Neutron Parton Structure and the Light-Front Spectral Function of ^{3}He

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INPC - September 15th, 2016

Outline

- **SIDIS off ^{3}He** and information on the **neutron** parton structure

  Theoretical developments in SiDIS studies including the final state interaction between the observed pion and the remnant : **distorted spectral function**

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

- **Extraction of Collins and Sivers neutron asymmetries** from the measured Collins and Sivers asymmetries off ^{3}He

- A relativistic treatment to accurately describe the JLab program @ 12 GeV
  A Poincarè covariant spectral function for ^{3}He within the light-front dynamics

  E. P., A. Del Dotto, L. Kaptari, M. Rinaldi, G. Salmè, S. Scopetta

  Few Body Syst. 54 (2013) 1079; Few Body Syst. 55 (2014) 87; Few Body Syst. 56 (2015) 425;

  Few-Body Syst. 57 (2016) 601; arXiv:1609.03804

- EMC effect in ^{3}He with the LF spectral function : **preliminary results**

- Conclusions and Perpectives

Forthcoming 12 GeV Experiments at TJLAB

- SIDIS regime on polarized ^{3}He , e.g.

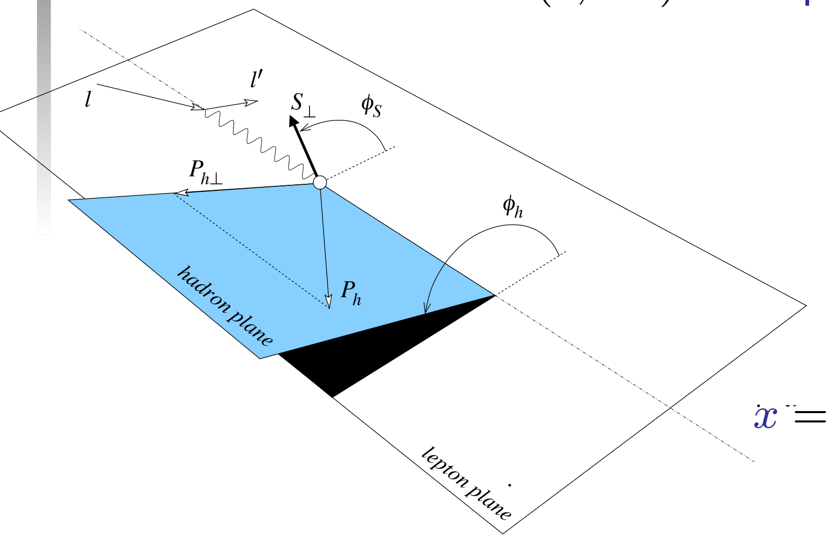
  Hall A, $http://hallaweb.jlab.org/12GeV/$
  H. Gao et al, PR12-09-014 (Rating A): Target Single-Spin Asymmetry in Semi-Inclusive Deep-Inelastic $(e, e'\pi^{\pm})$ Reaction on a Transversely Polarized ^{3}He Target

  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
  $www.jlab.org/\ jinhuang/12GeV/12GeVLongitudinalHe3.pdf$

  Cates G. et al., E12-09-018, JLAB approved experiment : Target Single-Spin Asymmetries in Semi-Inclusive Pion and Kaon Electroproduction on a Transversely Polarized ^{3}He Target
  $hallaweb.jlab.org/collab/PAC/PAC38/E12-09-018-SIDIS.pdf$

Single Spin Asymmetries (SSAs)

$\vec{A}(e,e'h)X$: 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 $\rightarrow$ the neutron $\rightarrow$ ^{3}He

SSAs for a nucleon in terms of

$h_1^{q,N}$, $f_{1T}^{\perp q,N}$, $f_1^{q,N}$ Sivers, transversity and unpolarized parton distributions
and $H_1^{\perp q,h}$, $D_1^{q,h}$ fragmentation functions:

- $A_{UT}^{Sivers} = \Delta\sigma_S^N\,(x,Q^2)/\sigma^N$ $\qquad$ $A_{UT}^{Collins} = \Delta\sigma_C^N\,(x,Q^2)/\sigma^N$

$$\Delta\sigma_C^N = \sum_q e_q^2 \int d^2\kappa_{\mathbf{T}} d^2\mathbf{k}_{\mathbf{T}} \delta^2(\mathbf{k}_{\mathbf{T}} + \mathbf{q}_{\mathbf{T}} - \kappa_{\mathbf{T}})\, \frac{\hat{h}_\perp \cdot \kappa_{\mathbf{T}}}{m_h} h_1^{q,N}(x, \mathbf{k}_{\mathbf{T}}{}^{\mathbf{2}})\, H_1^{\perp q,h}(z,(z\kappa_{\mathbf{T}})^{\mathbf{2}})\,,$$

$$\Delta\sigma_S^N = \sum_q e_q^2 \int d^2\kappa_{\mathbf{T}} d^2\mathbf{k}_{\mathbf{T}} \delta^2(\mathbf{k}_{\mathbf{T}} + \mathbf{q}_{\mathbf{T}} - \kappa_{\mathbf{T}})\, \frac{\hat{h}_\perp \cdot \mathbf{k}_{\mathbf{T}}}{m_N} f_{1T}^{\perp q,N}(x, \mathbf{k}_{\mathbf{T}}{}^{\mathbf{2}})\, D_1^{q,h}(z,(z\kappa_{\mathbf{T}})^{\mathbf{2}})\,,$$

$$\sigma^N(x,Q^2) = \sum_q e_q^2 \int d^2\kappa_{\mathbf{T}} d^2\mathbf{k}_{\mathbf{T}} \delta^2(\mathbf{k}_{\mathbf{T}} + \mathbf{q}_{\mathbf{T}} - \kappa_{\mathbf{T}})\; f_1^{q,N}(x, \mathbf{k}_{\mathbf{T}}^{\mathbf{2}})\; D_1^{q,h}(z,(z\kappa_{\mathbf{T}})^{\mathbf{2}})\,,$$

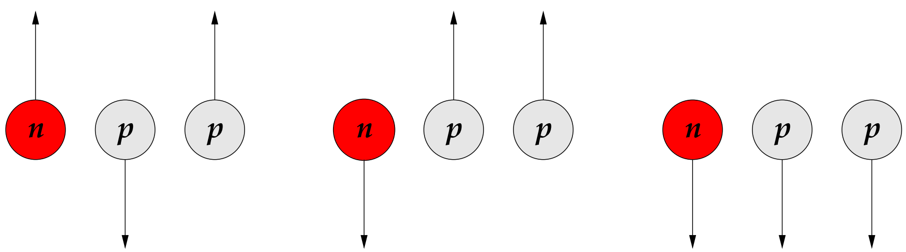
- LARGE A_{UT}^{Sivers} measured in $\vec{p}(e,e'\pi)x$ HERMES PRL 94, 012002 (2005)
- SMALL A_{UT}^{Sivers} measured in $\vec{D}(e,e'\pi)x$; COMPASS PRL 94, 202002 (2005)

A strong flavor dependence confirmed by recent data

Importance of the neutron for flavor decomposition!

The neutron information from ^{3}He

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



S (~ 90 %) S' D

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

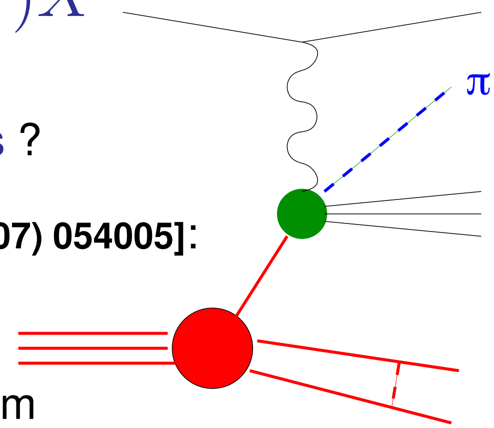
$$A_n \simeq \frac{1}{p_n d_n}\left(A_3^{exp} - 2 p_p d_p A_p^{exp}\right) , \quad (Ciofi\ degli\ Atti\ et\ al., PRC48(1993)R968)$$

$$(d_p, d_n \quad dilution factors)$$

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

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

$\vec{n}$ from $^3\vec{He}$: SiDIS case $\quad {}^3\vec{He}(e,e'\pi)X$



Can one use the same formula to extract the neutron SSAs ?

The process was first evaluated in IA **[S.Scopetta, PRD 75 (2007) 054005]**:

$\rightarrow$ no FSI between the measured fast, ultrarelativistic π
the remnant debris 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 transverse light-cone momentum distributions $f_N^\perp$ (m.d. for a transversely polarized nucleon in a transversely polarized nucleus) with parton distributions AND fragmentation functions :

$$A_3^{C(S)} = \frac{\int_x^A d\alpha \left[\Delta\sigma^n_{C(S)}\left(x/\alpha, Q^2\right) f_n^\perp(\alpha, Q^2) + 2\Delta\sigma^p_{C(S)}\left(x/\alpha, Q^2\right) f_p^\perp(\alpha, Q^2)\right]}{\int d\alpha \left[\sigma^n\left(x/\alpha, Q^2\right) f_n(\alpha, Q^2) + 2\sigma^p\left(x/\alpha, Q^2\right) f_p(\alpha, Q^2)\right]}$$

$$f_N^\perp(\alpha, Q^2) = \int dE \int_{p_m(\alpha,Q^2)}^{p_M(\alpha,Q^2)} P_N^\perp(E, \mathbf{p})\, \delta\left(\alpha - \frac{p\cdot q}{m_N \nu}\right) \theta\left(W_Y^2 - (m_N + m_\pi)^2\right) d^3\mathbf{p}$$

The nuclear effects were studied using the transverse spectral function $P_N^\perp(E, \mathbf{p})$ for a transv. polarized nucleon in a transv. polarized nucleus and models for $f_{1T}^{\perp q}$, $D_1^{q,h}$...

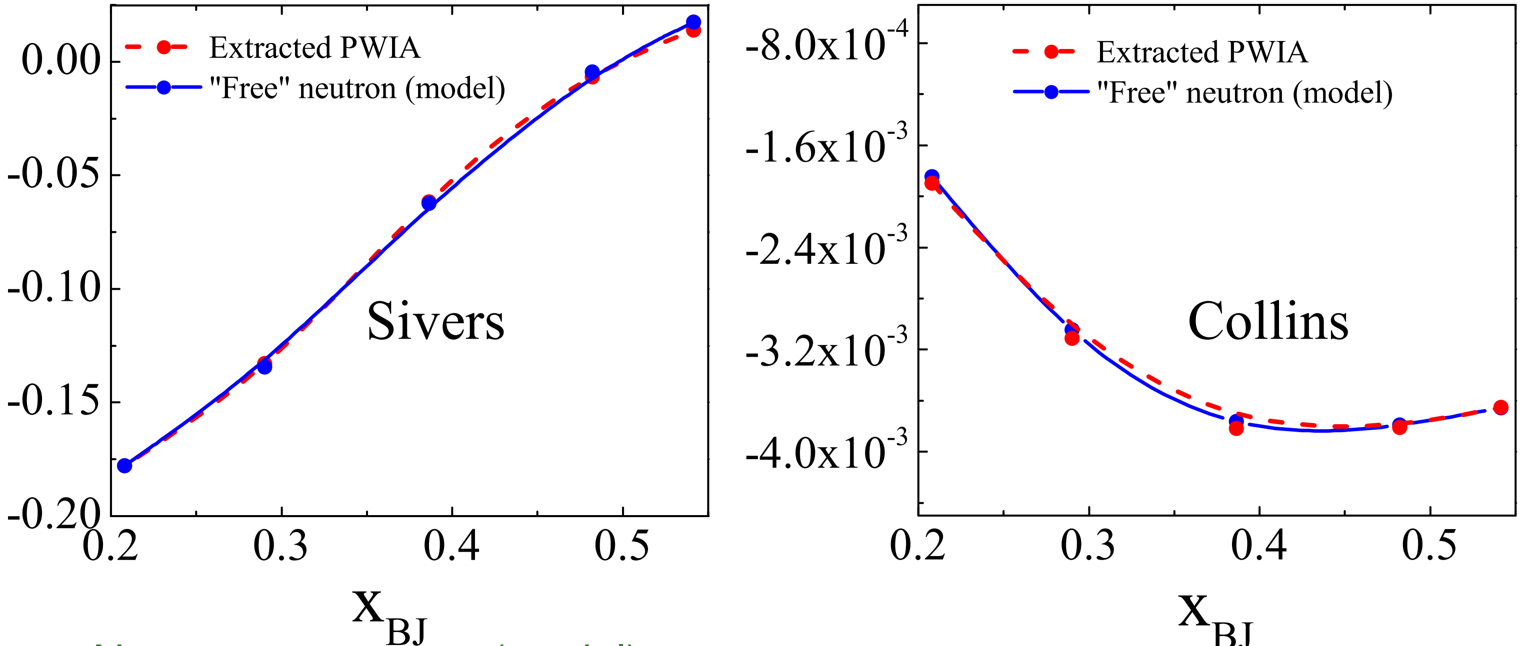
$\vec{n}$ from ${}^3\vec{H}e$: SiDIS case

Ingredients of the calculations :

- A realistic spin-dependent spectral function of ^{3}He (C. Ciofi degli Atti et al., PRC 46 (1992) R 1591; A. Kievsky et al., PRC 56 (1997) 64) obtained using the AV18 interaction and the wave functions evaluated by the Pisa group [A. Kievsky et al., NPA 577 (1994) 511] (small effects from 3-body interactions)
- Parametrizations of data for pdfs and fragmentation functions whenever available:
  $f_1^q(x, \mathbf{k_T^2})$, Glueck et al., EPJ C (1998) 461 ,
  $f_{1T}^{\perp q}(x, \mathbf{k_T}^2)$, Anselmino et al., PRD 72 (2005) 094007,
  $D_1^{q,h}(z, (z\kappa_{\mathbf{T}})^2)$, Kretzer, PRD 62 (2000) 054001
- Models for the unknown pdfs and fragmentation functions:
  $h_1^q(x, \mathbf{k_T}^2)$, Glueck et al., PRD 63 (2001) 094005,
  $H_1^{\perp q,h}(z, (z\kappa_{\mathbf{T}})^{\mathbf{2}})$ Amrath et al., PRD 71 (2005) 114018

Results will be model dependent. Anyway, the aim for the moment is to study nuclear effects.

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



FULL: Neutron asymmetry (model)

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

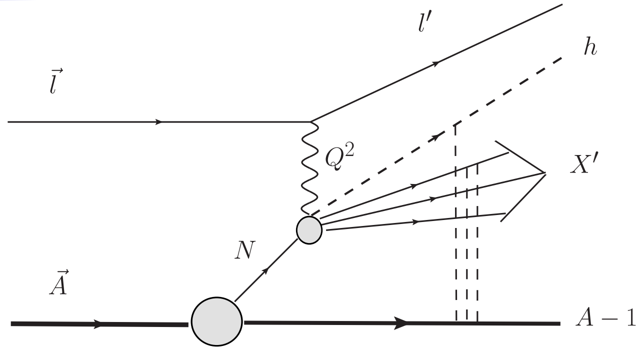
$$A_n \simeq \frac{1}{p_n d_n}\left(A_3^{calc} - 2p_p d_p A_p^{model}\right)$$

$$p_N = \int d\alpha f_N^{\perp}(\alpha, Q^2) \qquad d_N(x,z) = \frac{\sigma^N(x,Q^2,z)}{\sigma^n(x,Q^2,z) + 2\sigma^p(x,Q^2,z)}$$

The extraction procedure successful in DIS works also in SiDIS, for both Collins and Sivers SSAs !

FSI: Generalized Eikonal Approximation (GEA)

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



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

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

$$W^A_{\mu\nu}(S_A) \approx \sum\nolimits_{A-1,Y} J^A_\mu J^A_\nu \qquad J^A_\mu \simeq \sum_{i=1}^{3} \langle \hat{G}\{\Phi_{\epsilon^*_{A-1}}, \lambda', \mathbf{p}_N\} | \hat{j}_\mu(i) | S_A \mathbf{P} \rangle$$

$$\boxed{\hat{G} = Glauber\, operator} \qquad Y = h + X'$$

$$J_\mu(i) \approx \int d\mathbf{r_1} d\mathbf{r_2} d\mathbf{r_3} \Psi^{*f}_{23}(\mathbf{r_2}, \mathbf{r_3}) e^{-i\mathbf{p}_Y \mathbf{r_1}} \chi^+_{S_Y} \phi^*(\xi_Y) \cdot \hat{G}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) \hat{j}_\mu(\mathbf{r_1}) \Psi^{\mathbf{S}_A}_3(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3})$$

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

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

$w^{N,\lambda\lambda'}_{\mu\nu}(\mathbf{p})$ nucleon tensor

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

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

Relevant part of the GEA-distorted spectral function for transverse asymmetries:

$$P_N^{\perp, FSI}(E,\mathbf{p}) \equiv \left[P^{FSI\,\frac{1}{2}-\frac{1}{2}}_{N\,\frac{1}{2}-\frac{1}{2}}(E,\mathbf{p}) + P^{FSI\,-\frac{1}{2}\,\frac{1}{2}}_{N\,\frac{1}{2}-\frac{1}{2}}(E,\mathbf{p}) \right] \quad \text{with}$$

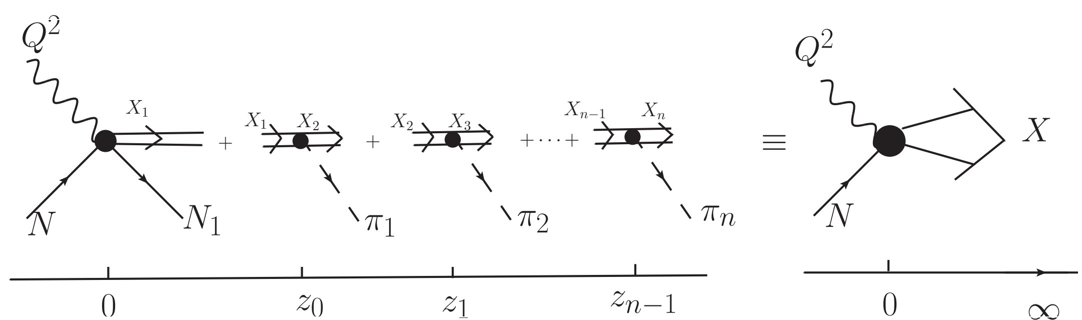
$$P^{FSI\,M,M'}_{N,\,\lambda\lambda'}(E,\mathbf{p}) = \sum_{f_{A-1}} \not\!\!\int_{\epsilon^*_{A-1}} \rho\left(\epsilon^*_{A-1}\right) \langle M', \mathbf{P_A} | \hat{G}\{\Phi^{f_{A-1}}_{\epsilon^*_{A-1}}, \lambda', \mathbf{p}_N\}\rangle \times$$

$$\langle \hat{G}\{\Phi^{f_{A-1}}_{\epsilon^*_{A-1}}, \lambda, \mathbf{p}_N\} | M, \mathbf{P_A}\rangle \delta\left(E - B_A - \epsilon^*_{A-1}\right) \qquad M, M' : polarizations\ along\ \mathbf{q}$$

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

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

(hadronization model: Kopeliovich et al., NPA 2004; σ_{eff} model: Ciofi & Kopeliovich, EPJA 2003; successfull application to unpolarized $^2H(e,e'p)X$: Ciofi & Kaptari PRC 2011)

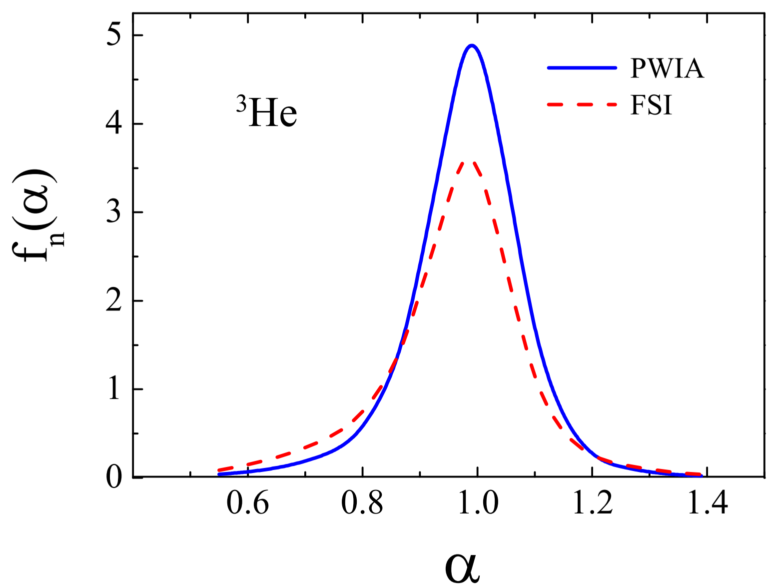


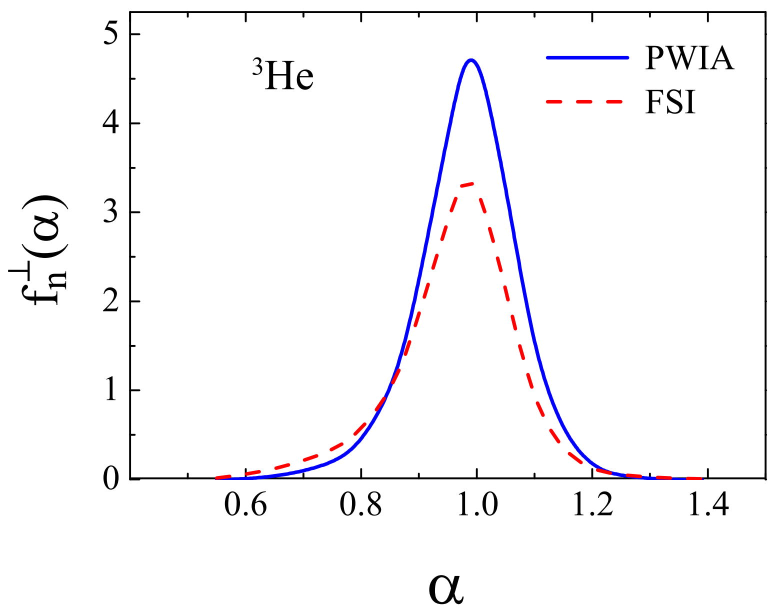
FSI: *distorted* spin-dependent spectral function of ^{3}He

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

- While P^{IA} depends on ground state properties, P^{FSI} is process dependent: for each experimental point $(x, Q^2 ...)$ a different P^{FSI} has to be evaluated !
- P^{FSI}: a really cumbersome quantity, a very demanding evaluation ($\approx$ 1 Mega CPU*hours @ "Zefiro" PC-farm, PISA, INFN "gruppo 4").

$\mathcal{P}^{IA}$ and $\mathcal{P}^{FSI}$, as well as the unpolarized and the transverse light-cone momentum distributions f_N^{IA} and f_N^{FSI} can be very different (JLAB kinematics - $\mathcal{E}$=8.8 GeV)



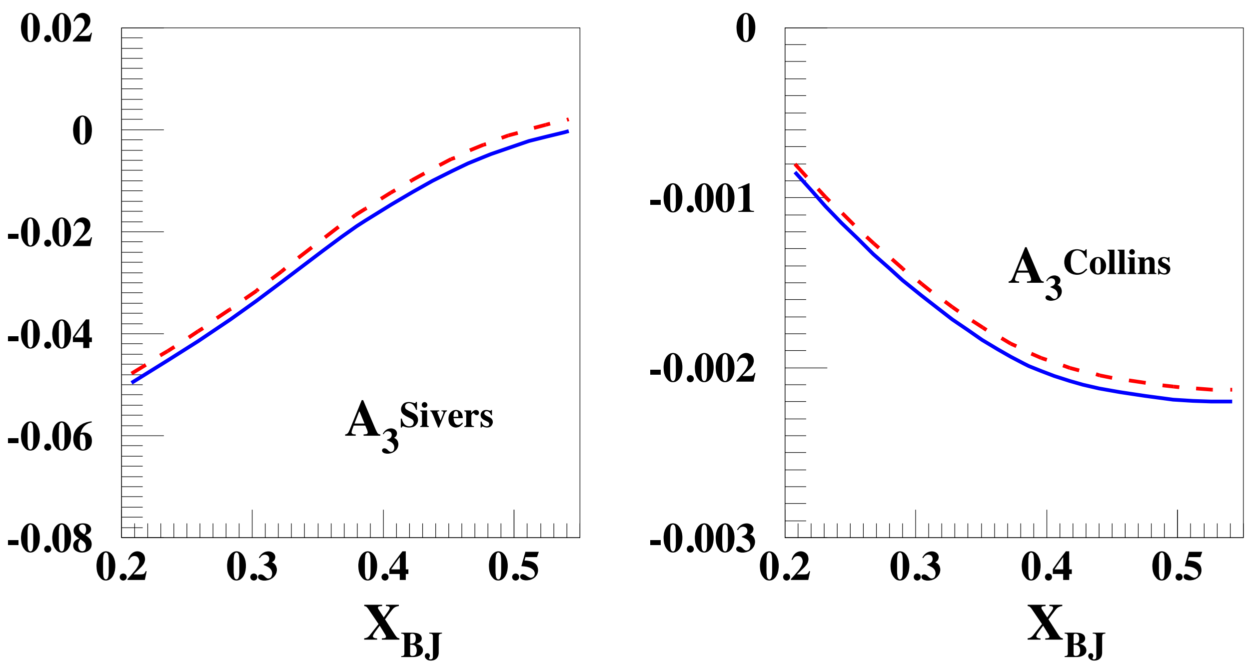


FSI's have therefore a strong effect on the spin-dependent and spin-independent SIDIS cross sections

FSI effects on asymmetries, polarizations and dilution factors

In asymmetries light-cone m. d. f_N appear in the numerator and in the denominator

$$A_3^{C(S)} = \frac{\int_x^A d\alpha \left[\Delta\sigma^n_{C(S)}\,(x/\alpha, Q^2)\; f_n^{\perp}(\alpha, Q^2) + 2\Delta\sigma^p_{C(S)}\,(x/\alpha, Q^2)\; f_p^{\perp}(\alpha, Q^2)\right]}{\int d\alpha \left[\sigma^n\,(x/\alpha, Q^2)\; f_n(\alpha, Q^2) + 2\sigma^p\,(x/\alpha, Q^2)\; f_p(\alpha, Q^2)\right]}$$

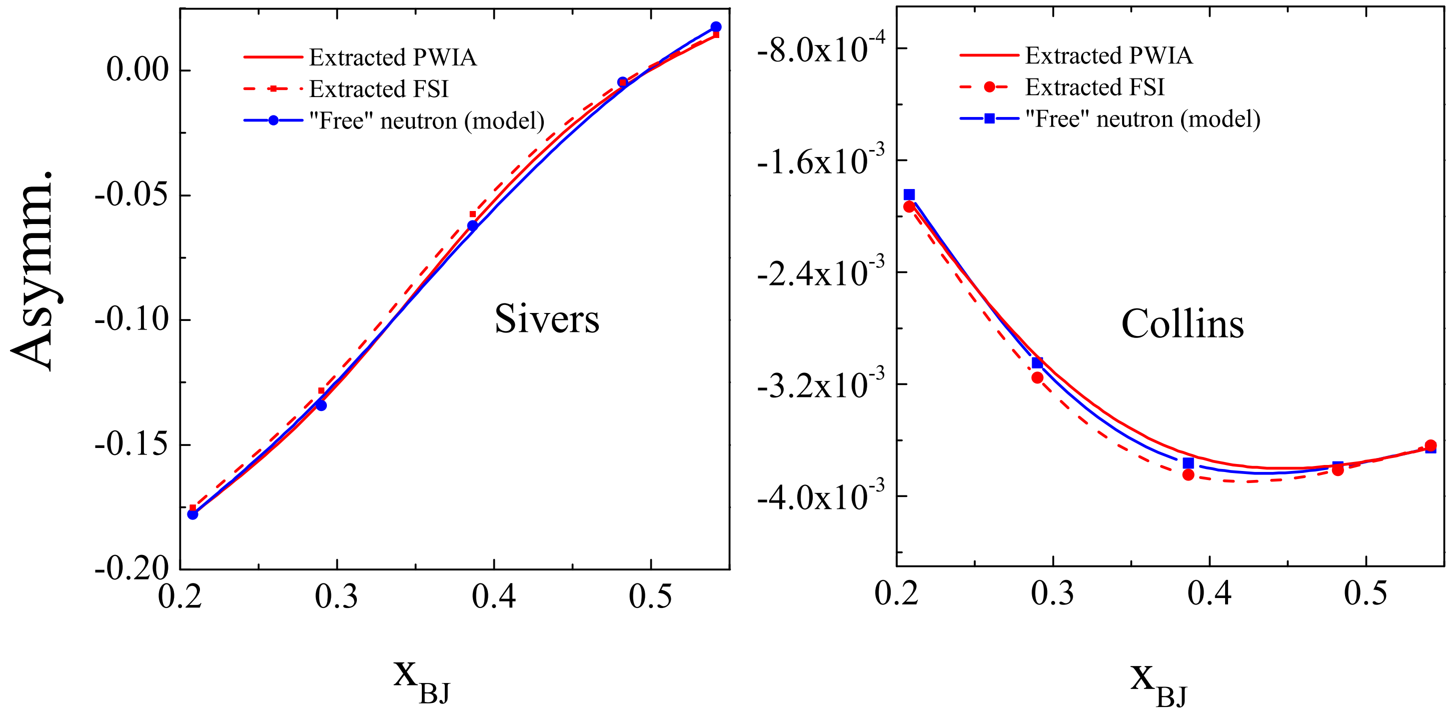


Sivers and Collins asymmetries evaluated taking into account FSI effects (full line) and in PWIA (dashed line).

FSI's change effective polarizations $p_{p(n)}$ by 10-15 %, but the products $p^{FSI}_{p(n)}\; d^{FSI}_{p(n)}$

and $p^{IA}_{p(n)}\; d^{IA}_{p(n)}$ are essentially the same.

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!

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

A. Del Dotto, L. Kaptari, E. Pace, G. Salmè, S. Scopetta, "ready" for submission

Poincarè covariance - JLAB experiments @12 GeV

The Relativistic Hamiltonian Dynamics (RHD) of an interacting system, introduced by Dirac (1949), *plus* the Bakamijan-Thomas construction of the Poincarè generators allow one to generate a description of DIS, SIDIS, DVCS off ^{3}He which :

- is fully Poincarè covariant
- has a fixed number of on-mass-shell constituents

The Light-Front form of RHD is adopted. It has 7 kinematical generators, a subgroup structure of the LF boosts (separation of the intrinsic motion from the global one: very important for us !) and a meaningful Fock expansion.

- It allows one to take advantage of the whole successfull non-relativistic phenomenology for the nuclear interaction
- DIS and SIDIS are sitting on the light cone

A Light-Front spin-dependent Spectral Function can be defined to be used to describe

DIS and SIDIS processes

Light-Front Hamiltonian Dynamics

Among the possible forms of RHD, the Light-Front one has several advantages:

- 7 Kinematical generators: i) three LF boosts (at variance with the dynamical nature of the Instant-form boosts), ii) $\tilde{P} = (P^+, \mathbf{P}_\perp)$, iii) Rotation around the z-axis.
- The LF boosts have a subgroup structure, then one gets a trivial separation of the intrinsic motion (as in the non relativistic case).
- $P^+ \geq 0$ leads to a meaningful Fock expansion.
- No square roots in the dynamical operator P^-, propagating the state in the LF-time.
- The IMF description of DIS is easily included.

Drawback: the transverse LF-rotations are dynamical

- However, using the BT construction, one can define a *kinematical*, intrinsic angular momentum (very important for us!) .

Bakamjian-Thomas construction and the Light-Front Hamiltonian Dynamics

- An explicit construction of the 10 Poincaré generators, in presence of interactions, was given by Bakamjian and Thomas (PR 92 (1953) 1300).

  The key ingredient is the mass operator :
  i) only the mass operator M contains the interaction;
  ii) it generates the dependence upon the interaction of the three dynamical generators in LFHD, namely P^- and the LF transverse rotations $\vec{F}_\perp$;

- The mass operator is the free mass, M_0, plus an interaction V, or M_0^2 + U.
  The interaction, U or V, must commute with all the kinematical generators, and with the non-interacting angular momentum, as in the non-relativistic case.

- For the two-nucleon case it allows one to embed easily the NR phenomenology:

$$[M_0^2 + U]\,|\psi_D\rangle = \left[4m^2 + 4k^2 + 4mV^{NR}\right]\,|\psi_D\rangle = M_D^2\,|\psi_D\rangle \sim \left[4m^2 - 4mB_D\right]|\psi_D\rangle$$

- For the three-body case the mass operator is

$$M_{BT}(123) = M_0(123) + V_{12,3}^{BT} + V_{23,1}^{BT} + V_{31,2}^{BT} + V_{123}^{BT} \sim M^{NR}$$

where
$M_0(123)$= $\sqrt{m^2 + k_1^2} + \sqrt{m^2 + k_2^2} + \sqrt{m^2 + k_3^2}$ is the free mass operator

LF Nucleon Spectral Function for ^3He

A. Del Dotto, E. Pace, G. Salmè, S. Scopetta, arXiv:1609.03804

$$\mathcal{P}^{\tau_1}_{\sigma'\sigma}(\tilde{\boldsymbol{\kappa}}, \epsilon, S) = \rho(\epsilon) \sum_{JJ_z\alpha} \sum_{T\tau} {}_{LF}\langle \tau T; \alpha, \epsilon; JJ_z; \tau_1 \sigma', \tilde{\boldsymbol{\kappa}} | \Psi_0; ST_z\rangle \, \langle ST_z; \Psi_0 | \tilde{\boldsymbol{\kappa}}, \sigma\tau_1; JJ_z; \epsilon, \alpha; T\tau\rangle_{LF}$$

$\rho(\epsilon) \equiv$ density of the t-b states: 1 for the bound state, and $m\sqrt{m\epsilon}/2$ for the excited ones

$${}_{LF}\langle T\tau; \alpha, \epsilon; JJ_z; \tau_1\sigma, \tilde{\boldsymbol{\kappa}} | j, j_z; \epsilon^3, \Pi; \frac{1}{2}T_z\rangle = \sum_{\tau_2\tau_3} \int d\mathbf{k}_{23} \sum_{\sigma_1'} D^{\frac{1}{2}}[\mathcal{R}_M(\tilde{\mathbf{k}})]_{\sigma\sigma_1'} \times$$

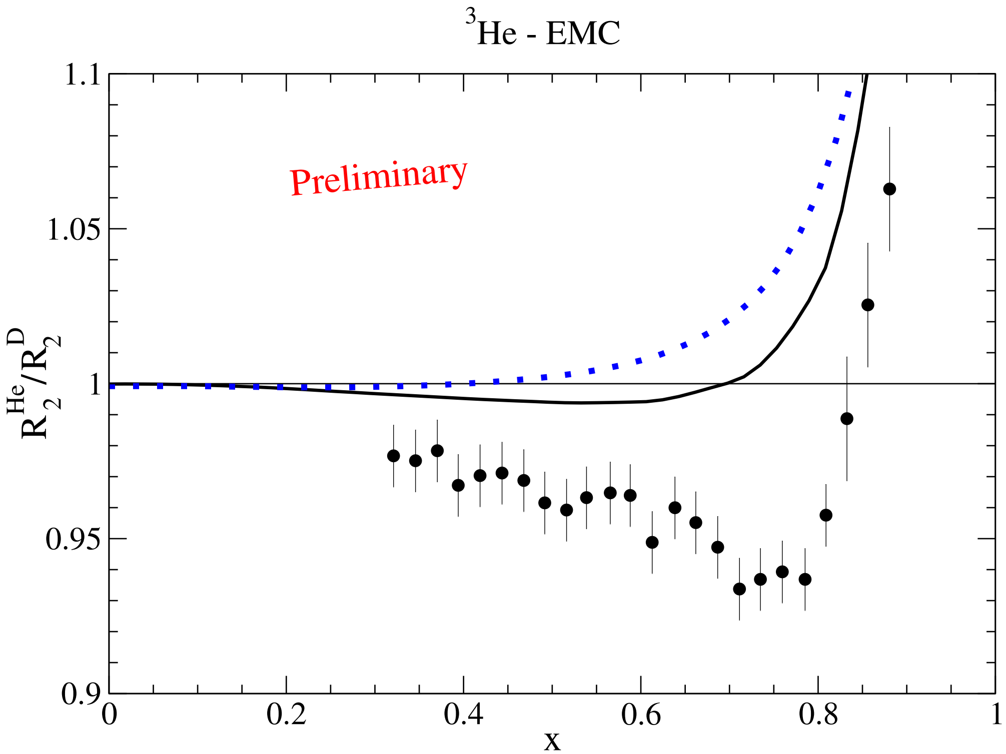
$$\sqrt{(2\pi)^3 \, 2E(\mathbf{k})} \sqrt{\frac{\kappa^+ E_{23}}{k^+ E_S}} \sum_{\sigma_2'', \sigma_3''} \sum_{\sigma_2', \sigma_3'} \mathcal{D}_{\sigma_2'', \sigma_2'}(\tilde{\mathbf{k}}_{23}, \tilde{\mathbf{k}}_2) \, \mathcal{D}_{\sigma_3'', \sigma_3'}(-\tilde{\mathbf{k}}_{23}, \tilde{\mathbf{k}}_3) \times$$

$${}_{NR}\langle T_{23}, \tau_{23}; \alpha, \epsilon_{23}; j_{23} j_{23z} | \mathbf{k}_{23}, \sigma_2'', \sigma_3''; \tau_2, \tau_3\rangle \, \langle \sigma_3', \sigma_2', \sigma_1'; \tau_3, \tau_2, \tau_1; \mathbf{k}_{23}, \mathbf{k} | j, j_z; \epsilon^3, \Pi; \frac{1}{2}T_z\rangle_{NR}$$

- $\mathbf{k}_\perp = \boldsymbol{\kappa}_\perp, \quad k^+ = \xi \, M_0(123) = \kappa^+ \, M_0(123)/\mathcal{M}_0(1,23)$
- $\mathcal{M}_0(1,23) = \sqrt{m^2 + |\boldsymbol{\kappa}_1|^2} + \sqrt{M_S^2 + |\boldsymbol{\kappa}|^2}$ with $M_S = 2\sqrt{m^2 + m\epsilon_S}$

  $$M_0^2(1,2,3) = \frac{m^2 + k_\perp^2}{\xi} + \frac{M_{23}^2 + k_\perp^2}{1-\xi} \qquad with \quad M_{23} = 2\sqrt{(m^2 + |\mathbf{k}_{23}|^2)}$$
- $D^{\frac{1}{2}}[\mathcal{R}_M(\tilde{\mathbf{k}})]_{\sigma\sigma_1'}$ Melosh operator

Preliminary results for ^3He EMC effect



Pace, Del Dotto, Kaptari, Rinaldi, Salmè, Scopetta, Few-Body Sist. 57(2016)601

$$R_2^A(x) = \frac{A\ F_2^A(x)}{Z\ F_2^p(x) + (A-Z)\ F_2^n(x)}$$

- Solid line: LF Spectral Function, with the exact calculation for the 2-body channel, and an average energy in the 3-body contribution: $<\bar{k}_{23}>=\ 113.53\ MeV$ (proton), $<\bar{k}_{23}>=\ 91.27\ MeV$ (neutron).
- Dotted line: LF momentum distribution

Within the LF framework normalization and momentum sum rule are fulfilled automatically.

Big difference from the IF approach !

What about relativity in SIDIS?

GOOD *preliminary* NEWS

We are now going to evaluate the SSAs using the LF hadronic tensor, to check whether the proposed extraction procedure still holds within the LF approach. We have preliminary encouraging indications:

- LF longitudinal and transverse polarizations change little from the NR ones:

	$proton\ NR$	$proton\ LF$	$neutron\ NR$	$neutron\ LF$
$\int dE d\vec{p}\, \frac{1}{2} Tr(\mathcal{P}\sigma_z)_{\vec{S}_A=\widehat{z}}$	-0.02263	-0.02231	0.87805	0.87248
$\int dE d\vec{p}\, \frac{1}{2} Tr(\mathcal{P}\sigma_y)_{\vec{S}_A=\widehat{y}}$	-0.02263	-0.02268	0.87805	0.87494

The difference between the effective longitudinal and transverse polarizations is a measure of the relativistic content of the system.

The extraction procedure should work well within the LF approach as it does in the non relativistic case.

Conclusions & Perspectives

DIS and SIDIS processes off ^{3}He are studied **beyond** the **NR**, **IA** approach.

- **FSI effects are studied by a Generalized Eikonal Approx.:**

  - a NR distorted spin-dependent spectral function is defined

- **A procedure to extract Sivers and Collins neutron asymmetries from ^3He asymmetries was shown useful, even taking into account the FSI**

- **A Poincaré covariant description for ^3He, based on the Light-front Hamiltonian Dynamics, has been proposed**

  - Encouraging test for the EMC effect in ^3He
  - Preliminary relativistic effective polarizations using the LF spectral function

- **Final goal : to evaluate SIDIS cross sections off ^{3}He with relativistic FSI, through our LF spin-dependent spectral function**

Why a relativistic treatment ?

- The Standard Model of Few-Nucleon Systems, where nucleon and pion degrees of freedom are taken into account, has achieved a very high degrees of sophistication.
- Nonetheless, one should try to fulfill, as much as possible, the relativistic constraints, dictated by the covariance with respect the Poincaré Group, $\mathcal{G}_P$, if processes involving nucleons with high 3-momentum are considered and a high precision is needed.
  This is the case if one studies, e.g., i) the nucleon structure functions (unpolarized and polarized); ii) the nucleon TMDs, iii) signatures of short-range correlations; iv) SIDIS processes.
- At least, one should carefully deal with the boosts of the nuclear states, $|\Psi_{init}\rangle$ and $|\Psi_{fin}\rangle$!

Poincaré covariance and locality

General principles to be implemented

★ Extended Poincaré covariance

$$[P^\mu, P^\nu] = 0, \quad [M^{\mu\nu}, P^\rho] = -\imath(g^{\mu\rho} P^\nu - g^{\nu\rho} P^\mu),$$

$$[M^{\mu\nu}, M^{\rho\sigma}] = -\imath(g^{\mu\rho} M^{\nu\sigma} + g^{\nu\sigma} M^{\mu\rho} - g^{\mu\sigma} M^{\nu\rho} - g^{\nu\rho} M^{\mu\sigma})$$

$\mathcal{P}$ and $\mathcal{T}$ have to be taken into account !

★ ★ Macroscopic locality ($\equiv$ cluster separability): i.e. observables associated with different space-time regions commute in the limit of large spacelike separation, rather than for arbitrary (μ-locality) spacelike separations (Keister-Polyzou, Adv. Nucl. Phys. **21**, 225 (1991))

Adopted Tool: The Dirac Relativistic Hamiltonian Dynamics in the Light-Front form

The BT Mass operator for A=2 and A=3 nuclei

- For the two-body case, e.g. the deuteron, the Schrödinger eq. can be rewritten as follows

$$\left[4m^2 + 4k^2 + 4mV^{NR}\right] |\psi_D\rangle = \left[4m^2 - 4mB_D\right] |\psi_D\rangle$$

$$\left[M_0^2(12) + 4mV^{NR}\right] |\psi_D\rangle = \left[M_D^2 - B_D^2\right] |\psi_D\rangle \sim M_D^2 |\psi_D\rangle$$

and the identification between v_{12}^{BT} and $4mV^{NR}$ naturally stems out, disregarding correction of the order $(B_D/M_D)^2$

- For the three-body case the mass operator is

$$M_{BT}(123) = M_0(123) + V_{12,3}^{BT} + V_{23,1}^{BT} + V_{31,2}^{BT} + V_{123}^{BT} \sim M^{NR}$$

where

$$M_0(123) = \sqrt{m^2 + k_1^2} + \sqrt{m^2 + k_2^2} + \sqrt{m^2 + k_3^2}$$

is the free mass operator, with $\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 = 0$

V_{123}^{BT} is a short-range three-body force

Final remark: the commutation rules impose to V^{BT} analogous properties as the ones of V^{NR}, with respect to the total 4-momentum and to the total angular momentum.

The BT Mass operator for A=3 nuclei

The NR mass operator is written as

$$M^{NR} = 3m + \sum_{i=1,3} \frac{k_i^2}{2m} + V_{12}^{NR} + V_{23}^{NR} + V_{31}^{NR} + V_{123}^{NR}$$

and must obey to the commutation rules proper of the Galilean group, leading to translational invariance and independence of total 3-momentum.
Those properties are analogous to the ones in the BT construction. This allows us to consider the standard non relativistic mass operator as a sensible BT mass operator, and embed it in a Poincaré covariant approach.

$$M_{BT}(123) = M_0(123) + V_{12,3}^{BT} + V_{23,1}^{BT} + V_{31,2}^{BT} + V_{123}^{BT} \sim M^{NR}$$

The 2-body phase-shifts contain the relativistic dynamics, and the Lippmann-Schwinger eq., like the Schrödinger one, has a suitable structure for the BT construction. Therefore what has been learned till now, within a non relativistic framework, about the nuclear interaction can be re-used in a Poincaré covariant framework

To complete the matter: the spin

- Coupling intrinsic spins and orbital angular momenta is easily accomplished within the Instant Form of RHD through the usual Clebsch-Gordan coefficients, since in this form the three generators of the rotations are independent of interaction.
- To embed this machinery in the LFHD one needs unitary operators, the so-called Melosh rotations that relate the LF spin wave function and the canonical one. For a (1/2)-particle with LF momentum $\tilde{k} \equiv \{k^+, \vec{k}_\perp\}$

$$|s, \sigma'\rangle_{LF} = \sum_{\sigma} D^{1/2}_{\sigma,\sigma'}(R_M(\tilde{k}))\, |s, \sigma\rangle_{IF}$$

where
$D^{1/2}_{\sigma,\sigma'}(R_M(\tilde{k}))$ is the standard Wigner function for the $J = 1/2$ case ,
$R_M(\tilde{k})$ is the rotation between the rest frames of the particle reached through a LF boost or a canonical boost.

- For quantities, like the Spectral Function, one can easily take care of the Melosh rotations. Schematically one has

$$O^{LF}_{\sigma''',\sigma} = \sum_{\sigma'',\sigma'} D^{1/2}_{\sigma''',\sigma''}(R^\dagger_M)\; O^{IF}_{\sigma'',\sigma'}\; D^{1/2}_{\sigma',\sigma}(R_M)$$

The Light-Front Nucleon Spectral Function

Nucleon Spectral Function: probability distribution to find a nucleon with given 3-momentum, and missing energy inside the nucleus.
For a polarized nucleus in a NR framework

$$P^N_{\sigma,\sigma',\mathcal{M}_z}(\vec{p},E) = \sum_{f_{(A-1)}} {}_N\langle \vec{p},\sigma;\psi_{f_{(A-1)}}|\psi^A_{J\mathcal{M}_z}\rangle \, \langle \psi^A_{J\mathcal{M}_z}|\psi_{f_{(A-1)}};\vec{p},\sigma'\rangle_N \; \delta(E - E_{f_{(A-1)}} + E_A)$$

- $|\psi^A_{J\mathcal{M}_z}\rangle$: ground state, eigensolution of

$$M^{NR}_A \, |\psi^A_{J\mathcal{M}_z}\rangle = E_A \, |\psi^A_{J\mathcal{M}_z}\rangle$$

- $|\psi_{f_{(A-1)}}\rangle$: a state of the $(A-1)$-nucleon spectator system: fully interacting !

$$M^{NR}_{(A-1)} \, |\psi_{f_{(A-1)}}\rangle = E_{f_{(A-1)}} \, |\psi_{f_{(A-1)}}\rangle$$

- $\mathbf{p}$ and E are the active nucleon 3-momentum and missing energy, respectively
- NR overlaps ${}_N\langle \vec{p},\sigma;\psi_{f_{(A-1)}}|\psi_{J\mathcal{M}_z}\rangle$ with the same interaction in A and $A-1$

Normalization and momentum sum rule

From the normalization of the Spectral Function one has

$$\int_0^\infty dz\ f^A_{p(n)}(z) = 1$$

Then one obtains

$$N_A = \frac{1}{A}\int_0^\infty dz\ \left[Z f_p^A(z) + (A-Z) f_n^A(z)\right] = 1$$

$$MSR = \frac{1}{A}\int_0^\infty dz\ z\ \left[Z f_p^A(z) + (A-Z) f_n^A(z)\right] = \frac{1}{A}$$

By using the ^3He wave function, corresponding to the NN interaction AV18, that was evaluated by Kievsky, Rosati and Viviani (Nucl. Phys. A551, 241 (1993)) we obtain

$$MSR_{calc} = 0.3331$$

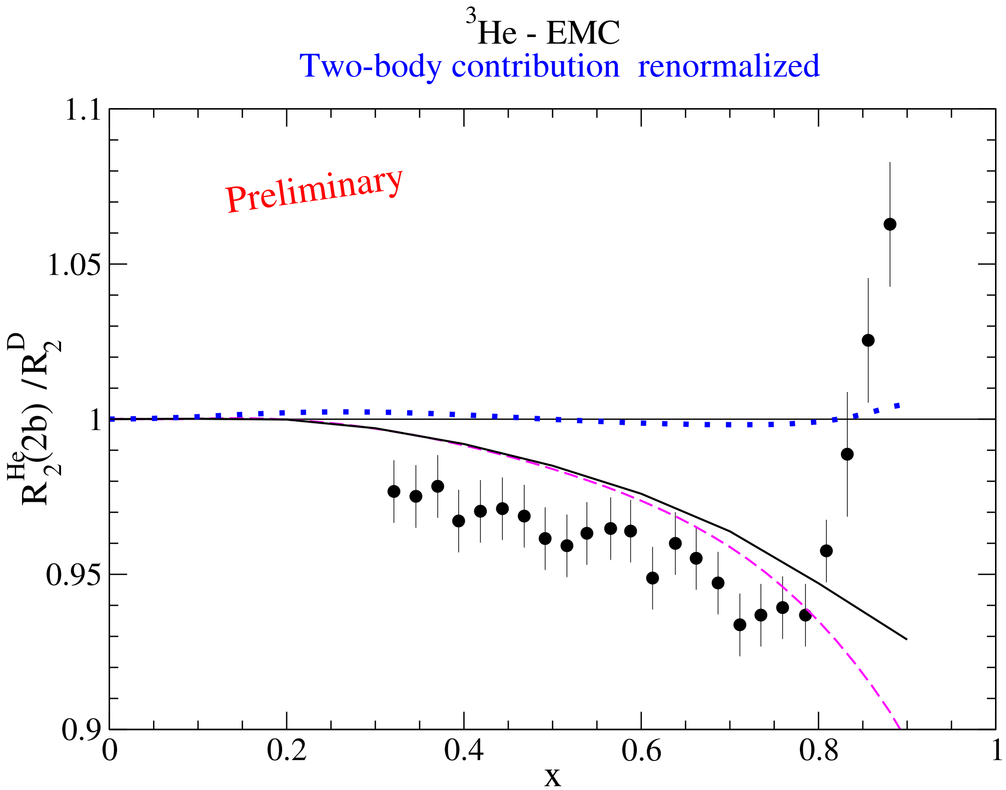
Namely, within LFHD normalization and momentum sum rule do not conflict !!

We used the Pisa group wave function to evaluate

$$R_2^A(x) = \frac{A\ F_2^A(x)}{Z\ F_2^p(x) + (A-Z)\ F_2^n(x)}$$

Preliminary Results for ^3He EMC effect

We have first calculated the contribution from the 2B channel, with the spectator pair in a deuteron state



- Solid line: calculation with the LF Spectral Function.
- Dashed line: as the solid line, but with $\sqrt{\bar{k}_{23}^2} = \ 136.37\ MeV$ for D (AV18).
- Dotted line: LF Momentum Distribution with only two-body contribution

Conclusions & Perspectives I

- **A Poincaré covariant description of a A=3 nucleus, based on the Light-front Hamiltonian Dynamics, has been proposed.**
  The Bakamjian-Thomas construction of the Poincaré generators allows one to embed the successful phenomenology for few-nucleon systems in a Poincaré covariant framework.
- We have evaluated the Nucleon Spectral function for ^3He, by approximating the IF overlaps with their non relativistic counterpart calculated with the AV18 NN interaction
- **A first test of our approach is the EMC effect for ^3He.** We have calculated the 2-body contribution to the Nucleon SF with the full expression, while the 3-body contribution has been evaluated with an average $|\mathbf{k}_{23}|^2$. Encouraging improvements clearly appear after comparing with experimental data.
- **Next step : full calculation of the 3-body contribution**