GPDs at JLab

March 8th 2022

F.-X. Girod-Gard

The Continuous Electron Beam Accelerator Facility

A.K.A. CEBAF

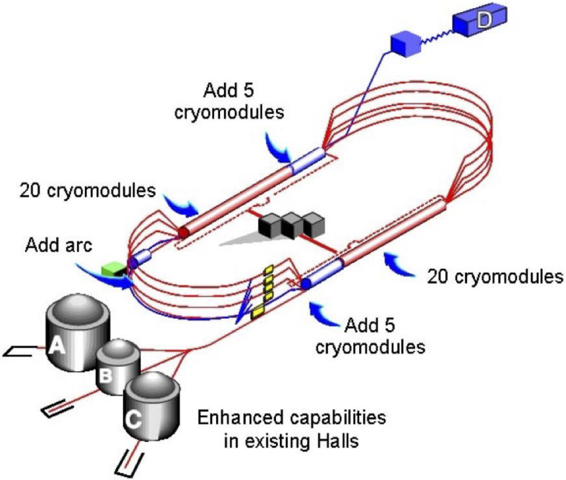
High duty factor (continuous)

Up to 12 GeV beam energy

High intensities
$\sim 100\,\mu\text{A}$ or $10^{38}\text{s}^{-1}\text{cm}^{-2}$

High polarizations

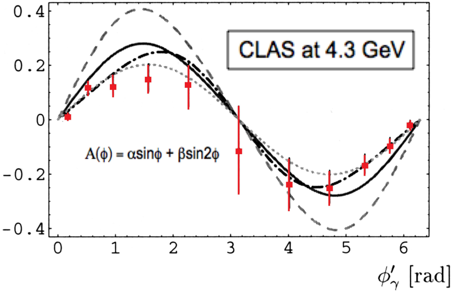
4 permanent spectrometers
additional experiments



Pioneering observations

First DVCS BSA and TSA observations

$$A_{LU} \propto F_1 \mathcal{H} + \xi G_M \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}$$

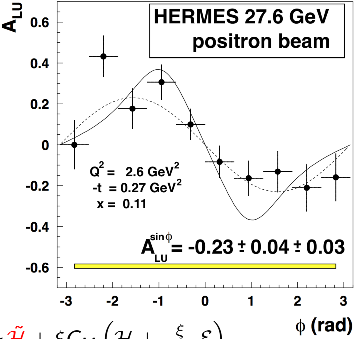


$Q^2 = 1.3$ GeV^2, $x_B = 0.2$, $-t = 0.2$ GeV^2

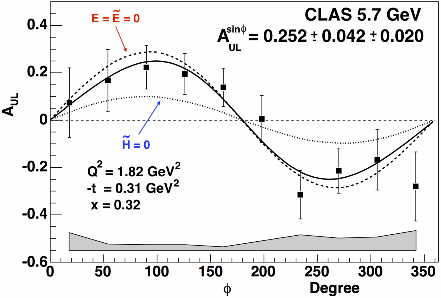
$$A(\phi) = \alpha \sin\phi + \beta \cos(2\phi)$$
$$\alpha = 0.202 \pm 0.028^{stat} \pm 0.013^{syst}$$
$$\beta = -0.024 \pm 0.021^{stat} \pm 0.009^{syst}$$

S. Stepanyan *at al.*, PRL **87** (2001) 182002

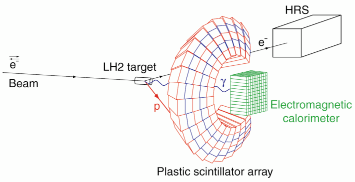
380+ citations

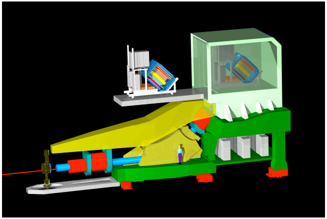


$$A_{UL} \propto F_1 \tilde{\mathcal{H}} + \xi G_M \left(\mathcal{H} + \frac{\xi}{1+\xi} \mathcal{E} \right) - \cdots$$

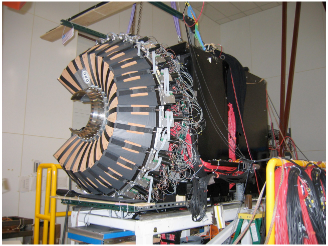


Scaling tests of $\Delta\sigma_{\text{DVCS}}$ E00-110

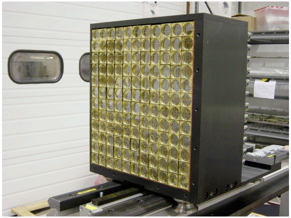




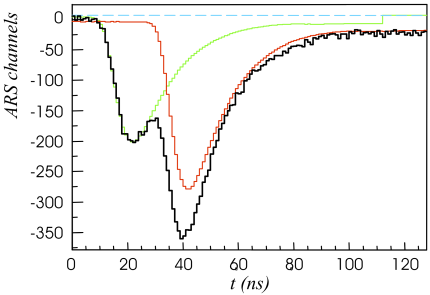
100-channel scintillator array



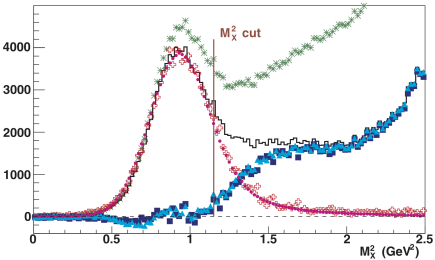
132-block PbF_2 electromagnetic calorimeter



Scaling tests of $\Delta\sigma_{DVCS}$ **E00-110**



Analog Ring Sampler
Quasi-continuous scan of amplitude
128 samples 1 GHz
Included in trigger LOT
Separated pile-up

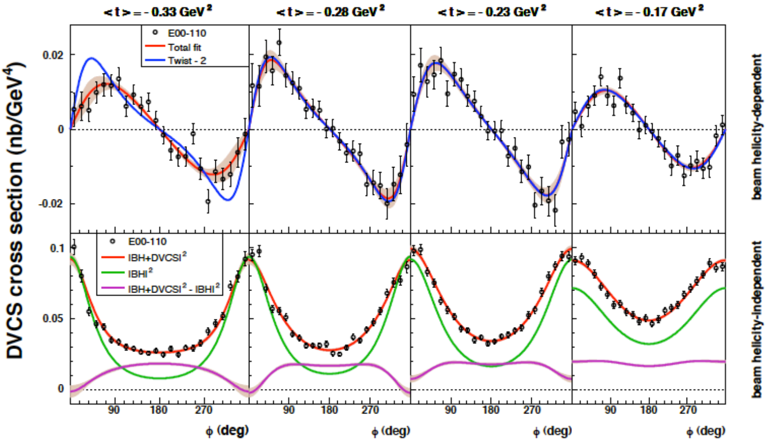


Missing-mass very clean
Inelastic background under control

Scaling tests of $\Delta\sigma_{\mathrm{DVCS}}$

E00-110

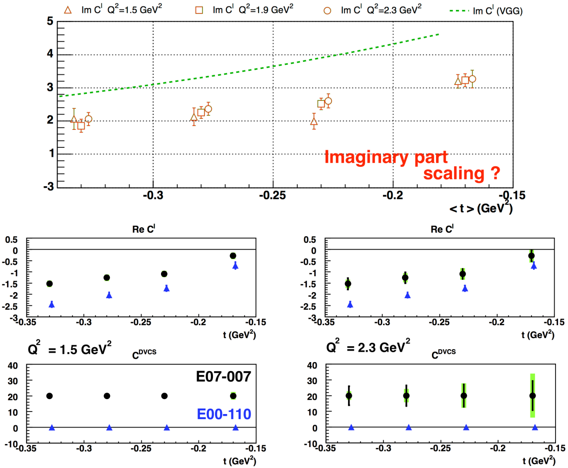
$$F_1\mathcal{H} + \xi G_M\tilde{\mathcal{H}} - F_2\frac{t}{4M^2}\mathcal{E} + \cdots$$



C. Muñoz *et al.*, PRL **97** (2006) 262002
High precision in a narrow kinematical range

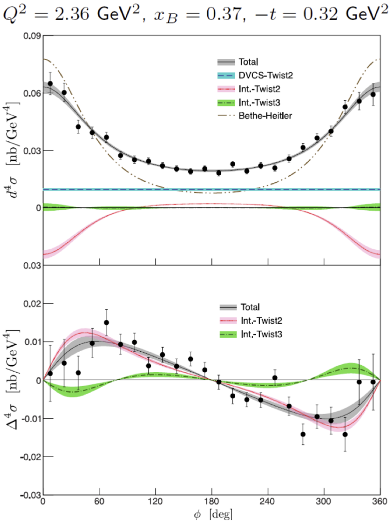
Separation of $\mathcal{I}$ and DVCS^2 E00-110/E07-007

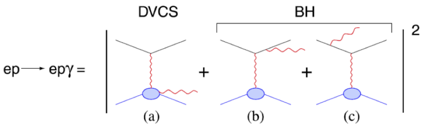
$$F_1\mathcal{H} + \xi G_M\tilde{\mathcal{H}} - F_2\frac{t}{4M^2}\mathcal{E} + \cdots$$



High precision in a narrow kinematical range

Hall A re-analysis with improved twist-3





$$d^4\sigma = \mathcal{T}_{\text{BH}}^2 + \mathcal{T}_{\text{BH}}\mathcal{R}e(\mathcal{T}_{\text{DVCS}}) + \mathcal{T}_{\text{DVCS}}^2$$

$$\mathcal{R}e(\mathcal{T}_{\text{DVCS}}) \sim c_0^{\mathcal{I}} + c_1^{\mathcal{I}}\cos\phi + c_2^{\mathcal{I}}\cos 2\phi$$

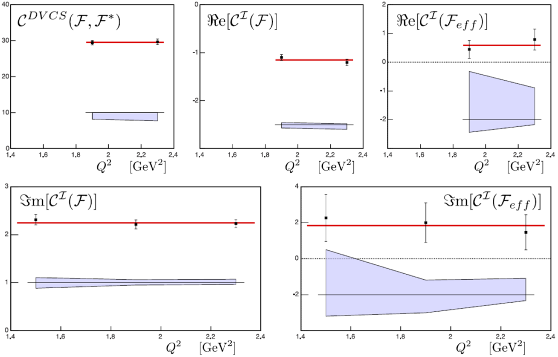
$$\mathcal{T}_{\text{DVCS}}^2 \sim c_0^{\text{DVCS}} + c_1^{\text{DVCS}}\cos\phi$$

$$\Delta^4\sigma = \frac{d^4\overrightarrow{\sigma} - d^4\overleftarrow{\sigma}}{2} = \mathcal{I}m(\mathcal{T}_{\text{DVCS}})$$

$$\mathcal{I}m(\mathcal{T}_{\text{DVCS}}) \sim s_1^{\mathcal{I}}\sin\phi + s_2^{\mathcal{I}}\sin 2\phi$$

M. Defurne *et al* PRC **92** (2015) 055202

Hall A re-analysis with improved twist-3



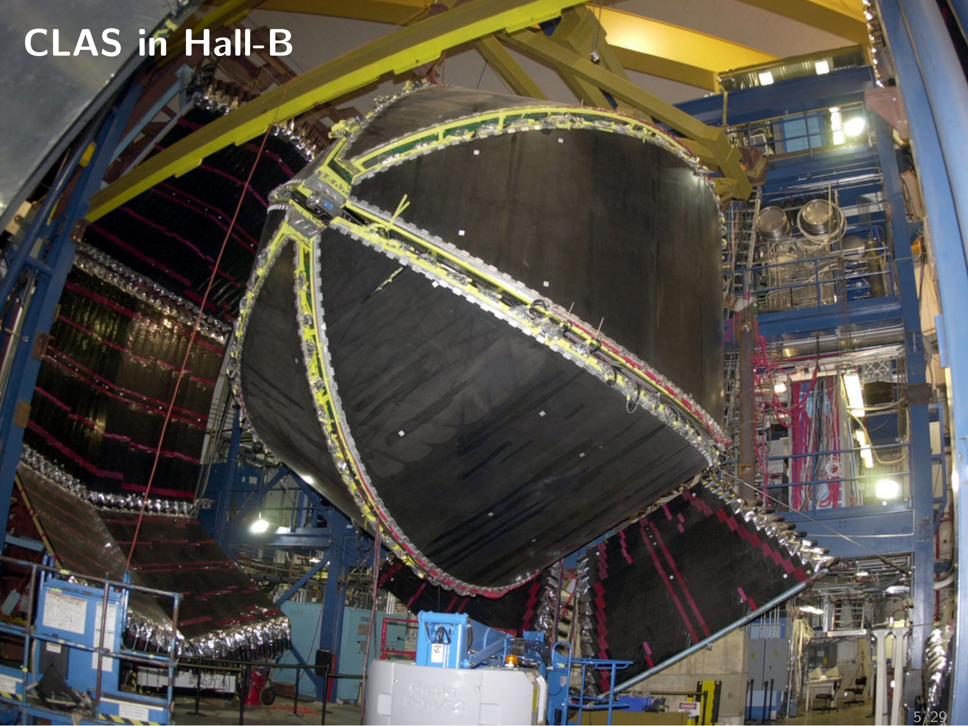
No evidence for Q^2 dependence

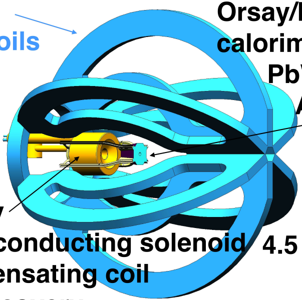
leading twist dominance
handbag diagram

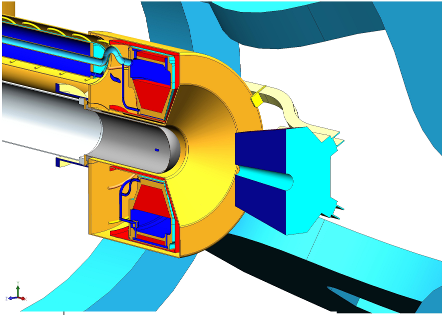
limited Q^2 lever arm

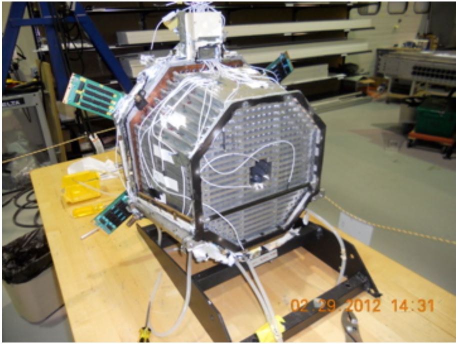
M. Defurne *et al* PR**C 92** (2015) 055202

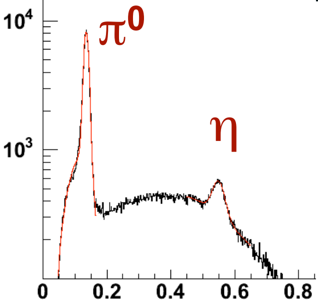
CLAS in Hall-B





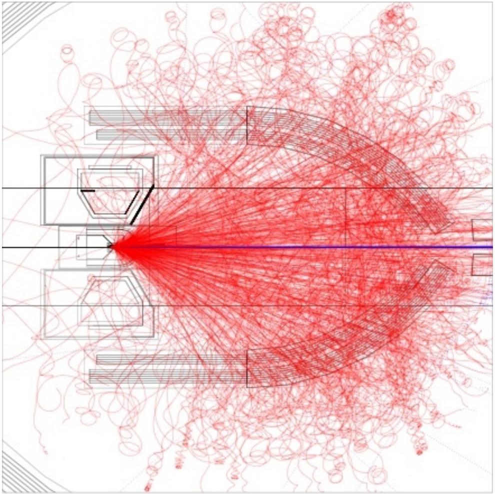




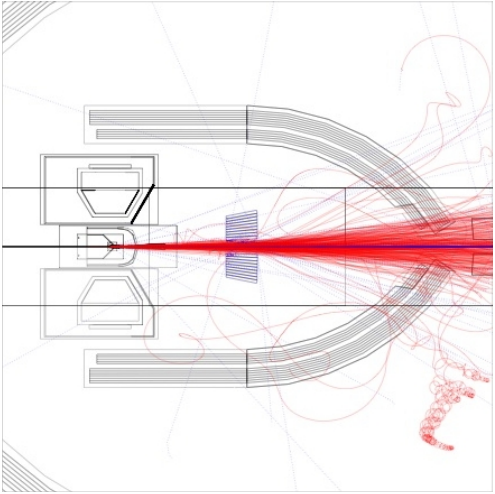


$$M_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}\left(1-\cos\theta_{\gamma\gamma}\right)}$$

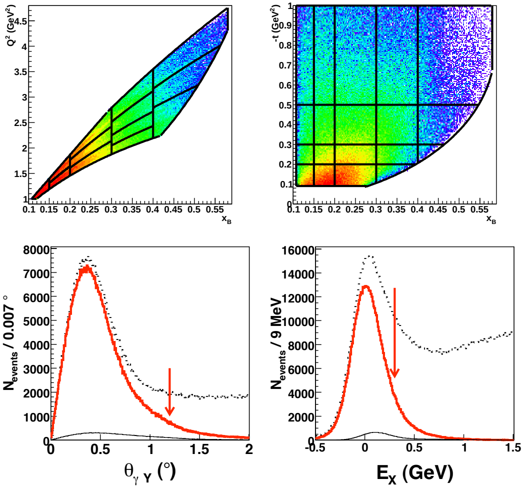
Solenoid and Inner Calorimeter



Solenoid and Inner Calorimeter



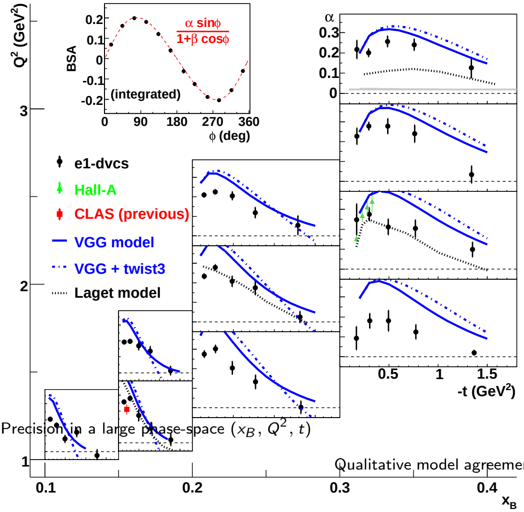
Flavor of analysis



- kinematical coverage
- exclusivity cuts
- π^0 subtraction

CLAS proton Beam Spin Asymmetry E01-113

$$F_1\mathcal{H} + \xi G_M\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$$

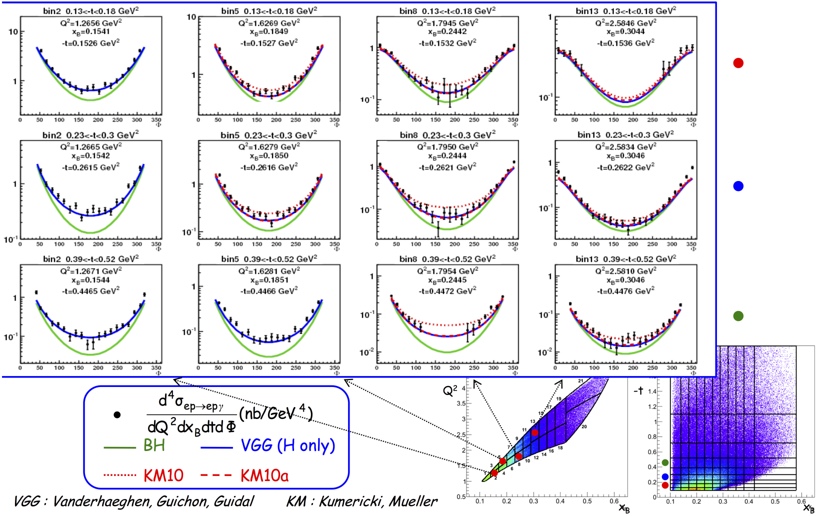


Precision in a large phase-space (x_B, Q^2, t)

Qualitative model agreement, quantitative constraints on parameters

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

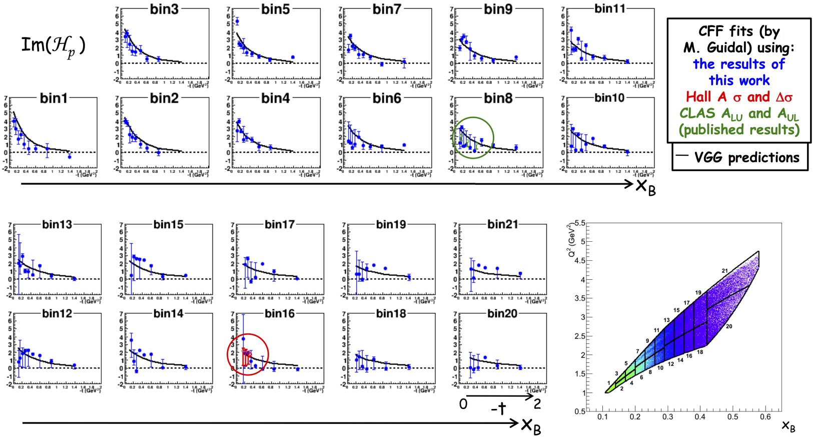
Unpolarized Cross-Sections E01-113



VGG : Vanderhaeghen, Guichon, Guidal *KM : Kumericki, Mueller*

H.-S. Jo *et al* PRL**115** (2015) 212003

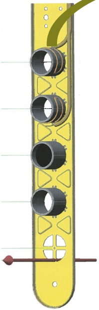
Compton Form Factors E01-113



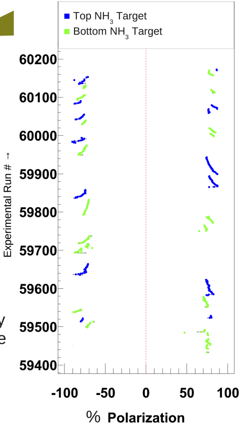
The t-slope becomes flatter with increasing x_B:
valence quarks (higher x_B) at the center of the nucleon and sea quarks (small x_B) at its periphery

H.-S. Jo *et al* PRL**115** (2015) 212003

NMR Measurement



- $^{14}NH_3$ target material
- Cooled to ~ 1 Kelvin using evaporative cooling on LHe
- Surrounded by a 5 Tesla superconducting magnet
- Continuously polarized using Dynamic Nuclear Polarization (DNP)
- Polarization during the experiment was monitored by Nuclear Magnetic Resonance (NMR) measurement →



- The target insert (shown above left) held 4 targets for use in the eg1-dvcs experiment: 2 polarized NH_3 targets, 1 carbon target, and 1 empty target cup.

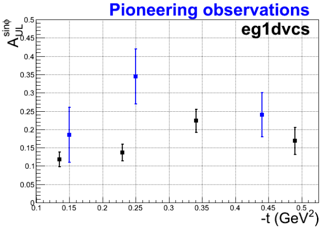
- Average achieved proton longitudinal polarization ~ 85%.

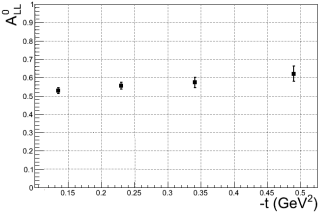
CLAS proton Target Spin Asymmetry **E05-114**

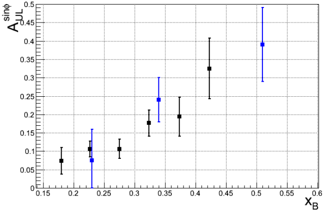
Ten fold improvement in statistics

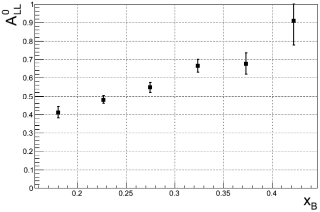
$$F_1 \tilde{\mathcal{H}} + \xi G_M \left(\mathcal{H} + \frac{\xi}{1+\xi} \mathcal{E} \right)$$

$$A_{UL} \propto F_1 \, \mathcal{I}\mathrm{m} \, \tilde{\mathcal{H}} \qquad A_{LL} \propto F_1 \, \mathcal{R}\mathrm{e} \, \tilde{\mathcal{H}}$$

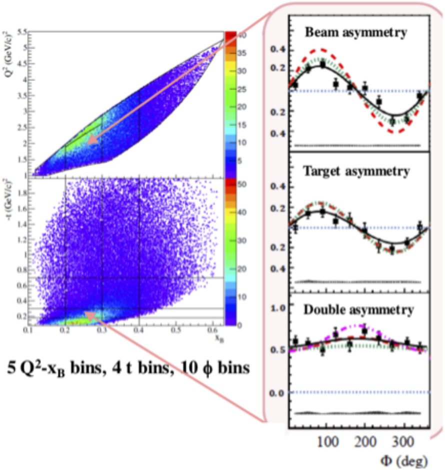


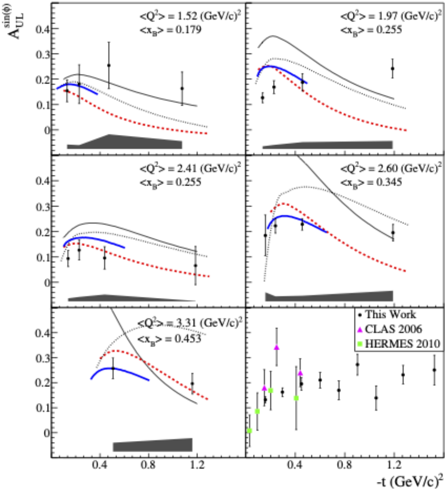






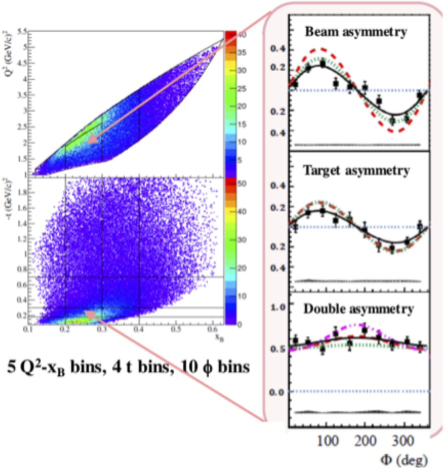
CLAS proton Target Spin Asymmetry E05-114



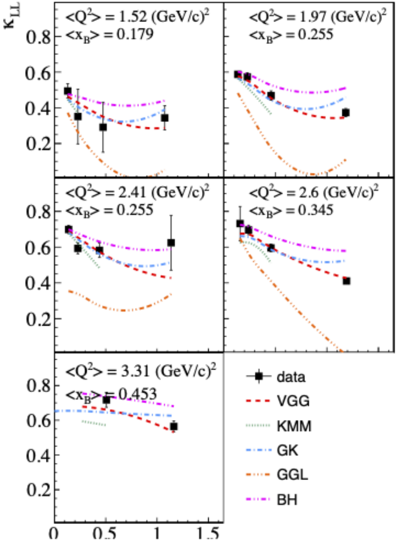


E. Seder *et al* PRL **114** (2015) 032001

CLAS proton Target Spin Asymmetry E05-114



5 Q^2-x_B bins, 4 t bins, 10 ϕ bins



S. Pisano *et al* PR**D 91** (2015) 052014

Extraction results

KMa/b : Kumerički and Müller, Nucl. Phys. B841 (2010)
Guidal : Phys.Lett. B689 (2010) 156
Phys.Lett. B693 (2010) 17
Moutarde : Phys. Rev. D79, 094021 (2009)

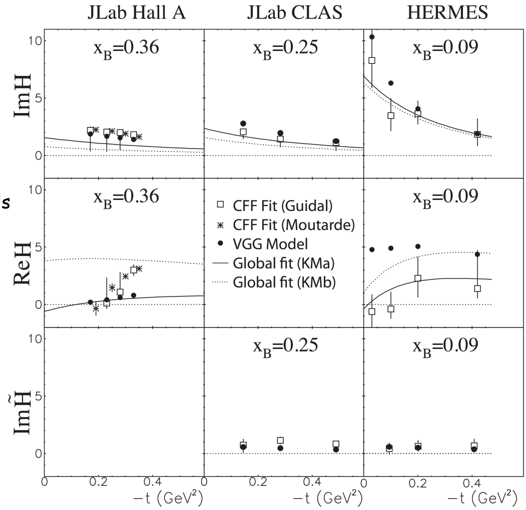
Local fits of DVCS :
fits of Re and Im parts of Compton Form Factors

Global fits of DVCS :
fits to parametrized GPD models

Findings :
Slope of ImH ↗ when x_B ↘

Accurate cross section data drive global fits to use more than just GPD H

Im$\tilde{H}$ seems to have weak t and x_B dependence

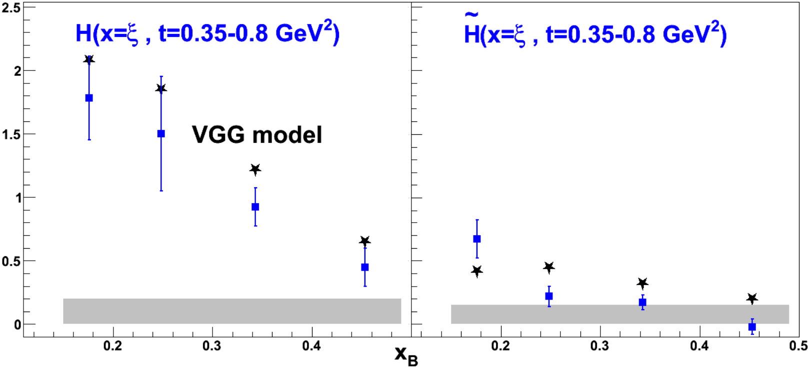


Model independent extraction

Using only A_{LU} and A_{UL}

Extraction with :

- Results from eg1dvcs A_{UL}
- Polarized cross-section from e1dvcs $\Delta\sigma$

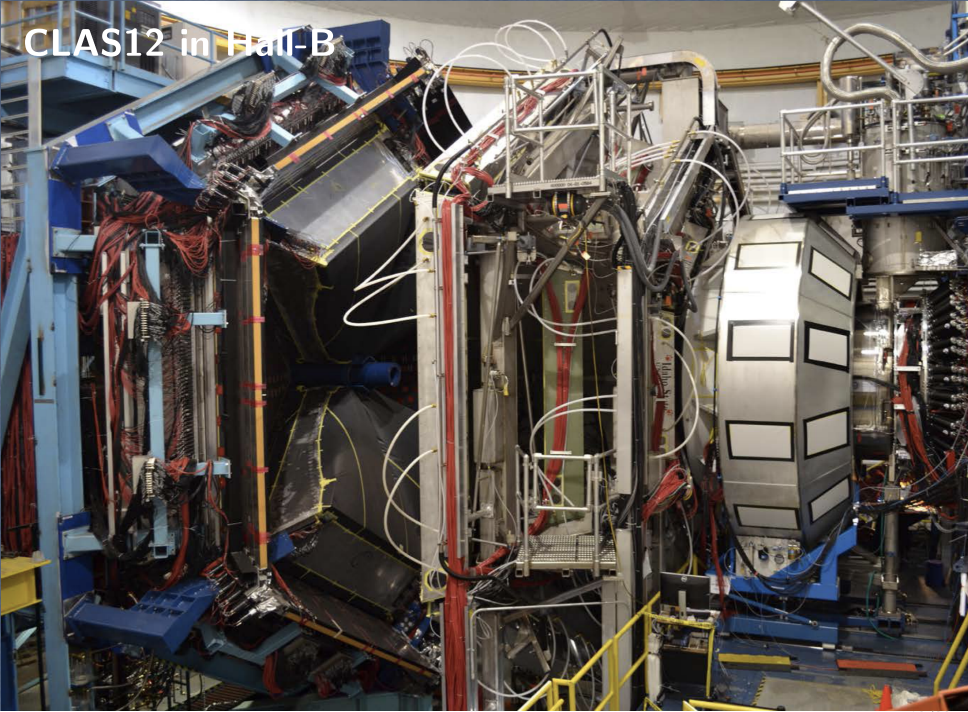


GPD dependencies versus x_B mirror their respective ordinary PDFs

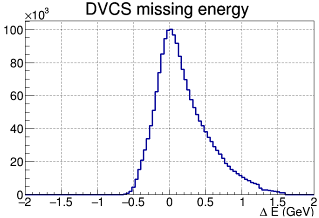
$\tilde{H}$ and $H \leftrightarrow \Delta q(x)$ and $q(x)$

Drop of $\Delta q(x)$ at low x_B will be seen at 12 GeV

CLAS12 in Hall-B



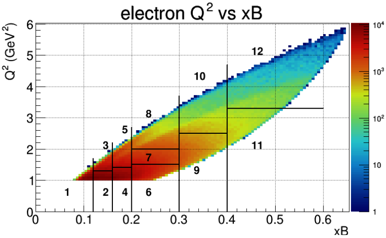
CLAS12 DVCS Analysis Strategy E12-16-010B

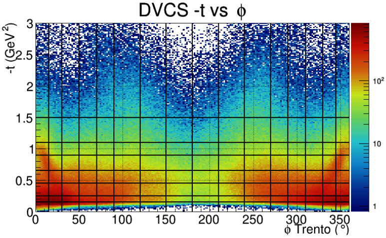


Detect all particles e, p, γ
Exclusivity from 4-momentum conservation

Background from asymmetric π^0 decay
Subtracted from symmetric decay data

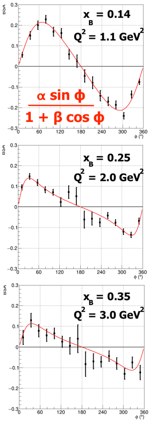
Extract A_{LU} and σ in bins of (x_B, Q^2, t)

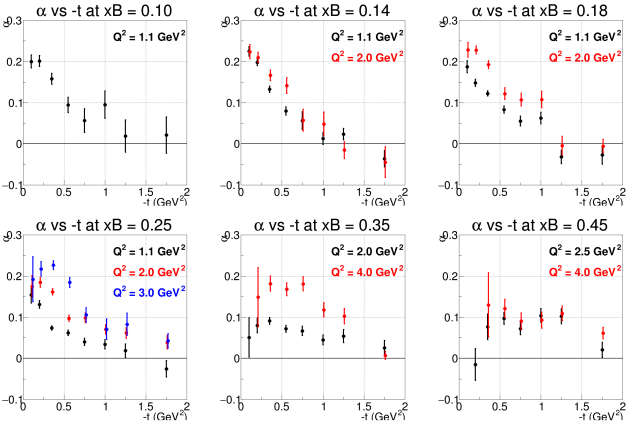




Need two beam energies in addition to RGA 10.6 GeV
Separate intereference $\mathcal{M}_{\text{BH}} \cdot \mathcal{M}_{\text{DVCS}} \sim \frac{1}{y^3}$ from $|\mathcal{M}_{\text{DVCS}}|^2 \sim \frac{1}{y^2}$

CLAS12 DVCS Preliminary Results E12-16-010B





Flattening of the $\alpha(t)$ slope with $x_B \implies$ change in nucleon radius

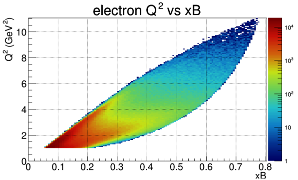
Dispersion relation gives $\beta \sim \mathcal{R}e\mathcal{M}(\xi)$ from $\alpha \sim \mathcal{I}m\mathcal{M}(\xi)$ and subtraction term $D(t)$

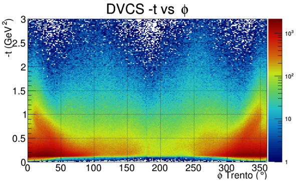
Coverage at large ξ crucial to minimize systematics uncertainties from extrapolation

CLAS12 DVCS Preliminary Results E12-06-009

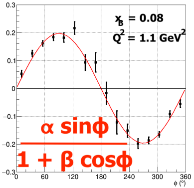
10.6 GeV
4M exclusive events

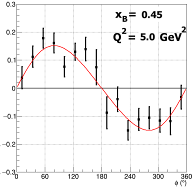
Up to $Q^2 \approx 11$ GeV^2
and $x_B \approx 0.75$

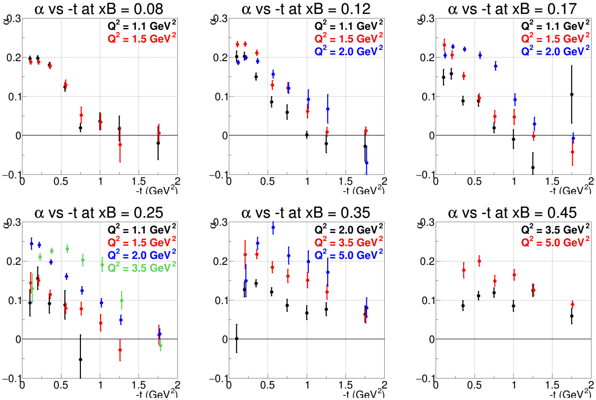




Fit $A_{LU}(\phi)$ vs (x_B, Q^2, t)







CLAS12 Extraction of gluonic profiles E12-12-007

Analyze decay $\phi \to K^+K^-$
All particles detected

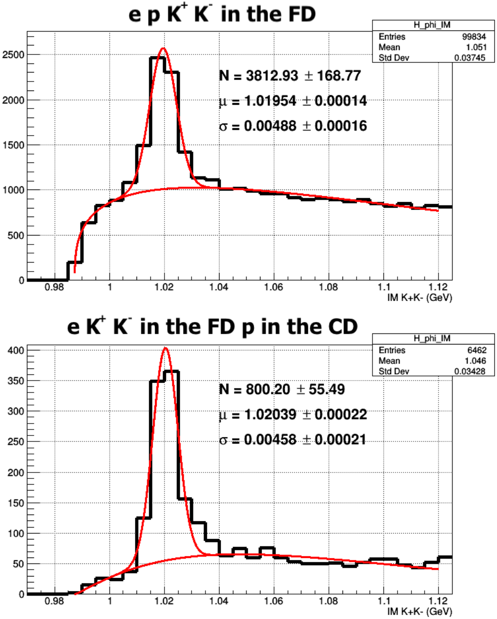
$$\frac{d\sigma_L}{dt} \sim (1-\xi^2)\,\mathcal{H}_g^2 + \cdots$$

σ_L t-slopes vs x_B

$$A_{LU}^{\sin\phi} \sim \mathcal{I}m\left[\mathcal{H}_T\mathcal{E} - \mathcal{H}\mathcal{E}_T\right]$$

A_{LU} vs W

Next steps:
Analyze one particle missing



CLAS12 Exclusive 2 and 3 πs

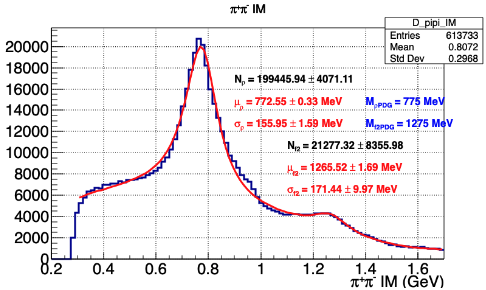
Pions detected in the FD
Protons in the FD or CD

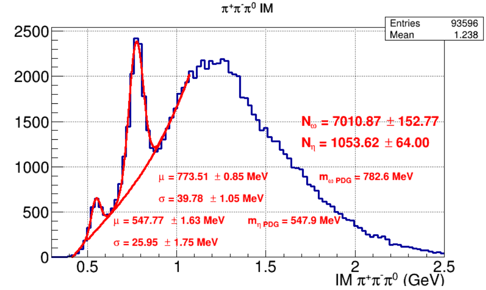
Angular decay analysis to test SCHC at 10.6 GeV

L/T Rosenbluth separation

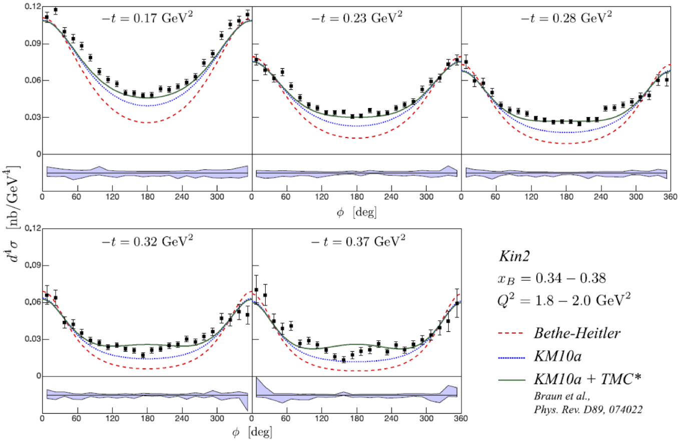
Exclusive ρ^0 electroproduction on the proton
Morrow *et al* Eur.Phys.J. **A39** (2009) 5-31

Deeply Virtual ω Electroproduction
Morand *et al* Eur.Phys.J.**A24** (2005) 445-458





Target mass corrections at JLab



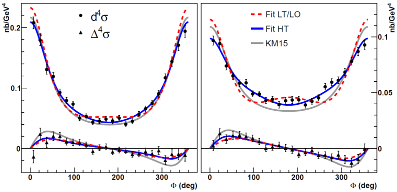
Target-mass corrections (TMC): $\sim \mathcal{O}(M^2/Q^2)$ and $\sim \mathcal{O}(t/Q^2)$

Braun, Manashov, Mueller and Pirnay (2014)

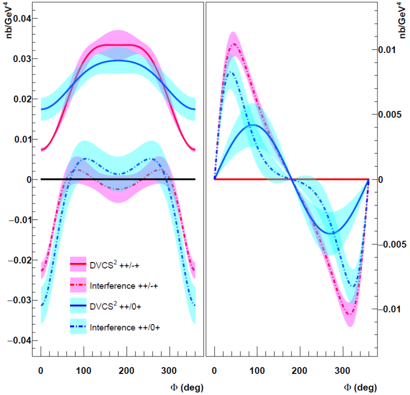
Rosenbluth separation

Pure DVCS process interferes with Bethe-Heitler process at the amplitude level
Separate interference and squared amplitudes using beam energy dependence

Fixed $(x_B, Q^2, -t)$ ϕ dependences



LT / LO incompatible with energy dependence



M. Defurne *et al* Nature Communication **8** (2017) 1408

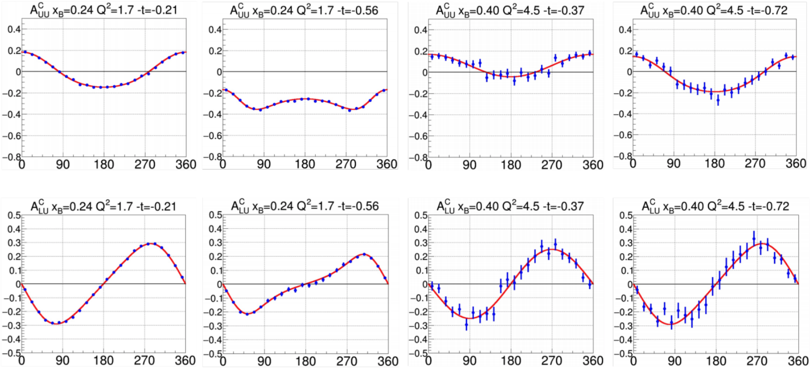
Full 12 GeV dataset will expand the Q^2 lever arm
Discriminate between Higher Twist and Higher Order scenarios

DVCS with a Polarized Positron beam

PEPPo production injecting 60 MeV **100 nA positron polarized at 60%**

(PEPPo Collaboration) D. Abbott *et al.* , **PRL**116 (2016) 214801 ; L. Cardman *et al.* AIP CP 1970 (2018) 050001

Proposal 100 days (80+20) at $\mathcal{L} = 0.6 \times 10^{35}$ cm^{-2}s^{-1}

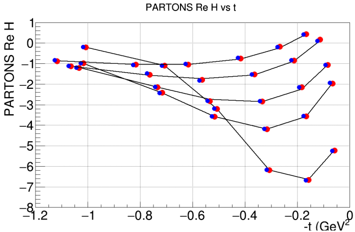


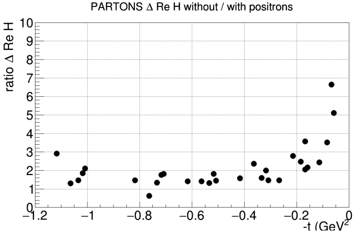
Impact of the CLAS12 Positron data

Global analysis of CLAS12 program observables $\{\sigma_{UU}, A_{LU}, A_{UL}, A_{LL}, A^{C}_{UU}, A^{C}_{LU}\}$

unpolarized beam charge asymmetry $\mathbf{A^{C}_{UU}}$ sensitive to the amplitude **real part**
polarized beam charge asymmetry $\mathbf{A^{C}_{UU}}$ sensitive to the amplitude **imaginary part**

Fitting $\{\mathcal{H}, \tilde{\mathcal{H}}\}$ assuming model values for $\{\mathcal{E}, \tilde{\mathcal{E}}\}$





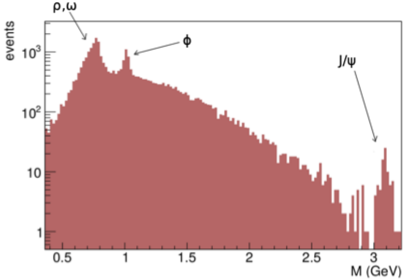
Improvement of the **statistical** and **systematical** uncertainties

Model independent separation of the Interference with BH and DVCS^2

Timelike Compton Scattering results

Test universality of GPDs
Access to the real part of the amplitude and the D-term in particular

Analysis: $ep \rightarrow (e')e^+e^-p$

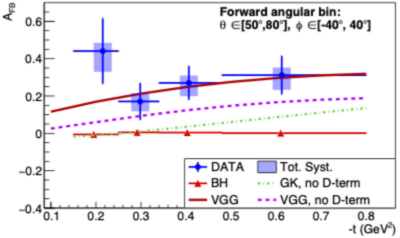


Forward Backward asymmetry:
different parities of BH and TCS

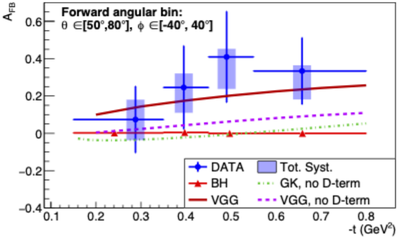
First clear TCS measurement

P. Chatagnon *et al* PRL **127** (2021) 262501

$< M >= 1.8$ GeV; $< E_\gamma >= 7.24$ GeV



$< M >= 2.25$ GeV; $< E_\gamma >= 8.13$ GeV



Summary Outlook

- From pioneering measurements to precision era
- Nucleon tomography: distributions of electric charge, mass, forces $\cdots$
- Complementarity between results from different Halls
- Complementarity with other facilities (including past and future)
- JLab upgrades: positron source, 24 GeV

- Due to time and personal bias, many ommissions:
  Processes on neutron
  Processes on nuclear target
  Chiral odd GPDs and exclusive pion production

- Many results expected from 12 GeV program!