From initial gluons to hydrodynamics: gluons inside hadrons and their thermalization

Oct 24 – 25, 2022 Institut Pascal

Shedding light on light nuclei with exclusive reactions

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October 24, 2022

- **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.

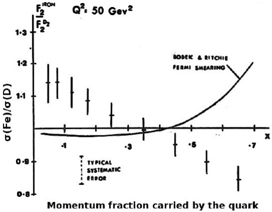
  V. L. Telegdi

- **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 the two communities of QNP

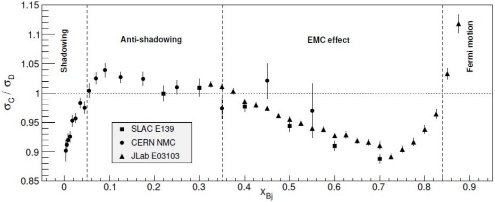
- High-energy physics
- Low-energy nuclear structure physics

The nuclear medium modifies the structure of bound nucleons



The European Muon Collaboration found

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



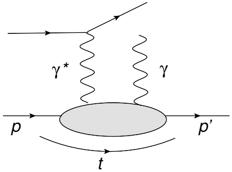
- $x \leq 0.05$: "Shadowing region"
- $0.3 \leq x \leq 0.85$: "EMC region"
- $0.85 \leq x \leq 1$: "Fermi motion region"

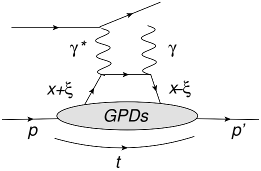
Collinear information led to many models but not yet to a complete explanation

(e.g., see **Cloët et al. JPG (2018)**, for a recent report)

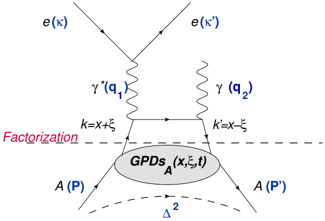
Deeply Virtual Compton Scattering off nuclei

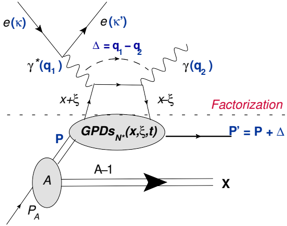
- **Exclusive electro-production of a real photon** → *clean access to* ***Generalized Parton Distributions***



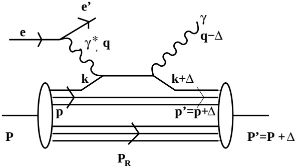


- **Two DVCS channels in nuclei**:
  - **Coherent channel** → GPDs of the **whole nucleus**
  - **Incoherent channel** ⟶ GPDs of the **bound nucleon**





Impulse approximation to the handbag approximation

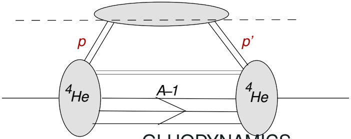


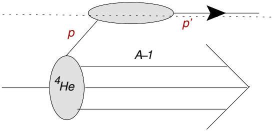
- Only nucleonic degrees of freedom
- The bound proton is **kinematically** off-shell

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

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

- Possible final state interaction (**FSI**) effects are neglected
- Convolution formulas (for the cross section, for the GPD...) between nuclear (**spectral functions** obtained with **realistic potential and 3-body forces**, i.e. Argonne 18 (Av18) + Urbana IX) and nucleonic ingredients

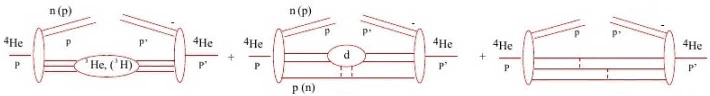




The nuclear ingredient

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

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



- 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 $\mathbf{n_1}(|\vec{p}|) = n(|\vec{p}|) - n_0(|\vec{p}|)$
- $\boldsymbol{n(p), n_0(p)}$ can be evaluated within the Av18 NN interaction + UIX 3-body forces

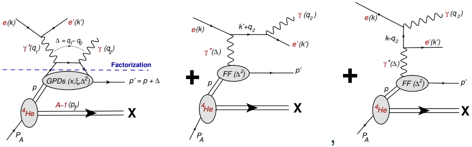
MESSAGE TO TAKE HOME

- Realistic calculations for **light nuclei** $A \leq 6$
- ab initio method / EFT approaches for *medium nuclei*
- Many body calculation accounting for mean field potential for **heavy nuclei** $A > 20$

The generalized EMC effect

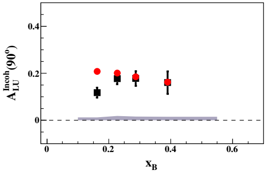
Incoherent DVCS: S.F., S. Scopetta, M. Viviani, PRC(2021)- PRD(2021)

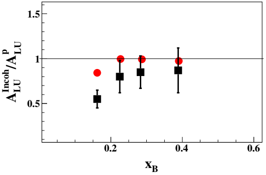
$$d\sigma^{\pm} \approx \int d\vec{p} dE P^{^4He}(\vec{p}, E) |\mathcal{A}^{\pm}(\vec{p}, E, K)|^2$$



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

- nuclear effects affect the motion of the proton in the nuclear medium (no modifications to the functional form of the GPDs and FFs)
- in $\mathcal{I}(\vec{p}, E, K) \propto \Im m \mathcal{H}(\xi', \Delta^2, Q^2)$, we used the nucleon **GPD model** evaluated for $\xi' = \frac{\mathbf{Q^2}}{(\mathbf{p}+\mathbf{p'})(\mathbf{q_1}+\mathbf{q_2})}$

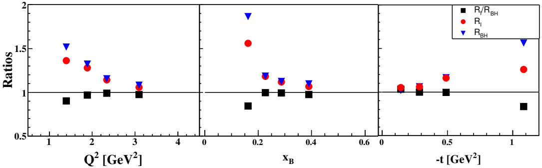




Nuclear effects in A_{LU}^{Incoh}: S.F., S. Scopetta, M. Viviani PRC(2021)

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

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

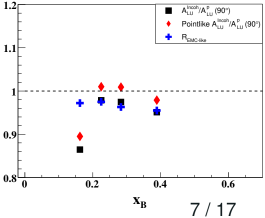


These effects are due to the ***dependence on the 4-momenta components*** *of the bound proton entering the amplitudes.*
This behaviour hasn't to do with a modification of the ***parton structure!***

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!)
- $\Delta^2 = (p_{final} - p_{inner})^2$ 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

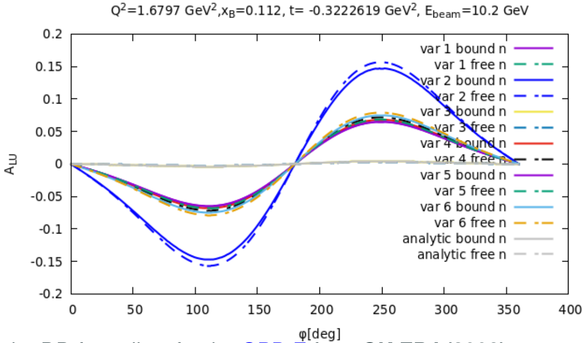
  In the meantime, our model can deliver

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

Stay tuned for the comparison with CLAS data!

nDVCS: preliminary results

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



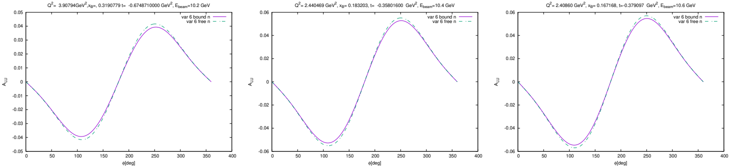
Considering the DD formalism for the GPD E from **GK EPJ (2008)**

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

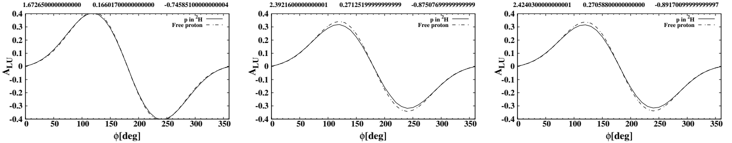
In variant 1-6 $\beta_{val,\,s}$ and N_s are varied to have still a reasonabe fit to the Pauli FF.

Incoherent on the deuteron

NDVCS



PDVCS



- Mild nuclear effects
- The contribution $\propto F_2\mathcal{E}$ is crucial in nDVCS

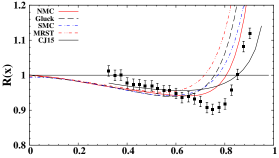
EMC effect on light nuclei

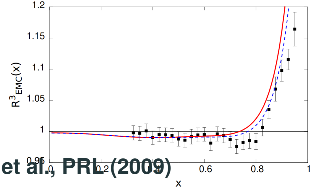
$$R(x) = \frac{R_2^A(x)}{R_2^d(x)} \text{ with } R_2^A(x) = \frac{F_2^A(x)}{ZF_2^p(x) + (A-Z)F_2^n(x)} \quad x \in [0 : M_A/M]$$

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



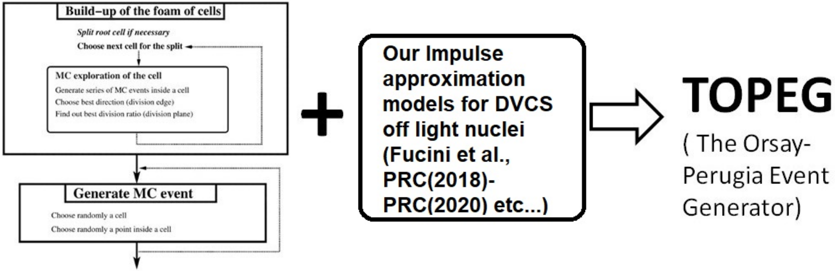


Data from the MARATHON collaboration **Seely et al., PRL (2009)**

From models to event generation

TOPEG: a Monte Carlo event generator for DVCS off light nuclei

TOPEG is a Root based generator (**S. Jadach (2005)**) + **our model** for the coherent/incoherent DVCS off light nuclei



Use of the TFoam class to create and memorize a grid and then to generate events

Putting these models in TOPEG

So far, we have results only for the coherent DVCS off ^{4}He based on **(S. F., S.Scopetta, M. Viviani, PRC 98 (2018) 015203**) (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** (e-Print: 2103.05419)

Promising results:

- the NUCLEAR DVCS can be observed at the EIC
- TOPEG is a flexible tool to do the GPDs phenomenology

Targets

- ^{4}He
- Deuteron
- Free proton/ bound proton
- Bound neutron/ free neutron (on going)

Observables

- Unpolarized 4-differential cross section
- Beam spin asimmetries
- Beam charge asimmetries

Reactions

- Coherent DVCS
- Incoherent DVCS
- Bethe Heitler
- Tagged DVCS (on going)

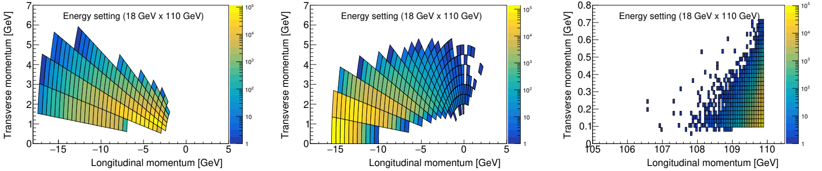
Is it possible to study the region around the first diffraction minimum in the ^{4}He FF ($t_{\mathrm{dif.\,min}} = -0.48$ GeV^2)? **YES, we can!**

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

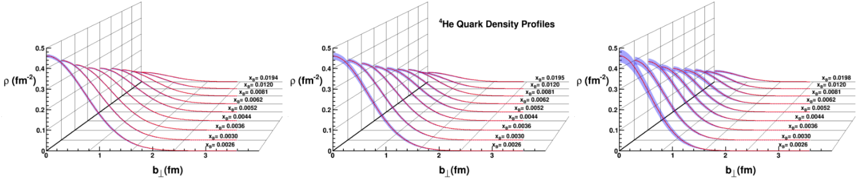
> Electrons and photons appear in easily accessible kinematics according to the detector matrix requirements (exceptions for small angles photons)

- 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



Toward the nuclear tomography



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

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

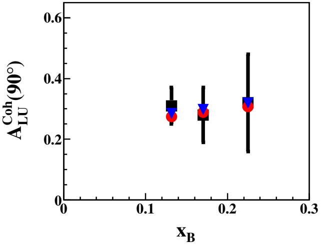
with AV18 and perform a Melosh rotation to relate the spin in the light-front with the spin in the instant-form frame of the dynamics

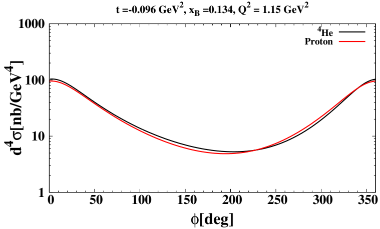
Coherent DVCS off ^{4}He

Model for the only one chiral-even GPD of ^{4}He in **S. Fucini, S.Scopetta, M. Viviani, PRC 98 (2018)**

$$\frac{d^4\sigma^{\lambda=\pm}}{dx_A dt dQ^2 d\phi} = \frac{\alpha^3 x_A y^2}{8\pi Q^4 \sqrt{1+\epsilon^2}} \frac{|\mathcal{A}|^2}{e^6}; A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-}$$

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





Data from **Hattawy et al., PRL (2017)**; our model including (red dots) or not (blue triangles) the real part of $\mathcal{H}$.

As an illustration, we plot $d^4\sigma_{^4He} \times (F_p^1/F_C^A)^2$ and $d^4\sigma_{proton} * 4$