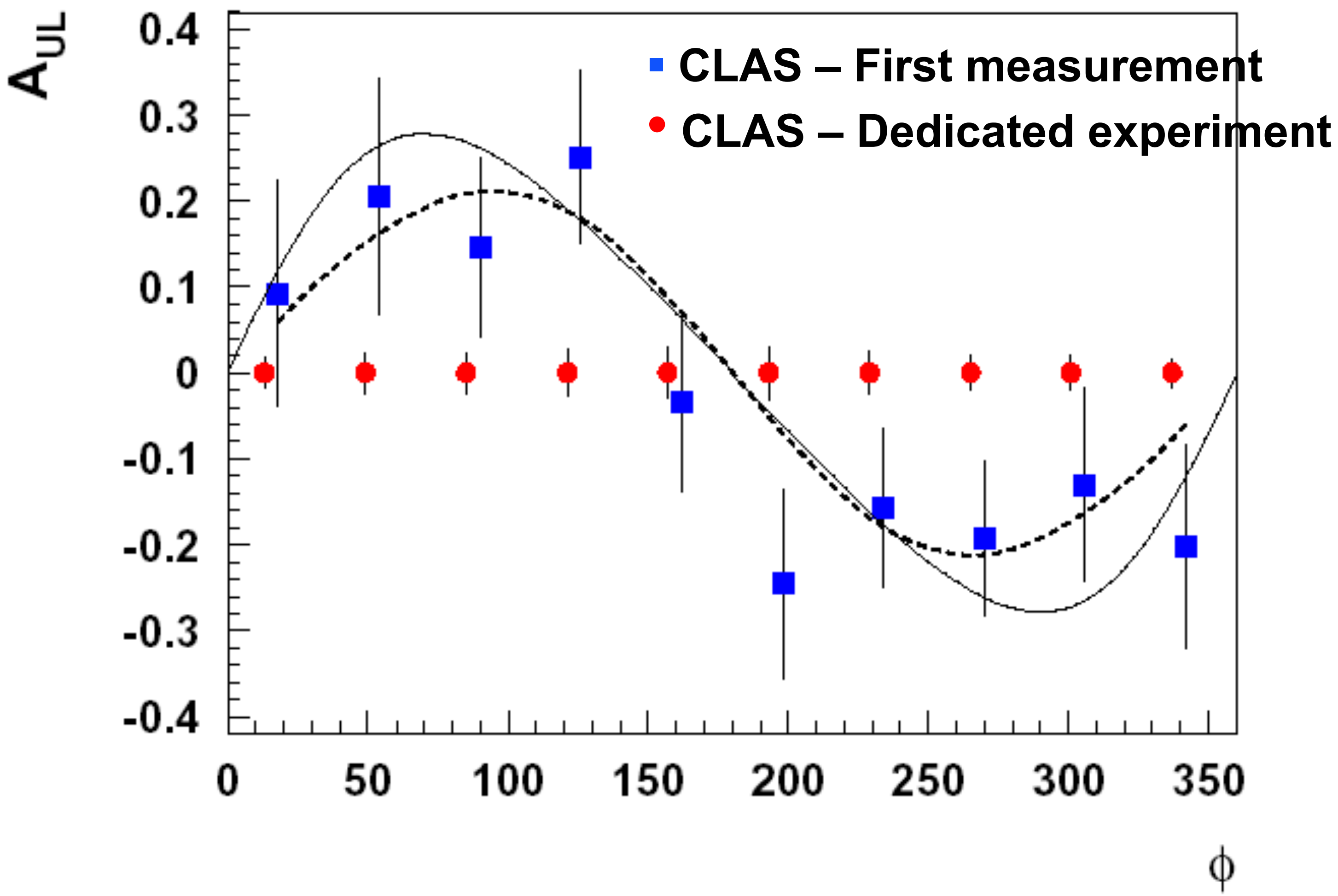



1) Polarized NH3 (2000, 5 days)
2) Polarized NH3/ND3 (2009 30+30 days)

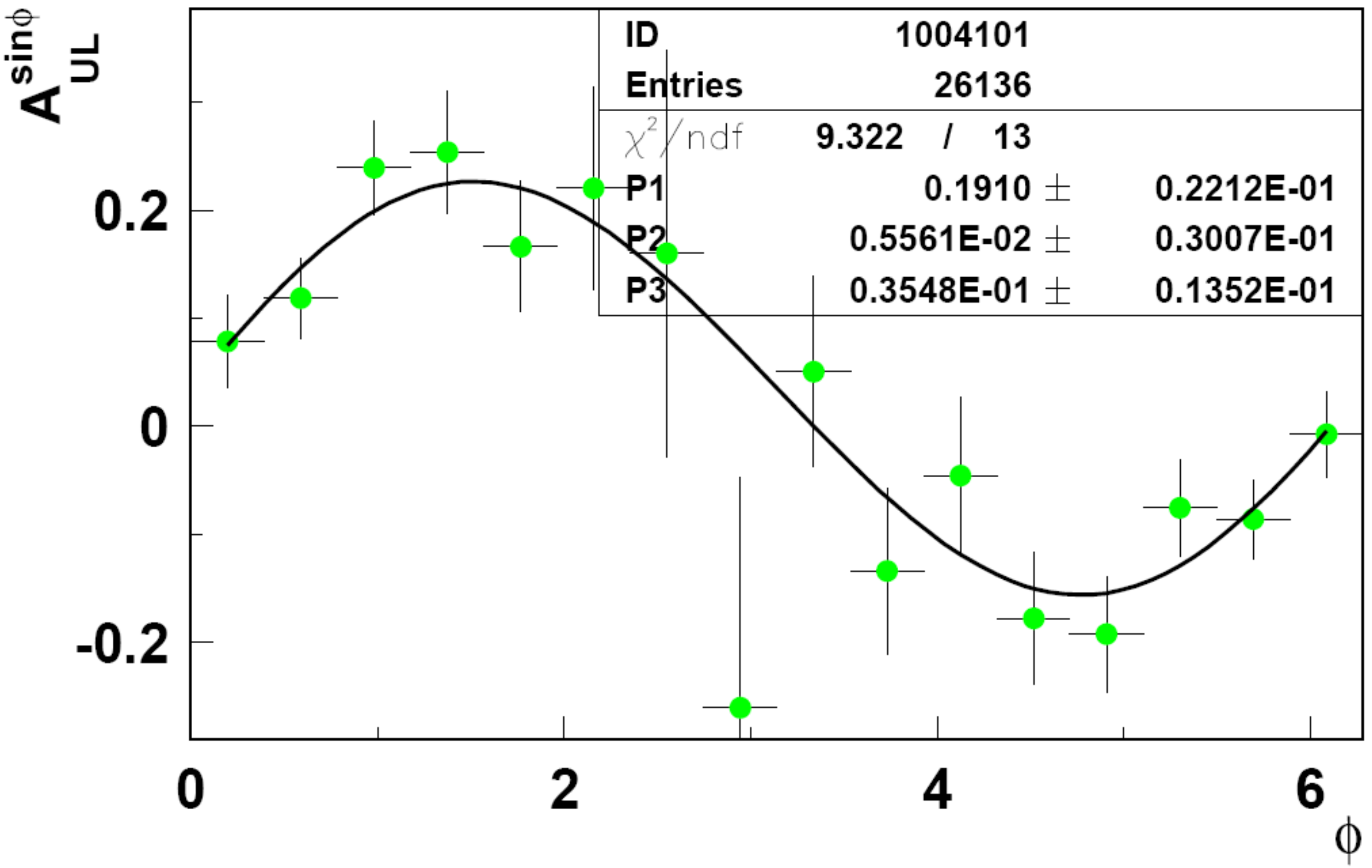
Inner Calorimeter (424 $PbWO_4$ crystals) to detect high energy photons at forward lab angles.

# Target Spin Asymmetry: $\phi$ Dependence




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

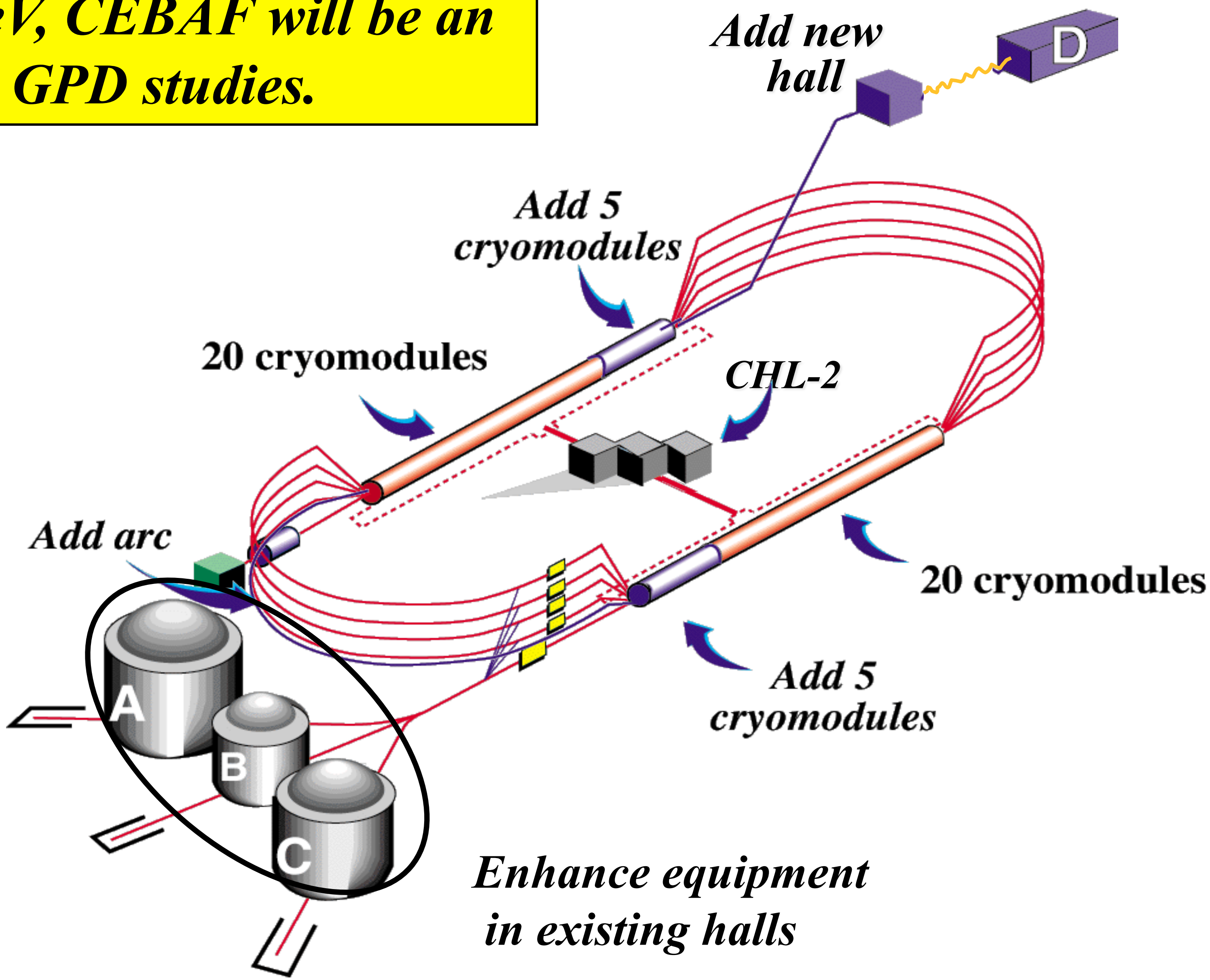
# Target Spin Asymmetry in DVCS – Preliminary Results




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

# JLab Upgrade to 12 GeV

***At 12 GeV, CEBAF will be an ideal for GPD studies.***

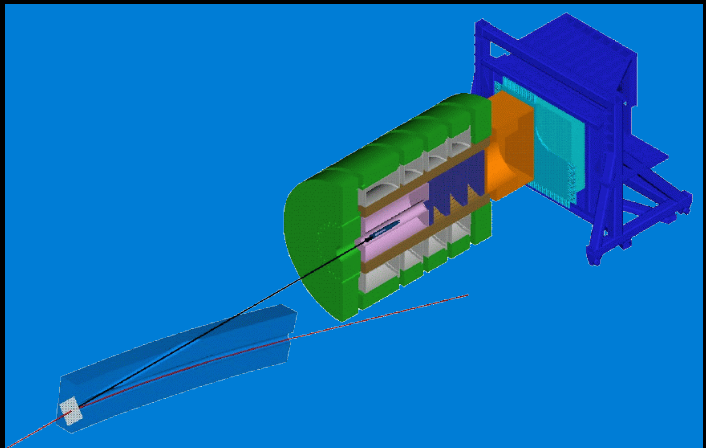


# Scope of the 12 GeV Upgrade

| Parameter | Present JLab | Upgraded JLab |
|---|---|---|
| Number of Halls | 3 | 4 |
| Number of passes Halls A/B/C | 5 (for max energy) | 5 (for max energy) |
| Max Energy to Halls A/B/C | up to ~6 GeV | up to ~11 GeV |
| Number of passes to Hall D | New Hall | 5.5 |
| Energy to Hall D | New Hall | 12 GeV |
| Current – Hall A & C | max ~180 μA combined | max ~85 μA combined (higher at lower energy) |
| Current – Hall B & D | (B) Up to 5 μA max | (B, D) Up to ~5 μA max each |
| Central Helium Liquefier (CHL) | 4.5 kW | 9 kW |
| # of cryomodules in LINACS | 40 | 50 |
| Accelerator energy per pass | 1.2 GeV | 2.2 GeV |

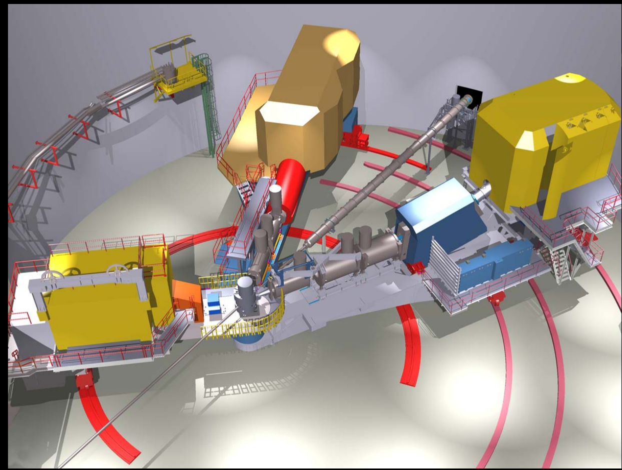
# New Capabilities in Halls A, B, & C, and a New Hall D

**D**



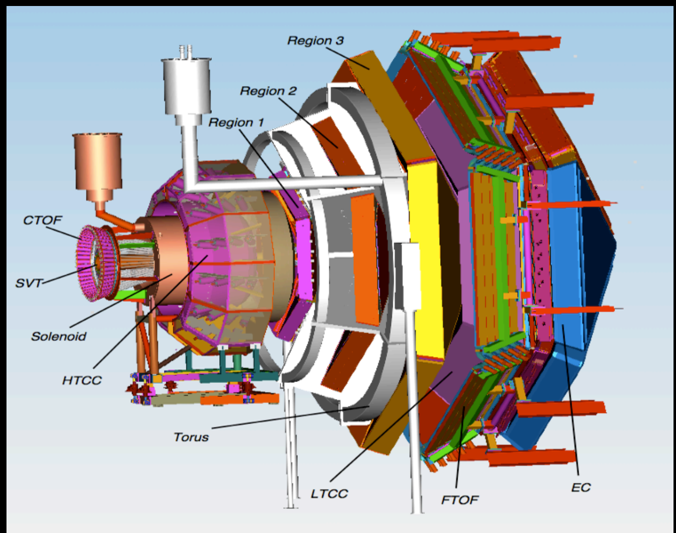
**9 GeV tagged polarized photons and a 4π hermetic detector**

**C**



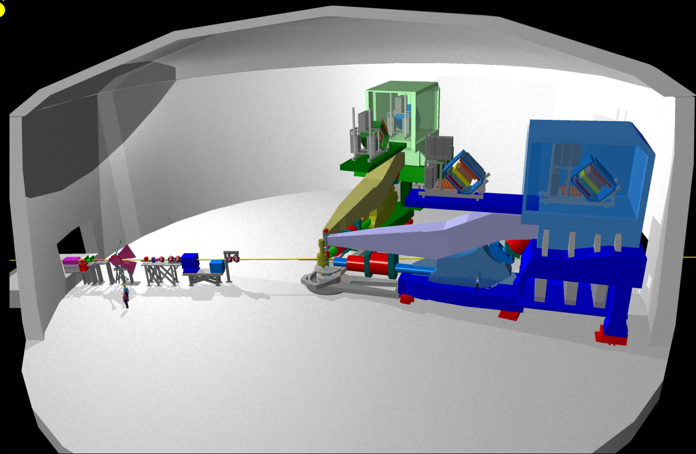
**Super High Momentum Spectrometer (SHMS) at high luminosity and forward angles**

**B**




**CLAS12 high luminosity, large acceptance.**

**A**



**High Resolution Spectrometer (HRS) Pair, and specialized large installation experiments**

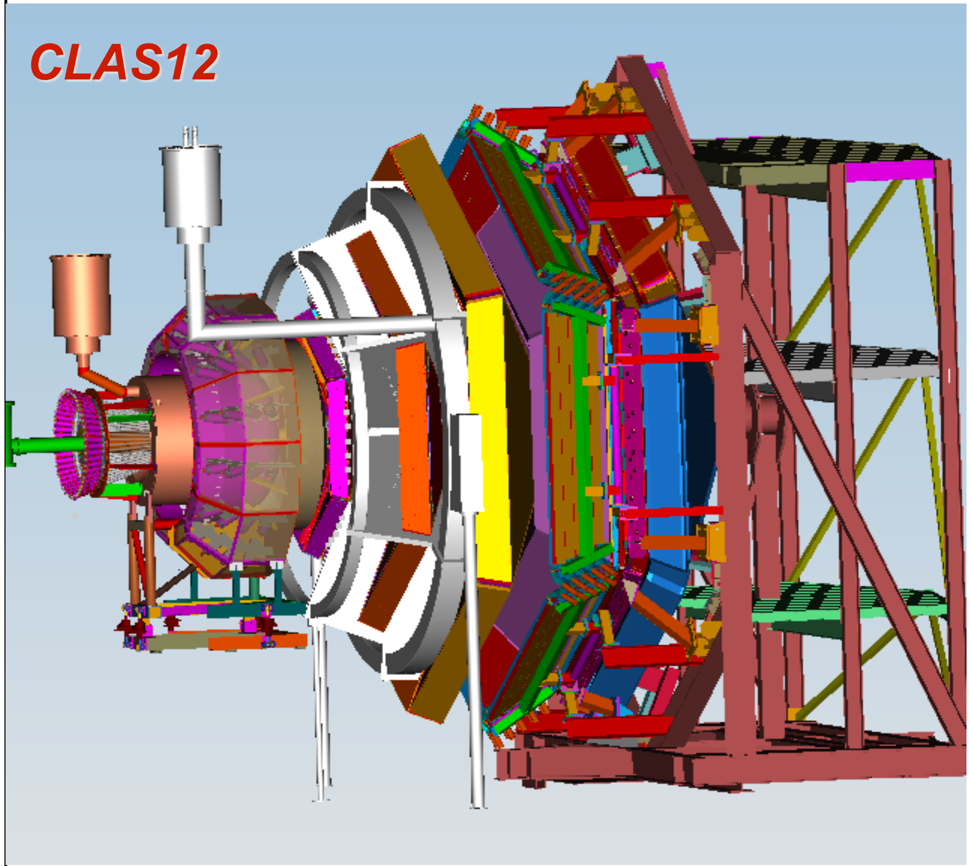
# Hall B 12GeV upgrade overview

Hall B currently houses the **C**EBAF **L**arge **A**cceptance **S**pectrometer (**CLAS**) **L=$10^{34}$ $cm^{-2}s^{-1}$**

**CLAS** will be replaced by ***CLAS12***

***CLAS12*** is designed to operate with an upgraded luminosity of **L=$10^{35}$ $cm^{-2}s^{-1}$**

***CLAS12*** will be world wide the only **large acceptance high luminosity spectrometer** for fixed target electron scattering experiments

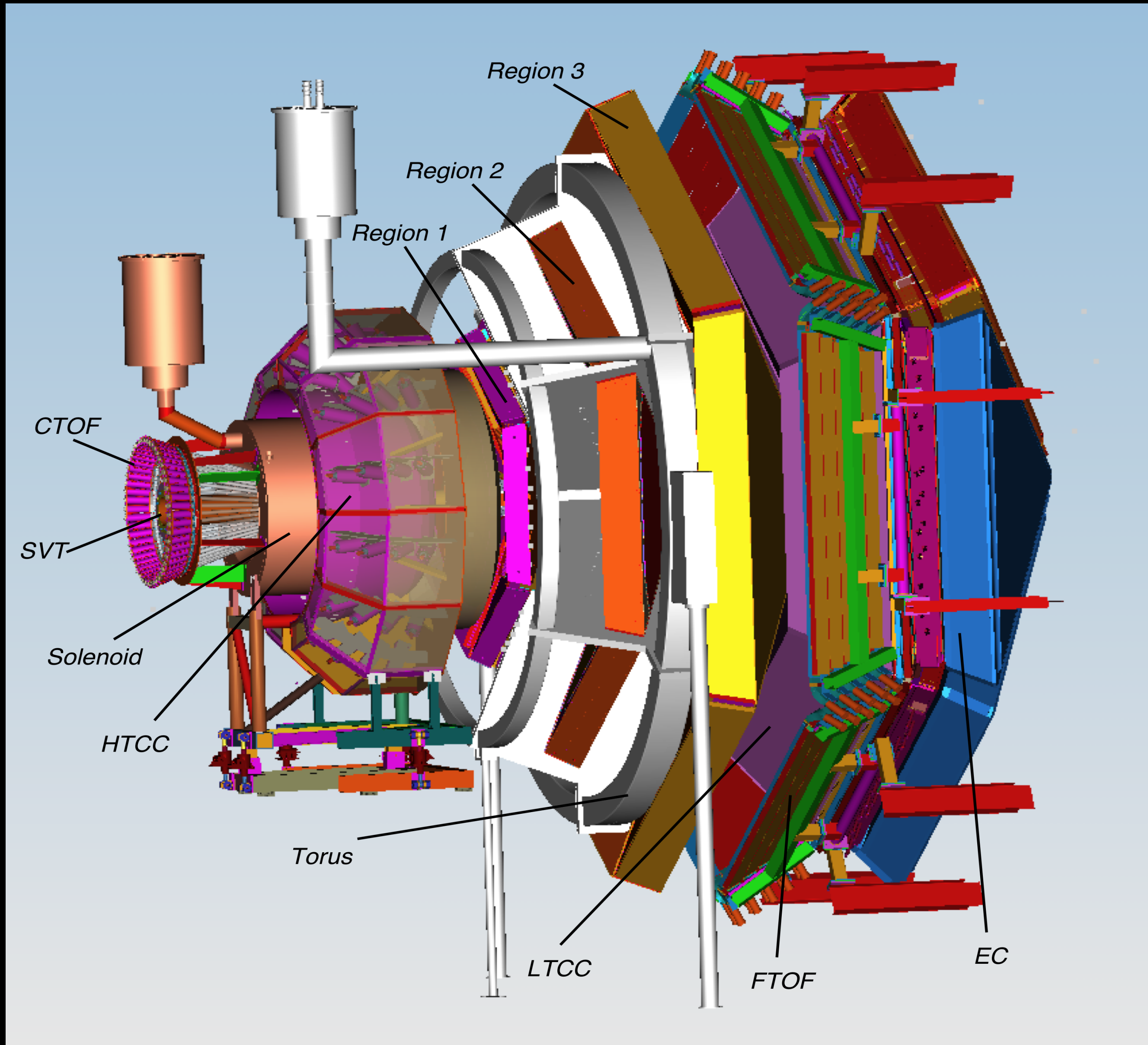


# CLAS12

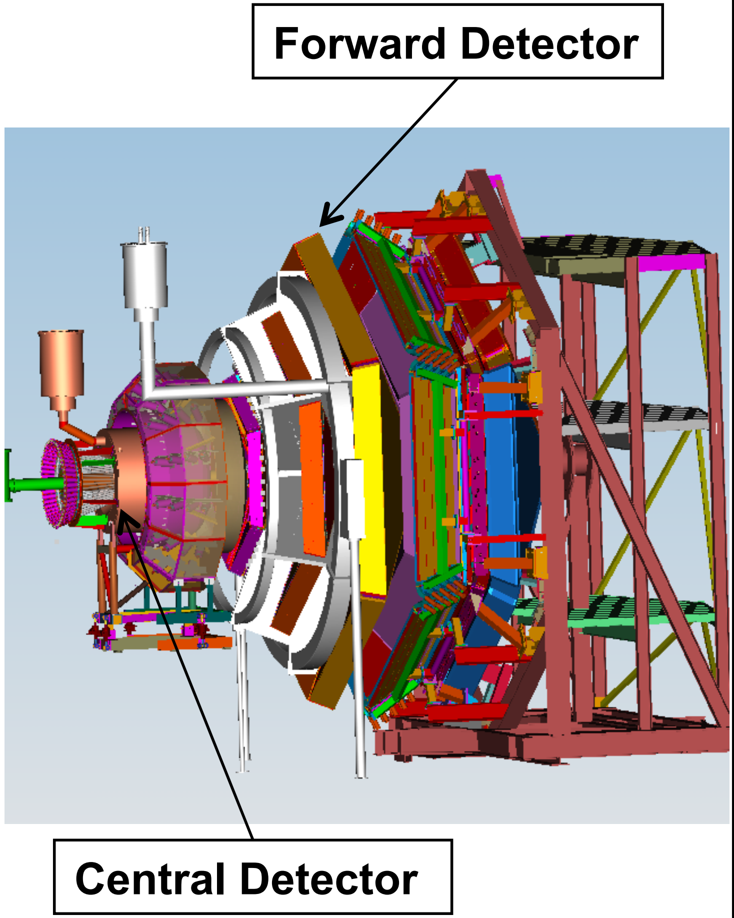
**Forward Detector:**
- TORUS magnet
- Forward SVT tracker
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward ToF System
- Preshower calorimeter
- E.M. calorimeter (EC)

**Central Detector:**
- SOLENOID magnet
- Barrel Silicon Tracker
- Central Time-of -Flight

**Proposed upgrades:**
- Micromegas (CD)
- Neutron detector (CD)
- RICH detector (FD)
- Forward Tagger (FD)



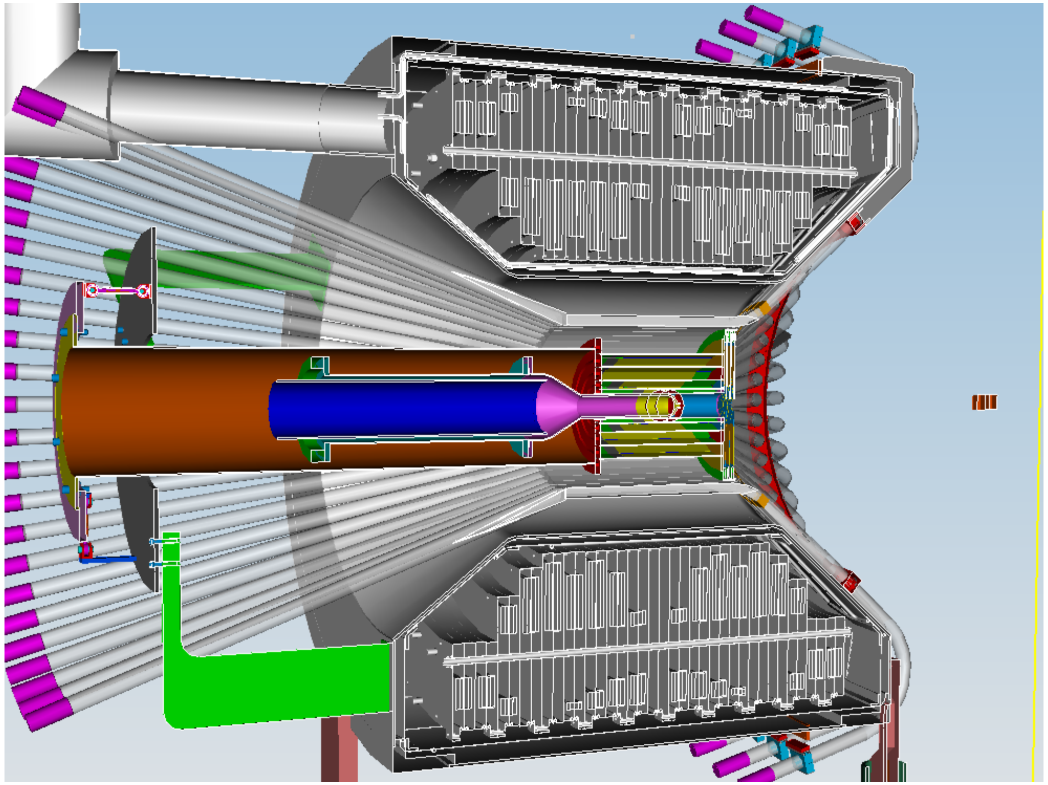
# *CLAS12* – Design parameters

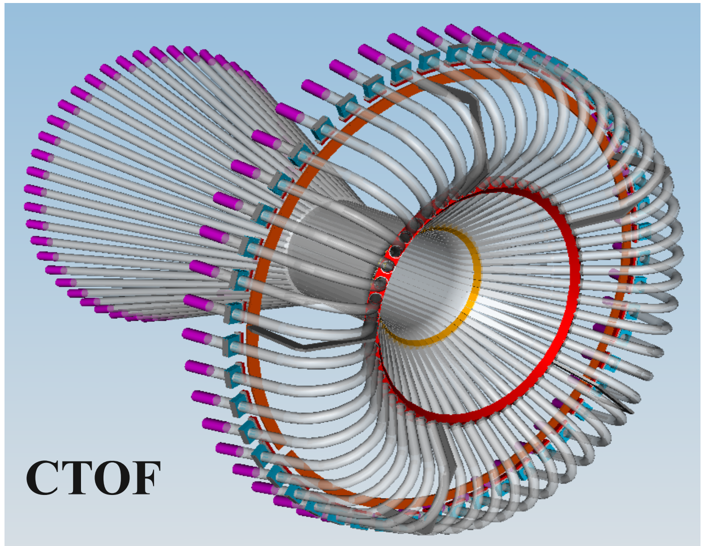


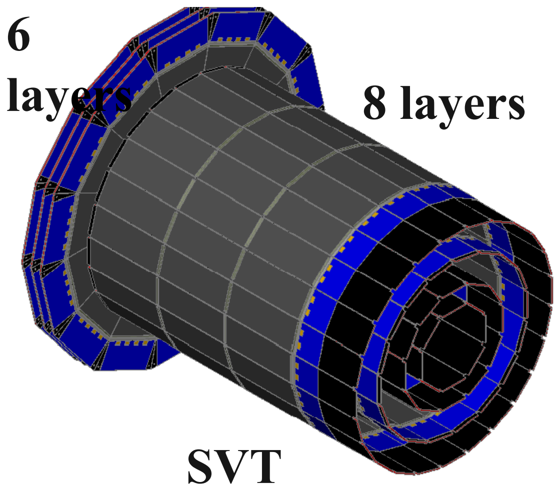

| | Forward Detector | Central Detector |
|---|---|---|
| **Angular range** | | |
| Tracks | $5^0 - 40^0$ | $35^0 - 125^0$ |
| Photons | $3^0 - 40^0$ | n.a. |
| **Resolution** | | |
| $\delta p/p$ (%) | < 1 @ 5 GeV/c | < 5 @ 1.5 GeV/c |
| $\delta\theta$ (mr) | < 1 | < 10 - 20 |
| $\Delta\phi$ (mr) | < 3 | < 5 |
| **Photon detection** | | |
| Energy (MeV) | >150 | n.a. |
| $\delta\theta$ (mr) | <4 @ 1 GeV | n.a. |
| **Neutron detection** efficiency | < 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 SVT, CTOF

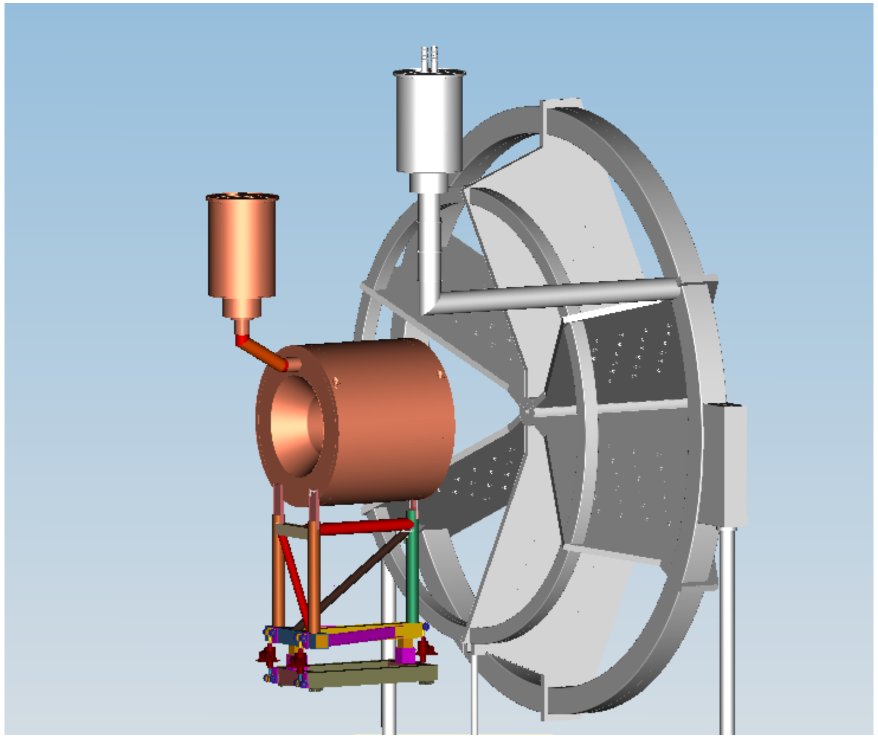
- SVT - Charged particle tracking in 5T field
- Vertex reconstruction
- ΔT < 60psec in CTOF for particle id
- Moller electron shield
- Polarized target operation $\Delta B/B < 10^{-4}$ in 3x5 cm cylinder around center

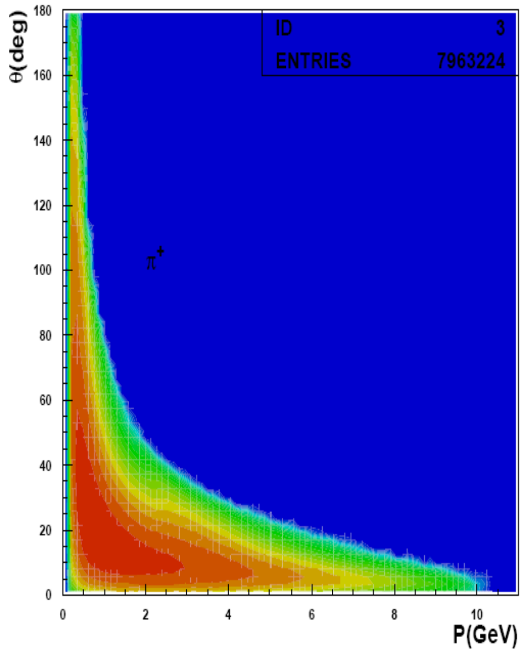


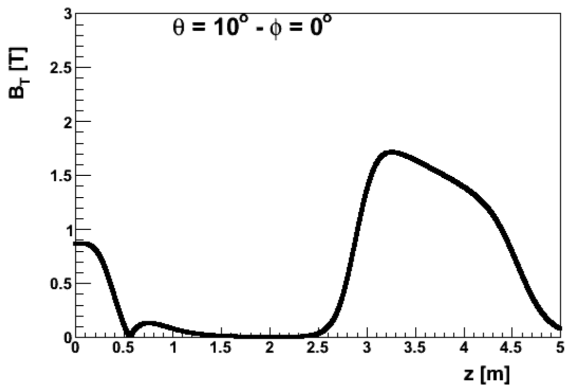


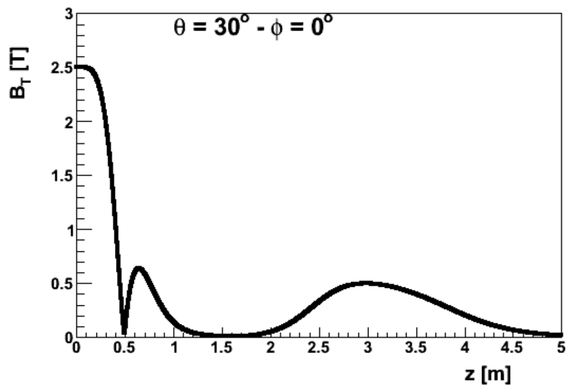



# *CLAS12* – Solenoid and Torus





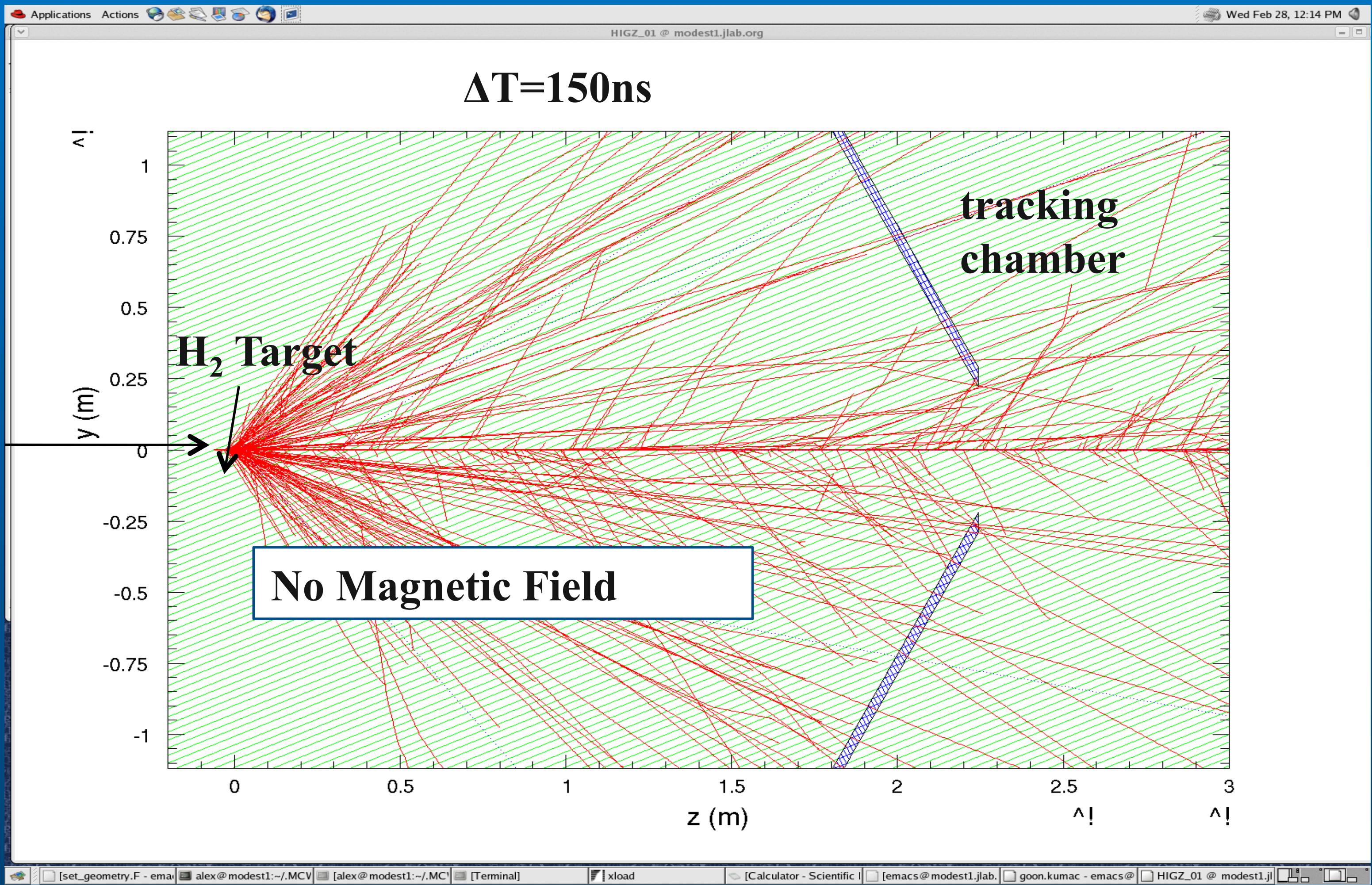




**The B-field transverse to the particle trajectory is approximately matched to the average particle momentum.**

# *CLAS12* Background Shielding

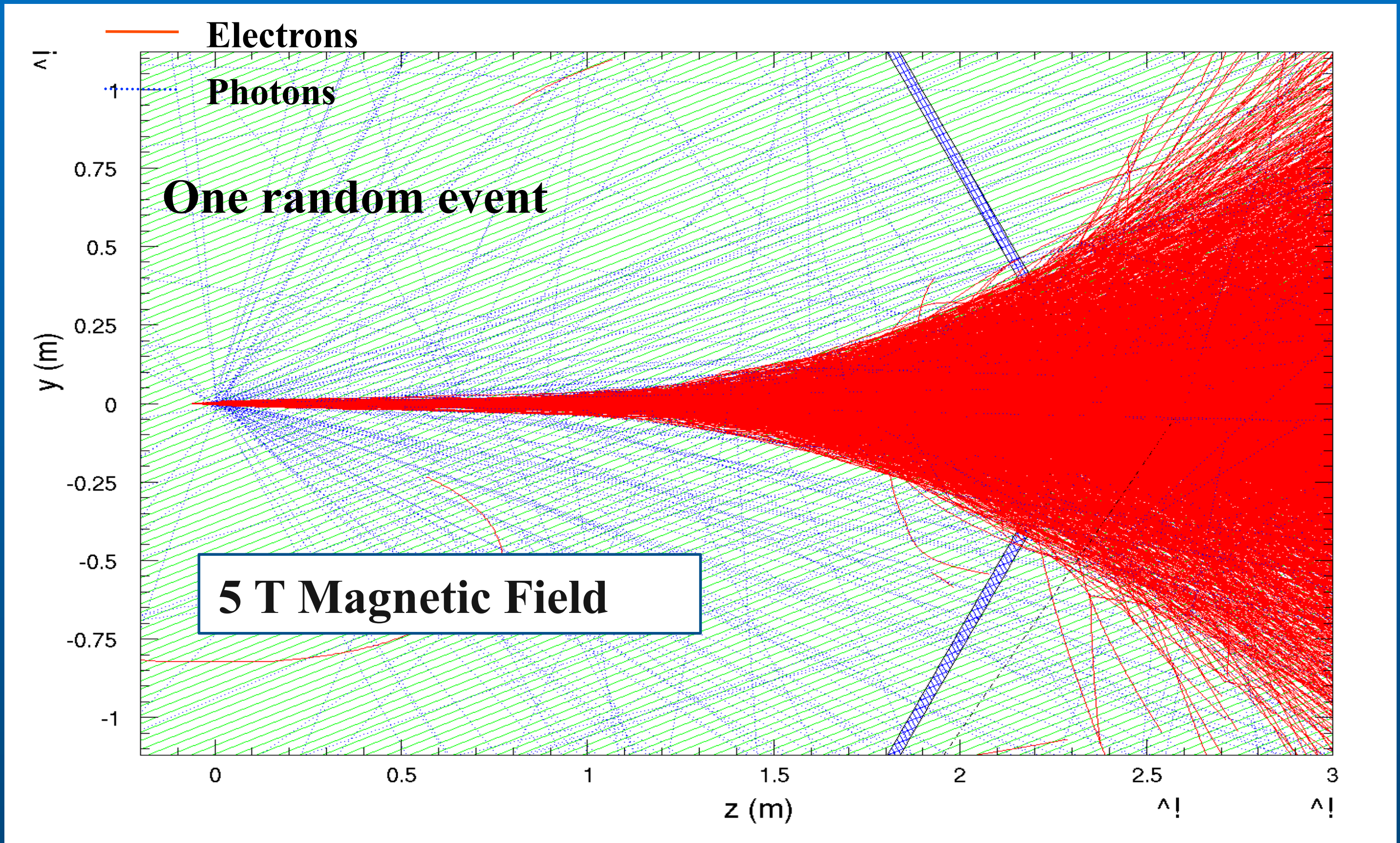
## Background at $L=10^{32} cm^{-2} s^{-1}$, $\Delta T$ = 150ns



*CLAS12*

# Background Shielding

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



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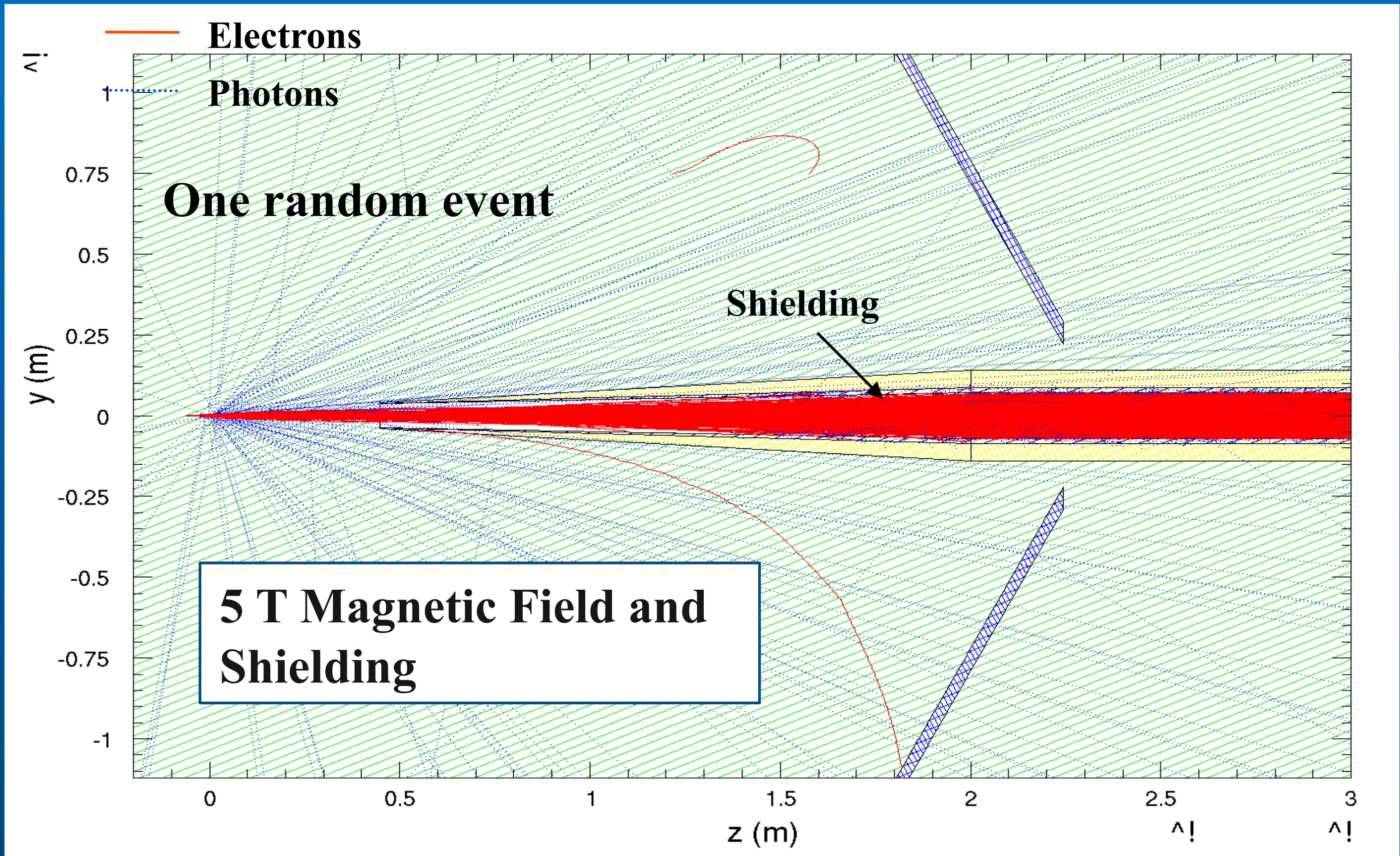
## Background at $L=10^{35}cm^{-2}s^{-1}$, $\Delta T$ = 150ns



# A Program at the Forefront of Hadron Physics

- 3D Structure of the Nucleon Structure - the new Frontier in Hadron Physics

- Nucleon GPDs and TMDs – exclusive and semi-inclusive processes with high precision

- Precision measurements of structure functions and forward parton distributions at high $x_B$

- Elastic & Transition Form Factors at high momentum transfer

# CLAS12 Initial Science Program

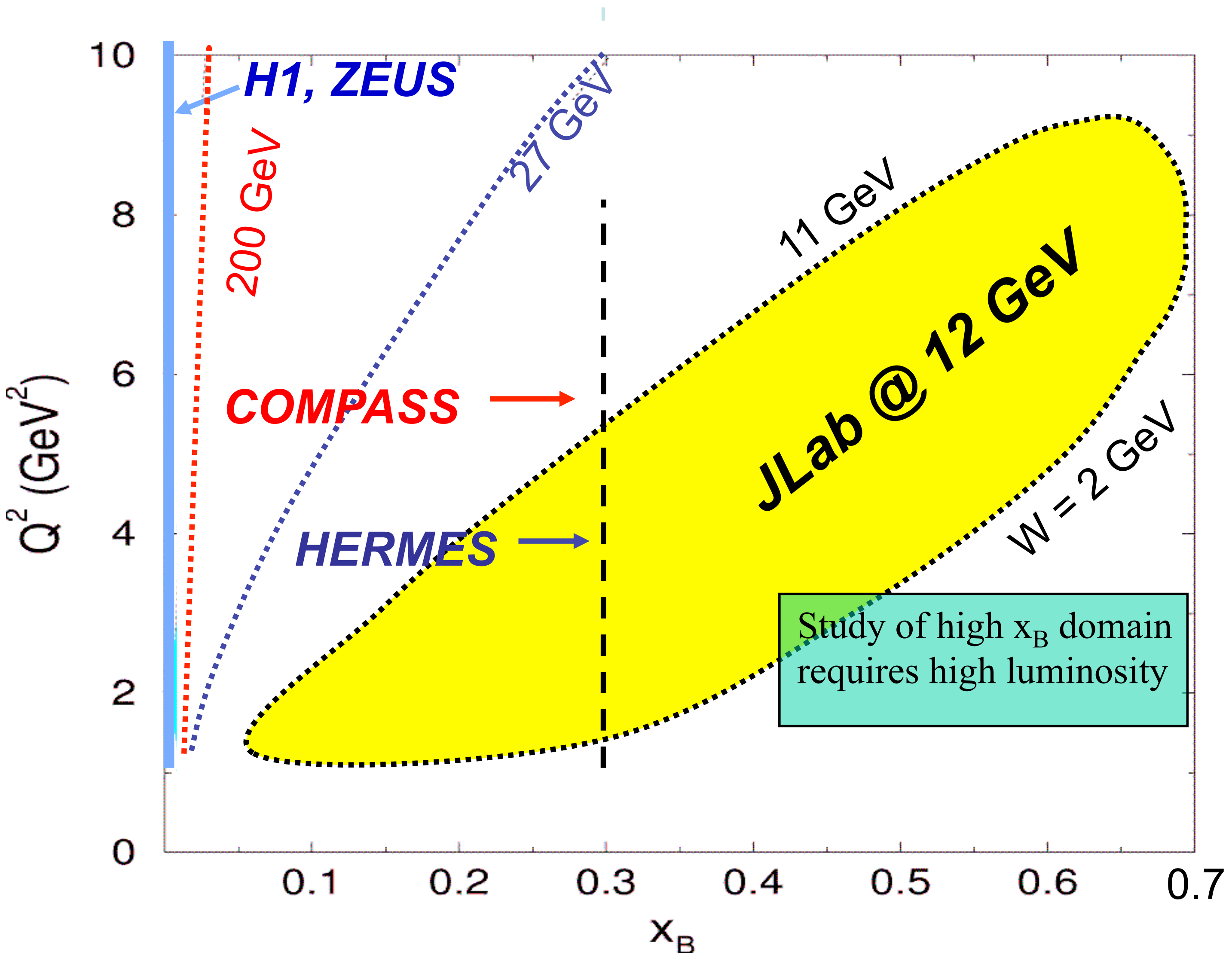
| Physics Focus | Approved experiments | LOIs supported |
|---|---|---|
| GPD's & exclusive Processes | 3 | 1 |
| TMDs & SIDIS | 4 | 4 |
| Parton Distribution Function & DIS | 2 | 1 |
| Elastic & resonance form factors | 2 | |
| Hadronization & Color Transparency | 2 | |
| Baryon Spectroscopy | | 1 |
| Total | 13 | 7 |

**Approved experiments correspond to about 5 years of scheduled beam operation .**

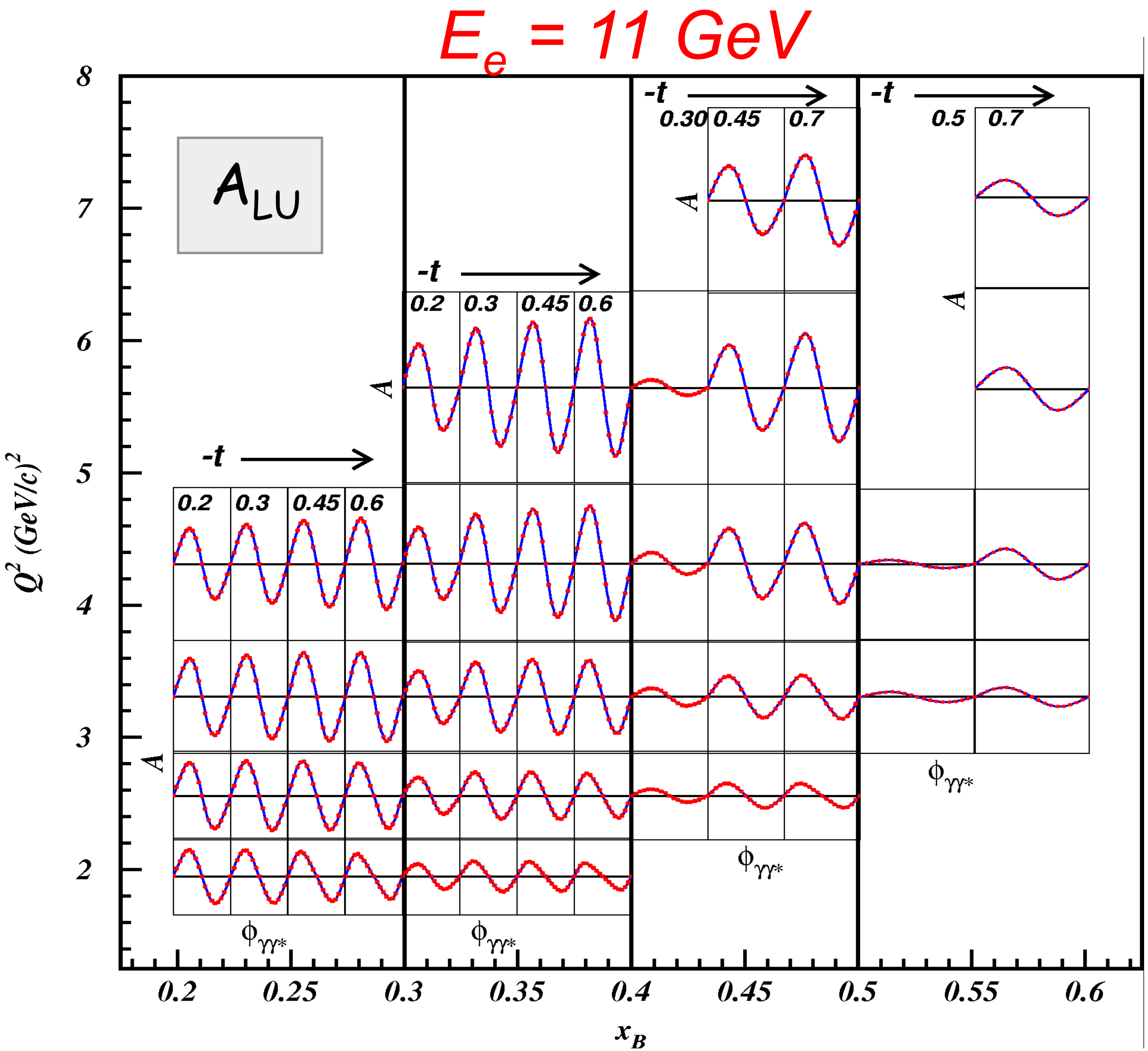
# CLAS12 Institutions

| Institution | Focus Area |
|---|---|
| | |
| Argonne National Laboratory (US) | Cerenkov Counter |
| California State University (US) | Cerenkov Counters |
| Catholic University of America (US) | Software |
| College of William & Mary (US) | Calorimetry, Magnet Mapping |
| Edinburgh University (UK) | Software |
| Fairfield University (US) | Polarized Target |
| Florida International University, Miami (US) | Beamline/Moller polarimeter |
| Glasgow University (UK) | Central Detector, DAQ, Forward Tagger, RICH |
| Grenoble University/IN2P3 (France) | Central Detector |
| Idaho State University (US) | Drift chambers |
| INFN –University Bari (Italy) | tbd, interest in RICH |
| INFN –University Catania (Italy) | tbd |
| INFN – Frascati and Fermi Center (Italy) | Central Neutron Detector+ interest show in RICH |
| INFN –University Ferrara (Italy) (will join in 2010) | tbd, interest in RICH |
| INFN – University Genoa (Italy) | Central Neutron Detector+ interest in Forward Tagger |
| INFN – ISS/Rome 1 (Italy) | tbd, interest in RICH |
| INFN – University of Rome Tor Vergata (Italy) | Central Neutron Detector+ HD target |
| Institute of Theoretical and Experimental Physics (Russia) | SC. Magnets, Simulations |
| James Madison University (US) | Calorimetry |
| Kyungpook National University (Republic of Korea) | CD TOF |
| Los Alamos National Laboratory (US) | Silicon Tracker |
| Moscow State University, Skobeltsin Institute for Nuclear Physics (Russia) | Software, SVT |
| Moscow State University (High Energy Physics) (Russia) | Silicon Tracker |
| Norfolk State University (US) | Preshower Calorimeter |
| Ohio University (US) | Preshower Calorimeter |
| Orsay University/IN2P3 (France) | Central Neutron Detector |
| Old Dominion University (US) | Drift Chambers |
| Renselear Polytechnic Institute (US) | Cerenkov Counters |
| CEA Saclay (France) | Central Tracker, Reconstruction software |
| Temple University, Philadelphia (US) | Cerenkov Counters |
| Thomas Jefferson National Accelerator Facility (US) | Project coordination & oversight |
| University of Connecticut (US) | Cerenkov Counters |
| University of New Hampshire (US) | Central Tracker, Offline Software |
| University of Richmond (US) | Offline Software |
| University of South Carolina (US) | Forward TOF |
| University of Virginia (US) | Beamline/Polarized Targets |
| Yerevan Physics Institute (Armenia) | Calorimetry |

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



# DVCS/BH- Beam Asymmetry



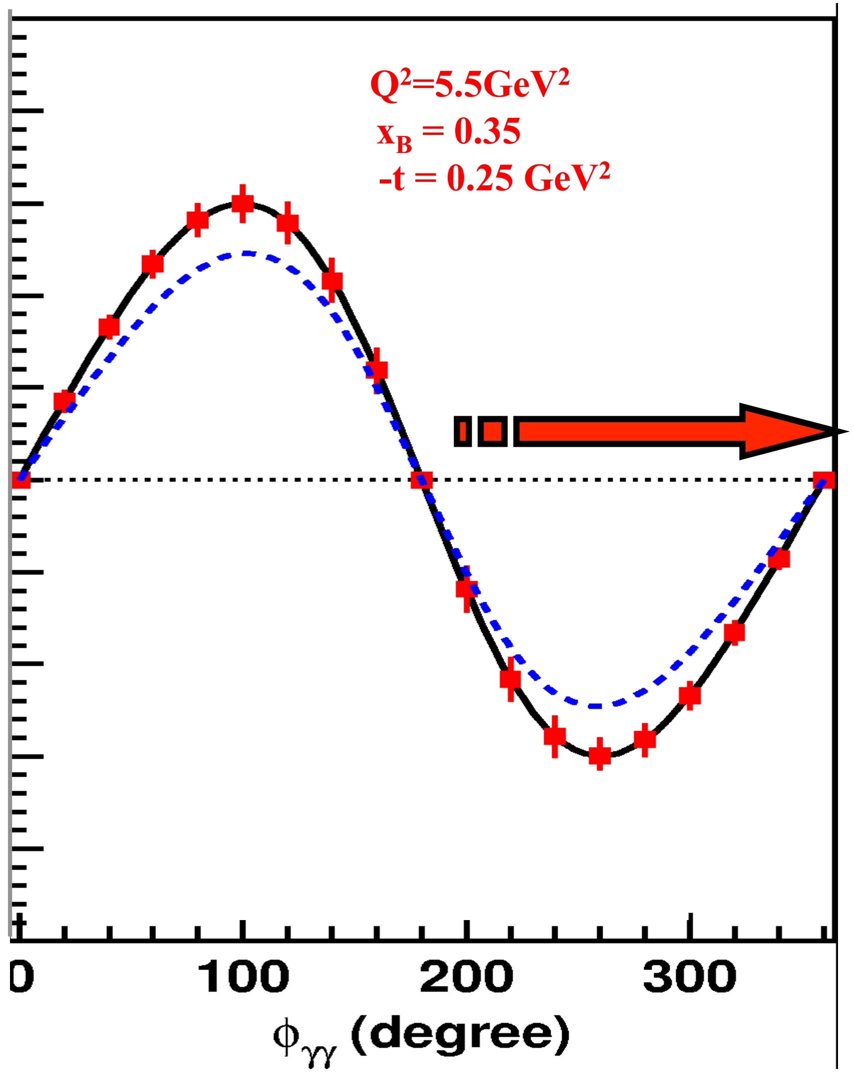

With large acceptance, measure large $Q^2$, $x_B$, t ranges simultaneously.

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

# *CLAS12* - DVCS/BH- Beam Asymmetry

*$E_e$ = 11 GeV*

*Luminosity = 720fb⁻¹*



# *CLAS12* - DVCS/BH Beam Asymmetry

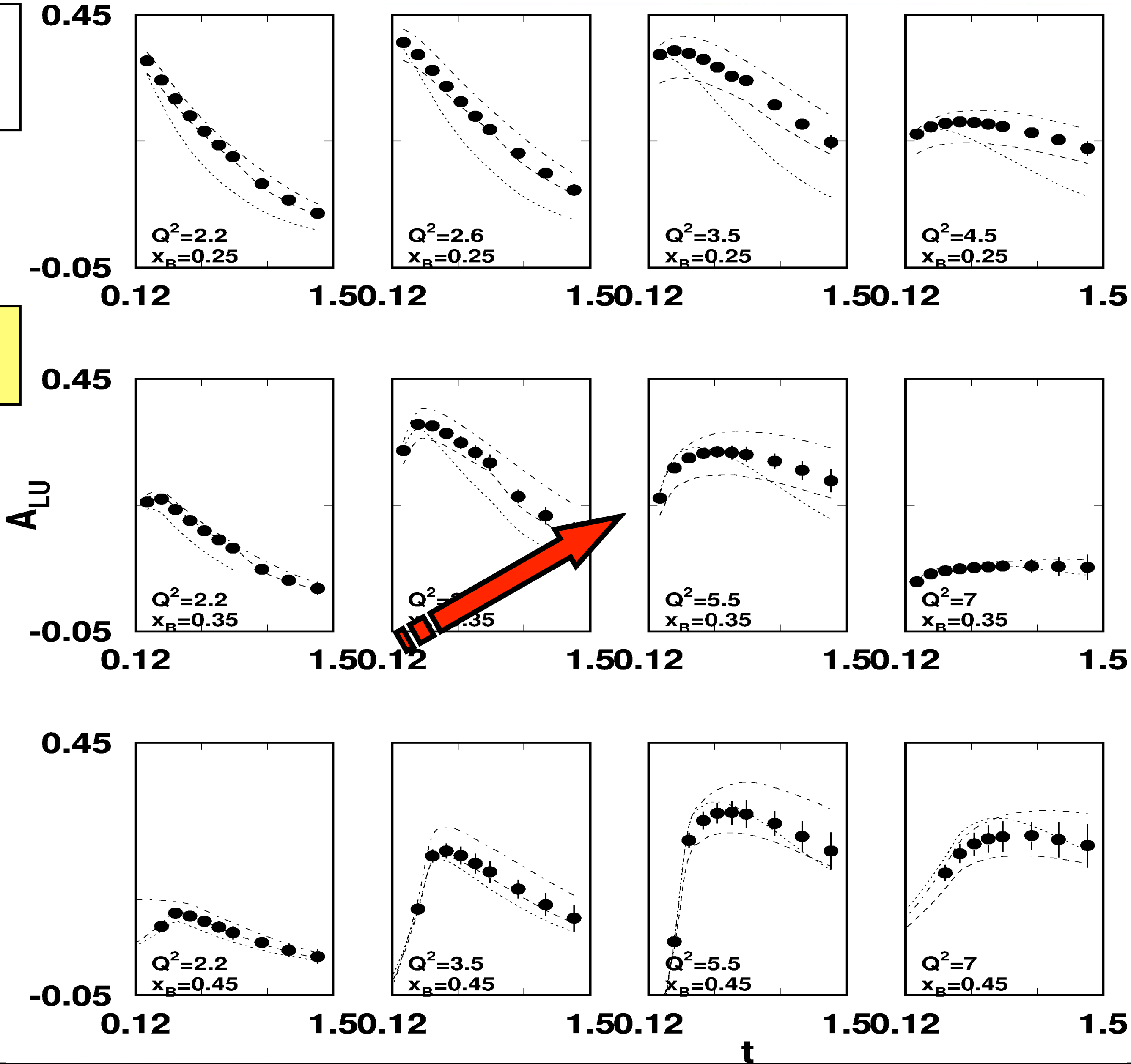
$\vec{e}p \longrightarrow ep\gamma$

***E = 11 GeV***

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

Selected Kinematics

L = 1x10$^{35}$
T = 2000 hrs
$\Delta Q^2$ = 1 GeV$^2$
$\Delta x$ = 0.05



# *CLAS12* - DVCS/BH Target Asymmetry

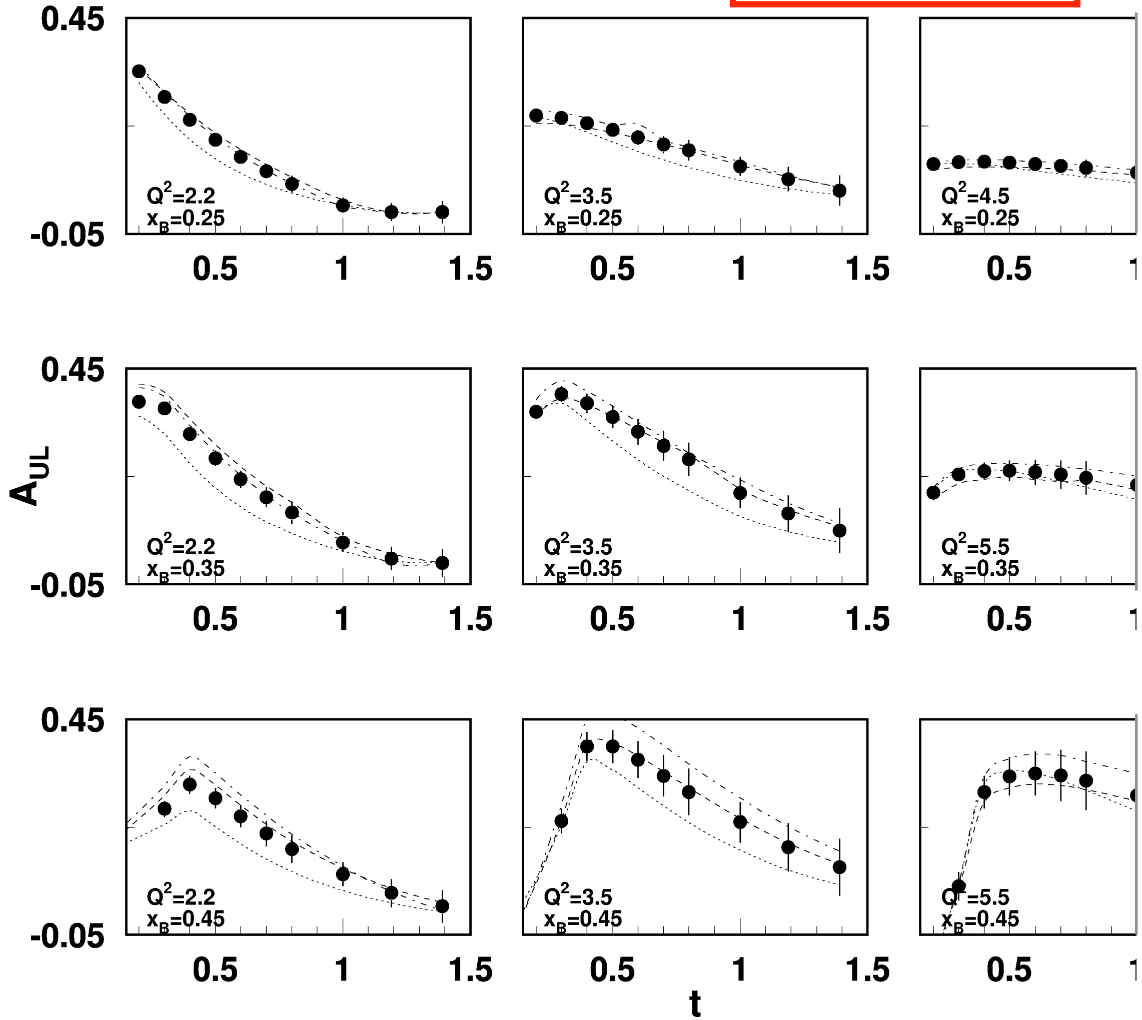
$$e\,\vec{p} \longrightarrow ep\gamma$$

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
$\Delta Q^2 = 1 GeV^2$
$\Delta x = 0.05$



# 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 = 0.5$GeV^2$

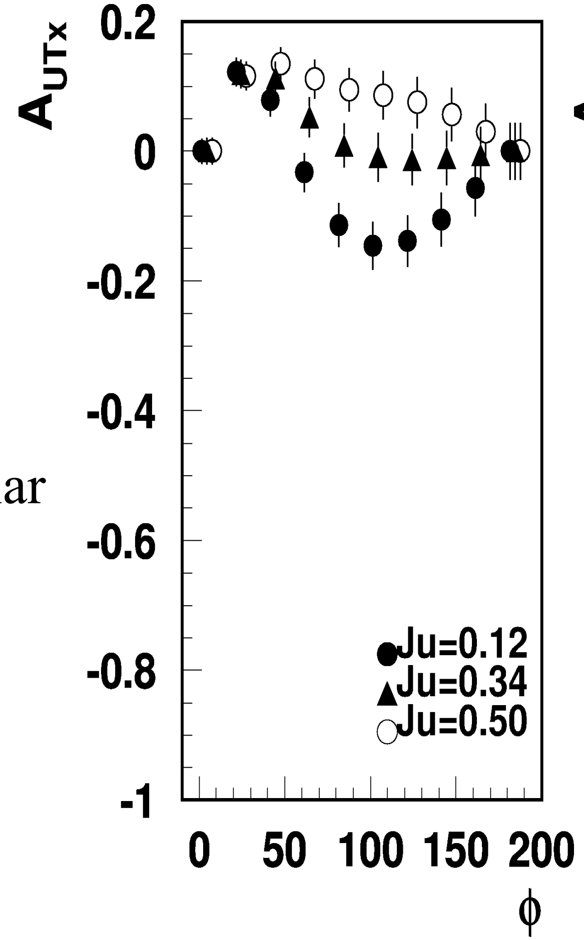
Transverse polarized target

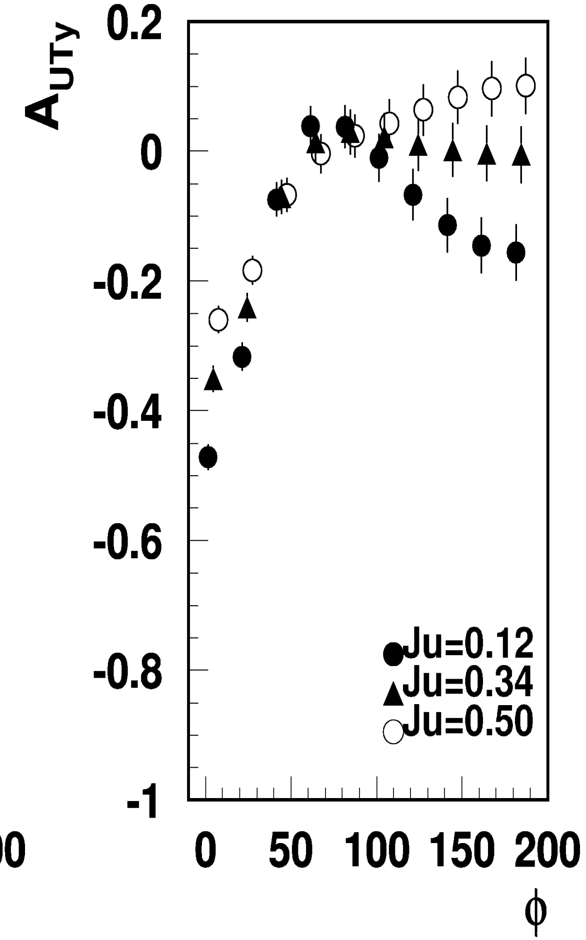
$$\Delta\sigma \sim \sin\phi \, \mathrm{Im}\{k_1(F_2 \mathcal{H} - F_1 \mathcal{E}) + \ldots\} d\phi$$

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

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

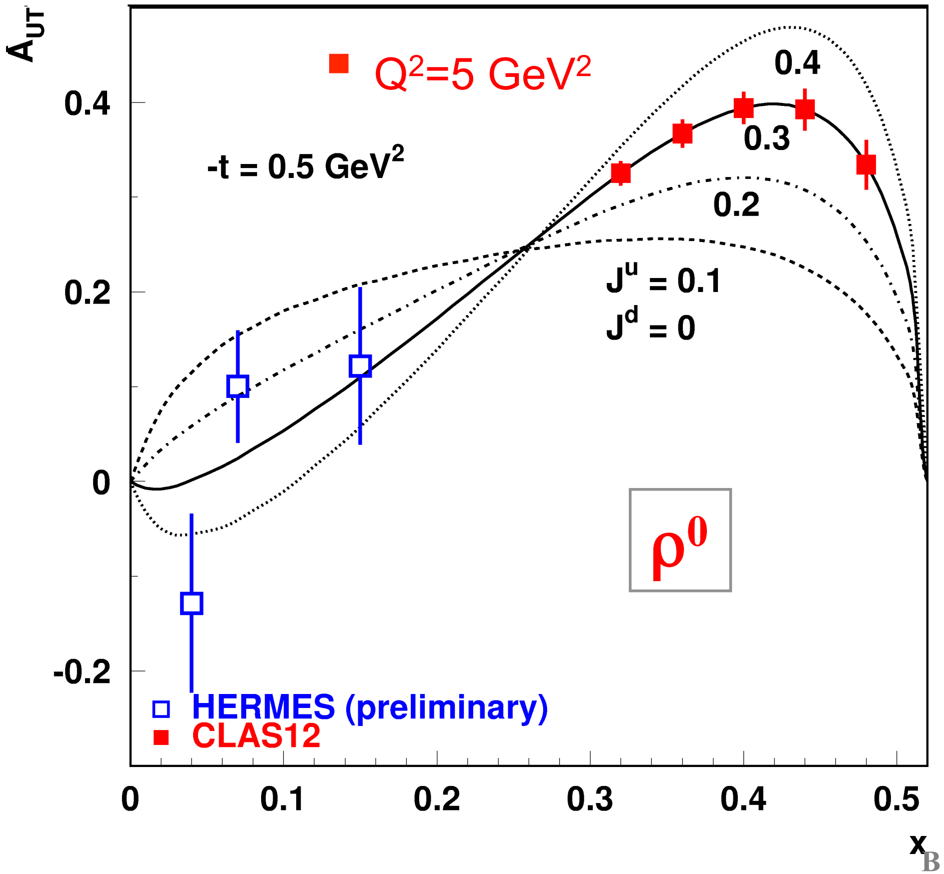
- Asymmetries highly sensitive to the u-quark contributions to the proton spin.



# Exclusive $\rho^0$ production on transverse target

$$A_{UT} \sim 2\Delta_{\perp}(\mathrm{Im}(AB^*))$$




K. Goeke, M.V. Polyakov, M. Vanderhaeghen, 2001

$\rho^0$: $A \sim 2H^u + H^d$, $B \sim 2E^u + E^d$

$\rho^+$: $A \sim H^u - H^d$, $B \sim E^u - E^d$

$E^u$, $E^d$ allow to map the *orbital motion* of *quarks*.

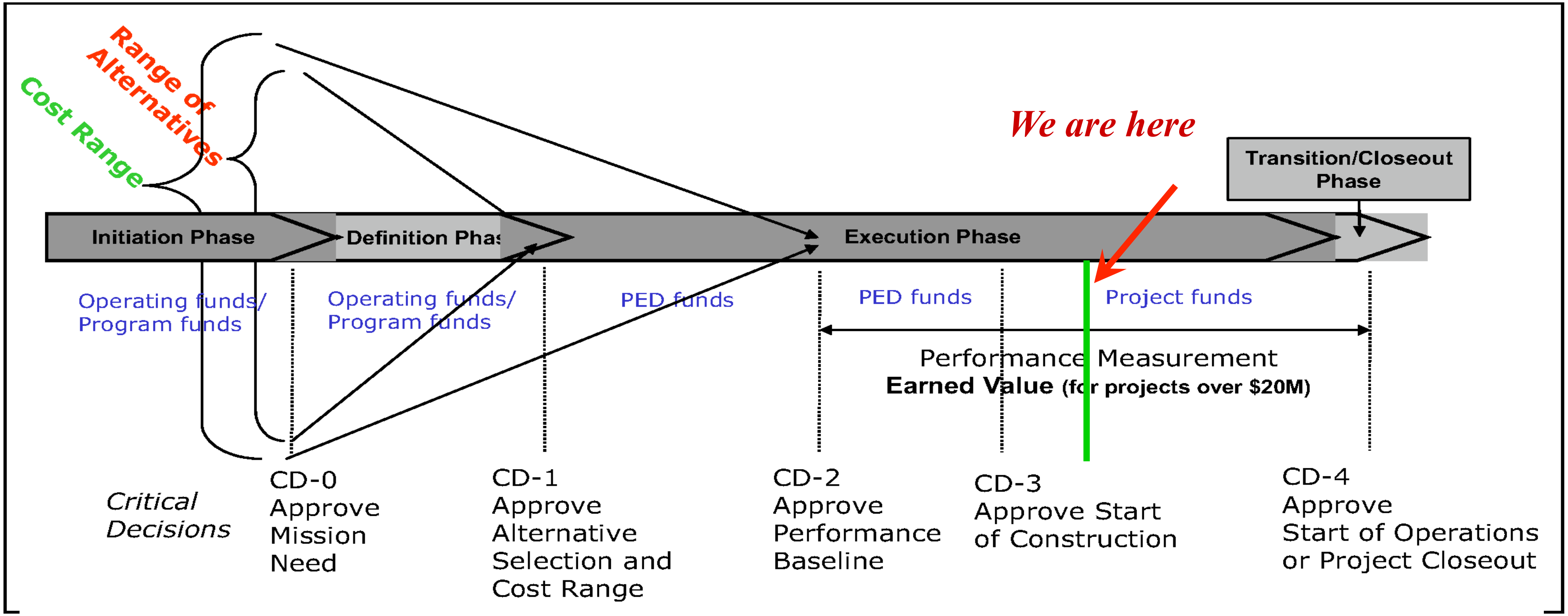
# 2007 NSAC Long Range Plan (4 recommendations)

## Recommendation 1

**We recommend the completion of the 12 GeV Upgrade at Jefferson Lab.**

- It will enable **three-dimensional imaging of the nucleon**, revealing hidden aspects of its internal dynamics.
- It will complete our understanding of the transition between the hadronic and quark/gluon descriptions of nuclei.
- It will test definitively the existence of exotic hadrons, long-predicted by QCD as arising from quark confinement.
- It will provide low-energy probes of physics beyond the Standard Model complementing anticipated measurements at the highest accessible energy scales.

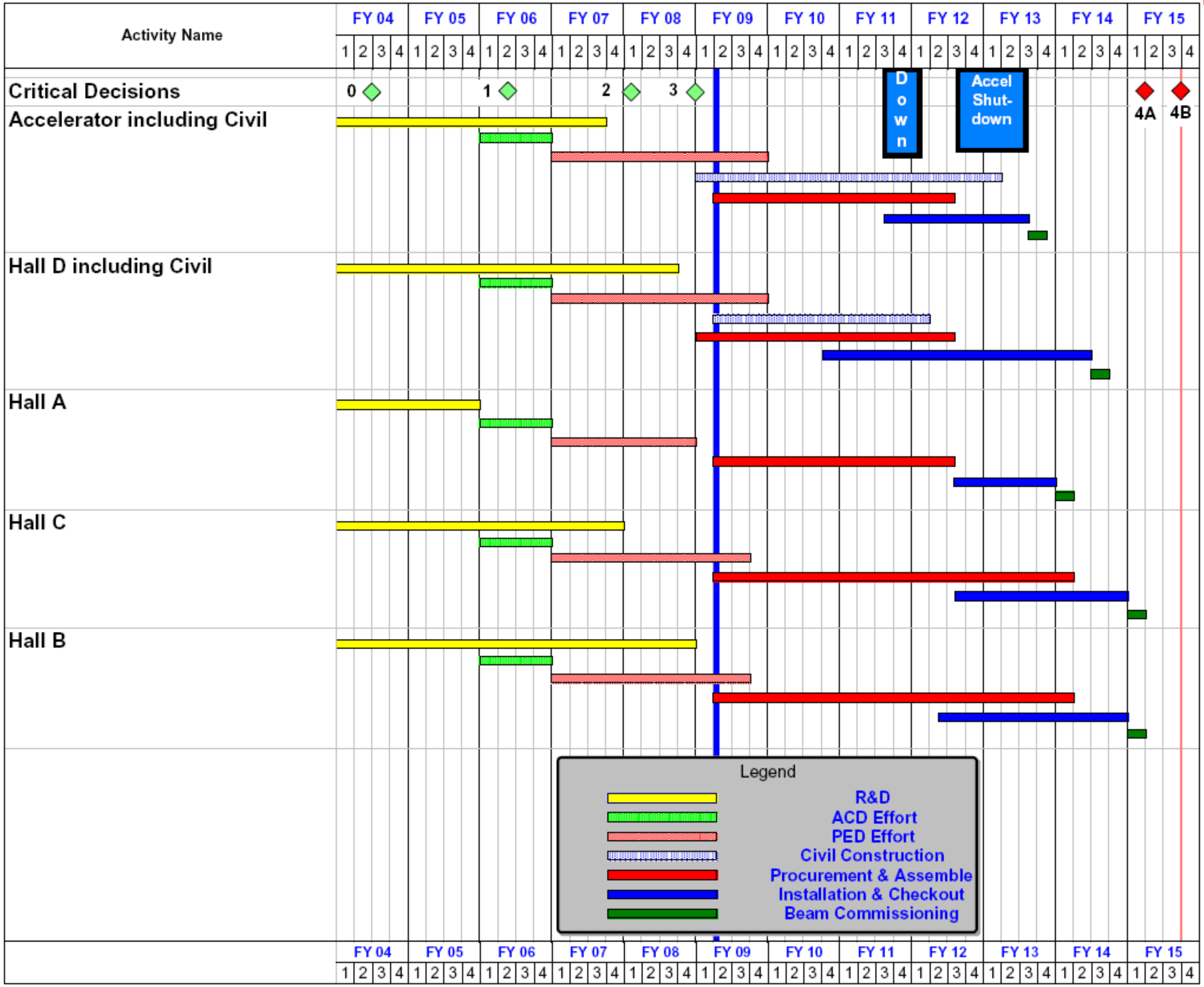
# DOE Generic Project Timeline



# DOE Project Critical Decisions – 12 GeV Schedule

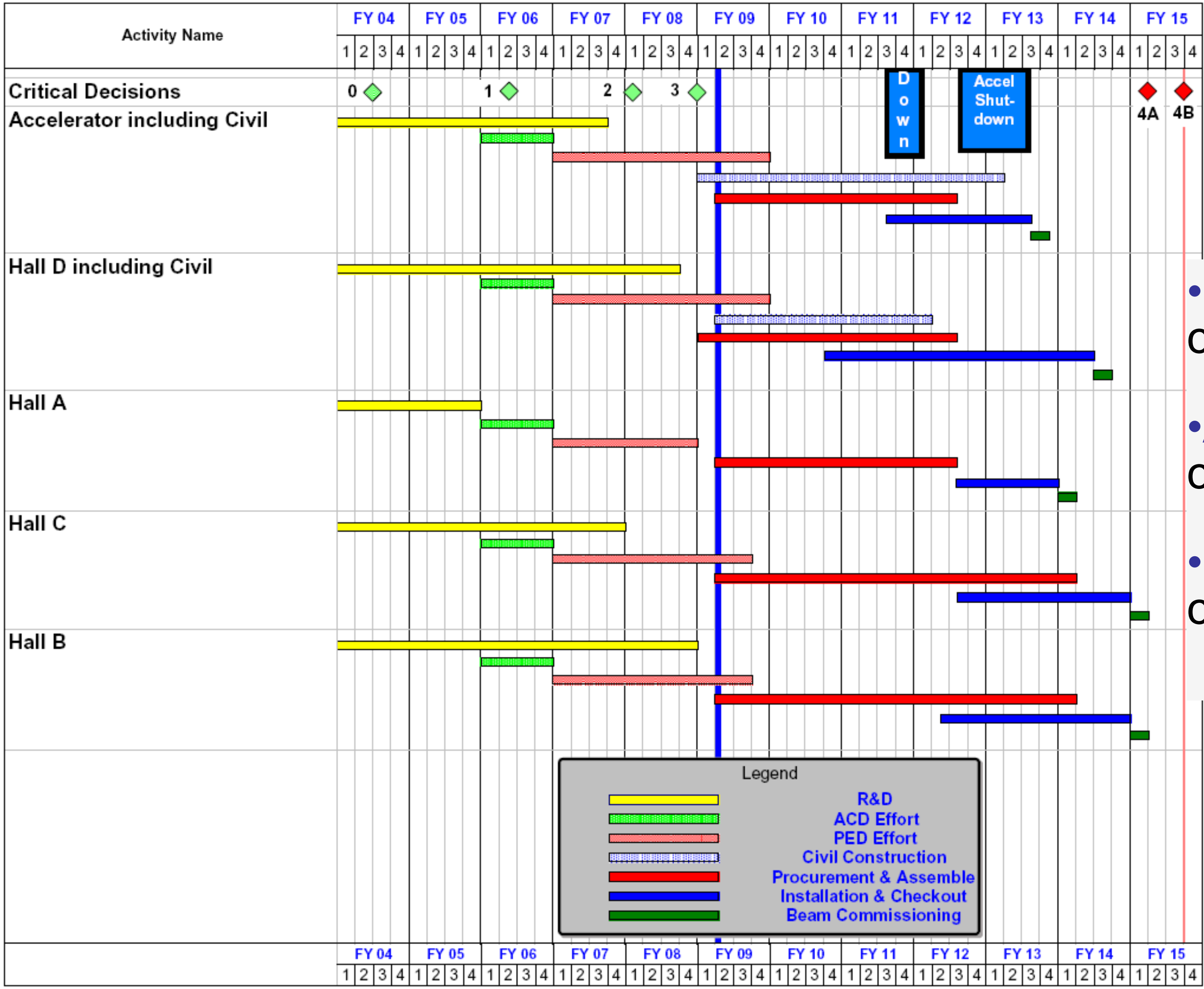
- CD-0 Approve Mission Need (Mar 2004)
- CD-1 Approve Alternative Selection and Cost Range (Feb 2006)
  - Permission to develop a Conceptual Design Report
  - Defines a range of cost, scope, and schedule options
- **CD-2 Approve Performance Baseline (Nov 2007)**
  - **Fixes "baseline" for scope, cost, and schedule**
  - **Now develop design to 100%**
  - **Begin monthly Earned Value progress reporting to DOE**
  - **Permission for DOE-NP to request construction funds**
- **CD-3 Approve Start of Construction**
  - **DOE Office of Science CD-3 Approval: September 15, 2008**
- CD-4 Approve Start of Operations or Project Close-out

# 12 GeV Schedule




- May ’11 - Oct ‘11
  6-month “down” for initial installations
- Nov ’11 - May ‘12
  6-month run 6GeV
- Jun ’12 - May ‘13:
  1-year “down” for major installation
- June ’13 - Sep ‘13:
  Accelerator commissioning

# 12 GeV Schedule




- Oct '13: Hall A commissioning start
- Apr '14: Hall D commissioning start
- Oct '14: Hall B & C commissioning start

# Summary

- The CLAS12 with the 12 GeV Upgrade has a well defined physics goals of fundamental importance for the future of hadron physics, addressing in new and revolutionary ways the quark and gluon structure of hadrons by
  - accessing GPDs
  - mapping the valence quark structure of nucleons with high precision
  - understanding hadronization processes
  - extending nucleon form factors to short distances
- Design of accelerator and equipment upgrades are underway
- Construction started October 2008

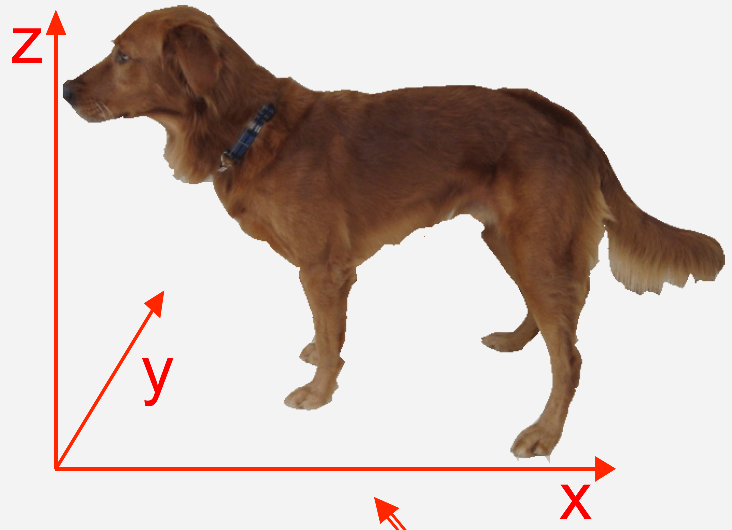
This is a very exciting time for hadronic physics,

and the perfect time for new collaborators to make significant contributions to the physics and equipment of ***CLAS12***

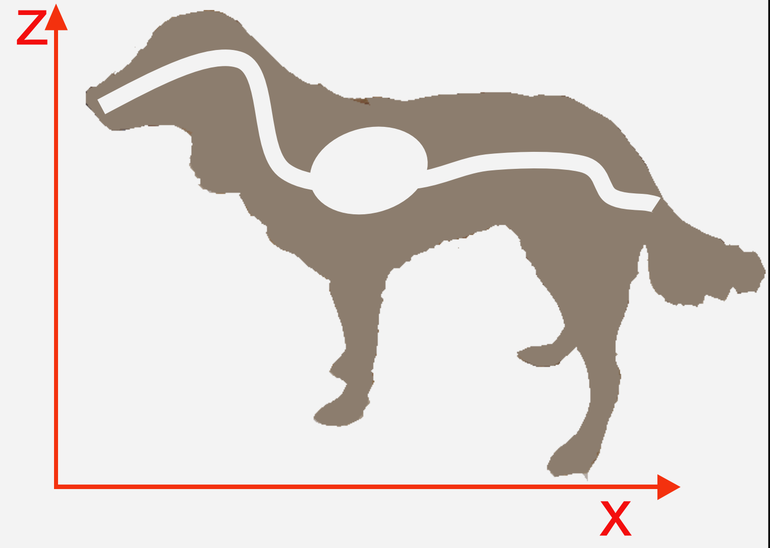
# Jefferson Laboratory
# 12 GeV Upgrade Science, Technology & Education Center Stage

# GPDs & PDFs

3-D Golden Retriever



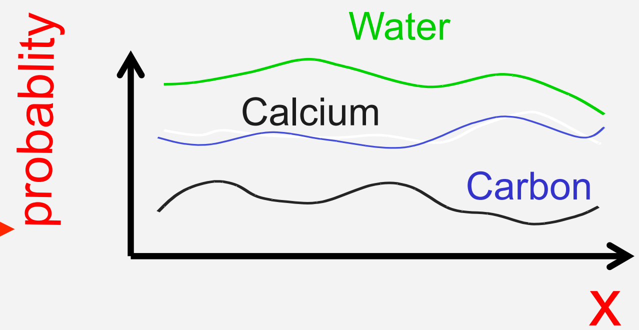

2-D Golden Retriever




Deeply Virtual Exclusive Processes & GPDs

Deep Inelastic Scattering & PDFs

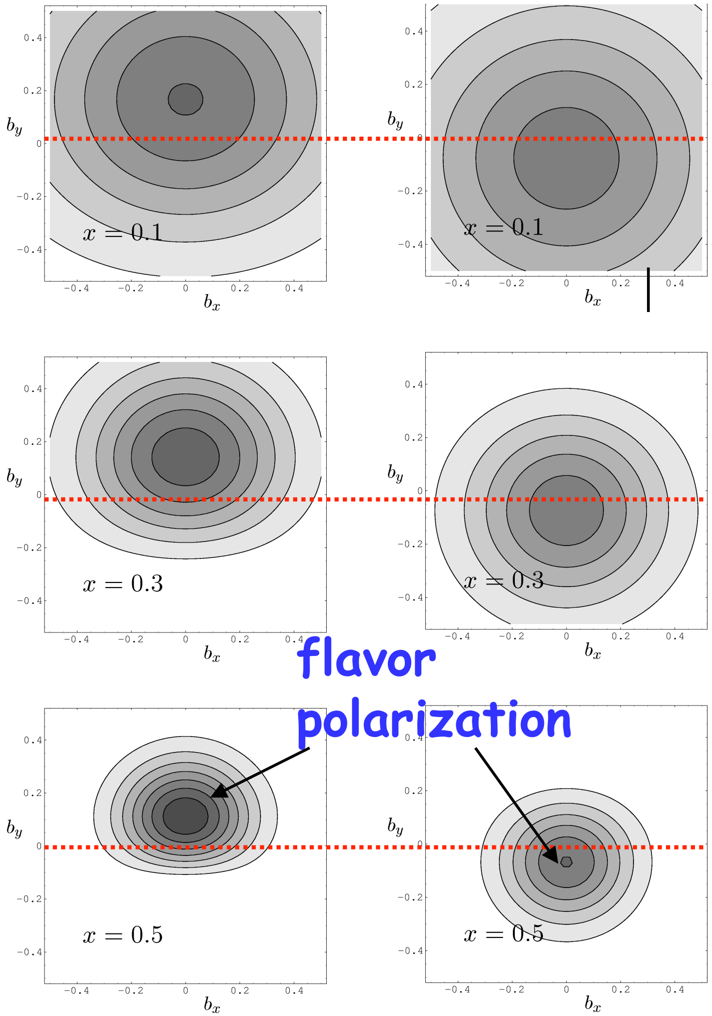
1-D Golden Retriever



# Tomographic Images of the Proton

Target polarization

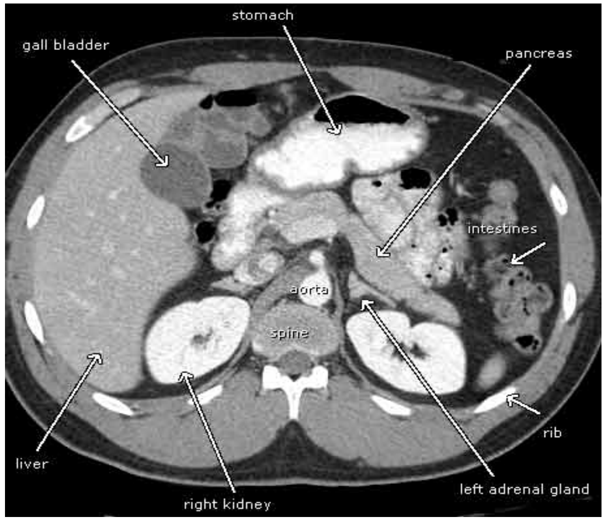
$d_X(x,b_\perp)$ $u_X(x,b_\perp)$




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

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

CAT scan slice
of human abdomen




M. Burkardt

# Jefferson Lab Today