GPDs of (He) nuclei: nuclear effects and extraction of the neutron information

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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

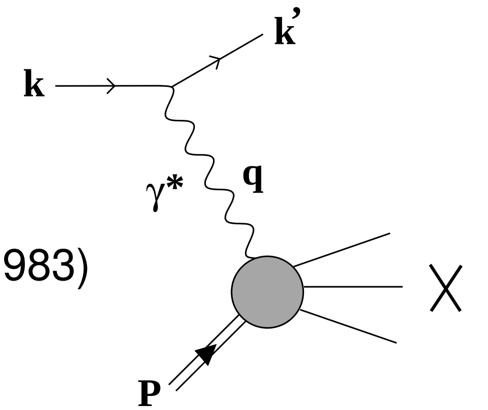
GPDs of light nuclei (deuteron aside):

- **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 al JLAB-12 and EIC;

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

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*

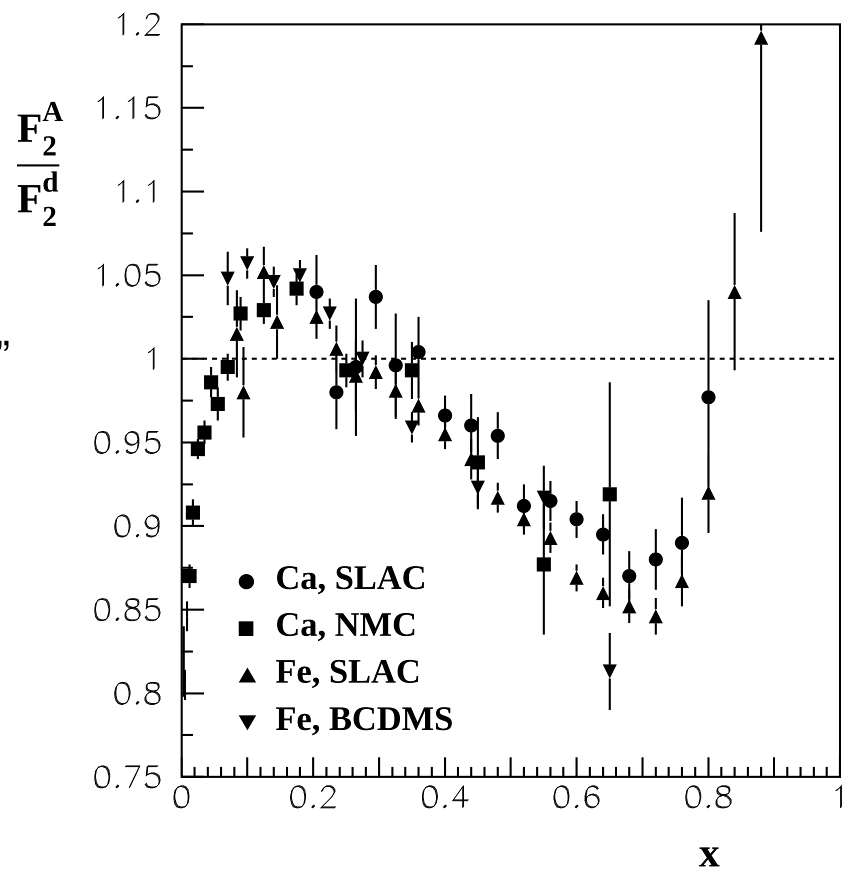
EMC effect in A-DIS



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

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

- $x \le 0.1$ "Shadowing region"
- $0.1 \le x \le 0.2$ "Enhancement region"
- $0.2 \le x \le 0.8$ "EMC (binding) region"
- $0.8 \le x \le 1$ "Fermi motion region"
- $x \ge 1$ "TERRA INCOGNITA"



EMC effect: explanations?

In general, with a few parameters any model explains the data:
EMC effect = "Everyone's Model is Cool" (G. Miller)

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

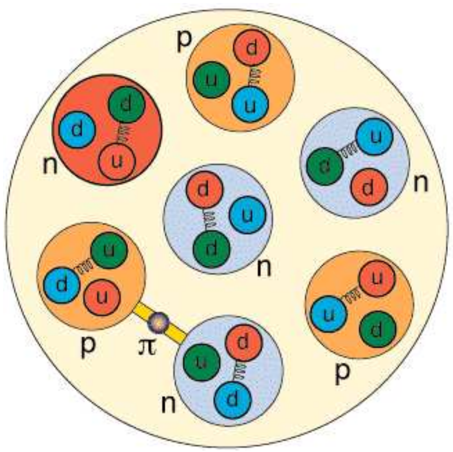
Inclusive measurements cannot distinguish between models

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?**



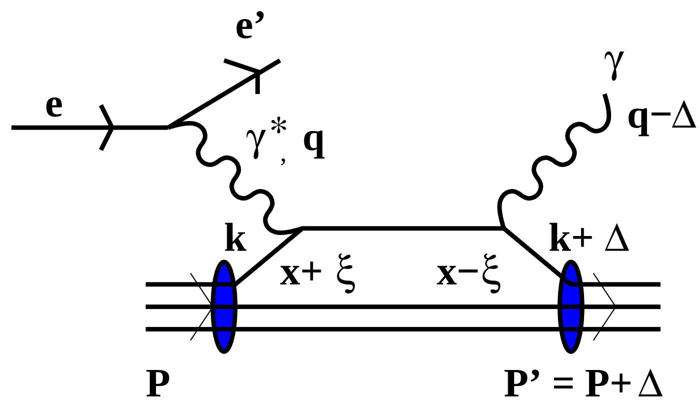
To answer, we should perform a *tomography...*

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

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

GPDs: 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:

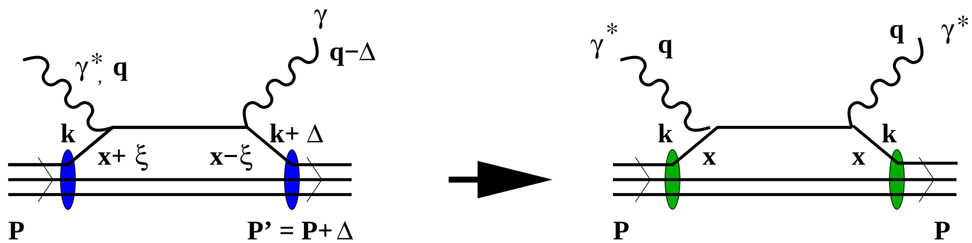
$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P' | \bar{\psi}_q(-\lambda n/2) \quad \gamma^\mu \quad \psi_q(\lambda n/2) | P \rangle = H_q(x, \xi, \Delta^2) \bar{U}(P') \gamma^\mu U(P)$$

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

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

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

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

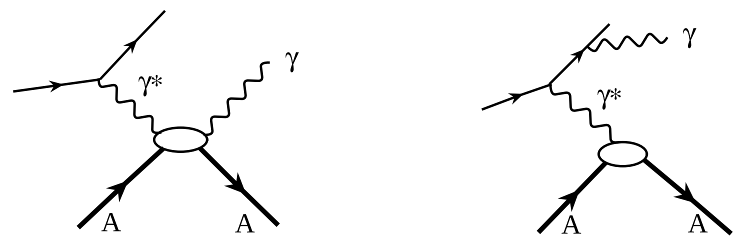
$$\Longrightarrow \int dx\, H_q(x,\xi,\Delta^2) = F_1^q(\Delta^2) \qquad \int dx\, E_q(x,\xi,\Delta^2) = F_2^q(\Delta^2)$$

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

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:

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

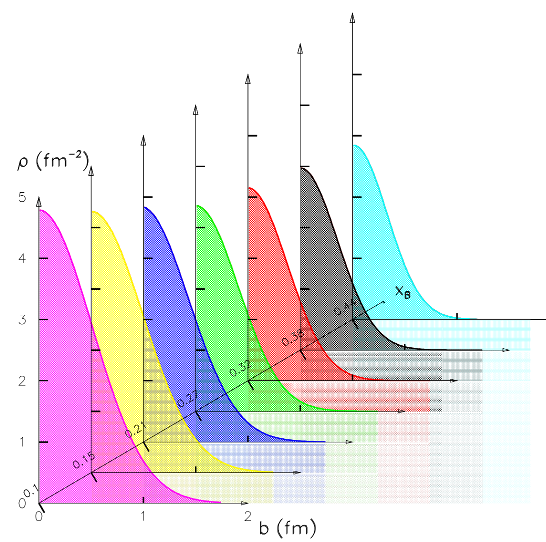
- Competition with the **BH** process! (σ asymmetries measured).

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

Nevertheless, for the proton, we have results:

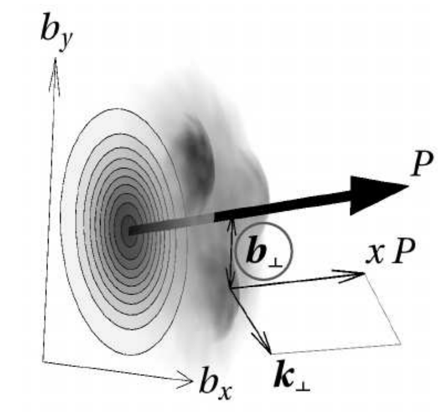
(Guidal et al., Rep. Prog. Phys. 2013...

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

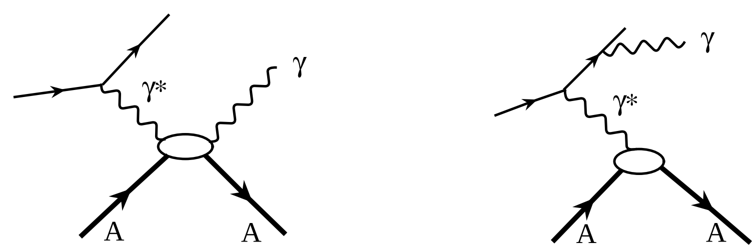


Nuclei and DVCS tomography

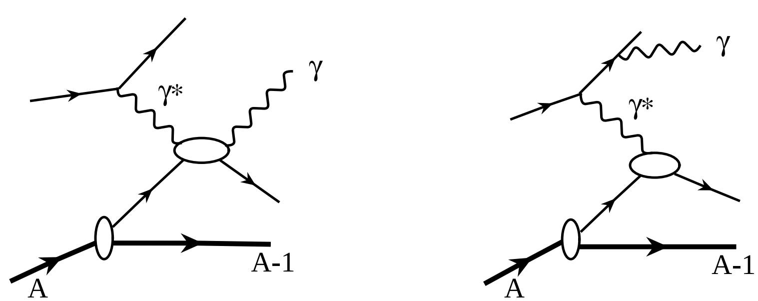
In impact parameter space, GPDs are *densities*:



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



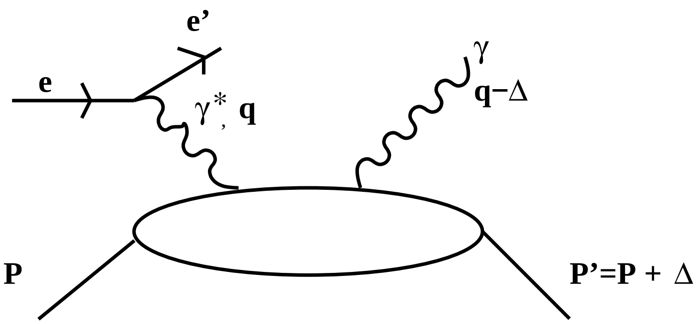
Coherent DVCS: nuclear tomography



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

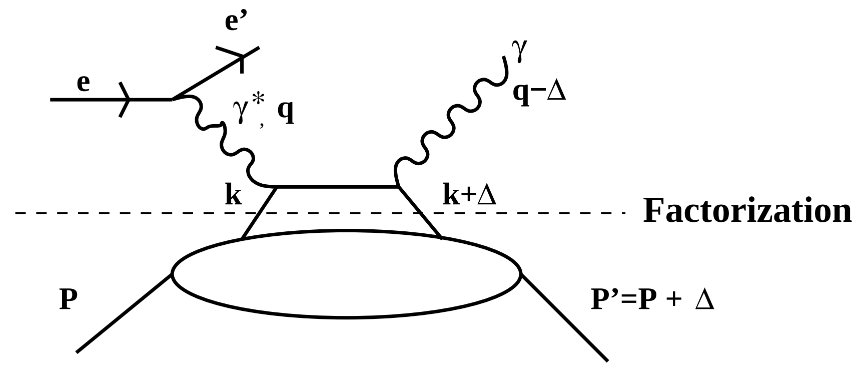
Nuclei: why? - not only tomography

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



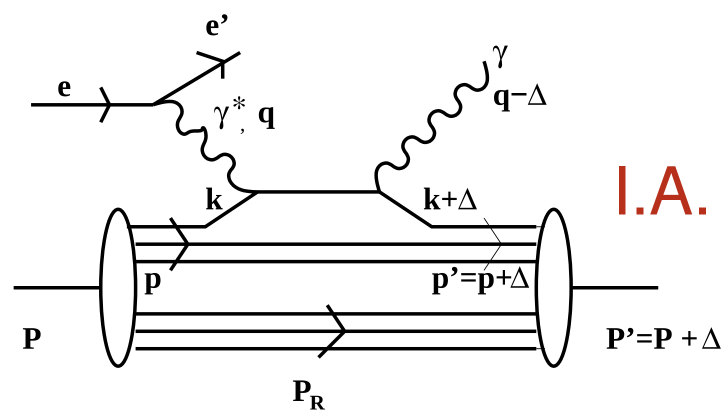
coherent DVCS

$\simeq$



handbag

$\simeq$



I.A.

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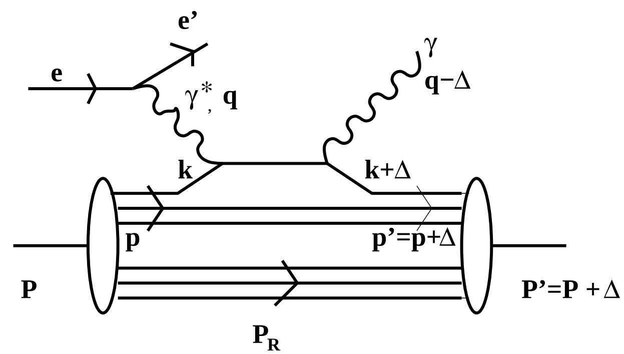

In a symmetric frame ($\bar{p} = (p + p')/2$) :

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

one has, for a given GPD

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

Nuclei: why? - not only tomography

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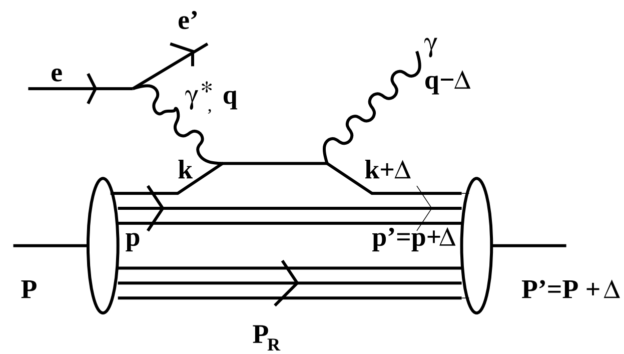

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$$

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

Nuclei: why? - not only tomography

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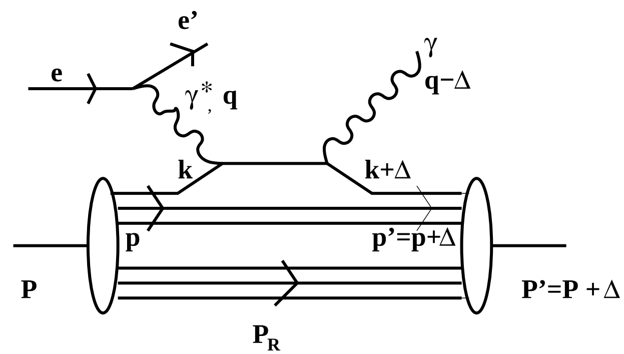

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$$
\begin{aligned}
GPD_q(x,\xi,\Delta^2) &= \int \frac{dz^-}{4\pi} e^{ix'\bar{p}^+ z^-} \langle P'S'| \sum_{\vec{P}'_R, S'_R, \vec{p}', s'} \{|P'_R S'_R\rangle |p's'\rangle\} \langle P'_R S'_R| \\
& \langle p's'|\, \hat{O}_q^+ \sum_{\vec{P}_R, S_R,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

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.:

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

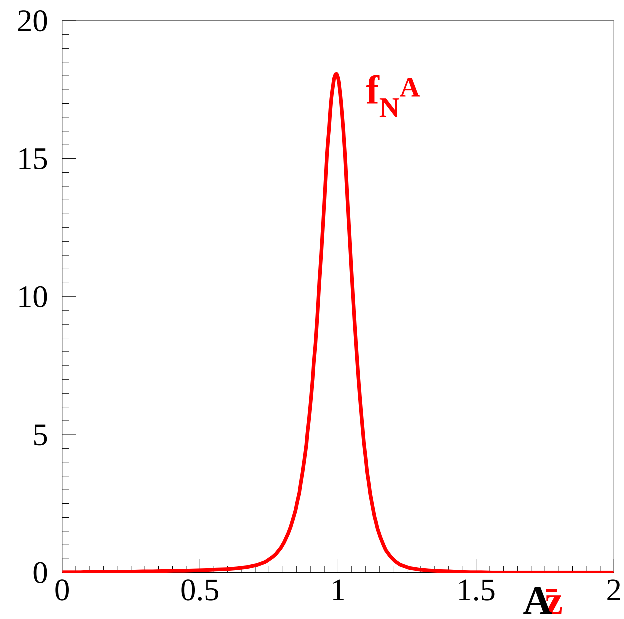
- forward limit (standard DIS):

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

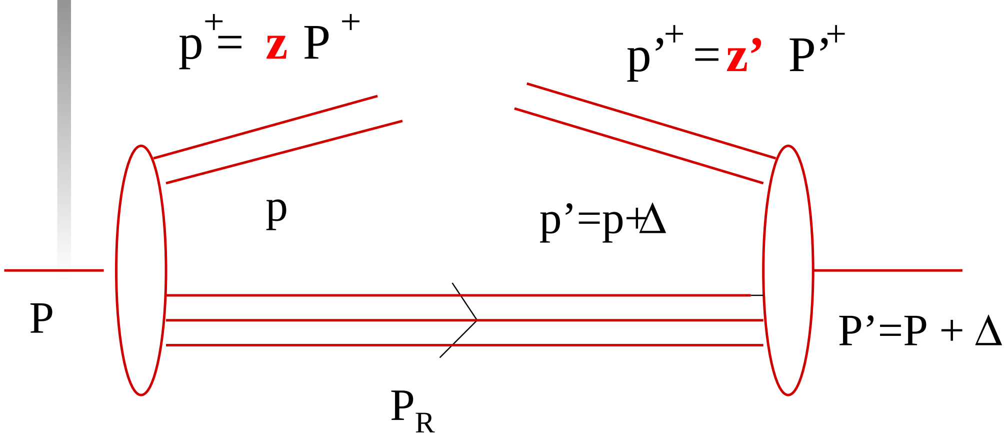
with the light-cone momentum distribution:

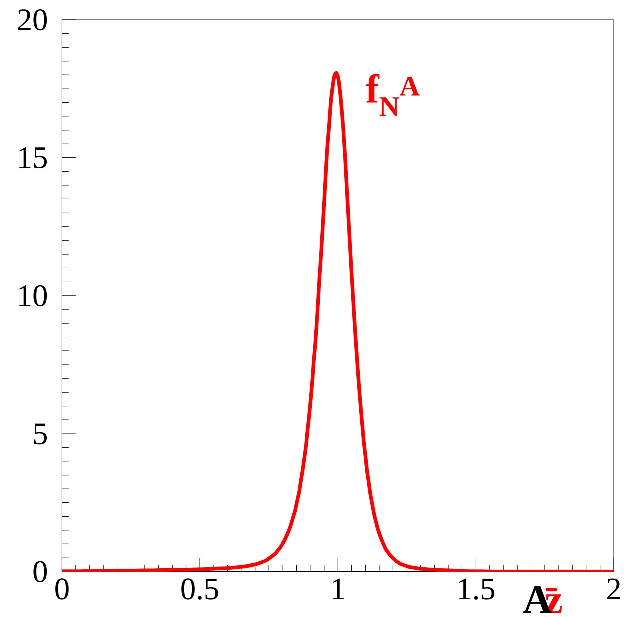
$f_N^A(\tilde{z}) = \int dE d\vec{p}\, P_N^A(\vec{p},E)\delta\left(\tilde{z} - \frac{p^+}{P^+}\right) \quad ,$

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



Why nuclei?





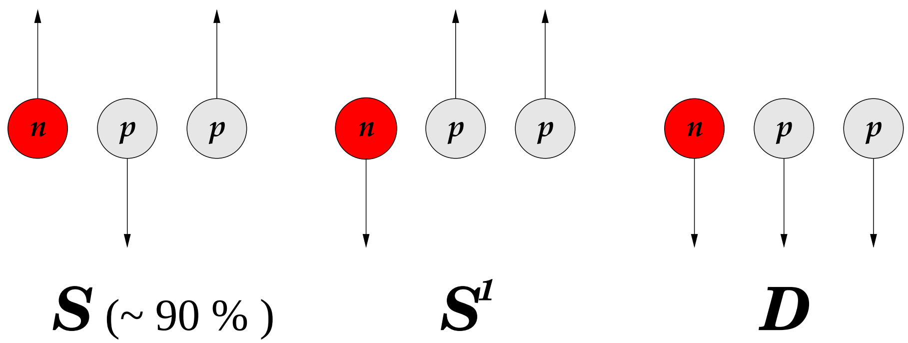
Since $z - z' = -x_B(1-z)/(1-x_B)\,,\qquad \xi \simeq x_B/(2-x_B)$ can be tuned to have $z - z'$ larger than the width of the narrow nuclear light-cone momentum distribution $f_N^A(\bar{z} = (z+z')/2)$: in this case IA predicts a $vanishing$ GPD, at $small\ x_B$.

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:

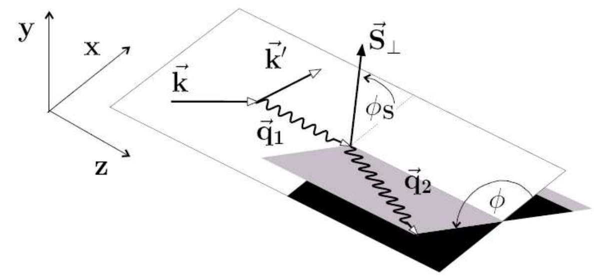


In $S-$wave
$^3\vec{He} = \vec{n}$!

^{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**
  * **heavier targets do not allow refined theoretical treatments. Test of the theory**
  * **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,

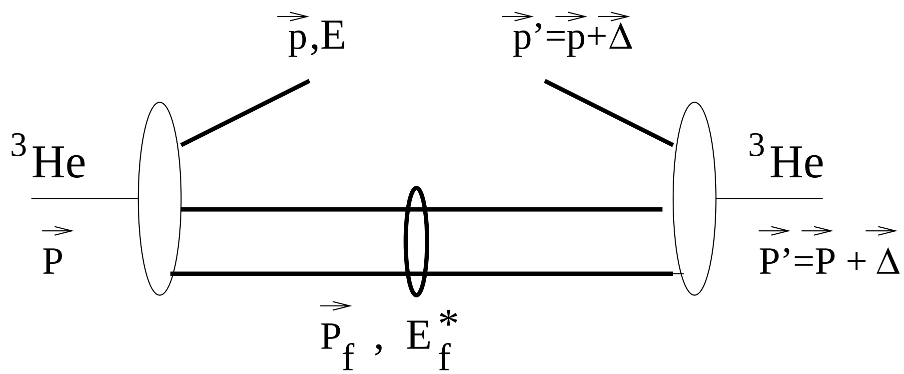
$$P^N_{SS',ss'}(\vec{p},\vec{p}\,',E) = \frac{1}{(2\pi)^6}\frac{M\sqrt{ME}}{2}\int d\Omega_t \sum_{s_t} \langle \vec{P}'S'|\vec{p}\,'s',\vec{t}s_t\rangle_N \langle \vec{p}s,\vec{t}s_t|\vec{P}S\rangle_N \,,$$

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)

A few words about $P_N^3(\vec{p}, \vec{p} + \vec{\Delta}, E)$:

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

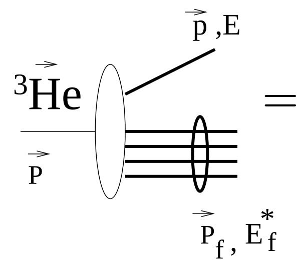


- the two-body recoiling system can be either the deuteron or a scattering state;
- when a deeply bound nucleon, with high removal energy $E = E_{min} + E_f^*$, leaves the nucleus, the recoling system is left with high excitation energy E_f^* ;
- the three-body bound state and the two-body bound or scattering state are evaluated within the same (Av18) interaction: the extension of the treatment to heavier nuclei is extremely difficult

Nucleon off-shellness in I.A. :

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

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



$\Bigg|^2$

↙ 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 and momentum sum rules not fulfilled at the same time

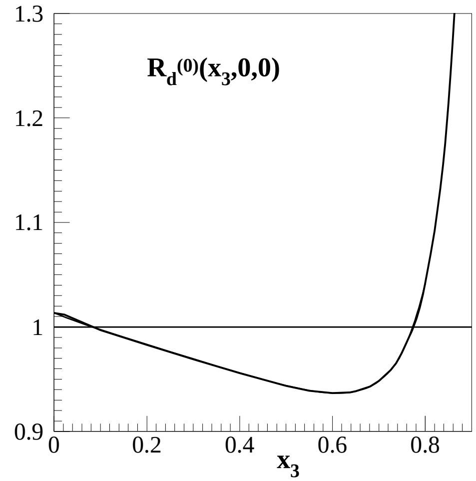
The calculation has the correct limits:

1 - Forward limit: the ratio:

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

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

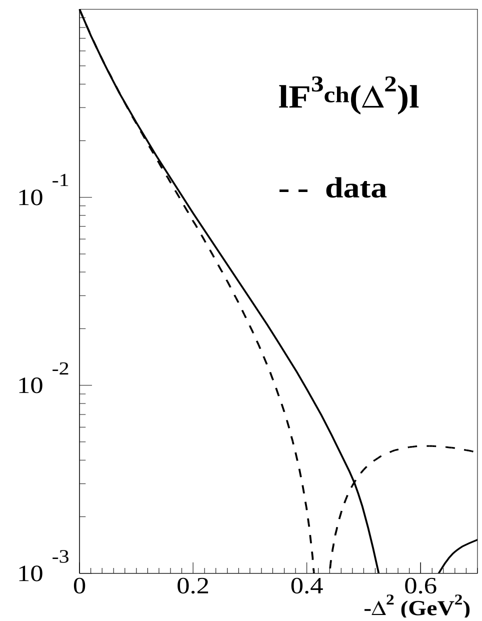
shows an EMC-like behavior;



2 - Charge F.F.:

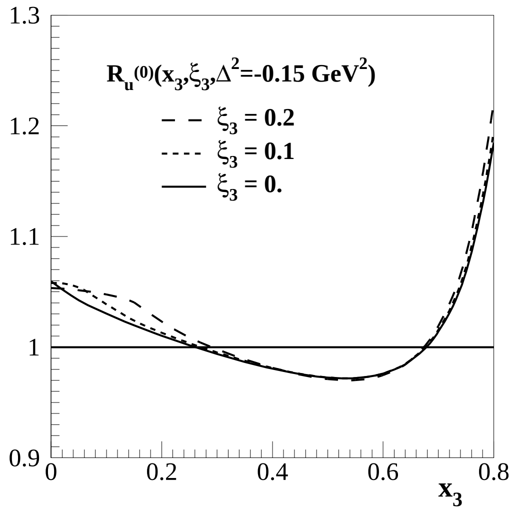
$$\sum_q e_q \int dx H_q^3(x,\xi,\Delta^2) = F^3(\Delta^2)$$

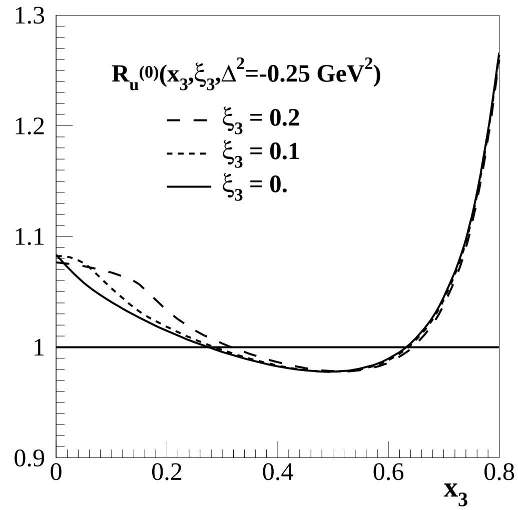
in good agreement with data in the region relevant to the coherent process, $-\Delta^2 \leq 0.2$ GeV^2.



Nuclear effects - general features

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





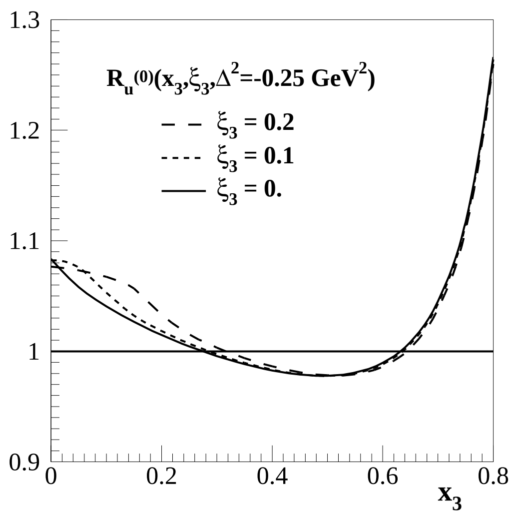
$$R_q^{(0)}(x,\xi,\Delta^2) = \frac{H_q^3(x,\xi,\Delta^2)}{2H_q^{3,p}(x,\xi,\Delta^2) + H_q^{3,n}(x,\xi,\Delta^2)}$$

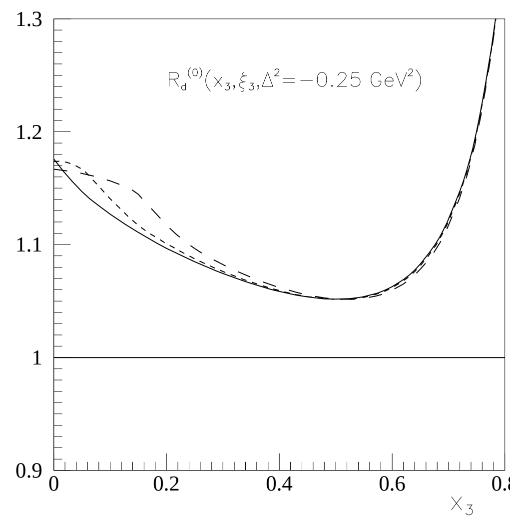
$$H_q^{3,N}(x,\xi,\Delta^2) = \tilde{H}_q^N(x,\xi)F_q^3(\Delta^2)$$

$R_q^{(0)}(x,\xi,\Delta^2)$ 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:





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

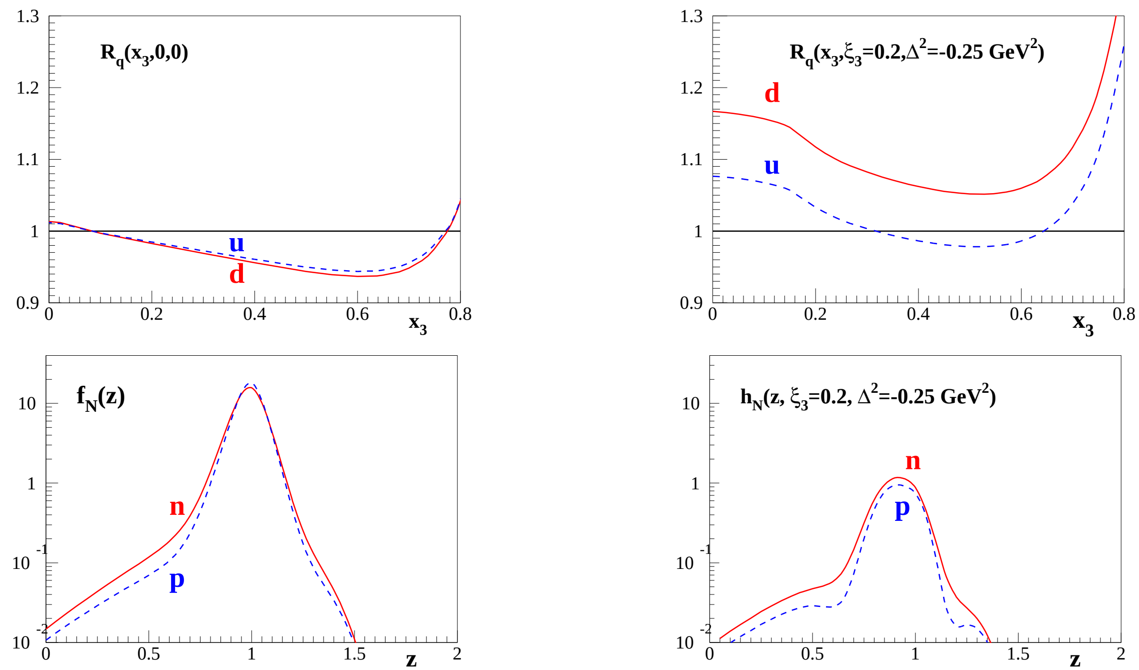
$$H_q^{3,N}(x,\xi,\Delta^2) = \tilde{H}_q^N(x,\xi)F_q^3(\Delta^2)$$

$R_q^{(0)}(x,\xi,\Delta^2)$ 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:

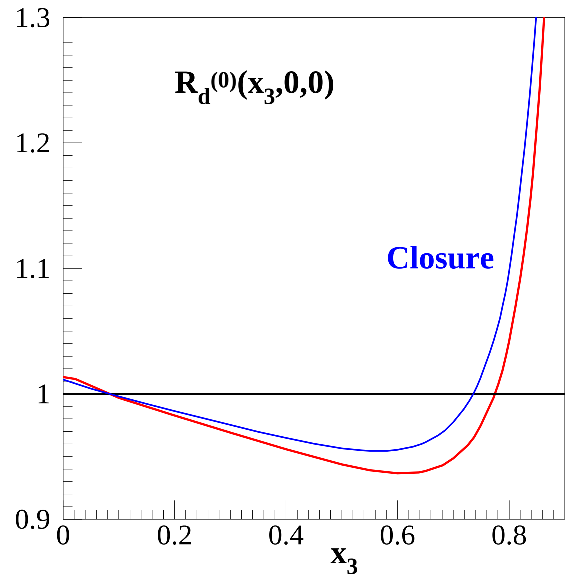


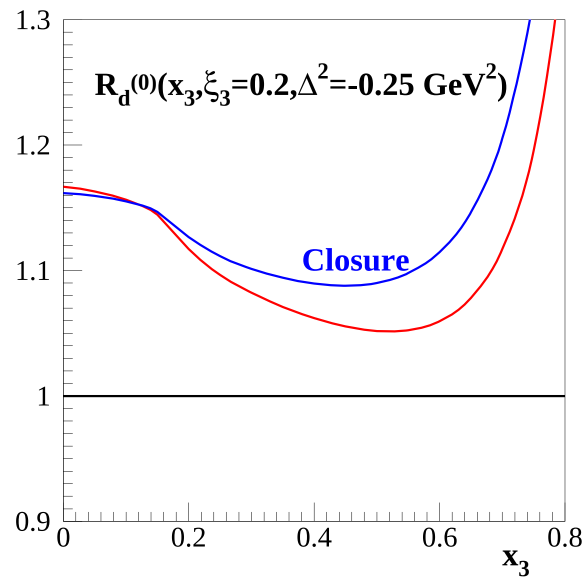
- How to perform a flavor separation? Take the triton ^{3}H !
  Possible (see MARATHON@JLab). Possible for DVCS (ALERT).
  Studied in **S.S. Phys. Rev. C 79 (2009) 025207**
  $H_t, H_H \to H_u^H \simeq H_d^t, H_d^H \simeq H_u^t$ in the valence region...

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.

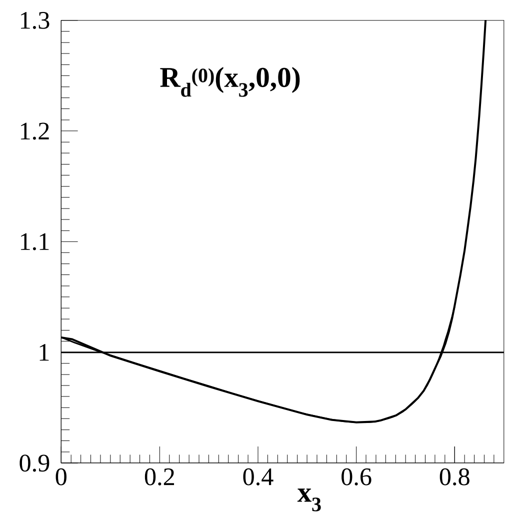




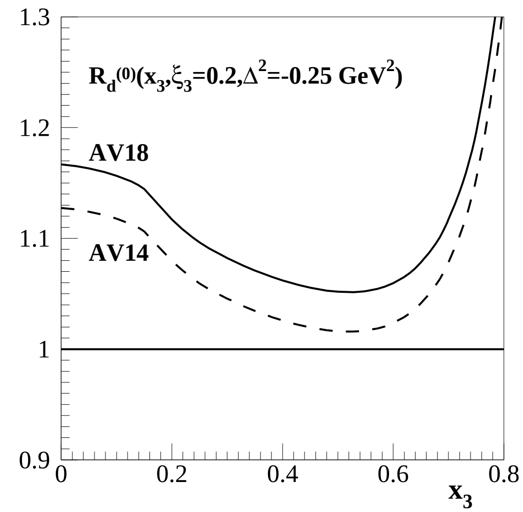
Dependence on the NN interaction

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

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



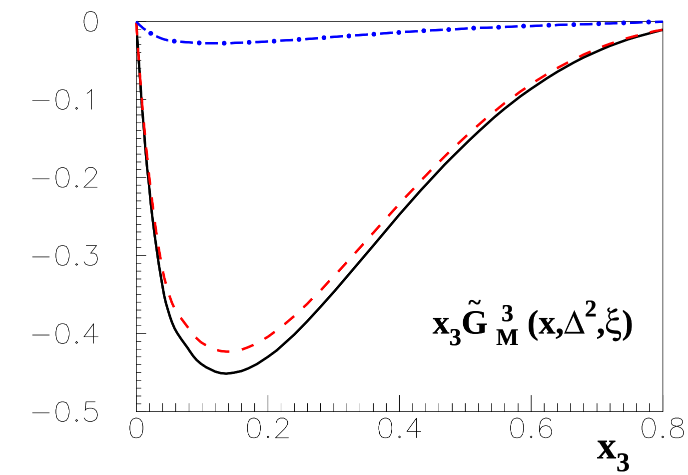
- Non-forward case: Calculations using the AV14 and AV18 interactions do differ:



$\tilde{G}_M^{3,q}$: proton and neutron contributions

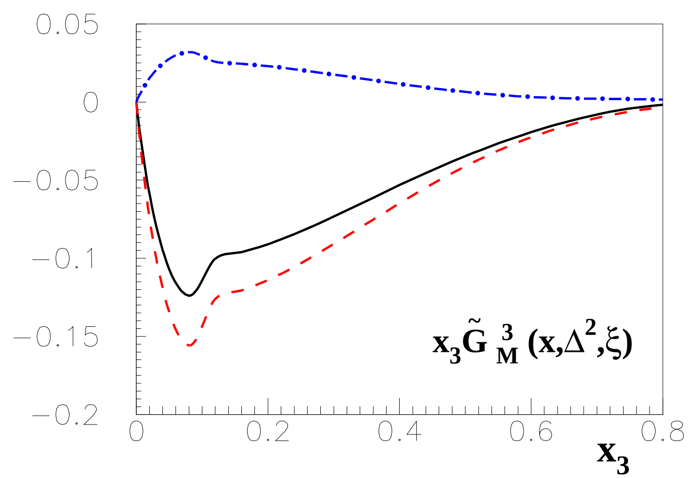
1 - Forward limit, $\Delta^2 = 0$, $\xi = 0$:

As we hoped, the neutron contribution to ^{3}He largely dominates!
($x_3 = (M_A/M)x \simeq 3x$):
The proton contribution to ^{3}He is almost negligible!



2 - Non-forward, $\Delta^2 = -0.1$ GeV^2, $\xi = 0.1$:

The neutron contribution to ^{3}He still dominates
The proton contribution to ^{3}He gets sizable



How to get the neutron information?

Extracting the neutron - I:

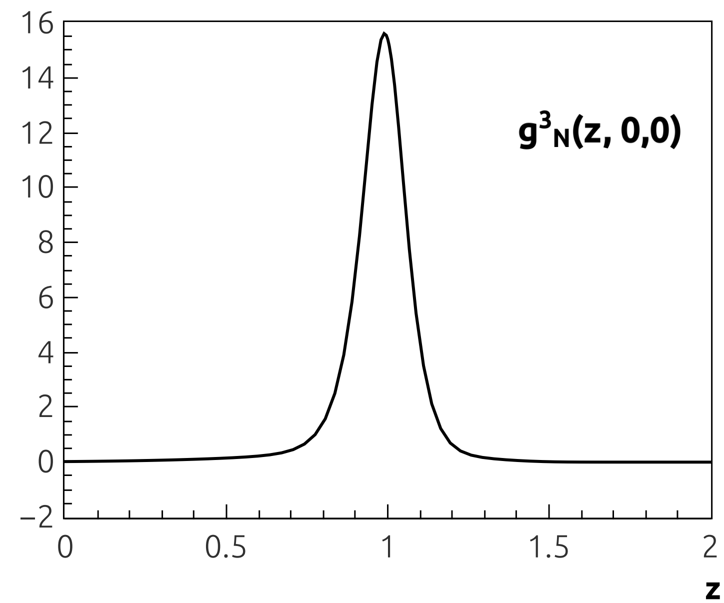
The convolution formula can be written as

$$\tilde{G}_M^{3,q}(x_3, \Delta^2, \xi) = \sum_N \int_{x_3}^{\frac{M_A}{M}} \frac{dz}{z} g_N^3(z, \Delta^2, \xi) \tilde{G}_M^{N,q}\left(\frac{x_3}{z}, \Delta^2, \frac{\xi}{z},\right) ,$$

where $g_N^3(z, \Delta^2, \xi)$ is a “light cone off-forward momentum distribution” and, since close to the forward limit it is strongly peaked around $z = 1$

$$g_N^3(z, \Delta^2, \xi) = \int dE \int d\vec{p}\, \tilde{P}_N^3(\vec{p}, \vec{p} + \vec{\Delta}, E)$$

$$\delta\left(z + \xi - \frac{M_A}{M}\frac{p^+}{\bar{P}^+}\right)$$



Extracting the neutron - I:

The convolution formula can be written as

$$\tilde{G}_M^{3,q}(x_3, \Delta^2, \xi) = \sum_N \int_{x_3}^{\frac{M_A}{M}} \frac{dz}{z} g_N^3(z, \Delta^2, \xi) \tilde{G}_M^{N,q}\left(\frac{x_3}{z}, \Delta^2, \frac{\xi}{z}, \right) ,$$

where $g_N^3(z, \Delta^2, \xi)$ is a “light cone off-forward momentum distribution” and, since close to the forward limit it is strongly peaked around $z = 1$

$$\begin{aligned} \tilde{G}_M^{3,q}(x_3, \Delta^2, \xi) \quad &\simeq \quad low\,\Delta^2 \simeq \sum_N \tilde{G}_M^{N,q}\left(x_3, \Delta^2, \xi\right) \int_0^{\frac{M_A}{M}} dz g_N^3(z, \Delta^2, \xi) \\ &= \quad G_M^{3,p,point}(\Delta^2) \tilde{G}_M^p(x_3, \Delta^2, \xi) + G_M^{3,n,point}(\Delta^2) \tilde{G}_M^n(x_3, \Delta^2, \xi) \,. \end{aligned}$$

where, at $x_3 < 0.7$, the magnetic point like ff has been introduced

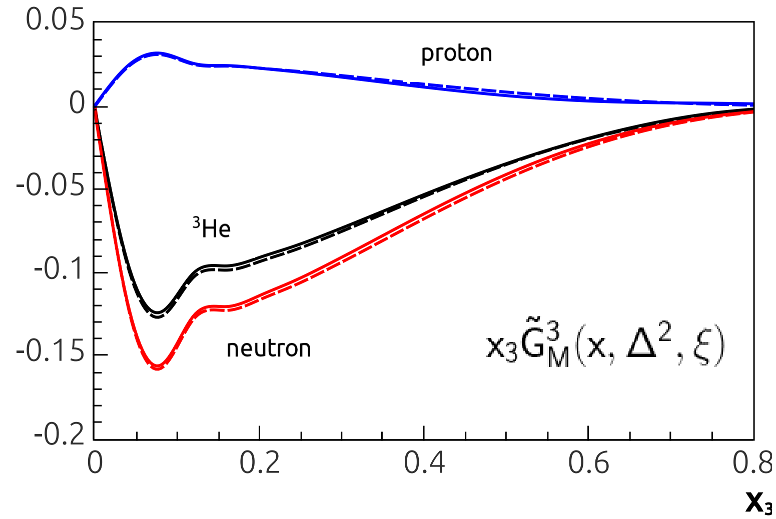
$$G_M^{3,N,point}(\Delta^2) = \int dE \int d\vec{p}\, \tilde{P}_N^3(\vec{p}, \vec{p} + \vec{\Delta}, E) = \int_0^{\frac{M_A}{M}} dz\, g_N^3(z, \Delta^2, \xi) \,.$$

Extracting the neutron - II:

Validity of the approximated formula:

full: IA calculation, $\tilde{G}^3_M(x, \Delta^2, \xi)$ and proton and neutron contributions to it, at $\Delta^2 = -0.1$ GeV^2, $\xi = 0.1$;

dashed: same quantities, with the approximated formula:



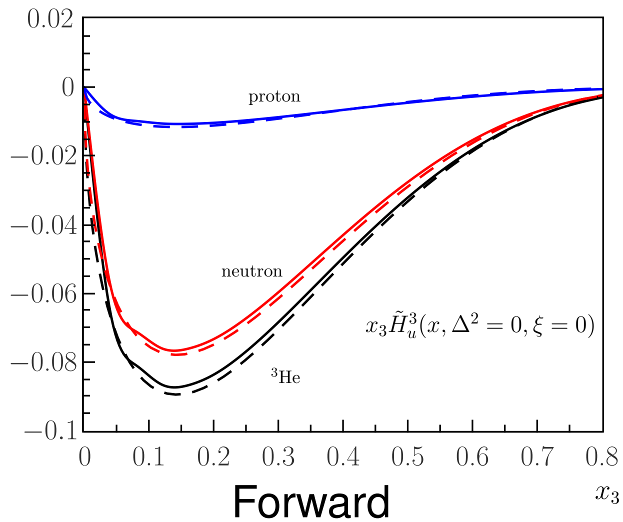
$$\tilde{G}^{3,q}_M(x, \Delta^2, \xi) \simeq G^{3,p,point}_M(\Delta^2)\tilde{G}^p_M(x, \Delta^2, \xi) + G^{3,n,point}_M(\Delta^2)\tilde{G}^n_M(x, \Delta^2, \xi)$$

Impressive agreement! The only Nuclear Physics ingredient in the approximated formula is the magnetic point like ff, which is under good theoretical control:

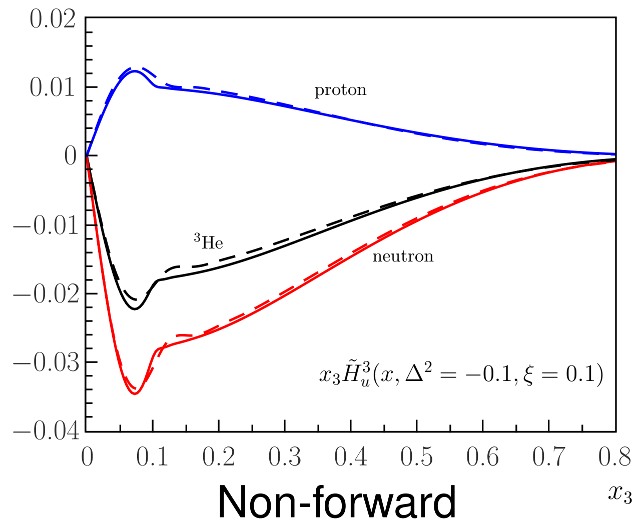
Δ^2 [GeV^2]	$G^{3,p,point}_M$ Av18	$G^{3,p,point}_M$ Av14	$G^{3,n,point}_M$ Av18	$G^{3,n,point}_M$ Av14
0	-0.044	-0.049	0.879	0.874
-0.1	0.040	0.038	0.305	0.297
-0.2	0.036	0.035	0.125	0.119

The GPD $\tilde{H}$: M. Rinaldi, S.S, Few-Body Systems 55, 861 (2014)

$\tilde{H}^{3,u}(x,\Delta^2,\xi)$ and proton and (dominant!) neutron contributions to it:



Forward



Non-forward

full: IA calculation; dashed: approximated formula:

$$\tilde{H}^{3,u}(x,\Delta^2,\xi) \simeq g_A^{3,p,point}(\Delta^2)\tilde{H}^{p,u}(x,\Delta^2,\xi) + g_A^{3,n,point}(\Delta^2)\tilde{H}^{n,u}(x,\Delta^2,\xi)$$

Good agreement! The only Nuclear Physics ingredient in the approximated formula is the axial point like ff, which is under good theoretical control.
One has $g_A^{3,N,point}(\Delta^2=0)=p_N$, nucleon effective polarizations (within AV18, $p_n=0.878$, $p_p=-0.024$), used in DIS for extracting the neutron information from ^{3}He (**C. Ciofi, S.S., E. Pace and G. Salmè, PRC 48 R968 (1993)**). Forward limit recovered!

$^3\vec{He}$ & $^3\vec{H}$ at the EIC

From $^3\vec{He}$, neutron spin-dependent information I^n ($I^n = g_1^n, I^n_{GDH}, \tilde{H}^n$...) is extracted using the free proton I^p according to (motivated within the IA)

$$I^n = \frac{1}{p_n}\left(I^{^3He} - 2p_p I^p\right) \qquad (1)$$

If one could use $^3\vec{H}$, the $proton$ I^p would be at hand:

$$I^p = \frac{1}{p_n}\left(I^{^3H} - 2p_p I^n\right) \qquad (2)$$

where $p_p = p_p^{^3He} = p_n^{^3H}$ and $p_n = p_n^{^3He} = p_p^{^3H}$ (Isospin symmetry assumed).

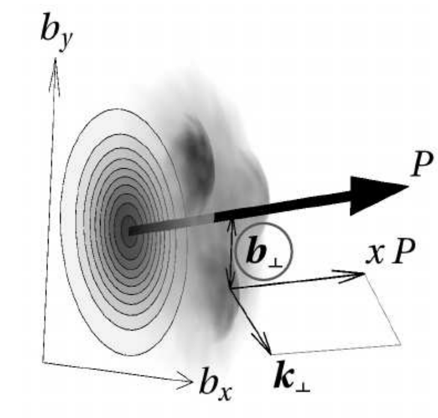
From Eqs. (1) and (2), I^n and I^p would be extracted from the measured $I^{^3He}$ and $I^{^3H}$, using $p_{p,n}$ as the only theoretical input.
The extraction does not require the knowledge of $I^{n,p}$ from other experiments!

If I^p extracted using Eq. (2) compared well with that of *free* protons, one could assume that the extraction procedure works and that I^n from $I^{^3He}$, Eq. (1), can be trusted; if not, interesting effects beyond IA, such as the effect of Δ's **(Frankfurt, Guzey, Strikman PLB 281, 379 (1996))**, would be exposed.

^{3}He calculations: summary

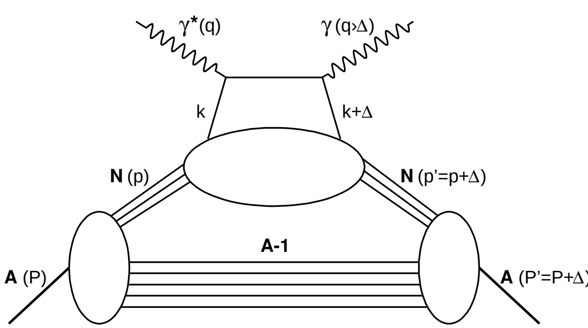
- Our results, for ^{3}**He: (S.S. PRC 2004, 2009; M. Rinaldi and S.S., PRC 2012, 2013)**
  - * I.A. calculation of $H_3, E_3, \tilde{H}_3$, within AV18;
  - * Interesting predictions: strong sensitivity to details of nuclear dynamics:
  - * extraction procedure of the neutron information, able to take 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.

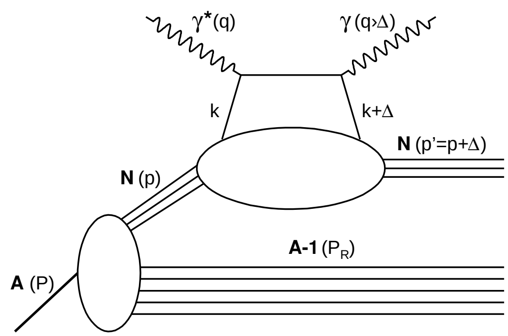
Data on nuclear DVCS



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 (in IA):
nuclear tomography;

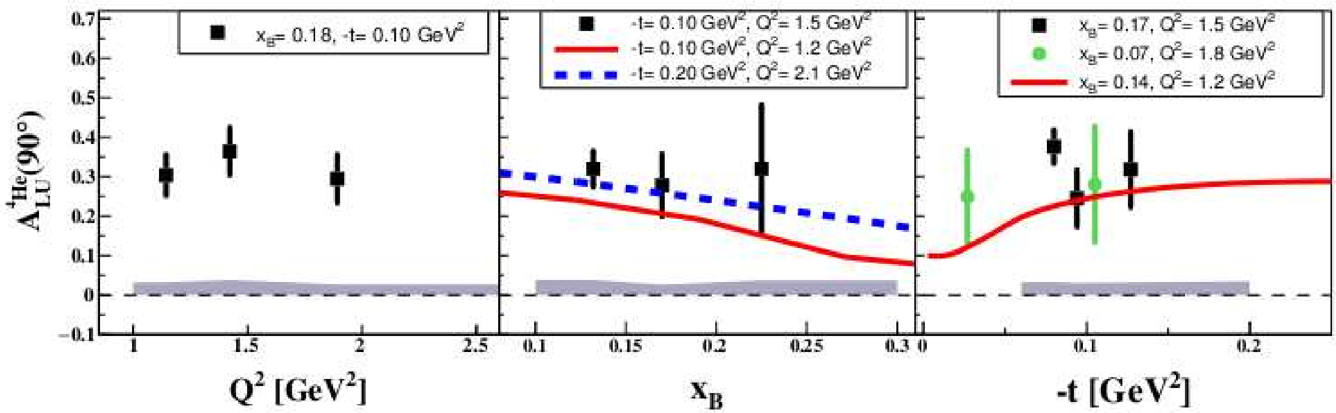
Incoherent DVCS (in IA):
tomography of bound nucleons:
realization of the EMC effect

- 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! recently released from EG6@CLAS

(M. Hattawy et al, PRL 119, 202004 (2017))

Coherent data (incoherent will follow) of DVCS off ^{4}He:



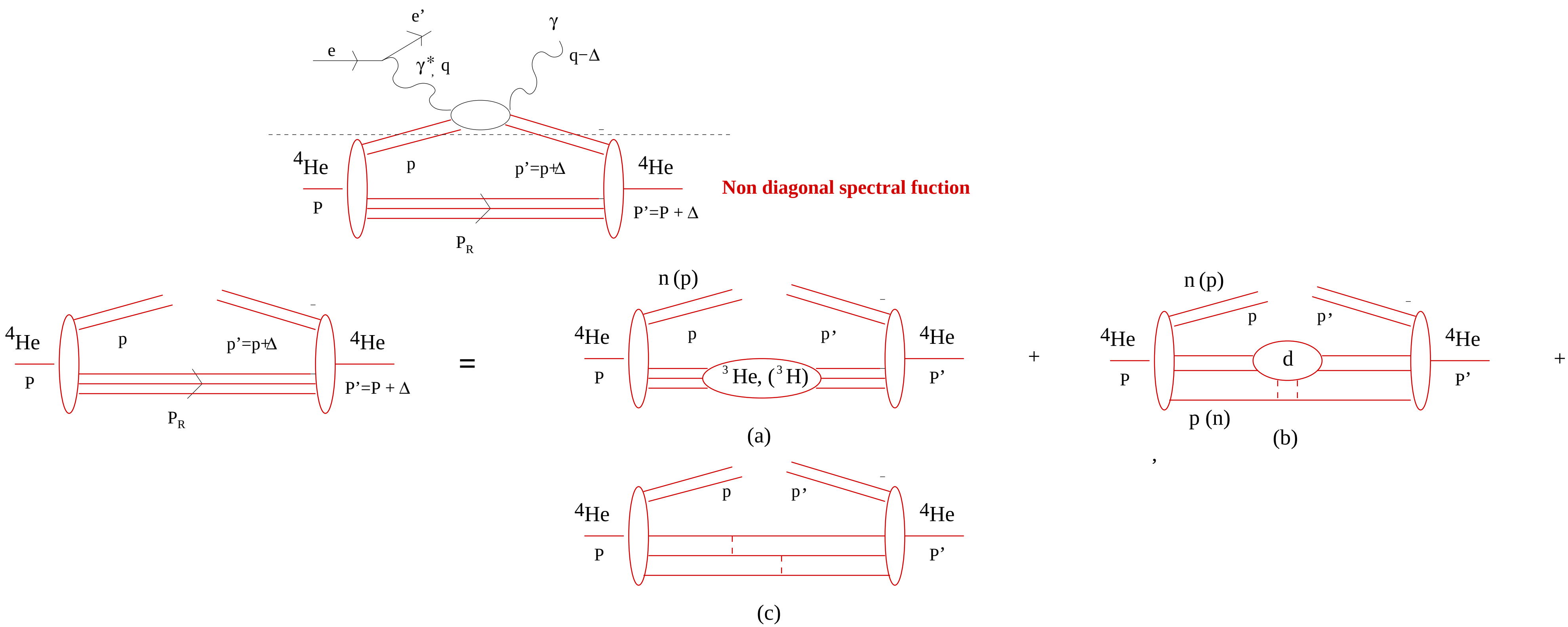
* "off-shell model" by Gonzalez, Liuti, Goldstein, Kathuria (**PRC 88, 065206 (2013)**)

* Relevant calculations by Guzey & Strikman (not shown here) (**PRC 78, 025211 (2008)**)

- ^{4}He: $J=0, I=0$, easy $formal$ description (1 chiral-even twist-2 GPD); but a true nucleus (deeply bound, dense...)
- Next generation of experiments (ALERT run-group), just approved (A-rate), will distinguish models: precisely what is needed to understand nuclei at parton level!
- Good prospects for the EIC at low x_B, easy recoil detection...

DVCS off ^{4}He

- CLAS data demonstrate that measurements are possible, separating coherent and incoherent channels;
- Realistic microscopic calculations are necessary. A collaboration is going on with Sara Fucini (Perugia, graduate student), Michele Viviani (INFN Pisa).
- **Coherent channel in IA:**



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:

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

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

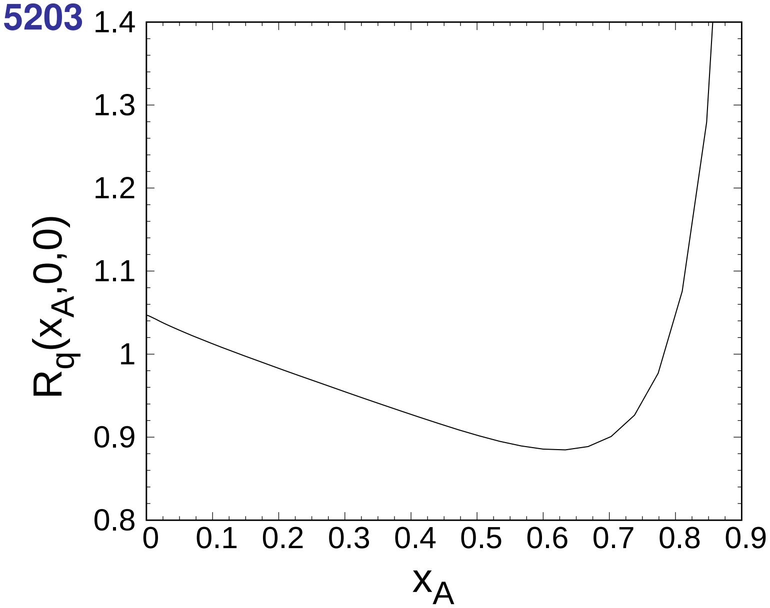
S.Fucini, SS., M. Viviani PRC 98 (2018) 015203

1 - Forward limit: the ratio:

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

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

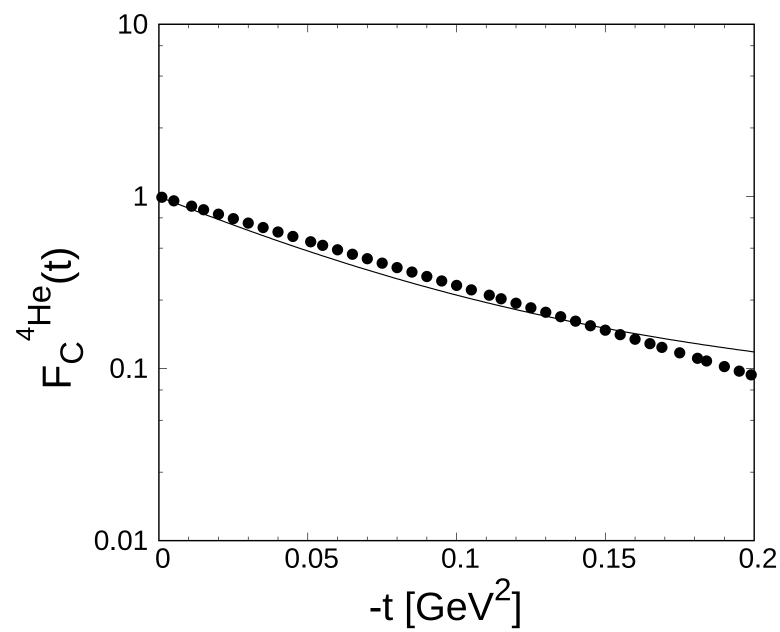
shows an EMC-like behavior;



2 - Charge F.F.:

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

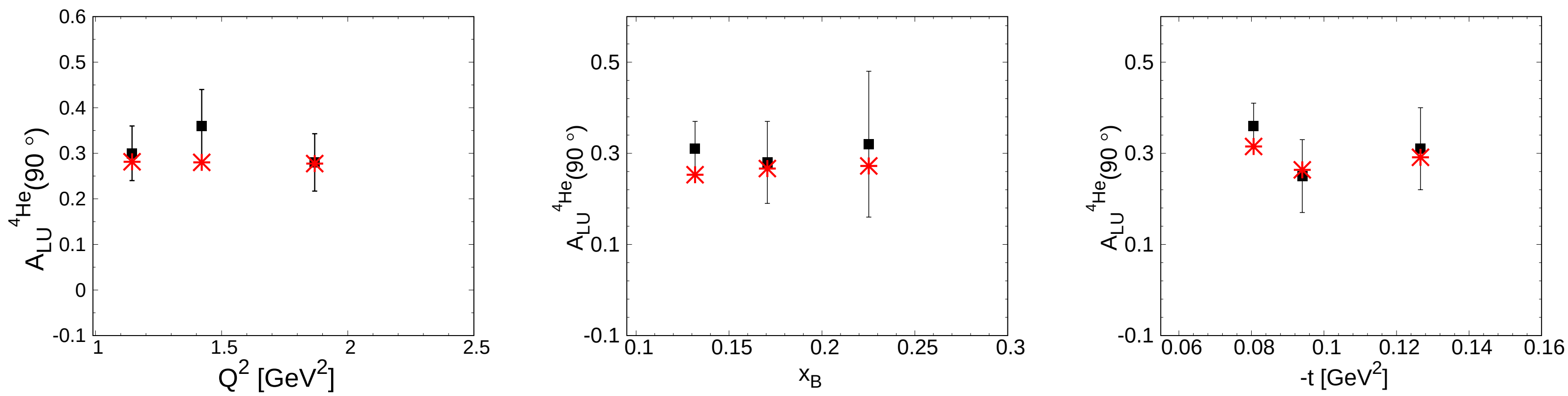
reasonable agreement with data in the region relevant to the coherent process, $-t = -\Delta^2 \leq 0.2$ GeV^2.



Comparison with EG6 data: A_{LU}

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

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



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

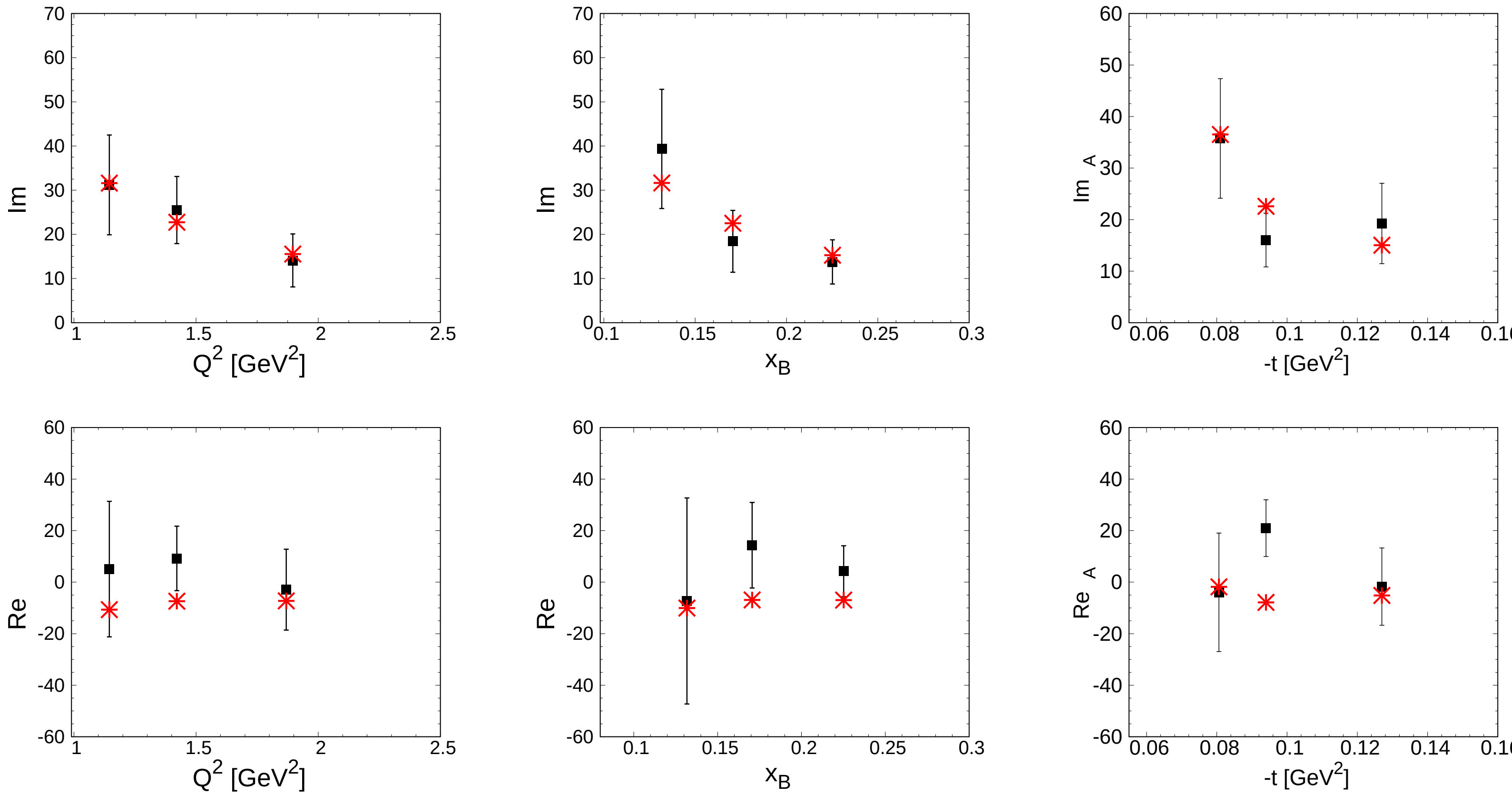
From left to right, the quantity is shown in the experimental Q^2, x_B and t bins, respectively: very good agreement

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

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



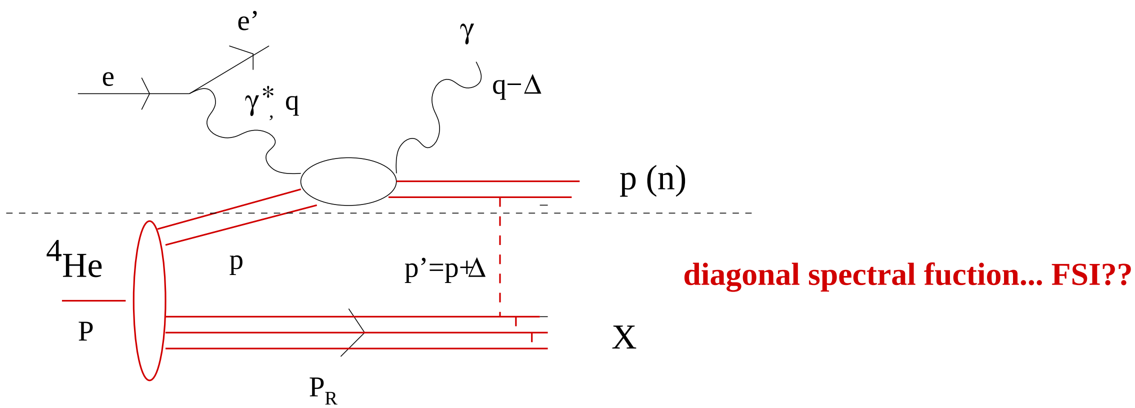
$$\Im m(\mathcal{H}_A) \quad = \quad H_A(\xi,\xi,t) - H_A(-\xi,\xi,t),$$

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

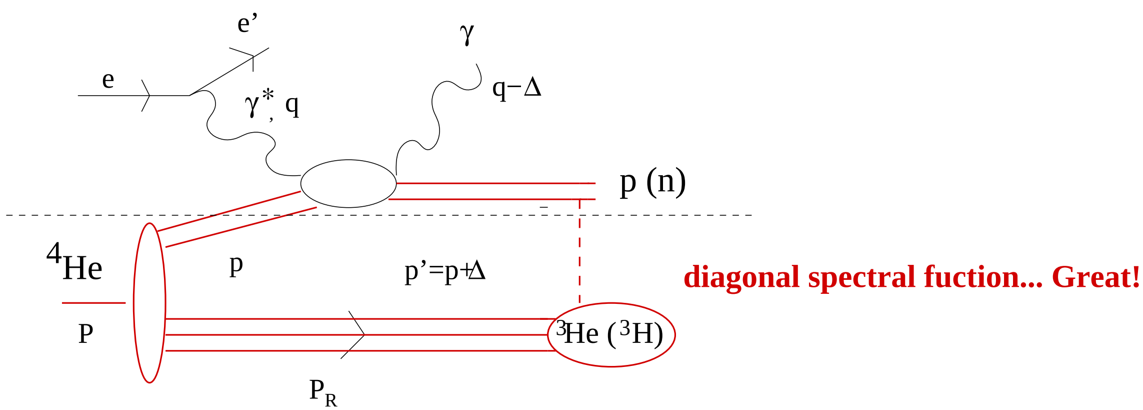
Very good agreement for $\Im m(\mathcal{H}_A)$, good agreement for $\Re e(\mathcal{H}_A)$
(data weakly sensitive to $\Re e(\mathcal{H}_A)$)

Incoherent DVCS off ^{4}He in IA

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



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



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

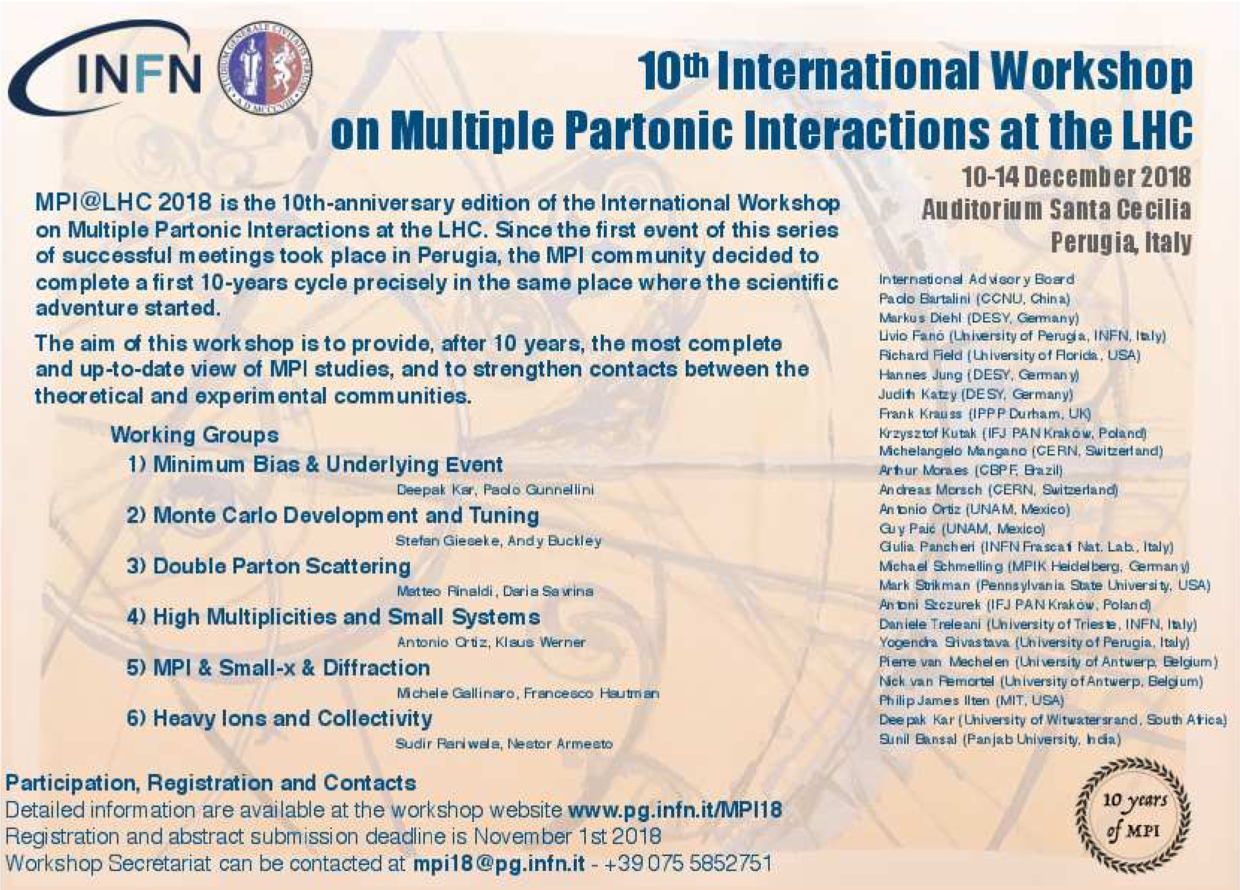
- **2 - DVCS off ^{4}He:**
  * Coherent: a calculation (not yet realistic) with basic ingredients (GK model plus a model spectral function based on Av18 + UIX) describe well the data available from JLab at 6 GeV; **(S. Fucini, S.S., M. Viviani, PRC 98 (2018) 015203).**
  Straightforward and workable approach, suitable for planning new measurements.
  * New data expected at 12 GeV will require much more precise nuclear description (in progress)
  * In the meantime we are facing the incoherent process

Our spirit: introduce new ingredients one at a time

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

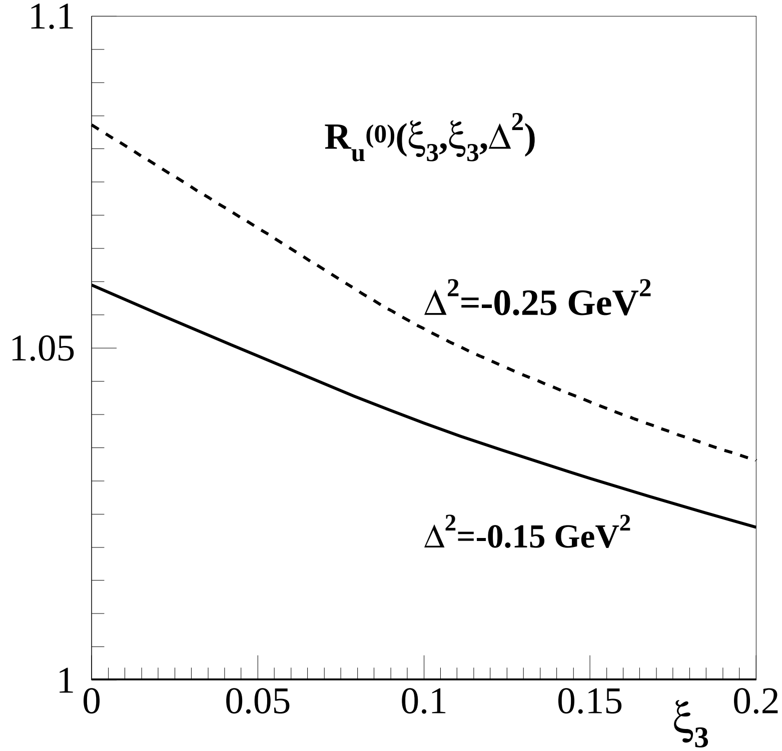
(*It is futile to do with more things what can be done with fewer*)

On a related subject...



Backup - Nuclear effects @ $x = \xi$

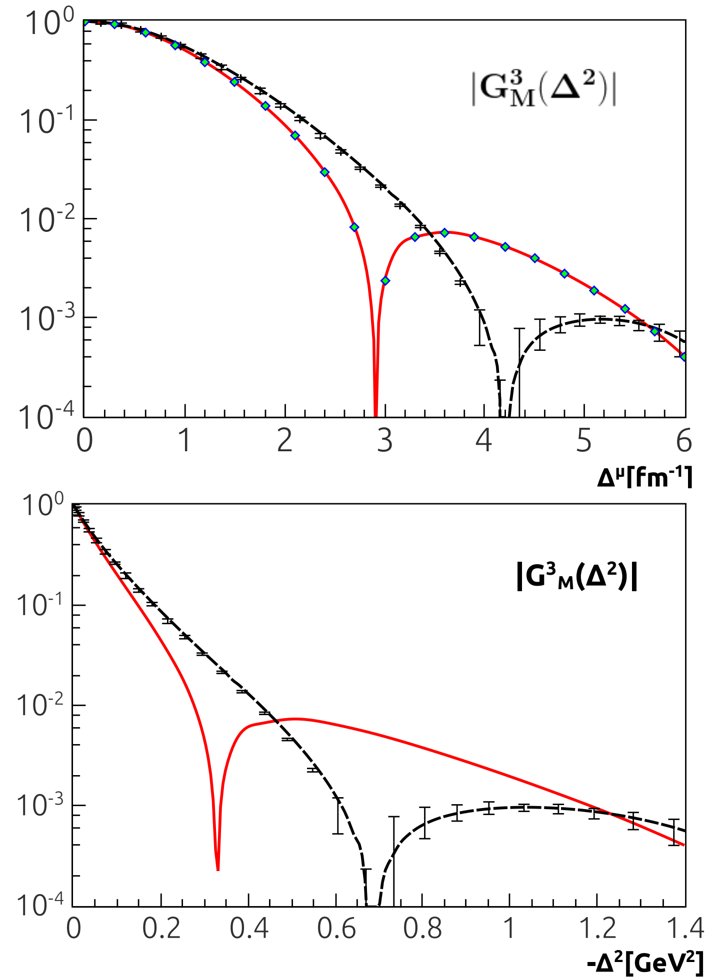
- Nuclear effects are large also in the important region $x = \xi$:



$\tilde{G}_M^{3,q}$ 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

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

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

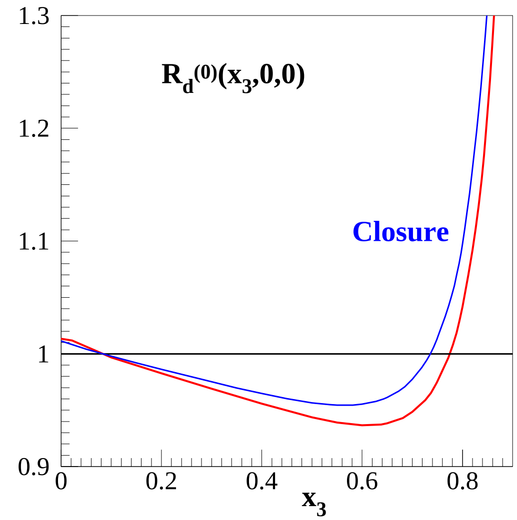
$$\times \langle \vec{P}_f, \vec{p}s | \vec{P}M\rangle \,\delta(E - E_{min} - E_f^*)$$

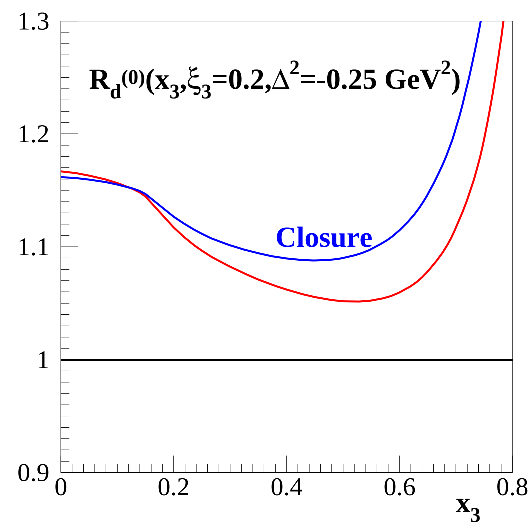
using the Closure Approximation, $E_f^* = \bar{E}$:

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

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

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

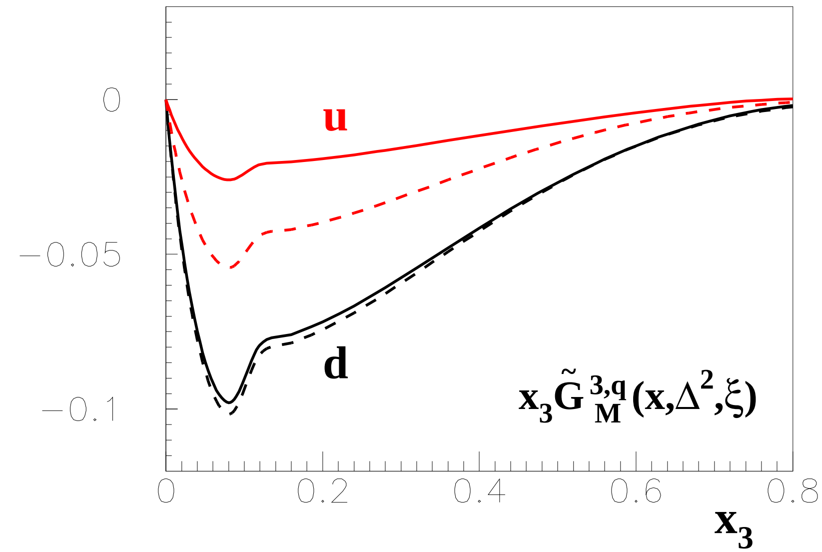




Spectral function substituted by a Momentum distribution
(forward case in **C. Ciofi, S. Liuti PRC 41 (1990) 1100**)

Backup: $\tilde{G}_M^{3,q}$: Flavor separation

For the u flavor, the neutron contribution (dashed) to ^{3}He (full) is less important than for the d flavor:



Understandable, sketching the formula:

$$\tilde{G}_M^{3,q} \approx P_p^3 \otimes \tilde{G}_M^{p,q} + P_n^3 \otimes \tilde{G}_M^{n,q} \; ,$$

where $P^3_{p(n)}$ describes the proton (neutron) dynamics in ^{3}He.

As already explained, due to the spin structure of ^{3}He, $P_n^3 >> P_p^3 \longrightarrow$ neutron dominates in the forward limit.

With increasing Δ^2, for the u flavor, $\tilde{G}_M^{p,u} >> \tilde{G}_M^{n,u} \longrightarrow$ the proton contribution grows. Not for d!

Besides, 1/2 of the d content of ^{3}He comes from the neutron, only 1/5 of the u one comes from it.

Extracting the neutron - III:

The approximated relation can now be solved to extract the neutron contribution:

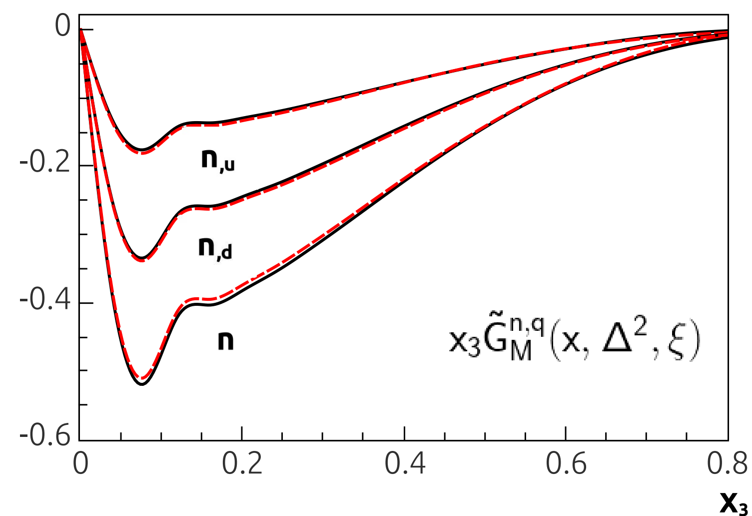
$$\tilde{G}_M^{n,extr}(x,\Delta^2,\xi) \simeq \frac{1}{G_M^{3,n,point}(\Delta^2)} \Big\{ \tilde{G}_M^{3}(x,\Delta^2,\xi) - G_M^{3,p,point}(\Delta^2)\tilde{G}_M^{p}(x,\Delta^2,\xi) \Big\} ,$$

from data for $\tilde{G}_M^3(x,\Delta^2,\xi)$ and $\tilde{G}_M^p(x,\Delta^2,\xi)$, using as theoretical ingredients the magnetic point like ffs only.

The procedure works nicely!

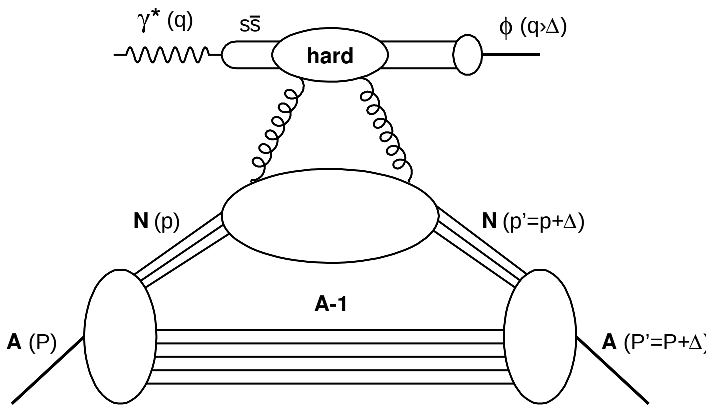
full : the neutron model for $\tilde{G}_M^n(x,\Delta^2,\xi)$ and the different flavor contributions to it used in the IA calculation, at $\Delta^2 = -0.1$ GeV^2, $\xi = 0.1$;

dashed: the neutron extracted using the IA calculation for $\tilde{G}_M^3(x,\Delta^2,\xi)$ and the model used in it for $\tilde{G}_M^p(x,\Delta^2,\xi)$ together with the magnetic point like ffs.



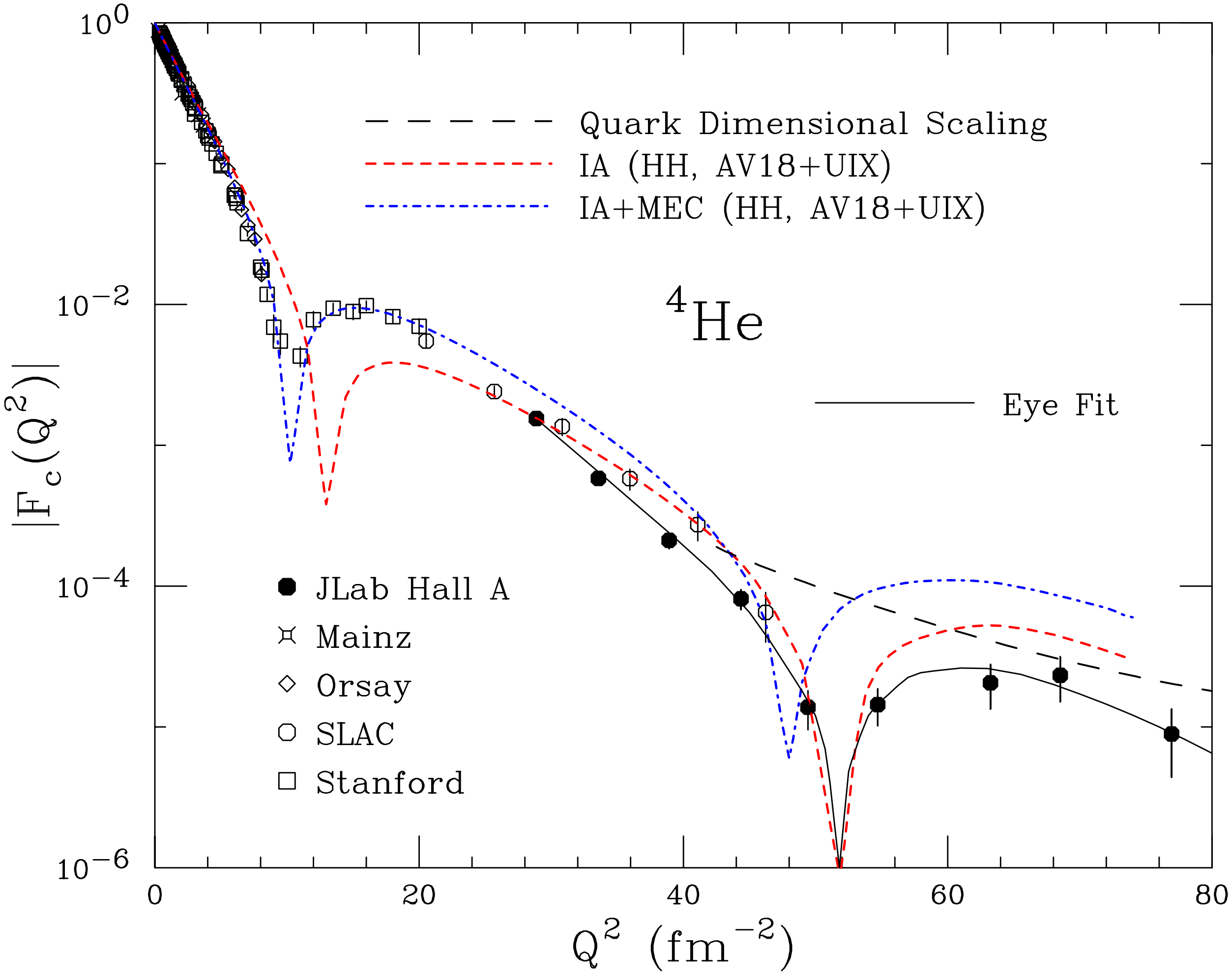
Backup: Many other issues...

- $x-$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

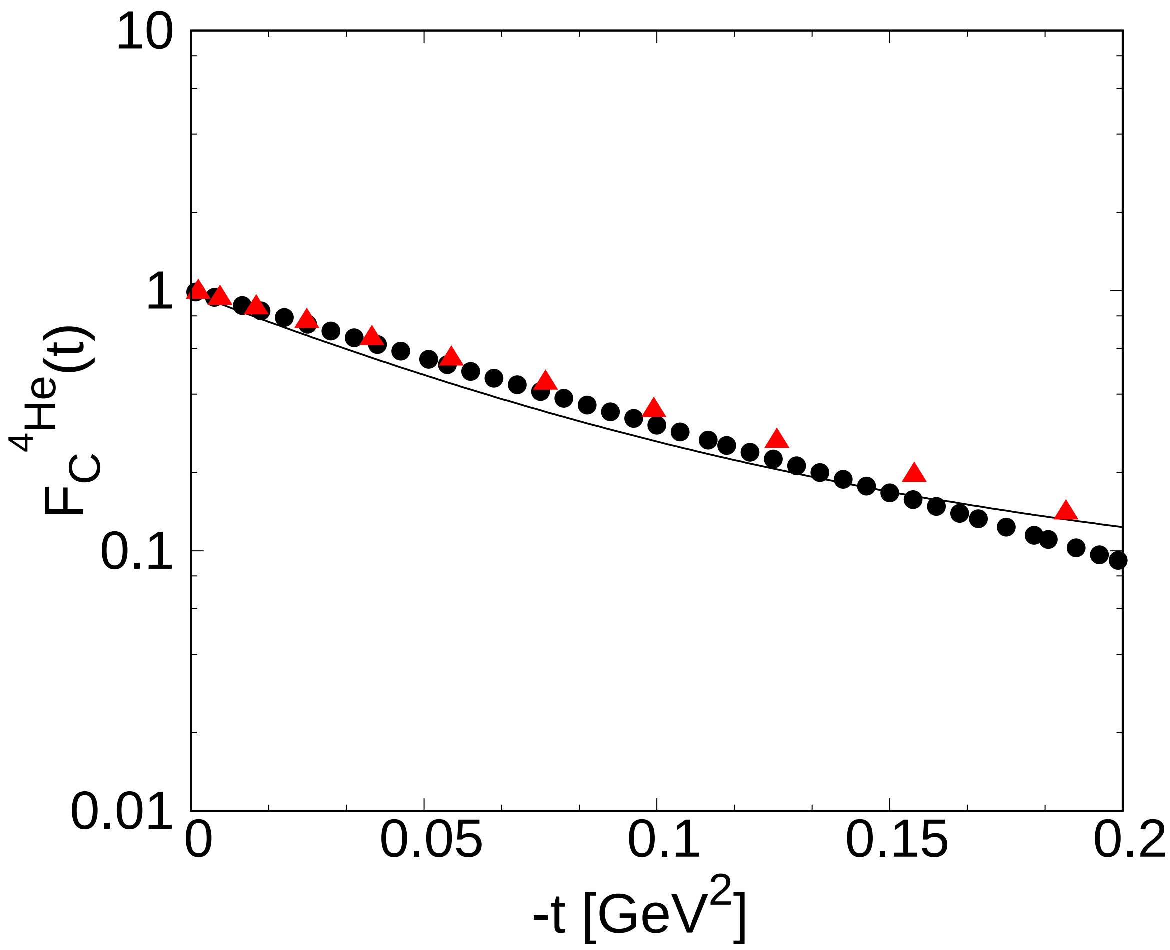


  For GPDs, shadowing (low x_B) stronger than for PDFs
  A. Freund and M. Strikman, PRC 69, 015203 (2004)...
  Exclusive $\phi-$ electroproduction, unique source of information, studied by ALERT, waiting for EIC...
- Deuteron: an issue aside.
  Extraction of the neutron information; access to a new class 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)...

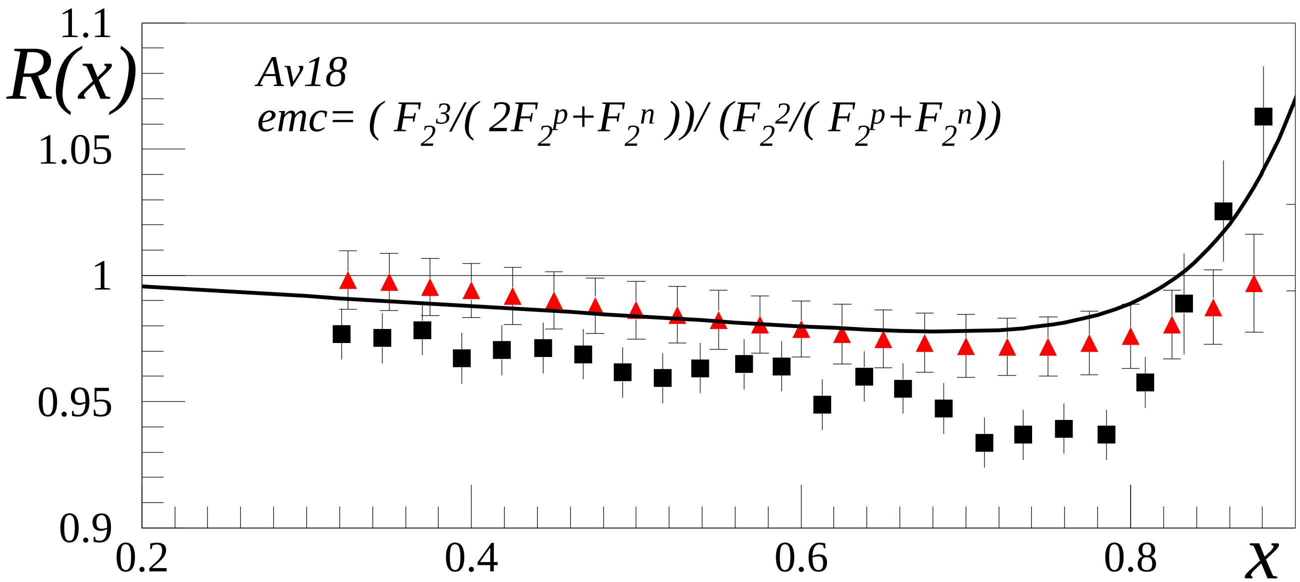
Backup: ^{4}He FF



Backup: ^{4}He FF - IA



Backup: ^{3}He EMC effect IF



- Black squares: Seely et al. (E03103), Hall A JLab, PRL 103 (2009) 202301
- Red triangles: reanalysis (currently accepted) by S. Kulagin and R. Petti, PRC 82 (2010) 054614