

# International workshop on CLAS12 physics and future perspectives at JLab

21-24 March 2023

## Models for DVCS off light nuclei (and beyond)

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# Sara Fucini

March 22, 2023



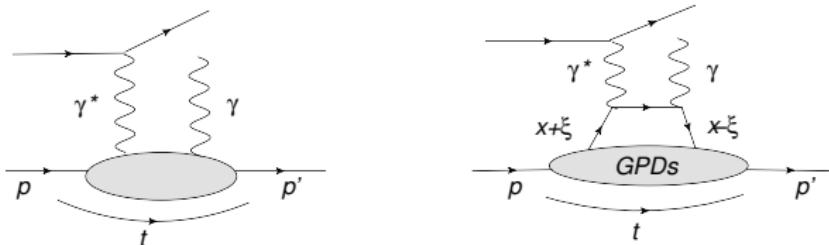
Laboratoire de Physique  
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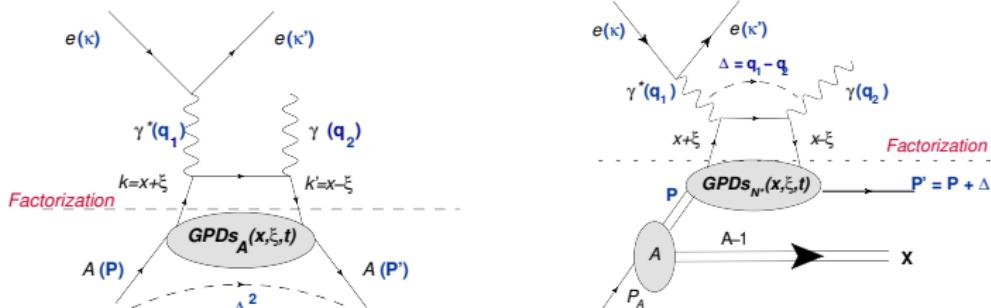
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# Deeply Virtual Compton Scattering off nuclei

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



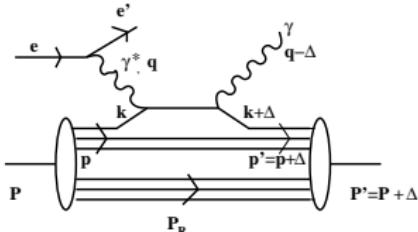
- Two DVCS channels in nuclei:
  - Coherent channel → GPDs of the whole nucleus
  - Incoherent channel → GPDs of the bound nucleon



# Making Impulse approximation models

## Impulse approximation to the handbag approximation

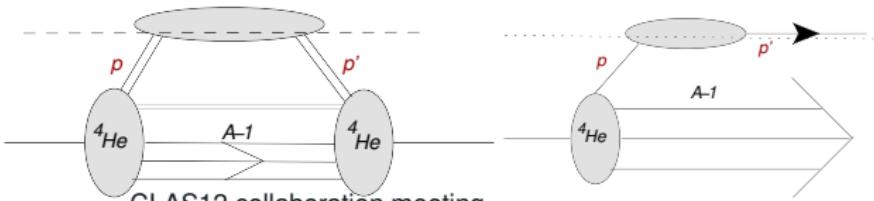
- Only nucleonic degrees of freedom
- The bound proton is **kinematically** off-shell



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

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

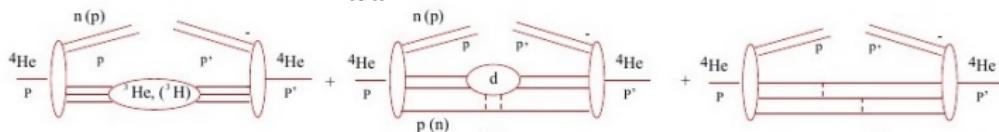
- Possible final state interaction (FSI) effects are neglected
- Convolution formulas of **nuclear**  $\left( \text{spectral functions etc ...} \right)$   
and **nucleonic** ingredients  $\left( \text{GPDs etc ...} \right)$



# The nuclear ingredient

- Off-diagonal spectral function

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



- Diagonal spectral function

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

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

## MESSAGE TO TAKE AWAY

- Realistic solution of the Schroedinger equation for **light nuclei**  
 $A \leq 6$
- Many body calculation accounting for mean field potential for  
**heavier nuclei**
- Ab initio calculations, EFT theories for the nuclear interactions...

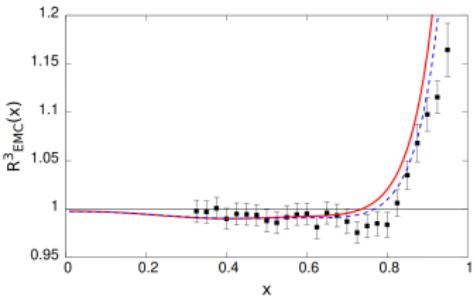
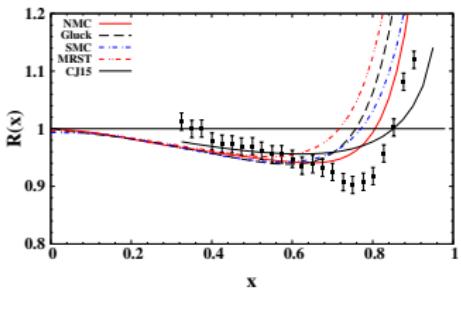
# EMC effect on light nuclei

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

where the **function structures**  $F_2$  for  $A = {}^4\text{He}, {}^3\text{He}, \text{d}$  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  ${}^3\text{He}$  (see **Pace E. et. al, e-Print: 2206.05485**), study the dependence upon the nuclear interaction vs **MARATHON** data
- For  ${}^4\text{He}$  (see **PRELIMINARY!**), study the dependence upon the nucleon model  $F_2$  vs **Seely et al., PRL (2009)**



## **Coherent DVCS off light nuclei**

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

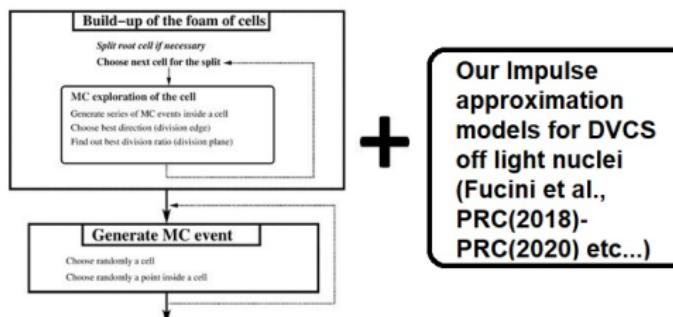
x-section of coherent DVCS off  ${}^4\text{He}$  (S. F., S.Scopetta, M. Viviani, PRC 98 (2018))

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

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

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

$$\mathbf{H}_{\mathbf{q}}^{\mathbf{A}}(\mathbf{x}, \xi, \Delta^2) \approx \sum_N \int \frac{dz}{z} \int dE d\vec{p} P_N^A(\vec{p}, \vec{p} + \vec{\Delta}, E) H_q^N \left( \frac{x}{z}, \frac{\xi}{z}, \Delta^2 \right) \delta \left( z - \frac{\vec{p}^+}{\vec{P}^+} \right)$$



**TOPEG**  
(The Orsay-Perugia Event Generator)

# Version 1.0 released:

## ► JLab

- Check for the events generated at the kinematics with 6 GeV electron beam
- Good for CLAS 12 GeV
- Introduction of **other channels** and structure functions (DVMP,TMDs ...) (ongoing)

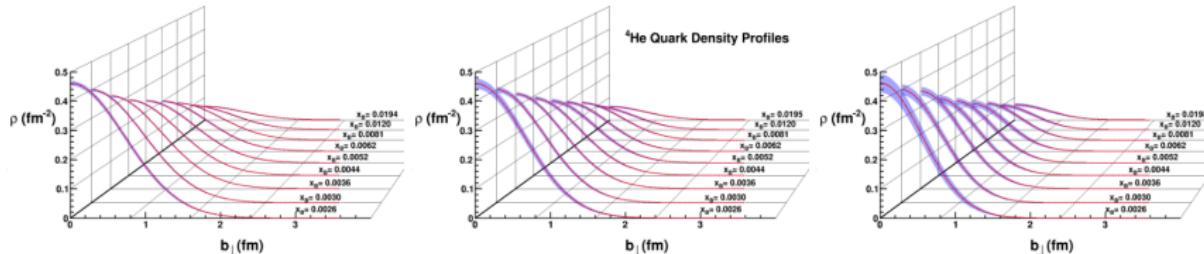
## ► EIC

- 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))**

- TOPEG is a flexible tool to do the GPDs phenomenology
- Soon arriving the version 1.1: coherent DVCS off  $^{16}\text{O}$ , fully differential cross section  $\frac{d\sigma}{dx_B dQ^2 dt d\phi d\vec{p} d \cos \vartheta d\varphi}$  for the tagged DVCS off deuterium

## Promising results at EIC!!



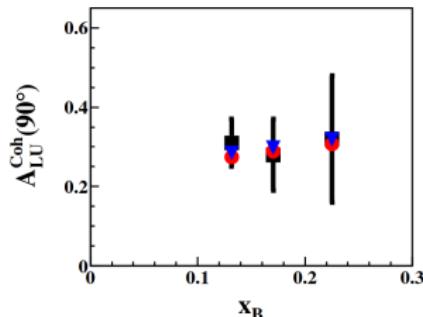
Our assumptions in doing the fit of the pseudo-data generated with TOPEG

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

### In conclusion

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

# DVCS with $e^+$ off light nuclei (EPJA(2021))



Data from CLAS6; theory from **Fucini et al., PRC (2018)**

$\Im m \mathcal{H} + \Re e \mathcal{H}_A$  (red) &  $\Re e \mathcal{H}_A$  (blue).

$$BSA_A = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

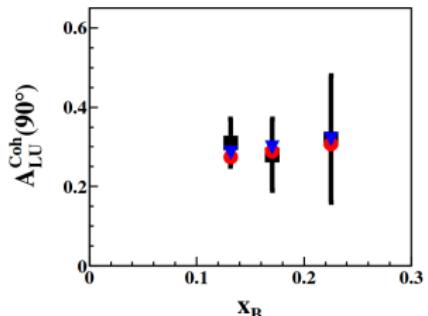
$$\approx \frac{x_B}{y} \frac{\textcolor{blue}{s_1^I}}{c_0^{BH}} \sin(\phi)$$

$$BCA_A = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ - d\sigma^-}$$

$$\approx \frac{x_B(1 + \varepsilon^2)^2}{y} \frac{\textcolor{red}{c_1^I} \cos(\phi)}{c_0^{BH} + c_1^{BH} \cos(\phi)}$$

$$s_1^I \propto \Im m c_{unp}^I \text{ and } \textcolor{red}{c_1^I} \propto \Re e c_{unp}^I$$

# DVCS with $e^+$ off light nuclei (EPJA(2021))



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$\Im m \mathcal{H} + \Re e \mathcal{H}_A$  (red) &  $\Re e \mathcal{H}_A$  (blue).

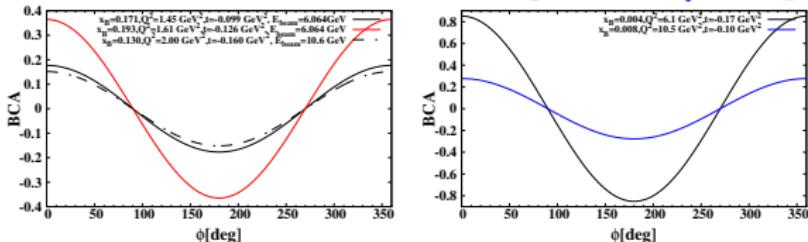
$$BSA_A = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

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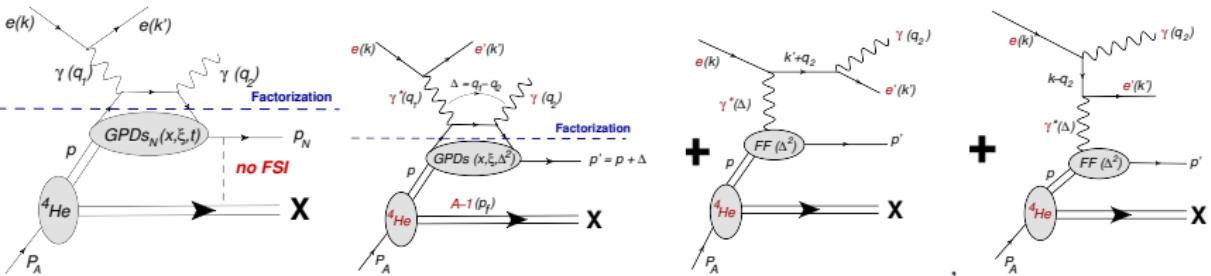


- in coherent DVCS off  ${}^3\text{He}$  and  ${}^4\text{He}$  with polarized  $e^-$  and unpolarized  $e^+$ , measurements of  $\Re e \mathcal{H} \implies$  study of **d-term**
- polarized  ${}^3\text{He} \implies$  spin dependent and parton helicity flip **CFFs of the neutron**
- incoherent DVCS with  $e^+ \implies$  to **gluon transversity GPD**

## **Incoherent DVCS off nuclei**

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



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

- the **diagonal spectral function**

$$d\sigma_{Incoh}^\pm = \int_{exp} dE d\vec{p} \frac{\vec{p} \cdot \vec{k}}{p_0 |\vec{k}|} P^A(\vec{p}, E) d\sigma_b^\pm(\vec{p}, E, K)$$

- the DVCS cross section off a bound proton

For the **BSA**

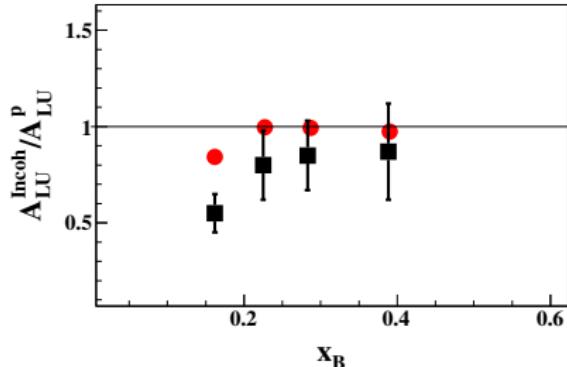
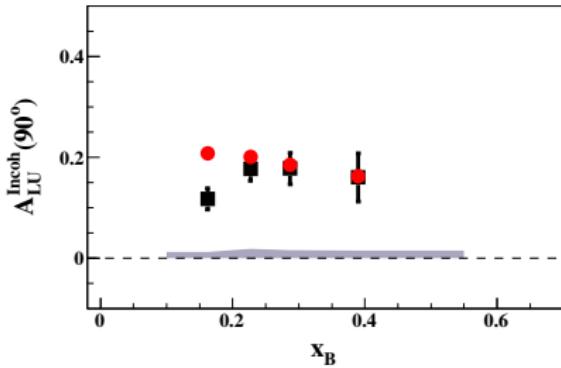
$$A_{LU}^{Incoh}(K) = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} \approx \frac{\mathcal{I}^A(K)}{T_{BH}^{2A}(K)} = \frac{\int_{\tilde{K}} dE d\vec{p} P^A(\vec{p}, E) g(\vec{p}, E, K) \mathcal{I}(\vec{p}, E, K)}{\int_{\tilde{K}} dE d\vec{p} P^A(\vec{p}, E) g(\vec{p}, E, K) T_{BH}^2(\vec{p},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

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

the nucleon **GPD**  $H$  is evaluated for  $\xi' = \frac{Q^2}{(\mathbf{p} + \mathbf{p}')(\mathbf{q}_1 + \mathbf{q}_2)}$

# Incoherent DVCS: results

Fucini et al. (2021) vs EG6 data (PRL 123 (2019)).



- PREVIOUS DEFINITION OF  $t$ :

$$\Delta_{vertex}^2 = (p_{final} - p_{moving})^2 \text{ with } \Delta_{exp}^2 \Big|_{photons} \text{ fixed in the process}$$

*à la HERMES*

- ACTUAL DEFINITION OF  $t$ :

$$\Delta_{vertex}^2 = (p_{final}^{\Delta_{exp}^2} - p_{inner})^2 \implies p_{final} \text{ fixed with } \Delta_{exp}^2 \Big|_{p_{initial}^{rest}}$$

*à la CLAS*

- we are integrating  $t_{min} = -Q^2 - \left(\frac{s-M^2}{\sqrt{s}}\right)(\nu^{C.O.M} - |\bar{q}^{C.O.M}|)$

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- Need to introduce **radiative corrections** (see **M. Vanderhaeghen et al., PRC (2000), Akushevich et al., PRD (1018)**)

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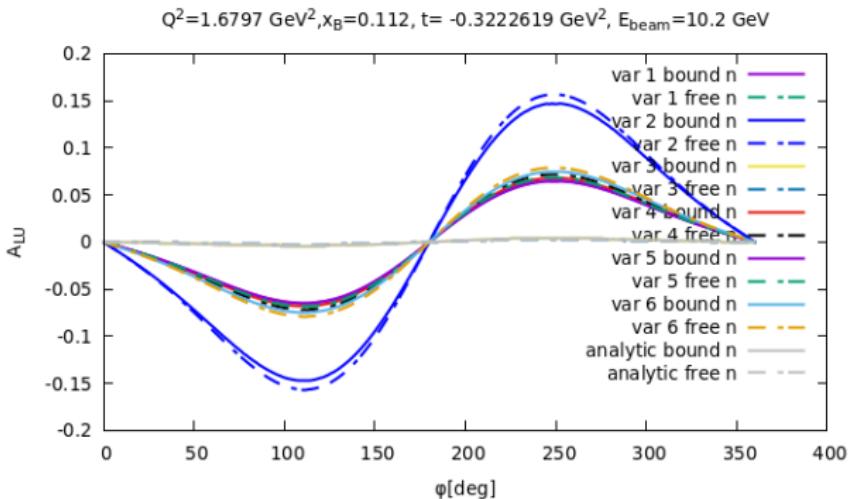
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*à la CLAS*

- we are integrating  $t_{min} = -Q^2 - \left( \frac{s-M^2}{\sqrt{s}} \right) (\nu^{C.O.M} - |\vec{q}^{C.O.M}|)$
- Need to introduce **radiative corrections** (see **M. Vanderhaeghen et al., PRC (2000), Akushevich et al., PRD (2018)**)
- ${}^2\text{H}$ : just **momentum distribution** (totally realistic within AV18 potential!)
- ${}^4\text{He}$ : totally realistic **spectral function**
- ${}^{12}\text{C}$  and  ${}^{16}\text{O}$ : simple momentum distribution à la Ciofi-Simula

# nDVCS off deuterium

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

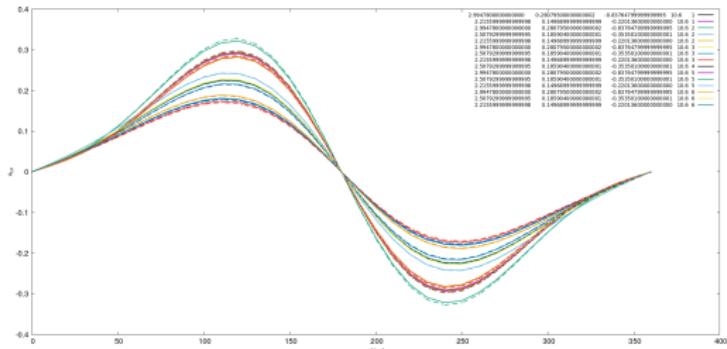


Considering the DD formalism for the [GPD E](#) from [GK EPJ \(2008\)](#)

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

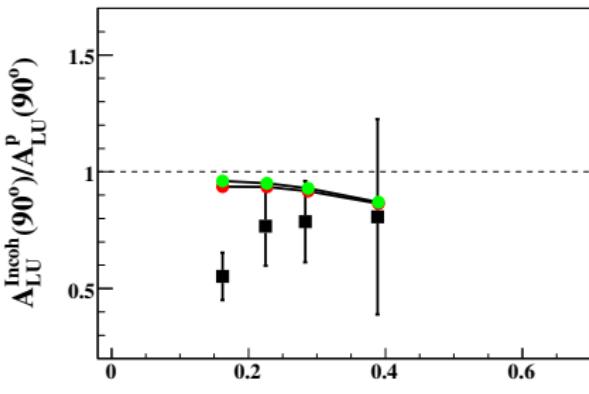
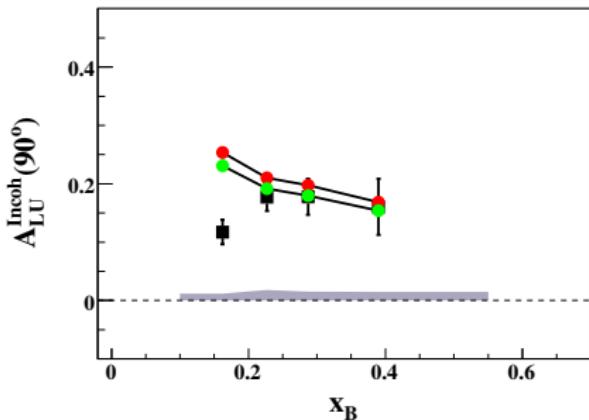
In variant 1-6  $\beta_{val, s}$  and  $N_s$  are varied to have still a reasonable **fit to the Pauli FF**.

# Incoherent on the deuteron: preliminary results for pdvcs



- Comparison with data (see Hobart's talk h 10:25, 22/03/2023)
- The contribution  $\propto F_2 \mathcal{E}$  is crucial in nDVCS  $\implies$  **new constraints** for the GPD E are needed (see Cuic's talk h 10:55, 22/03/2023)
- Better understanding of the flipped sign for pDVCS and nDVCS  $\implies$  insights on the value of  $J_{u,d}$

## Which is the impact of the $E$ variants in our previous predictions?

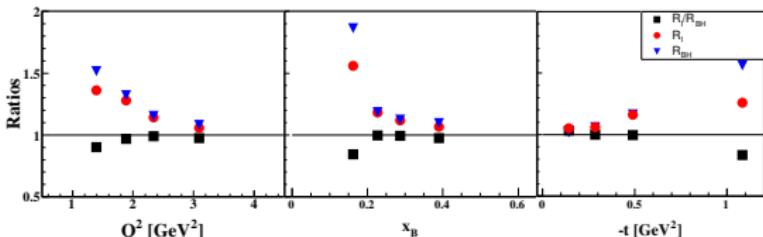


# Need for x-sections

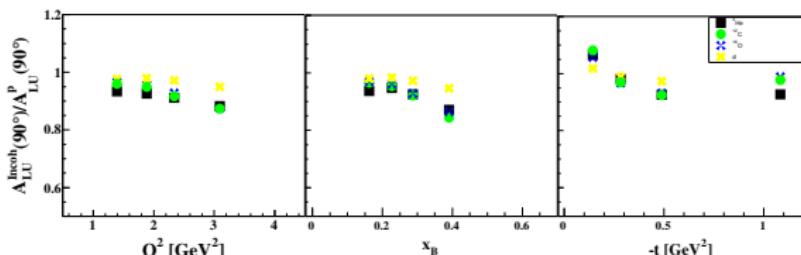
See **S.F., S. Scopetta, M. Viviani PRC (2021)** for a further discussion on the nuclear effects

- To appreciate our conventional nuclear effects

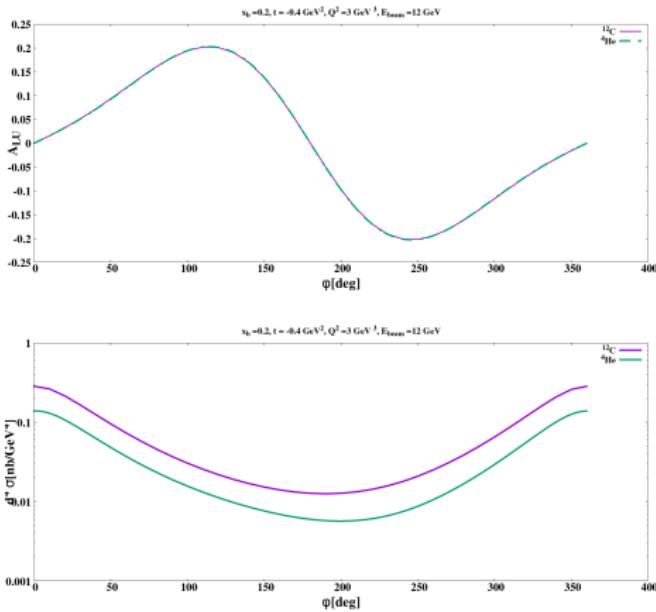
$$A_{LU}^{Incoh}/A_{LU}^p = \frac{\mathcal{I}^4He}{\mathcal{I}^p} \frac{T_{BH}^{2p}}{T_{BH}^{2^4He}} = \frac{R_{\mathcal{I}}}{R_{BH}} \propto \frac{(nucl.eff.)_{\mathcal{I}}}{(nucl.eff.)_{BH}},$$



- To infer the depend on  $A$  of the EMC effect



# Quest for the cross sections



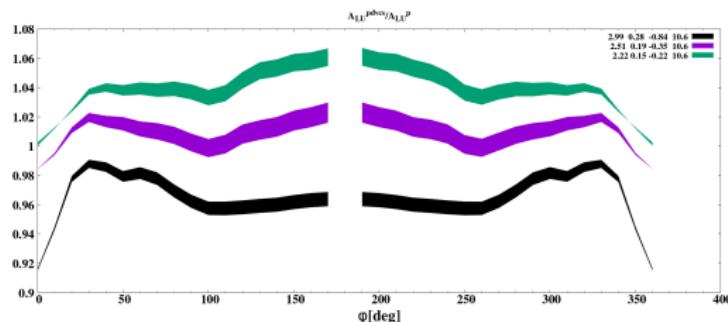
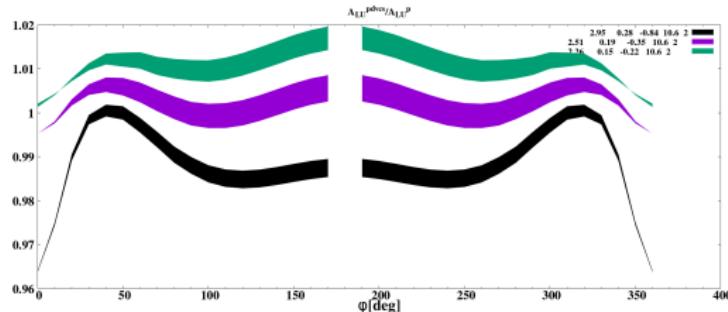
## MESSAGE TO TAKE HOME

- Measurements of the cross sections themselves could be important to control properly the nuclear effects
- This behaviour is true at  $E_{beam} = 6 \text{ GeV}$  and even more at  $E_{beam} = 12 \text{ GeV}$

# Nuclear effects in pDVCS

$E_{beam} = 10.6 \text{ GeV}$

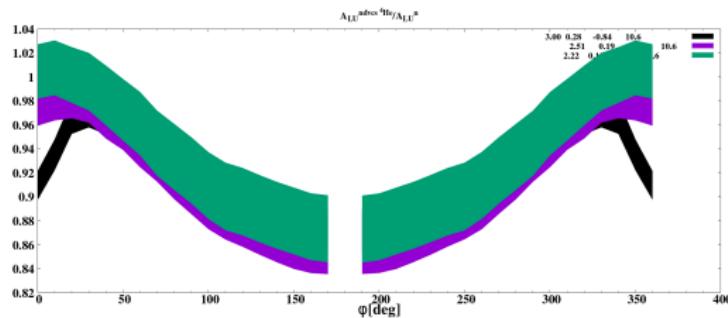
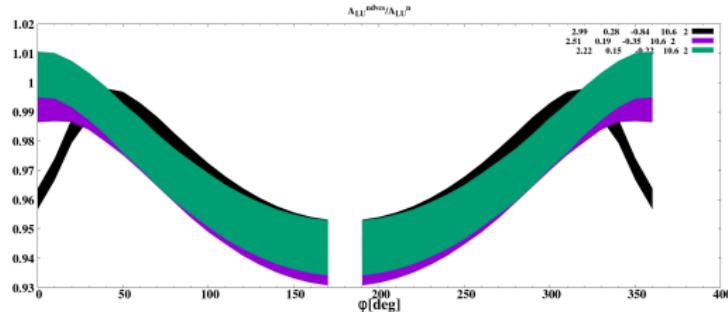
**Bound proton** in the deuteron and in  ${}^4\text{He}$ , respectively.



# Nuclear effects in nDVCS

$E_{beam} = 10.6 \text{ GeV}$

Bound neutron in the deuteron and in  $^4\text{He}$ , respectively.



## Conclusions

### ► Coherent DVCS off $^4\text{He}$

- Improvement of the  $^4\text{He}$  spectral function (fully realistic calculation)  
**(in slow progress)**
- Impact of the **target mass corrections** on the observables and of  
**shadowing effects (planned)**
- Extend the model of the s.f to  $^{16}\text{O}$  and  $^{12}\text{C}$   
**(in progress)**

### ► Incoherent DVCS off $^4\text{He}$ and $^2\text{H}$ (and heavier nuclei)

- New formalism for  $^4\text{He}$  and the **deuteron (in progress)**
- Introduction of some **final state interaction effects (TBD)**
- Study of the  **$A -$  dependence** of the average BSA for light-medium nuclei **(in progress)**

### ► TOPEG

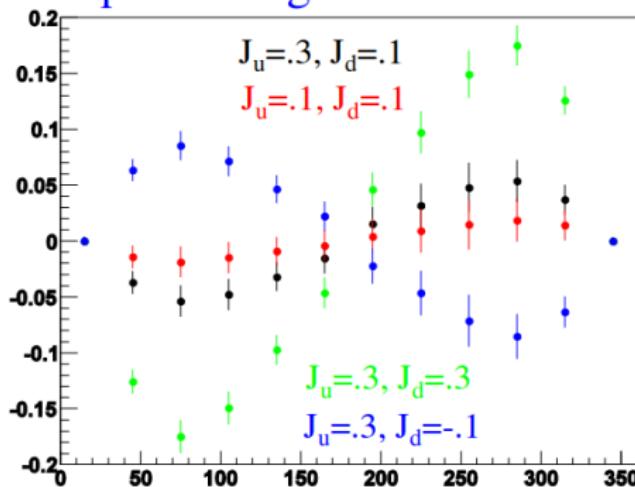
- Nuclear DVCS can be performed at the EIC: toward the **3D imaging** of nuclei
- TOPEG is a suitable **phenomenological tool** to study light nuclei **(in progress)**

# **Backup slides**

From Hobart's talk

[https://indico.cern.ch/event/1104299/contributions/5055280/  
attachments/2536704/4365938/EuNPC2022\\_ajh.pdf](https://indico.cern.ch/event/1104299/contributions/5055280/attachments/2536704/4365938/EuNPC2022_ajh.pdf)

Model predictions (VGG)  
for different values of  
quarks' angular momentum



# Going to heavier nuclei

