Evaluating Final-state Interaction effects in SIDIS by a $^3\vec{\mathrm{He}}$ target

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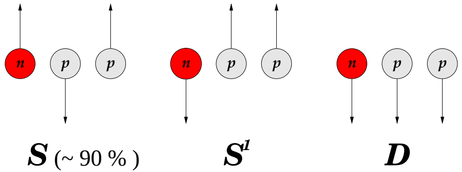
PRC 89, 035206, (2014): FSI in spectator SIDIS a $^3\vec{\mathrm{He}}$ target
Submitted to PRC and arXiv:1704.06182: FSI and SIDIS by a $\perp$-polarized $^3\mathrm{He}$

Outline

Polarized $^3\mathrm{He}$ as an effective neutron target: why?



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

$\mu_{^3He} \sim \mu_n$ $\qquad$ $\mu_D \sim \mu_p + \mu_n$

Sound information on the neutron from asymmetries measured in both inclusive and exclusive reactions and very different kinematical regimes

$$\vec{He}(\vec{e}, e')X, \quad \vec{He}(\vec{e}, e'n)pp, \quad \vec{He}(\vec{e}, e'\pi)X \; .....$$

$\Rightarrow$ neutron FF, structure functions, TMDs,

Holy Grail: Flavor decompositions ....

A 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...
  Recall: in ^{3}He target, conventional nuclear effects under control... Hence, exotic effects could be disentangled

From the theoretical side: **two** main issues + ... **one**

- A careful description of the nuclear *initial* state.

  Very refined solutions for both $^3\mathrm{He}$ and ^{3}H exist, like the ones obtained by the Pisa group (Kievsky, Marcucci, Rosati and Viviani Few-Body Syst. 22(1997)) with an accuracy of about 1 keV for the binding energies

  2N potential: AV18 (Wiringa, Stoks, and Schiavilla, PRC 51 (1995))

  3N potential: Urbana IX (Pieper, Pandharipande, Wiringa,and Carlson,PRC 64 (2001))

- The final-state challenge:
  taking into account not only the interaction inside the spectator pair (plane-wave impulse approximation), but also the interaction with the recoiling hadronic states.

  ⋮

- A Poincaré covariant description of the nuclear environment: Light-front A=3 spectral function: Del Dotto et al PRC 95, 014001 (2017) ⇒ EMC effect

  N.B. at the present stage, the relativistic effects in the theoretical description of SIDIS are taken into account through kinematics and elementary cross-section.

Plane-wave Impulse Approximation for SIDIS

★ Assumptions:

i) the relevant em nuclear current can be approximated by the sum of only one-body terms

ii) the virtual photon does not interact with the spectator pair

iii) the final state is: $|\Psi_{fin}\rangle = |\Phi_{spec}\rangle \otimes |h\rangle \otimes |B'\rangle$, with $|\Phi_{spec}\rangle$ a fully interacting spectator pair

★ ★ SIDIS cross-section with a polarized target=
electron-nucleon transition x-section properly folded with *the nucleon spin-dependent Spectral Function*

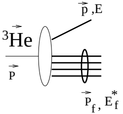
★ ★ ★ The nucleon *spin-dependent* Spectral Function yields the probability distribution to find a nucleon, with given

- spin projection,
- three-momentum (absolute value),
- removal energy $E_{rem} = B_3 - E_{spec}$ ($B_3 \equiv$ $^3\mathrm{He}$ binding energy and E_{spec} eigen-energy of a fully interacting spectator pair)

N.B. Through the nucleon Spectral Function one takes into account a first contribution by FSIs to the x-section,

The Spectral Function for a nucleon with given spin-projection

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



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

- $|\pi_A J_A \mathcal{M}'; \Psi_A\rangle_{S_A} \equiv$ ground state, polarized along the direction $\hat{\mathbf{S}}_A$
- $|\vec{p}, \sigma; \phi_f(E^*_f)\rangle \equiv |\vec{p}, \sigma\rangle \otimes |\phi_f(E^*_f)\rangle$,
  N.B. $\phi_f(E^*_f)$ is a fully interacting spectator state, with the **same** interaction adopted for the ground state (in our. case AV18 NN)
- $\phi_f(E^*_f)$ can be either a deuteron or a scattering state: when a deeply bound nucleon, with high removal energy $E = E_{min} + E^*_f$, leaves the nucleus, the recoiling system is left with high excitation energy E^*_f.
- Recall: $\mathbf{P}^N_{\mathcal{M}\sigma\sigma'}(\vec{p},, E)$ is a 2×2 matrix. Only the diagonal terms have a probabilistic interpretation.
- General structure

$$\hat{\mathbf{P}}^N_{\mathcal{M}}(\vec{p}, E) = \frac{1}{2}\left\{B^N_0(|\vec{p}|, E) + \vec{\sigma} \cdot \left[\vec{S}_A \; B^N_{1,\mathcal{M}}(|\vec{p}|, E) + \hat{p}\; (\hat{p} \cdot \vec{S}_A)\; B^N_{2,\mathcal{M}}(|\vec{p}|, E)\right]\right\}$$

But, the extension to heavier polarized nuclei is highly non trivial. For $J > 1/2$ $(\vec{p} \cdot \vec{S}_A)^{2n}$ dependence in the scalar functions $B^N_{i,\mathcal{M}}$

Status (Impulse Approximation and beyond)

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

- Ciofi degli Atti, Pace, G.S. PRC 21 (1980) 505, unpol. SF ($B_0^N(|\vec{p}|, E)$)
- Ciofi degli Atti, Pace, G.S. PRC 46 (1991) 1591: spin dependence in PWIA

$$\hat{\mathbf{P}}^N_{\mathcal{M}}(\vec{p}, E) = \frac{1}{2}\left\{B_0^N(|\vec{p}|, E) + \vec{\sigma} \cdot \left[\vec{S}_A\ B^N_{1,\mathcal{M}}(|\vec{p}|, E) + \hat{p}\ (\hat{p} \cdot \vec{S}_A)\ B^N_{2,\mathcal{M}}(|\vec{p}|, E)\right]\right\}$$

- E. Pace, G.S., S.Scopetta, A. Kievsky PRC 64 (2001) 055203, spin-dependent SF with AV18 and U-IX
- E. Pace, G.S. and A. Kievsky, EPJA 19 (2004) 87, exact FSI in the $\{p, d\}$ channel.
- Ciofi degli Atti, Kaptari, PRC 66 (2002) 044004, unpolarized SF with FSI in eikonal approximation (QE)
- Spin-dependent SF with FSI in the two-body channel, L. Kaptari, Del Dotto, Pace, G.S., S.Scopetta, PRC 89 (2014),
- Light-Front SF, A. Del Dotto et al, PRC 95 (2017). Preliminary calculation of EMC effect in $^3\mathrm{He}$: E. Pace et al, arXiv:1705.00966.

The polarized structure function g_1^n from DIS by $^3\vec{\mathrm{He}}$

(The first application of a spin-dependent Spectral Function)

DIS of longitudinally polarized electrons by a $^3\vec{\mathrm{He}}$ target: dynamical effects are evaluated through the spin-dependent spectral function $\mathbf{P}_{\sigma,\sigma'}(p,E)$.
In IA, the *nuclear* structure function g_1^A is given

$$g_1^A(x) = \int_x^{M_A/M} dz \left[Z\ g_1^p(x/z) f_p^{pol}(z) + N\ g_1^n(x/z) f_n^{pol}(z) \right]$$

$f_N^{pol}(z) \equiv$ the nucleon polarized light-cone distribution, determined through B_1 and B_2, i.e.

$$\hat{\mathbf{P}}^N_{\mathcal{M}}(\vec{p},E) = \frac{1}{2}\left\{ B_0^N(|\vec{p}|,E) + \vec{\sigma}\cdot\left[\vec{S}_A\ B^N_{1,\mathcal{M}}(|\vec{p}|,E) + \hat{p}\ (\hat{p}\cdot\vec{S}_A)\ B^N_{2,\mathcal{M}}(|\vec{p}|,E)\right]\right\}$$

To extract the *nucleon* g_1^n one has to get $A_{1n} = 2xg_1^n/F_2^n(x)$, but one measures the inclusive asymmetry with parallel or antiparallel alignments of $^3\mathrm{He}$ polarization and electron helicity

$$A_3^{exp} = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\uparrow\downarrow}}$$

One can safely adopts (as done by experimental Collaborations for the actual extraction)

$$A_{1n} \simeq \frac{1}{p_n d_n} \left(A_3^{exp} - 2 p_p d_p A_p^{exp}\right) \; , \quad (\textit{Ciofi degli Atti et al., PRC48(1993)R968})$$

with $d_{p(n)}$ the dilution factors and $p_{p(n)}$ *the nucleon effective polarizations*

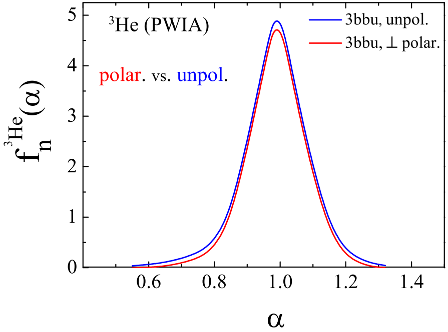
The nuclear effects are hidden in the *effective polarizations* to be evaluated through the spin-dependent SF $\mathbf{P}_{\sigma,\sigma'}(\vec{p}, E)$

$$p_p = -0.023 \qquad (AV18)$$

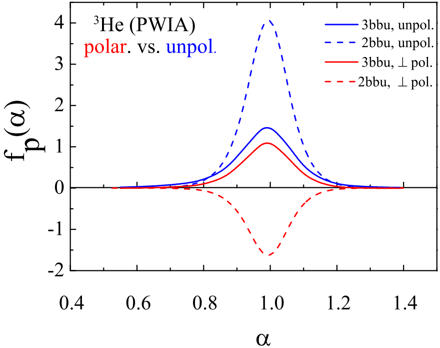
$$p_n = 0.878 \qquad (AV18)$$

Light-cone momentum distributions in IA (α = LC variable)

Neutron: only 3-body break-up



Proton: 2bbu + 3bbu

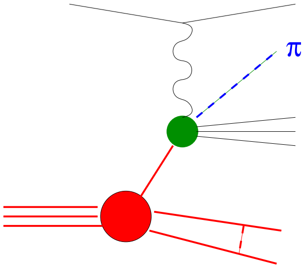


- weak depolarization of the neutron: Red line: polar. vs Blue line: unpolar.
- strong depolarization of the protons:
  cancellation between contributions in the 2-body (dashed) and 3-body (solid) channels

Neutron TMDs from SIDIS by $^3\vec{\mathrm{He}}$ target

What occurs with SIDIS processes?

In IA :

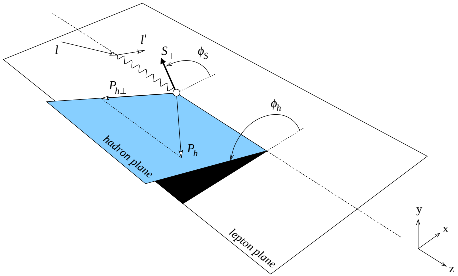


Can one use an analogous formalism to extract the TMDs from the relevant asymmetries? Namely, by using PWIA only?

In principle NO: since we are in an exclusive regime and we have to carefully investigate the role of FSIs (remind that the values of the kinetic energies of the hadrons in the final state are the relevant quantities)

E.g.: $E_\pi \simeq 2.4$ GeV in JLAB exp at 6 GeV - Qian et al., PRL 107 (2011) 072003

To start: IA calculations needed!



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

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

$$x = \frac{Q^2}{2P\cdot q} \quad y = \frac{P\cdot q}{P\cdot l} \quad z = \frac{P\cdot h}{P\cdot q}$$

$$\boxed{\hat{q} = -\hat{e}_z}$$

In the Lab-frame

$$x = \frac{Q^2}{2M\nu} \quad y = \frac{\nu}{\mathcal{E}} \quad z = \frac{E_h}{\nu}$$

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

In SSA studies where a fast hadron is detected in coincidence with the final electron , two different mechanisms can be experimentally singled out

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

with

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

For a nucleon target, we assume the convolution of TMDs and fragmentation functions

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

with

$$N^{Sivers} \propto \sum_q e_q^2 \int d^2\boldsymbol{\kappa}_T \int d^2\mathbf{k}_T \ \delta^2(\mathbf{k}_T + \mathbf{q}_T - \boldsymbol{\kappa}_T) \frac{\hat{\mathbf{P}}_{\perp h} \cdot \mathbf{k}_T}{M} f_1^q(x, \mathbf{k}_T^2) \ D_1^{\perp q,h}(z, (z\boldsymbol{\kappa}_T)^2)$$

$$N^{Collins} \propto \sum_q e_q^2 \int d^2\boldsymbol{\kappa}_T \int d^2\mathbf{k}_T \ \delta^2(\mathbf{k}_T + \mathbf{q}_T - \boldsymbol{\kappa}_T) \frac{\hat{\mathbf{P}}_{\perp h} \cdot \boldsymbol{\kappa}_T}{M_h} h_1^q(x, \mathbf{k}_T^2) \ H_1^{\perp q,h}(z, (z\boldsymbol{\kappa}_T)^2)$$

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

f_1^q and h_1^q are two TMDs
$D_1^{q,h}$ and $H_1^{\perp q,h}$ are fragmentation function (describing the hadronization processes).

Experimental outcomes

★ 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**

Fundamental role of the neutron for the **flavor** decomposition!

Theoretical analysis in IA addressed

★ SSAs in the process $^3\vec{\mathrm{He}}(e, e'\pi)X$ [S.Scopetta, PRD 75 (2007) 054005]

★ ★ Assumptions: i) Bjorken limit, ii) FSI only in the two-nucleon spectator pair (PWIA) and iii) no FSI between the measured fast, ultrarelativistic π and the baryonic remnant

Aim: to extend an expression, analogous to the one adopted in DIS, to the realm of SIDIS, and eventually to extract the relevant neutron TMDs !

$$A_n^{S(C)} \simeq \frac{1}{p_n d_n}\left(A_{3;exp}^{S(C)} - 2 p_p d_p A_{p;exp}^{S(C)}\right) \qquad (1)$$

S=Sivers and C=Collins

To check: i) calculate $A_{3;theo}^{S(C)}$ (as well as p_N and d_N), where models for $A_N^{S(C)}$ and the spin-dependent Spectral function are adopted; ii) insert in (1) $A_{3;theo}^{S(C)}$ and $A_{p;mod}^{S(C)}$ on place of $A_{3;exp}^{S(C)}$ and $A_{p;exp}^{S(C)}$, respectively.

Expected result for assessing the self-consistency of (1)

$$A_{n;mod}^{S(C)} \simeq \frac{1}{p_n d_n}\left(A_{3;theo}^{S(C)} - 2 p_p d_p A_{p;mod}^{S(C)}\right) \qquad (1)$$

Studying the model dependence is a fundamental step.

The theoretical calculations of $A^{S(C)}_{3;theo}$ is a proper folding of the the spin-dependent Spectral Function, $\hat{\mathbf{P}}^N_{\mathcal{M}}(\vec{p}, E)$, TMDs AND fragmentation functions (that can be modified by the nuclear environment !) :

$$A^{S(C)}_{3;theo} \propto \frac{N^{S(C)}_3}{D_3}$$

with $(z = p \cdot h / p \cdot q)$

$$D_3 = \sum_{N=n,p} \sum_q e_q^2 \int dE \int d\vec{p} \int_x^{\frac{M_3}{M}} \frac{d\alpha}{\alpha} \frac{\sqrt{2}p^+}{p_0} P^N(\vec{p}, E)\, \delta\left(\alpha - \frac{\sqrt{2}p^+}{M}\right)$$
$$\times \left\{ \int d\phi_S\, d\phi_h\, d^2\kappa_{\mathbf{T}}\, d^2\mathbf{k_T}\, \delta^2(\mathbf{k_T} + \mathbf{q_T} - \kappa_{\mathbf{T}}) D_1^{q,h}\left(z, (z\kappa_{\mathbf{T}})^2\right)\ f_1^{q,N}\left(\frac{x}{\alpha}, \mathbf{k_T}^2\right) \right\}$$

$$P^N(\vec{p}, E) = P^N_{\frac{1}{2}\frac{1}{2},\frac{1}{2}}(\vec{p}, E) + P^N_{-\frac{1}{2}-\frac{1}{2},\frac{1}{2}}(\vec{p}, E)$$

$$N_3^S = \sum_{N=n,p} \sum_q e_q^2 \int dE \int d\vec{p} \int_x^{\frac{M_3}{M}} \frac{d\alpha}{\alpha} \frac{\sqrt{2}p^+}{p_0} P_\perp^N(\vec{p}, E)\, \delta\left(\alpha - \frac{\sqrt{2}p^+}{M}\right)$$

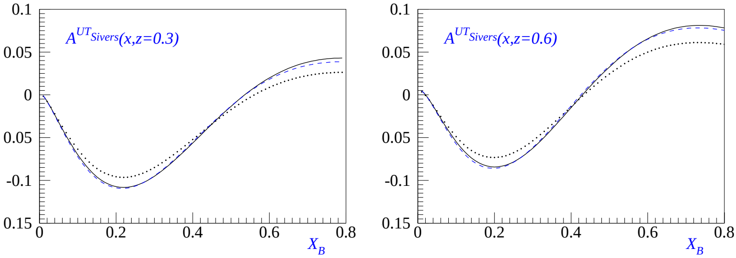
$$\times \left\{ \int d\phi_S\, d\phi_h\, d^2\kappa_{\mathbf{T}}\, d^2\mathbf{k_T}\, \delta^2(\mathbf{k_T} + \mathbf{q_T} - \kappa_{\mathbf{T}}) \frac{\hat{\mathbf{h}} \cdot \mathbf{k_T}}{\mathbf{M}} D_1^{q,h}(z, (z\kappa_{\mathbf{T}})^2) f_{1T}^{\perp q,N}\left(\frac{x}{\alpha}, \mathbf{k_T}^2\right) \right\}$$

$$N_3^C = \sum_{N=n,p} \sum_q e_q^2 \int dE \int d\vec{p} \int_x^{\frac{M_3}{M}} \frac{d\alpha}{\alpha} \frac{\sqrt{2}p^+}{p_0} P_\perp^N(\vec{p}, E)\, \delta\left(\alpha - \frac{\sqrt{2}p^+}{M}\right)$$

$$\times \left\{ \int d\phi_S\, d\phi_h\, d^2\kappa_{\mathbf{T}}\, d^2\mathbf{k_T}\, \delta^2(\mathbf{k_T} + \mathbf{q_T} - \kappa_{\mathbf{T}}) \frac{\hat{\mathbf{h}} \cdot \kappa_{\mathbf{T}}}{\mathbf{M_h}} H_1^{\perp q,h}(z, (z\kappa_{\mathbf{T}})^2) \right\}$$

$$P_\perp^N(\vec{p}, E) = P^N_{\frac{1}{2}\frac{1}{2},\frac{1}{2}}(\vec{p}, E) - P^N_{-\frac{1}{2}-\frac{1}{2},\frac{1}{2}}(\vec{p}, E)$$

Results (by S. Scopetta): $\vec{n}$ from $^3\vec{\mathrm{He}}$: A_{UT}^{Sivers} ($\Rightarrow f_1^q(x, \mathbf{k}_T^2)$), @ JLab, in IA



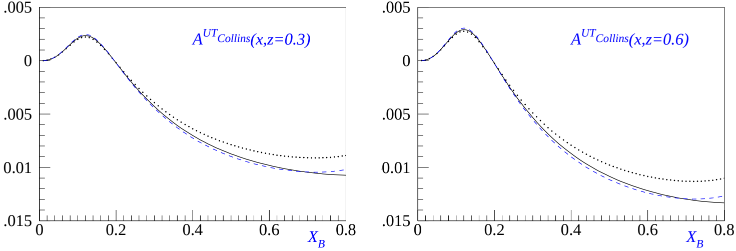
FULL: Neutron asymmetry (model: from parametrizations or models of TMDs and FFs)

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

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

$$A_n \simeq \frac{1}{p_n d_n} \left(A_{3UT}^{calc} - 2 p_p d_p A_p^{model} \right)$$

Results (S. Scopetta): $\vec{n}$ from ${}^3\vec{He}$: $A_{UT}^{Collins}$ ($\Rightarrow h_1^q(x, \mathbf{k}_T^2)$), @ JLab



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

Could FSI effects, partially included in PWIA (interacting two-nucleon spectator, only), have some impact on TMD extractions from future measurements @ JLab-12 ?

FSI: Generalized Eikonal Approximation (GEA)

Glauber Approximation

- The N-(A-1) scattering amplitude, needed to describe the interaction between emitted nucleon and spectator pair, is obtained within the eikonal approximation, taking into account multiple elastic scatterings of a fast nucleon by a spectator system. Therefore, most of the scattering processes takes places in the forward direction.
- The nucleons of the (A-1) spectator system are stationary during the multiple scattering with the struck nucleon (the *frozen-core approx.*)
- Only perpendicular momentum transfer components are present in the NN scattering amplitude ($f(q_\perp) = ik_{in}/(2\pi) \int d\mathbf{b}\ e^{-i\mathbf{q}_\perp\cdot\mathbf{b}}\Gamma(\mathbf{b})$.)

Generalized Eikonal Approximation

- the frozen-core approximation is released, by taking into account the excitation energy of the (A-1) spectator system (i.e. introducing the Spectral Function).
- Then, a correction term to the standard profile function in GA occurs, leading to an additional contribution from the longitudinal separation z_{1i}, due to the dependence of $\sigma_{eff}(z)$, describing the interaction of the debris of the struck nucleon 1 and the nucleon i in the spectator pair.

GEA is based on a diagrammatic approach, suitable for the relativistic generalization !

For $A(e, e'p)B$ L. L. Frankfurt,W. R. Greenberg, G. A. Miller, M. M. Sargsian and M. I. Strikman, Z. Phys. A 352, 97 (1995) and L. L. Frankfurt, M. M. Sargsian, and M. I. Strikman, PRC 56, 1124 (1997).

For $A(e, e'pp)B$ M. M. Sargsian, T. V. Abrahamyan, M. I. Strikman, and L. L. Frankfurt PRC 71 044614 (2005).

★ From the unpolarized case (^{2}H and $^3\mathrm{He}$)

C. Ciofi degli Atti L. Kaptari PRC 71, 024005 (2005) and M. Alvioli C. Ciofi degli Atti L. Kaptari PRC 81, 021001(R) (2010)

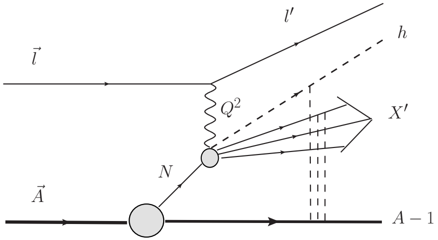
★★ $\Rightarrow$ the polarized $^3\mathrm{He}$ case

Spectator SIDIS: L. Kaptari, A. Del Dotto, E. Pace, G. S., Scopetta, PRC 89 (2014) 035206

Standard SIDIS: L. Kaptari, A. Del Dotto, E. Pace, G. S., Scopetta, submitted to PRC and arXiv:1704.06182:

FSI-GEA 1:

$$d\sigma \simeq \ell^{\mu\nu} W^A_{\mu\nu}(S_A) \to \ell^{\mu\nu} \sum_{S_{A-1},S_X} J^A_\mu J^A_\nu$$



Relative energy between $A-1$ and the remnants: a few GeV $\Rightarrow$ eikonal approximation $\to$ Glauber multipole scatterings $\to$ GEA

m.e. of the transition nuclear current: $J^A_\mu \simeq \langle S_A \mathbf{P} | \hat{\mathbf{J}}^A_\mu(0) | \mathbf{S_X}, \mathbf{S_{A-1}}, \mathbf{P_{A-1}} \mathbf{E^f_{A-1}} \rangle$

Nucleus ground-state: $\langle S_A \mathbf{P} | \mathbf{r_1 r_2 r_3} \rangle = \mathbf{\Phi_{^3He}}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) = \mathbf{e^{iPR}} \left[\mathbf{\Psi_3^{S_A}}(\rho, \mathbf{r}) \right]^*$

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

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

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

FSI-GEA 2

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

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

Exactwhen the one-body operator does not contain dependence upon the momentum $\hat{\mathbf{p}}$

$[\hat{\mathbf{p}}, \mathcal{G}(1,2,3)] \sim \partial/\partial\boldsymbol{\rho}\ \mathcal{G}(\mathbf{r},\boldsymbol{\rho}) \sim 0$ is OK if only the longitudinal part of the current operator is relevant and $\mathcal{G}(1,2,3)$ mainly depends by the transverse components, as it is.
Under the above assumption, a convolution formula can be still written:

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

The *Distorted*, spin-dependent nucleon Spectral Function is the basic quantity to be evaluated

$$P^{FSI,A,N}_{\lambda\lambda'}(E,\mathbf{p},...)$$

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

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Distorted spin-dependent Spectral Function for a nucleon inside $^3\vec{\mathrm{He}}$ is given in terms of *distorted* overlaps.

No longer a tensor product of a plane-wave and a spectator eigenstate

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

$$\times\ \langle(\hat{S}_{Gl})\{\Phi_{\epsilon^*_{A-1}}, \lambda, \mathbf{p}_N\}|S_A, \mathbf{P_A}\rangle\delta\,(E - B_A - \epsilon^*_{A-1})\,.$$

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

GEA, through $\Gamma(\mathbf{b}_{1i}, z_{1i})$, depends also on the traveled longitudinal distance (z_{1i}!) very successful in QE. semi-inclusive and exclusive processes off unpolarized $^3\mathrm{He}$

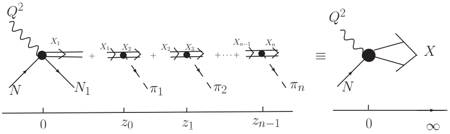
see, e.g., Alvioli, Ciofi & Kaptari PRC 81 (2010) 02100

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

The hadronization model

σ_{eff} model for SIDIS **(Ciofi & Kopeliovich, EPJA 2003)**

GEA + hadronization model successfully applied to unpolarized SIDIS $^2H(e,e'p)X$ **(Ciofi & Kaptari PRC 2011)**.



At the interaction point, a color string, X_1, and a nucleon N_1, arising from target fragmentation, are formed; the color string propagates and gluon radiation begins. The first pion is created at z_0....

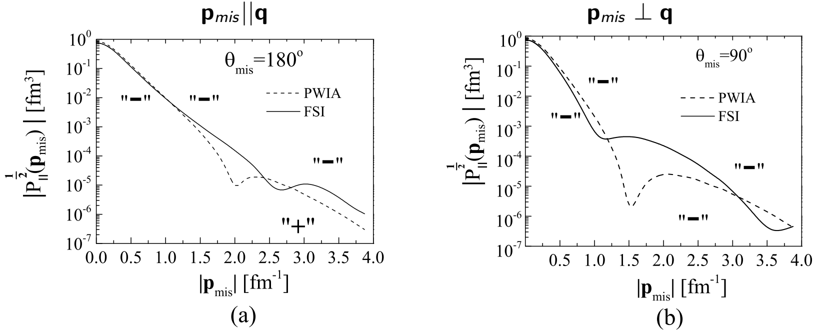
$$\sigma_{eff}(z) = \sigma^{NN}_{tot} + \sigma^{\pi N}_{tot}\,[n_M(z) + n_g(z)]$$

- $n_M(z)$ and $n_g(z)$ are the pion multiplicities ($\approx 2,3$) due to i) the breaking of the color string and ii) to gluon radiation, respectively.
- The hadronization model is phenomenological: parameters are chosen to describe the scenario of JLab experiments (e.g., $\sigma^{tot}_{NN} = 40$ mb, $\sigma^{tot}_{\pi N} = 25$ mb, $\alpha = -0.5$ for both NN and πN...).

First application to *spectator SIDIS*: a recoiling deuteron is detected, i.e $^3\vec{\mathrm{He}}(\vec{e}, e' \; D)X$

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

Msg: one can safely extract the polarized structure function of a bound proton, g_1^p, avoiding a region where the FSI has a maximal effect.



Relevant component of the nucleon SF for $^3\vec{\mathrm{He}}(\vec{e}, e' D)X$: $\left|\mathcal{P}_{||}^{\frac{1}{2}}\right| = \mathcal{F}'\left[B_1^{FSI}, B_2^{FSI}\right]$,

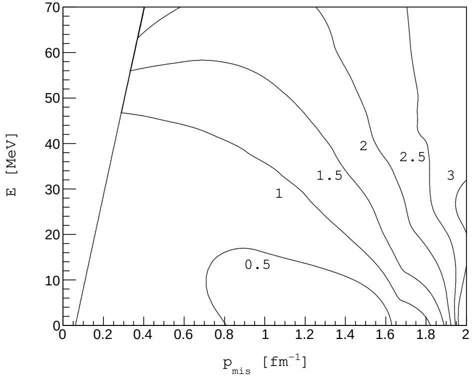
relevant vs the missing momentum ($\mathbf{p}_{mis} \equiv \mathbf{P}_D$),
Dashed line: PWIA calculations. Solid line: calculations with FSI effects.

N.B One should carefully choose the kinematical region for minimizing FSI

Second step: FSI also in three-body channels, for evaluating standard SIDIS

L. Kaptari, A. Del Dotto, E. Pace, G. S., S.Scopetta, submitted to PRC and 1704.06182

$\mathcal{P}^n_{unp}(p_{mis}, E)/P^n_{unp}(p_{mis}, E)$



Ratio between the unpolarized neutron SF with FSI and the corresponding PWIA quantity

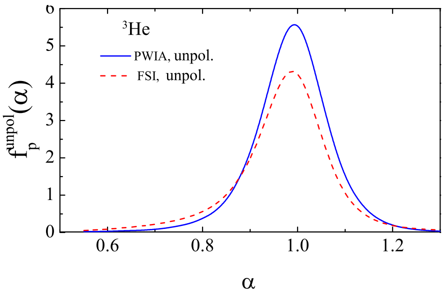
A simple example

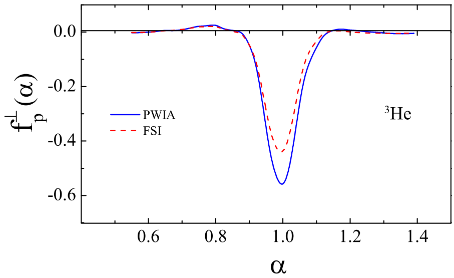
the distorted light-cone momentum distribution:

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

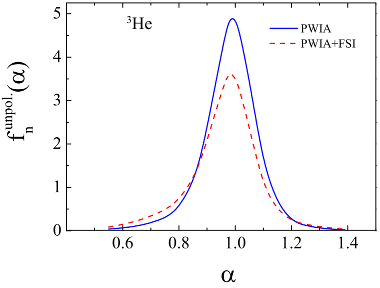
N.B. The spin-dependent components of the SF lead to spin-dependent LC distributions!

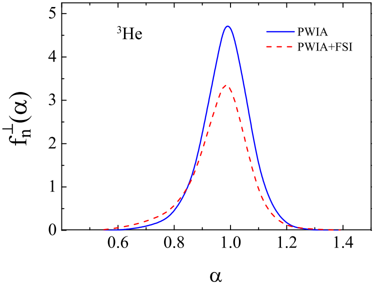
PROTON @ E_i = 8.8 GeV, $\bar{Q}^2 = 5.73$ (GeV/c)^2

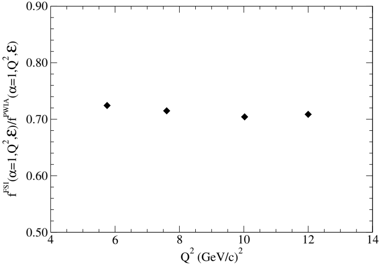




NEUTRON @ $E_i = 8.8$ GeV, $\bar{Q}^2 = 5.73$ (GeV/c)^2

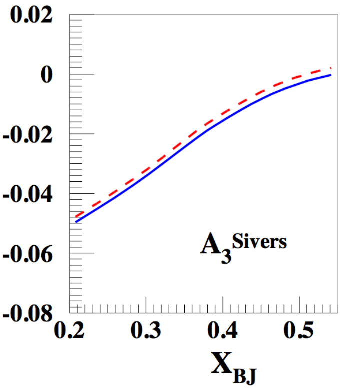






Ratio of the unpolarized LC momentum distribution evaluated taking into account FSI to the corresponding quantity obtained in PWIA, for the neutron

Full calculations of Sivers and Collins Asymmetries for a polarized ^{3}He target



Solid line: FSI — Dashed line: PWIA

Calculations have been performed at $\bar{Q}^2 = 5.73$ (GeV/c)^2, i.e. the central Q^2 value for an energy beam $\mathcal{E}$=8.8 GeV

Let us go back to our original question:

★ Can a simple procedure for extracting Sivers and Collins neutron asymmetries be applied to $^3\mathrm{He}$ data, or not?

★ ★ How this question is related to a full calculation of the corresponding asymmetries for the $^3\mathrm{He}$ nucleus?

IF the experimental data for the $^3\mathrm{He}$ asymmetries could be approximated as follows

$$A^{Col(Siv)}_{^3He} \simeq p^{\perp}_n \, d_n A^{Col(Siv)}_n + 2 \, p^{\perp}_p \, d_p A^{Col(Siv)}_p \ ,$$

$A^{Col(Siv)}_N \equiv$ free nucleon asymmetries
$p^{\perp}_N \equiv$ effective nucleon transverse polarizations
$d_N(x_{Bj}, z) \equiv$ dilution factors
THEN

$$A_n \approx \frac{1}{p^{FSI}_n d^{FSI}_n} \left(A^{exp}_3 - 2 {p_p}^{FSI} d^{FSI}_p A^{exp}_p \right) \approx \frac{1}{p_n d_n} \left(A^{exp}_3 - 2 p_p d_p A^{exp}_p \right)$$

By simulating the experimental $A^{Col(Siv)}_{^3He}$ with a PWIA calculations, one can accomplish a theoretical check, and Scopetta got a favorable result.

But including FSI, what happens?

Validation of the simple formula when FSI is acting

Effective polarizations change... But also the dilution factors

$$d_{N)}(x_{Bj}, z) = \frac{\sigma^{p(n)}(x_{Bj}, Q^2, z)}{\langle N_n \rangle \sigma^n(x_{Bj}, Q^2, z) + 2\langle N_p \rangle \sigma^p(x_{Bj}, Q^2, z)}$$

with

$$\langle N_{p(n)} \rangle = \int_{E_{min}}^{E_{max}} dE \int d\mathbf{p}_{mis} \;\; \mathcal{P}^{p(n)}(E, \mathbf{p}_{mis}) \theta \left(W_Y^2 - (m_{p(n)} + m_\pi)^2 \right) \;,$$

The relevant effective polarization is the transverse one,for a transversely polarized $^3\mathrm{He}$ target:

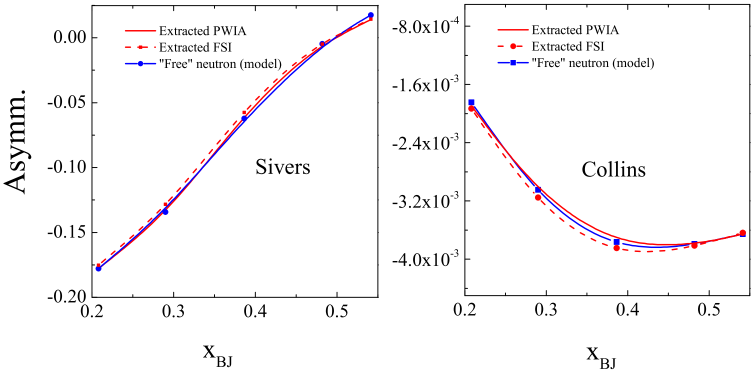
$$p_N^\perp = \int_{E_{min}}^{E_{max}} dE \int d\mathbf{p}_{mis} \;\; \mathcal{P}^{p(n)\,\perp}(E, \mathbf{p}_{mis}) \theta \left(W_Y^2 - (m_{p(n)} + m_\pi)^2 \right) \;.$$

Without relativistic effects

$$p_N^\perp = p_N^{||} = p_N$$

Good news from GEA studies of FSI!

Large cancellations between FSI effects in both numerator and denominator !!



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!

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

Conclusions and Perspectives

- Our knowledge of nuclear corrections, needed to extract information on the neutron from $^3\vec{\mathrm{He}}$ target, is steadily increasing, both for inclusive and exclusive reactions
- Full calculation of the $^3\mathrm{He}$ Sivers and Collins asymmetries within a framework based on GEA and the convolution with nucleons have been accomplished
- First Good news: the extraction procedure based on

$$A_n = \frac{1}{p_n d_n} \left(A^{exp}_{3UT} - 2 p_p d_p A^{exp}_p \right)$$

holds also in presence of FSI !
⇒ nuclear effects do not seem to represent an obstacle.

L. Kaptari, A. Del Dotto, E. Pace, G. S., S.Scopetta, submitted and 1705.00966

- A Poincaré covariant description of the Nucleon Spectral function has been completed. ⇒ EMC calculations are in progress

Back-up slides

$\mathcal{E}$, GeV	x_{Bj}	ν GeV	P_π GeV/c	$d_n(x_{Bj}, z)$	$p_n d_n$	$d_p(x_{Bj}, z)$	$p_p d_p$
8.8	0.21	7.55	3.40	0.304	0.266	0.348	-8.410^{-3}
8.8	0.29	7.15	3.19	0.286	0.251	0.357	-8.510^{-3}
8.8	0.48	6.36	2.77	0.257	0.225	0.372	-8.910^{-3}
11	0.21	9.68	4.29	0.302	0.265	0.349	-8.310^{-3}
11	0.29	9.28	4.11	0.285	0.250	0.357	-8.510^{-3}

Table: The PWIA values for the kinematical conditions of the planned experiments at JLab, with scattering angle $\theta_e = 30^o$ and detected pion angle $\theta_\pi = 14^o$. p_n= 0.876, p_p= -0.024, at $Q^2 = 5.73$ (GeV/c)^2, $\mathcal{E} = 8.8$ GeV

$\mathcal{E}$, GeV	x_{Bj}	ν GeV	P_π GeV/c	$d_n(x_{Bj}, z)$	$p_n d_n$	$d_p(x_{Bj}, z)$	$p_p d_p$
8.8	0.21	7.55	3.40	0.353	0.267	0.405	$-1.1 \cdot 10^{-2}$
8.8	0.29	7.15	3.19	0.332	0.251	0.415	$-1.1 \cdot 10^{-2}$
8.8	0.48	6.36	2.77	0.298	0.225	0.432	$-1.2 \cdot 10^{-2}$
11	0.21	9.68	4.29	0.351	0.266	0.405	$-1.0 \cdot 10^{-2}$
11	0.29	9.28	4.11	0.331	0.250	0.415	$-1.1 \cdot 10^{-2}$

Table: The same as in Table I, but taking into account FSI . $p_n \simeq 0.756$, $p_p \simeq -0.0265$ for $\bar{Q}^2 = 5.73$ (GeV/c)^2, $\mathcal{E} = 8.8$ GeV. $< N_n >$ and $< N_p >$, hold 0.85 and 0.87, respectively.