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Deeply Virtual Compton Scattering off light nuclei: a phenomenological study

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- **How do the nucleons interact to hold a nucleus together?**

  Unfortunately, nuclear physics has not profited as much from analogy as has atomic physics. The reason seems to be that the nucleus is the domain of new and unfamiliar forces, for which men have not yet developed an intuitive feeling.

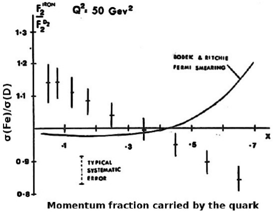
  V. L. Telegdi

- **How does the nucleus emerge from QCD?**
  - Comparison of the behaviour of hadrons in nuclear matter with the one of hadrons in free space
  - Need to get a handle on medium modifications for a QCD based understanding of nuclei

Alliance of two communities

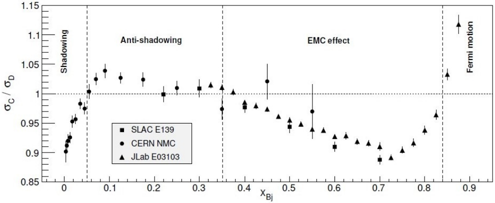
- High-energy physics
- Low-energy nuclear structure physics

The nuclear medium modifies the structure of bound nucleons



The European Muon Collaboration found

$$R(x) = \frac{F_2^A(x)}{F_2^d(x)} \neq 1 \ , x = \frac{Q^2}{2M\nu} \in \left[0; \frac{M_A}{M}\right]$$

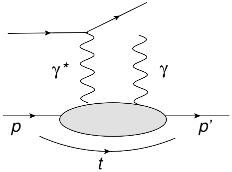


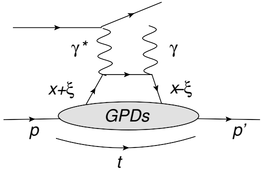
- $x \leq 0.05$: "Shadowing region"
- $0.3 \leq x \leq 0.85$: "EMC region"
- $0.85 \leq x \leq 1$: "Fermi motion region"

Collinear information led to many models but not yet to a complete explanation
(e.g., see **Cloët et al. JPG (2018)**, for a recent report)

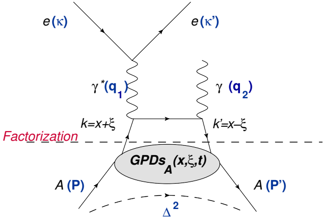
Deeply Virtual Compton Scattering off nuclei

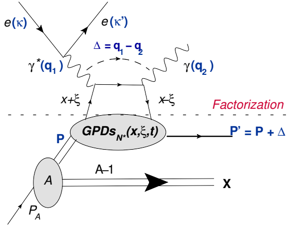
- **Exclusive electro-production of a real photon** $\rightarrow$ *clean access to* ***Generalized Parton Distributions***





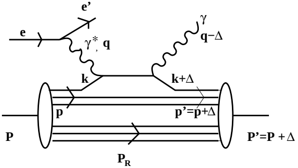
- **Two DVCS channels in nuclei**:
  - **Coherent channel** $\rightarrow$ GPDs of the **whole nucleus**
  - **Incoherent channel** $\longrightarrow$ GPDs of the **bound nucleon**





Making Impulse approximation models

Impulse approximation to the handbag approximation



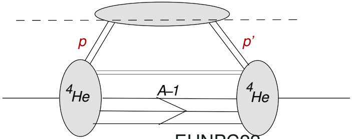
- Only nucleonic degrees of freedom
- The bound proton is **kinematically** off-shell

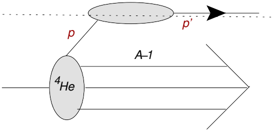
$$p_0 = M_A - \sqrt{M^{*2}_{A-1} + \vec{p}^2} \simeq M - E - T_{rec} \longrightarrow \mathbf{p^2 \neq M^2}$$

where the ***removal energy*** is $E = |E_A| - |E_{A-1}| - E^*$

- Possible final state interaction (**FSI**) effects are neglected
- Convolution formulas of **nuclear** (**spectral functions** etc ...)

  and **nucleonic** ingredients (**GPDs** etc ...)

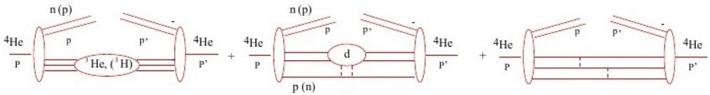




The nuclear ingredient

$$P_N^A(\vec{p}, \vec{p}+\vec{\Delta}, E) = \rho(E) \sum_{\alpha\,\sigma} \langle P+\Delta| -p\,E\,\alpha, p+\Delta\,\sigma\rangle \langle p\,\sigma_N, -p\,E\,\alpha|P\rangle$$

$$P_N^A(\vec{p}, E) = P_0(\vec{p}, E) + P_1(\vec{p}, E) \approx n_0(\vec{p})\delta(E - E_{min}) + n_1(\vec{p})\delta(E - \bar{E})$$



- the **total momentum distribution** is $n(p) \propto \int d\vec{r}_1 d\vec{r}_1' e^{i\vec{p}\cdot(\vec{r}_1 - \vec{r}_1')} \rho_1(\vec{r}_1, \vec{r}_1')$
- the **ground momentum distribution** is $n_0(|\vec{p}|) = |a_0(|\vec{p}|)|^2$ with

$$a_0(|\vec{p}|) \approx \langle \Phi_{^3He/^3H} | \Phi_{^4He} \rangle \,.$$

- the **excited momentum distribution** is $\mathbf{n_1}(|\vec{p}|) = n(|\vec{p}|) - n_0(|\vec{p}|)$
- $\boldsymbol{n(p)}$, $\mathbf{0(p)}$ can be evaluated within the Av18 NN interaction **(Wiringa et al., PRC (1995))** + UIX 3-body forces **(Pudliner et al., PRL (1995))**
- $\boldsymbol{P_1^{\text{our model}}(\vec{p}, E) = N(p) P_{exc}^{\text{Ciofi's model (PRC(1996))}}(\vec{p}, E)}$

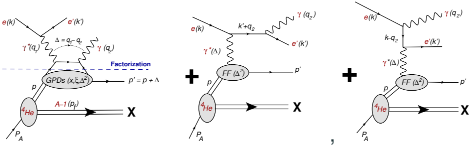
MESSAGE TO TAKE AWAY

- Realistic calculations for **light nuclei** $A \leq 6$
- Many body calculation accounting for mean field potential for **heavier nuclei**

The generalized EMC effect

Incoherent DVCS off ^{4}He: S.F., S. Scopetta, M. Viviani, PRC(2021)-PRD(2021)

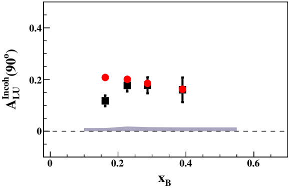
$$d\sigma^{\pm} \approx \int d\vec{p} dE P^{^4He}(\vec{p}, E) |\mathcal{A}^{\pm}(\vec{p}, E, K)|^2$$

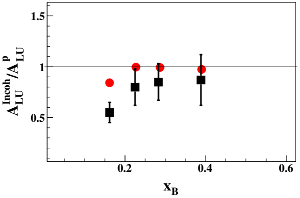


$$A_{LU}^{Incoh}(K) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \approx \frac{\mathcal{I}^{^4He}(K)}{T_{BH}^{2\,^4He}(K)} = \frac{\int_{exp} dE\, d\vec{p}\, P^{^4He}(\vec{p}, E)\, g(\vec{p}, E, K)\, \mathcal{I}(\vec{p}, E, K)}{\int_{exp} dE\, d\vec{p}\, P^{^4He}(\vec{p}, E)\, g(\vec{p}, E, K) T_{BH}^2(\vec{p}, E, K)}$$

- $\mathcal{I}(\vec{p}, E, K) \propto \Im m \mathcal{H}(\xi', \Delta^2) = H(\xi', \xi', \Delta^2) - H(-\xi', \xi', \Delta^2)$,
  the nucleon **GPD** H is evaluated for $\xi' = \frac{\mathbf{Q^2}}{(\mathbf{p}+\mathbf{p}')(\mathbf{q_1}+\mathbf{q_2})}$

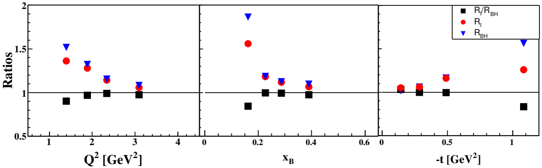
*Data from JLab (**M. Hattawy , PRL (2019)**)*





What kind of nuclear effects are we describing? Let us consider the *super ratio*

$$A_{LU}^{Incoh}/A_{LU}^{p} = \frac{\mathcal{I}^{^4He}}{\mathcal{I}^{p}} \frac{T_{BH}^{2\ p}}{T_{BH}^{2\ ^4He}} = \frac{R_{\mathcal{I}}}{R_{BH}} \propto \frac{(nucl.eff.)_{\mathcal{I}}}{(nucl.eff.)_{BH}},$$

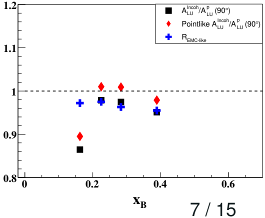


> *These effects are due to the* ***dependence on the 4-momenta components*** *of the bound proton entering the amplitudes.*
> *This behaviour hasn't to do with a modification of the* ***parton structure!***

It is confirmed by:

- the ratio $A_{LU}^{Incoh}/A_{LU}^{p}$ for **"pointlike" protons**
- the **"EMC-like" trend**

$$R_{EMC-like} = \frac{1}{\mathcal{N}} \frac{\int_{exp} dE\, d\vec{p}\, P^{^4He}(\vec{p}, E)\, \Im m\, \mathcal{H}(\xi', \Delta^2)}{\Im m\, \mathcal{H}(\xi, \Delta^2)}$$



- The nuclear ingredient is easier than for ^{4}He: just **momentum distribution** (totally realistic within AV18 potential!)
- $\Delta^2 = (p_{final} - p_{inner})^2$ or $\Delta^2 = (p_{final} - p_{rest})^2$
- Analitycal expression for p'

$$\begin{cases} \sqrt{|\vec{p}|^2 + |\vec{p}'|^2 + |q_1^z|^2 - 2|\vec{p}||\vec{p}'|\cos\theta_{pp'} - 2|\vec{p}'|q_1^z\cos\theta_N + 2|\vec{p}|q_1^z\cos\vartheta} - p_0 + E_2 - \nu = \\ -\Delta^2 + M^2 + p_0^2 - |\vec{p}|^2 - 2p_0\sqrt{M^2 + |\vec{p}'|^2} + 2|\vec{p}'||\vec{p}|\cos\theta_{\widehat{pp'}} = 0 \end{cases}$$

- **Experimental data** for pDVCS and nDVCS are coming out at JLab using a 12 GeV electron beam *(see Hobart's talk)*

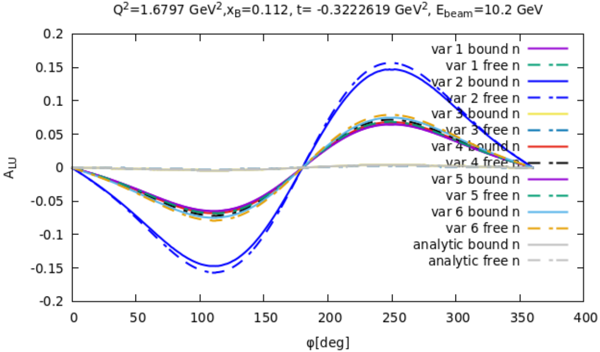
  In the meantime, our model can deliver

  - Predictions for **pDVCS**
  - Preliminary results for **nDVCS**

Stay tuned for the comparison with CLAS data!

nDVCS: preliminary results

$$\mathcal{I}(\vec{p}, E, K) \propto Im\left[F_1(\Delta^2)\mathcal{H}(\xi', \Delta^2) - F_2(\Delta^2)\mathcal{E}(\xi', \Delta^2)\left(\frac{\Delta^2}{4M^2} + \frac{\xi'(\Delta^2 - 2M^2 + 2p \cdot p'))}{4M^2}\right)\right]$$



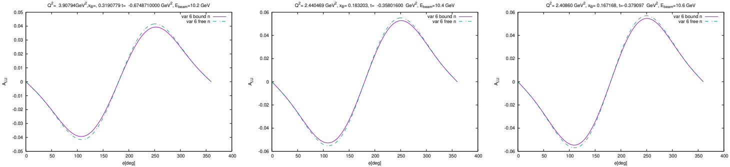
Considering the DD formalism for the GPD E from **GK EPJ (2008)**

$$e_{val}(x) \propto B(\beta_{val})(1-x)^{\beta_{val}}$$
$$e_s(x) \propto N_s(1-x)^{\beta_s}$$

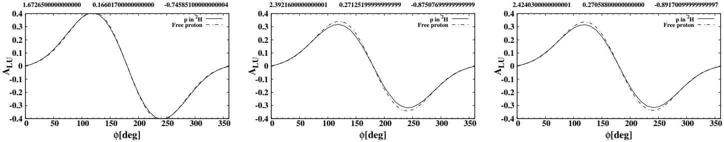
In variant 1-6 $\beta_{val,\,s}$ and N_s are varied to have still a reasonabe fit to the Pauli FF.

Incoherent on the deuteron: preliminary results

NDVCS



PDVCS



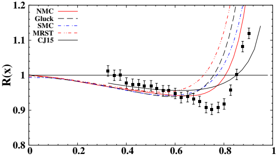
- Mild nuclear effects
- The contribution $\propto F_2\mathcal{E}$ is crucial in nDVCS
- Better understanding of the flipped sign for pDVCS and nDVCS
- Include possible FSI

$$R(x) = \frac{R_2^A(x)}{R_2^d(x)} \quad \text{with} \quad R_2^A(x) = \frac{F_2^A(x)}{ZF_2^p(x) + (A-Z)F_2^n(x)} \quad x \in [0 : M_A/M]$$

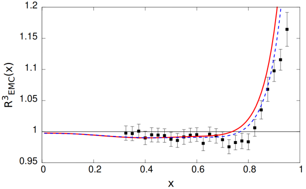
where the **function structures** F_2 for $A = {}^4$He, ^{3}He, d are defined as

$$F_2^A(x) = \sum_N \int_x^{M_A/M} dz f_N^A(z) F_2^N\left(\frac{x}{z}, Q^2\right)$$

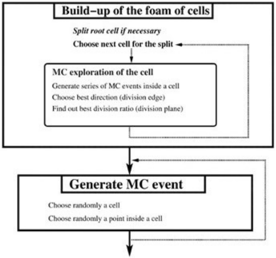
- For ^{3}He (see **Pace E. et. al, e-Print: 2206.05485**), study the dependence upon the nuclear interaction
- For ^{4}He (see **PRELIMINARY!**), study the dependence upon the nucleon model F_2



Data from JLab, **Seely et al., PRL (2009)**



From models to event generation



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Our Impulse approximation models for DVCS off light nuclei (Fucini et al., PRC(2018)-PRC(2020) etc...)

⇒

TOPEG

(The Orsay-Perugia Event Generator)

x-section of coherent DVCS off ^{4}He **(S. F., S.Scopetta, M. Viviani, PRC 98 (2018)**)

$$\frac{d^4\sigma^{\lambda=\pm}}{dx_A dt dQ^2 d\phi} = \frac{\alpha^3 x_A y^2}{8\pi Q^4\sqrt{1+\epsilon^2}} \frac{|T_{BH}|^2 + |T_{DVCS}|^2 + I^{\lambda}_{BH-DVCS}}{e^6}$$

$$T^2_{BH} \propto F^2_A(t);\; T^2_{DVCS} \propto \Im m\mathcal{H}^2 + \Re e\mathcal{H}^2;\; I^{\lambda}_{BH-DVCS} \propto F_A(t)\Im m\mathcal{H}$$

$$\mathcal{H}_q(\xi,t) = \int_0^1 dx\left(\frac{1}{x+\xi} + \frac{1}{x-\xi}\right)\left(\mathbf{H^A_q(x,\xi,t)} - \mathbf{H^A_q(x,-\xi,t)}\right)$$

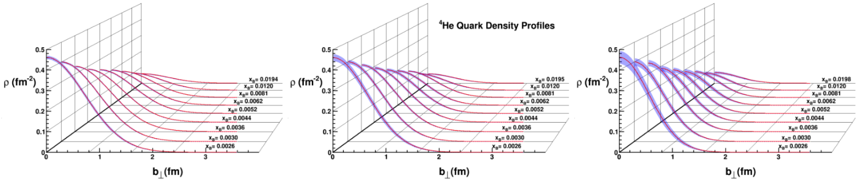
$$\mathbf{H^A_q(x,\xi,\Delta^2)} \approx \sum_N \int \frac{dz}{z} \int dE d\vec{p} P^A_N(\vec{p},\vec{p}+\vec{\Delta},E) H^N_q\left(\frac{x}{z},\frac{\xi}{z},\Delta^2\right)\delta\left(z - \frac{\bar{p}^+}{\bar{P}^+}\right)$$

Version **1.0** released:

- **JLab**
  - Check for the events generated at the kinematics with 6 GeV electron beam
  - Good also for CLAS 12 GeV
- **EIC**
  - We generated events for the three electron - helium-4 beam energy configurations
    - **(5x41) GeV**
    - **(10x110) GeV**
    - **(18x110) GeV**
- These latter results are included in the **EIC Yellow Report** (**Nucl.Phys.A 1026 (2022)**)

> - the NUCLEAR DVCS can be observed at the EIC
> - TOPEG is a flexible tool to do the GPDs phenomenology
> - Soon arriving the version 1.1

Promising results!!



Our assumptions in doing the fit of the pseudo-data generated with `TOPEG`

- using the leading order formalism
- 3 different **minimum transverse momenta** for the Roman pots
- 10 fb^{-1} integrated luminosity

We conclude that

- the **error** is highly correlated to the measurement **threshold of the Roman Pots**
- the **density profile extraction** is anyway doable

- **Coherent DVCS off ^{4}He**
  - Improvement of the ^{4}**He spectral function** (fully realistic calculation) **(in slow progress)**
  - Toward the semi-realistic description of the **EMC effect** in the helium-4 **(in progress)**
  - Impact of the **target mass corrections** on the observables and of **shadowing effects** **(planned)**
- **Incoherent DVCS off ^{4}He and ^{2}H**
  - New formalism for ^{4}**He** and the **deuteron** **(in progress)**
  - Introduction of some **final state interaction effects** **(TBD)**
  - Study of the $A-$ **dependence** of the average BSA for light nuclei (nitrogen data)
- **TOPEG**
  - Nuclear DVCS can be performed at the EIC: toward the **3D imaging** of nuclei
  - TOPEG is a suitable **phenomenological tool** to study light nuclei **(in progress)**

Backup slides

DVCS off deuterium

Incoherent channel

- Nuclear part: momentum distribution (it is exact: instant form or light front)
- Key study also for heavier nuclei

Coherent channel

- 9 quark GPDs
- Formalism already developed and established (see **Cano, Pire EPJA (2004)**)
- there is a connection between the light-cone wave function of the deuteron (helicity amplitudes$\longrightarrow$ **GPDs**) in terms of light-cone coordinates and the ordinary (instant-form) relativistic wave function that fulfills a Schrödinger type equation (we can update the potential)
- we can compute

$$\chi(\vec{k};\mu_1,\mu_2) = \sum_{L;m_L;m_S} \langle \frac{1}{2}\frac{1}{2}1|\mu_1,\mu_2,m_S\rangle\langle L11|m_L m_S\lambda\rangle Y_{L,M_L}(\hat{k})u_L(k)$$

with AV18 and perform a Melosh rotation to relate the spin in the light-front with the spin in the instant-form frame of the dynamics

(18 x 110) GeV: analysis

Is it possible to study the region around the first diffraction minimum in the ^{4}He FF ($t_{\text{dif. min}} = -0.48$ GeV^2)? YES, we can!

- 99%+ electrons and photons are in the acceptance of the detector matrix
- This is true for all energy configurations

> Electrons and photons appear in easily accessible kinematics according to the detector matrix requirements (exceptions for small angles photons)

- Acceptance at low -t will be cut passing through the detectors
  - t_{min} is set by the detector features
  - t_{max} is fixed by the luminosity (billion of events to generate)

From left to right, the kinematical distributions of the final particles: electron, photon and ^{4}He