Deep Exclusive Processes

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Outline

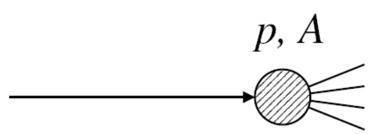
- Some basics about the proton
- Generalized Parton Distributions (GPDs) and what they can tell us
- experiments to access GPDs
- CEBAF future experiments & JLab @ 12 GeV
- Imaging of the Proton's Quark Structure
- Conclusions

Some well known facts about the proton

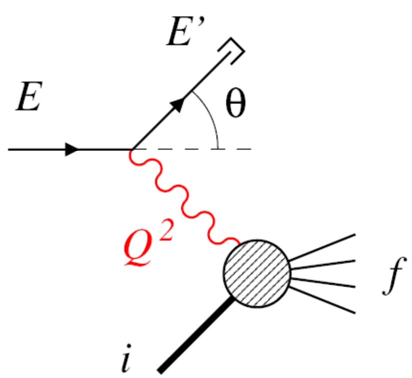
- Charge: $Q_p = +1$
  - It has a neutral partner, the neutron, $Q_n = 0$
- Spin: $s = \frac{1}{2}\hbar$
  - Magnetic moment $\mu_p = 2.79\mu_N$
  - Anomalous magnetic moment $m_a = 1.79m_N$
- Mass: $M_p \sim 940$ MeV/c^2
  - Protons + neutrons make up 99.9% of the mass of the visible universe

1950's: Does the proton have finite size?

Scattering Experiments in Nuclear Physics



$p, \pi, \ldots$	hadron
$e, \mu, \nu, \ldots$	lepton
γ	photon

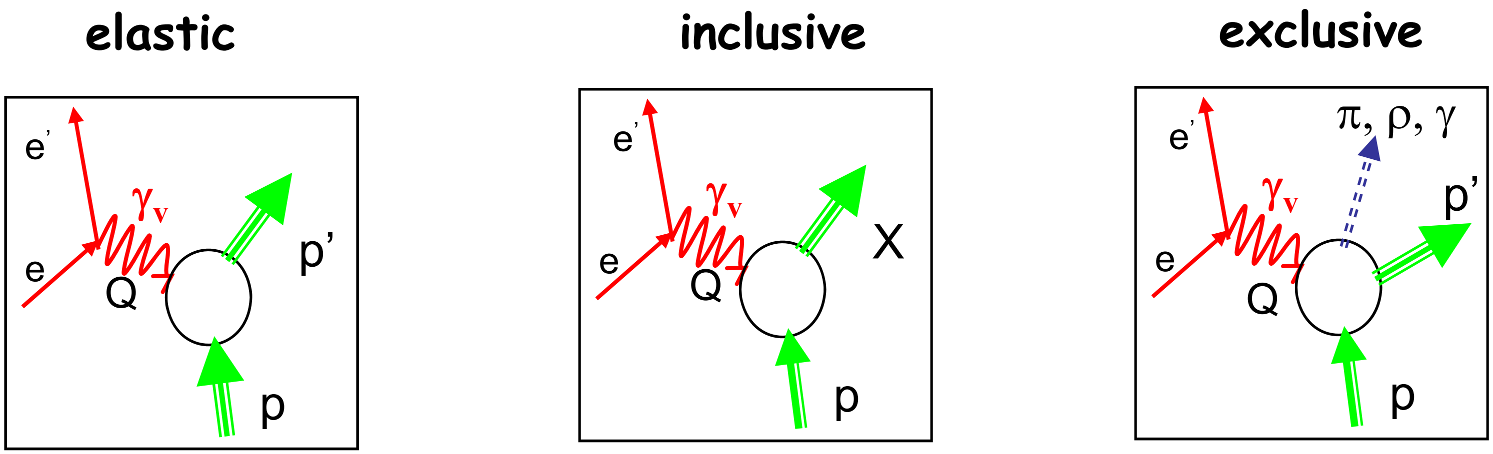


$$\langle f|\, J_\mu(x)\, |i\rangle$$

- Uses of scattering experiments
  - Structure target
  - Produced system (meson, resonances)

- Advantages of electron scattering
  - Structureless probe. “clean”
  - Controlled energy/momentum transfer, “microscope” with resolution Q^2
  - Interaction through well-known EM current operator

Electron Scattering a clean probe of the Proton Structure



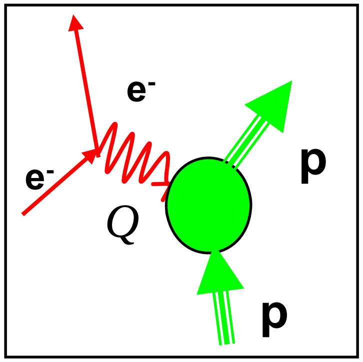
Interaction described by:

$Q^2 = -(e-e')^2$
$\nu = E_e - E_{e'}$
$x_B = Q^2/2M\nu$
$t = (p-p')^2$

$1/\sqrt{Q^2}$ is the space-time resolution of the virtual γ

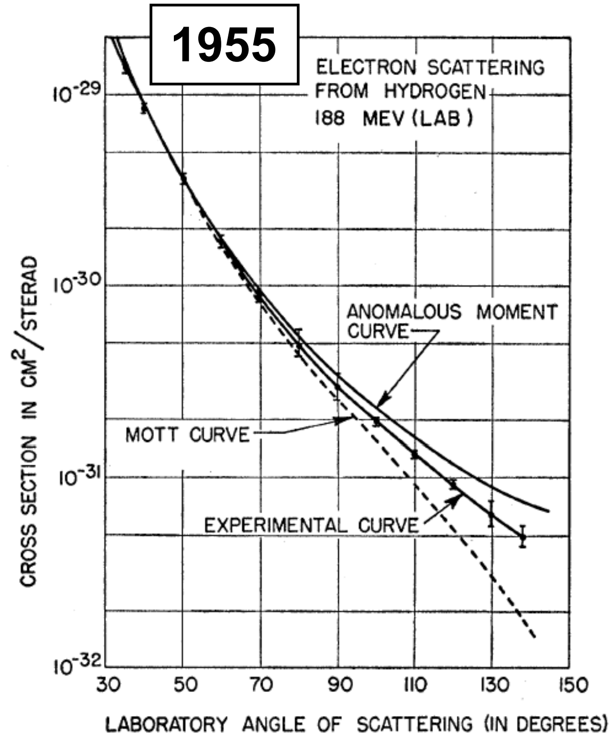
The exploration of the internal structure of the proton began in the 1950's with Hofstadter's experiments.

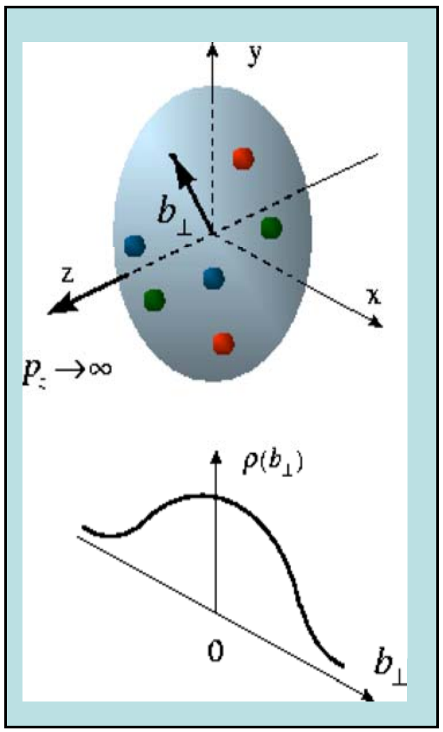
Does the Proton have finite size?



$$d\sigma/d\Omega = [d\sigma/d\Omega]_{n.s.} |F(\vec{q})|$$

$$F(q) = \int dr\, e^{-iq\,r} \rho(r)$$





Proton form factors, transverse charge & current densities

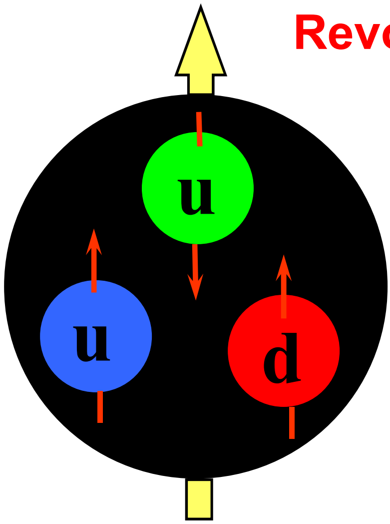
Nobel Prize for Physics. 1961

R. Hofstadter

- Elastic electron-proton scattering ⇨ the proton is not a point-like particle, it has finite size.

Constituent Quark Model

Revolutionized our way of thinking about proton structure



The proton is build from three quarks of spin s = 1/2 moving in the s-state (L = 0) and having masses m_q ~ 300 MeV.

M. Gell-Mann, 1964
G. Zweig, 1964

- Proton mass: $m_p \approx 3m_q$
- Proton spin: $S = \frac{1}{2} \oplus \frac{1}{2} \oplus \frac{1}{2}$

Solely built from the quark spins!

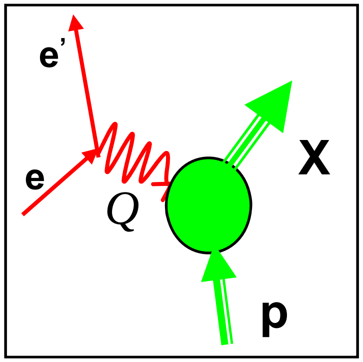
Tremendously successful model in description of

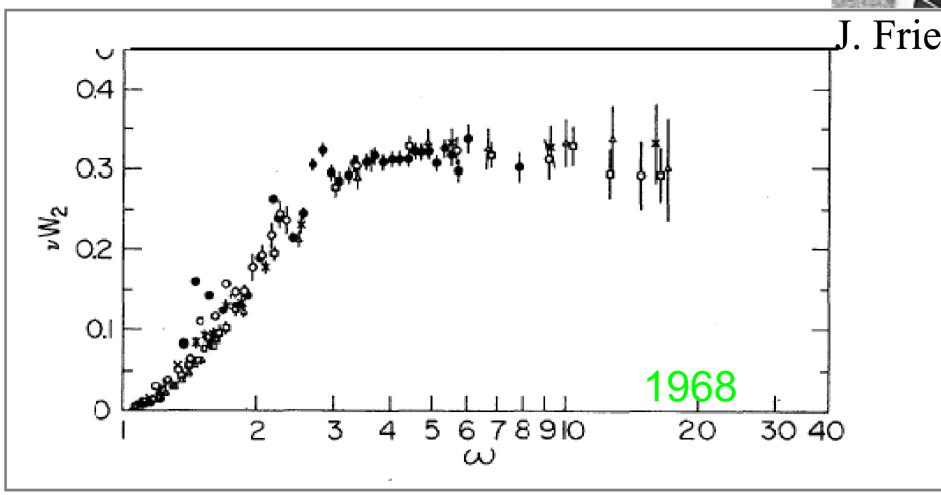
- Hadron mass spectra
- Magnetic moments

e.g. $\mu_p = 2.79 \frac{e}{2m_p c} \approx \frac{e}{2(m_p/3)c}$

What is the internal structure of the proton?

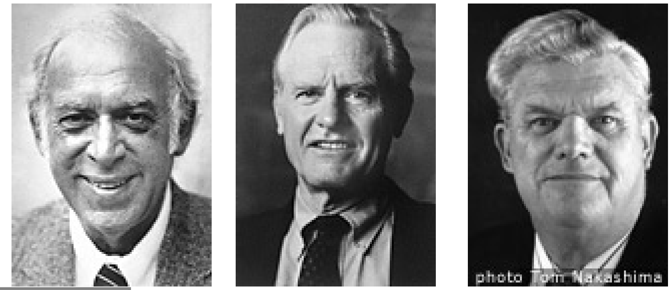
Deep inelastic electron-proton scattering   ep→e'X



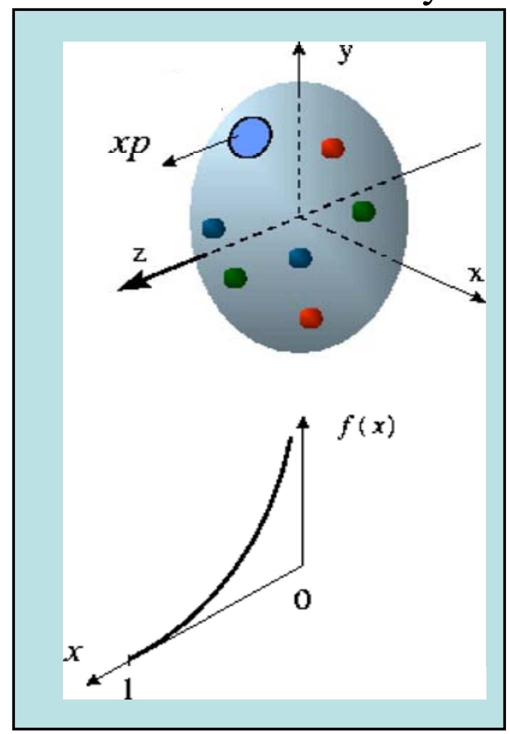


$= 1/x_B$

Nobel prize 1990



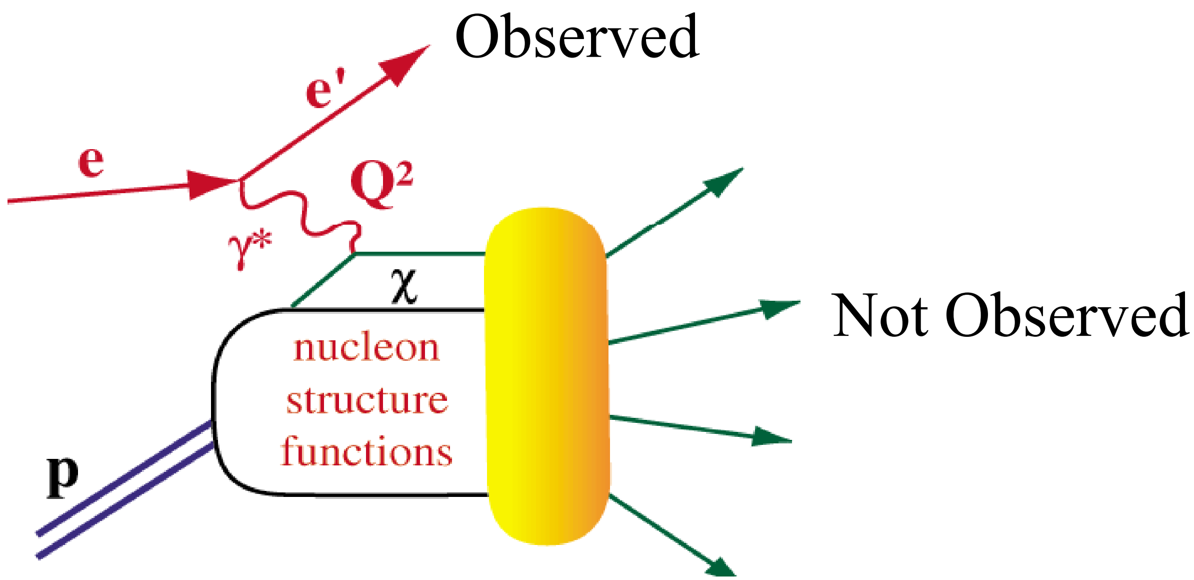
J. Friedman   H. Kendall   R. Taylor



Scaling → Quarks are point-like objects!

Quarks carry ~ 50% of the proton momentum =>glue=>QCD
The quark spins contributes only 25% to the proton spin.

Deep Inclusive Scattering (DIS)



What have we learned?

- **quarks-substructure of the nucleon**
- **50% of the nucleon momentum is carried by quarks, the remainder by gluons**
- **quarks are spin ½ objects**
- **less than 25% of the nucleon spin is carried by quark helicity**

Some Open Questions in Nucleon Physics in the Valence Quark Region

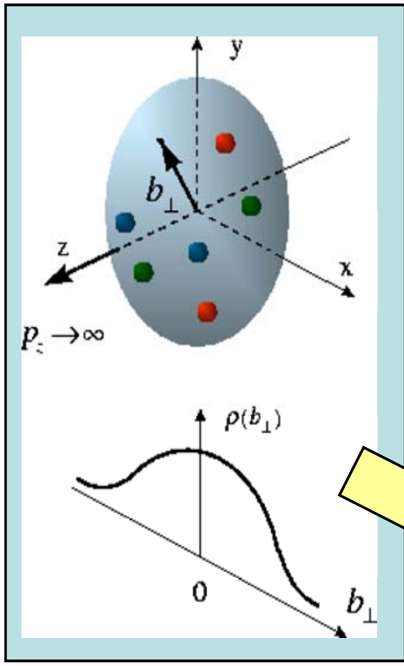
- Internal nucleon dynamics
- Transverse momentum distributions
- Quark-quark correlations
- Full (complex) quark wave functions
- Origin of the nucleon spin

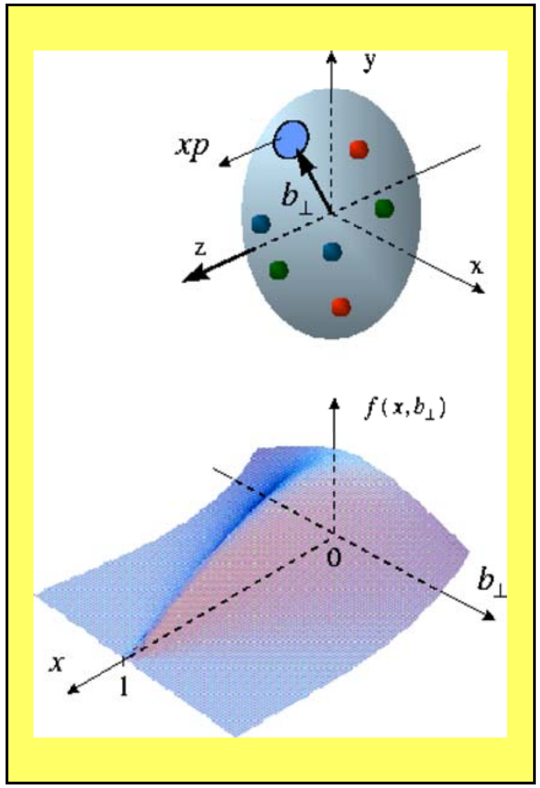
⬇

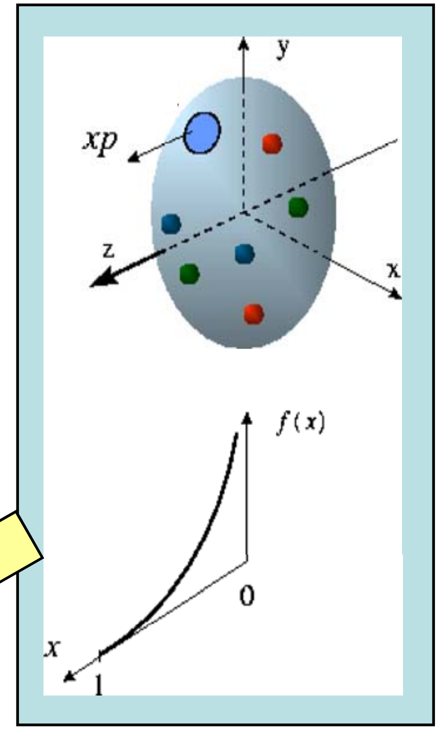
GPDs and Exclusive processes

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





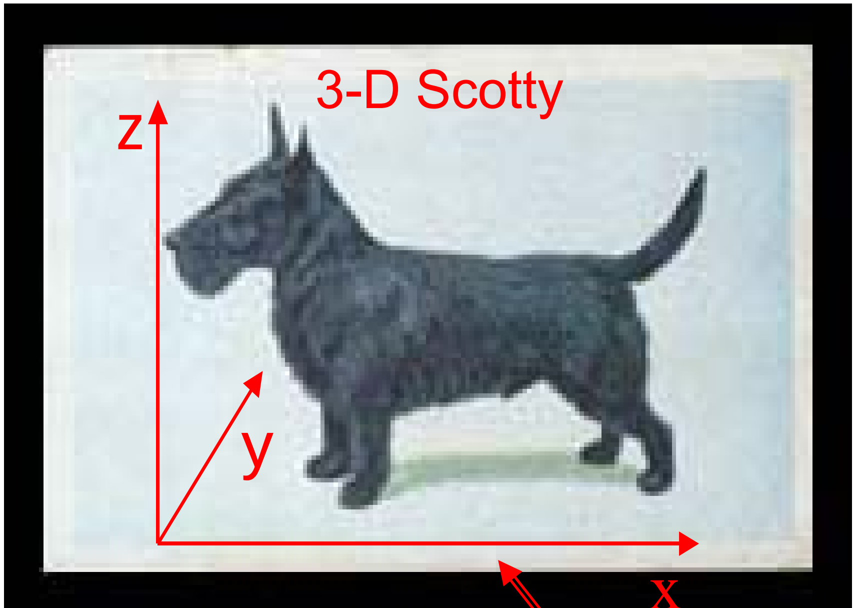


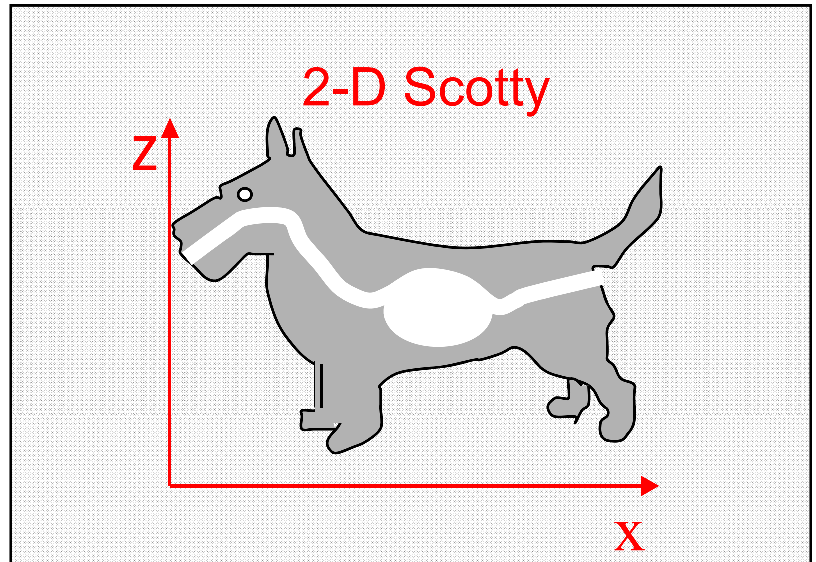
Proton form factors, transverse charge & current densities

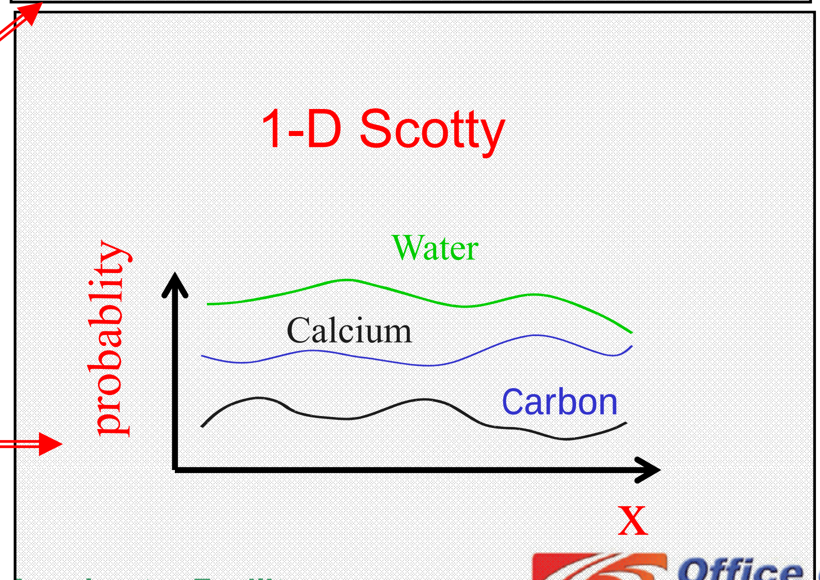
Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & spin distributions

GPDs & PDFs





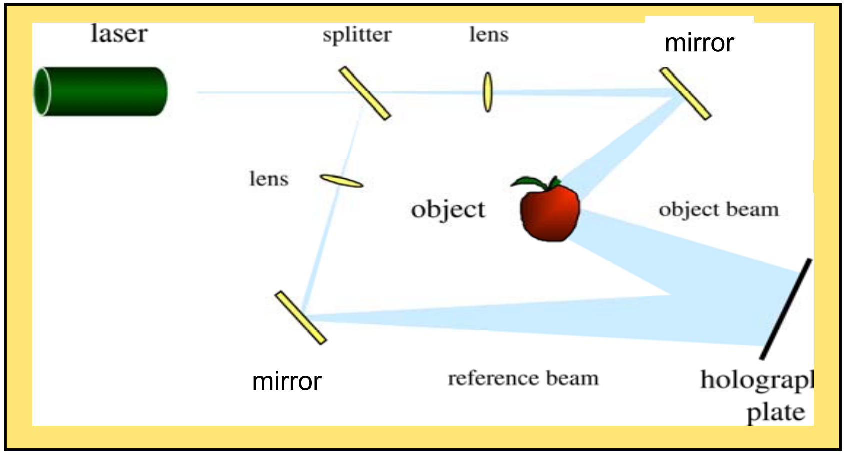


Deeply Virtual Exclusive Processes & GPDs

Deep Inelastic Scattering & Parton Distribution Functions.

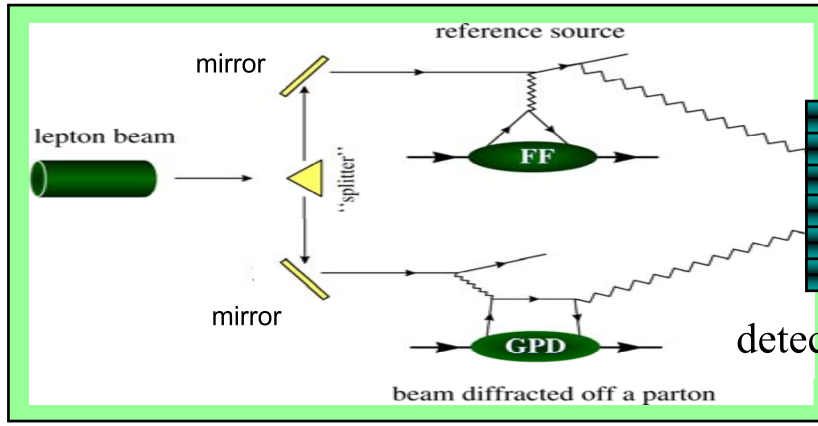
From Holography to Tomography

A. Belitsky, B. Mueller, NPA711 (2002) 118



An Apple

A Proton

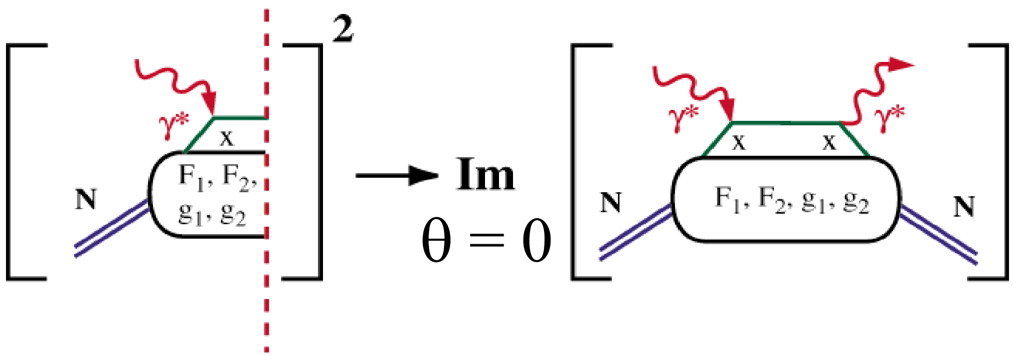


detector

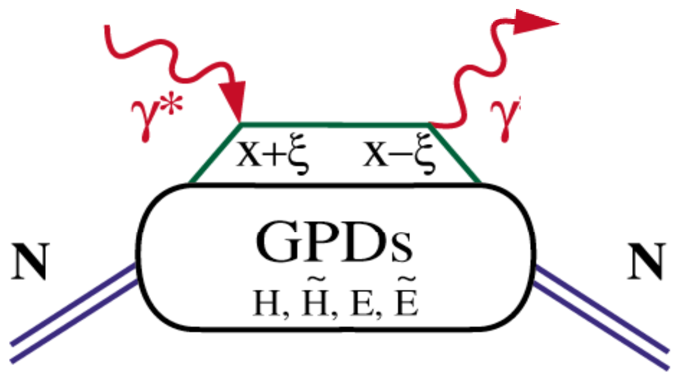
By varying the energy and momentum transfer to the proton we probe its interior and generate images of the proton's quark content.

Deeply Exclusive Scattering (DES)

Inclusive Scattering ⇒ Compton Scattering



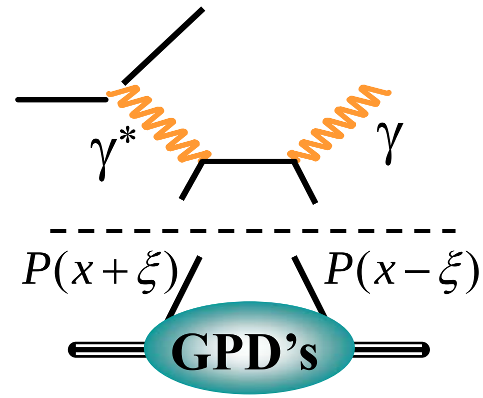
Deeply Virtual Compton Scattering (DVCS)



⇒ Probes the nucleon quark structure and correlations at the amplitude level

DVCS and Generalized Parton Distributions (GPDs)

GPDs: H, E unpolarized, $\tilde{H}$, $\tilde{E}$ polarized



e.g. $$\mathcal{H}(\xi, t, Q^2) = \int \frac{H^q(x, \xi, t, Q^2)dx}{x-\xi + i\varepsilon}$$

$$= \int \frac{H^q(x, \xi, t, Q^2)dx}{x-\xi} + i\pi H^q(\xi, \xi, t, Q^2)$$

real part

imaginary part

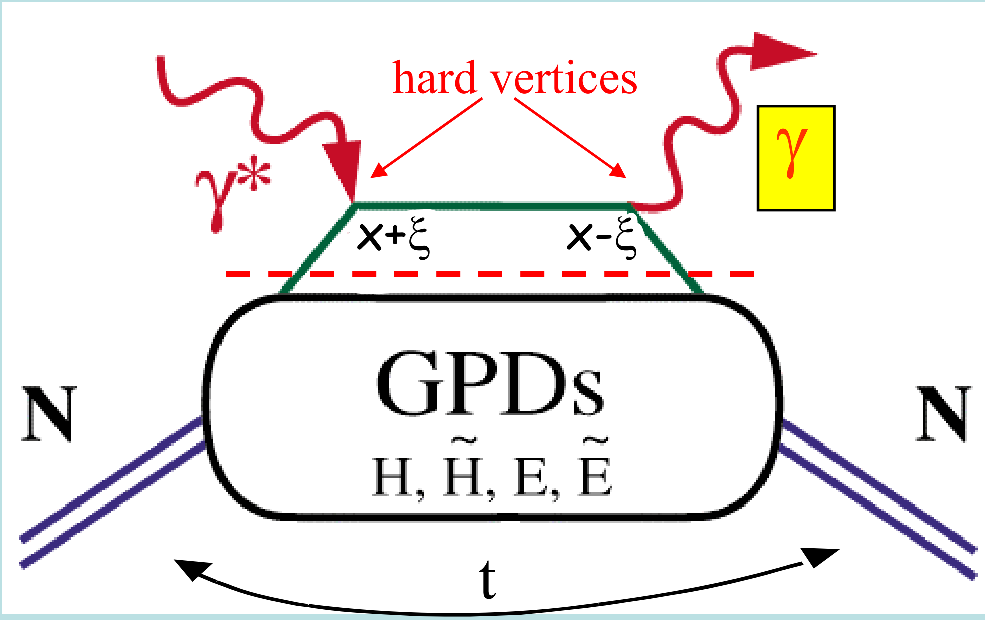
cross section difference

$$\frac{d^3\sigma}{dQ^2 dx_B dt} \sim [a\mathcal{H}(\xi, t, Q^2) + b\mathcal{E}(\xi, t, Q^2) + c\tilde{\mathcal{H}}(\xi, t, Q^2) + d\tilde{\mathcal{E}}(\xi, t, Q^2)]^2$$

H^q: Probability amplitude for N to emit a parton q with x+ξ and N' to absorb it with x- ξ.

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.

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

Link to DIS and Elastic Form Factors

DIS at $\xi=t=0$

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

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

Form factors

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

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

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

Forward limit

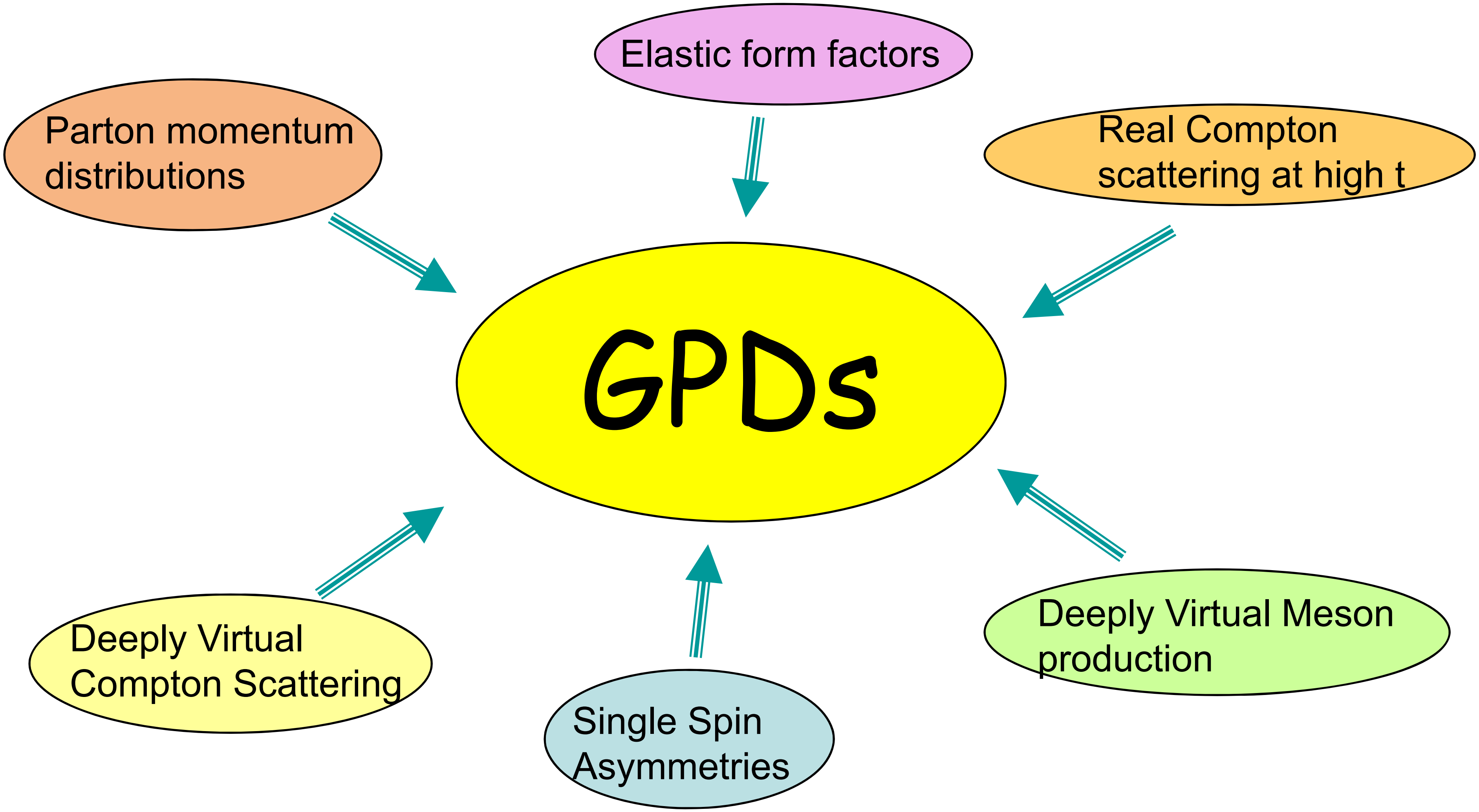
Sum rules

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

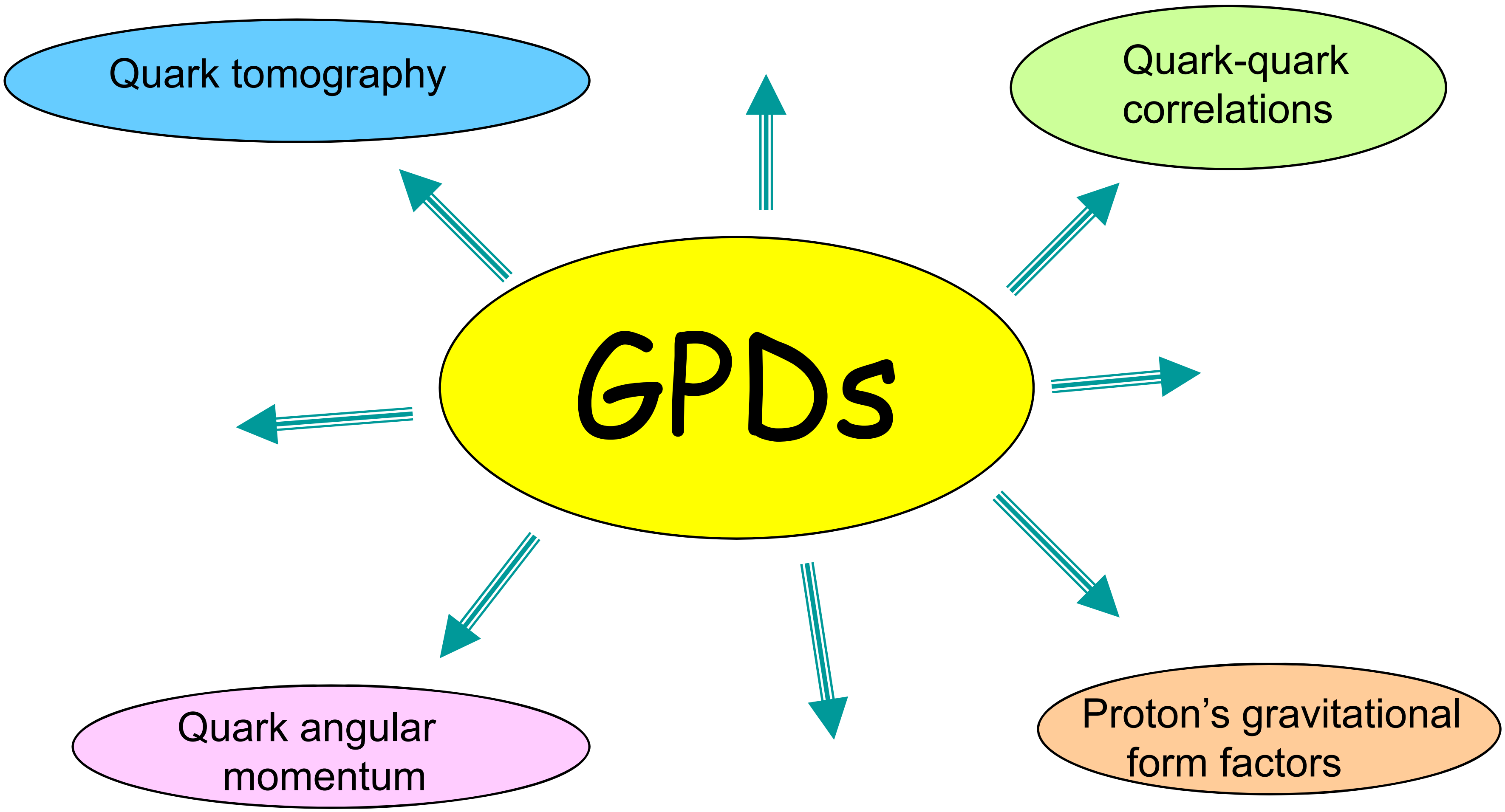
$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x dx \left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

Ji's Angular Momentum Sum Rule

Universality of GPDs



Universality of GPDs



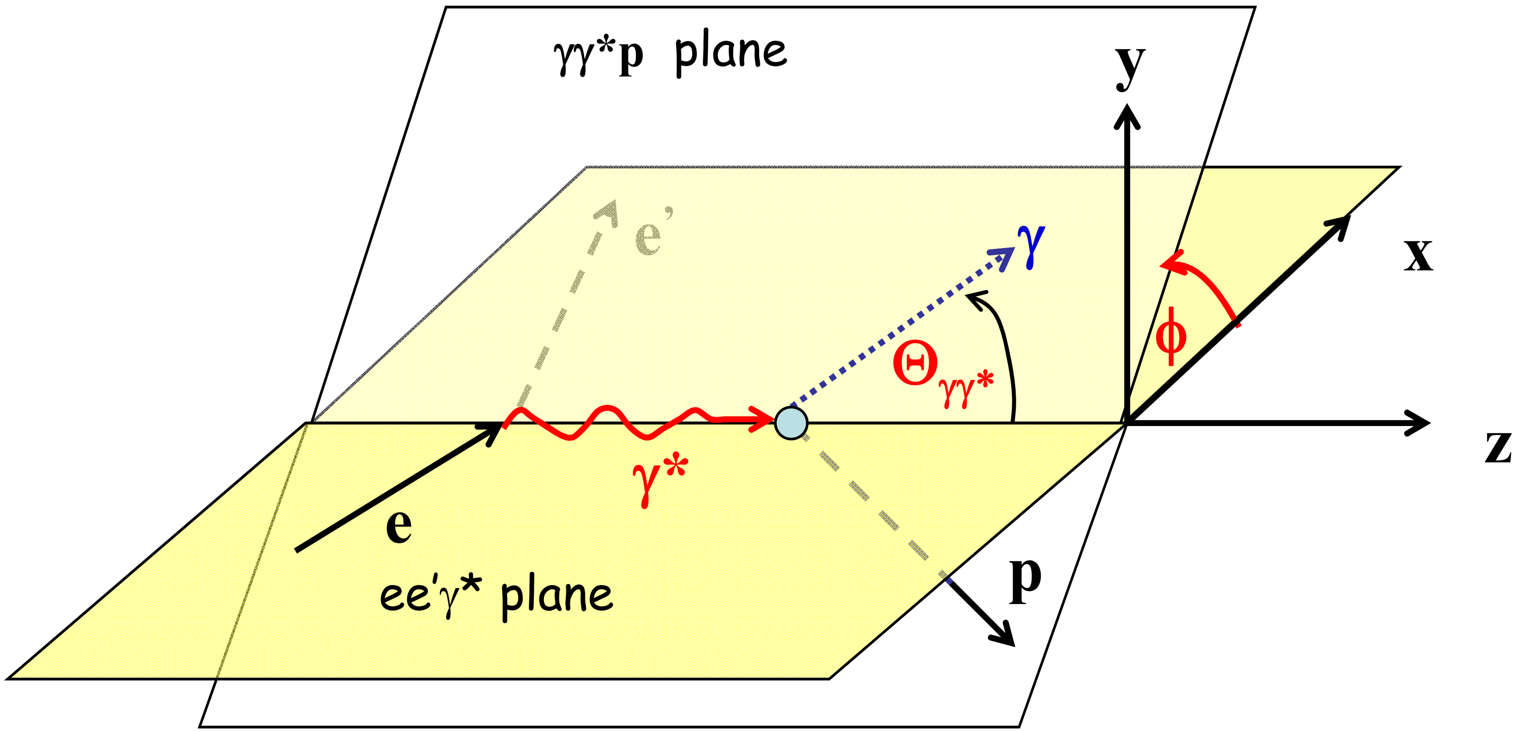
So, GPDs give access to complex Proton Structure, but …

How can be determine them?

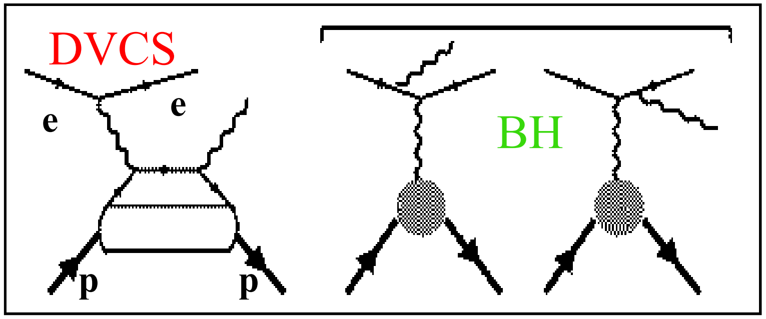
Deeply Virtual Compton Scattering

$ep \longrightarrow ep\gamma$

Kinematics



Access GPDs through Interference

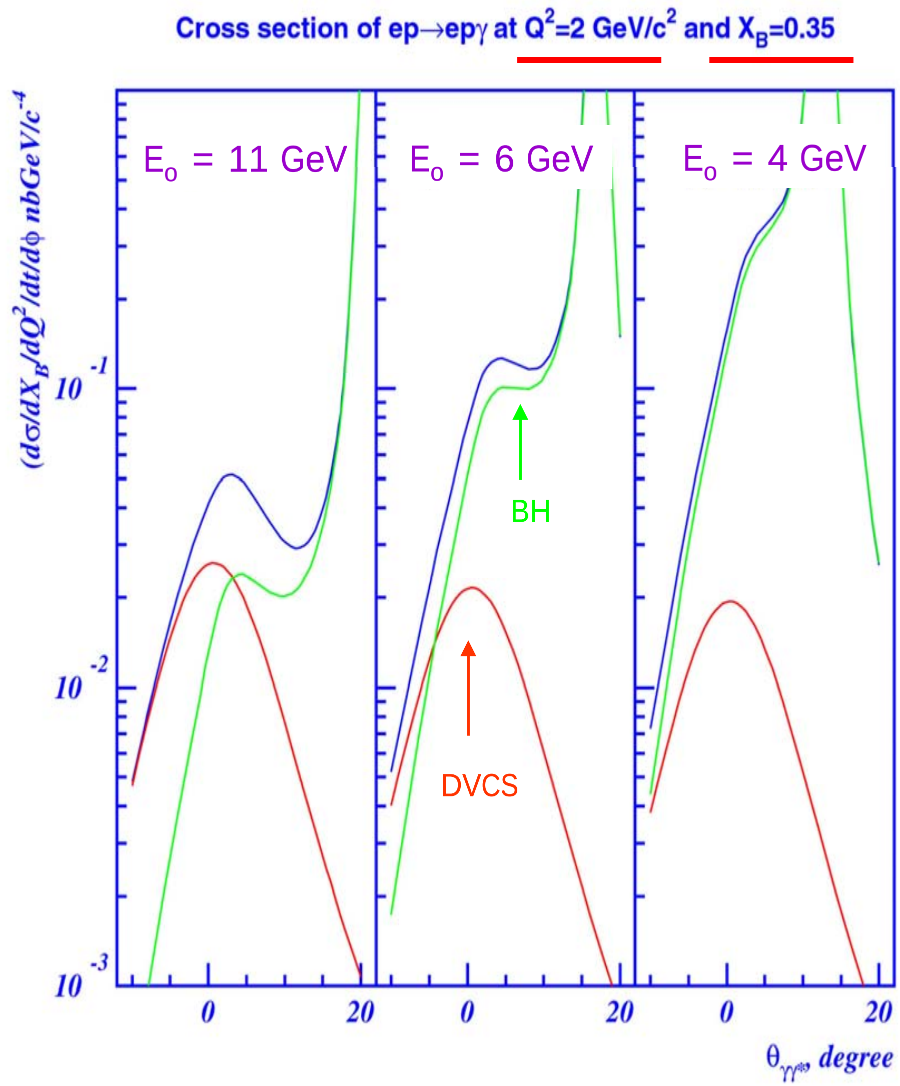


$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |T^{DVCS} + T^{BH}|^2$$

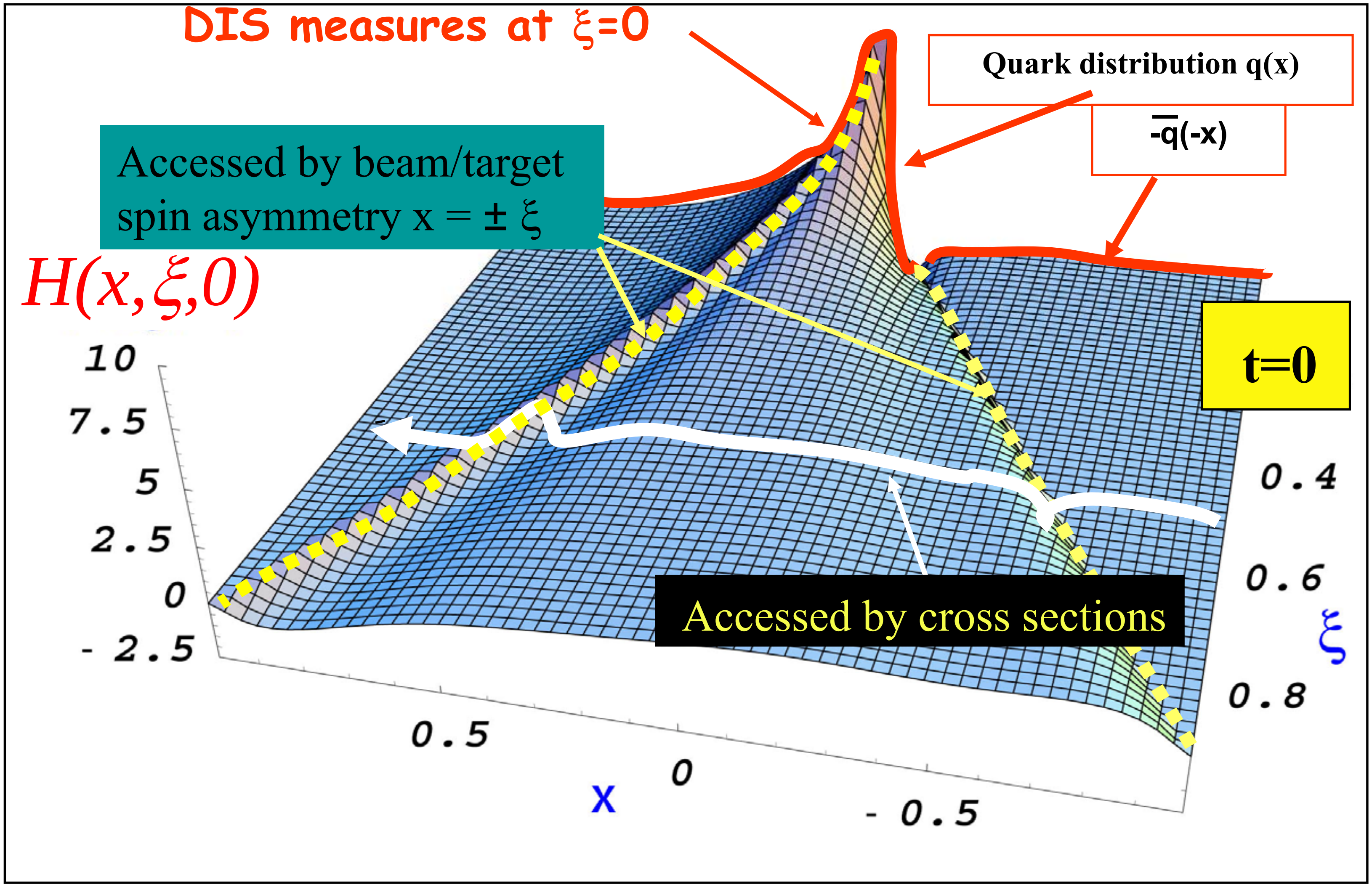
T^{BH}: given by elastic form factors F_1, F_2
T^{DVCS}: determined by GPDs

$$I \sim 2(T^{BH})\mathrm{Im}(T^{DVCS})$$

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



Model representation of GPD $H(x,\xi,0)$



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

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

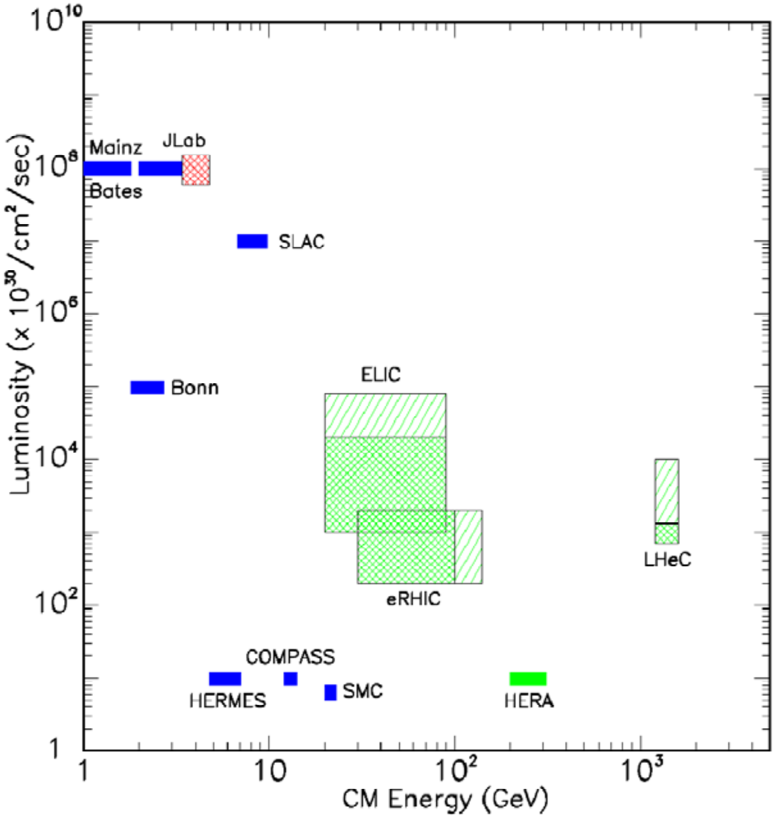
Typical cross sections and rates in eN/eA

Process		Cross section	Rate*,** (s^{-1})
$ep \to e'X$	inclusive DIS	$\sim$ few 10 nb	10^5
$ep \to e'\gamma p$	exclusive DVCS	$\sim$ 1 nb	10^4
$eA \to e'X$	nuclear DIS at $x > 1$	$\sim$ 1 pb	10
$eA \to e'A$	nuclear elastic FF at high t	$\sim$ 1 pb	10

$*$ Luminosity $L = 10^{37}\text{cm}^{-2}\text{s}^{-1}$ [1 nb $= 10^{-33}$ cm^2]

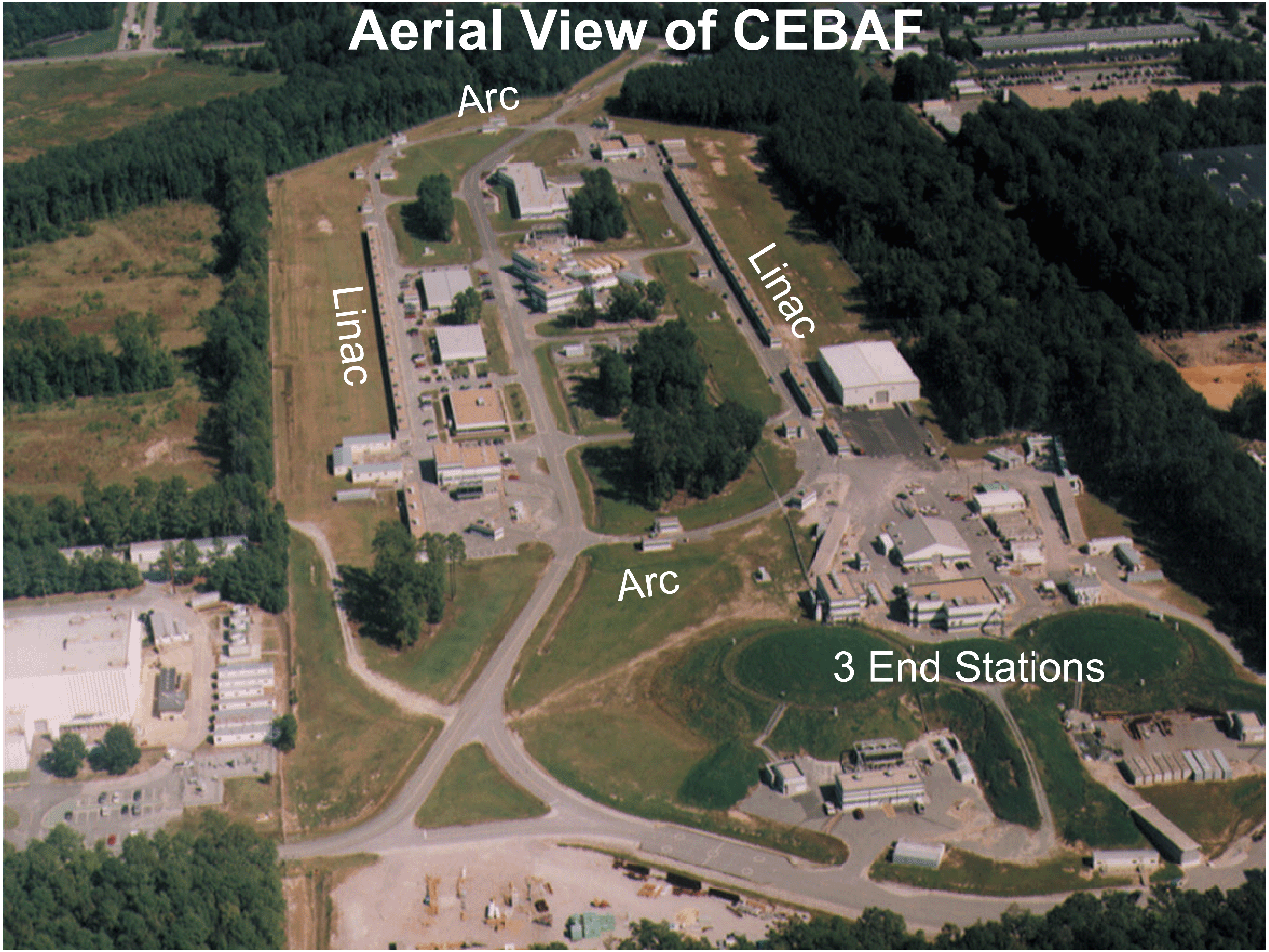
$**$ Does not include detector acceptance, kinematic cuts etc.

Characteristics of eN facilities

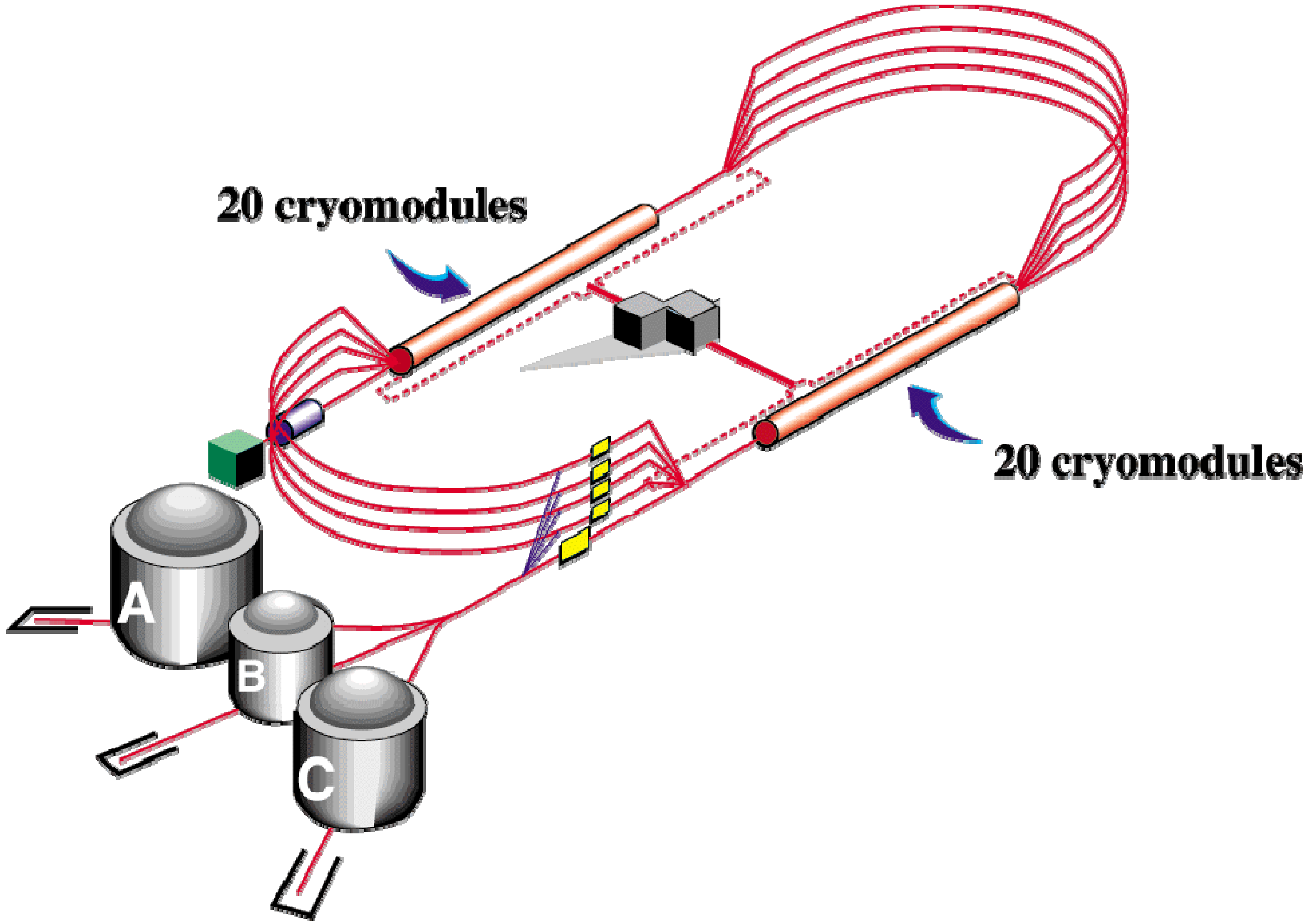


- Luminosity L: Number of possible eN collisions per time [$cm^{-2}S^{-1}$]
  $dN_{event} = L\sigma dt$
- Polarization (beam, target)

JLab: High –luminosity frontier


Aerial View of CEBAF
Arc
Linac
Linac
Arc
3 End Stations

6 GeV CEBAF



CEBAF Actual Parameters

- **Primary Beam: Electrons**
- **Beam Energy: 6 GeV**

nucleon → quark transition

baryon and meson excited states

- **100% Duty Factor (CW) Beam**

    •**coincidence experiments** ⇒ excite system with a known (q,ω) and observe its evolution

- **Three Simultaneous Beams with Independently Variable Energy and Intensity**

    •**complementary, long experiments**

- **Polarization (85% beam (!) and reaction products)**

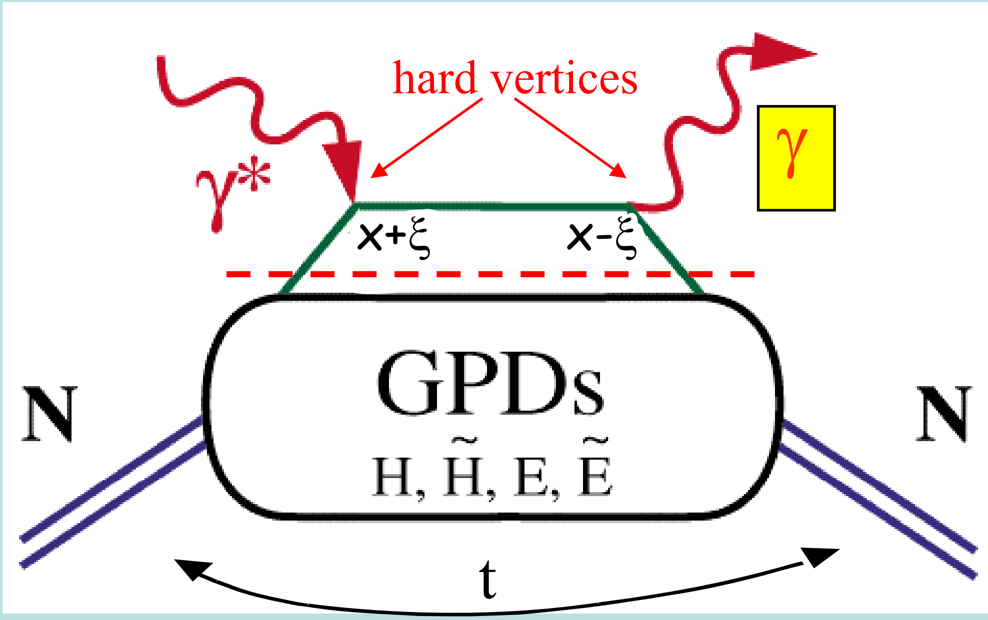
    •**spin degrees of freedom**

    weak neutral currents (extremely small helicity-correlated changes)

□ > 10^6 X SLAC at the time of the original DIS experiments

Basic Process – Handbag Mechanism

Deeply Virtual Compton Scattering (DVCS)



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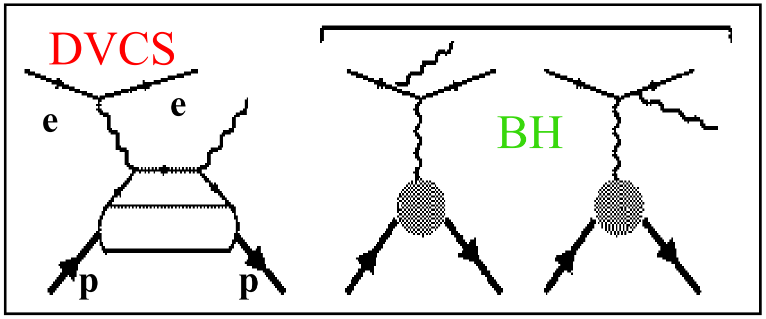

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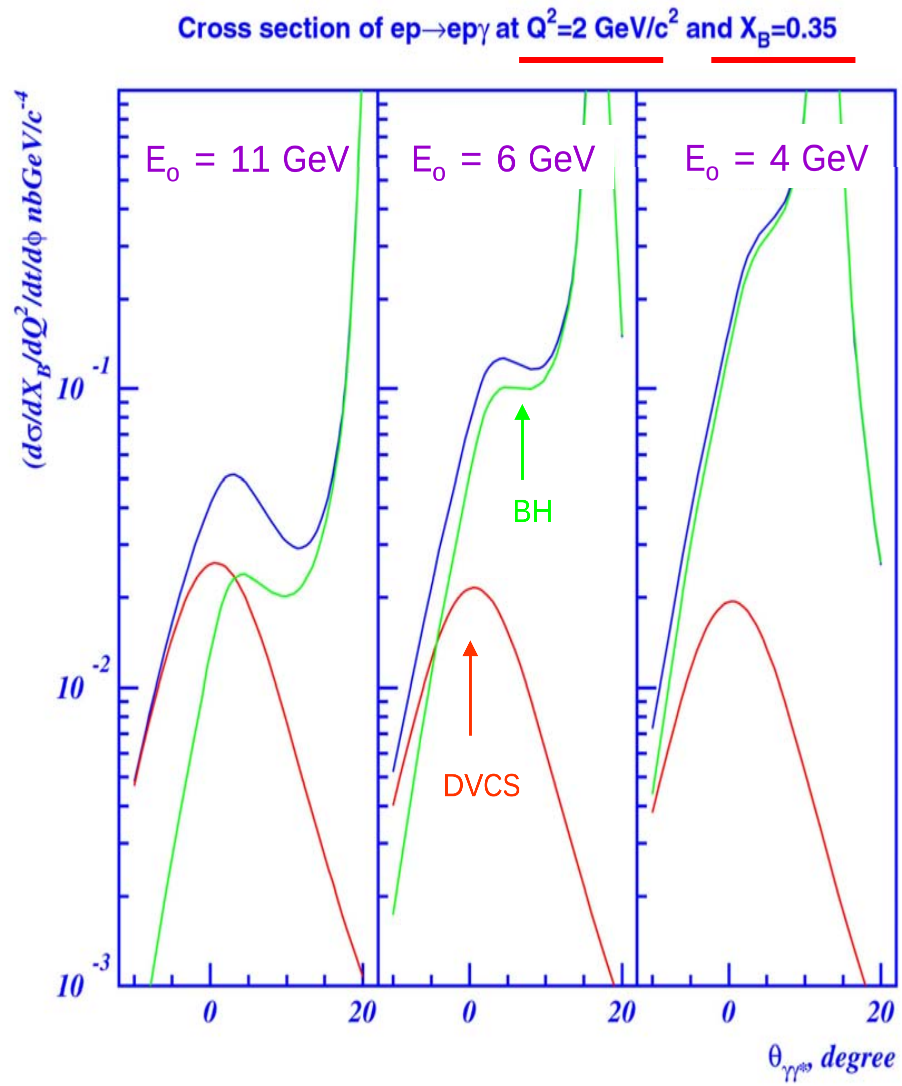
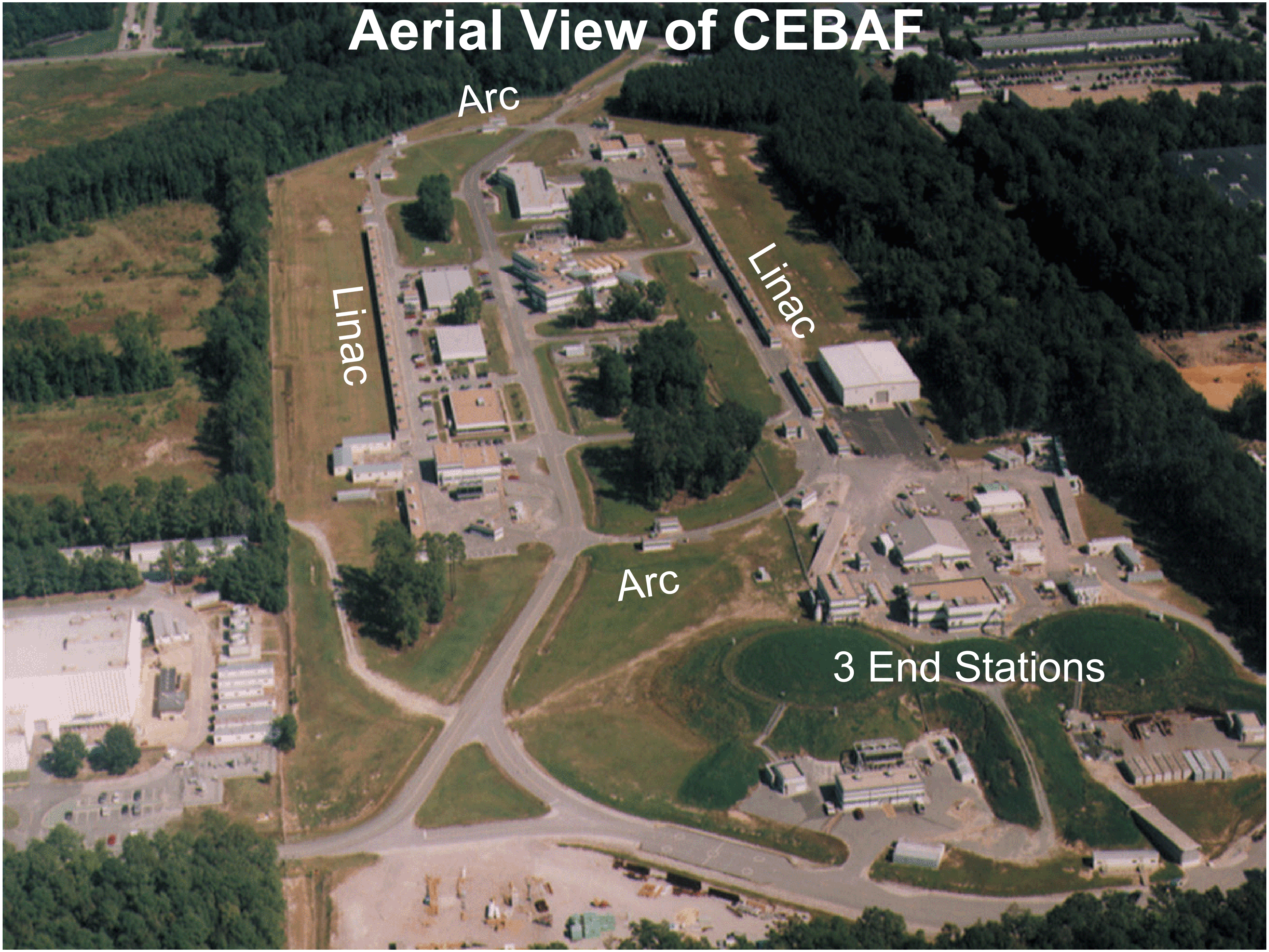
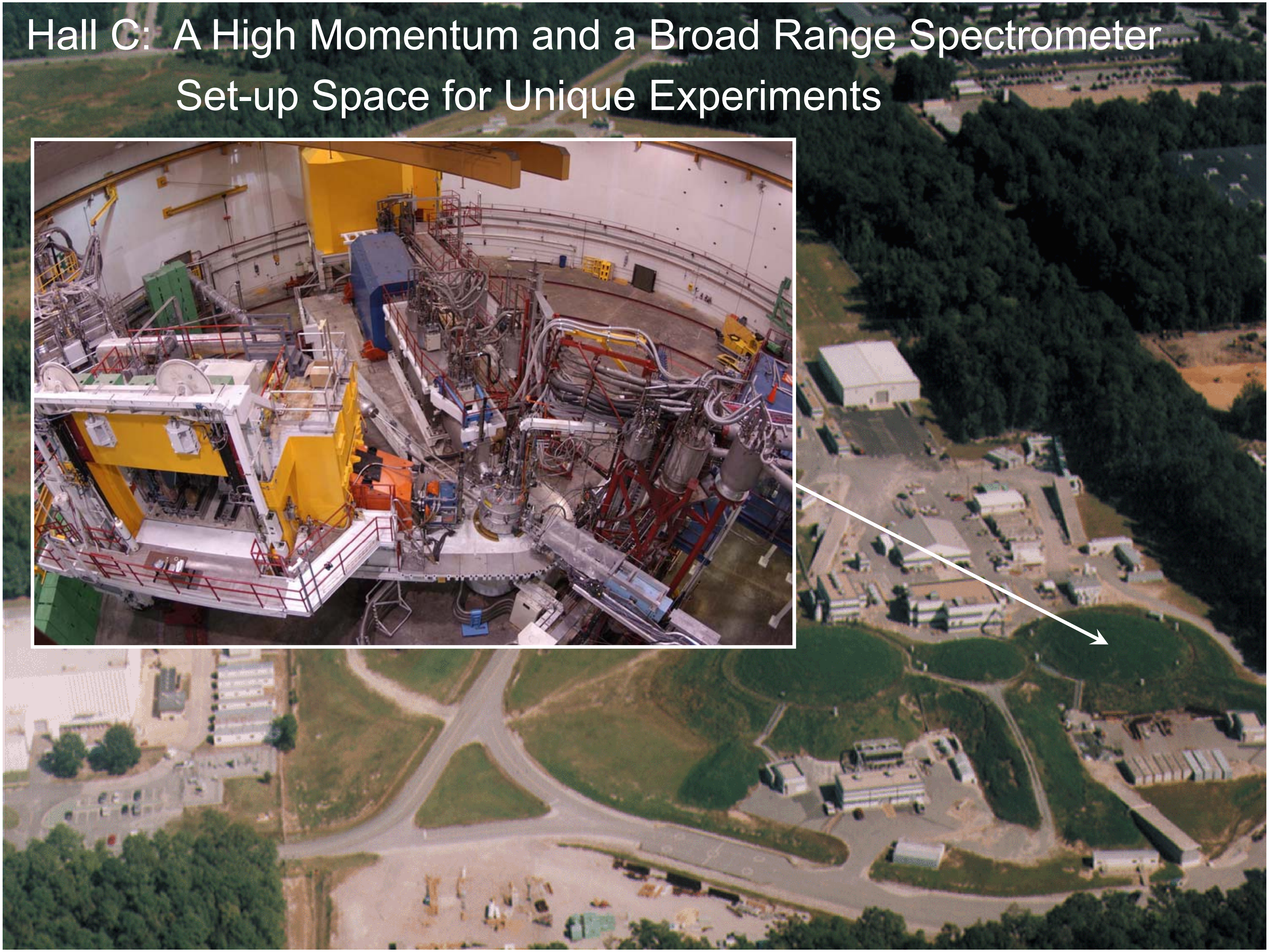


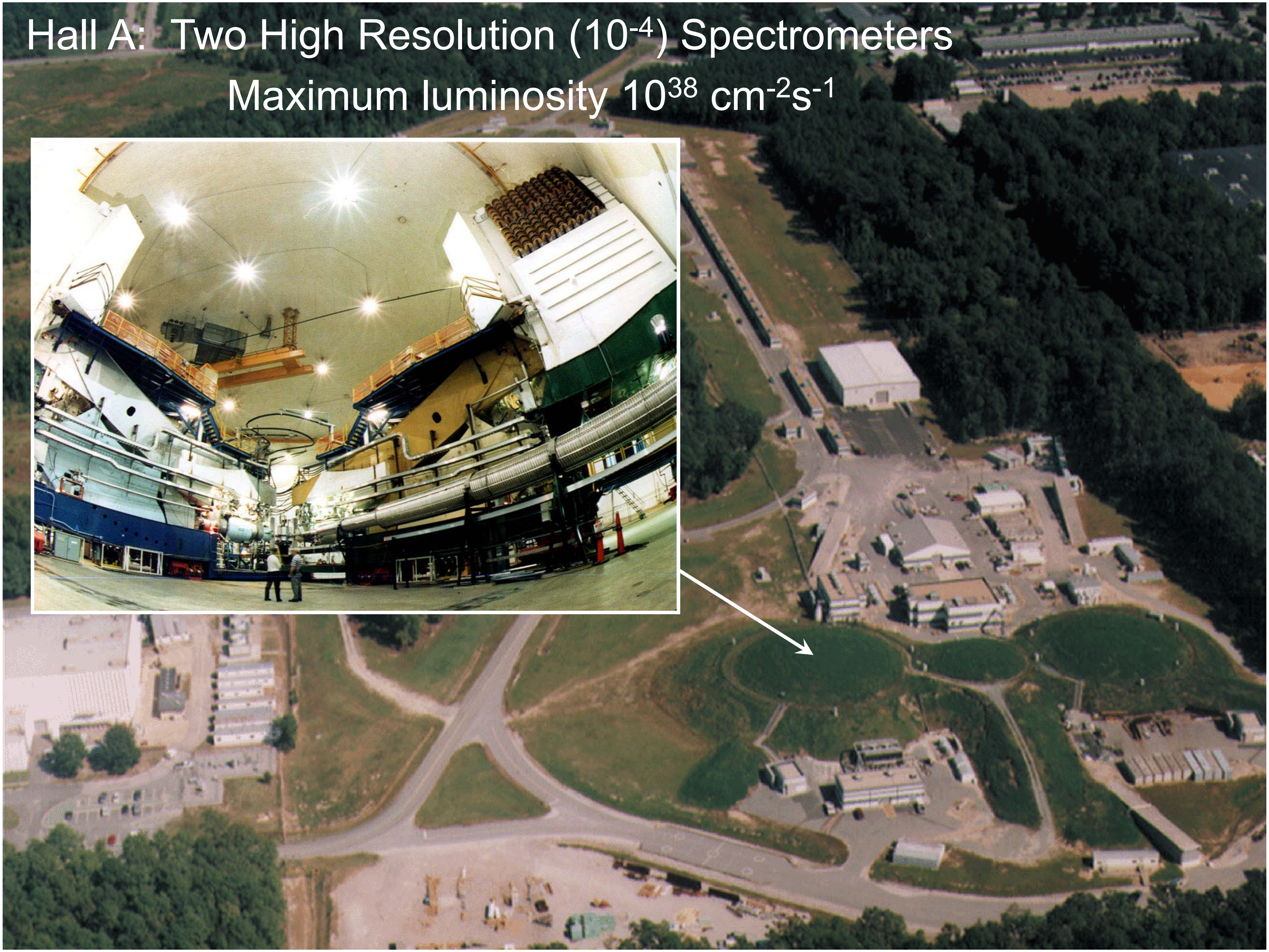

Aerial View of CEBAF
Arc
Linac
Linac
Arc
3 End Stations

Hall C: A High Momentum and a Broad Range Spectrometer
Set-up Space for Unique Experiments



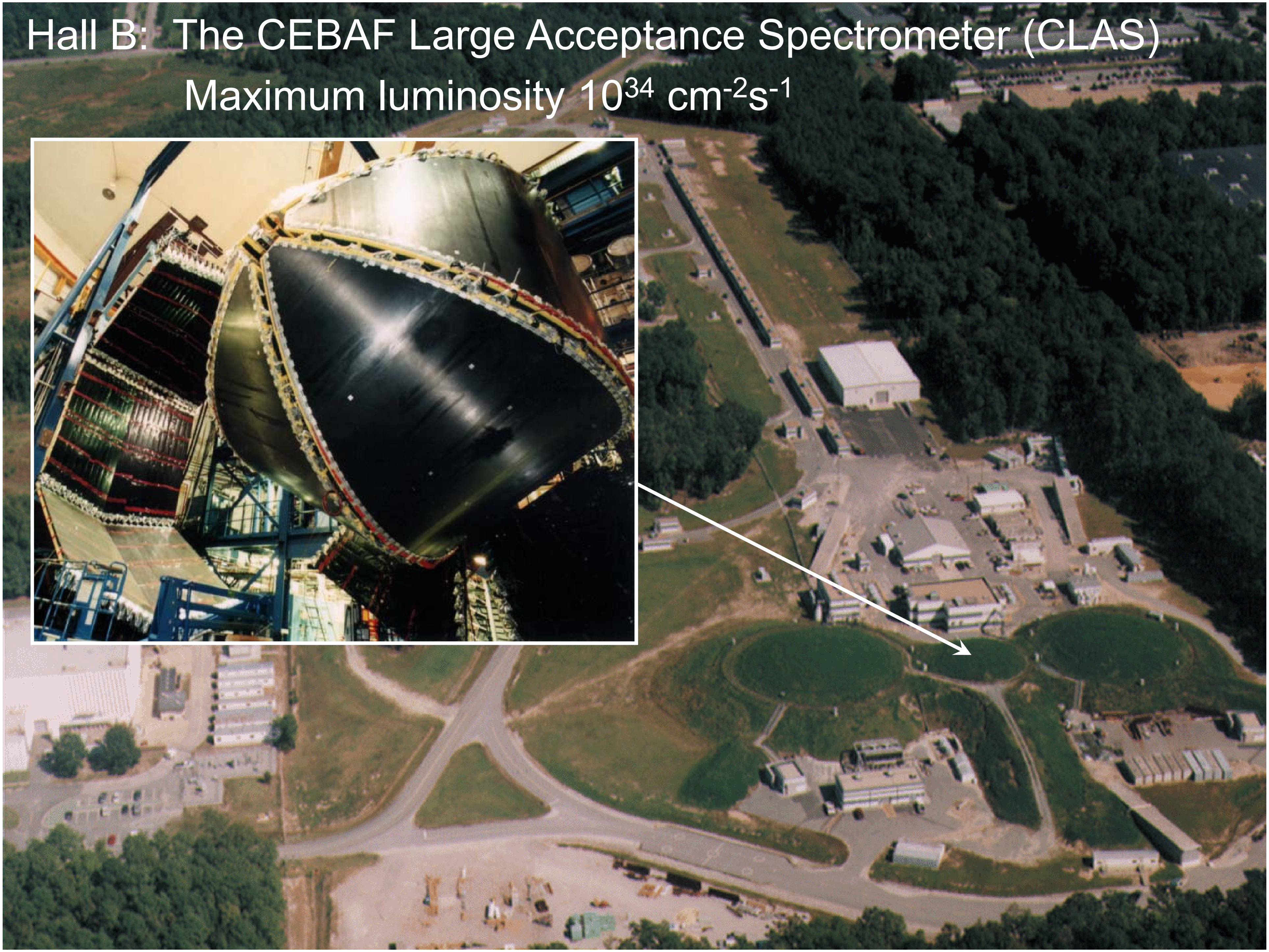
Hall A: Two High Resolution (10^{-4}) Spectrometers

Maximum luminosity 10^{38} $cm^{-2}s^{-1}$

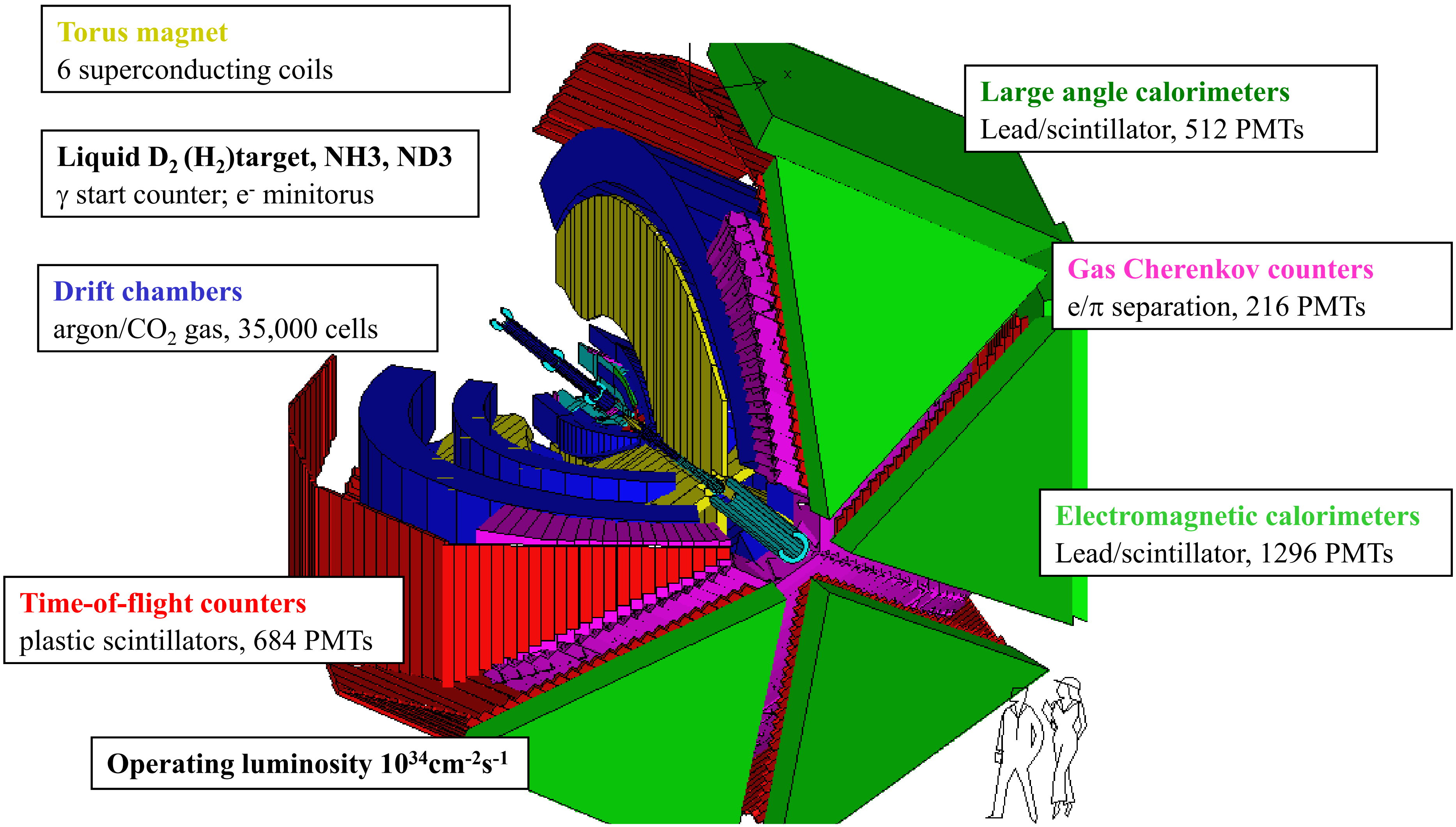


Hall B: The CEBAF Large Acceptance Spectrometer (CLAS)

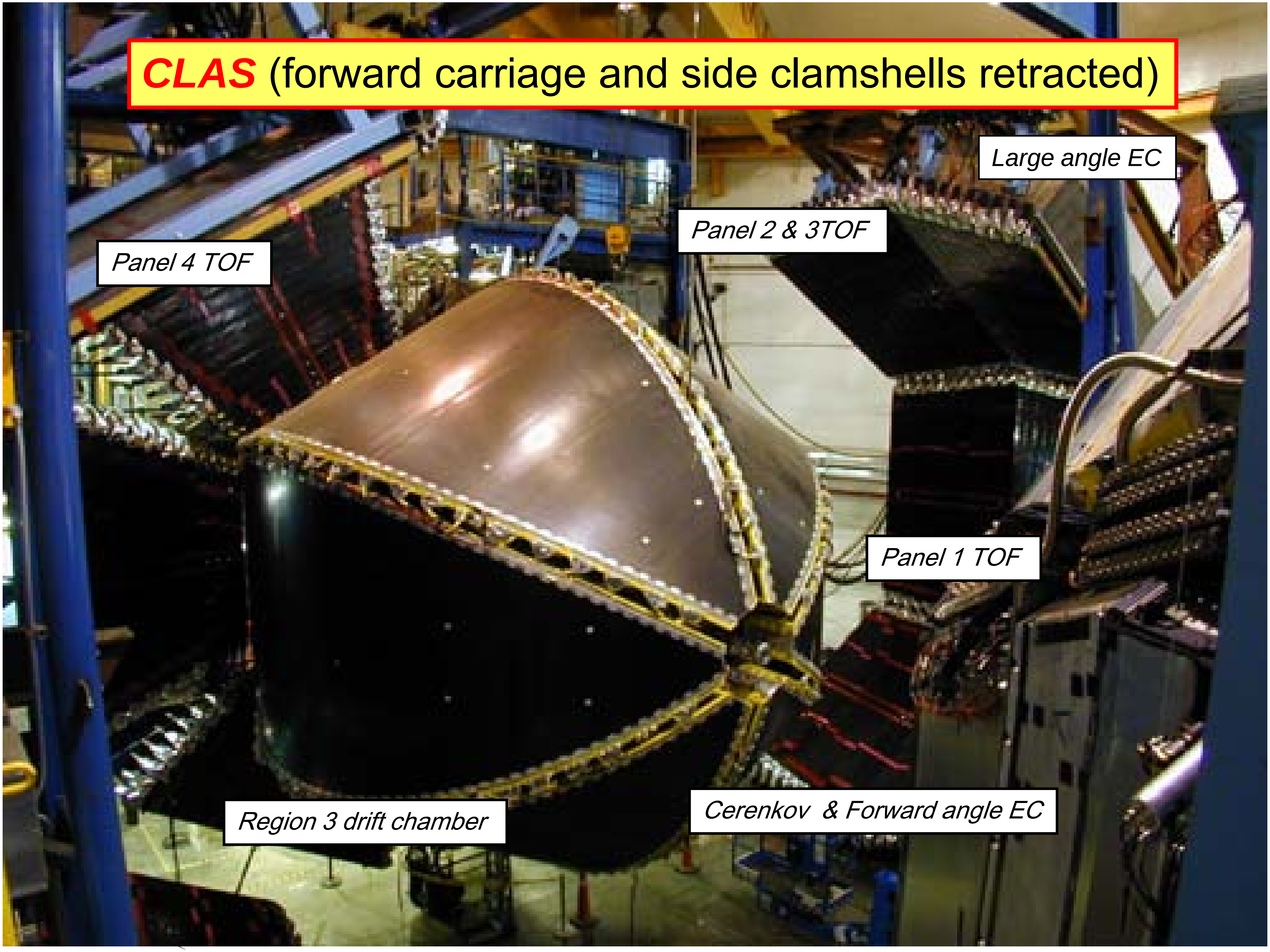
Maximum luminosity 10^{34} $cm^{-2}s^{-1}$



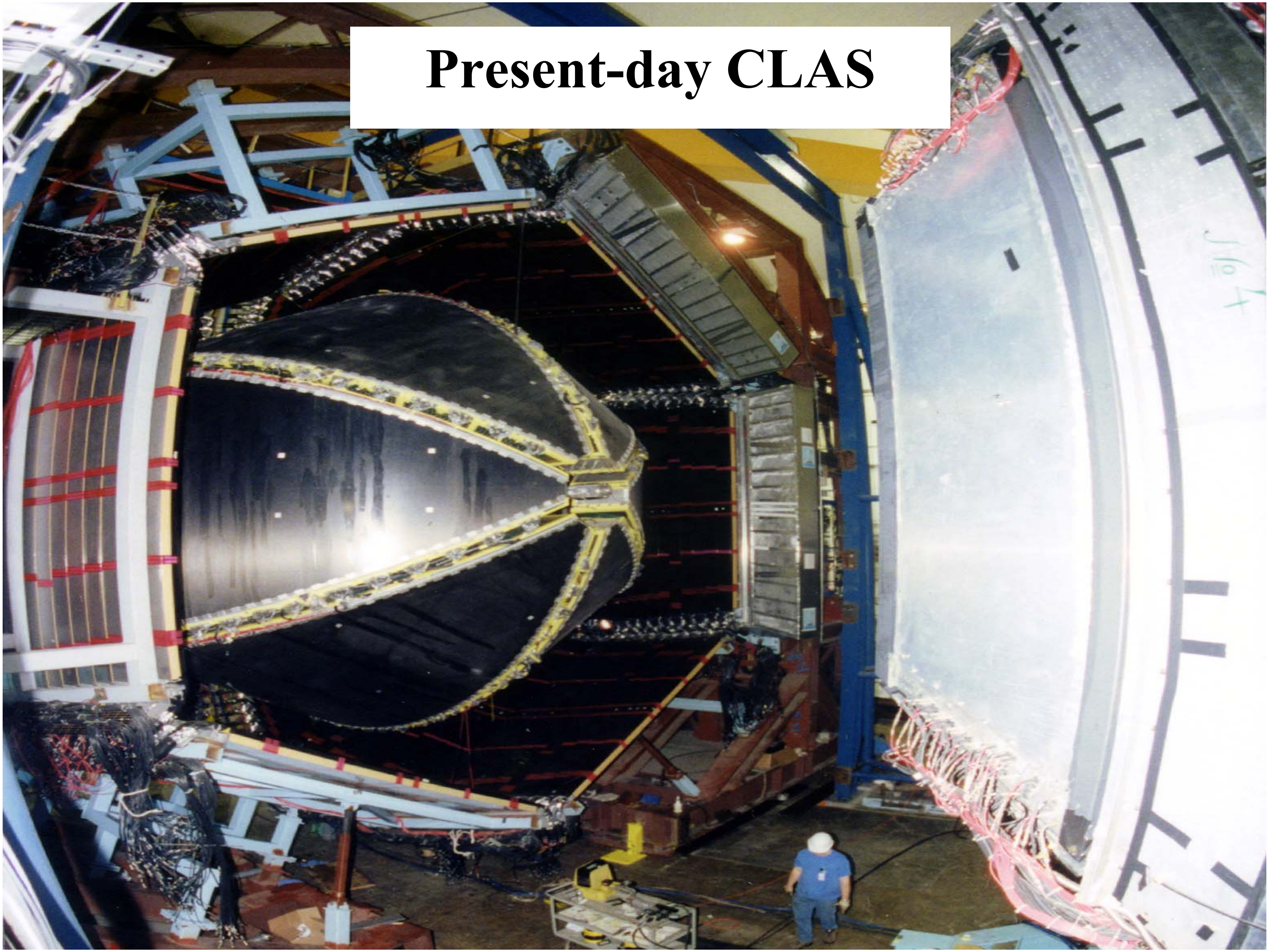
CEBAF Large Acceptance Spectrometer (CLAS)



CLAS (forward carriage and side clamshells retracted)

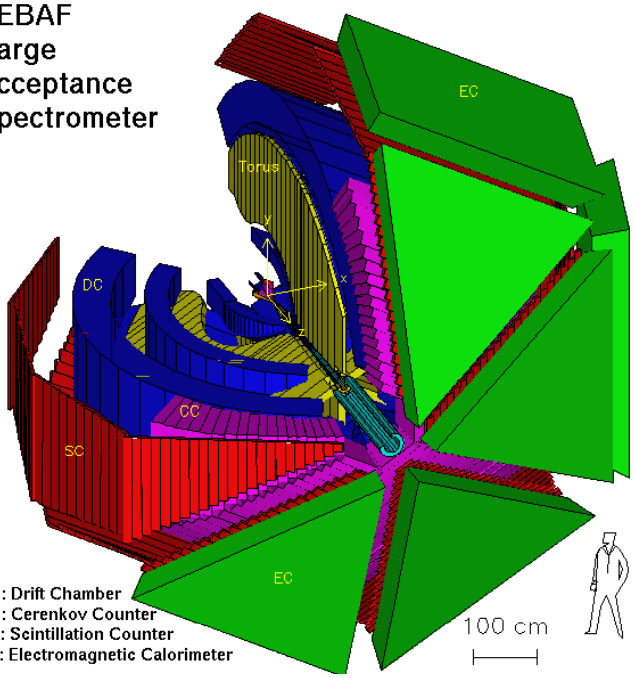


Present-day CLAS



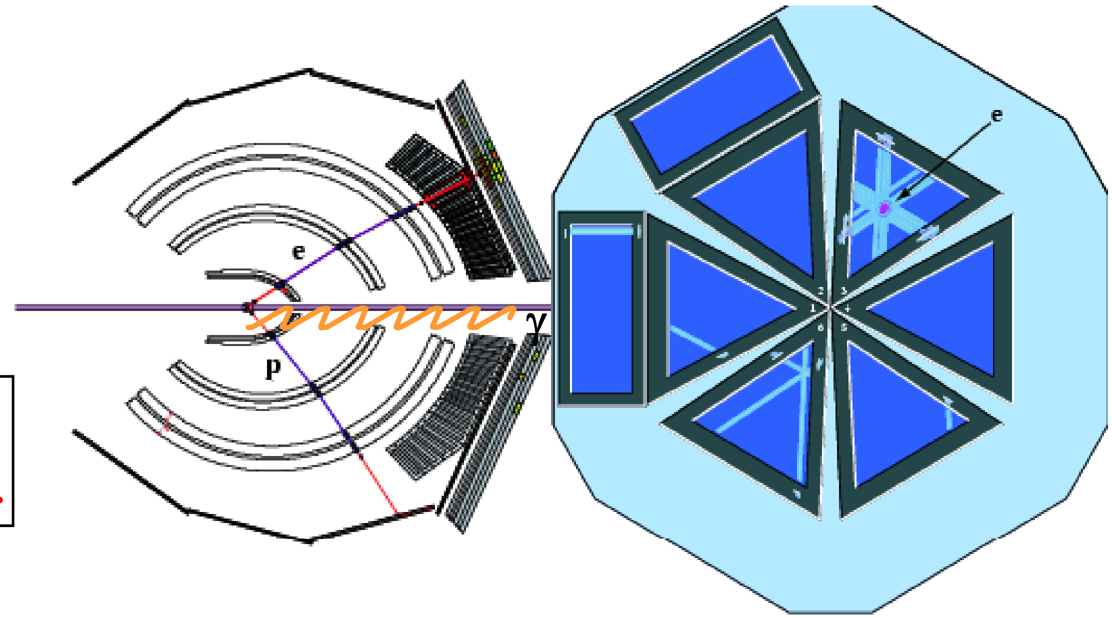
Analysis of CLAS 4.2 and 4.8 GeV data

CEBAF
Large
Acceptance
Spectrometer



Polarized electrons, E = 4.25 GeV and 4.8 GeV

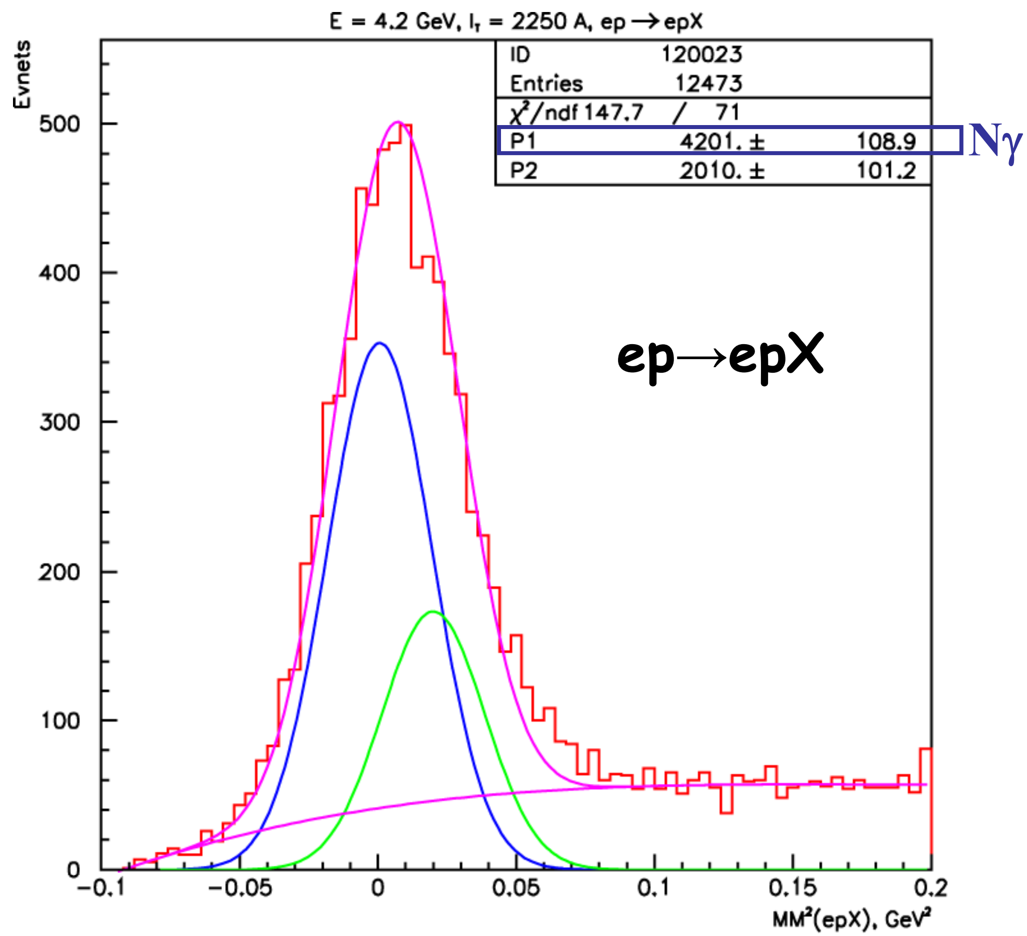
An $\vec{e}p \rightarrow epX$ event in CLAS



Separation of single γ from $\pi^0 \rightarrow \gamma\gamma$ using missing mass.

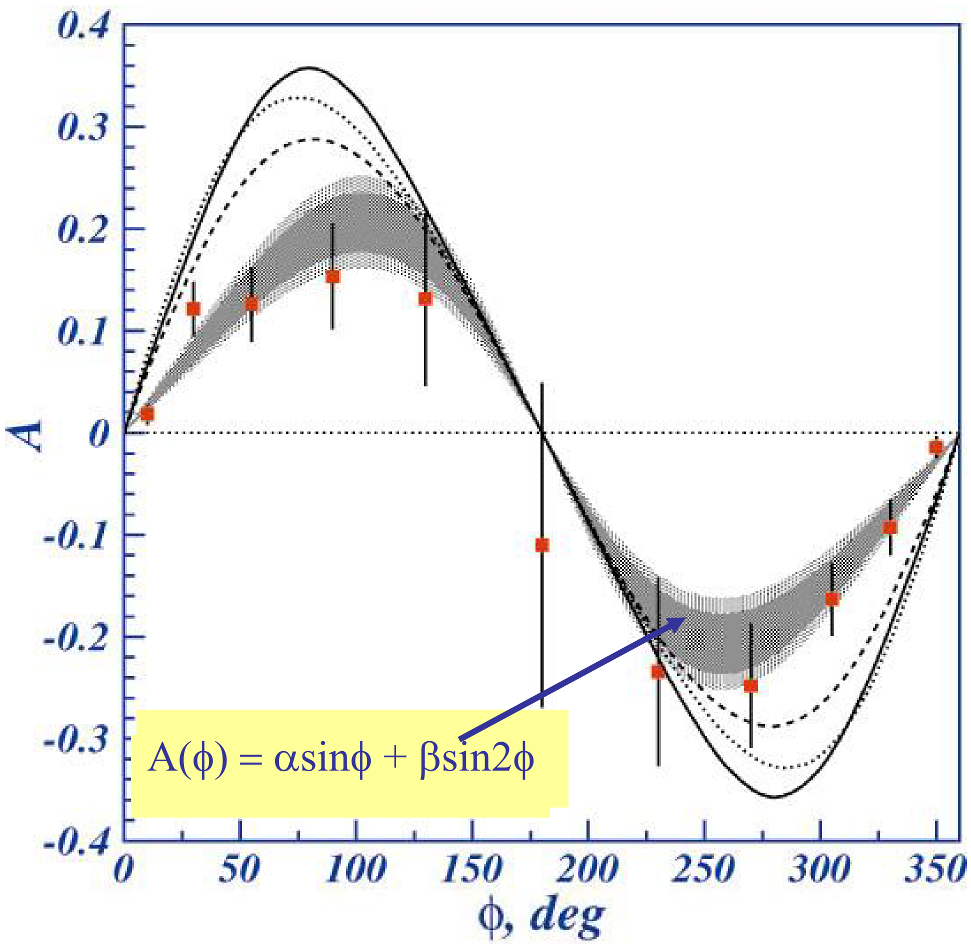
Background

Only 2-parameter fit: N_γ and N_{π^0}



Exclusive DVCS with CLAS

Beam Spin Asymmetry



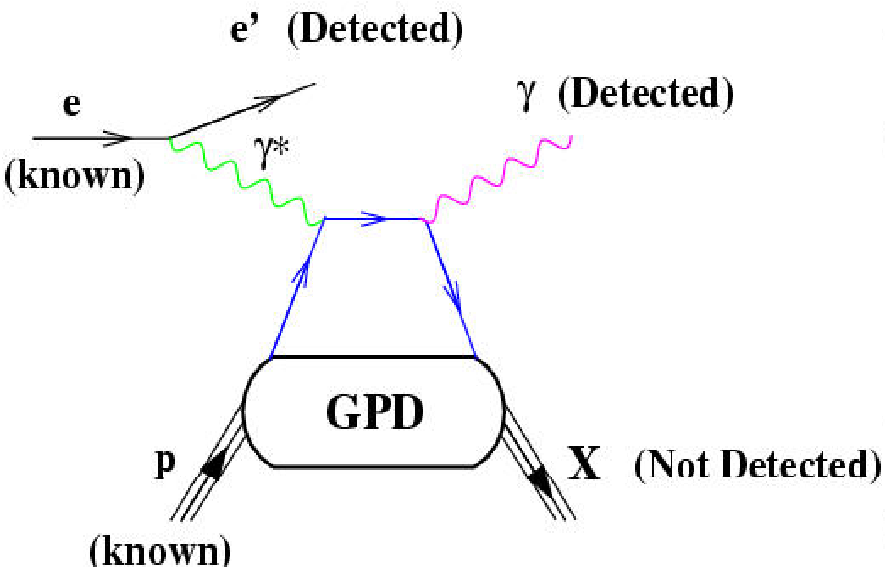
- Beam energy – 4.25 GeV
- $ep \to ep\gamma$ identified by analyzing the missing mass distribution $ep \to epX$

- W > 2 GeV
- $1 (GeV/c)^2 < Q^2 < 1.75 (GeV/c)^2$
- $0.1 (GeV/c)^2 < -t < 0.3 (GeV/c)^2$

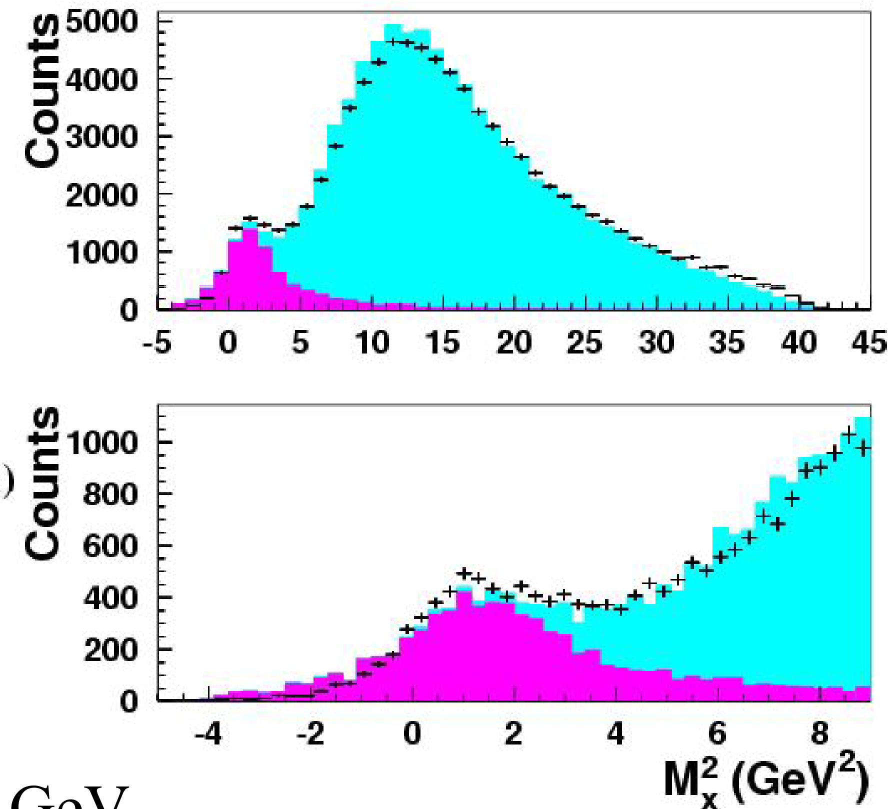
The measured asymmetry:

$$\alpha = 0.202 \pm 0.028^{stat} \pm 0.013^{sys}$$

Exclusivity for e p → e p γ



Missing Mass^2 = (p + γ* – γ)^2

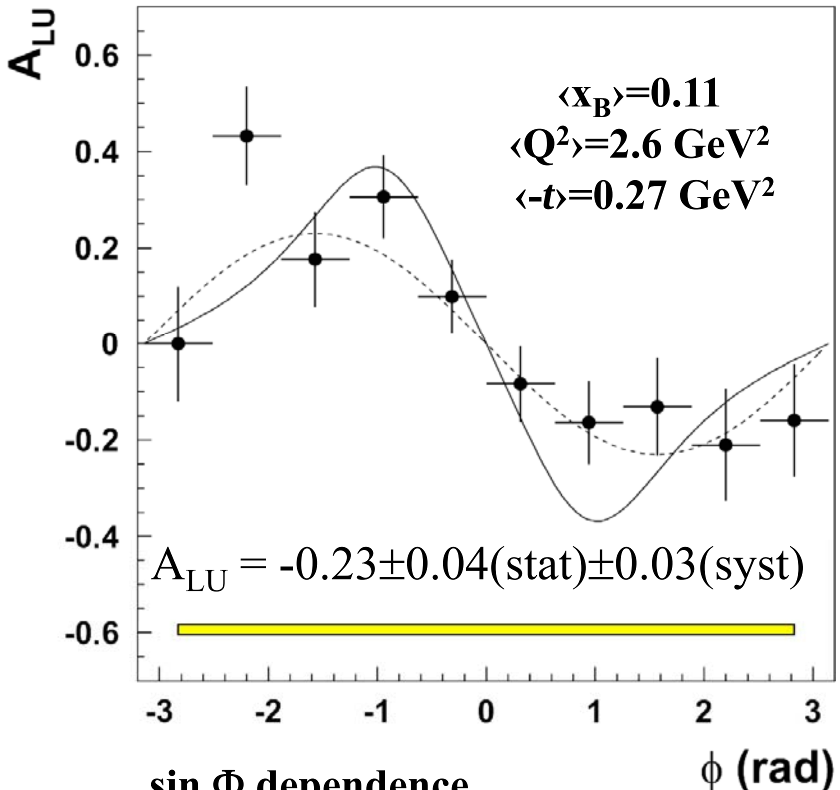


Missing Mass resolution : 0.8 GeV

Exclusive region: Missing Mass < 1.7 GeV

DVCS asymmetry measurement

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



.... **sin Φ dependence**

——— ***-Kivel, Polyakov & Vanderhaeghen (2001)***

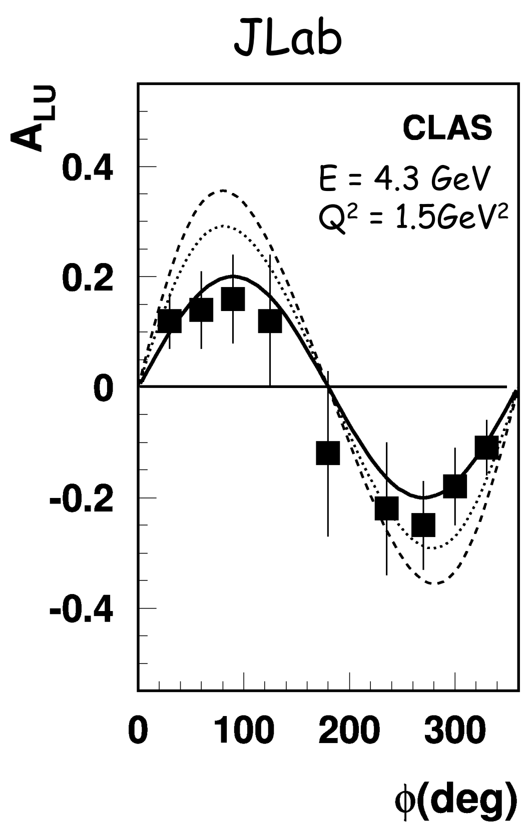
→ Signal of DVCS process

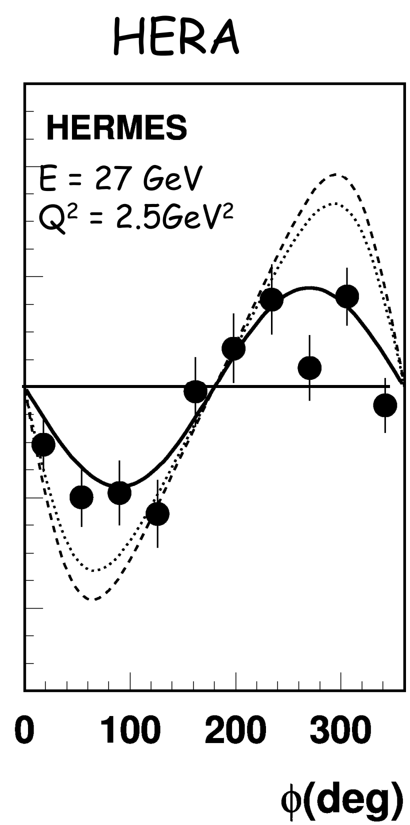
→ Can be described by GPD calculation

Pioneering experiments observe interference !

2001

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





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

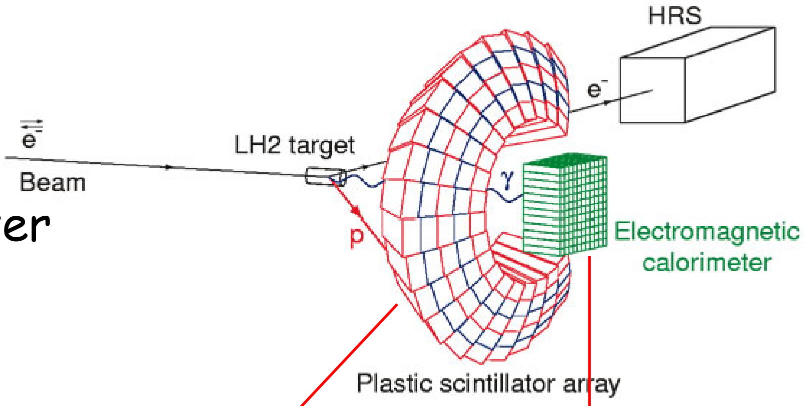
$$A_{UL} = \alpha \sin\phi + \beta \sin 2\phi$$

↑ Leading term ↑ non-leading

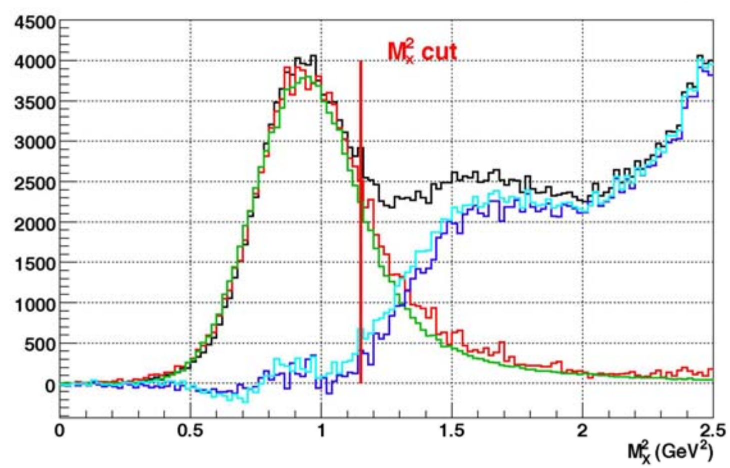
Non-leading contributions are small!

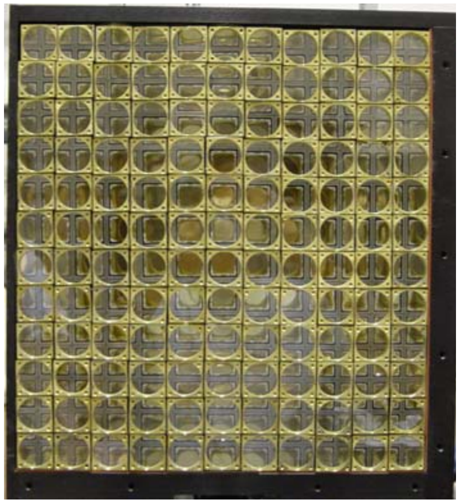
DVCS in Hall A (E00-110 and E03-106)

- 75% polarized 2.5 μA electron beam
- 15 cm LH2 target -> L = 10^{37} $cm^{-2}s^{-1}$
- Left Hall A HRS with electron package
- 11x12 blocks PbF_2 electromagnetic calorimeter
- 5x20 blocks plastic scintillator array



- Clear DVCS identification from HRS+calo



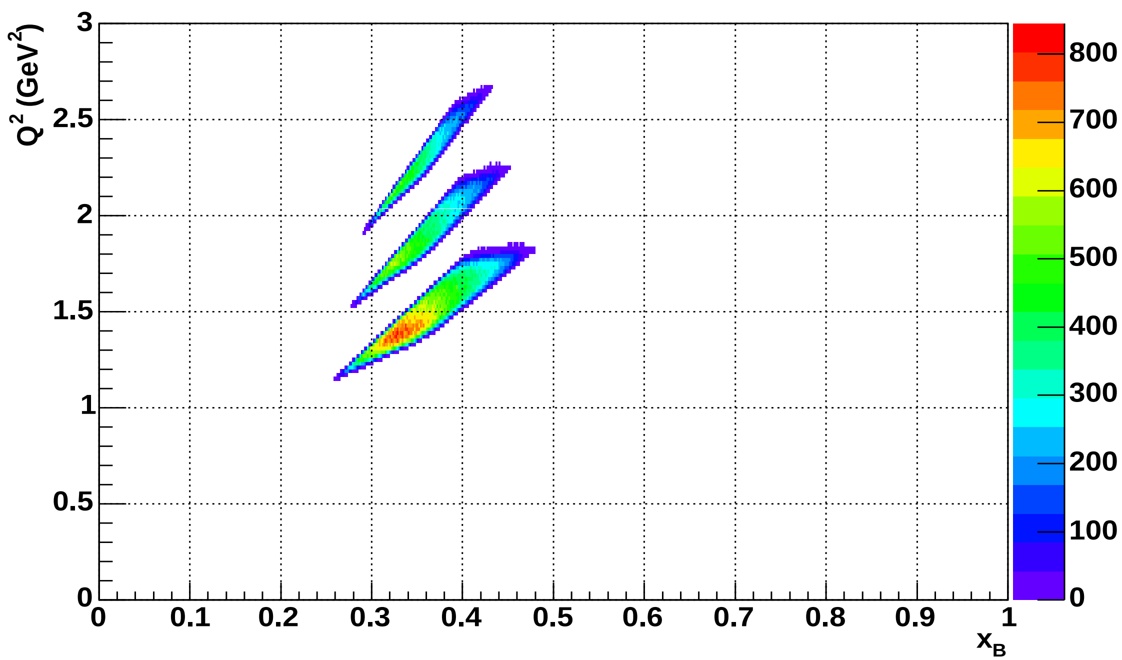


Clermont-Ferrand, Saclay, Grenoble, ODU, Rutgers

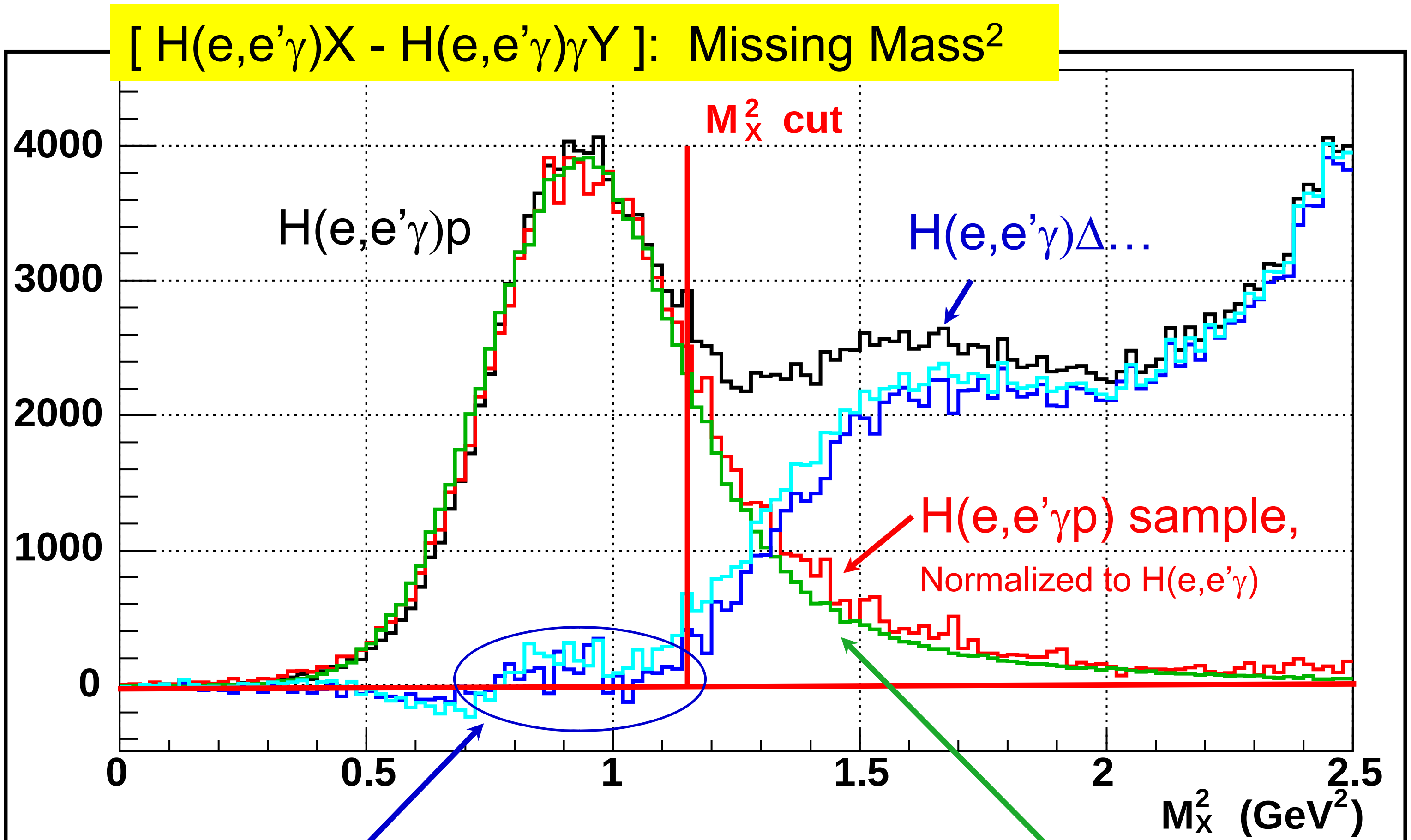
E00-110 kinematics

Kin	Q^2 (GeV^2)	x_B	θ_{γ^*} (deg.)	W (GeV)
1	**1.5**	0.36	**22.3**	1.9
2	**1.9**	0.36	**18.3**	2.0
3	**2.3**	0.36	**14.8**	2.2

The calorimeter is centered on the virtual photon direction.



H(e,e'γ) Exclusivity



<2% in estimate of H(e,eγ)Nπ… below threshold $M_X^2 < (M+m)^2$

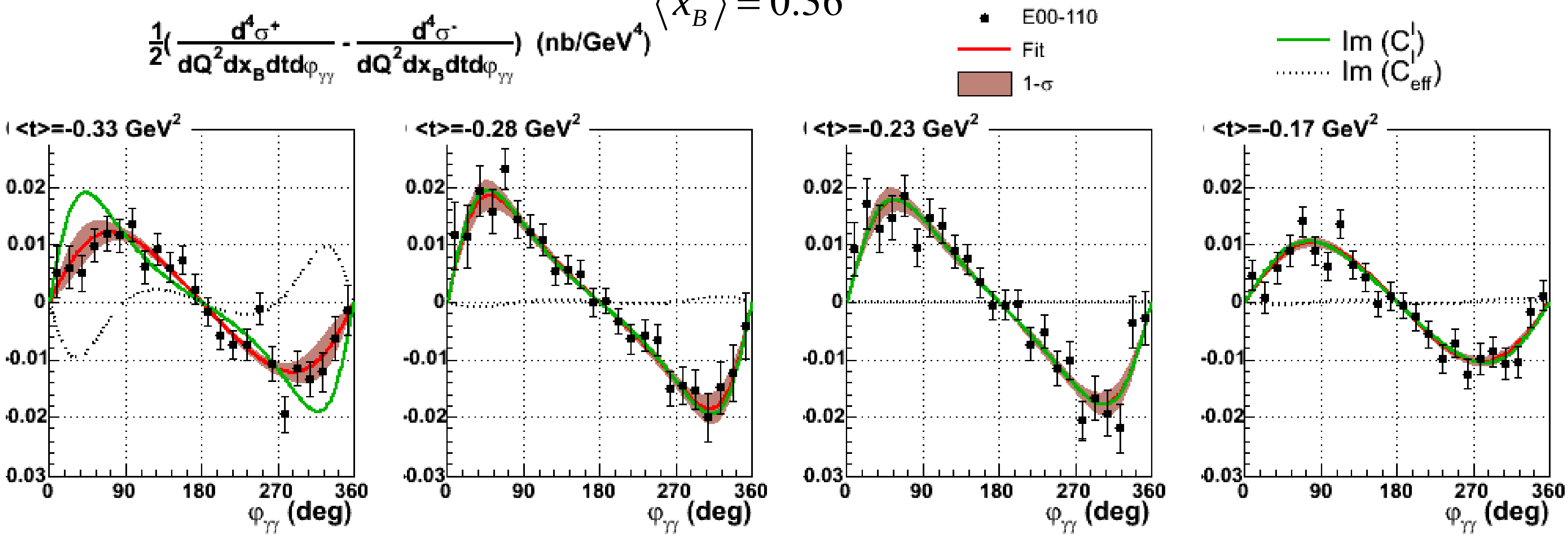
H(e,e'γp) simulation, Normalized to data

Difference of cross sections

PRL97, 262002 (2006)

$$\langle Q^2 \rangle = 2.3 \text{ GeV}^2$$

$$\langle x_B \rangle = 0.36$$



Corrected for real+virtual RadCor

Corrected for efficiency

Corrected for acceptance

Corrected for resolution effects

Checked elastic cross section @ ~1%

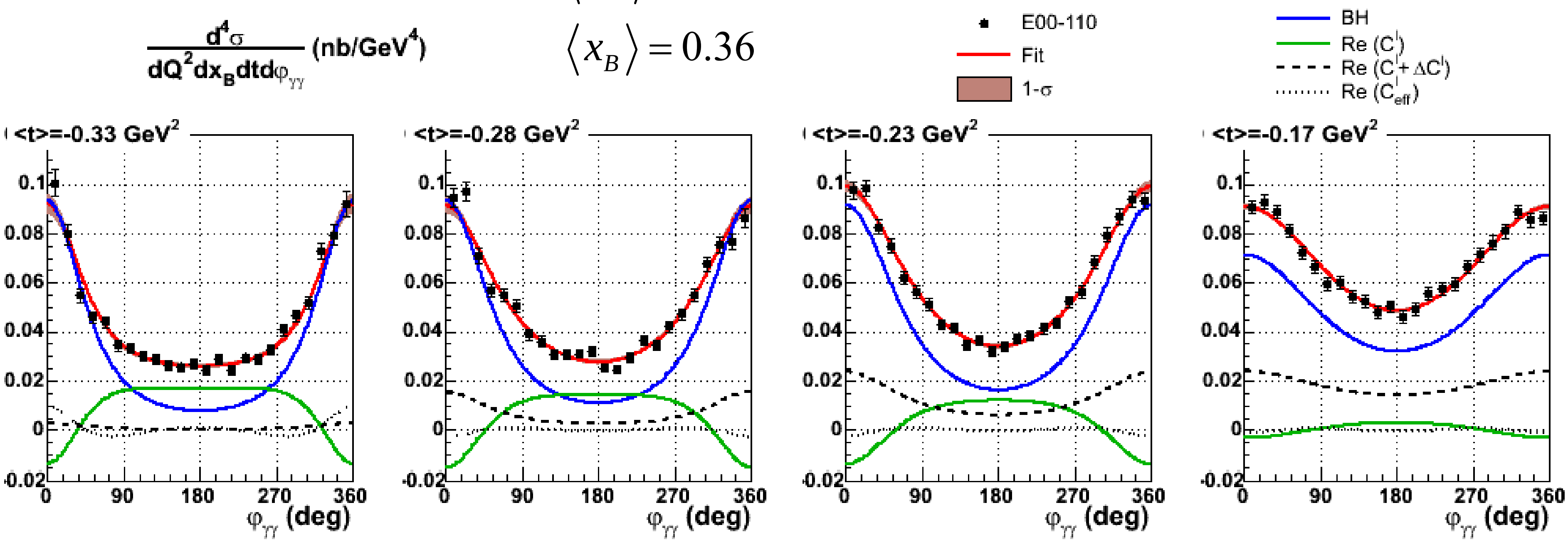
New work by P. Guichon

Total cross section

PRL97, 262002 (2006)

$$\langle Q^2 \rangle = 2.3 \text{ GeV}^2$$

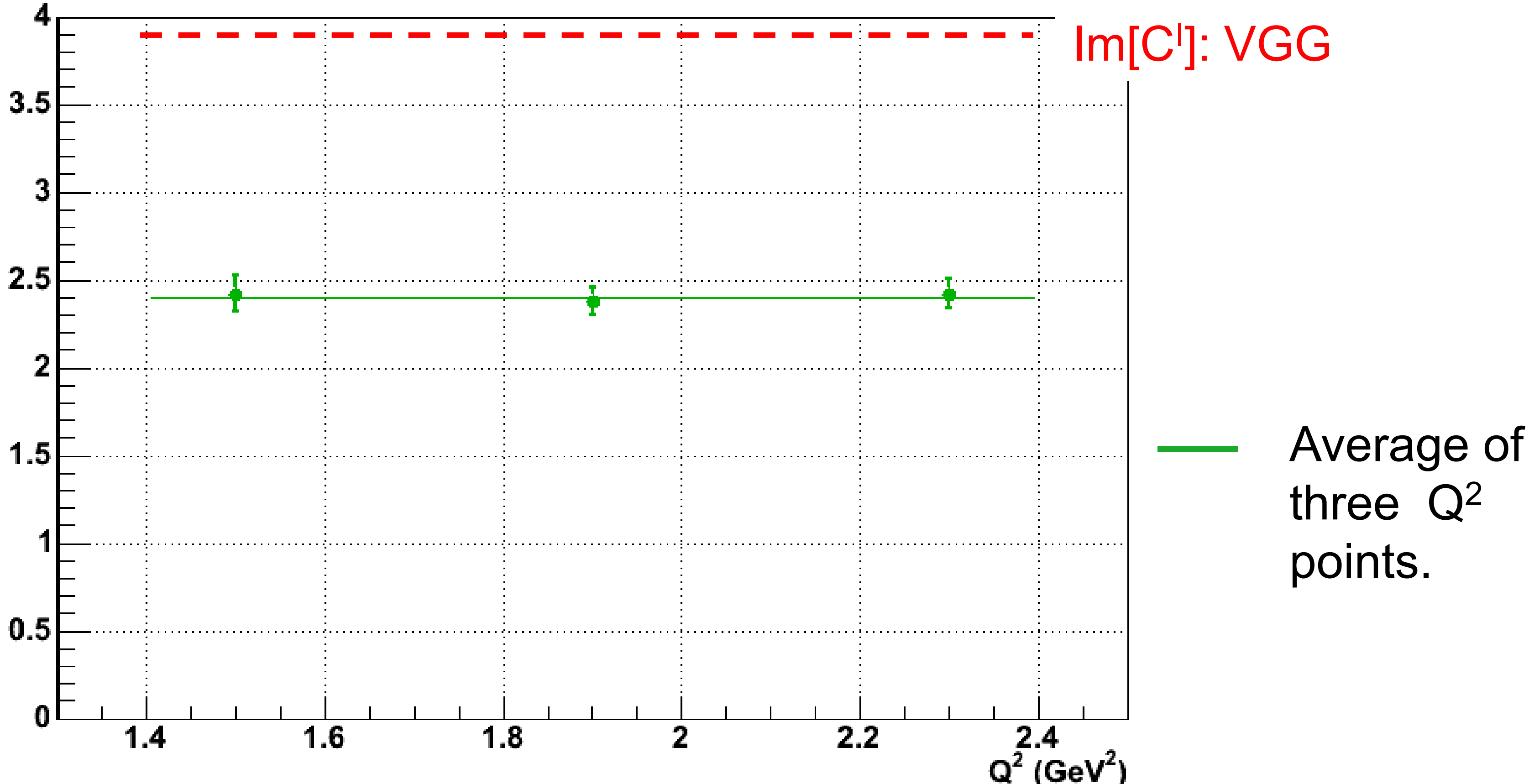
$$\langle x_B \rangle = 0.36$$



Corrected for real+virtual RC
Corrected for efficiency
Corrected for acceptance
Corrected for resolution effects

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

$Im[C^I(\mathcal{F})]$:   'sinφ term'

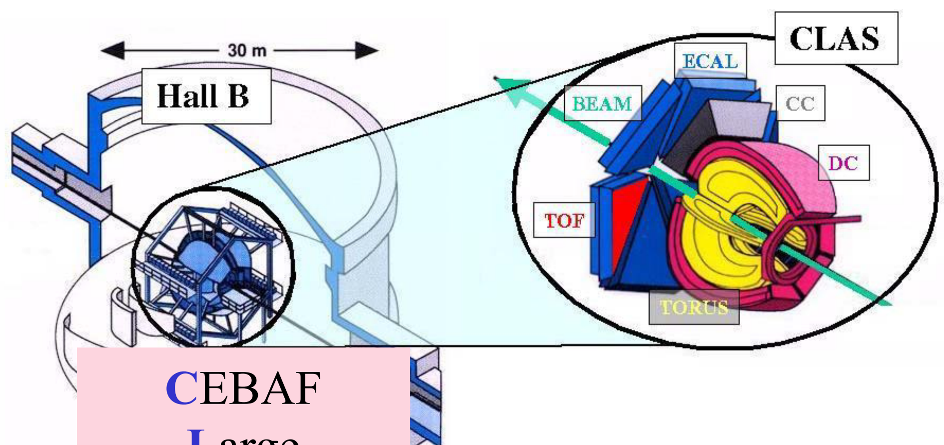


No Q^2 dependence: strong indication for scaling behavior and handbag dominance

Jefferson Laboratory
Newport News, USA

$I_{max} \sim 200\ \mu A$
Duty Factor ~ 100%
$\sigma_E/E \sim 2.5\ 10^{-5}$
Beam Pol ~ 80%

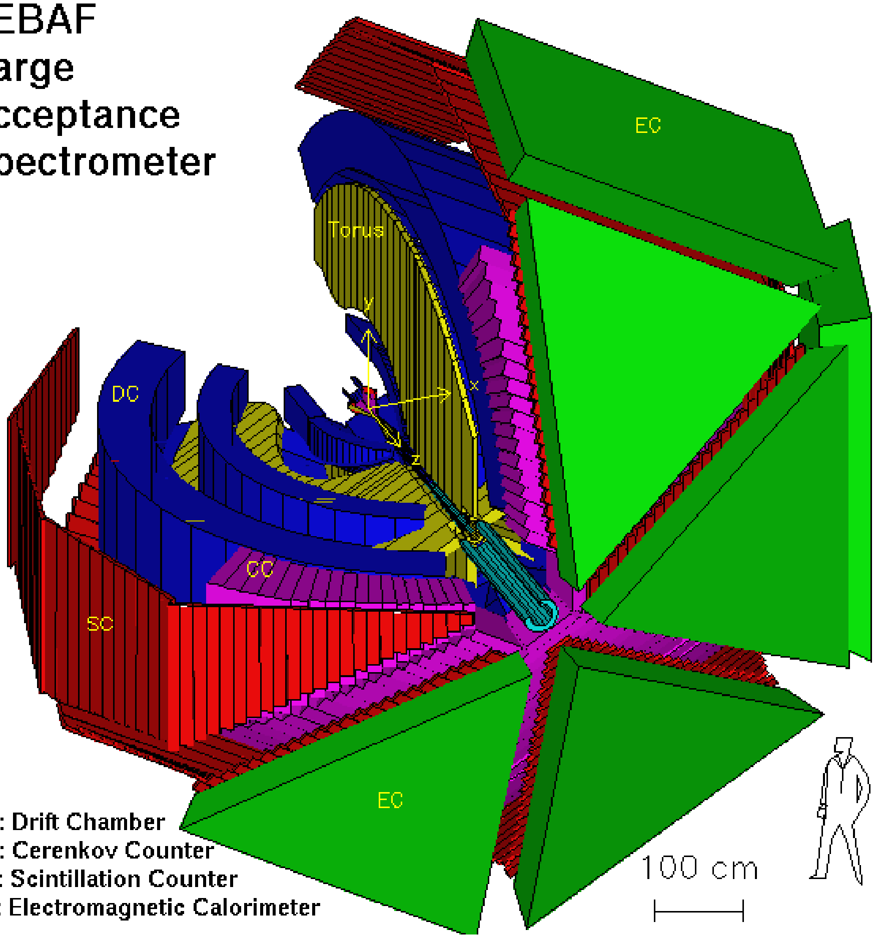
Continuous
Electron
Beam
Accelerator
Facility



CEBAF
Large
Acceptance
Spectrometer

The CLAS detector

CEBAF
Large
Acceptance
Spectrometer



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

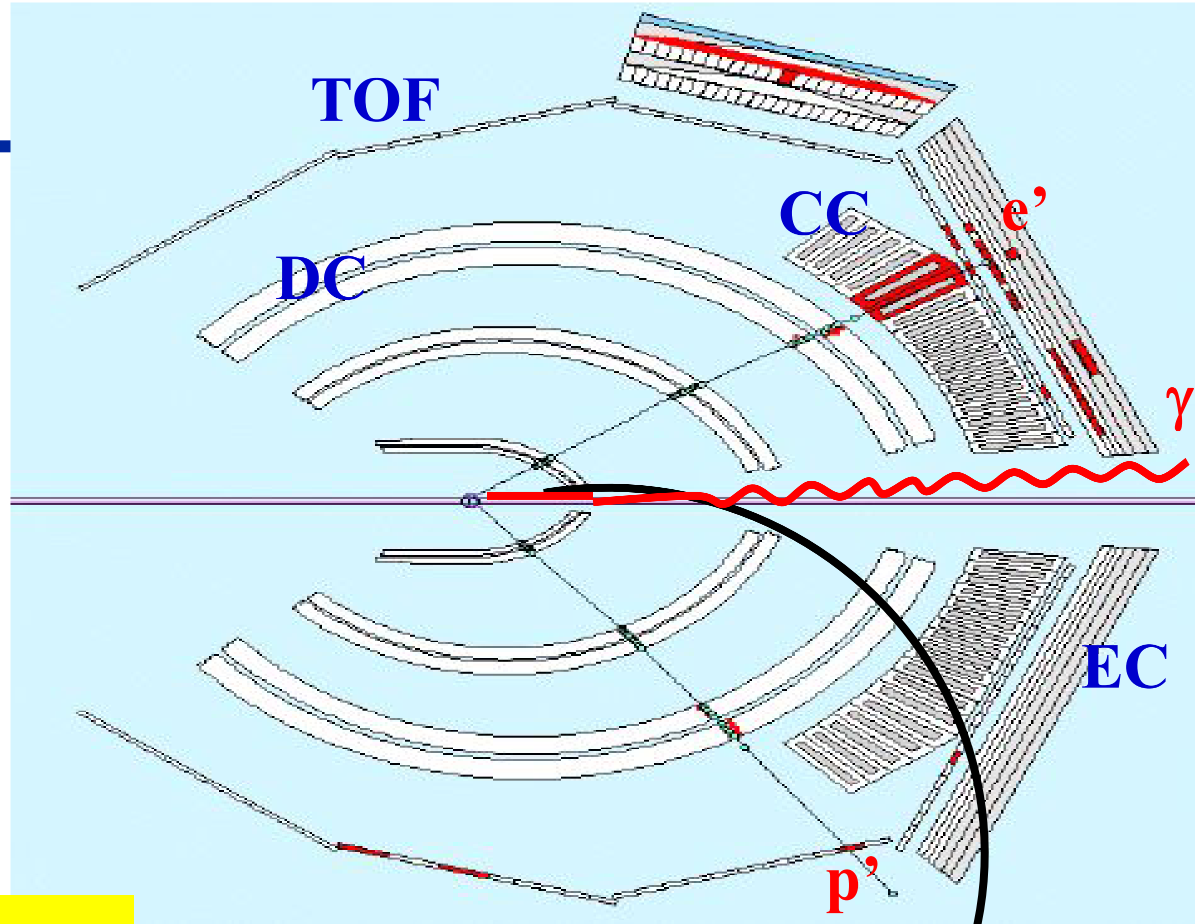
- **Toroidal magnetic field (6 supercond. coils)**
- **Drift chambers (argon/CO_2 gas, 35000 cells)**
- **Time-of-flight scintillators**
- **Electromagnetic calorimeters**
- **Cherenkov Counters (e/π separation)**

Performances:

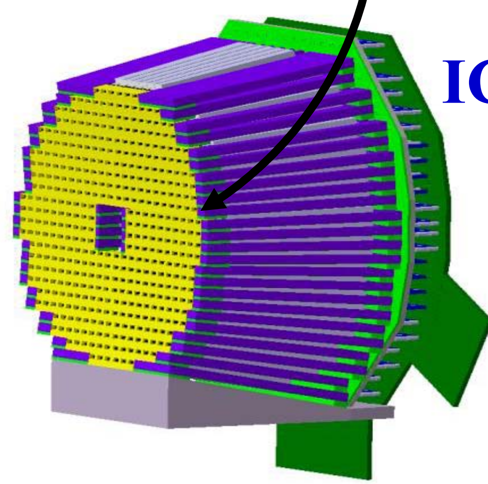
- **large acceptance** for charged particles
  $8° < \theta < 142°$, $p_p > 0.3$ GeV/c, $p_\pi > 0.1$GeV/c
- **good momentum and angular resolution**
  $\Delta p/p \leq 0.5\%$- 1.5%, $\Delta\theta$, $\Delta\phi \leq 1$ mrad

ep→e'p'γ in CLAS

All 3 particles are detected

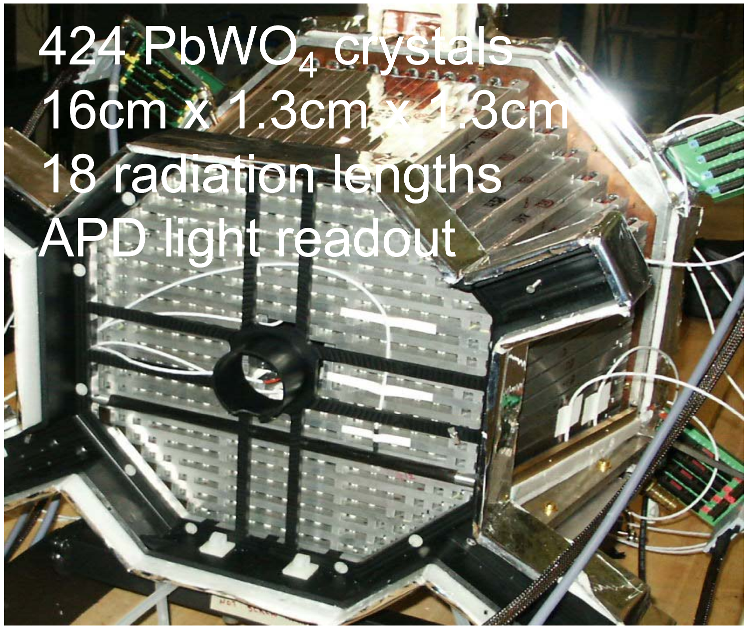


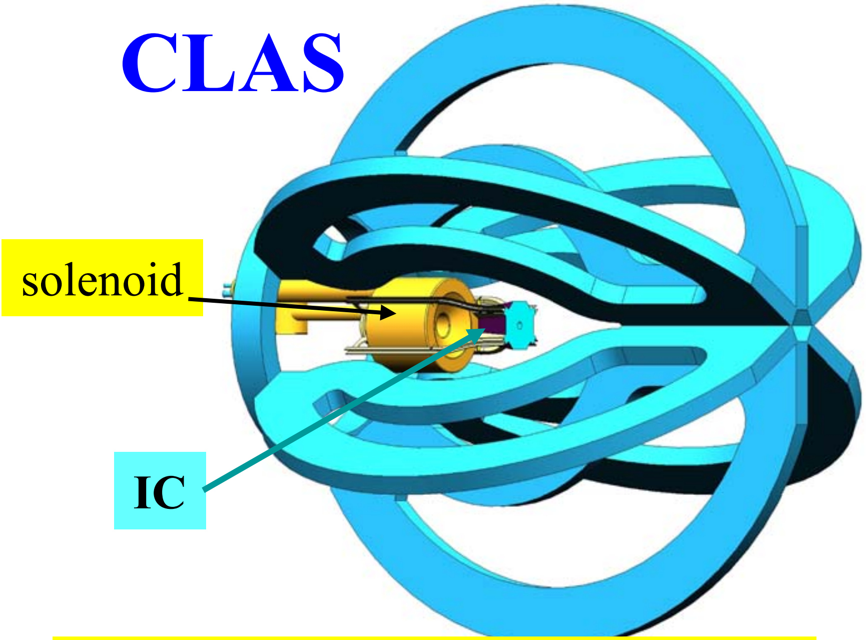
- **electron ID**:
  - ➢ EC, CC, DC and TOF
- **proton ID**:
  - ➢DC and TOF
- **photon ID**:
  - ➢IC or EC



The e1-dvcs experiment at CLAS

- Experiment: March - May 2005
- E_e = 5.77 GeV
- Polarization: 76% - 82%
- Current: 20-25 nA
- Integrated luminosity: $3.33 \cdot 10^7$ nb^{-1}



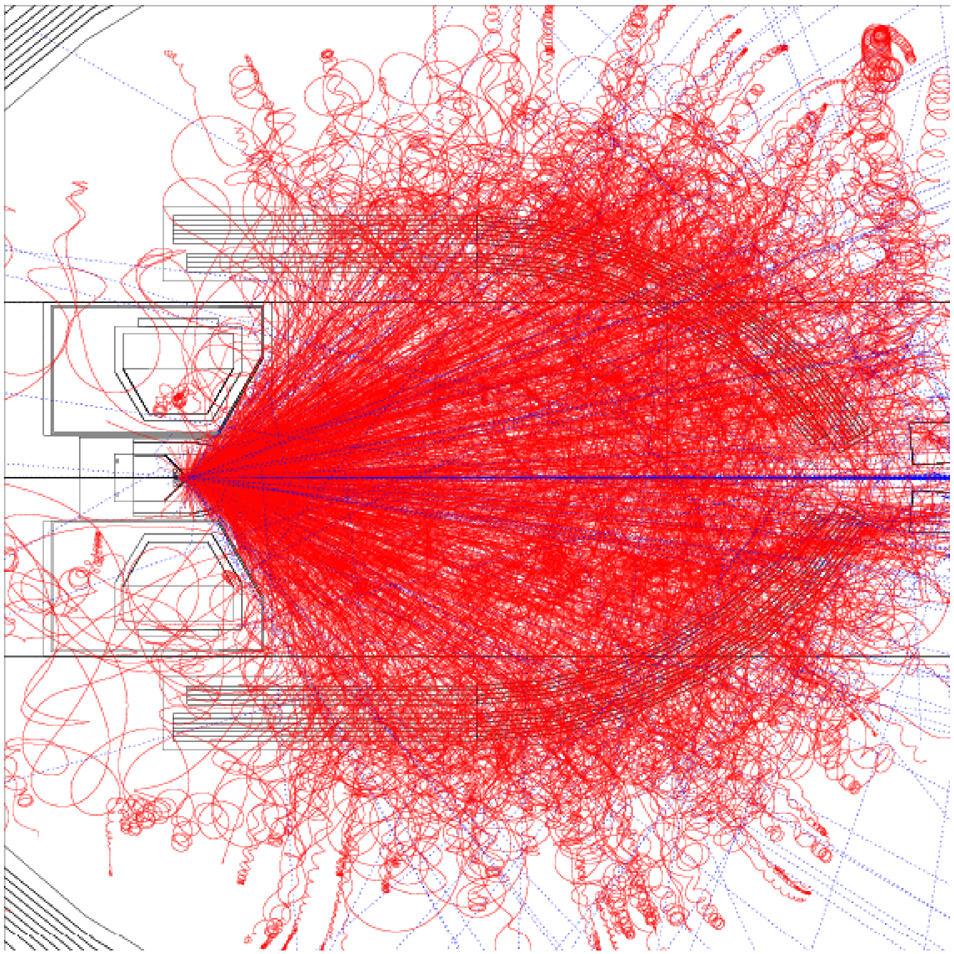


Standard CLAS acceptance for photons: $\theta \in [17^o;43^o]$

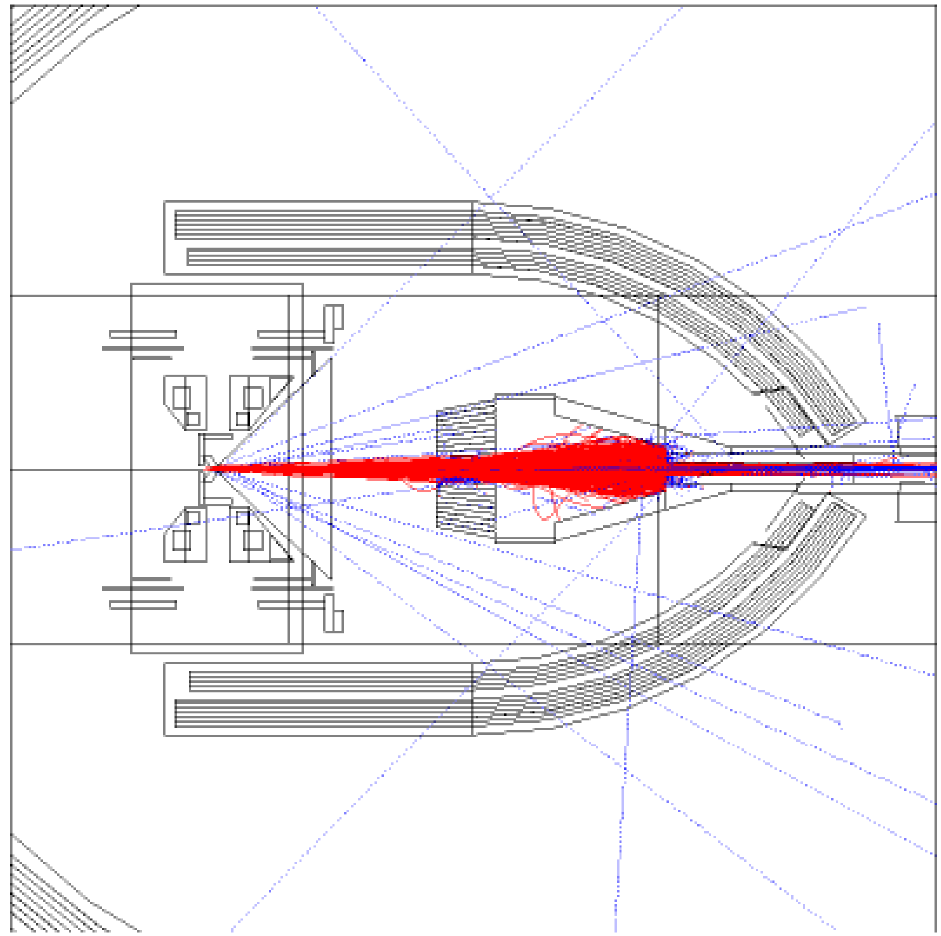
Superconducting solenoid magnet (shielding for Moeller electrons)

Inner calorimeter: $\theta \in [4^o;15^o]$

Magnetic Shielding for Møller Electrons

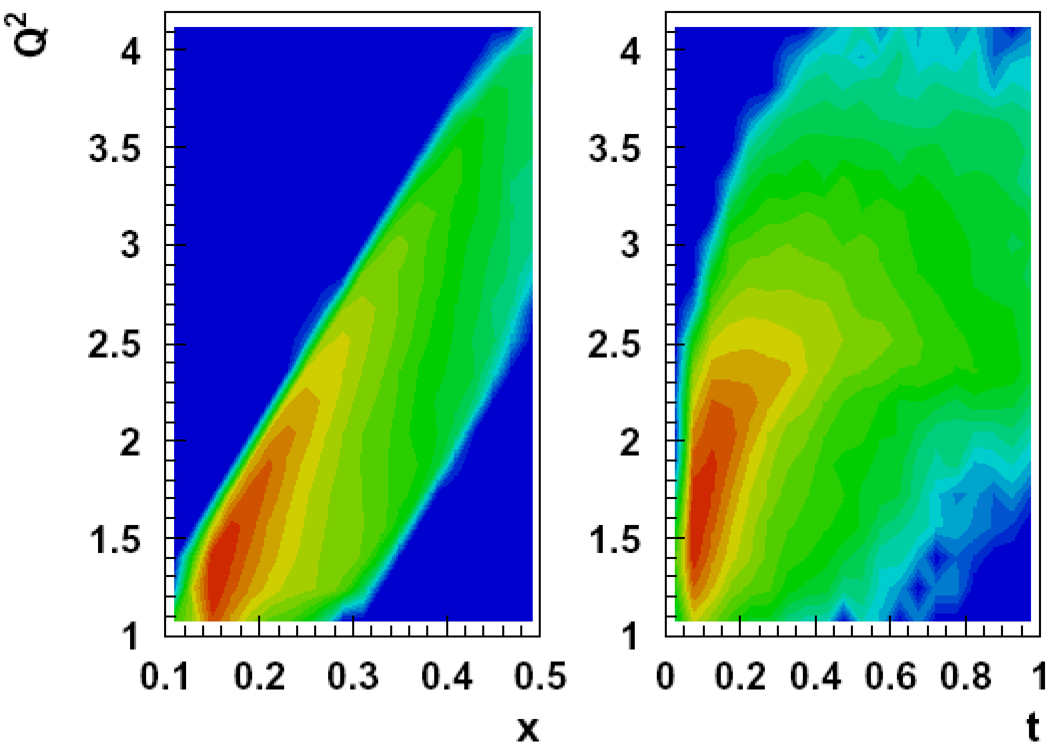


without magnetic field

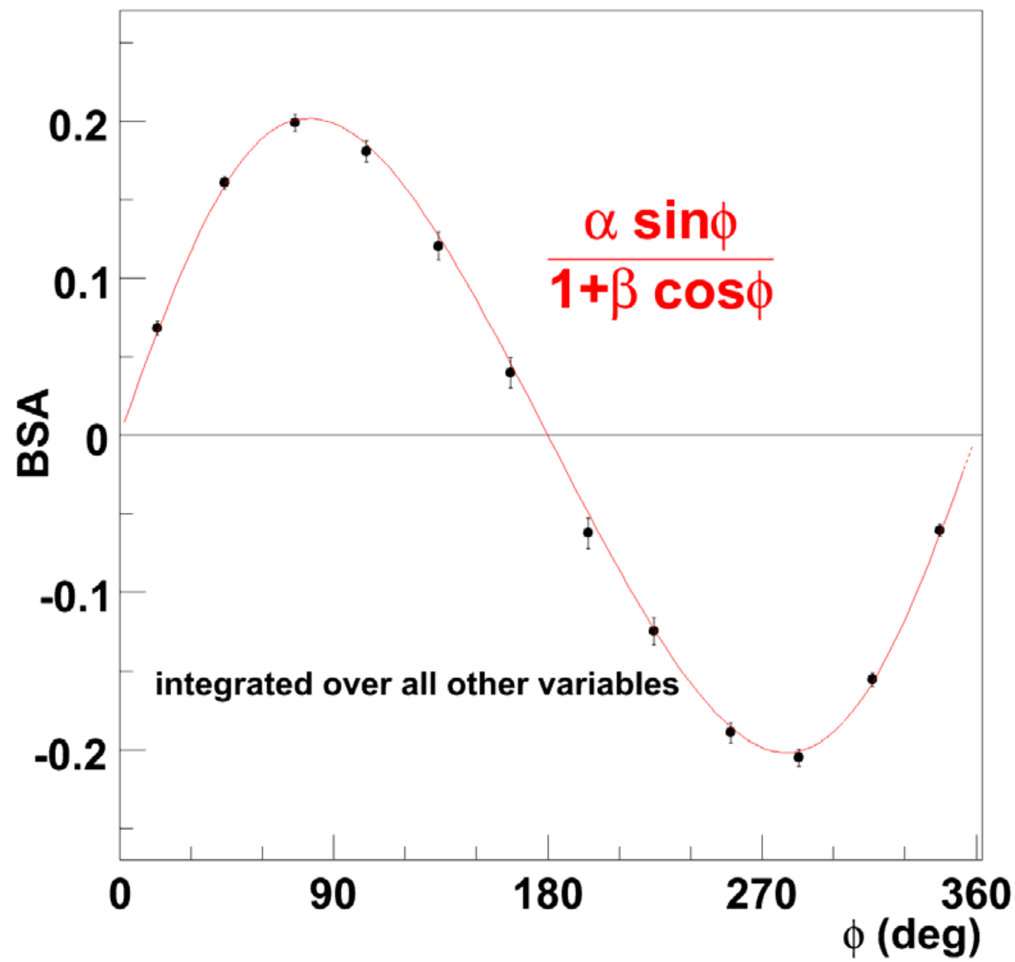


with magnetic field

Kinematics and Acceptance with CLAS + IC

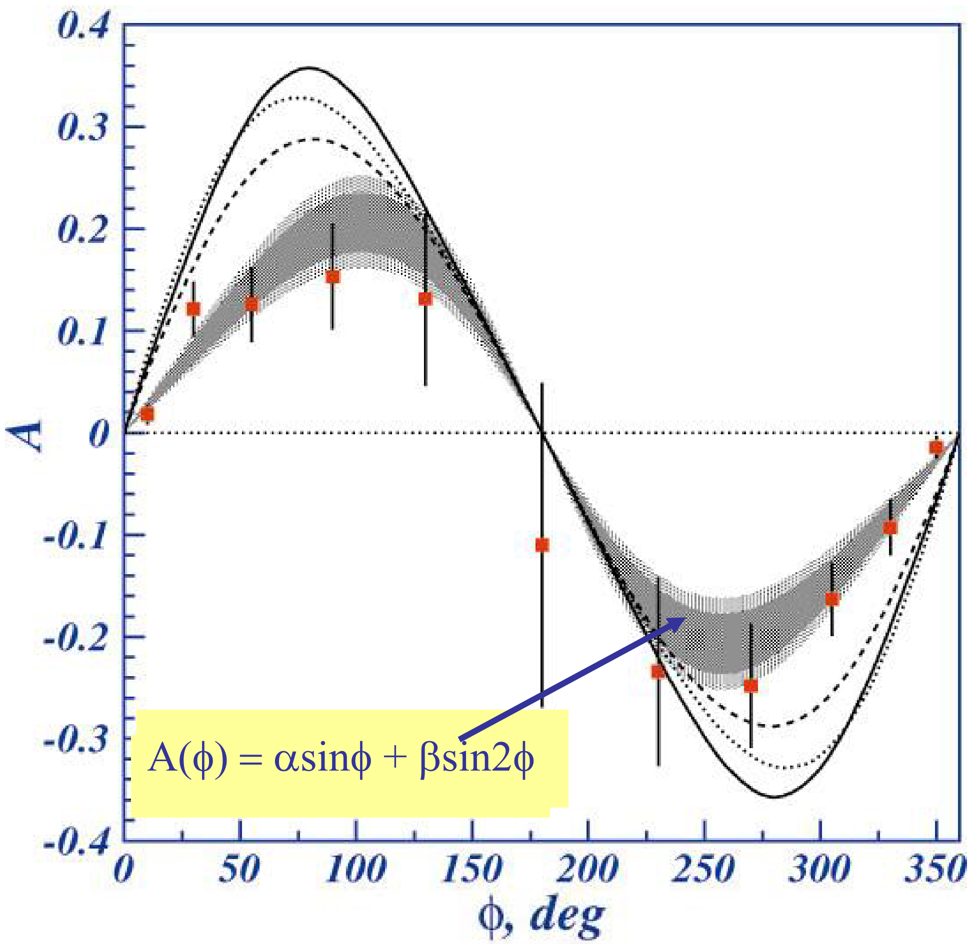


CLAS e1-DVCs Results



Exclusive DVCS with CLAS

Beam Spin Asymmetry



- Beam energy – 4.25 GeV
- ep→epγ identified by analyzing the missing mass distribution ep→epX

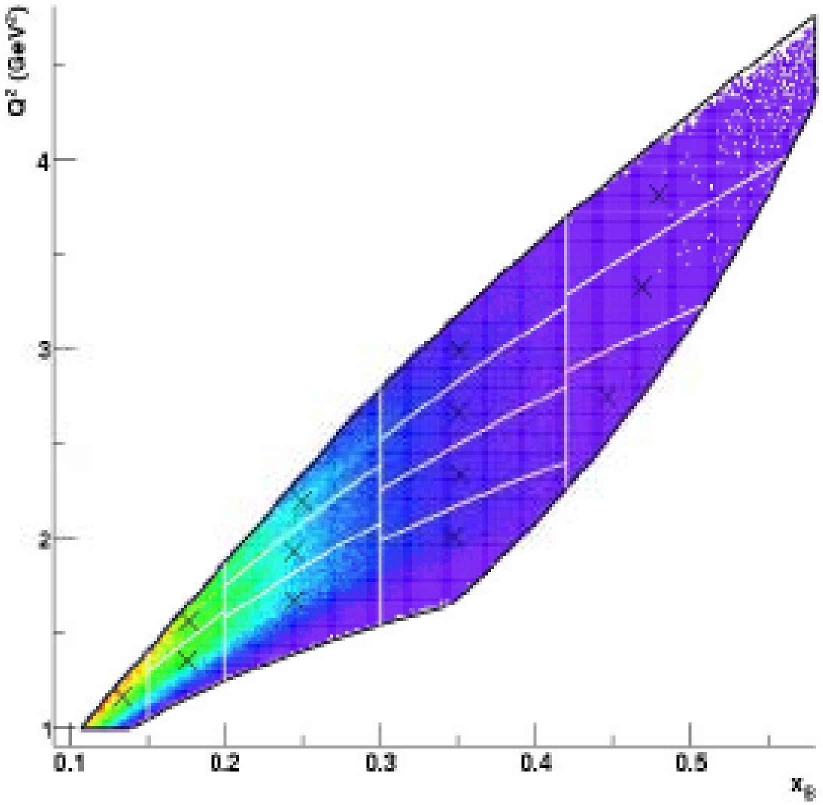
- W > 2 GeV
- $1 (GeV/c)^2 < Q^2 < 1.75 (GeV/c)^2$
- $0.1 (GeV/c)^2 < -t < 0.3 (GeV/c)^2$

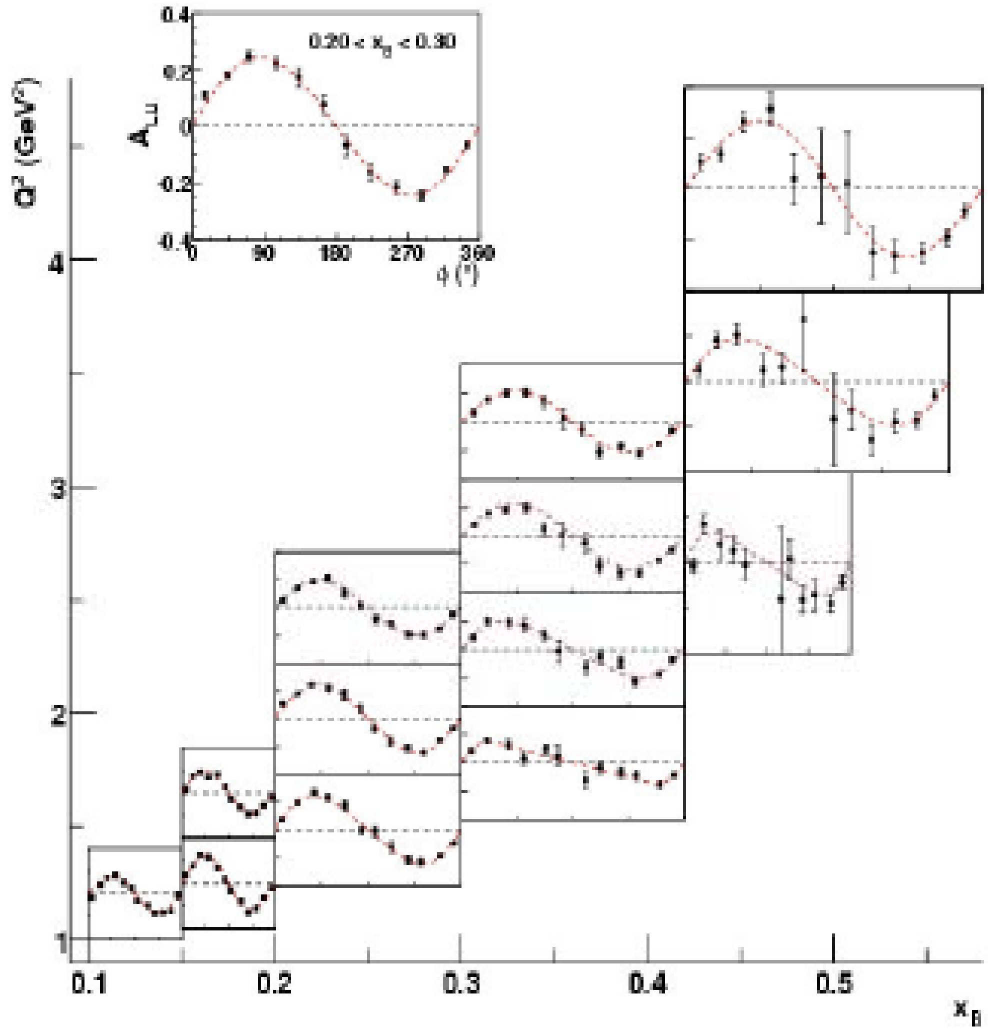
The measured asymmetry:

$$\alpha = 0.202 \pm 0.028^{stat} \pm 0.013^{sys}$$

BSA: coverage and distributions

Data integrated over t

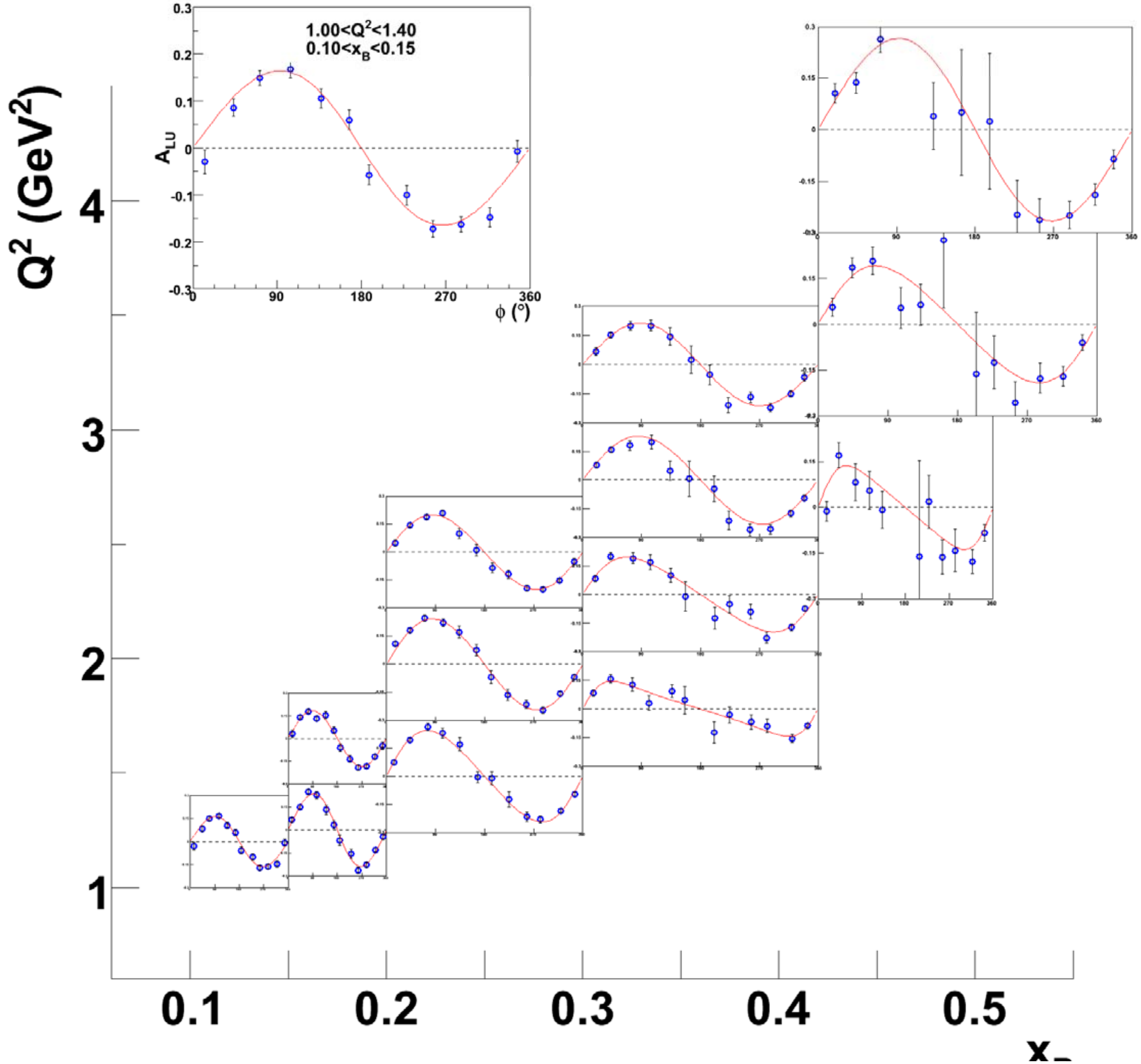




- 13 Q^2, x_B bins
- 5 t bins
- 12 ϕ bins

Fit = $\alpha \sin\phi/(1+\beta\cos\phi)$

Ph.D. Thesis of F.X. Girod



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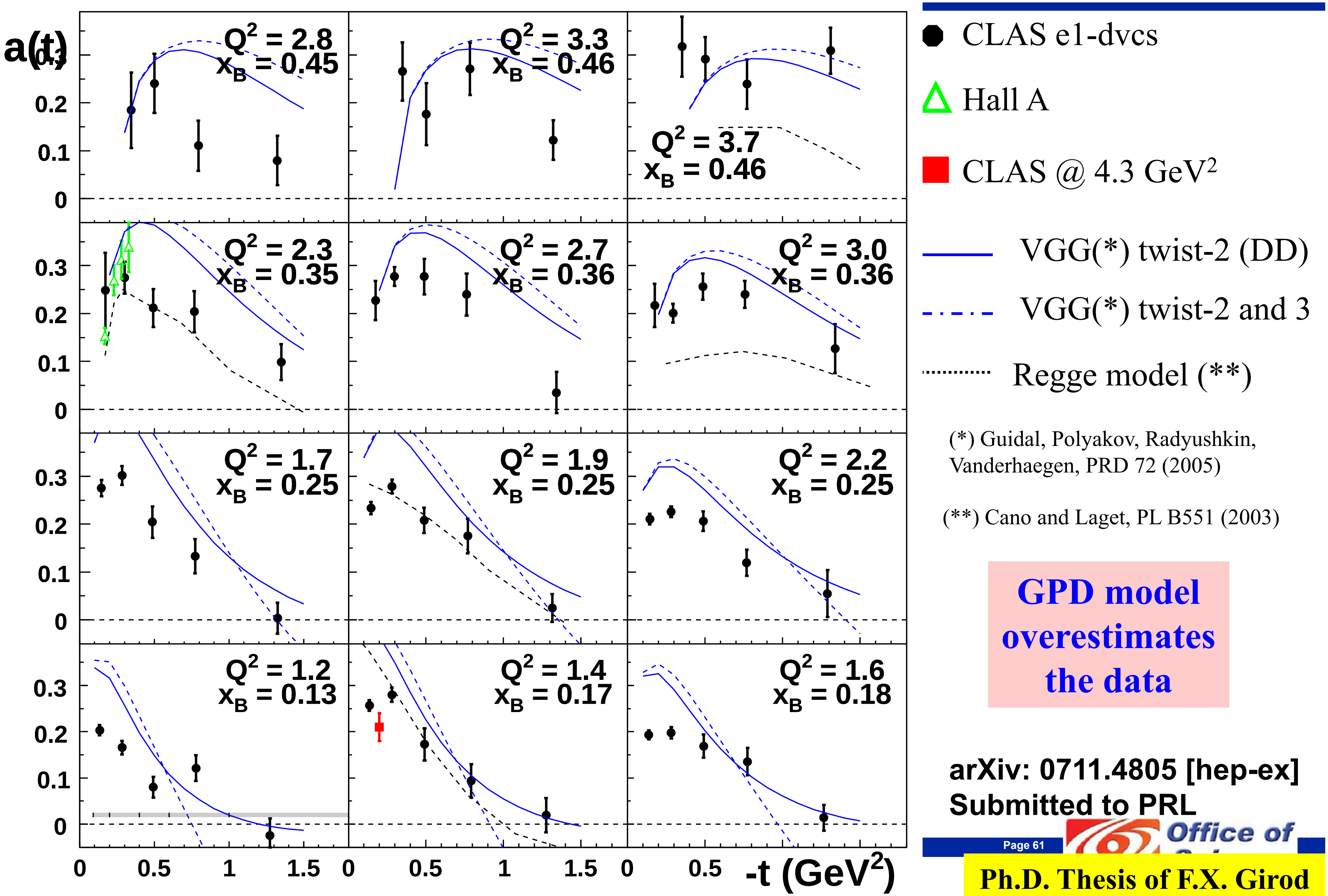
BSA: a vs. t



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

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

GPD model overestimates the data

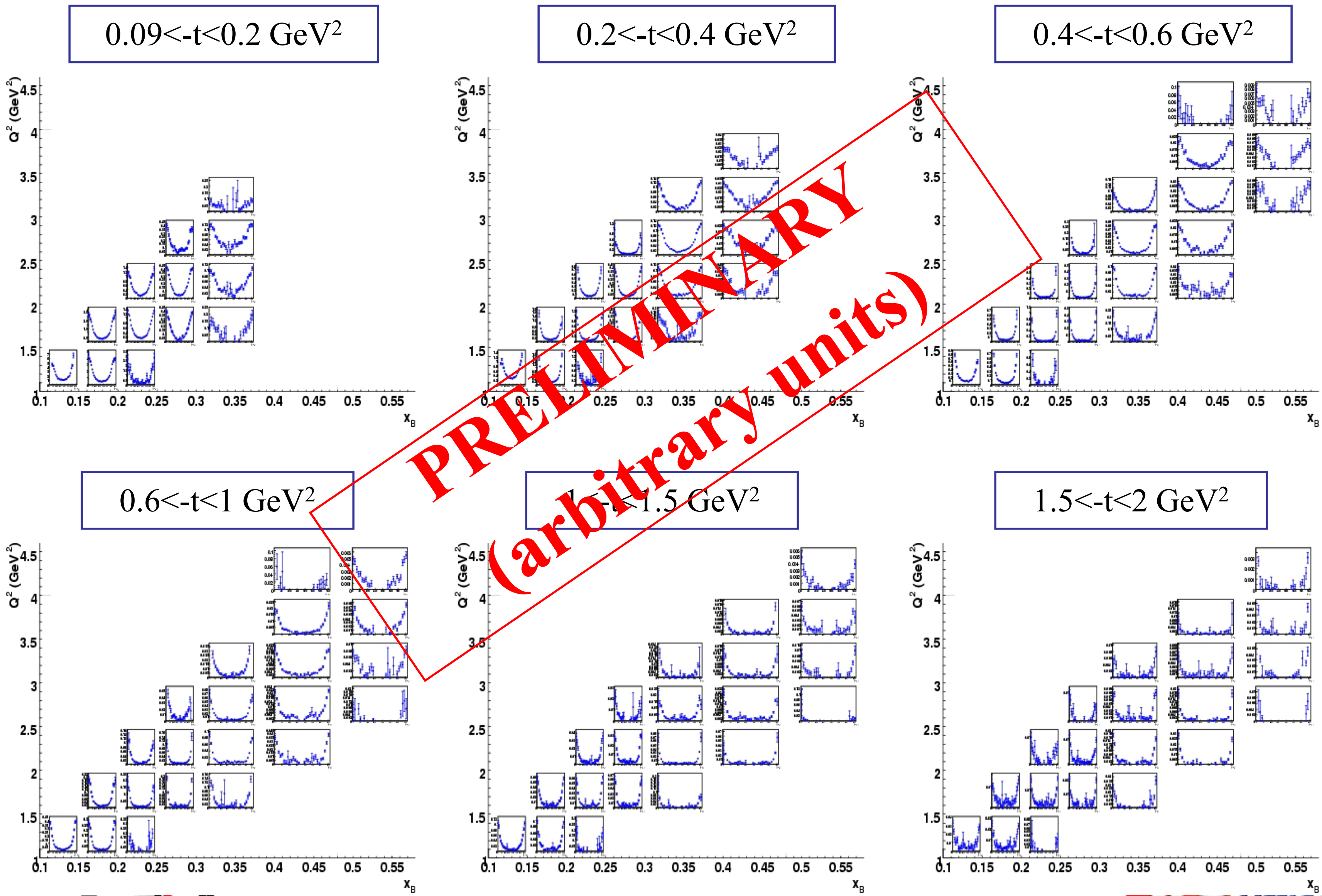
arXiv: 0711.4805 [hep-ex]
Submitted to PRL

Office of ...

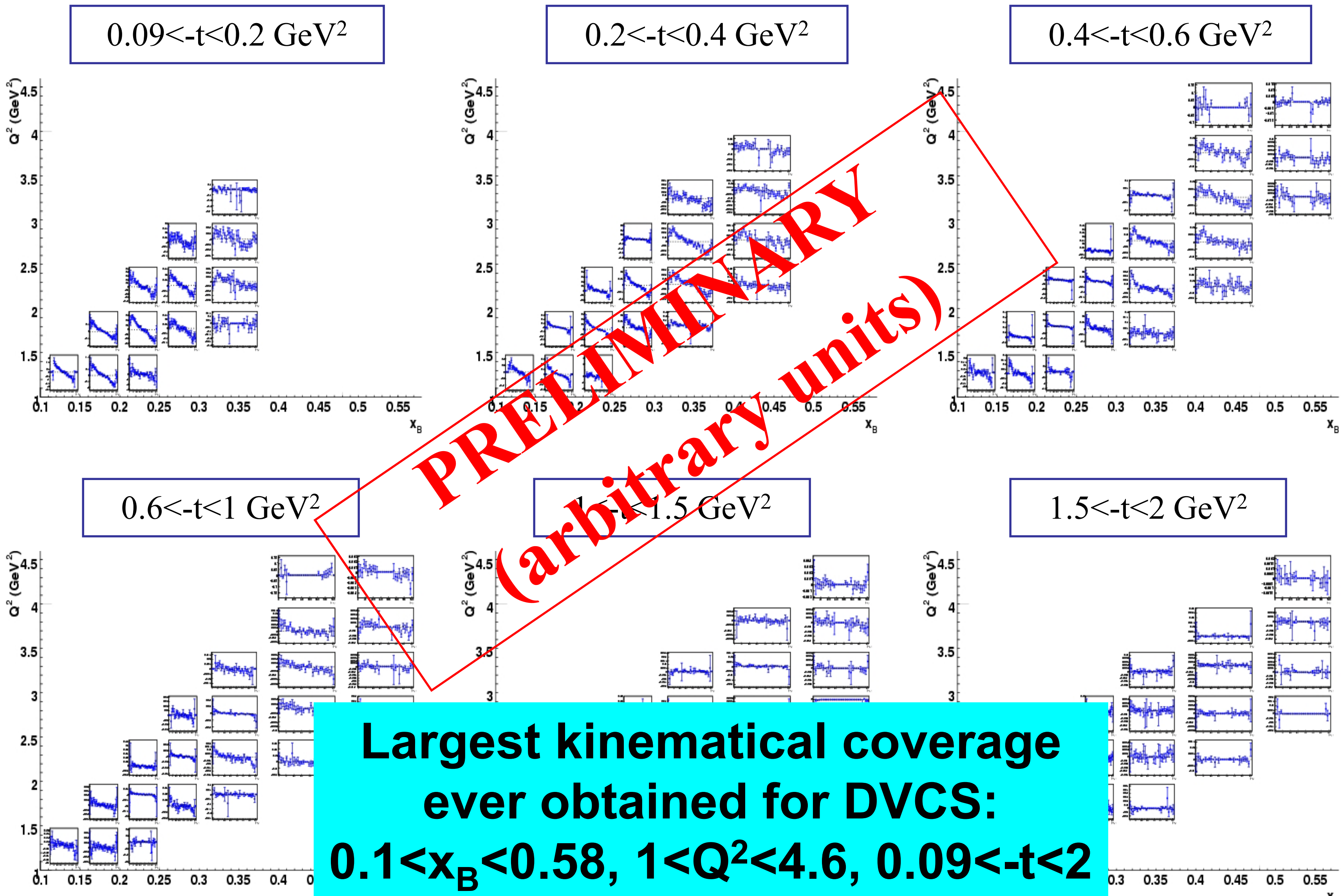
Ph.D. Thesis of F.X. Girod

Unpolarized Cross Sections

$$\frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2 dx_B dt d\phi}$$ as a function of ϕ



Difference of Polarized Cross Sections $\frac{d^4\vec{\sigma}_{ep\to ep\gamma}}{dQ^2dx_Bdtd\phi} - \frac{d^4\overleftarrow{\sigma}_{ep\to ep\gamma}}{dQ^2dx_Bdtd\phi}$ as a function of ϕ



Largest kinematical coverage ever obtained for DVCS:
$0.1<x_B<0.58$, $1<Q^2<4.6$, $0.09<-t<2$

Ph.D. Thesis of H.S. Jo

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:

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

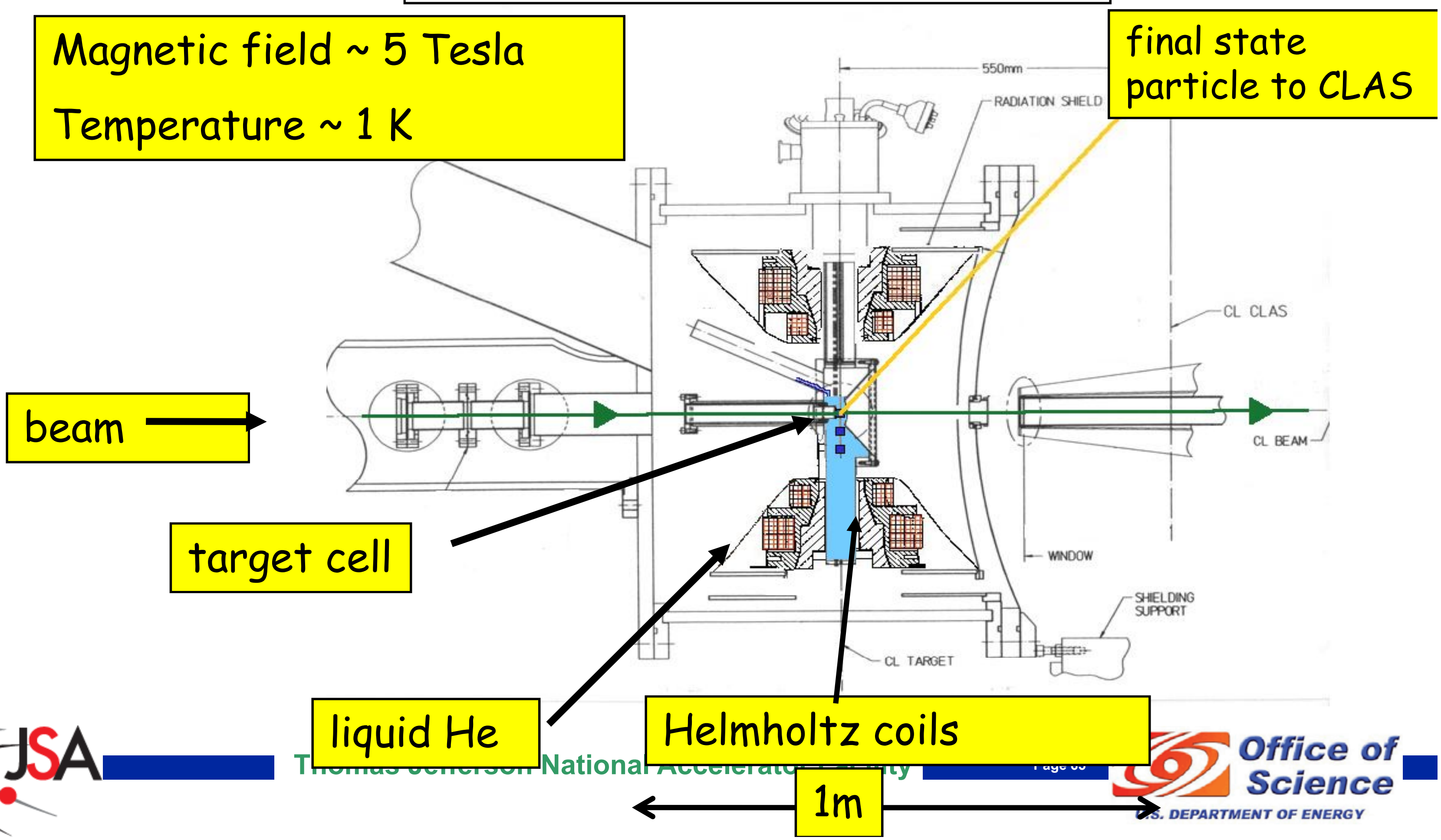
Kinematically suppressed

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

Spin polarized proton target

The separation of GPDs requires measurements on polarized hydrogen targets.
Measurements on such a target are more difficult than on unpolarized hydrogen.
A typical polarized target NH_3 contains only 3 protons with spins aligned out of 17 nucleons.

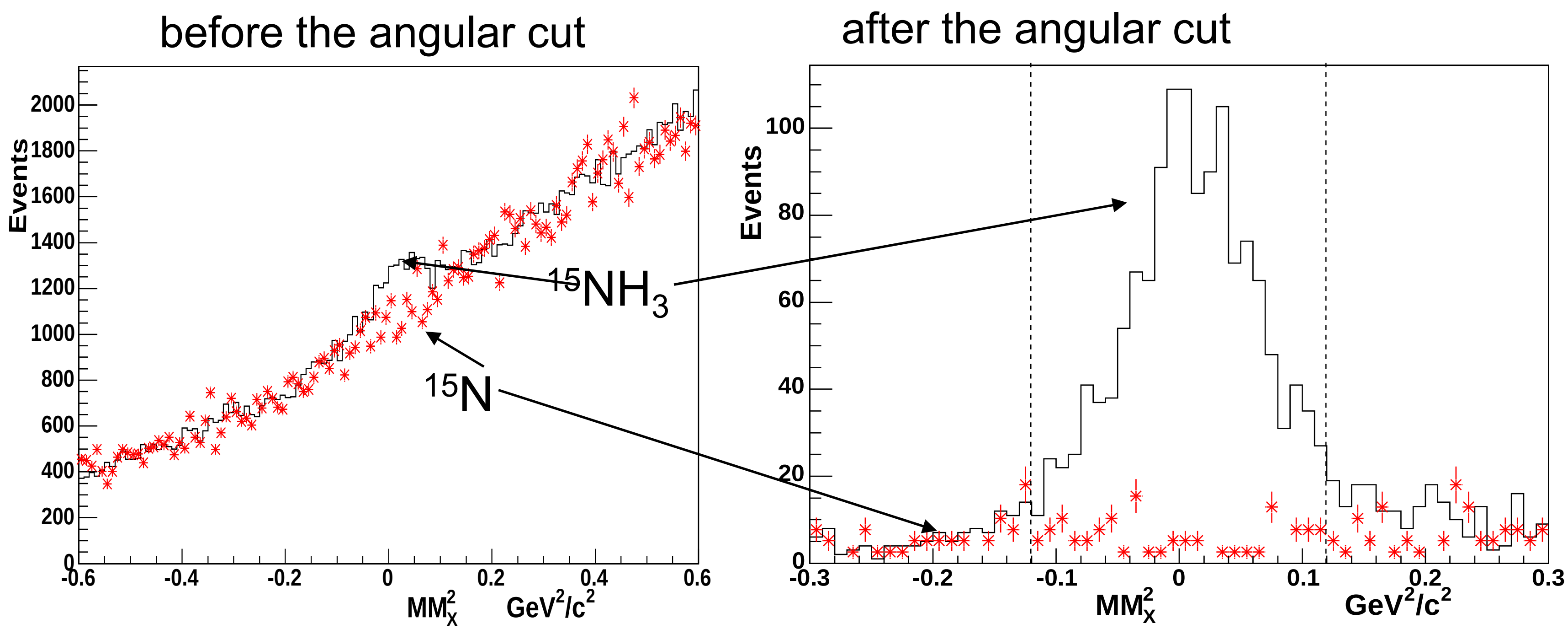
Dynamically polarized NH3 target



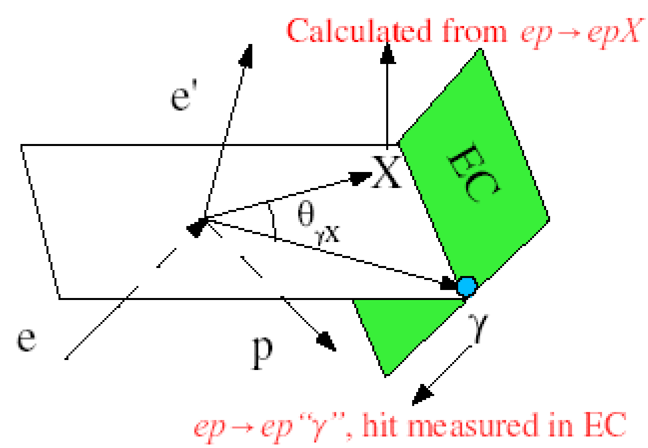
Hall B Longitudinally Polarized Target

- Dynamically polarized NH_3
- 5 Tesla magnetic field
- $\delta B/B \approx 10^{-4}$
- 1K LHe cooling bath
- NH_3 polarization:75%
- ^{12}C, ^{15}N, and ^{4}He targets to measure the dilution factor

DVCS eg1: Separating DVCS Photons from Polarized Protons in NH_3



Events from both π^0 and unpolarized target nucleons are suppressed



Geometry cut: $\theta_{\gamma X} < 1^o$

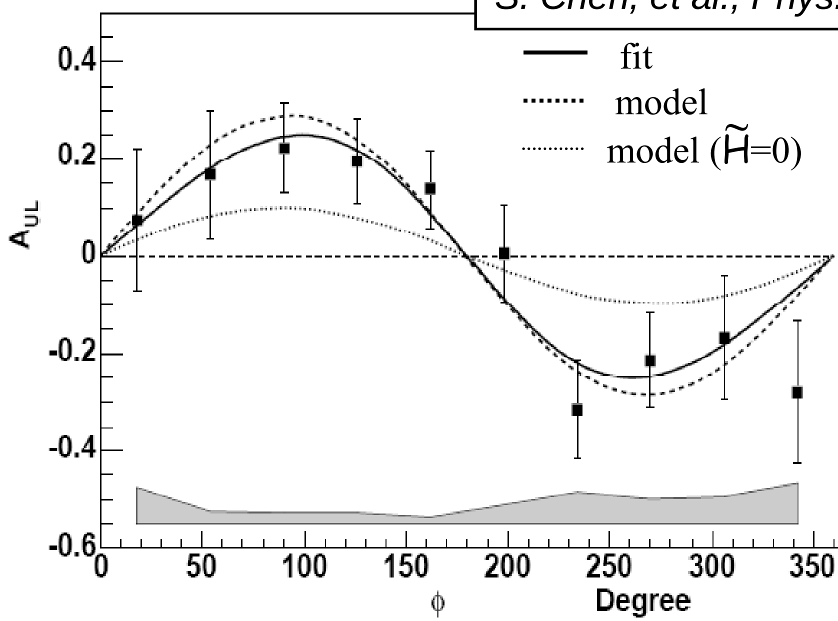
First DVCS measurement with spin-aligned target

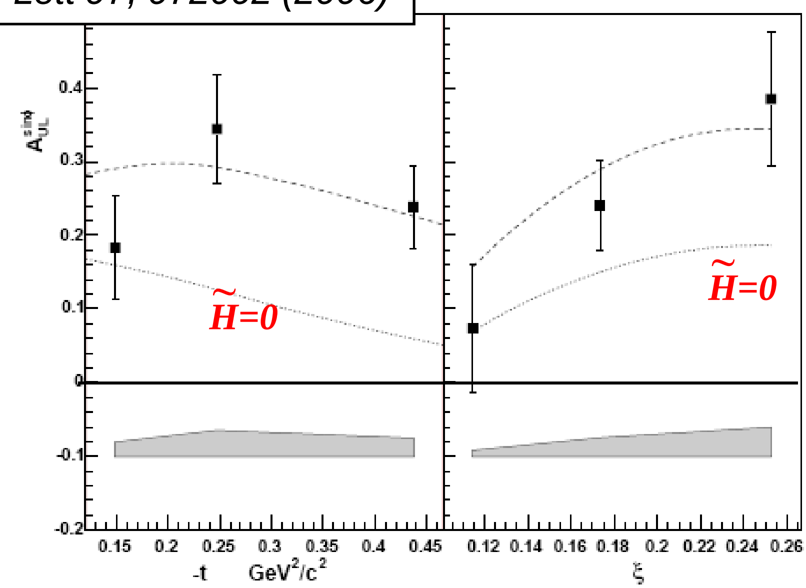
Unpolarized beam, longitudinally spin-aligned target:

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

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

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



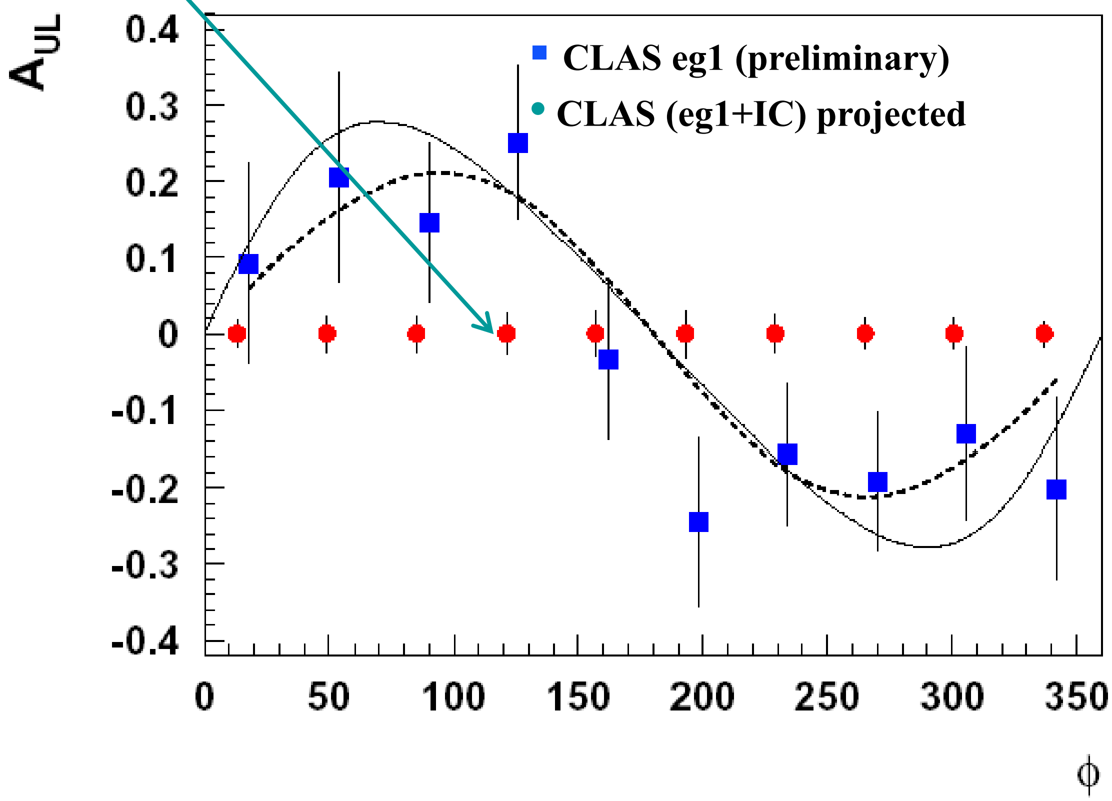


α = 0.252 ± 0.042
β = -0.022 ± 0.045

Planned experiment in 2008 will improve accuracy dramatically.

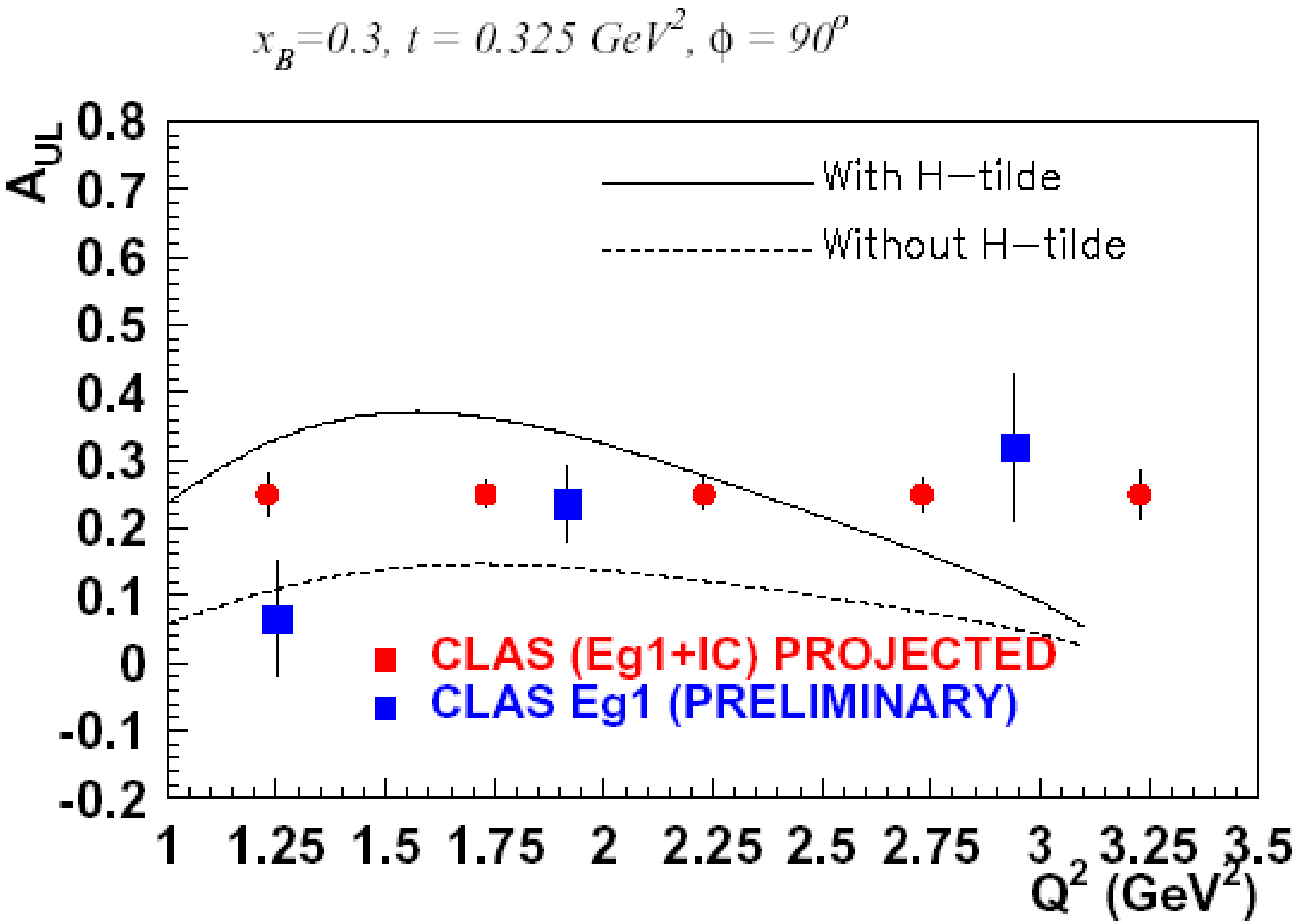
Target Spin Asymmetry: ϕ Dependence

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



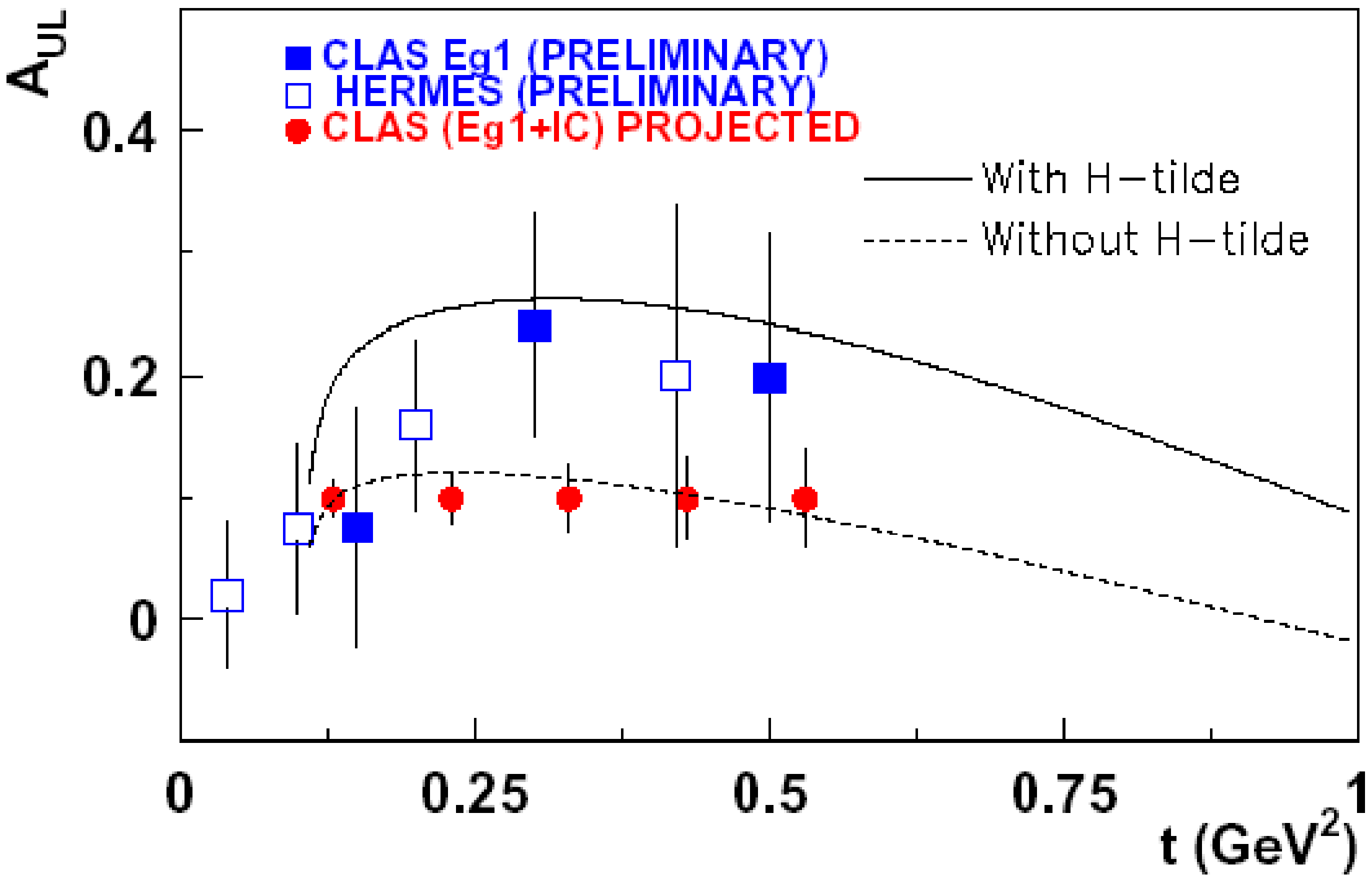
A dedicated CLAS experiment with longitudinally polarized target will provide a statistically significant measurement of the kinematical dependences of the DVCS target SSA

Target Spin Asymmetry: Q^2 Dependence



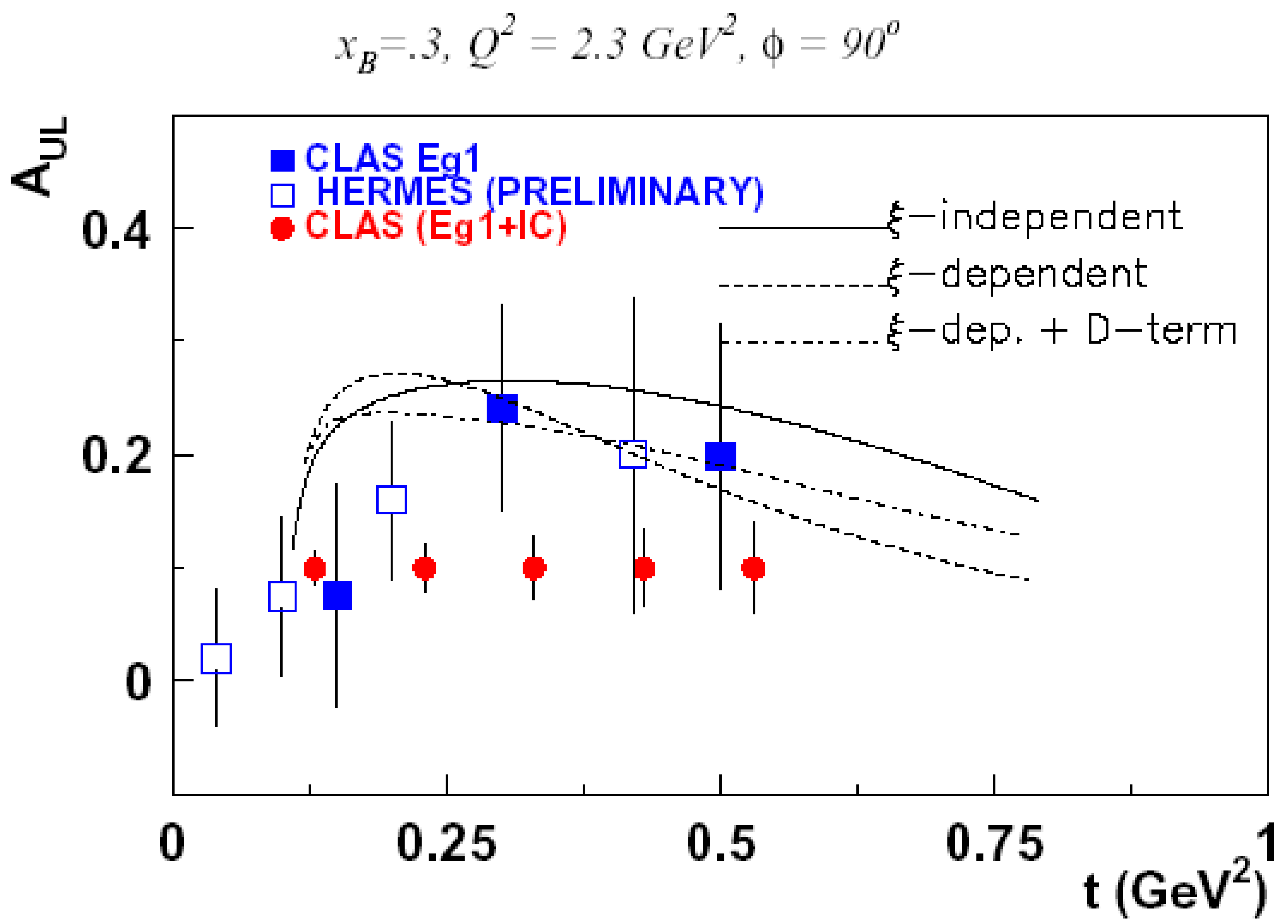
Target Spin Asymmetry: t- Dependence

$x_B = .3,\ Q^2 = 2.3\ GeV^2,\ \phi = 90^o$



Higher t values will also be measured. The interpretation within the handbag formalism needs to be clarified.

Target Spin Asymmetry: t- Dependence



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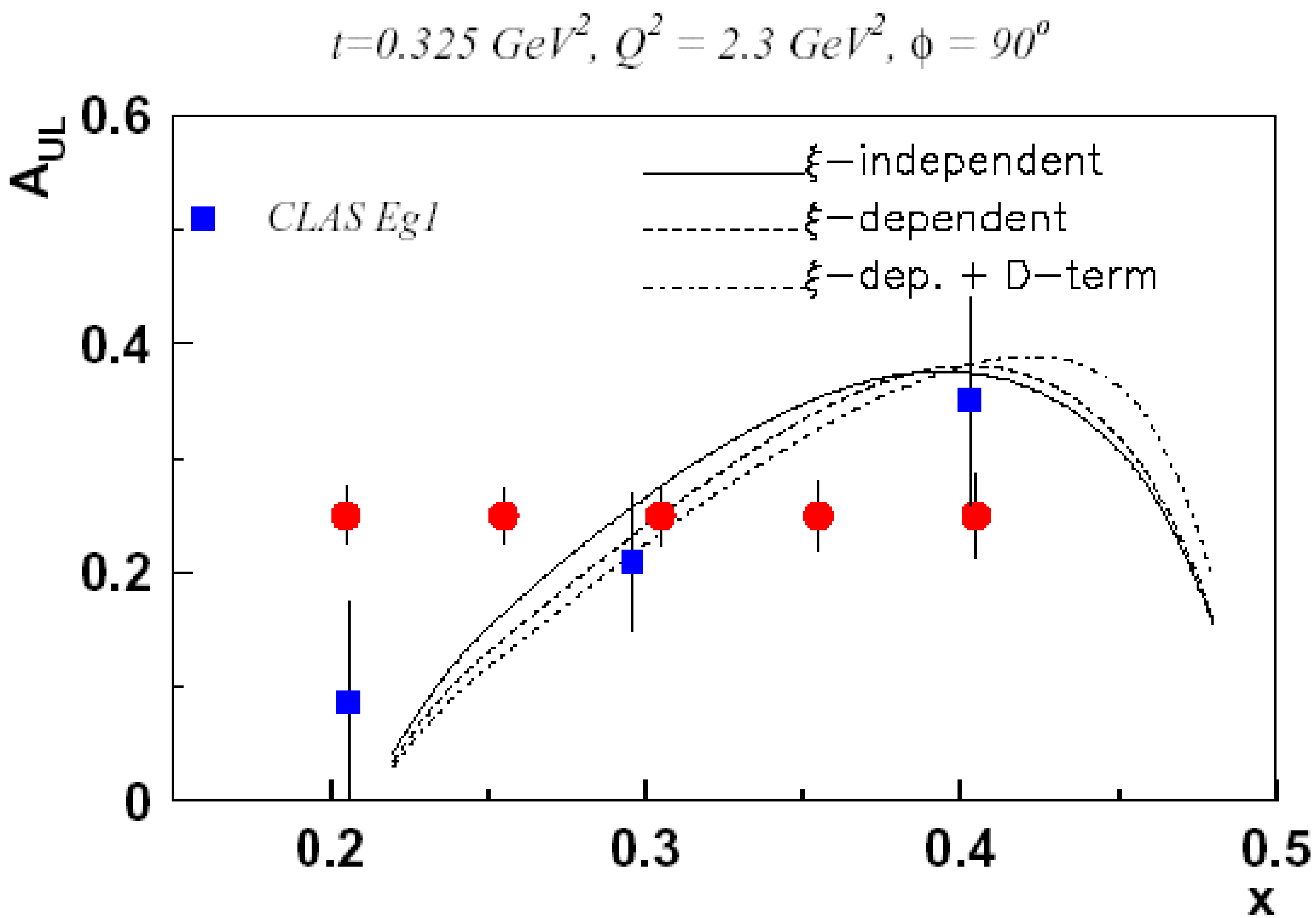
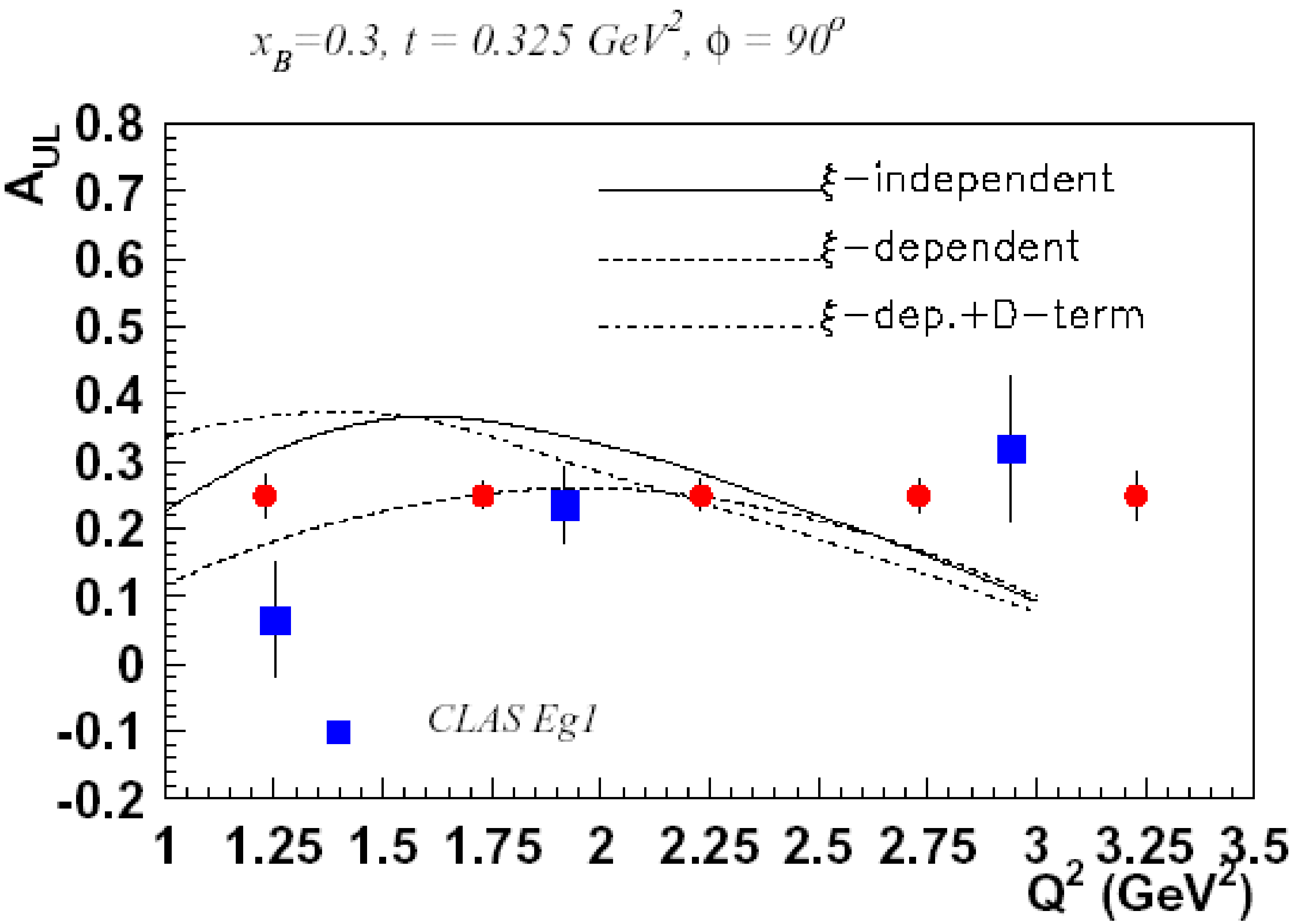
Target Spin Asymmetry: x- Dependence



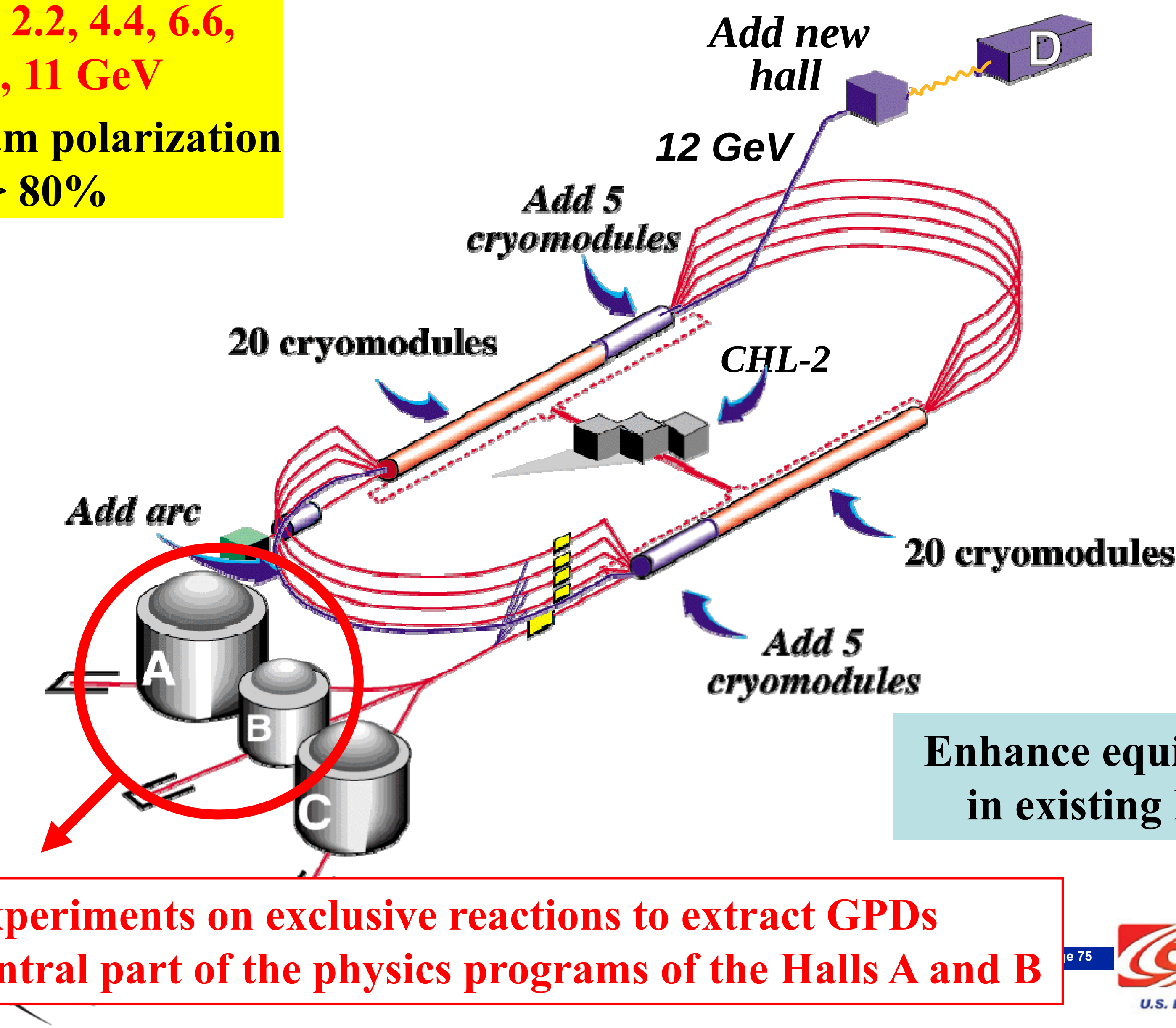
Target Spin Asymmetry: Q^2- Dependence



JLab Upgrade to 12 GeV

E= 2.2, 4.4, 6.6, 8.8, 11 GeV

Beam polarization $P_e > 80\%$

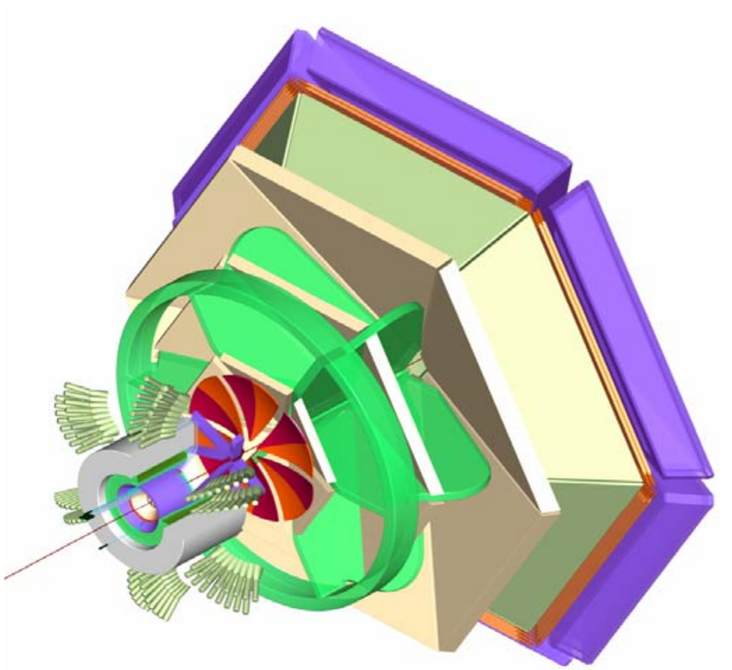


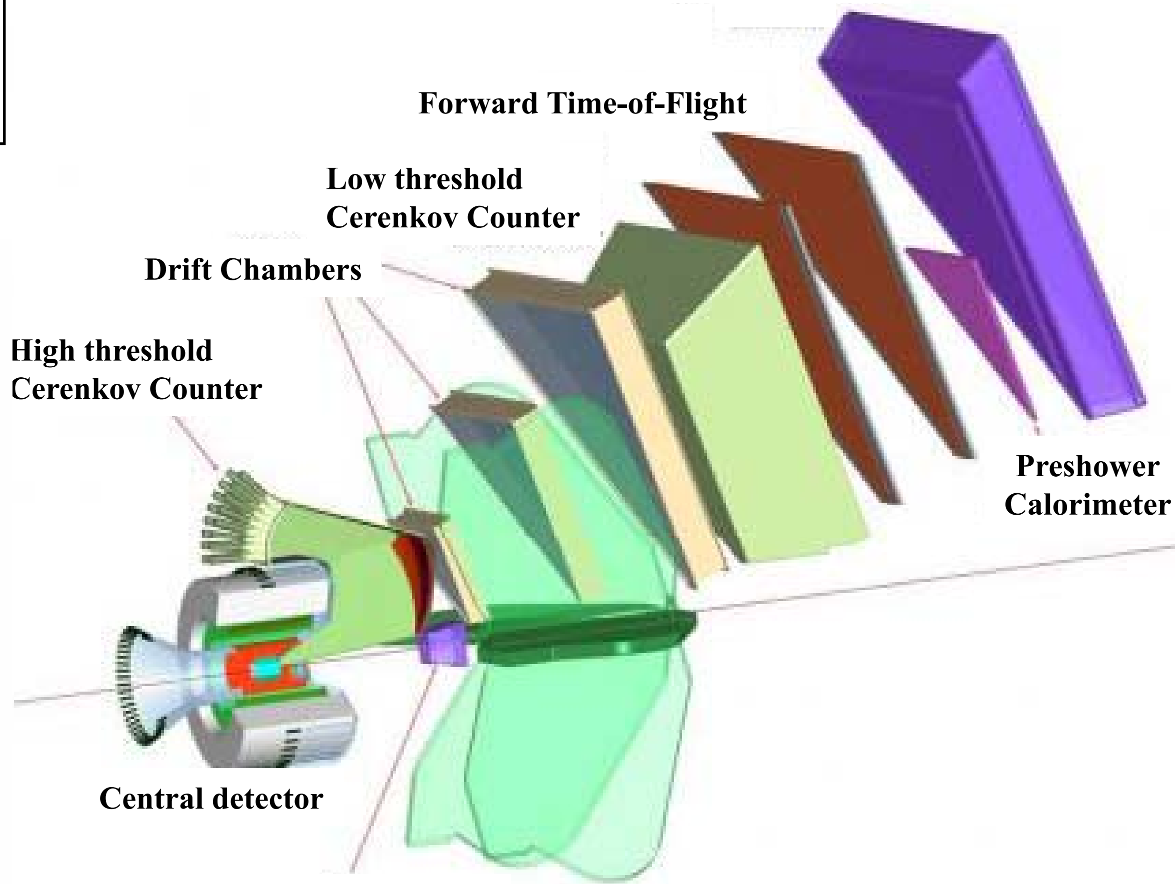
Enhance equipment in existing halls

Experiments on exclusive reactions to extract GPDs are a central part of the physics programs of the Halls A and B

Hall B @12 GeV: CLAS12

Concurrent measurement of deeply virtual exclusive, semi-inclusive, and inclusive processes



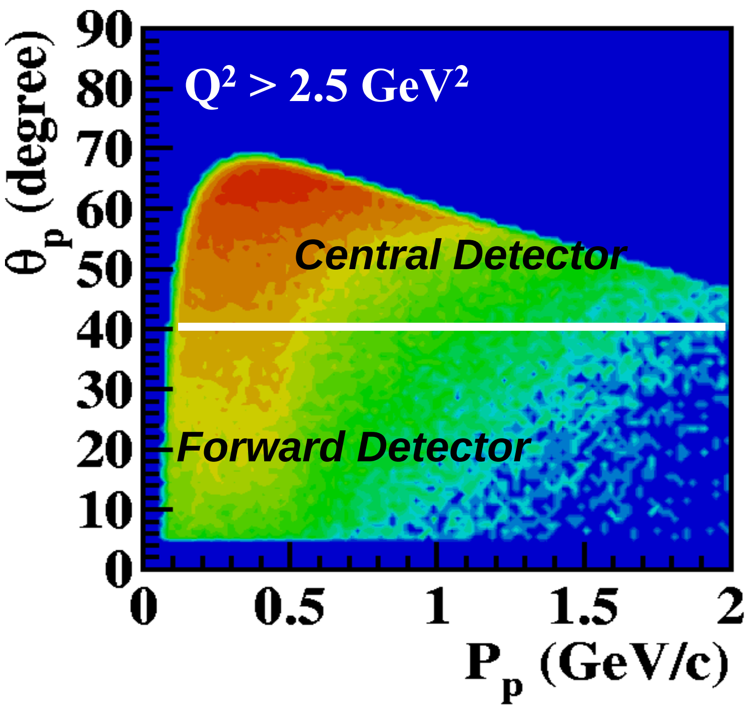


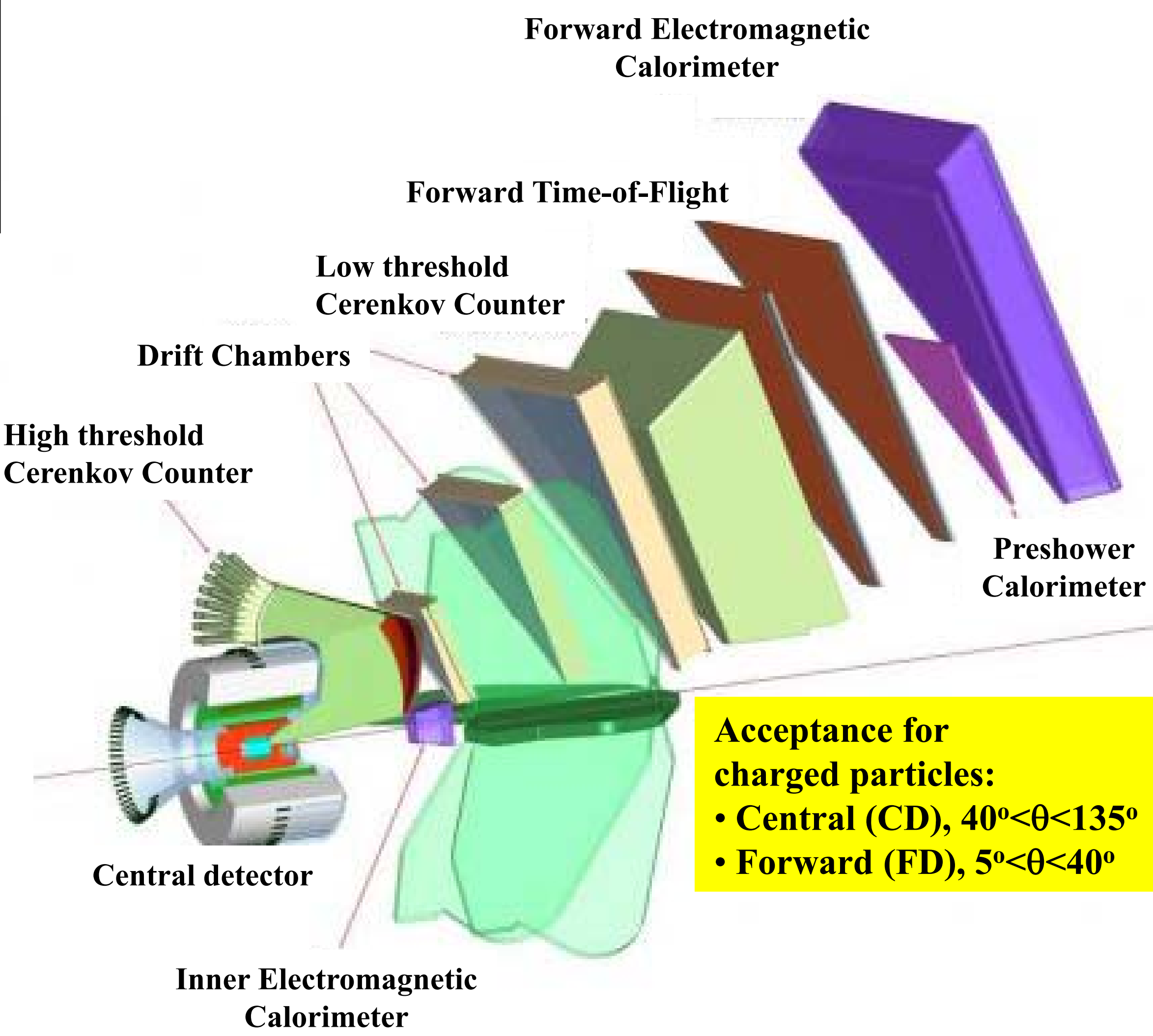
Design luminosity ~ 10^{35} cm^{-2}s^{-1}

Hall B @12 GeV: CLAS12

Concurrent measurement of deeply virtual exclusive, semi-inclusive, and inclusive processes

ep ⟶ eγp





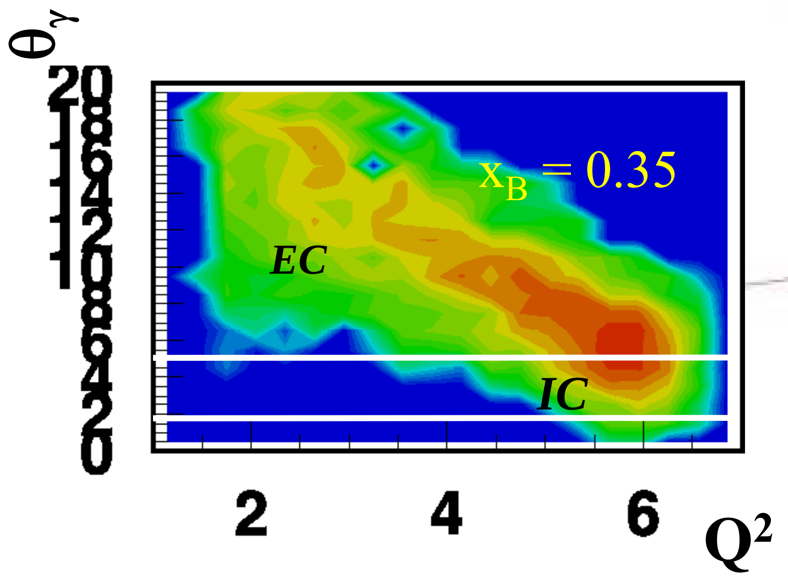
Acceptance for charged particles:
- Central (CD), $40^o<\theta<135^o$
- Forward (FD), $5^o<\theta<40^o$

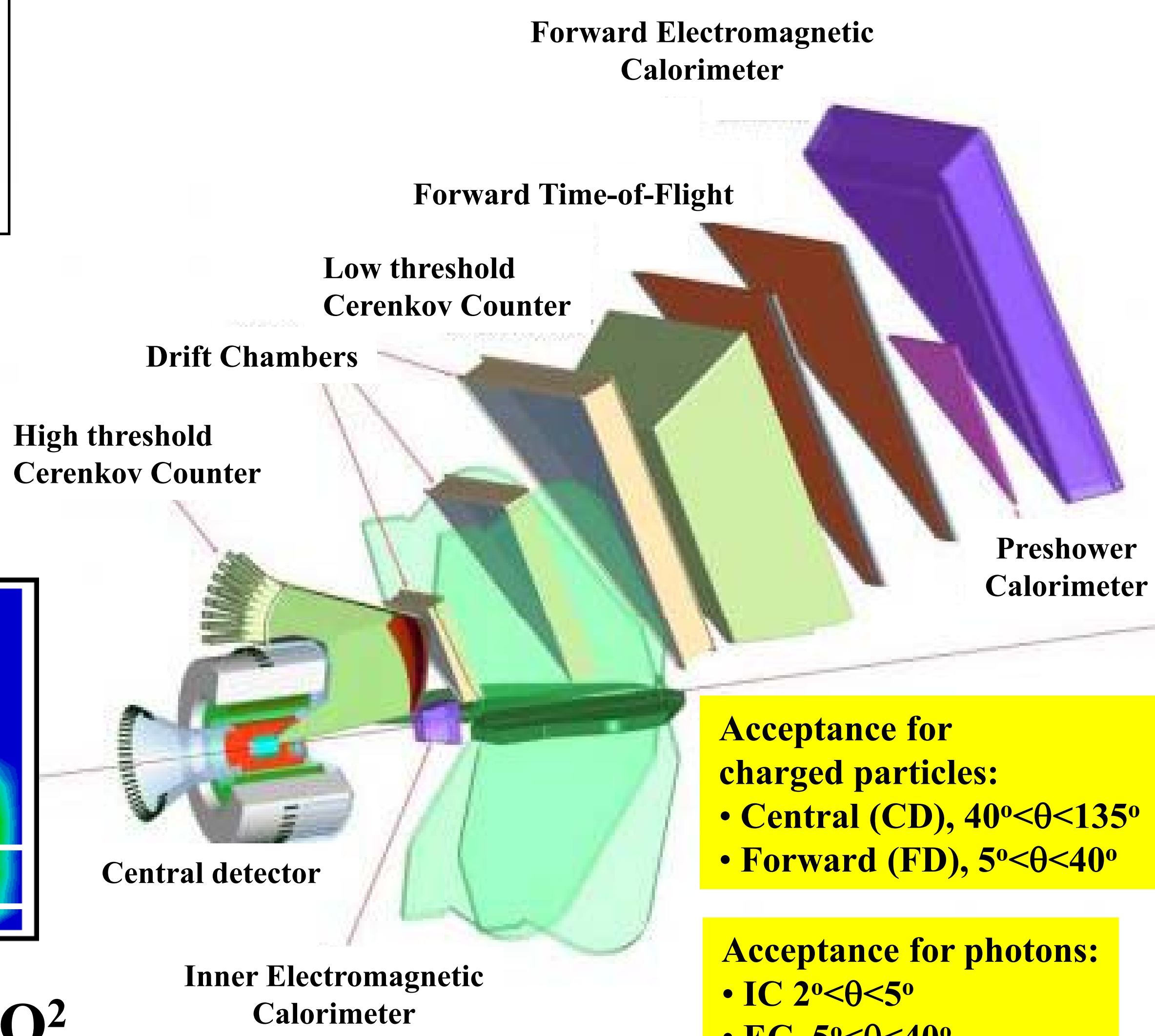
Design luminosity ~ 10^{35} cm^{-2}s^{-1}

Hall B @12 GeV: CLAS12

Concurrent measurement of deeply virtual **exclusive**, **semi-inclusive**, and **inclusive** processes

$ep \longrightarrow e\gamma p$





Acceptance for charged particles:
- Central (CD), $40^o<\theta<135^o$
- Forward (FD), $5^o<\theta<40^o$

Acceptance for photons:
- IC $2^o<\theta<5^o$
- EC, $5^o<\theta<40^o$

Design luminosity ~ 10^{35} $cm^{-2}s^{-1}$

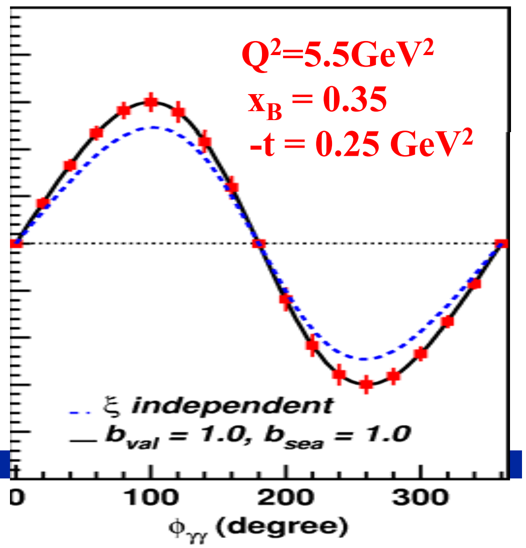
CLAS12: DVCS beam-spin asymmetry

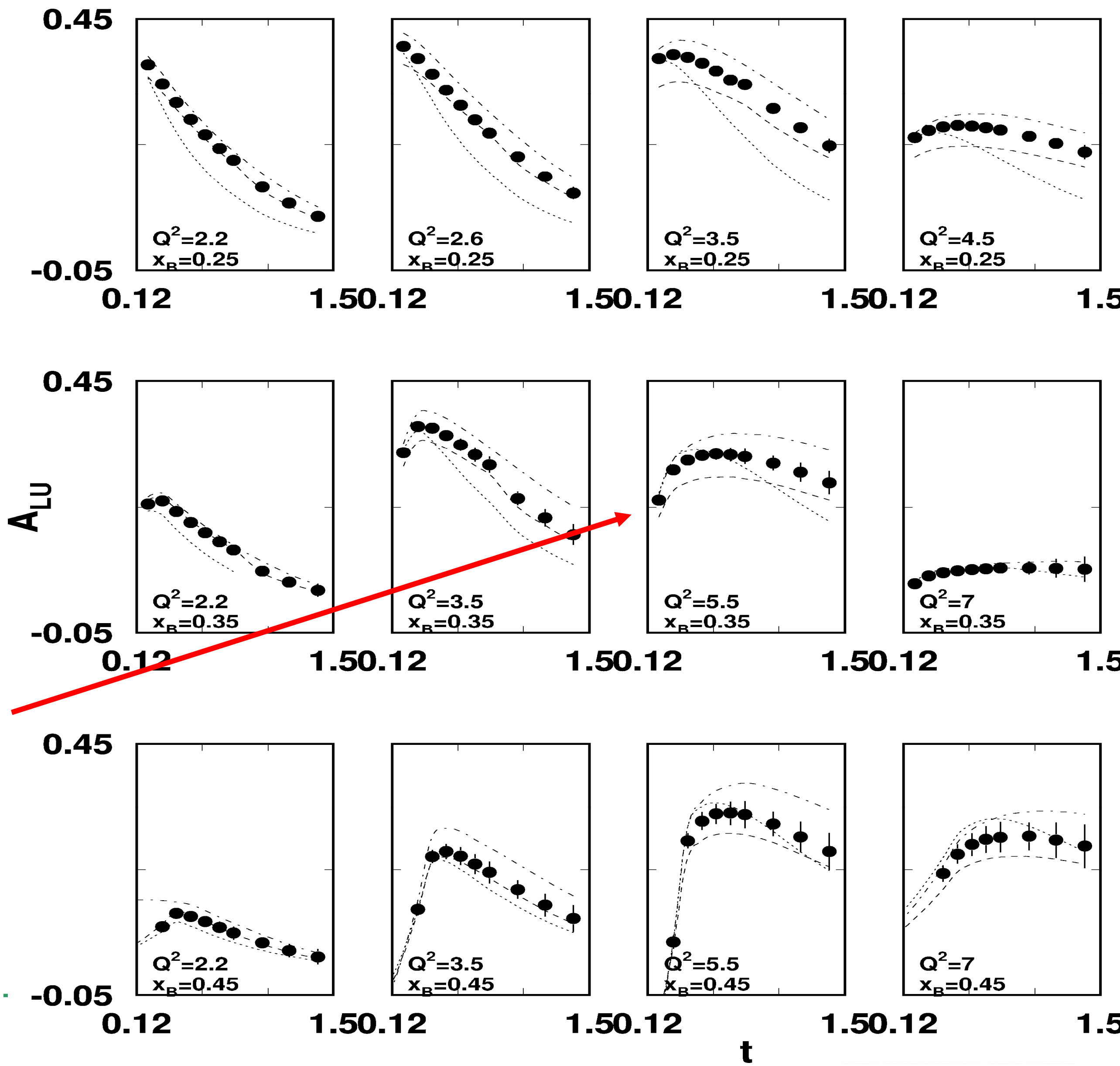
$\vec{e}\,p \longrightarrow ep\gamma$

E = 11 GeV

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

L = 1x10^35
T = 2000 hrs
ΔQ^2 = 1 GeV^2
Δx = 0.05





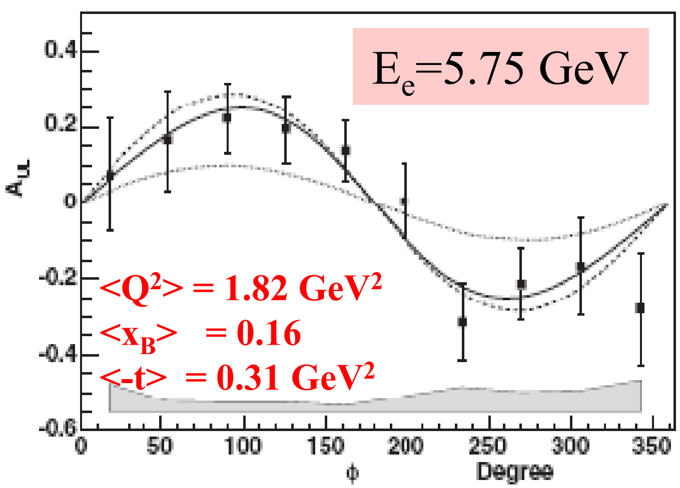
CLAS12: DVCS target-spin asymmetry

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

Longitudinally polarized target

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

S. Chen et al., PRL 97 (2006)

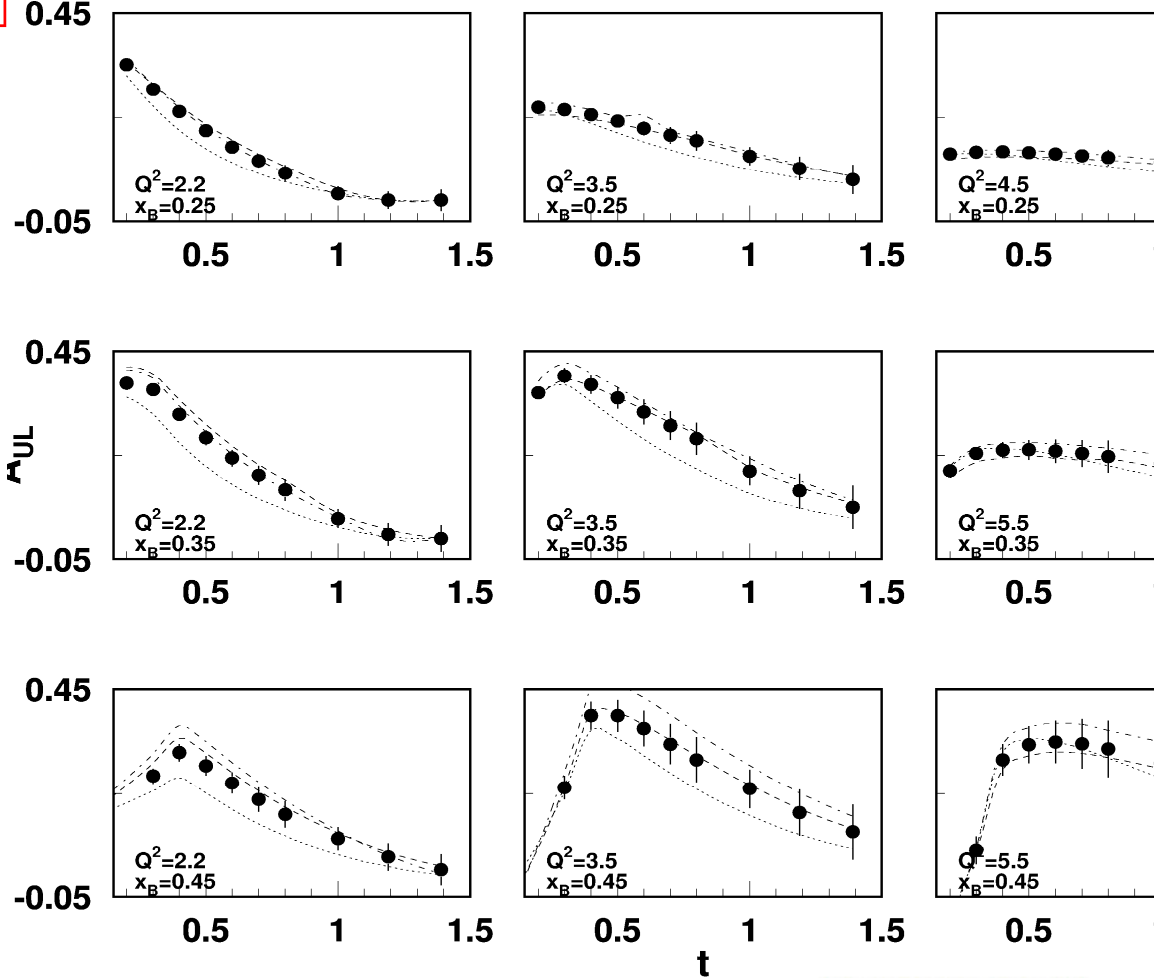


Dedicated experiment at 6 GeV scheduled for next year

E = 11 GeV

Projected results

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



CLAS 12: DVCS *transverse* target-spin asymmetry

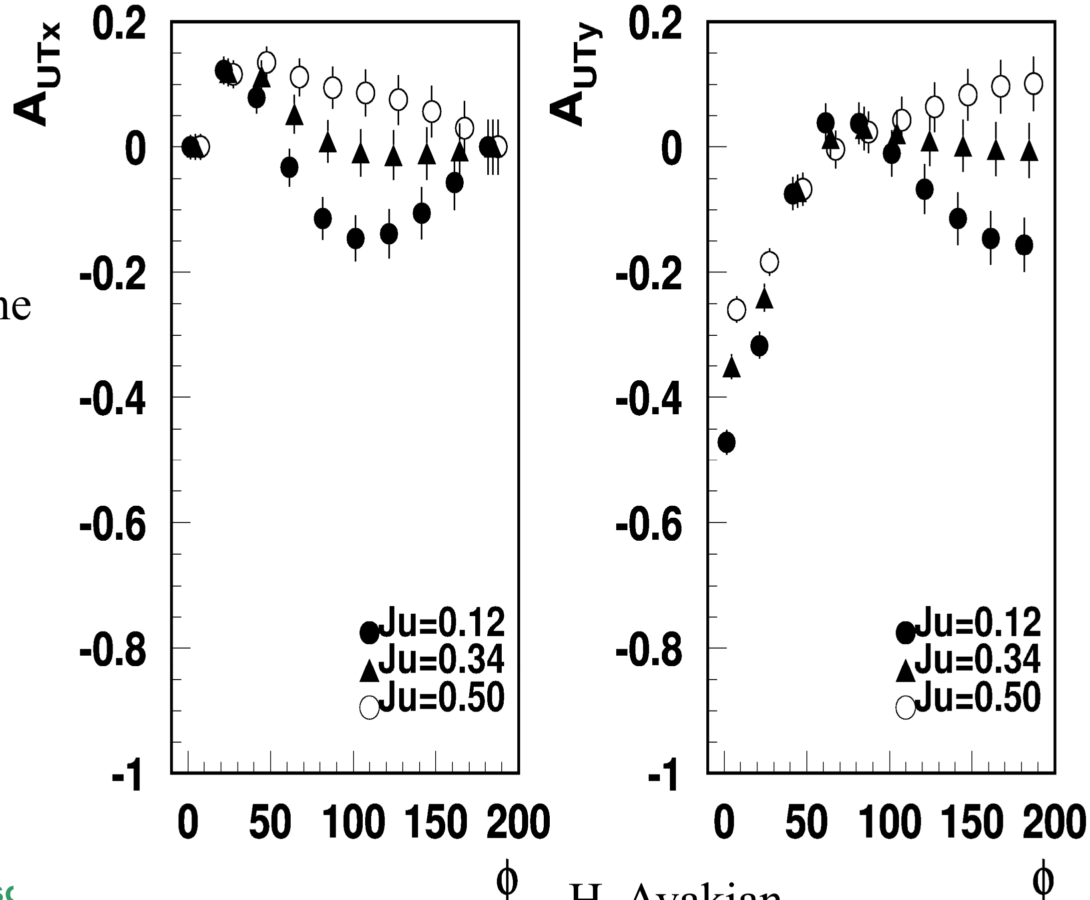
E = 11 GeV

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

Projected results

Transversely polarized target

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



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

A_{UTx} Target polarization in scattering plane

A_{UTy} Target polarization perpedicular to scattering plane

Transverse-target spin asymmetry is **highly sensitive** to the **u-quark contributions** to proton spin.

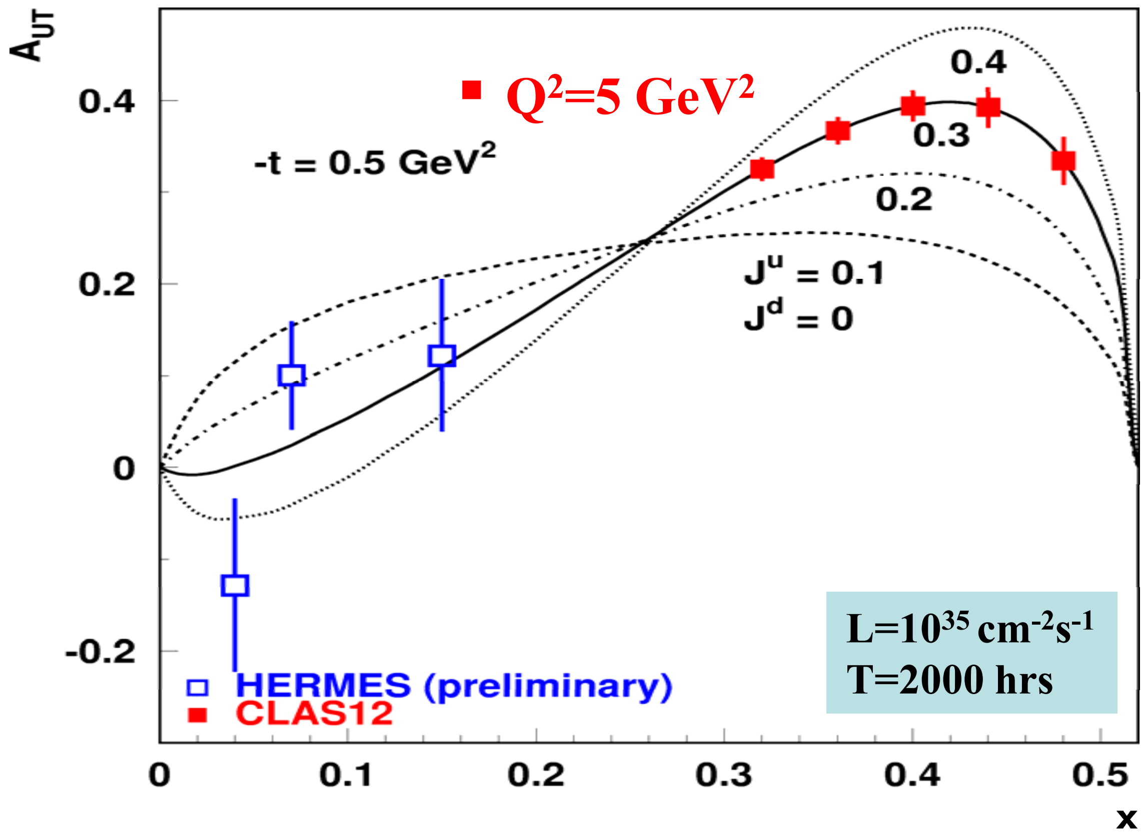
CLAS12: $ep^{\uparrow} \rightarrow ep\rho^0$

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

ρ^0

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

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



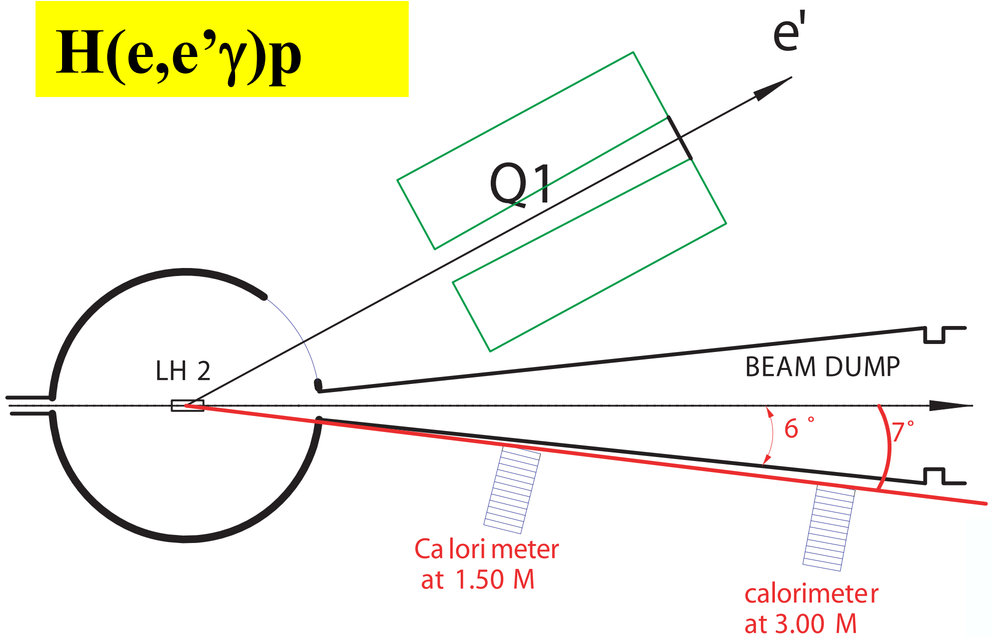
Asymmetry depends on the GPD E, necessary for Ji's sum rule

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…

JLab@12 GeV: DVCS setup for Hall A

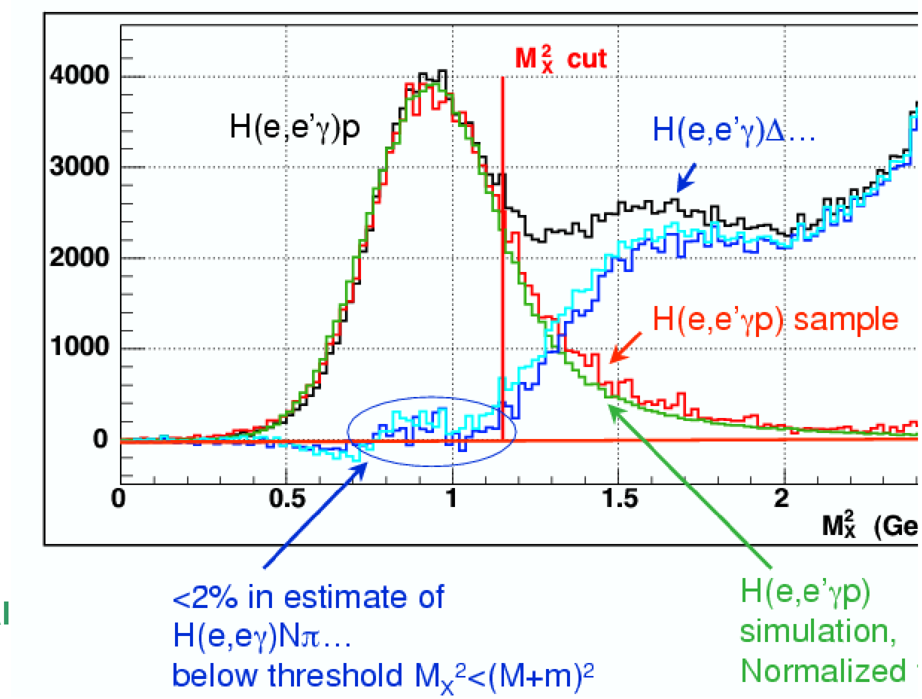
H(e,e'γ)p



- **e' detected in HRS-L**
- **γ detected in PbF2 calorimeter**

(upgraded with 76 additional elements)

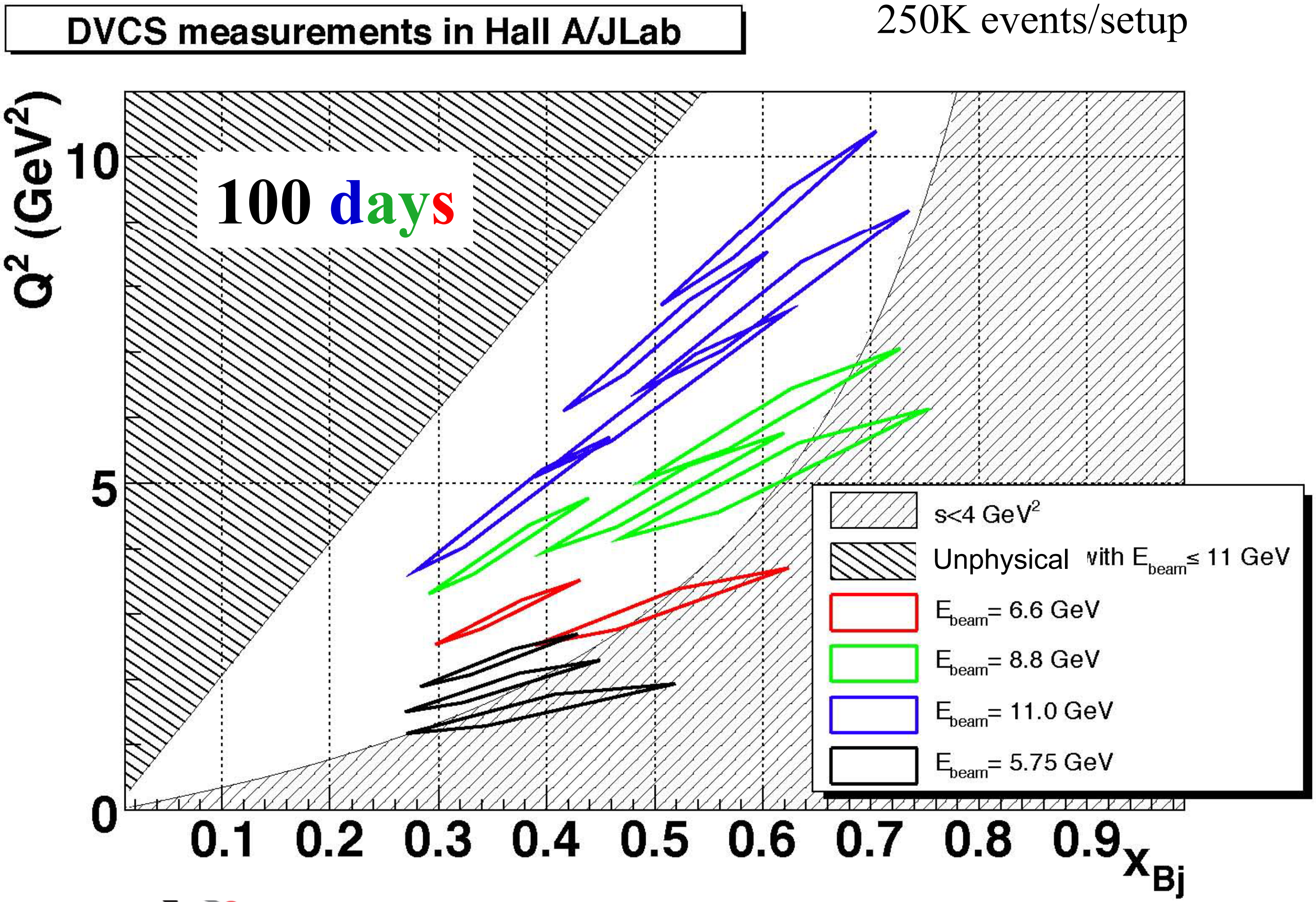
Extraction of epγ final state for published DVCS @ 6 GeV



High resolution allows exclusivity without requiring detection of recoil proton

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

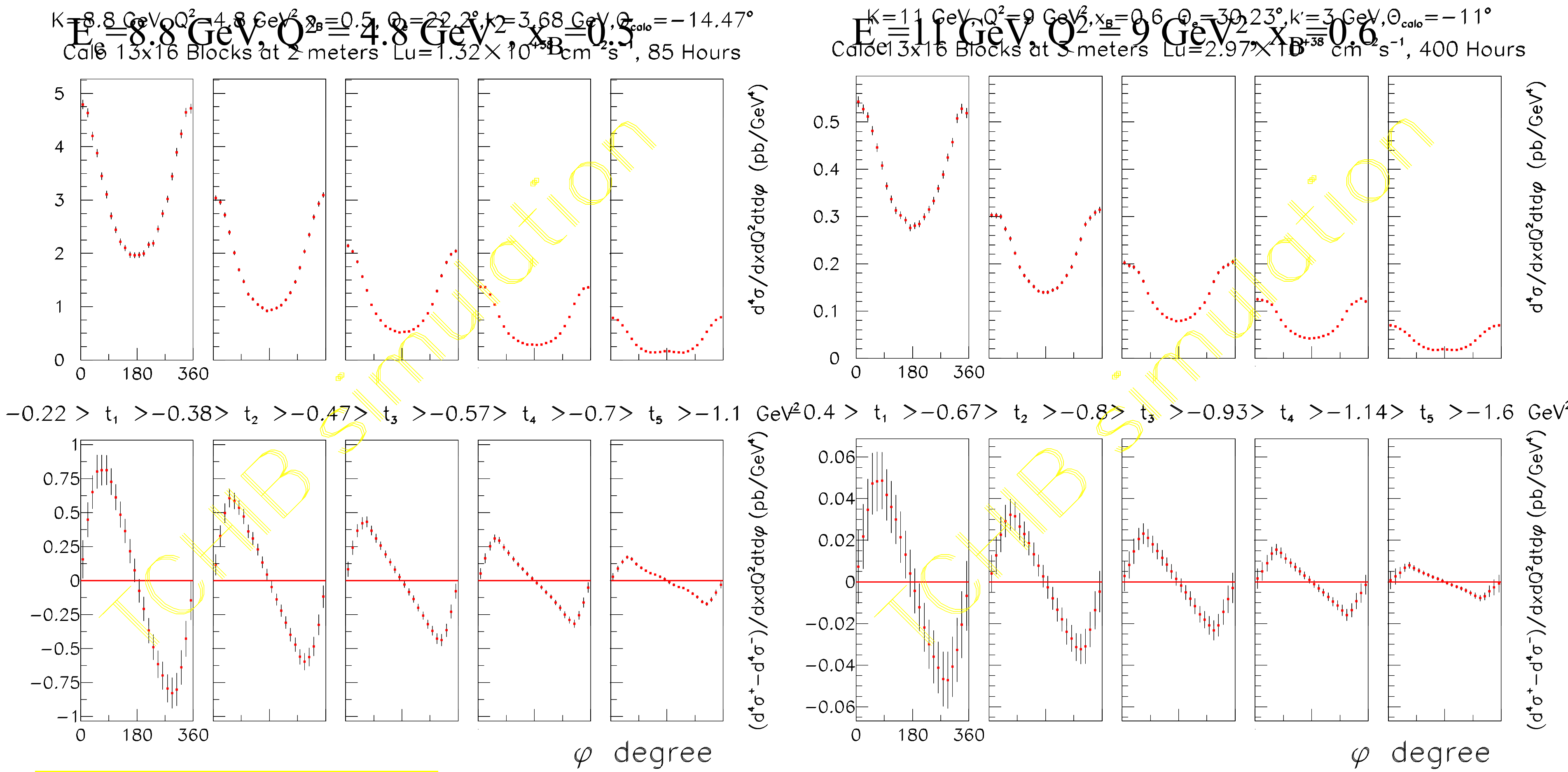
Im{DVCS*BH} $+\varepsilon \mathrm{DVCS}^2$

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

JLab12: projected results for DVCS in Hall A

Unpolarized cross sections (pb/GeV⁴)

400 hours



Polarized cross section differences (pb/GeV⁴)

…and exclusive π^0 electroproduction will also be measured

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