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Theoretical investigation of deeply Virtual Compton Scattering of ^{4}He

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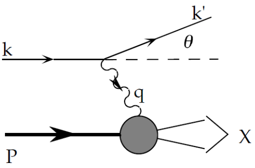
Introduction

Some history

Inclusive DIS process $A(e, e')X \implies$ *Parton distribution functions (PDFs)*



$$\frac{d^2\sigma}{d\theta d\nu} \propto F_2^N(x) = \sum_q e_q^2 x f_q^N(x)$$

x is the longitudinal momentum fraction for a quark q in a nucleon N

Consider the ratio

$$R(x) = \frac{F_2^A(x)}{F_2^d(x)}$$

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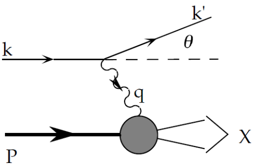
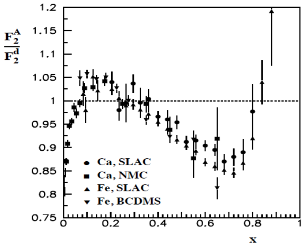


$$\frac{d^2\sigma}{d\theta d\nu} \propto F_2^N(x) = \sum_q e_q^2 x f_q^N(x)$$

x is the longitudinal momentum fraction for a quark q in a nucleon N

Consider the ratio

$$\boldsymbol{R(x) = \frac{F_2^A(x)}{F_2^d(x)}} \longrightarrow \text{EMC (Cern (1983))} \longrightarrow \boldsymbol{R(x) \neq 1}$$



$$x = \frac{Q^2}{2M_A\nu} \to x \in [0; \frac{M_A}{M} \approx A]$$

- $x \leq 0.2$: "Shadowing region"
- $0.3 \leq x \leq 0.7$: "EMC region"
- $0.8 \leq x \leq 1$: "Fermi motion region"

What is the right way to explain the EMC trend?

- ***Elastic scattering*** $\longrightarrow$ **Form factors**
  $F(Q^2) \longrightarrow$ no inner parton structure

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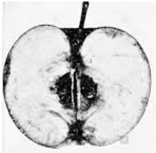
What is the right way to explain the EMC trend?

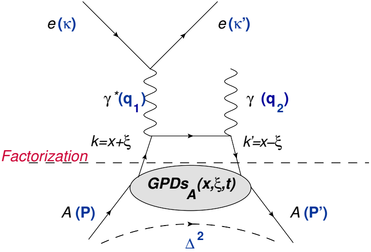
- ***Elastic scattering*** $\longrightarrow$ **Form factors** $F(Q^2) \longrightarrow$ no inner parton structure
- ***Inclusive DIS*** $\longrightarrow$ **PDFs** $f_q(x, Q^2) \longrightarrow$ Longitudinal momentum space
- **????** $\longrightarrow \mathcal{F}_q(x, Q^2, ??..) \longrightarrow$ *Transverse plane*

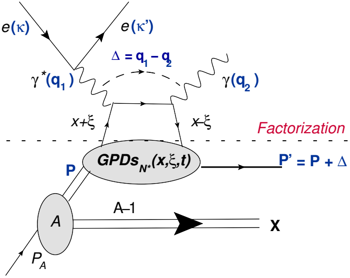


We can do a *tomography* of nuclei in coordinate space.

Exclusive processes: DVCS off nuclei in handbag approximation

Two different *channel* for DVCS off nuclei: **coherent and incoherent**





- Factorization property($\Delta^2 \ll Q^2$):
  - **HARD PART** $\Longrightarrow$ **perturbative QED & QCD**
  - **SOFT PART** $\Longrightarrow$ **non-perturbative QCD** $\longrightarrow$ **Generalized Parton Distributions**
- GPDs depend on :
  - $\Delta^2 = (P' - P)^2 = (q_1 - q_2)^2$
  - $\xi = -\frac{\Delta^+}{2\bar{P}^+}$
  - $x = \frac{\bar{k}^+}{\bar{P}^+}$
  - $Q^2 = -(\kappa - \kappa')^2$
- $x \leq \xi$: GPDs describe **antiquarks**;$-\xi \leq x \leq \xi$: GPDs describe $q\bar{q}$ **pairs**; $x \geq \xi$: GPDs describe **quarks**

GPDs are introduced considering the *light cone correlator*:

$$F^A_{S,S'} = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle P'S'|\bar{\psi}\Big(-\frac{z^-}{2}\Big)\gamma^+\psi\Big(\frac{z^-}{2}\Big)|PS\rangle$$
$$= \frac{1}{2P^+}\Big[H^A_q(x,\xi,t)\bar{u}(P',S')\gamma^+u(P,S) + E^A_q(x,\xi,t)\bar{u}(P',S')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2M}u(P,S)\Big] + ..$$

→ For a target of spin S, the number of GPDs is **(2S+1)^2**

Form factor

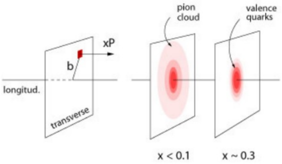
$$\sum_N \int_{-1}^{1} dx \sum_q e_q H^A_q(x,\xi,t) = F^A_1(t)$$

PDFs (when $P = P'$, i.e $t = \xi = 0$)

$$H^A_q(x,0,0) = q^A_q(x)$$

Probabilistic interpretation in *impact parameter space*

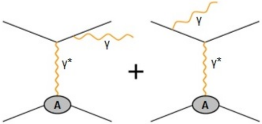
$$\rho^q(x,\vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} e^{-i\vec{b}_\perp\vec{\Delta}_\perp} H^q(x,0,\Delta^2_\perp)$$



GPDs in a nutshell (ii)

- At JLab kinematics, ***Bethe Heitler*** process interferes with DVCS enhancing this latter. For this reason, it is convenient to measure **asymmetries**, ie.
  $A_{LU} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$

  $\sigma \propto T^2_{BH} + T^2_{DVCS} + \mathcal{I}_{BH-DVCS}$



  that can be expressed in terms of
  - **Form Factors**

  $$T_{BH} \propto F_i(\Delta^2)$$

  - **Compton Form Factor** ($\propto$ GPDs)

  $$T_{DVCS} \propto \mathcal{H}(\xi, \Delta^2) = \int dx \frac{H_q^A(x, \xi, \Delta^2)}{x \pm \xi + i\epsilon} = \Re e\mathcal{H}(\xi, \Delta^2) + i\Im m\mathcal{H}(\xi, \Delta^2)$$

- for a **nuclear target**, it is difficult to disentangle coherent and incoherent channels because of the large energy gap between the photons and the slow-recoiling systems which requires different detectors

Why is ^{4}He a golden nucleus?

- ^{4}He is a typical few body system and it is theoretically well known
- exact and realistic calculations are difficult BUT possible
- $J^{\pi}_{^4He} = 0^+$ and $I_{^4He} = 0 \implies$ only one chiral-even GPD at LO
- CLAS and ALERT collaboration are carrying on an experimental program at JLab using ^{4}He target

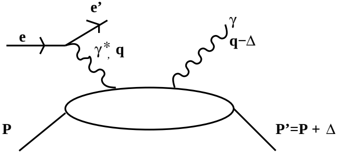
Coherent (**PRL 119, 202004 (2017)**) and incoherent (**PRL 123, 032502 (2019)**) DVCS off ^{4}He has been measured at the Jefferson Laboratory!

- good perspectives at JLab with a 12 GeV electron beam and the forthcoming EIC

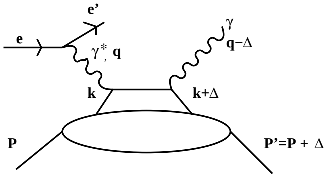
Our point is to obtain models necessary to distinguish effects due to “conventional” or to “exotic” nuclear structure in order to proper interpret the data.

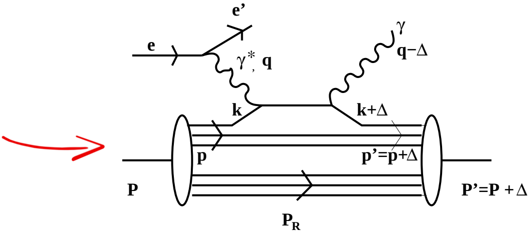
Coherent DVCS off ^{4}He

Coherent DVCS channel



Handbag approximation





Impulse approximation (IA)

Our formalism for the nuclear GPD (S. F., S.Scopetta, M. Viviani, PRC 98 (2018) 015203)

A convolution formula for the GPD H_q can be obtained in terms of:

- GPDs of the inner nucleons

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

- light-cone momentum distribution

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

$$= \frac{M_A}{M}\int dE \int_{p_{min}}^{\infty} dp \int_0^{2\pi} d\phi\, p\, \tilde{M}\, P_N^{^4He}(\vec{p},\vec{p}+\vec{\Delta},E)$$

where $\xi_A = \frac{M_A}{M}\xi$, $\tilde{z} = z+\xi_A$, $\tilde{M} = \frac{M}{M_A}\left(M_A+\frac{\Delta^+}{\sqrt{2}}\right), p_{min} = f(z,\xi_A,E)$

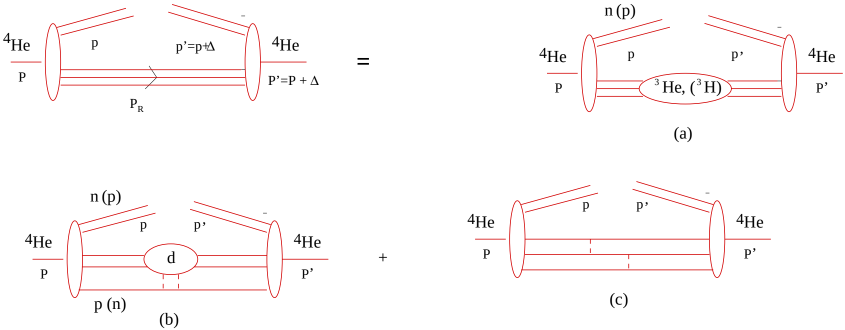
As an input, one needs the non-diagonal spectral function and the nucleonic GPDs (we used the Goloskokov-Kroll model (EPJA 47 212 (2014)).

The ^{4}He spectral function: off diagonal case

$$P_N^{^4He}(\vec{p}, \vec{p} + \vec{\Delta}, E) = \rho(E) \sum_{\alpha\, \sigma_N} \langle P + \Delta | -p\, E\, \alpha, p + \Delta\, \sigma_N \rangle$$
$$\langle p\, \sigma_N, -p\, E\, \alpha | P \rangle$$

2-body channel

- $\langle ^4$ He $|p, {}^3$H $\rangle$;
- $\langle ^4$ He $|n, {}^3$He $\rangle$;



3-body channel

- $\langle ^4$ He $|p, d\ n\rangle$;
- $\langle ^4$ He $|n, d\ p\ \rangle$;

4-body channel

- $\langle ^4$ He $|n, p\ n\ p\rangle$;
- $\langle ^4$ He $|p, n\ p\ n\ \rangle$.

Our model for the spectral function (S. F., S.Scopetta, M. Viviani, PRC 98 (2018) 015203)

$$
\begin{aligned}
P_N^{^4He}(\vec{p}, \vec{p}+\vec{\Delta}, E) &= n_0(\vec{p}, \vec{p}+\vec{\Delta})\delta(E) + P_1(\vec{p}, \vec{p}+\vec{\Delta}, E) \\
&= n_0(|\vec{p}|, |\vec{p}+\vec{\Delta}|, \cos\theta_{\vec{p},\vec{p}+\vec{\Delta}})\delta(E) + P_1(|\vec{p}|, |\vec{p}+\vec{\Delta}|, \cos\theta_{\vec{p},\vec{p}+\vec{\Delta}}, E) \\
&\simeq a_0(|\vec{p}|)a_0(|\vec{p}+\vec{\Delta}|)\delta(E) + \sqrt{n_1(|\vec{p}|)n_1(|\vec{p}+\vec{\Delta}|)}\delta(E-\bar{E})
\end{aligned}
$$

where

- the total momentum distribution is $n(p)$

$$n_1(|\vec{p}|) = n(|\vec{p}|) - n_0(|\vec{p}|)$$

- $n_0(k)$ is the momentum distribution when the recoiling system in the ground state

$$n_0(|\vec{p}|) = |a_0(|\vec{p}|)|^2$$

  with

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

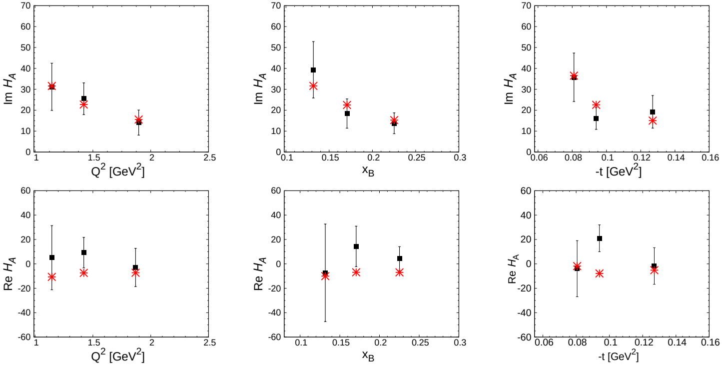
- $\boldsymbol{n(p)}$ has been evaluated for the 4-body and 3-body systems within the Av18 NN interaction + UIX three-body forces
- $\bar{E}$ is the average excitation energy of the recoiling system (model of diagonal s.f. by **M. Viviani et al., PRC 67(2003) 034003**).

Coherent DVCS: a comparison with EG6 data, $\mathcal{H}_A$ (S. F., S.Scopetta, M. Viviani, PRC 98 (2018) 015203)

Our results (**red stars**) compared with experimental results (**black squares**)

$$\Im m\mathcal{H}_A(\xi,t) = \sum_{q=u,d,s} e_q^2 (H_q^A(\xi,\xi,\Delta^2) - H_q^A(-\xi,\xi,\Delta^2))$$

$$\Re e\mathcal{H}_A(\xi,t) = \mathrm{Pr}\sum_{q=u,d,s} e_q^2 \int_0^1 \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right)(H_q^A(x,\xi,t) - H_q^A(-x,\xi,t))$$



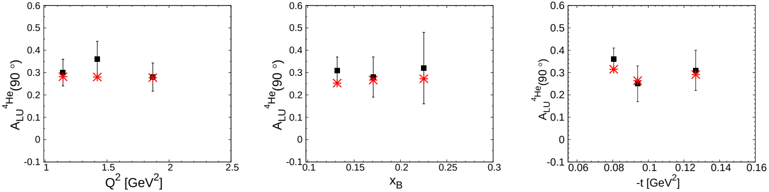
Coherent DVCS: a comparison with EG6 data, A_{LU} (S. F., S.Scopetta, M. Viviani, PRC 98 (2018) 015203)

Beam spin asymmetry as a function of azimuthal angle $\phi = 90^o$

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

where $\alpha_i(\phi)$ are kinematical coefficients from **A. V. Belitsky et al., Phys. Rev. D 79, 014017 (2009)**.

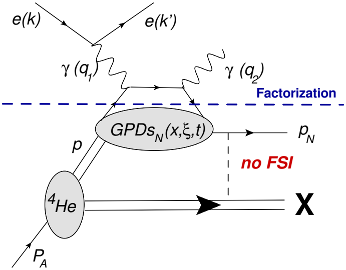
Results of our approach VS **EG6 data**



From left to right, the quantity is shown in the experimental Q^2, x_B and $-t$ bins, respectively.

Incoherent DVCS off ^{4}He

Framework for incoherent DVCS off ^{4}He in IA (S. F., S. Scopetta, M. Viviani, arXiv:1909.12261)



The **beam spin asymmetry** (BSA) measured is:

$$A_{LU} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

where
$\pm$refers to positive(negative) beam polarizations.

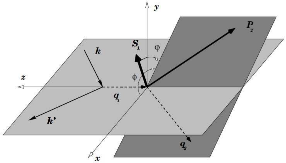
Fundamental starting points for our **Impulse Approximation** approach are:

- kinematical **off shellness**:
  $p_0 = M_A - \sqrt{M^{*\,2}_{A-1} + \vec{p}^2} \simeq M_N - E - T_{rec} \implies p^2 \neq m^2$
- general expression for **cross section**

$$(d\sigma^{\pm})_{INC} = (2\pi)^4 \frac{1}{2P_A \cdot k} \sum_N \sum_X |\mathcal{A}^{\pm}|^2 \delta^4(P_A + k - k' - p_X - p_N - q_2) LIPS$$

where $LIPS = d\tilde{p}_X d\tilde{k}' d\tilde{q}_2 d\tilde{p}_N$

In a frame where the target nucleus is at rest, the cross section and its azimuthal dependence are expressed in terms of a ***convolution formula*** between:



- the **diagonal** spectral function $P^{^4He}$ of the inner nucleons

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

- the DVCS cross section off a bound proton

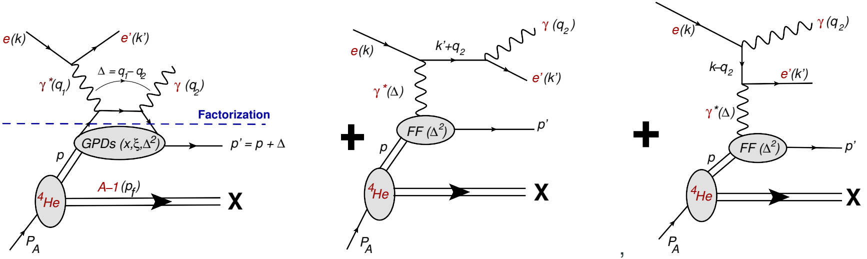
The differential cross section appearing in A_{LU} is

$$\frac{d\sigma^{\pm}_{Incoh}}{dx_B dQ^2 d\Delta^2 d\phi} = \int_{exp} dE d\vec{p}\, P^{^4He}(\vec{p}, E) |\mathcal{A}^{\pm}(\vec{p}, E, K)|^2 g(\vec{p}, E, K)$$

where

- $K = \{x_B = \frac{Q^2}{M\nu}, Q^2, \phi, \Delta^2\}$ fixes the proper range of integration
- $g(\vec{p}, E, K)$ arises from the integration of LIPS and includes also the flux factor

Schematically $d\sigma^{\pm} \approx \int d\vec{p}dEP^{^4He}(\vec{p},E)|A^{\pm}(\vec{p},E,K)|^2$ with $|\mathcal{A}^{\pm}|^2 = \mathcal{T}^2_{BH} + \mathcal{T}^2_{DVCS} + \mathcal{I}^{\pm}_{DVCS-BH}$.



The BSA for the incoherent DVCS reads:

$$A^{Incoh}_{LU}(K) = \frac{\mathcal{I}^{^4He}(K)}{T^{2\,^4He}_{BH}(K)}$$

$$\mathcal{I}^{^4He}(K) = \int_{exp} dE\, d\vec{p}\, P^{^4He}(\vec{p},E)\, g(\vec{p},E,K)\, \mathcal{I}(\vec{p},E,K)$$

$$T^{2\,^4He}_{BH}(K) = \int_{exp} dE\, d\vec{p}\, P^{^4He}(\vec{p},E)\, g(\vec{p},E,K) T^2_{BH}(\vec{p},E,K)$$

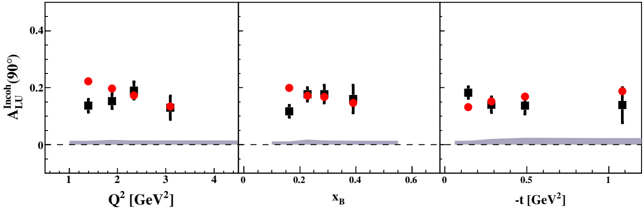
Ingredients for $A_{LU}^{Incoh}(K)$

$$A_{LU}^{Incoh}(K) = \frac{\mathcal{I}^{^4He}(K)}{T_{BH}^{2\,^4He}(K)}$$

- Our expression for $|\mathcal{T}_{BH}(\vec{p}, E, K)|^2 = c_0^{BH} + c_1^{BH}\cos(\phi) + c_2^{BH}\cos(2\phi)$ is a generalization for a moving bound nucleon of results by **Muller et al.(2002)**
- the interference BH-DVCS $\mathcal{I}(\vec{p}, E, K) \approx s_1^{\mathcal{I}}(\vec{p}, E, K)\Im m\mathcal{H}(\xi', \Delta^2, Q^2)$.
- For the proton GPD H_q^N, again, we used **GK model (2013)** evaluated for $\xi' = \frac{Q^2}{(p+p_N)(q_1+q_2)} \neq \frac{x_B}{2-x_B} = \xi_{rest}$
- No nuclear modifactions occur for the **form factors** of the bound proton
- For the diagonal spectral function $P^{^4He}(\vec{p}, E)$ we use an Av18-based model (**M. Viviani et al., PRC 67, 034003 (2003)**)
  - the ground state of the recoiling system is described in terms of exact wave functions for the 4-body and 3-body systems
  - the excited state of the recoiling system is un update of the 2-nucleon correlation model by **Ciofi et al., PRC 53 1689 (1996)**.

Incoherent DVCS: results

- Our results are compared with the experimental data from EG6 collaboration at JLab (**M. Hattawy et al., PRL 123, 032502 (2019)**).
  From left to right, the quantity is shown in the experimental Q^2, x_B and $-t$ bins



✓ **Good agreement in the region of high Q^2**

> An analysis of the interplay between the t and Q^2 dependence could reveal if FSI effects could be responsible of the disagreement in low Q^2 region

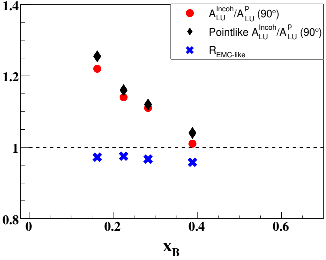
Nuclear effects in A_{LU}^{Incoh}

Are the nuclear effects measured depending on the modification of the bound proton partonic structure?

We consider the ratio between the BSA for bound and that for a free proton:

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

- We find that the nuclear dynamics modifies the BH and the interference contribution in a different way $\Longrightarrow$ this fact hasn't to do with the **parton structure**



This fact is confirmed by

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

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

Conclusions and outlooks

Our workable approaches to DVCS off ^{4}He allow to constrain conventional nuclear effects. It is helpful for planning new measurements and interpreting the present data.

Formal development of a theoretical formula for the only **GPD** describing the ^{4}He with an overall good agreement with data.

- Realistic AV18 + UIX momentum dependence
- Dependence on E, angles and Δ in the s.f is modeled and not yet realistic

Explicit calculation of the **beam spin asymmetry of a bound moving nucleon**

Evaluation of the incoherent channel considering Final State Interaction

A full realistic evaluation of the spectral function, both diagonal and off-diagonal

Relativistic description of both channels in a Light Front scenario

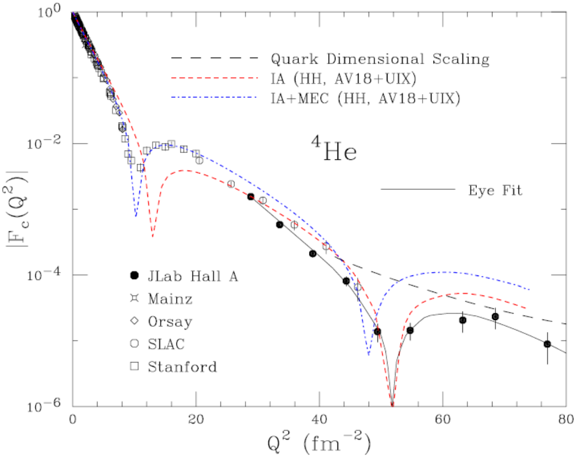
Thank you ...

Questions?

Backup slides

Form factor of the ^{4} He at high Q^2

Red dashed line: One body part of the form factor from a direct integration of the diagonal momentum distribution of the ^{4}He within Av18+UIX calculation (**Phys. Rev. Lett. 112, 132503**)

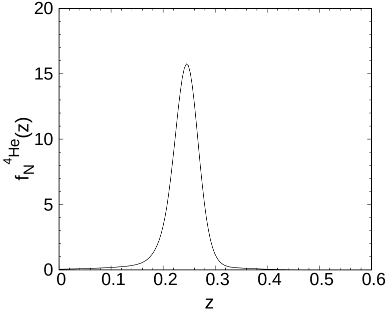


Light cone momentum distribution

Forward limit

$$h_N^{4He}(z,0,0) = f_N^{4He}(z) = \int dE \int d\vec{p}\, P_N(\vec{p},E)\,\delta\left(z - \frac{\sqrt{2}p^+}{M}\right).$$

It reproduces in the forward limit the correct IA result for the nuclear PDF



$z \in [x:1]$

$f(z)$ is strongly picked around $z \simeq 0.25$

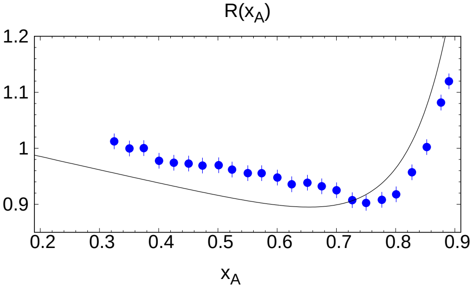
EMC effect with our model for the off diagonal spectral function

$$R(x_A) = \frac{F_2^{^4He}(x_A)}{2F^d_{2\,l.f}(x_A)}$$

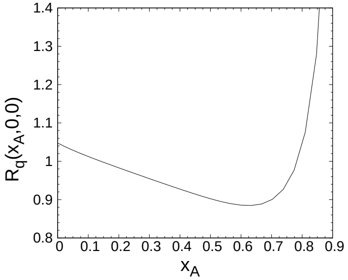
where

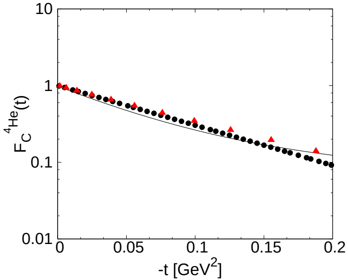
$$F_2^A(x) = \sum_q e_q^2 x H_q^{^4He}(x,0,0)$$

$$F^d_{2\;l.f.}(x) = \int_x^{M_d/M} dz \int d\vec{k}\; n_d(|\vec{k}|)\delta\left(z - \frac{M_d}{M}\frac{k_z + \sqrt{k^2+M^2}}{2\sqrt{k^2+M^2}}\right) F_2^N\left(\frac{x}{z}\right)$$



Some checks for our model





- **EMC-like effect**

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

✓ Good EMC-like behavior;

- **Charge form factor**

$$F_C^{^4He}(\Delta^2) = \frac{1}{2}\sum_q e_q \int_0^1 dx H_q^{^4He}(x,\xi,\Delta^2)$$

Data (●) from **PRC 160, 4 (1987)**, theoretical one-body calculation (▲) by **Marcucci et al., PRC 58, 3069 (1998)**.

✓ Good agreement with the experimental data.