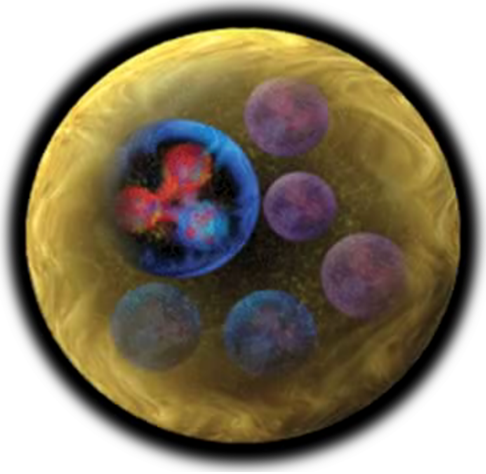
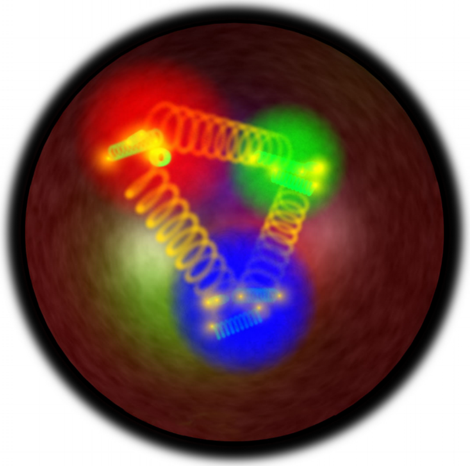
OLD DOMINION UNIVERSITY

3D Partonic Structure of Nucleons and Nuclei

M. Hattawy

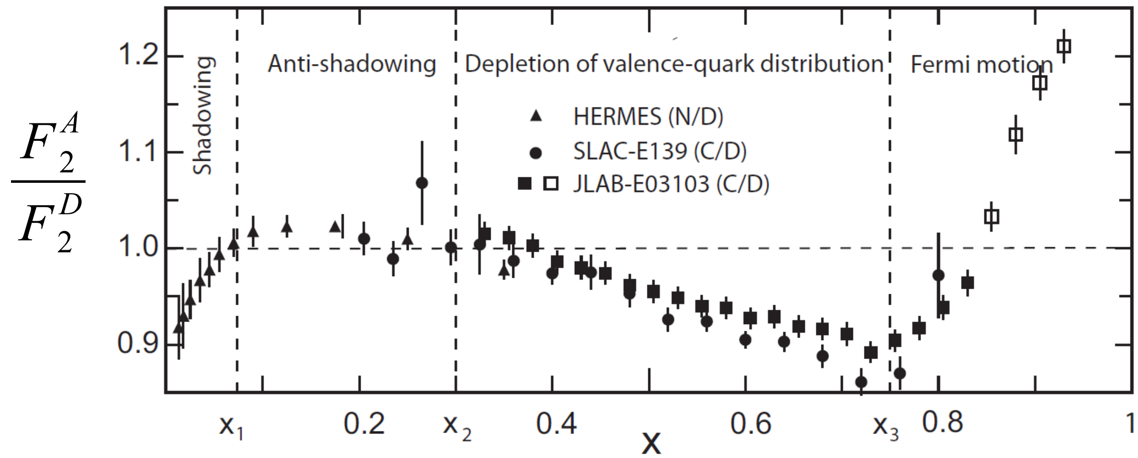


- Physics Motivations
- Recent Results.
- Future Measurements.



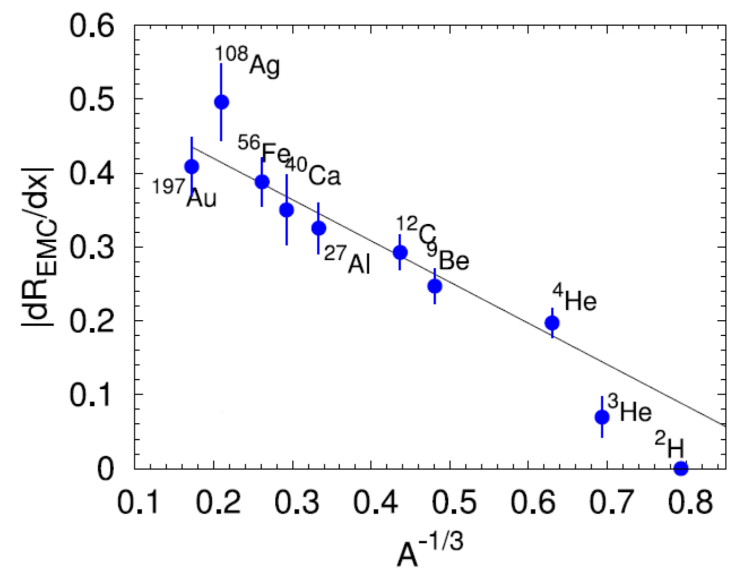
Light Cone 2018, 14-18 May 2018, Jefferson Lab

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

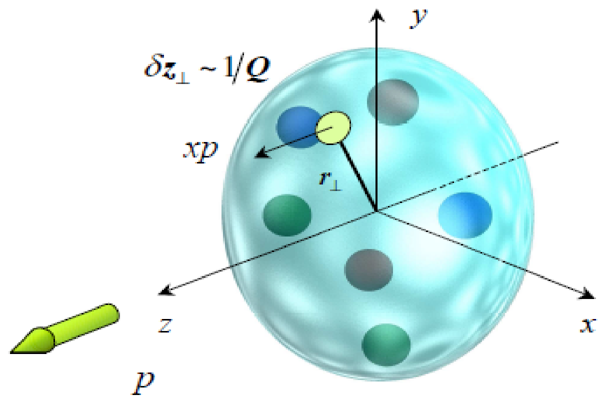
- The origin of the EMC effect is still not fully understood, but possible explanations:
  → Modifications of the nucleons themselves
  → Effect of non-nucleonic degrees of freedom, e.g. pions exchange
  → Modifications from multi-nucleon effects (binding, N-N correlations, etc...)

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

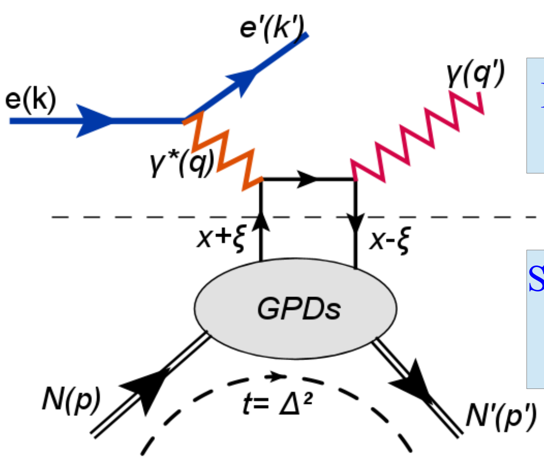
Generalized Parton Distributions

- 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)

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

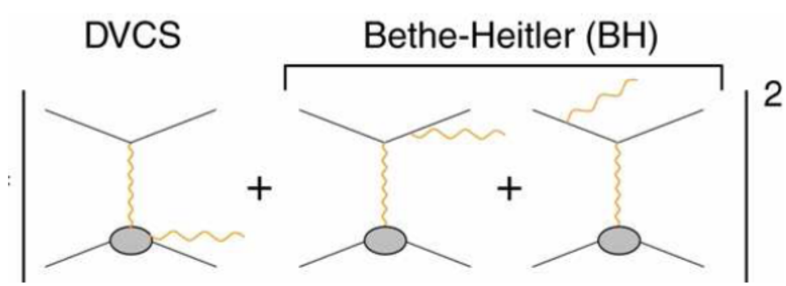
$$\xi \simeq x_B/(2-x_B) \qquad x_B = Q^2/2\text{p.q}$$

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

* 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:

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



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

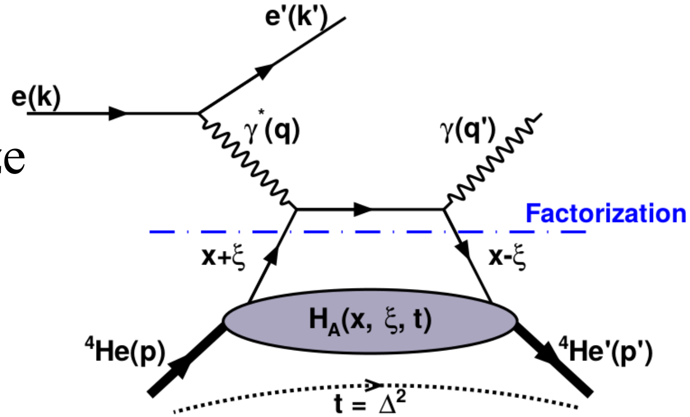
DVCS off Nuclei

Two DVCS channels are accessible with nuclear targets:

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

→ Study the partonic structure of the nucleus.

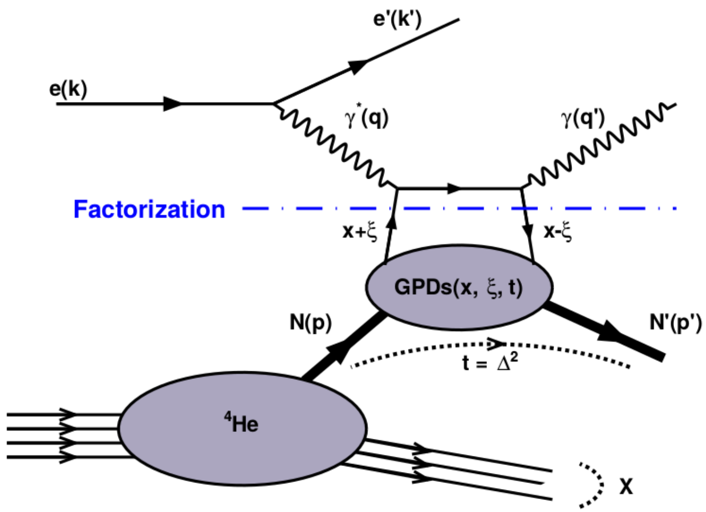
→ One chiral-even GPD (**$H_A(x,\xi,t)$**) is needed to parametrize the structure of the spinless nuclei (^{4}He, ^{12}C, ^{16}O, ...).

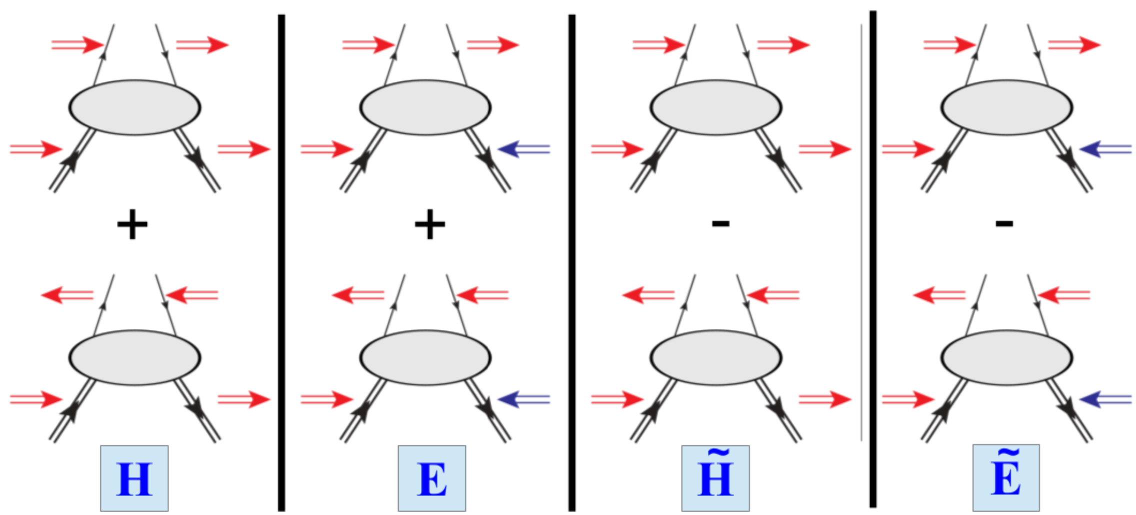


◊ **Incoherent DVCS: $e^- A \rightarrow e^- N \gamma\ \ X$**

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

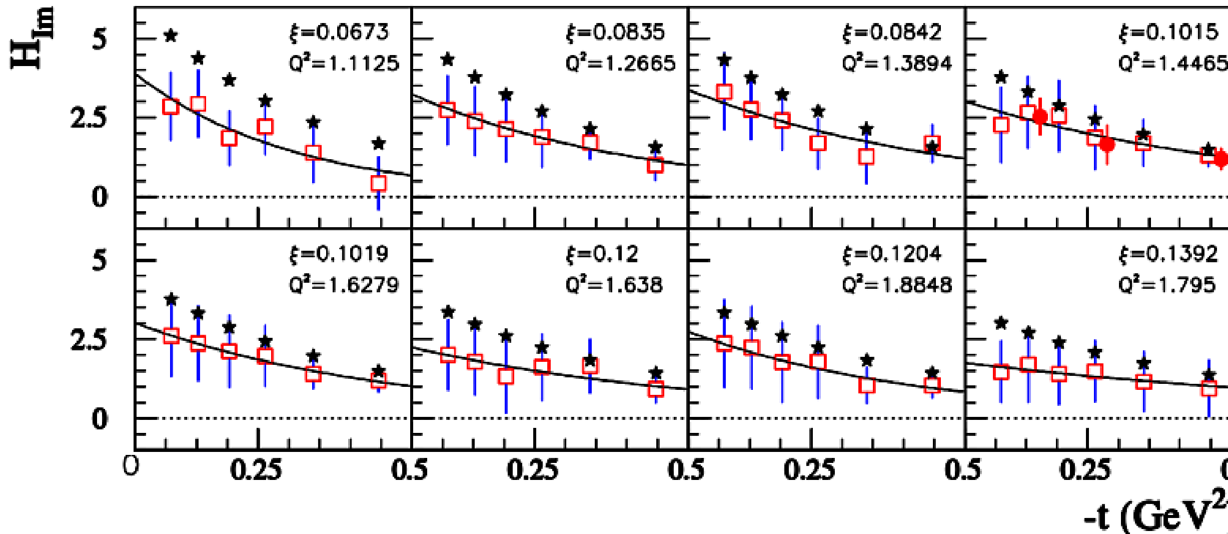
→ Study the partonic structure of the bound nucleons (4 chiral-even GPDs are needed to parametrize their structure).





Proton Tomography via DVCS

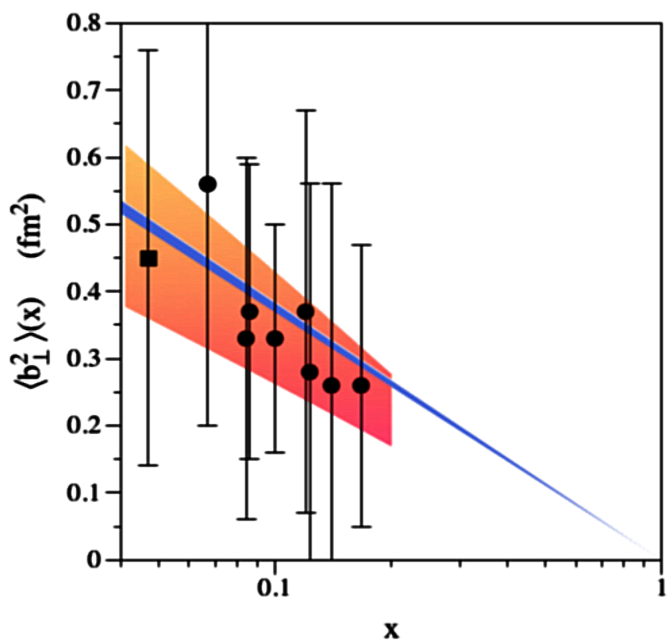
- Local fit of all the JLab data
  - Jlab Hall A (σ, Δσ)
  - CLAS (σ, Δσ, lTSA, DSA)

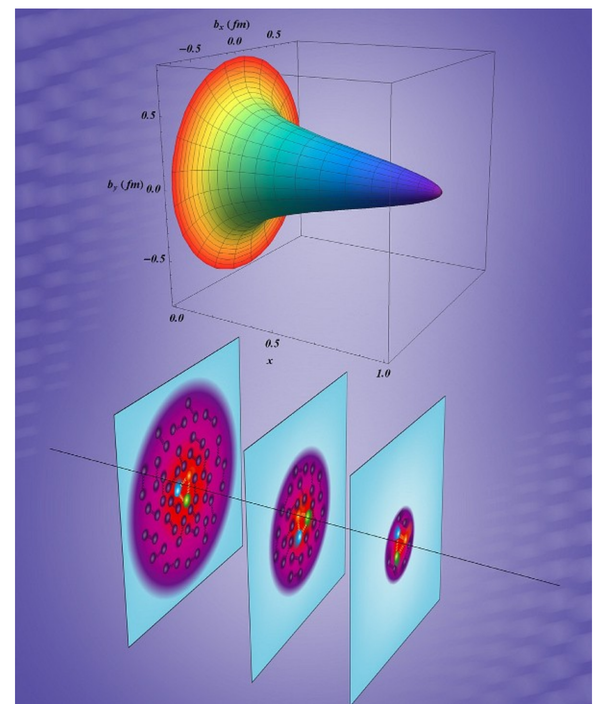


- Enough coverage to explore the t and x_B (→ξ) dependence of H_{Im}.

- 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 Spin-Zero DVCS Observables

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

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

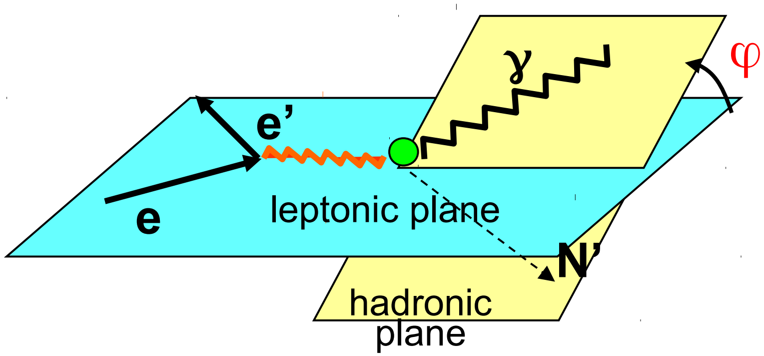
$$Im(\mathcal{H}_A(\xi,t)) = H_A(\xi,\xi,t) - H_A(-\xi,\xi,t)$$

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

Quark propagator

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

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



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

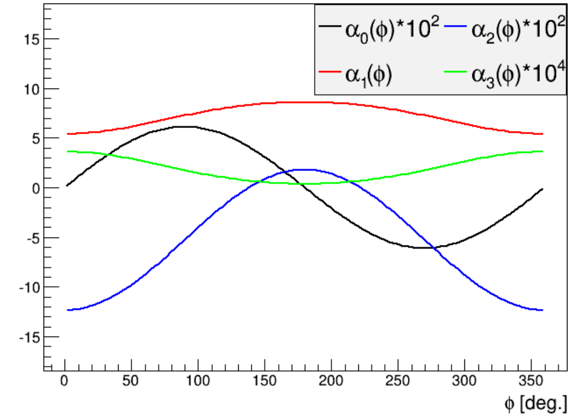
$$= \frac{\alpha_0(\phi)\,\Im m(\mathcal{H}_A)}{\alpha_1(\phi) + \alpha_2(\phi)\,\Re e(\mathcal{H}_A) + \alpha_3(\phi)\left(\Re e(\mathcal{H}_A)^2 + \Im m(\mathcal{H}_A)^2\right)}$$

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

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

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

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



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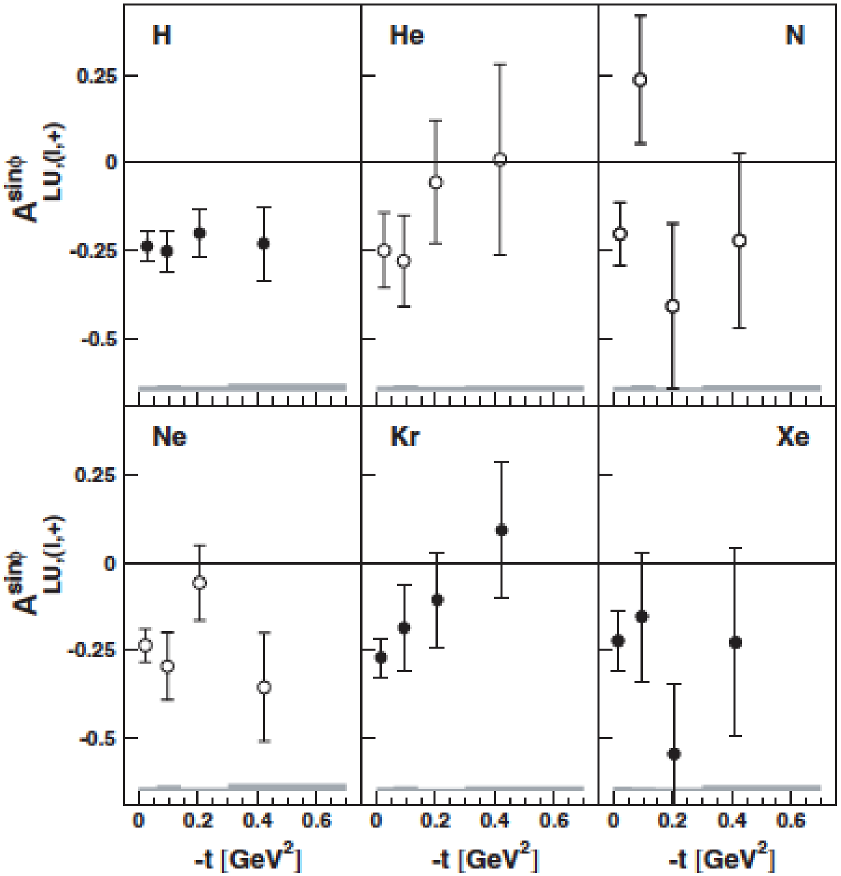
Nuclear DVCS Measurements: HERMES

- 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

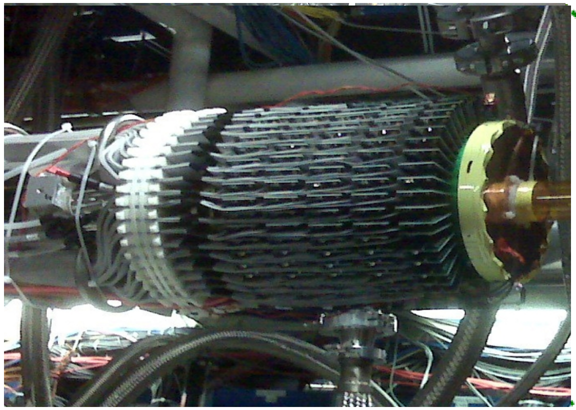
CLAS - E08-024 Experimental Setup

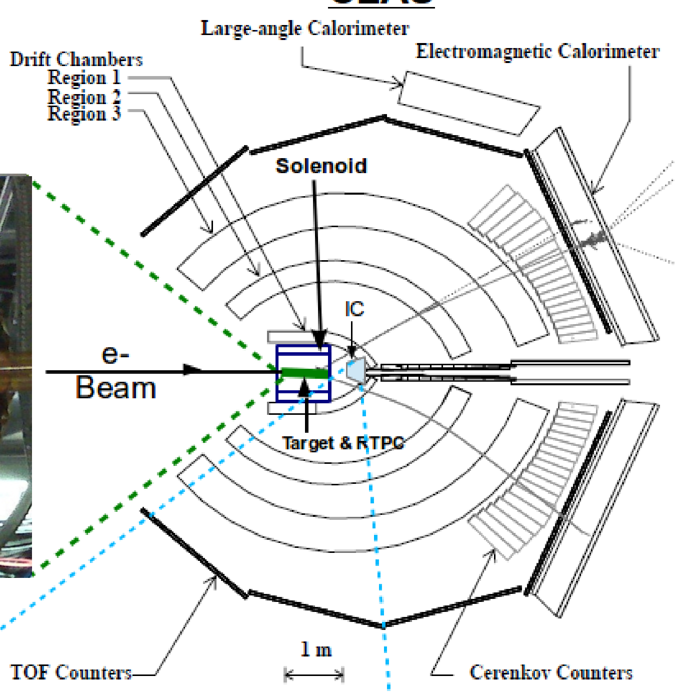
$e^- \, {}^4He \rightarrow e^- \, ({}^4He/pX) \, \gamma$

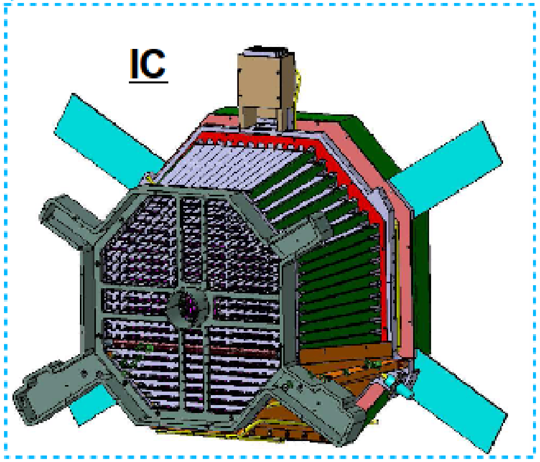
6 GeV,
L. polarized

Beam polarization (P_B) = 83%

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

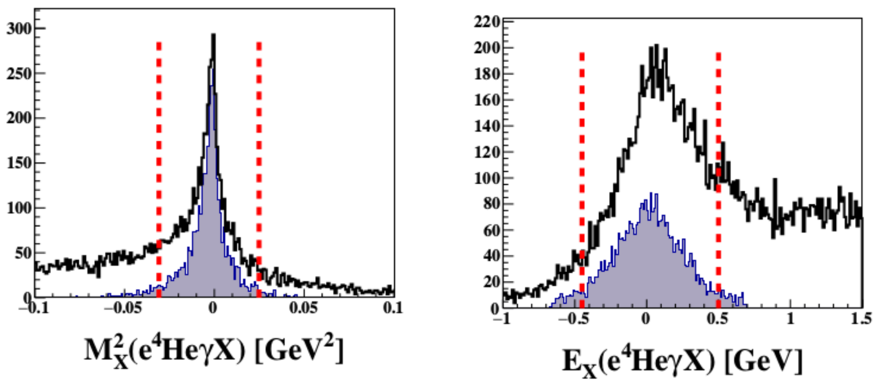
Coherent DVCS Selection & Asymmetries

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).

◊ $Q^2 > 1$ GeV^2.

◊ Exclusivity cuts.

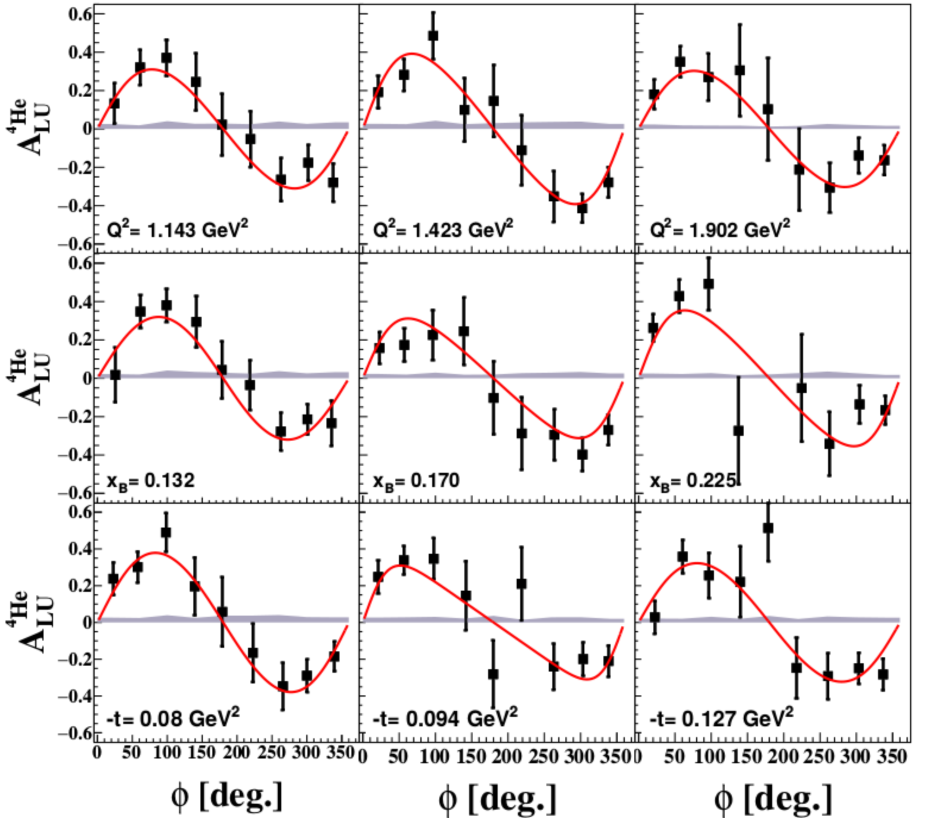


2. π^0 background subtraction based on data and simulation (cont. ~ 2 – 4%)

3. Beam-spin asymmetry:

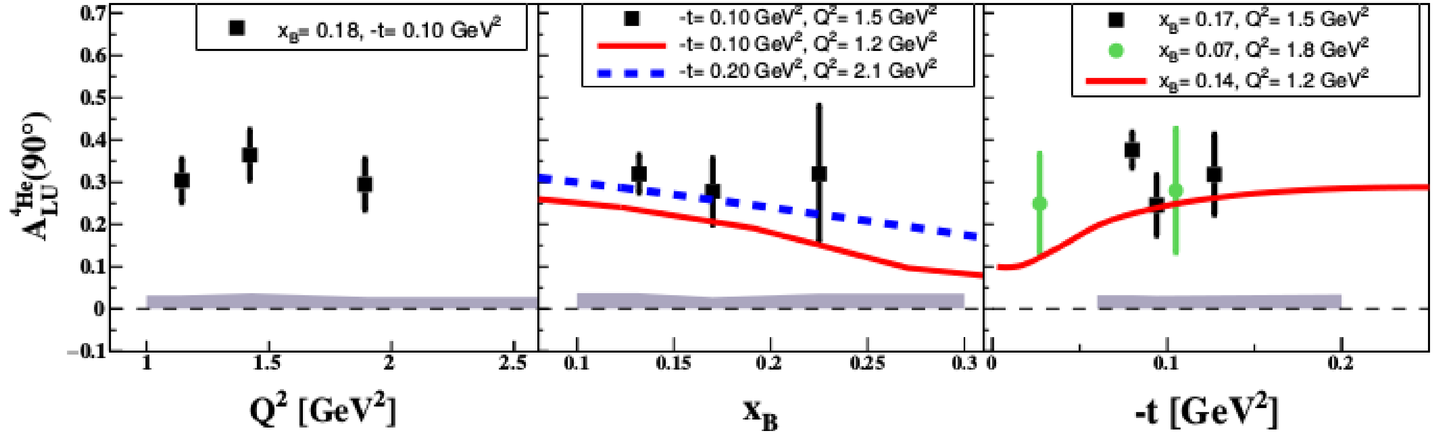
$$A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$$

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

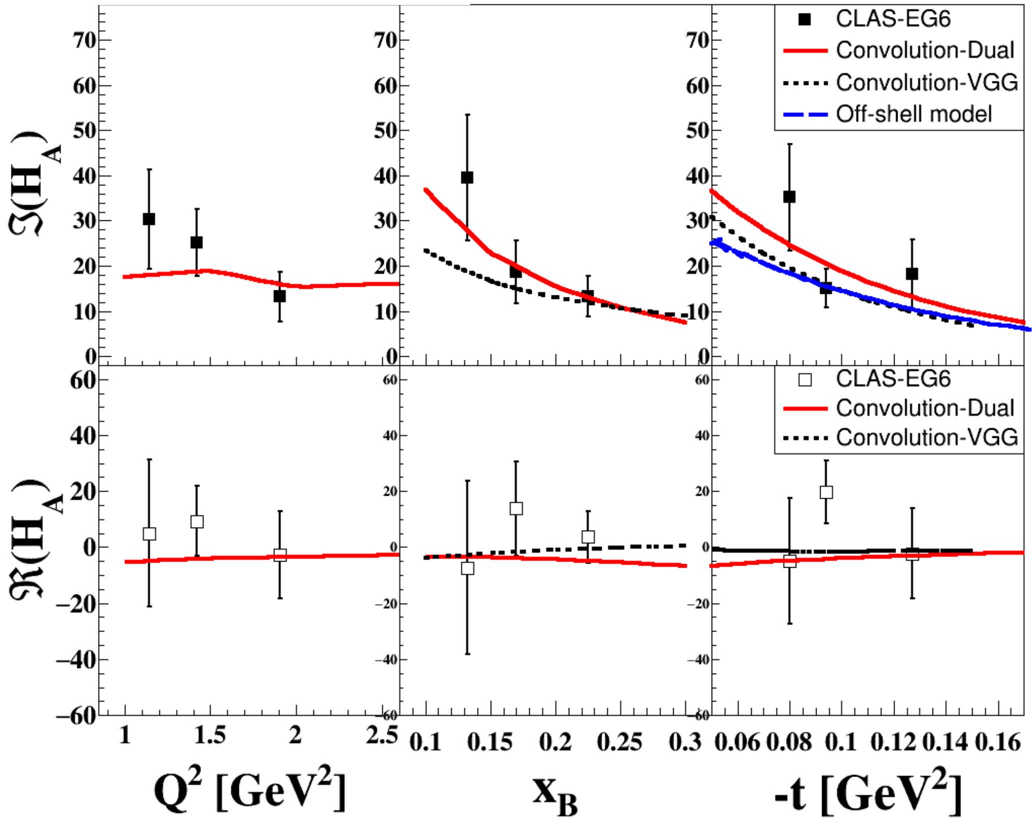


- 2D bins due to limited statistics
- Uncertainities dominated by statictics
- Systematic uncertainities (~ 10 %)
- dominated by exclusivity cuts (~8 %) and large phi bining (~5 %)

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

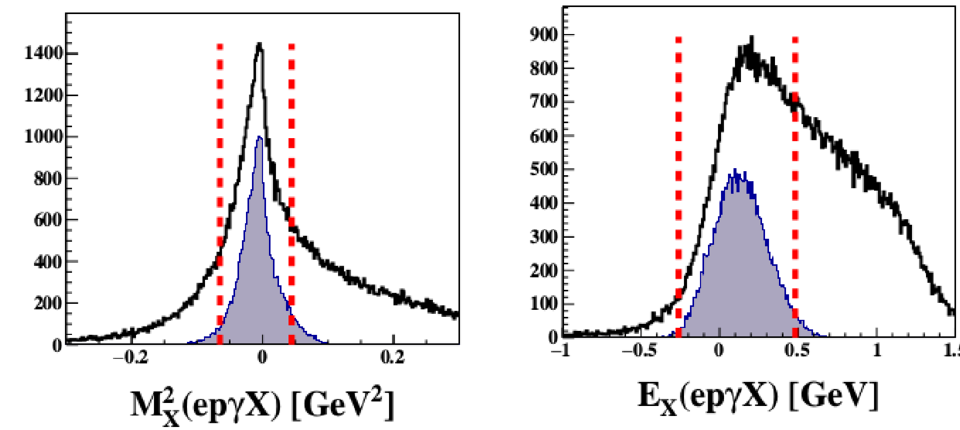
1. We select events which have:

◊ Events with :

- Only one good electron in CLAS
- At least one high-energy photon ($E\gamma > 2$ GeV)
- Only one proton in CLAS.

◊ $Q^2 > 1$ GeV² and W> 2 GeV/c²

◊ Exclusivity cuts (3 sigmas).

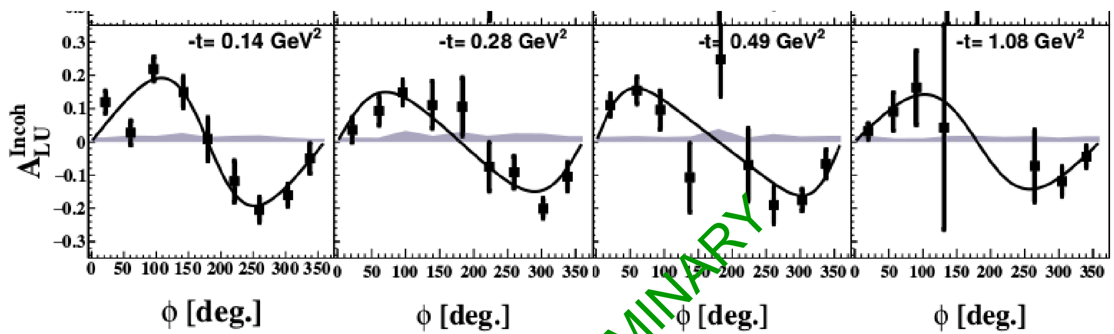


2. π^0 background subtraction (contaminations ~ 8 - 11%)

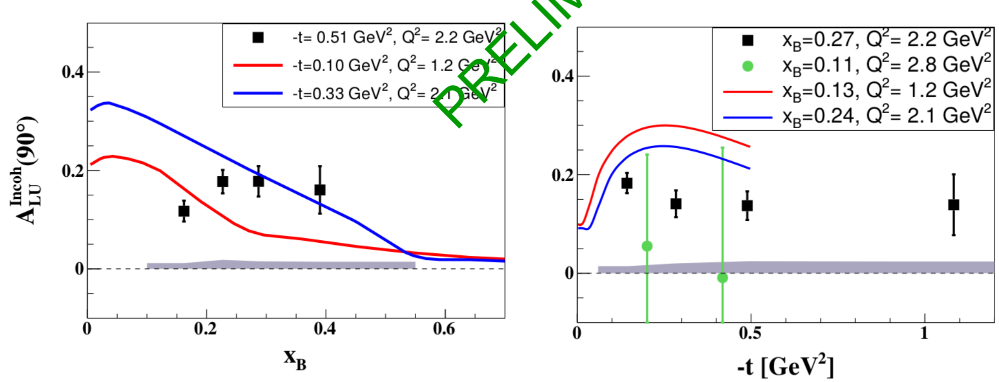
3. Beam-spin asymmetry:

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

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



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



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

* A PRL presenting the incoherent results is under progress.

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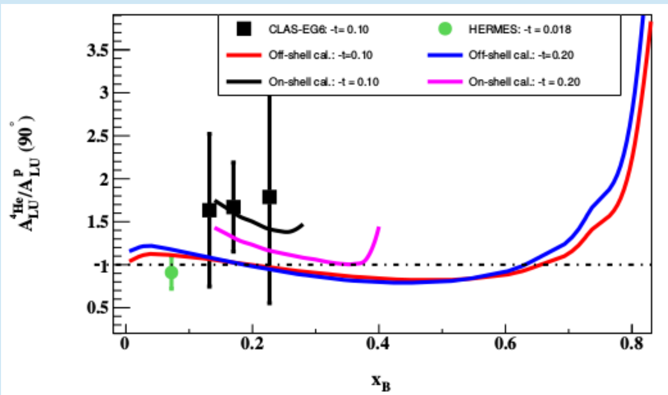
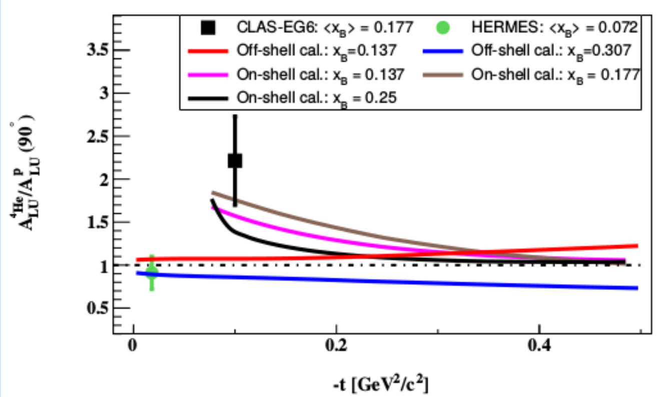
Generalized EMC Ratio

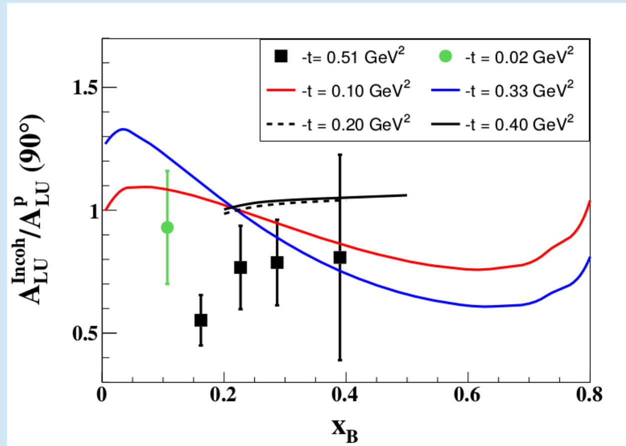
◊ We comparing our measured coherent/incoherent asymmetries to the asymmetries measured in CLAS DVCS experiment on free proton

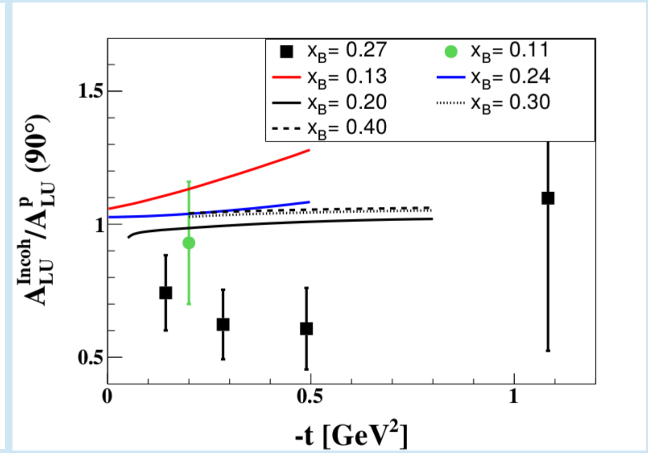
- Coherent/proton:





- 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]

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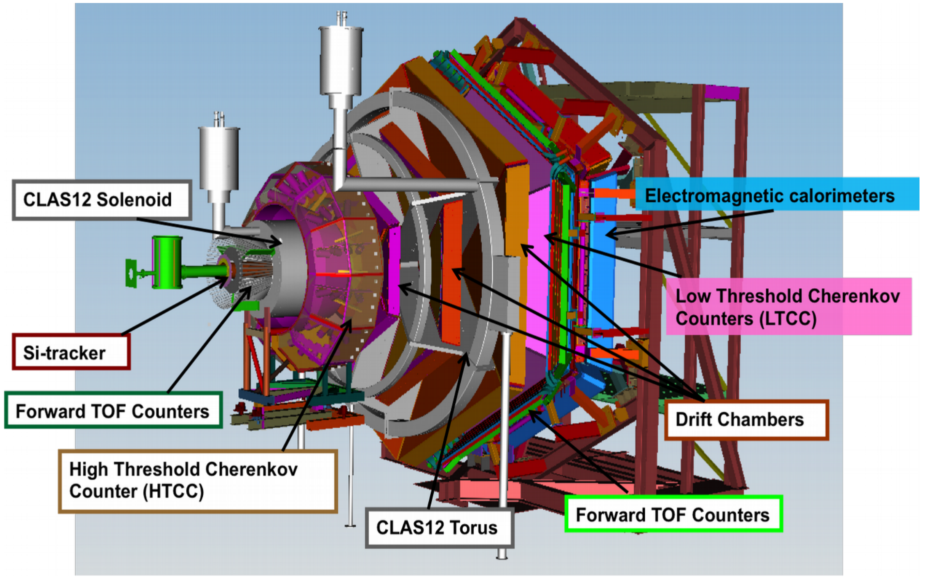
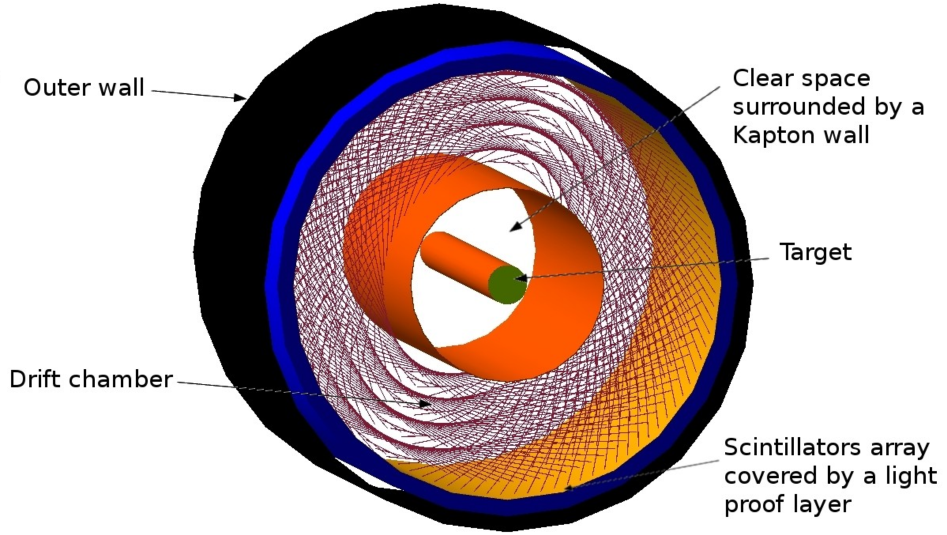
CLAS12-ALERT Program

- 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.



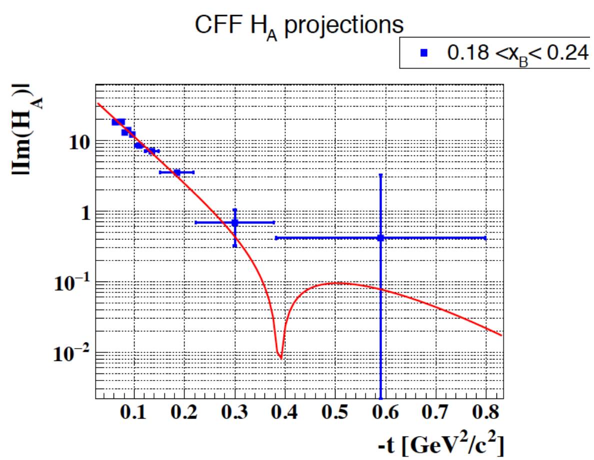
Partonic Structure of Light Nuclei (PR12-17-012)

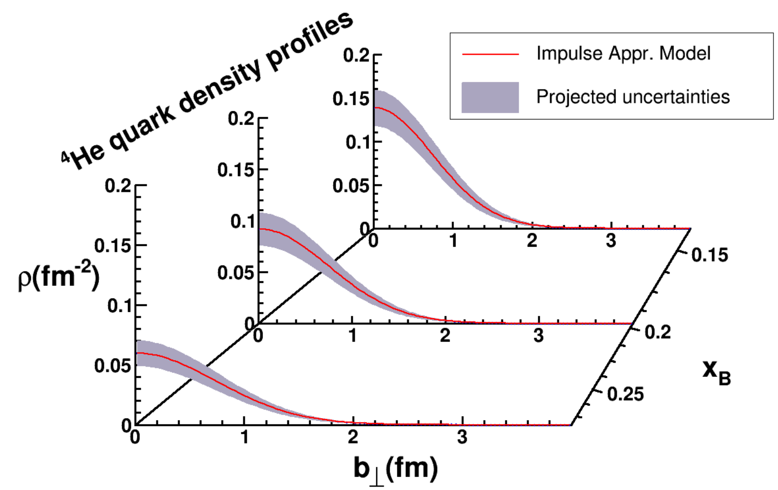
- Map the fundamental structure of nuclei within the GPD framework
- Compare the quark and gluon 3D structure of the Helium nucleus

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.

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

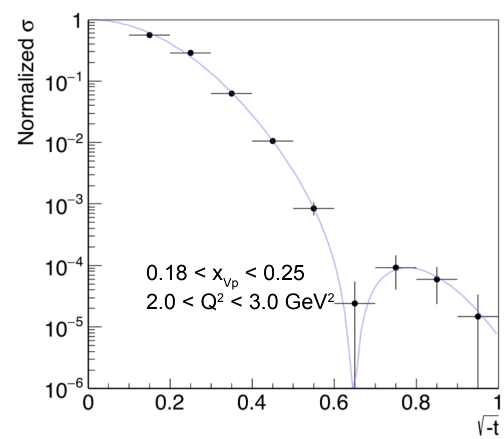


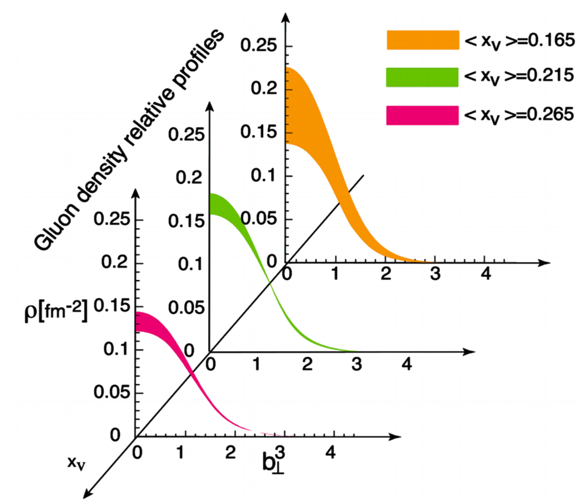


e ^{4}He→e\` $^4$He\`φ:

- 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.)

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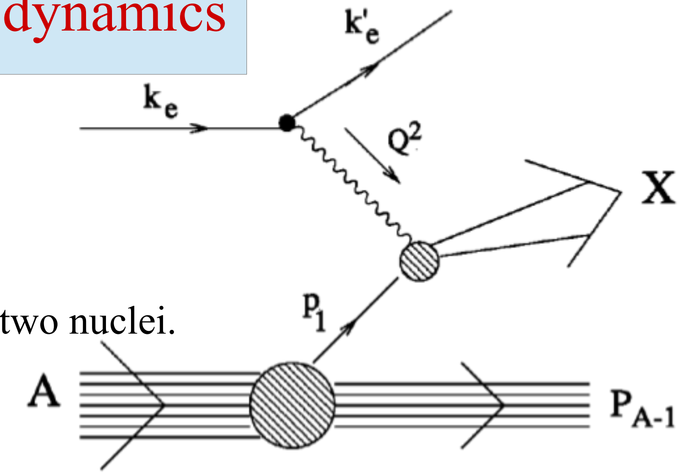
Tagged EMC Measurements (PR12-17-012A)

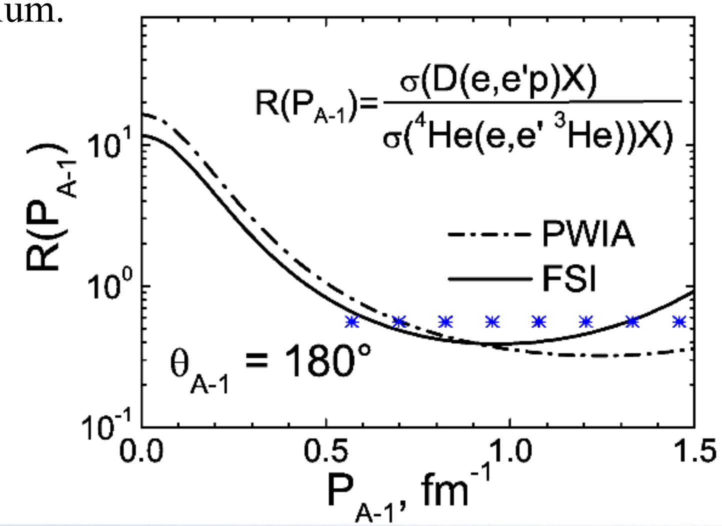
DIS, with tagged spectator, provides access to new variables and explore links between EMC effect and intranuclear dynamics

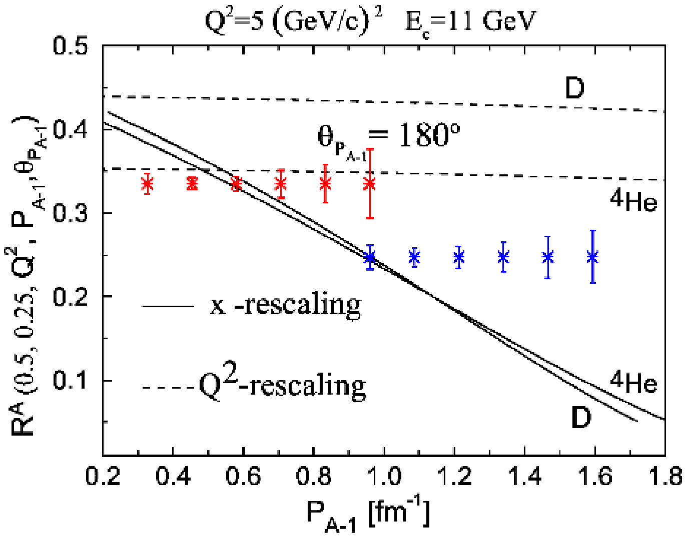


- Comparing D to ^{4}He is particularly interesting:
  - It conserves the nucleus isospin symmetry.
  - ^{4}He is a light nuclei with a sizable EMC effect.
  - The two rescaling effects are cleanly separated by the comparison between the two nuclei.
  - They complement each other in spectator momentum 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 ($3x10^{34}$ $cm^{-2}s^{-1}$).
  - 20 on D $3x10^{34}$ $cm^{-2}s^{-1}$).



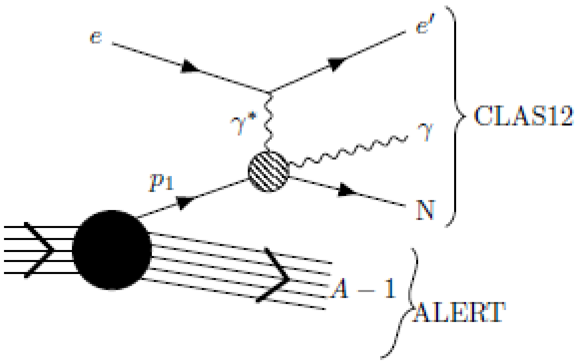


Spectator-Tagged DVCS On Light Nuclei (PR12-17-012B)

- 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:

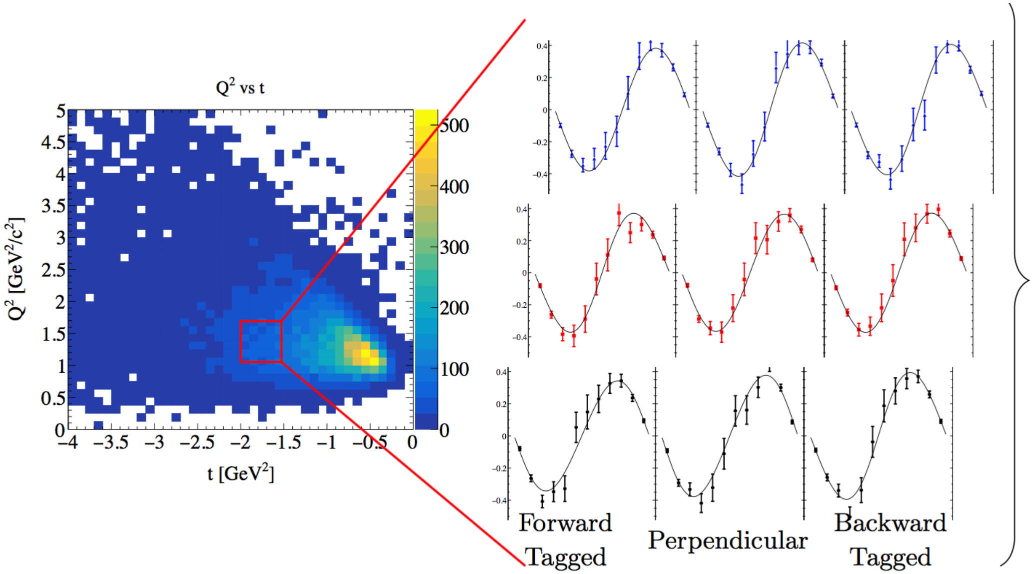
- Fully detected ep^3H final state, provides unique opportunity to study FSI, test PWIA, identify kinematics with small/large FSI.

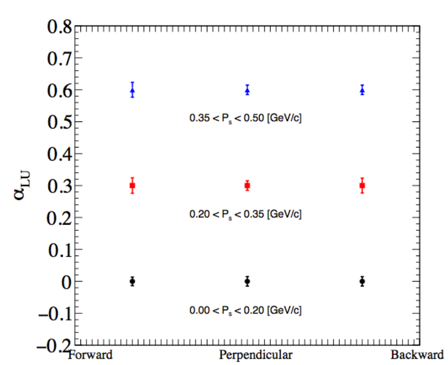


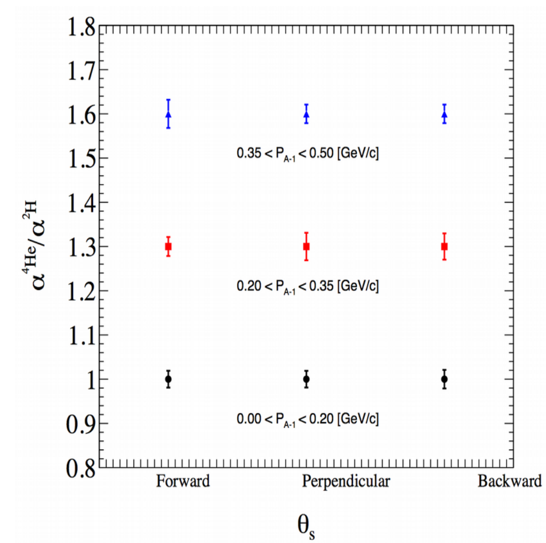
Bound neutron in ^{4}He/quasi-free in ^{2}H:

- 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







Other Physics Opportunities (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

Conclusions & Perspectives

◊ **Several decades of elastic and DIS experiments on hadrons** have provided one-dimensional views of hadrons' structure.

◊ **We are now exploring the 3D structure of nucleons within the GPD framework**
→ Fifteen years of successful experiments at JLab.
→ Accumulated a wide array of proton data.
→ The first tomography was extracted.

◊ **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.
→ 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.

◊ **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.

Theoretical Predictions of the EMC in ^{4}He

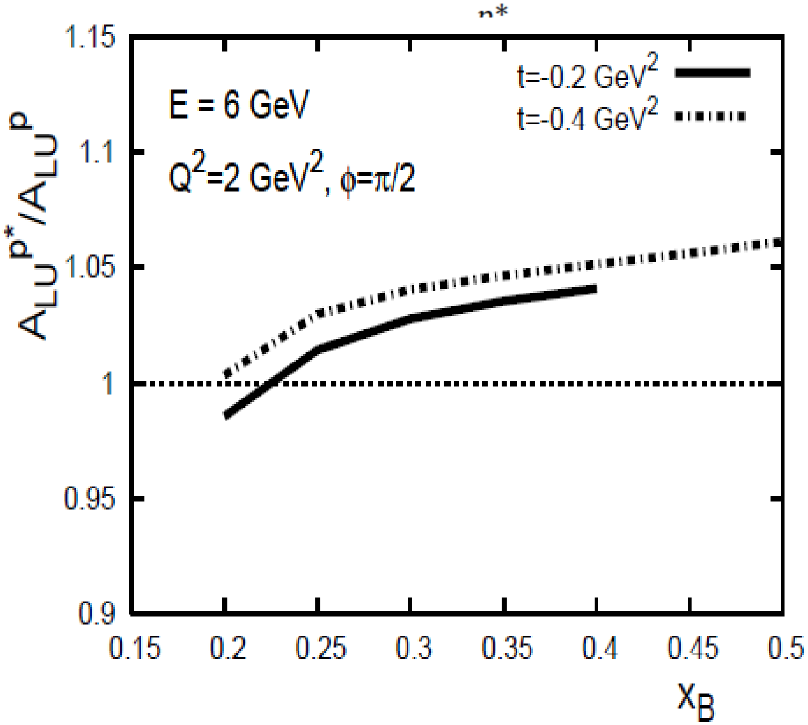
On-shell calculations:

(1) Impulse approximation

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

(2) Medium modifications:

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



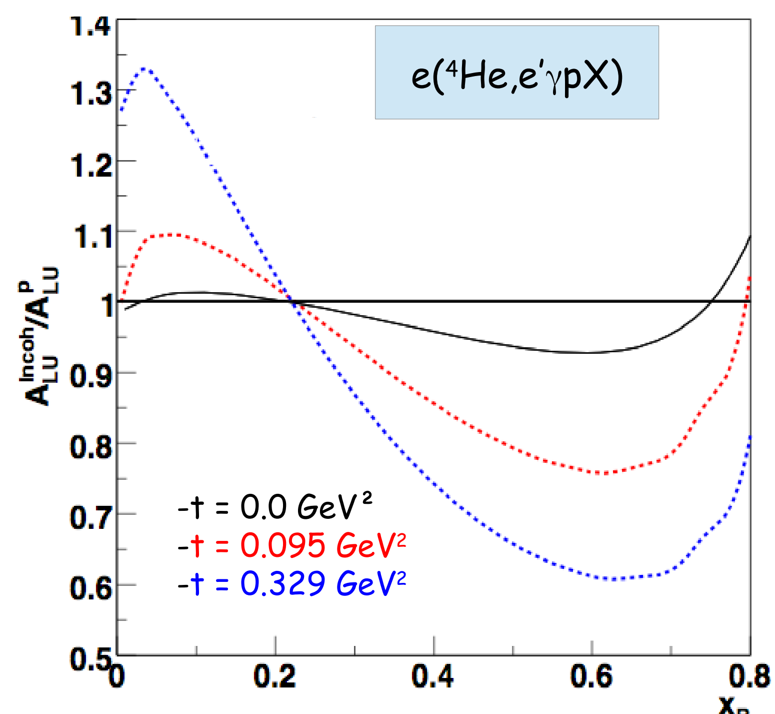
[V. Guzey, A. W. Thomas, K. Tsushima, PRC 79 (2009) 055205]

Off-shell calculations:

Nucleus = bound nucleons + nuclear binding effects

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

Nuclear spectral function



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

New ^{4}He GPDs calculation is coming

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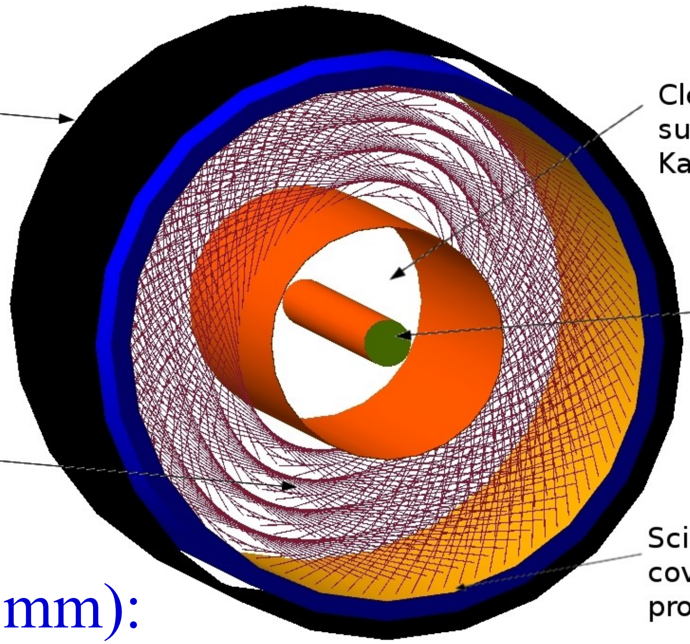
ALERT Detector



- **Cylindrical target:**
  - 30 cm long
  - 6 mm outer radius.
  - Target at 3 atm pressure.
  - 25µm target wall (Kapton).

- **A clear space filled with helium**
  to reduce secondary scattering from the high rate Moller electrons (R_{out} = 30 mm).

- **Hyperbolic drift chamber (32 mm< R< 85 mm):**
  →Will detect the trajectory of the low energy nuclear recoils.
  - 8 circular layers of 2mm hexagonal cells.
  - 10° stereo-angle to give z-resoluation.
  - Total of 2600 wires, < 600 kg tension.
  - Maximum drift time ~ 250 ns, will be included in the trigger.

- **Two rings of plastic scintillators** (Total thickness of 20 mm, SIPMs directly attached):
  → TOF (< 150 ps resolution) and deposited energy measurements.

→ Separate protons, deuterium, tritium, alpha, ^{3}He

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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