Neutron spin structure from polarized ^{3}He

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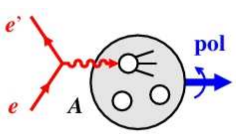


February 5^{th}, 2018

Example: 12 GeV Experiments @JLab, with ^{3}He

- DIS regime, e.g.

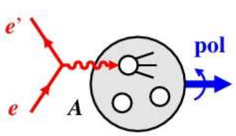
  Hall A, $http://hallaweb.jlab.org/12GeV/$
  MARATHON Coll. E12-10-103 (Rating A): MeAsurement of the F_{2n}/F_{2p}, d/u Ratios and A=3 EMC Effect in Deep Inelastic Electron Scattering Off the Tritium and Helium MirrOr Nuclei

  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



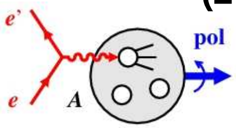
Outline

Selected topics:

- Impulse Approximation and the Spectral Function.
  DIS ${}^3\vec{H}e(e,e')X$ and extraction of g_1^n.
- Beyond the impulse approximation.
  Final state interactions (FSI) and the distorted spectral function.
  - **SIDIS ${}^3\vec{H}e(\vec{e},e'\pi)X$ and the extraction of neutron SSAs;**
  - **spectator SIDIS ${}^3\vec{H}e(\vec{e},e'd)X$ and the spin dependent EMC effect.**
- Coherent DVCS off ${}^3He$ (quickly):
  - **extraction of neutron GPDs;**
  - **flavor (isospin) dependence of nuclear effects.**

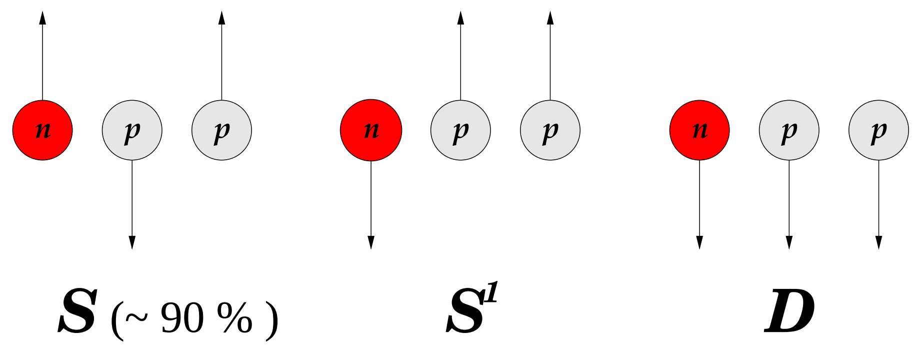
Relevant new calculations to be performed and proper measurements to check theoretical methods, thinking to the EIC, will be addressed.

Our calculations are valid in the valence region. Coherent effects at low x, relevant for the EIC, not implemented yet. (**See F. Bissey, V. Guzey, M. Strikman and A. Thomas, PRC 65 (2002) 064317; L. Frankfurt, V. Guzey, M. Strikman, Phys. Rep. 512 (2012) 255**)



The neutron information from ^{3}He

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



$\mu_{^3He} \simeq \mu_n$!

(deuteron: $\mu_{^2H} \simeq \mu_n + \mu_p$)

... But the bound nucleons in ^{3}He are moving! $\longrightarrow$ theoretical ingredient: a realistic spin-dependent spectral function for $^3\vec{H}e$, $P_{\sigma,\sigma'}(\vec{p}, E)$.

Example: dynamical nuclear effects in inclusive DIS ($^3\vec{H}e(e, e')X$). The formula

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

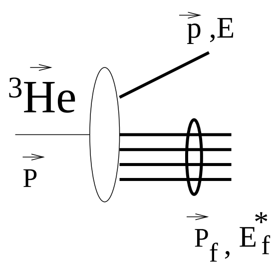
$$(f_p, f_n \quad dilution\,factors,\ from\ unpolarized\ data)$$

can be safely used $\longrightarrow$ widely adopted by experimental collaborations.

Nuclear effects hidden in the "effective polarizations", p_p and p_n, obtained from the nuclear w.f... But to proof this possibility, the spectral function had to be evaluated

The spectral function (Impulse Approximation)

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



$\swarrow$ intrinsic overlaps $\searrow$

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

- probability distribution to find a nucleon with given 3-momentum and removal energy E in the nucleus. It arises in q.e., DIS, SIDIS, DVCS...
- In general, if spin is involved, a 2x2 matrix, $\mathbf{P}^N_{\mathcal{M}\sigma\sigma'}(\vec{p},,E)$, not a density;
- the two-body recoiling system can be either the deuteron or a scattering state: when a deeply bound nucleon, with high $E = E_{min} + E_f^*$, leaves the nucleus, the recoiling system has high excitation energy E_f^* ;
- Realistic Spectral Function: 3-body bound state and 2-body final state evaluated within the same Realistic interaction (in our case, Av18, from the Pisa group **(Kievsky, Viviani)**). Extension to heavier nuclei very difficult

Is the spectral function useful?

Does the Impulse Approximation work?

The answer in the data.

Example: ${}^3\vec{H}e(\vec{e},e')X$ in q.e. kinematics

(**K. Slifer et al, PRL 101 (2008) 022303**)

- Faddeev calc. at low Q^2

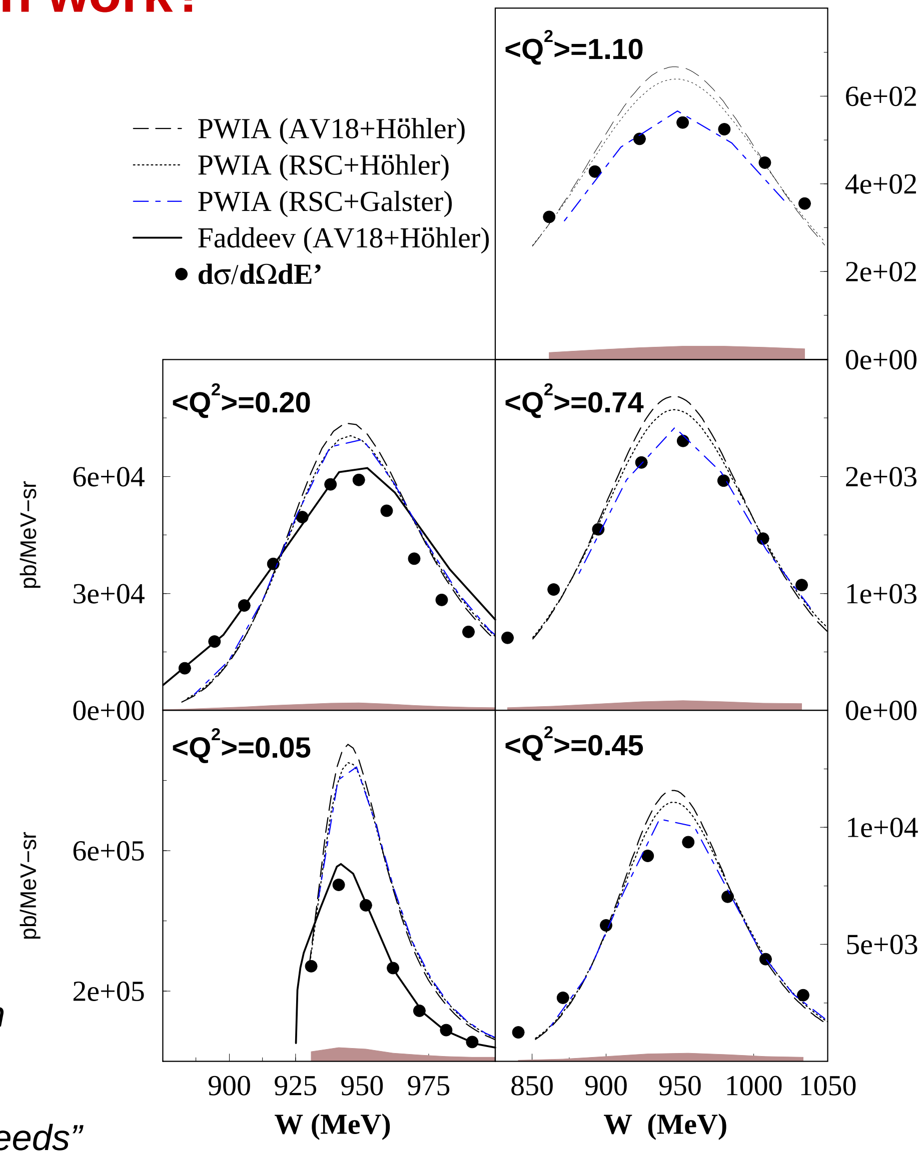
  J. Golak et al. Phys. Rept. 415 (2005) 89

- PWIA (Av18) calc.

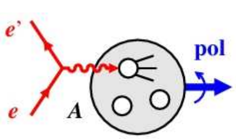
  E. Pace et al, PRC 64 (2001) 055203

- 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)

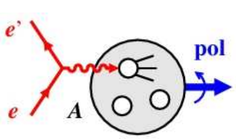


Status (Impulse Approximation and beyond)

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

Selected contributions from Rome-Perugia:

- Ciofi, Pace, Salmè PRC 21 (1980) 505 ...
- Ciofi, Pace, Salmè PRC 46 (1991) 1591: spin dependence
- Pace, Salmè, S.S., Kievsky PRC 64 (2001) 055203, first Av18 calculation
- Ciofi, Kaptari, PRC 66 (2002) 044004, unpolarized with FSI (q.e.)
- S.S. PRC 70 (2004) 015205, non diagonal SF for DVCS
- Kaptari, Del Dotto, Pace, Salmè, S.S., PRC 89 (2014), spin dependent with FSI
- LF, formal: Del Dotto, Pace, Salmè, SS, PRC 95 (2017) 014001; preliminary calc., S.S., Del Dotto, Kaptari, Pace, Rinaldi, Salmè, Few Body Syst. 56 (2015) 6

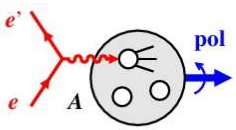


SIDIS off ^{3}He and neutron TMDs

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



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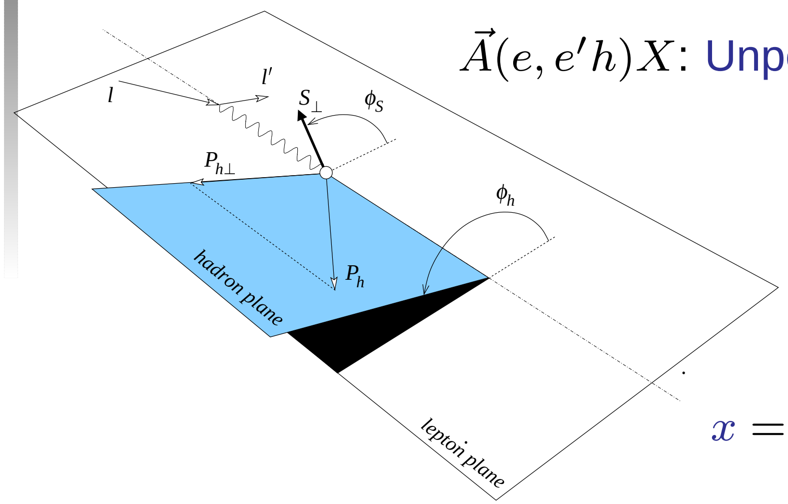
Single Spin Asymmetries (SSAs) - 1



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

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

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

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

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

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:

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

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

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

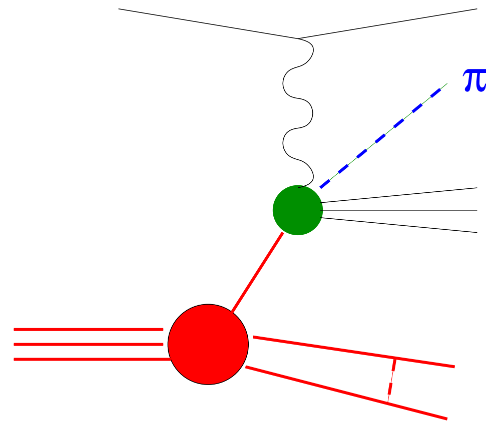
$$D \propto \sum_q e_q^2 f_1^q(x) D_1^{q,h}(z)$$

- 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!

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



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

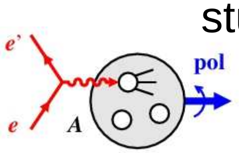
In a first paper on this subject,
(S.Scopetta, PRD 75 (2007) 054005)
the process ${}^3\vec{He}(e, e'\pi)X$ has been evaluated :

* 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



The IA @ JLab kinematics: a few words more

The convolution formulae for a generic structure function can be cast in the form

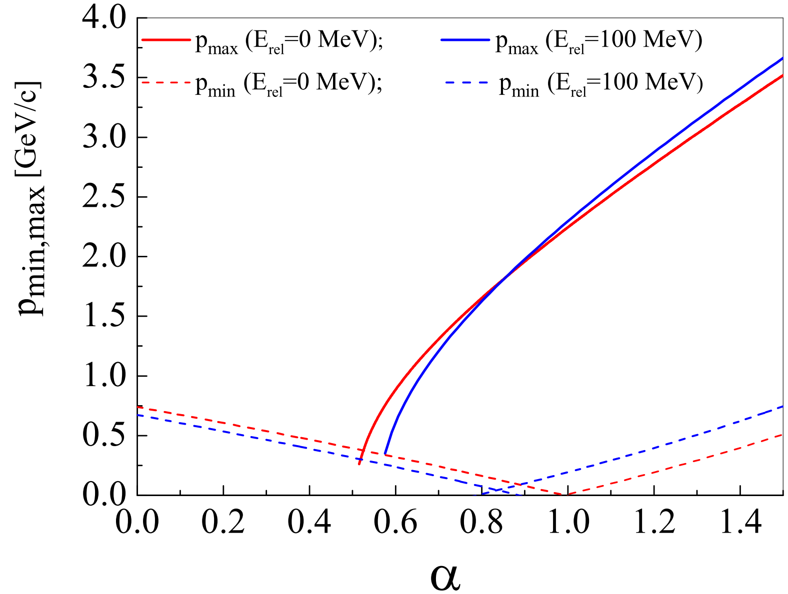
$$\mathcal{F}^A(x_{Bj}, Q^2, ...) = \sum_N \int_{x_{Bj}}^{A} f_N^A(\alpha, Q^2, ...) \, \mathcal{F}^N(x_{Bj}/\alpha, Q^2, ...) \, d\alpha$$

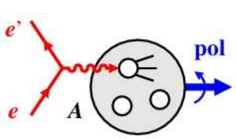
with the light-cone momentum distribution:

$$f_N^A(\alpha, Q^2, ...) = \int dE \int_{p_{min}(\alpha,Q^2,...)}^{p_{max}(\alpha,Q^2,...)} P_N^A(\mathbf{p}, \mathbf{E}) \, \delta\left(\alpha - \frac{\mathbf{pq}}{\mathbf{m}\nu}\right) \theta\left(\mathbf{W_x^2} - (\mathbf{M_N} + \mathbf{M_\pi})^\mathbf{2}\right) \mathbf{d^3p}$$

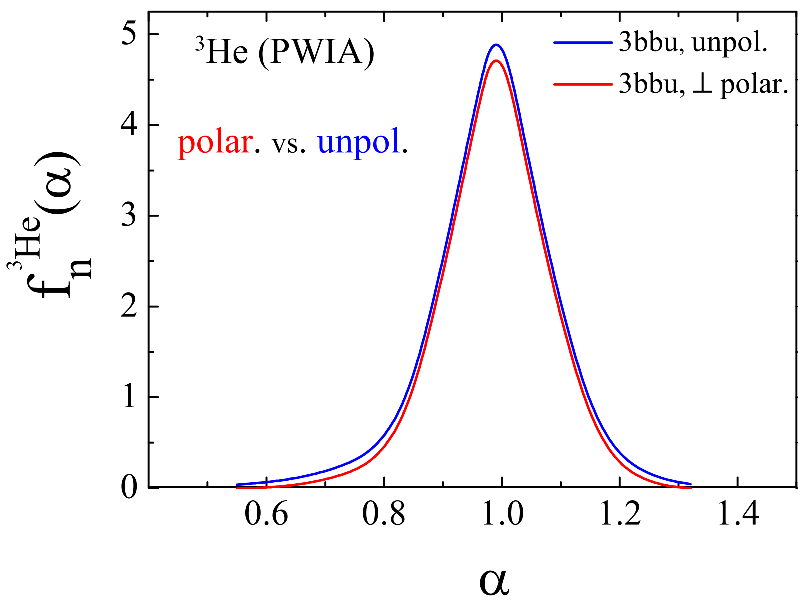
- Bjorken limit:
  $p_{min,max}$ not dependent on Q^2, x:
  $f_N^A(\alpha)$ depends on α only,
  $0 \leq \alpha \leq A$

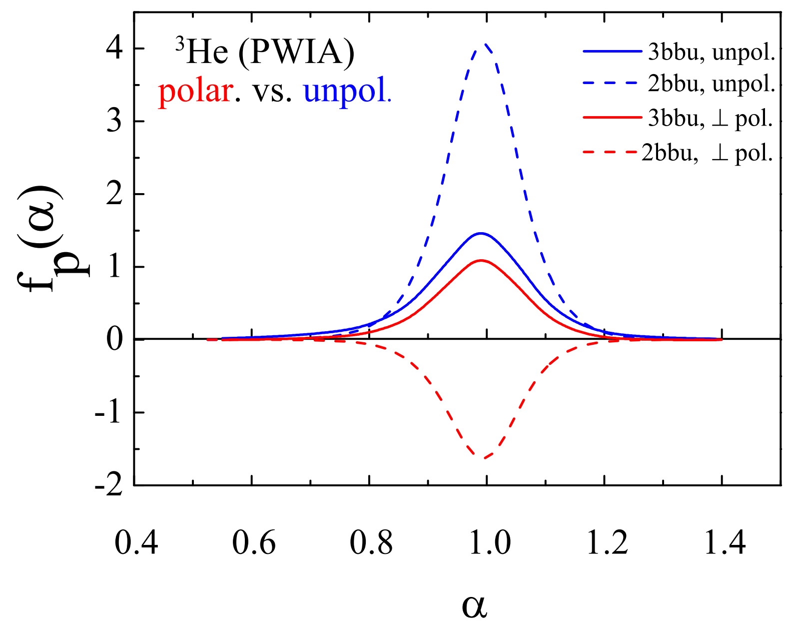
- @ JLab kinematics,
  ($E = 8.8$ GeV, $E' \simeq 2 \div 3$ GeV,
  $\theta_e \simeq 30^o$) $q \neq \nu$ and $\alpha_{min} \neq 0$





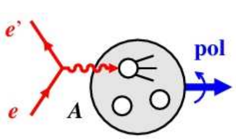
Light-cone momentum distributions in IA



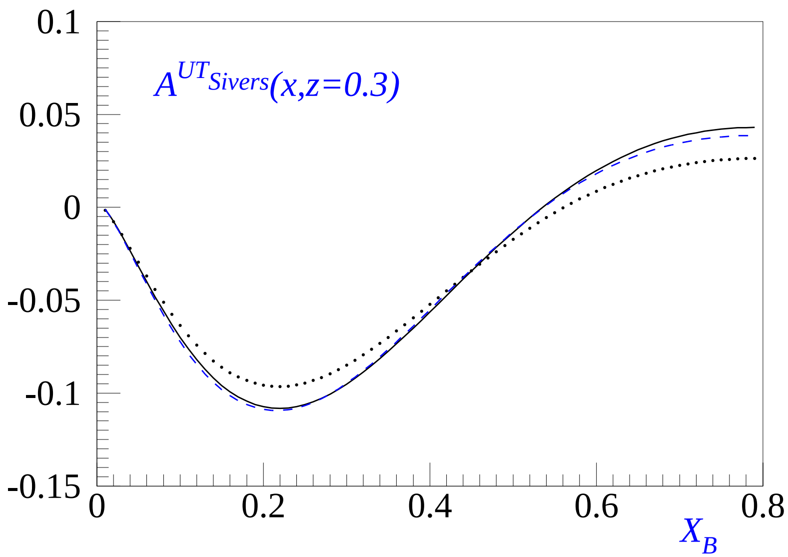


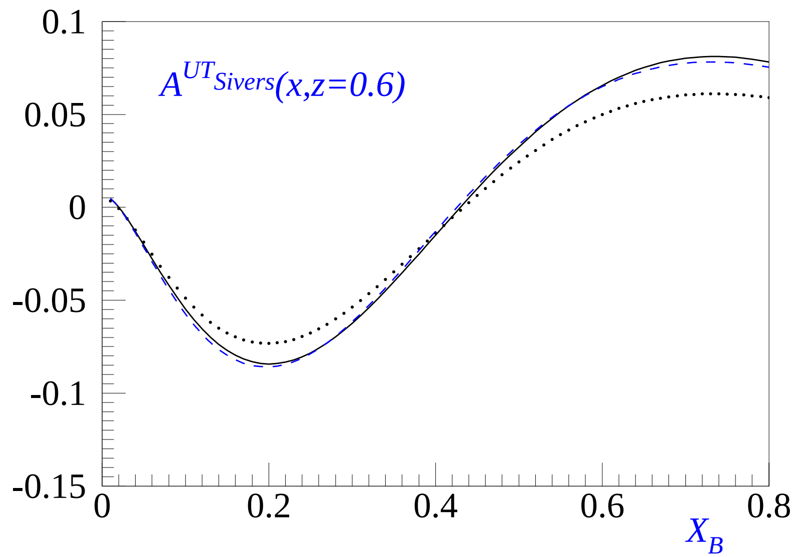
Calculation within the **Av18** interaction:

- weak depolarization of the neutron, $p_n = \int d\alpha\, f_n^{3He}(\alpha) = 0.878$
- strong depolarization of the protons, $p_p = \int d\alpha\, f_p^{3He}(\alpha) = -0.023$
  (cancellation between contributions in the 2-body and 3-body channels)



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





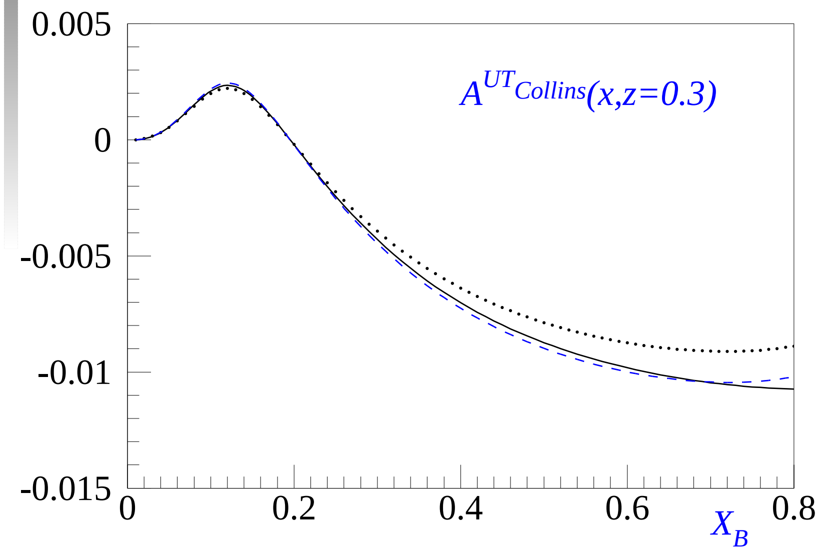
FULL: Neutron asymmetry (model: from parameterizations or models of TMDs and FFs)

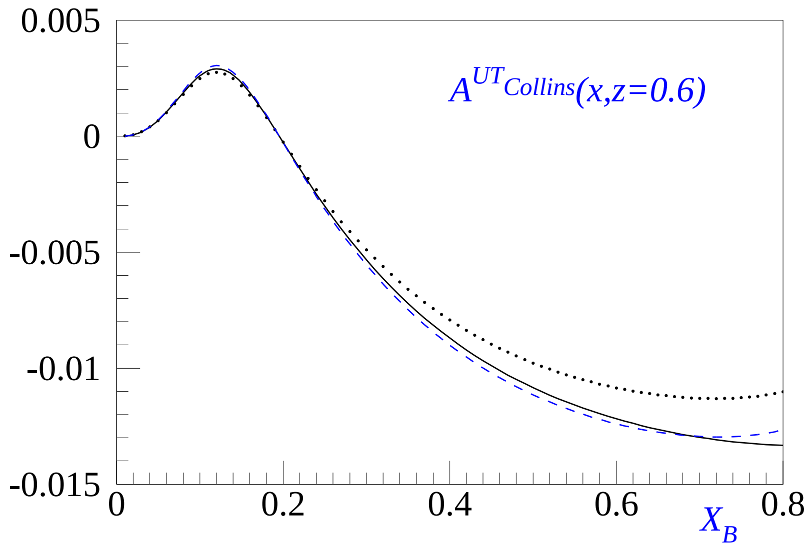
DOTS: Neutron asymmetry extracted from ^3He (calculation) neglecting the contribution of the proton polarization $\bar{A}_n \simeq \frac{1}{f_n} A_3^{calc}$

DASHED : Neutron asymmetry extracted from ^3He (calculation) taking into account nuclear structure effects through the formula:

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

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





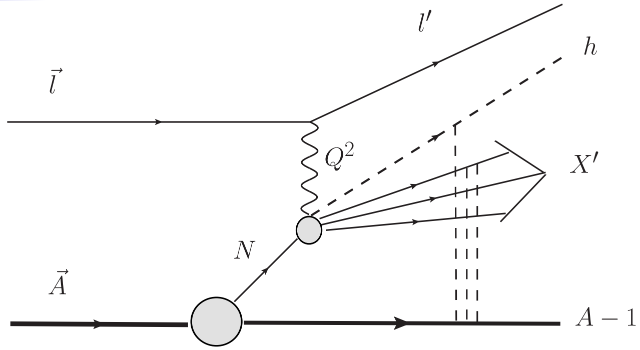
In the Bjorken limit the extraction procedure successful in DIS works also in SiDIS, for both the Collins and the Sivers SSAs !

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.

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

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

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

$$\begin{aligned} \langle \mathbf{r_1 r_2 r_3} | S_X, S_{A-1} \mathbf{P_{A-1}} \mathbf{E^f_{A-1}} \rangle &= \Phi^*_f(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) \approx \hat{S}_{Gl}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) \mathbf{\Psi}^{*\mathbf{f}}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) \\ &\approx \hat{S}_{Gl}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) \sum_{\mathbf{j>k}} \chi^+_{\mathbf{S_X}} \phi^*(\xi_{\mathbf{x}}) \mathbf{e}^{-\mathbf{i p_X r_i}} \mathbf{\Psi}^{*\mathbf{f}}_{\mathbf{jk}}(\mathbf{r_j}, \mathbf{r_k}) , \end{aligned}$$

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

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

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

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

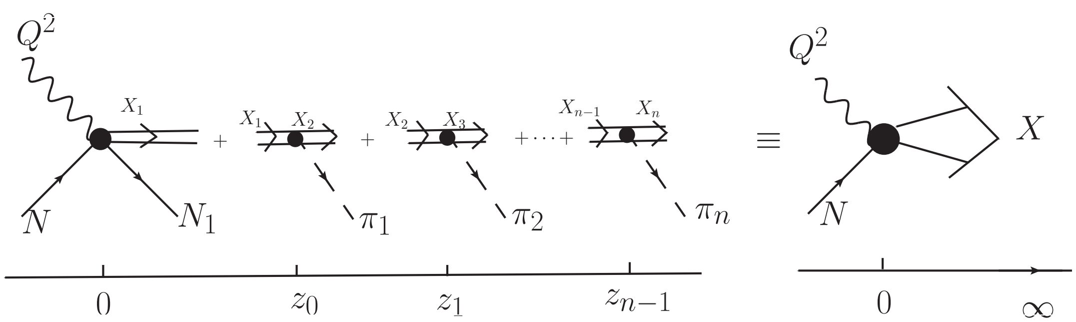
GEA (Γ depends also on the longitudinal distance between the debris and the scattering centers z_{1i}!) very successful in q.e. semi-inclusive and exclusive processes off ^{3}He

see, e.g., Alvioli, Ciofi & Kaptari PRC 81 (2010) 02100 and references there in

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

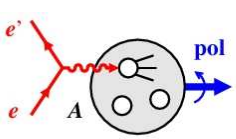
FSI: *the hadronization model*

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**)



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

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

- While P^{IA} is "static",i.e. depends on ground state properties, P^{FSI} is dynamical ($\propto \sigma_{eff}$) and process dependent;
- For each experimental point (given x, Q^2...), a different spectral function has to be evaluated!
- Quantization axis (w.r.t. which polarizations are fixed) and eikonal direction (fixing the "longitudinal" propagation) are different)... States have to be rotated...
- P^{FSI}: a really cumbersome quantity, a very demanding evaluation ($\approx$ 1 Mega CPU*hours @ "Zefiro" PC-farm, PISA, INFN "gruppo 4").

The convolution formulae for a generic structure function can be cast in the form

$$\mathcal{F}^A(x_{Bj}, Q^2, ...) = \sum_N \int_{x_{Bj}}^A f_N^A(\alpha, Q^2, ...)\, \mathcal{F}^N(x_{Bj}/\alpha, Q^2, ...)\, d\alpha$$

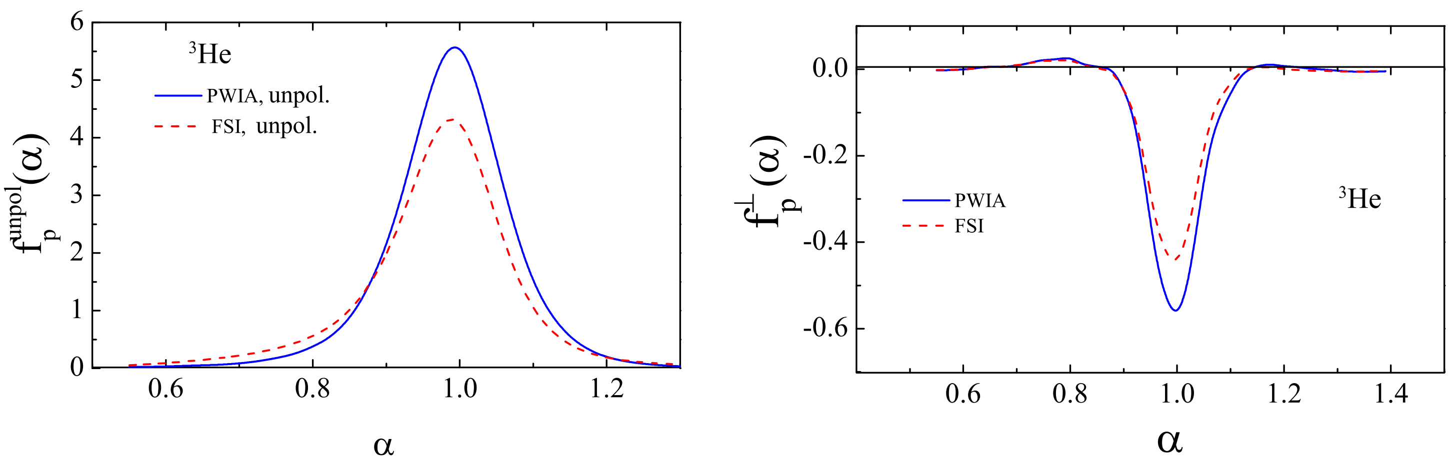
with the distorted light-cone momentum distribution:

$$f_N^A(\alpha, Q^2, ..) = \int dE \int_{p_m(\alpha,Q^2,..)}^{p_M(\alpha,Q^2,..)} P_N^{A,FSI}(\mathbf{p}, E, \sigma..)\, \delta\left(\alpha - \frac{pq}{m\nu}\right)\, \theta\left(W_x^2 - (M_N + M_\pi)^2\right) d^3\mathbf{p}$$

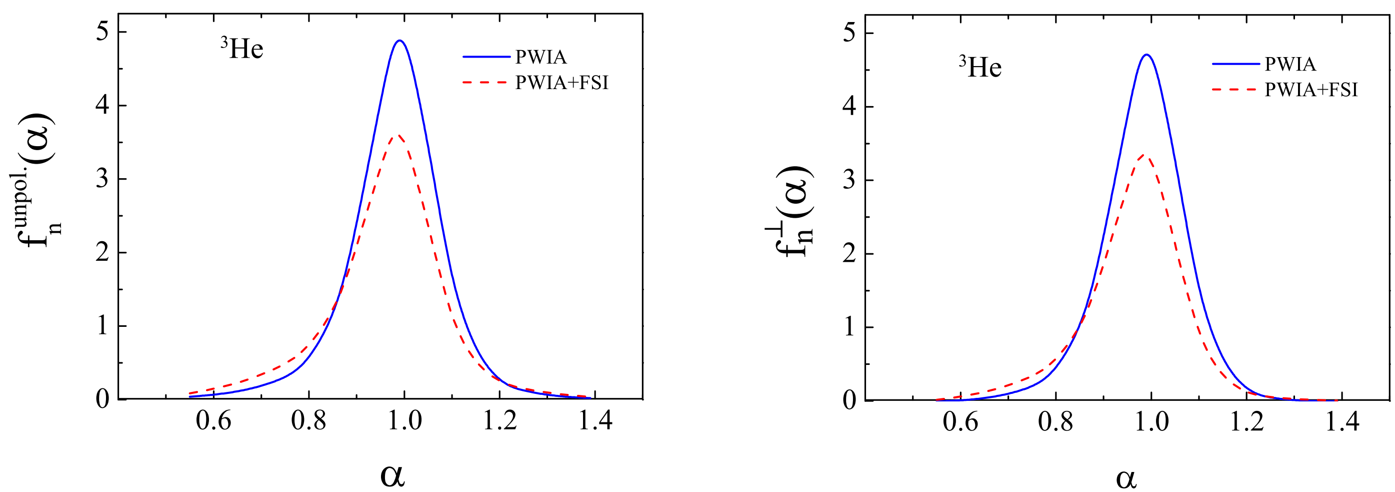
light-cone momentum distributions with FSI:

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

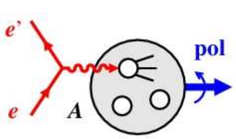
PROTON @ E_i = 8.8 GeV



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

$$A_3^{exp} \simeq \frac{\Delta\vec{\sigma}_3^{exp.}}{\sigma_{unpol.}^{exp.}} \Longrightarrow \frac{\langle \vec{\mathbf{s}}_\mathbf{n}\rangle \boldsymbol{\Delta}\vec{\sigma}(\mathbf{n}) + \mathbf{2}\langle \vec{\mathbf{s}}_\mathbf{p}\rangle \boldsymbol{\Delta}\vec{\sigma}(\mathbf{p})}{\langle \mathbf{N}_\mathbf{n}\rangle \sigma_{\mathbf{unpol.}}(\mathbf{n}) + \mathbf{2}\langle \mathbf{N}_\mathbf{p}\rangle \sigma_{\mathbf{unpol.}}(\mathbf{p})} = \langle \vec{\mathbf{s}}_\mathbf{n}\rangle \mathbf{f}_\mathbf{n}\mathbf{A}_\mathbf{n} + \mathbf{2}\langle \vec{\mathbf{s}}_\mathbf{p}\rangle \mathbf{f}_\mathbf{p}\mathbf{A}_\mathbf{p}$$

PWIA:

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

$$\Longrightarrow \quad \mathbf{f}_{\mathbf{n},(\mathbf{p})}(\mathbf{x},\mathbf{z}) = \frac{\sum_\mathbf{q} \mathbf{e}_\mathbf{q}^2 \mathbf{f}_1^{\mathbf{q},\mathbf{n}(\mathbf{p})}(\mathbf{x})\mathbf{D}_1^{\mathbf{q},\mathbf{h}}(\mathbf{z})}{\sum_\mathbf{N}\sum_\mathbf{q} \mathbf{e}_\mathbf{q}^2 \mathbf{f}_1^{\mathbf{q},\mathbf{N}}(\mathbf{x})\mathbf{D}_1^{\mathbf{q},\mathbf{h}}(\mathbf{z})}$$

FSI:

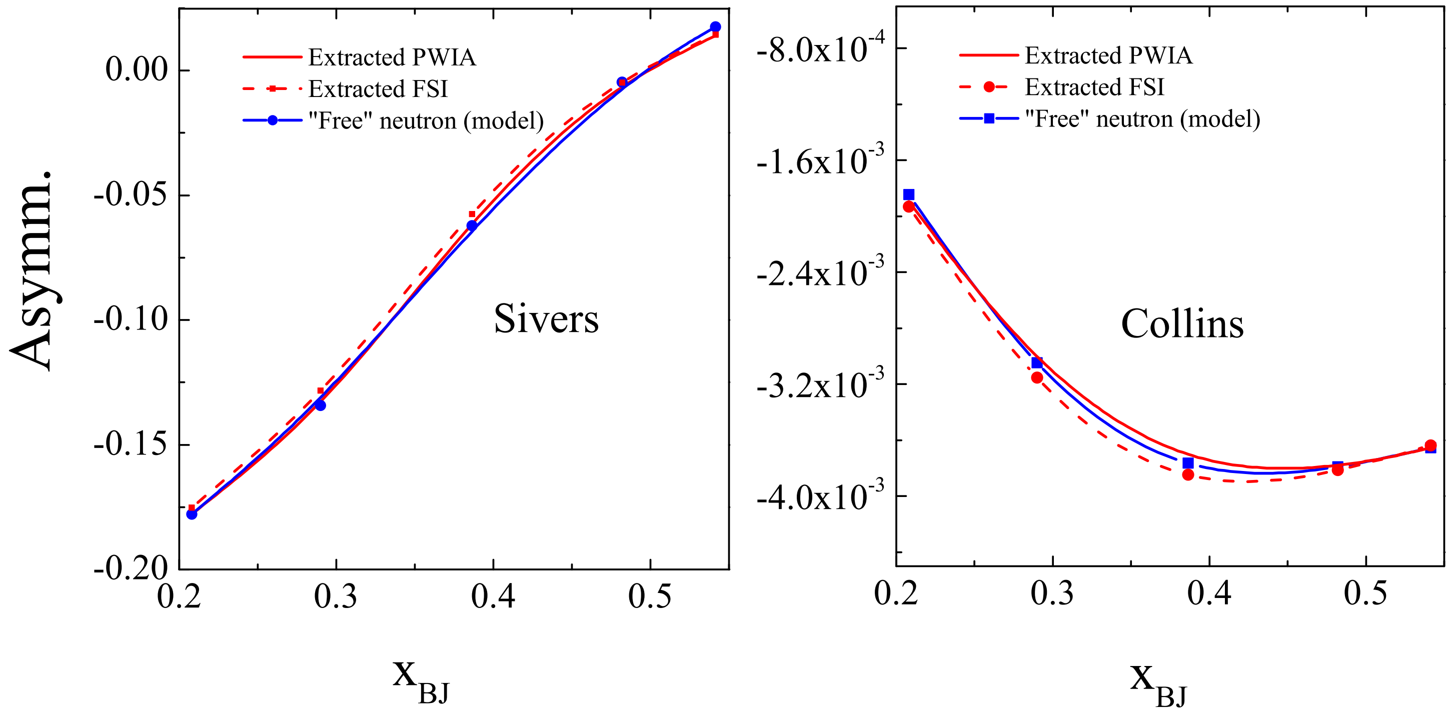
$$\langle \vec{s}_{n(p)}\rangle = \int dE \int d^3p P_{||}^{FSI}(E,\mathbf{p}) = \mathbf{p}_{\mathbf{n(p)}}^{\mathbf{FSI}};$$
$$\langle N\rangle = \int dE \int d^3p P_{unpol.}^{FSI}(E,\mathbf{p}) < 1.$$

$$\Longrightarrow \quad \mathbf{f}_{\mathbf{n},(\mathbf{p})}^{\mathbf{FSI}}(\mathbf{x},\mathbf{z}) = \frac{\sum_\mathbf{q} \mathbf{e}_\mathbf{q}^2 \mathbf{f}_1^{\mathbf{q},\mathbf{n}(\mathbf{p})}(\mathbf{x})\mathbf{D}_1^{\mathbf{q},\mathbf{h}}(\mathbf{z})}{\sum_\mathbf{N}\langle \mathbf{N}\rangle \sum_\mathbf{q} \mathbf{e}_\mathbf{q}^2 \mathbf{f}_1^{\mathbf{q},\mathbf{N}}(\mathbf{x})\mathbf{D}_1^{\mathbf{q},\mathbf{h}}(\mathbf{z})}$$

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

2

Good news from GEA studies of FSI!



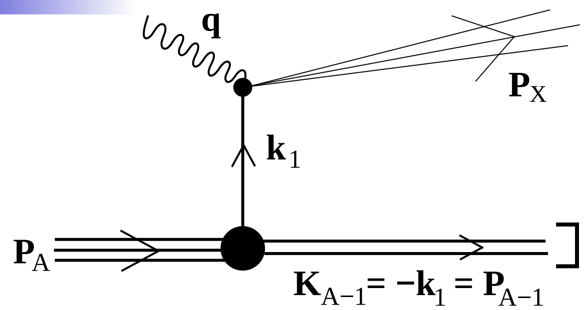
Effects of GEA-FSI (shown at $E_i = 8.8$ GeV) in the dilution factors and in the effective polarizations compensate each other to a large extent: the usual extraction is safe!

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

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 coll., 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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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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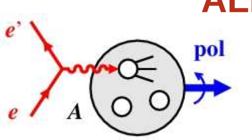
(Dated: November 24, 2010)

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 $^3\vec{\rm He}(\vec{e}, e'\,^2{\rm H})X \longrightarrow\ g_1^p$ 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 $\hat{z} \equiv \hat{\mathbf{q}}$)

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

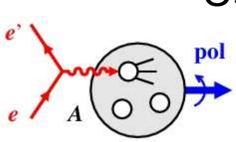
$$\approx 4\frac{\alpha_{em}^2}{Q^2 z_N \mathcal{E}}\frac{m_N}{E_N}\ g_1^p\left(\frac{x}{z}\right)\mathcal{P}_{||}^{\frac{1}{2}}(\mathbf{p}_{mis})\mathcal{E}(2-y)\left[1-\frac{|\mathbf{p}_{mis}|}{m_N}\right] \qquad \textit{Bjorken limit}$$

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

$\mathcal{P}_{||}^{\frac{1}{2}}(\mathbf{p}_{mis}) = \mathcal{O}_{\frac{1}{2}\frac{1}{2}}^{\frac{1}{2}\frac{1}{2}} - \mathcal{O}_{-\frac{1}{2}-\frac{1}{2}}^{\frac{1}{2}\frac{1}{2}}$ 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!



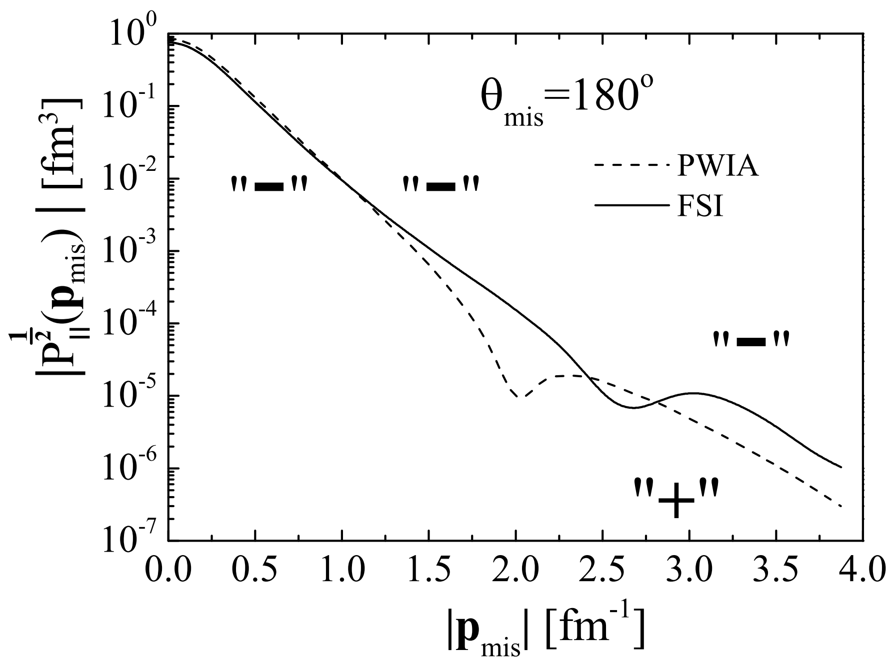
Spectator SIDIS $^3\vec{\mathrm{H}}\mathrm{e}(\vec{e}, e'\,^2\mathrm{H})X \to g_1^p$ for a bound proton

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



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

Even if $^3\vec{\rm H}$ is not available, relevant information is at hand:

- g_1^p for the bound proton: comparison with the free case, polarized EMC effect and possible evidence of off-shell effects, beyond the IA;
- these effects are neglected in the extraction formula used in DIS for g_1^n

$$g_1^n \simeq \frac{1}{p_n}\left(g_1^3 - 2p_p g_1^p\right) ,$$

Nonetheless it was noted long time ago (**L.Frankfurt, V. Guzey, M. Strikman PLB 381 (1996) 379**) that, if the IA is used to describe $g_1^{^3He}$ and $g_1^{^3H}$, the Bjorken Sum Rule for the trinucleon system is violated by 4 %: possible evidence of explicit Δ isobar degrees of freedom in the nuclear wave function.

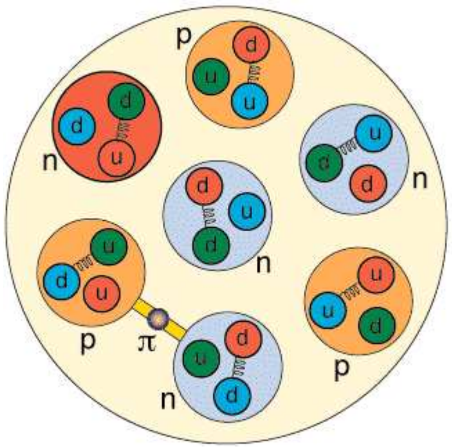
- the Bjorken Sum Rule (in the nucleon case) is obtained considering also ^{3}He data; used even to constrain $\alpha_s(Q^2)$ (**see, e.g., A. Deur et al, Prog.Part.Nucl.Phys. 90 (2016) 1**)
- FSI under control in specific regions; they can be evaluated elsewhere

I understand that at JLab the use of a recoil detector in a polarized set-up is difficult, and the use of ^{3}H targets complicated...

Actually none of these problems occur at the EIC

DVCS off ^{3}He and neutron GPDs (a fast look)

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

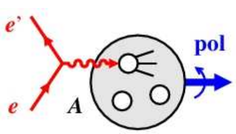


To answer, we should perform a *tomography...*

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

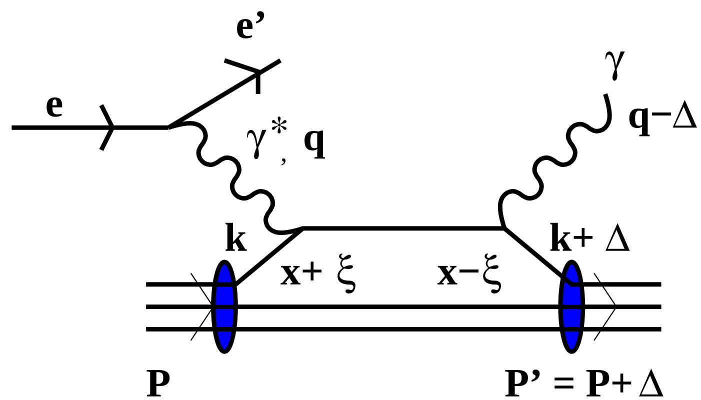
Answer: Deeply Virtual Compton Scattering & Generalized Parton Distributions (GPDs)

For ^{4}He, recent data (M. Hattawy et al., PRL 119, (2017) 20204) and new experiments approved (ALERT coll., e-Print: arXiv:1708.00888 [nucl-ex])



GPDs: Definition (X. Ji PRL 78 (97) 610)

For a $J = \frac{1}{2}$ target,
in a hard-exclusive process,
(handbag approximation)
such as (coherent) DVCS:



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

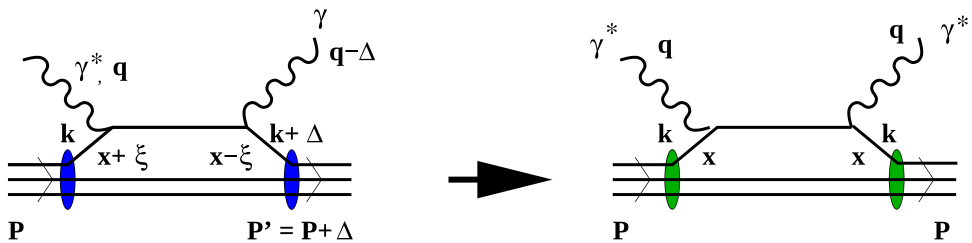
$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P' | \bar{\psi}_q(-\lambda n/2) \quad \gamma^\mu \quad \psi_q(\lambda n/2) | P \rangle = H_q(x,\xi,\Delta^2) \bar{U}(P')\gamma^\mu U(P)$$

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

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

GPDs: constraints

- when $P' = P$, i.e., $\Delta^2 = \xi = 0$, one recovers the usual PDFs:



$$H_q(x,\xi,\Delta^2) \Longrightarrow H_q(x,0,0) = q(x); \quad E_q(x,0,0)\ unknown$$

- the x–integration yields the q-contribution to the Form Factors (ffs)

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

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

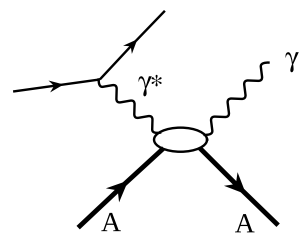
$$\Longrightarrow \int dx\, H_q(x,\xi,\Delta^2) = F_1^q(\Delta^2) \qquad \int dx\, E_q(x,\xi,\Delta^2) = F_2^q(\Delta^2)$$

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

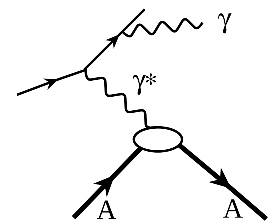
GPDs: a unique tool...

- not only 3D structure, at parton level; many other aspects, e.g., contribution to the solution to the “Spin Crisis” (**J.Ashman et al., EMC collaboration, PLB 206, 364 (1988)**), yielding parton total angular momentum...

... but also an experimental challenge:



DVCS



BH

- Hard exclusive process $\longrightarrow$ small σ;
- Difficult extraction:

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

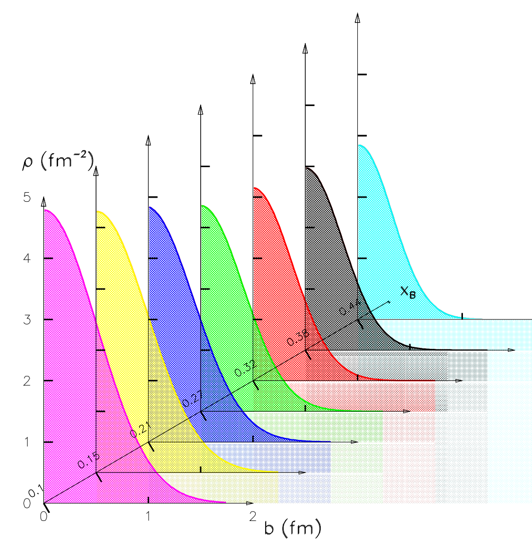
- Competition with the **BH** process! (σ asymmetries measured).

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

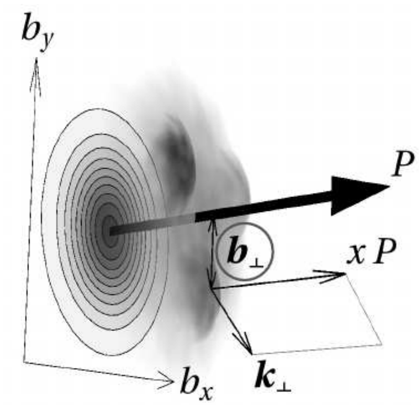
Nevertheless, for the proton, we have results:

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

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

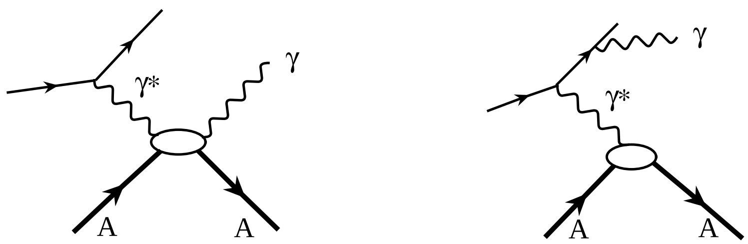


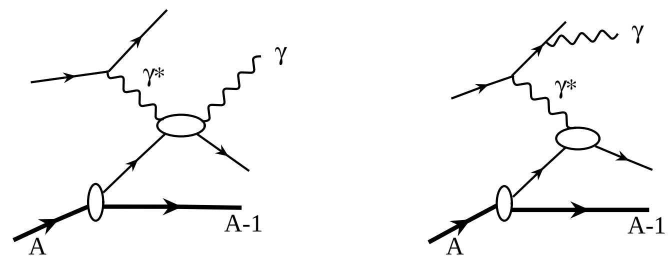
Nuclei and DVCS tomography



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

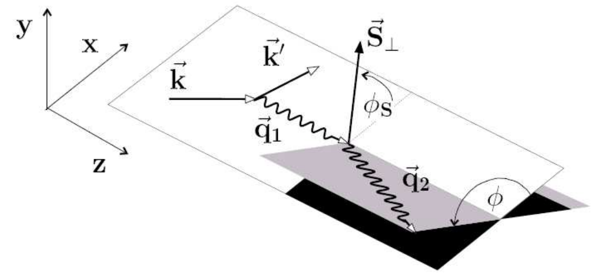
Incoherent DVCS: tomography of bound nucleons, realization of the EMC effect

^{3}He is a unique target for GPDs studies. Examples:

* **access to the neutron information in coherent processes**
* **heavier targets do not allow refined theoretical treatments. Test of the theory**
* **Between ^{2}H (“not a nucleus”) and ^{4}He (a true one).** Not isoscalar!

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

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



- Polarized beam, unpolarized target:

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

- 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)**):

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

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,

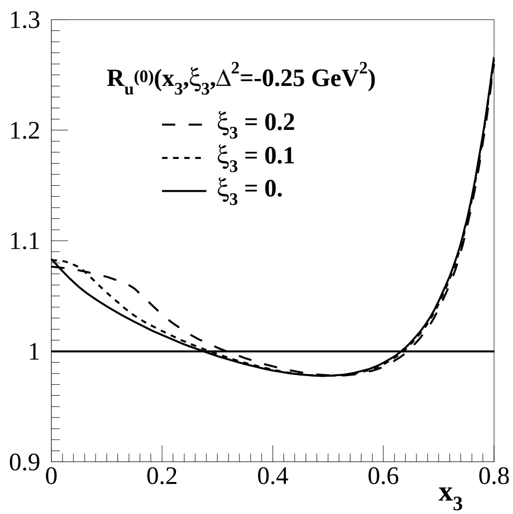
$$P^N_{SS',ss'}(\vec{p},\vec{p}\,',E) = \frac{1}{(2\pi)^6} \frac{M\sqrt{ME}}{2} \int d\Omega_t \sum_{s_t} \langle \vec{P}' S' | \vec{p}\,' s', \vec{t} s_t \rangle_N \langle \vec{p} s, \vec{t} s_t | \vec{P} S \rangle_N \,,$$

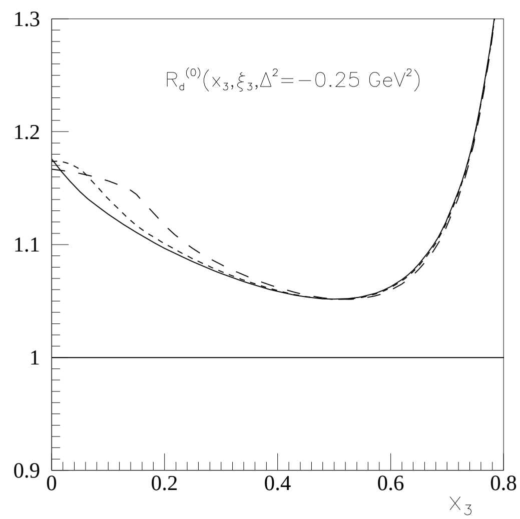
evaluated by means of a realistic treatment based on Av18 wave functions (**“CHH” method in A. Kievsky** *et al* **NPA 577, 511 (1994); Av18 + UIX overlaps in E. Pace** *et. al*, **PRC 64, 055203 (2001)**).

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

Nuclear effects - flavor dependence

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





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

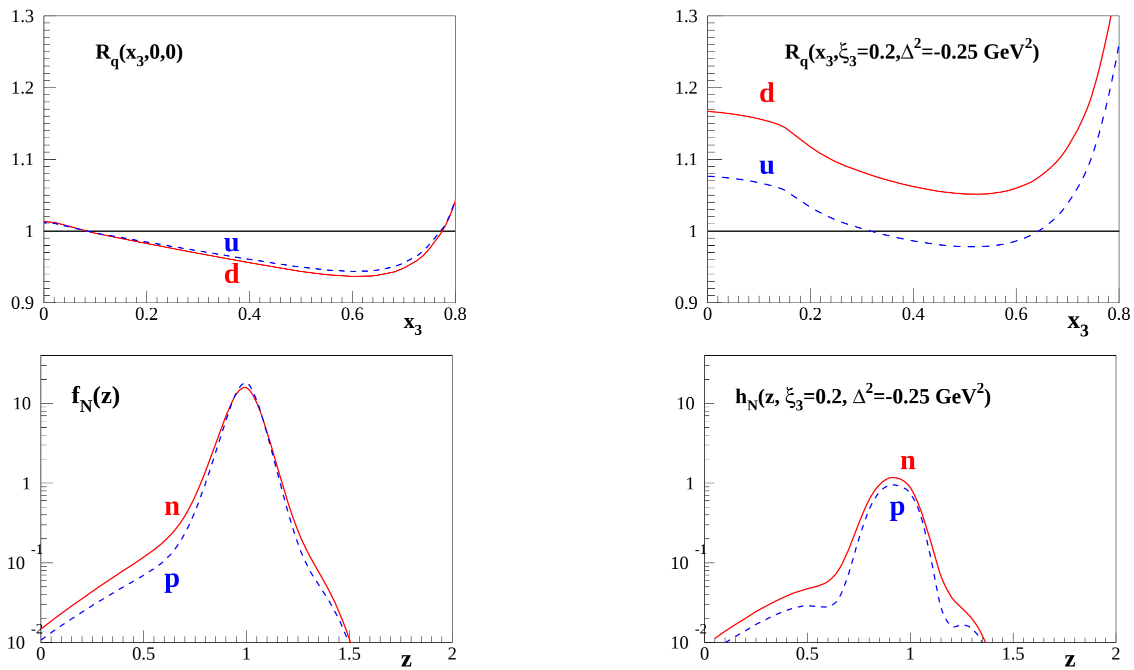
$$H_q^{3,N}(x,\xi,\Delta^2) = \tilde{H}_q^N(x,\xi) F_q^3(\Delta^2)$$

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

Calculations of ^{3}He GPDs: 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-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.

Conclusions

Further calculations to support DIS EIC measurements:

1. Calculations with a Light-Front spectral function (in IA);
   LF, formal: Del Dotto, Pace, Salmè, SS, PRC 95 (2017) 014001. Relativistic FSI?
2. Extension to low x kinematics (coherent effects)
3. Towards 4-body systems: DVCS off ^{4}He (in collaboration with M. Viviani, Pisa), non diagonal spectral function. Upgrade, using realistic dynamics, of old results for (unp.) spectator tagging. (also for JLab, ALERT collaboration)

Contribution of EIC to validate underlying assumptions

1. Provide also absolute cross sections, not only asymmetries!
2. Spectator tagging (any kind of): off-shell effects, (polarized) EMC effect, validity of the impulse approximation
3. SIDIS $^3\vec{H}e(\vec{e}, e'd)X$ measurements and polarized EMC effect
4. Even better with $^3\vec{H}$ beams: direct access to g_1^n; check of IA and extraction formulae (even the inclusive measurement is sufficient for this)
5. Even unpolarized ^3H very interesting (DVCS) for isospin dependent nuclear effects and the possible breaking of IA
6. DVCS off ^{3}He: onset of nuclear effects, great theoretical control