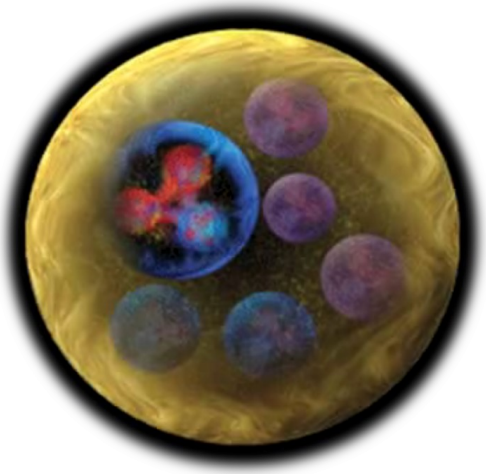
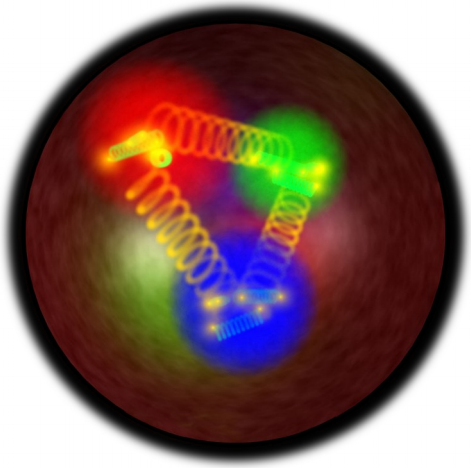
OLD DOMINION UNIVERSITY

Exploring the 3D Partonic Structure of Nucleons and Nuclei

M. Hattawy

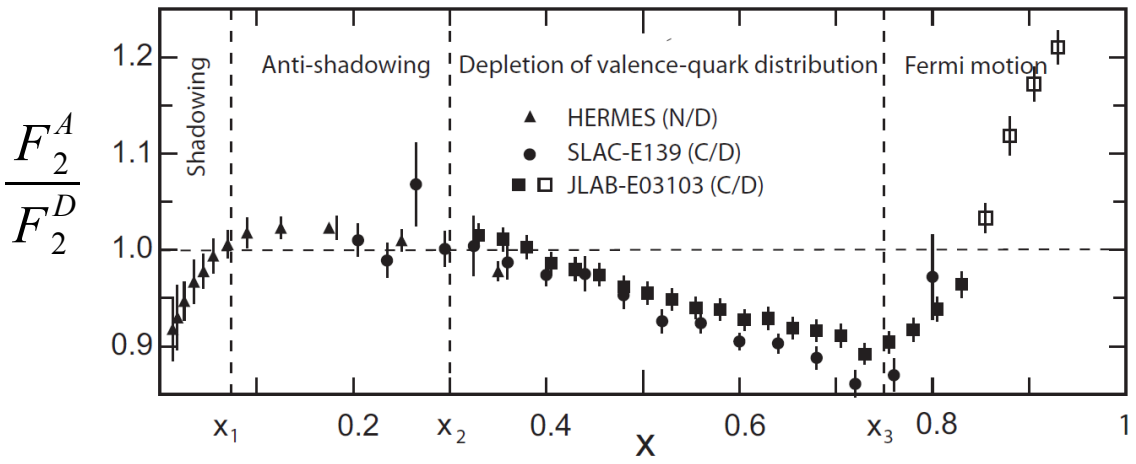


- Physics Motivations
- Recent Results.
- Future Measurements.



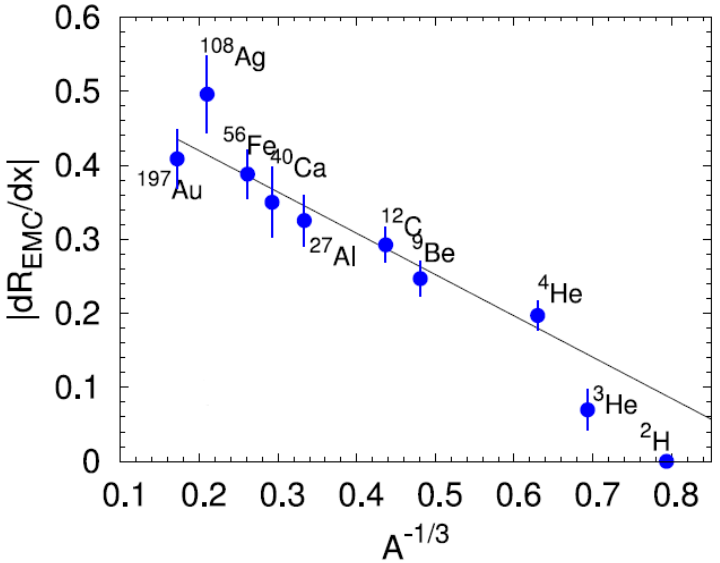
2019 Jefferson Lab Users Organization Annual Meeting, June 24-26

EMC Effect



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

EMC effect: the modification of the PDF F_2 as a function of the longitudinal momentum fraction 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...)

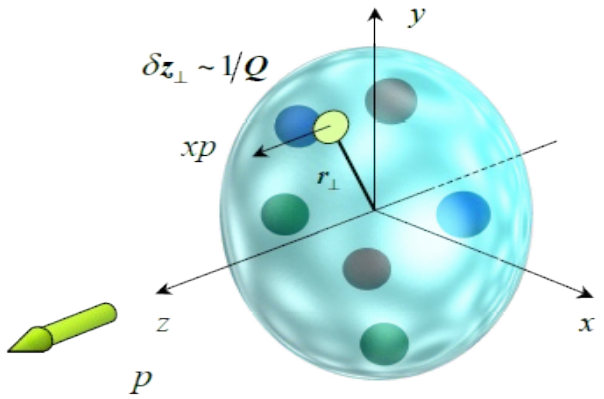
Clear explanations may arise from measuring the nuclear modifications via measuring the Generalized Parton Distributions.

Generalized Parton Distributions

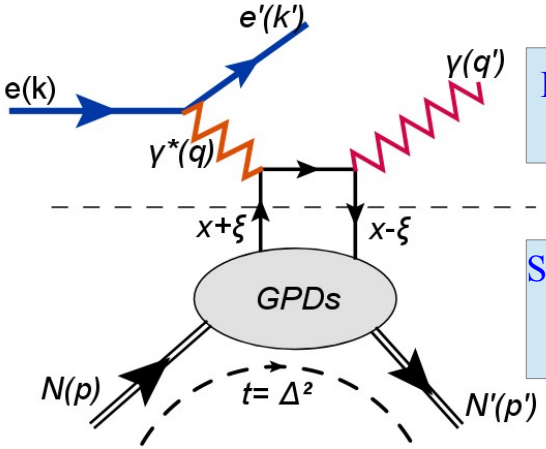
- Contain information on:

→ Correlation between quarks and anti-quarks

→ Correlation between longitudinal momentum and transverse spatial position of partons



- Can be accessed via hard exclusive processes such as deeply virtual Compton scattering (DVCS):



Hard part (perturbative, calculable in PQED)

Factorization

Soft part (non-perturbative, parameterized in terms of GPDs)

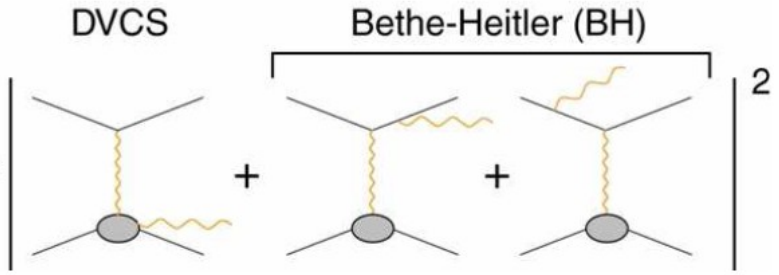
$$\xi \simeq x_B/(2-x_B) \qquad x_B = Q^2/2\mathrm{p.q}$$

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

* At leading order in $1/Q^2$ (twist-2) and in the coupling constant of QCD (α_s).

- **Experimentally,** the measured photon-electroproduction cross section (ep → epγ) is:

$$d\sigma \propto |\tau_{\mathrm{BH}}|^2 + \underbrace{(\tau^*_{\mathrm{DVCS}}\tau_{\mathrm{BH}} + \tau^*_{\mathrm{BH}}\tau_{\mathrm{DVCS}})}_{\mathcal{I}} + |\tau_{\mathrm{DVCS}}|^2$$



- The DVCS signal is enhanced by the interference with BH.

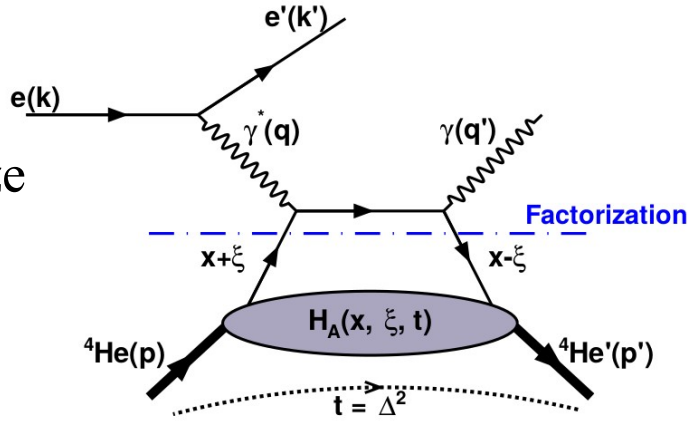
DVCS off Nuclei

Two DVCS channels are accessible with nuclear targets:

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

→ Study the partonic structure of the nucleus.

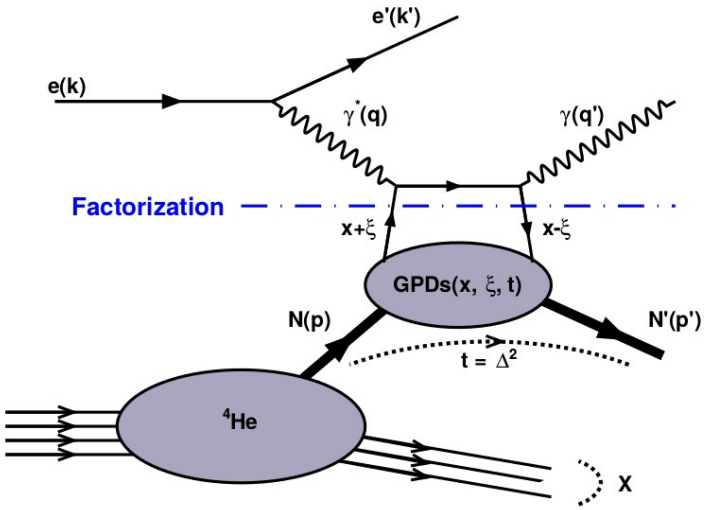
→ One chiral-even GPD ($\mathbf{H_A(x,\xi,t)}$) is needed to parametrize the structure of the spinless nuclei (^{4}He, ^{12}C, ^{16}O, ...).

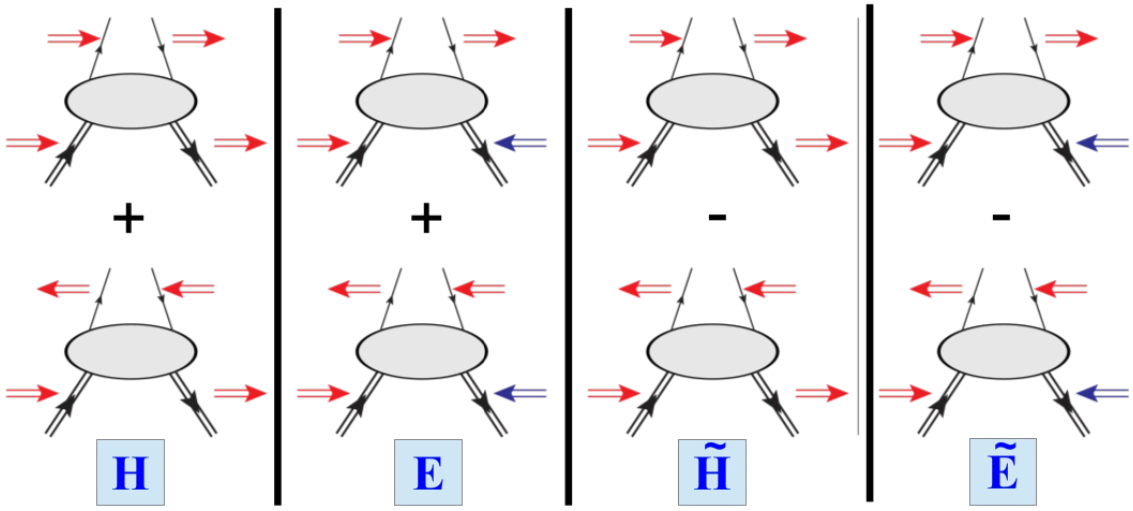


◊ **Incoherent DVCS: $e^- A \to e^- N \gamma X$**

→ 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, …)

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

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

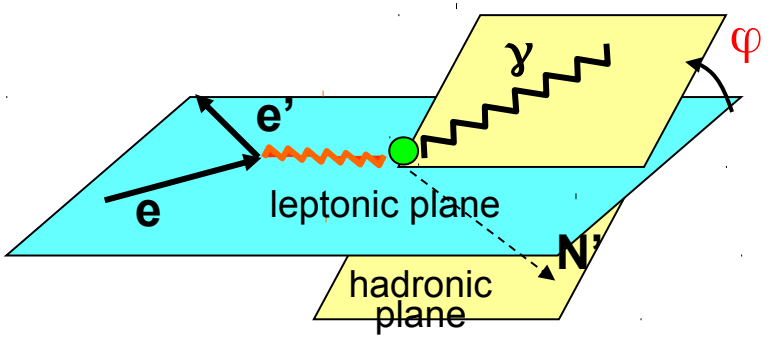
$$Re(\mathcal{H}_A(\xi,t)) = \mathcal{P}\int_0^1 dx[H_A(x,\xi,t) - H_A(-x,\xi,t)]C^+(x,\xi)$$

Quark propagator

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

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

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



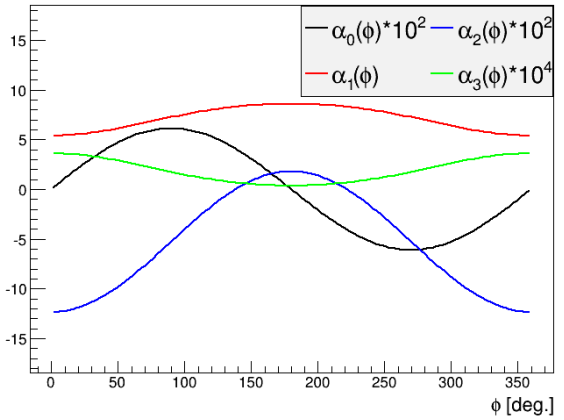
$$= \frac{\alpha_0(\phi)\,\Im m(\mathcal{H}_A)}{\alpha_1(\phi) + \alpha_2(\phi)\,\Re e(\mathcal{H}_A) + \alpha_3(\phi)\left(\Re e(\mathcal{H}_A)^2 + \Im m(\mathcal{H}_A)^2\right)}$$

$$\alpha_0(\phi) = \frac{x_A(1+\varepsilon^2)^2}{y} S_{++}(1)\sin(\phi)$$

$$\alpha_1(\phi) = c_0^{BH} + c_1^{BH}\cos(\phi) + c_2^{BH}\cos(2\phi)$$

$$\alpha_2(\phi) = \frac{x_A(1+\varepsilon^2)^2}{y}\left(C_{++}(0) + C_{++}(1)cos(\phi)\right)$$

$$\alpha_3(\phi) = \frac{x_A^2 t(1+\varepsilon^2)^2}{y}\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)\cdot 2\frac{2-2y+y^2+\frac{\varepsilon^2}{2}y^2}{1+\varepsilon^2}$$



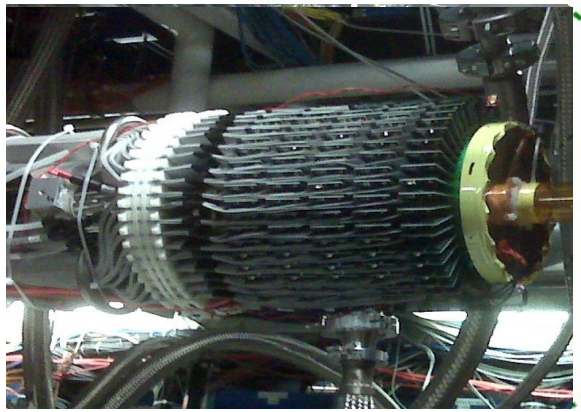
CLAS - E08-024 Experimental Setup

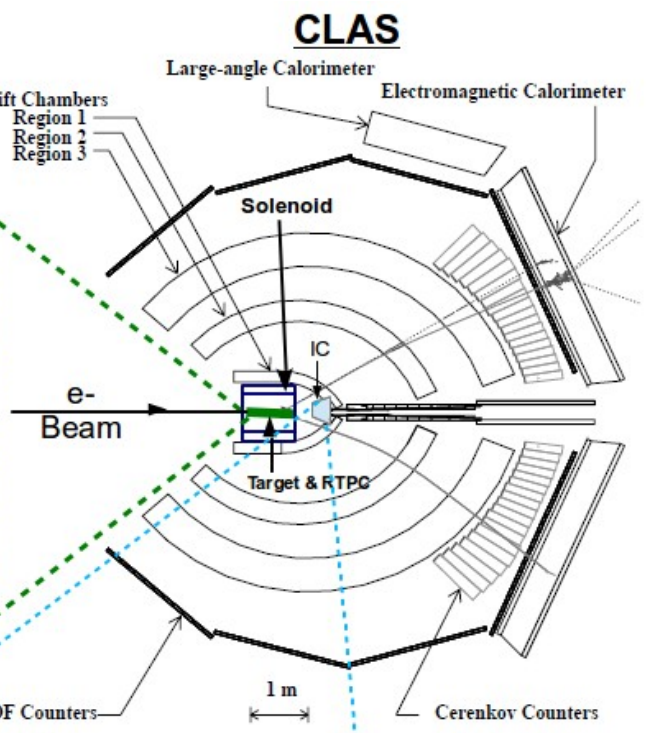
$e^- {}^4He \rightarrow e^- ({}^4He/pX)\ \gamma$

6 GeV,
L. polarized

Beam polarization (P_B) = 83%

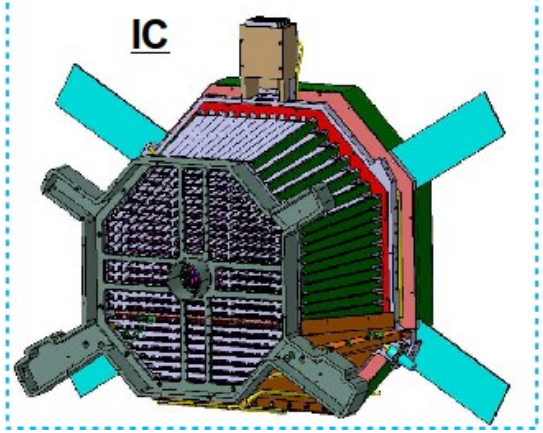
RTPC





- **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

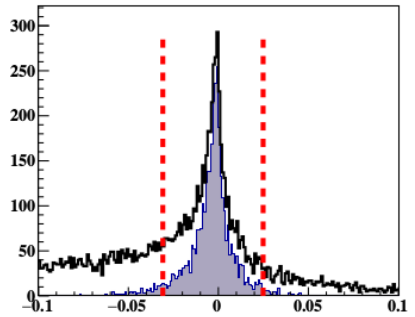
Coherent DVCS Selection & Asymmetries

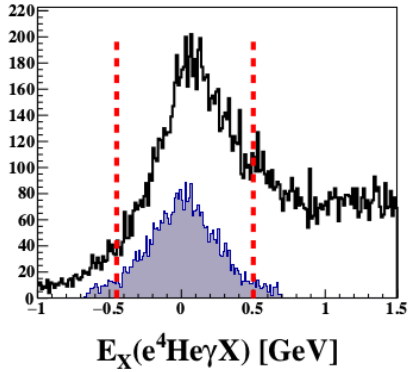
1. We select COHERENT events which have:

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

◊ $Q^2 > 1$ GeV².

◊ Exclusivity cuts.



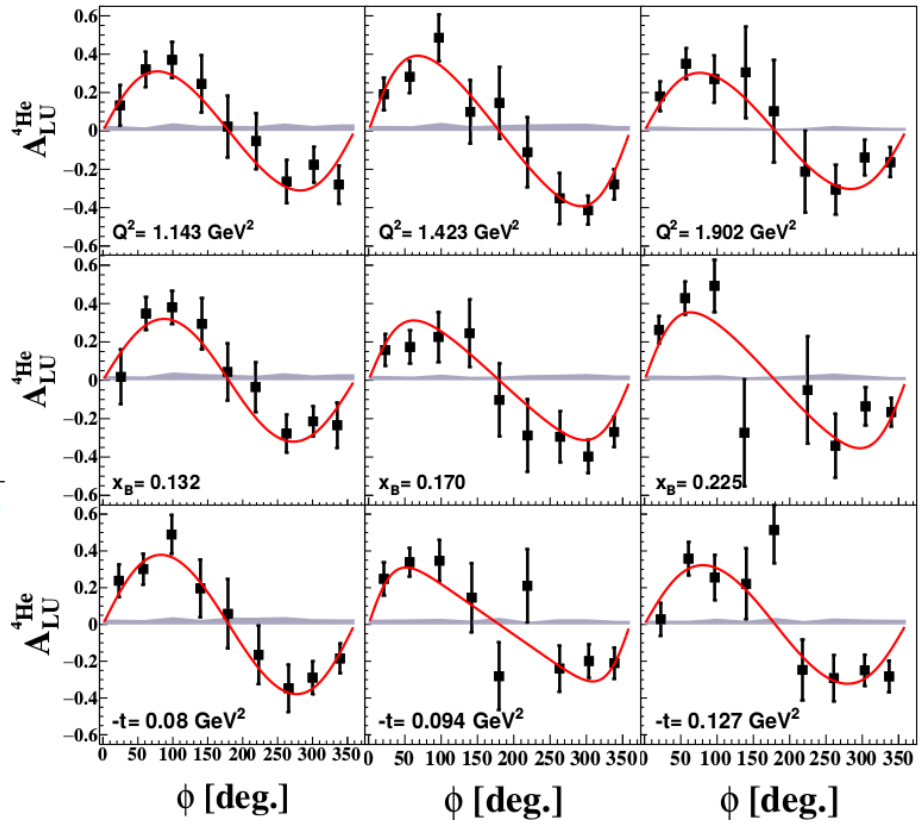


2. π^0 background subtraction based on data and simulation (cont. ~ 2 – 4%)

3. Beam-spin asymmetry:

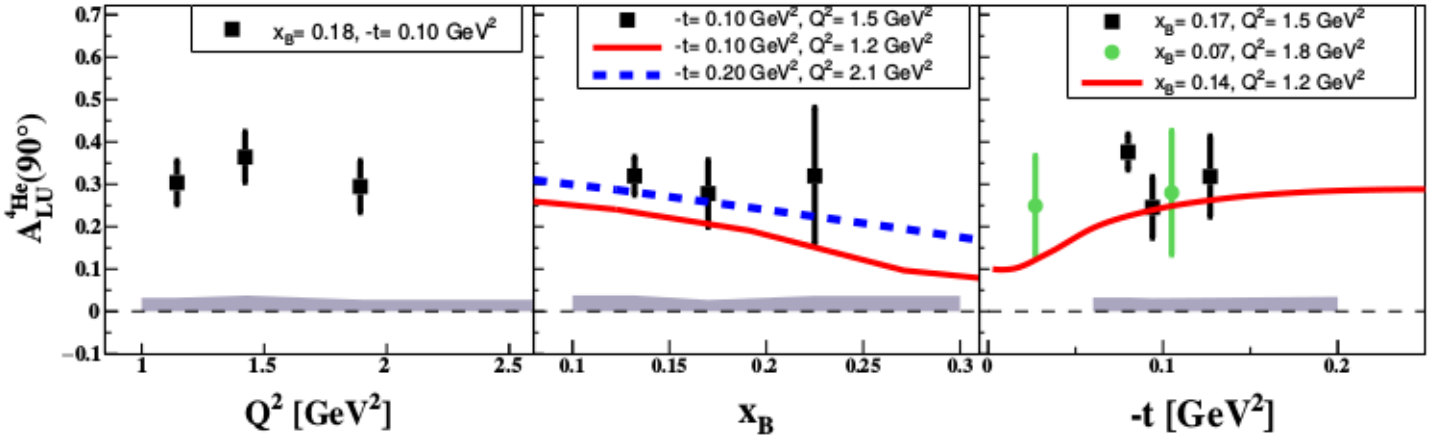
$$A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$$

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



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

Coherent A_{LU} and CFFs



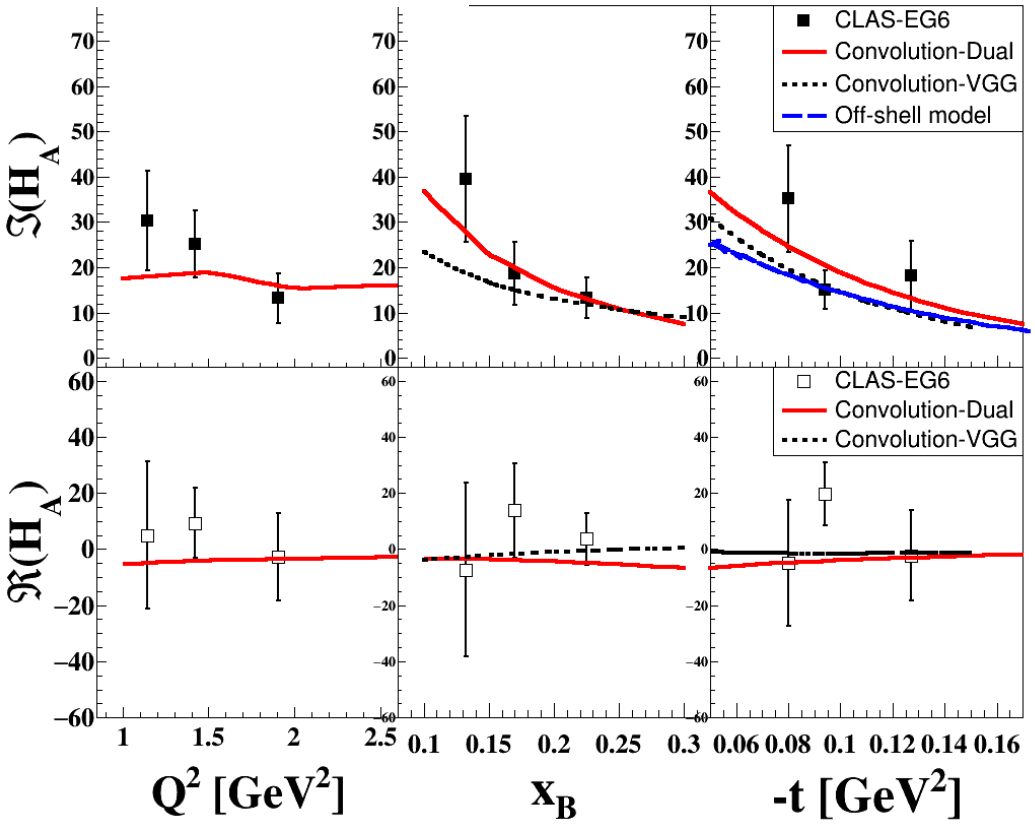
[S. Liuti and K. Taneja. PRC 72 (2005) 032201]
[HERMES: A. Airapetian, et al., PRC 81, 035202 (2010)]

→Same A_{LU} sign as HERMES.

→Asymmetries are in agreement with the available models.

→The first ever experimental extraction of the real and the imaginary parts of the ^{4}He CFF. Compatible with the calculations.

→More precise extraction of Im(H_A).



CLAS-EG6: M. Hattawy et al., Phys. Rev. Lett. 119, 202004 (2017)
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)

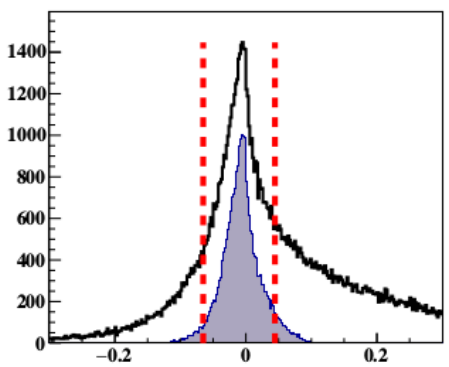
Incoherent DVCS Selection & Asymmetries

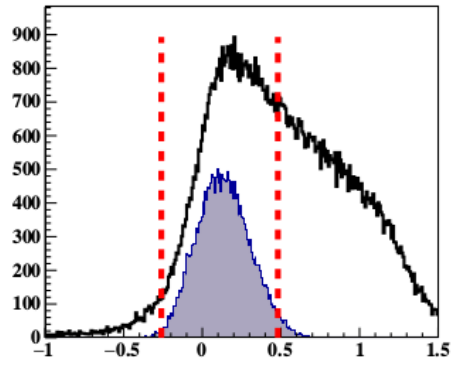
1. We select events which have:

◊ 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 and W> 2 GeV/c²

◊ Exclusivity cuts (3 sigmas).



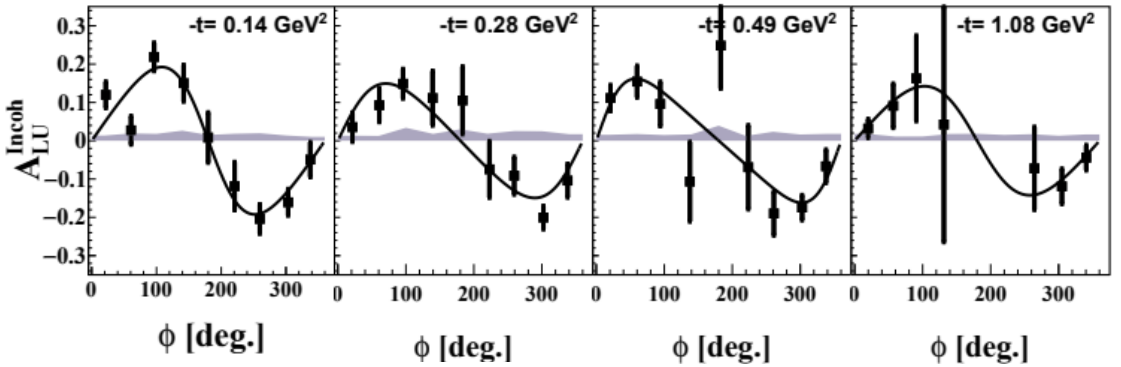


2. π^0 background subtraction (contaminations ~ 8 - 11%)

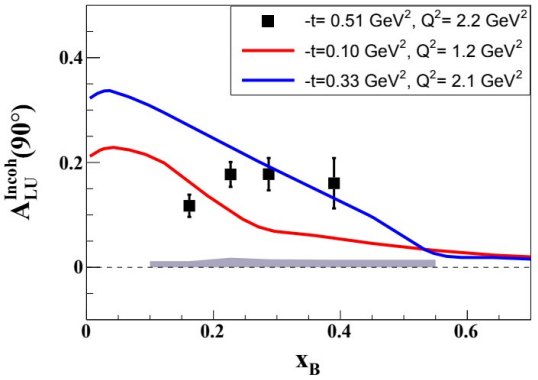
3. Beam-spin asymmetry:

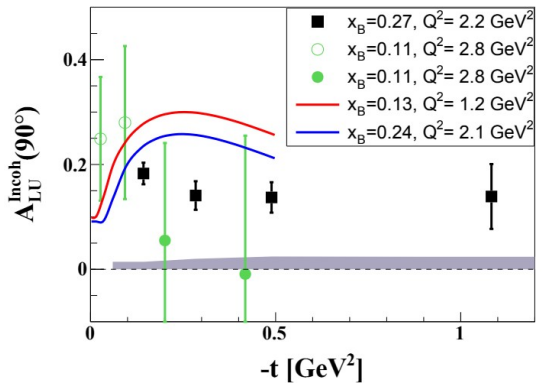
$$A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$$

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



- 2D bins due to limited statistics
- Fits in the form: $\frac{\alpha * \sin(\phi)}{(1 + \beta * \cos(\phi))}$





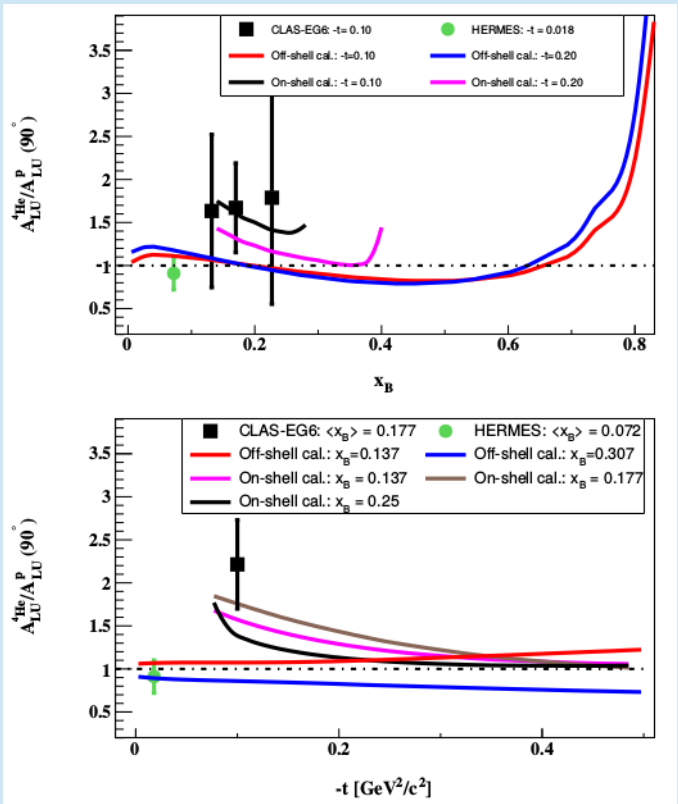
[S. Liuti and K. Taneja. PRC 72 (2005) 032201]

* A PRL presenting the incoherent results at the journal's proof stage.

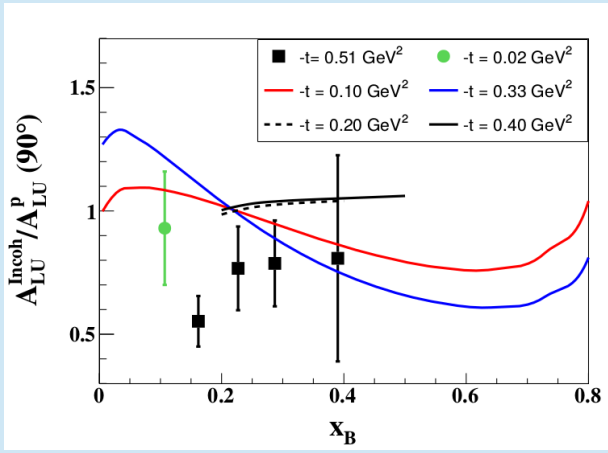
Generalized EMC Ratio

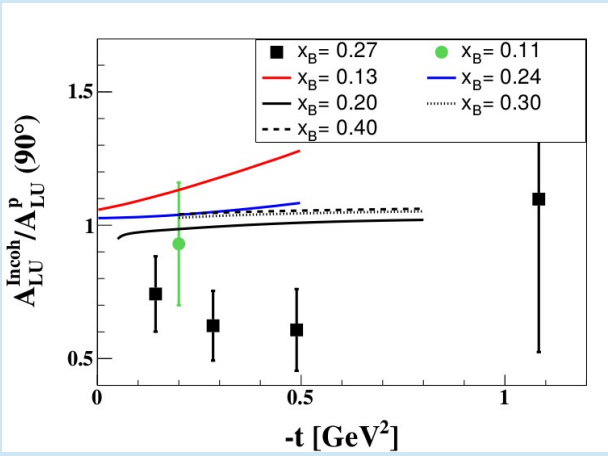
◊ We comparing our measured coherent/incoherent asymmetries to the asymmetries measured in CLAS DVCS experiment on free proton

- Coherent/proton:



- Incoherent/proton:





→ **Coherent/proton** is:

- Consistent with the enhancement predicted by the Impulse approximation model [V. Guezy et al., PRC 78 (2008) 025211]
- Does not match the inclusive measurement of HERMES.

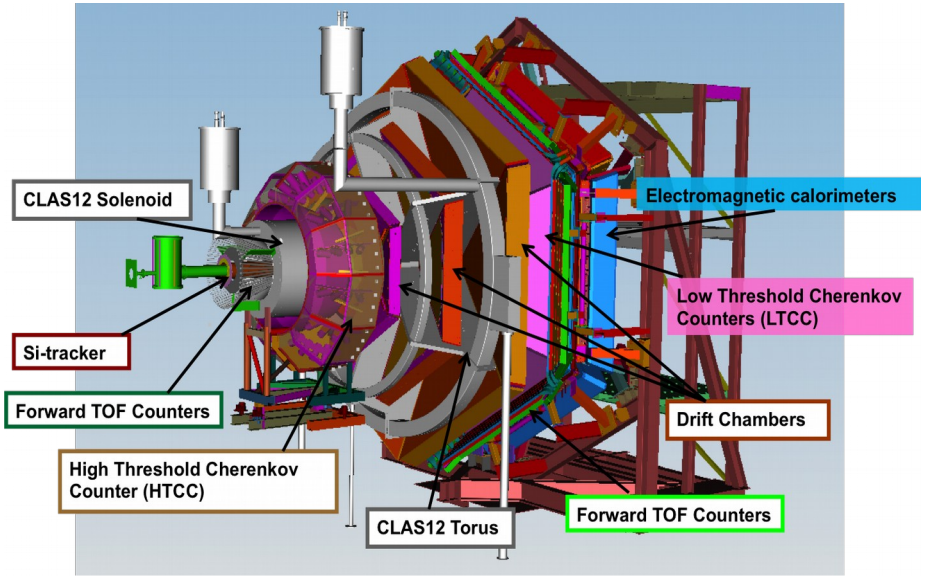
[A. Airapetian, et al., Phys. Rev. C 81, 035202 (2010)]

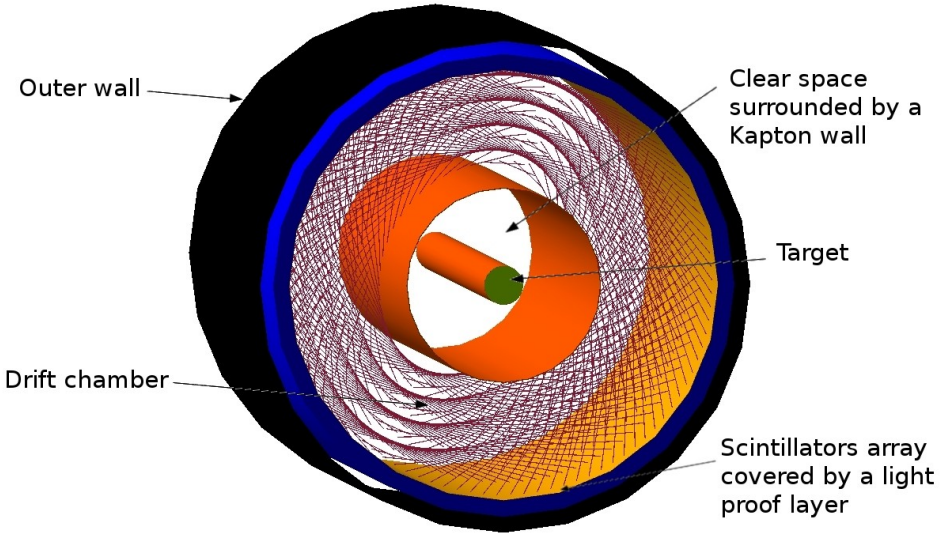
→ **Incoherent/proton** is supressed compared to both the PWIA and the nuclear spectral function calculations.

[S. Liuti and K. Taneja. PRC 72 (2005) 032201]
[V. Guezy et al., PRC 78 (2008) 025211]

CLAS12-ALERT Program

- CLAS–E08-024 experiment:
  - 2D binning due to limited statistics
  - Limited phase-space.
- CLAS12 experimental apparatus:
  - High luminosity & large acceptance.
  - Measurements of deeply virtual exclusive, semi-inclusive, and inclusive processes.
- We proposed to measure with CLAS12:
  - Partonic Structure of Light Nuclei.
  - Tagged EMC Measurements on Light Nuclei.
  - Spectator-Tagged DVCS Off Light Nuclei.
  - Other Physics Opportunities.
- The momentum threshold of the CLAS12 inner tracker is too high to be used for our measurements.
- Proposed experimental setup:
  - CLAS12 forward detectors.
  - A Low Eenergy Recoil Tracker (ALERT) in place of CLAS12 Central detector (SVT & MVT).
- CLAS12-ALERT setup will allow higher statistics and wider kinematical coverage.





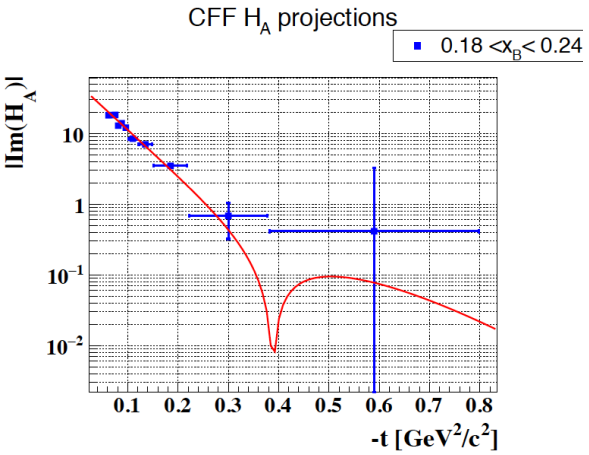
Partonic Structure of Light Nuclei (PR12-17-012)

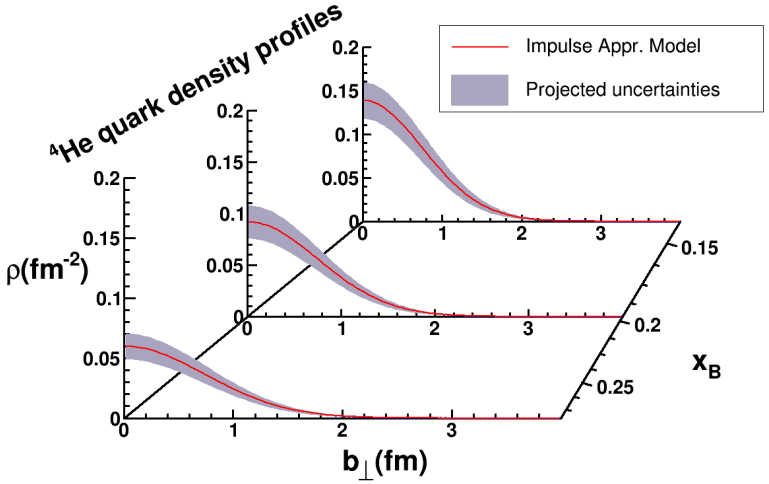
- Map the fundamental structure of nuclei within the GPD framework
- Compare the quark and gluon 3D structure of the Helium nucleus

e ^{4}He→e` $^4$He`γ:

- Fully model independent extracion of H_A CFF from fitting the BSA.
- Fourier transform of Im(H_A) at ξ=0 gives probability densitiy of quarks as function of x and impact parameter.

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

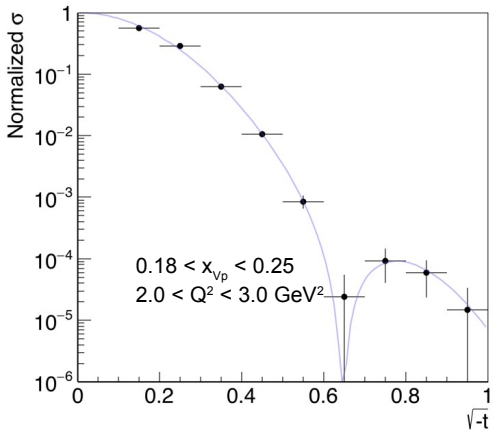


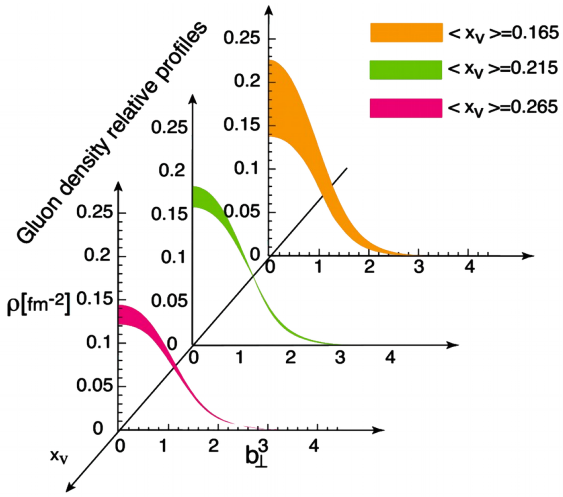


e ^{4}He→e` $^4$He`φ:

- Detect recoil ^{4}He, e, and K^+ (missing K^-)
- The longitudinal cross-section will be extracted from the angular distribution of the kaon decay in the phi helicity frame.
- Gluon density extraction:

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

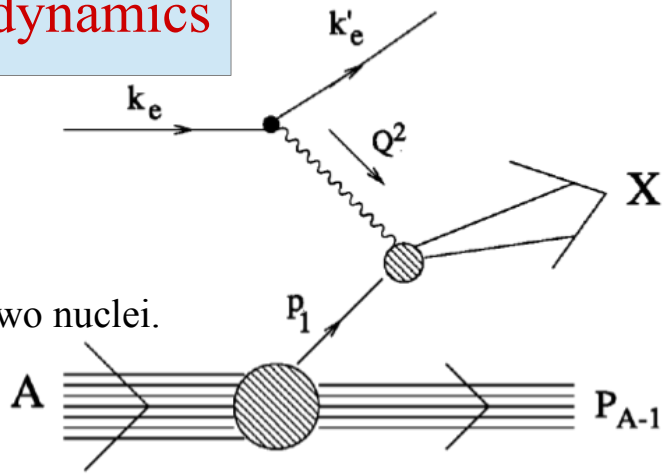




Requested PAC days: 20 days at 3x10^{34} cm^{-2}s^{-1} + 10 days at 6x10^{34} cm^{-2}s^{-1} + (5 Com.)

Tagged EMC Measurements (PR12-17-012A)

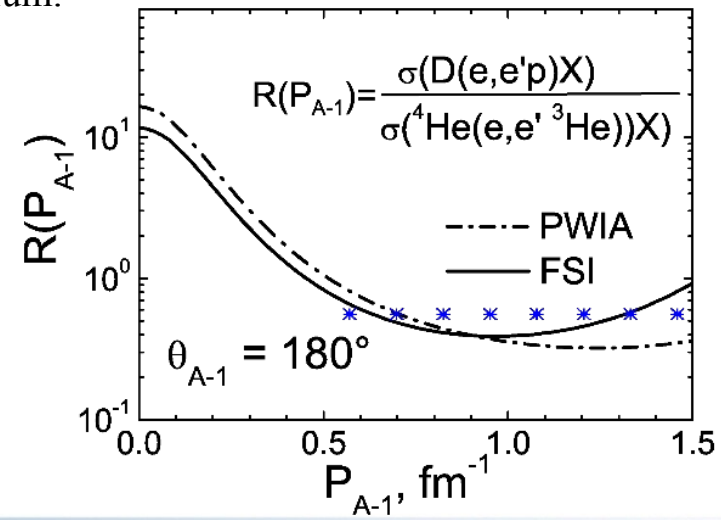
DIS, with tagged spectator, provides access to new variables and explore links between EMC effect and intranuclear dynamics

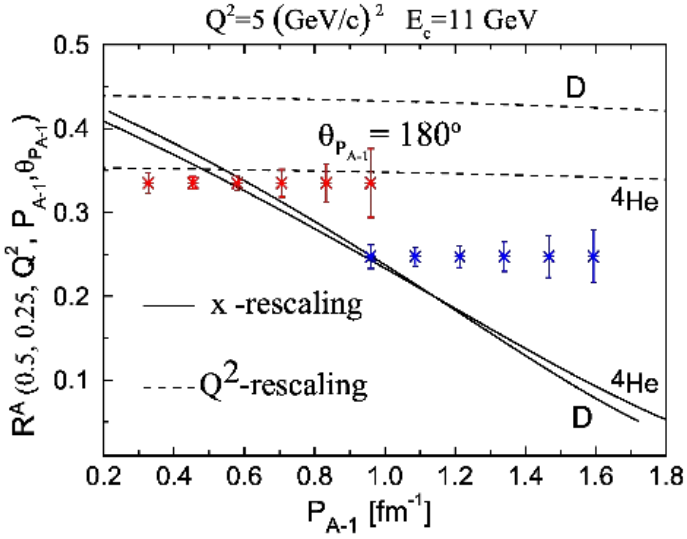


- Comparing D to ^{4}He is particularly interesting:
  - It conserves the nucleus isospin symmetry.
  - ^{4}He is a light nuclei with a sizable EMC effect.
  - The two rescaling effects are cleanly separated by the comparison between the two nuclei.
  - They complement each other in spectator momentum coverage.

- Tagged DIS provides test for:
  - FSI models over wide momentum and angle ranges.
  - EMC effect models: x/Q^2 scaling.
  - d/u ratio changes in nuclear medium.

- 40 (+5) PAC days
  - 20 on ^{4}He (3×10^{34} cm^{-2}s^{-1}).
  - 20 on D 3×10^{34} cm^{-2}s^{-1}).

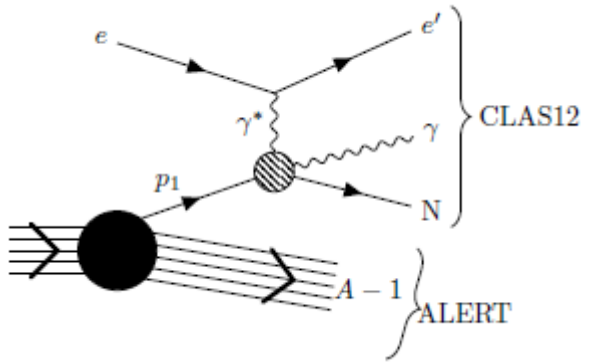


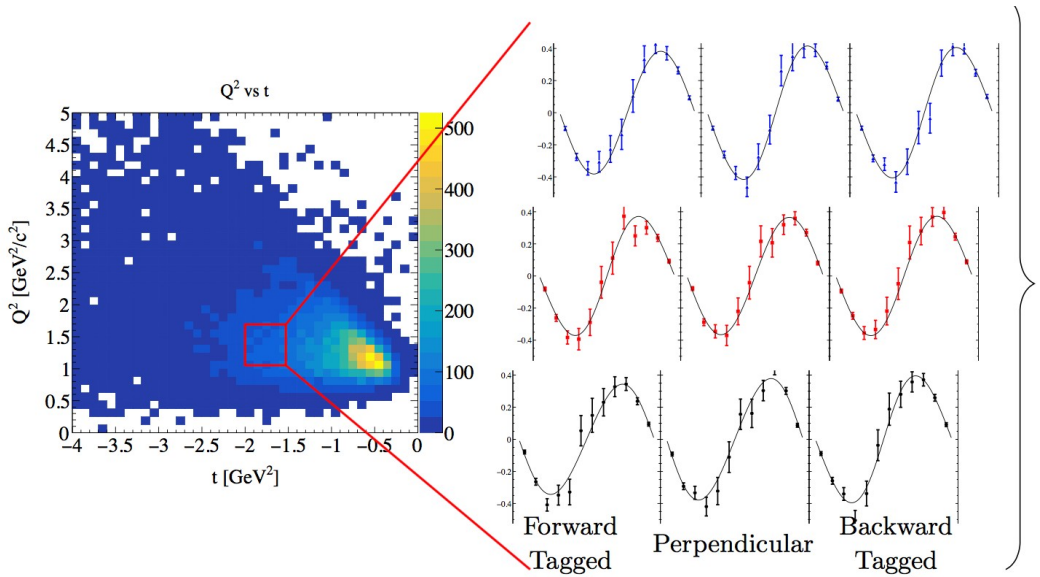


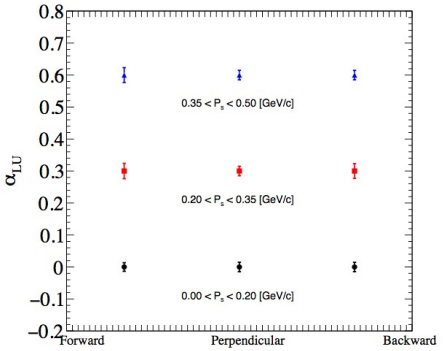
Spectator-Tagged DVCS on Light Nuclei (PR12-17-012B)

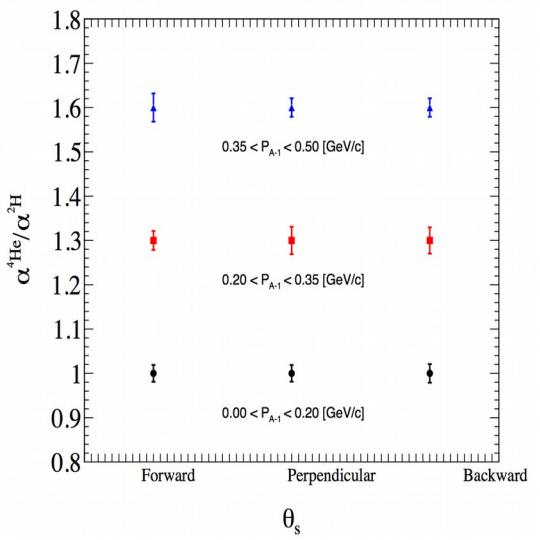
- Probe connection between partonic and nucleonic interpretations via DVCS
- Partonic interpretation and in-medium hadron tomography of nucleons
- Study of Off-Forward EMC effect in incoherent DVCS

- **Bound-p DVCS:**
  - Fully detected ep^{3}H final state, provides unique opportunity to study FSI, test PWIA, identify kinematics with small/large FSI.
- **Bound neutron in ^{4}He/quasi-free in ^{2}H:**
  - e ^{3}He(n) / ep(n) final states (p detection down to ~70 MeV, ^{3}He to ~120 MeV).
  - Six-dimensional binning (Q^2, x_B, t, φ, p_s, θ_s).
- **No additional PAC days**









nDVCS with BONuS12 (Submitted to PAC47)

11 GeV

$e^- D \rightarrow$ .....

- CLAS12 Forward Detector:

→ Superconducting Torus magnet.

→ 6 independent sectors:

→ HTCC: identifying π^- (p >5.0 GeV/c).

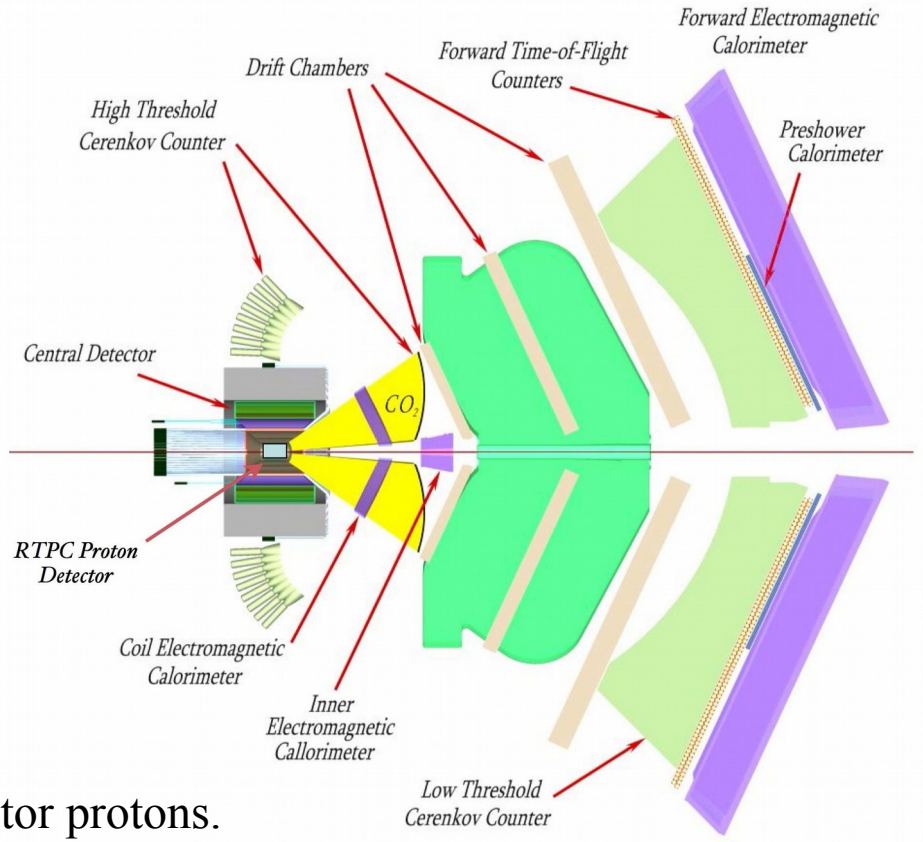
→ 3 regions of DCs: tracking charged particles.

→ LTCC: π^- identification (p >3.0 GeV/c).

→ FTOF Counters: identifying hadrons.

→ PCAL and Ecs: detecting γ, e^- and n [5º,40º].

→ FT : detecting γ, e^- [2.5º,4.5º]



- Central Detector:

- Target: D gas @ 7.5 atm, 293 K

- BONuS12 RTPC: Detects low energy spectator protons.

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

- Additonal detectors to be used: CTOF, CND, and FMT

35 days on D

5 days on H_2

with $L = 2 \cdot 10^{34}$ cm^{-2} sec^{-1}

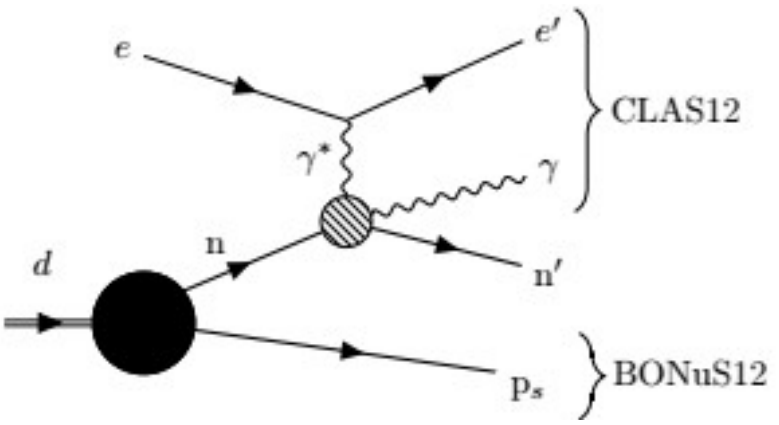
nDVCS & GPDs

Two nDVCS channels are accessible with BONuS12:

◊ **Tagged-proton nDVCS: $e^- D \rightarrow e^- p \gamma (n)$**

→ Study the partonic structure of the neutron via measuring the A_{LU}

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

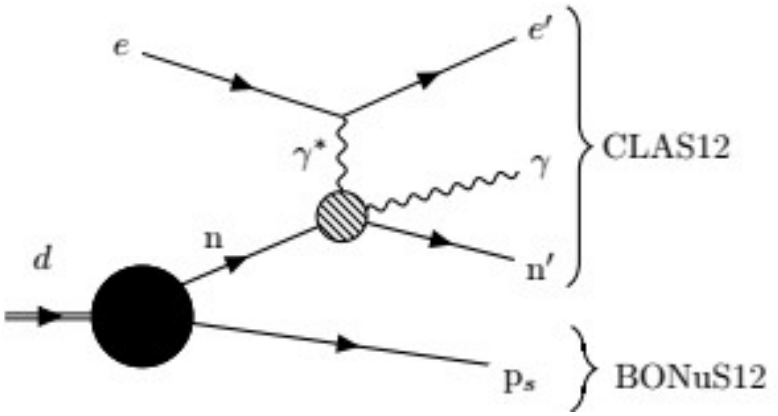


◊ **Fully exclusive nDVCS: $e^- D \rightarrow e^- n \gamma p$**

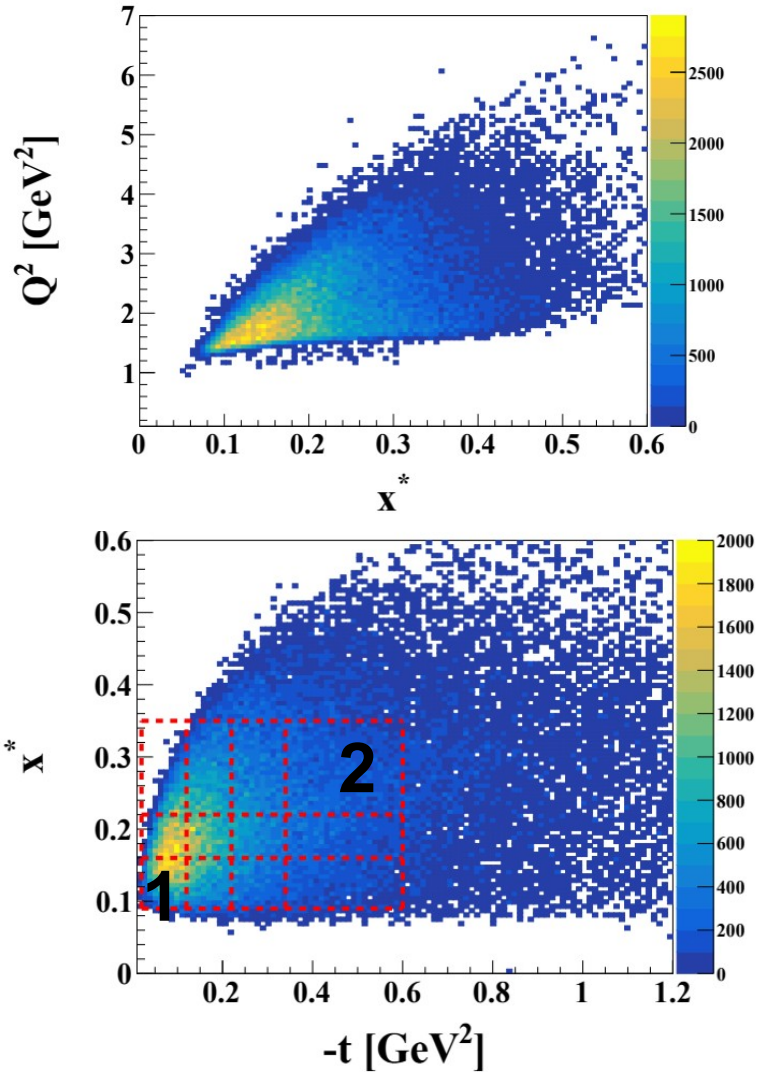
→ Study the Fermi motion effect on A_{LU}

→ Measure the size of the FSI on A_{LU}

→ Explore the size of the systematic uncertainties on RG-B measurement.



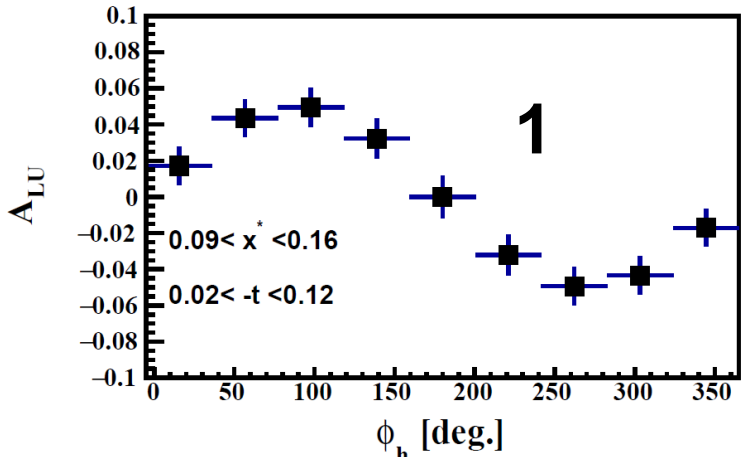
Tagged-proton nDVCS Phase-Space

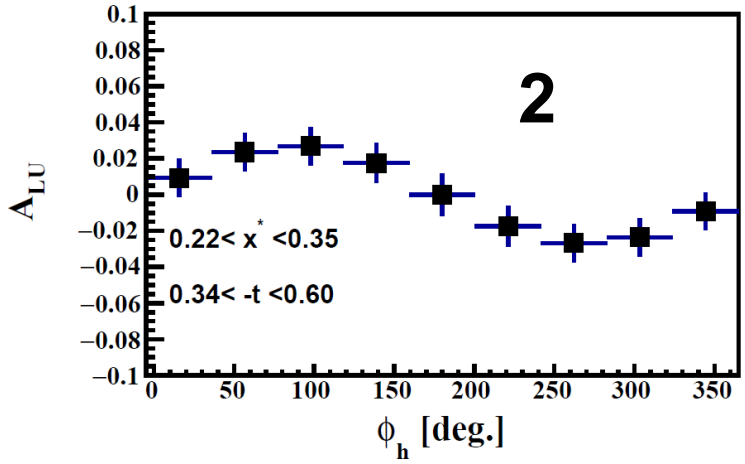


$$x^* = \frac{Q^2}{2M_N E y(2-\alpha_{sp})} = \frac{x_B}{2-\alpha_{sp}},$$

$$\alpha_{sp} = \frac{E_s - p_s^z}{M_N}$$

◊ 9M expected events.
◊ Total of 108 bins in x* vs. t vs. phi
◊ 20% conservative sys. Uncertainities.
◊ Exploring the neutron's CFF via the BSA.
◊ Compare the nDVCS to Free proton DVCS.

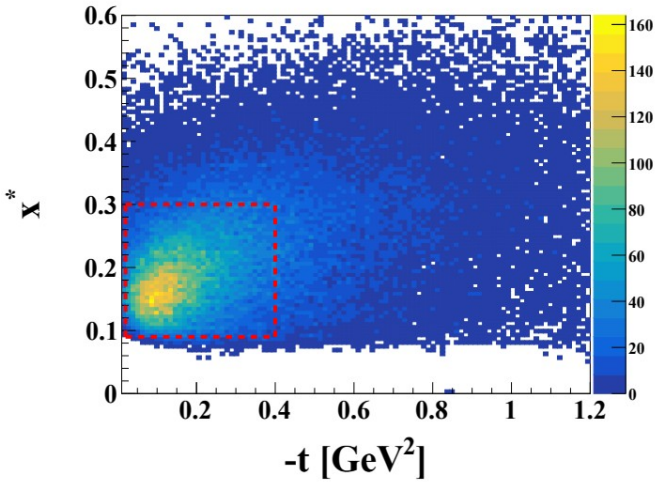


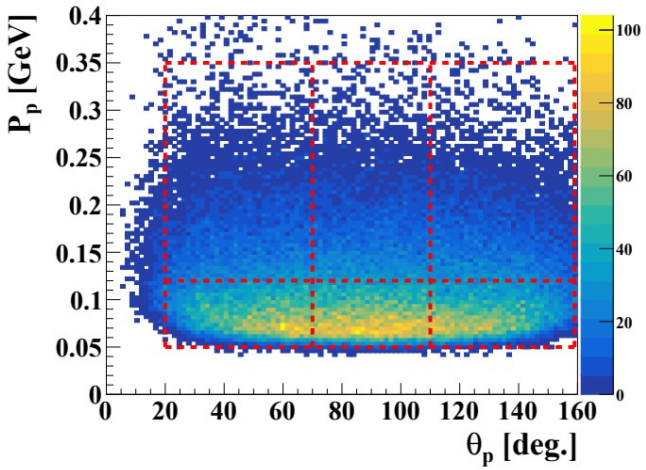


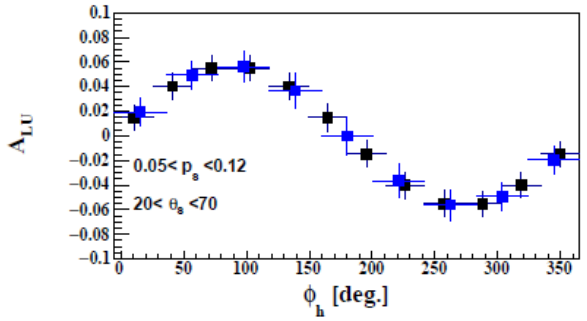
Fully exclusive nDVCS Projections

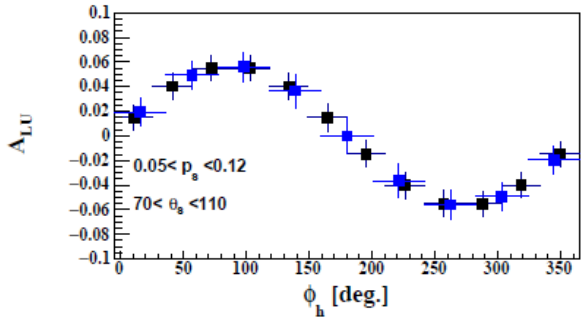
a. Initial bin in x* vs. t
b. 6 bins in p_s vs. θ_s
c. Binning in φ

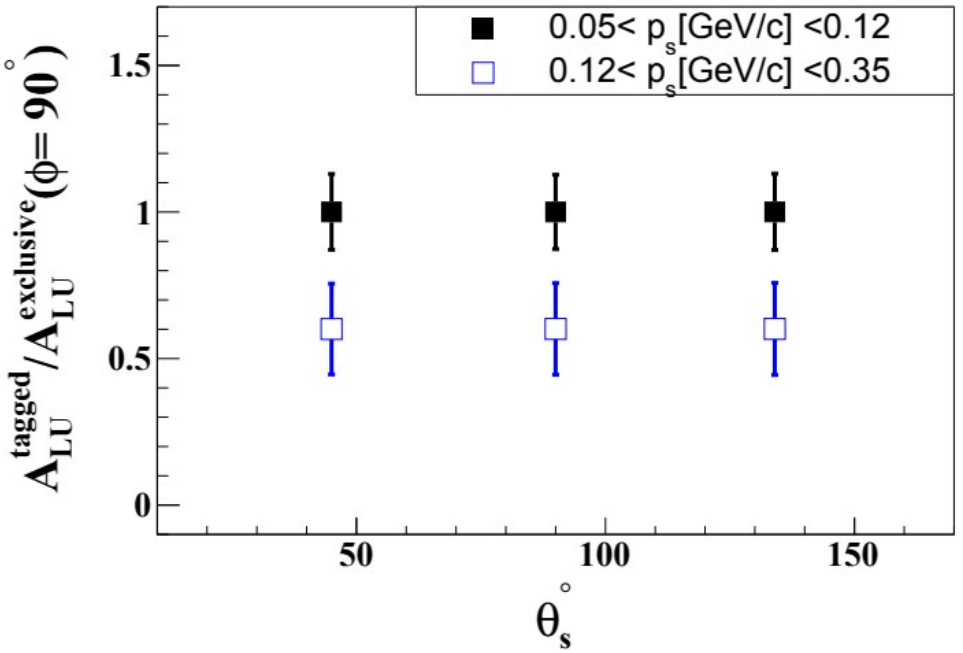
◊ 9M tagged nDVCS events (**black**)
~ 0.8M fully exclusive nDVCS (**blue**).
◊ Exploring the Fermi motion and FSI effects on BSA.











Conclusions & Perspectives

◊ **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 ^{4}He CFF.
→ 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.

◊ **CLAS12-ALERT** will provide wider kinematical coverage and better statistics that will:
→ Allow performing ^{4}He tomography in terms of quarks and gluons.
→ Allow comparing the gluon radius to the charge radius.
→ Use tagging methods to study EMC effect via DIS measurements.
→ Use Tagged-DVCS techniques to study in-medium nucleon interpretations.
→ Reinforce EIC physics program by proving their usefulness in the valence region.

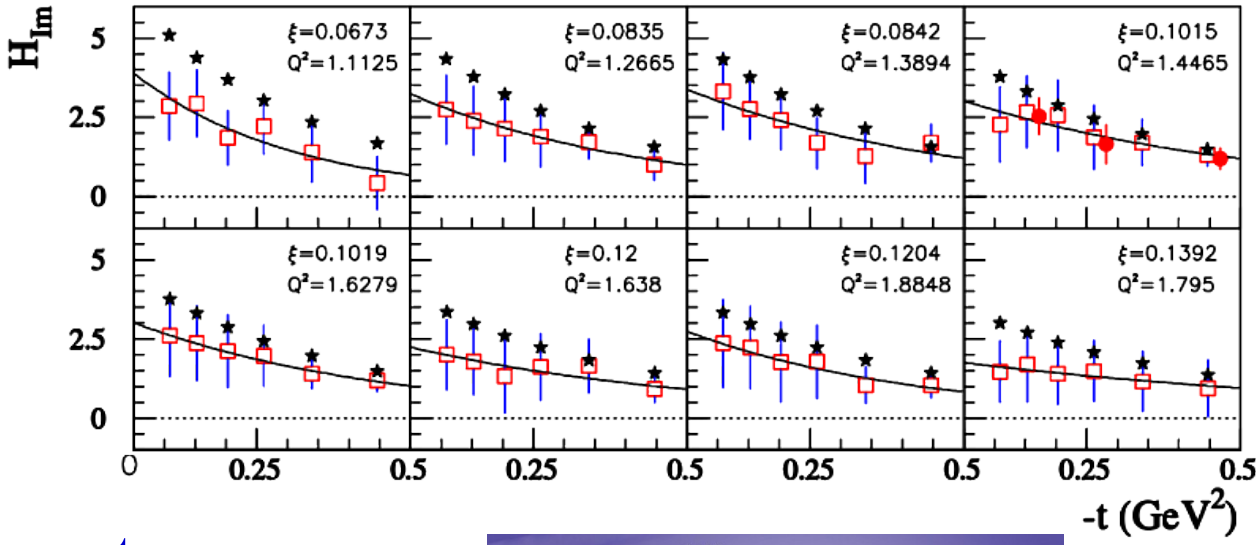
◊ **CLAS12-RGF** we intend to measure the neutron DVCS beam-spin asymmetry by:
→ Tagging the spectator slow-recoiling proton
→ Measuring the fully exclusive neutron DVCS channel.

Thank you!

Proton Tomography via DVCS

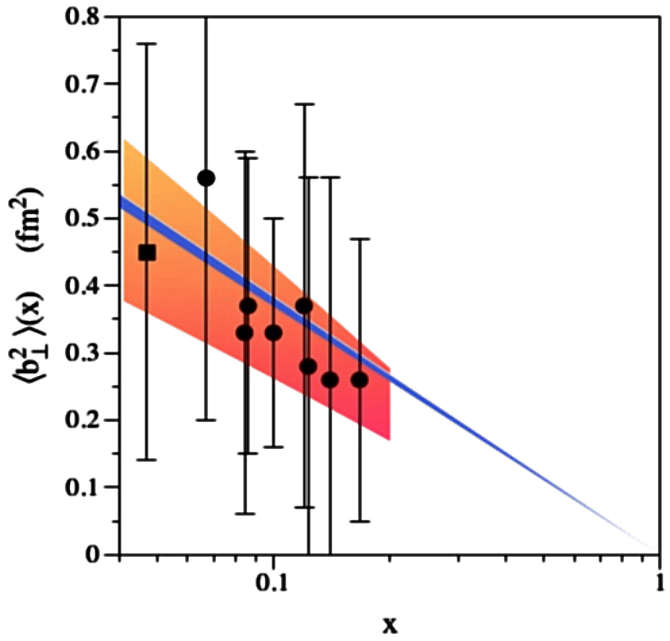
- Local fit of all the JLab data
  - Jlab Hall A (σ, Δσ)
  - CLAS (σ, Δσ, lTSA, DSA)

- Enough coverage to explore the t and x_B (→ξ) dependence of H_{Im}.

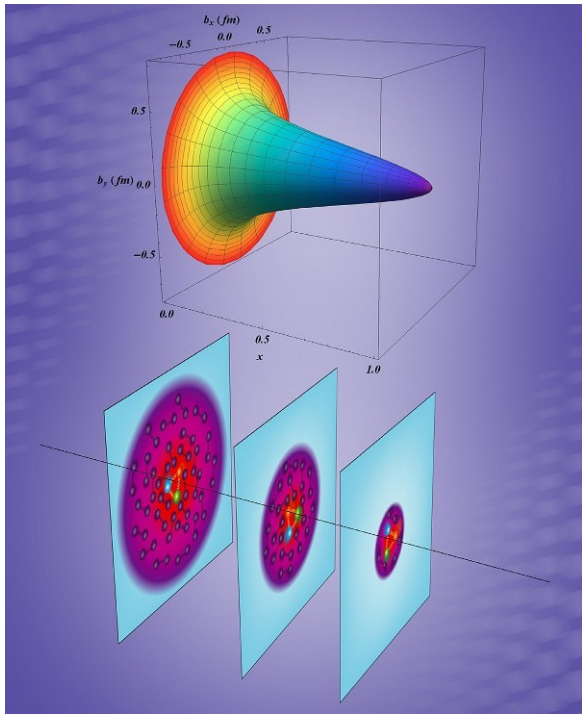


- Obtaining the tomography of the proton

– Represented is the mean square charge radius of the proton for slices of x.



- The nucleon size is shrinking with x.



[R. Dupré et al. Phys.Rev. D95 (2017) no.1, 011501]

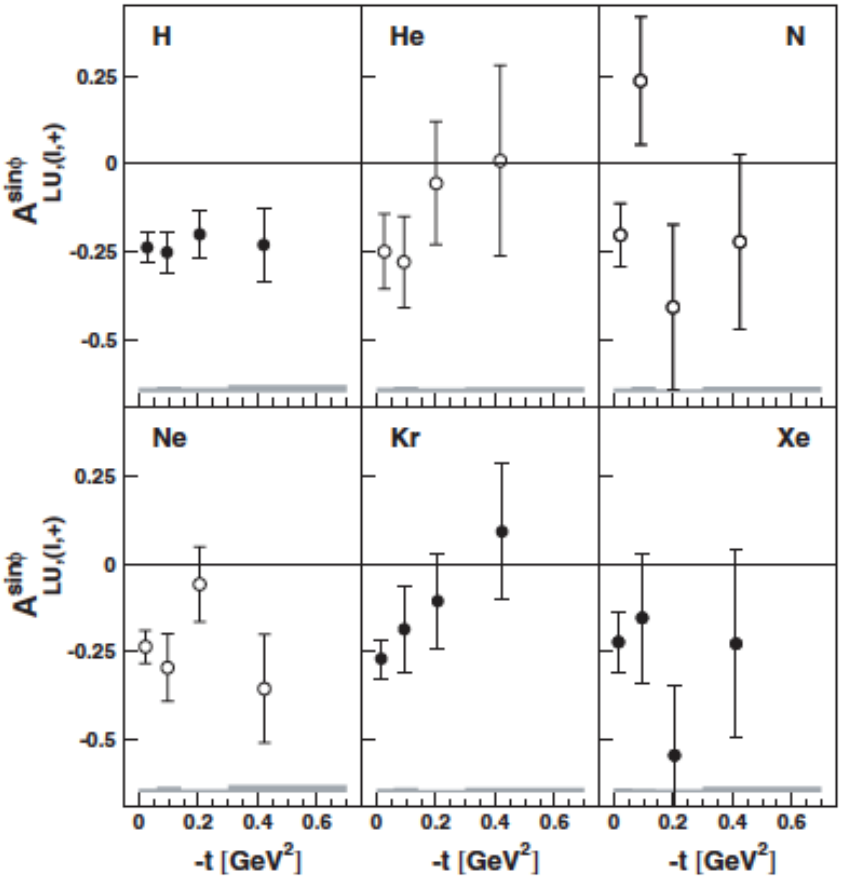
Nuclear DVCS Measurements: HERMES

- 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

Other Physics Topics with ALERT (PR12-17-012C)

The three main proposals of the ALERT run group is only a fraction of the physics that can be achieved by successfully analyzing the ALERT run group data

- π^0 production off ^{4}He
  - Coherent and incoherent production.
  - Measure BSA, leading to chiral-odd CFFs.
  - Also as a DVCS background.
- Coherent DVCS off D
  - Access to new GPDs, H_3 , with relationships to dueteron charge form factors.
- Coherent DVMP off D
  - π^0 , φ, ω and ρ mesons.
- Semi-inclusive reaction p(e,e`p)X
  - Study the π^0 cloud of the proton.
- D(e, e`pp$_s$)X
  - Study the π^- cloud of the neutron.

- More Physics:
  - Helium GPDs beyond the DVCS at leading order and leading twist.
  - Tagged nuclear form factors measurements.
  - The role of Δs in short-range correlations.
  - The role of the final state interaction in hadronization and medium modified fragmentation functions.
  - The medium modification of the transverse momentum dependent parton distributions.
  - ... and more

Other Topics with Polarized Beam During RG-F

The proposed nDVCS measurments is only a fraction of the physics that can be achieved by successfully analyzing the polarized beam data from RG-F.

- π^0 production off D
  - Coherent and incoherent production.
  - Measure BSA, leading to chiral-odd CFFs.
  - Also as a DVCS background.
- Coherent DVCS off D
  - Access to new GPDs, H_3 , with relationships to dueteron charge form factors.
- Coherent DVMP off D
  - π^0 , φ, ω and ρ mesons.
- Semi-inclusive reaction p(e,e`p)X
  - Study the π^0 cloud of the proton.
- D(e, e`pp$_s$)X
  - Study the π^- cloud of the neutron.
- Incoherent p DVCS & DVMP
- More Physics:
  - Transverse momentum distributions (TMDs) on the neutron (twist-3).
  - The medium modification of the transverse momentum dependent parton distributions.
  - Final state interactions through the 5 th structure function in D(e, e 0 p s)n.