3D nuclear parton structure

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Outline

The nucleus:

- very interesting by itself;
- *"a Lab for QCD fundamental studies"*

Selected topics **(based on R. Dupré, S,S. EPJA 52 (2016) 159)**:

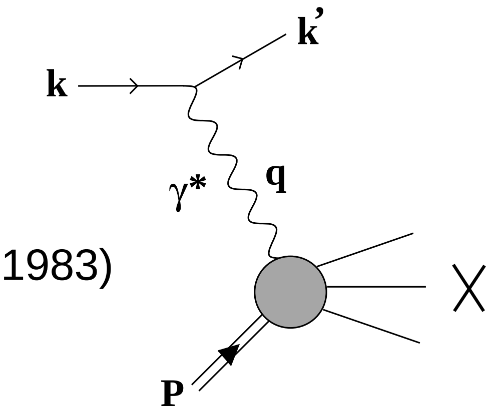
- **1 - DVCS off nuclei (GPDs)**:
  Medium modification of the 3D nucleon structure - origin of the EMC effect
  nuclei as a Lab to study the parton structure of $bound$ nucleon

- **2 - SIDIS off nuclei (TMDs)**:
  Neutron TMDs from SIDIS off light nuclei
  nuclei as a Lab to study the $free$ nucleon

Prospects at the EIC

(issues concerning the onset of saturation scale and related to gluon TMDs, as well as in-medium hadronization as a probe of confinement, motivating the EIC, discussed in other sessions and not addressed here...)

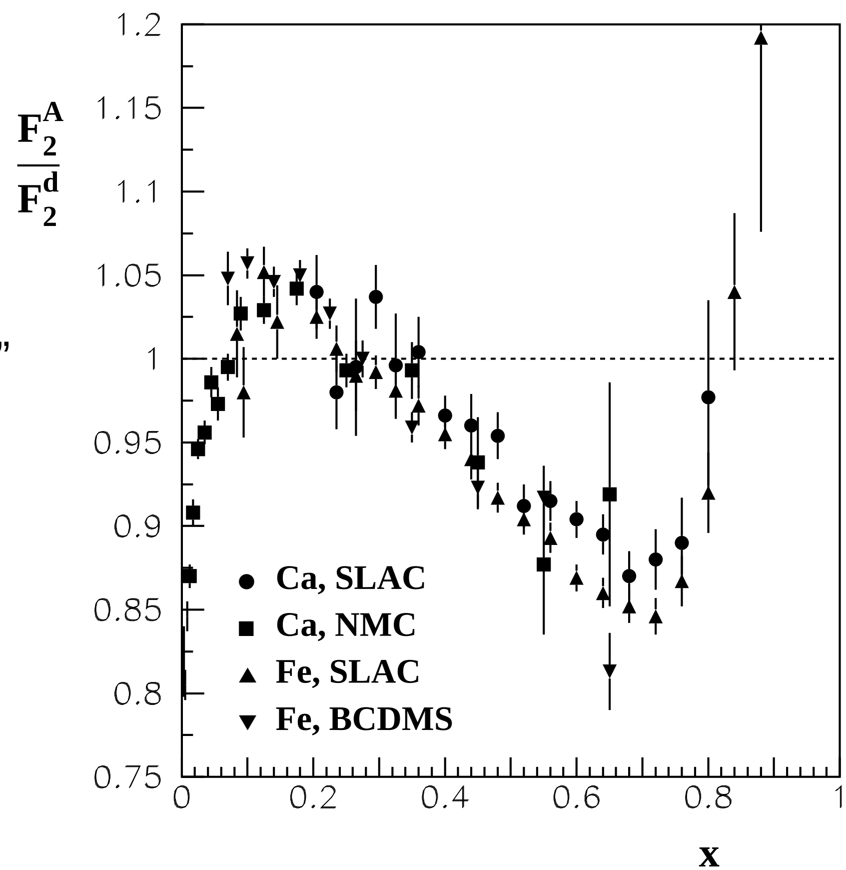
EMC effect in A-DIS



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?

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

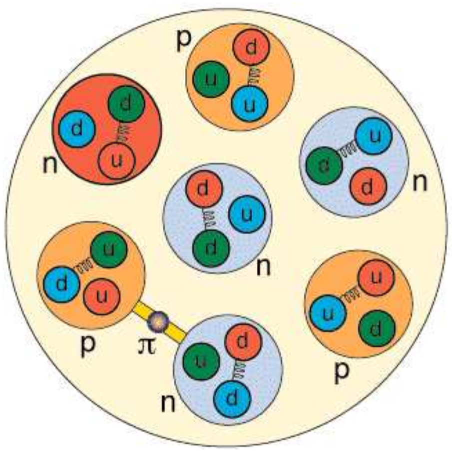
One has to go beyond

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

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

EMC effect: way out?

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



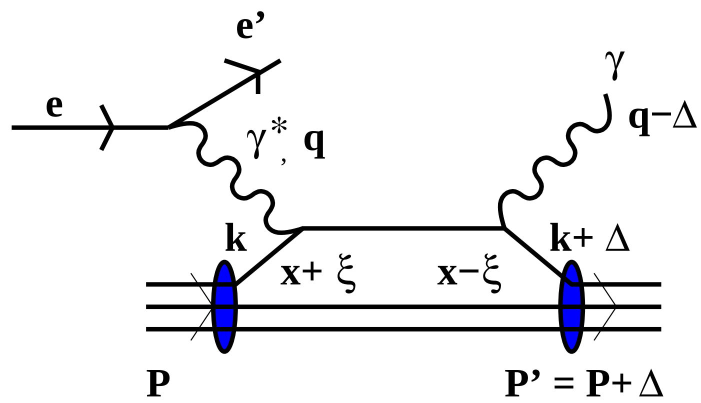
To answer, we should perform a *tomography...*

We can!

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,
($Q^2, \nu \to \infty$)
such as (coherent) DVCS:



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

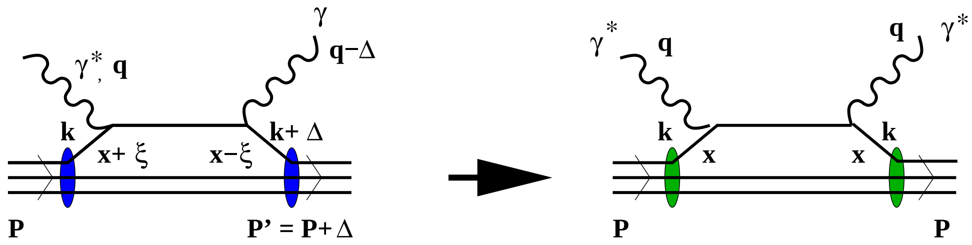
$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P' | \bar{\psi}_q(-\lambda n/2) \quad \gamma^\mu \quad \psi_q(\lambda n/2) | P \rangle = H_q(x,\xi,\Delta^2) \bar{U}(P')\gamma^\mu U(P)$$

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

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

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

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

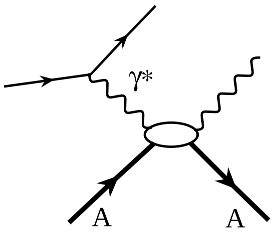
$$\Longrightarrow \int dx\, H_q(x,\xi,\Delta^2) = F_1^q(\Delta^2) \qquad \int dx\, E_q(x,\xi,\Delta^2) = F_2^q(\Delta^2)$$

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

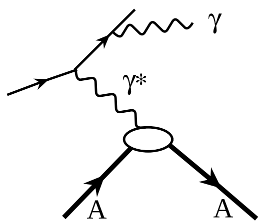
GPDs: a unique tool...

- 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:

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

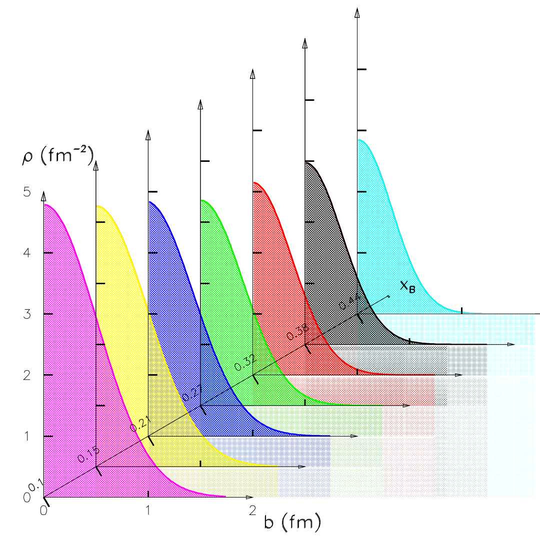
- Competition with the **BH** process! (σ asymmetries measured).

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

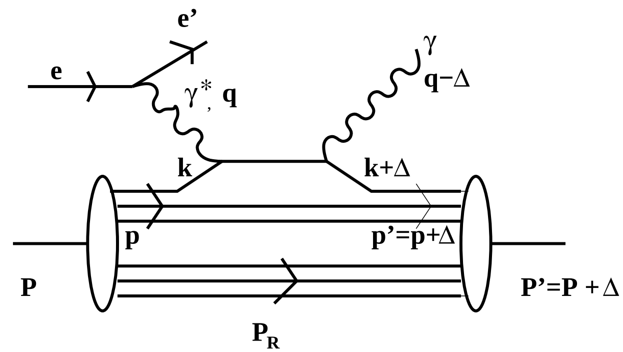
Nevertheless, for the proton, we have results:

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

Dupré, Guidal, Niccolai, Vanderhaeghen arXiv:1704.07330 [hep-ph])



Nuclei: why?



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

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

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

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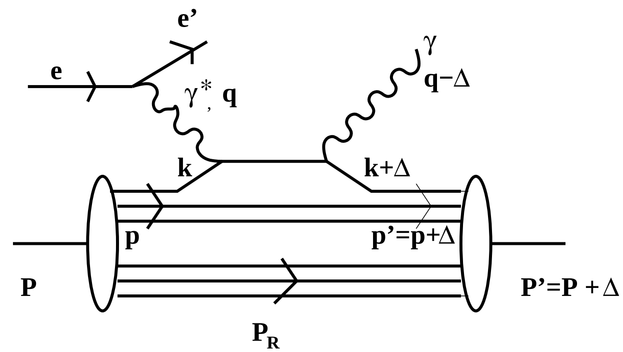

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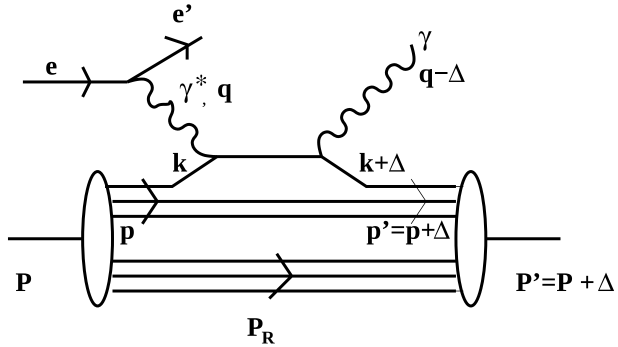
$$

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

Nuclei: why?



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\end{aligned}
$$

one has, for a given GPD

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

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,

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

$$\times \quad \langle(\vec{P}-\vec{p})S_R,\vec{p}s|\vec{P}M\rangle\, \delta(E-E_{min}-E_R^*)\ .$$

Why nuclei?

The obtained expressions have the correct limits:

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

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

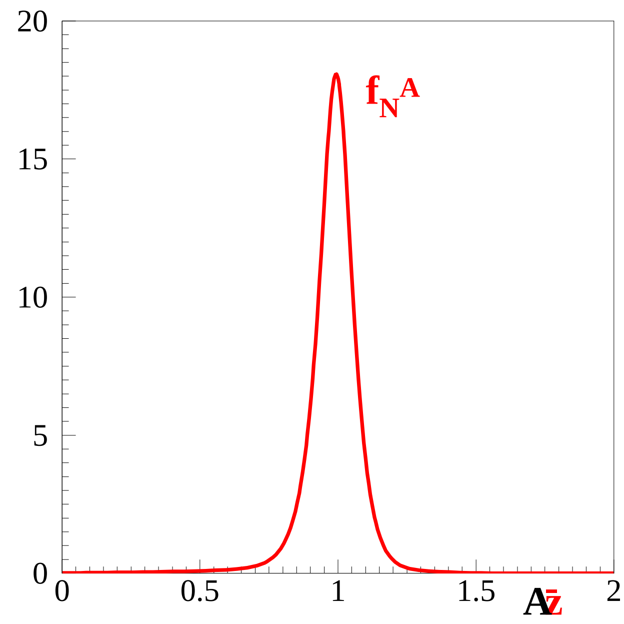
- forward limit (standard DIS):

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

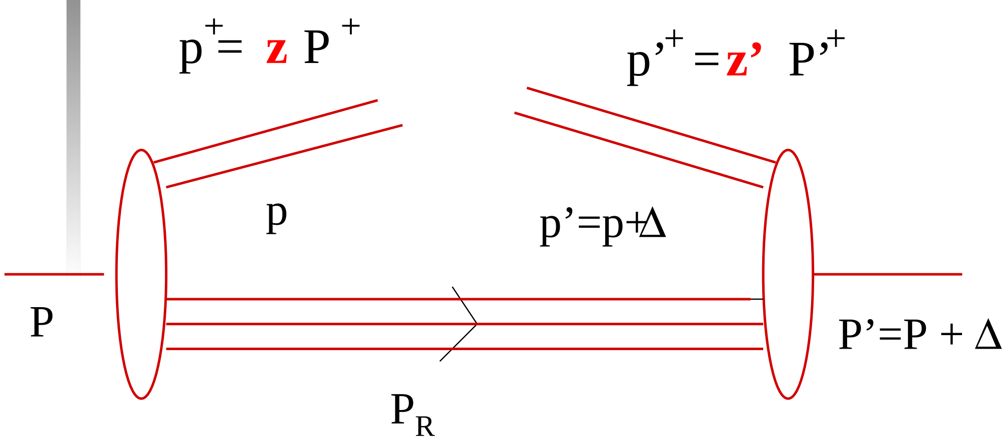
with the light-cone momentum distribution:

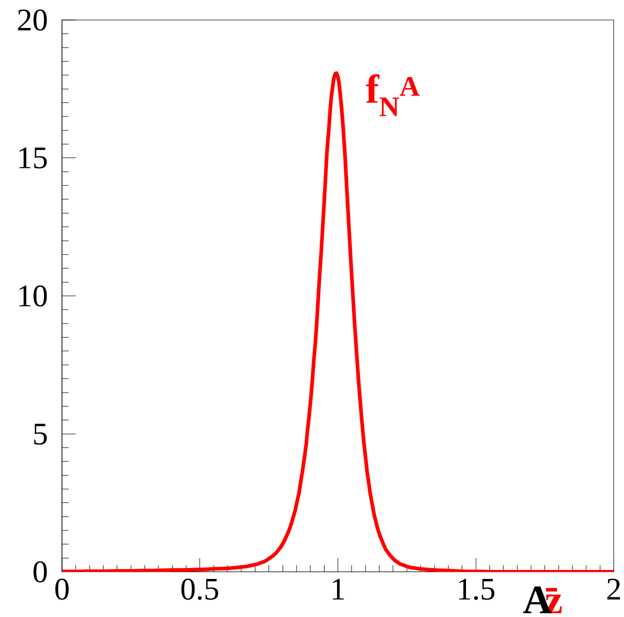
$f_N^A(\tilde{z}) = \int dE d\vec{p}\, P_N^A(\vec{p},E)\delta\left(\tilde{z} - \frac{p^+}{P^+}\right)$,

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



Why nuclei?



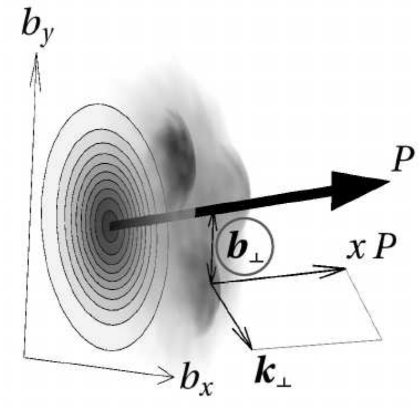


Since $z - z' = -x_B(1-z)/(1-x_B)\,,$ $\xi \simeq x_B/(2-x_B)$ can be tuned to have $z - z'$ larger than the width of the narrow nuclear light-cone momentum distribution $f_N^A(\bar{z} = (z+z')/2)$: in this case IA predicts a $vanishing$ GPD, at $small\ x_B$.

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

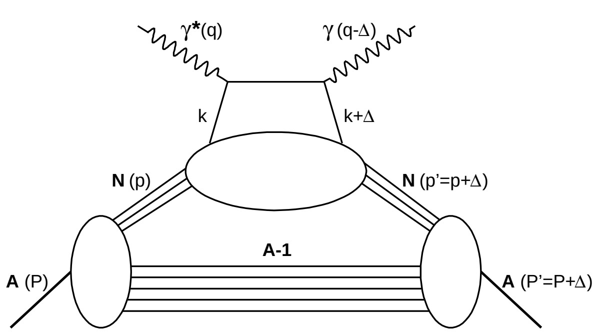
Similar effect predicted in DIS at $x_B > 1$, where DIS data are not accurate enough.

Nuclei and DVCS tomography

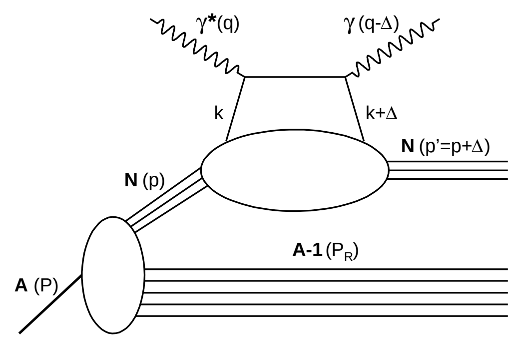


In impact parameter space, GPDs are *densities*:

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



Coherent DVCS:
nuclear tomography;



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

- 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...

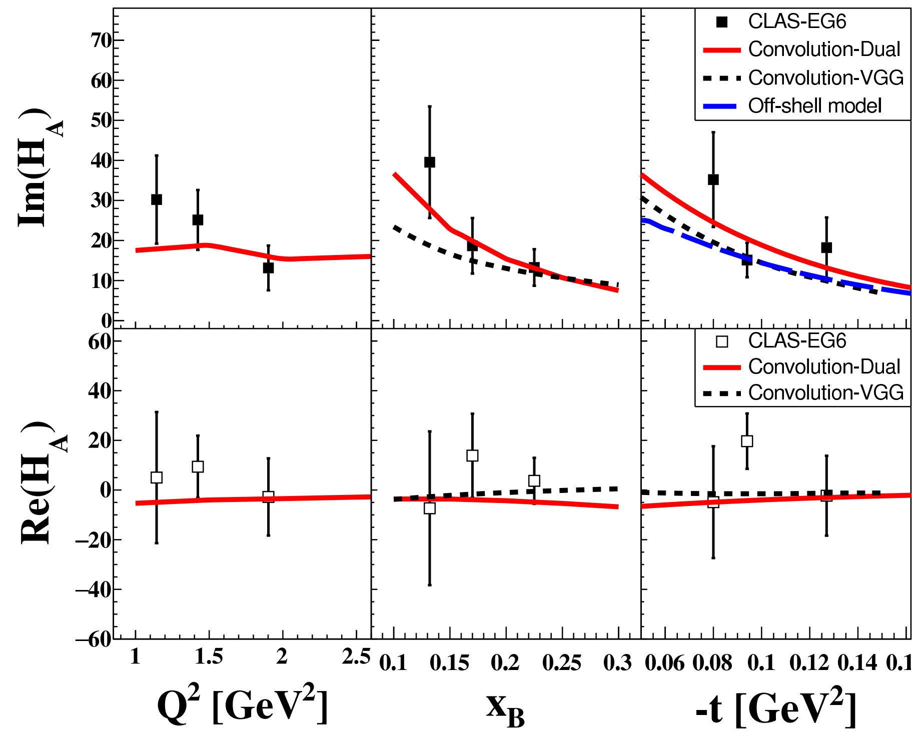
... But possible! Just released from CLAS!

(M. Hattawy et al. arXiv:1707.03361v1 [nucl-ex])

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

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

IA calculation, Guzey
(full, dashed, different GPD models)
(**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...**

Nuclear GPDs: ^{3}He calculations

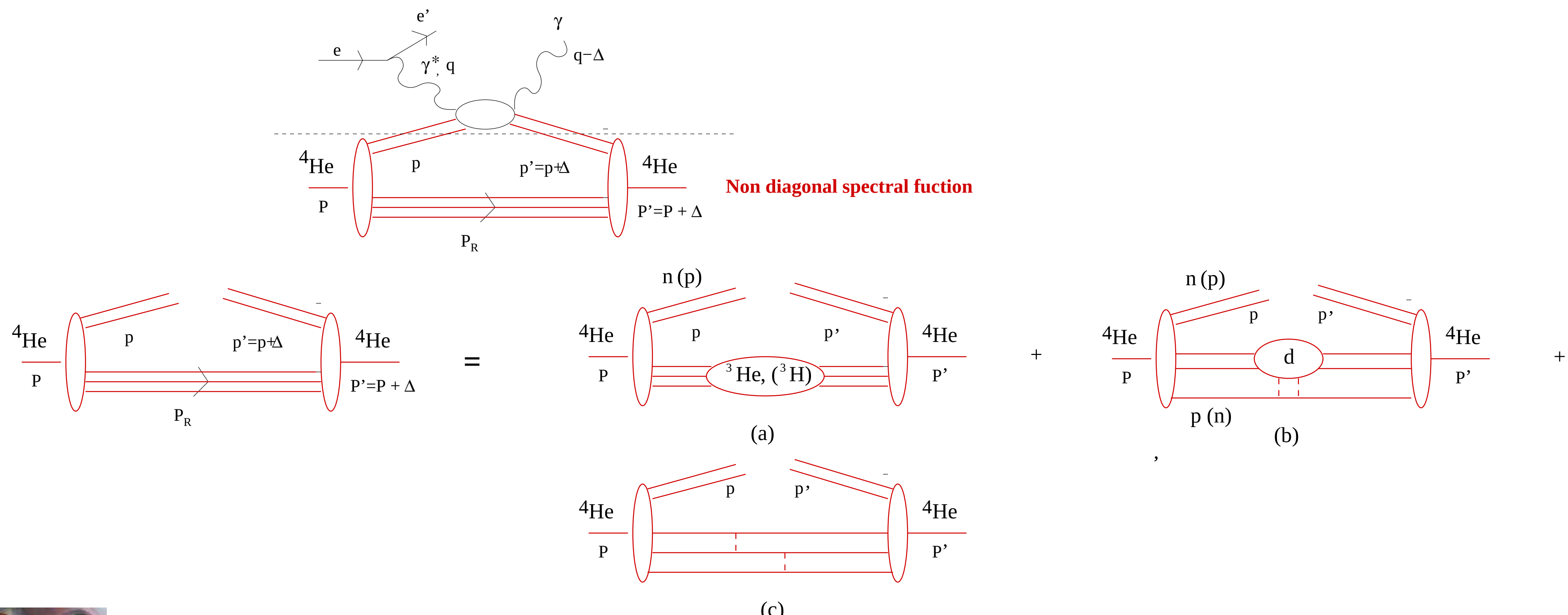
- $^3\vec{He}$ used as an effective polarized neutron target; isoscalar systems, e.g. ^{2}H and ^{4}He, not suitable to extract the neutron E_q in coherent experiments;
- Our results, for ^{3}**He: (S.S. PRC 2004, 2009; M. Rinaldi and S.S., PRC 2012, 2013)**
  - * I.A. calculation of $H_3, E_3, \tilde{H}_3$, within AV18;
  - * extraction procedure of the neutron information, able to take into account all the nuclear effects encoded in an IA analysis;
  - * Interesting features: sensitivity of the results to nuclear dynamics: binding effects bigger than in DIS; different potentials give different results
  - * control on conventional nuclear effects, possible evidence of exotic ones; possible relativistic (LF) extension...
  - * No data; no proposals at JLAB... difficult to detect slow recoils using a polarized target...

BUT

- **at the EIC beams of polarized light nuclei will operate!**
  $^3\vec{He}$ **can be used!**
  Our codes available for interested colleagues

DVCS off ^{4}He

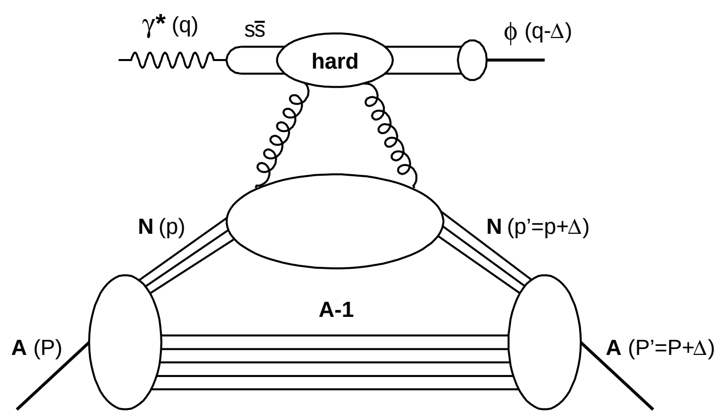
- CLAS data demonstrate that measurements are possible, separating coherent and incoherent channels;
- Realistic microscopic calculations are necessary. A collaboration has started with Sara Fucini (Perugia, graduating student), Michele Viviani (INFN Pisa).
- **Coherent channel in IA:**



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

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)...

nuclear 3D in momentum space

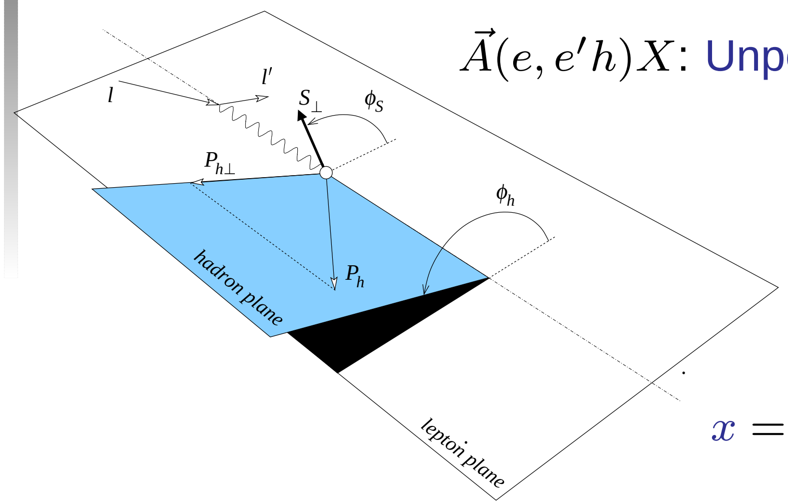
Related issues widely discussed in other sessions:

- From the gluon unintegrated PDF to the onset of CGC: anticipated in nuclei (at higher x_B with respect to free nucelon), motivating the EIC and discussed in other sessions;
- In-medium hadronization as a fundamental test of confinement;
- From in-medium transverse momentum broadening or jet broadening, access to the quark transport parameter, sensitive to the gluon PDF as $x_B \to 0$;

In general:
importance of luminosity and polarization: great help expected from EIC

Here: extraction of neutron TMDs from nuclear data.
In the following, some details for the Sivers and Collins functions

TMDS: Single Spin Asymmetries - 1



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

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

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

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:

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

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

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

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

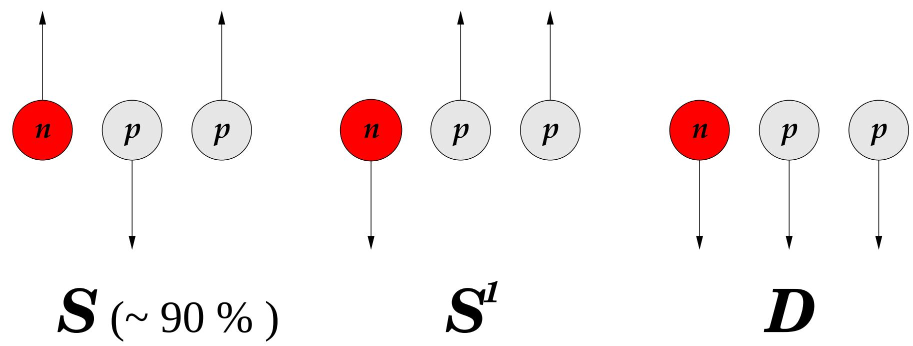
- LARGE A_{UT}^{Sivers} measured in $\vec{p}(e, e'\pi)x$ HERMES PRL 94, 012002 (2005)
- SMALL A_{UT}^{Sivers} measured in $\vec{D}(e, e'\pi)x$; COMPASS PRL 94, 202002 (2005)

A strong flavor dependence

Importance of the neutron for flavor decomposition!

The neutron information from ^{3}He

^{3}He is the ideal target to study the polarized neutron:



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

... But the bound nucleons in ^{3}He are moving!

Dynamical nuclear effects in inclusive DIS ($^3\vec{He}(e,e')X$) were evaluated with a realistic spin-dependent spectral function for $^3\vec{He}$, $P_{\sigma,\sigma'}(\vec{p},E)$. It was found that the formula

$$A_n \simeq \frac{1}{p_n f_n}\left(A_3^{exp} - 2p_p f_p A_p^{exp}\right), \quad (Ciofi\ degli\ Atti\ et\ al., PRC48(1993)R968)$$

$$(f_p, f_n \quad dilution\,factors)$$

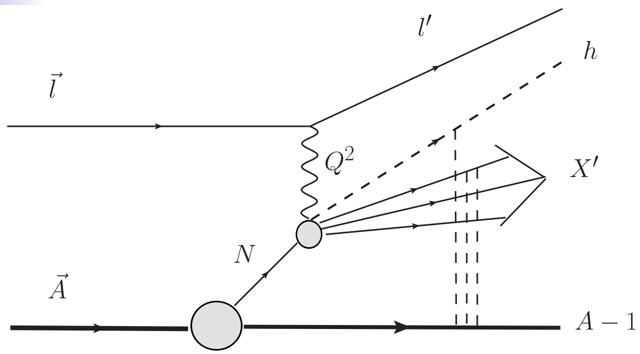
can be safely used $\longrightarrow$ widely used by experimental collaborations.
The nuclear effects are hidden in the "effective polarizations"

$$p_p = -0.023 \quad (Av18) \qquad p_n = 0.878 \quad (Av18)$$

Valid also in SIDIS, proven in IA **(S.S., PRD 75, 054005 (2007))**. **FSI?**

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.

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

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

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

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

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

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

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

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

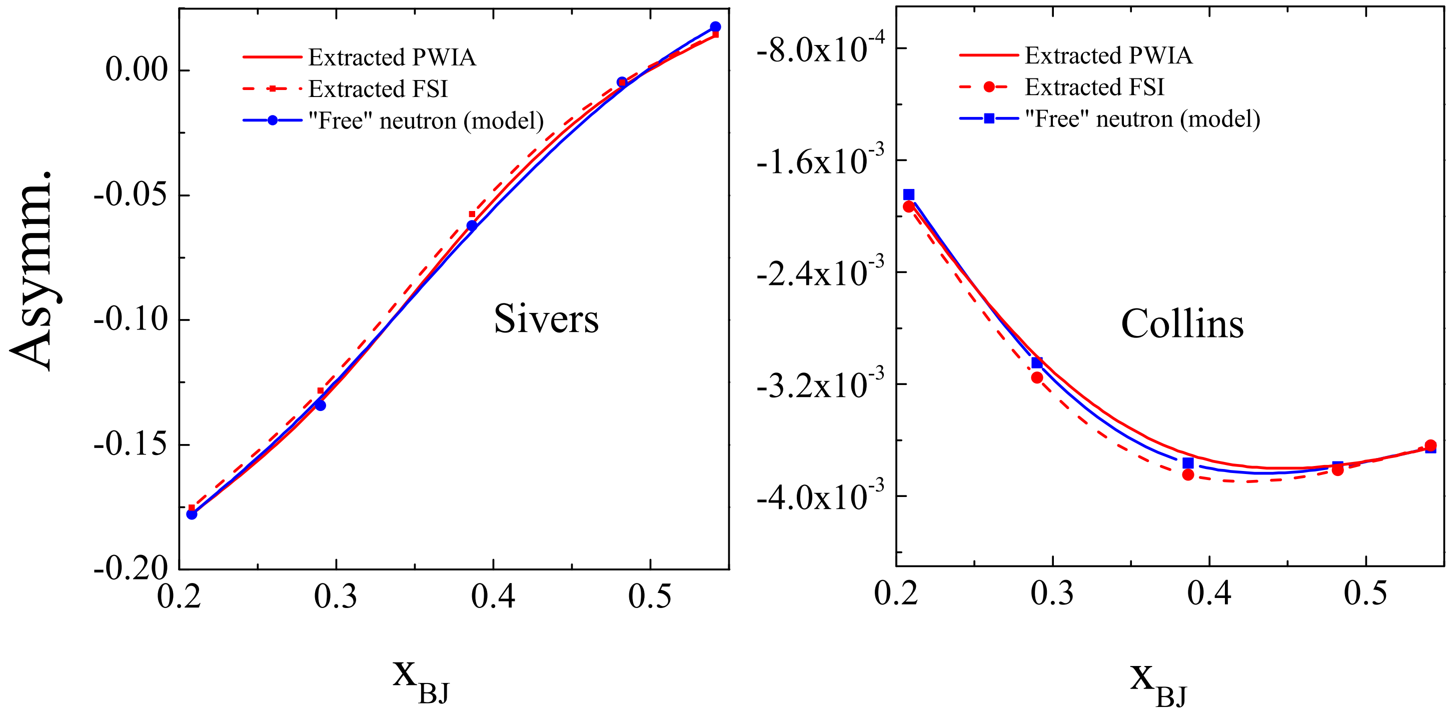
GEA (Γ depends also on the longitudinal distance z_{1i}!) very succesfull in q.e. semi-inclusive and exclusive processes off ^{3}He

see, e.g., Alvioli, Ciofi & Kaptari PRC 81 (2010) 02100

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

Ciofi, Kaptari, Kopeliovich, EPJA 19, 145 (2004)

Good news from GEA studies of FSI!



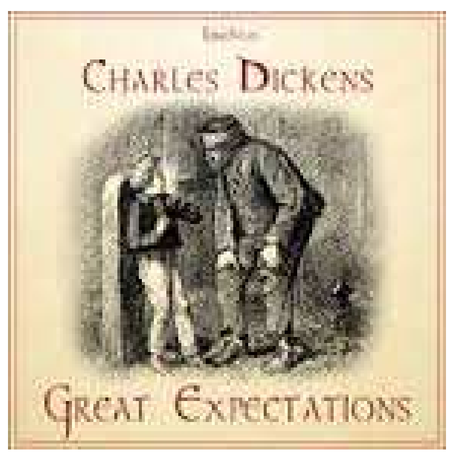
Effects of GEA-FSI (shown at $E_i = 8.8$ GeV) in the dilution factors and in the effective polarizations compensate each other to a large extent: the usual extraction is safe!

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

A. Del Dotto, L. Kaptari, E. Pace, G. Salmè, S.S., arXiv:1704.06182 [nucl-th]

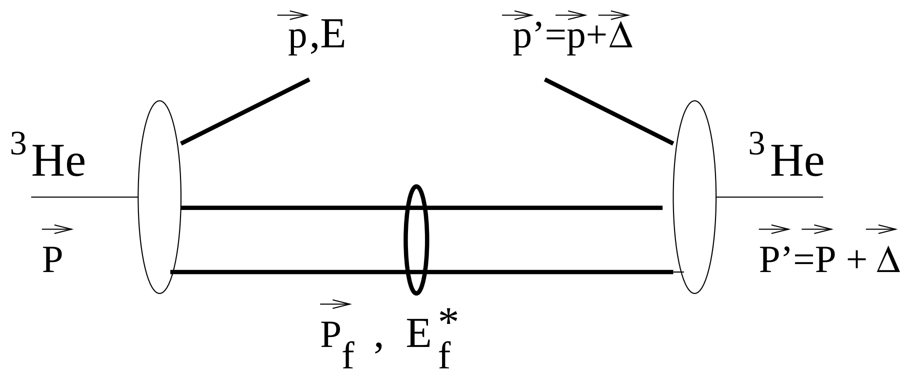
Conclusions

- **Exciting time thanks to new data and accepted next-generation experiments at JLab...**
- **... a prelude to “Great expectations” for the E-Ion-C**
- **“Ion” structure effects: not only relevant. Essential**
- **Easy to predict a growing interest and an important contribution from (low-energy) nuclear theorists**



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

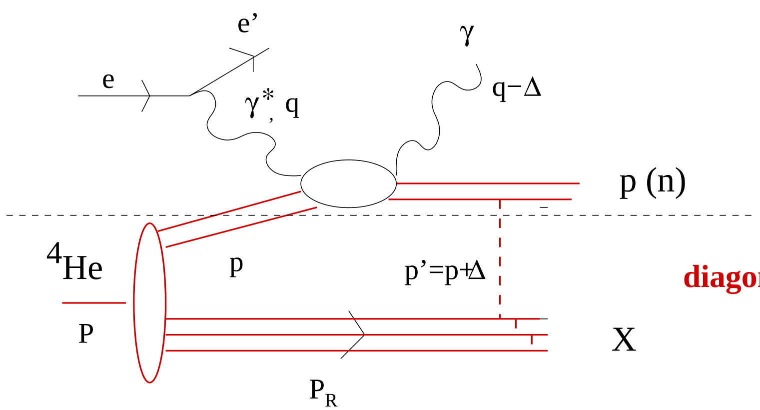
$$P^3_N(\vec{p}, \vec{p} + \vec{\Delta}, E) = \frac{1}{(2\pi)^3} \frac{1}{2} \sum_M \sum_{f,s} \langle \vec{P}' M | (\vec{P} - \vec{p}) S_f, (\vec{p} + \vec{\Delta}) s \rangle$$
$$\times \langle (\vec{P} - \vec{p}) S_f, \vec{p} s | \vec{P} M \rangle \, \delta(E - E_{min} - E^*_f) \, .$$



- 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 would be extremely difficult

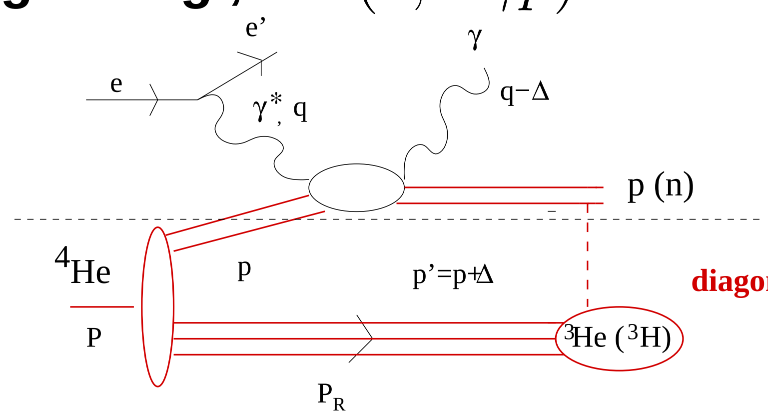
Incoherent DVCS off ^{4}He in IA

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



diagonal spectral fuction... FSI??

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



diagonal spectral fuction... Great!

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

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

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

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

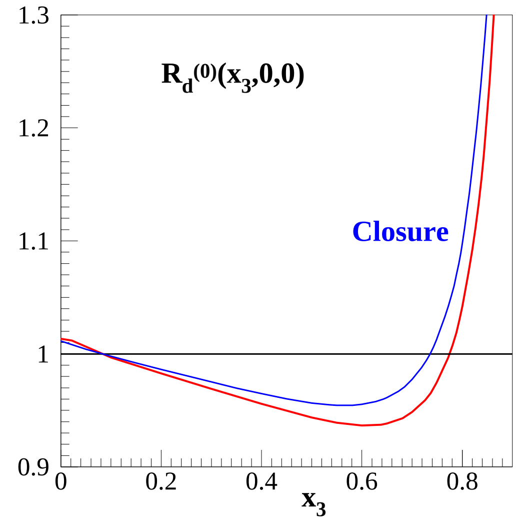
using the Closure Approximation, $E_f^* = \bar{E}$:

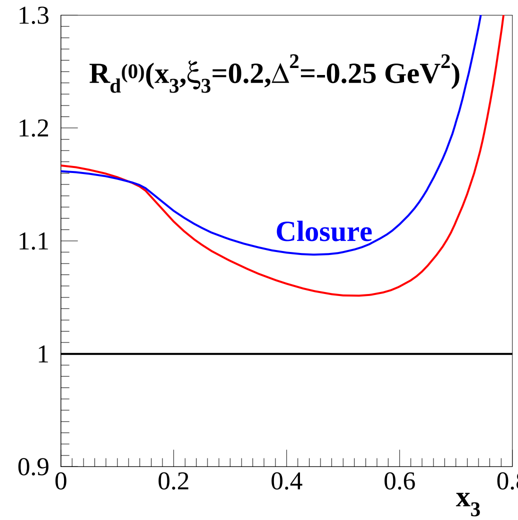
$$P_N^3(\vec{p},\vec{p}+\vec{\Delta},E) \simeq \bar{\sum}_M \sum_s \langle \vec{P}' M | a_{\vec{p}+\vec{\Delta},s} a^\dagger_{\vec{p},s} | \vec{P} M\rangle$$

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

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

Spectral function substituted by a Momentum distribution

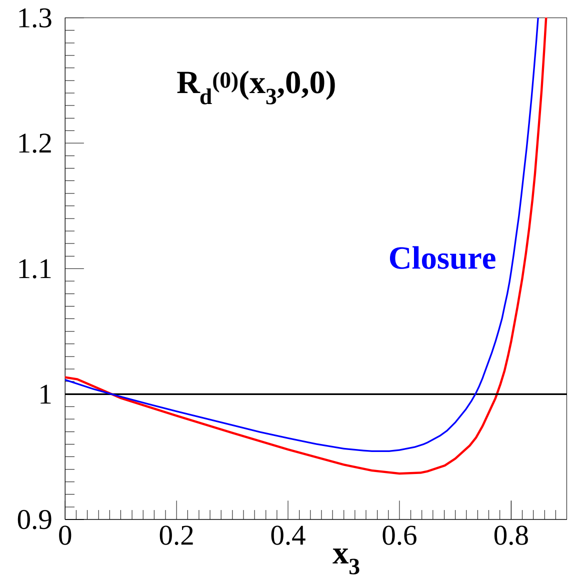


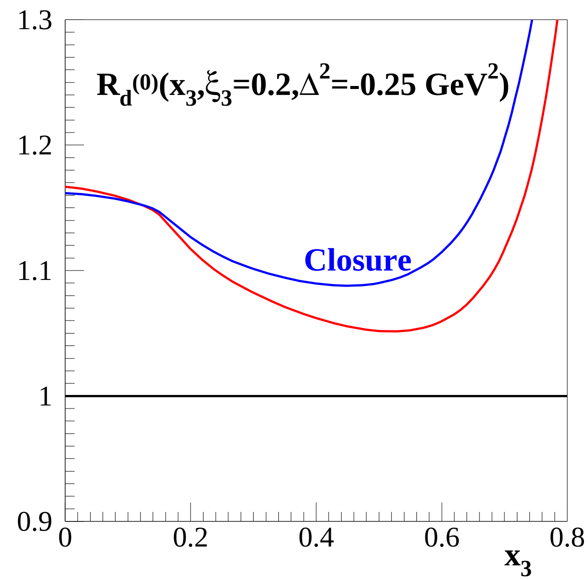


Nuclear effects - the binding

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

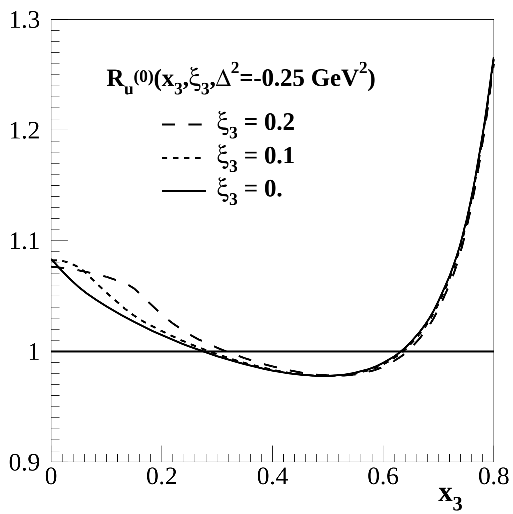
- In calculations using $n(\vec{p}, \vec{p} + \vec{\Delta})$ instead of $P_N^3(\vec{p}, \vec{p} + \vec{\Delta}, E)$, in addition to the IA, also the Closure approximation has been assumed;
- 5 % to 10 % binding effect between $x = 0.4$ and 0.7 - much bigger than in the forward case;
- for $A > 3$, the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

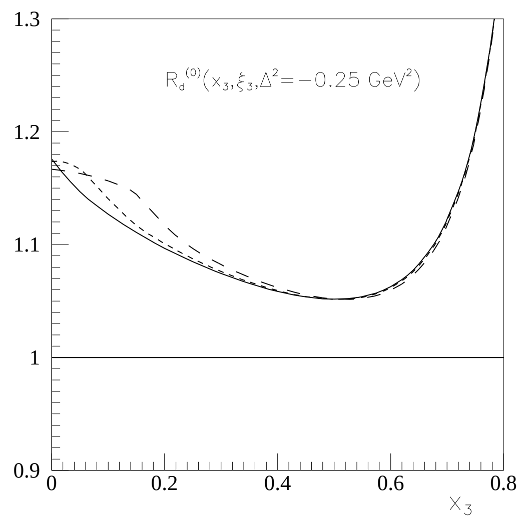




Example of nuclear effects - flavor dependence

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





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

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

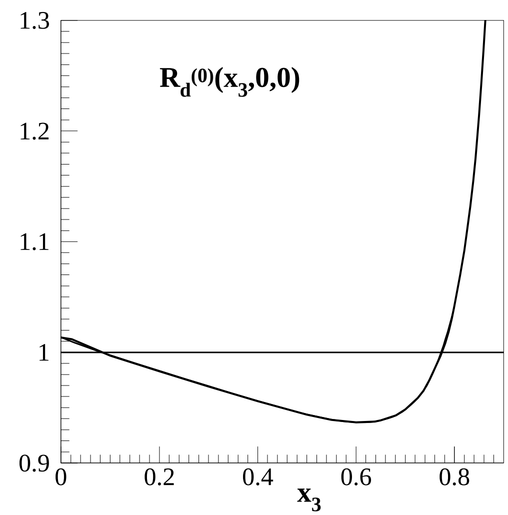
$R_q^{(0)}(x,\xi,\Delta^2)$ would be one if there were no nuclear effects;

- 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.

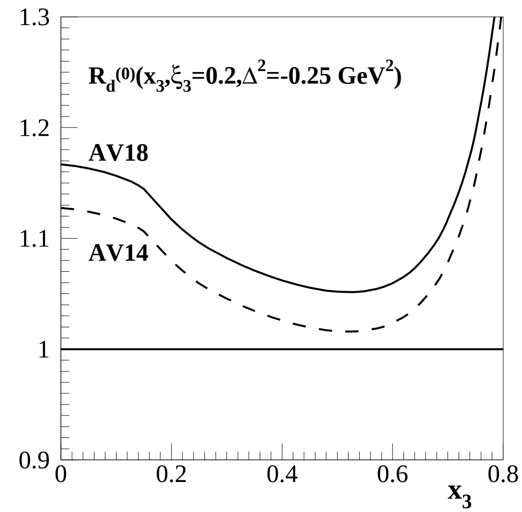
Dependence on the NN interaction

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:

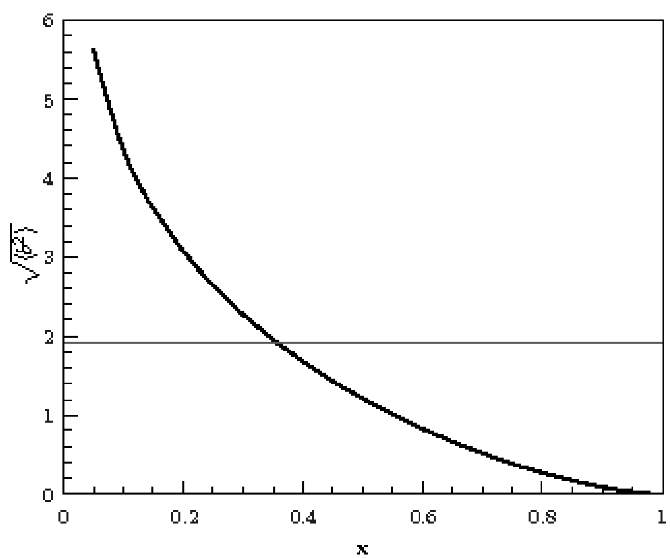


^{3}He tomography (preliminary)

Analysis of the "x-dependent charge radius" of ^{3}He.

From GPDs in impact parameter space, this quantity, $\sqrt{b^2(x)}$, can be obtained from:

$\langle b^2 \rangle (x) = \int d\vec{b}_\perp \; b_\perp^2 \left(\rho_u(x, |\vec{b}_\perp|) + \rho_d(x, |\vec{b}_\perp|) \right)$

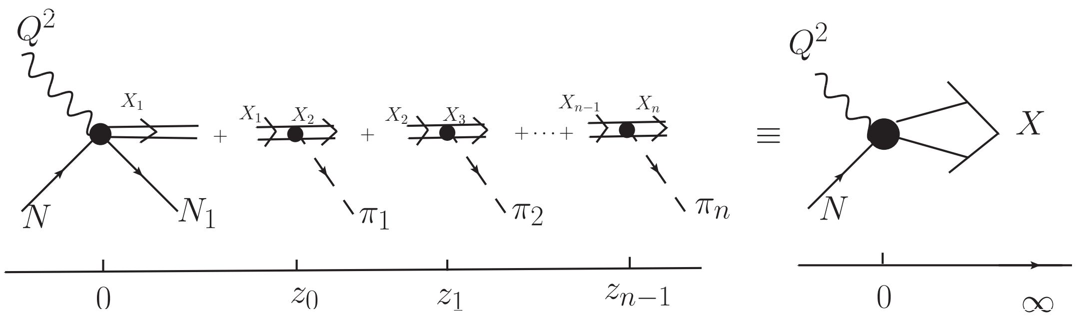


reference line: $\sqrt{\langle b^2 \rangle}$ from the calculations of the ^{3}He charge f.f. in IA. (see **L.E. Marcucci et al. PRC 58 (1998)**).

$\sqrt{< r^2 >}$ **corresponding to the Av18 calculation is similar to** $\sqrt{< b^2(x) >}$ **in the valence region**.

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).



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

- 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...).