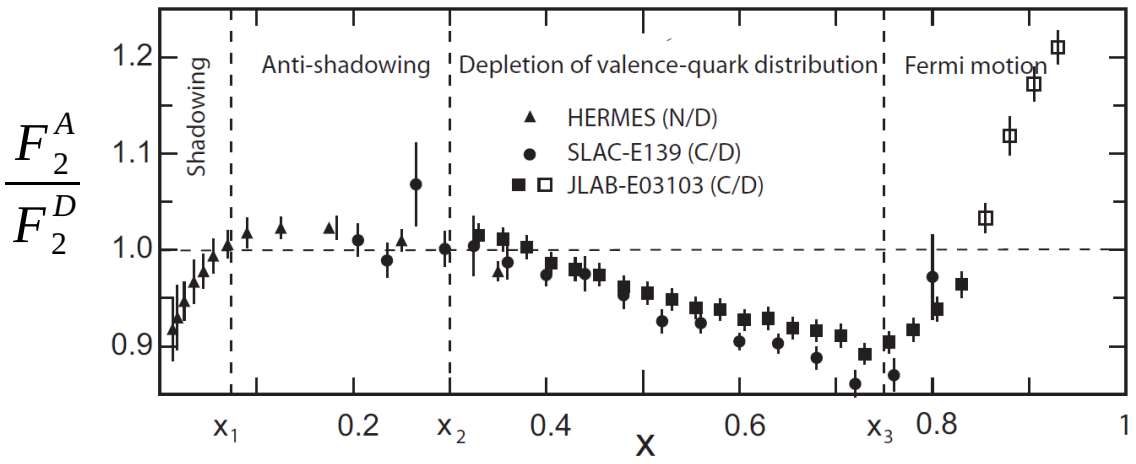
Partonic Structure of Light Nuclei

M. Hattawy

- **Physics motivations**
- **Recent results from CLAS**
- **Proposed measurements with CLAS12**

INT 17-3 , Thursday, August 31st 2017

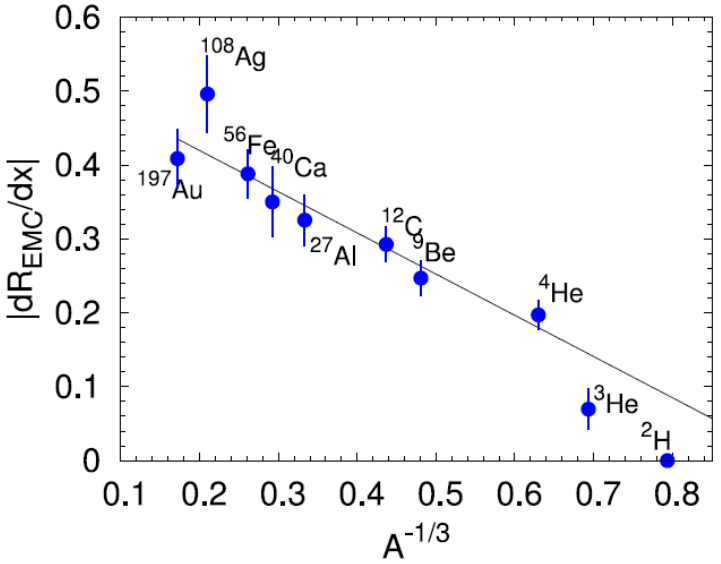
EMC Effect



[K. Rith, arXiv:1402.5000 [hep-ph], 2014]

EMC effect: the modification of the PDF f_2 as a function of x [0.3, 0.75] carried by the parton.

[J. Arrington et al., Phys. Rev. C 86 (2012) 065204]



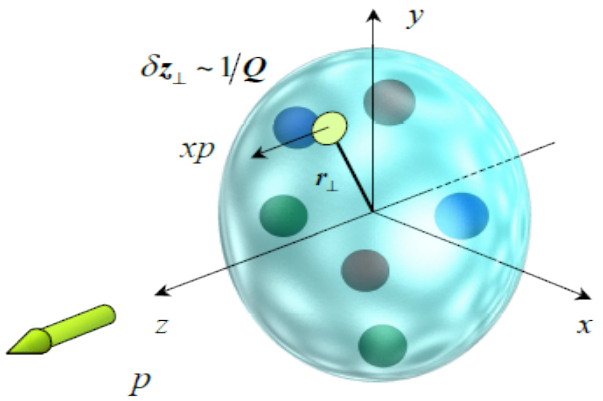
- Precise measurements at CERN, SLAC and JLab
  → Links with the nuclear properties, i.e. mass & density

- The origin of the EMC effect is still not fully understood, but possible explanations:
  → Modifications of the nucleons themselves
  → Effect of non-nucleonic degrees of freedom, e.g. pions exchange
  → Modifications from multi-nucleon effects (binding, N-N correlations, etc...)

- Clear explanations may arise from measuring the nuclear modifications via measuring the Generalized Parton Distributions.

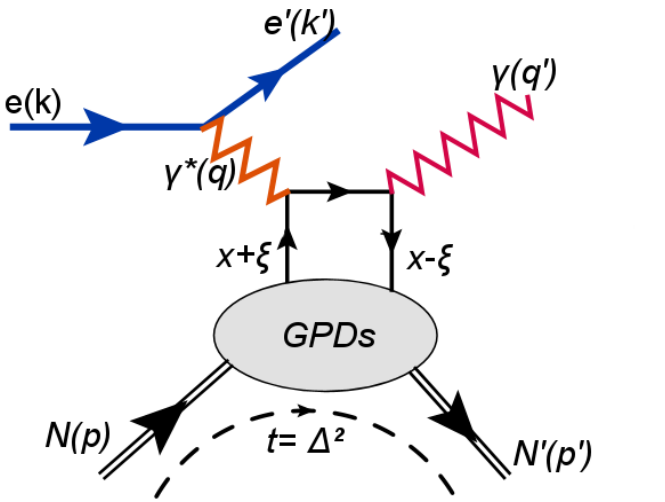
Generalized Parton Distributions

- **Contain information on:**
  - → Correlation between quarks and anti-quarks
  - → Correlation between longitudinal momentum and transverse spatial position of partons



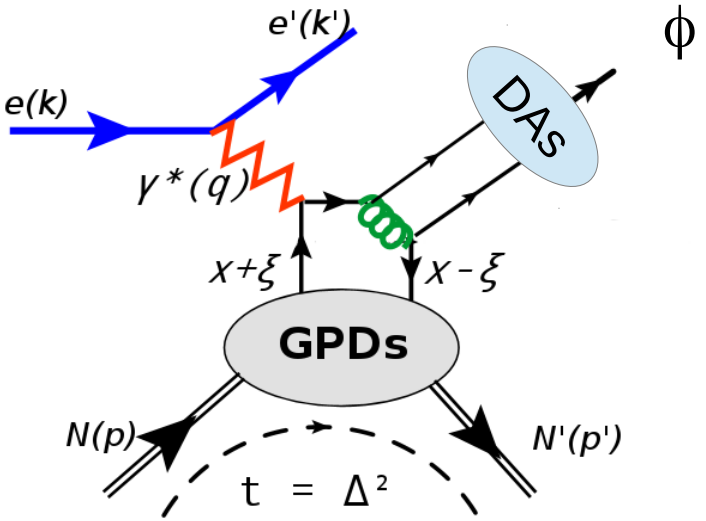
- **Can be accessed via exclusive processes:**

At leading twist and leading order α_s,



Deeply Virtual Compton Scattering

Access charge profiles



Deeply Virtual Meson Production

Access gluon profiles

$$GPD(x,\xi,t)$$

$$\xi \simeq x_B/(2-x_B)$$

$$x_B = Q^2/2\,p.q$$

$$t = (p-p')^2$$

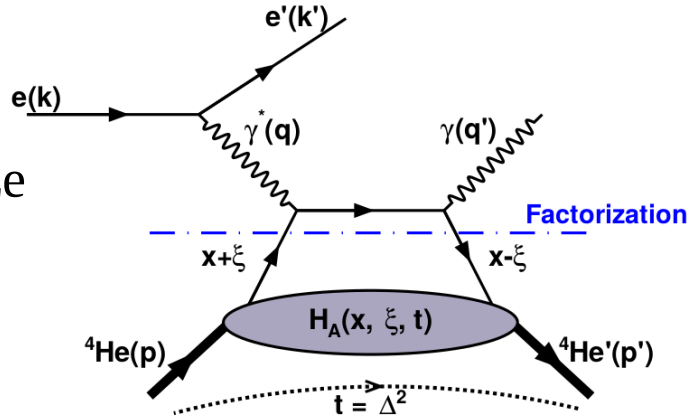
DVCS off Nuclei

Two DVCS channels are accessible with nuclear targets:

◊ **Coherent DVCS: $e^- A \rightarrow e^- A \gamma$**

→ Study the partonic structure of the nucleus.

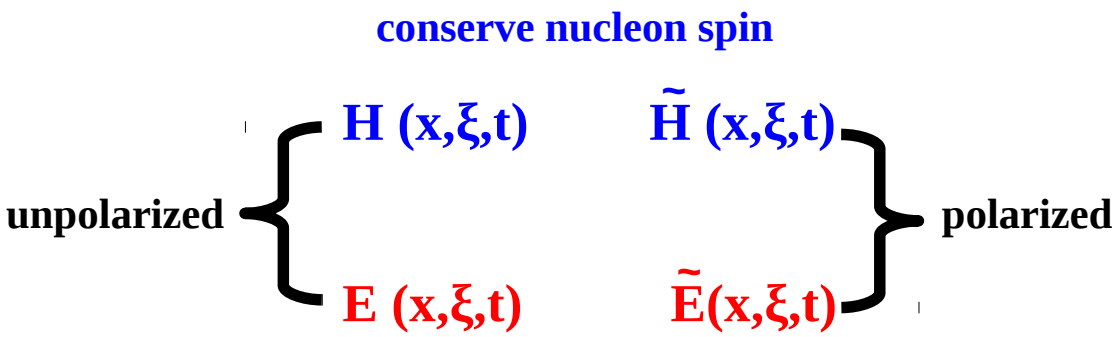
→ One chiral-even GPD ($\mathbf{H_A(x,\xi,t)}$) is needed to parametrize the structure of the spinless nuclei (^{4}He, ^{12}C, ^{16}O, ...).

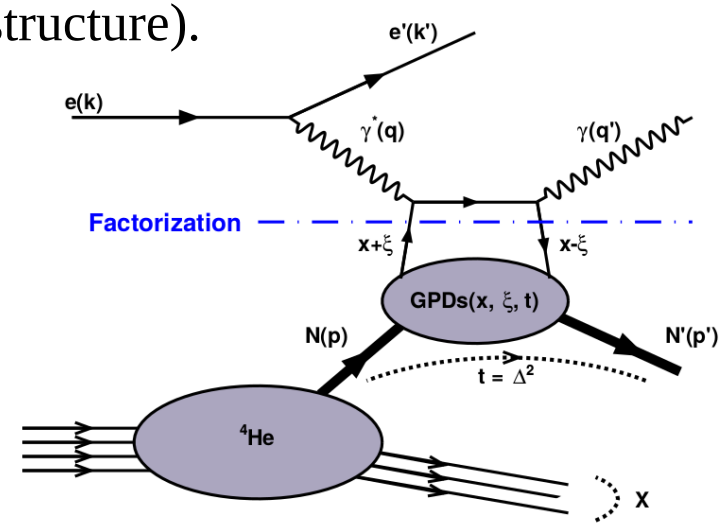


◊ **Incoherent DVCS: $e^- A \rightarrow e^- N \gamma$ X**

→ The nucleus breaks and the DVCS takes place on a nucleon.

→ Study the partonic structure of the bound nucleons (4 chiral-even GPDs are needed to parametrize their structure).





Nuclear Spin-Zero DVCS Observables

The GPD H_A parametrizes the structure of the spinless nuclei (^{4}He,^{12}C …)

$$\mathcal{H}_A(\xi,t) = Re(\mathcal{H}_A(\xi,t)) - i\pi Im(\mathcal{H}_A(\xi,t))$$

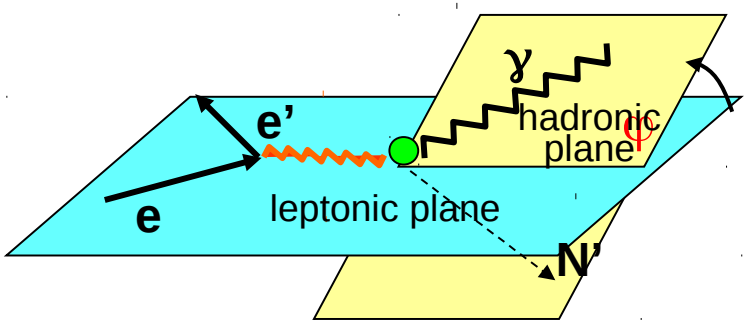
$$Im(\mathcal{H}_A(\xi,t)) = H_A(\xi,\xi,t) - H_A(-\xi,\xi,t)$$

$$Re(\mathcal{H}_A(\xi,t)) = \mathcal{P}\int_0^1 dx[H_A(x,\xi,t) - H_A(-x,\xi,t)]C^+(x,\xi)$$

Quark propagator

$$C^+(x,\xi) = \frac{1}{x-\xi} + \frac{1}{x+\xi}$$

→ Beam-spin asymmetry ($A_{LU}(\varphi)$) : (+/- beam helicity)



$$A_{LU}(\phi) = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$$

$$= \frac{x_A(1+\epsilon^2)^2}{y} s_1^{INT}\sin(\phi) \Big/ \left[\sum_{n=0}^{n=2} c_n^{BH}\cos(n\phi) + \right.$$

$$\left. \frac{x_A^2 t(1+\epsilon^2)^2}{Q^2} P_1(\phi)P_2(\phi)\, c_0^{DVCS} + \frac{x_A(1+\epsilon^2)^2}{y}\sum_{n=0}^{n=1} c_n^{INT}\cos(n\phi)\right]$$

Theoretical Predictions of the EMC in ^{4}He

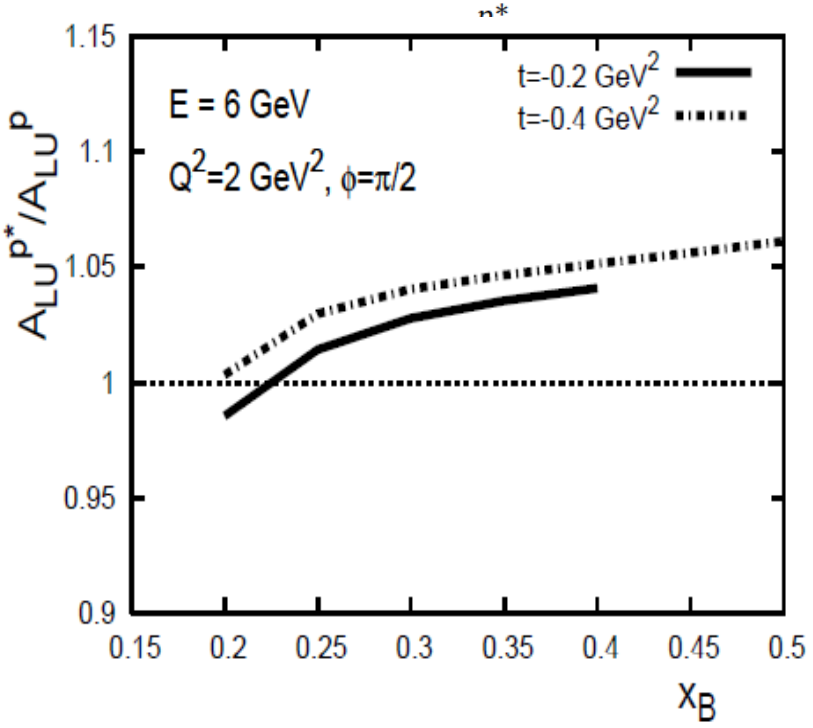
On-shell calculations:

(1) Impulse approximation

$GPD^{4He}(x,\xi,t) = \Sigma$ (free p and n GPDs)*$F_{4He}(t)$

(2) Medium modifications:

$$H^{q/p^*}(x,\xi,t,Q^2) = \frac{F_1^{p^*}(t)}{F_1^{p}(t)} H^{q}(x,\xi,t,Q^2),$$



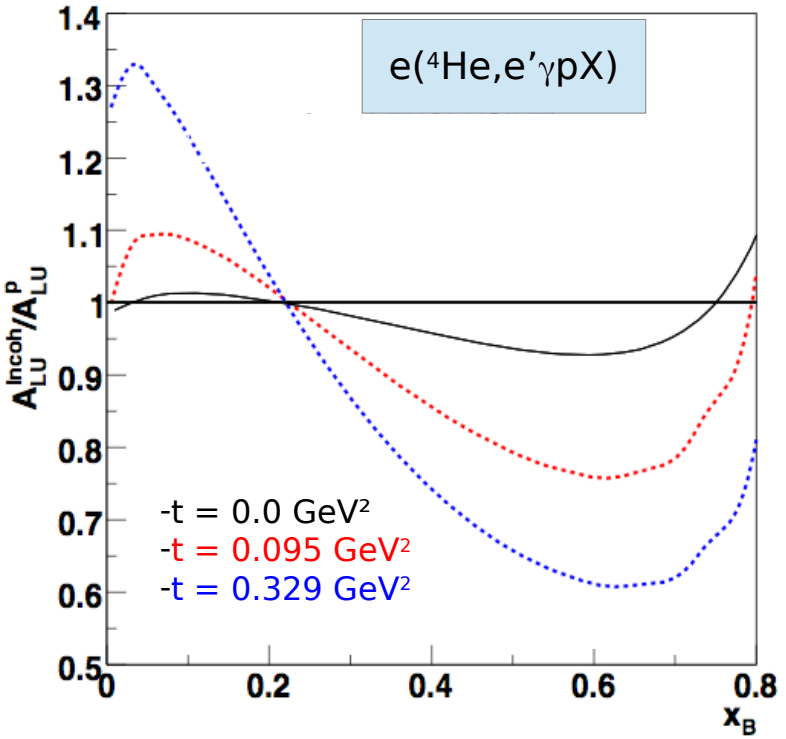
[V. Guzey, A. W. Thomas, K. Tsushima, PRC 79 (2009) 055205]

Off-shell calculations:

Nucleus = bound nucleons + nuclear binding effects

$$H^A(x,\xi,t) = \sum_N \int \frac{d^2P_\perp dY}{2(2\pi)^3} \frac{1}{A-Y} \mathcal{A}\rho^A(P^2,P'^2) \times \sqrt{\frac{Y-\xi}{Y}} \left[H^N_{OFF}(\frac{x}{Y},\frac{\xi}{Y},P^2,t) - \frac{1}{4}\frac{(\xi/Y)^2}{1-\xi/Y} E^N_{OFF}(\frac{x}{Y},\frac{\xi}{Y},P^2,t) \right]$$

Nuclear spectral function



[S. Liuti, K.Taneja, PRC 72 (2005) 034902]

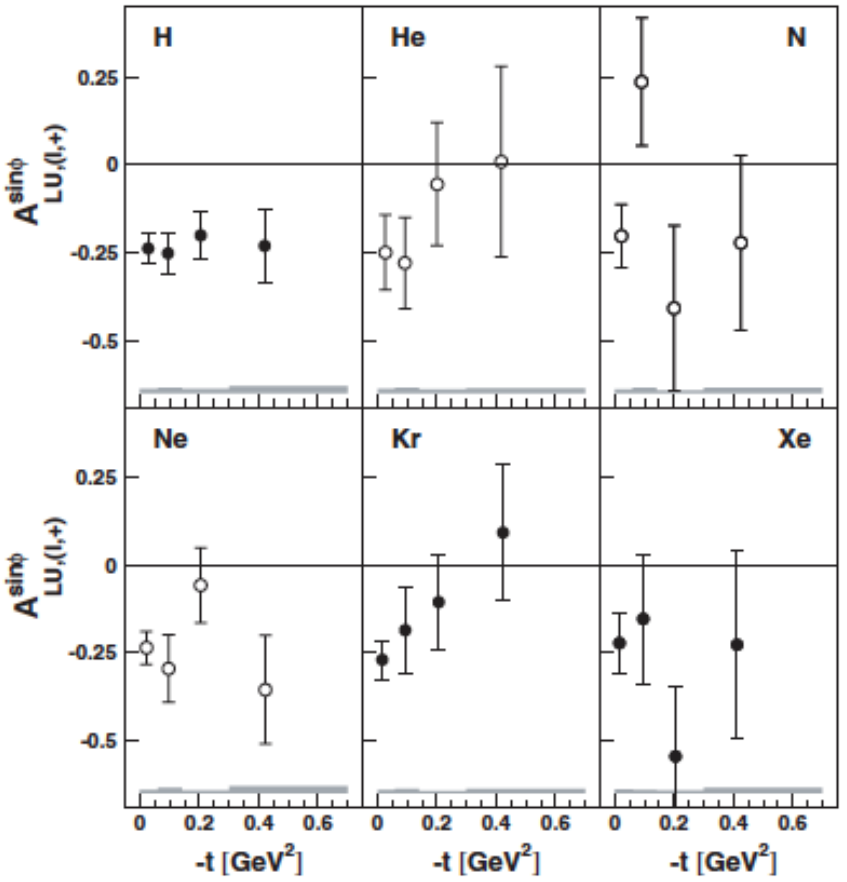
Nuclear DVCS Measurements: HERMES

- The exclusivity is ensured via cut on the missing mass of eγX final state configuration.

- Coherent and incoherent separation depending on -t, i.e. coherent rich at small -t.

- Conclusions from HERMES:
No nuclear-mass dependence has been observed.

$$A_{LU}^{sin} = \frac{1}{\pi}\int_0^{2\pi} d\phi \, \sin\phi \, A_{LU}(\phi)$$



[A. Airapetian, et al., Phys Rev. C 81 (2010) 035202]

In CLAS - E08-024, we measured EXCLUSIVELY the coherent and incoherent DVCS channels off ^{4}He

CLAS - E08-024 Experimental Setup

$$e^- \, {}^4He \rightarrow e^- \, ({}^4He/pX) \, \gamma$$

6 GeV,
L. polarized

Beam polarization (P_B) = 83%

- **CLAS:**
  - → Superconducting Torus magnet.
  - → 6 independent sectors:
    - → DCs track charged particles.
    - → CCs separate e^-/π^-.
    - → TOF Counters identify hadrons.
    - → ECs detect γ, e^- and n [8º,45º].

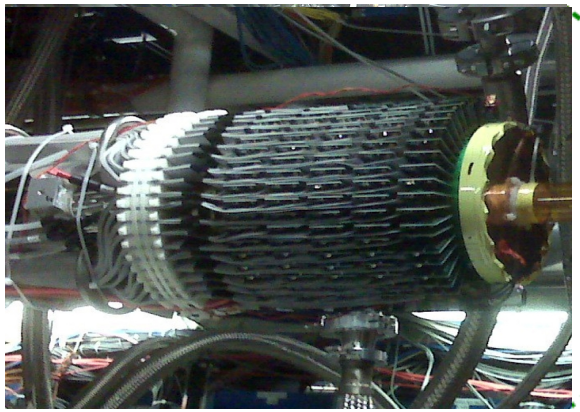
- **IC:** Improves γ detection acceptance [4º,14º].

- **RTPC:** Detects low energy nuclear recoils.

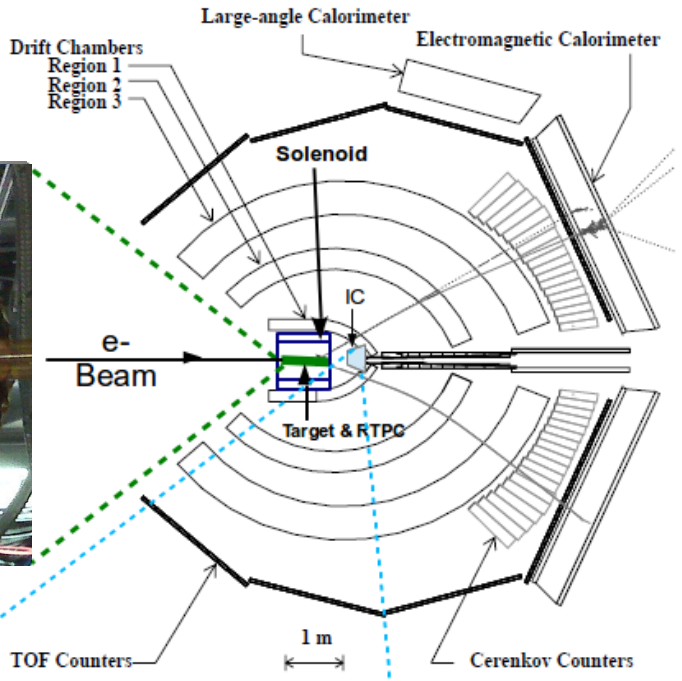
- **Solenoid:** - Shields the detectors from Møller electrons.
  - Enables tracking in the RTPC.

- **Target:** ^{4}He gas @ 6 atm, 293 K

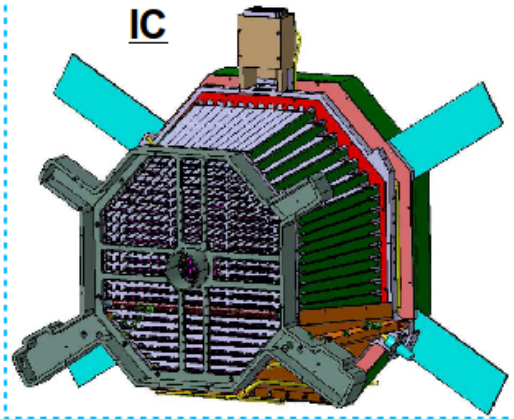
RTPC



CLAS



IC



Coherent DVCS Selection

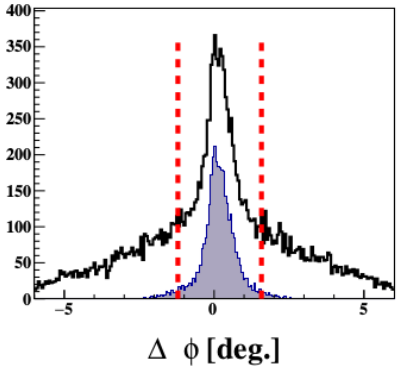
1. We select COHERENT events which have:

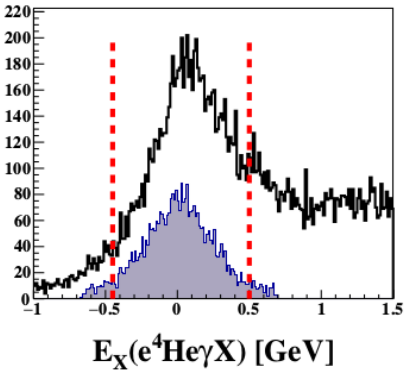
◊ Events with :
- Only one good electron in CLAS
- At least one high-energy photon (Eγ > 2 GeV) in IC
- Only one ^{4}He in RTPC (p ~ 250-400 MeV).

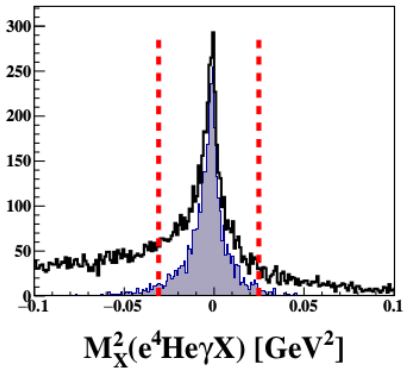
◊ The interaction occurs at the partonic level and applicability of the factorization on the DVCS handbag diagram (Q^2 > 1 GeV^2)

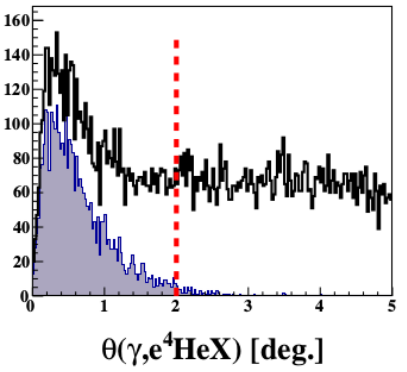
◊ Exclusivity cuts (3 sigmas).

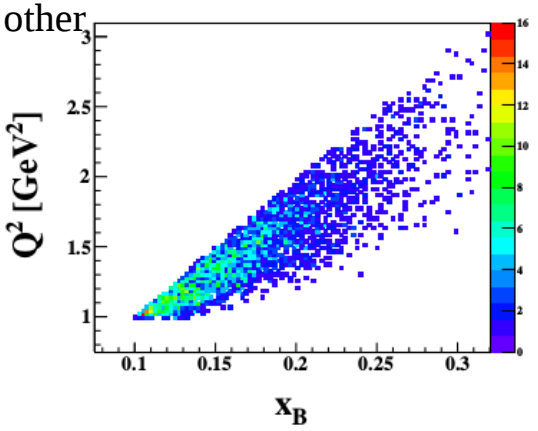
- In Black, coherent events before all exclusivity cuts.
- In shaded gray, coherent DVCS events which pass all the other exclusivity cuts except the one on the quantity itself.

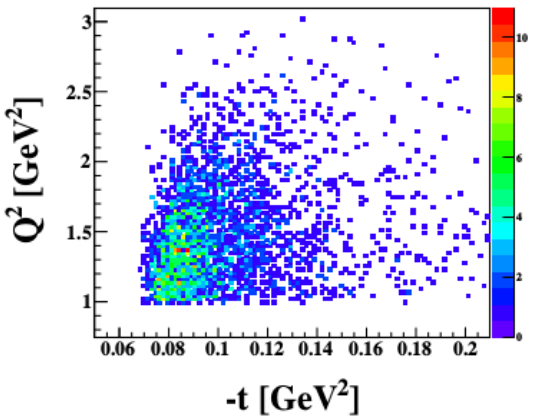










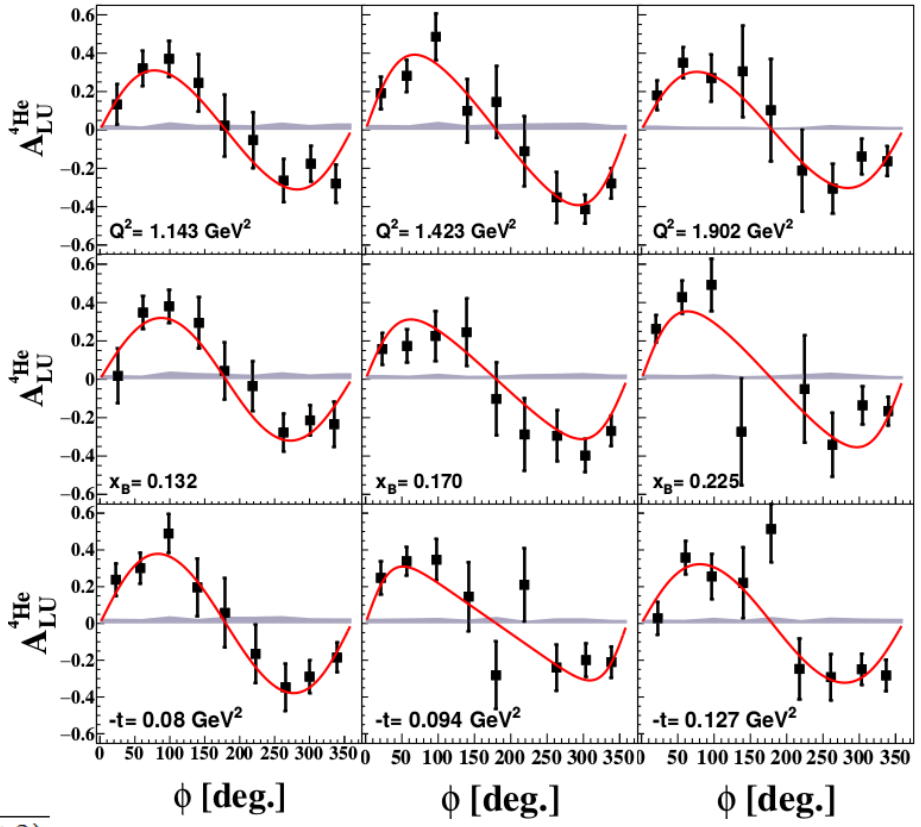


2. π^0 background subtraction based on data and simulation (contaminations ~ 2 - 4%)

Coherent Beam-Spin Asymmetry Fitting

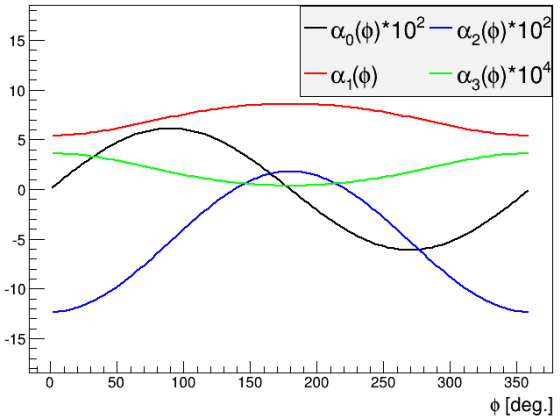
$$A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$$

- 2D bins due to limited statistics
- Uncertainities dominated by statictics
- Systematic uncertainities (~ 10 %) dominated by exclusivity cuts (~8 %) and large phi bining (~5 %)

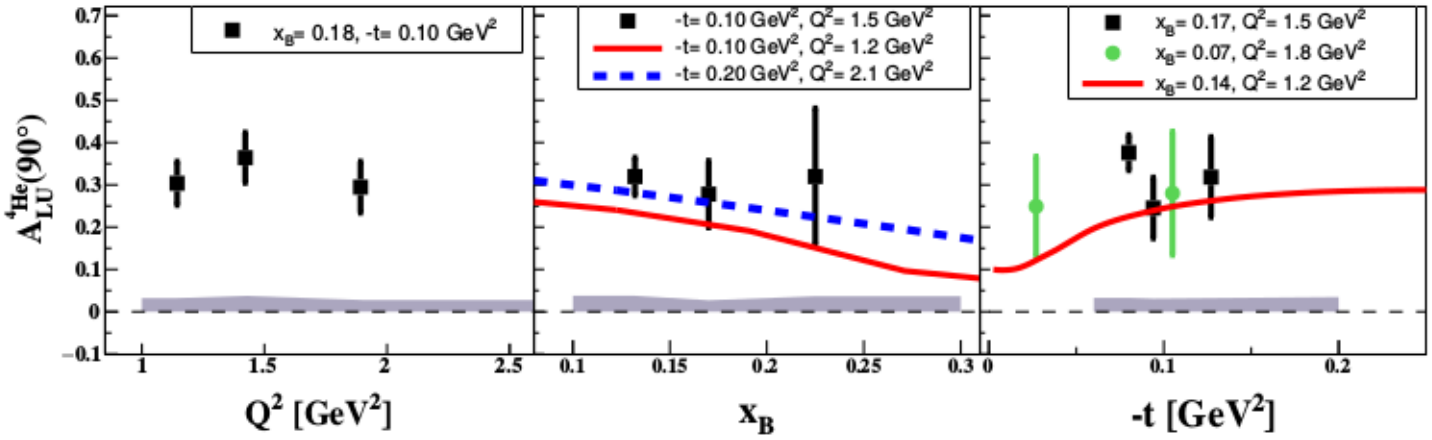


$$A_{LU}(\phi) = \frac{\alpha_0(\phi)\,\Im m(\mathcal{H}_A)}{\alpha_1(\phi) + \alpha_2(\phi)\,\Re e(\mathcal{H}_A) + \alpha_3(\phi)\left(\Re e(\mathcal{H}_A)^2 + \Im m(\mathcal{H}_A)^2\right)}$$

$$\begin{aligned}
\alpha_0(\phi) &= \frac{x_A(1+\varepsilon^2)^2}{y} S_{++}(1)\sin(\phi) \\
\alpha_1(\phi) &= c_0^{BH} + c_1^{BH}\cos(\phi) + c_2^{BH}\cos(2\phi) \\
\alpha_2(\phi) &= \frac{x_A(1+\varepsilon^2)^2}{y}\left(C_{++}(0) + C_{++}(1)cos(\phi)\right) \\
\alpha_3(\phi) &= \frac{x_A^2 t(1+\varepsilon^2)^2}{y}\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)\cdot 2\frac{2-2y+y^2+\frac{\varepsilon^2}{2}y^2}{1+\varepsilon^2}
\end{aligned}$$

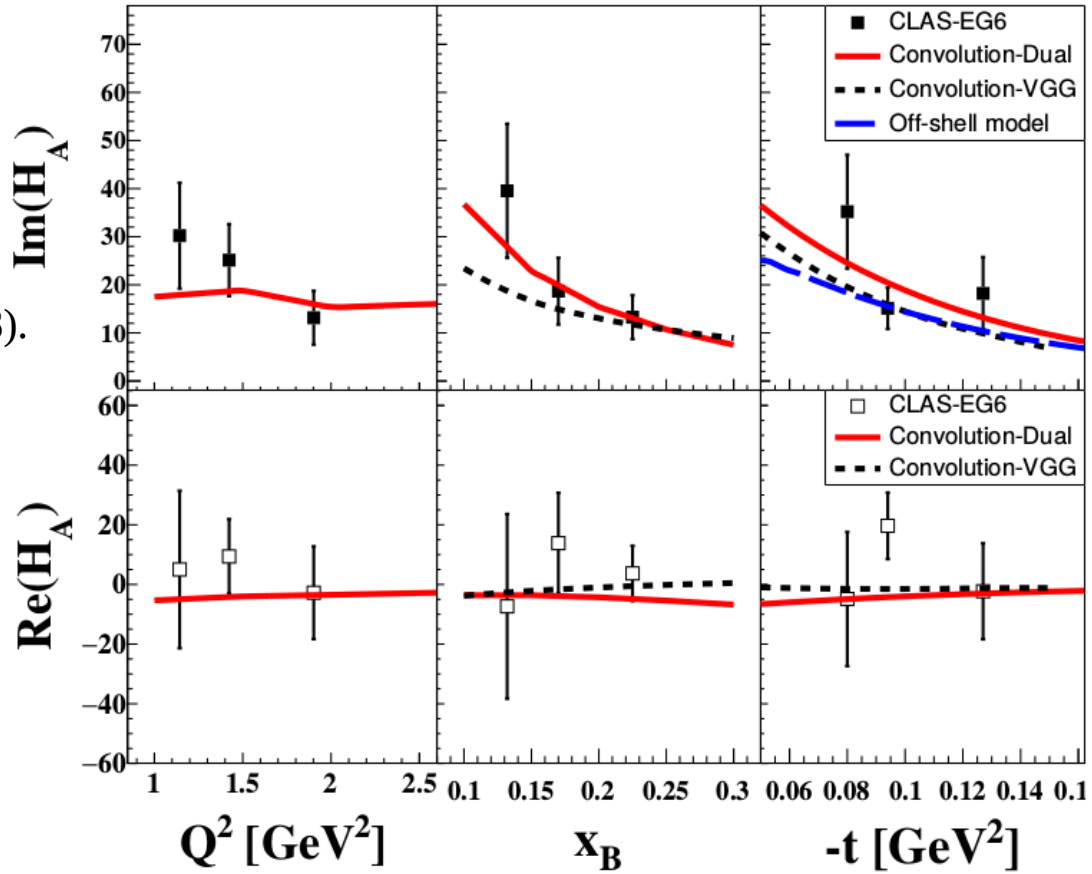


Coherent ALU and CFF



- S. Liuti and S. K. Taneja, PRC 72 (2005) 034902.
- HERMES: A. Airapetian, et al., PRC 81, 035202 (2010).

→ The first ever experimental extraction of the real and the imaginary parts of the He-4 CFF:



Convolution-Dual: V. Guzey, PRC 78, 025211 (2008).
Convolution-VGG: M. Guidal, M. V. Polyakov, A. V. Radyushkin and M. Vanderhaeghen, PRD 72, 054013 (2005).
Off-shell model: J. O. Gonzalez-Hernandez, S. Liuti, G. R. Goldstein and K. Kathuria, PRC 88, no. 6, 065206 (2013)

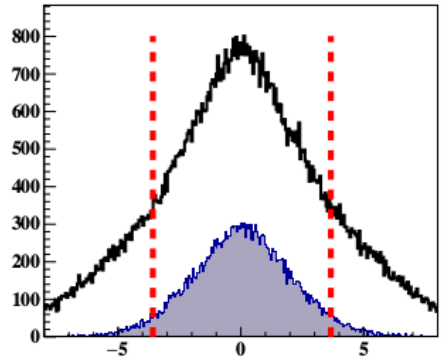
Incoherent DVCS Selection

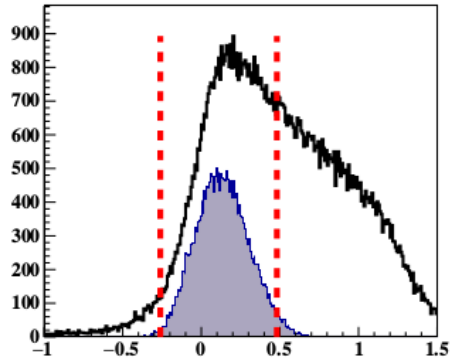
1. We select events which have:

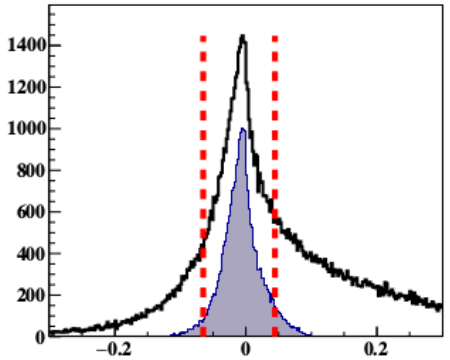
◊ Events with :
- Only one good electron in CLAS
- At least one high-energy photon (Eγ > 2 GeV)
- Only one proton in CLAS.

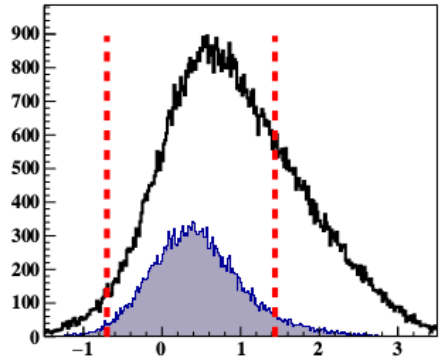
◊ $Q^2 > 1$ GeV²
◊ Exclusivity cuts (3 sigmas).

- In Black, incoherent events before all exclusivity cuts.
- In shaded gray, incoherent DVCS events which pass all the othe exclusivity cuts except the one on the quantity itself.

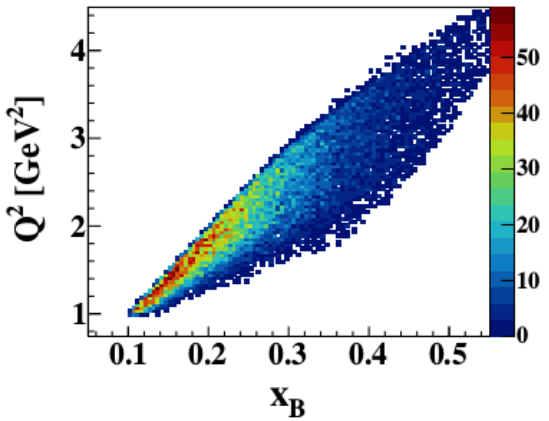


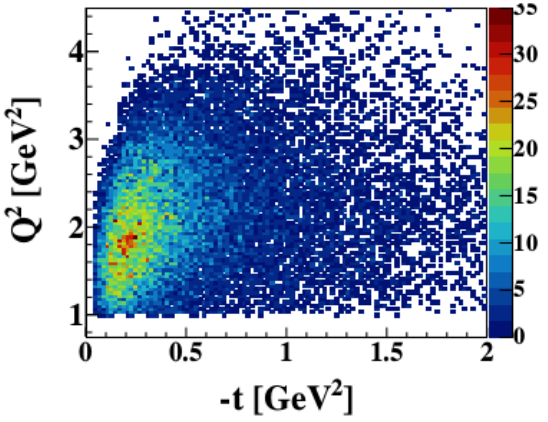




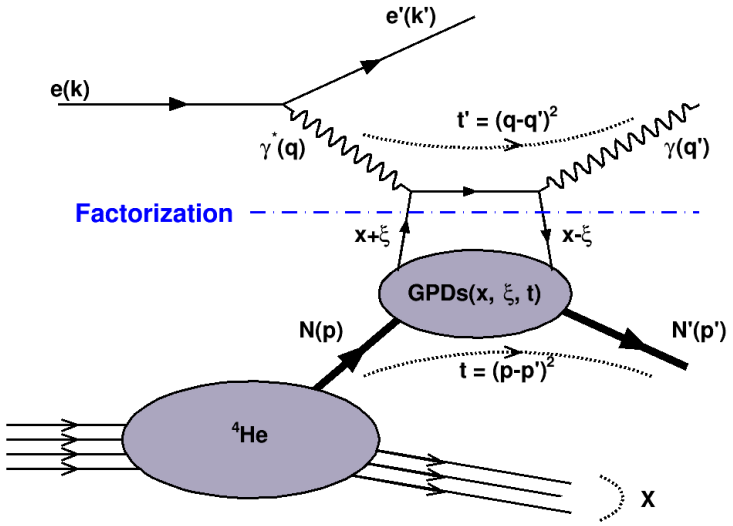


2. π^0 background subtraction based on data and simulation (contaminations ~ 8 - 11%)





Incoherent Beam-Spin Asymmetry Fitting

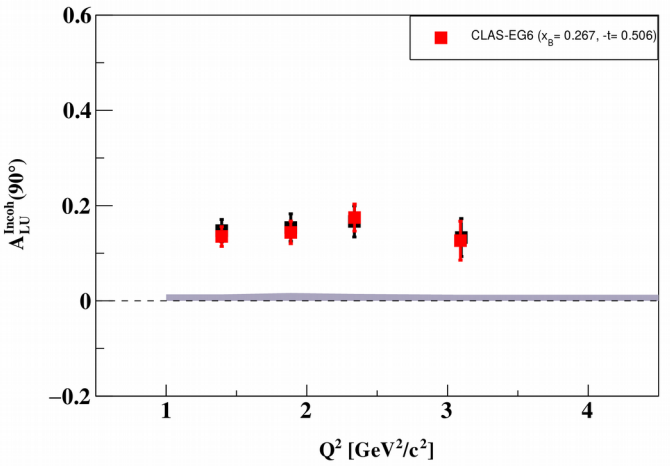


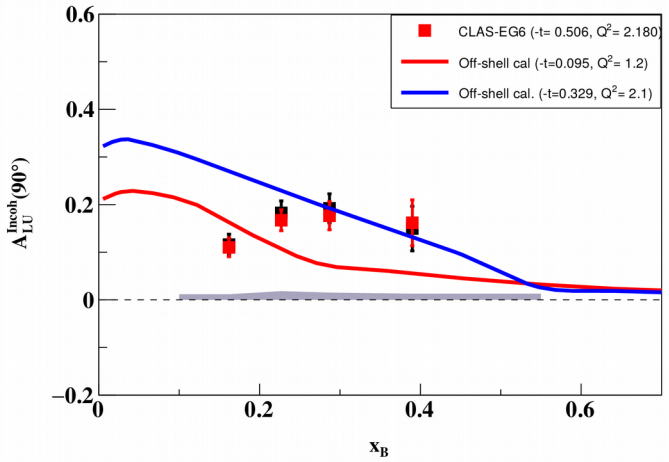
$$A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$$

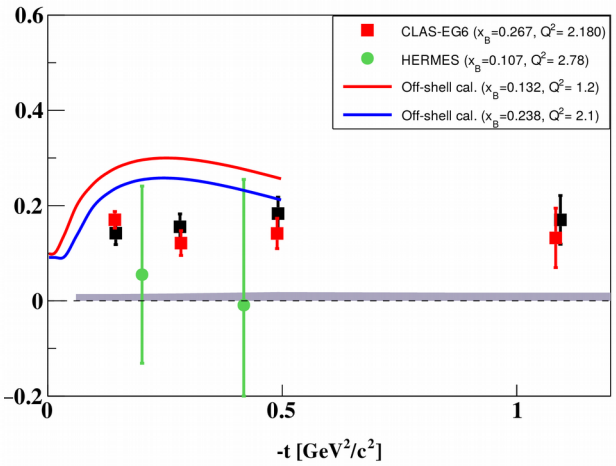
$$A_{LU} \propto \alpha(\phi)\{F_1 H + \xi(F_1 + F_2)\tilde{H} + \kappa F_2 E\}$$

- **bins in t':** smeared due to radiative effects
- **bins in t:** smeared due to Fermi motion

- 2D bins due to limited statistics
- Systematic uncertainities (~ 10%) dominated by exclusivity cuts (~ 6%) and large phi bining (~ 7%)
- Fits in the form: $\frac{\alpha * \sin(\phi)}{(1+\beta*\cos(\phi))}$

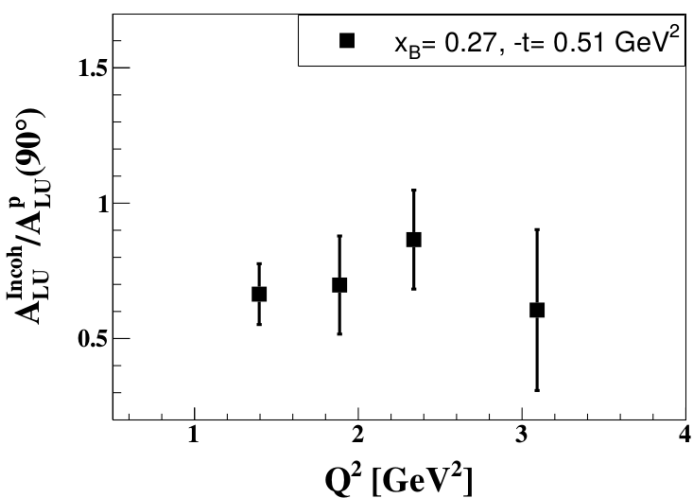


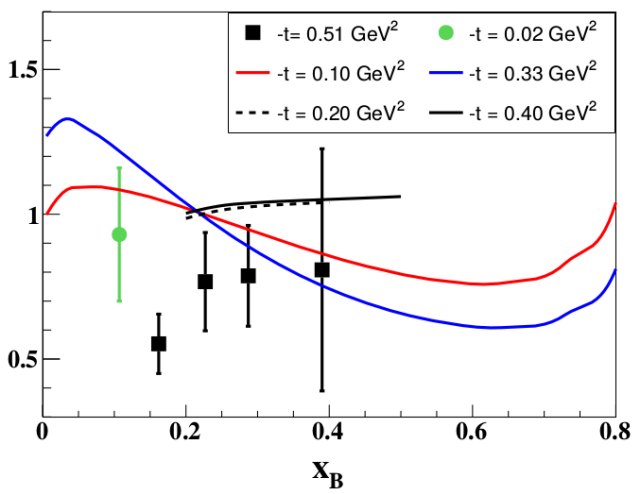


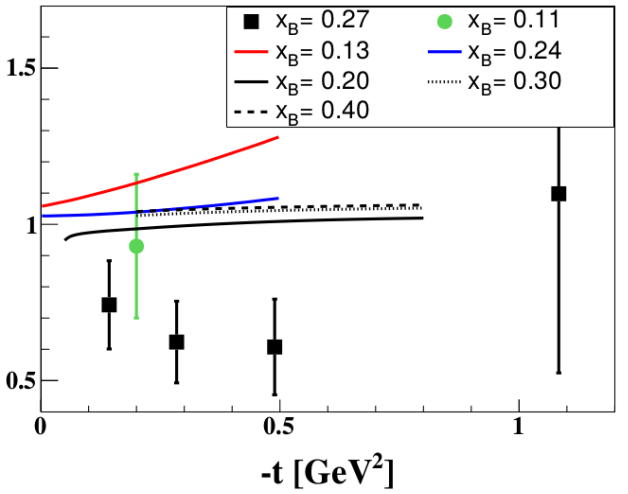


Incoherent Generalized EMC

◊ Comparing our measured incoherent asymmetries with the asymmetries measured in CLAS DVCS experiment on the proton.







[S. Liuti and K. Taneja. PRC 72 (2005) 032201]

[V. Guezy et al., PRC 78 (2008) 025211]

◊ The bound proton shows a lower asymmetry relative to the free one in the different bins in x_B.

◊ At small -t, the bound proton shows lower asymmetry than the free one.

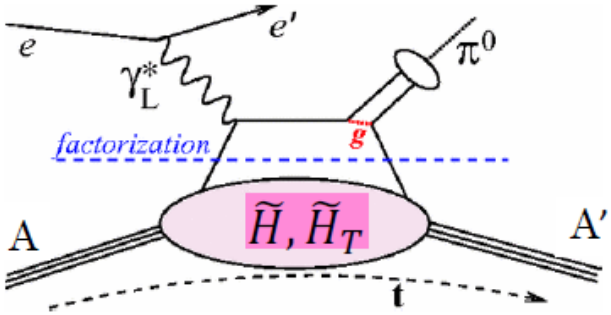
◊ At high -t, the two asymmetries are compatible.

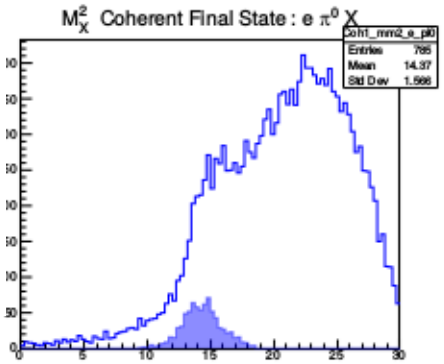
Ongoing coherent/incoherent π^0 production off He4

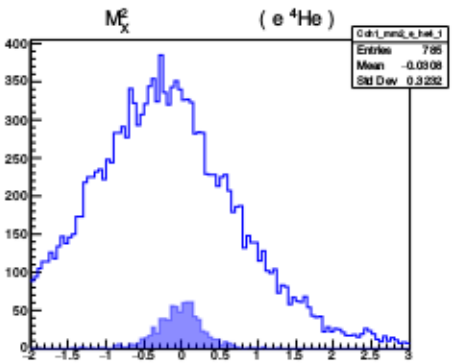
(Frank Coa and Bayram Torayev)

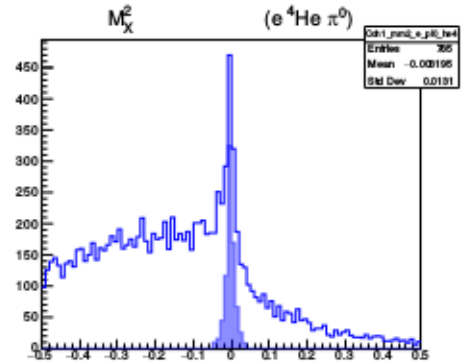
$$A_{LU} \sim \sigma_{LT'} \sim \tilde{H} * \tilde{H}_T$$

$$\frac{d^2\sigma}{d\varphi dt} = \frac{1}{2\pi}\left[\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\varphi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos(2\varphi) + h\sqrt{2\varepsilon(\varepsilon-1)}\frac{d\sigma_{LT'}}{dt}\sin(\varphi)\right]$$



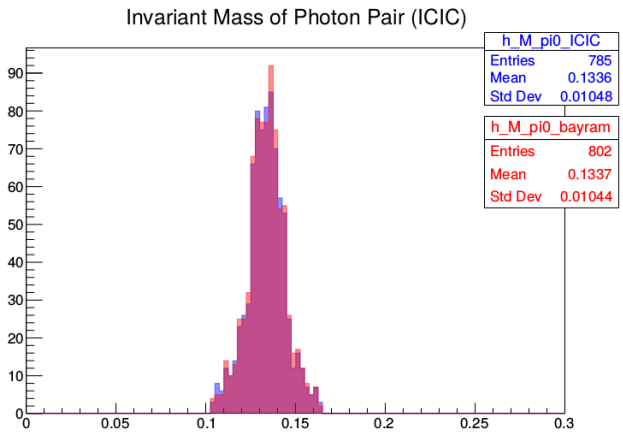


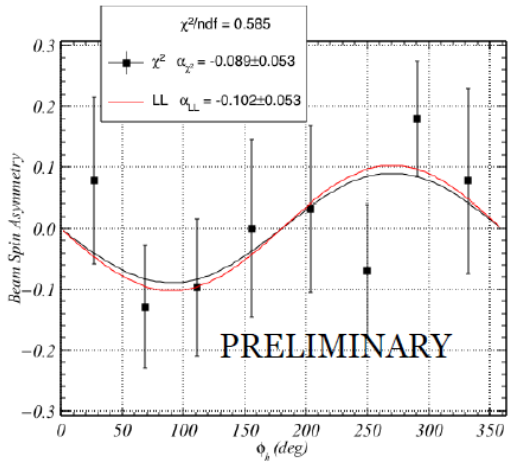


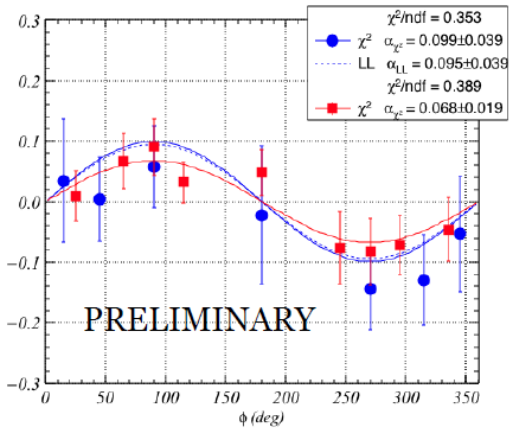


$\vec{e}^4He \rightarrow e'^4He'\pi^0$

$\vec{e}^4He \rightarrow e'N\pi^0X$







Contrary to the π^0 production off proton, the coherent π^0 production off He4 has a sign flip in the beam-spin asymmetry!

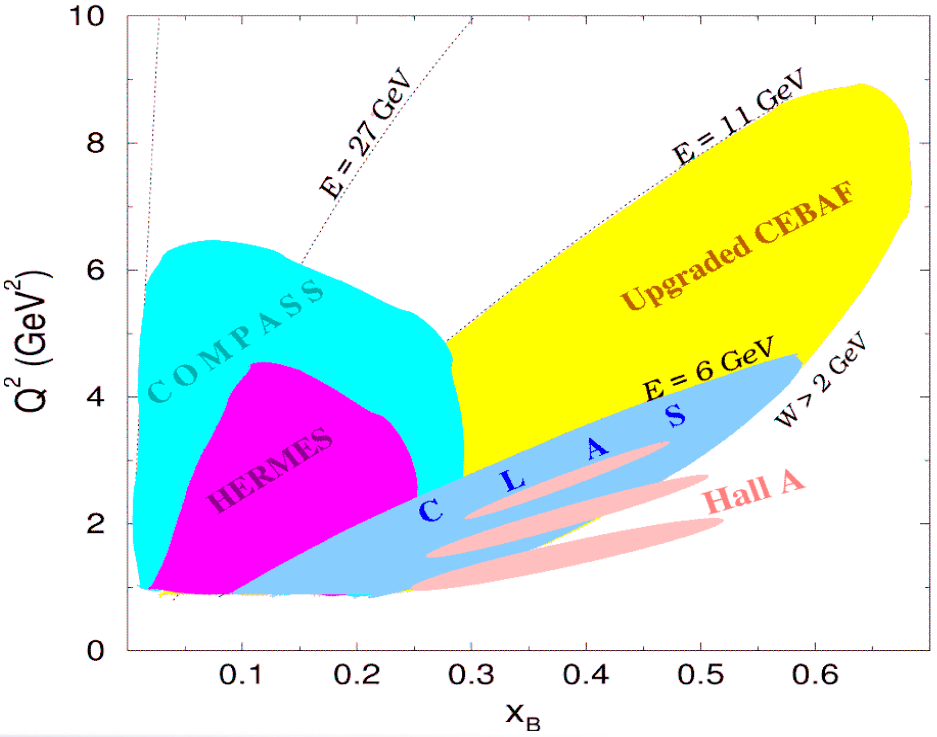
CLAS12-ALERT Proposed 11 GeV Measurements:

◊ CLAS–E08-024 experiment:
→ 2D binning due to limited statistics and limited phase-space.

◊ We propose to measure:

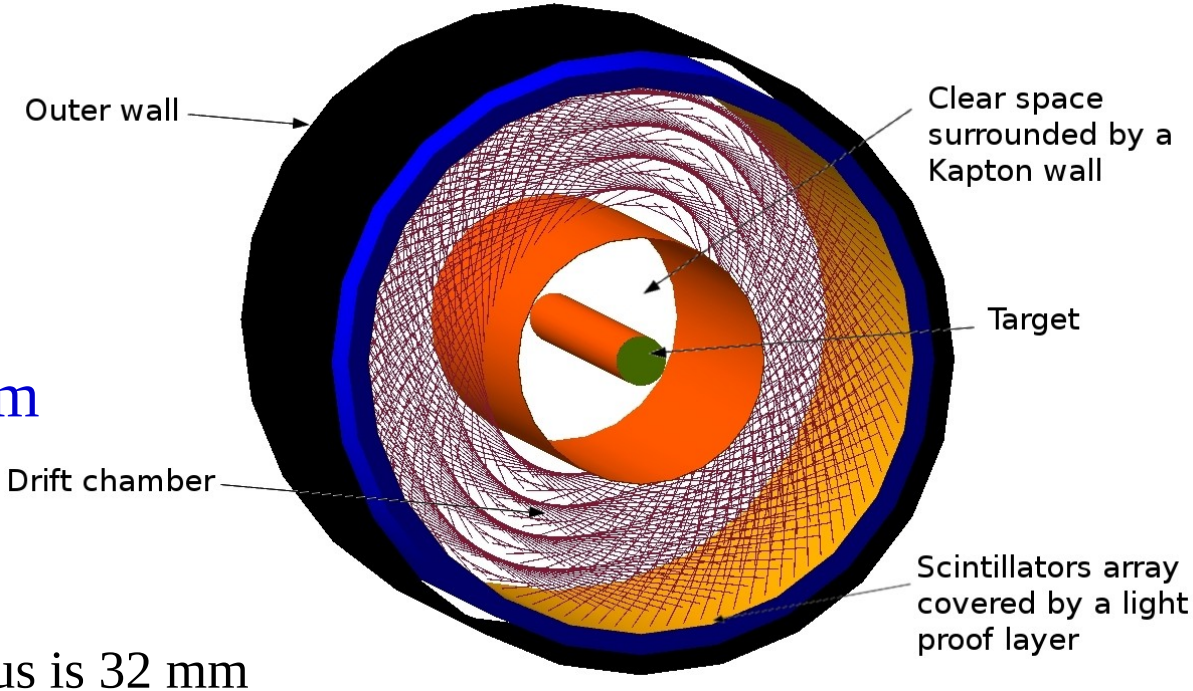
- Partonic Structure of Light Nuclei (DVCS/ DVMP off He4/D).
- Tagged DVCS Off Light Nuclei (See W. Armstrong's talk)
- Tagged EMC on Light Nuclei (See W. Armstrong's talk)

→ CLAS12-ALERT setup will allow higher statistics and wider kinematical coverage
→ 4D binning
→ Precise CFF extractions.



CLAS12-ALERT: ALERT Detector

- Cylindrical target:
  - 30 cm long
  - 6 mm outer radius.
  - operating at 3 atm pressure.
  - 25μm target wall (Kapton).
- A clear space filled with helium
  to reduce secondary scattering from the high rate Moller electrons (outer radius is 30 mm).

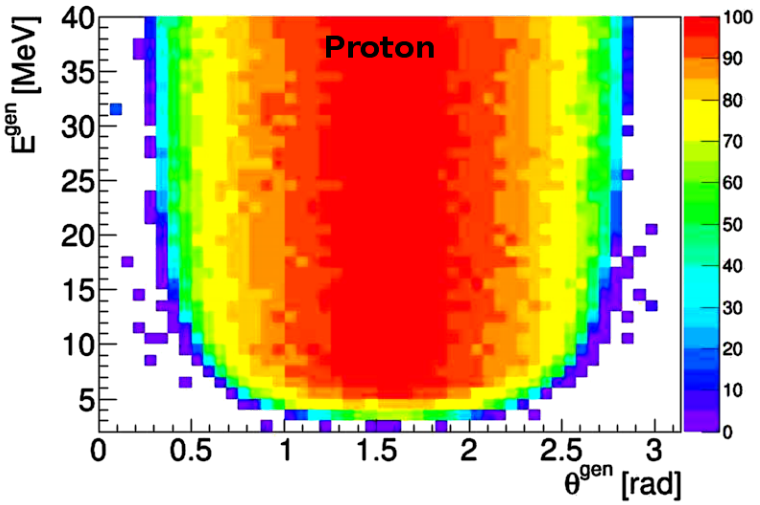


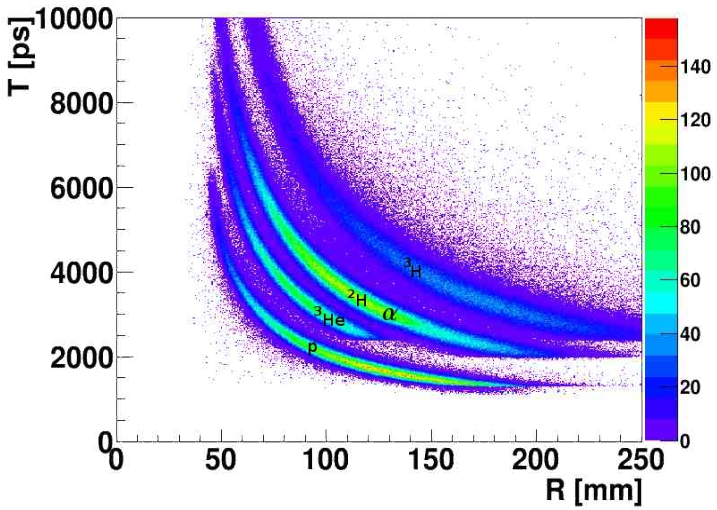
- The drift chamber, its inner radius is 32 mm and its outer radius is 85 mm. It will detect the trajectory of the low energy nuclear recoils.
- Two rings of plastic scintillators with total thickness of roughly 20 mm.

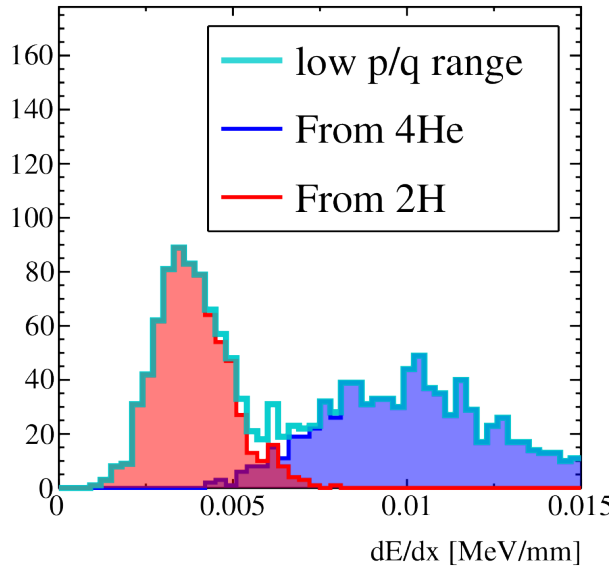
→ **Separate protons, deuterium, tritium, alpha, He-3**
→ **Can be used for BoNuS12, tagged EMC and DVCS/DVMP off He4 ...**

ALERT Expected Performance:

- **Capabilities for very low momentum detection**
  - As low as 70 MeV/c for protons and 240 MeV/c for ^{4}He
  - Forward and backward detections (25° from the beam).
- **Capabilities to handle high rates**
  - Small distance between wires leads to short drift time <250 ns (5 μs in a similar RTPC)
  - This translates into 20× less accidental hits
  - Will be integrated in the trigger for significantly reduced DAQ rate
- **Improved PID**
  - Like in the RTPC, we get dE/dx measurment
  - We have more resolution on the curvature due to the large pad size in previous RTPCs
  - TOF information



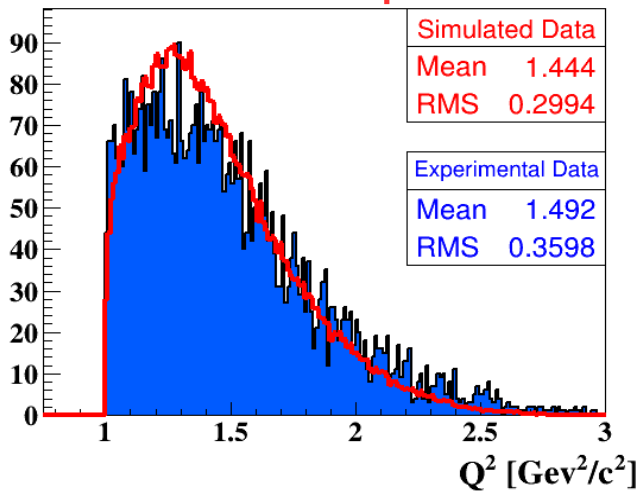




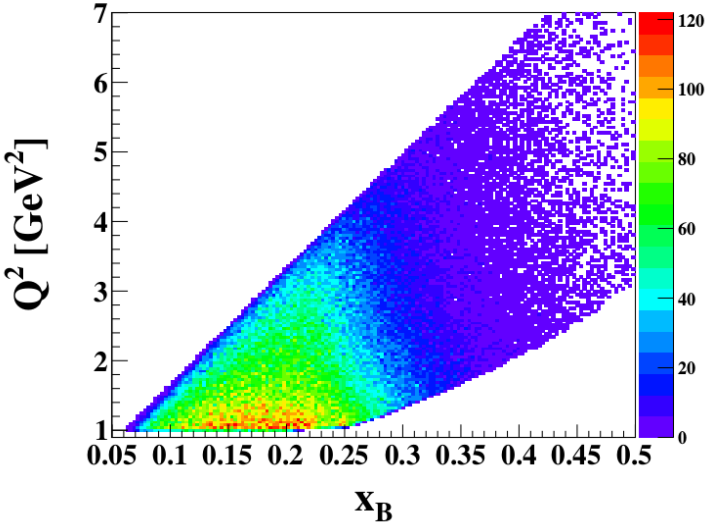
DVCS off He-4: Event Generator

- Parametrized cross section which parameters were calibrated to reproduce CLAS-E08-024 data.

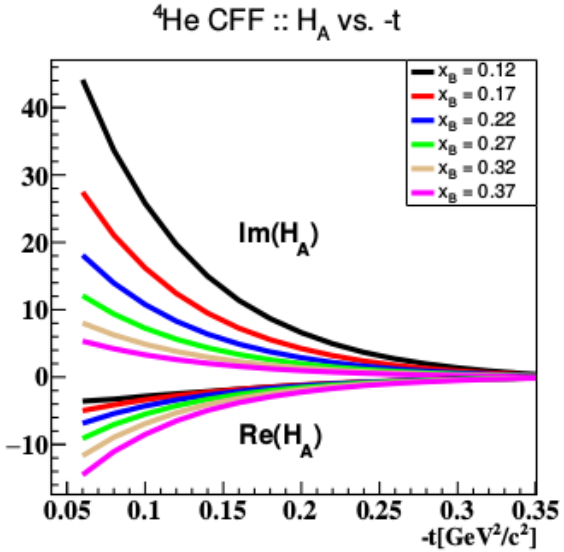
6 GeV comparison

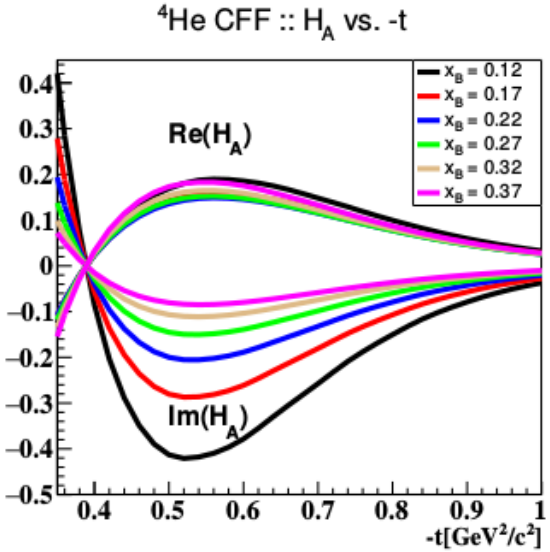


Projected 11 GeV phase-space



- Fed the generator with ^{4}He CFF calculated from the Impulse Approx.

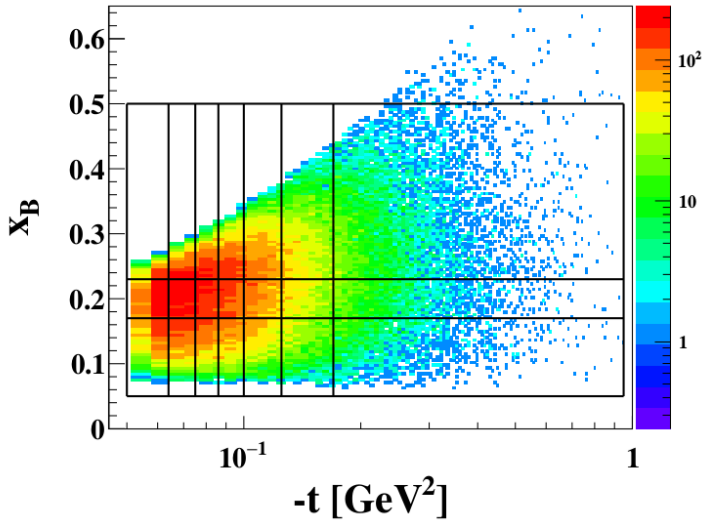


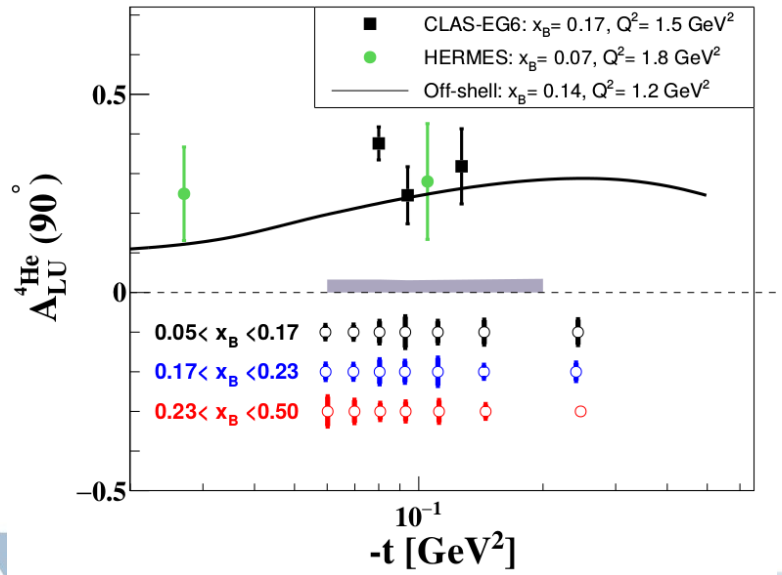


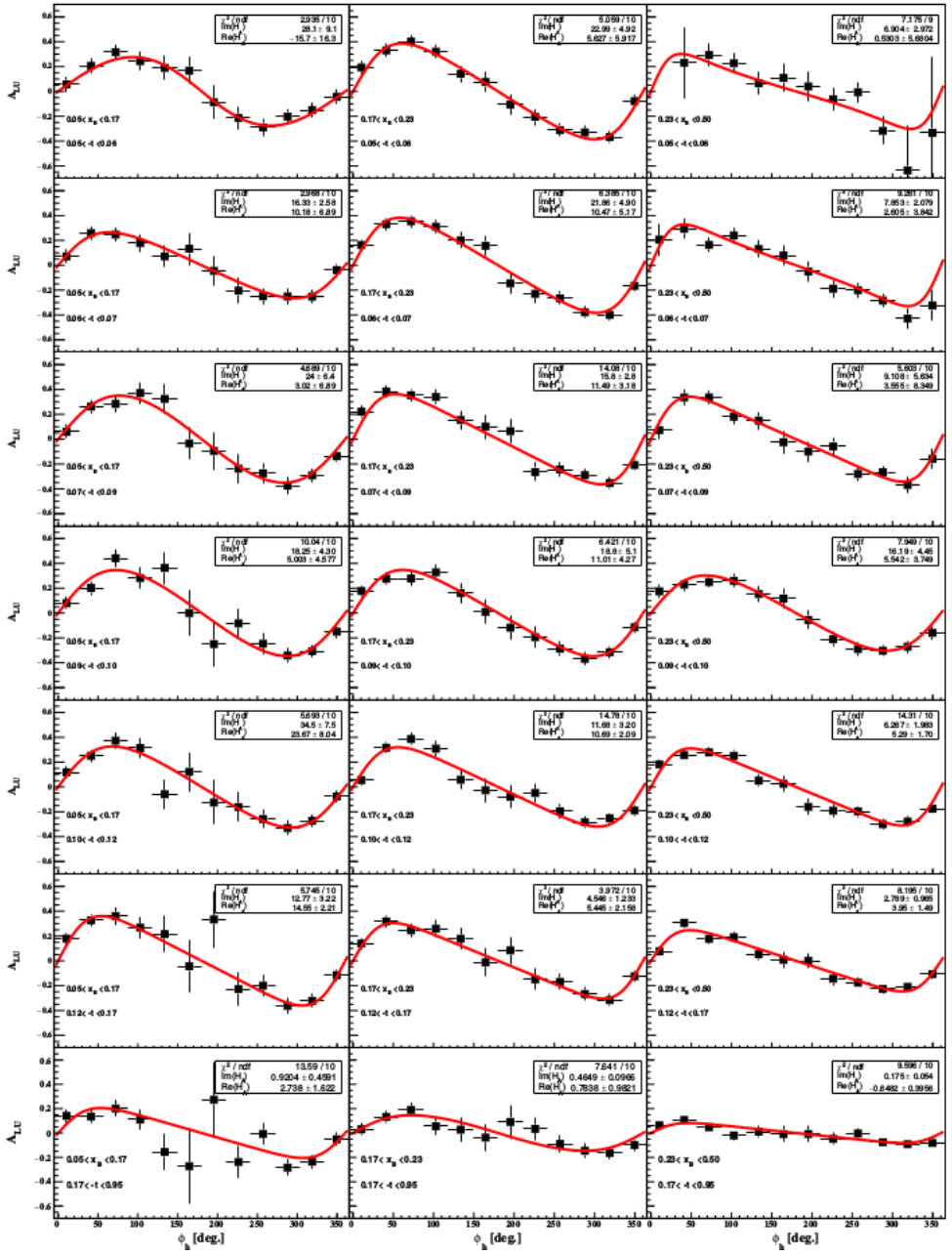
DVCS off He-4: Projected Precisions

The statistical error bars are for:

- 20 days at a luminosity of 3.0 X 10^{34} $cm^{-2}s^{-1}$.
- 10 days at a luminosity of 6 X 10^{34} $cm^{-2}s^{-1}$.





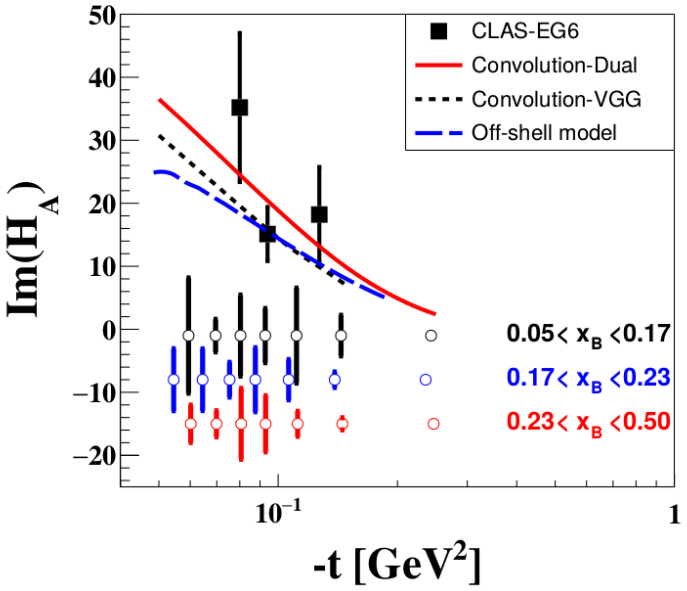


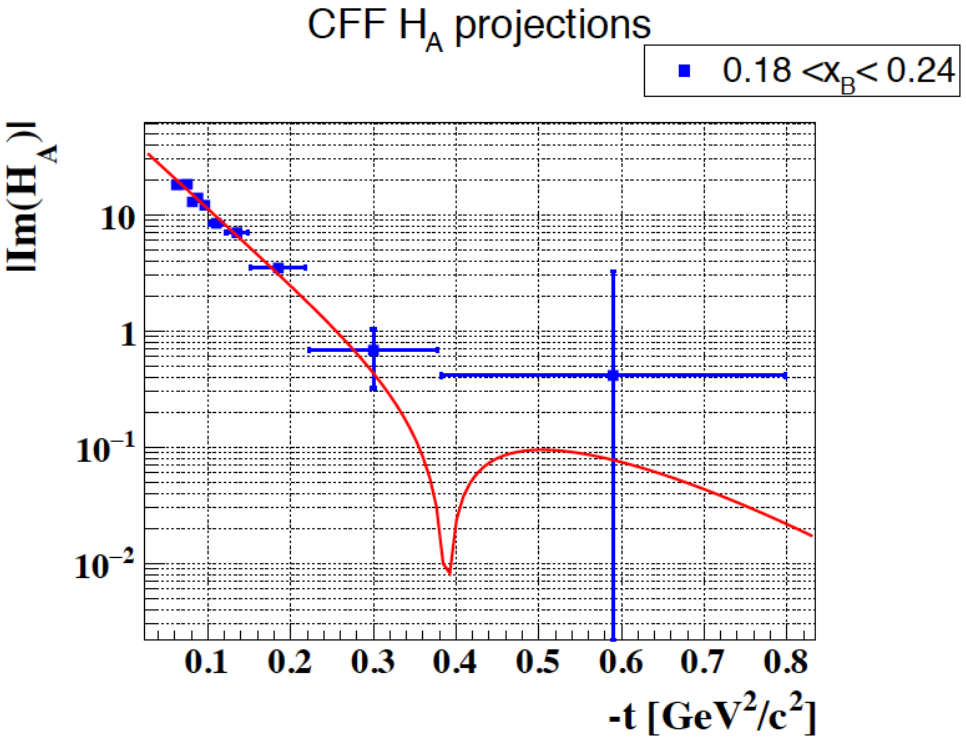
He4 Charge Profile Extraction

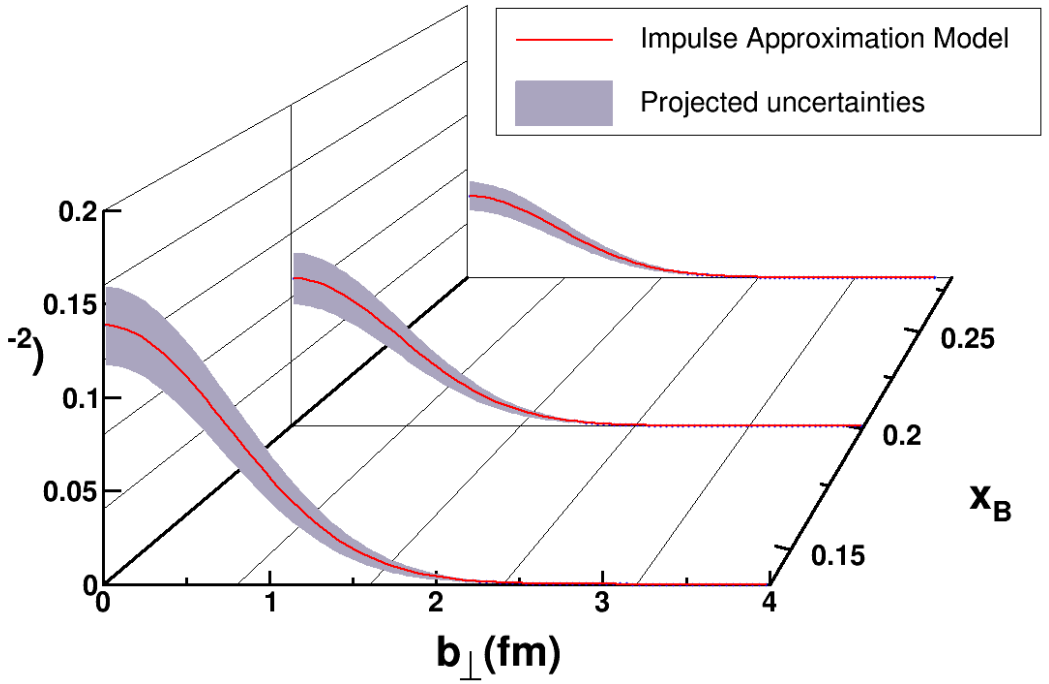
Quarks CFF —FT→ Charge density

$$\rho(x,0,b_\perp) = \int_0^\infty J_0(b\sqrt{t}) H^A(x,0,t) \frac{\sqrt{t}}{2\pi} d\sqrt{t}$$

J_0 is the first order cylindrical Bessel function.





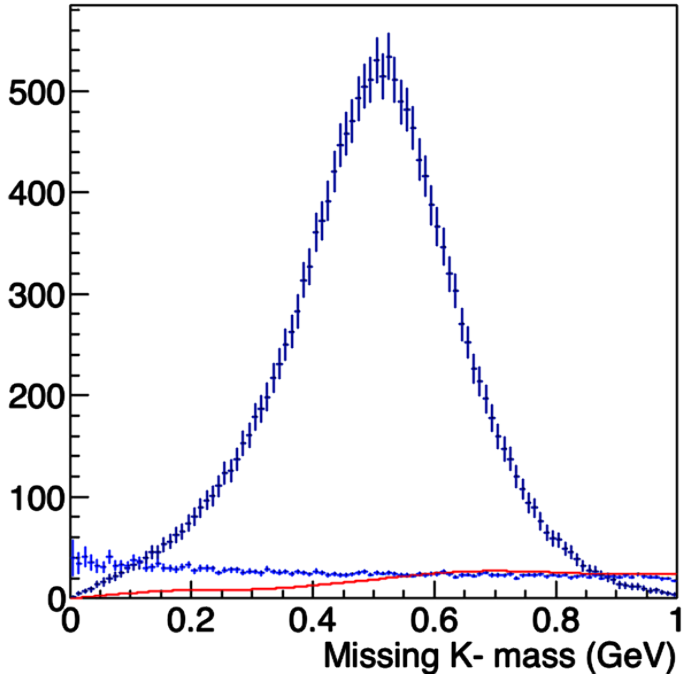


φ production off He-4: Gluon profiles

Production of mostly strange φ meson off a mostly up-down nucleus favors a gluon exchange mechanism.

$$e + {}^4He \rightarrow e' + {}^4He + \phi$$
$$\hookrightarrow K^+ + K^-$$

Detect recoil ^{4}He', e', and K^+ (missing K^-)



Gluon density calculation:

$$\rho_g(x, 0, b_\perp) \rightarrow \int_0^\infty J_0(b\sqrt{t}) \sqrt{\frac{d\sigma_L}{dt}} \frac{\sqrt{t}}{2\pi} d\sqrt{t}$$

-> Need longitudinal differential cross-section

φ off He-4: Longitudinal cross-section cal.

Total cross-section for phi production:

$$\frac{d^3\sigma}{dx_B\,dQ^2\,dt} = \Gamma(x_B, Q^2, E)\left(\frac{d\sigma_T}{dt}(W, Q^2, t) + \varepsilon\frac{d\sigma_L}{dt}(W, Q^2, t)\right)$$

$$R = \frac{\sigma_L}{\sigma_T} \longrightarrow \frac{d\sigma_L}{dt} = \frac{1}{(\varepsilon + 1/R)\Gamma(Q^2, x_B, E)}\frac{d^3\sigma}{dQ^2 dx_B dt}$$

R can be extracted from the angular distribution of the kaon decay in the phi helicity frame, assuming s-channel helicity conservation:

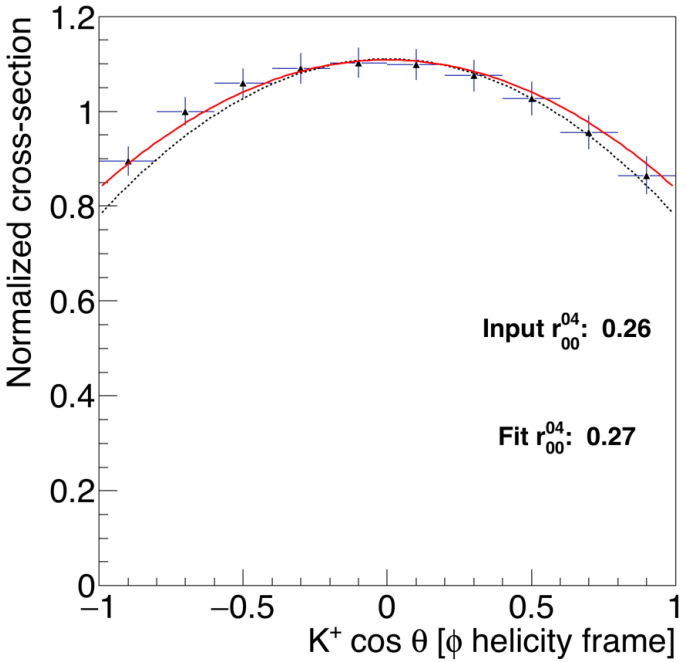
$$W(\cos\theta_H) = \frac{3}{4}\left[(1 - r_{00}^{04}) + (3r_{00}^{04} - 1)\cos^2\theta_H\right]$$

Angular distribution amplitude

Spin-density matrix coefficient:

$$r_{00}^{04} = \frac{\epsilon R}{1 + \epsilon R}$$

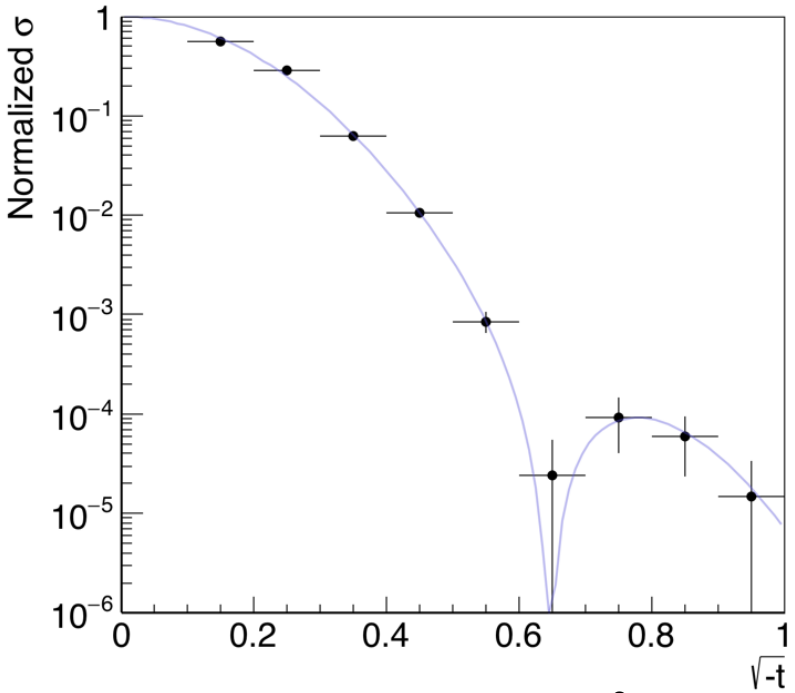
Angle of kaon decay In phi helicity frame



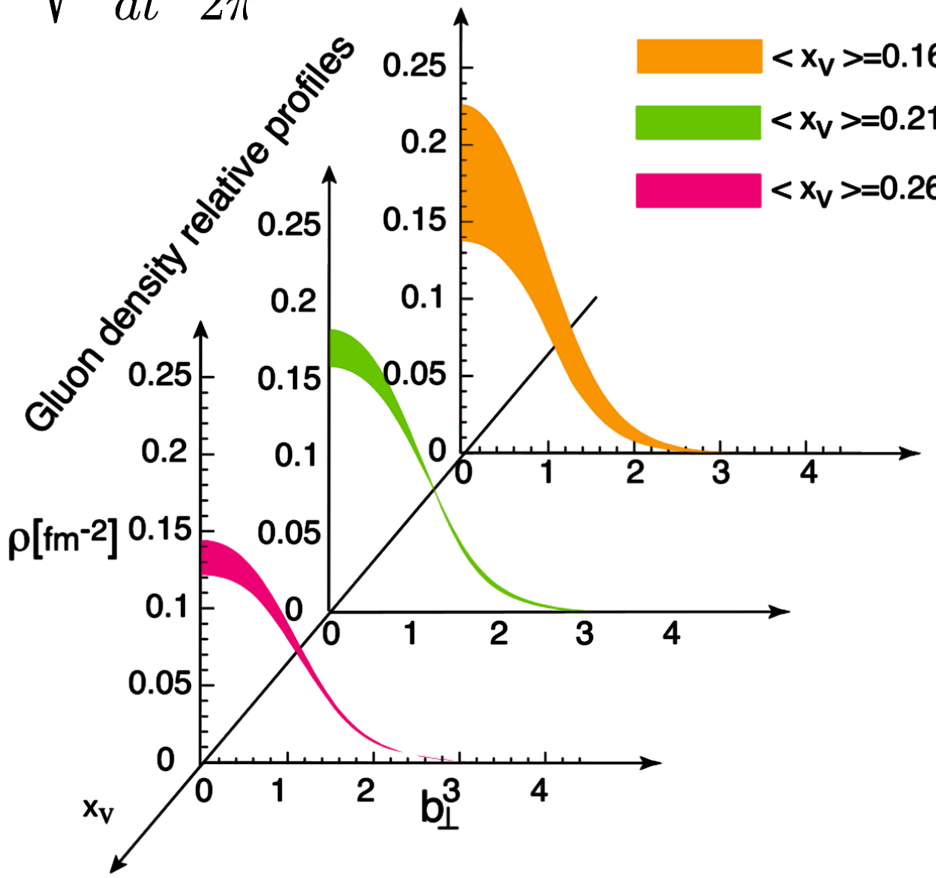
φ off He-4: Calculating the gluon density

The longitudinal cross-section can be normalized to t' = 0 and the Hankel transformation can be applied.

$$\rho_g(x,0,b_\perp) \rightarrow \int_0^\infty J_0(b\sqrt{t})\sqrt{\frac{d\sigma_L}{dt}}\frac{\sqrt{t}}{2\pi}d\sqrt{t}$$



$0.18 < x_{Vp} < 0.25, \quad 2.0 < Q^2 < 3.0\ GeV^2$



Conclusions

◊ **CLAS – E08-024 experiment:**

→ The first exclusive measurement of DVCS off ^{4}He.

→ The coherent DVCS shows a stronger asymmetry than the free proton as was expected from theory.

→ We performed the first ever model independent extraction of the He-4 CFF.

→ We extracted EMC ratios and compared them to theoretical predictions.

→ The bound proton has shown a different trend compared to the free one indicating the medium modifications of the GPDs and opening up new opportunities to study the EMC effect.

→ The BSA of the coherent π^0 production has a different sign than the BSA on the nucleon.

◊ **CLAS12-ALERT** will provide wider kinematical coverage and better statistics that will allow 3D binnings for both the DVCS and DVMP channels

→ Allows performing ^{4}He tomography in terms of quarks and gluons.

→ Allows comparing the gluon radius to the charge radius.