Deeply Virtual Compton Scattering off the Neutron: measurements with CLAS and CLAS12 at Jefferson Lab

Daria Sokhan

University of Glasgow, UK

on behalf of the CLAS Collaboration

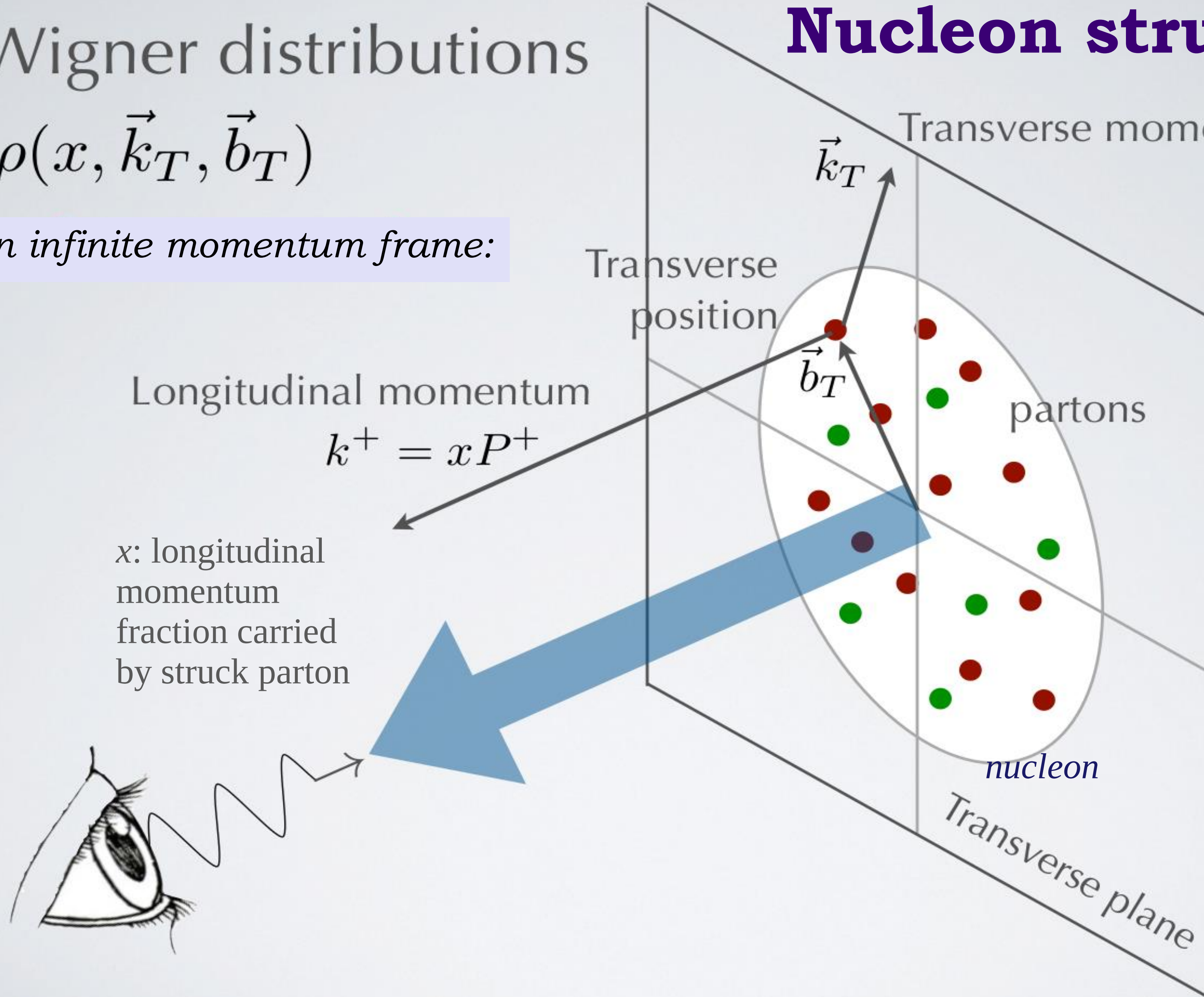
NSTAR 2015 – Osaka, Japan, 25th May 2015

Nucleon structure

Wigner distributions

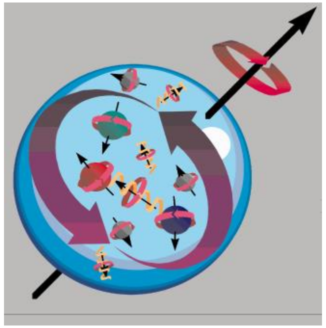
$$\rho(x, \vec{k}_T, \vec{b}_T)$$

In infinite momentum frame:



x: longitudinal momentum fraction carried by struck parton

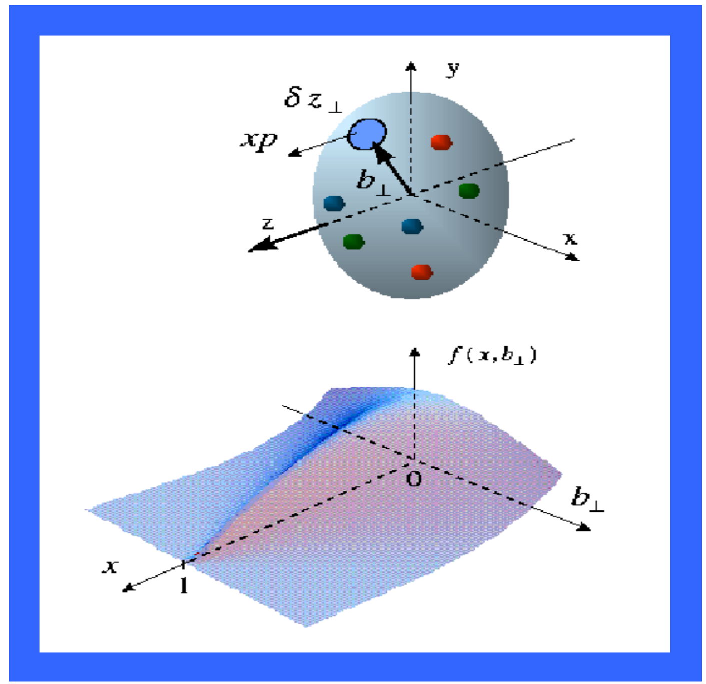
Generalised Parton Distributions



Wigner function:
full phase space parton
distribution of the nucleon

$$\int d^2k_T$$

Generalised Parton Distributions
(GPDs)



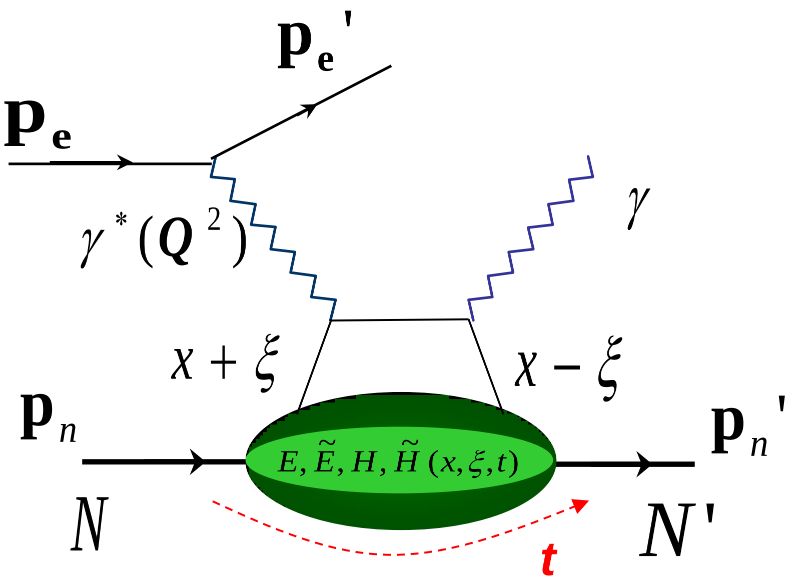
- Relate transverse position of partons ($b_\perp$) to longitudinal momentum (x).
- Deep exclusive reactions.

Deeply Virtual Compton Scattering

- **GPDs** relate transverse position of partons to longitudinal momentum.

  → contain information on angular momentum of quarks

- "Golden channel" for GPD extraction: **Deeply Virtual Compton Scattering** (DVCS).



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

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

$x \pm \xi$ *longitudinal momentum fractions of quarks* $\qquad \xi \cong \dfrac{x_B}{2 - x_B}$

- At high exchanged Q^2, access to four **GPDs**: $E_q, \tilde{E}_q, H_q, \tilde{H}_q\,(x,\xi,t)$

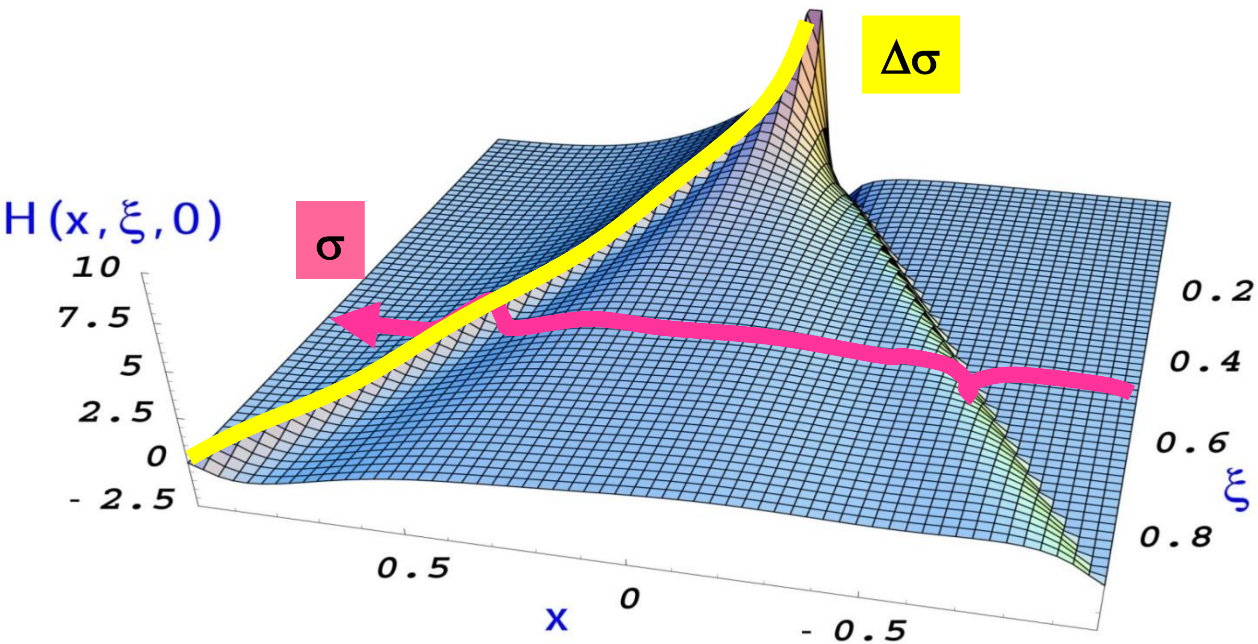
Compton Form Factors in DVCS

CFFs: complex functions directly accessible in DVCS cross-sections and spin asymmetries, eg:

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

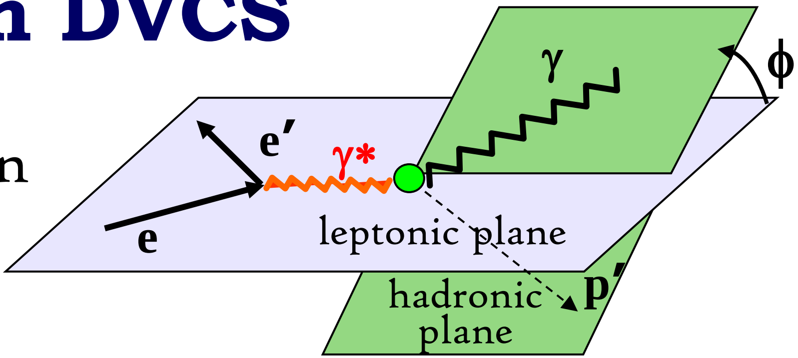
Related to GPDs:

$$T^{DVCS} \sim \int_{-1}^{+1} \frac{GPDs(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim \quad P\int_{-1}^{+1} \frac{GPDs(x,\xi,t)}{x \pm \xi} dx \pm i\pi GPDs(\pm\xi,\xi,t) + \ldots$$



Only ξ and t are accessible experimentally!

Compton Form Factors in DVCS

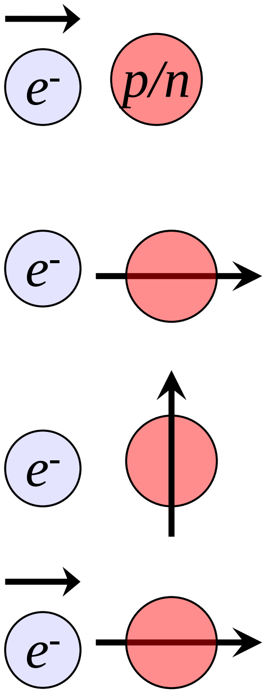


- Experimentally accessible in DVCS spin asymmetries, eg:

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

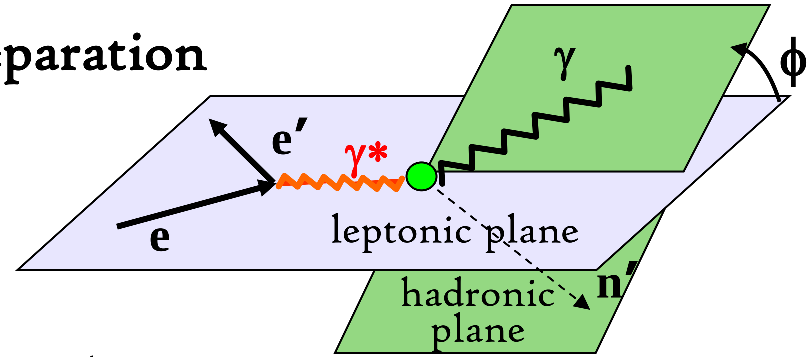
$\xi = x_B/(2-x_B) \quad k = t/4M^2$

Beam, target polarisation

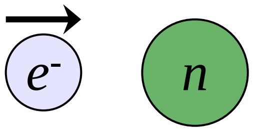


Beam, target polarisation		Proton / Neutron
LU	$\Delta\sigma_{LU} \sim \sin\phi \; \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$	$Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$ $Im\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\}$
UL	$\Delta\sigma_{UL} \sim \sin\phi \; \mathrm{Im}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi kF_2\tilde{\mathcal{E}} + \ldots\}d\phi$	$Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$ $Im\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\}$
UT	$\Delta\sigma_{UT} \sim \cos\phi \; \mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}d\phi$	$Im\{\mathcal{H}_p, \mathcal{E}_p\}$ $Im\{\mathcal{H}_n\}$
LL	$\Delta\sigma_{LL} \sim (A+B\cos\phi) \; \mathrm{Re}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E})\ldots\}d\phi$	$Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$ $Re\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\}$

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:*

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

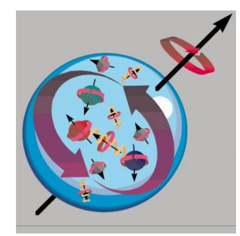
Suppressed because $F_1(t)$ is small

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**!



Neutron DVCS: eg1-dvcs experiment @ Jefferson Lab (Hall B)

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)

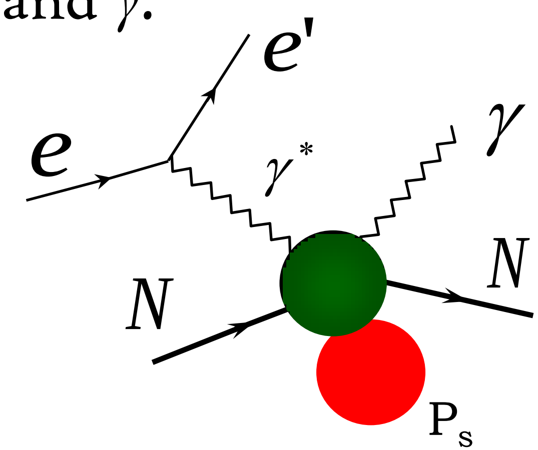
Proton / neutron pol. ~ 80 / 40 %

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

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

plus

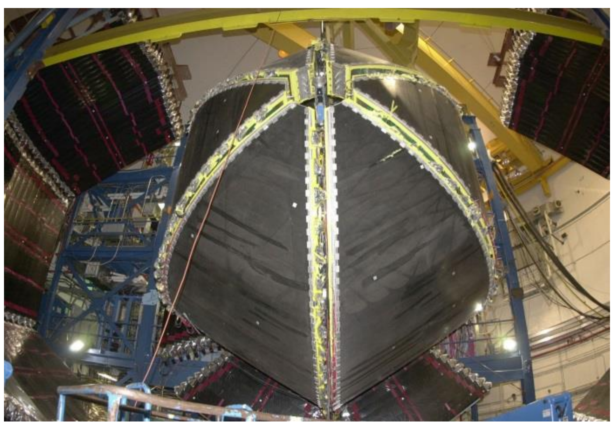
Inner Calorimeter (IC) → high-energy forward photon detection

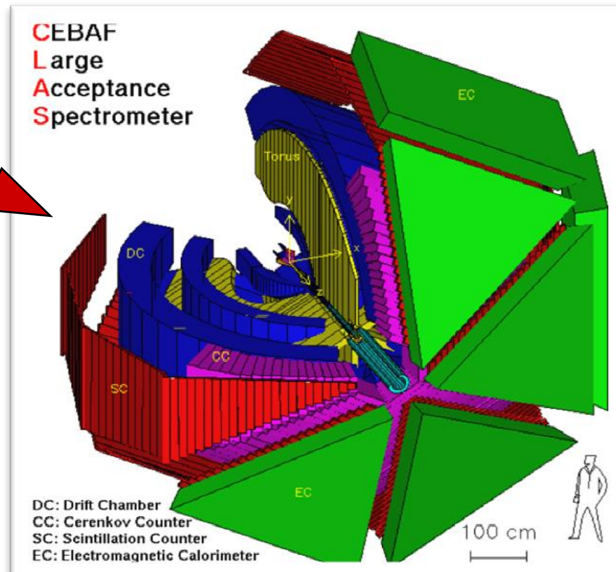


CLAS @ Jefferson Lab (Virginia, USA)

CEBAF: Continuous Electron Beam Accelerator Facility:

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



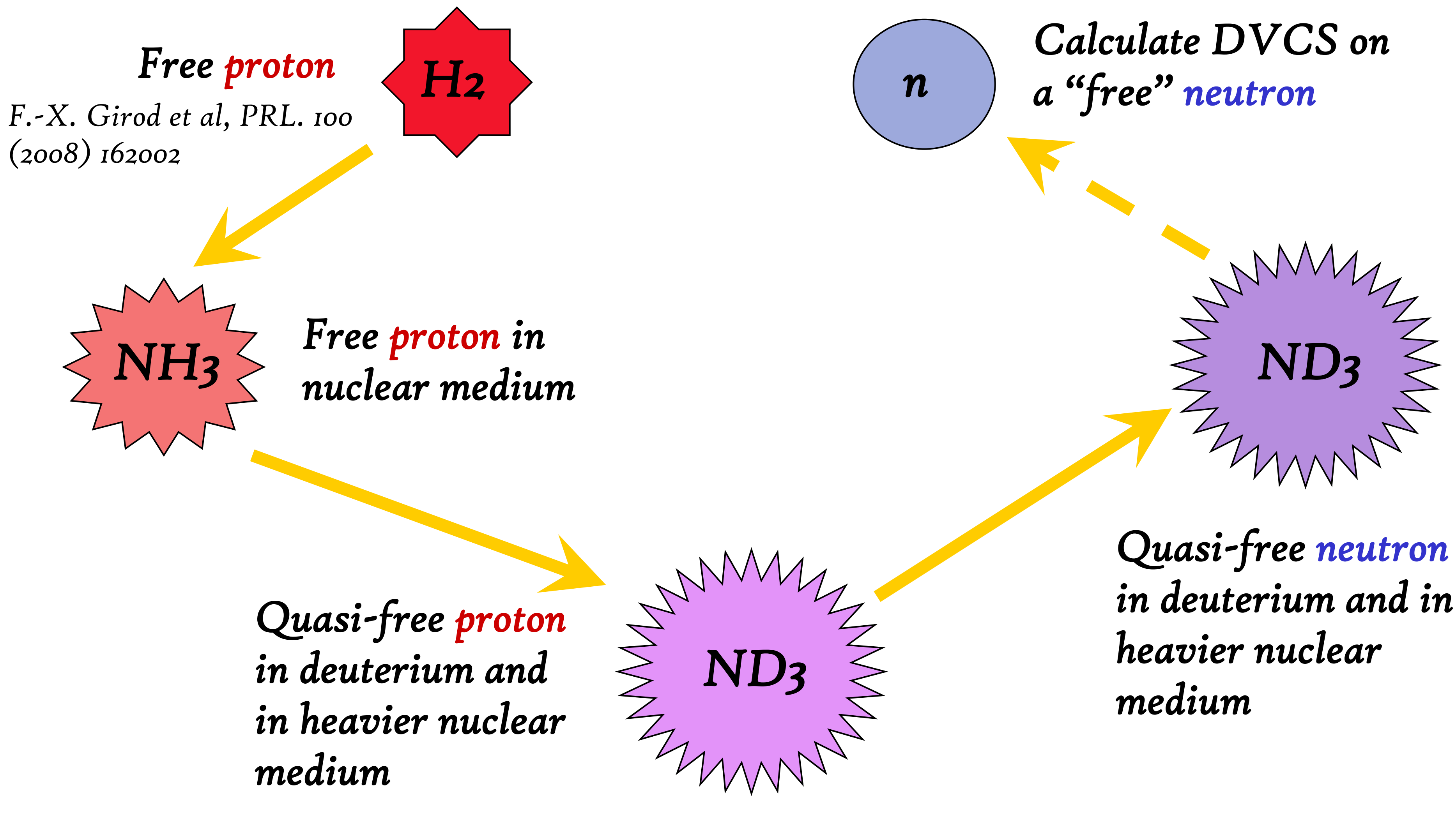


CLAS in Hall B:

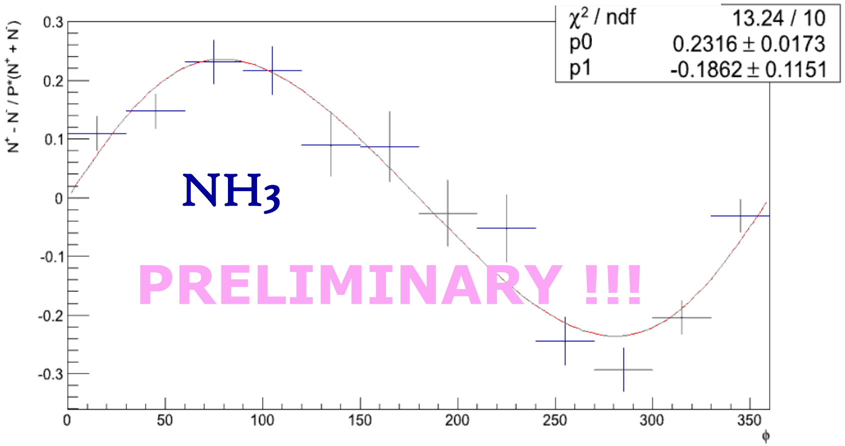
- Drift chambers
- Toroidal magnetic field
- Cerenkov Counters
- Scintillator Time of Flight
- Electromagnetic Calorimeters

→ ***Extremely large angular coverage***

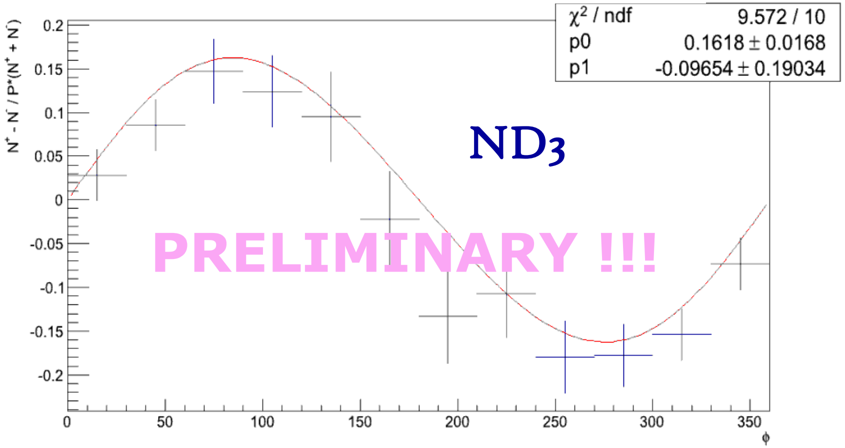
DVCS on different targets



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^o 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^o contamination more significant

→ *measured A_{LU} lower than on NH3.*

Neutron DVCS in ND_3 – identifying reaction

"Deep Inelastic Scattering" cuts:

❖ $W > 2$ GeV/c² where W is the missing mass of $(eN \rightarrow e' X)$, isolate resonance region of remaining γN

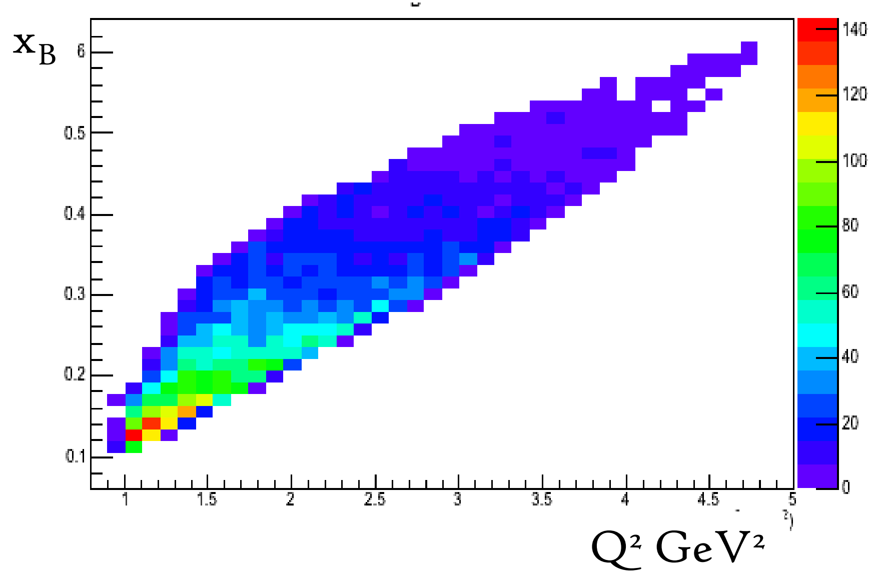
❖ $Q^2 > 1$ GeV² ❖ $Q^2 > -t$ Region where factorisation applies

Additional DVCS cuts:

❖ $E_\gamma > 1$ GeV

❖ $p_n > 0.4$ GeV/c

Recoiling nucleon should not have a low p

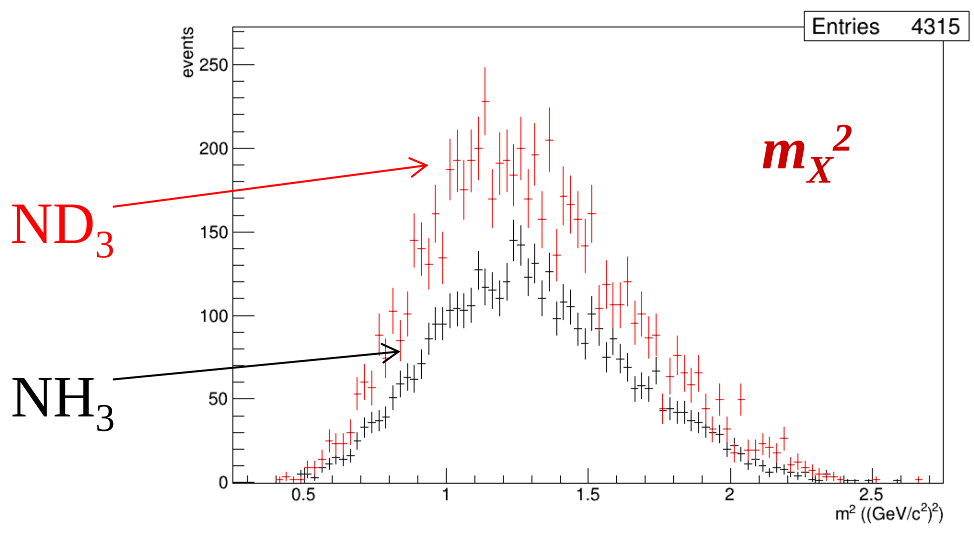


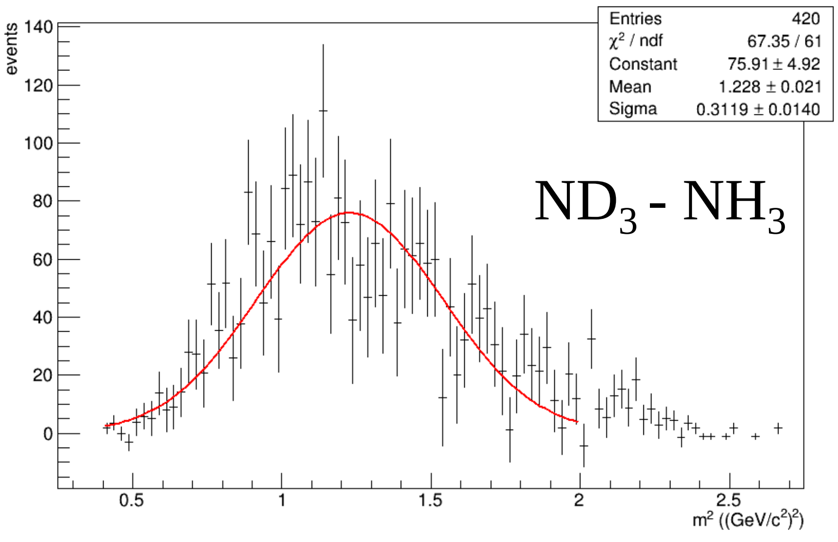
Exclusivity cuts: spectator

Use NH_3 data to subtract the nuclear background from the ND_3 distributions:

❖ **Missing momentum** from $ed \rightarrow e'N'\gamma\ X$ should be low for spectator nucleon in quasi-free reaction: $p_X < 0.2$ **GeV/c**

❖ **Missing mass** of spectator from $ed \rightarrow e'N'\gamma\ X$: $0.5 < |m_X^2| < 2$ **GeV²/c⁴**

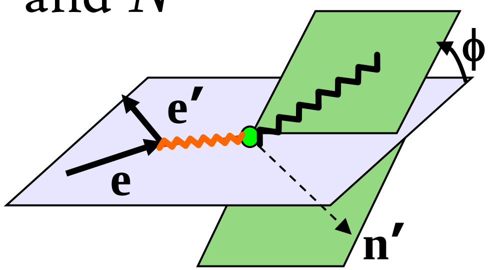


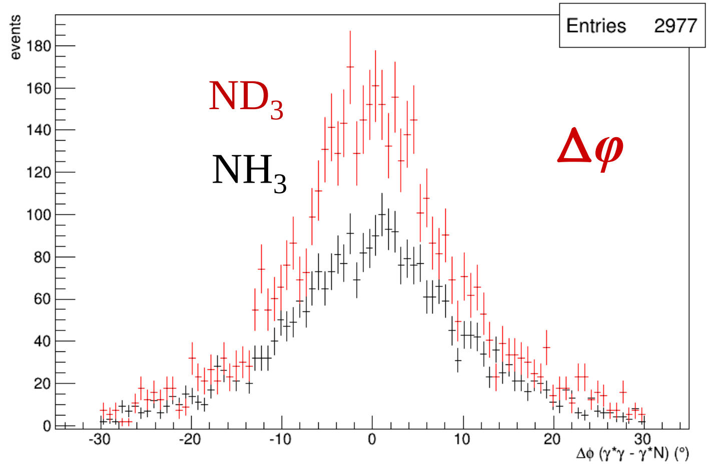


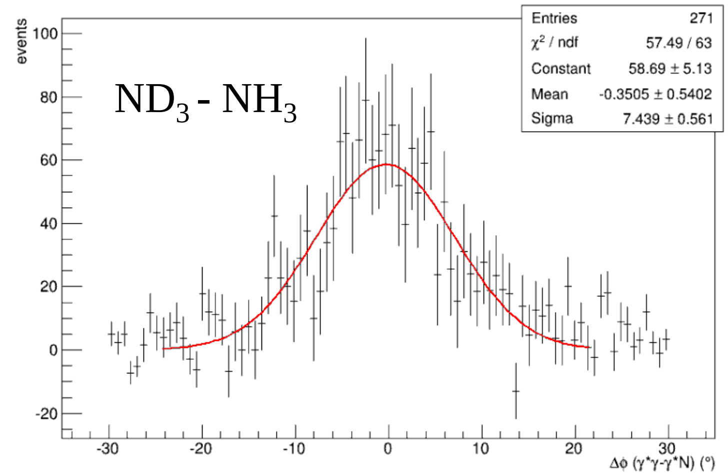
Exclusivity cuts: angular distributions

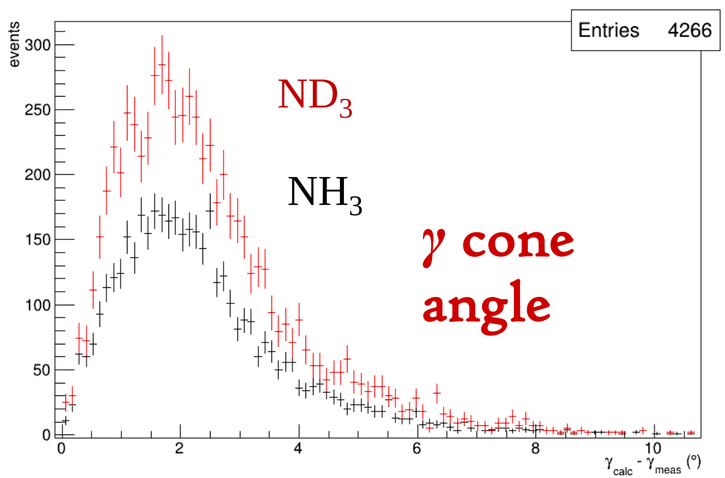
❖ $|\Delta\varphi| < 5°$

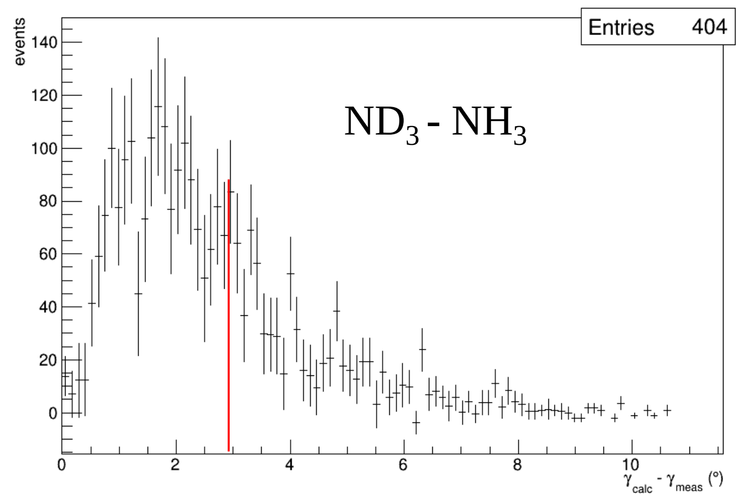
Coplanarity between γ and N











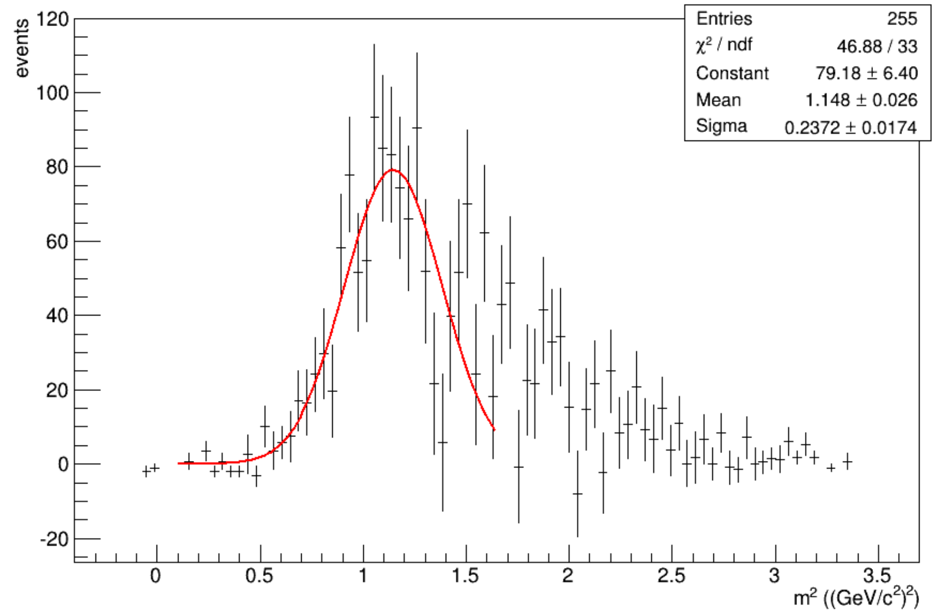
❖ γ cone angle < 3°

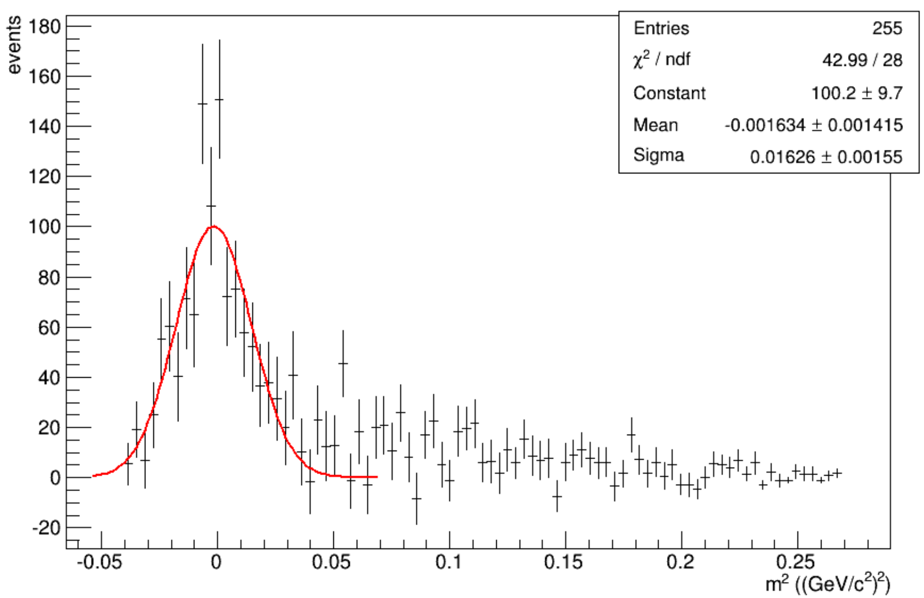
Difference between calculated and measured γ direction

After exclusivity cuts

❖ **Missing mass** from $eN \rightarrow e'\gamma\ X$

(should correspond to recoil neutron)





❖ **Missing mass** from $eN \rightarrow e'N\gamma\ X$

(should correspond to nothing)

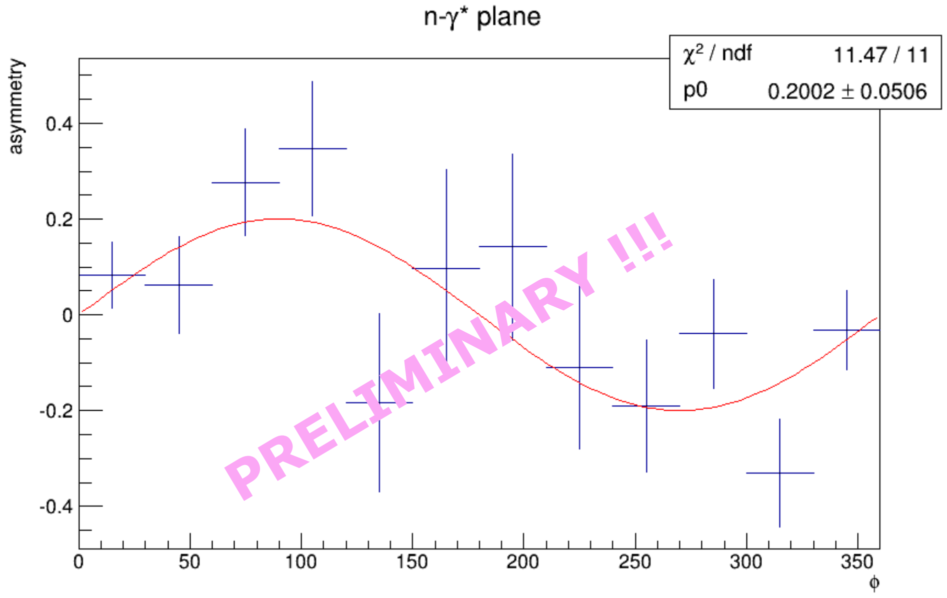
Distributions shown after nuclear background subtraction.

A_{LU} in neutron DVCS on ND_3

- **Beam-spin asymmetry (A_{LU}):**

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)



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

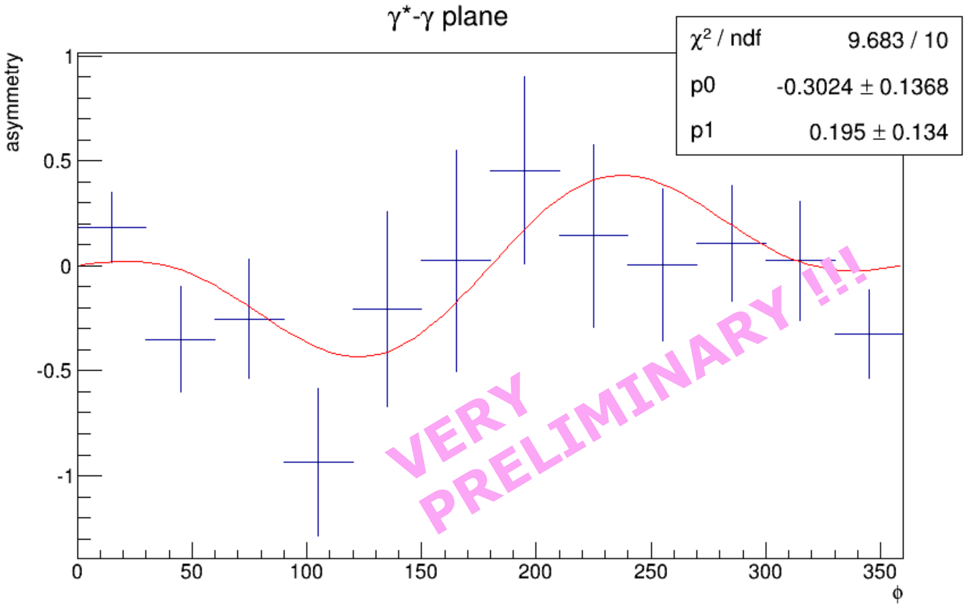
$$\frac{N^+ - N^-}{P(N^+ + N^-)} \approx 0.20 \pm 0.05$$

Uncorrected for π^0 contamination, which has an asymmetry of its own!

A_{UL} in neutron DVCS on ND_3

First measurement.

- Target-spin asymmetry (A_{UL}):



Fit: $$A_{UL} = \frac{p_0 \sin\varphi}{1 + p_1 \cos\varphi}$$

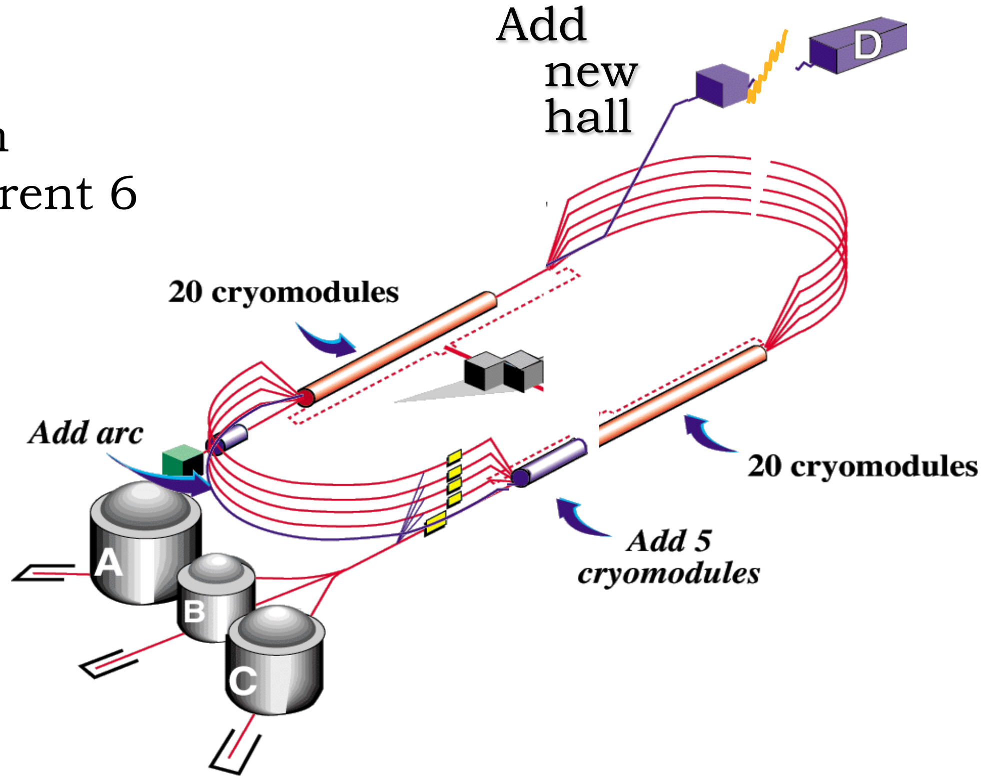
$p_0 < 0$

p_1 small

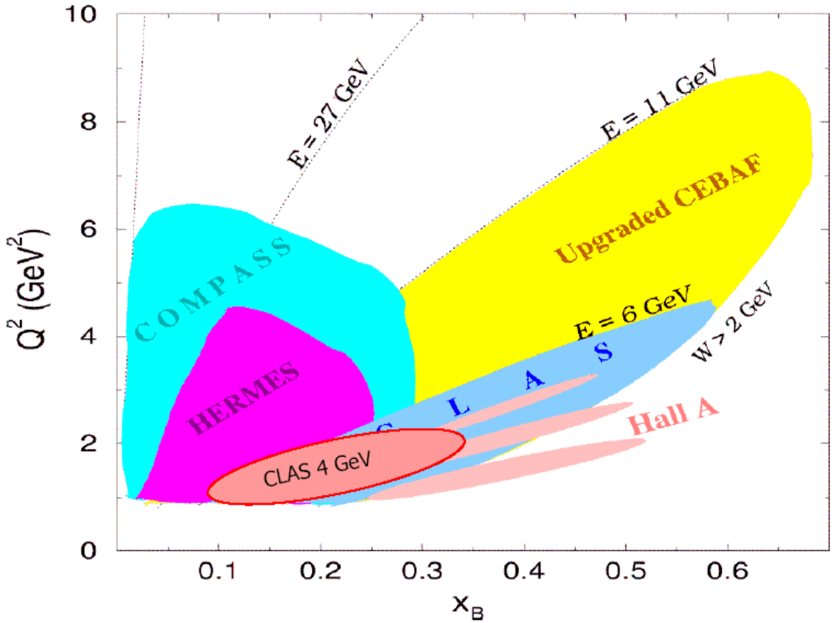
Uncorrected by the dilution factor due to the nuclear background!

Jefferson Lab @ 12 GeV

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



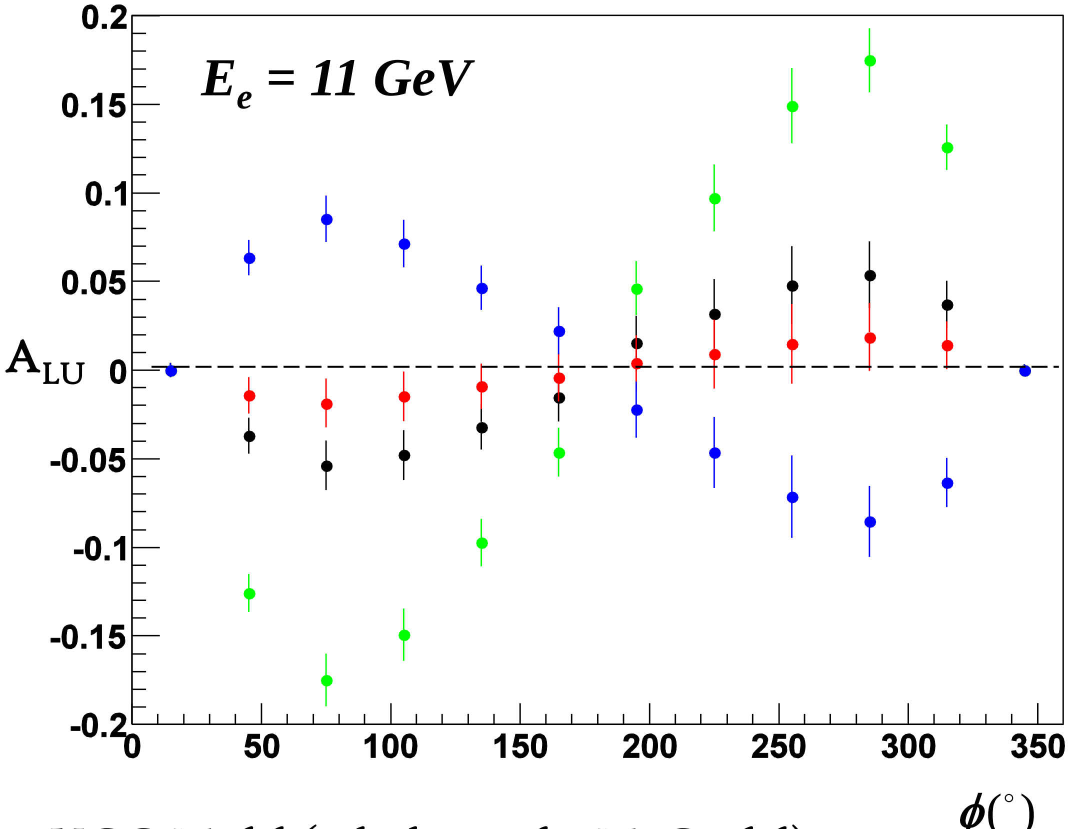
❖ Open up much larger phase space in $\mathbf{Q^2}$ **and** $\mathbf{x_B}$



❖ Hall B – 11 GeV to the upgraded detector system **CLAS12**

❖ CLAS12 experiments: expected 2016

A_{LU} in Neutron DVCS @ 11 GeV



VGG Model (calculations by M. Guidal)

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

$t = -0.4\ \mathrm{GeV}^2$

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

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

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

- Exclusive reconstruction of the DVCS process

$$en \rightarrow e'n'\gamma$$

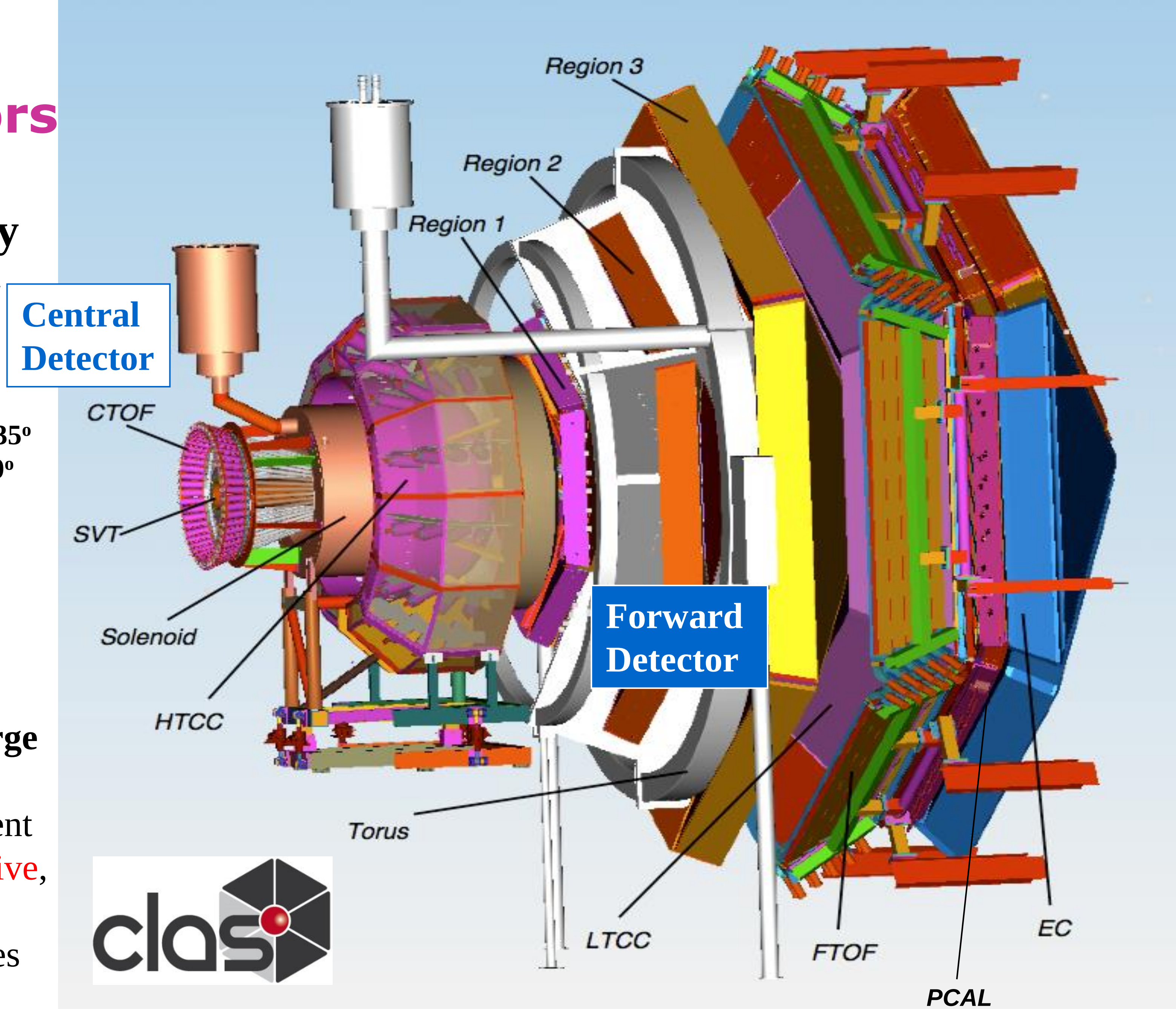
requires detection and measurement of all three final state particles.

CLAS12: base detectors

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

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

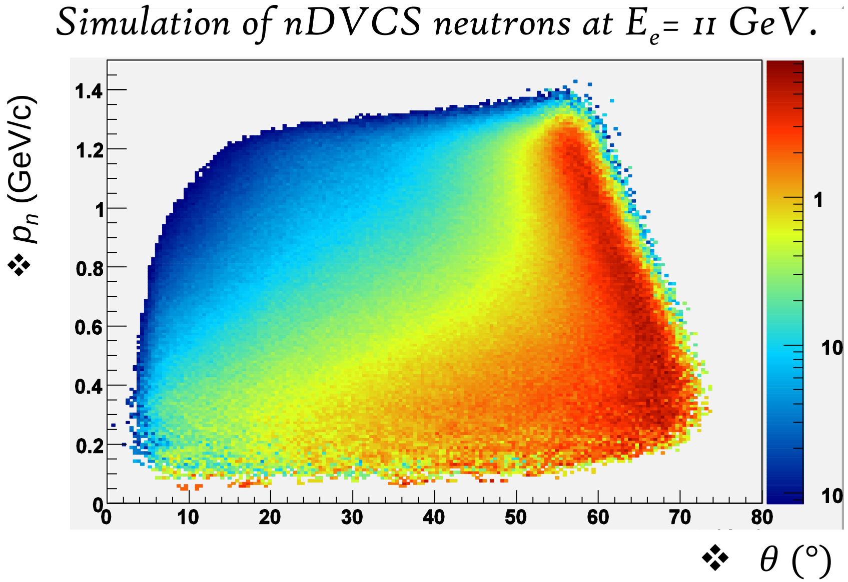
Acceptance for photons:
- **IC $2^{o} < \theta < 5^{o}$**
- **EC, $5^{o} < \theta < 40^{o}$**



High luminosity & large acceptance:

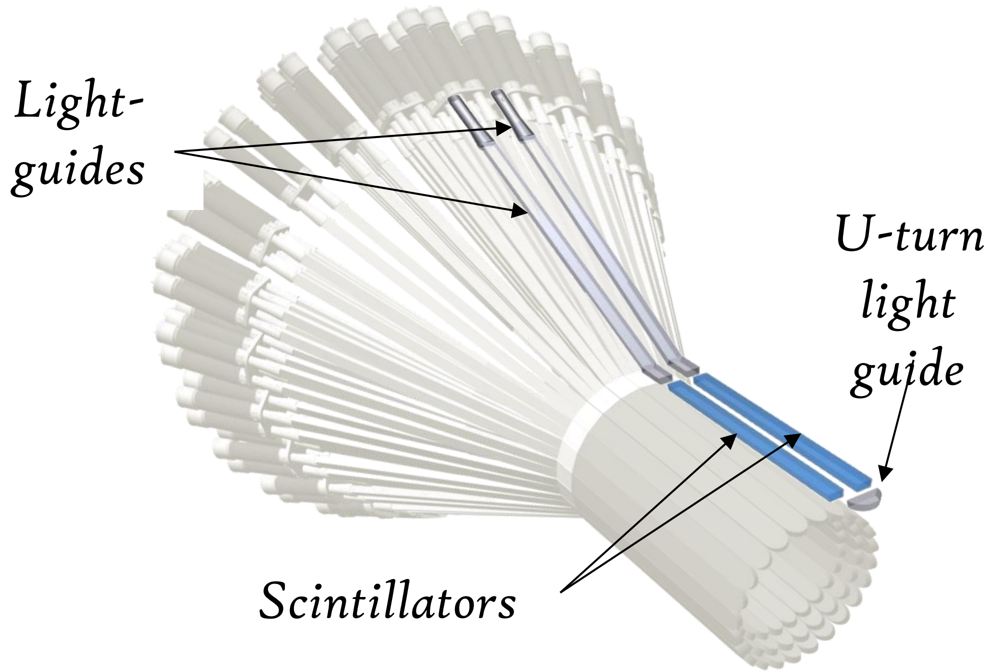
Concurrent measurement of deeply virtual exclusive, semi-inclusive, and inclusive processes

Recoil DVCS neutrons in CLAS12

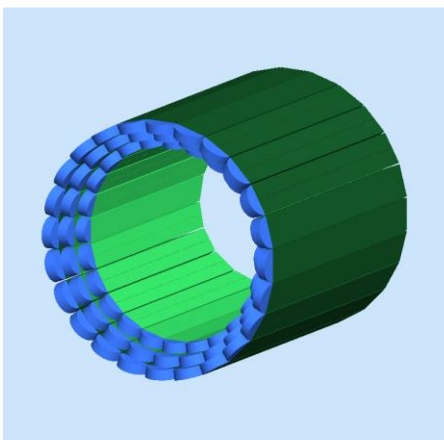


Over **80%** of neutrons recoil at θ_{lab} > **40°** with peak momentum at **~ 0.4 GeV/c**.

Neutron detector for CLAS12: 3-layer scintillator barrel, 48 paddles/layer.



- Neutron **efficiency** ~ 8-9 %



- $\frac{\sigma_p}{p} \approx 5-12\%$
- $\sigma_\theta \approx 2-3^\circ$
- $\sigma_\phi = 3.75^\circ$

Limitations of space and high magnetic field (5T) in central region necessitate a u-turn geometry.

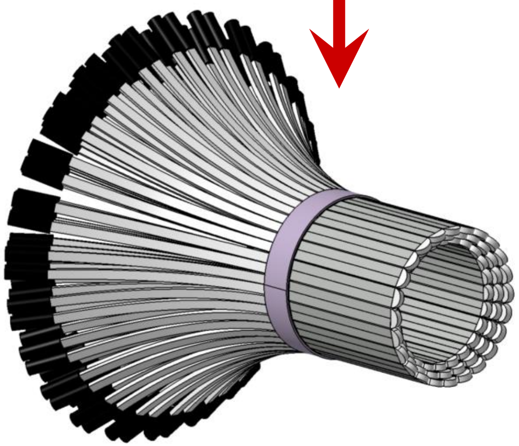
A_{LU} in Neutron DVCS with CLAS12

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

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

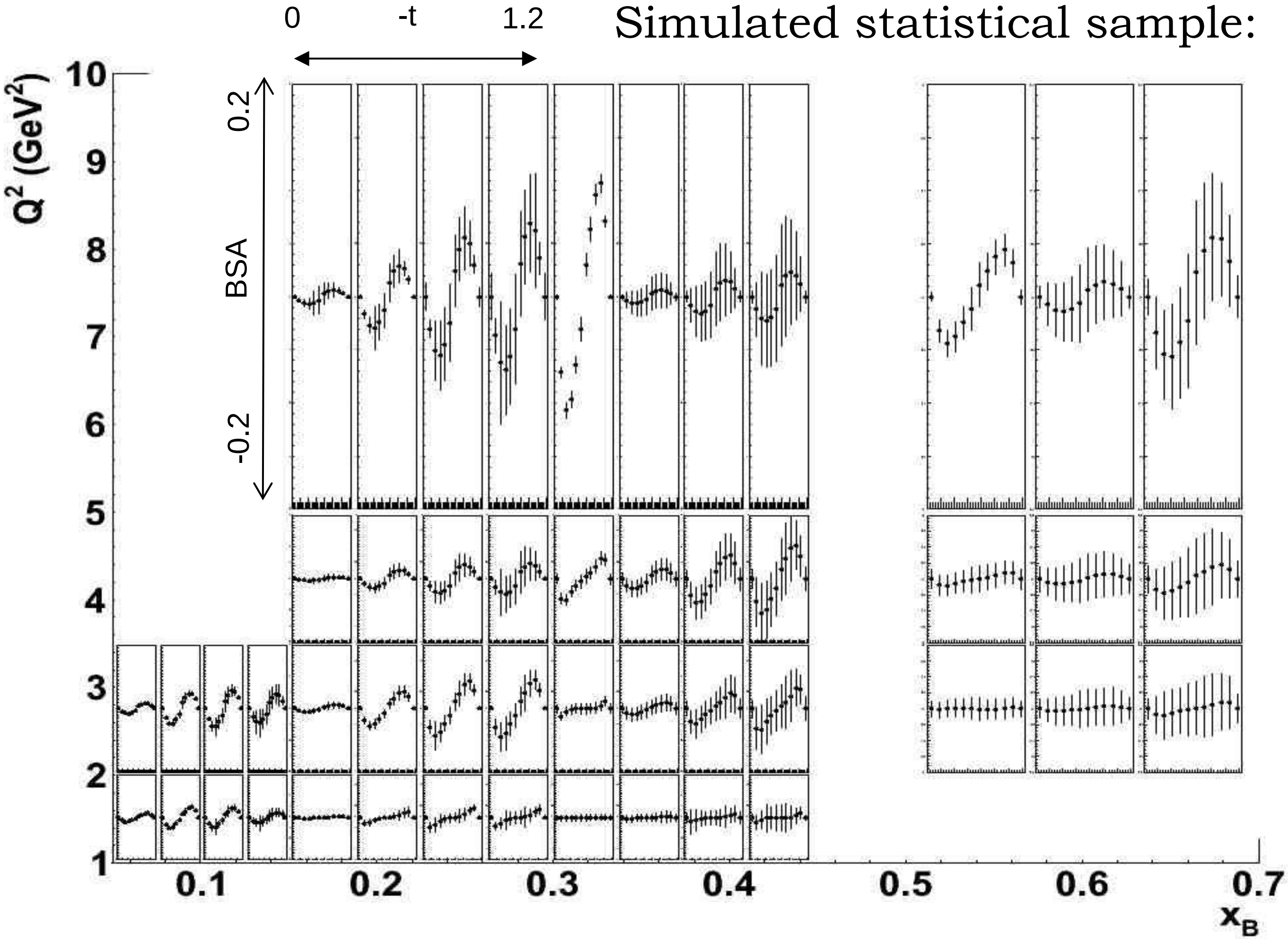
80 days of data taking
L = 10^{35} cm^{-2}s^{-1}/nucleon

CLAS12 +
Forward Calorimeter
+
Neutron Detector



Experiment approved, detector constructed.

Simulated statistical sample:



Neutron DVCS with polarised targets

- DVCS **transverse target** spin asymmetry

$$ep^{\uparrow} \rightarrow ep\gamma$$

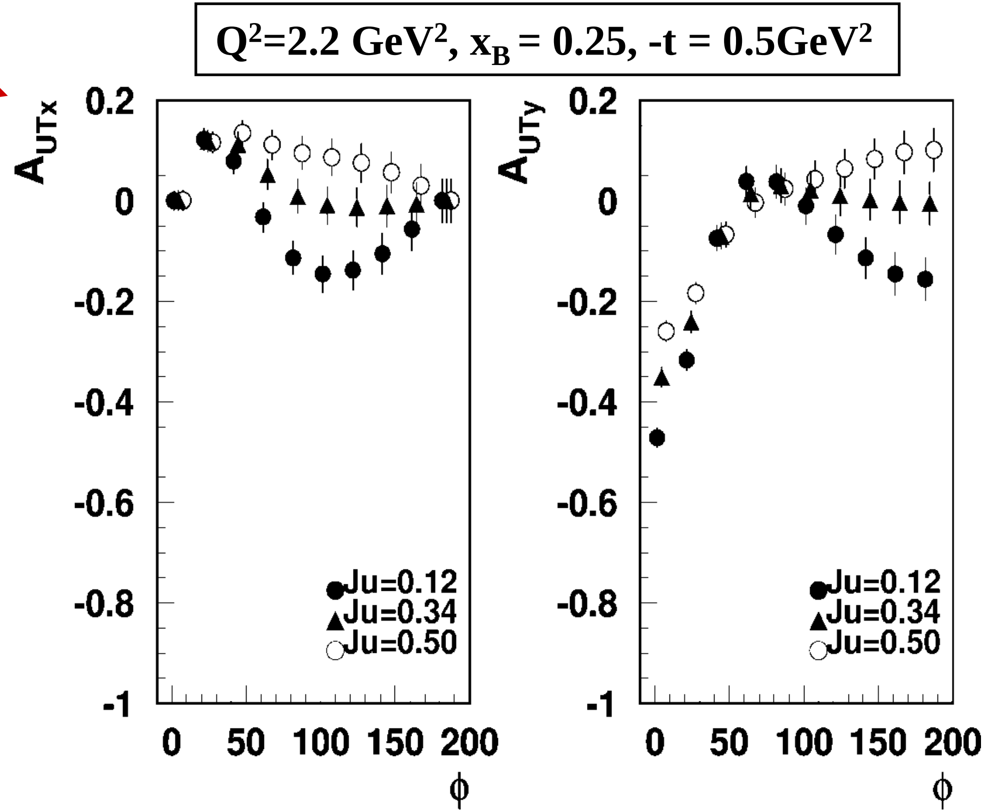
Transverse-target spin asymmetry is **highly sensitive** to the **u-quark contributions** to proton spin.

LOI approved at PAC38, target R&D under way.

- DVCS on **longitudinally polarised (ND3) target:** proposal submitted to PAC40 (July 2015).

Crucial for flavour-decomposition of the GPDs.

Projected results



A_{UTx} Target polarization in scattering plane

A_{UTy} Target polarization perpendicular to scattering plane

Summary

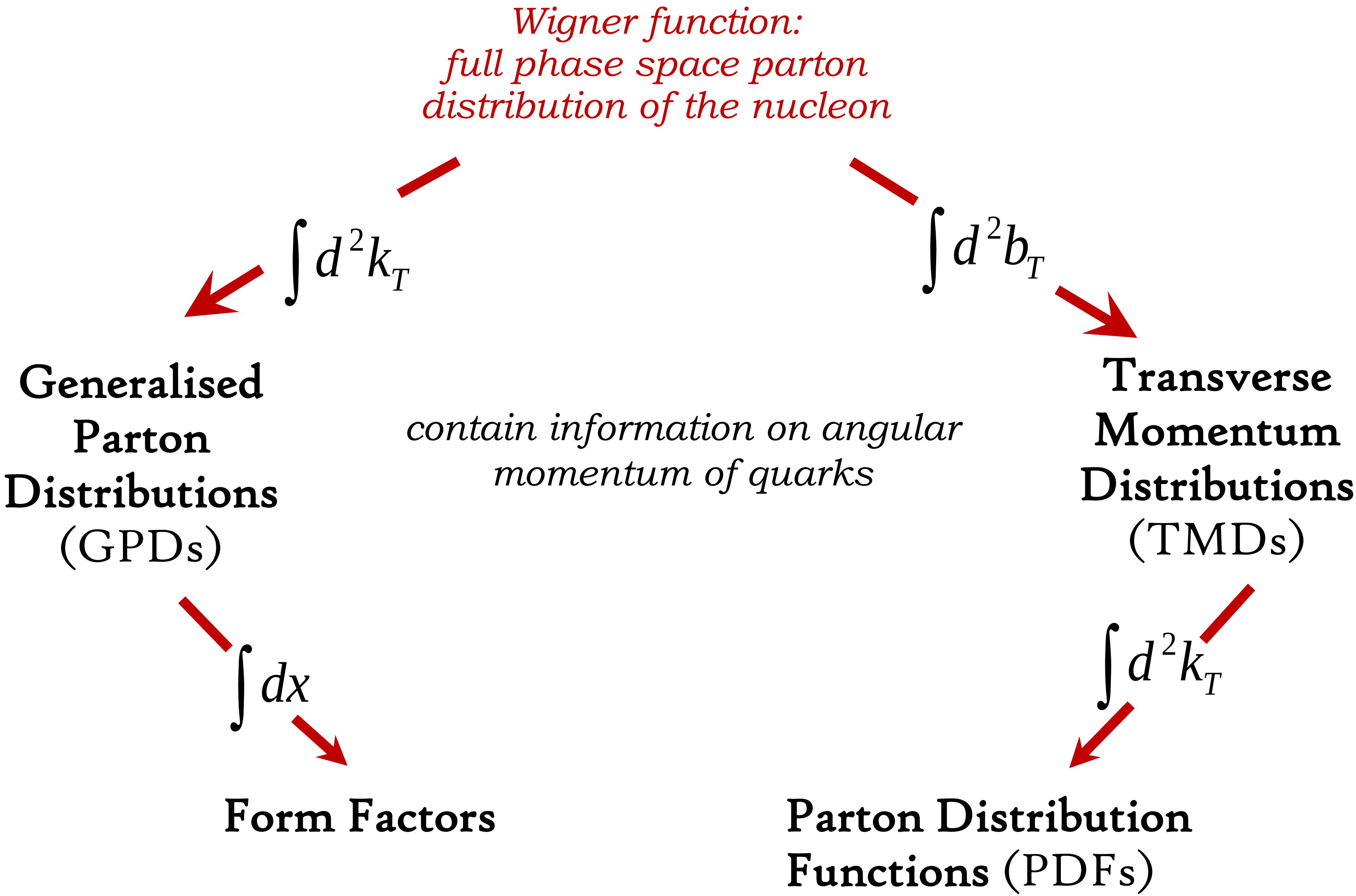
- **GPDs** provide a 3D image of the internal dynamics of the nucleon and carry information on the composition of nucleon spin. They are experimentally accessible in exclusive reactions such as DVCS.

- Exclusive measurements of the **beam- and target-spin asymmetries in DVCS** on the **neutron** in the kinematic range opening up with CLAS12, in conjunction with those on the proton, will provide flavour decomposition of the GPDs and yield insight on the total angular momentum contribution of u, d quarks.

- An extraction of DVCS on **deuterium** @ 6GeV is underway – indications of a very low but measurable beam-spin asymmetry from the neutron and a first measurement of a target-spin asymmetry in nDVCS.

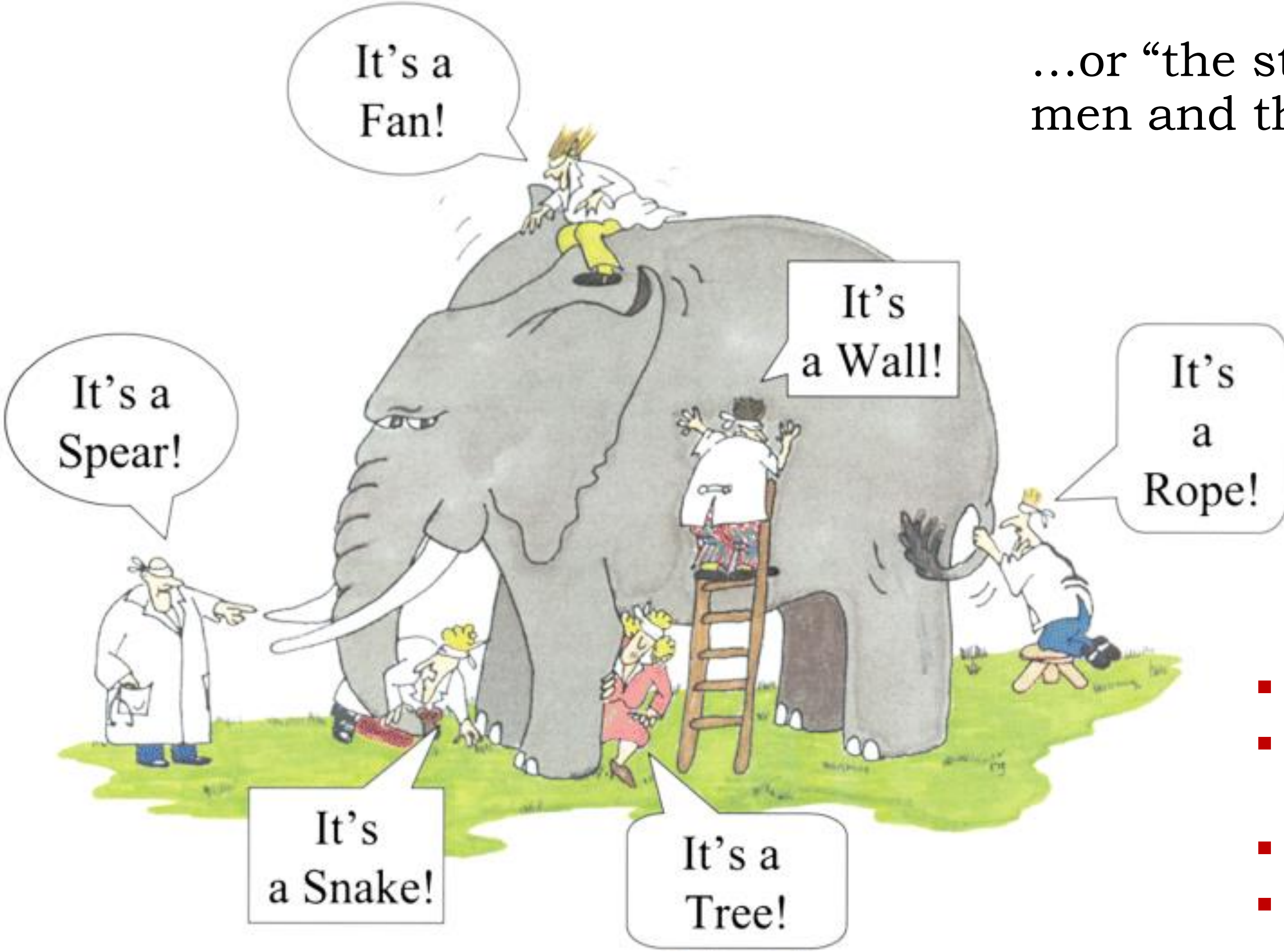
Thank you!

Back-up slides


Wigner function:
full phase space parton
distribution of the nucleon
$\int d^2 k_T$
$\int d^2 b_T$
Generalised
Parton
Distributions
(GPDs)
contain information on angular
momentum of quarks
Transverse
Momentum
Distributions
(TMDs)
$\int dx$
$\int d^2 k_T$
Form Factors
Parton Distribution
Functions (PDFs)

A 100 views of the nucleon…

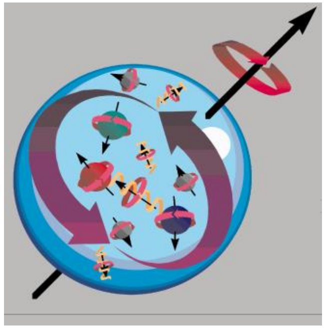
…or "the story of the blind men and the elephant"



G. Renee Guzlas, artist.

- Elastic scattering
- Deep Inealstic Scattering (DIS)
- Semi-inclusive DIS
- Deep exclusive reactions

Views of a nucleon: I

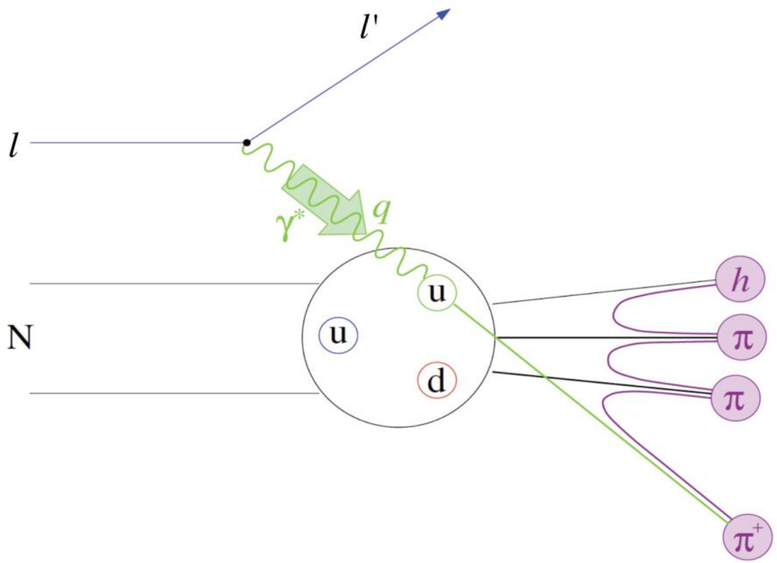


Wigner function:
full phase space parton distribution of the nucleon

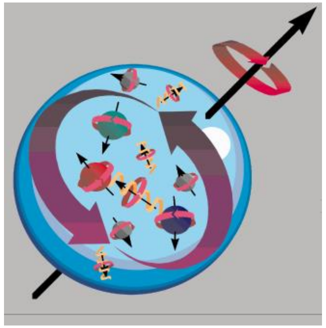
$$\int d^2 b_T$$

Transverse Momentum Distributions (TMDs)

❖ Semi-inclusive Deep Inelastic Scattering:



Views of a nucleon: I



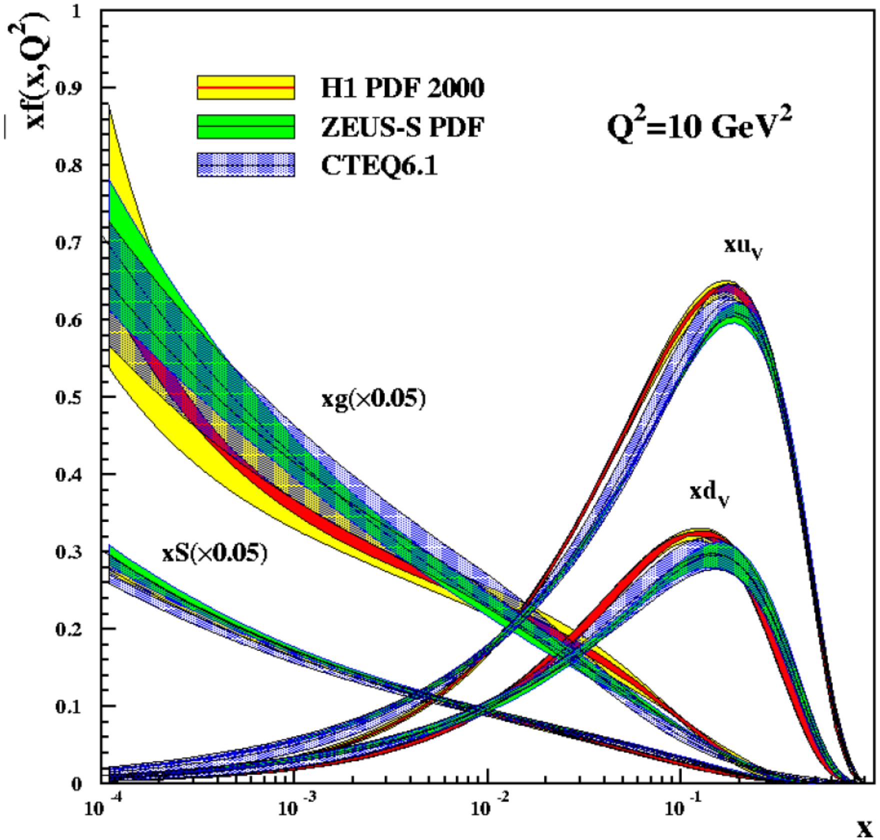
Wigner function:
full phase space parton
distribution of the nucleon

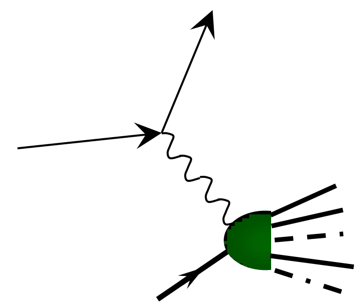
$$\int d^2 b_T$$

Transverse Momentum Distributions (TMDs)

- Deep Inelastic Scattering

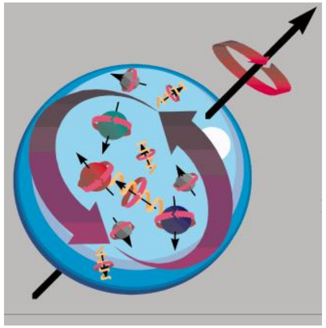
$$\int d^2 k_T$$





Parton Distribution Functions (PDFs)

Views of a nucleon: II

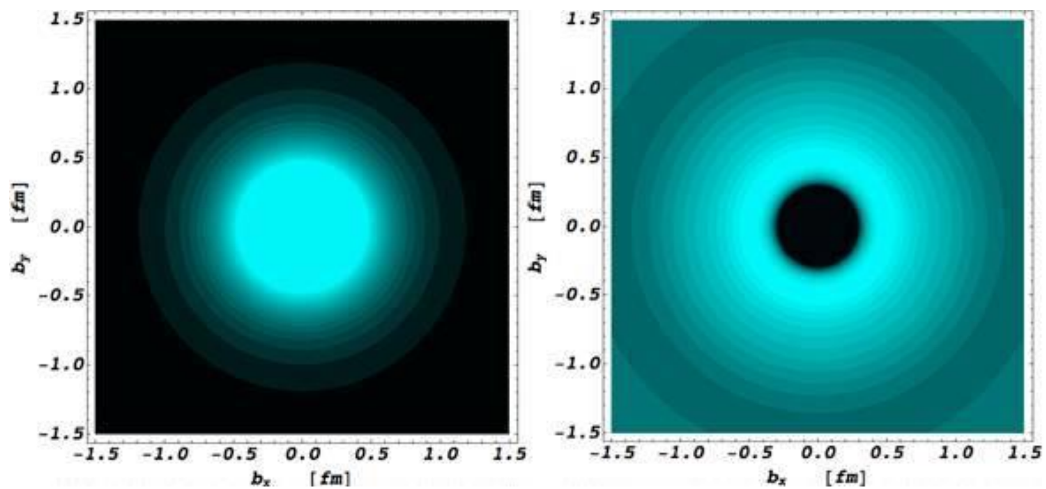


Wigner function:
full phase space parton
distribution of the nucleon

$\int d^2 k_T$

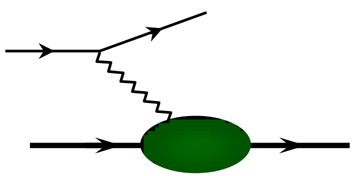
Generalised Parton Distributions (GPDs)

Fourier Transform of electric Form Factor:
transverse charge density of a nucleon



proton   neutron

- Elastic scattering



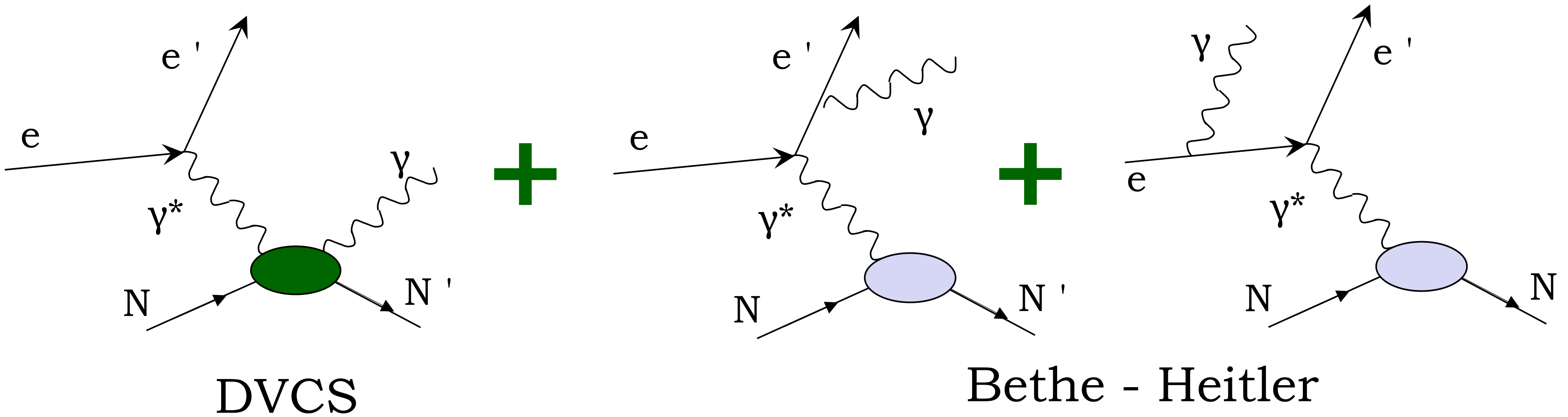
$\int dx$

Form Factors
G_E, G_M

C. Carlson, M. Vanderhaeghen
PRL 100, 032004 (2008)

Measuring DVCS

- Process measured in experiment:



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

Amplitude parameterised in terms of Compton Form Factors

Amplitude calculable from elastic Form Factors and QED!

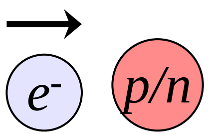
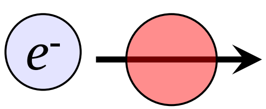
Interference term

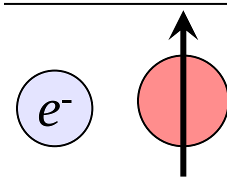
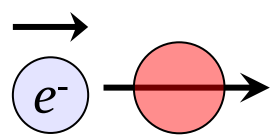
$$|T_{DVCS}|^2 << |T_{BH}|^2$$

Which DVCS experiment?

$H(x,\xi,t)$, $E(x,\xi,t)$: Independent of quark helicity, unpolarised GPDs

$\tilde{H}(x,\xi,t)$, $\tilde{E}(x,\xi,t)$: Helicity-dependent, polarised GPDs.

Beam, target polarisation	Proton	Neutron
	$Im\{\boldsymbol{\mathcal{H}_p}, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$	$Im\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \boldsymbol{\mathcal{E}_n}\}$
	$Im\{\boldsymbol{\mathcal{H}_p}, \boldsymbol{\tilde{\mathcal{H}}_p}\}$	$Im\{\boldsymbol{\mathcal{H}_n}, \mathcal{E}_n, \tilde{\mathcal{E}}_n\}$

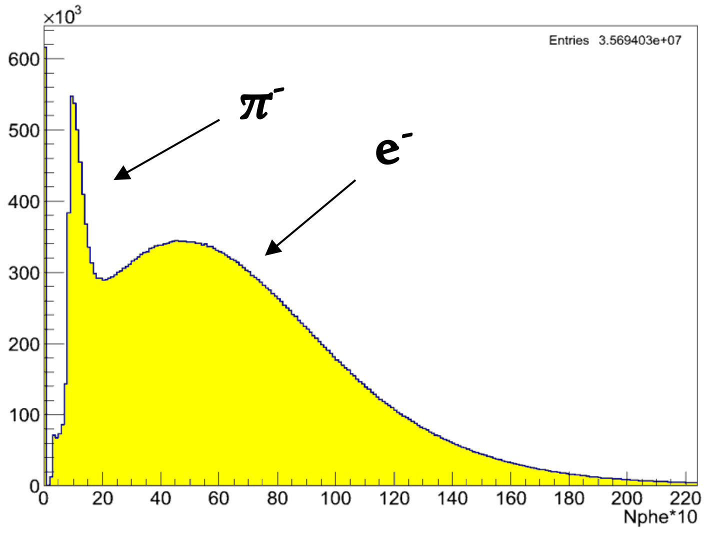
Beam, target polarisation	Proton	Neutron
	$Im\{\boldsymbol{\mathcal{H}_p}, \boldsymbol{\mathcal{E}_p}\}$	$Im\{\boldsymbol{\mathcal{H}_n}\}$
	$Re\{\boldsymbol{\mathcal{H}_p}, \boldsymbol{\tilde{\mathcal{H}}_p}\}$	$Re\{\boldsymbol{\mathcal{H}_n}, \mathcal{E}_n, \tilde{\mathcal{E}}_n\}$

Particle ID – Electrons

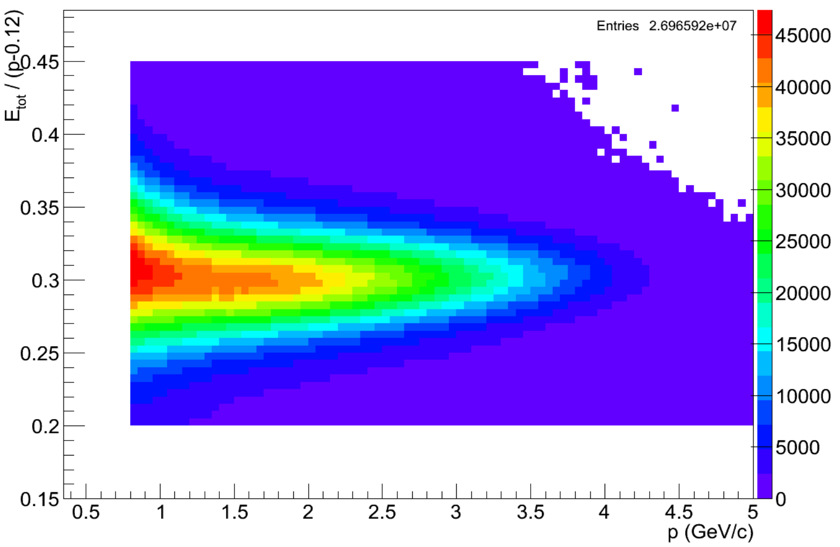
- ***q*** and ***p*** from track-curvature through drift chambers in magnetic field

- **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

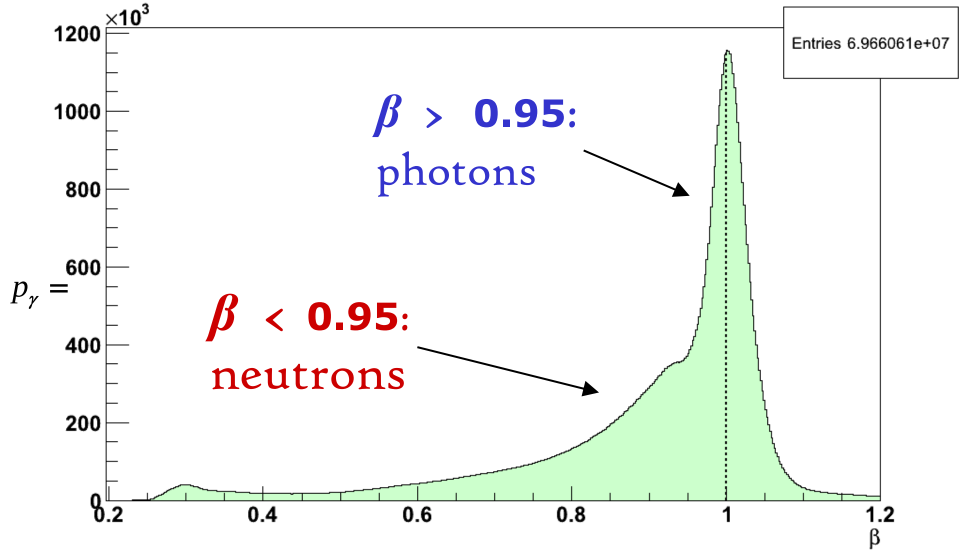


E deposit in EC / *p* vs. *p*



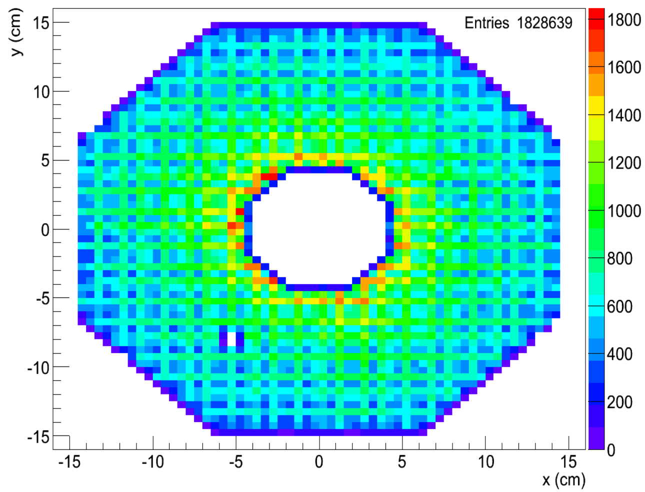
Particle ID – Photons and Neutrons

- ***β*** from neutral particles' time of flight to EC



- Forward, low-angle photons in additional Inner Calorimeter

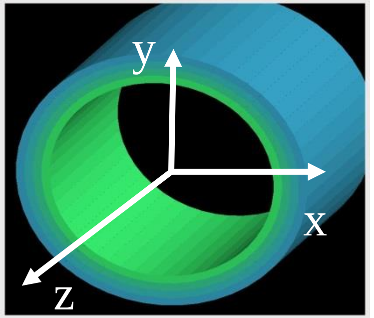
Hits in IC with E deposit > 1 GeV



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

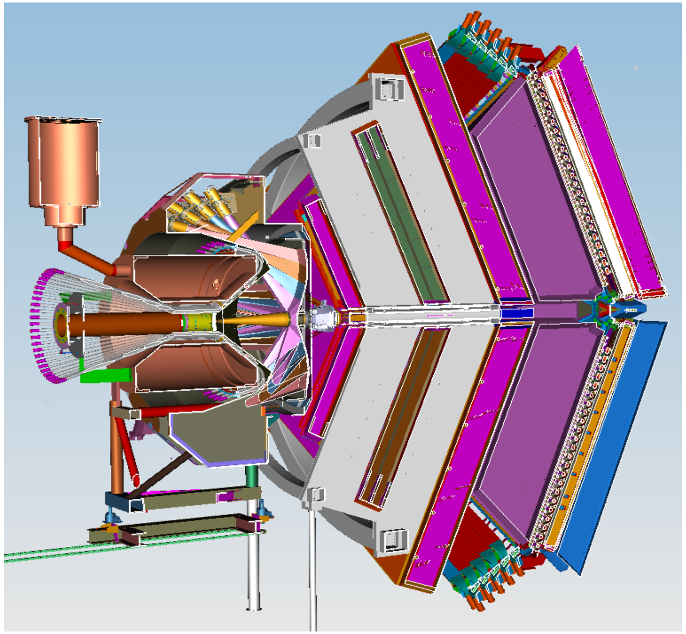
- Photons: E deposited in calorimeter

Neutron Detector for CLAS12



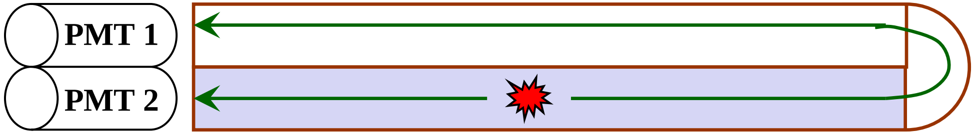
Available:

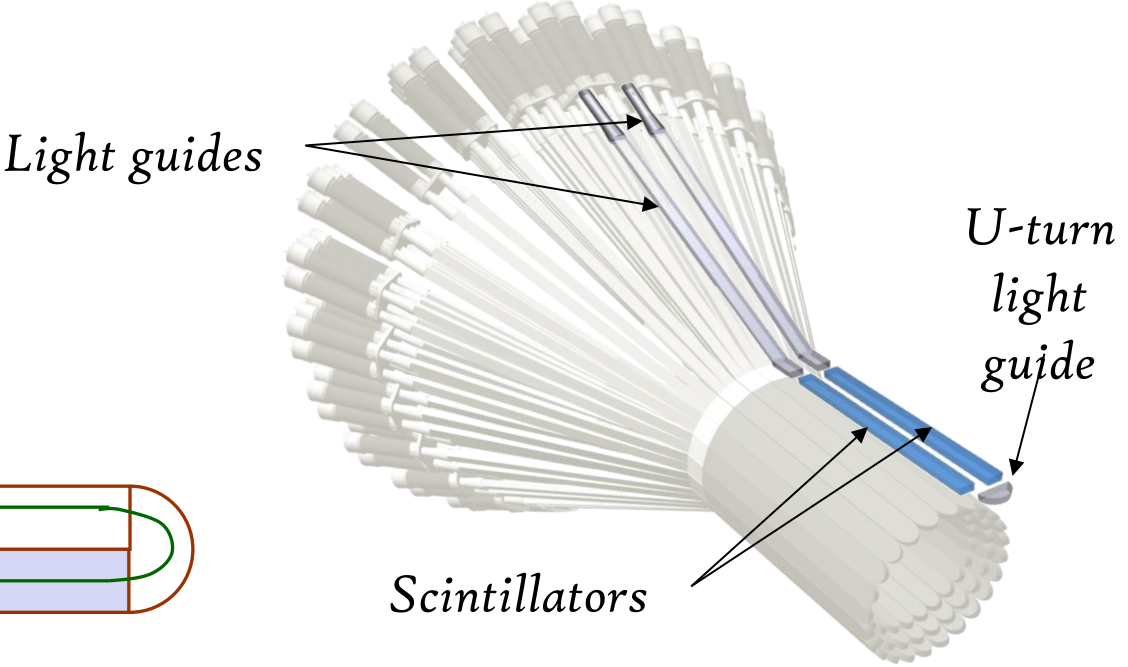
- 10 cm of radial space
- in a high magnetic field (~ 5T)



Detector proposal **approved:**

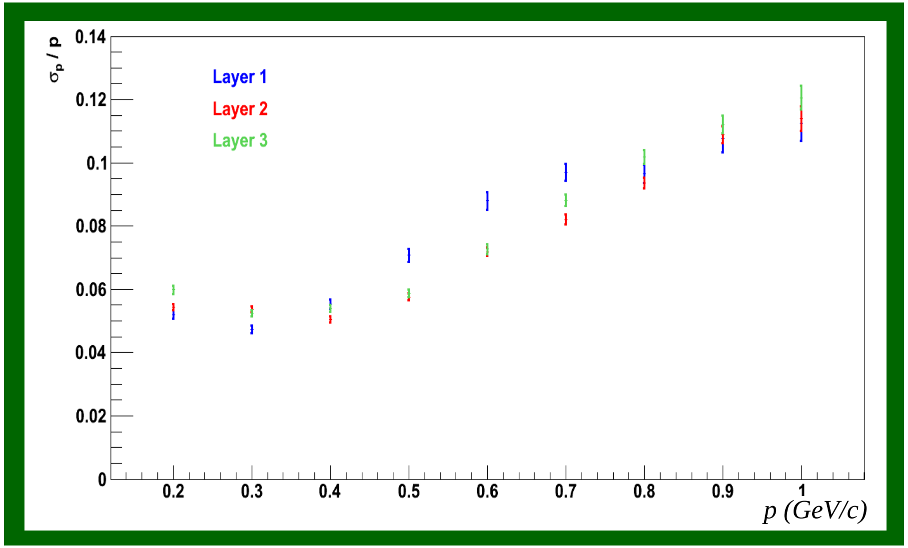
- Plastic scintillator barrel: 3 layers, 48 paddles in each
- Length ~ 70 cm, inner radius 29 cm
- Long (~ 1.5 m) light-guides
- PMT read-out upstream, out of high **B** field

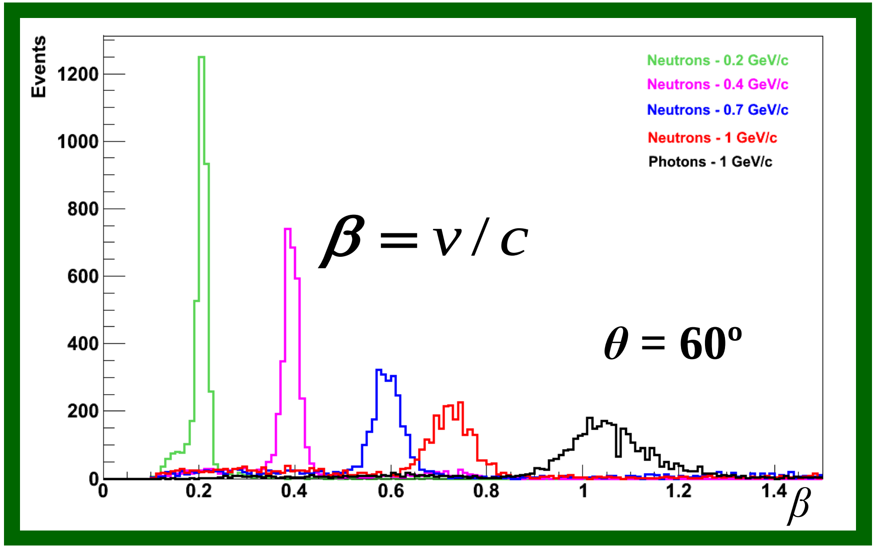




CND Simulation (Geant 4)

- Neutron **efficiency** ~ 8-9 %
- Good **separation of neutrons and γ** up to ~ 1 GeV/c
- $\frac{\sigma_p}{p} \approx 5-12\%$ $\sigma_\theta \approx 2-3^\circ$
- 1 – 3% contamination from mis-reconstructed hits





Proposal Accepted in 2011 – detector constructed at IPN Orsay, France, by 2015. Installation in CLAS12: 2016.