Deeply virtual Compton Scattering off ^{4}He

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Outline

The nucleus: *"a Lab for QCD fundamental studies"*

Realistic calculations: use of few-body wave functions, exact solutions of the Schrödinger equation, with realistic NN potentials (Av18, Nijmegen, CD Bonn) and 3-body forces

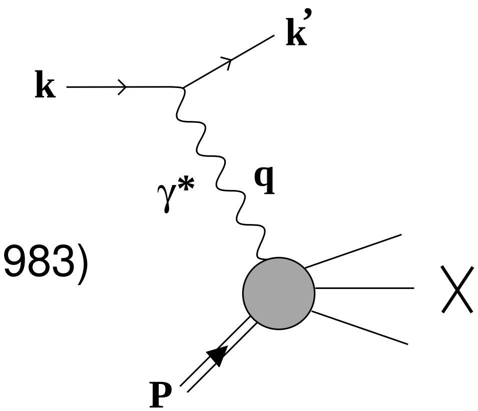
Importance of GPDs of light nuclei ^{2}H,^{3}He; HERE, ^{4}He :

- **1 - Coherent DVCS off ^{4}He :**
  data available from JLab at 6 GeV; new data expected at 12 GeV; EIC...
  our calculation (not yet fully realistic)
  (S. Fucini, S.S., M. Viviani, Phys.Rev. C98 (2018) no.1, 015203) .

- **2 - Incoherent DVCS off ^{4}He :**
  data available from JLab at 6 GeV; new data expected at 12 GeV; EIC...
  our preliminary results (not yet fully realistic)
  (S. Fucini, S.S., M. Viviani, in preparation) .

My point: *I do not know if realistic calculations will describe the data. I think they are necessary to distinguish effects due to "conventional" or to "exotic" nuclear structure*

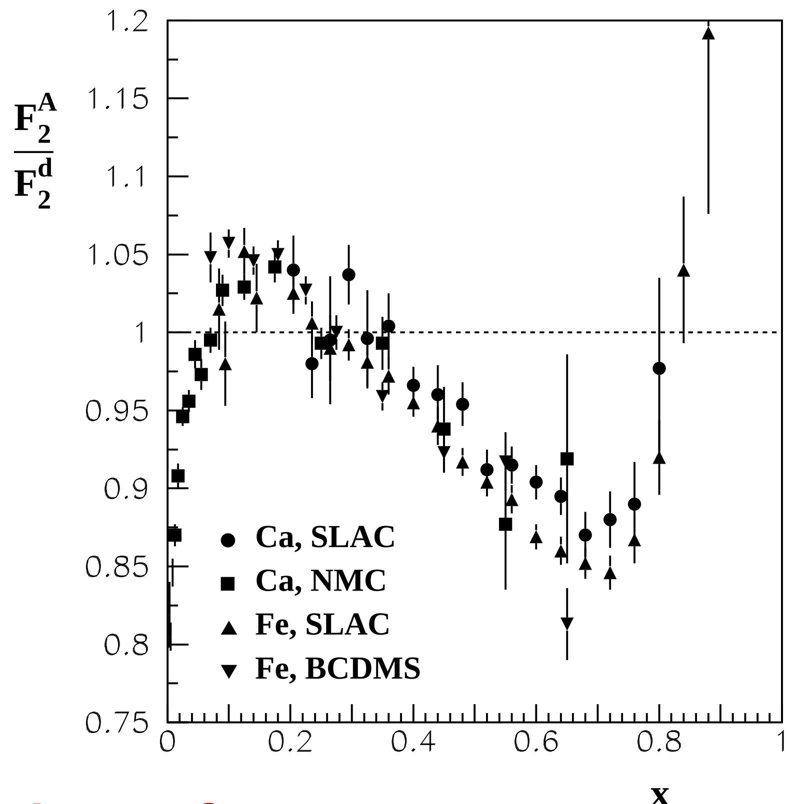
EMC effect in A-DIS



Measured in $A(e,e')X$, ratio of A to d SFs F_2 (EMC Coll., 1983)

One has $0 \leq x = \frac{Q^2}{2M\nu} \leq \frac{M_A}{M} \simeq A$

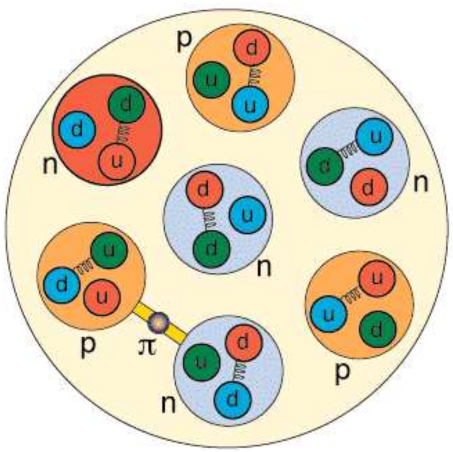
- $x \leq 0.1$ “Shadowing region”
- $0.1 \leq x \leq 0.2$ “Enhancement region”
- $0.2 \leq x \leq 0.8$ “EMC (binding) region”
- $0.8 \leq x \leq 1$ “Fermi motion region”
- $x \geq 1$ “TERRA INCOGNITA”



Many explanations... Which is the right one?

EMC effect: way out?

Question: Which of these transverse sections is more similar to that of a nucleus?



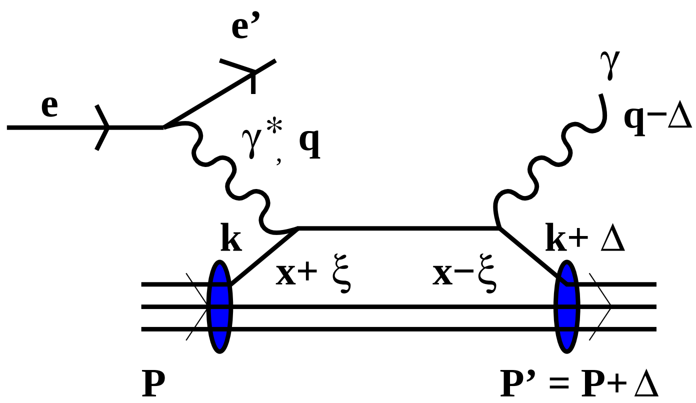
To answer, we should perform a *tomography...*

We can! **M. Burkardt, PRD 62 (2000) 07153**

Answer: Deeply Virtual Compton Scattering & Generalized Parton Distributions (GPDs)

GPDs: Definition (X. Ji PRL 78 (97) 610)

For a $J = \frac{1}{2}$ target,
in a hard-exclusive process,
(handbag approximation)
such as (coherent) DVCS:



the GPDs $H_q(x, \xi, \Delta^2)$ and $E_q(x, \xi, \Delta^2)$ are introduced:

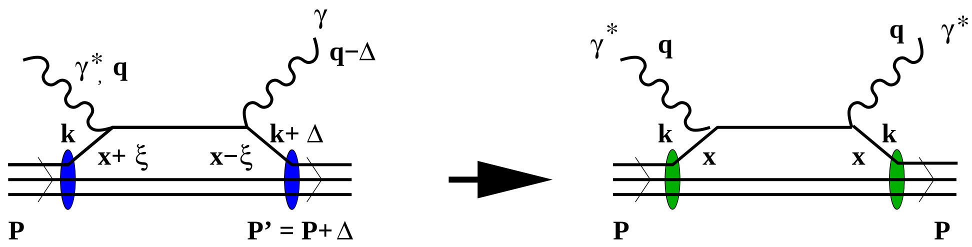
$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P' | \bar{\psi}_q(-\lambda n/2) \quad \gamma^\mu \quad \psi_q(\lambda n/2) | P \rangle = H_q(x, \xi, \Delta^2) \bar{U}(P') \gamma^\mu U(P)$$

$$+ \quad E_q(x, \xi, \Delta^2) \bar{U}(P') \frac{i\sigma^{\mu\nu}\Delta_\nu}{2M} U(P) + \ldots$$

- $\Delta = P' - P$, $q^\mu = (q_0, \vec{q})$, and $\bar{P} = (P + P')^\mu / 2$
- $x = k^+/P^+$; ξ = "skewness" = $-\Delta^+/(2\bar{P}^+)$
- $x \leq -\xi \longrightarrow$ GPDs describe $antiquarks$;
  $-\xi \leq x \leq \xi \longrightarrow$ GPDs describe $q\bar{q}$ $pairs$; $x \geq \xi \longrightarrow$ GPDs describe $quarks$

GPDs: properties

- when $P' = P$, i.e., $\Delta^2 = \xi = 0$, one recovers the usual PDFs:



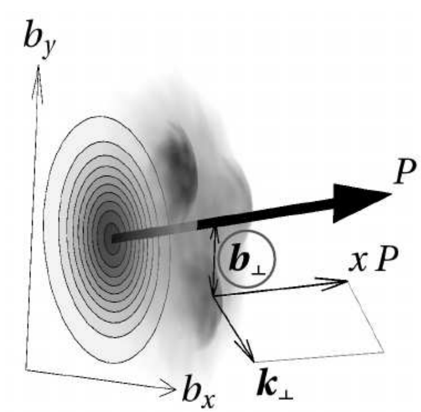
$$H_q(x,\xi,\Delta^2) \Longrightarrow H_q(x,0,0) = q(x); \quad E_q(x,0,0)\ unknown$$

- the x–integration yields the q-contribution to the Form Factors (ffs)

$$\int dx\, H_q(x,\xi,\Delta^2) = F_1^q(\Delta^2) \qquad \int dx\, E_q(x,\xi,\Delta^2) = F_2^q(\Delta^2)$$

- In impact parameter space, GPDs are *densities*:

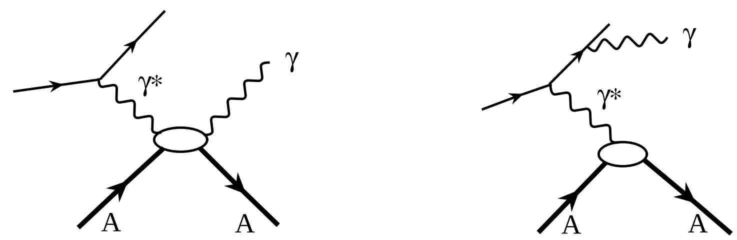
$$\rho_q(x,\vec{b}_\perp) = \int \frac{d\vec{\Delta}_\perp}{(2\pi)^2} e^{i\vec{b}_\perp\cdot\vec{\Delta}_\perp} H^q(x,0,\Delta^2)$$



GPDs: a unique tool...

- not only 3D structure, at parton level; many other aspects, e.g., contribution to the solution to the "Spin Crisis" (**J.Ashman et al., EMC collaboration, PLB 206, 364 (1988)**), yielding parton total angular momentum...

... but also an experimental challenge:



DVCS **BH**

- Hard exclusive process $\longrightarrow$ small σ;
- Difficult extraction:

$$T_{\mathbf{DVCS}} \propto CFF \propto \int_{-1}^{1} dx \, \frac{H_q(x, \xi, \Delta^2)}{x - \xi + i\epsilon} + \ldots \qquad ,$$

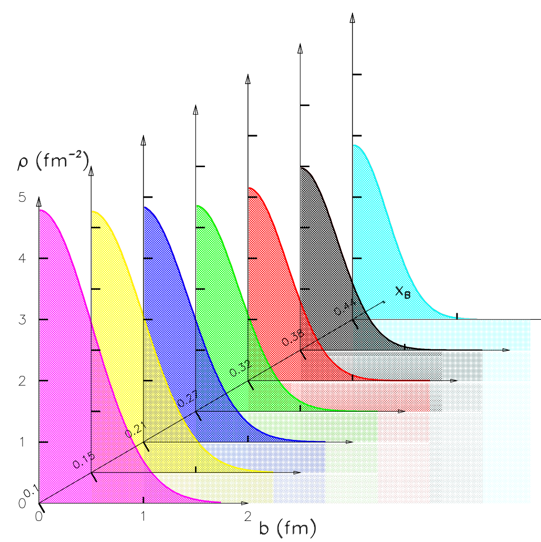
- Competition with the **BH** process! (σ asymmetries measured).

$$d\sigma \propto |T_{\mathbf{DVCS}}|^2 + |T_{\mathbf{BH}}|^2 + 2\,\Re\{T_{\mathbf{DVCS}} T^*_{\mathbf{BH}}\}$$

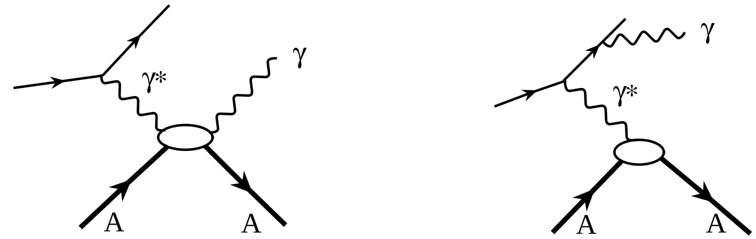
Nevertheless, for the proton, we have results:

(Guidal et al., Rep. Prog. Phys. 2013...

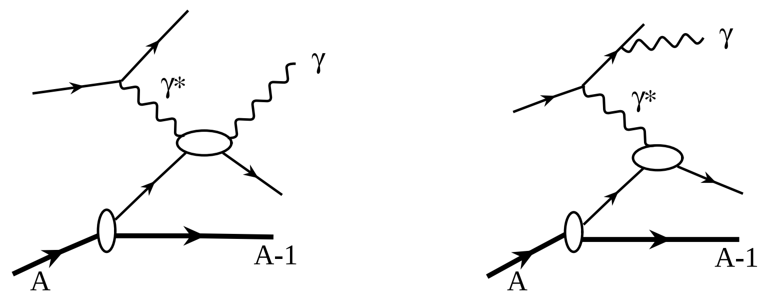
Dupré, Guidal, Niccolai, Vanderhaeghen Eur.Phys.J. A53 (2017) 171)



Nuclei and DVCS tomography



Coherent DVCS: nuclear tomography

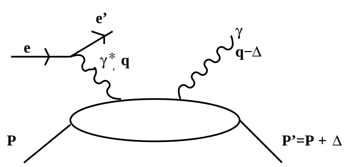


Incoherent DVCS: tomography of bound nucleons: realization of the EMC effect

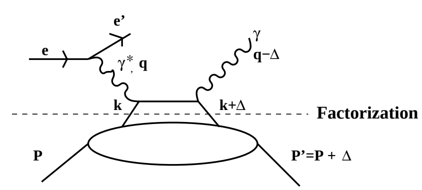
- Very difficult to distinguish coherent and incoherent channels (for example, in Hermes data, **Airapetian et al., PRC 2011**).
- Large energy gap between the photons and the slow-recoiling systems: very different detection systems required at the same time... Very difficult...
- But possible! CLAS, ^{4}He: separation of coherent (**Hattawy et al., PRL 119, 202004 (2017)**) and incoherent (**Hattawy et al., arXiv:1812.07628, PRL 2019 in press**) channels

Our IA approach to coherent DVCS off ^{4}He

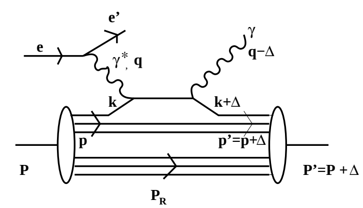
- Realistic microscopic calculations are necessary. A collaboration is going on with Sara Fucini (Perugia, graduate student), Michele Viviani (INFN Pisa).
- coherent DVCS in the Impulse Approximation (I.A.) to the handbag contribution:



$\simeq$

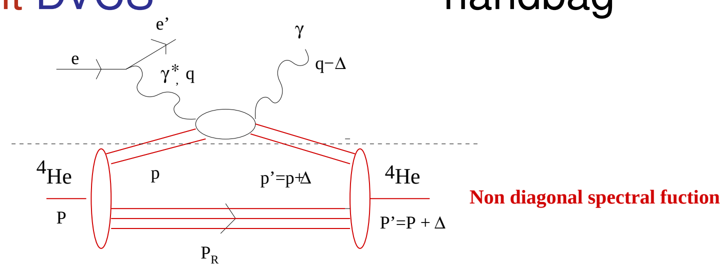


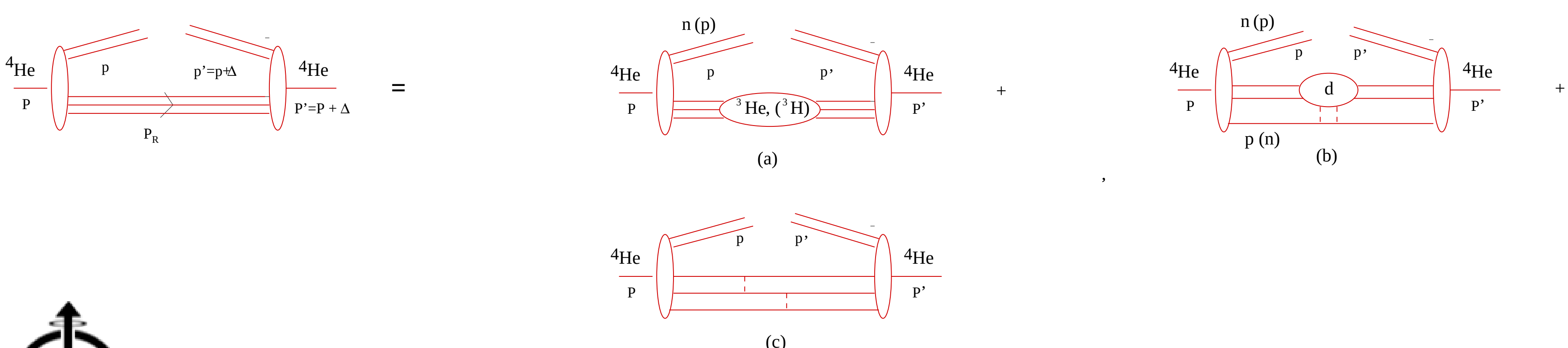
$\simeq$



coherent DVCS | handbag | I.A.

- I.A. :





we are working on a); b) is feasible; c) is really challenging

Coherent DVCS off ^{4}He: IA formalism

Convolution formula (E_q^N neglected) **(S.Fucini, SS, M.Viviani PRC. 98 (2018) 015203)**:

$$H_q^{^4He}(x, \Delta^2, \xi) = \sum_N \int_{|x|}^1 \frac{dz}{z} h_N^{^4He}(z, \Delta^2, \xi)\, H_q^N\left(\frac{x}{z}, \Delta^2, \frac{\xi}{z}\right)$$

Non-diagonal light-cone momentum distribution:

$$h_N^{^4He}(z, \Delta^2, \xi) = \int dE \int d\vec{p}\, P_N^{^4He}(\vec{p}, \vec{p} + \vec{\Delta}, E)\, \delta(z - \bar{p}^+ / \bar{P}^+)$$

$$= \frac{M_A}{M} \int dE \int_{p_{min}}^{\infty} dp \tilde{M} p P_N^{^4He}(\vec{p}, \vec{p} + \vec{\Delta}, E)\, \delta\left(\tilde{z}\frac{\tilde{M}}{p} - \frac{p^0}{p} - \cos\theta\right)$$

with $\xi_A = \frac{M_A}{M}\xi$, $\tilde{z} = z + \xi_A$, $\tilde{M} = \frac{M}{M_A}(M_A + \frac{\Delta^+}{\sqrt{2}})$ and M_{A-1}^{2*} is the squared mass of the final excited $A-1$-body state.

One needs therefore the non-diagonal spectral function and a model for nucleon GPDs.

Well known GPDs model of Goloskokov-Kroll **(EPJA 47 212 (2011))** used for the nucleonic part. In principle valid at Q^2 values larger than those of interest here.

Coherent DVCS off ^{4}He: our nuclear model input

$$
\begin{aligned}
P(\vec{p}, \vec{p}+\vec{\Delta}, E) &= n_0(\vec{p}, \vec{p}+\vec{\Delta})\delta(E^*) + P_1(\vec{p}, \vec{p}+\vec{\Delta}, E) \\
&= n_0(|\vec{p}|, |\vec{p}+\vec{\Delta}|, \cos\theta_{\vec{p},\vec{p}+\vec{\Delta}})\delta(E^*) + P_1(|\vec{p}|, |\vec{p}+\vec{\Delta}|, \cos\theta_{\vec{p},\vec{p}+\vec{\Delta}}, E) \\
&\simeq a_0(|\vec{p}|)a_0(|\vec{p}+\vec{\Delta}|)\delta(E^*) + n_1(|\vec{p}|, |\vec{p}+\vec{\Delta}|)\delta(E^* - \bar{E})
\end{aligned}
$$

with $n_1(|\vec{p}|) = n(|\vec{p}|) - n_0(|\vec{p}|),\ E = E_{min} + E^*,\ n_0(|\vec{p}|) = |a_0(|\vec{p}|)|^2$, and

$$
a_0(|\vec{p}|) =< \Phi_3(1,2,3)\chi_4\eta_4|j_0(|\vec{p}|R_{123,4})\Phi_4(1,2,3,4) >
$$

- $n_0(p)$, “ground”, and $n(p)$, “total” momentum distributions, evaluated realistically through 4-body and 3-body variational CHH wave functions, within the Av18 NN interaction, including UIX three-body forces.
- $\bar{E}$, average excitation energy of the recoiling system, given by the model diagonal spectral function, also based on Av18+UIX, described in **M. Viviani et al., PRC 67 (2003) 034003** , update of **Ciofi & Simula, PRC 53 (1996) 1689 .**
- In summary: realistic Av18 + UIX momentum dependence; the dependence on E, angles and Δ is modelled and not yet realistic

Limits

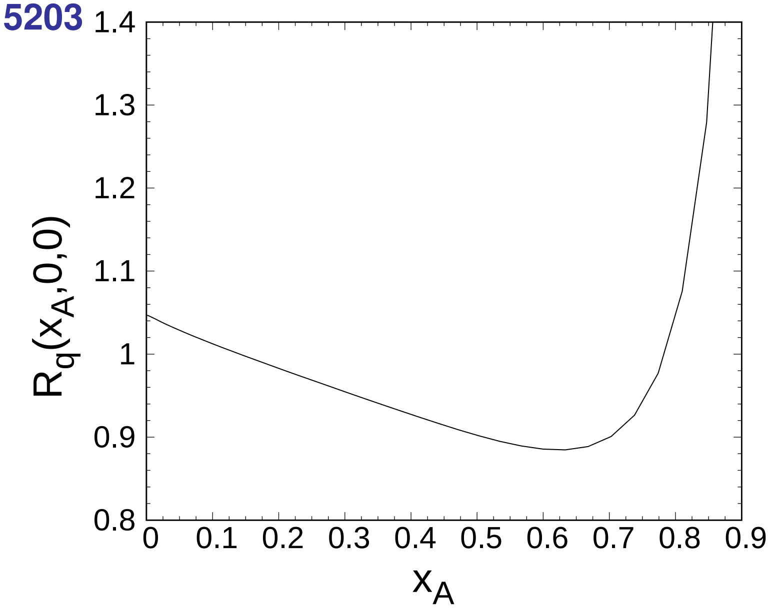
S.Fucini, SS., M. Viviani PRC 98 (2018) 015203

1 - Forward limit: the ratio:

$$R_q(x,0,0) = \frac{H_q^{^4He}(x,0,0)}{2H_q^p(x,0,0)+2H_q^n(x,0,0)}$$

$$= \frac{q^{^4He}(x)}{2q^p(x)+2q^n(x)}$$

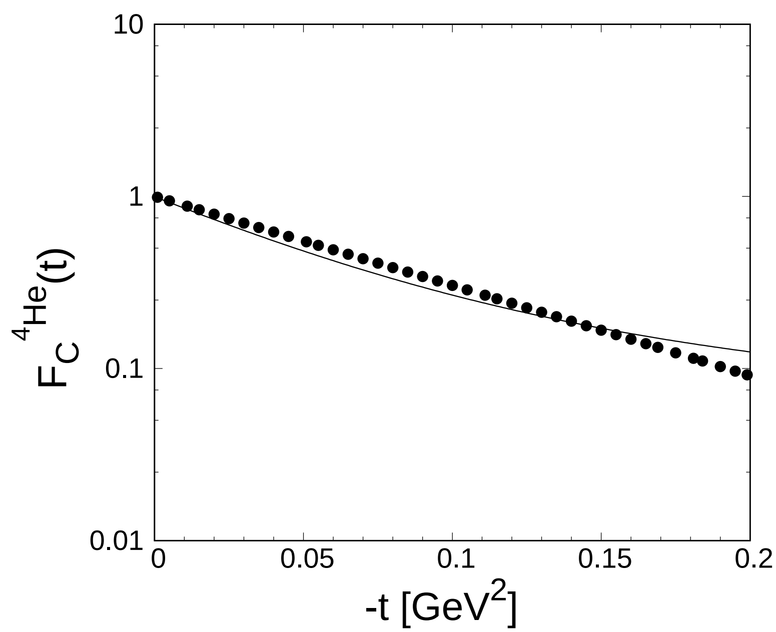
shows an EMC-like behavior;



2 - Charge F.F.:

$$\sum_q e_q \int dx H_q^{^4He}(x,\xi,\Delta^2) = F_C^{^4He}(\Delta^2)$$

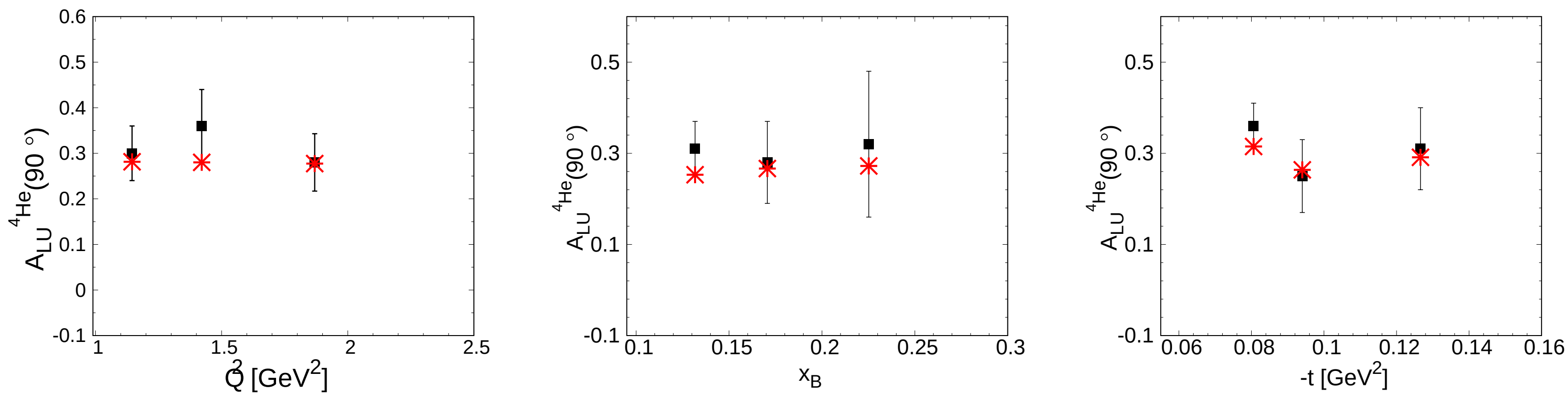
reasonable agreement with data in the region relevant to the coherent process, $-t = -\Delta^2 \leq 0.2$ GeV^2.



Comparison with EG6 data: A_{LU}

S. Fucini, S.S., M. Viviani PRC 98 (2018) 015203

^{4}He azimuthal beam-spin asymmetry $A_{LU}(\phi)$, for $\phi = 90^o$:



results of this aproach (stars) vs **EG6 data (squares)**

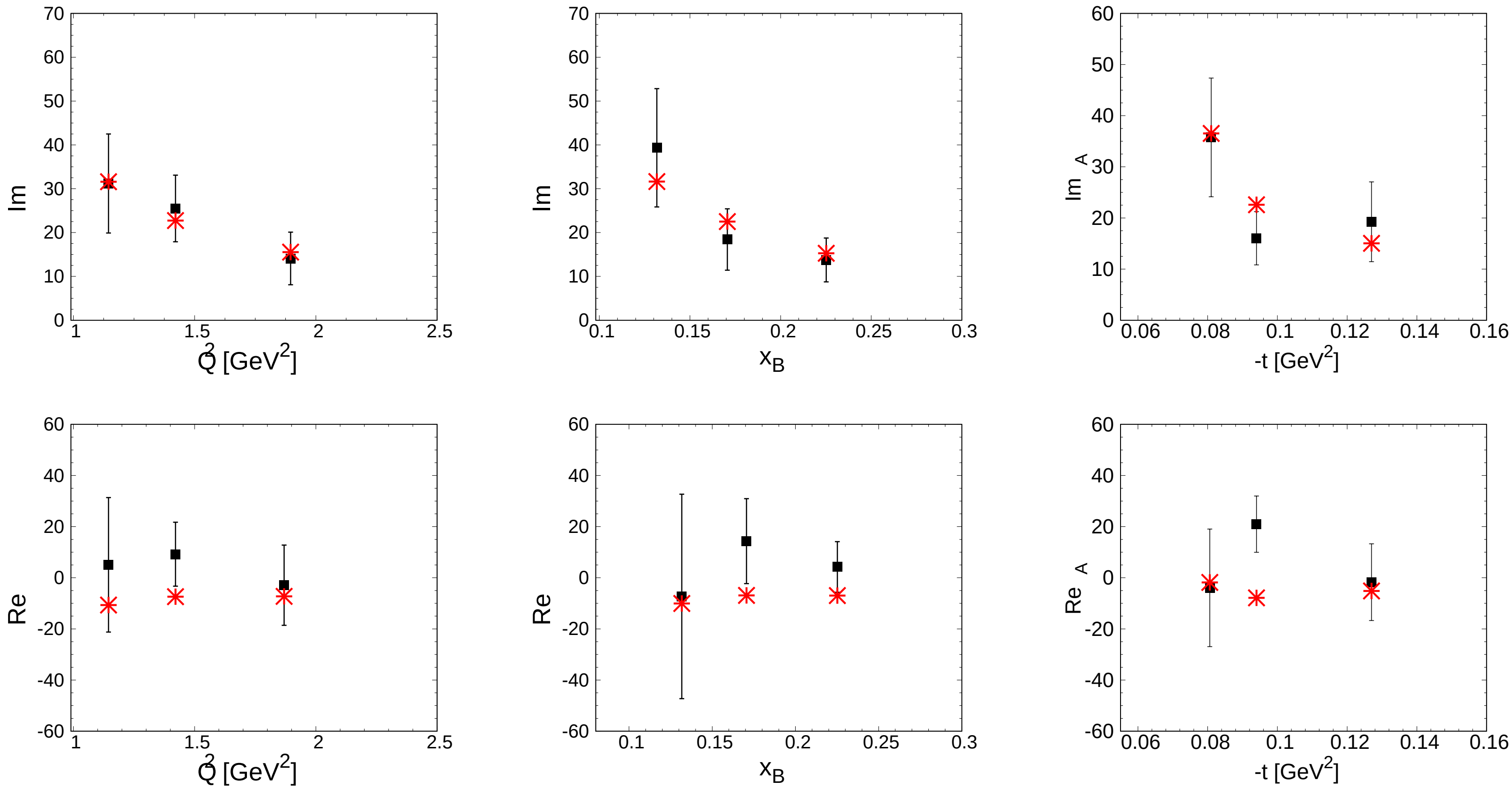
From left to right, the quantity is shown in the experimental Q^2, x_B and t bins, respectively: very good agreement

$$A_{LU}(\phi) = \frac{\alpha_0(\phi)\,\Im m(\mathcal{H}_A)}{\alpha_1(\phi) + \alpha_2(\phi)\,\Re e(\mathcal{H}_A) + \alpha_3(\phi)\left(\Re e(\mathcal{H}_A)^2 + \Im m(\mathcal{H}_A)^2\right)}$$

$\Re e(\mathcal{H}_A)$ and $\Im m(\mathcal{H}_A)$ experimentally extracted fitting these data using explicit forms for the kinematic factors α_i **(Belitsky et al. PRD 2009)**

Comparison with EG6 data: $\Im m(\mathcal{H}_A)$ & $\Re e(\mathcal{H}_A)$

S. Fucini, S.S., M. Viviani PRC 98 (2018) 015203



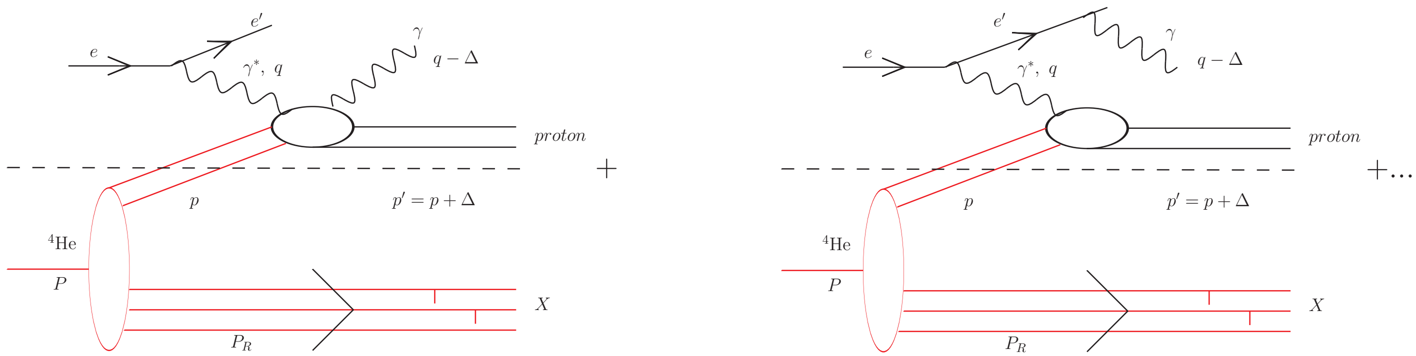
$$\Im m(\mathcal{H}_A) = H_A(\xi,\xi,t) - H_A(-\xi,\xi,t),$$

$$\Re e(\mathcal{H}_A) = \mathcal{P}\int_0^1 dx[H_A(x,\xi,t) - H_A(-x,\xi,t)]\left(\frac{1}{x-\xi} + \frac{1}{x+\xi}\right)$$

Very good agreement for $\Im m(\mathcal{H}_A)$, good agreement for $\Re e(\mathcal{H}_A)$ (data weakly sensitive to $\Re e(\mathcal{H}_A)$)

Our IA approach to incoherent DVCS off ^{4}He

S. Fucini, S.S., M. Viviani - in preparation



$$A_{LU}^{4,p} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \qquad d\sigma^{\lambda,4} = \int dE \int d\vec{p}\, \frac{p \cdot k}{p_0 E_k}\, P^{4,p}(\vec{p}, E)\, d\sigma^{\lambda,p}$$

In IA, Instant Form approach, the diagonal spectral function $P^{4,p}(\vec{p}, E)$ arises:

- off-shellness driven by nuclear dynamics:

  $$p_0 = M_A - \sqrt{M_{A-1}^{*\,2} + p^2} \simeq M - E - T_f \longrightarrow p^2 \neq M^2$$

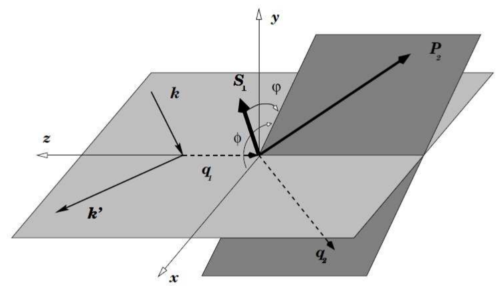
  $$\xi = Q^2/[(p+p')\cdot(q+q')] \neq x_B/(2-x_B)$$

- number and momentum sum rules not fulfilled at the same time (one of the two slightly violated: polinomiality violated)

Incoherent DVCS off ^{4}He: formalism, ingredients

General structure of the differential cross section $(i = DVCS, BH, Int)$:

$$\frac{d\sigma_i^{\lambda,4}}{dkin} \propto \int dE \int d\vec{p}\, P^{4,p}(\vec{p},E)\, g(kin,\vec{p},E)\, A_i(kin,\vec{p},E)$$



$d\,kin = dx_B\, dQ^2\, dt\, d\Phi$

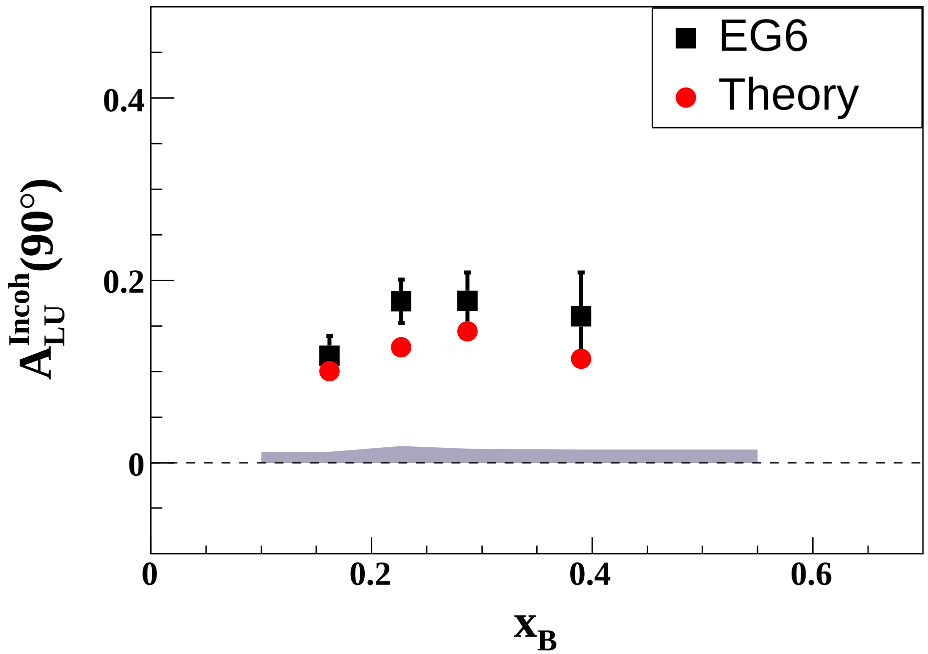
$g(kin,\vec{p},E)$: a complicated function

$A_{BH} = T^2_{BH}, \quad A_{DVCS} = T^2_{DVCS}, \quad A_{Int} = Int_{BH-DVCS}$ for a bound proton

$$A^{4,p}_{LU} \simeq \frac{\int dE \int d\vec{p}\, P^{4,p}(\vec{p},E)\, g(kin,\vec{p},E)\, Int_{BH-DVCS}(kin,\vec{p},E)}{\int dE \int d\vec{p}\, P^{4,p}(\vec{p},E)\, g(kin,\vec{p},E)\, T^2_{BH}(kin,\vec{p},E)}$$

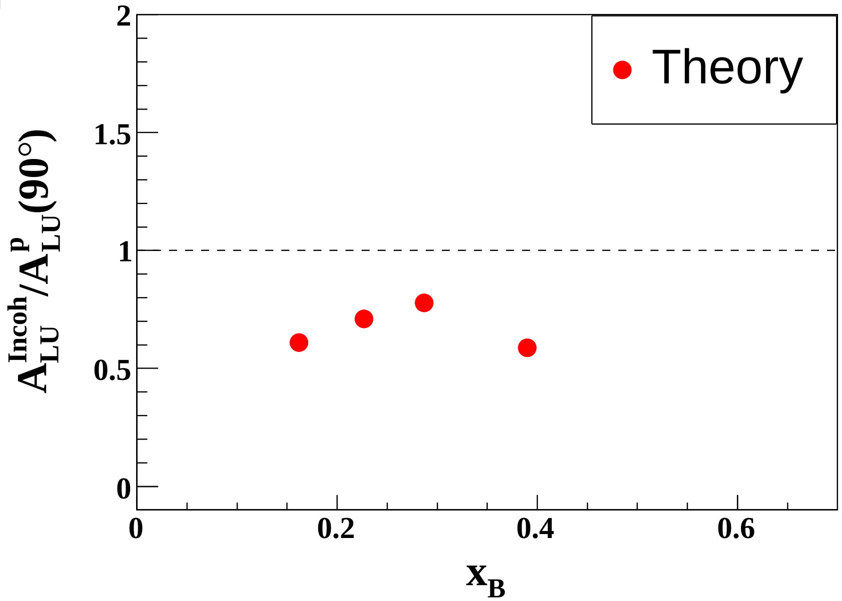
- $T^2_{BH}, T^2_{DVCS}, Int_{BH-DVCS}$ for a moving bound nucleon; our expressions, obtained generalizing the ones at leading twist for nucleons at rest (**Belitski et al. (2002)**); $T^2_{BH} = c_0^{bound} + c_1^{bound}(\cos\Phi) + c_2^{bound}\cos(2\Phi)$
- In $Int_{BH-DVCS}$, the H GPD in $\Im m(\mathcal{H}_N)$ evaluated in the GK model;
- Av18-based model of the diagonal spectral function $P^{4,p}(\vec{p},E)$ (**M. Viviani et al., PRC 67 (2003) 034003**)

Preliminary results (I)



- "preliminary" also because calculations are performed, for each experimental x_B bin, at values of t and Q^2 corresponding to an $almost$ definitive experimental analysis. We are waiting to know the definitive values. We find a strong dependence on the experimental kinematics and results could slightly change.
- In any case: the trend of EG6 data is correctly reproduced using conventional ingredients.

Preliminary results (II) - nuclear effects



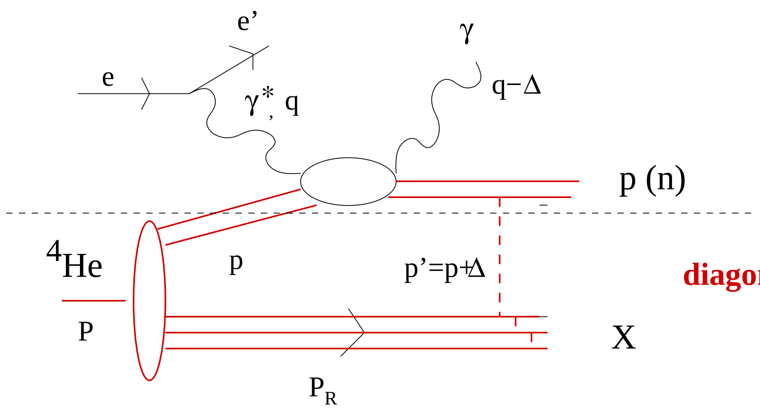
- As an illustration we divide our theoretical $A_{LU}^{4,p}$ by the corresponding proton quantity, based on the GK model used in the calculation: a big effect.
- Is that a medium modification of the parton structure? Actually:

$$\frac{A_{LU}^{4,p}}{A_{LU}^{p}} \propto \frac{Int^{4}_{DVCS-BH}}{Int^{p}_{DVCS-BH}} \frac{T^{p,2}_{BH}}{T^{4,2}_{BH}} = \frac{(nucl.mod.)_{Int}}{(nucl.mod.)_{BH}}$$

We find that the nuclear dynamics modifies the $Int_{DVCS-BH}$ and the BH cross sections in a different way; this has little to do with the parton structure.
We find that the medium modification of the parton structure, present in the Compton Form Factor (GPD), by itself produces a small effect.

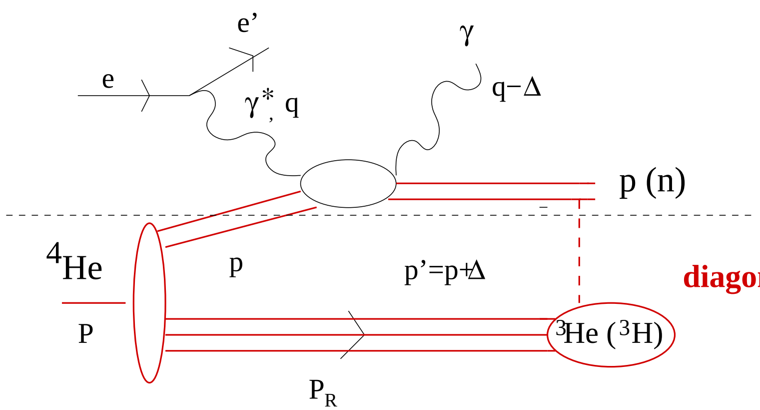
Incoherent DVCS off ^{4}He: beyond IA; FSI?

- $^4\text{He}(e, e'\gamma p(n))X$



diagonal spectral fuction... FSI??

- **Tagged! e.g.,** $^4\text{He}(e, e'\gamma p)^3\text{H}$ **(arXiv:1708.00835 [nucl-ex])** $\longrightarrow$ **EIC!!!**



diagonal spectral fuction... Great!

The quest for covariance

- Mandatory to achieve polinomiality for GPDs, and sum rules in DIS: number of particle and momentum sum rule not fulfilled at the same time in not covariant IA calculations
- Numerically not very relevant for forward Physics. It becomes relevant for non-diagonal observables at high momentum transfer. Example: form factors (well known since a long time, see, i.e.,**Cardarelli et al., PLB 357 (1995) 267)**
- I do not expect big problems in the coherent case at low t;
  Crucial for incoherent at higher t, as well as finite t corrections (target mass corrections at least for scalar nuclei under control)
- Certainly it has to be studied.
  For ^{3}He, formal developments available in a Light-Front framework
  (**A. Del Dotto, E. Pace, S.S., G. Salmè, PRC 95 (2017) 014001**).
  Calculations in progress, starting from a diagonal, spin-independent spectral function.
  ^{4}He... Later (very cumbersome).

Conclusions

DVCS off ^{4}He:

Calculations (not yet realistic) with basic ingredients (GK model plus a model spectral function based on Av18 + UIX)

- **1 - Coherent DVCS off ^{4}He:**

  * The data available from JLab at 6 GeV are well described

  (S. Fucini, S.S., M. Viviani, PRC 98 (2018) 015203).

- **2 - Incoherent DVCS off ^{4}He:**

  * Preliminary results show a reasonable agreement with the data available from JLab at 6 GeV; **(S. Fucini, S.S., M. Viviani, in preparation).**

- Straightforward and workable approach, suitable for planning new measurements. New data expected at 12 GeV and at the EIC will require much more precise nuclear description (in progress: FSI, fully realistic $P(\vec{p}, E)$...)

Great opportunities at the EIC with tagged measurements (also for (polarized) ^{3}He (^{3}H?)...)

Our spirit: introduce new ingredients one at a time