Proton structure from deeply virtual Compton scattering with the CLAS detector at

Jefferson Lab

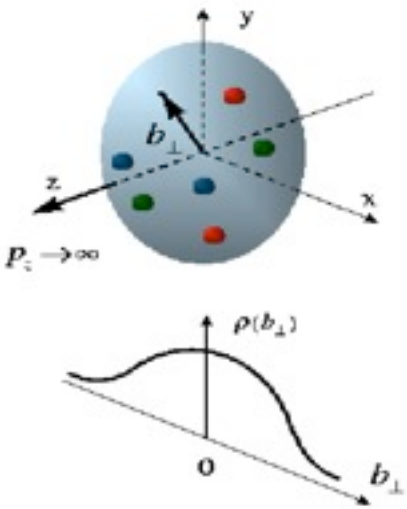
Gary Smith
garys@jlab.org

University of Glasgow

Proton Structure

Form Factors

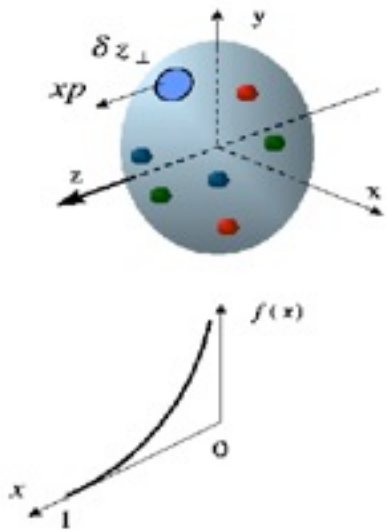
Elastic Scattering



spatial distributions of currents and charges in the transverse plane

Parton Distribution Functions

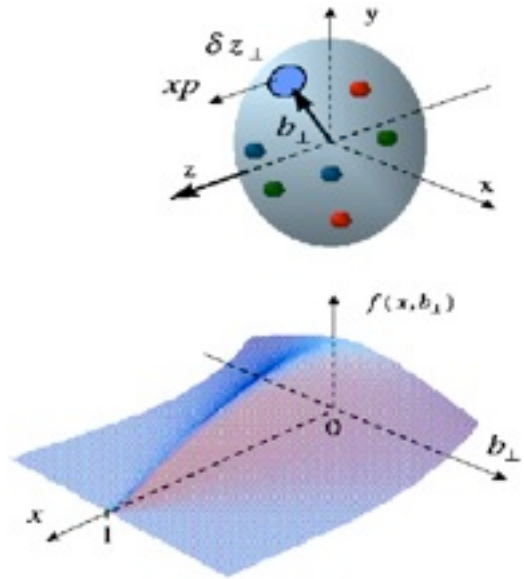
Deep Inelastic Scattering



longitudinal **momentum** distributions of quarks and gluons

Generalised Parton Distributions

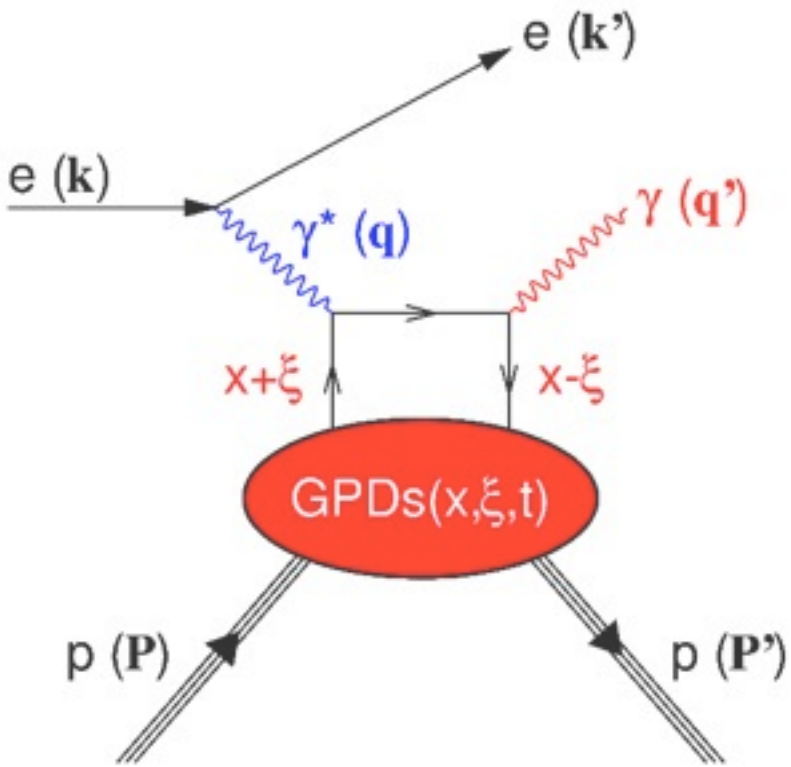
Deep Exclusive Reactions (e.g. DVCS)



correlated **transverse spacial and longitudinal momentum** distributions of quarks and gluons

Image adapted from Belitsky, Mueller 2002
Nuclear hologram with exclusive leptoproduction

Deeply Virtual Compton Scattering (DVCS)



Kinematic Variables

Q^2 negative four momentum of virtual photon squared

ξ 1/2 longitudinal momentum fraction of struck quark
x average total momentum fraction of struck quark
t four momentum transfer to proton squared

Bjorken scaling regime
momentum transfer Q^2 large

↓

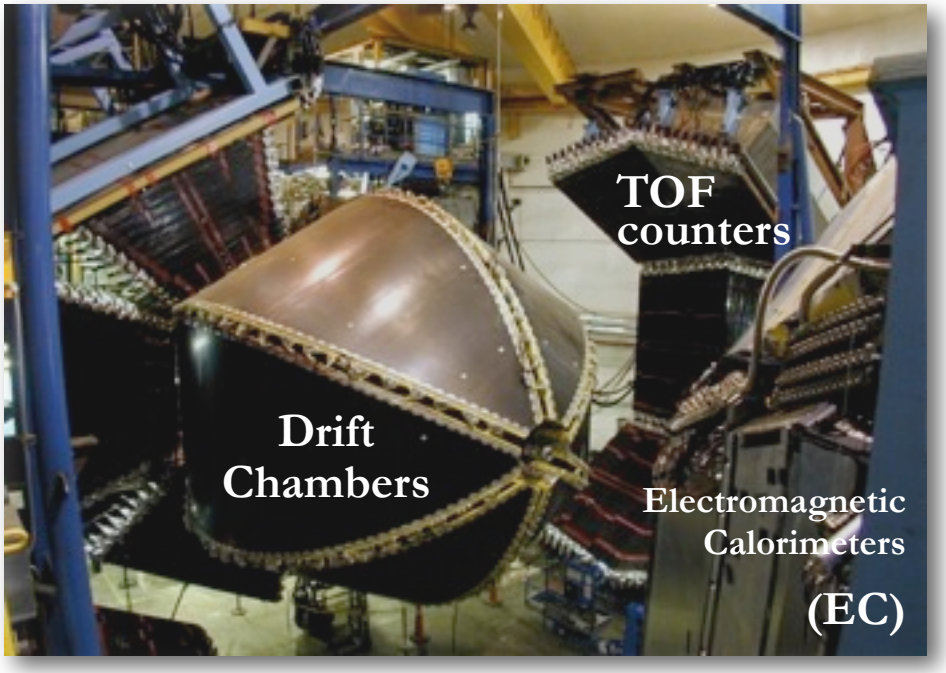
handbag approximation
electron interacts with a single quark

↓

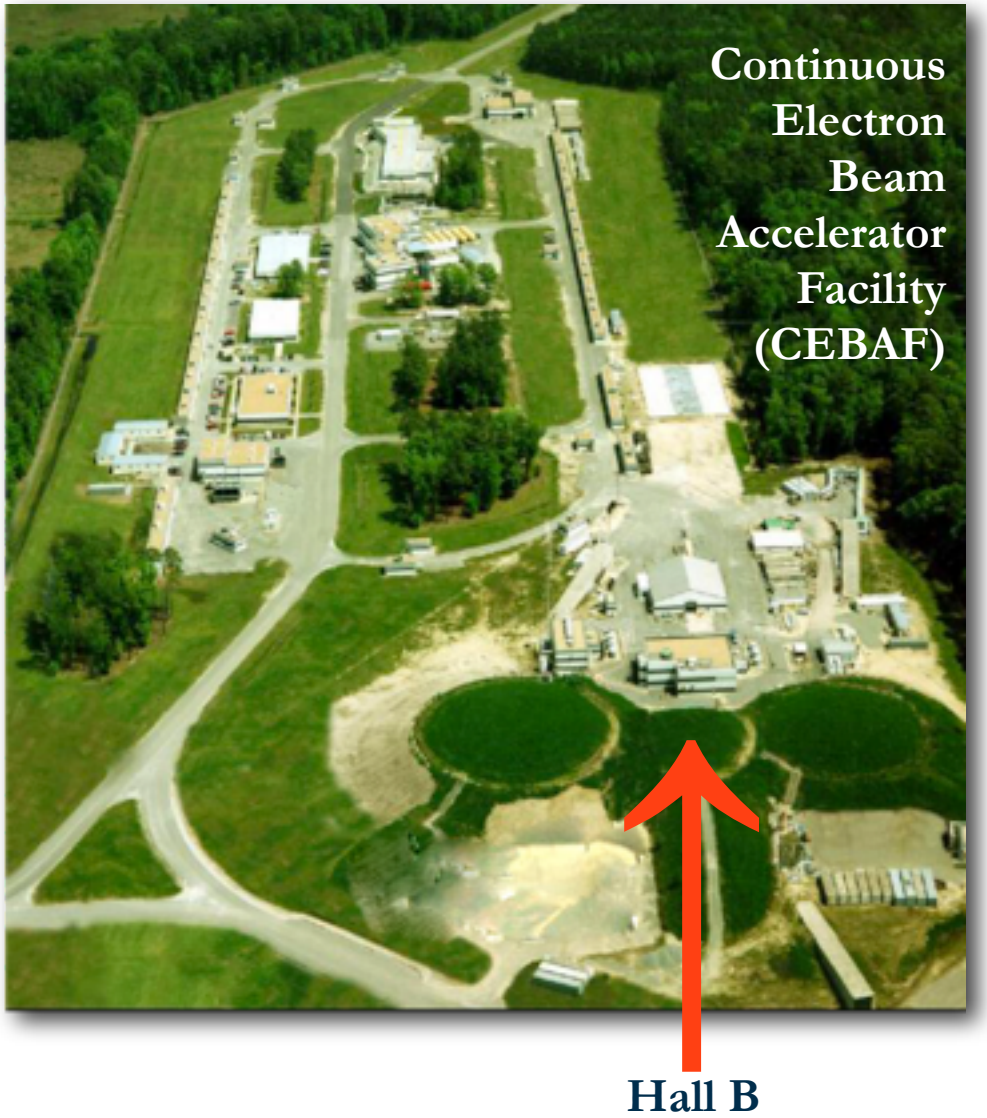
Factorisation
hard scattering + parameterisation
(calculable) (measured)

Image from D.Mahon HERMES thesis 2010
DVCS off longitudinally polarised protons at HERMES

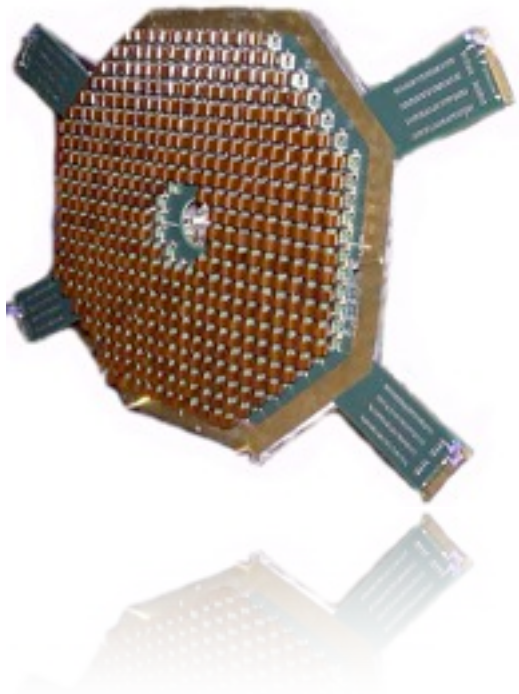
EG1DVCS experiment



CEBAF Large Acceptance Spectrometer (CLAS) in experimental Hall B



EG1DVCS experiment

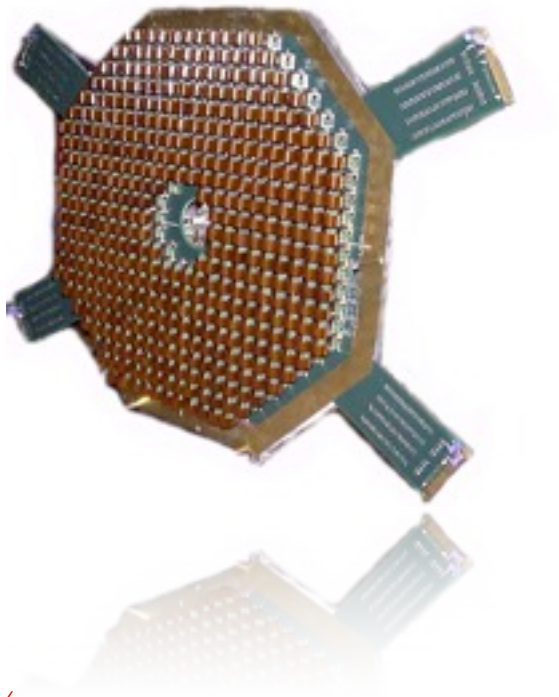


- over 80 days of data taken with polarised proton target
- > 70 fb^{-1} (>20 billion triggers) on proton target
- ~10 x statistics of previous CLAS target spin asymmetry result
- polarised (~85%) electron beam up to 6 GeV
- undergoing analyses include DIS, SIDIS, DVCS, DVMP

EG1DVCS experiment

Dynamically polarised target

Accommodates measurement of target spin asymmetry



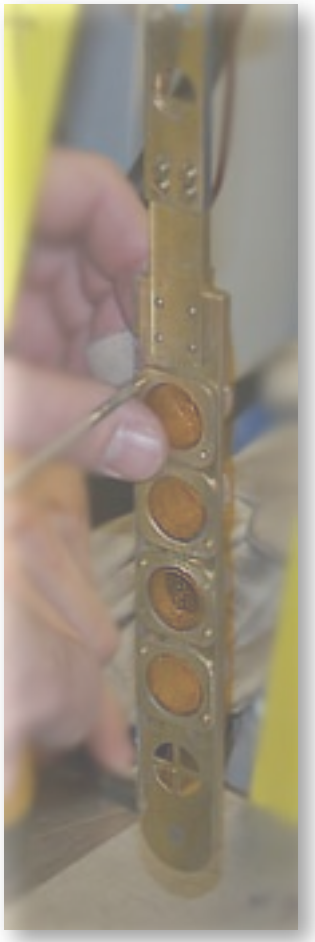
Ammonia NH3/ND3 — proton polarisation ~75%

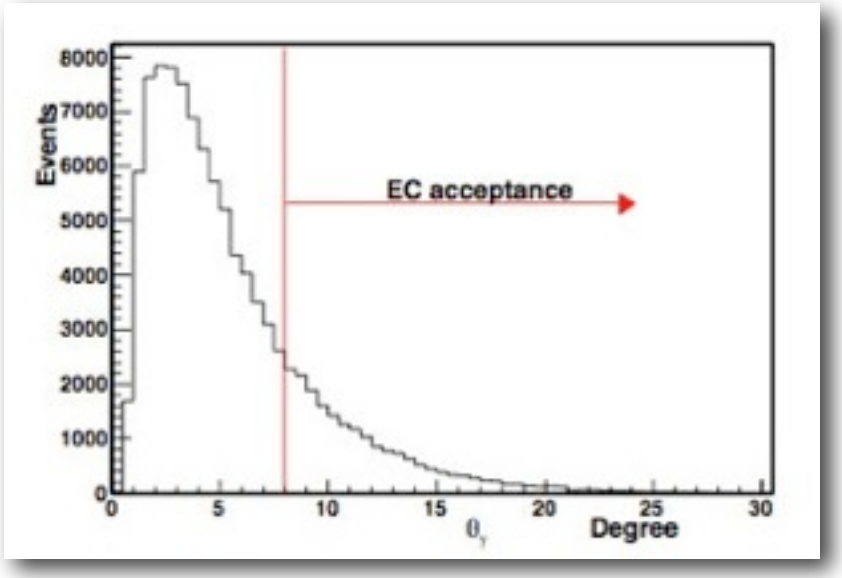
Carbon

Empty

additional targets for background studies

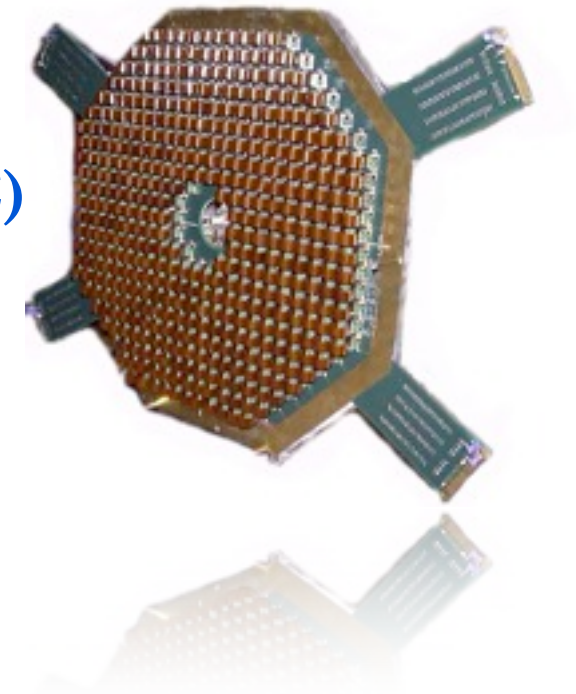
EG1DVCS experiment





Monte Carlo simulation of DVCS photon angle

Inner Calorimeter (IC)

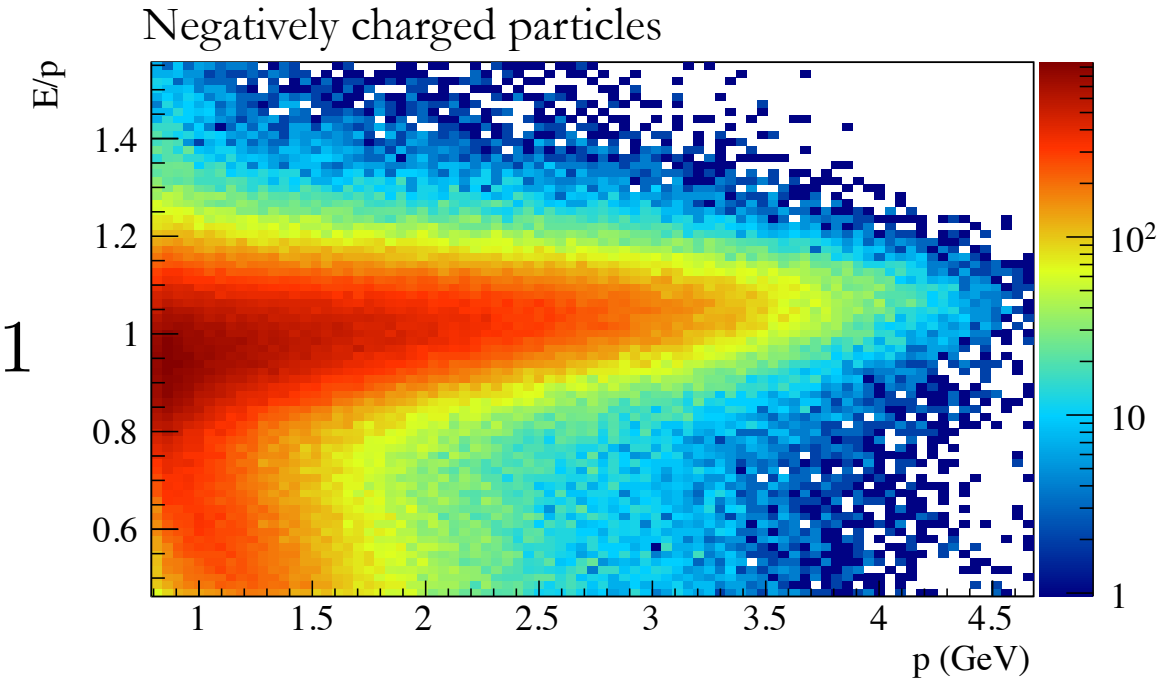


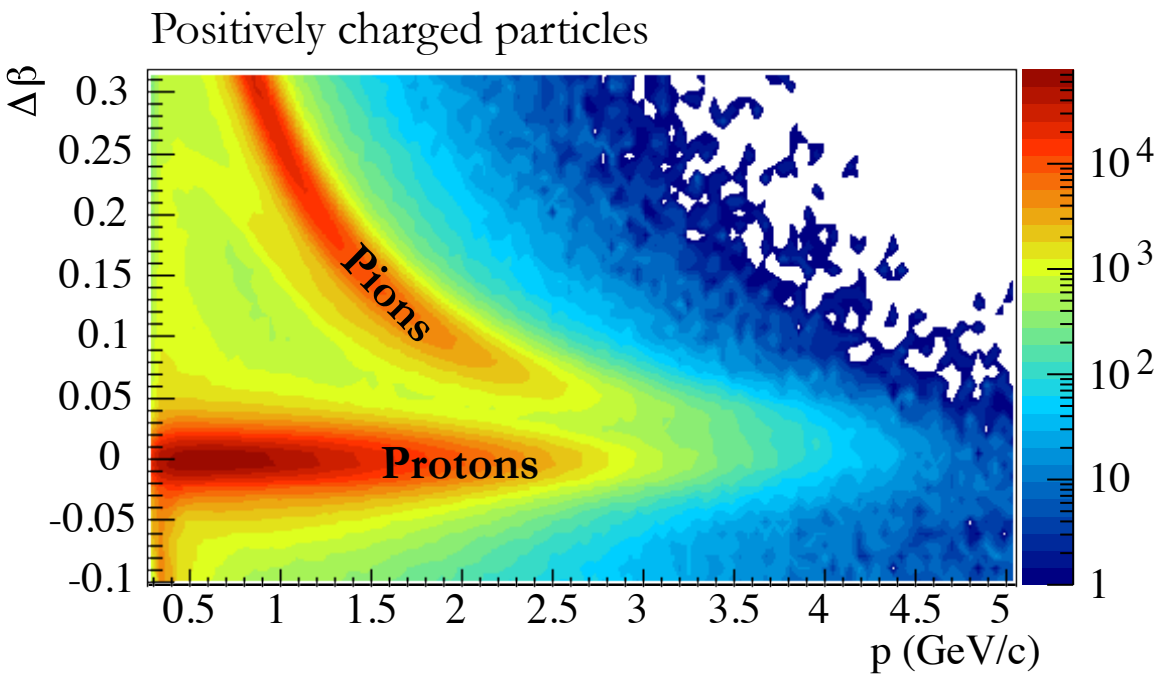
- Enhanced photon acceptance at small angles (4-16 degrees)

Particle data cuts

electron ID

$$e/p = \beta \approx 1$$





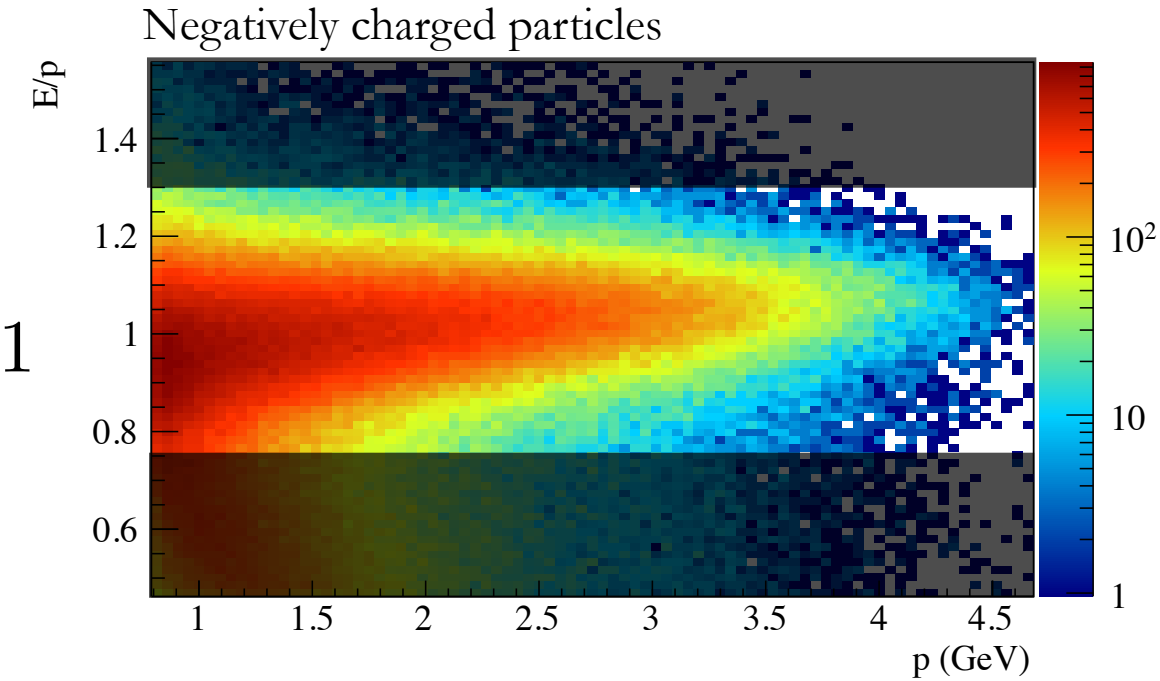
proton ID

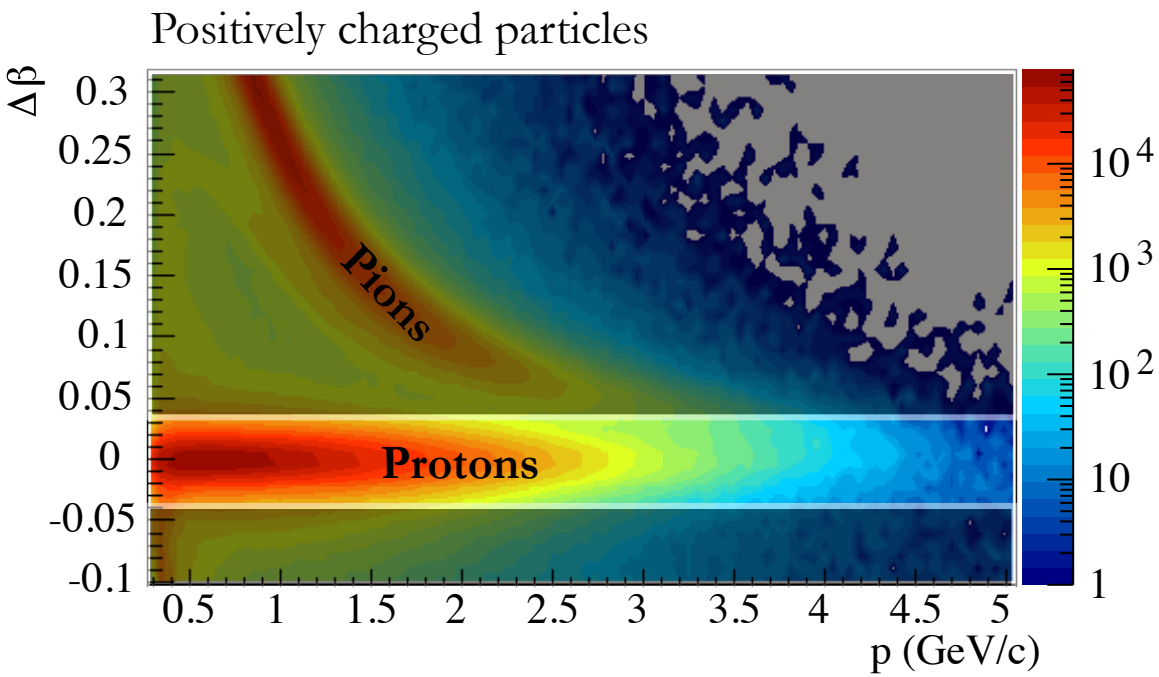
$$\beta = \frac{d}{ct} = \frac{p}{\sqrt{p^2 + M_p^2}} \approx 0$$

Particle data cuts

electron ID

$$e/p = \beta \approx 1$$



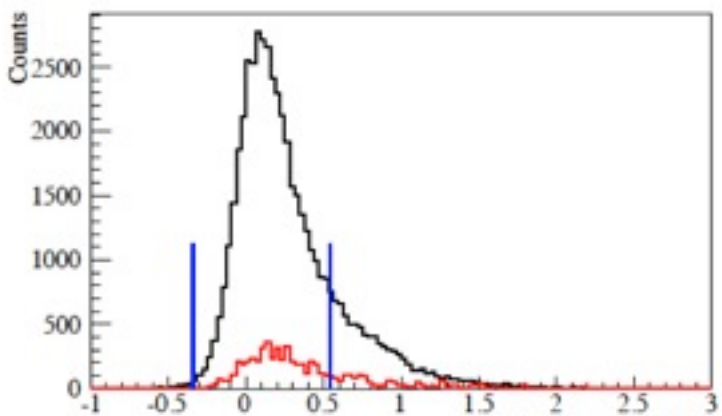


proton ID

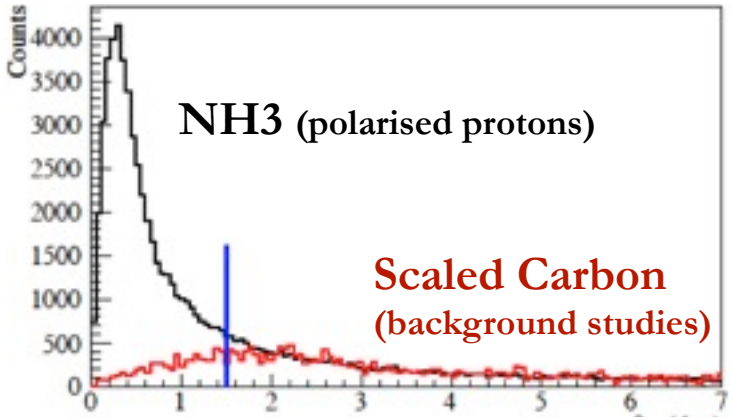
$$\beta = \frac{d}{ct} = \frac{p}{\sqrt{p^2 + M_p^2}} \approx 0$$

Exclusivity data cuts

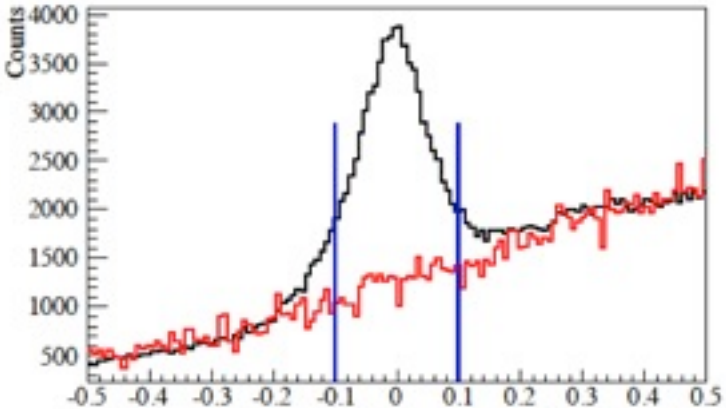
$ep \rightarrow epg$



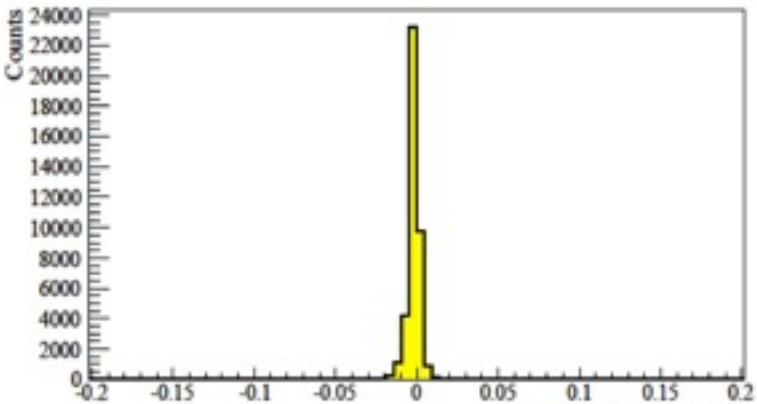
missing energy (GeV)



missing photon angle (deg)



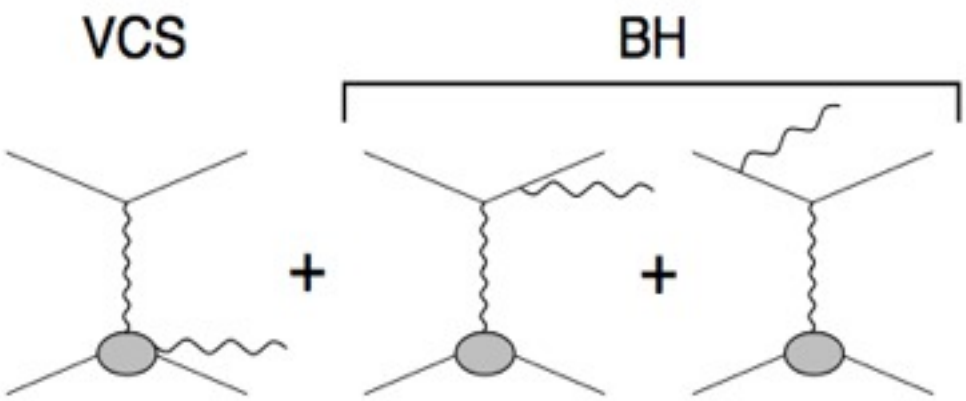
missing mass ep (GeV/c²)



missing mass epg (GeV/c²)

Asymmetries

$$\frac{d\sigma}{dx_B dy dt d\phi d\varphi} \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \mathcal{I}$$



Bethe-Heitler Process (BH)

Asymmetries

$$\frac{d\sigma}{dx_B dy dt d\phi d\varphi} \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \mathcal{I}$$

$$\mathcal{I} \propto \sum_{n=0}^{3} \left[c_n^{\mathcal{I}} cos(n\phi) + s_n^{\mathcal{I}} sin(n\phi) \right]$$

Fourier deconvolution
(Belitsky, Mueller, Kirchner 2002 Nuclear Physics B)

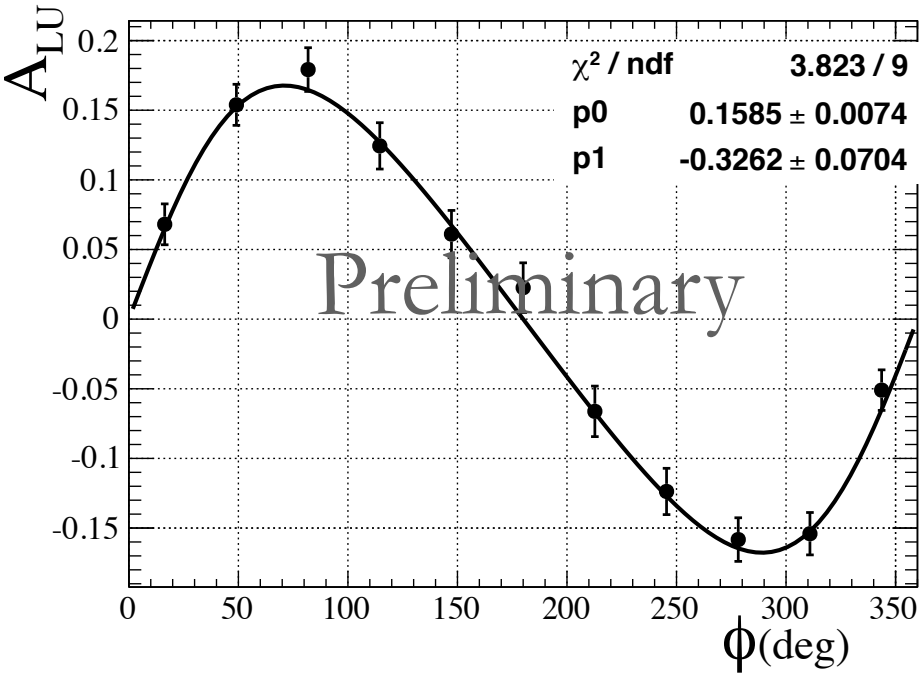
$$A_{UL} = \frac{d\sigma^{\Rightarrow} - d\sigma^{\Leftarrow}}{d\sigma^{\Rightarrow} + d\sigma^{\Leftarrow}} \sim \frac{x_B}{y} \frac{s_{1,LP}^{\mathcal{I}}}{c_{0,unp}^{BH} + \ldots} sin(\phi)$$

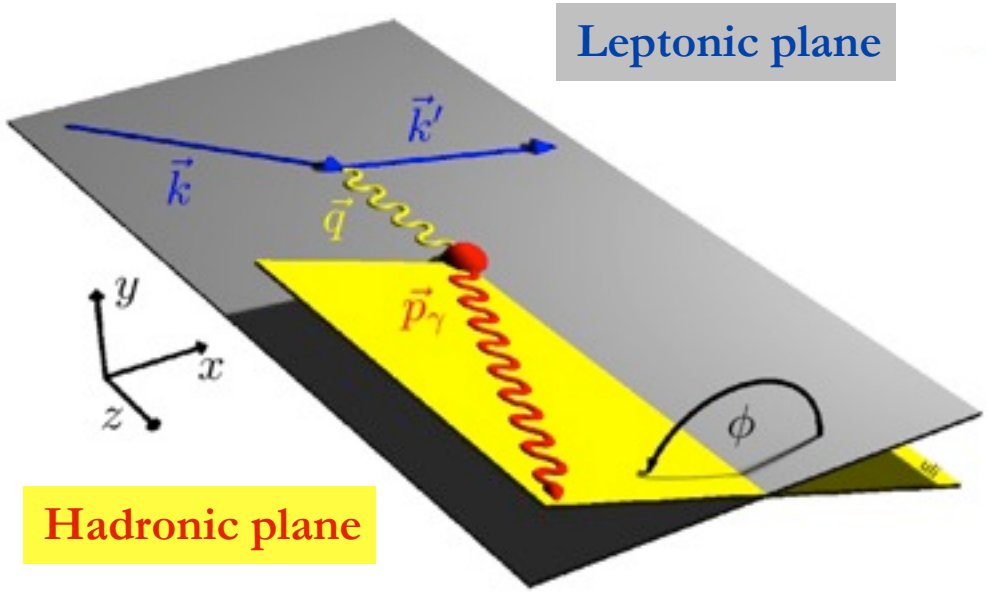
Target Spin Asymmetry
(longitudinal polarisation)

Asymmetries ⟶ **Fourier coefficients** ⟶ Compton Form Factors ⟶ GPDs

Asymmetries

Fit function $p_0 \sin\phi/(1 + p_1 \cos\phi)$





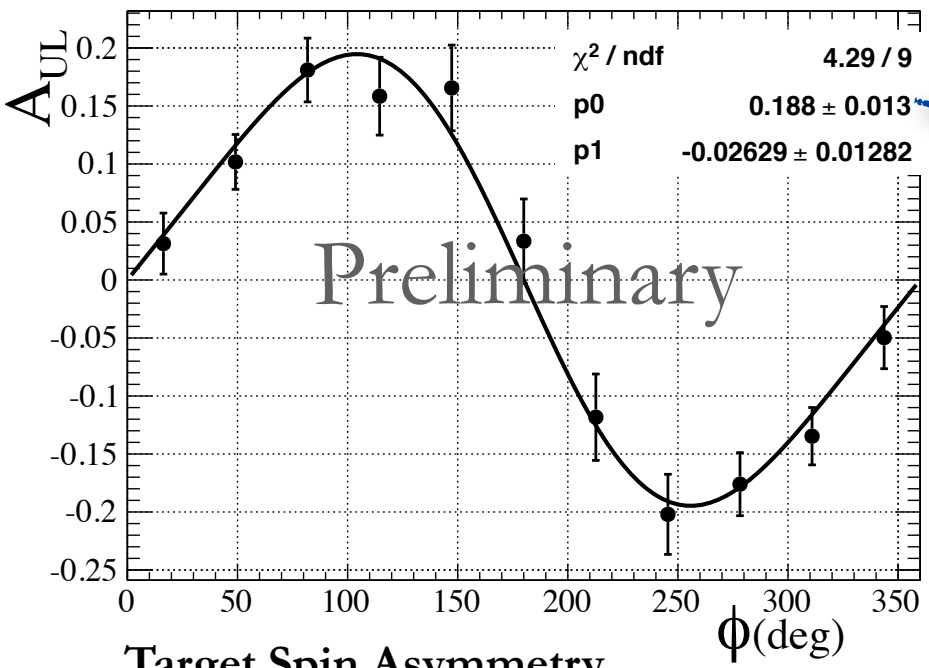
Beam Spin Asymmetry (Integrated)

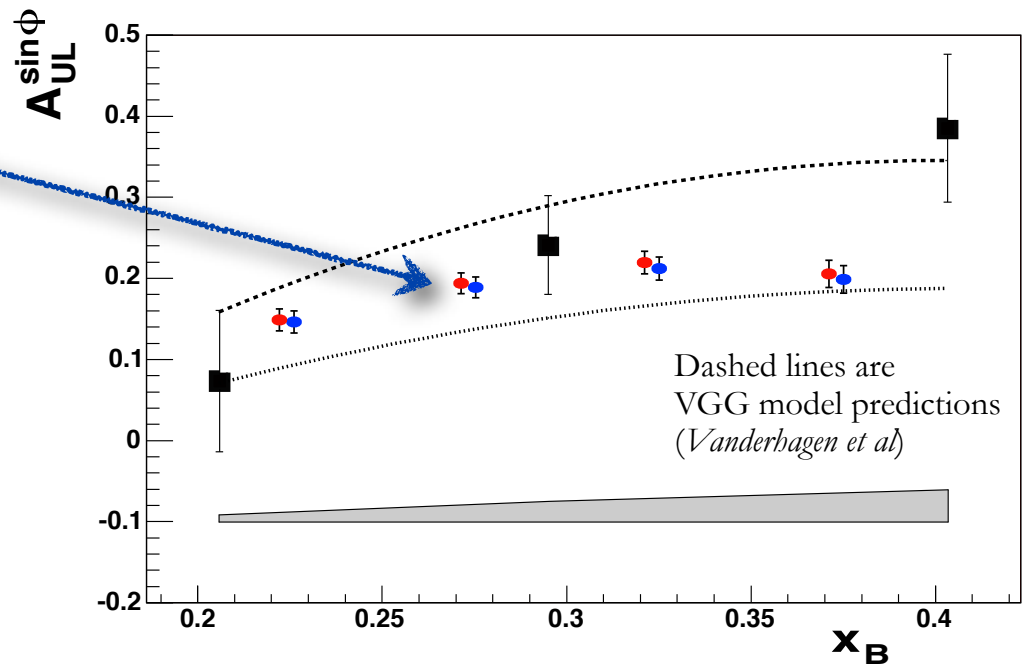
$$A_{LU} = \frac{d\sigma^{\rightarrow} - d\sigma^{\leftarrow}}{d\sigma^{\rightarrow} + d\sigma^{\leftarrow}} = \frac{1}{P_B}\frac{N^{\rightarrow} - N^{\leftarrow}}{N^{\rightarrow} + N^{\leftarrow}}$$

Asymmetries

Black squares — previous result *(Chen PRL 2006)*
Blue circles — Chi-squared fit
Red circles — Maximum Likelihood fit

Fit function $\mathbf{p_0 \sin\phi + p_1 \sin 2\phi}$





Target Spin Asymmetry
(binned in x_B)

$$A_{UL} = \frac{d\sigma^{\Rightarrow} - d\sigma^{\Leftarrow}}{d\sigma^{\Rightarrow} + d\sigma^{\Leftarrow}} = \frac{1}{P_T D}\frac{N^{\Rightarrow} - N^{\Leftarrow}}{N^{\Rightarrow} + N^{\Leftarrow}}$$

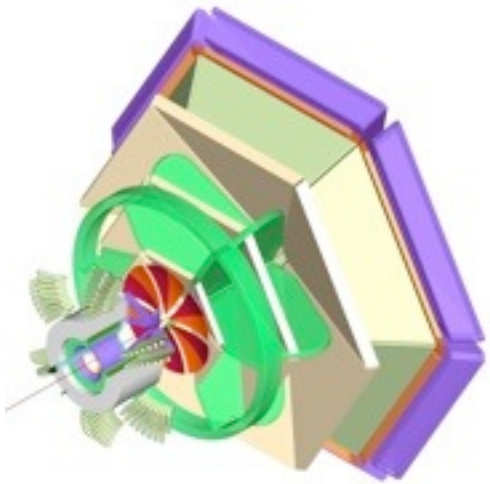
$$\mathbf{x_B \overset{lab}{=} \frac{Q^2}{2M_p(E - E')}}$$

Conclusions

- GPDs are accessible through DVCS spin asymmetries and give access to new information about proton structure

- Beam, Target and Double Spin Asymmetry amplitudes are used to constrain Compton Form Factors which are used to measure GPDs

- EG1DVCS data accommodates precise measurements of asymmetry amplitudes as a function of DVCS kinematics

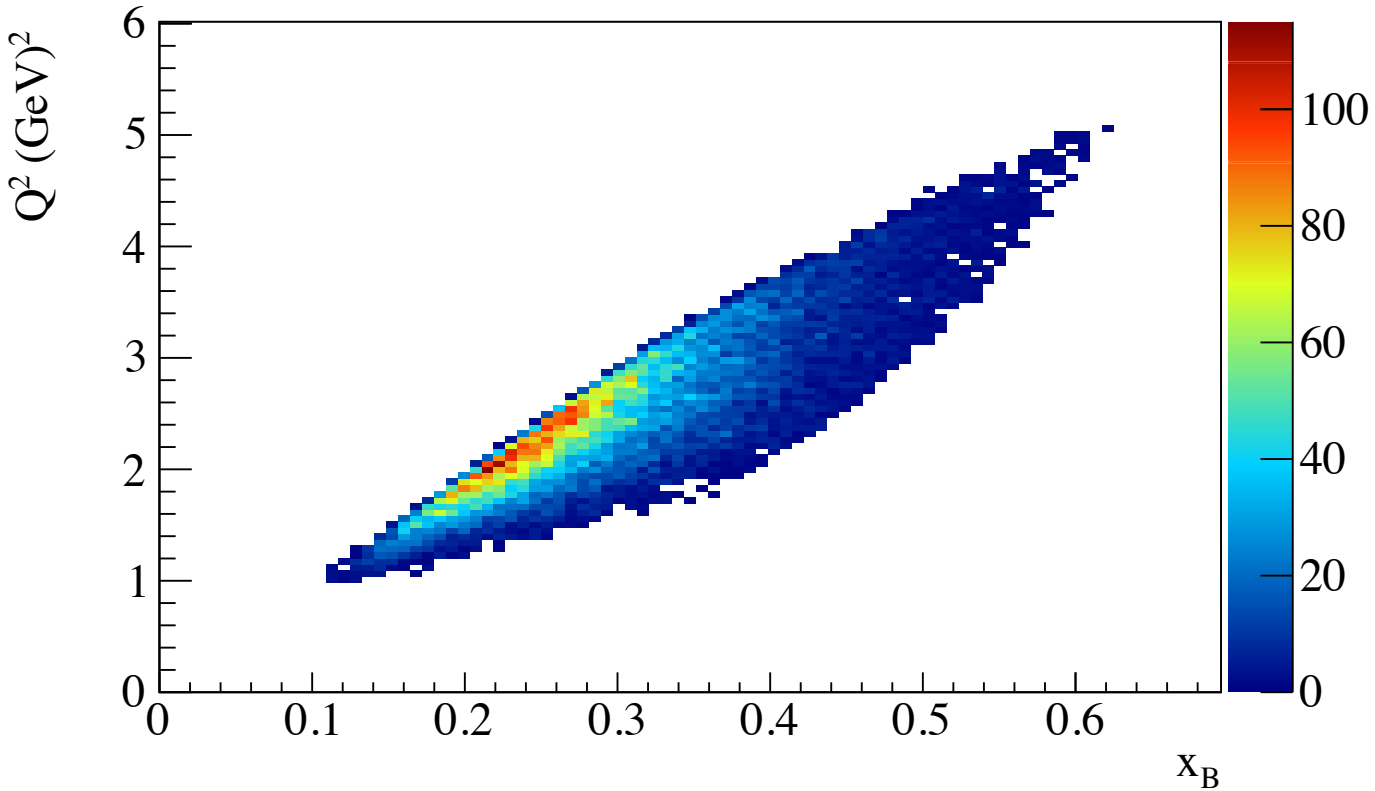


- From 2015 experiments will begin with CLAS12

- Higher Q^2 available and forward focussed design will suit DVCS and other exclusive channels (e.g. DVMP)

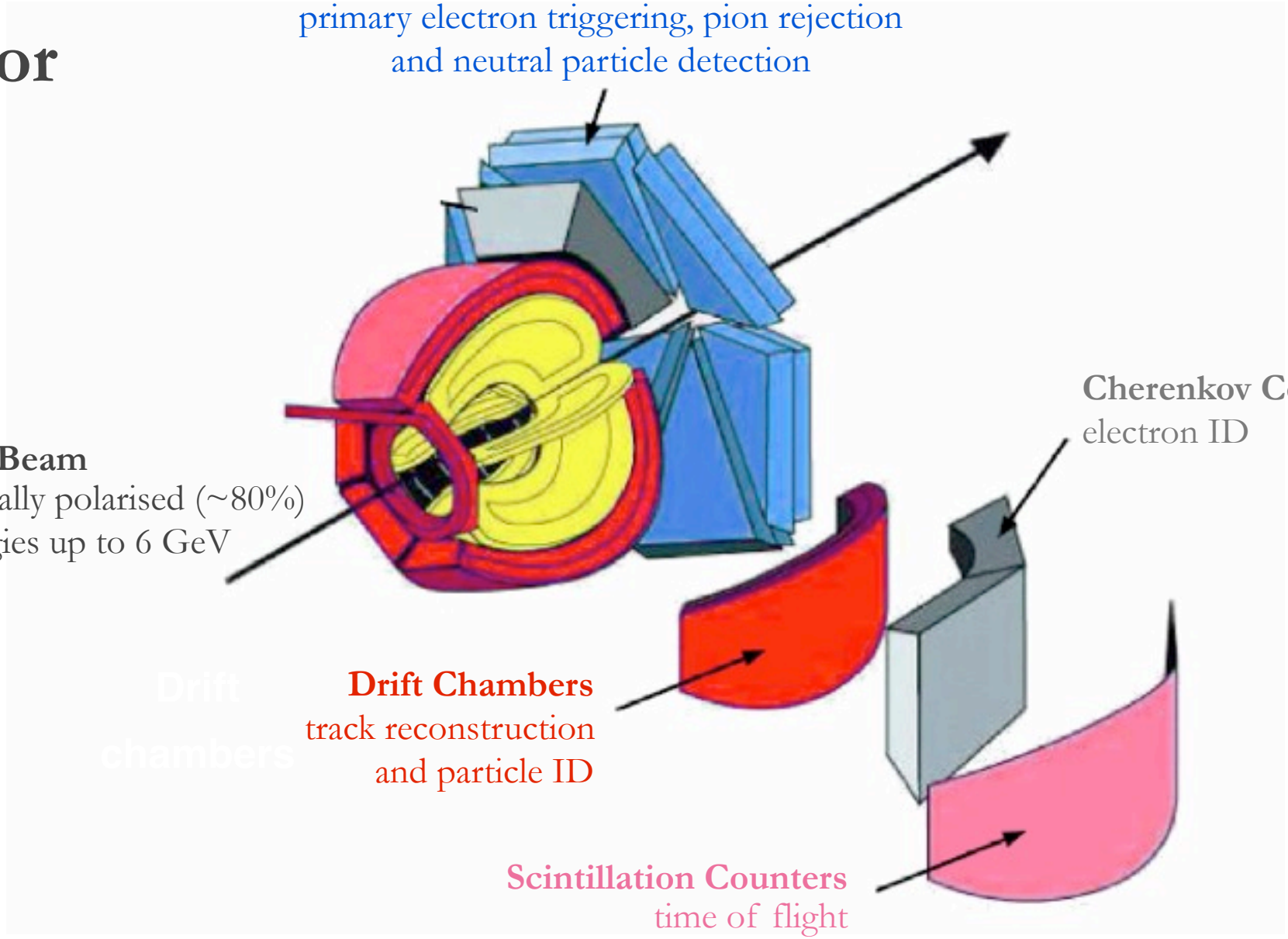
Backup Slides

Kinematic coverage



CLAS detector

Electromagnetic Calorimeters (EC)
primary electron triggering, pion rejection and neutral particle detection



Cherenkov Counters
electron ID

Electron Beam
longitudinally polarised (~80%) with energies up to 6 GeV

Drift Chambers
track reconstruction and particle ID

Scintillation Counters
time of flight

Asymmetries and Compton Form factors

$$A_{UL}(\phi) \sim \frac{x_B}{y} \frac{s^{\mathcal{I}}_{1,LP}}{c^{BH}_{0,unp} + \ldots} sin(\phi)$$

$$\propto \Im m\left\{F_1 \tilde{\mathcal{H}} + \frac{x_B}{2-x_B}(F_1+F_2)(\mathcal{H} + \frac{x_B}{2}\mathcal{E}) + \ldots\right\} sin(\phi)$$

$$A_{LU} \propto \Im m\left\{F_1 \mathcal{H} + \frac{x_B}{2-x_B}(F_1+F_2)(\tilde{\mathcal{H}} - \frac{\Delta^2}{4M^2}F_2\mathcal{E}) + \ldots\right\} sin(\phi)$$

$$A_{LL}(\phi) \sim \frac{x_B}{y} \frac{c^{BH}_{0,LP} + c^{\mathcal{I}}_{0,LP} + (c^{BH}_{1,LP} + c^{\mathcal{I}}_{1,LP}) cos(\phi)}{c^{BH}_{0,unp} + \ldots}$$

$$\propto \Re e\left\{F_1 \tilde{\mathcal{H}} + \frac{x_B}{2-x_B}(F_1+F_2)(\mathcal{H} + \frac{x_B}{2}\mathcal{E}) + \ldots\right\}$$

dominant terms at twist level 2 for CLAS kinematics

Asymmetry Amplitude	Contributing Fourier-Coefficient	Twist Level	CFF Dependence
$A_{UL}^{\sin\phi}$	$s^{\mathcal{I}}_{1,LP}$	2	$\Im m\, \mathcal{C}^{\mathcal{I}}_{LP}$
	$s^{DVCS}_{1,LP}$	3	$\Im m\, \mathcal{C}^{DVCS}_{LP}$
$A_{UL}^{\sin(2\phi)}$	$s^{\mathcal{I}}_{2,LP}$	3	$\Im m\, \mathcal{C}^{\mathcal{I}}_{LP}$
	$s^{DVCS}_{2,LP}$	2	$\Im m\, \mathcal{C}^{DVCS}_{T,LP}$
$A_{UL}^{\sin(3\phi)}$	$s^{\mathcal{I}}_{3,LP}$	2	$\Im m\, \mathcal{C}^{\mathcal{I}}_{T,LP}$
$A_{LL}^{\cos(0\phi)}$	$c^{\mathcal{I}}_{0,LP}$	2	$\Re e\, \mathcal{C}^{\mathcal{I}}_{LP}$
	$c^{DVCS}_{0,LP}$	2	$\Re e\, \mathcal{C}^{DVCS}_{LP}$
	$c^{BH}_{0,LP}$	-	-
$A_{LL}^{\cos\phi}$	$c^{\mathcal{I}}_{1,LP}$	2	$\Re e\, \mathcal{C}^{\mathcal{I}}_{LP}$
	$c^{DVCS}_{1,LP}$	3	$\Re e\, \mathcal{C}^{DVCS}_{LP}$
	$c^{BH}_{1,LP}$	-	-
$A_{LL}^{\cos(2\phi)}$	$c^{\mathcal{I}}_{2,LP}$	3	$\Re e\, \mathcal{C}^{\mathcal{I}}_{LP}$
$A_{LU}^{\sin\phi}$	$s^{\mathcal{I}}_{1,u}$	2	$\Im m\, \mathcal{C}^{\mathcal{I}}_{u}$
	$s^{DVCS}_{1,u}$	3	$\Im m\, \mathcal{C}^{DVCS}_{u}$
$A_{LU}^{\sin(2\phi)}$	$s^{\mathcal{I}}_{2,u}$	3	$\Im m\, \mathcal{C}^{\mathcal{I}}_{u}$

Target

- four cells on insert controlled by stepper motor
- Dynamic Nuclear Polarisation

  target cooled to 1K using Helium

  uniform 5T field $\Delta B/B \sim 10^{-4}$
- polarisation monitored with NMR system
- precise value: compare elastic and measured elastic asymmetries

Inner Calorimeter (IC)

- 424 lead tungstate tapered crystals
- light measurement with Avalanche Photodiodes (APDs)
- laser system to monitor gain changes with temperature
- low noise (7-8 MeV) fast pre-amps
- placed in the centre of CLAS ~65cm from target
- angular coverage of 4 -16 degrees