Incoherent Deeply Virtual Compton Scattering on nuclei

Mathieu Ehrhart

Laboratoire de Physique des 2 Infinis Irène Joliot-Curie
Université Paris-Saclay

Exploring QCD with Tagged Processes - 13 October 2021

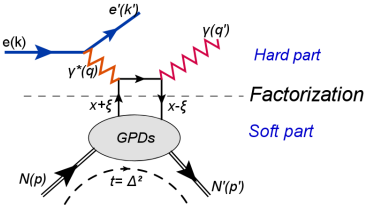
Generalized Parton Distributions

4 structure functions (spin-1/2 particles):

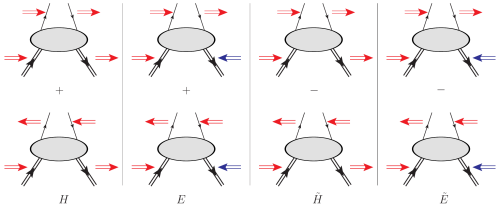
- Unpolarized GPDs: $H(x,\xi,t)$ and $E(x,\xi,t)$
- Polarized GPDs: $\widetilde{H}(x,\xi,t)$ and $\widetilde{E}(x,\xi,t)$

Accessible through hard exclusive processes:

- Deeply Virtual Compton Scattering (DVCS)



Deeply Virtual Compton Scattering



x : average parton momentum fraction

$\xi = \dfrac{2x_B}{2-x_B}$: skewness

$t = (p-p')^2$: momentum transfer between initial and final nucleons

ϕ : angle between the leptonic and hadronic plane

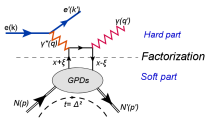
Deeply Virtual Compton Scattering (DVCS)

DVCS cross section:

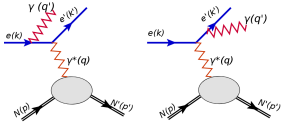
$$\frac{d^5\sigma}{dQ^2 dx_B dt d\phi d\phi_e} = \frac{\alpha^3}{16\pi^2} \frac{x_B y}{Q^2\sqrt{1+\epsilon}} \frac{|\mathcal{A}|^2}{e^6}$$

with :

$$|\mathcal{A}|^2 = |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \mathcal{I}_{BH\times DVCS}$$



DVCS



Bethe-Heitler (BH)

Compton Form Factor

$$\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx\, H(x,\xi,t)\left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right)$$
$$= \Re\mathfrak{e}\,\mathcal{H}(\xi,t) + i\,\Im\mathfrak{m}\,\mathcal{H}(\xi,t)$$

Beam Spin Asymmetry A_{LU}

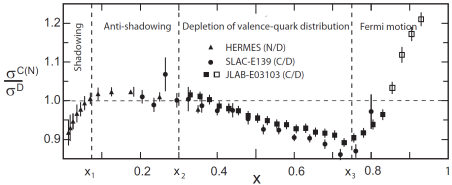
$$A_{LU} = \frac{d^5\sigma^+ - d^5\sigma^-}{d^5\sigma^+ + d^5\sigma^-}$$

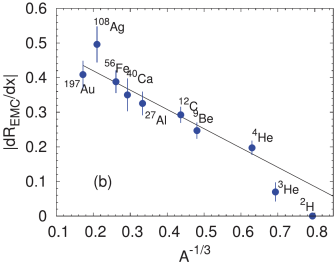
$$A_{LU} \propto$$

$$\Im\mathfrak{m}\left\{F_1\,\mathcal{H} + \frac{x_B}{2-x_B}(F_1+F_2)\,\tilde{\mathcal{H}} - \frac{t^2}{4M^2}F_2\,\mathcal{E} + \ldots\right\}\sin\phi$$

EMC effect

Nuclear binding energy scale (MeV) $\ll$ DIS energy scale (GeV) $\Rightarrow$ Naive assumption $\frac{F_2^A}{F_2^D} = 1$





- Difference in the F_2^A and F_2^D
  - Quarks inside bound nucleons (nuclei) have different properties than quarks in free nucleon
- No clear explanations:
  - Nuclear binding
  - Pion enhancement
  - Rescaling, ...

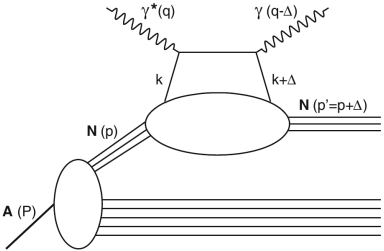
- Dependence of the EMC ratio slope with the nucleus mass and density

The GPD framework and DVCS could offer a new way to study the EMC effect ?

DVCS on nuclei

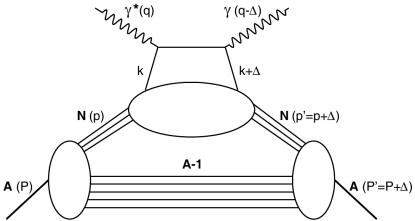
Incoherent Nuclear DVCS ($eA \to e'p\gamma$)

- Study the partonic structure of bound nucleons
- 4 GPDs (spin-1/2)
- Offers a new way to study nuclear effects $\to$ Generalized EMC effect

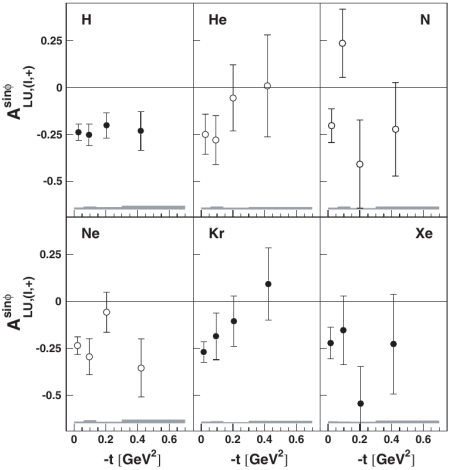


Coherent DVCS ($eA \to e'A'\gamma$)

- Study the partonic structure of nuclei
- Access to different spins
  - Spin-0 (^{4}He) $\to$ 1 GPD
  - Spin-1 (^{2}H) $\to$ 9 GPDs



Previous Nuclear DVCS results

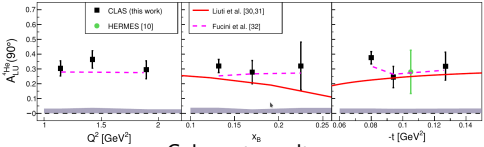


[A. Airapetian et al., Phys. Rev. C 81, 035202, 2010]

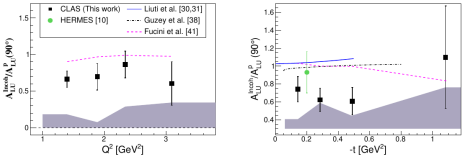
HERMES

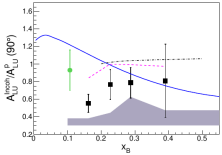
- 27.6 GeV longitudinally polarized electron beam from HERA
- Nuclear targets : H, He, N, Ne, Kr, Xe
- Inclusive reaction : eA $\rightarrow$ e'γX
  - Coherent DVCS (low $-t$)
  - Incoherent DVCS (high $-t$)
- Separation does not appear
- Expected A dependence not observed

Previous Nuclear DVCS results



Coherent results





Incoherent results

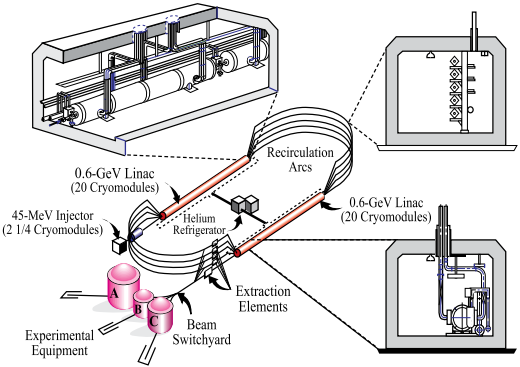
[M. Hattawy et al., Phys. Rev. Lett. 119, 202004 , 2017]

CLAS results on ^{4}He

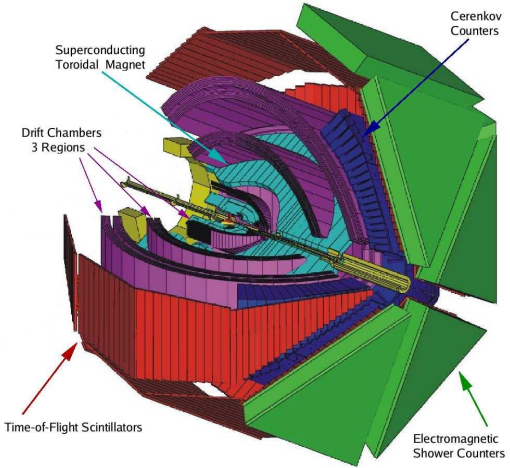
- Radial Time Projection Chamber to measure recoiled nucleus
  - Coherent DVCS
  - Incoherent DVCS
- Coherent BSA are larger than free protons
  - Factor ~ 2, as expected
- Incoherent BSA are small
  - Unexpected by theory
  - Raise the question to know if depends on A

Jefferson Laboratory

- Located in Newport News, Virginia, USA
- Continuous Electron Beam Accelerator Facility (CEBAF)
  - 6 GeV electron beam
  - 100% duty cycle
  - Superconducting Radio Frequency (SRF) cavities technology
- 3 experimental halls
  - Halls A and C: High luminosity
  - Hall B: Large Acceptance



The CEBAF Large Acceptance Spectrometer (CLAS)



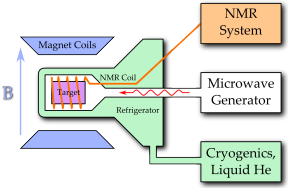
- 6 sectors inside superconducting torus magnet
- Drift Chambers
  - 3 regions
- Sampling Electromagnetic Calorimeters
  - Sampling fraction ≈ 0.3
- Cherenkov Counters
  - C_4F_{10}, $n = 1.00153$
  - π^- threshold ~ 2.5 GeV$/c$
- Scintillator Counters
  - Time of Flight
  - ~ 100 ps resolution

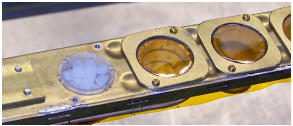
EG1-DVCS experimental run

- January to September 2009
- DVCS on polarized protons/neutrons
  - NH_3 and ND_3 longitudinal polarized target
- 10% carbon data
- Beam energy : 4.730 and 5.887 GeV
- 20 M events triggered
- $\sim$ 85 % beam polarization
- Extraction of A_{LU}, A_{UL} and A_{LL}

Longitudinally Polarized Target

- Ammonia (NH_3)
- Dynamic Nuclear Polarization (DNP)
- Inside Helmholtz coils
  - To polarize the target
  - Reduces Møller background

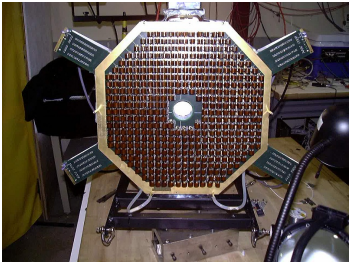


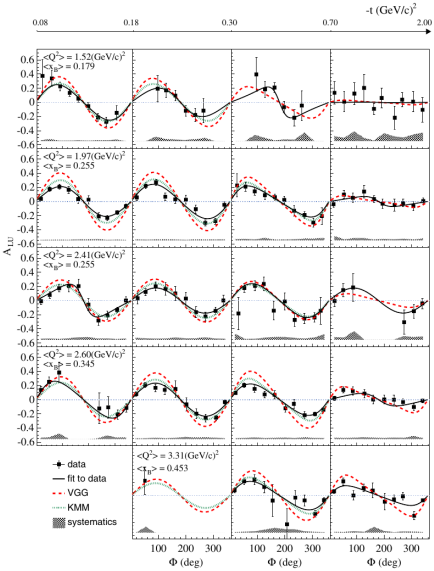


EG1-DVCS experimental run

Inner Calorimeter

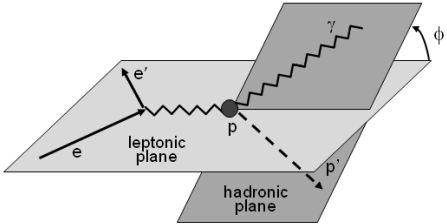
- 424 lead-tungsten crystals
- θ coverage : 3.5° to 17°
  - Most DVCS events will be detected in this region





[S. Pisano et al. - Phys. Rev. D 91, 052014, 2015]
[E. Seder et al. - Phys. Rev. Lett. 114, 032001, 2015]

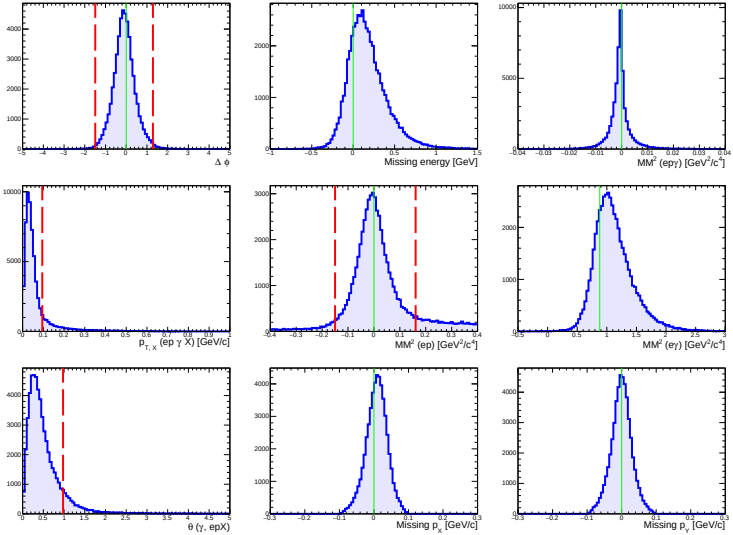
Definition of exclusivity variables



To select DVCS events, we use several exclusivity variables:

- The choice of variables is made to best exploit detectors resolution
- Missing Masses Squared
  - $MM^2(ep)$, $MM^2(e\gamma)$, $MM^2(ep\gamma)$
- $\Delta\phi$: Coplanarity
  - Difference between the two ways to calculate ϕ
- Missing Energy ($ep\gamma$)
- Missing transverse momentum: $p_{\perp,X}(ep\gamma X)$
- $\theta(\gamma, epX)$ angle between the measured photon and calculated photon

Proton event selection

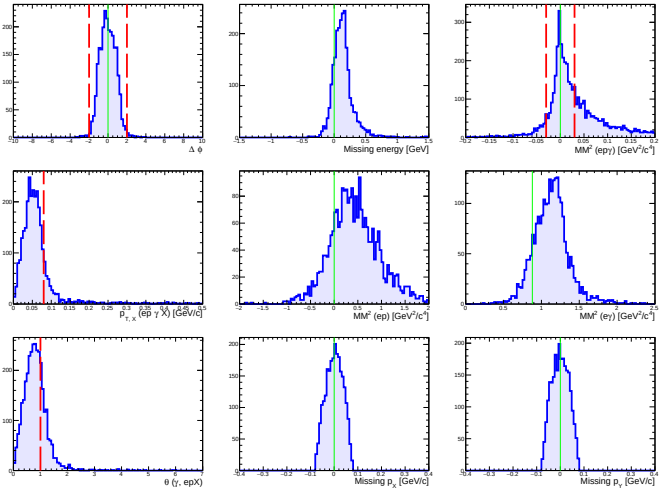


- Identify hydrogen events in order to be able to subtract them from NH_3 data
- Cuts from the published analysis

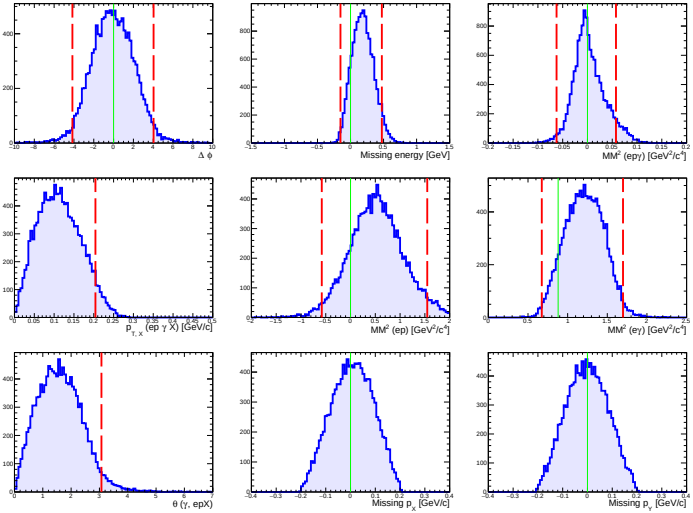
  [S. Pisano et al. - Phys. Rev. D 91, 052014]
- Offsets observed in $MM^2(e\gamma)$ and Missing energy
  - Remaining calibration imperfections
  - Contamination from π^0 and nuclear processes
  - Treated by specific corrections

Carbon data studies - Distribution centers

- Similar size to nitrogen
- No proton in the sample
- Apply narrow cuts to $\Delta\phi$, $p_{\perp,X}(ep\gamma X)$, $\theta(\gamma, epX)$ and $MM^2(ep\gamma)$
- Verify the distribution centers for nuclei
  - Missing Energy $\sim$ 0.1-0.2 GeV
  - $MM^2(e\gamma) \sim$ 1.1-1.2 GeV^2/c^4
  - $MM^2(ep) \sim$ 0.4-0.5 GeV^2/c^4
- Extra shift also observed in the ^{4}He experiment
  - Likely linked to nuclear effects

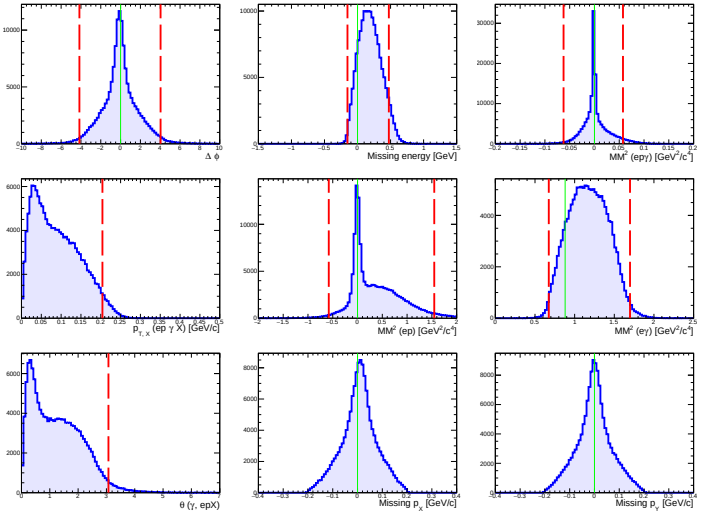


Carbon data studies - Exclusivity cuts



- Setup 2σ cuts
- Larger distributions than the proton
  - Due to nuclear effects
  - More exclusivity cuts
  - Cuts are wider than proton in absolute value
- Shift in the $MM^2(ep)$
  - Also observed in the ^4He analysis
  - Probably nuclear effect

NH_3 data with carbon exclusivity cuts

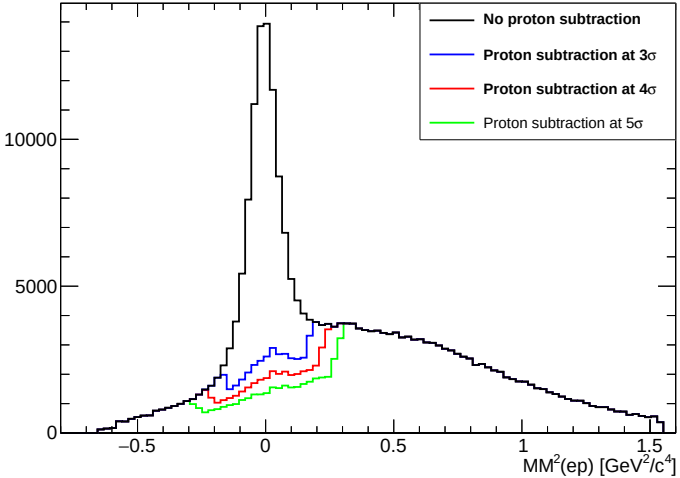


- We apply the carbon cuts to NH_3
- Hydrogen DVCS clearly visible in:
  - $MM^2(ep)$
  - $p_{\perp,X}(ep\gamma X)$
  - $\theta(\gamma, epX)$
- Proton signal is much thinner than the nuclear signal
- Signal is also offset in $MM^2(ep)$

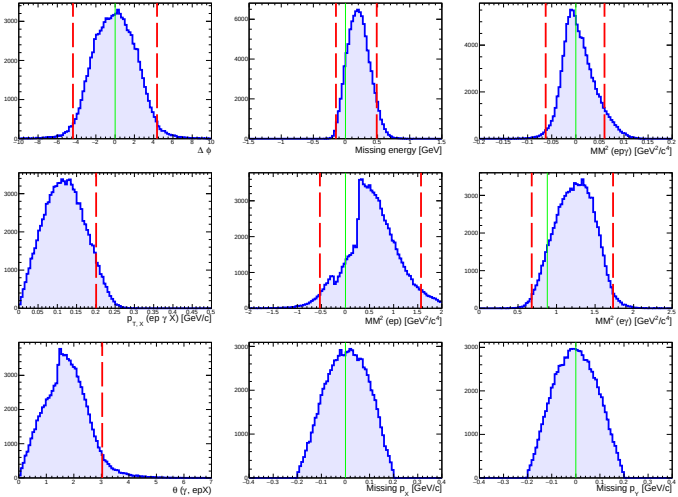
$\Rightarrow$ Subtraction of protons should work

Hydrogen subtraction in the NH_3 data

- Wide distribution ⇒ Incoherent nitrogen
- Narrow peak ⇒ Hydrogen
- Variation of the hydrogen exclusivity cuts and subtraction of events within:
  - 3σ (original hydrogen analysis)
  - 4σ
  - $\boxed{5\sigma}$
- The proton peak at $MM^2(ep)$ fully disappears



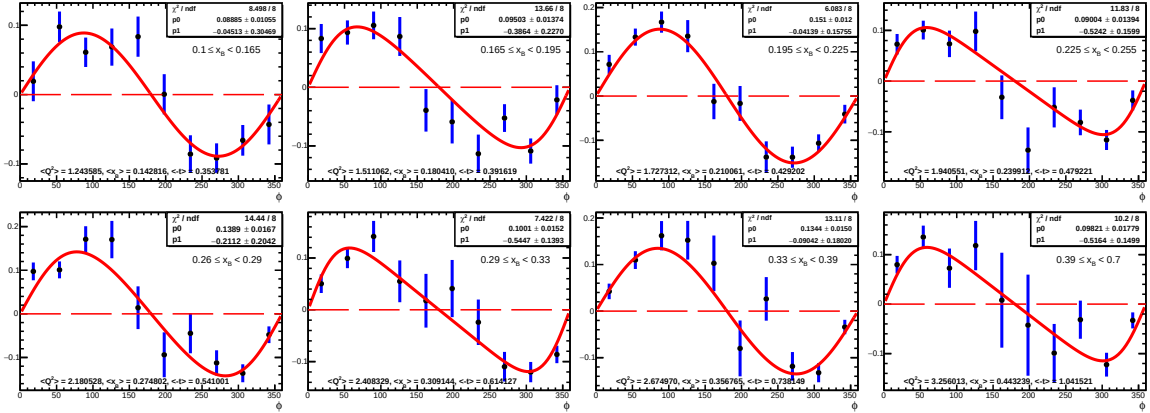
Nitrogen - Exclusivity Cuts



- Missing portions of the exclusive distribution due to hydrogen subtraction
  - $MM^2(ep)$
  - $\theta(\gamma, epX)$
- The proton subtraction is not visible in other variables
  - Thanks to the use of many variables
- Exclusivity cuts and width of the distributions similar to carbon
  - We are still selecting incoherent nuclear DVCS

Extraction of BSA

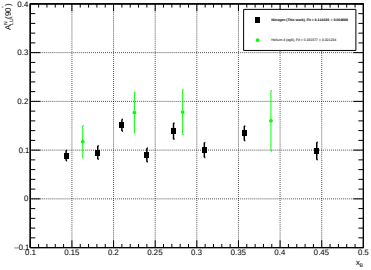
$$A_{LU} = \frac{1}{P_B} \quad \frac{N^+ - N^-}{N^+ + N^-}$$

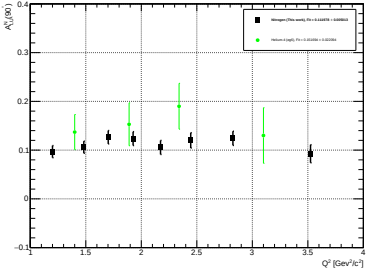


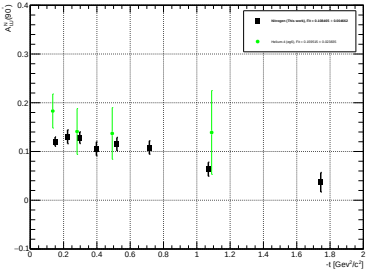
$$\text{Fit} : \frac{\alpha \sin(\phi)}{1 + \beta \cos(\phi)}$$

- Some fit instability is noticeable
- Asymmetries smaller than free proton

$A_{LU}(90^\circ)$



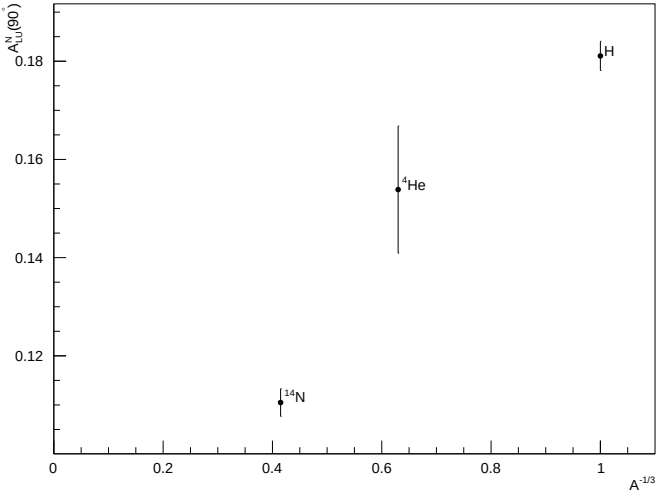


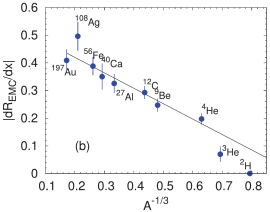


- More statistics than the CLAS ^{4}He results
  - more bins
  - smaller error bars
- Nitrogen amplitudes are $\sim 30\%$ smaller than the helium-4 amplitudes
- No significant shape difference

[M. Hattawy et al., Phys. Rev. Lett. 119, 202004 , 2017]

Nuclear dependence





- Correlation between the nucleus density and the amplitude of the BSAs:
  - as A increases, the amplitude of the BSAs decrease
  - Similar to the EMC effect
- Raw nitrogen BSA
  - π^0 correction, on the way, will likely increase the nitrogen amplitude values

Conclusion

- GPDs could give a new avenue to study nuclear effects
- Incoherent ^{4}He DVCS:
  - Published
  - Phenomenological work in progress
- Incoherent nitrogen DVCS:
  - π^0 correction needed before publication
- Suppression of BSA amplitudes as the nuclear density decreases
- Tagged incoherent DVCS on nuclei (eA $\rightarrow$ e'p'γA^{A-1}):
  - Better control of the initial and final nuclear effects
- Proposed programs:
  - ALERT at CLAS : Tagged DVCS at 12 GeV
  - Wider scan in A at CLAS

Merci !