Deeply Virtual Compton Scattering off He nuclei

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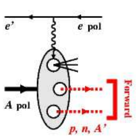


Outline

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

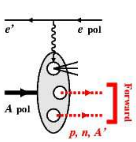
Realistic calculations: use of exact wave functions, solutions of the Schrödinger equation, with realistic NN potentials (Av18, Nijmegen, CD Bonn) and 3-body forces

GPDs of light nuclei (deuteron aside):

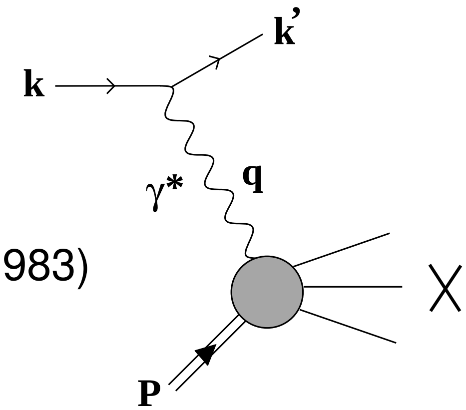
- **1 - GPDs for ^{3}He:**
  A complete impulse approximation realistic study is reviewed
  (S.S. PRC 2004, PRC 2009; M. Rinaldi and S.S., PRC 2012, PRC 2013)
  No data; proposals? Prospects at JLAB-12 and EIC;

- **2 - DVCS off ^{4}He:**
  data available from JLab at 6 GeV; new data expected at 12 GeV;
  our calculations (not yet realistic)
  (Coherent: S. Fucini, S.S., M. Viviani, Phys.Rev. C98 (2018) no.1, 015203)
  (Incoherent: S. Fucini, S.S., M. Viviani, arXiv:1909.12261 [nucl-th]) .

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*



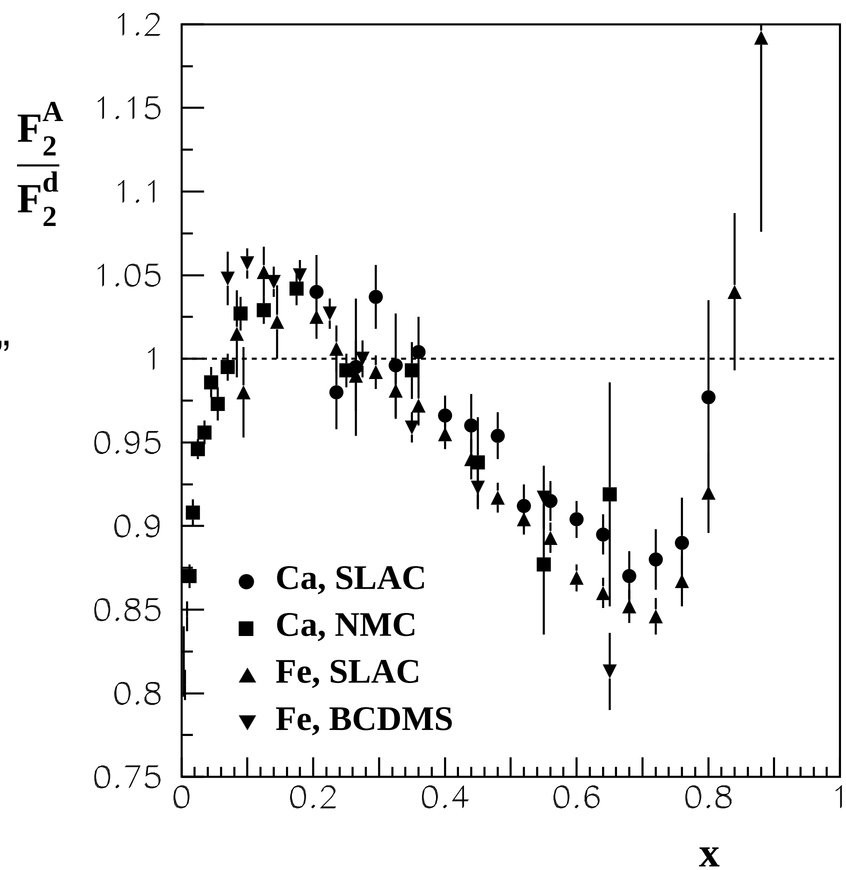
EMC effect in A-DIS



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”



EMC effect: explanations?

Situation: basically not understood. Very unsatisfactory. We need to know the reaction mechanism of hard processes off nuclei and the degrees of freedom which are involved:

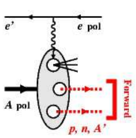
- the knowledge of nuclear parton distributions is crucial for the data analysis of heavy ions collisions;
- the partonic structure of the neutron is measured with nuclear targets and several QCD sum rules involve the neutron information (Bjorken SR, for example): importance of Nuclear Physics for QCD

Inclusive measurements cannot distinguish between models

One has to go beyond

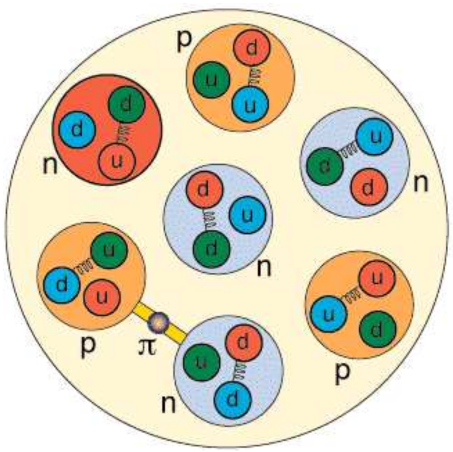
(R. Dupré and S.S., EPJA 52 (2016) 159)

- **SIDIS (TMDs)** - not treated here
- **Hard Exclusive Processes (GPDs)**



EMC effect: way out?

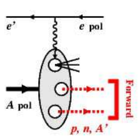
Question: **Which of these transverse sections is more similar to that of a nucleus?**



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

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

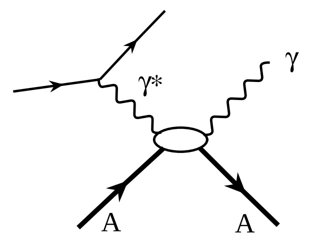
Answer: **Deeply Virtual Compton Scattering**
& Generalized Parton Distributions (GPDs)



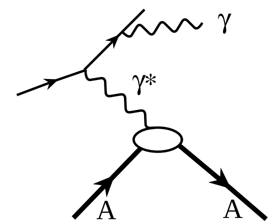
GPDs: a unique tool...

- 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:

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

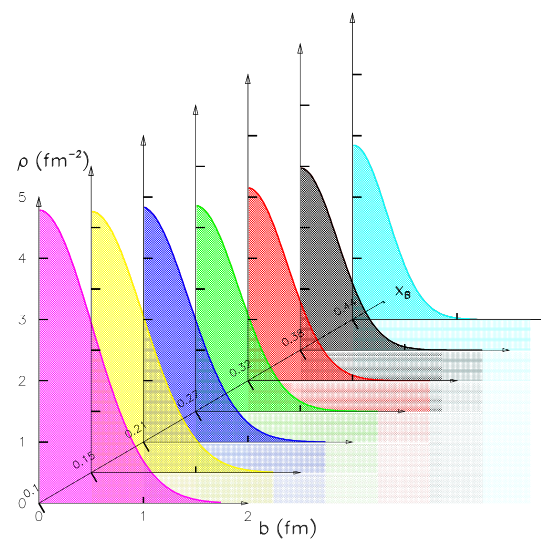
- Competition with the **BH** process! (σ asymmetries measured).

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

Nevertheless, for the proton, we have results:

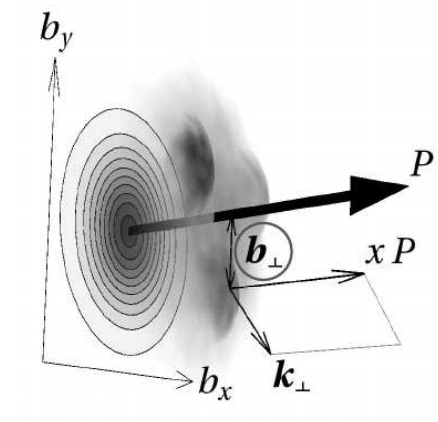
(Guidal et al., Rep. Prog. Phys. 2013...

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

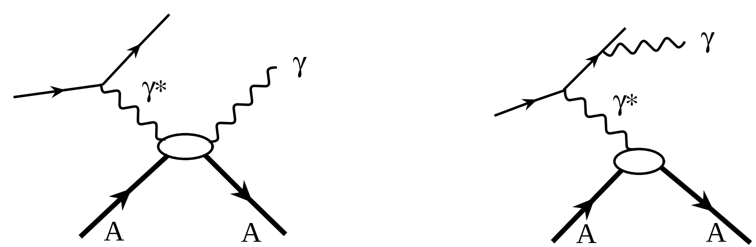


Nuclei and DVCS tomography

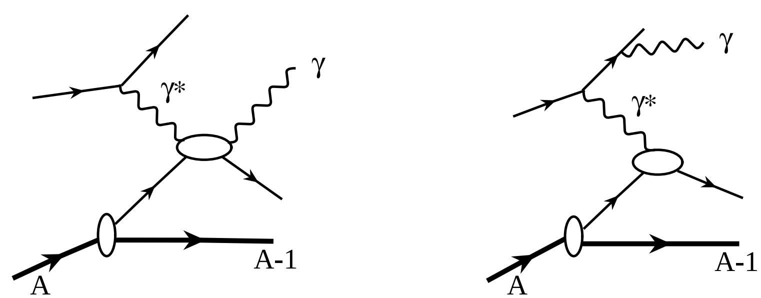
In impact parameter space, GPDs are *densities*:



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



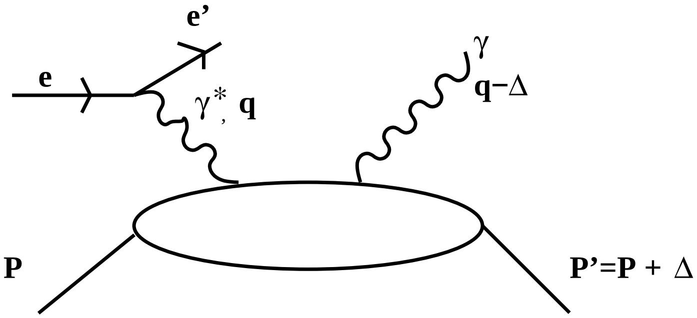
Coherent DVCS: nuclear tomography



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

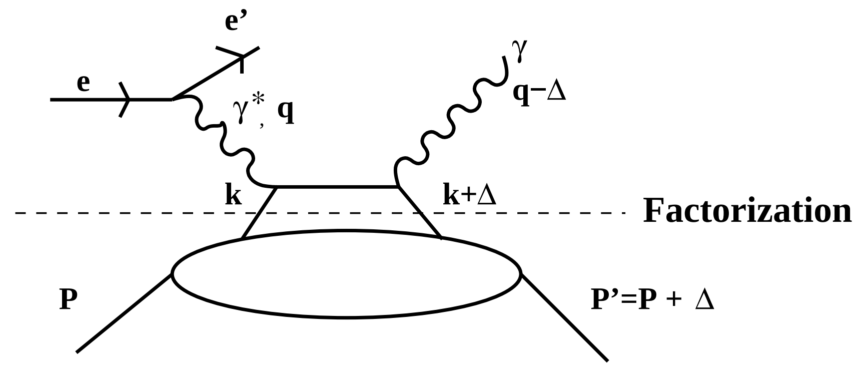
Nuclei: why? - not only tomography

ONE of the reasons is understood by studying coherent DVCS in the I.A. to the handbag contribution:



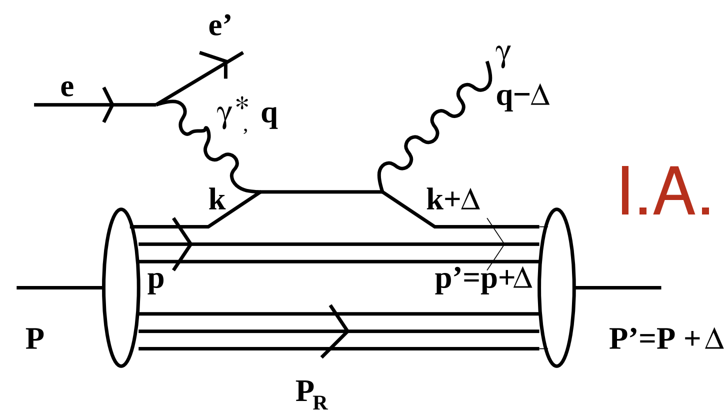
coherent DVCS

$\simeq$

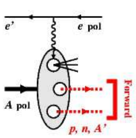


handbag

$\simeq$



I.A.



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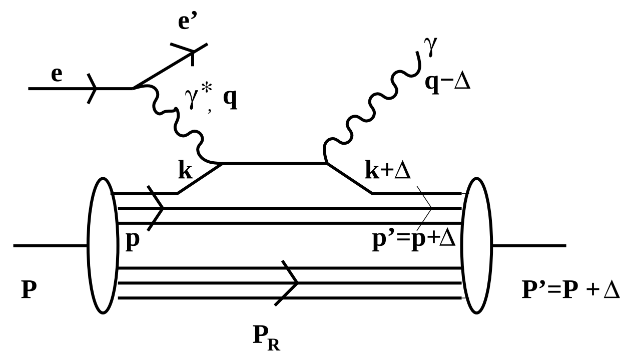
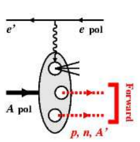


In a symmetric frame ($\bar{p} = (p + p')/2$) :

$$
\begin{aligned}
k^+ &= (x+\xi)\bar{P}^+ = (x'+\xi')\bar{p}^+ \ , \\
(k+\Delta)^+ &= (x-\xi)\bar{P}^+ = (x'-\xi')\bar{p}^+ \ ,
\end{aligned}
$$

one has, for a given GPD

$$
GPD_q(x,\xi,\Delta^2) \simeq \int \frac{dz^-}{4\pi} e^{ix\bar{P}^+ z^-} {}_A\langle P'S'|\hat{O}_q^+|PS\rangle_A|_{z^+=0, z_\perp=0} \ .
$$



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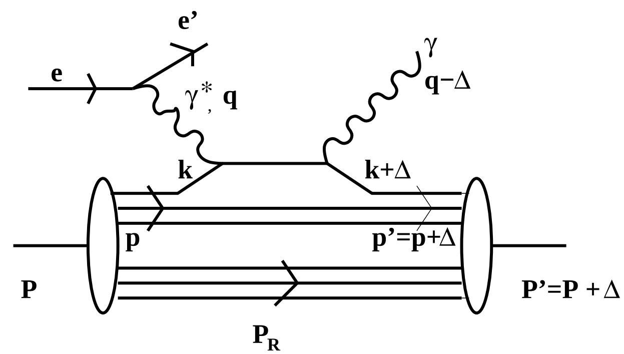


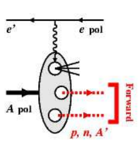
In a symmetric frame ($\bar{p} = (p + p')/2$) :

$$k^+ = (x + \xi)\bar{P}^+ = (x' + \xi')\bar{p}^+ \ ,$$
$$(k + \Delta)^+ = (x - \xi)\bar{P}^+ = (x' - \xi')\bar{p}^+ \ ,$$

one has, for a given GPD

$$GPD_q(x, \xi, \Delta^2) \simeq \int \frac{dz^-}{4\pi} e^{ix\bar{P}^+ z^-} {}_A\langle P'S'|\hat{O}_q^+|PS\rangle_A|_{z^+=0, z_\perp=0} \ .$$

By properly inserting complete sets of states for the interacting nucleon and the recoiling system :



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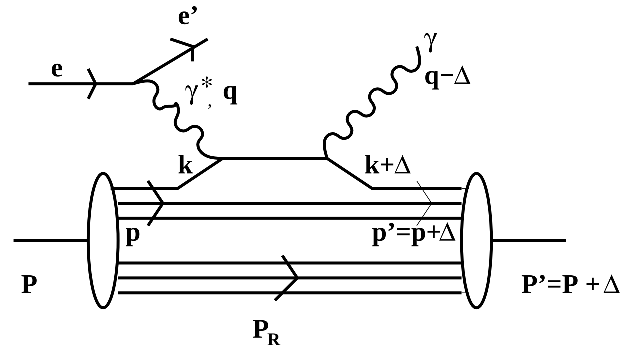

In a symmetric frame ($\bar{p} = (p+p')/2$) :

$$
\begin{aligned}
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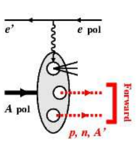
\end{aligned}
$$

one has, for a given GPD

$$
\begin{aligned}
GPD_q(x,\xi,\Delta^2) = & \int \frac{dz^-}{4\pi} e^{ix'\bar{p}^+z^-} \langle P'S'| \sum_{\vec{P}'_R,S'_R,\vec{p}',s'} \{|P'_R S'_R\rangle |p's'\rangle\} \langle P'_R S'_R| \\
& \langle p's'|\, \hat{O}_q^+ \sum_{\vec{P}_R,S_R,\vec{p},s} \{|P_R S_R\rangle |ps\rangle\} \{\langle P_R S_R| \langle ps|\} \ \ |PS\rangle \ ,
\end{aligned}
$$

and, since $\{\langle P_R S_R|\langle ps|\}|PS\rangle = \langle P_R S_R, ps|PS\rangle (2\pi)^3 \delta^3(\vec{P} - \vec{P}_R - \vec{p}) \delta_{S,S_R\,s}$,



Why nuclei?

a convolution formula can be obtained **(S.S. PRC 70, 015205 (2004))**:

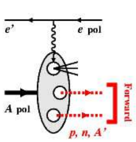
$$H_q^A(x,\xi,\Delta^2) \simeq \sum_N \int \frac{d\bar{z}}{\bar{z}} h_N^A(\bar{z},\xi,\Delta^2) H_q^N\left(\frac{x}{\bar{z}},\frac{\xi}{\bar{z}},\Delta^2\right)$$

in terms of $H_q^N(x',\xi',\Delta^2)$, the GPD of the free nucleon N, and of the light-cone off-diagonal momentum distribution:

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

where $P_N^A(\vec{p},\vec{p}+\vec{\Delta},E)$, is the one-body off-diagonal spectral function for the nucleon N in the nucleus,

$$\begin{aligned} P_N^3(\vec{p},\vec{p}+\vec{\Delta},E) &= \frac{1}{(2\pi)^3}\frac{1}{2}\sum_M \sum_{R,s} \langle \vec{P}' M|(\vec{P}-\vec{p})S_R,(\vec{p}+\vec{\Delta})s\rangle \\ &\times \langle (\vec{P}-\vec{p})S_R,\vec{p}s|\vec{P}M\rangle\, \delta(E-E_{min}-E_R^*)\,. \end{aligned}$$



Why nuclei?

The obtained expressions have the correct limits:

- the x-integral gives the f.f. $F_q^A(\Delta^2)$ in I.A.:

$$\int dx H_q^A(x,\xi,\Delta^2) = F_q^N(\Delta^2) \int dE d\vec{p}\, P_N^A(\vec{p},\vec{p}+\vec{\Delta},E) = F_q^A(\Delta^2)$$

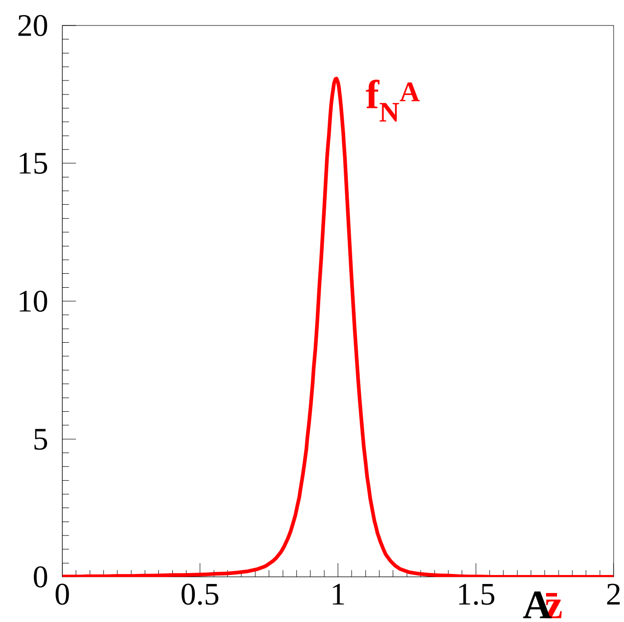
- forward limit (standard DIS):

$q^A(x) \simeq \sum_N \int_x^1 \frac{d\tilde{z}}{\tilde{z}} f_N^A(\tilde{z}) q^N\left(\frac{x}{\tilde{z}}\right)$

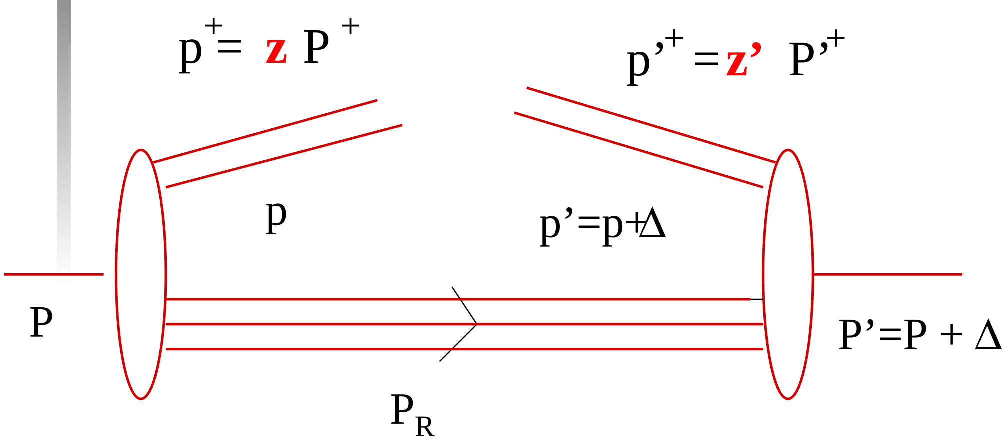
with the light-cone momentum distribution:

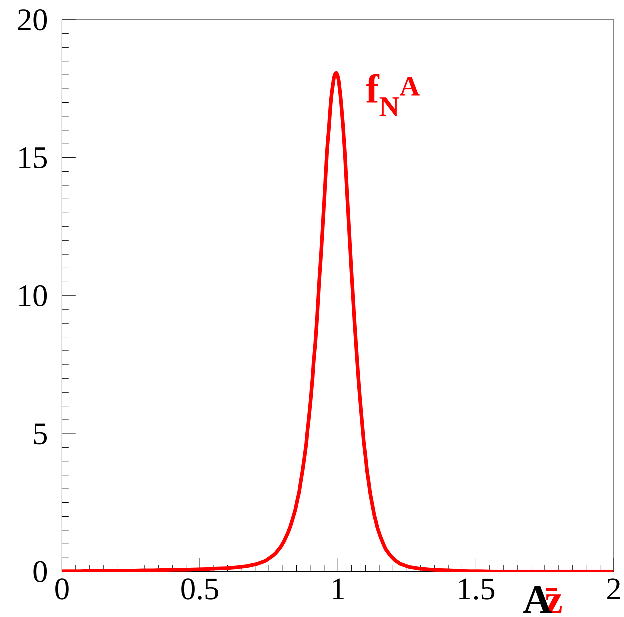
$f_N^A(\tilde{z}) = \int dE d\vec{p}\, P_N^A(\vec{p},E)\,\delta\left(\tilde{z} - \frac{p^+}{P^+}\right)$,

which is strongly peaked around $A\tilde{z} = 1$:



Why nuclei?





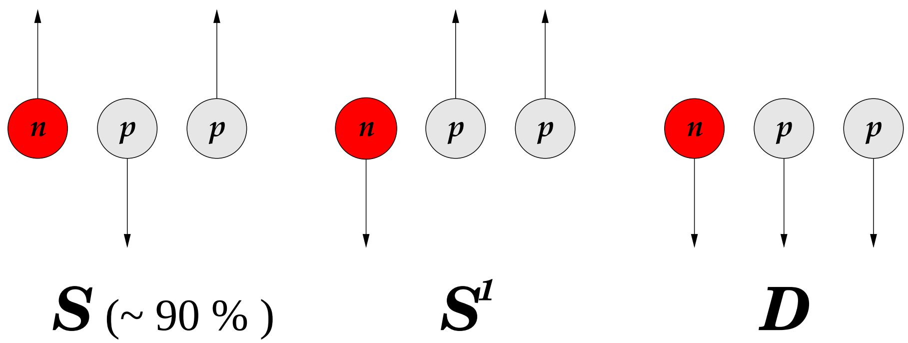
Since $z - z' = -x_B(1-z)/(1-x_B)\,,$ $\xi \simeq x_B/(2-x_B)$ can be tuned to have $z - z'$ larger than the width of the narrow nuclear light-cone momentum distribution $f_N^A(\bar{z} = (z+z')/2)$: in this case IA predicts a $vanishing$ GPD, at $small$ x_B.

If DVCS were observed at this kinematics, exotic effects beyond IA, non-nucleonic degrees of freedom, would be pointed out **(Berger, Cano, Diehl and Pire, PRL 87 (2001) 142302)**

Similar effect predicted in DIS at $x_B > 1$, where DIS data are not accurate enough.

GPDs for ^{3}He: why?

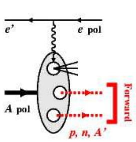
- ^{3}He is theoretically well known. Even a relativistic treatment may be implemented.
- ^{3}He has been used extensively as an effective neutron target, especially to unveil the spin content of the free neutron, due to its peculiar spin structure:



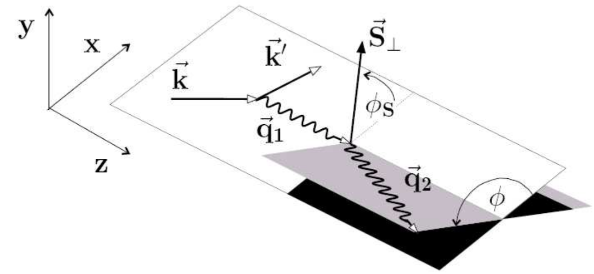
In $S-$wave
$^3\vec{He} = \vec{n}$!

^{3}He always promising when the neutron angular momentum properties have to be studied. To what extent for total J?

- ^{3}He is a unique target for GPDs studies. Examples:
  - * **access to the neutron information in coherent processes**
  - * **HERE: heavier targets do not allow refined theoretical treatments. Test of the theory**
  - * **HERE: Between ^{2}H (“not a nucleus”) and ^{4}He (a true one).** Not isoscalar!



Extracting GPDs: ^{3}He $\simeq p$



One measures asymmetries: $A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$

- Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \simeq \sin\phi \left[F_1 \mathcal{H} + \xi (F_1 + F_2) \tilde{\mathcal{H}} + (\Delta^2 F_2 / M^2) \mathcal{E} / 4 \right] d\phi \qquad \Longrightarrow \qquad H$$

- Unpolarized beam, longitudinally polarized target:

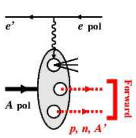
$$\Delta\sigma_{UL} \simeq \sin\phi \left\{ F_1 \tilde{\mathcal{H}} + \xi (F_1 + F_2) \left[\mathcal{H} + \xi/(1+\xi) \mathcal{E} \right] \right\} d\phi \qquad \Longrightarrow \qquad \tilde{H}$$

- Unpolarized beam, transversely polarized target:

$$\Delta\sigma_{UT} \simeq \cos\phi \sin(\phi_S - \phi) \left[\Delta^2 (F_2 \mathcal{H} - F_1 \mathcal{E}) / M^2 \right] d\phi \qquad \Longrightarrow \qquad E$$

To evaluate cross sections, e.g. for experiments planning, one needs $H, \tilde{H}, E$

This is what we have calculated for ^{3}He . H alone, already very interesting.



GPDs of ^{3}He in IA

H_q^A can be obtained in terms of H_q^N (**S.S. PRC 70, 015205 (2004), PRC 79, 025207 (2009)**):

$$H_q^A(x,\xi,\Delta^2) = \sum_N \int dE \int d\vec{p} \overline{\sum_S} \sum_s P^N_{SS,ss}(\vec{p},\vec{p}\,',E) \frac{\xi'}{\xi} H_q^N(x',\Delta^2,\xi') \; ,$$

and $\tilde{G}_M^{3,q}$ in terms of $\tilde{G}_M^{N,q}$ (**M. Rinaldi, S.S. PRC 85, 062201(R) (2012); PRC 87, 035208 (2013)**):

$$\tilde{G}_M^{3,q}(x,\Delta^2,\xi) = \sum_N \int dE \int d\vec{p} \left[P^N_{+-,+-} - P^N_{+-,-+} \right] (\vec{p},\vec{p}\,',E) \frac{\xi'}{\xi} \tilde{G}_M^{N,q}(x',\Delta^2,\xi') \; ,$$

($\tilde{G}_M^q = H^q + E^q$) where $P^N_{SS,ss}(\vec{p},\vec{p}\,',E)$ is the one-body, spin-dependent, off-diagonal spectral function for the nucleon N in the nucleus,

$$P^N_{SS',ss'}(\vec{p},\vec{p}\,',E) = \frac{1}{(2\pi)^6} \frac{M\sqrt{ME}}{2} \int d\Omega_t \sum_{s_t} \langle \vec{P}'S'|\vec{p}\,'s',\vec{t}s_t\rangle_N \langle \vec{p}s,\vec{t}s_t|\vec{P}S\rangle_N \; ,$$

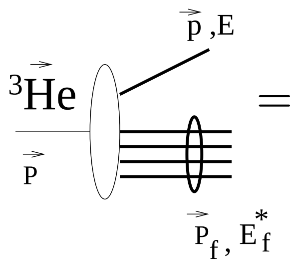
evaluated by means of a realistic treatment based on Av18 wave functions (**"CHH" method in A. Kievsky** *et al* **NPA 577, 511 (1994); Av18 + UIX overlaps in E. Pace** *et. al*, **PRC 64, 055203 (2001)**).

Nucleon GPDs in ^{3}He calculations given by an old version of the VGG model (VGG 1999, $x-$ and Δ^2- dependencies factorized)

Nucleon off-shellness in I.A. :

In the forward limit $f_N^A(\tilde{z}) = \int dE d\vec{p}\, P_N^A(\vec{p}, E)\, \delta\left(\tilde{z} - \frac{p^+}{P^+}\right)$,

$P_N^A(\vec{p}, E) \; = \sum_f$



$= \left| \cdots \right|^2$

↙ intrinsic overlaps ↘

$$\sum_f \delta(E - E_{min} - E_f^*) \overbrace{{}_{S_A}\langle \Psi_A; J_A \mathcal{M} \pi_A | \vec{p}, \sigma; \phi_f(E_f^*) \rangle} \overbrace{\langle \phi_f(E_f^*); \sigma \vec{p} | \pi_A J_A \mathcal{M}'; \Psi_A \rangle_{S_A}}$$

$\tilde{z} = \frac{p_0 - p_3}{M_A} \qquad p_0 = M_A - \sqrt{M_{A-1}^{*\,2} + p^2} \simeq M - E - T_f \longrightarrow p^2 \neq M^2$

“Instant-Form” I.A.:

- off-shellness driven by nuclear dynamics
  (all NN correlations included in the realistic wf)
- number SR fulfilled; momentum SR violated by 2 %

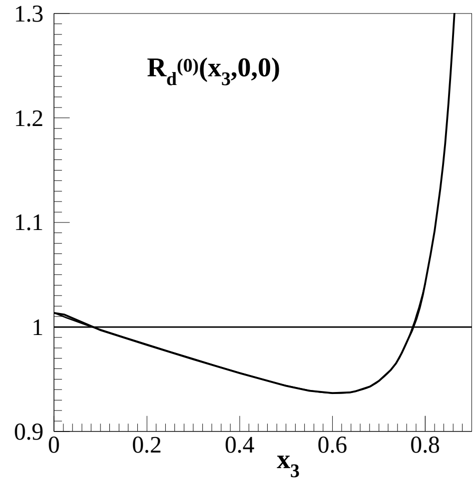
The calculation has the correct limits:

1 - Forward limit: the ratio:

$$R_q(x,0,0) = \frac{H_q^3(x,0,0)}{2H_q^p(x,0,0)+H_q^n(x,0,0)}$$

$$= \frac{q^3(x)}{2q^p(x)+q^n(x)}$$

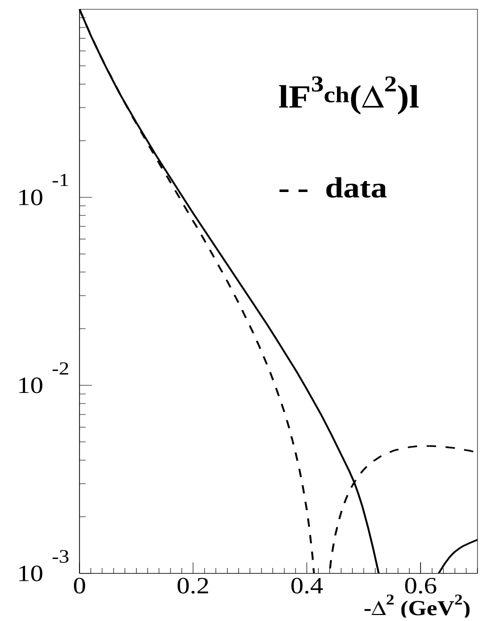
shows an EMC-like behavior;



2 - Charge F.F.:

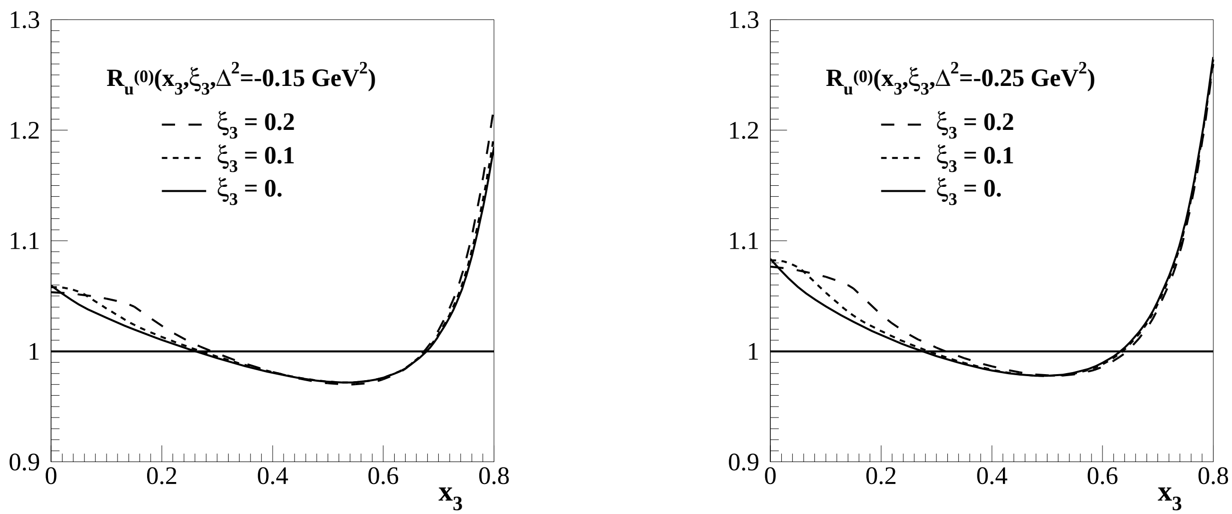
$$\sum_q e_q \int dx H_q^3(x,\xi,\Delta^2) = F^3(\Delta^2)$$

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



Nuclear effects - general features

- Nuclear effects grow with ξ at fixed Δ^2, and with Δ^2 at fixed ξ:



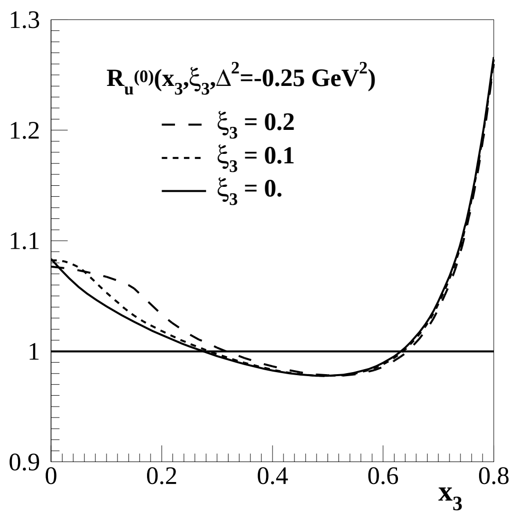
$$R_q^{(0)}(x,\xi,\Delta^2) = \frac{H_q^3(x,\xi,\Delta^2)}{2H_q^{3,p}(x,\xi,\Delta^2) + H_q^{3,n}(x,\xi,\Delta^2)}$$

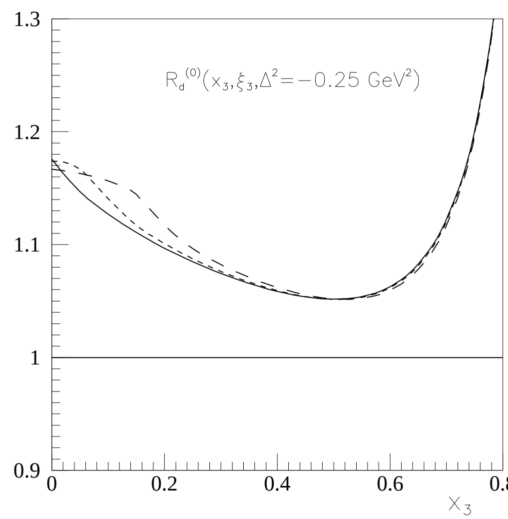
$$H_q^{3,N}(x,\xi,\Delta^2) = \tilde{H}_q^N(x,\xi)F_q^3(\Delta^2)$$

$R_q^{(0)}(x,\xi,\Delta^2)$ would be one if there were no nuclear effects;
as it is found also for the deuteron, there is no factorization into terms dependent separately on Δ^2 and x,ξ (the factorization hypotheses has been used to estimate nuclear GPDs), even if the nucleonic model is factorized

Nuclear effects - flavor dependence

- Nuclear effects are bigger for the d flavor rather than for the u flavor:



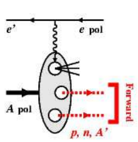


$$R_q^{(0)}(x,\xi,\Delta^2) = \frac{H_q^3(x,\xi,\Delta^2)}{2H_q^{3,p}(x,\xi,\Delta^2) + H_q^{3,n}(x,\xi,\Delta^2)}$$

$$H_q^{3,N}(x,\xi,\Delta^2) = \tilde{H}_q^N(x,\xi) F_q^3(\Delta^2)$$

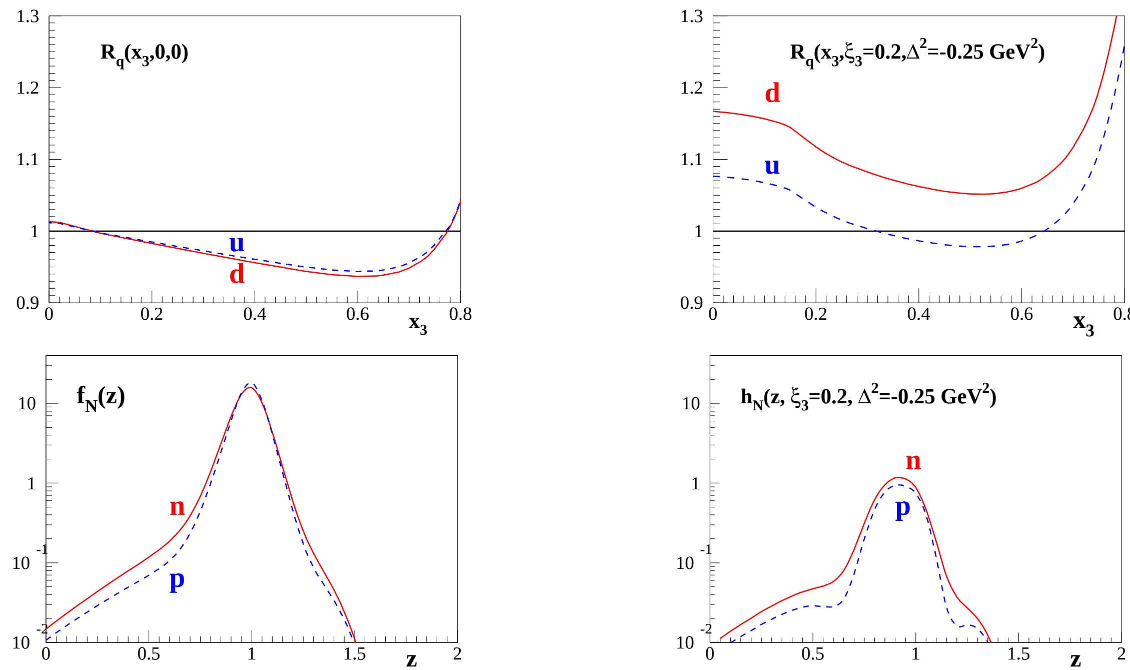
$R_q^{(0)}(x,\xi,\Delta^2)$ would be one if there were no nuclear effects;

- This is a typical conventional, IA effect (spectral functions are different for p and n in ^{3}He, not isoscalar!); if (not) found, clear indication on the reaction mechanism of DIS off nuclei. Not seen in ^{2}H, ^{4}He

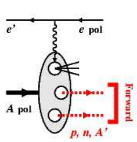


Nuclear effects - flavor dependence

- The d and u distributions follow the pattern of the neutron and proton light-cone momentum distributions, respectively:



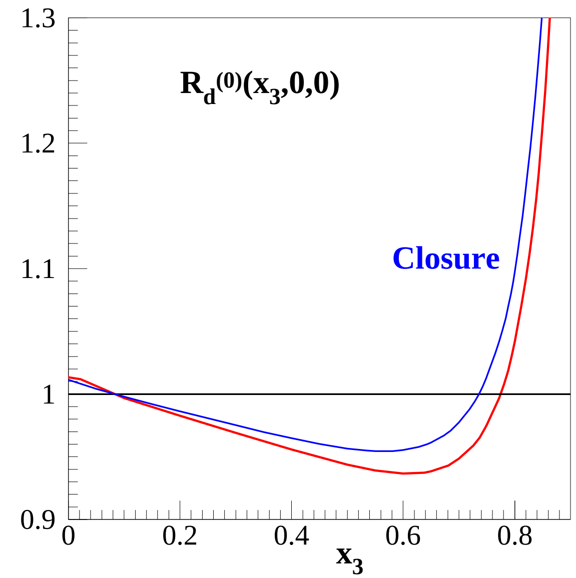
- How to perform a flavor separation? Take the triton ^{3}H !
  Possible (see MARATHON@JLab). Possible for DVCS (ALERT).
  Studied in **S.S. Phys. Rev. C 79 (2009) 025207**
  $H_t, H_H \to H_u^H \simeq H_d^t, H_d^H \simeq H_u^t$ in the valence region...

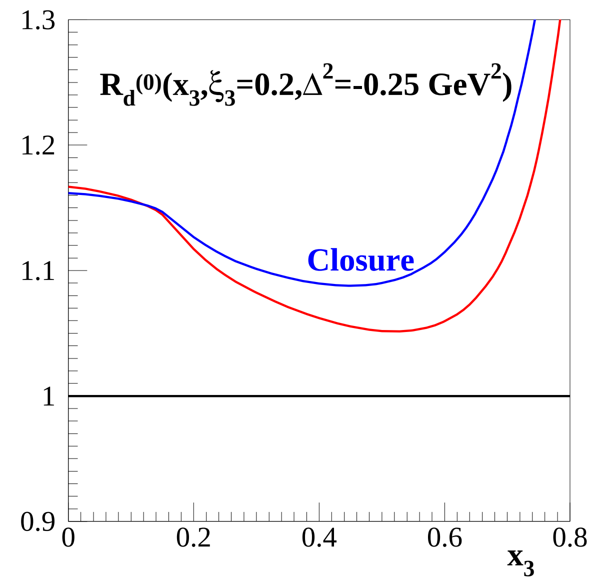


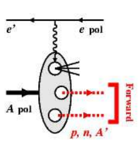
Nuclear effects - the binding

Nuclear effects are bigger than in the forward case: dependence on the binding

- In calculations using $n(\vec{p}, \vec{p}+\vec{\Delta})$ instead of $P_N^3(\vec{p}, \vec{p}+\vec{\Delta}, E)$, in addition to the IA, also the Closure approximation has been assumed;
- 5 % to 10 % binding effect between $x = 0.4$ and 0.7 - much bigger than in the forward case;
- for $A > 3$, the evaluation of $P_N^3(\vec{p}, \vec{p}+\vec{\Delta}, E)$ is difficult - such an effect is not under control: Conventional nuclear effects can be mistaken for exotic ones;
- for ^{3}He it is possible : this makes it a unique target, even among the Few-Body systems.



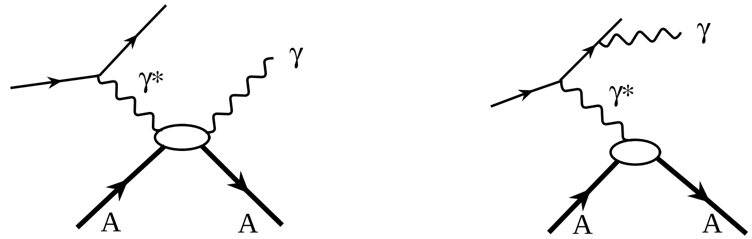




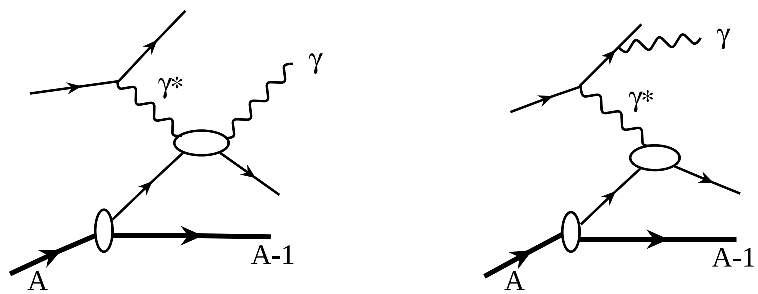
^{3}He calculations: summary

- Our results, for ^{3}**He:** **(S.S. PRC 2004, 2009; M. Rinaldi and S.S., PRC 2012, 2013)**
  - * I.A. calculation of $H_3, E_3, \tilde{H}_3$, within AV18;
  - * Interesting predictions: strong sensitivity to details of nuclear dynamics:
  - * extraction procedure of the neutron information, able to take into account all the nuclear effects encoded in an IA analysis;
- Coherent DVCS off ^{3}He would be:
  - * a test of IA; relevance of non-nucleonic degrees of freedom;
  - * a test of the A- and isospin dependence of nuclear effects;
  - * complementary to incoherent DVCS off the deuteron in extracting the neutron information (with polarized targets).
- No data; no proposals at JLAB... difficult to detect slow recoils using a polarized target... But even unpolarized, ^{3}He would be interesting!
  Together with ^{3}H, nice posibilities (flavor separation of nuclear effects, test of IA)
- at the EIC, beams of polarized light nuclei will operate. $^3\vec{He}$ can be used.
- Our codes available to interested colleagues.

Nuclei and DVCS tomography



Coherent DVCS: nuclear tomography

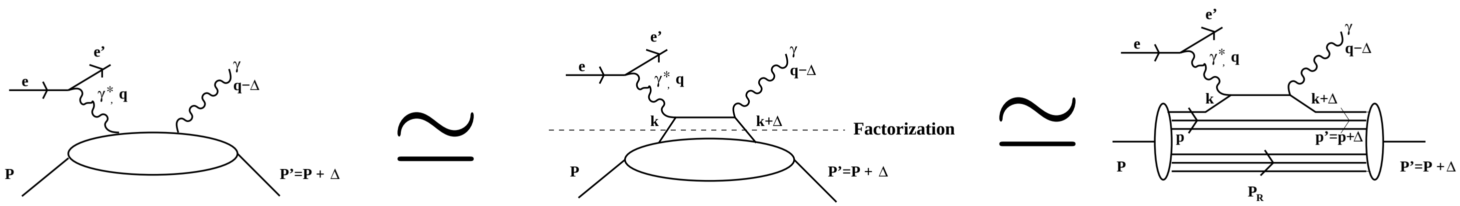


Incoherent DVCS: tomography of bound nucleons: realization of the EMC effect

- 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., PRL 123 (2019) no.3, 032502**) channels

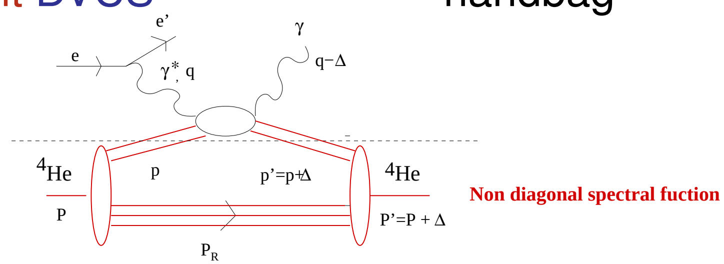
Our IA approach to coherent DVCS off ^{4}He

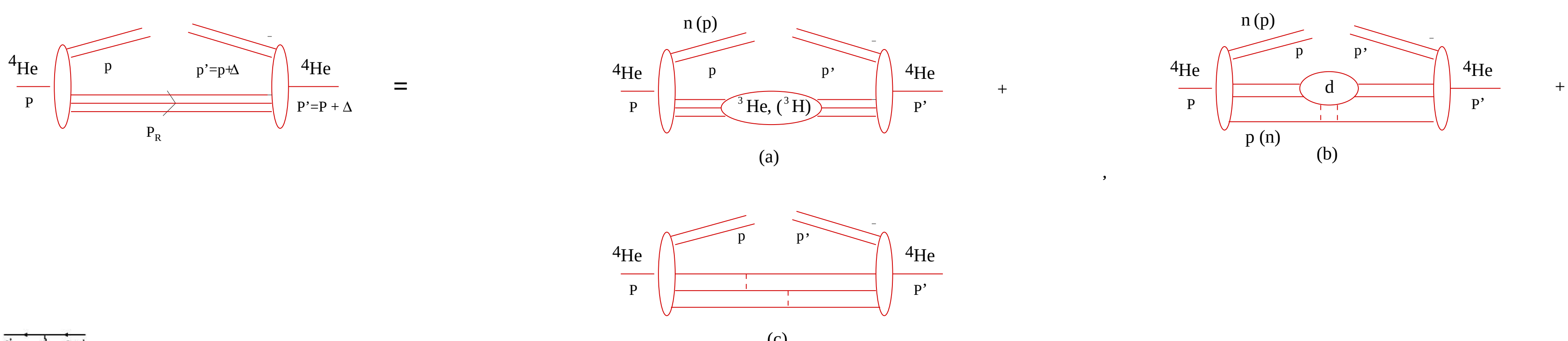
- Realistic microscopic calculations are necessary. A collaboration is going on with Sara Fucini (Perugia, Ph.D. student), Michele Viviani (INFN Pisa).
- coherent DVCS in the Impulse Approximation (I.A.) to the handbag contribution:



coherent DVCS handbag I.A.

- I.A. :





a) worked out; 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)**:

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

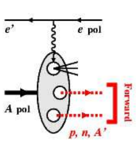
Non-diagonal light-cone momentum distribution:

$$\begin{aligned} h_N^{^4He}(z,\Delta^2,\xi) &= \int dE \int d\vec{p}\, P_N^{^4He}(\vec{p},\vec{p}+\vec{\Delta},E)\,\delta(z-\bar{p}^+/\bar{P}^+) \\ &= \frac{M_A}{M}\int dE \int_{p_{min}}^{\infty} dp\tilde{M}p P_N^{^4He}(\vec{p},\vec{p}+\vec{\Delta},E)\,\delta\left(\tilde{z}\frac{\tilde{M}}{p}-\frac{p^0}{p}-\cos\theta\right) \end{aligned}$$

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

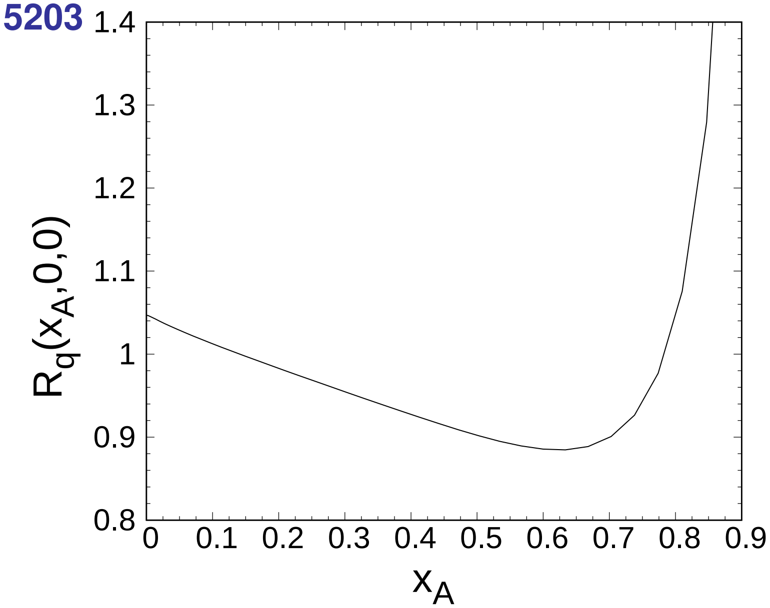
S.Fucini, SS., M. Viviani PRC 98 (2018) 015203

1 - Forward limit: the ratio:

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

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

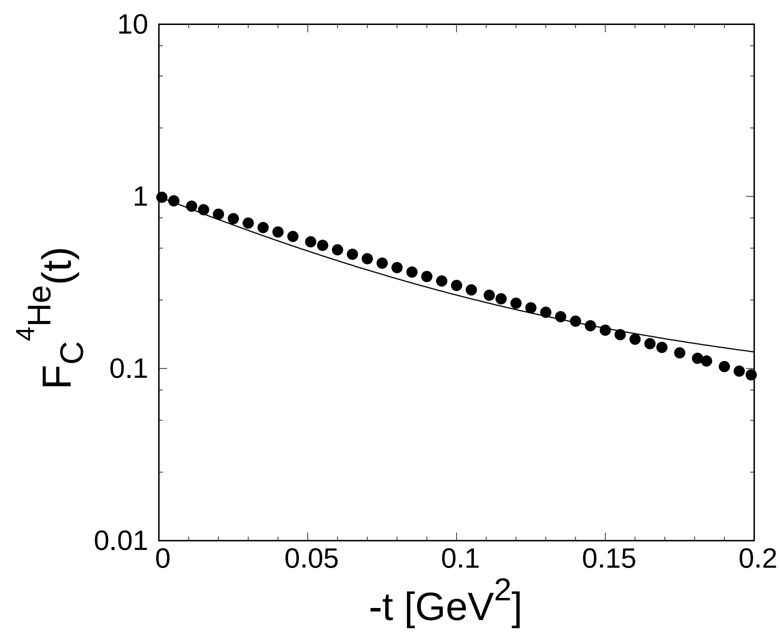
shows an EMC-like behavior;



2 - Charge F.F.:

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

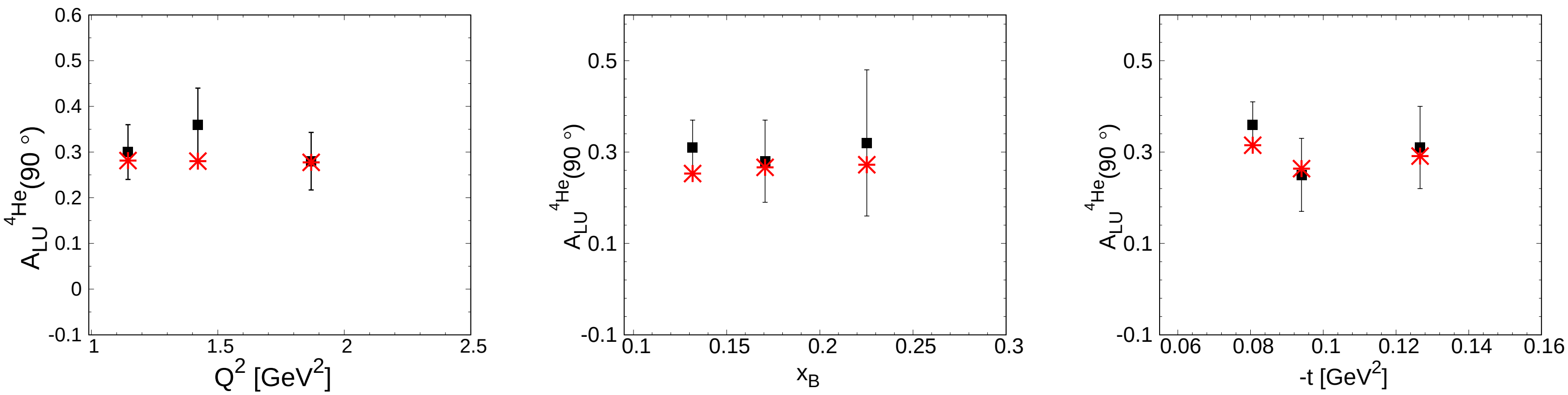
reasonable agreement with data in the region relevant to the coherent process, $-t = -\Delta^2 \leq 0.2$ GeV^2.



Comparison with EG6 data: A_{LU}

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

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

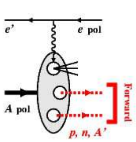


results of this aproach (stars) vs **EG6 data (squares)**

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

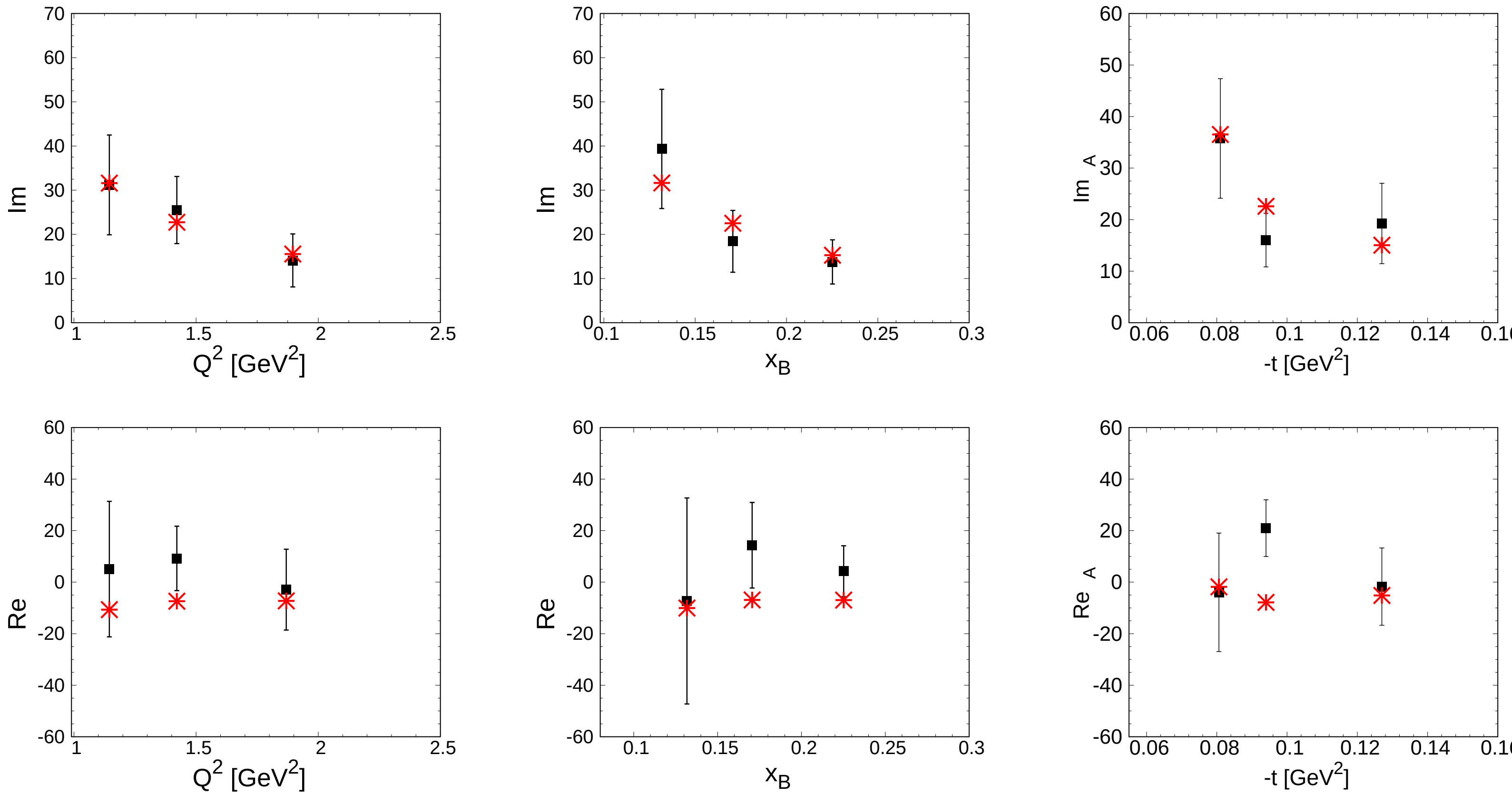
$$A_{LU}(\phi) = \frac{\alpha_0(\phi)\, \Im m(\mathcal{H}_A)}{\alpha_1(\phi) + \alpha_2(\phi)\, \Re e(\mathcal{H}_A) + \alpha_3(\phi)\left(\Re e(\mathcal{H}_A)^2 + \Im m(\mathcal{H}_A)^2\right)}$$

$\Re e(\mathcal{H}_A)$ 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



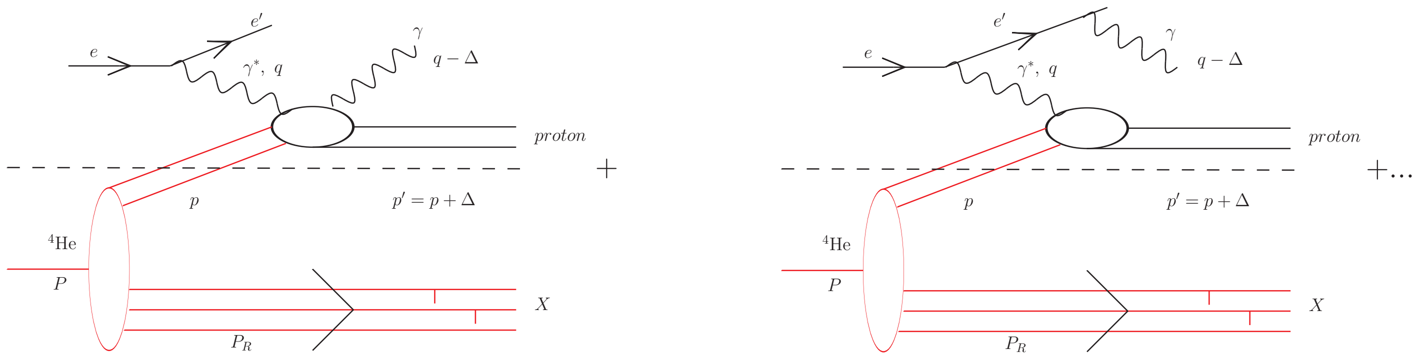
$$\Im m(\mathcal{H}_A) = H_A(\xi,\xi,t) - H_A(-\xi,\xi,t),$$

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

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 - arXiv:1909.12261 [nucl-th]



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

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

- off-shellness driven by nuclear dynamics:

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

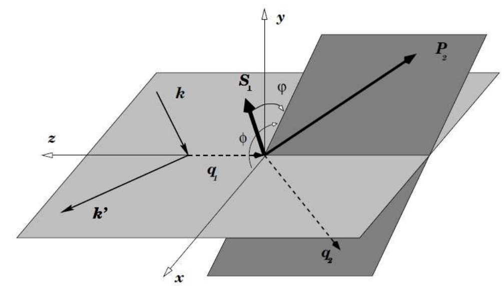
  $$\xi = Q^2/[(p+p')\cdot(q+q')] \neq x_B/(2-x_B)$$

- number SR fulfilled; momentum SR violated by 2 % (polinomiality violated)

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

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

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



.

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

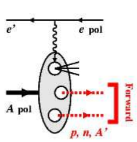
$g(kin,\vec{p},E)$: a complicated function

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

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

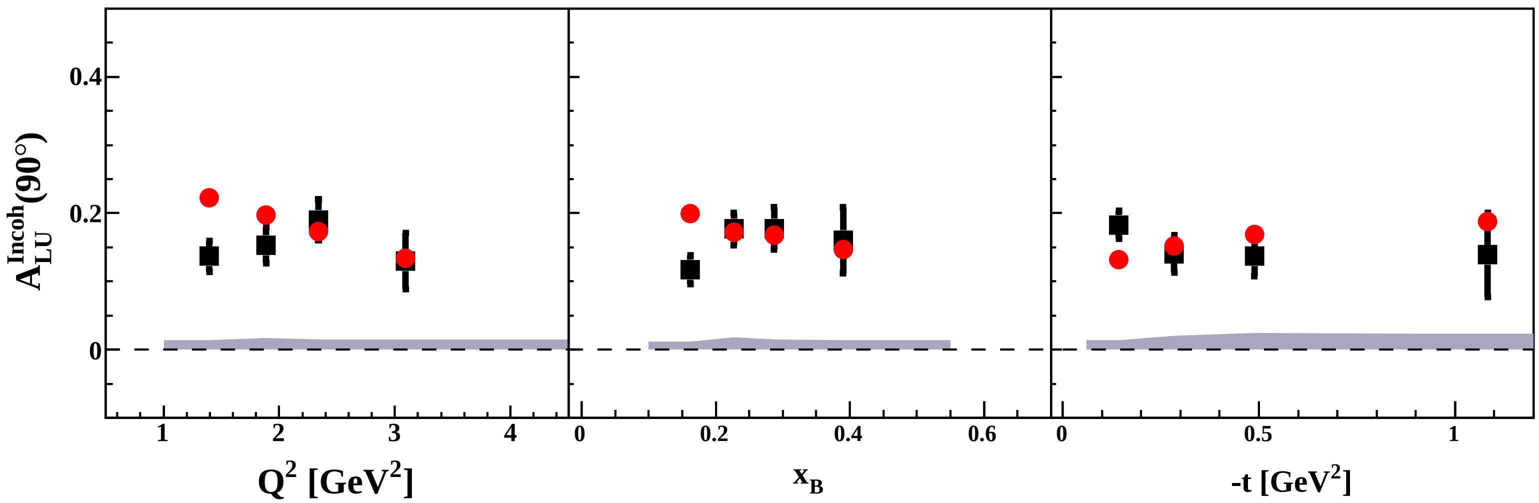
- $T_{BH}^2, T_{DVCS}^2, Int_{BH-DVCS}$ for a moving bound nucleon; our expressions, obtained generalizing the ones at leading twist for nucleons at rest (**Belitski et al. (2002)**); $T_{BH}^2 = c_0^{bound} + c_1^{bound}(\cos\Phi) + c_2^{bound}\cos(2\Phi)$
- In $Int_{BH-DVCS}$, the H GPD in $\Im m(\mathcal{H}_N)$ 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)



Results for A_{LU}

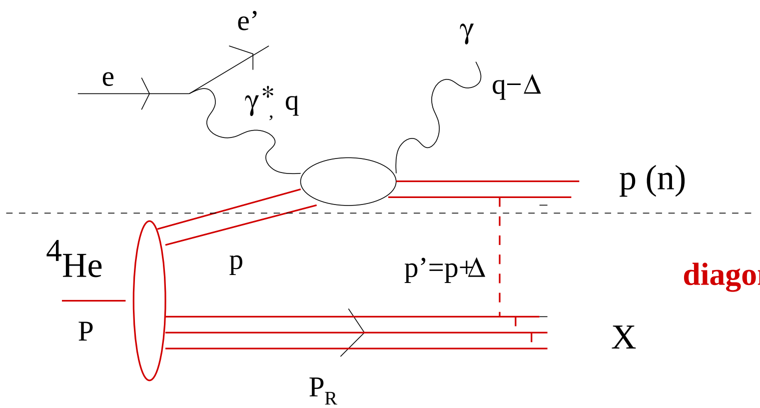
S. Fucini, S.S., M. Viviani - arXiv:1909.12261 [nucl-th]



- Calculations are performed in each experimental bin, at values of x_B, t and Q^2 corresponding to the experimental EG6 analysis. A strong dependence on the experimental kinematics is found.
- EG6 data correctly reproduced using conventional ingredients up to data corresponding to low values of Q^2...
  Possible important t/Q^2 effects to be added (other GPDs involved?)...
  Complicated interplay between t and Q^2 to realize if this could be due to FSI effects or to not conventional effects... Work in progress.

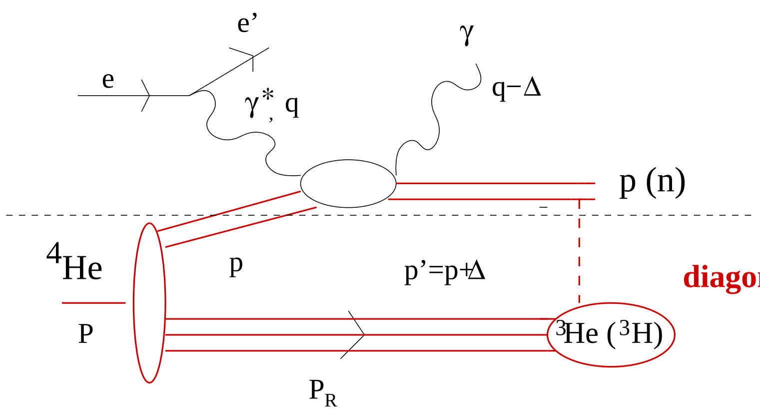
Incoherent DVCS off ^{4}He: beyond IA; FSI?

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



diagonal spectral fuction... FSI??

- **Tagged! e.g.,** $^4\textbf{He}(e, e'\gamma p)^3\textbf{H}$ **(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

GPDs of He nuclei:

- **1 - GPDs for ^{3}He:**

  A complete impulse approximation realistic study is available
  (S.S. PRC 2004, PRC 2009; M. Rinaldi and S.S., PRC 2012, PRC 2013)
  * No data; proposals? Prospects al JLAB-12 and EIC;
  * planned LF calculation

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

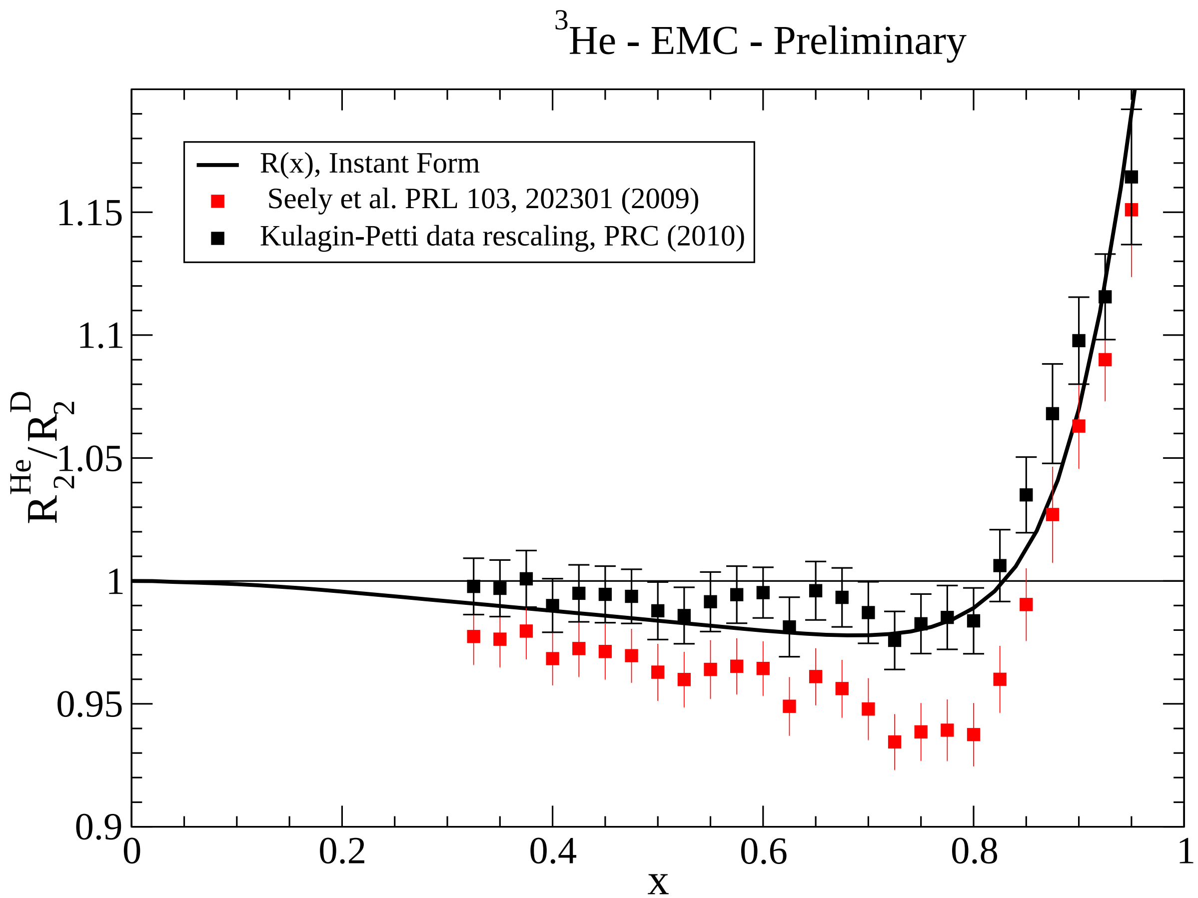
  * Coherent and Incoherent channel: a calculation (not yet realistic) with basic ingredients (GK model plus a model spectral function based on Av18 + UIX) describe well most of the data available from JLab at 6 GeV; **(S. Fucini, S.S., M. Viviani, PRC 98 (2018) 015203; arXiv:1909.12261 [nucl-th]).**
  Straightforward and workable approach, suitable for planning new measurements.
  * New data expected at 12 GeV will require much more precise nuclear description (in progress)

Our spirit: introduce new ingredients one at a time

Occam's razor: *"Frustra fit per plura quod potest fieri per pauciora"*

(*It is futile to do with more things what can be done with fewer*)

Backup: ^{3}He EMC effect IF - preliminary



- Red squares: **Seely et al. (E03103), Hall A JLab, PRL 103 (2009) 202301**
- Black squares: reanalysis (currently accepted) **Kulagin and Petti, PRC 82 (2010) 054614**
- particle SR fulfilled; momentum SR violated by 2 %

Backup: ^{4}He EMC effect IF - preliminary

EMC effect: PRELIMINARY

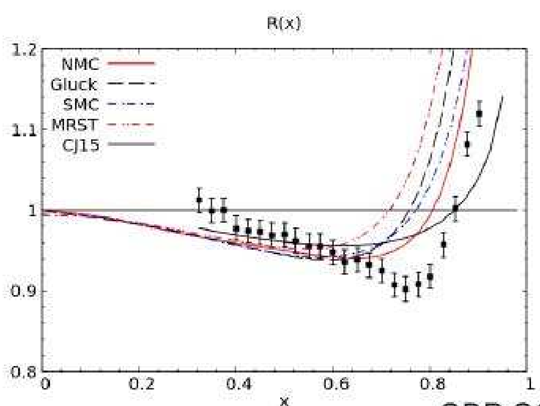
$$R(x) = \frac{F_2^{^4He}(x)}{F_2^d(x)} \qquad x \in [0 : M_A/M]$$

where the **function structures** F_2 for $A = {}^4$He,d are defined as

$$F_2^A(x) = \sum_N \int_x^{M_A/M} dz\, f_N^A(z) F_2^N\left(\frac{x}{z}, Q^2\right)$$

in terms of the *light cone momentum distribution*

$$f_N^A(z) = \int d\vec{p} \int dE P_N^A(\vec{p}, E)\, \frac{p^+}{p_0}\, \delta\left(z - \sqrt{2}\frac{p^+}{M_A}\right)$$



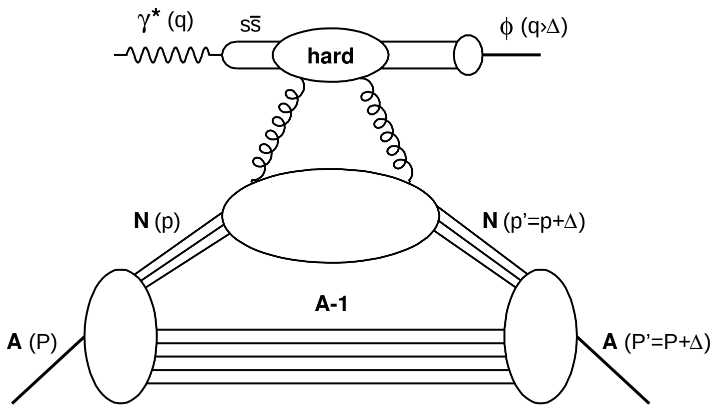
- Our model isn't predictive at small x
- Good agreement in the valence region
- Strong dependence on the model for F_2^N at large x
- Need to better unravel the Q^2 dependence of $R(x)$

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

GDR QCD 2019 12 / 23

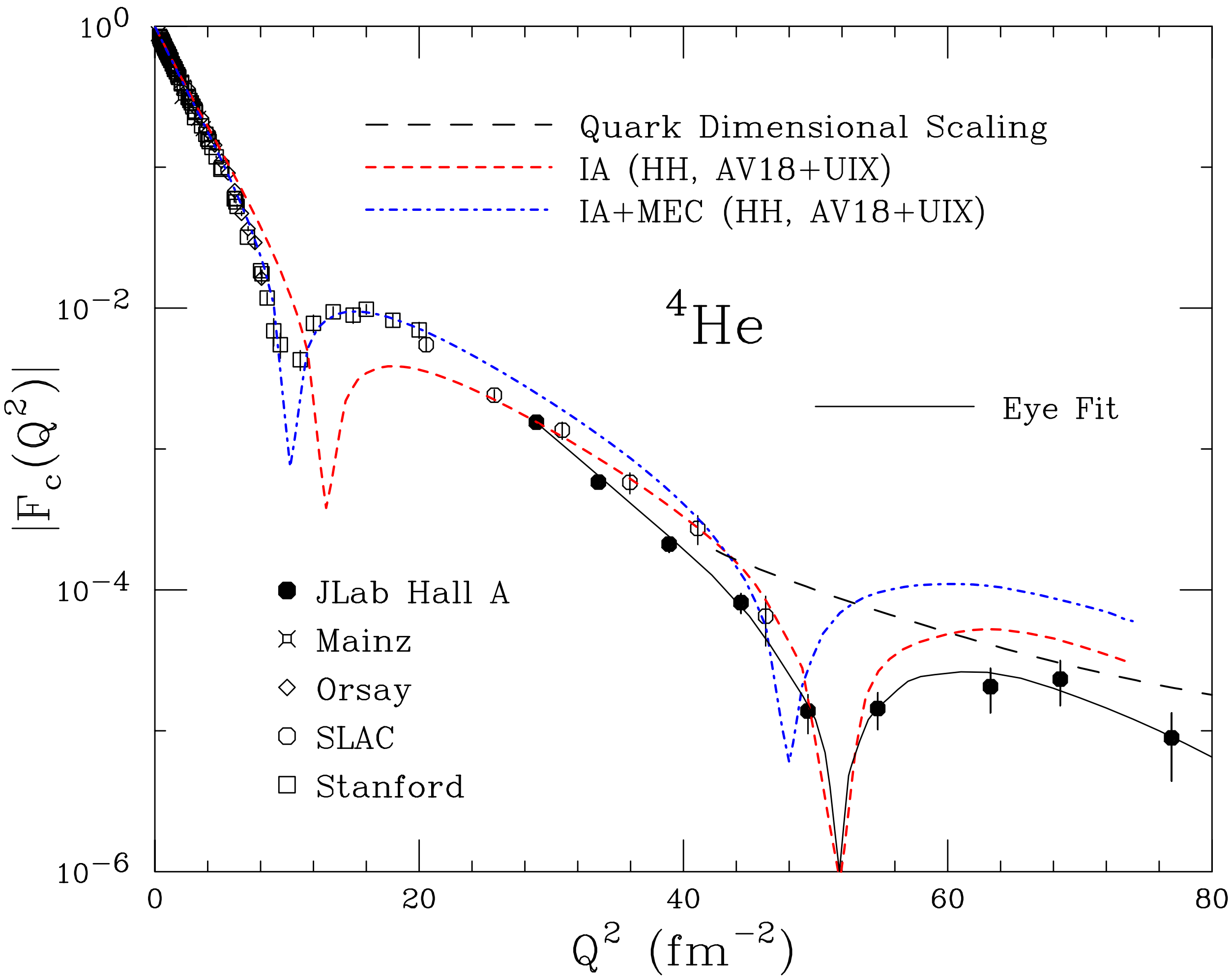
Backup: Many other issues...

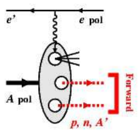
- $x-$moments of GPDs (ffs of energy momentum tensor): information on spatial distribution of energy, momentum and forces experienced by the partons. Predicted an A dependence stronger than in IA (not seen at HERMES);
  M. Polyakov, PLB 555, 57 (2003); H.C. Kim et al. PLB 718, 625 (2012)...
- Gluon GPDs in nuclei



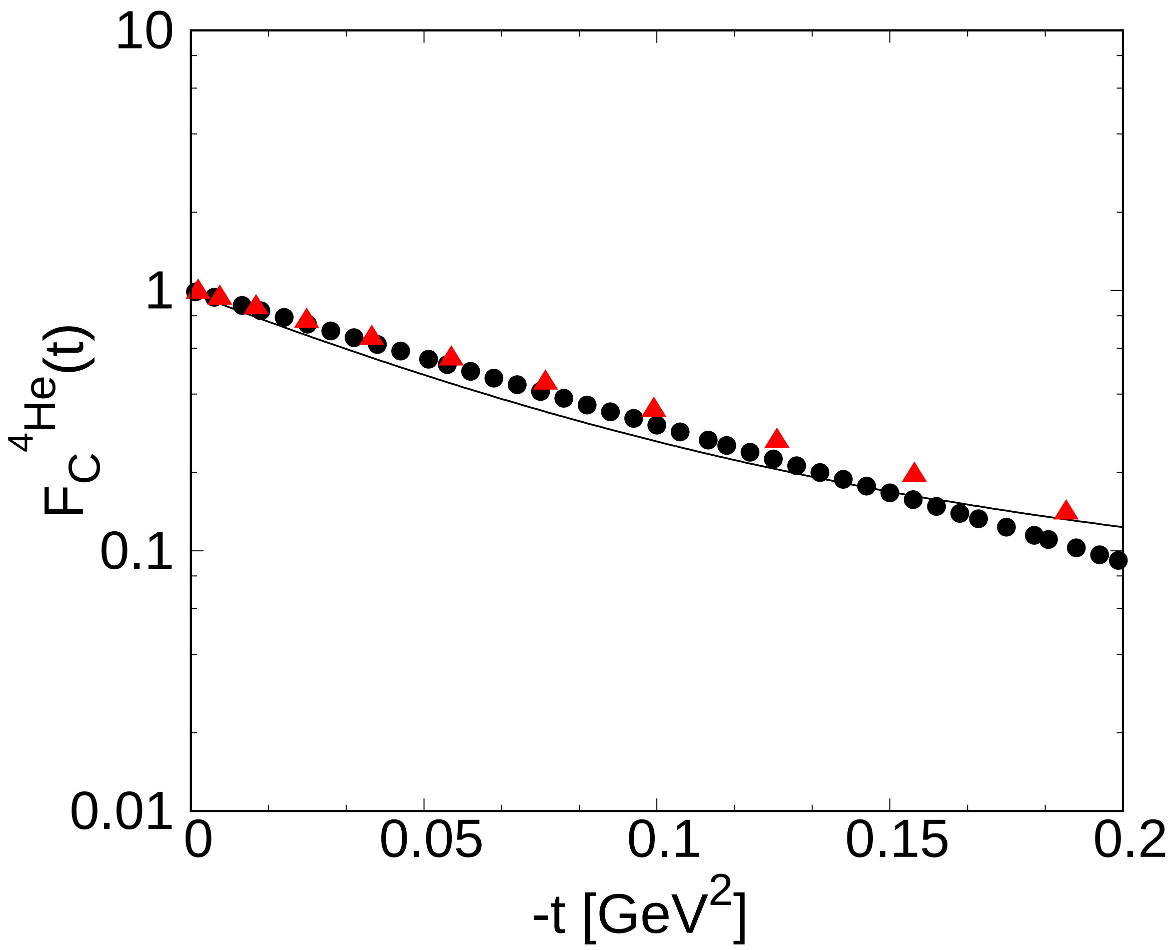
  For GPDs, shadowing (low x_B) stronger than for PDFs
  A. Freund and M. Strikman, PRC 69, 015203 (2004)...
  Exclusive $\phi-$ electroproduction, unique source of information, studied by ALERT, waiting for EIC...
- Deuteron: an issue aside.
  Extraction of the neutron information; access to a new class of distribution ($J = 1$)
  Studied by different collaborations (by ALERT too, coherent and incoherent DVCS)
  theory: Cano and Pire EPJA 19,423 (2004); Taneja et al. PRD 86,036008 (2012)...

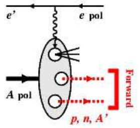
Backup: ^{4}He FF





Backup: ^{4}He FF - IA





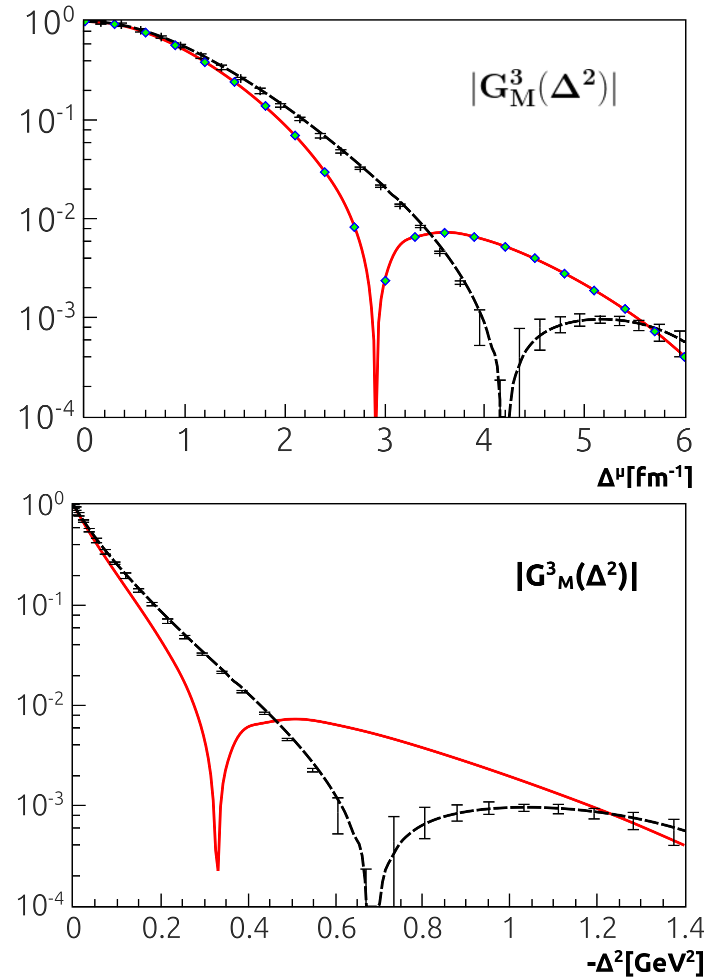
Backup: $\tilde{G}_M^{3,q}$ calculation: correct limits

For $\tilde{G}_M^{3}$ (**M. Rinaldi, S.S. PRC 85, 062201(R) (2012); PRC 87, 035208 (2013)**):

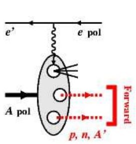
1 - Forward limit: no control on $E_q^3(x,0,0)$
no possible check;

2 - Magnetic F.F.:

$\sum_q \int dx\, \tilde{G}_M^{3,q}(x,\xi,\Delta^2) = G_M^3(\Delta^2)$



- in perfect agreement with previous IA, Av18 calculations (**L.E. Marcucci et al. PRC 58 (1998)**)
- in good agreement with data in the region relevant to the coherent process, $-\Delta^2 \ll 0.15$ GeV^2
- To have agreement at higher Δ^2, effects beyond IA are necessary: not important for the coherent channel!



Backup: Nuclear effects - the binding

General IA formula: $H_q^A(x,\xi,\Delta^2) \simeq \sum_N \int_x^1 \frac{dz}{z} h_N^A(z,\xi,\Delta^2) H_q^N\left(\frac{x}{z},\frac{\xi}{z},\Delta^2\right)$

where

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

$$P_N^3(\vec{p},\vec{p}+\vec{\Delta},E) = \bar{\sum}_M \sum_{s,f} \langle \vec{P}' M | \vec{P}_f, (\vec{p}+\vec{\Delta})s\rangle$$

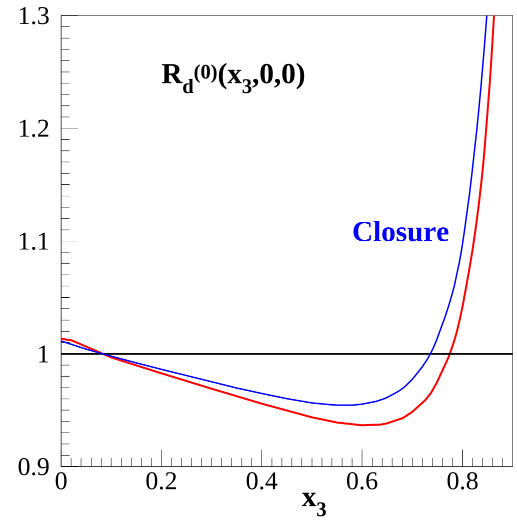
$$\times \langle \vec{P}_f, \vec{p}s | \vec{P} M\rangle\, \delta(E - E_{min} - E_f^*)$$

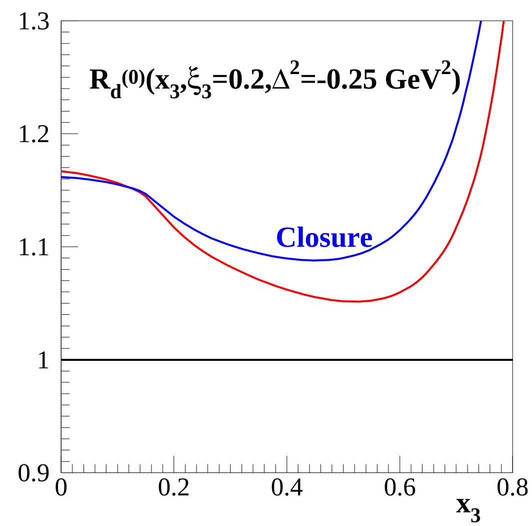
using the Closure Approximation, $E_f^* = \bar{E}$:

$$P_N^3(\vec{p},\vec{p}+\vec{\Delta},E) \simeq \bar{\sum}_M \sum_s \langle \vec{P}' M | a_{\vec{p}+\vec{\Delta},s}\, a^\dagger_{\vec{p},s} | \vec{P} M\rangle$$

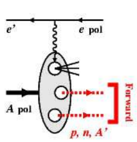
$$\delta(E - E_{min} - \bar{E}) =$$

$$= n(\vec{p},\vec{p}+\vec{\Delta})\,\delta(E - E_{min} - \bar{E})\ ,$$





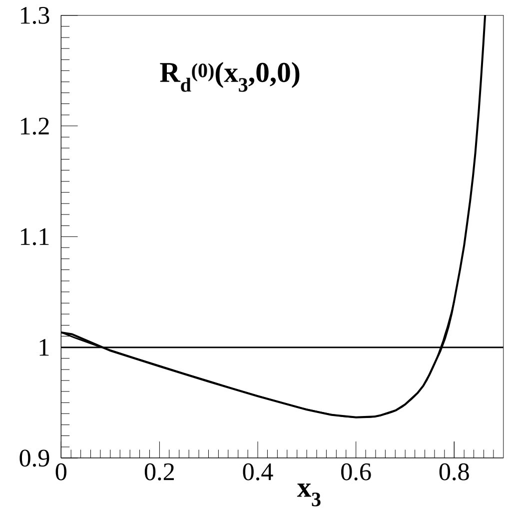
Spectral function substituted by a Momentum distribution (forward case in **C. Ciofi, S. Liuti PRC 41 (1990) 1100**)



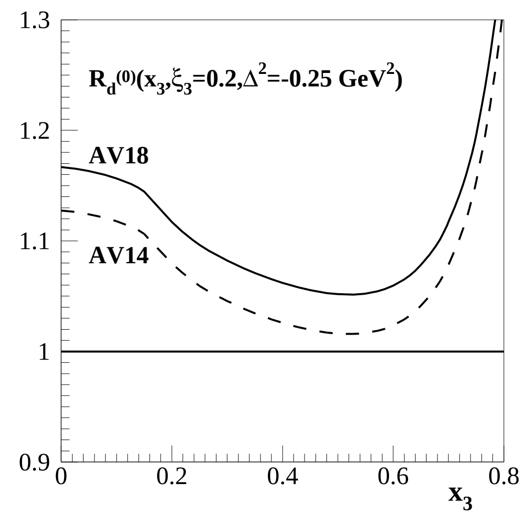
Backup: Dependence on the NN interaction

Nuclear effects are bigger than in the forward case: dependence on the potential

- Forward case: Calculations using the AV14 or AV18 interactions are indistinguishable

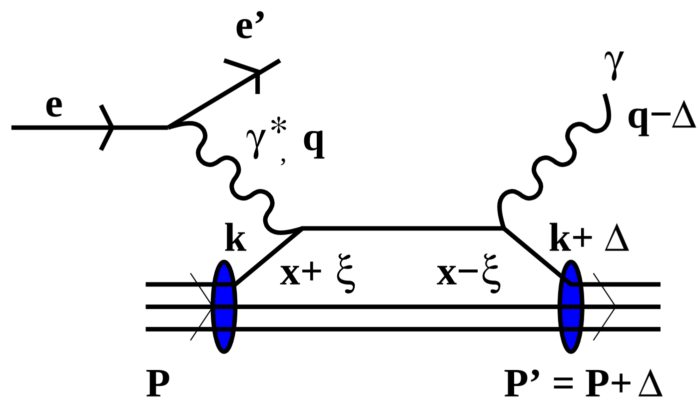


- Non-forward case: Calculations using the AV14 and AV18 interactions do differ:



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:

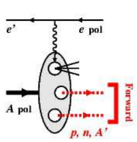


the GPDs $H_q(x,\xi,\Delta^2)$ and $E_q(x,\xi,\Delta^2)$ are introduced:

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

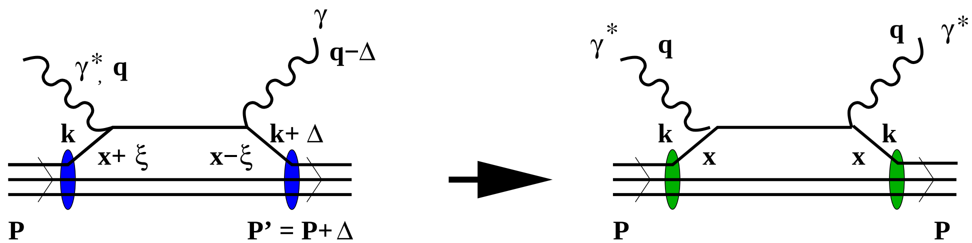
$$+ \quad E_q(x,\xi,\Delta^2) \bar{U}(P') \frac{i\sigma^{\mu\nu}\Delta_\nu}{2M} U(P) + ...$$

- $\Delta = P' - P$, $q^\mu = (q_0, \vec{q})$, 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: constraints

- 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)

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

$$\int dx\, H_q(x, \xi, \Delta^2) \bar{U}(P') \gamma^\mu U(P) + \int dx\, E_q(x, \xi, \Delta^2) \bar{U}(P') \frac{\sigma^{\mu\nu} \Delta_\nu}{2M} U(P) + ...$$

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

$\Longrightarrow$ Defining $\boxed{\tilde{G}_M^q = H_q + E_q}$ one has $\int dx\, \tilde{G}_M^q(x, \xi, \Delta^2) = G_M^q(\Delta^2)$