Neutrons in a Spin: Nucleon Structure at Jefferson Lab

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on behalf of the CLAS Collaboration

IoP Nuclear Physics Group Conference, York – 8th April 2013

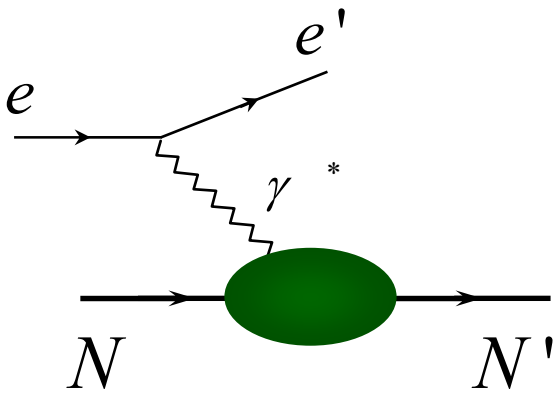
Jefferson Lab

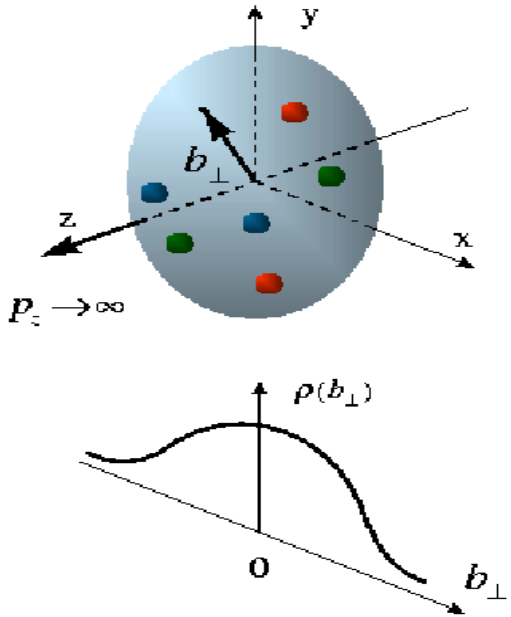
University of Glasgow

Nucleon structure

Lepton (eg: electron, neutrino) scattering off a nucleon reveals different aspects of nucleon structure.

Elastic Scattering

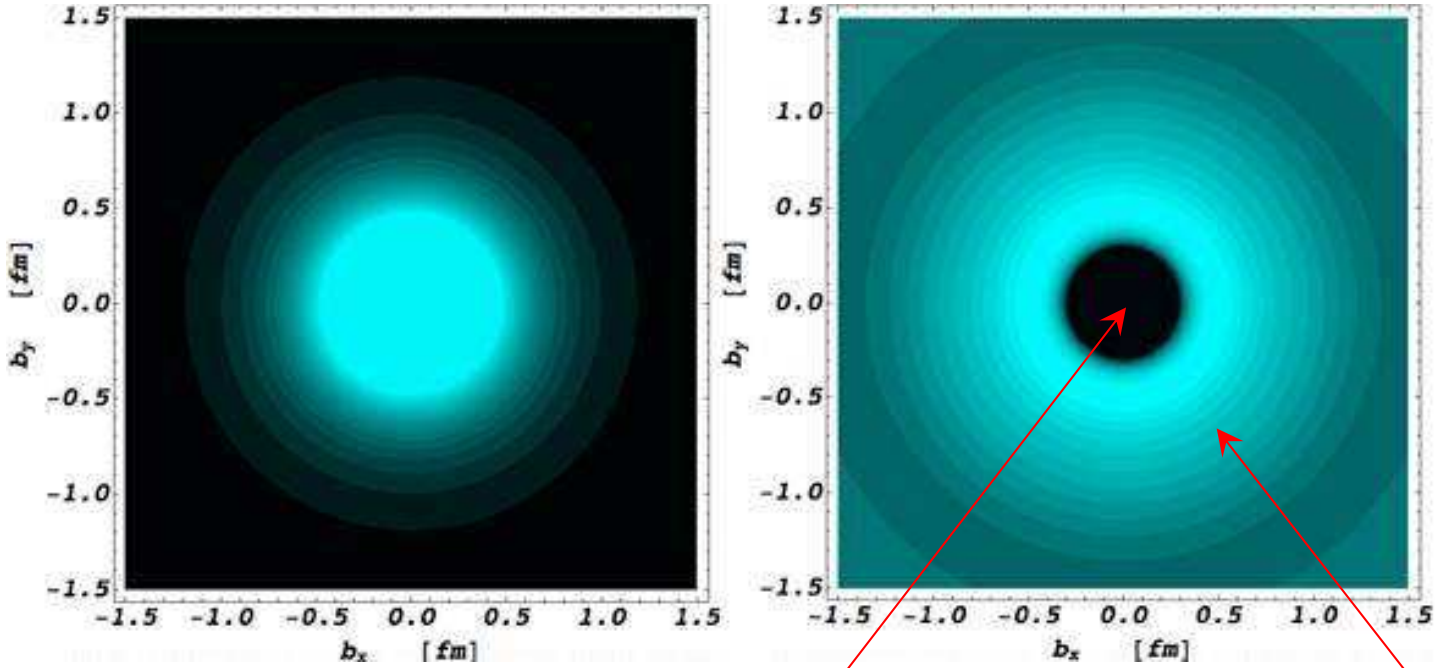




Cross-section parameterised in terms of Form Factors → Transverse quark distributions: charge, magnetisation.

Charge density inside a nucleon

Proton **Neutron**

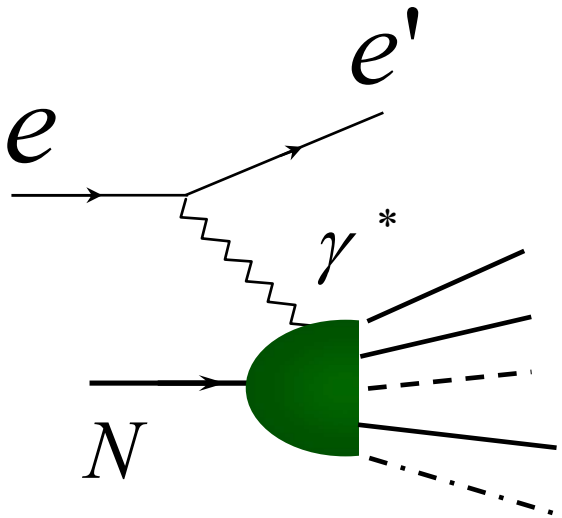


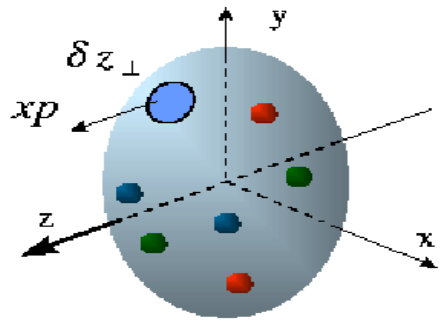
negative inner core

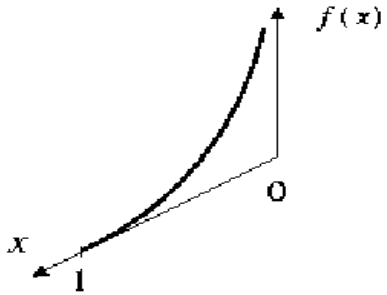
positive outer surface

G. Miller, PRL **99**, 112001 (2007)

Deep Inelastic Scattering







First experimental evidence of partons inside a nucleon

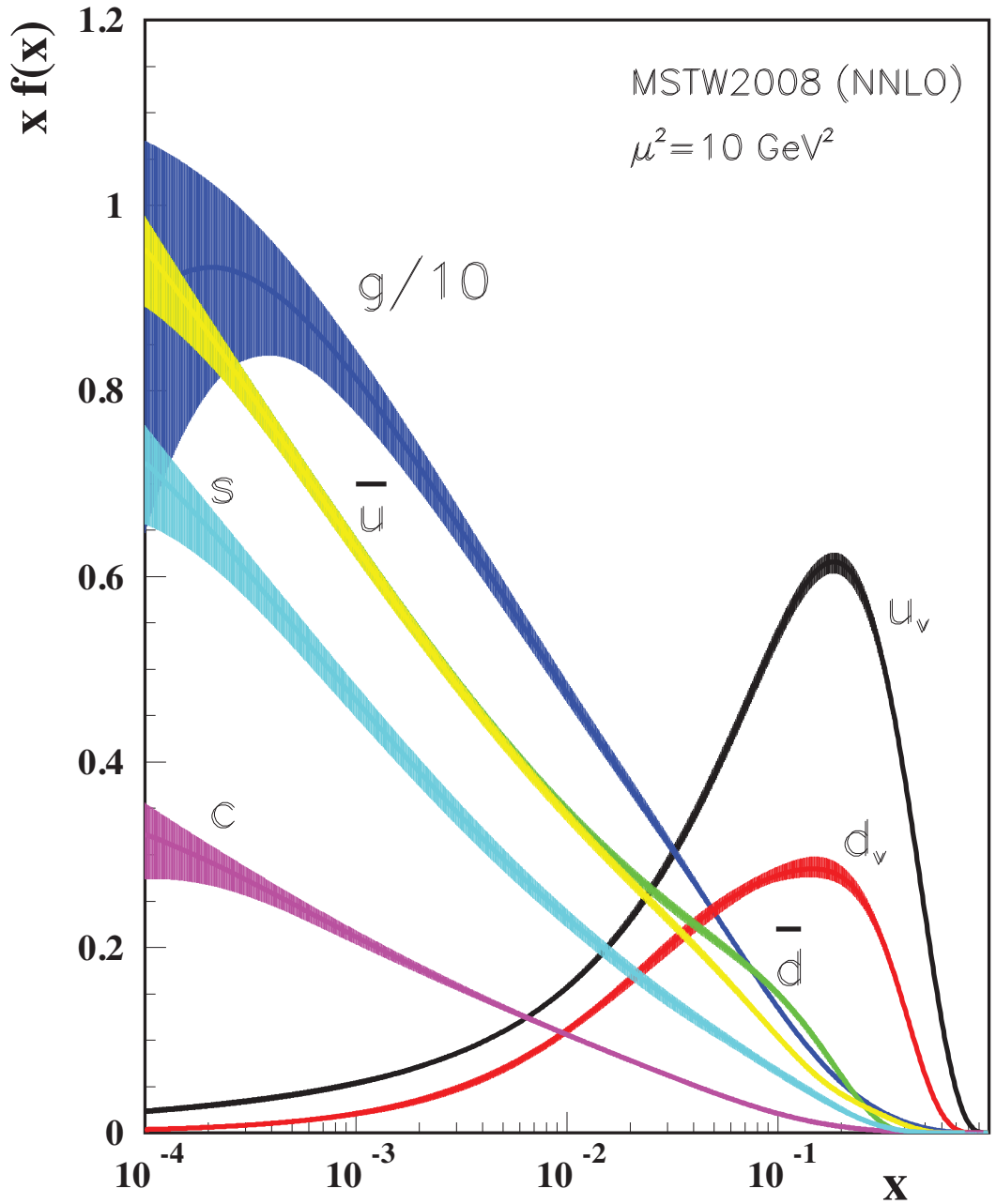
Cross-section parameterised in terms of Structure Functions

→ Longitudinal momentum distributions of partons

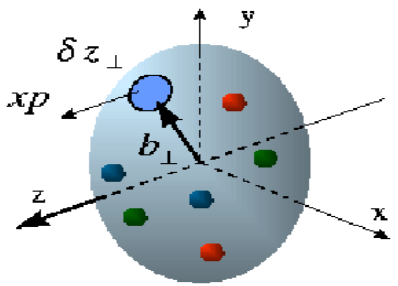
Parton Distribution Functions

Momentum distributions of quarks and gluons within a nucleon.

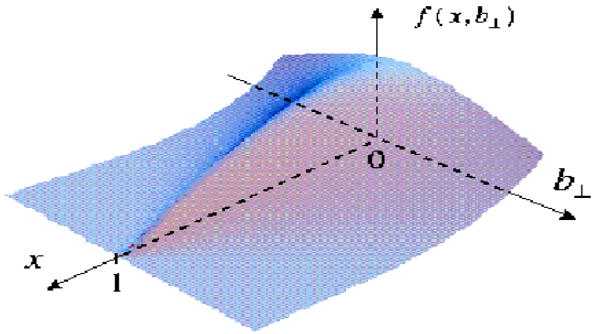
x: longitudinal momentum of parton as a fraction of nucleon's momentum.



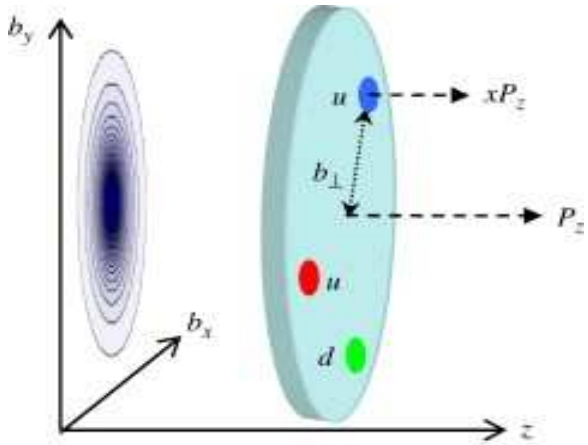
Deep Exclusive Reactions

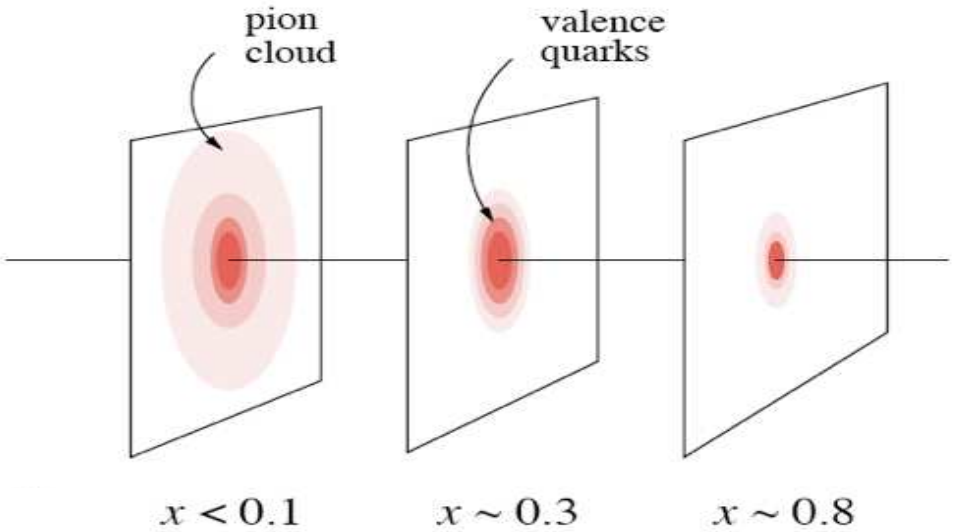


Generalised Parton Distributions (GPDs) relate transverse position of partons, $b_\perp$, to their longitudinal momentum.



Tomography: 3D image of the nucleon.





The Nucleon Spin Puzzle

- What contributes to nucleon spin?
- 1980's: European Muon Collaboration (EMC) measures contribution of valence quarks to proton spin to be ~ 30 %. Subsequent deep inelastic scattering (DIS) experiments confirm.

Where is the rest? → **Proton spin crisis!**

Quark spin: extracted from helicity distributions measured in polarised DIS.

Gluon spin: measurements of DIS and polarised proton collisions indicate ΔG is very small.

$$J_N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

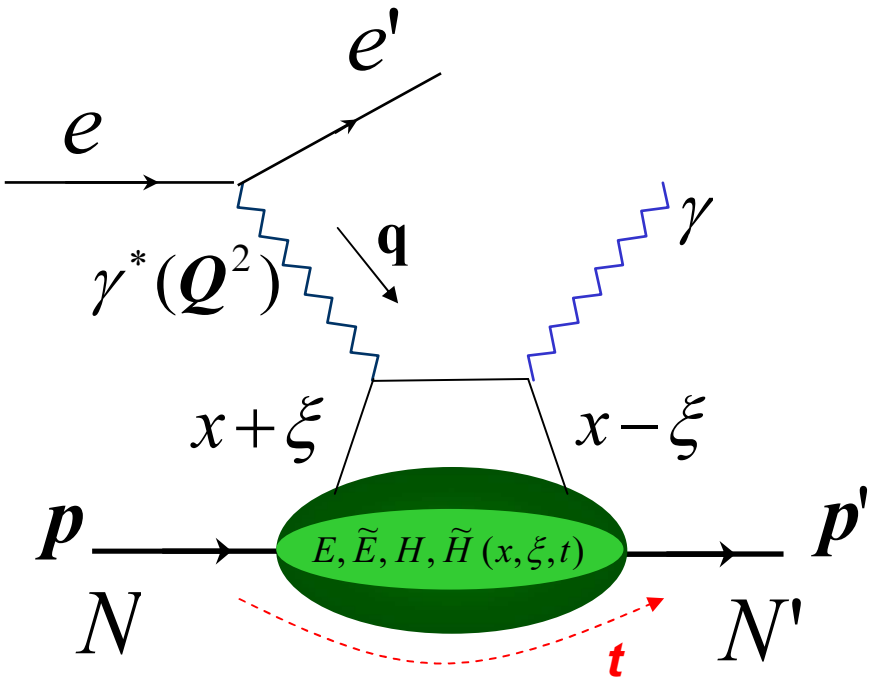
Quark orbital angular momentum: can be accessed via **GPDs**, which contain information on total angular momentum, J_q.

Caveat:

The three terms not yet accessible within a single formalism.

Deeply Virtual Compton Scattering

✸ One of the cleanest experimental processes in which GPDs can be accessed is **Deeply Virtual Compton Scattering** (DVCS).



$$Q^2 = -\mathbf{q}^2 = -(\mathbf{e}-\mathbf{e}')^2 \qquad t^2 = -(\mathbf{p}-\mathbf{p}')^2$$

Bjorken variable $x_B = \dfrac{Q^2}{2\mathbf{p}\cdot\mathbf{q}}$

$x \pm \xi$: *longitudinal momentum fractions of struck quark*

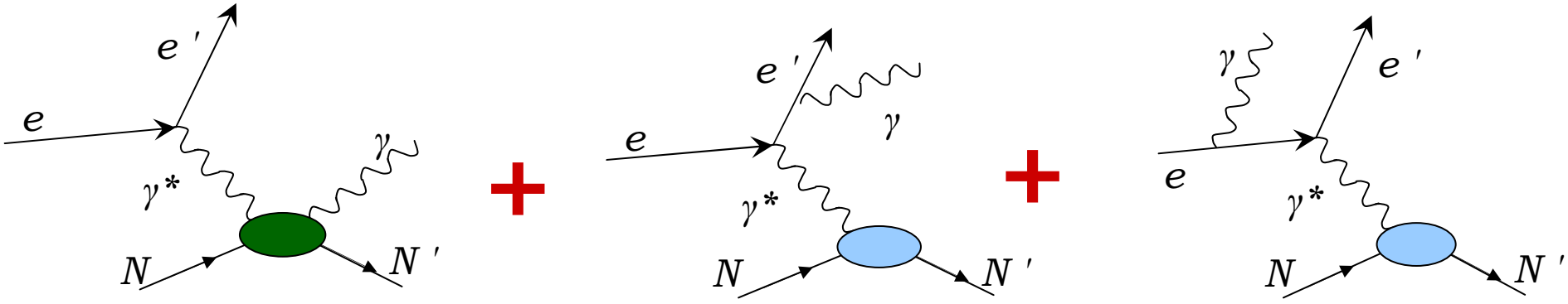
$$\xi \cong \frac{x_B}{2 - x_B}$$

✸ At high exchanged Q^2, access to four **GPD**s: $E_q, \widetilde{E}_q, H_q, \widetilde{H}_q\ (x,\xi,t)$

Experimental extraction of GPDs

✸ DVCS and Bethe-Heitler (BH) experimentally indistinguishable.

Process measured in experiment:



DVCS Bethe - Heitler

$$d\sigma \propto |T_{DVCS}|^2 + |T_{BH}|^2 + T_{BH}T^*_{DVCS} + T_{DVCS}T^*_{BH}$$

Amplitude parameterised in terms of Compton Form Factors

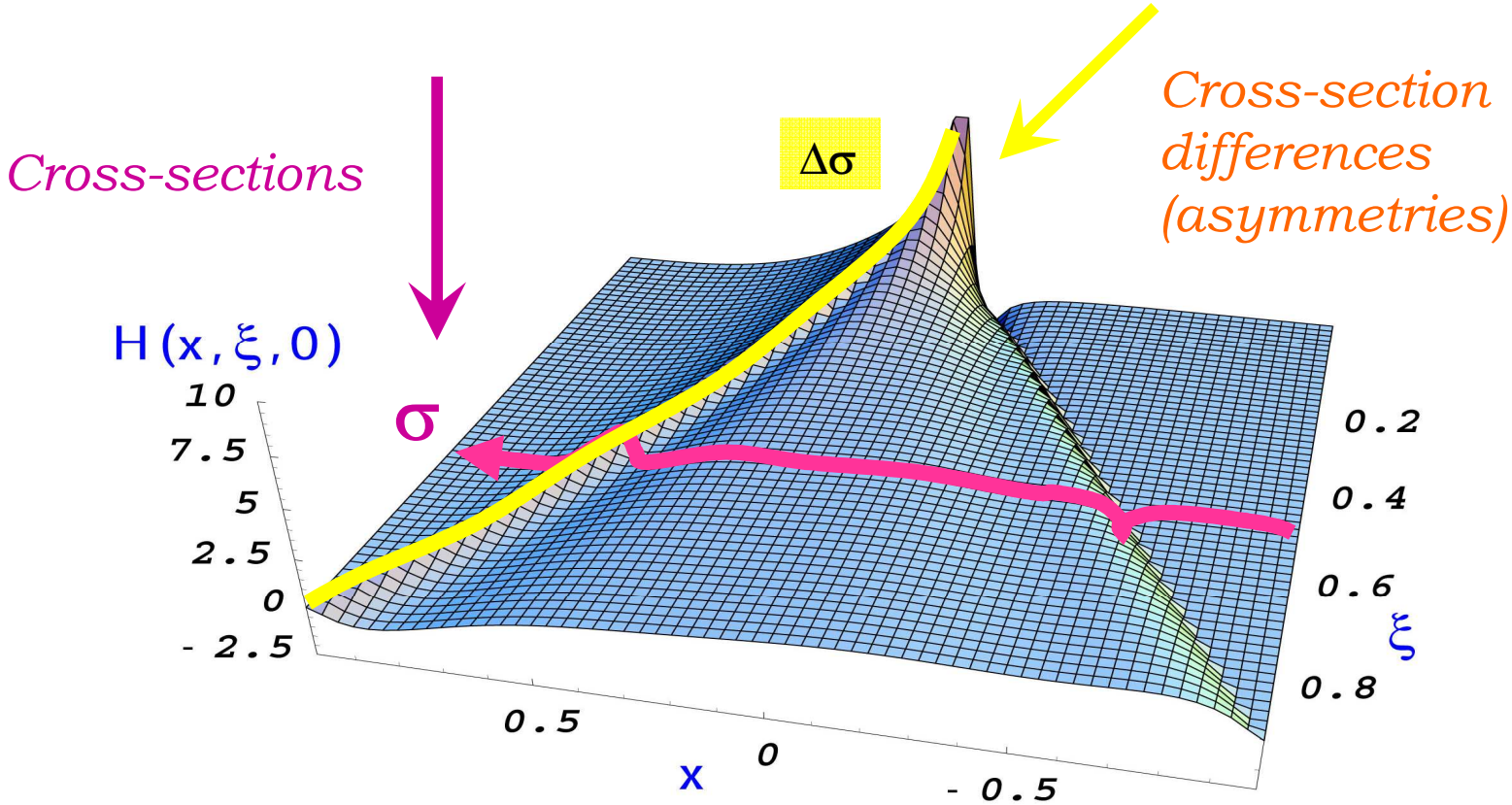
Amplitude calculable from elastic Form Factors and QED!

Interference term

$$|T_{DVCS}|^2 << |T_{BH}|^2$$

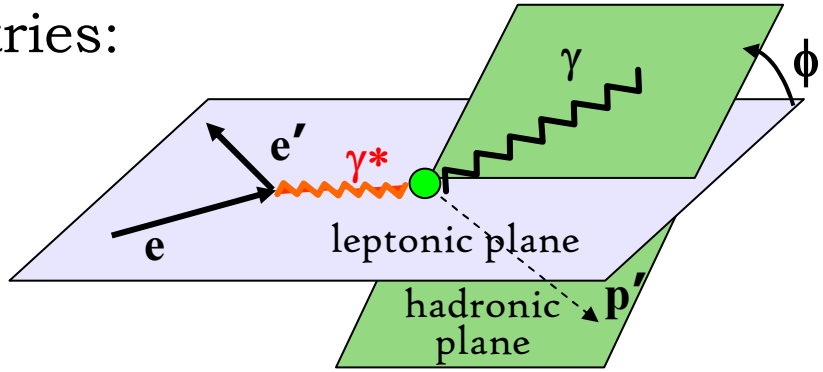
✸ Experimentally, access Compton Form Factors (CFF), which are combinations of GPDs integrated over x and functions of GPDs at $x=\xi$. Only ξ and t are thus experimentally directly accessible!

$$T_{DVCS} \propto \int_{-1}^{+1} \frac{GPDs\ (x,\xi,t)}{x \pm \xi} dx \pm i\pi\ GPDs\ (\pm\xi,\xi,t) + \ldots$$



Extracting Compton Form Factors

- For example, from DVCS spin asymmetries:



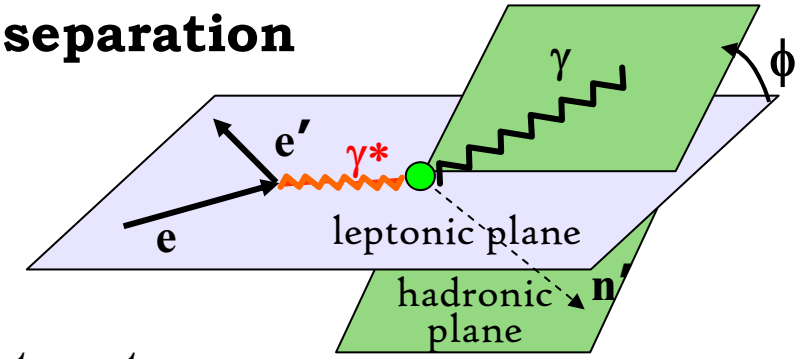
$$A_{LU} = \frac{d\vec{\sigma} - d\overleftarrow{\sigma}}{d\vec{\sigma} + d\overleftarrow{\sigma}} = \frac{\Delta\sigma_{LU}}{d\vec{\sigma} + d\overleftarrow{\sigma}}$$

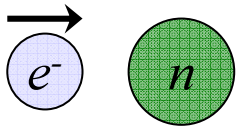
Beam, target polarisation		Proton	Neutron
$\vec{e}^-$ p/n	$\Delta\sigma_{LU} \sim \sin\phi \, \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$ $\xi = x_B/(2-x_B) \quad k = t/4M^2$	$Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$	$Im\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\}$
e^- ↑	$\Delta\sigma_{UT} \sim \cos\phi \, \mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\ldots\}d\phi$	$Im\{\mathcal{H}_p, \mathcal{E}_p\}$	$Im\{\mathcal{H}_n\}$
$\vec{e}^-$ →	$\Delta\sigma_{LL} \sim (A+B\cos\phi)\,\mathrm{Re}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E})\ldots\}d\phi$	$Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$	$Re\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\}$

Neutron DVCS

- GPDs from proton and neutron: **flavour separation**

- **Neutron DVCS** extremely sensitive to ***E***, least-known and least-constrained GPD.





*Polarized beam, unpolarized **neutron** target:*

$$\Delta\sigma_{LU} \sim \sin\phi\ \mathbf{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} - kF_2 E\}d\phi \longrightarrow H_n,\ \tilde{H}_n,\ \mathbf{E_n}$$

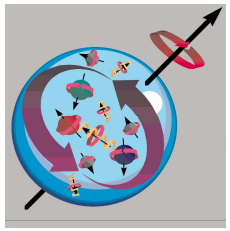
Suppressed because $F_1(t)$ is small

Suppressed because of cancellation between PDF's of u and d quarks

- Ji's "Sum Rule": $J_q = \frac{1}{2} - J_g = \frac{1}{2}\int_{-1}^{1} x dx \left\{ H_q(x,\xi,0) + E_q(x,\xi,0) \right\}$

$$J_N = \frac{1}{2} = \frac{1}{2}\Sigma_q + L_q + J_g$$

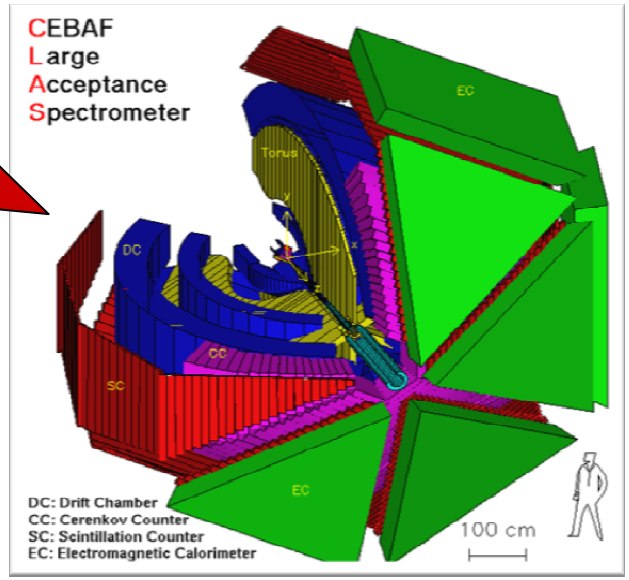
Important missing link in the **nucleon spin puzzle**!

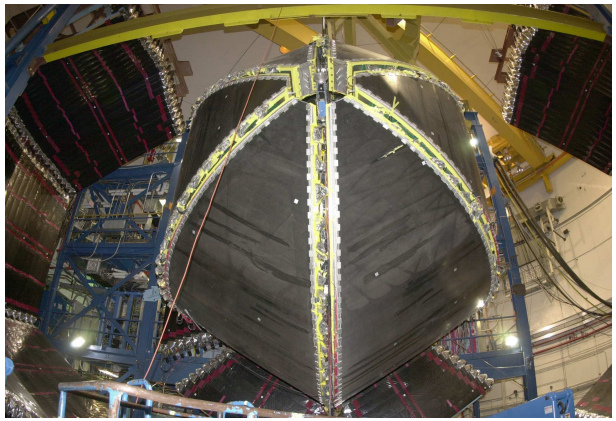


CLAS @ Jefferson Lab (Virginia, USA)

CEBAF: Continuous Electron Beam Accelerator Facility:

- Duty cycle: ~ 100%
- Energy up to ~6 GeV
- Electron polarisation up to ~85%





CLAS in Hall B:

- Drift chambers
- Toroidal magnetic field
- Cerenkov Counters
- Scintillator Time of Flight
- Electromagnetic Calorimeters

→ *Extremely large angular coverage*

Neutron DVCS: Eg1-dvcs experiment

Data taken: Feb – Sept 2009

Beam: polarised electrons
E_e = 4.7 to 6 GeV
polarisation ~ 85%

Longitudinally polarised targets:
NH_3 (95 days)
ND_3 (33 days)

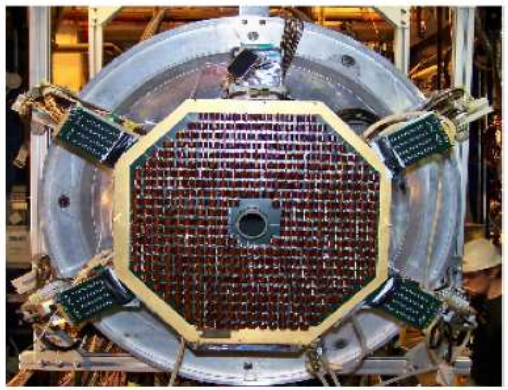
Proton / neutron pol. ~ 80 / 40 %

$$\vec{e} + \vec{d} \rightarrow e' + \gamma + n + (p_s)$$

CLAS → **Exclusive** reconstruction of *e'*, *N*, and *γ*.
Spectator proton identified via missing mass.

plus

Inner Calorimeter (IC) → high-energy forward photon detection

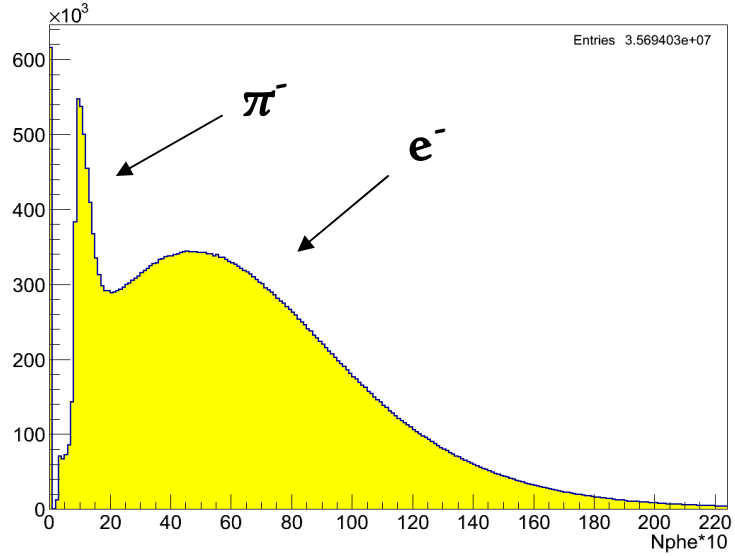


Particle ID in CLAS

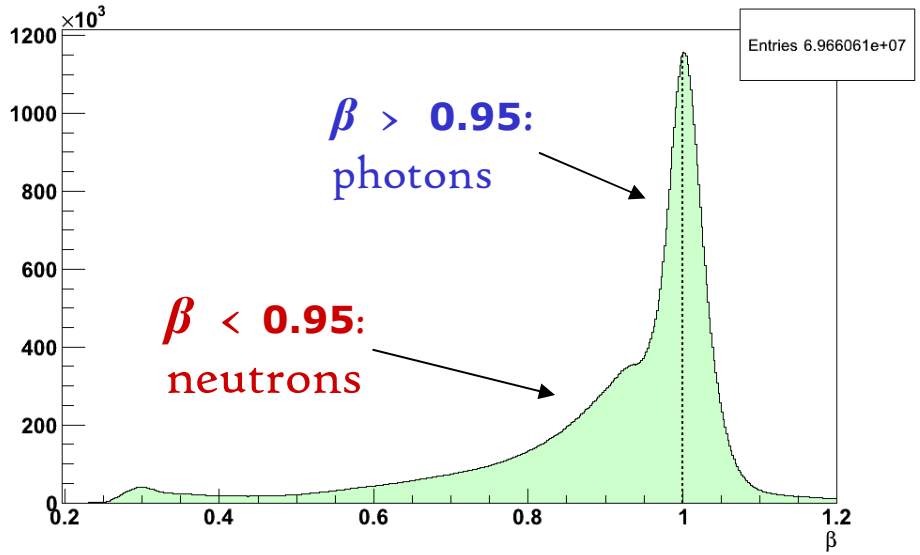
- q and p from track-curvature through drift chambers in magnetic field

- **Separation from π^-:** on basis of energy deposit in electromagnetic calorimeter (EC) and number of photoelectrons produced in Cerenkov counters (CC).

# of photoelectrons (x10) in CC



- β from neutral particles' time of flight to EC



- Forward, low-angle photons in additional Inner Calorimeter

Reaction Identification

Select kinematic region where GPD formalism holds: ❖ $Q^2 > 1\ GeV^2$

Energetic photon and recoil nucleon: ❖ $E_\gamma > 1$ GeV ❖ $p_n > 0.4$ GeV/c

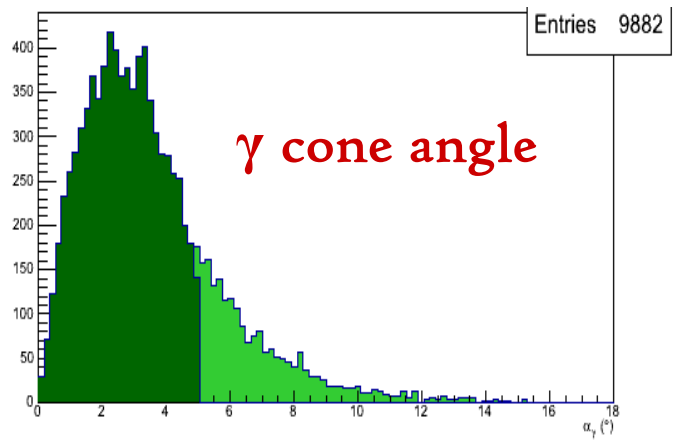
❖ $W > 2\ GeV/c^2$ where W is the missing mass of $(eN \rightarrow e'X)$, remove resonance region of remaining γN

Additionally, require:

❖ Coplanarity between γ and N

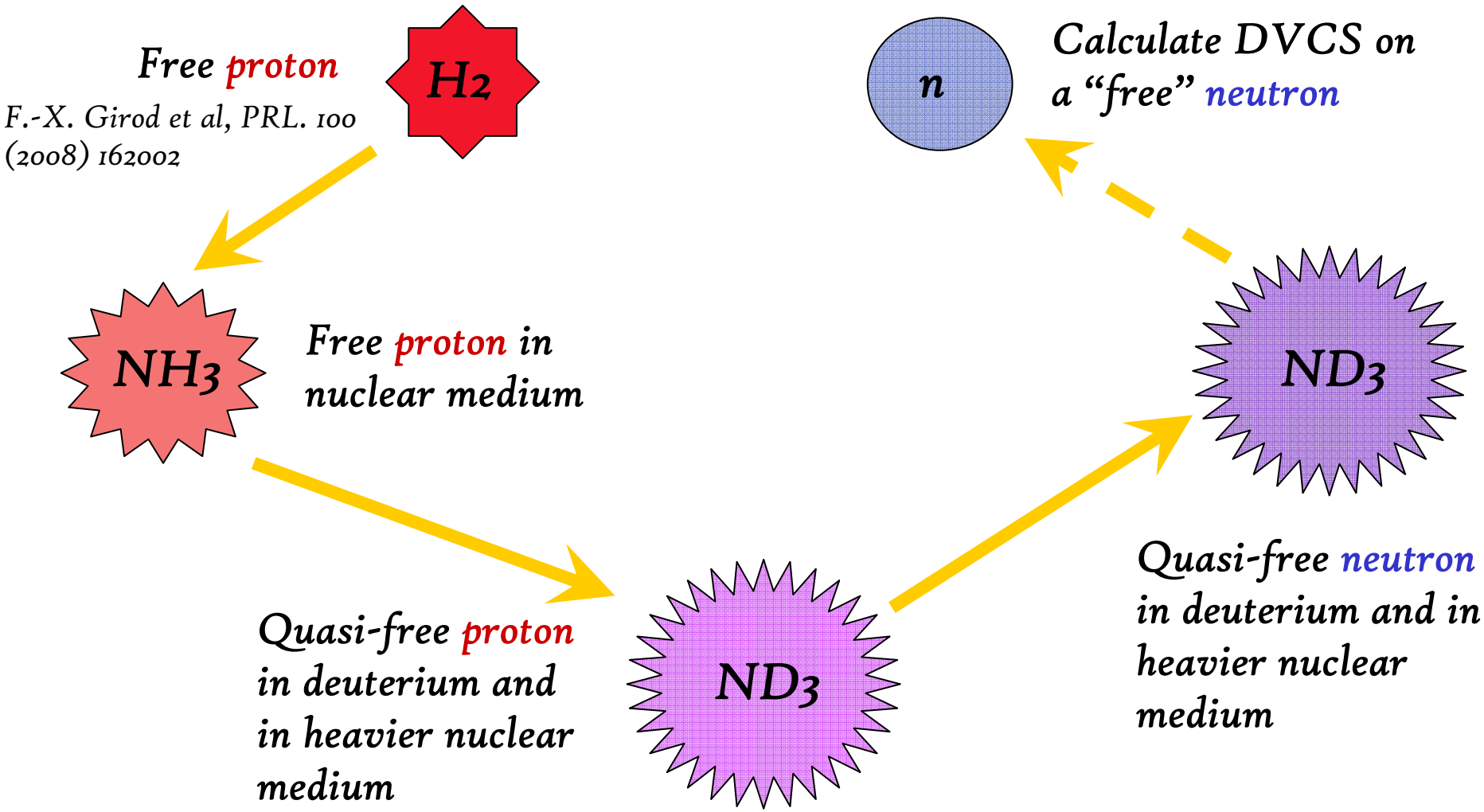
❖ Missing momentum from $ed \rightarrow e'N'\gamma\ X$
Should be low for spectator nucleon in quasi-free reaction

❖ Missing mass from the above reaction should correspond to mass of nucleon.

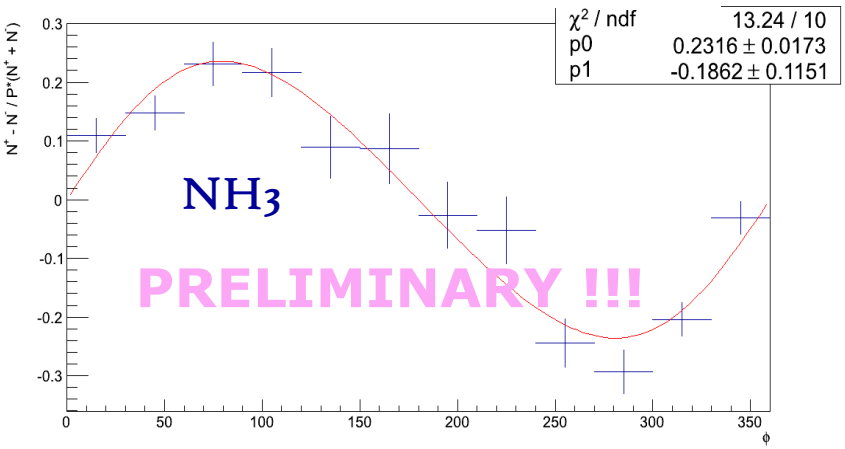


❖ Difference between calculated and measured γ direction should be low.

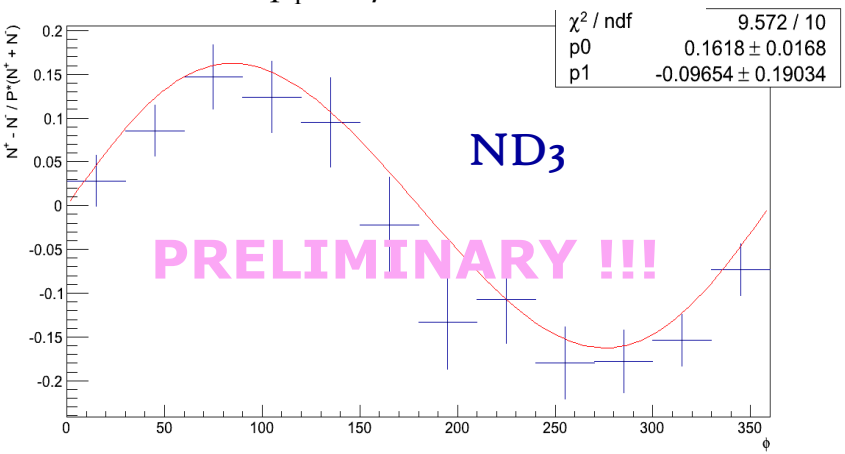
DVCS on different targets



A_{LU} – check on proton DVCS in NH_3 and ND_3



Fit: $A = \dfrac{p_0 \sin\varphi}{1 + p_1 \cos\varphi}$



Previously measured result on H_2 is in range 0.2 -0.3.

F.-X. Girod et al, PRL. 100 (2008) 162002

$$\frac{N^+ - N^-}{P(N^+ + N^-)} \approx 0.23 \pm 0.02$$

Uncorrected for π^0 contamination

→ *actual A_{LU} larger!*

Deuterium target – smearing due to Fermi motion requires wider data cuts.

$$\frac{N^+ - N^-}{P(N^+ + N^-)} \approx 0.16 \pm 0.02$$

π^0 contamination more significant

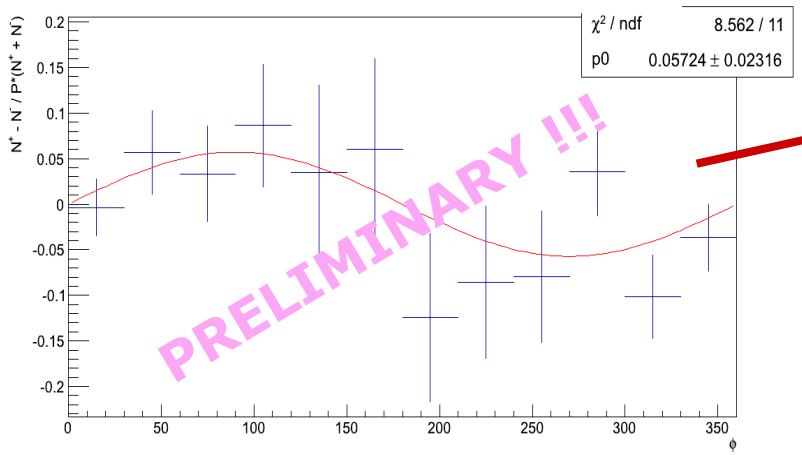
→ *measured A_{LU} lower than on NH_3.*

A_{LU} and A_{UL} in neutron DVCS on ND_3

- **Beam-spin asymmetry:**

One previous measurement from Hall A @ JLab, A_{LU} ~ 0. Big statistical and systematic uncertainties, slightly different kinematic region.

(M. Mazouz et al, PRL 99 (2007) 242501)



$$\frac{N^+ - N^-}{P(N^+ + N^-)} \approx 0.06 \pm 0.02$$

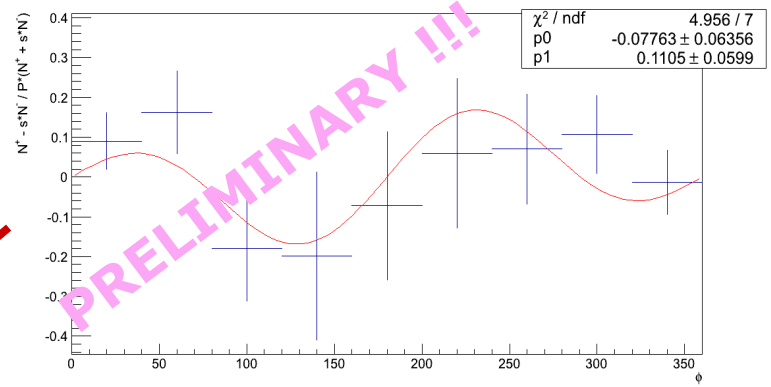
Fit: $A_{LU} = p_0 \sin\varphi$

Uncorrected for π^0 contamination, includes neutrons from N!

$p_0 \approx 0.077 \pm 0.06$ $\quad p_1 \approx 0.11 \pm 0.06$

- **Target-spin asymmetry:**

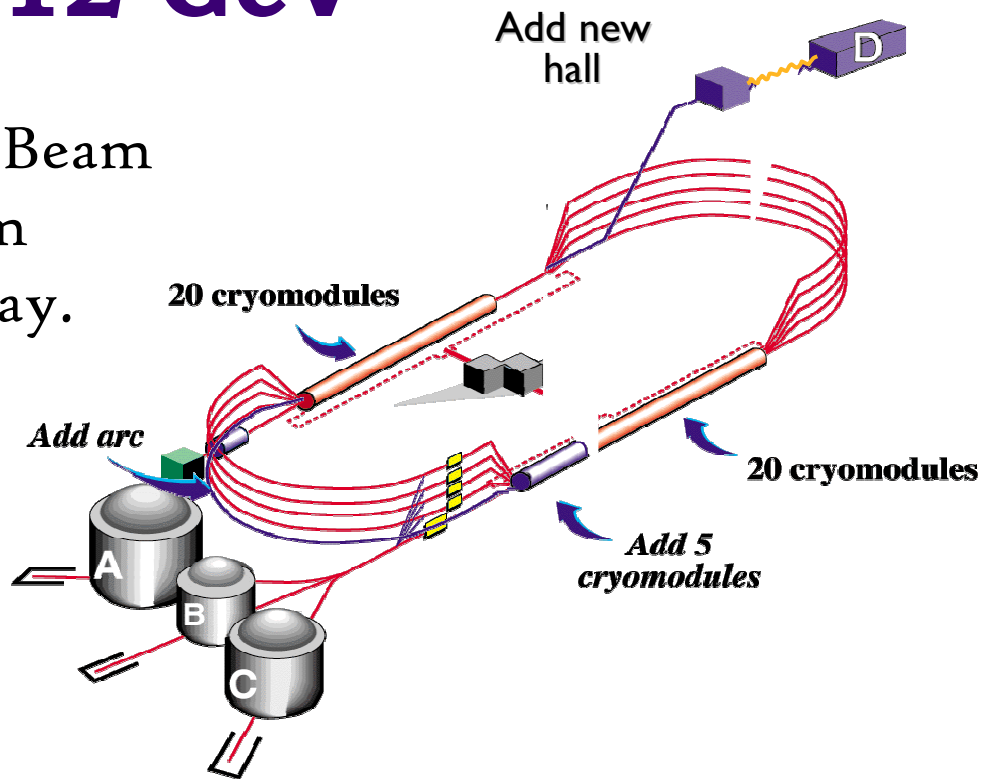
First measurement!



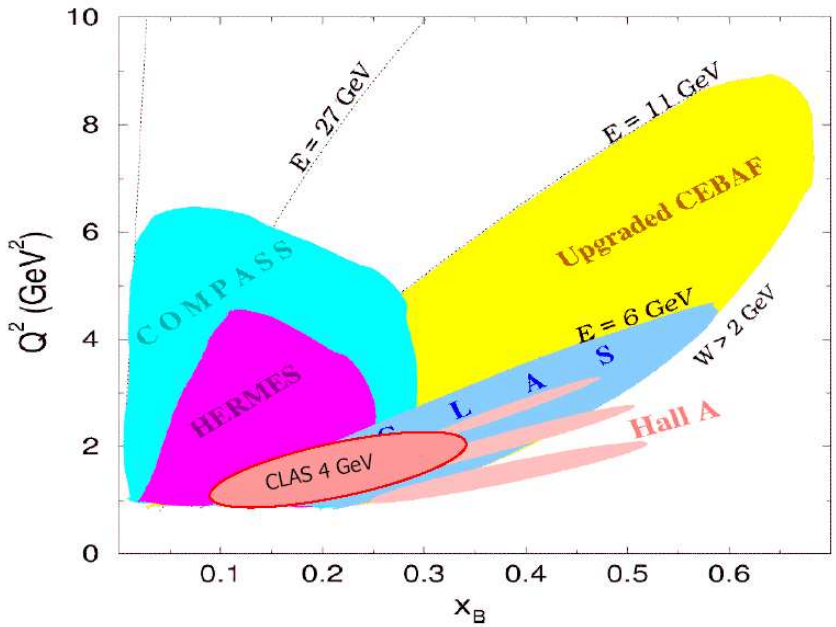
Fit: $A_{UL} = p_0 \sin\varphi + p_0 \sin 2\varphi$

Jefferson Lab @ 12 GeV

- CEBAF: Continuous Electron Beam Accelerator Facility, upgrade from current 6 GeV to 12 GeV underway.



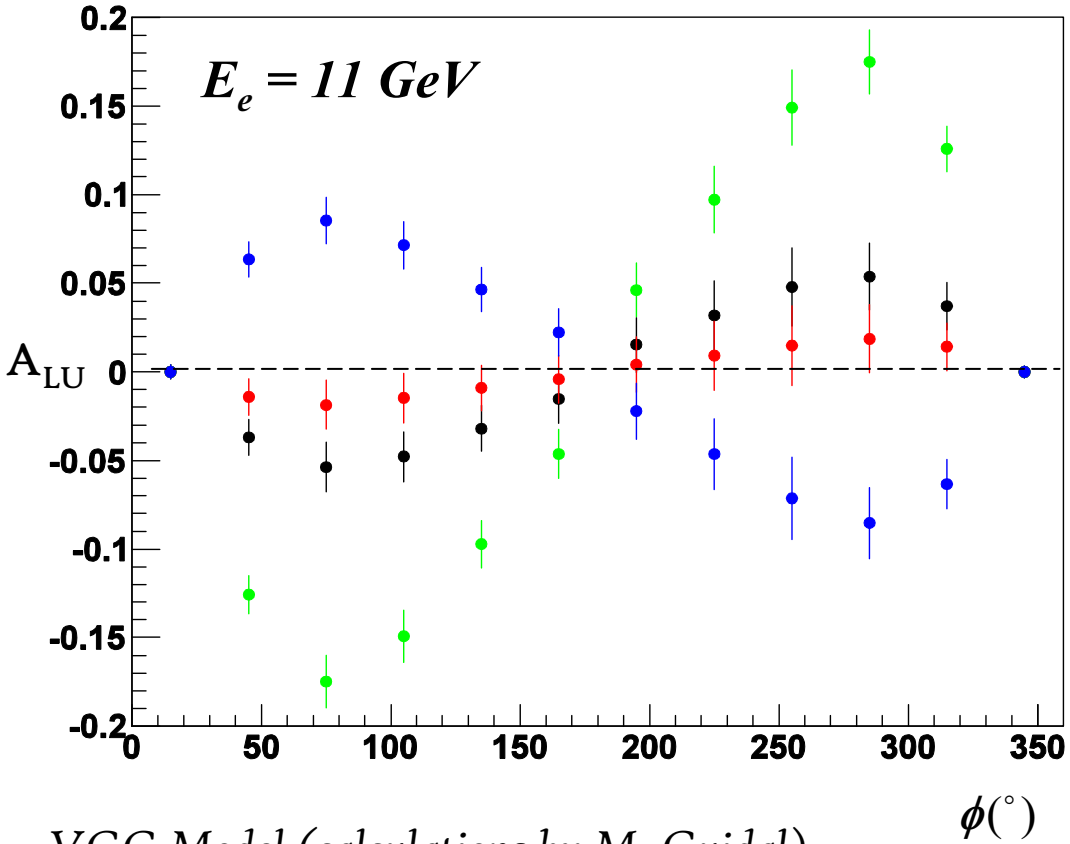
- Open up much larger phase space in Q^2 and x_B



- Hall B – 11 GeV to the upgraded detector system CLAS12

- Scheduled completion ~ 2014

A_{LU} in Neutron DVCS @ 11 GeV



VGG Model (calculations by M. Guidal)

$J_u = 0.3, J_d = -0.1$ $J_u = 0.3, J_d = 0.1$

$J_u = 0.1, J_d = 0.1$ $J_u = 0.3, J_d = 0.3$

- At 11 GeV, beam spin asymmetry (A_{LU}) in neutron DVCS *is* very sensitive to J_u, J_d
- Wide coverage needed!

Fixed kinematics: $x_B = 0.17 \quad Q^2 = 2\ \mathrm{GeV}^2 \quad t = -0.4\ \mathrm{GeV}^2$

CLAS12

Design luminosity
$L \sim 10^{35}\ cm^{-2}\ s^{-1}$

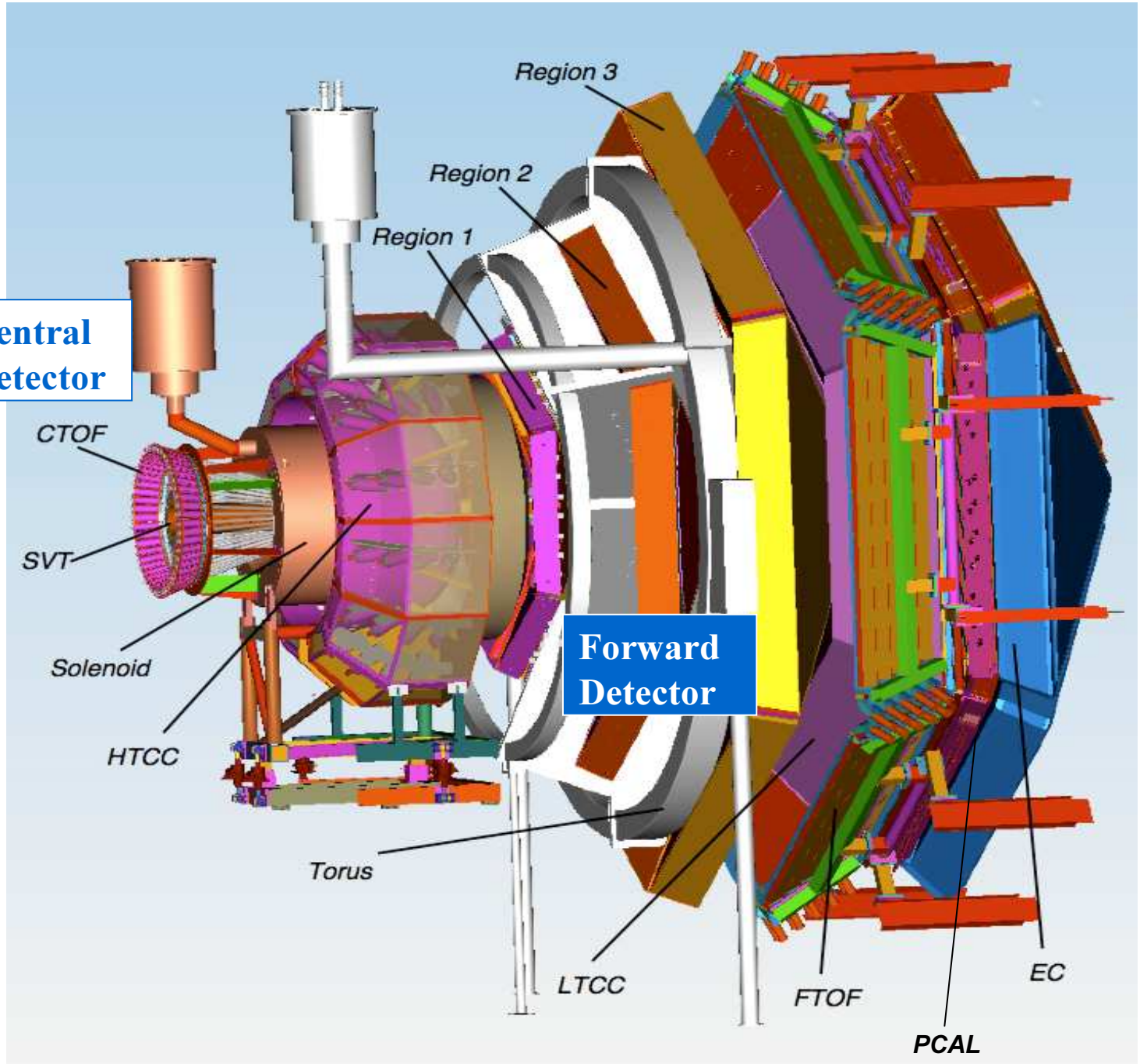
Acceptance for **charged particles**:

- Central (CD) $40^o < \theta < 135^o$
- Forward (FD) $5^o < \theta < 40^o$

Acceptance for **photons**:

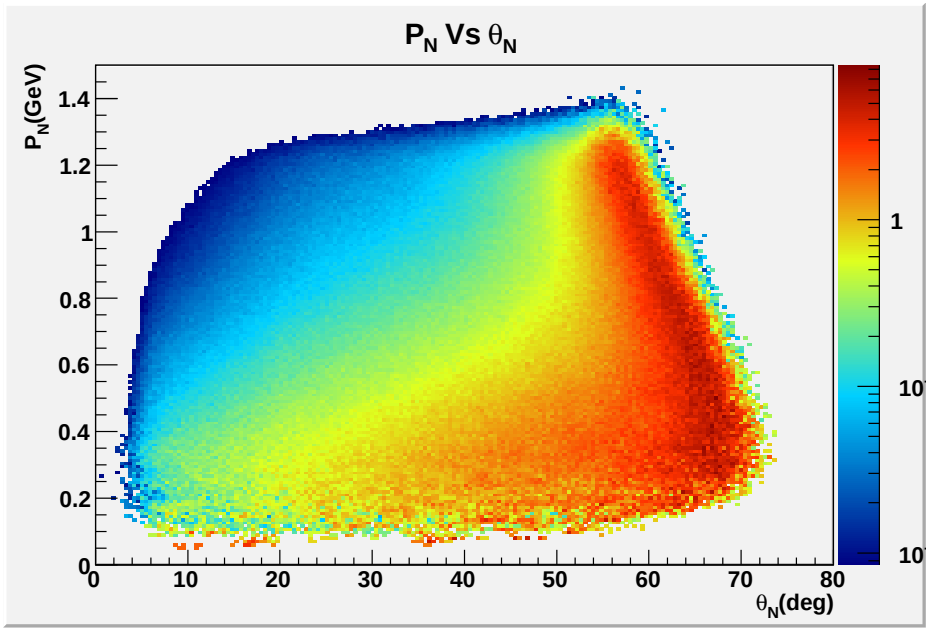
- IC $2^o < \theta < 5^o$
- EC $5^o < \theta < 40^o$

High luminosity & large acceptance:
Concurrent measurement of deeply virtual exclusive, semi-inclusive, and inclusive processes



Recoil DVCS neutrons in CLAS12

- Beam-spin asymmetry in neutron DVCS at 11 GeV – extremely sensitive to J_q
- Exclusive reconstruction of the DVCS process $en \rightarrow e'n'\gamma$ require detection and measurement of all three final state particles.

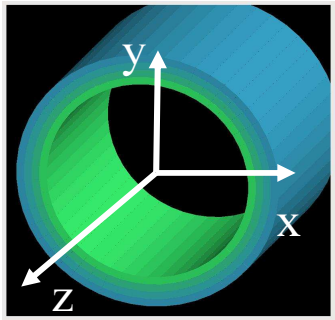


Simulation at E_e= 11 GeV

Over **80%** of neutrons recoil at θ_{lab} > **40°** with peak momentum at ~ **0.4 GeV/c**.

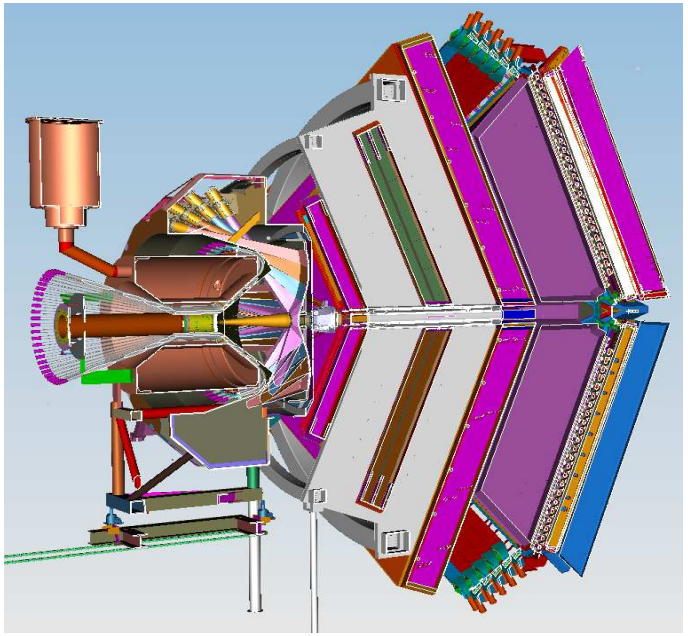
Requires central neutron detector sensitive to $0.2 < p_n < 1.2$ GeV/c.

Neutron Detector for CLAS12



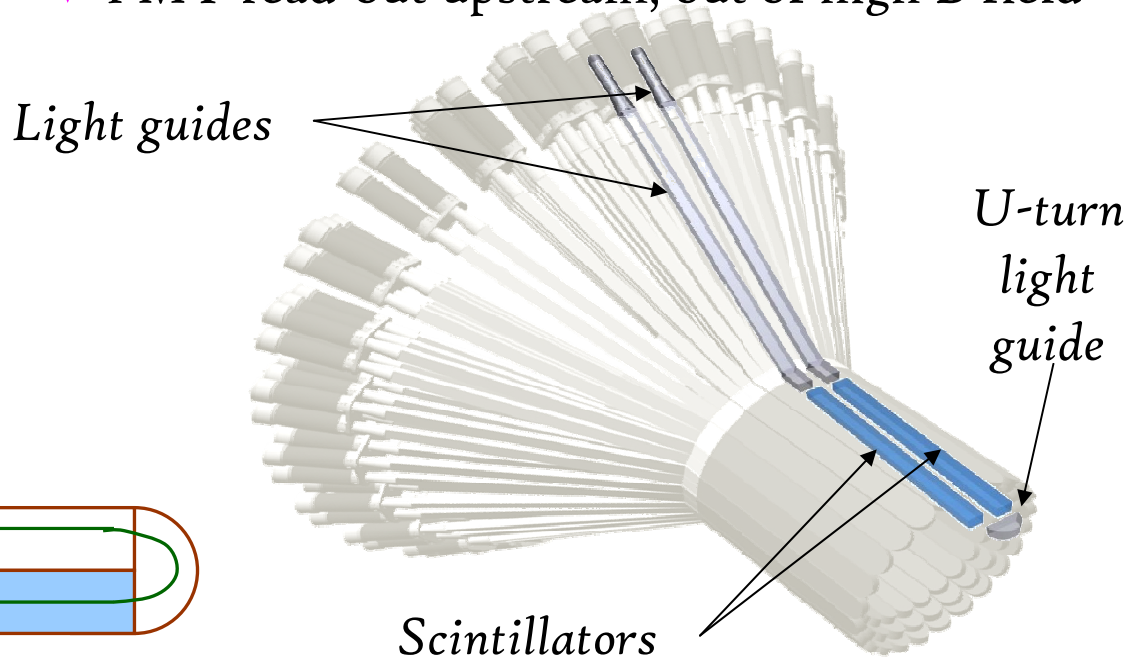
Available:

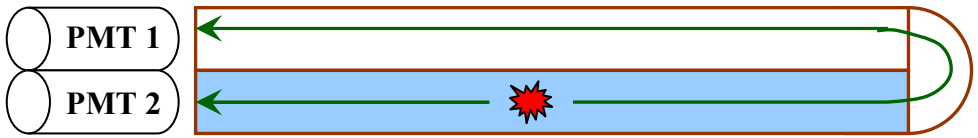
- 10 cm of radial space
- in a high magnetic field (~ 5T)



Detector proposal **approved:**

- Plastic scintillator barrel:
  3 layers, 48 paddles in each
- Length ~ 70 cm, inner radius 28.5 cm
- Long (~ 1.5 m) light-guides
- PMT read-out upstream, out of high **B** field

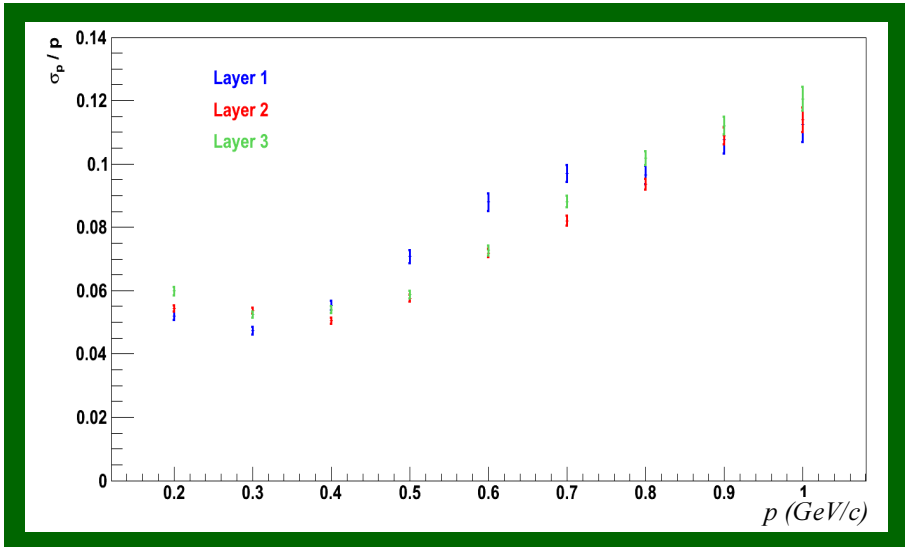


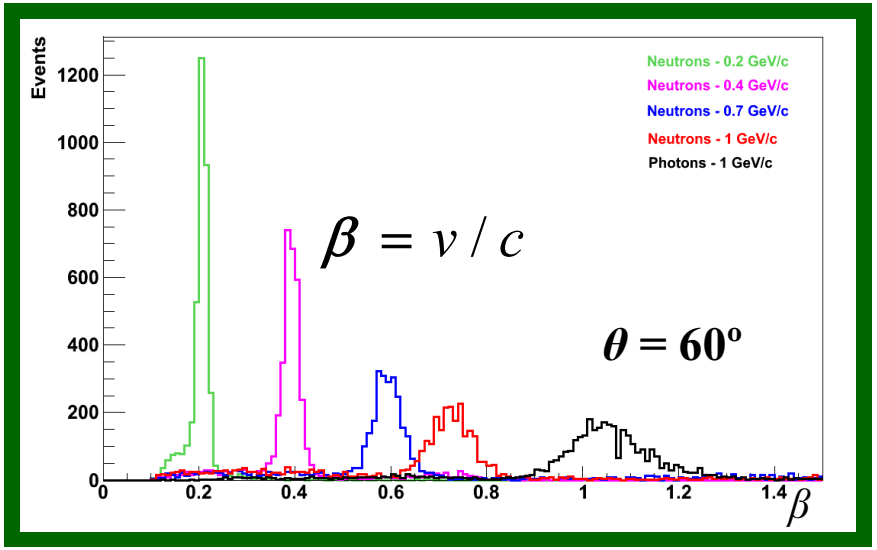


CND Simulation (Geant 4)

- Neutron **efficiency** ~ 8-9 %
- Good **separation of neutrons and γ** up to ~ 1 GeV/c

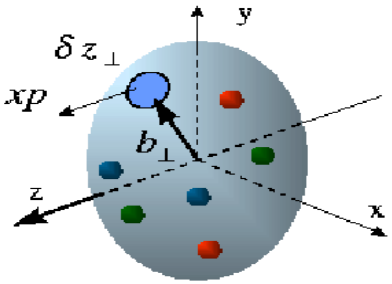
- $\frac{\sigma_p}{p} \approx 5 - 12\ \%$ $\quad \sigma_\theta \approx 2 - 3^\circ$
- 1 – 3% contamination from mis-reconstructed hits





Detector under construction at IPN Orsay, France, for 2014.

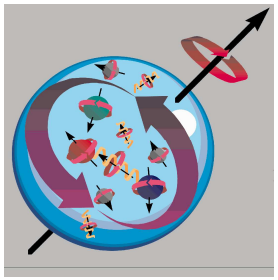
In Conclusion:

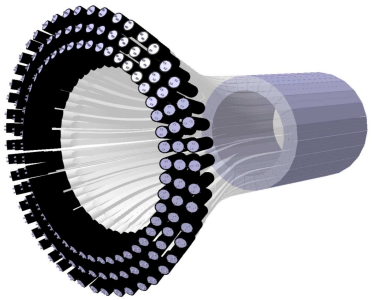


✸ **GPDs** provide a 3D image of the **internal dynamics** of the nucleon and are experimentally accessible in exclusive reactions such as DVCS.

→ More on testing GPD predictions in talk by **J. Sjögren:** Mon 14.45, Session 2

✸ **Beam-spin asymmetry in DVCS** on the **neutron**, particularly in the kinematic range opening up with CLAS12, will offer vital information on the composition of **nucleon spin.**





✸ The **Central Neutron Detector** is under construction – to allow exclusive reconstruction of **neutron DVCS** with **CLAS12** at Jefferson Lab.

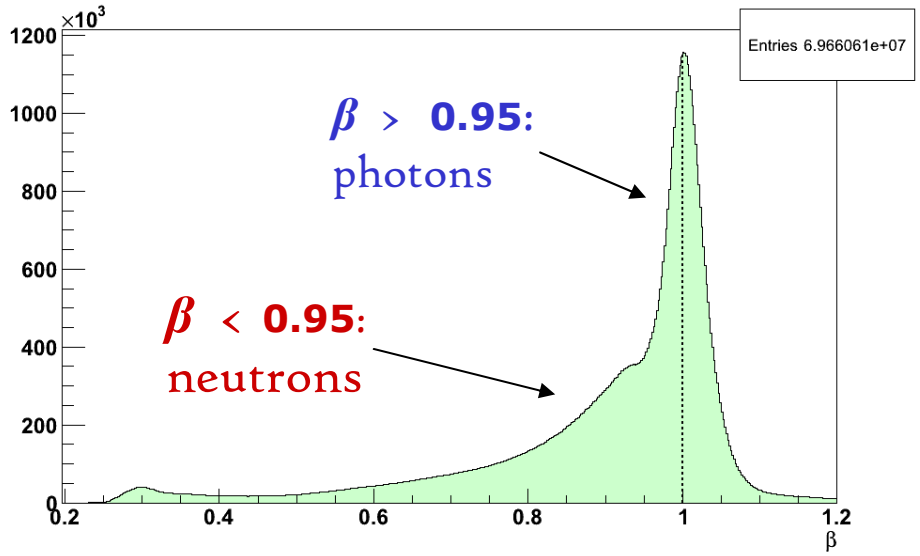
✸ A preliminary extraction of DVCS on **deuterium** @ 6GeV is underway – indications of a low measurable beam-spin and target-spin asymmetry on the neutron.


Thank you!

Back-up slides

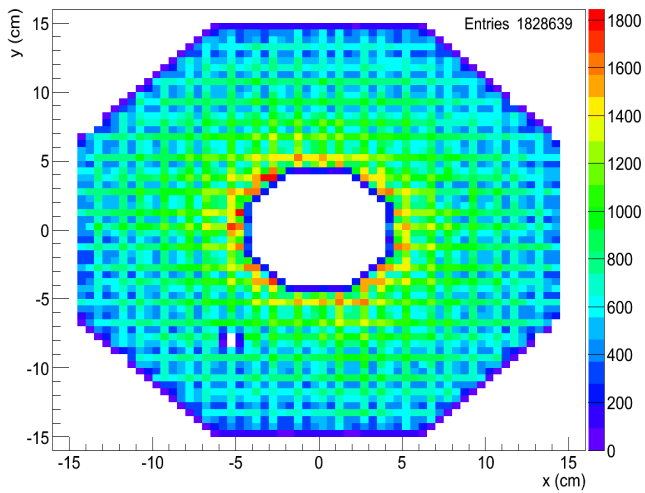
Particle ID – Photons and Neutrons

- β from neutral particles' time of flight to EC



- Forward, low-angle photons in additional Inner Calorimeter

Hits in IC with E deposit > 1 GeV

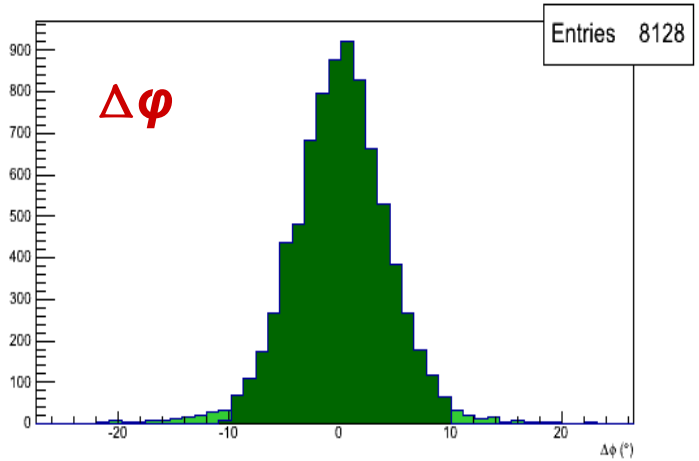


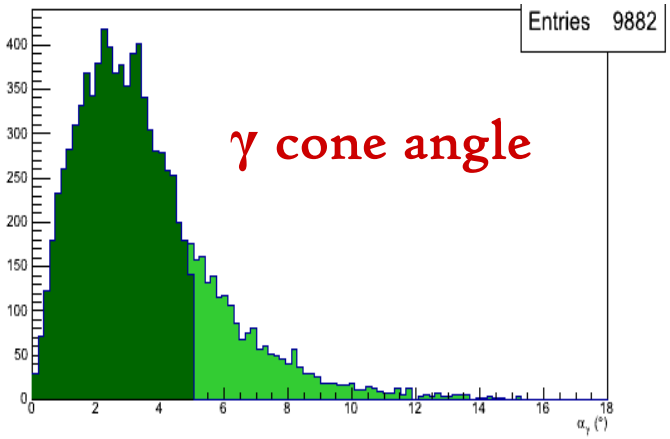
- Neutrons: $p_n = \dfrac{\beta m_n}{\sqrt{1-\beta^2}}$ $\quad E_n = \sqrt{m_n^2 + p_n^2}$

- Photons: $p_\gamma = E$ deposited in calorimeter

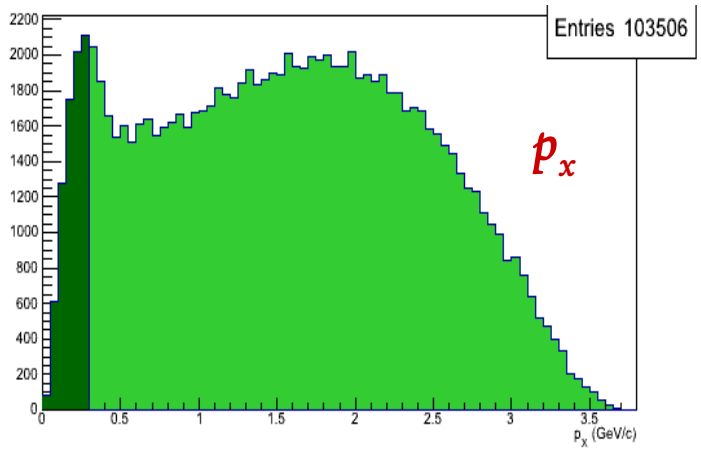
Neutron DVCS in ND_3 – data cuts II

- $p_n > 0.4$ GeV/c Recoiling nucleon should not have a low p
- $|\Delta\varphi| < 10°$ Coplanarity between γ and N
- γ cone angle < 5° Difference between calculated and measured γ direction





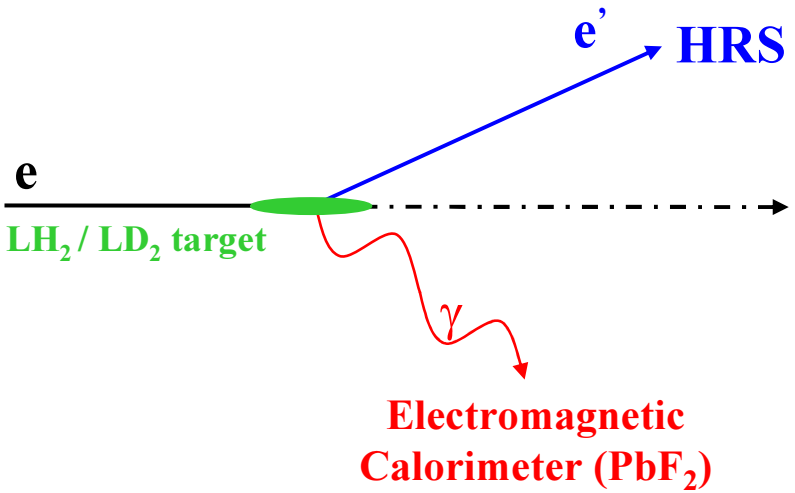
- Missing momentum from $ed \rightarrow e'N'\gamma X$ Should be low for spectator nucleon in quasi-free reaction

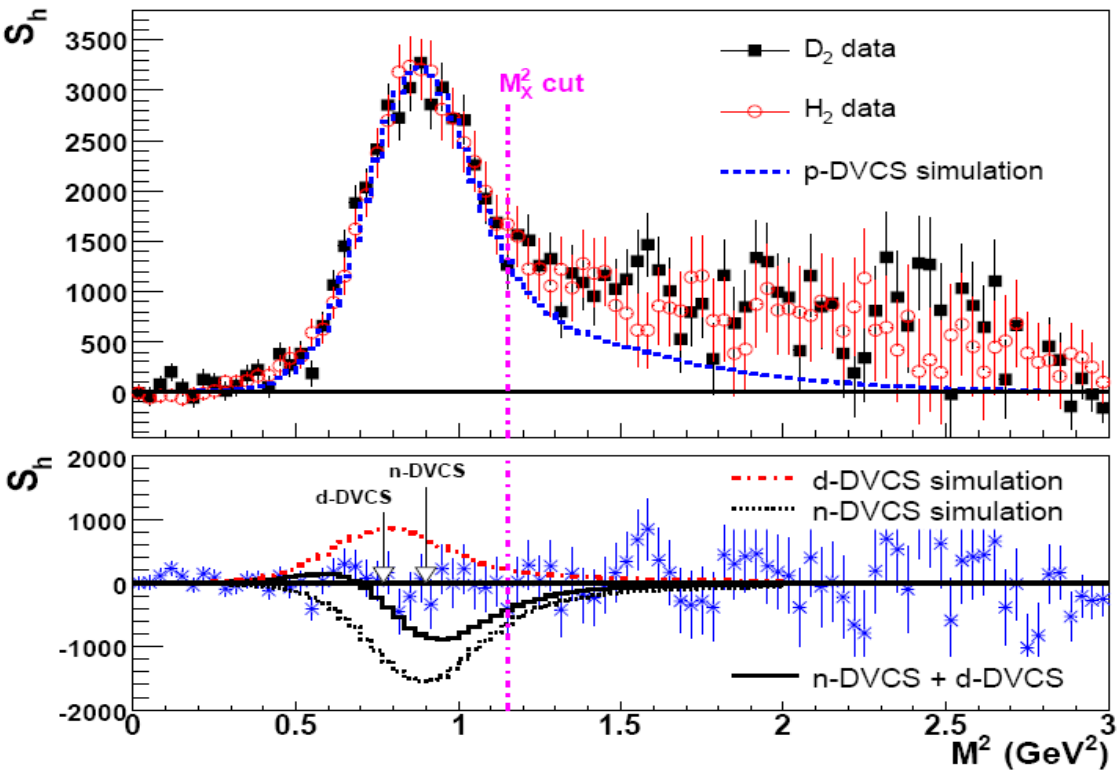


First measurement of nDVCS: Hall A

M. Mazouz et al., PRL 99 (2007) 242501

$E_e = 5.75$ GeV/c $P_e = 75$ %
$L = 4 \cdot 10^{37}$ cm^{-2} · s^{-1}/nucleon





Active nucleon identified via missing mass

Analysis done in the impulse approximation:

$$D(e,e'\gamma)X = p(e,e'\gamma)p + n(e,e'\gamma)n + d(e,e'\gamma)d + \cdots$$

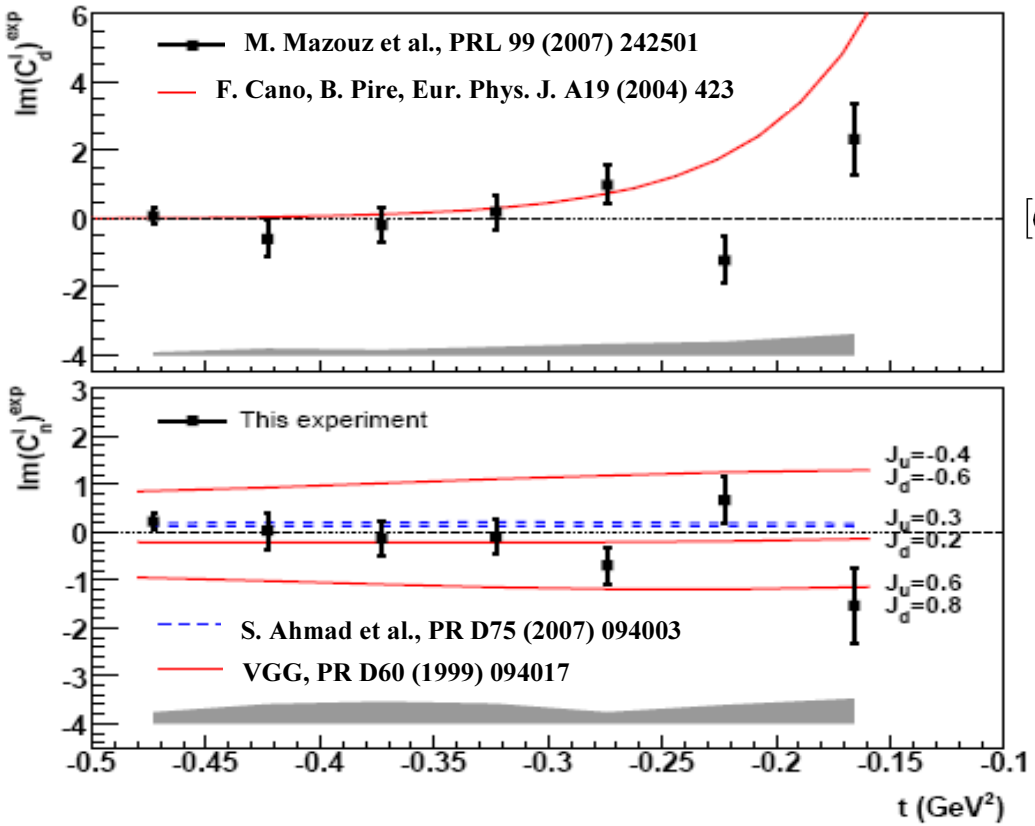
$Q^2 = 1.9$ GeV^2
$x_B = 0.36$
0.1 GeV^2 < -t < 0.5 GeV^2

Subtraction of **quasi-elastic proton** contribution deduced from H_2 data convoluted with initial motion of the nucleon

Twist-2

$$\frac{d^5\Sigma_{D-H}}{d^5\Phi} = \frac{1}{2}\left[\frac{d^5\sigma^+}{d^5\Phi} - \frac{d^5\sigma^-}{d^5\Phi}\right]$$
$$= \left(\Gamma_d^{\Im}\,\Im\mathrm{m}\left[\mathcal{C}_d^I\right]^{exp} + \Gamma_n^{\Im}\,\Im\mathrm{m}\left[\mathcal{C}_n^I\right]^{exp}\right)\sin(\phi_{\gamma\gamma})$$

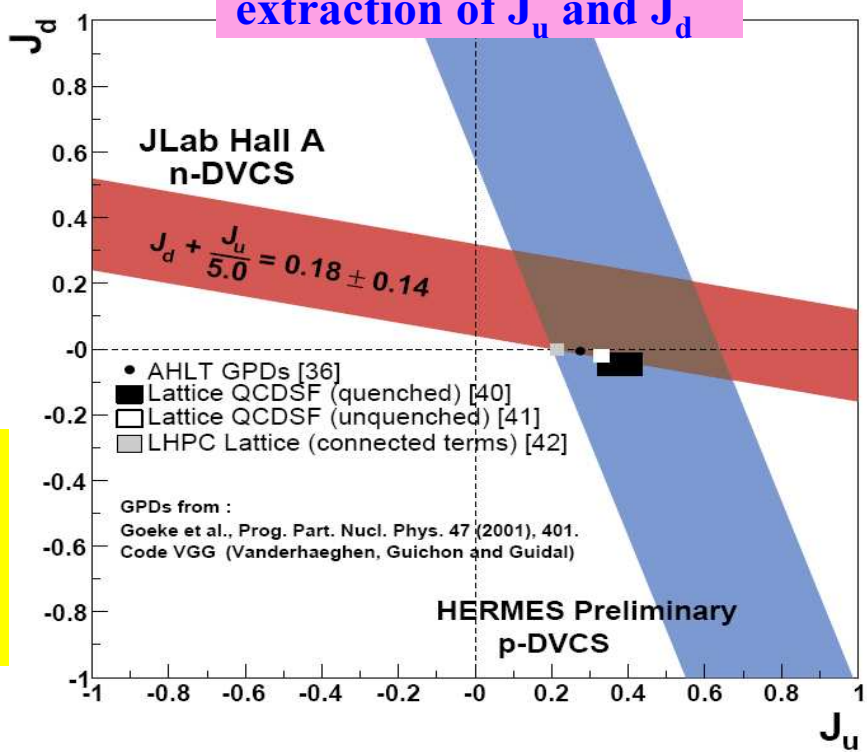
nDVCS in Hall A: results



$Q^2 = 1.9$ GeV^2 - $x_B = 0.36$

$$[\mathcal{C}_n^I]^{exp} \simeq [\mathcal{C}_n^I] = F_1\mathcal{H} + \xi(F_1 + F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$$

Model dependent extraction of J_u and J_d



$Im(C^I_n)$ compatible with zero (→ too high x_B?)
Strong correlation between $Im[C^I_d]$ and $Im[C^I_n]$
Big statistical and systematic uncertainties
(mostly coming from H^2 and π^0 subtraction)

A_{LU} from *neutron DVCS* with CLAS12

$$\vec{e} + d \rightarrow e' + n + \gamma + (p_s)$$

$\Delta\sigma_{LU} \sim \sin\phi\ \mathbf{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\mathcal{H} - \tilde{k}F_2\mathcal{E}\}d\phi$

The **most sensitive** observable to the GPD **E**

80 days of data taking

$L = 10^{35}\ cm^{-2}s^{-1}$/nucleon

CLAS12 +
Forward Calorimeter +
Neutron Detector

Model predictions (VGG) for different values of quarks' angular momentum: