**Tomography of light nuclei at an EIC**
9-10 November 2022
ECT* (ITALY)

# Deeply Virtual Compton Scattering off light nuclei: where do we stand?


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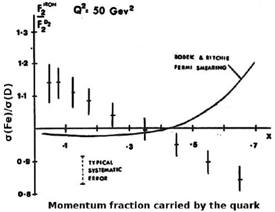
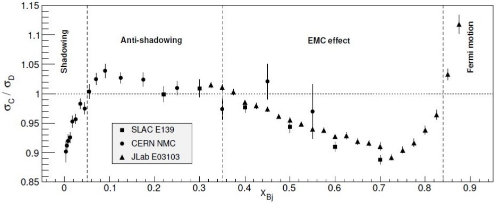
## The nuclear medium modifies the structure of bound nucleons

The European Muon Collaboration found

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



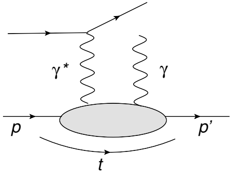



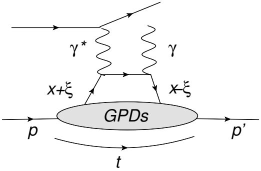

- $x \leq 0.05$: "Shadowing region"
- $0.3 \leq x \leq 0.85$ : "EMC region"
- $0.85 \leq x \leq 1$ : "Fermi motion region"

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

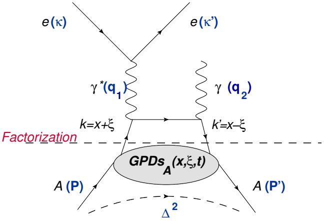
(e.g., see **Cloët et al. JPG (2018)**, for a recent report)

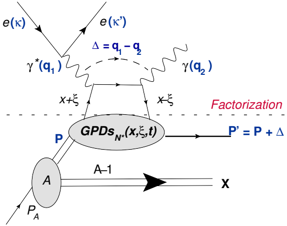
- **Exclusive electro-production of a real photon** → *clean access to* ***Generalized Parton Distributions***




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



## GPDs from lattice QCD

- *Transversity GPDs of the proton from lattice QCD* (**Alexandrou at al., arXiv:2108.10789 (2021)**)
- *Pion generalized parton distribution from lattice QCD* (**Chen et al., NPB, 952 (2020)**)

## Deconvolution from CFFs

- *The deconvolution problem of DVCS*, see **Bertone et al., PRD 103 (2021)**
- *Global fit* (**Guidal et al., Rept. Prog. Phys. 76 (2013)**) and *local fit* (**Dupré et al., PRD 95.1 (2017)**)

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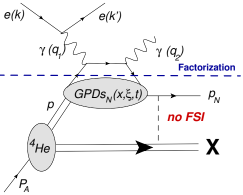
## All this concerns the free proton!

## What about nuclei?

- Position-momentum structure of SRC for **$^{40}$Ca, $^{48}$Ca, $^{12}$C** (**Cosyn et al. ,PLB 820 (2021)**)
- FSI in DIS off **deuteron** (**Strikman et Weiss, PRC 57 (2018)** , transversity GPDs (**Cosyn et al., PRD 98 (2018)**)
- NPLQCD collaboration (e.g., **PRL 120 (2018)**): **nuclei with A$<$5** but unphysical $q$ masses
- **Phenomenological models** for **helium targets** (ours or e.g. **Liuti et al., PRC 72 (2005)**)

# Incoherent DVCS off light nuclei

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



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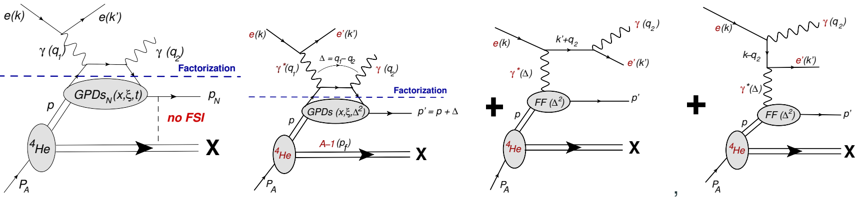



In **impulse approximation**, for the cross section we get

- the **diagonal** spectral function

$$d\sigma^{\pm}_{Incoh} = \int_{exp} dE d\vec{p} \frac{p \cdot k}{p_0 |\vec{k}|} P^{^4He}(\vec{p}, E) \; d\sigma^{\pm}_{b}(\vec{p}, E, K)$$

- the DVCS cross section off a bound proton

For the **BSA**

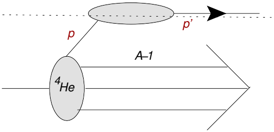
$$A^{Incoh}_{LU}(K) = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} \approx \frac{\mathcal{I}^{^4He}(K)}{T^{2\,^4He}_{BH}(K)} = \frac{\int_{\tilde{K}} dE \, d\vec{p} \, P^{^4He}(\vec{p}, E) \, g(\vec{p}, E, K) \, \mathcal{I}(\vec{p}, E, K)}{\int_{\tilde{K}} dE \, d\vec{p} \, P^{^4He}(\vec{p},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

- $\mathcal{I}(\vec{p}, E, K) \propto \Im m \mathcal{H}(\xi', \Delta^2) = H(\xi', \xi', \Delta^2) - H(-\xi', \xi', \Delta^2)$,

  the nucleon **GPD** $H$ is evaluated for $\xi' = \dfrac{\mathbf{Q^2}}{(\mathbf{p} + \mathbf{p'})(\mathbf{q_1} + \mathbf{q_2})}$

$$P_N^A(\vec{p}, E) = \sum_{f_{A-1}} \langle {}^4He | f_{A-1}; N\vec{p} \rangle \langle f_{A-1}; N\vec{p} | {}^4He \rangle \delta(E - E_{min} - \epsilon^*_{A-1})$$

$$\xrightarrow[closure]{} P_0(\vec{p}, E) + P_1(\vec{p}, E) \approx n_0(\vec{p})\delta(E - E_{min}) + n_1(\vec{p})\delta(E - \bar{E})$$




- 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

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

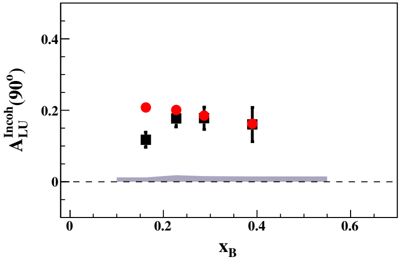
- the **excited momentum distribution** is $\mathbf{n_1}(|\vec{p}|) = n(|\vec{p}|) - n_0(|\vec{p}|)$
- $\boldsymbol{n(p)}$ , $\boldsymbol{n_0(p)}$ can be evaluated within the Av18 NN interaction **(Wiringa et al., PRC (1995))** + UIX 3-body forces **(Pudliner et al., PRL (1995))**
- $\boldsymbol{P_1^{\text{our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

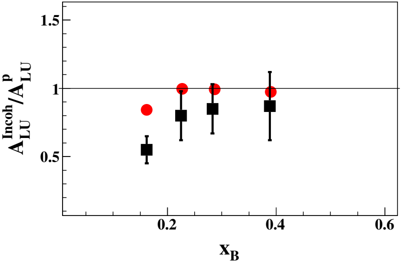
## MESSAGE TO TAKE HOME

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

# Incoherent DVCS: results

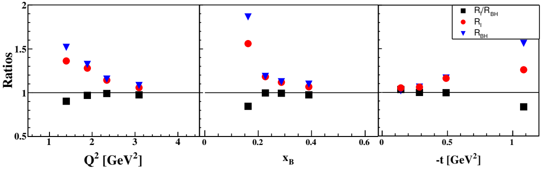
Our results compared with the data from EG6 collaboration at JLab (**PRL 123 (2019)**).



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

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




Is this behaviour due to a modification of the **parton structure?**

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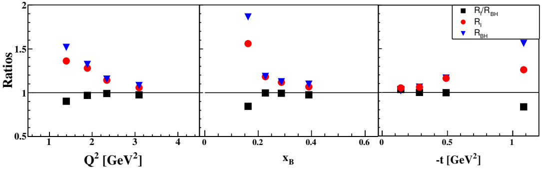
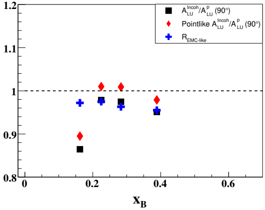



Is this behaviour due to a modification of the **parton structure?**

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

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



# Incoherent DVCS off unpolarized deuteron

- The nuclear ingredient is easier than for $^4$He: just **momentum distribution** (totally realistic within AV18 potential!)
- $\Delta^2_{vertex} = (p_{final} - p_{inner})^2 \implies p_{final}$ fixed with $\Delta^2_{exp}\Big|_{p^{rest}_{initial}}$ *à la CLAS*
- $\Delta^2_{vertex} = (p_{final} - p_{rest})^2 \implies p_{final}$ fixed with $\Delta^2_{exp}\Big|_{photons}$ *à la HERMES*
- **Experimental data** for pDVCS and nDVCS are coming out at JLab using a 12 GeV electron beam.

  Analysis under review, see e.g. `https://indico.cern.ch/event/1104299/contributions/5055280/attachments/2536704/4365938/EuNPC2022_ajh.pdf`.

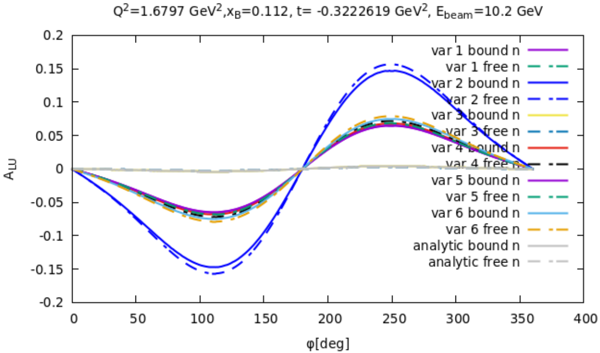
  Within our model we can deliver

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

**Stay tuned for the comparison with CLAS data!**

# nDVCS: preliminary results

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



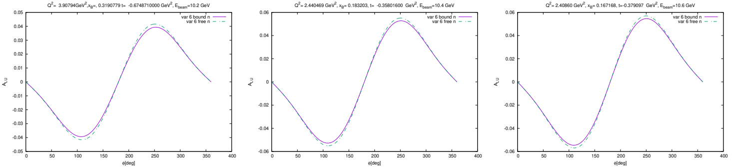

Considering the DD formalism for the GPD E from **GK EPJ (2008)**

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

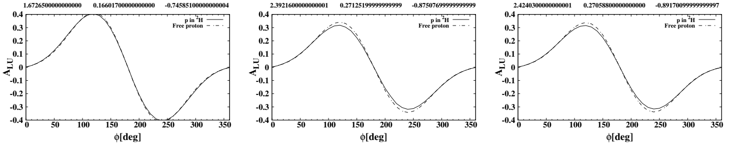
In variant 1-6 $\beta_{val,\,s}$ and $N_s$ are varied to have still a reasonabe **fit to the Pauli FF**.

# Incoherent on the deuteron: preliminary results

**NDVCS**

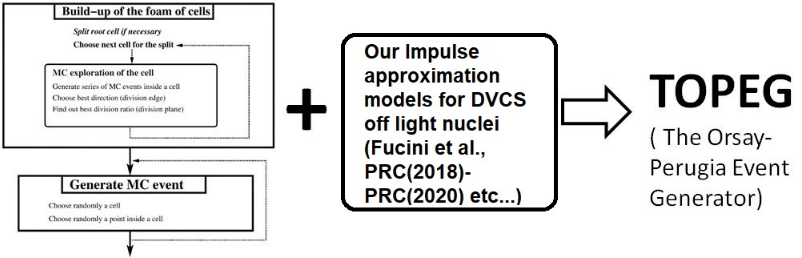



**PDVCS**




- Mild nuclear effects $\Longrightarrow$ scan in $x_B$ for $\Delta^2$ fixed and viceversa
- The contribution $\propto F_2 \mathcal{E}$ is crucial in nDVCS
- Better understanding of the flipped sign for pDVCS and nDVCS $\Longrightarrow$ insights on the the value of $J_{u,\,d}$
- Include possible FSI

# Toward the tomography of $^4$He at the EIC




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

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

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

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

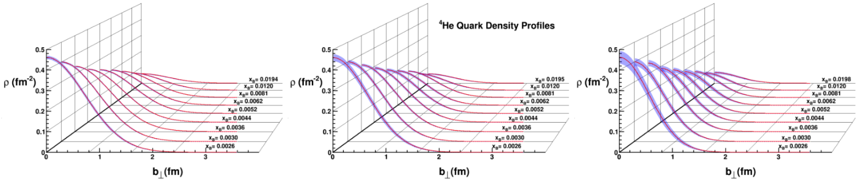
$$\mathbf{H^A_q(x,\xi,\Delta^2)} \approx \sum_N \int \frac{dz}{z} \int dE d\vec{p} P^A_N(\vec{p},\vec{p}+\vec{\Delta},E) H^N_q\left(\frac{x}{z},\frac{\xi}{z},\Delta^2\right)\delta\left(z - \frac{\bar{p}^+}{\bar{P}^+}\right)$$

# 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

- **Incoherent DVCS off $^{4}$He and $^{2}$H**
  - New formalism for $^{4}$**He** and the **deuteron** **(in progress)**
  - Insights for the generalized EMC effect
  - Introduction of some **final state interaction effects** **(TBD)**
  - Study of the $A-$ **dependence** of the average BSA for light nuclei (see *Dupré's talk*)
- **TOPEG**
  - For the **coherent DVCS off $^{4}$He**
    - Nuclear DVCS can be performed at the EIC: toward the **3D imaging** of nuclei
    - Constrain the calculation of the nuclear spectral function with the help of **tagged measuments**
  - TOPEG is a suitable **phenomenological tool** to study light nuclei at the EIC.

# 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

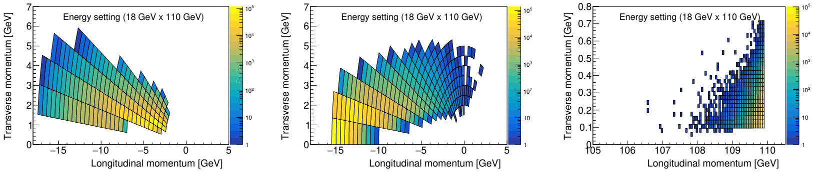
**Is it possible to study the region around the first diffraction minimum in the $^4$He FF ($t_{\text{dif. min}} = -0.48$ GeV$^2$)? YES, we can!**

- 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)

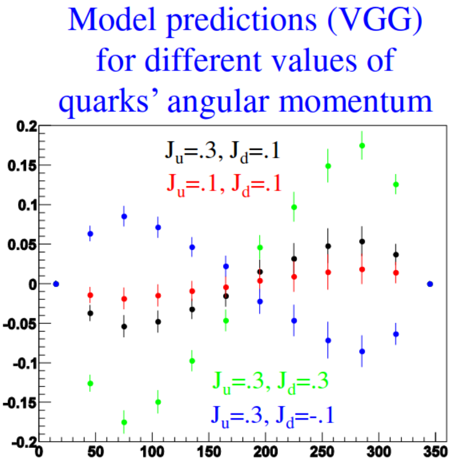
**From left to right, the kinematical distributions of the final particles: electron, photon and $^4$He**



# nDVCS

From Hobart's talk

https://indico.cern.ch/event/1104299/contributions/5055280/attachments/2536704/4365938/EuNPC2022_ajh.pdf



# Spectral function in the incoherent DVCS