Realistic studies of the 3D parton structure of He nuclei

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List of 12 GeV Experiments @JLab, with ^{3}He...

- DIS regime, e.g.

  Hall A, $http://hallaweb.jlab.org/12GeV/$
  MARATHON Coll. E12-10-103 (Rating A): MeAsurement of the F_{2n}/F_{2p}, d/u Ratios and A=3 EMC Effect in Deep Inelastic Electron Scattering Off the Tritium and Helium MirrOr Nuclei

  Hall C, $https://www.jlab.org/Hall-C/$
  J. Arrington, et al PR12-10-008 (Rating A$^-$): Detailed studies of the nuclear dependence of F_2 in light nuclei

- SIDIS regime, e.g.

  Hall A, $http://hallaweb.jlab.org/12GeV/$
  H. Gao et al, PR12-09-014 (Rating A): Target Single Spin Asymmetry in Semi-Inclusive Deep-Inelastic $(e, e'\pi^{\pm})$ Reaction on a Transversely Polarized ^{3}He Target
  J.P. Chen et al, PR12-11-007 (Rating A): Asymmetries in Semi-Inclusive Deep-Inelastic $(e, e'\pi^{\pm})$ Reactions on a Longitudinally Polarized ^{3}He Target

- Others? DVCS, spectator tagging...
  In ^{3}He conventional nuclear effects under control... Exotic ones disentangled

Outline

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

Realistic calculations: use of exact solutions of the Schrödinger equation, with realistic NN potentials (e.g., Av18) and 3-body forces $\rightarrow$ spectral functions

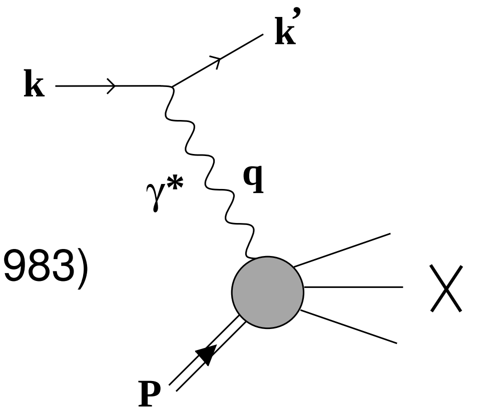
- **1 - GPDs for ^{3}He:**
  A complete impulse approximation realistic study is reviewed
  (S.S. PRC 2004, PRC 2009; M. Rinaldi and S.S., PRC 2012, PRC 2013)
  No data; proposals? Prospects at JLAB-12 and EIC;

- **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]) .

- **3 - SIDIS off ^{3}He: $^3\vec{H}e(e, e'A)X$:**
  Beyond IA (quickly) **(A. Del Dotto, L. Kaptari, E. Pace, G. Salmè, S.S., PRC 96 (2017) 065203)**

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*

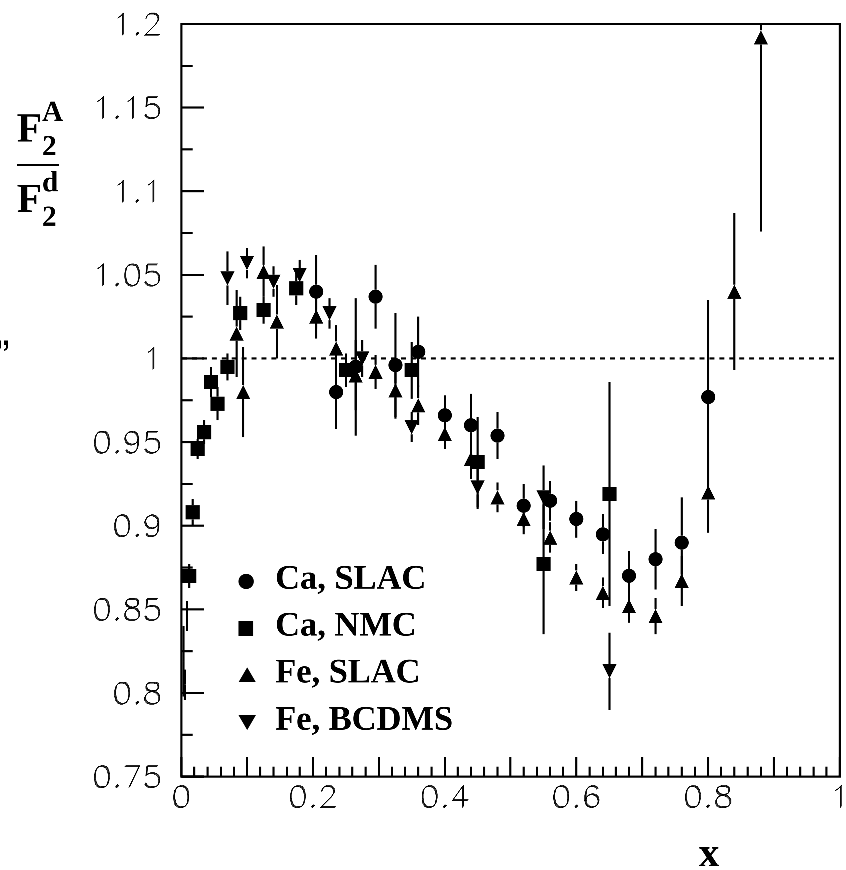
EMC effect in A-DIS



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

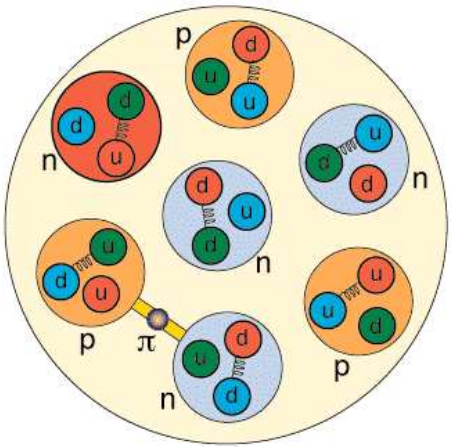
One has to go beyond

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

- **Hard Exclusive Processes (GPDs)**
- **SIDIS (TMDs)**

EMC effect: way out?

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



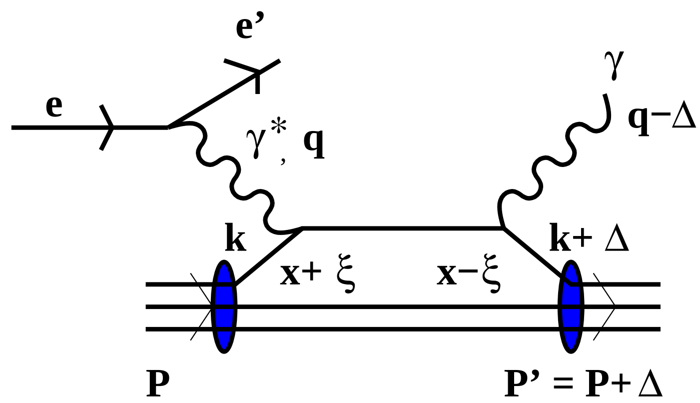
To answer, we should perform a *tomography...*

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:

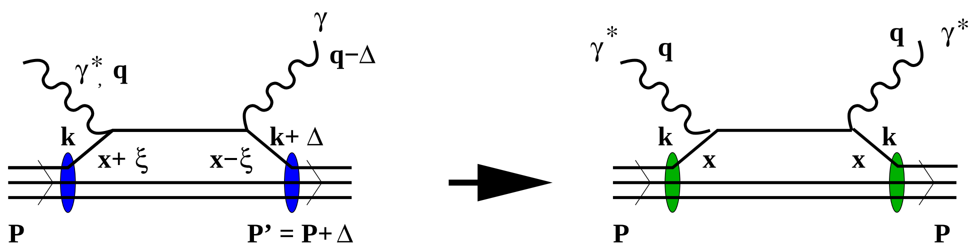
$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P' | \bar{\psi}_q(-\lambda n/2) \quad \gamma^\mu \quad \psi_q(\lambda n/2) | P \rangle = H_q(x, \xi, \Delta^2) \bar{U}(P') \gamma^\mu U(P)$$

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

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

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

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

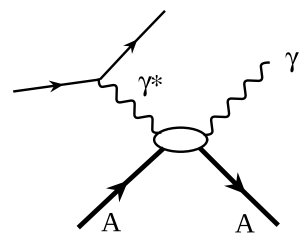
$$\Longrightarrow \int dx\, H_q(x,\xi,\Delta^2) = F_1^q(\Delta^2) \qquad \int dx\, E_q(x,\xi,\Delta^2) = F_2^q(\Delta^2)$$

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

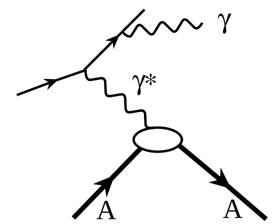
GPDs: a unique tool...

- 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:

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

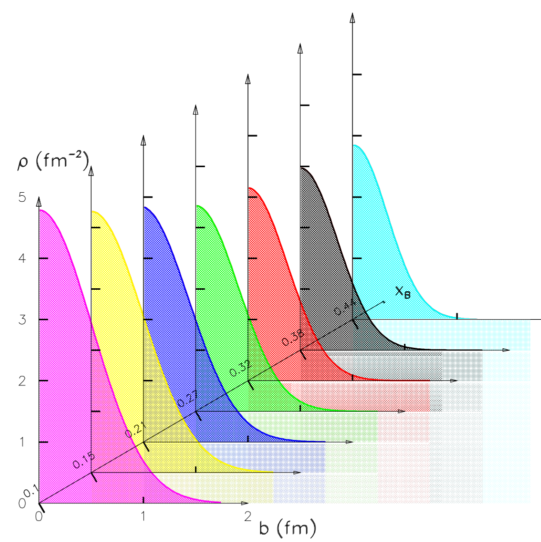
- Competition with the **BH** process! (σ asymmetries measured).

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

Nevertheless, for the proton, we have results:

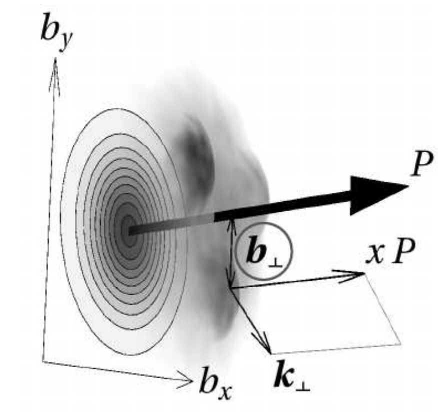
(Guidal et al., Rep. Prog. Phys. 2013...

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

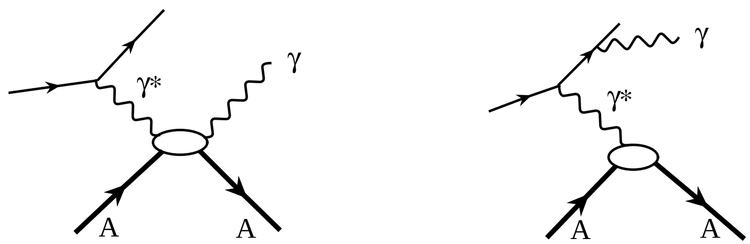


Nuclei and DVCS tomography

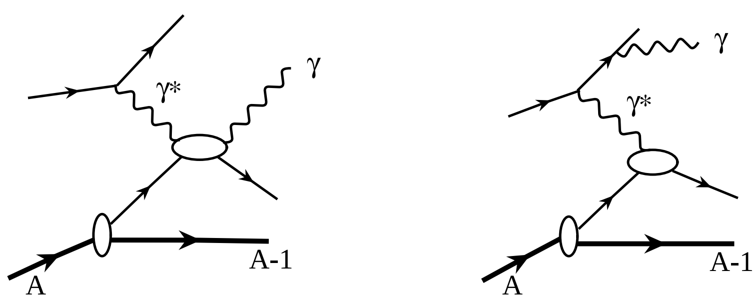
In impact parameter space, GPDs are *densities*:



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



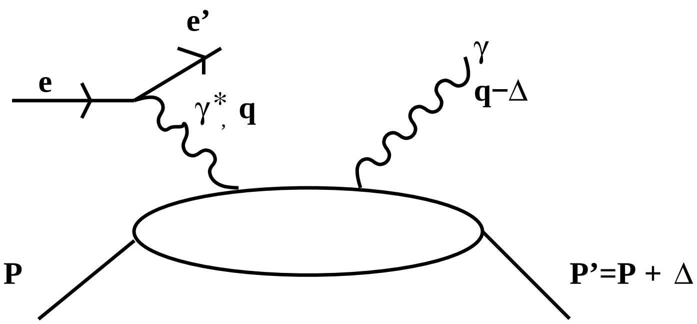
Coherent DVCS: nuclear tomography



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

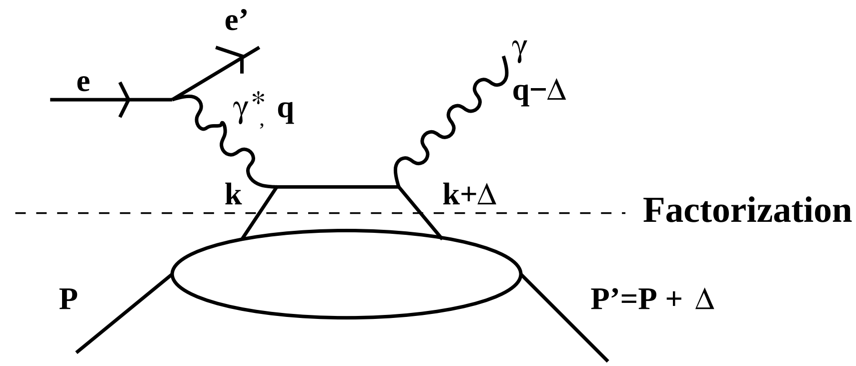
Nuclei: why? - not only tomography

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



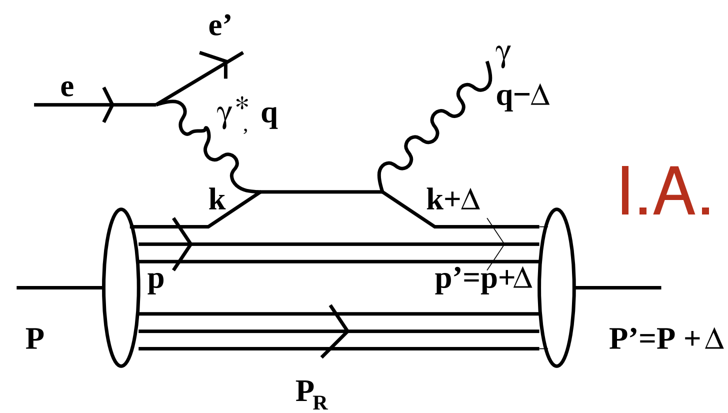
coherent DVCS

$\simeq$



handbag

$\simeq$



I.A.

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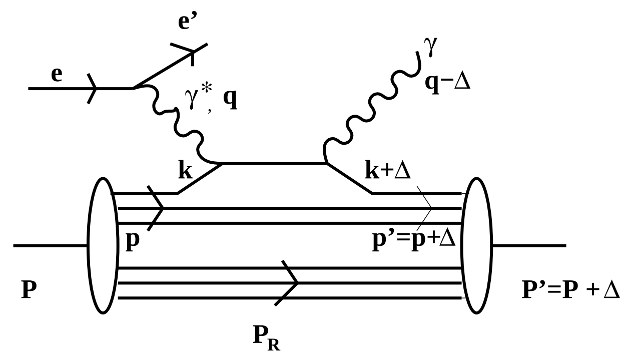

For the internal target ($\bar{p} = (p + p')/2$) :

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

one has, for a given GPD

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

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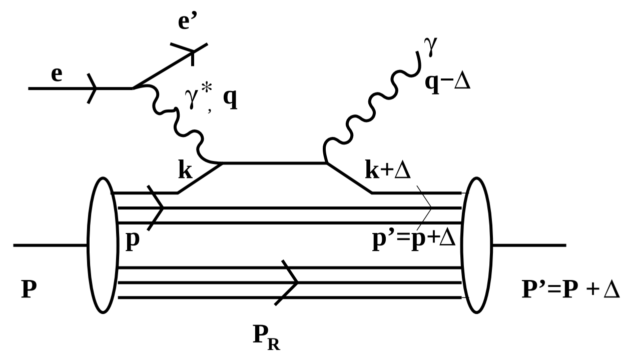

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By properly inserting complete sets of states for the interacting nucleon and the recoiling system, considering $\hat{O}_q = \sum_N \hat{O}_q^N$:

Nuclei: why? - not only tomography

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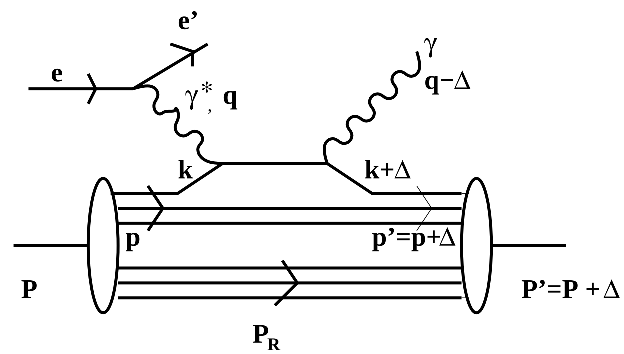

For the internal target ($\bar{p} = (p + p')/2$) :

$$k^+ = (x+\xi)\bar{P}^+ = (x'+\xi')\bar{p}^+ \,,$$
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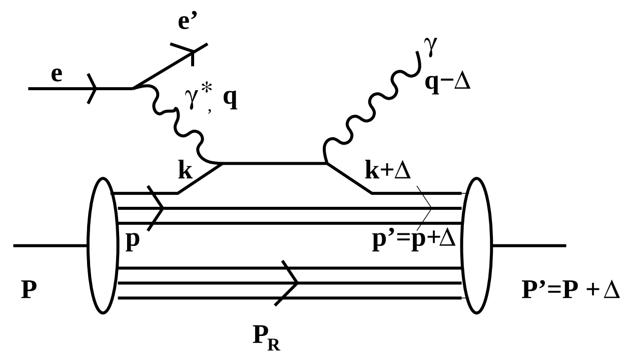
one has, for a given GPD

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

Nuclei: why? - not only tomography

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



For the internal target ($\bar{p} = (p + p')/2$) :

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

one has, for a given GPD

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

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))**:

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

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,

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

Never forget: IA is an Approximation (more, later);
in many cases, a framework for further improvements

(Kaptari, Del Dotto, Pace, Salmè, S.S., PRC 89 (2014) 035206; P. Mulders, Phys.Rept. 185 (1990) 83))

Why nuclei?

The obtained expressions have the correct limits:

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

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

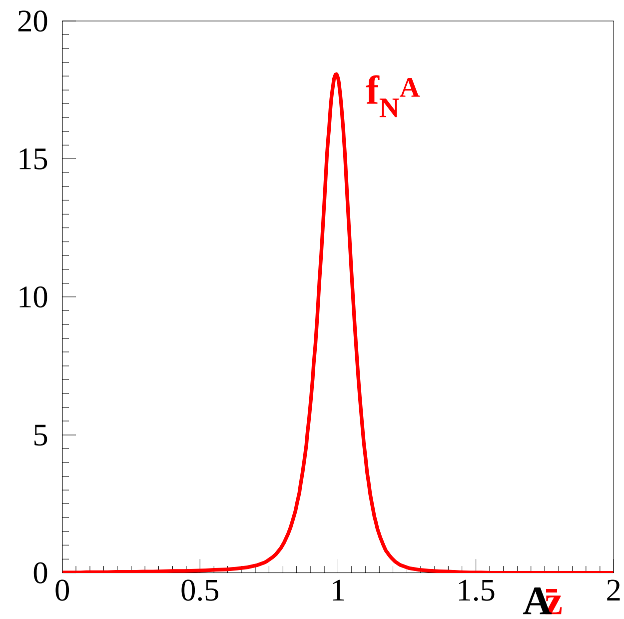
- forward limit (standard DIS):

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

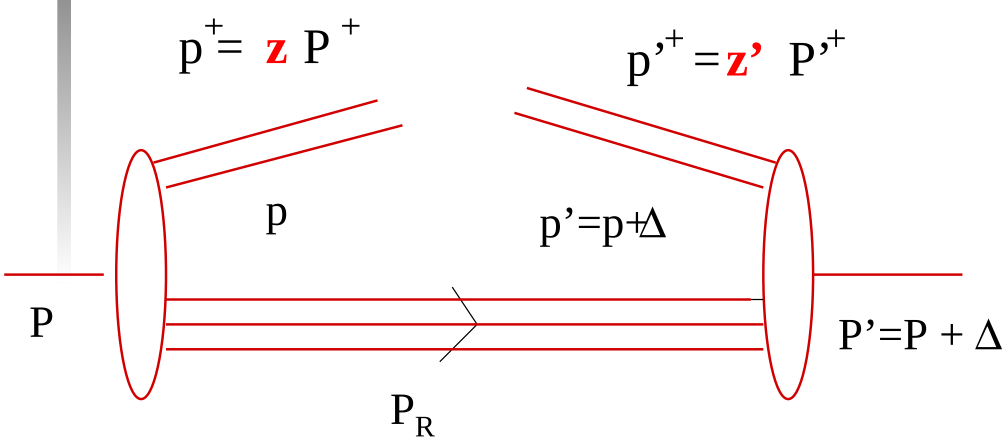
with the light-cone momentum distribution:

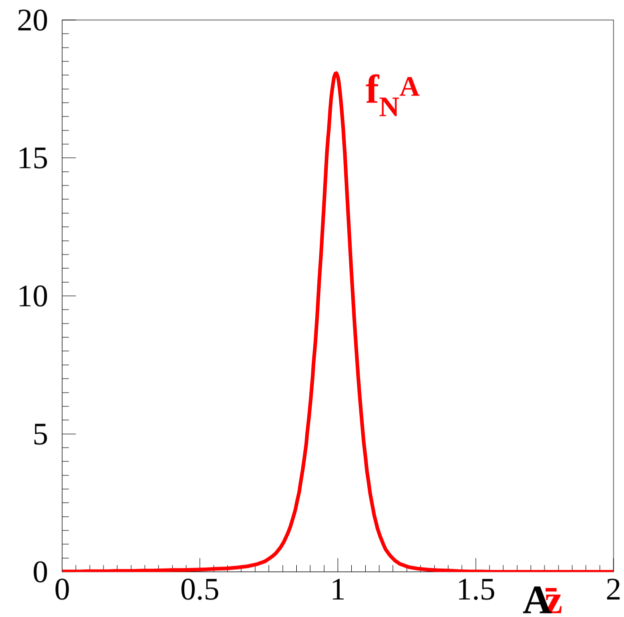
$f_N^A(\tilde{z}) = \int dE d\vec{p}\, P_N^A(\vec{p},E)\delta\left(\tilde{z} - \frac{p^+}{P^+}\right)$,

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



Why nuclei?





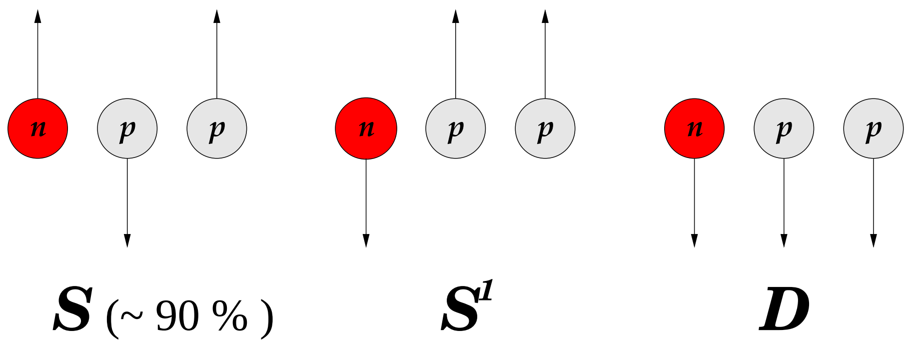
Since $z - z' = -x_B(1-z)/(1-x_B)\,,\quad \xi \simeq x_B/(2-x_B)$ can be tuned to have $z - z'$ larger than the width of the narrow nuclear light-cone momentum distribution $f_N^A(\bar{z} = (z+z')/2)$: in this case IA predicts a $vanishing$ GPD, at $small\ x_B$.

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:

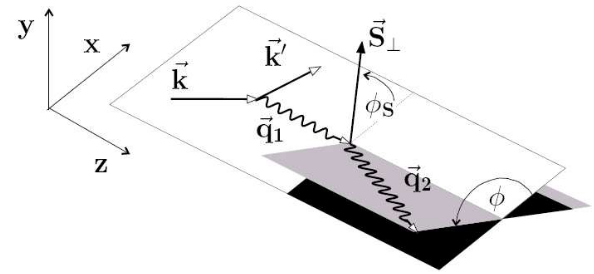


In $S-$wave $^3\vec{He} = \vec{n}$!

^{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:

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

- Unpolarized beam, longitudinally polarized target:

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

- Unpolarized beam, transversely polarized target:

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

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)**):

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

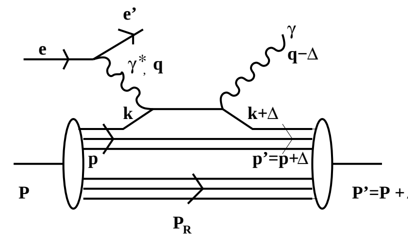
($\tilde{G}_M^q = H^q + E^q$) where $P^N_{SS,ss}(\vec{p},\vec{p}\,',E)$ is the one-body, spin-dependent, off-diagonal spectral function for the nucleon N in the nucleus,

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

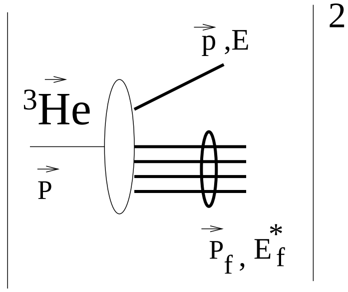
evaluated by means of a realistic treatment based on Av18 wave functions (**"CHH" method in A. Kievsky** *et al* **NPA 577, 511 (1994); Av18 + UIX overlaps in E. Pace** *et. al*, **PRC 64, 055203 (2001)**).

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

The spectral function (Impulse Approximation)



$$\mathbf{P}^N_{\mathcal{M}\sigma\sigma}(\vec{p},, E) = \sum_f \left| \quad \right|^2 =$$



intrinsic overlaps

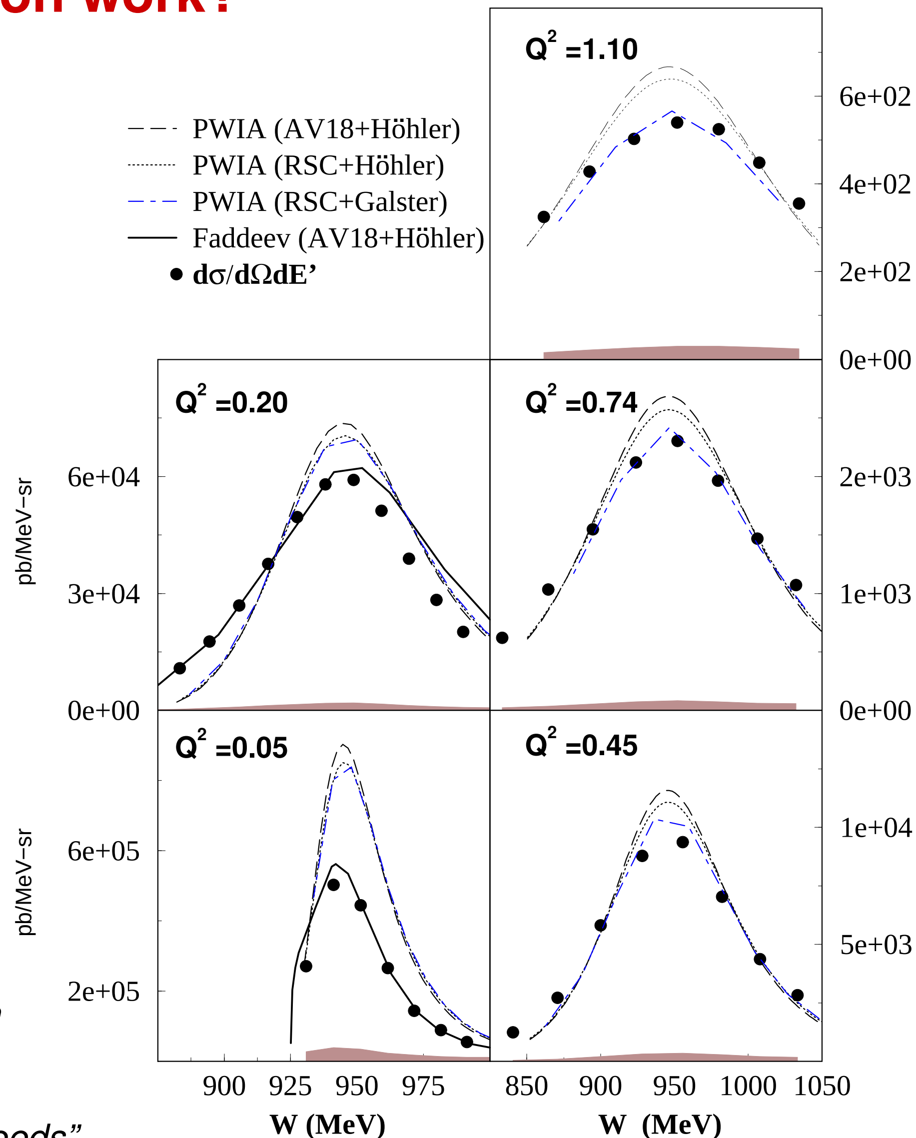
$$\sum_f \delta(E - E_{min} - E^*_f) \underbrace{{}_{S_A}\langle \Psi_A; J_A \mathcal{M} \pi_A | \vec{p}, \sigma; \phi_f(E^*_f) \rangle} \underbrace{\langle \phi_f(E^*_f); \sigma \vec{p} | \pi_A J_A \mathcal{M}'; \Psi_A \rangle_{S_A}}$$

- probability distribution to find a nucleon with 3-momentum $\vec{p}$ and a residual system with excitation energy E^*_f in the nucleus. Found in q.e., DIS, SIDIS, DVCS...
- the two-body recoiling system can be either the deuteron or a scattering state; to obtain a reasonable normalization of the spectral function, more than 50 final states f have to be summed
- In general, if spin is involved, a 2x2 matrix, $\mathbf{P}^N_{\mathcal{M}\sigma\sigma'}(\vec{p},, E)$, not a density;
- Realistic Spectral Function: 3-body bound state and 2-body final state evaluated within the same Realistic interaction (in our case, Av18+UIX, from the Pisa group **(Kievsky, Viviani)**). Extension to heavier nuclei very difficult

Is the spectral function a useful tool?
Does the Impulse Approximation work?

The answer in the data.

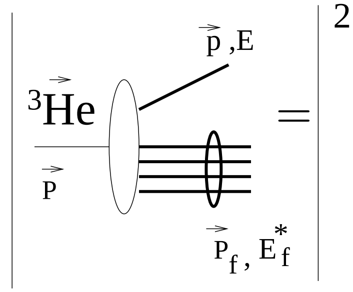
Example: $^3\vec{He}(\vec{e},e')X$ in q.e. kinematics
(**K. Slifer et al, PRL 101 (2008) 022303**)



- Faddeev calc. at low Q^2
  J. Golak et al. Phys. Rept. 415 (2005) 89
- PWIA (Av18) calc.
  E. Pace et al, PRC 64 (2001) 055203
- Conclusion of the Slifer et al. paper:
  "A full three-body Faddeev calculation agrees well with the data but starts to exhibit discrepancies as the energy increases, possibly due to growing relativistic effects. As the momentum transfer increases, the PWIA approach reproduces the data well, but there exists an intermediate range where neither calculation succeeds"
- caveat: always check kinematics and set-up (this is q.e., inclusive)

Nucleon off-shellness in I.A. :

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

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

↙ intrinsic overlaps ↘

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

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

"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 %

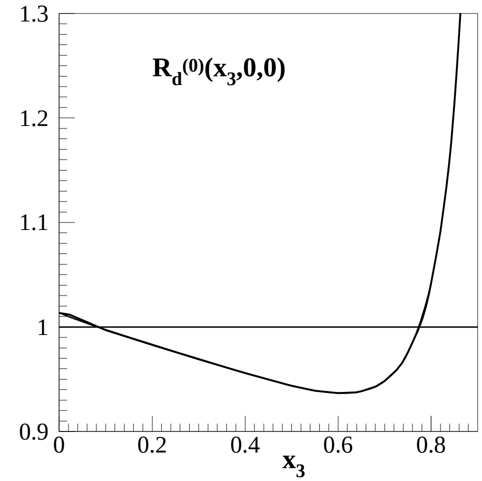
The calculation has the correct limits:

1 - Forward limit: the ratio:

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

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

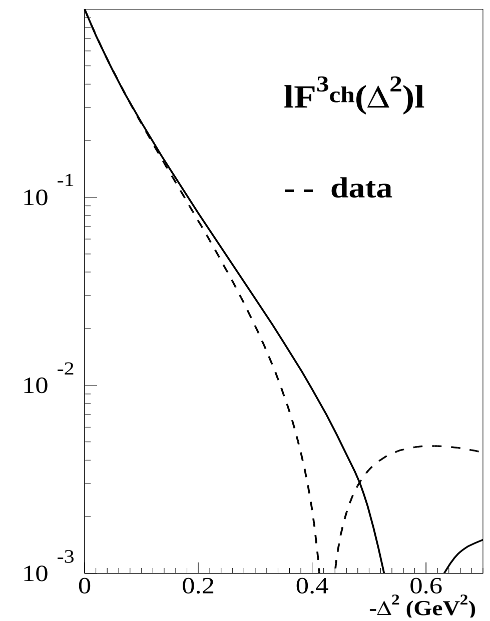
shows an EMC-like behavior;



2 - Charge F.F.:

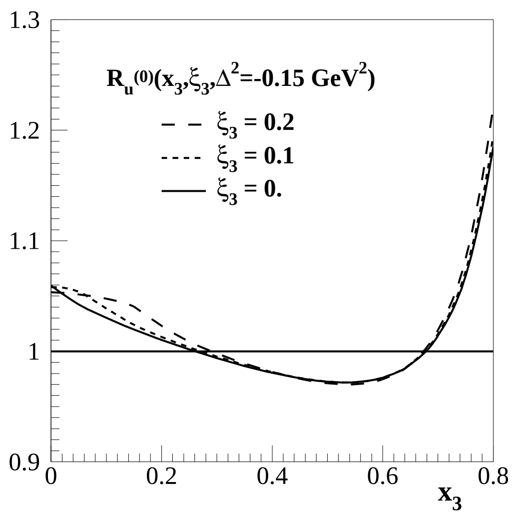
$$\sum_q e_q \int dx H_q^3(x,\xi,\Delta^2) = F^3(\Delta^2)$$

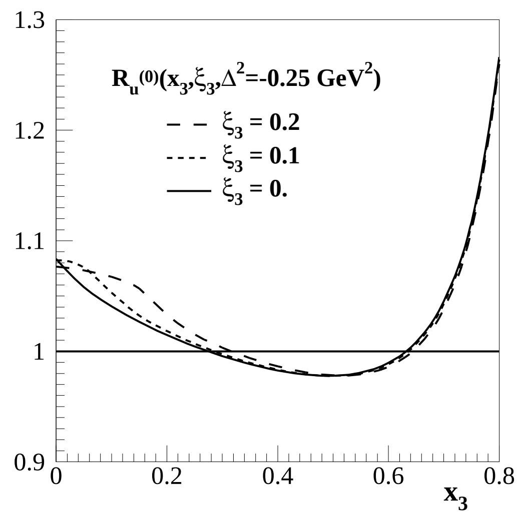
in good agreement with data in the region relevant to the coherent process, $-\Delta^2 \leq 0.2$ GeV^2.



Nuclear effects - general features

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





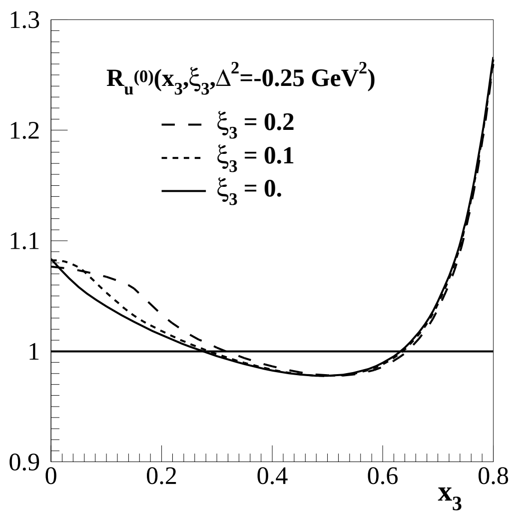
$$R_q^{(0)}(x,\xi,\Delta^2) = \frac{H_q^3(x,\xi,\Delta^2)}{2H_q^{3,p}(x,\xi,\Delta^2) + H_q^{3,n}(x,\xi,\Delta^2)}$$

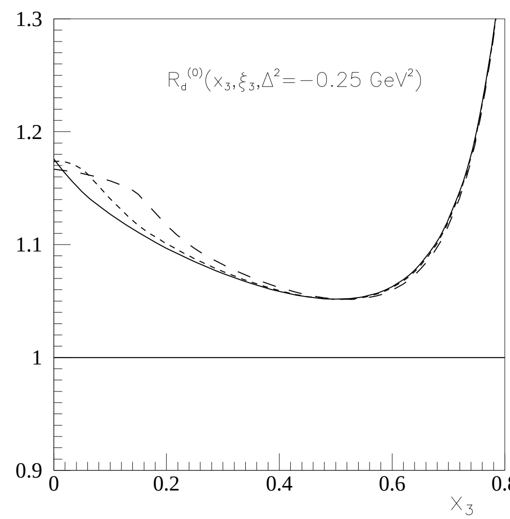
$$H_q^{3,N}(x,\xi,\Delta^2) = \tilde{H}_q^N(x,\xi)F_q^3(\Delta^2)$$

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





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

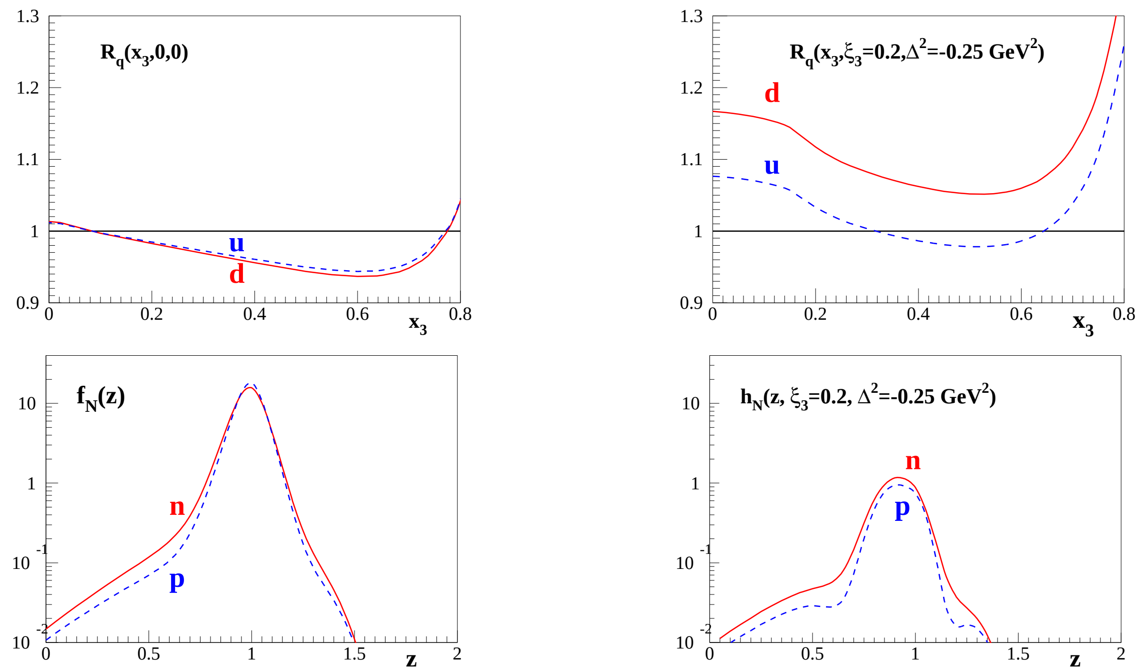
$$H_q^{3,N}(x,\xi,\Delta^2) = \tilde{H}_q^N(x,\xi) F_q^3(\Delta^2)$$

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

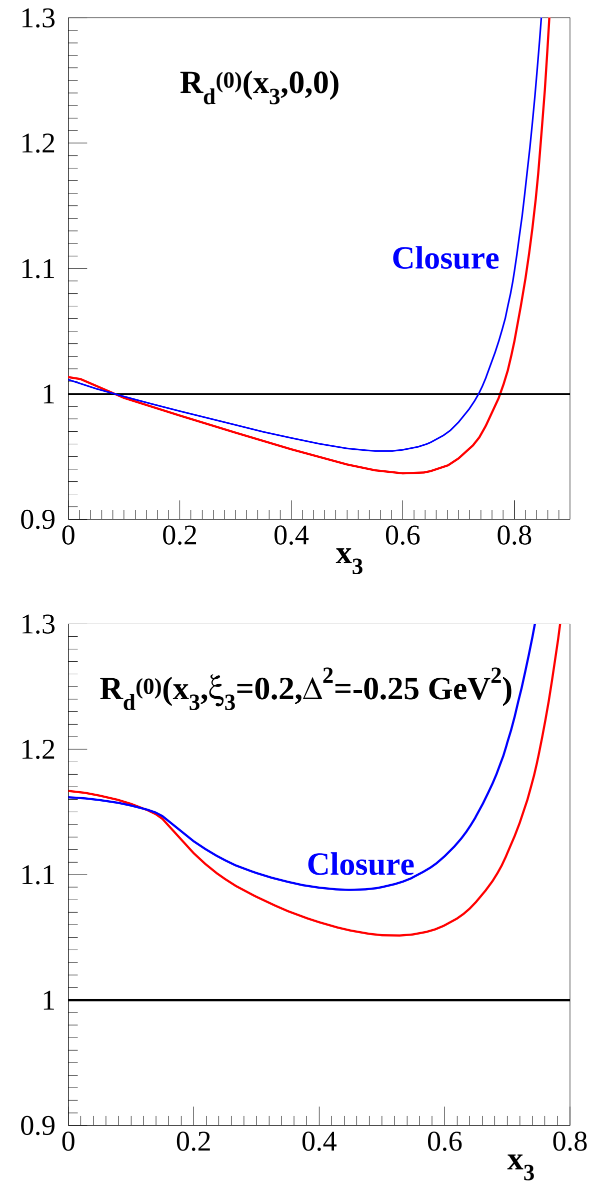


- How to perform a flavor separation? Take the triton ^{3}H !
  Possible (see MARATHON@JLab). Possible for DVCS (ALERT).
  Studied in **S.S. Phys. Rev. C 79 (2009) 025207**
  $H_t, H_H \rightarrow H_u^H \simeq H_d^t, H_d^H \simeq H_u^t$ in the valence region...

Nuclear effects - the binding

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

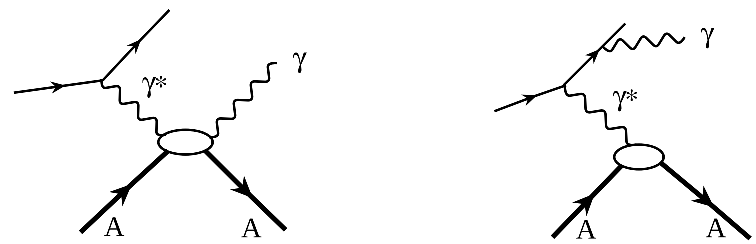
- In calculations using $n(\vec{p}, \vec{p} + \vec{\Delta})$ instead of $P_N^3(\vec{p}, \vec{p} + \vec{\Delta}, E)$, in addition to the IA, also the Closure approximation has been assumed;
- 5 % to 10 % binding effect between $x = 0.4$ and 0.7 - much bigger than in the forward case;
- for $A > 3$, the 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.



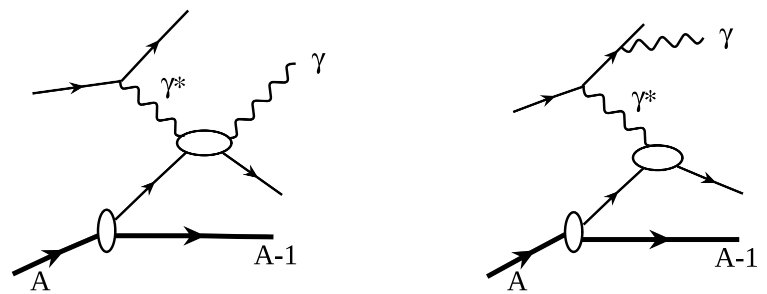
^{3}He calculations: summary

- 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

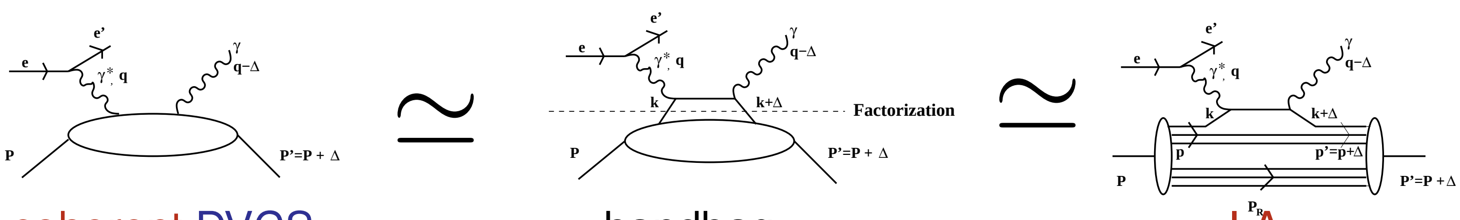


Incoherent DVCS: tomography of bound nucleons: realization of the EMC effect

- 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

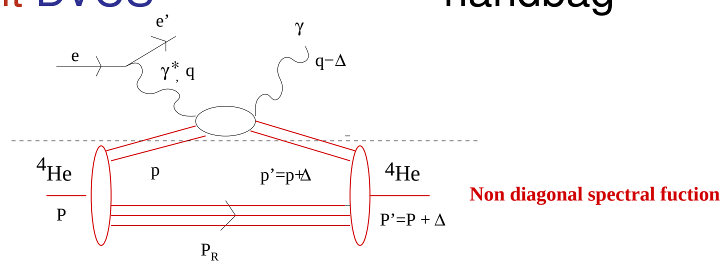
Our IA approach to coherent DVCS off ^{4}He

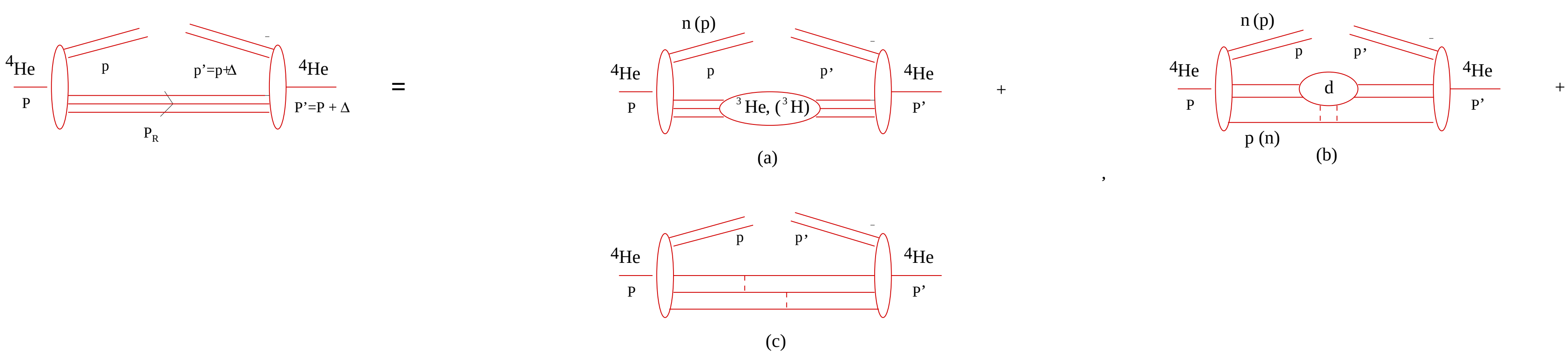
- Realistic microscopic calculations are necessary. A collaboration is going on with Sara Fucini (Perugia, Ph.D. student), Michele Viviani (INFN Pisa).
- coherent DVCS in the Impulse Approximation (I.A.) to the handbag contribution:



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

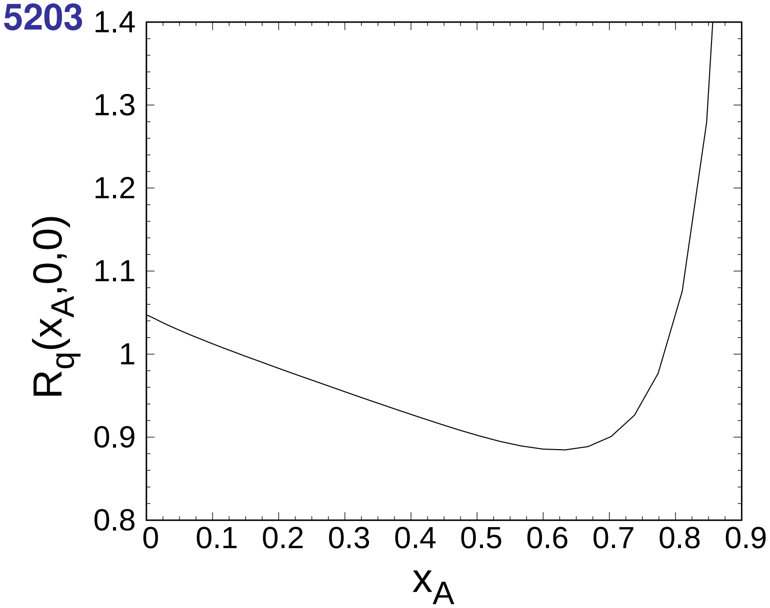
S.Fucini, SS., M. Viviani PRC 98 (2018) 015203

1 - Forward limit: the ratio:

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

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

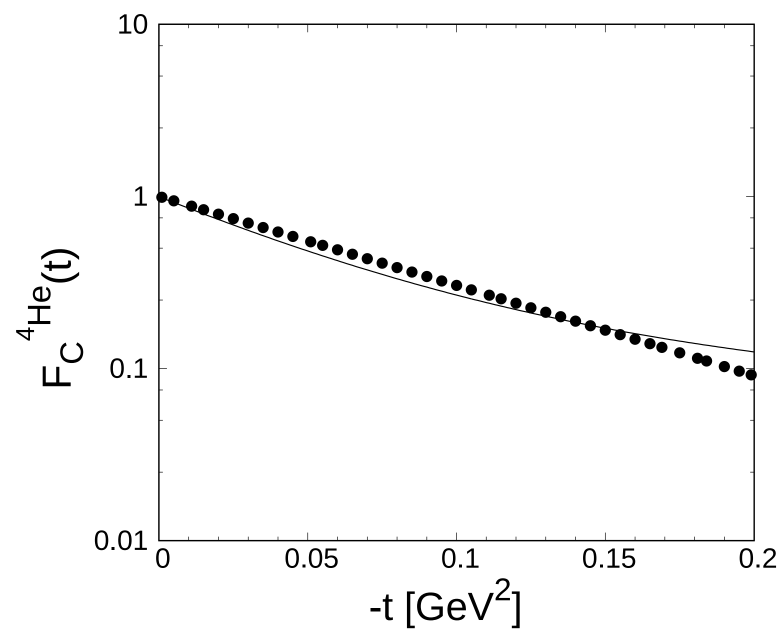
shows an EMC-like behavior;



2 - Charge F.F.:

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

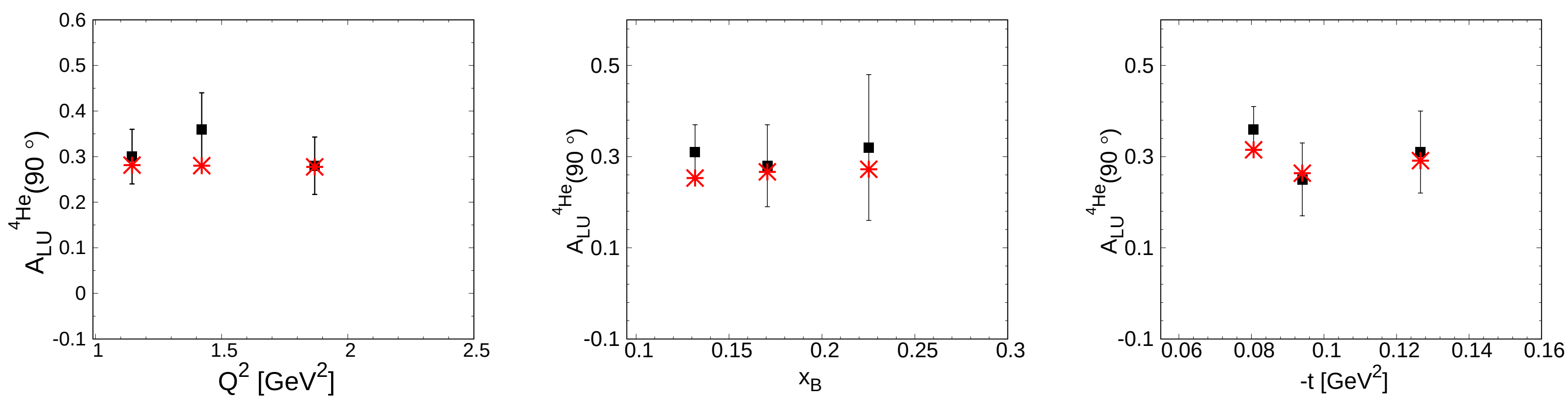
reasonable agreement with data in the region relevant to the coherent process, $-t = -\Delta^2 \leq 0.2$ GeV^2.



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)**

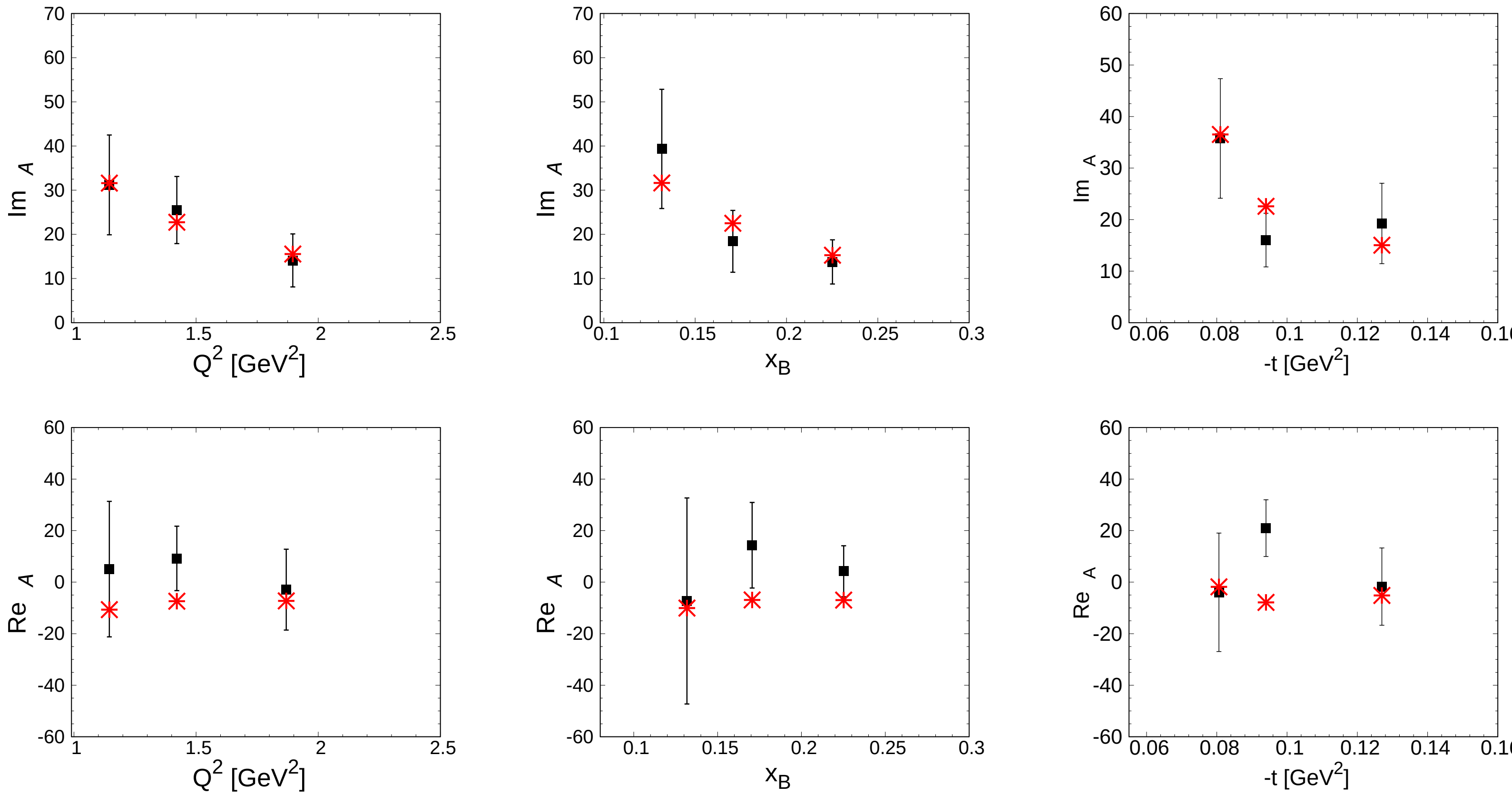
From left to right, the quantity is shown in the experimental Q^2, x_B and t bins, respectively: very good agreement

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

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



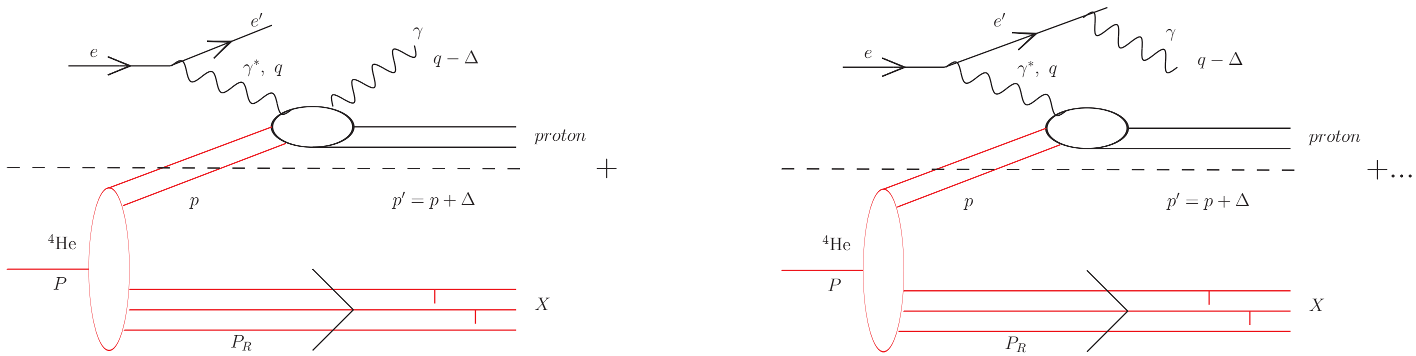
$$\Im m(\mathcal{H}_A) = H_A(\xi,\xi,t) - H_A(-\xi,\xi,t),$$

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

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:

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

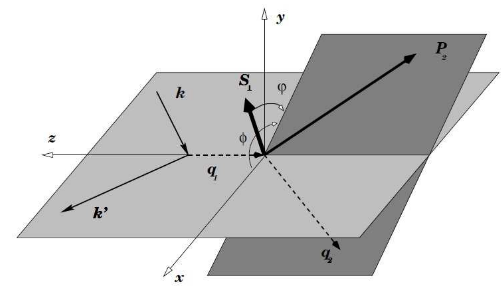
$$\xi = Q^2/[(p+p')\cdot(q+q')] \neq x_B/(2-x_B)$$

- number 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

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

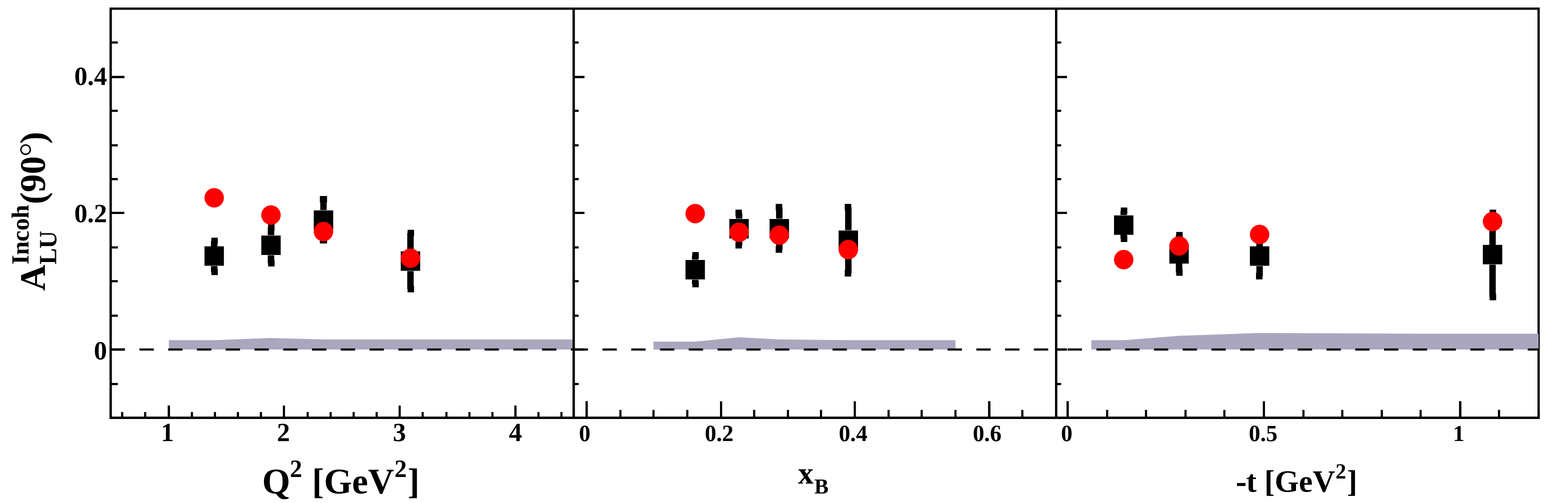
$$A^{4,p}_{LU} \simeq \frac{\int dE \int d\vec{p}\, P^{4,p}(\vec{p},E)\, g(kin,\vec{p},E)\, Int_{BH-DVCS}(kin,\vec{p},E)}{\int dE \int d\vec{p}\, P^{4,p}(\vec{p},E)\, g(kin,\vec{p},E)\, T^2_{BH}(kin,\vec{p},E)}$$

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

(**M. Viviani et al., PRC 67 (2003) 034003**)

Results for A_{LU}

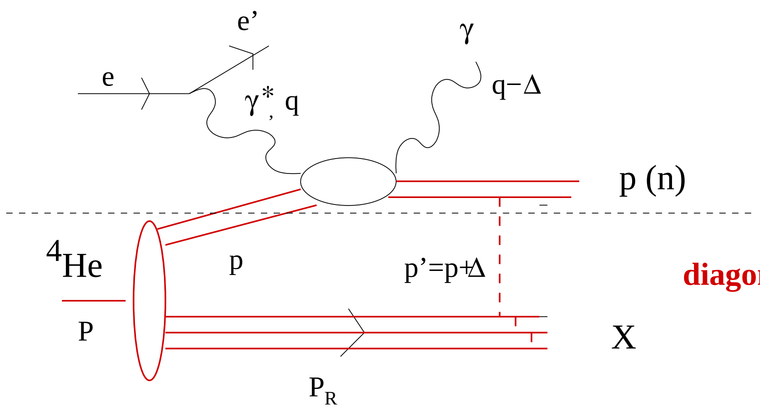
S. Fucini, S.S., M. Viviani - arXiv:1909.12261 [nucl-th]



- 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... But not at 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 be studied, to realize if this could be due to FSI or to unconventional effects... Work in progress.

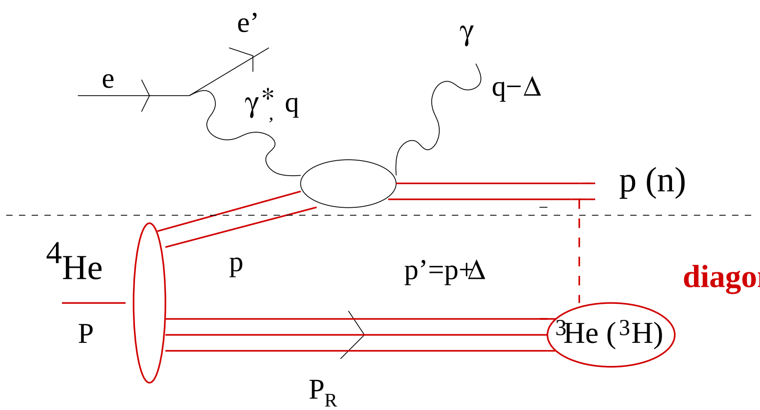
Incoherent DVCS off ^{4}He: beyond IA; FSI?

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



diagonal spectral fuction... FSI??

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



diagonal spectral fuction... Great!

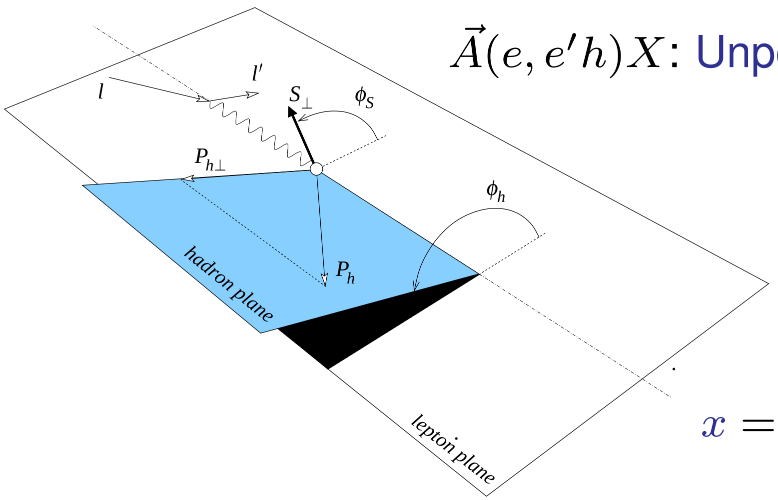
SIDIS off ^{3}He and neutron TMDs

	Impulse Approximation		including FSI	
	unpolarized	spin dep.	unpolarized	spin dep.
Non Relativistic	✓	✓	✓	✓
Light-Front	Def: ✓	Def: ✓	WORK IN PROGRESS	WORK IN PROGRESS
	Calc:	Calc:		

- Extracting the neutron information from SiDIS off $^3\vec{He}$.
  Basic approach: Impulse Approximation in the Bjorken limit
  (S.S., PRD 75 (2007) 054005)

- **Main topic:**
  - * **Evaluation of Final State Interactions (FSI): distorted spectral function SIDIS**
    (A. Del Dotto, L. Kaptari, E. Pace, G. Salmè, S.S., PRC 96 (2017) 065203)
  - * **Evaluation of FSI: distorted spectral function and spectator SIDIS**
    (L. Kaptari, A. Del Dotto, E. Pace, G. Salmè, S.S., PRC 89 (2014) 035206)

SIDIS off ^{3}He and neutron TMDs: Single Spin Asymmetries (SSAs) - 1



$\vec{A}(e,e'h)X$: Unpolarized beam and T-polarized target $\to \sigma_{UT}$

$$d^6\sigma \equiv \frac{d^6\sigma}{dx\,dy\,dz\,d\phi_S\,d^2P_{h\perp}}$$

$$x = \frac{Q^2}{2P\cdot q} \qquad y = \frac{P\cdot q}{P\cdot l} \qquad z = \frac{P\cdot h}{P\cdot q} \qquad \boxed{\hat{q} = -\hat{e}_z}$$

The number of emitted hadrons at a given ϕ_h depends on the orientation of $\vec{S}_\perp$!

In SSAs 2 different mechanisms can be experimentally distinguished

$$A_{UT}^{Sivers(Collins)} = \frac{\int d\phi_S d^2P_{h\perp} \sin(\phi_h - (+)\phi_S) d^6\sigma_{UT}}{\int d\phi_S d^2P_{h\perp} d^6\sigma_{UU}}$$

with $\quad d^6\sigma_{UT} = \frac{1}{2}(d^6\sigma_{U\uparrow} - d^6\sigma_{U\downarrow}) \qquad d^6\sigma_{UU} = \frac{1}{2}(d^6\sigma_{U\uparrow} + d^6\sigma_{U\downarrow})$

SSAs - 2

SSAs in terms of parton distributions and fragmentation functions:

- $A_{UT}^{Sivers} = N^{Sivers}/D \qquad A_{UT}^{Collins} = N^{Collins}/D$

$$N^{Sivers} \propto \sum_q e_q^2 \int d^2\kappa_{\mathbf{T}} d^2\mathbf{k_T} \delta^2(\mathbf{k_T} + \mathbf{q_T} - \kappa_{\mathbf{T}}) \frac{\hat{\mathbf{P_{h\perp}}} \cdot \mathbf{k_T}}{\mathbf{M}} f_{1T}^{\perp q}(x, \mathbf{k_T}^2) D_1^{q,h}(z, (z\kappa_{\mathbf{T}})^2)$$

$$N^{Collins} \propto \sum_q e_q^2 \int d^2\kappa_{\mathbf{T}} d^2\mathbf{k_T} \delta^2(\mathbf{k_T} + \mathbf{q_T} - \kappa_{\mathbf{T}}) \frac{\hat{\mathbf{P_{h\perp}}} \cdot \kappa_{\mathbf{T}}}{\mathbf{M_h}} h_1^q(x, \mathbf{k_T}^2) H_1^{\perp q,h}(z, (z\kappa_{\mathbf{T}})^2)$$

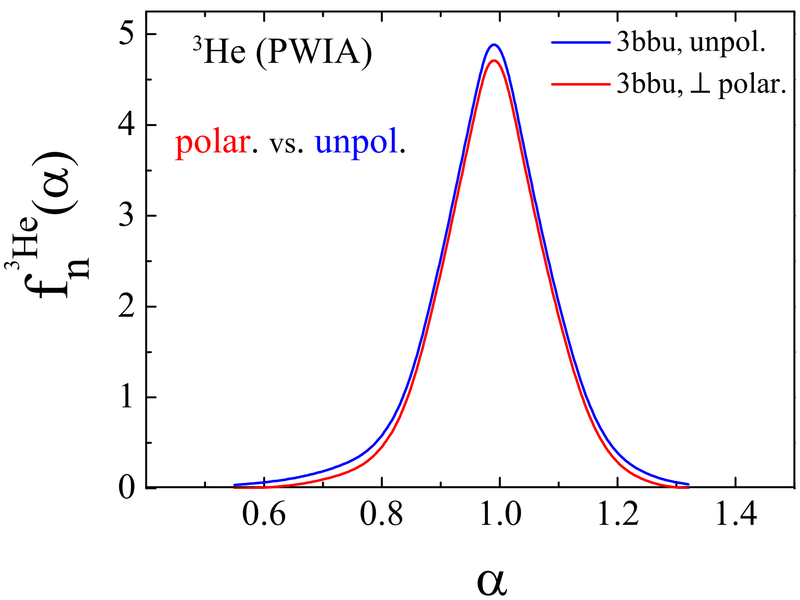
$$D \propto \sum_q e_q^2 f_1^q(x) D_1^{q,h}(z)$$

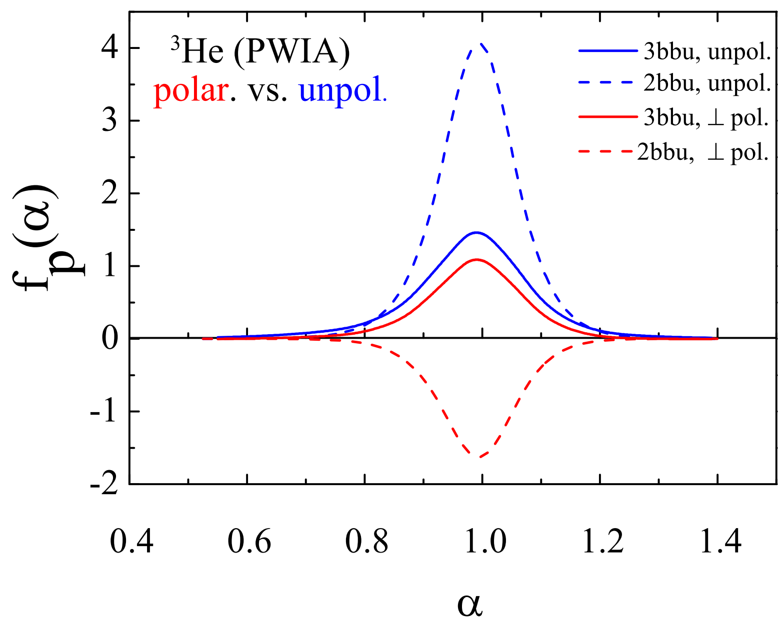
- LARGE A_{UT}^{Sivers} measured in $\vec{p}(e, e'\pi)x$ HERMES PRL 94, 012002 (2005)
- SMALL A_{UT}^{Sivers} measured in $\vec{D}(e, e'\pi)x$; COMPASS PRL 94, 202002 (2005)

A strong flavor dependence

Importance of the neutron for flavor decomposition!

Light-cone momentum distributions in IA



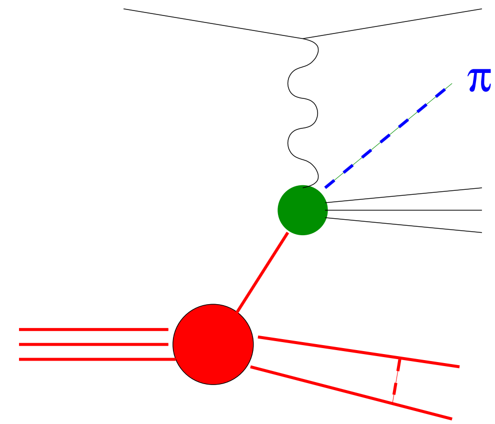


Calculation within the **Av18+UIX** interaction:

- weak depolarization of the neutron, $p_n = \int d\alpha \, f_n^{3He}(\alpha) = 0.878$
- strong depolarization of the protons, $p_p = \int d\alpha \, f_p^{3He}(\alpha) = -0.023$
- According to IA, in DIS, p_p and p_n safely take care of nuclear effects:

$$A_n \simeq \frac{1}{p_n f_n} \left(A_3^{exp} - 2 p_p f_p A_p^{exp} \right)$$

$\vec{n}$ from $^3\vec{H}e$: SIDIS case, IA



Is the extraction procedure tested in DIS valid also for the SSAs in SIDIS?

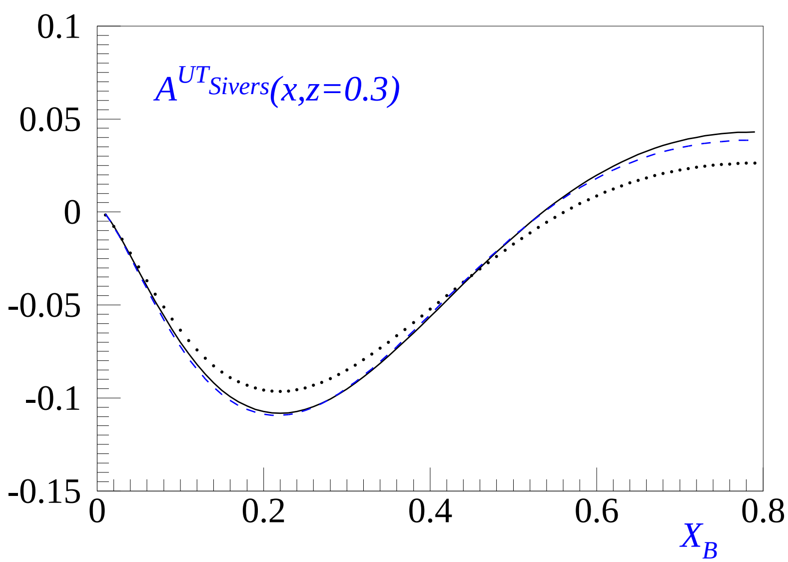
In a first paper on this subject,
(S.S., PRD 75 (2007) 054005)
the process $^3\vec{H}e(e,e'\pi)X$ has been evaluated :
* in the Bjorken limit
* in IA $\rightarrow$ no FSI between the measured fast, ultrarelativistic π the remnant and the two nucleon recoiling system
$E_\pi \simeq 2.4\ GeV$ in JLAB exp at $6\ GeV$ - Qian et al., PRL 107 (2011) 072003

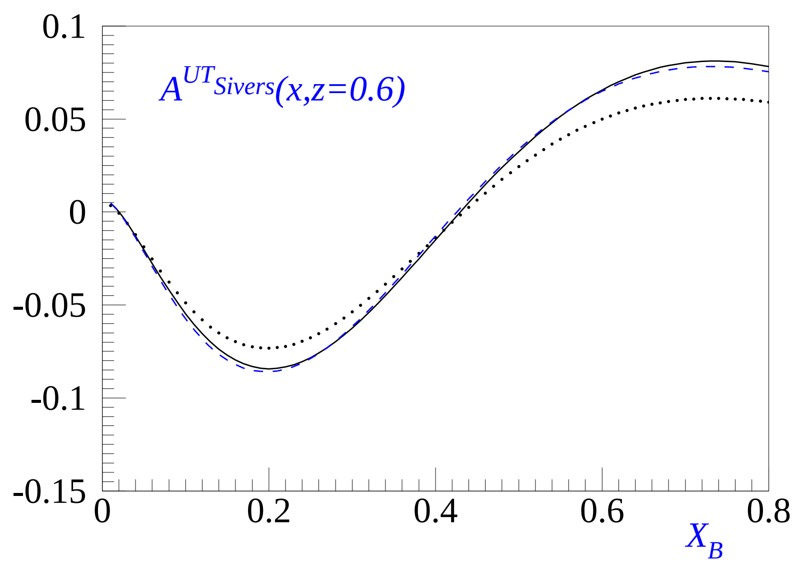
SSAs involve convolutions of the spin-dependent nuclear spectral function, $\vec{P}(\vec{p},E)$, with parton distributions and fragmentation functions

$$A \simeq \int d\vec{p}\, dE....\vec{P}(\vec{p},E)\ f_{1T}^{\perp q}\left(\frac{Q^2}{2p\cdot q},\mathbf{k_T^2}\right)\ D_1^{q,h}\left(\frac{p\cdot h}{p\cdot q},\left(\frac{p\cdot h}{p\cdot q}\kappa_{\mathbf{T}}\right)^2\right)$$

Specific nuclear effects, new with respect to the DIS case, can arise and have to be studied carefully

Results: $\vec{n}$ from ${}^3\vec{He}$: A_{UT}^{Sivers} , @ JLab, in IA





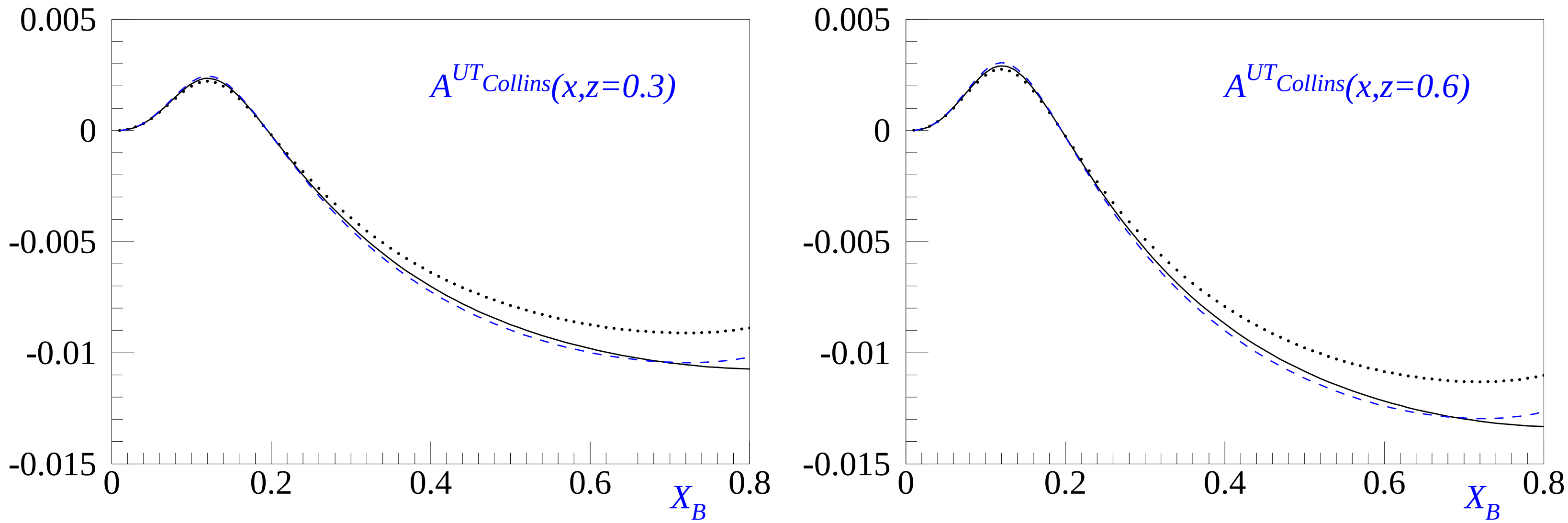
FULL: Neutron asymmetry (model: from parameterizations or models of TMDs and FFs)

DOTS: Neutron asymmetry extracted from ${}^3He$ (calculation) neglecting the contribution of the proton polarization $\bar{A}_n \simeq \frac{1}{f_n} A_3^{calc}$

DASHED : Neutron asymmetry extracted from ${}^3He$ (calculation) taking into account nuclear structure effects through the formula (f_n, f_p = "dilution factors"):

$$A_n \simeq \frac{1}{p_n f_n} \left(A_3^{calc} - 2 p_p f_p A_p^{model} \right)$$

Results: $\vec{n}$ from $^3\vec{He}$: $A_{UT}^{Collins}$, @ JLab



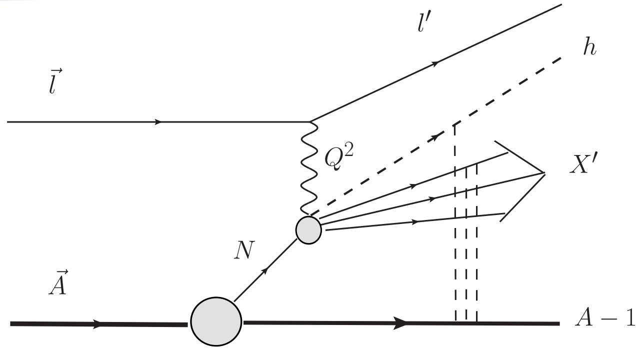
In the Bjorken limit the extraction procedure successful in DIS works also in SiDIS, for both the Collins and the Sivers SSAs !

What about FSI effects ?

(thinking to E12-09-018, A.G. Cates et al., approved with rate A @JLab 12)

FSI: Generalized Eikonal Approximation (GEA)

L. Kaptari, A. Del Dotto, E. Pace, G. Salmè, S.S., PRC 89 (2014) 035206



Relative energy between $A-1$ and the remnants: a few GeV
$\longrightarrow$ eikonal approximation.

$$d\sigma \simeq l^{\mu\nu} W^A_{\mu\nu}(S_A)$$

$$W^A_{\mu\nu}(S_A) \approx \sum_{S_{A-1},S_X} J^A_\mu J^A_\nu \qquad J^A_\mu \simeq \langle S_A \mathbf{P} | \hat{\mathbf{J}}^{\mathbf{A}}_\mu(\mathbf{0}) | \mathbf{S_X}, \mathbf{S_{A-1}}, \mathbf{P_{A-1}} \mathbf{E^f_{A-1}} \rangle$$

$$\langle S_A \mathbf{P} | \mathbf{r_1 r_2 r_3} \rangle = \mathbf{\Phi_{3_{He}}}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) = \mathcal{A}\, \mathbf{e^{iPR}} \mathbf{\Psi_3^{S_A}}(\rho, \mathbf{r})$$

$$\langle \mathbf{r_1 r_2 r_3} | S_X, S_{A-1} \mathbf{P_{A-1}} \mathbf{E^f_{A-1}} \rangle = \Phi^*_f(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) \approx \hat{S}_{Gl}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) \mathbf{\Psi}^{*\mathbf{f}}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3})$$

$$\approx \hat{S}_{Gl}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) \sum_{\mathbf{j>k}} \chi^+_{\mathbf{S_X}} \phi^*(\xi_{\mathbf{x}}) \mathbf{e^{-ip_X r_i}} \mathbf{\Psi^{*f}_{jk}}(\mathbf{r_j}, \mathbf{r_k}) \, ,$$

$$\boxed{\hat{S}_{Gl} = Glauber\ operator}$$

$$J^A_\mu \approx \int d\mathbf{r_1} d\mathbf{r_2} d\mathbf{r_3} \Psi^{*f}_{23}(\mathbf{r_2}, \mathbf{r_3}) e^{-i\mathbf{p}_X \mathbf{r_i}} \chi^+_{S_X} \phi^*(\xi_x) \cdot \hat{S}_{Gl}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) \hat{j}_\mu(\mathbf{r_1}, X) \vec{\Psi}_3^{\mathbf{S}_A}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3})$$ (-6

IF ($FACTORIZED$ FSI !) $\left[\hat{S}_{Gl}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3), \hat{j}_\mu(\mathbf{r_1})\right] = 0$ THEN:

$$W^A_{\mu\nu} = \sum_{N,\lambda,\lambda'} \int dE\, d\mathbf{p}\, w^{N,\lambda\lambda'}_{\mu\nu}(\mathbf{p})\, P^{FSI,A,N}_{\lambda\lambda'}(E, \mathbf{p}, ...) \qquad CONVOLUTION!$$

FSI: *distorted* spin-dependent spectral function of ^{3}He

L. Kaptari, A. Del Dotto, E. Pace, G. Salmè, S.S., PRC 89 (2014) 035206

Relevant part of the (GEA-distorted) spin dependent spectral function:

$$\mathcal{P}_{||}^{IA(FSI)} = \mathcal{O}_{\frac{1}{2}\frac{1}{2}}^{IA(FSI)} - \mathcal{O}_{-\frac{1}{2}-\frac{1}{2}}^{IA(FSI)}; \qquad \text{with:}$$

$$\mathcal{O}_{\lambda\lambda'}^{IA(FSI)}(p_N, E) = \sum\!\!\!\!\!\!\int_{\epsilon^*_{A-1}} \rho\left(\epsilon^*_{A-1}\right) \langle S_A, \mathbf{P_A}|(\hat{S}_{Gl})\{\Phi_{\epsilon^*_{A-1}}, \lambda', \mathbf{p}_N\}\rangle \times$$
$$\langle(\hat{S}_{Gl})\{\Phi_{\epsilon^*_{A-1}}, \lambda, \mathbf{p}_N\}|S_A, \mathbf{P_A}\rangle \delta\left(E - B_A - \epsilon^*_{A-1}\right).$$

Glauber operator: $\hat{S}_{Gl}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3) = \prod_{i=2,3}\left[1 - \theta(z_i - z_1)\Gamma(\mathbf{b}_1 - \mathbf{b}_i, z_1 - z_i)\right]$

(generalized) profile function: $\Gamma(\mathbf{b}_{1i}, z_{1i}) = \frac{(1-i\,\alpha)\ \sigma_{eff}(z_{1i})}{4\,\pi\,b_0^2} \exp\left[-\frac{\mathbf{b}_{1i}^2}{2\,b_0^2}\right]$,

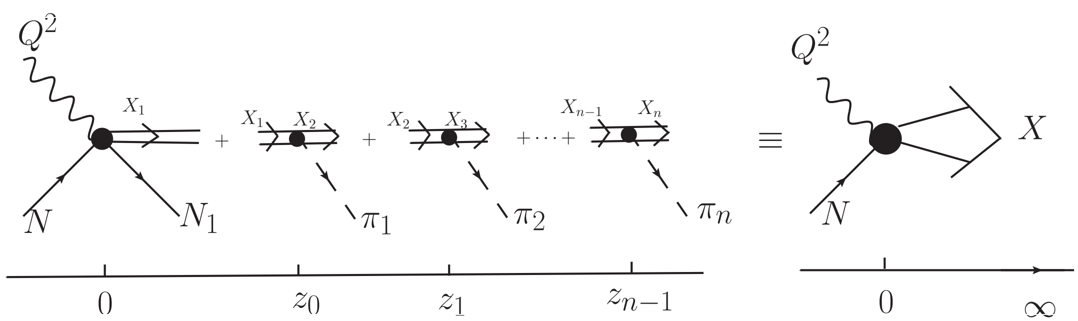
GEA (Γ depends also on the longitudinal distance between the debris and the scattering centers z_{1i}!) very successful in q.e. semi-inclusive and exclusive processes off ^{3}He

see, e.g., Frankfurt, Sargsian, Strikman PRC 56 (1997) 1124; Alvioli, Ciofi & Kaptari PRC 81 (2010) 02100 and references there in

A hadronization model is necessary to define $\sigma_{eff}(z_{1i})$...

FSI: *the hadronization model*

Hadronization model **(Kopeliovich et al., NPA 2004)**
+ σ_{eff} model for SIDIS **(Ciofi & Kopeliovich, EPJA 2003)**
GEA + hadronization model succesfully applied to unpolarized SIDIS $^2H(e,e'p)X$
(Ciofi & Kaptari PRC 2011).



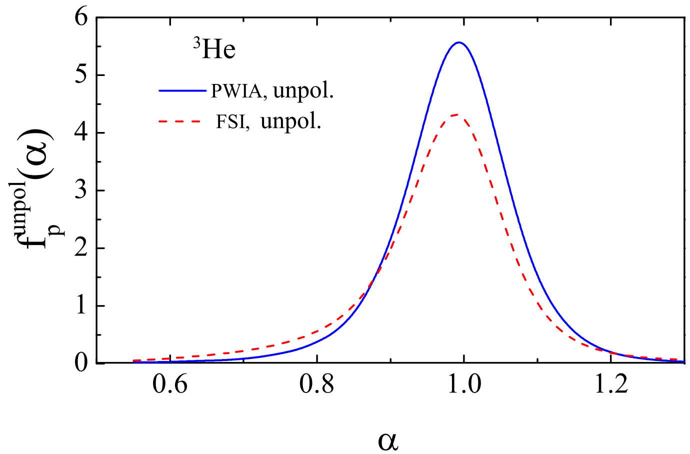
$$\sigma_{eff}(z) = \sigma_{tot}^{NN} + \sigma_{tot}^{\pi N}\,[n_M(z) + n_g(z)]$$

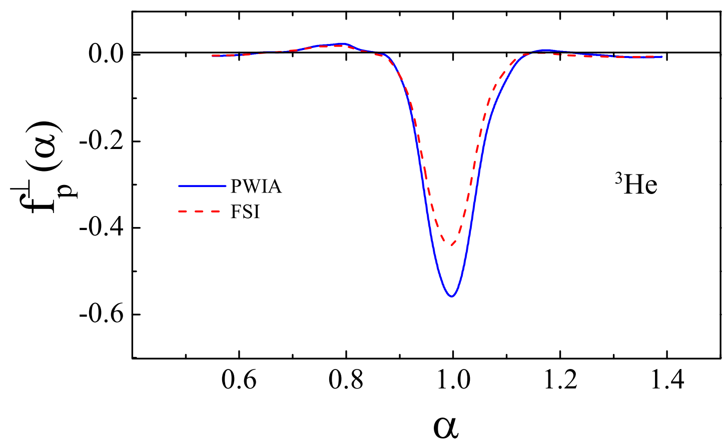
- The hadronization model is phenomenological: parameters are chosen to describe the scenario of JLab experiments (e.g., $\sigma_{NN}^{tot} = 40$ mb, $\sigma_{\pi N}^{tot} = 25$ mb, $\alpha = -0.5$ for both NN and πN...).
  According to high energy $N-N$ scattering data, $\sigma_{eff}(z)$ is taken spin-independent (see, e.g., **Alekseev et al., PRD 79 (2009) 094014**)

light-cone momentum distributions with FSI:

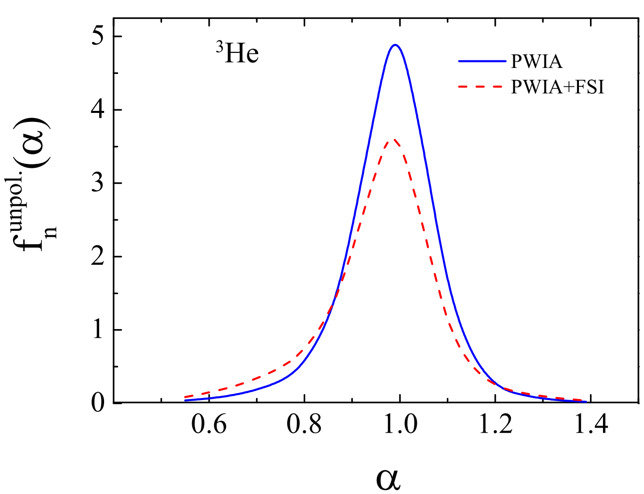
Del Dotto, Kaptari, Pace, Salmè, S.S., PRC 96 (2017) 065203

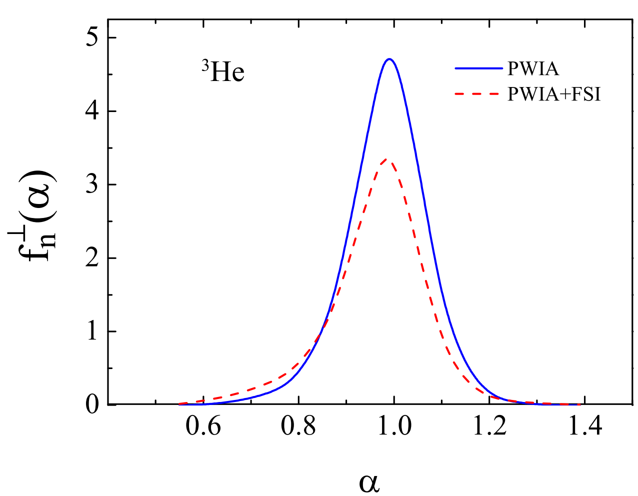
PROTON @ E_i = 8.8 GeV





NEUTRON @ E_i = 8.8 GeV





Effective polarizations change...

Does the strong FSI effect hinder the neutron extraction?

Actually, one should also consider the effect on dilution factors f_N

DILUTION FACTORS

$$A_3^{exp} \simeq \frac{\Delta\vec{\sigma}_3^{exp.}}{\sigma_{unpol.}^{exp.}} \Longrightarrow \frac{\langle \vec{s}_n \rangle \Delta\vec{\sigma}(n) + 2\langle \vec{s}_p \rangle \Delta\vec{\sigma}(p)}{\langle N_n \rangle \sigma_{unpol.}(n) + 2\langle N_p \rangle \sigma_{unpol.}(p)} = \langle \vec{s}_n \rangle f_n A_n + 2\langle \vec{s}_p \rangle f_p A_p$$

PWIA:

$$\langle \vec{s}_{n(p)} \rangle = \int dE \int d^3p P_{||}(E, \mathbf{p}) = p_{n(p)};$$
$$\langle N \rangle = \int dE \int d^3p P_{unpol.}(E, \mathbf{p}) = 1.$$

$$\Longrightarrow \quad f_{n,(p)}(x,z) = \frac{\sum_q e_q^2 f_1^{q,n(p)}(x) D_1^{q,h}(z)}{\sum_N \sum_q e_q^2 f_1^{q,N}(x) D_1^{q,h}(z)}$$

FSI:

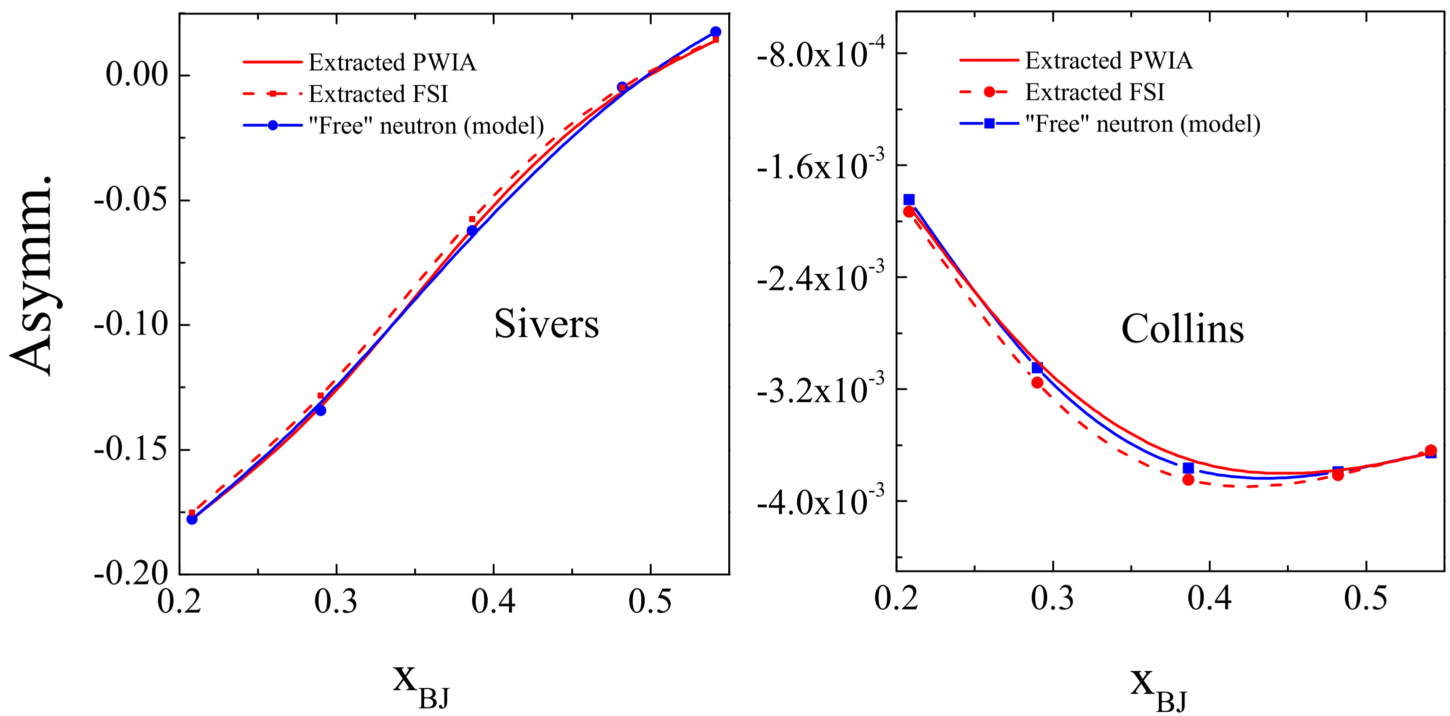
$$\langle \vec{s}_{n(p)} \rangle = \int dE \int d^3p P_{||}^{FSI}(E, \mathbf{p}) = p_{n(p)}^{FSI};$$
$$\langle N \rangle = \int dE \int d^3p P_{unpol.}^{FSI}(E, \mathbf{p}) < 1.$$

$$\Longrightarrow \quad f_{n,(p)}^{FSI}(x,z) = \frac{\sum_q e_q^2 f_1^{q,n(p)}(x) D_1^{q,h}(z)}{\sum_N \langle N \rangle \sum_q e_q^2 f_1^{q,N}(x) D_1^{q,h}(z)}$$

$$A_n \approx \frac{1}{p_n^{FSI} f_n^{FSI}} \left(A_3^{exp} - 2 p_p^{FSI} f_p^{FSI} A_p^{exp} \right) \approx \frac{1}{p_n f_n} \left(A_3^{exp} - 2 p_p f_p A_p^{exp} \right)$$

2

Good news from GEA studies of FSI!



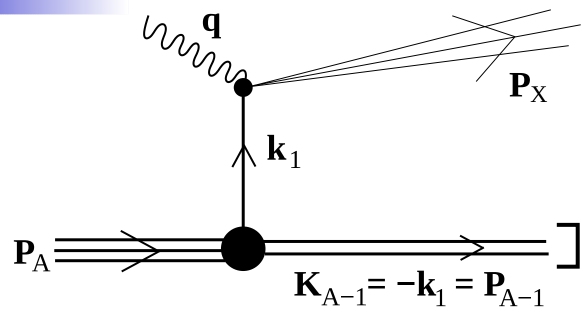
Effects of GEA-FSI (shown at $E_i = 8.8$ GeV) in the dilution factors and in the effective polarizations compensate each other to a large extent: the usual extraction is safe!

$$A_n \approx \frac{1}{p_n^{FSI} f_n^{FSI}} \left(A_3^{exp} - 2 p_p{}^{FSI} f_p^{FSI} A_p^{exp} \right) \approx \frac{1}{p_n f_n} \left(A_3^{exp} - 2 p_p f_p A_p^{exp} \right)$$

A. Del Dotto, L. Kaptari, E. Pace, G. Salmè, S.S., PRC 96 (2017) 065203

Now: *spectator* SIDIS...

We studied the process $A(e, e'(A-1))X$ many years ago



In this process, in IA, no convolution!

$$d^2\sigma_A \propto F_2^N(x)$$

for the deuteron: Simula PLB 1997;

Melnitchouk, Sargsian, Strikman ZPA 1997; BONUS@JLab

Example: through ^{3}He(e,e'd)X, F_2^p, check of the reaction mechanism (EMC effect); measuring ^{3}H(e,e'd)X, direct access to the neutron F_2^n!

new perspectives: loi to the JLab PAC, already in November 2010;

now: approved experiments at JLab!

ALERT run group, arXiv:1708.00891 [nucl-ex], for ^{4}He...

Eur. Phys. J. A 5, 191–207 (1999)

THE EUROPEAN PHYSICAL JOURNAL A

Semi-inclusive deep inelastic lepton scattering off complex nuclei

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Communicated by B. Povh

Abstract. It is shown that in semi-inclusive deep inelastic scattering (DIS) of electrons off complex nuclei, the detection, in coincidence with the scattered electron, of a nucleus $(A-1)$ in the ground state, as well as of a nucleon and a nucleus $(A-2)$, also in the ground state, may provide unique information on several long standing problems, such as: *i*) the nature and the relevance of the final state interaction in DIS; *ii*) the validity of the spectator mechanism in DIS; *iii*) the medium induced modifications of the nucleon structure function; *iv*) the origin of the *EMC* effect.

PACS. 13.40.-f Electromagnetic processes and properties – 21.60.-n Nuclear-structure models and methods – 24.85.+p Quarks, gluons, and QCD in nuclei and nuclear processes – 25.60.Gc Breakup and momentum distributions

Semi-inclusive Deep Inelastic Scattering from Light Nuclei by Tagging Low Momentum Spectators

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(Dated: November 24, 2010)

Abstract

We propose to measure the semi-inclusive deep inelastic scattering from light nuclei (D,^{3}He, ^{4}He). The detection of the low energy recoil nucleus in the final state will provide unique information about the nature of nuclear EMC effect and will permit to investigate the modifications of the nucleon structure functions in the nucleus. We propose to measure a set of observable by using the future 11 GeV electron beam in Hall B CLAS12. The baseline CLAS12 detector is suitable to detect electrons in the valence region, and a new low energy recoil detector with good performance is required to achieve the proposed physics goals.

Spectator SIDIS $^3\vec{\mathrm{He}}(\vec{e}, e'\ ^2\mathrm{H})X \rightarrow\ g_1^p$ for a bound proton

Kaptari, Del Dotto, Pace, Salmè, Scopetta PRC 89, 035206 (2014)

The distorted spin-dependent spectral function with the Glauber operator $\hat{G}$ can be applied to the "spectator SIDIS" process, where a slow deuteron is detected.

Goal $\longrightarrow$ $g_1^N(x_N = \frac{Q^2}{2p_N q})$ of a bound nucleon.

A_{LL} of electrons with opposite helicities scattered off a longitudinally polarized ^{3}He for parallel kinematics ($\mathbf{p}_N = -\mathbf{p}_{mis} \equiv -\mathbf{P}_{A-1} \parallel \hat{z}$, with $\hat{z} \equiv \hat{\mathbf{q}}$)

$$\frac{\Delta\sigma^{\hat{\mathbf{S}}_A}}{d\varphi_e\, dx\, dy\, d\mathbf{P}_D} \equiv \frac{d\sigma^{\hat{\mathbf{S}}_A}(h_e = 1) - d\sigma^{\hat{\mathbf{S}}_A}(h_e = -1)}{d\varphi_e\, dx\, dy\, d\mathbf{P}_D} =$$

$$\approx 4\frac{\alpha_{em}^2}{Q^2 z_N \mathcal{E}} \frac{m_N}{E_N}\, g_1^p\left(\frac{x}{z}\right)\mathcal{P}_{||}^{\frac{1}{2}}(\mathbf{p}_{mis})\mathcal{E}(2-y)\left[1 - \frac{|\mathbf{p}_{mis}|}{m_N}\right] \qquad \textit{Bjorken limit}$$

$$x = \frac{Q^2}{2m_N\nu}, \quad y = (\mathcal{E} - \mathcal{E}')/\mathcal{E}, \quad z = (p_N \cdot q)/m_N\nu$$

$$\mathcal{P}_{||}^{\frac{1}{2}}(\mathbf{p}_{mis}) = \mathcal{O}_{\frac{1}{2}\frac{1}{2}}^{\frac{1}{2}\frac{1}{2}} - \mathcal{O}_{-\frac{1}{2}-\frac{1}{2}}^{\frac{1}{2}\frac{1}{2}}$$ parallel component of the spectral function

$$\mathcal{O}_{\lambda\lambda'}^{\mathcal{M}\mathcal{M}'(FSI)}(\mathbf{P_D}, E_{2bbu}) = \left\langle \hat{G}\left\{\Psi_{\mathbf{P}_D}, \lambda, \mathbf{p}_N\right\}|\Psi_A^{\mathcal{M}}\right\rangle_{\hat{\mathbf{q}}} \left\langle \Psi_A^{\mathcal{M}'}|\hat{G}\left\{\Psi_{\mathbf{P}_D}, \lambda', \mathbf{p}_N\right\}\right\rangle_{\hat{\mathbf{q}}}$$

Using ^{3}H one would get the neutron!

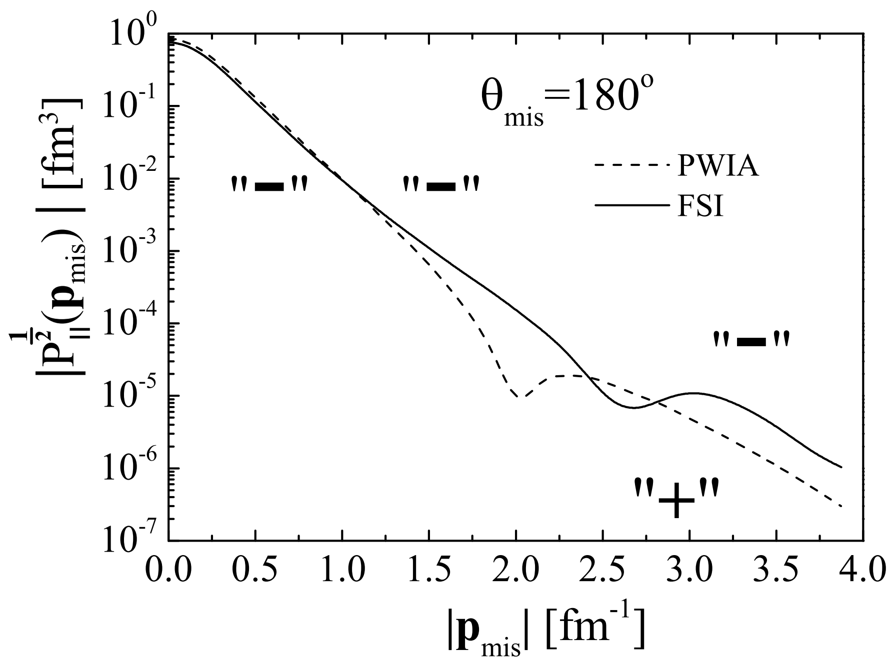
Spectator SIDIS $^3\vec{\mathrm{He}}(\vec{e}, e'\,^2\mathrm{H})X \rightarrow g_1^p$ for a bound proton

Kaptari, Del Dotto, Pace, Salme', Scopetta PRC 89, 035206 (2014)

The kinematical variables upon which $g_1^N(x_N)$ depends can be changed independently from the ones of the nuclear-structure $\mathcal{P}^{\frac{1}{2}}_{||}(\mathbf{p}_{mis})$. This allows to single out a kinematical region region where the final-state effects are minimized: $|\mathbf{p}_{mis} \equiv \mathbf{P}_D| \simeq 1 fm^{-1}$

Possible direct access to $g_1^N(x_N)$.

At JLab, $\mathcal{E} = 12\ GeV$, $-\mathbf{p}_{mis} \parallel \mathbf{q}$:



The quest for covariance

- Mandatory to achieve polinomiality for GPDs, and sum rules satisfied in DIS: number of particle and momentum sum rule not fulfilled at the same time in IF
- Numerically not very relevant for forward Physics. 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).

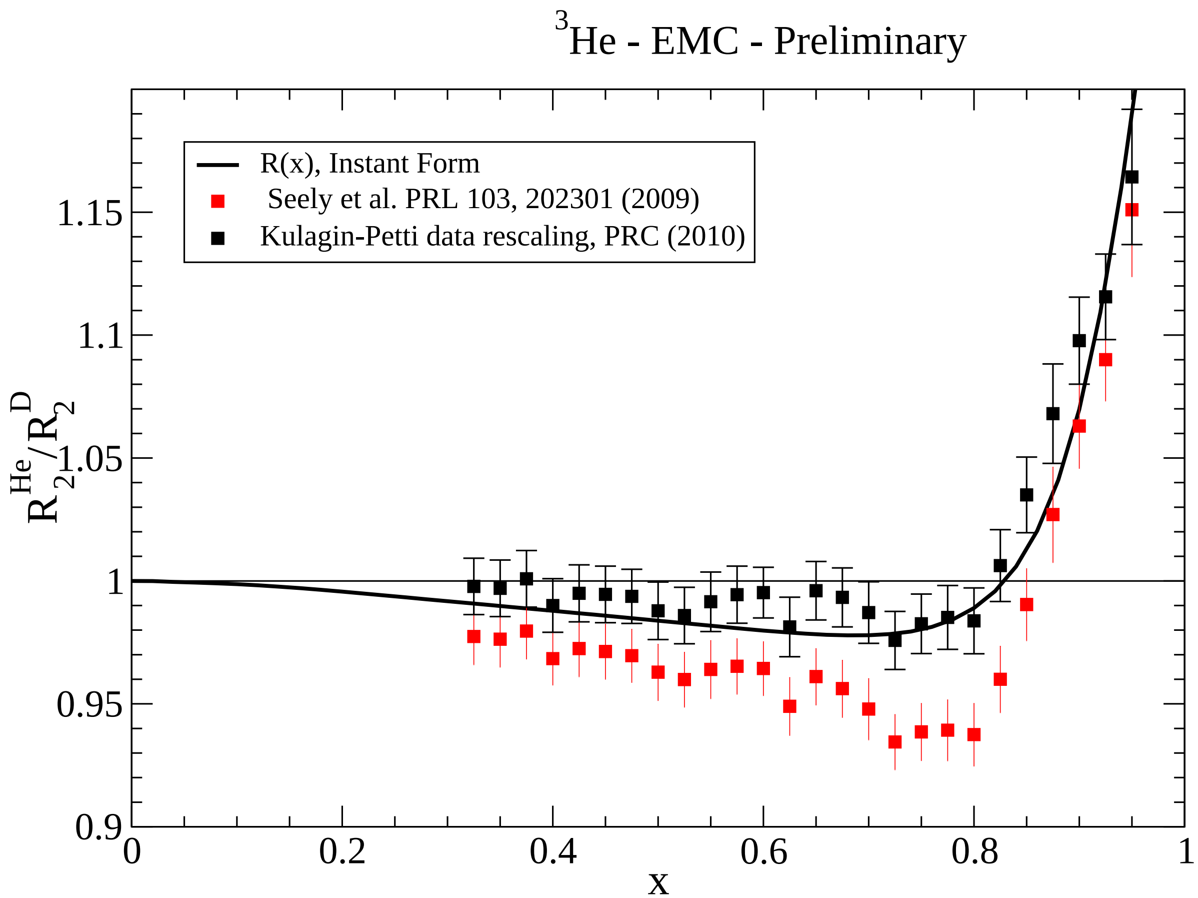
Perspectives

- **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

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

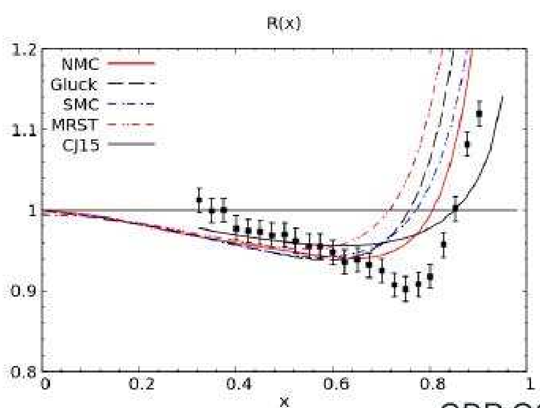
$$R(x) = \frac{F_2^{^4He}(x)}{F_2^d(x)} \qquad x \in [0 : M_A/M]$$

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*

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

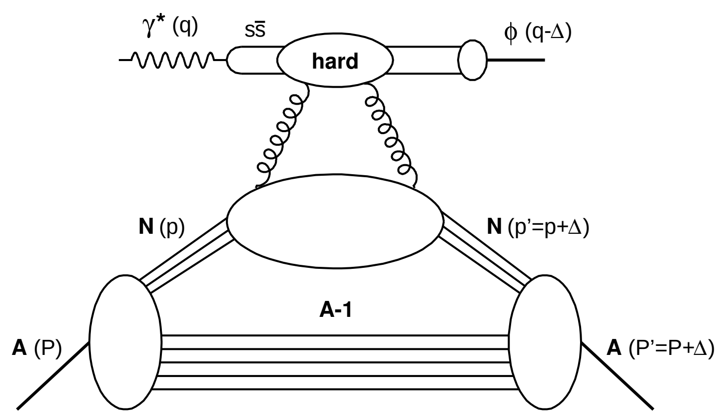


- Our model isn't predictive at small x
- Good agreement in the valence region
- Strong dependence on the model for F_2^N at large x
- Need to better unravel the Q^2 dependence of $R(x)$

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

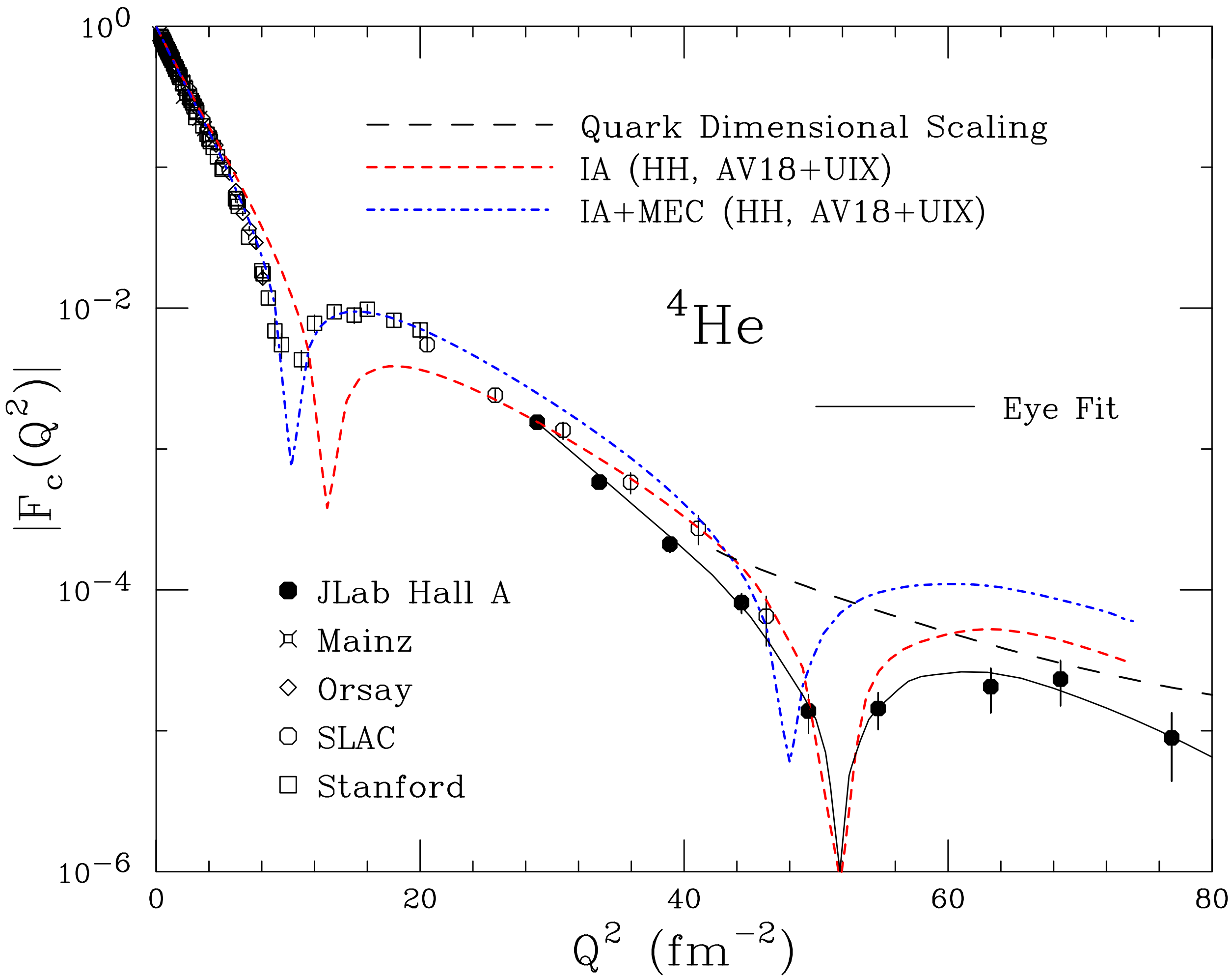
Backup: Many other issues...

- $x-$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

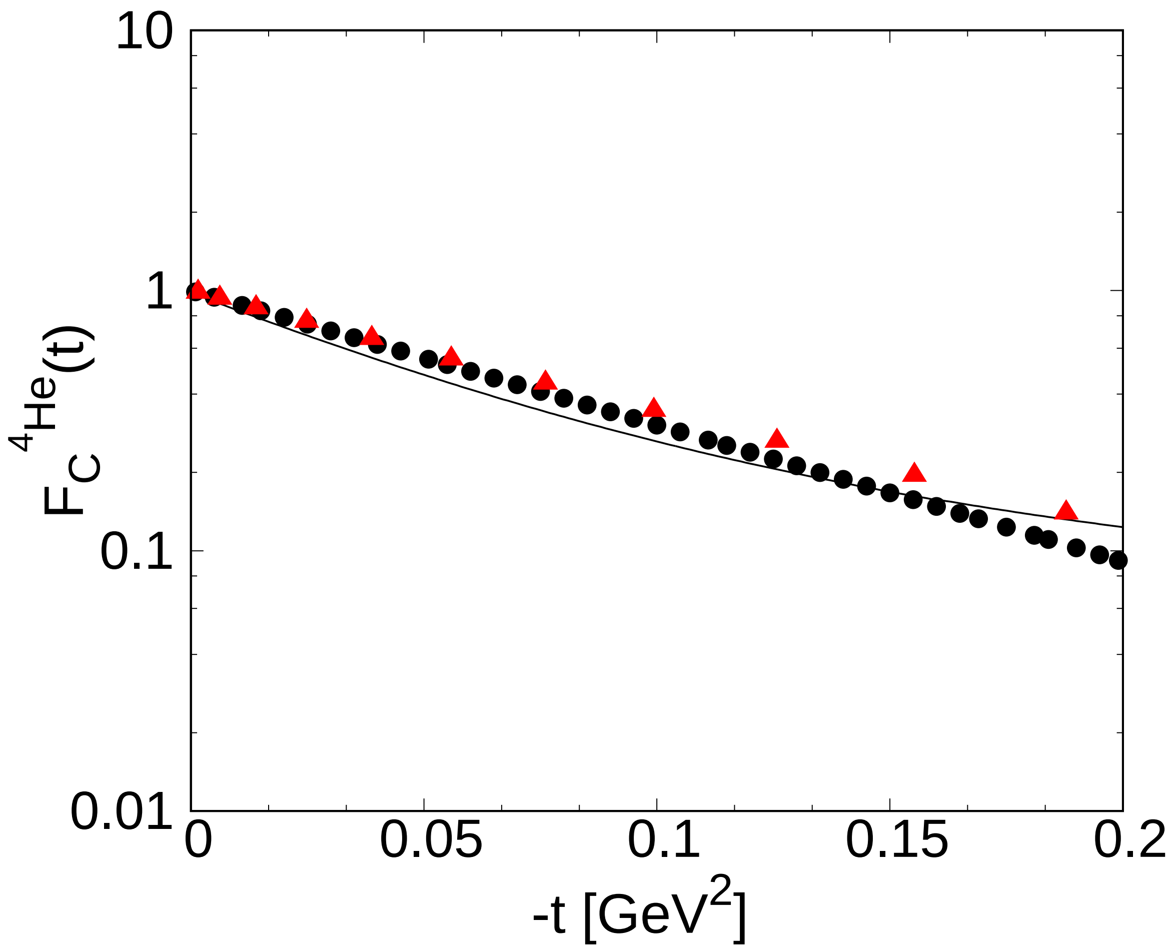


  For GPDs, shadowing (low x_B) stronger than for PDFs
  A. Freund and M. Strikman, PRC 69, 015203 (2004)...
  Exclusive $\phi-$ electroproduction, unique source of information, studied by ALERT, waiting for EIC...
- Deuteron: an issue aside.
  Extraction of the neutron information; access to a new class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

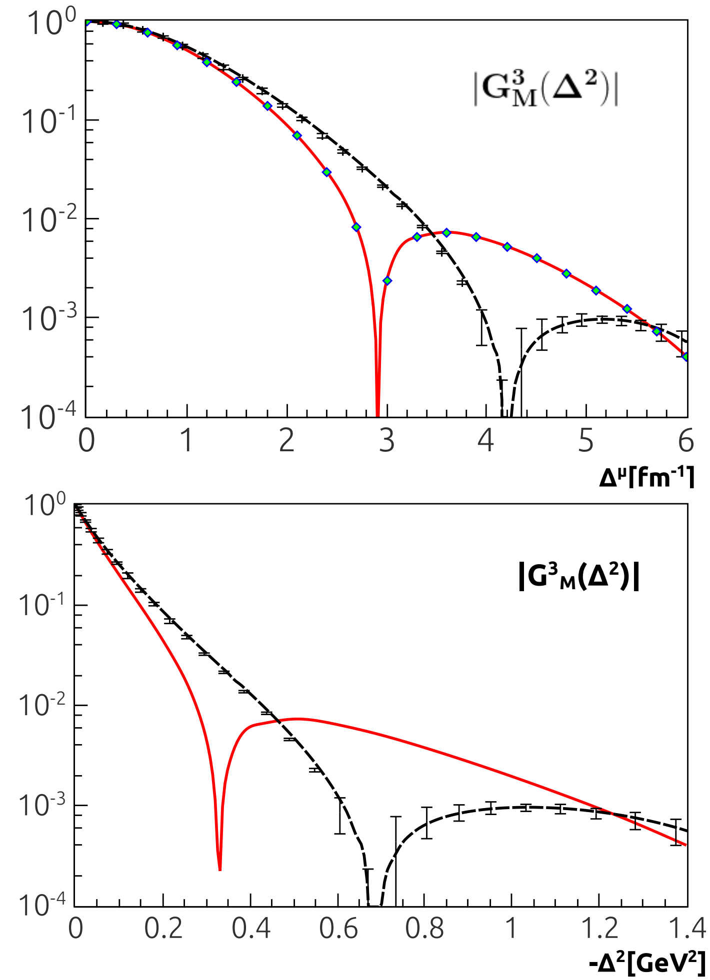
For $\tilde{G}_M^{3}$ (**M. Rinaldi, S.S. PRC 85, 062201(R) (2012); PRC 87, 035208 (2013)**):

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

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

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

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

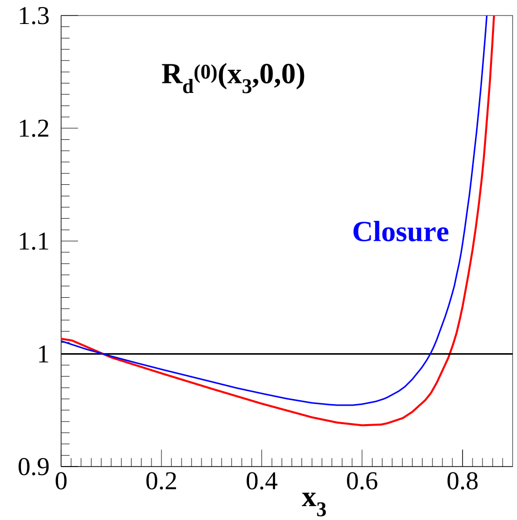
using the Closure Approximation, $E_f^* = \bar{E}$:

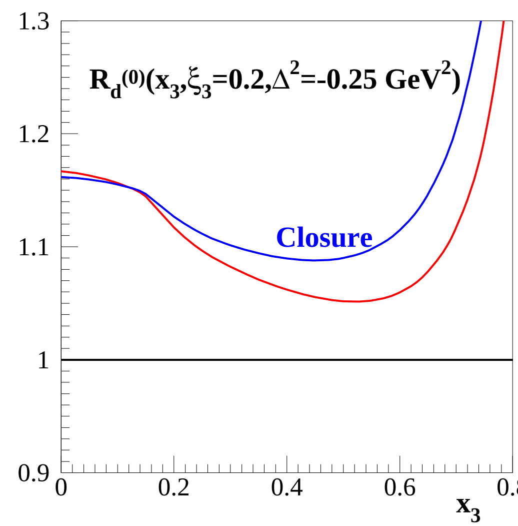
$$P_N^3(\vec{p},\vec{p}+\vec{\Delta},E) \simeq \bar{\sum}_M \sum_s \langle \vec{P}'M|a_{\vec{p}+\vec{\Delta},s}\,a^\dagger_{\vec{p},s}|\vec{P}M\rangle$$

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

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

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

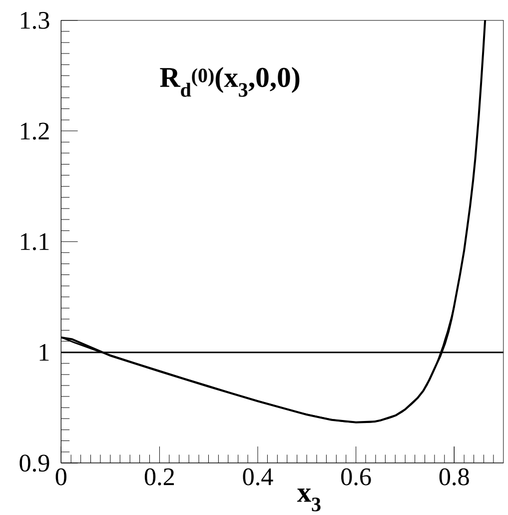




Backup: Dependence on the NN interaction

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: