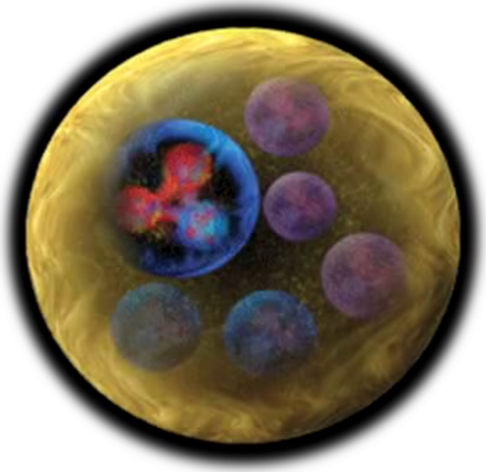
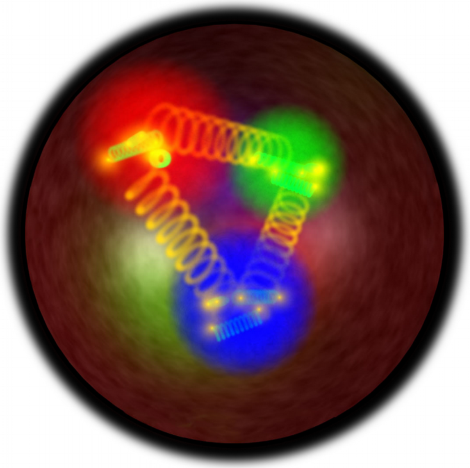
3D Partonic Structure of Nucleons and Nuclei

M. Hattawy



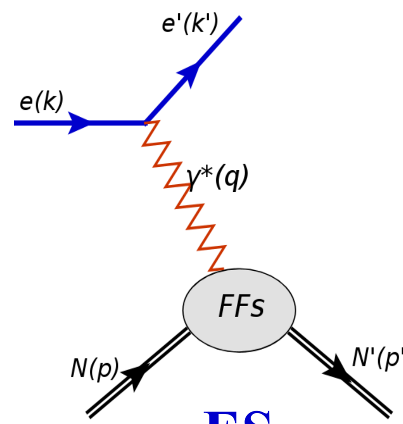
- Physics Motivations
- Recent Results.
- Future Measurements.



Exposing Novel Quark and Gluon Effects in Nuclei, ECT*, 16-20 April 2018

Exploring the Hadron Structure

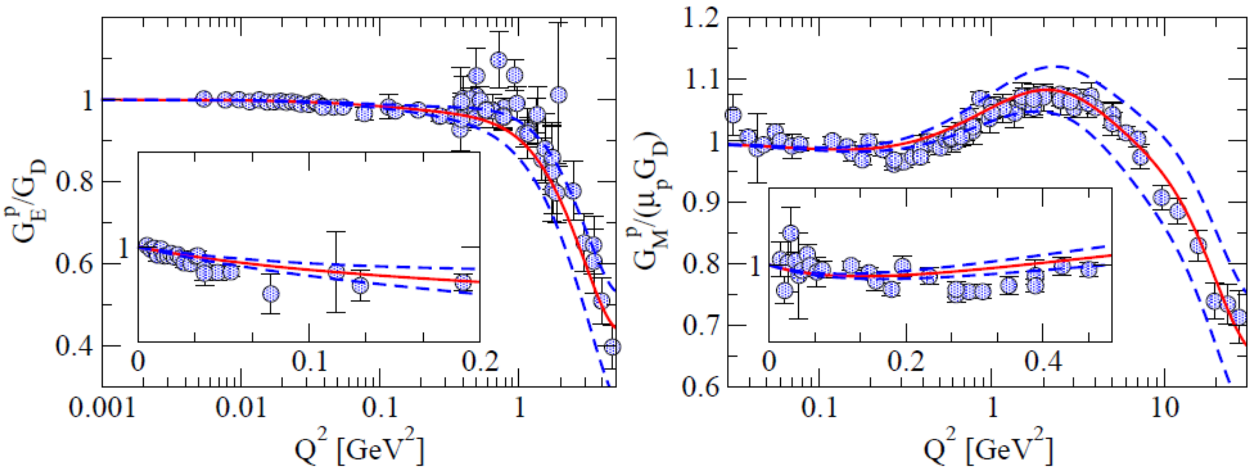
Most of what we know today about hadrons' structure has come from the electromagnetic probes which give access to measure structure functions that quantify the properties of partons in hadrons.

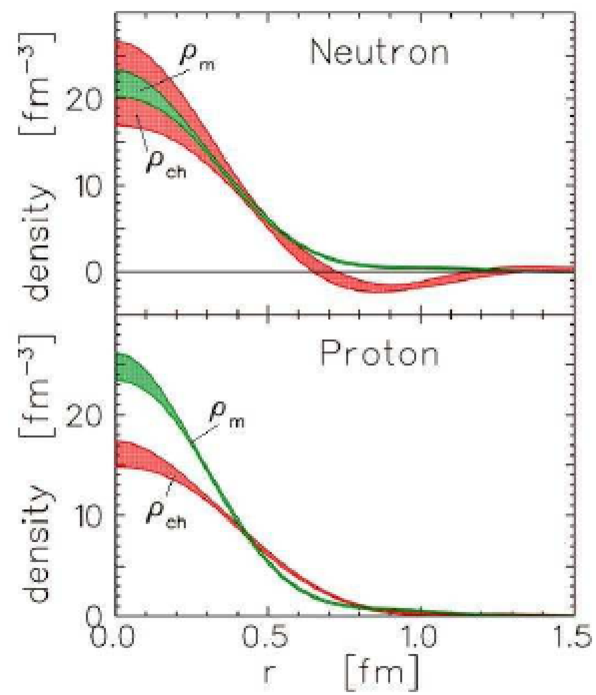


ES

- **Form Factors (FFs)**
  → Provide the charge and magnetization distributions inside a hadron.
  → Accessible via Elastic Scattering (ES).

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{E'}{E}\left(\frac{G_E^2(Q^2)+\tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\left(\frac{\theta_e}{2}\right)\right)$$



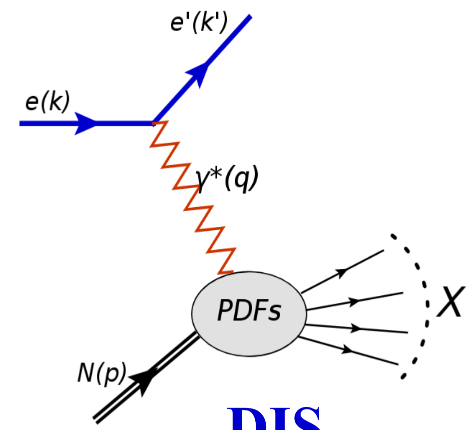


- C. F. Perdrisat, V. Punjabi and M. Vanderhaeghen, Prog. Part. Nucl. Phys. 59, 694-764 (2007)
- Kelly J. J., Phys. Rev. C 66, 065203 (2002)

Exploring the Hadron Structure

Structure functions that quantify the properties of the partons in a hadron:

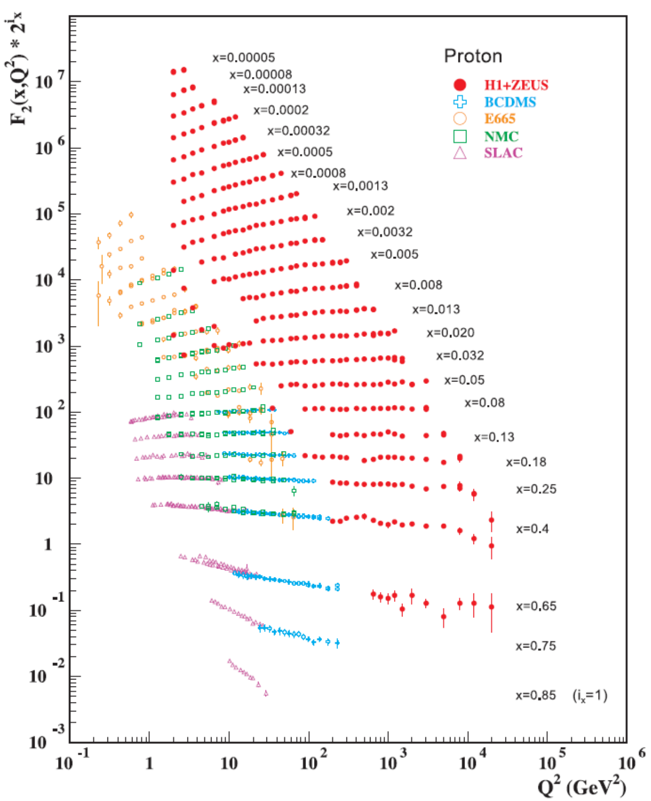
- **Form Factors (FFs)**
- **Parton Distribution Functions (PDFs)**

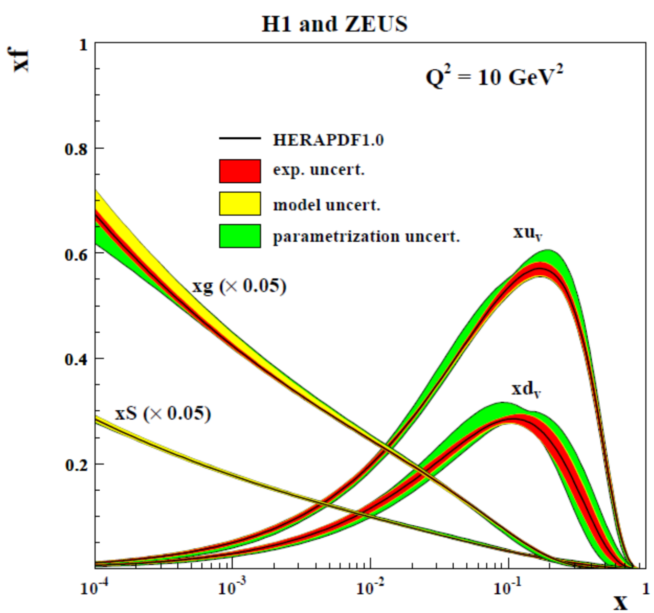


DIS

→ Provide partons longitudinal momentum distributions
→ Measurable via Deep Inelastic Scattering (DIS).

- For nucleons, the unpolarized DIS cross section is parametrized by two PDFs: $F_{1,2}(x)$, with $\mathcal{F}_1(x) = \frac{1}{2}\sum_q e_q^2 f_q(x)$ and $\mathcal{F}_2(x) = x\sum_q e_q^2 f_q(x)$

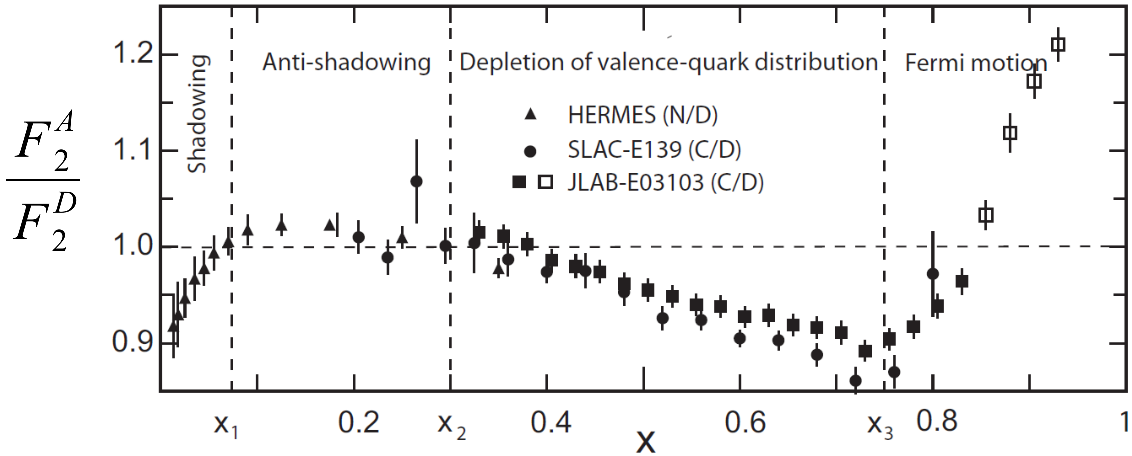




Proton structure:
→ Large x, $u_v(x) \sim 2\, d_v(x)$
→ Low x, more gluons radiated and slpitting producing sea quarks

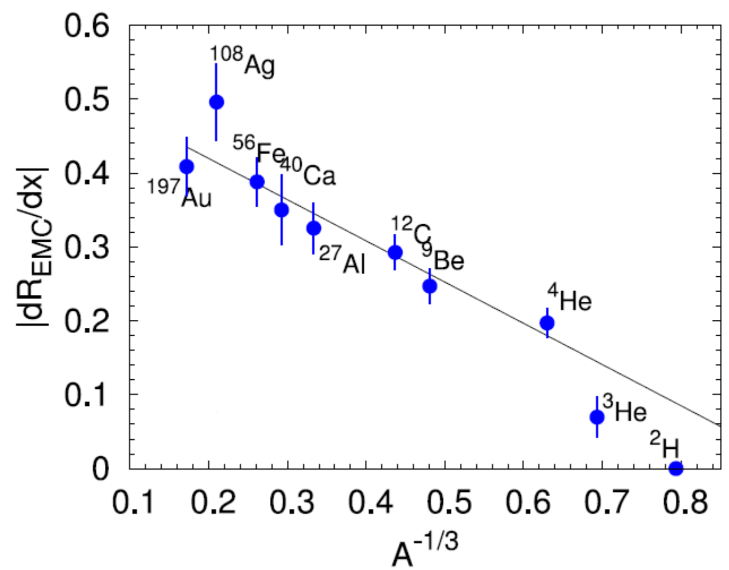
- J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001, page241, 2012.
- R. Placakyte et al. (H1 and ZEUS Collaborations), arXiv:1111.5452 [hep-ph], 2010.

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

More details will be given by Seamus, William, Gerald, Misak, John, and Ian

- 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...)

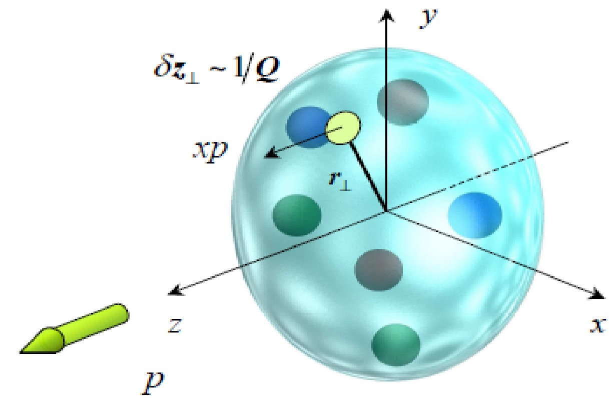
Clear explanations may arise from measuring the nuclear modifications via measuring the Generalized Parton Distributions.

Generalized Parton Distributions

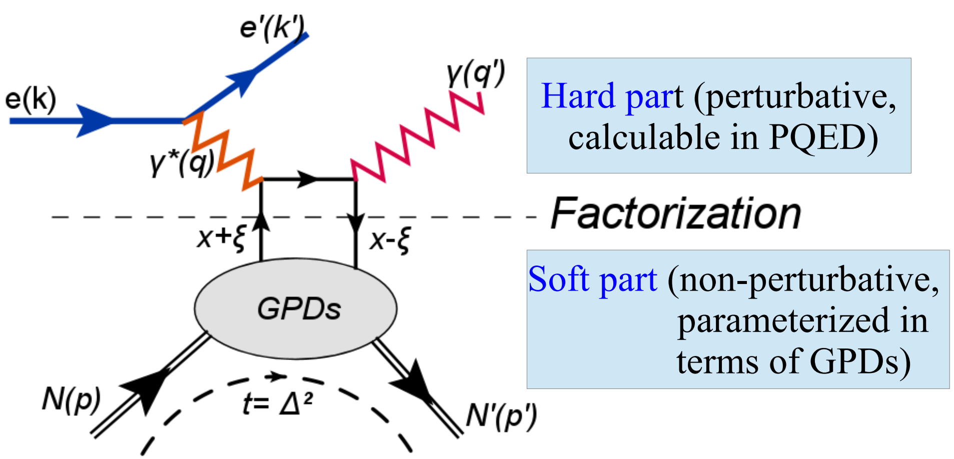
- Contain information on:

→ 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):



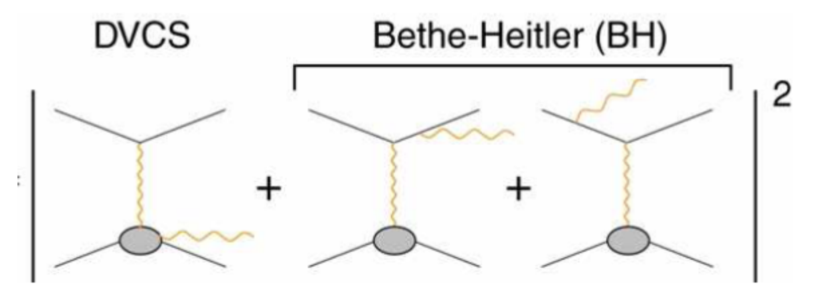
$$\xi \simeq x_B/(2-x_B) \qquad x_B = Q^2/2p.q$$

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

* 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.

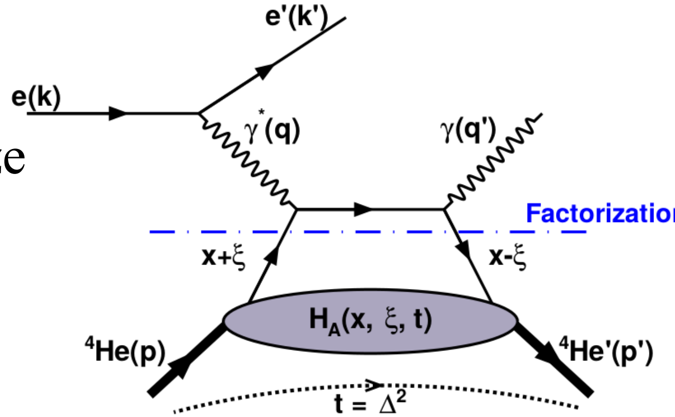
DVCS off Nuclei

Two DVCS channels are accessible with nuclear targets:

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

→ Study the partonic structure of the nucleus.

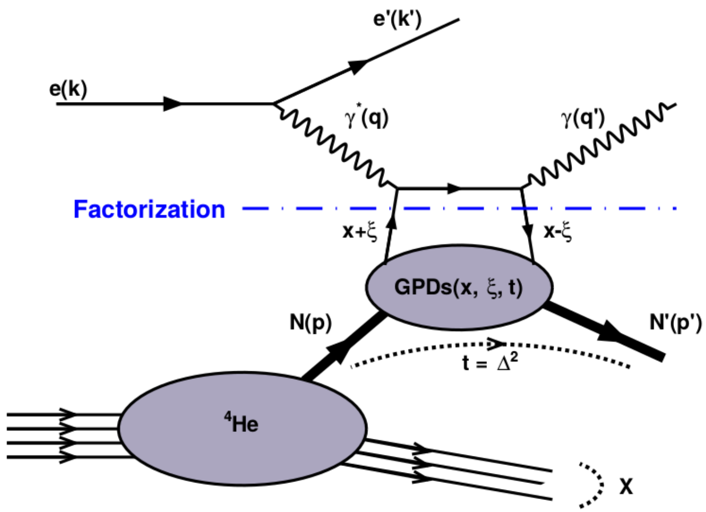
→ One chiral-even GPD (**$H_A(x,\xi,t)$**) is needed to parametrize the structure of the spinless nuclei (^{4}He, ^{12}C, ^{16}O, ...).

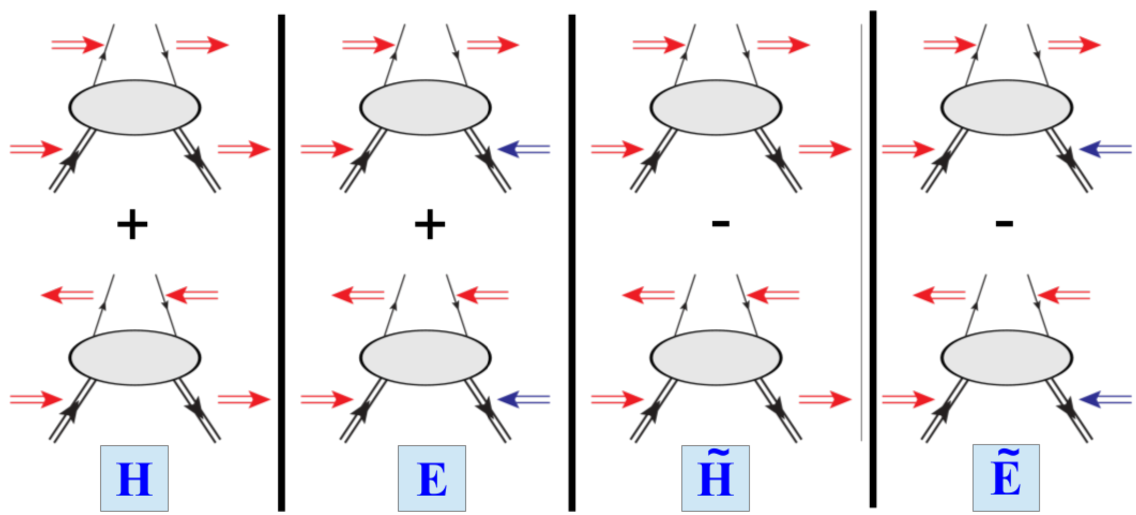


◊ **Incoherent DVCS: $e^- A \rightarrow e^- N \gamma \; X$**

→ 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).





Nuclear Spin-Zero DVCS Observables

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

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

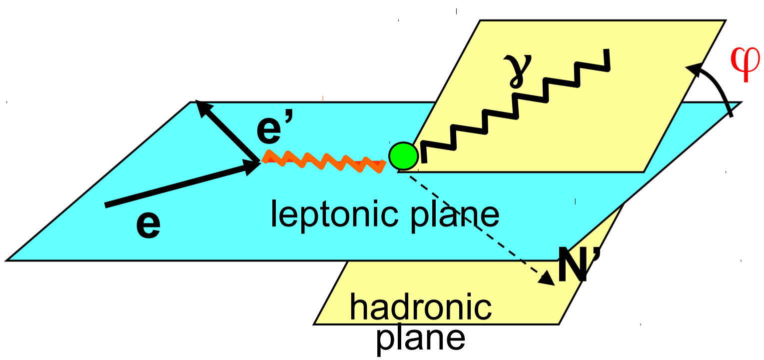
$$Im(\mathcal{H}_A(\xi,t)) = H_A(\xi,\xi,t) - H_A(-\xi,\xi,t)$$

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

Quark propagator

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

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



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

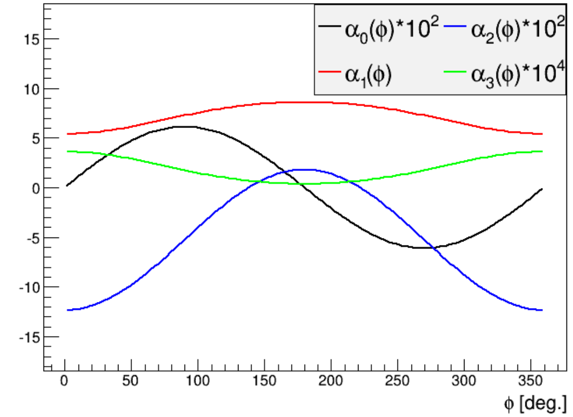
$$= \frac{\alpha_0(\phi)\,\Im m(\mathcal{H}_A)}{\alpha_1(\phi) + \alpha_2(\phi)\,\Re e(\mathcal{H}_A) + \alpha_3(\phi)\left(\Re e(\mathcal{H}_A)^2 + \Im m(\mathcal{H}_A)^2\right)}$$

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

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

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

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



Theoretical Predictions of the EMC in ^{4}He

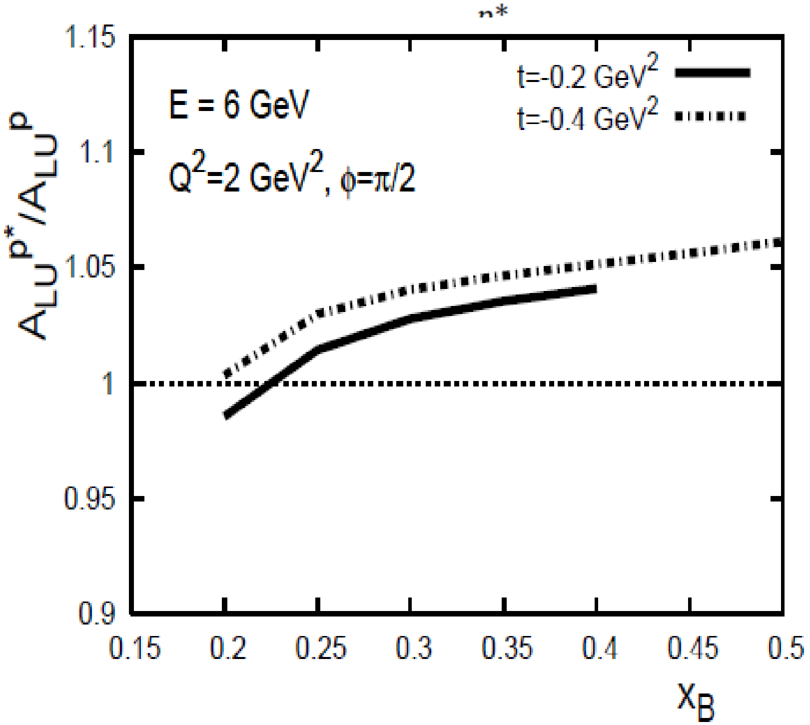
On-shell calculations:

(1) Impulse approximation

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

(2) Medium modifications:

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



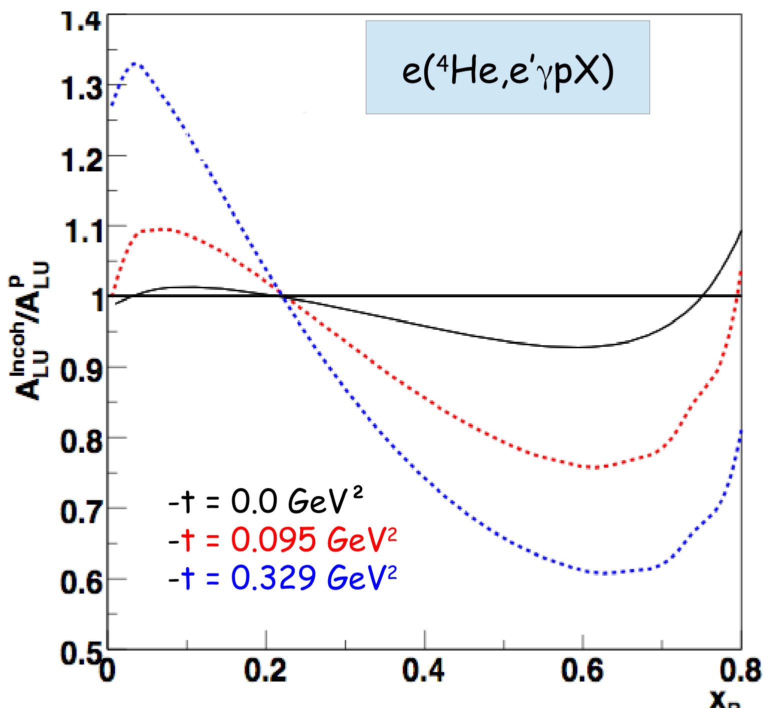
[V. Guzey, A. W. Thomas, K. Tsushima, PRC 79 (2009) 055205]

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

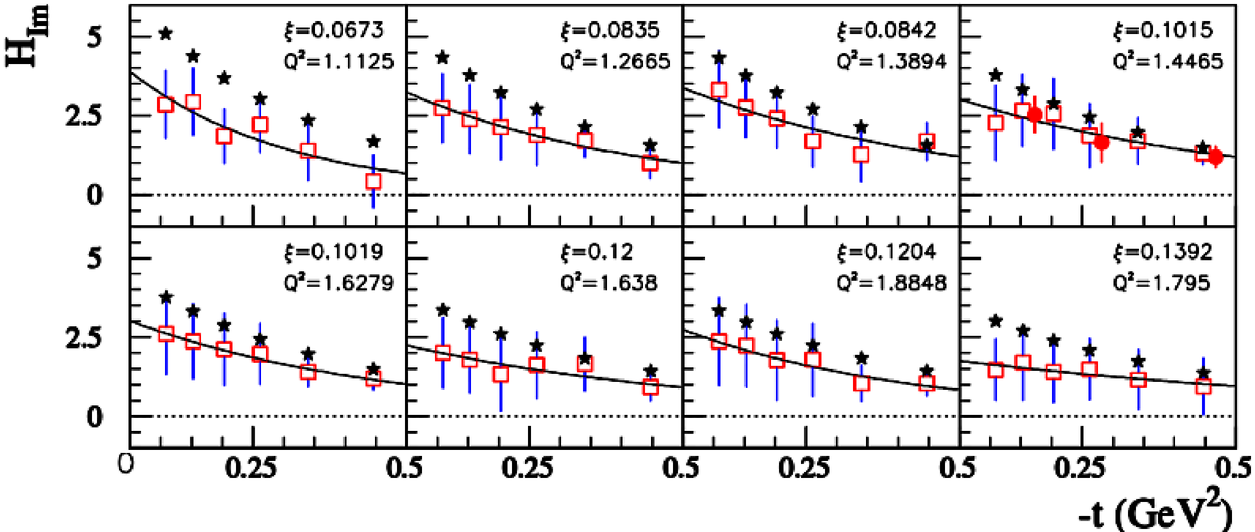


[S. Liuti, K.Taneja, PRC 72 (2005) 034902]

New ^{4}He GPDs calculation is coming, see Sergio's talk on Friday

Proton Tomography via DVCS

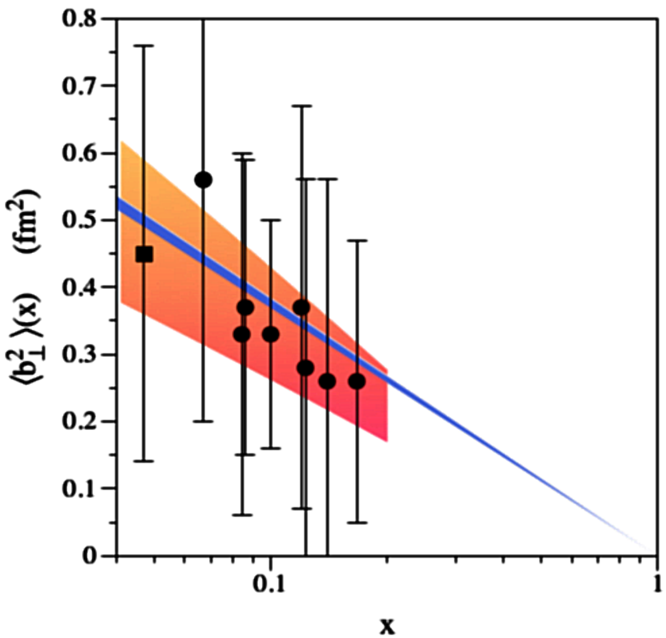
- Local fit of all the JLab data
  - Jlab Hall A (σ, Δσ)
  - CLAS (σ, Δσ, lTSA, DSA)

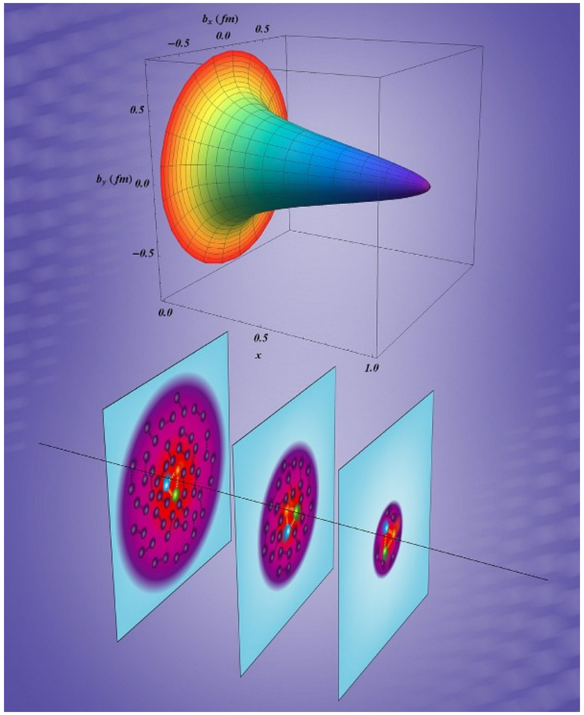


- Enough coverage to explore the t and x_B (→ξ) dependence of H_{Im}.

- 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]

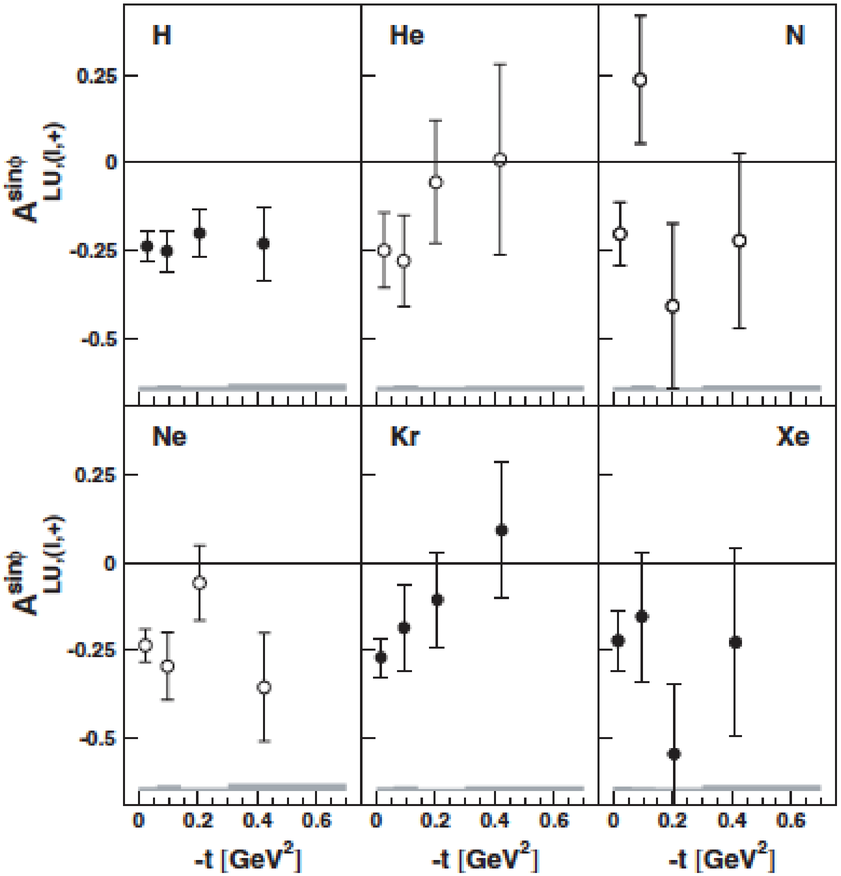
Nuclear DVCS Measurements: HERMES

- 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

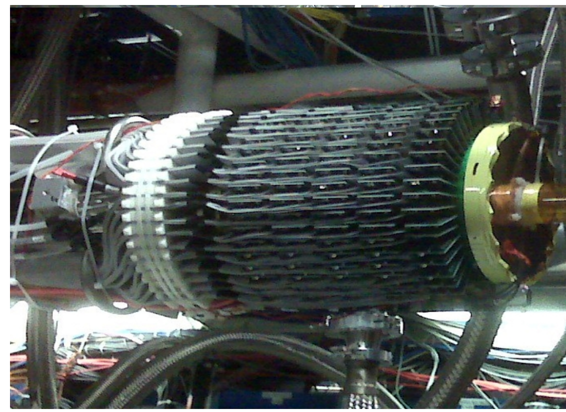
CLAS - E08-024 Experimental Setup

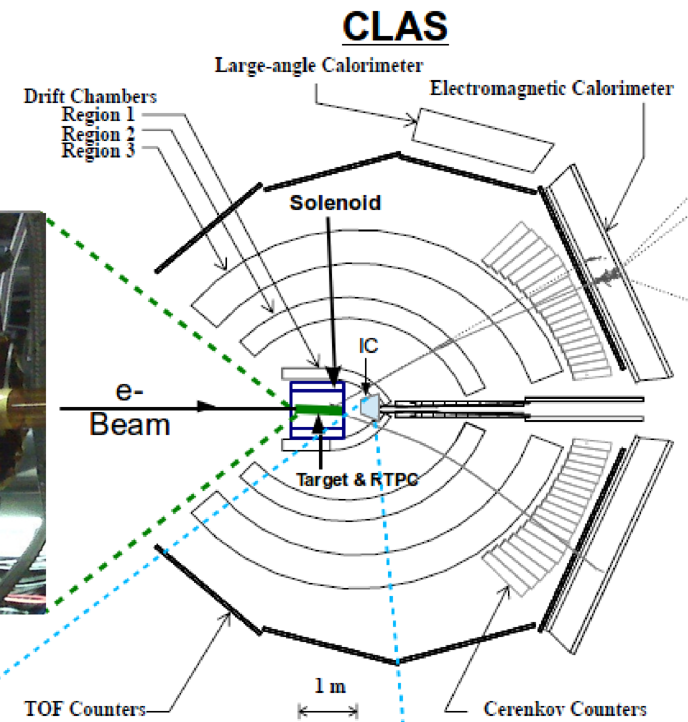
$e^- \, {}^4He \rightarrow e^- \, ({}^4He/pX) \, \gamma$

6 GeV,
L. polarized

Beam polarization (P_B) = 83%

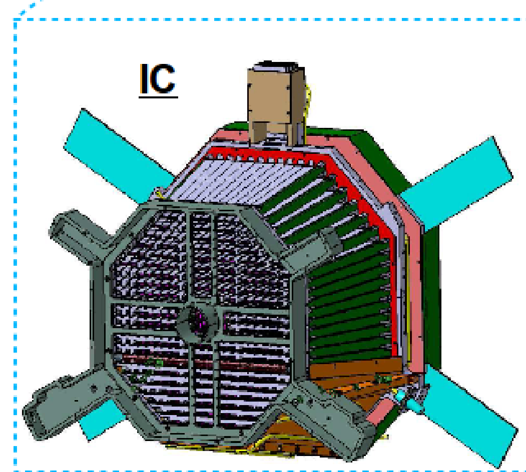
RTPC





- **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

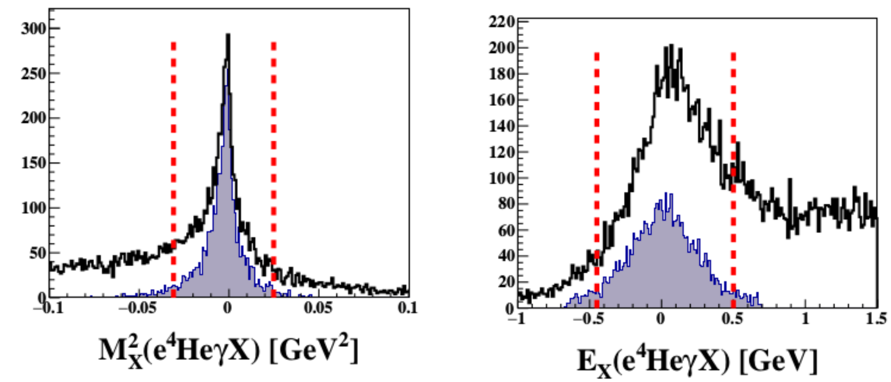
Coherent DVCS Selection & Asymmetries

1. We select COHERENT events which have:

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

◊ $Q^2 > 1$ GeV².

◊ Exclusivity cuts.

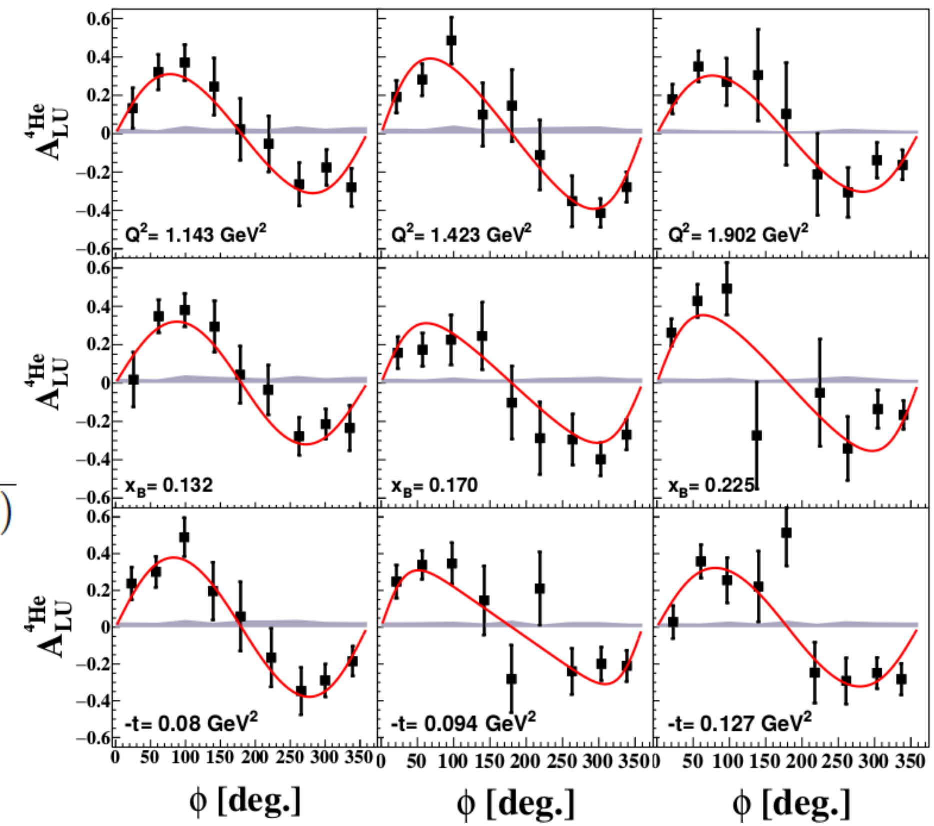


2. π^0 background subtraction based on data and simulation (cont. ~ 2 – 4%)

3. Beam-spin asymmetry:

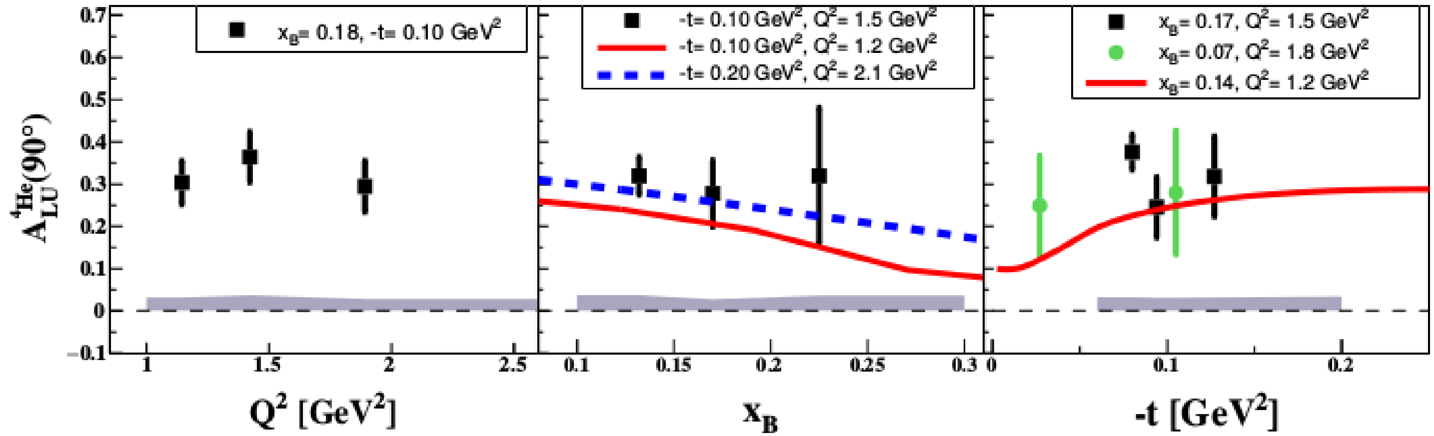
$$A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$$

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



- 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



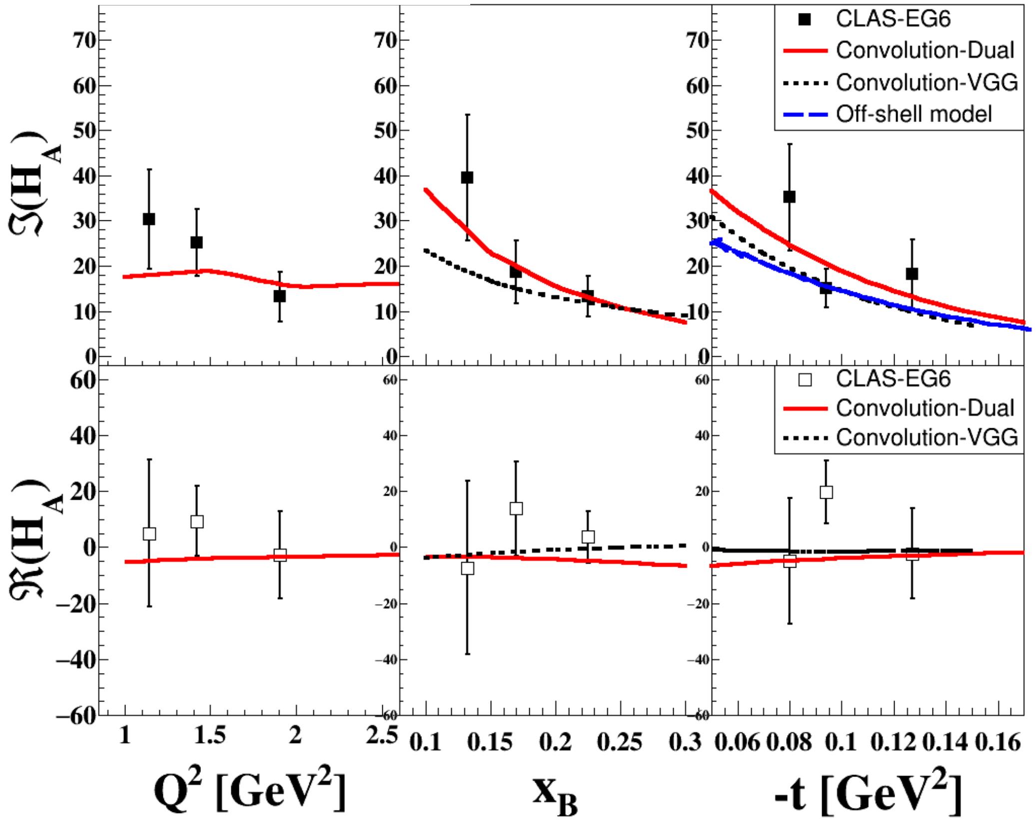
[S. Liuti and K. Taneja. PRC 72 (2005) 032201]
[HERMES: A. Airapetian, et al., PRC 81, 035202 (2010)]

→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. Hattaway 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)

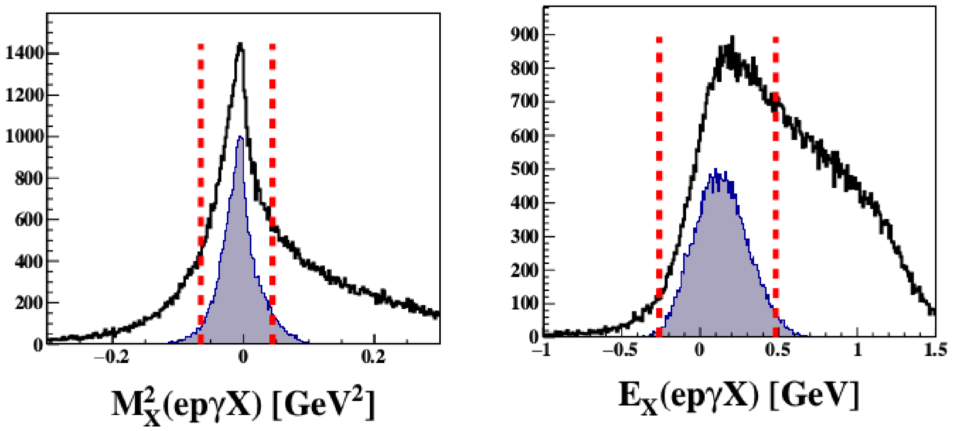
Incoherent DVCS Selection & Asymmetries

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).



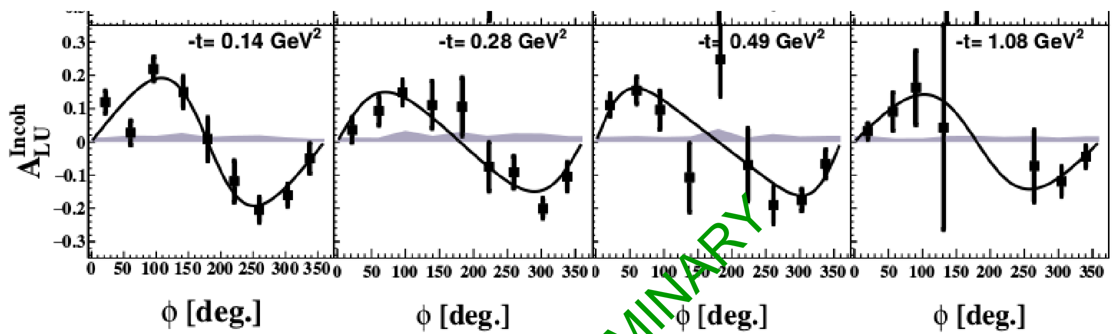
2. π^0 background subtraction (contaminations ~ 8 - 11%)

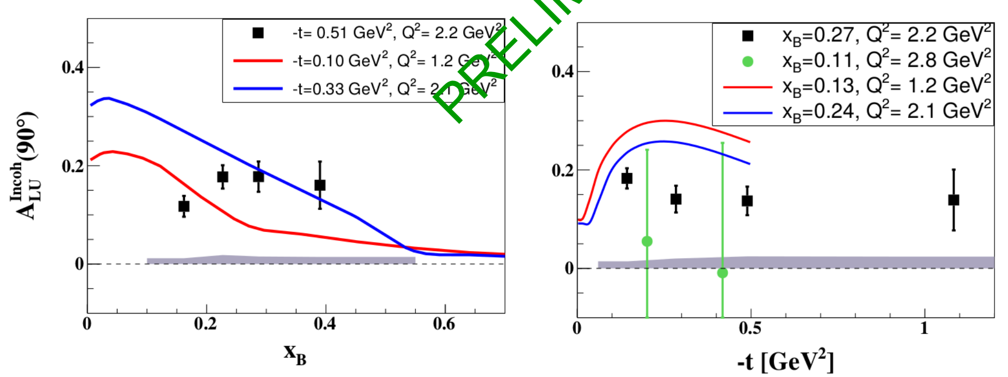
3. Beam-spin asymmetry:

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

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

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





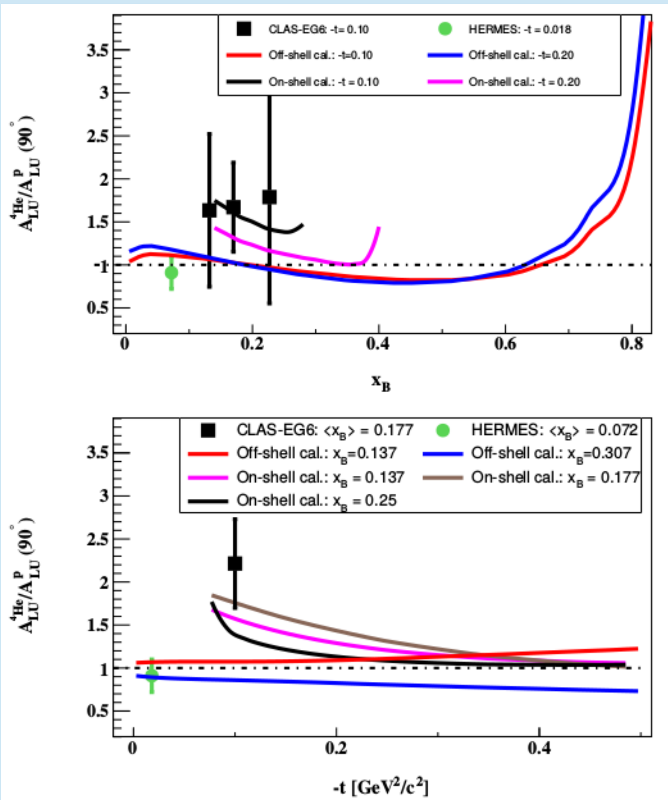
[S. Liuti and K. Taneja. PRC 72 (2005) 032201]

* A PRL presenting the incoherent results is under progress.

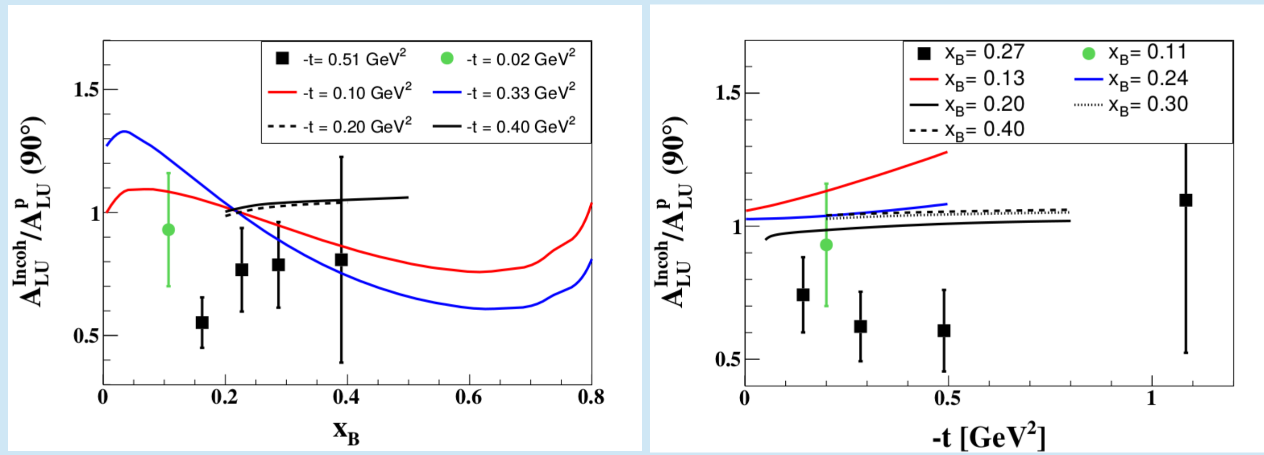
Generalized EMC Ratio

◊ 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.

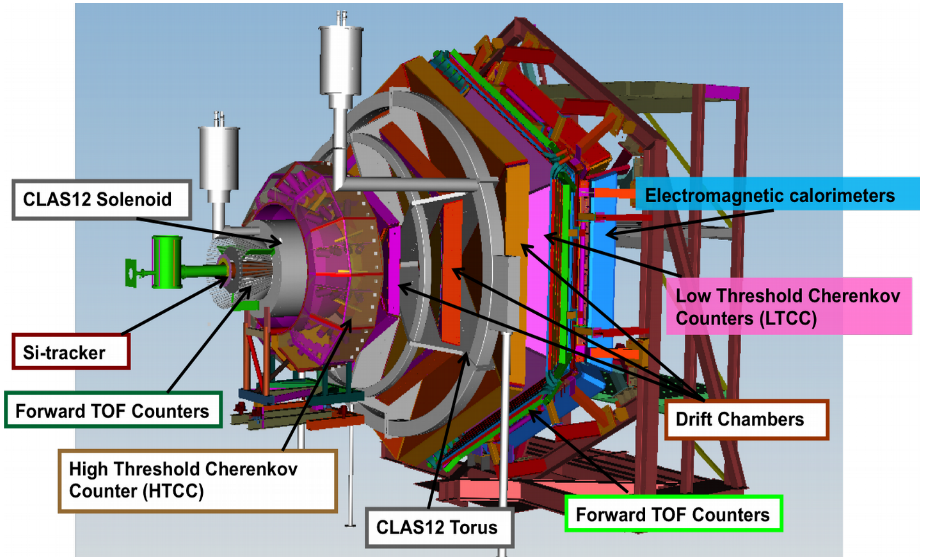
[A. Airapetian, et al., Phys. Rev. C 81, 035202 (2010)]

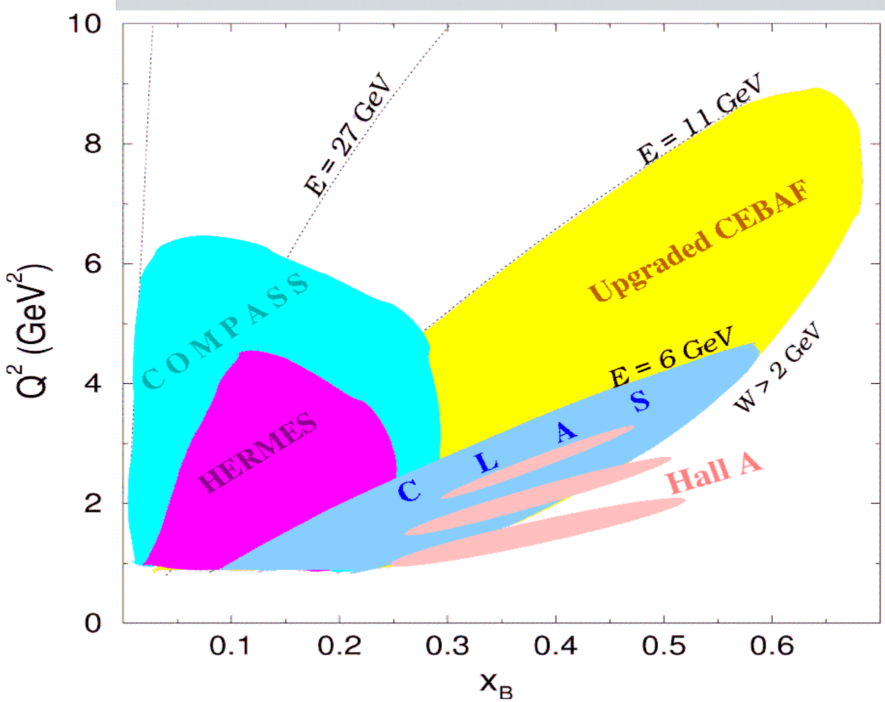
→ **Incoherent/proton** is supressed compared to both the PWIA and the nuclear spectral function calculations.

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

CLAS12-ALERT Program

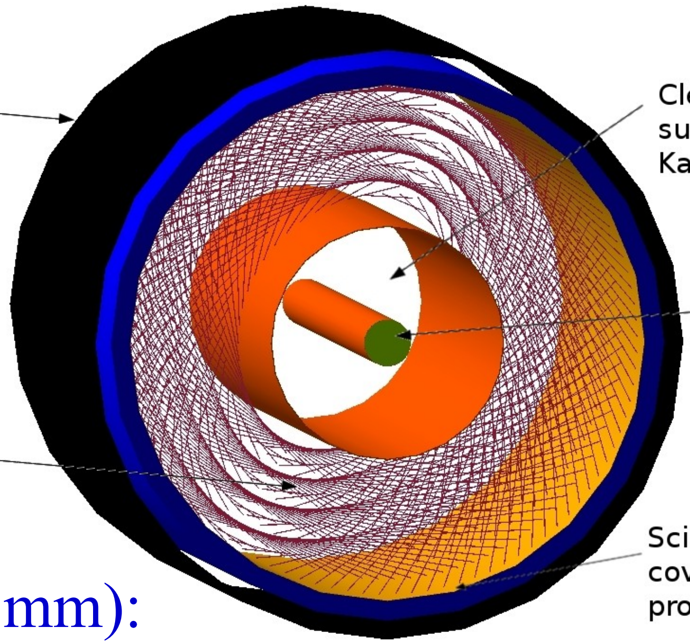
- CLAS–E08-024 experiment:
  - 2D binning due to limited statistics
  - Limited phase-space.
- CLAS12 experimental apparatus:
  - High luminosity & large acceptance.
  - Measurements of deeply virtual exclusive, semi-inclusive, and inclusive processes.
- We proposed to measure with CLAS12:
  - Partonic 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.





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.

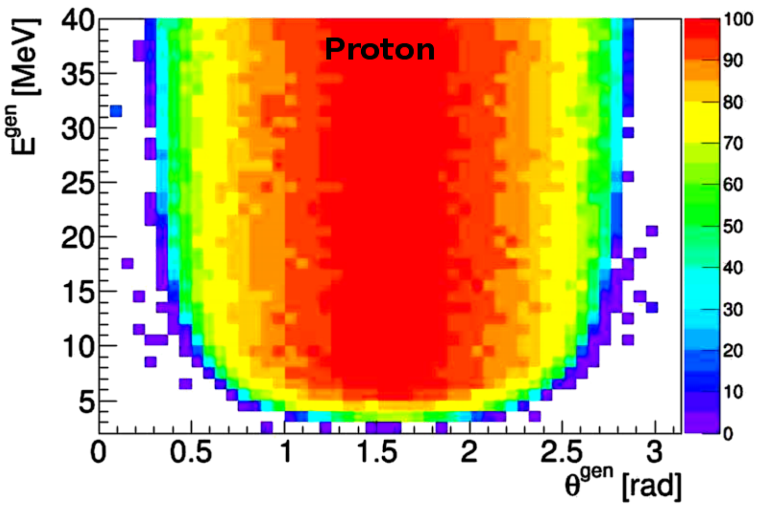
- Two rings of plastic scintillators (Total thickness of 20 mm, SIPMs directly attached):

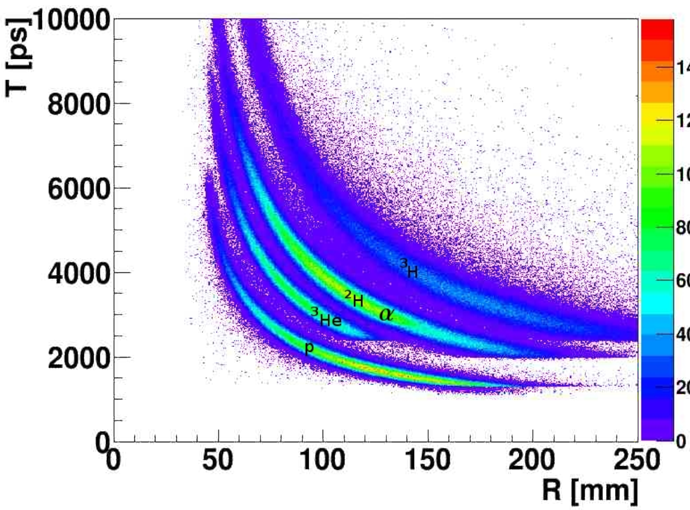
→ TOF (< 150 ps resolution) and deposited energy measurements.

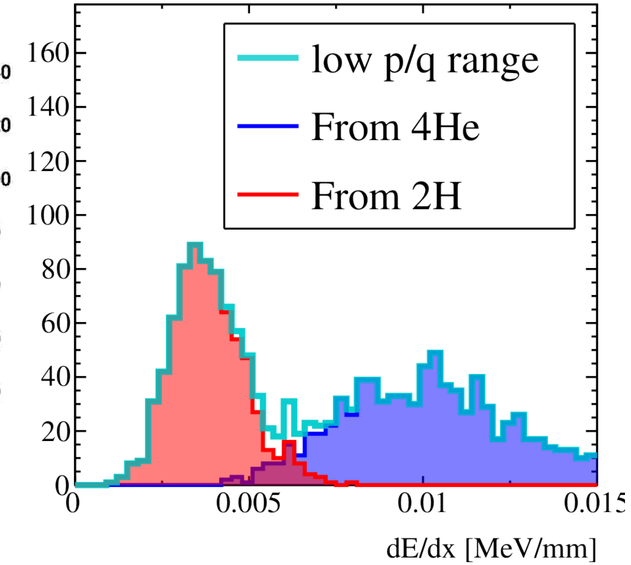
→ Separate protons, deuterium, tritium, alpha, ^{3}He

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







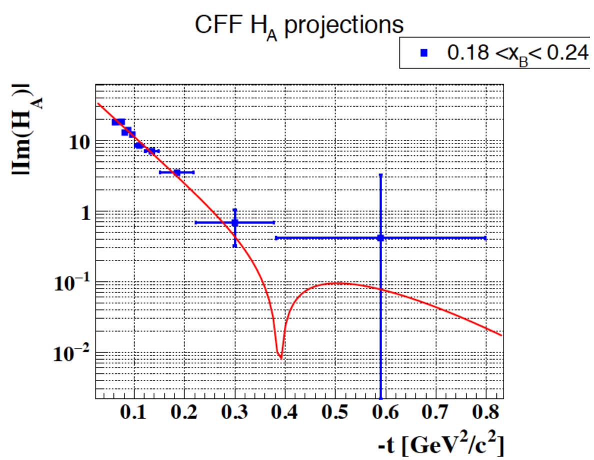
Partonic Structure of Light Nuclei (PR12-17-012)

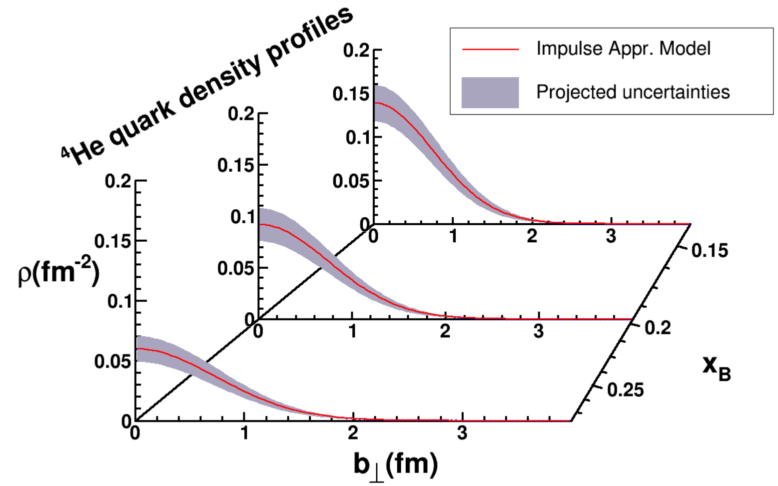
- Map the fundamental structure of nuclei within the GPD framework
- Compare the quark and gluon 3D structure of the Helium nucleus

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.

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

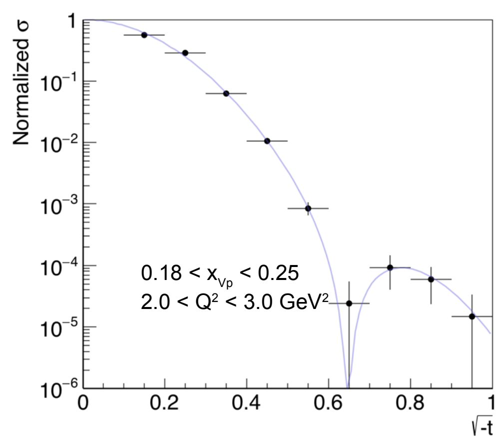


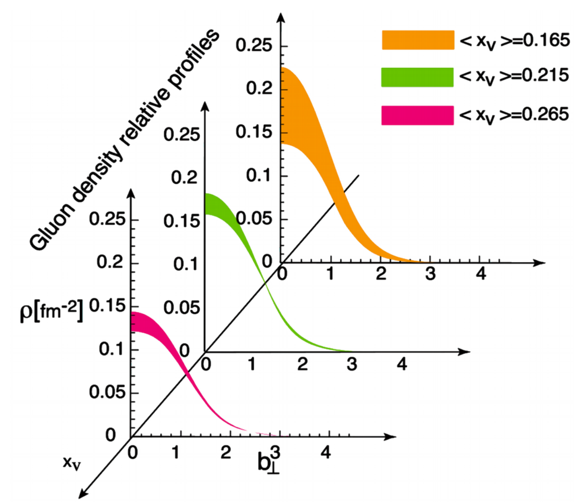


e ^{4}He→e\` $^4$He\`φ:

- 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:

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

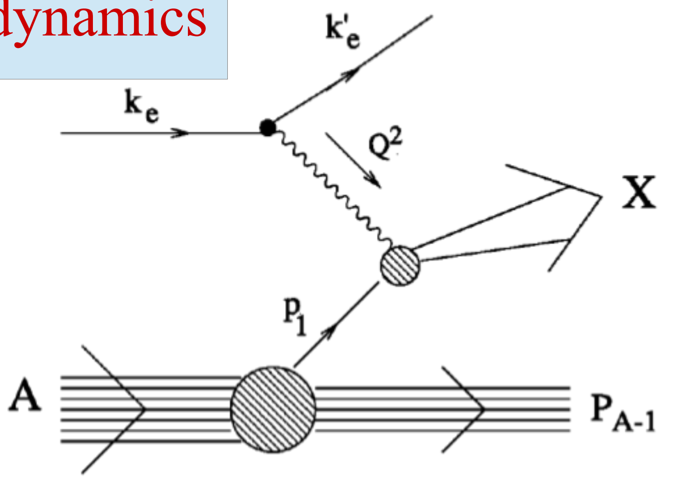




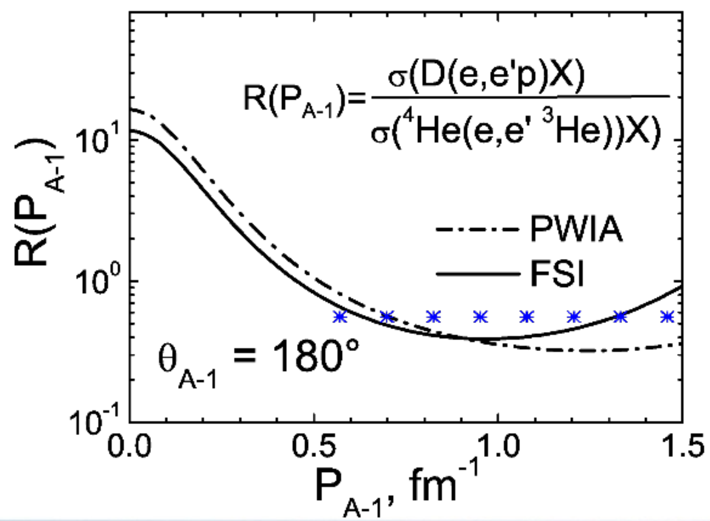
Requested PAC days: 20 days at 3×10^{34} cm^{-2}s^{-1} + 10 days at 6×10^{34} cm^{-2}s^{-1} + (5 Com.)

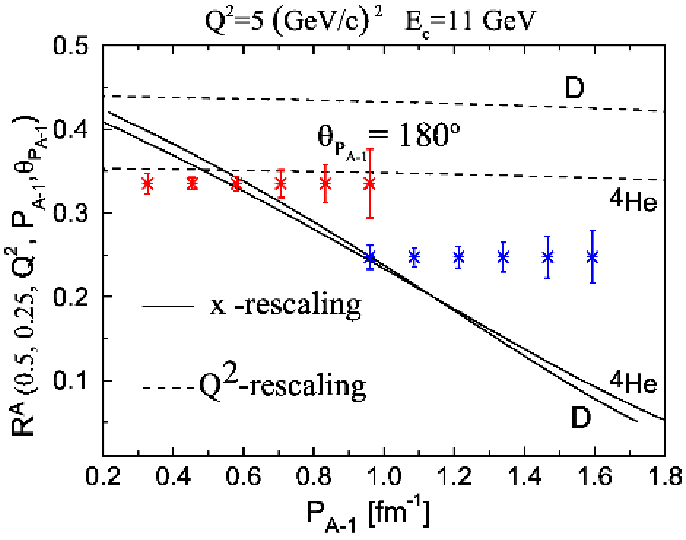
Tagged EMC Measurements (PR12-17-012A)

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



- 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.
- 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.
- 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}).

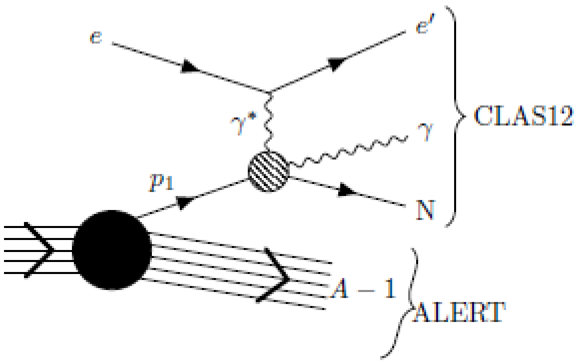


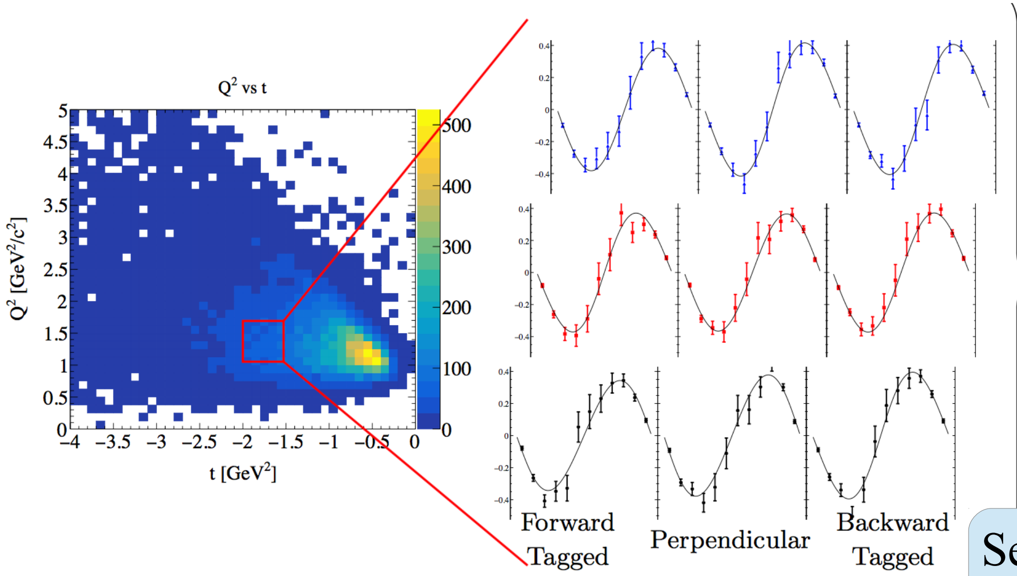


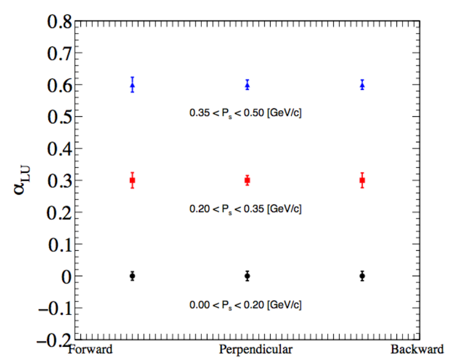
Spectator-Tagged DVCS On Light Nuclei (PR12-17-012B)

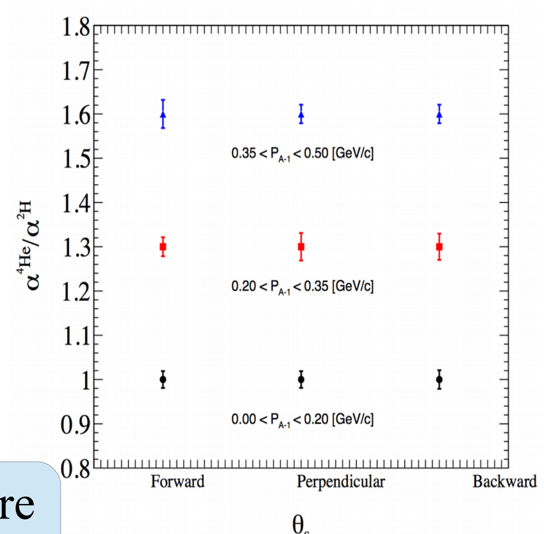
- Probe connection between partonic and nucleonic interpretations via DVCS
- Partonic interpretation and in-medium hadron tomography of nucleons
- Study of Off-Forward EMC effect in incoherent DVCS

- **Bound-p DVCS:**
  - Fully detected ep^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**









See Whitney's talk for more details on this proposal

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.