# Extracting information on the neutron from electron scattering by a $^3\vec{\mathrm{He}}$ target

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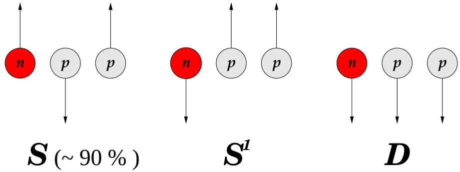
# Outline

1. The polarized $^3$He as an effective neutron target
2. The Nucleon Spectral Function and the Plane-wave Impulse Approx.
3. The inclusive transverse response and $G_M^n$ + a short detour: RCQM
4. Inclusive and Exclusive experiments at high $Q^2$: DIS and SIDIS
5. Generalized Eikonal Approximation and the $^3\vec{\mathrm{He}}$ target for SIDIS
6. Conclusions and Perspectives

## Information on the neutron from polarized $^3\mathrm{He}$ : why?




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

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

Information on the neutron from asymmetries measured in both inclusive and exclusive reactions

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

Very different kinematical regimes adopted: Quasi-elastic scattering, DIS, SIDIS

⇒ neutron FF, structure functions, TMDs, all needed for accomplishing Flavor decompositions ....

Aim: To investigate nuclear corrections for disentangling the neutron information from the measured asymmetries

**Two** main issues + **one**

- the careful description of the nuclear *initial* state
- as well as the *final states*, taking into account not only the interaction inside the spectator pair, but also the interaction with the recoiling hadronic states
- the construction of a Poincaré covariant description of the nuclear environment (see, e.g. G. Miller PRC 56, 2789 (1997) within a field theoretical approach), with the aim of embedding the successful phenomenology elaborated within a non relativistic framework.

As to the first issue, very accurate solutions of the three-nucleon bound state are currently available, like the ones obtained by the Pisa group (Kievsky, Marcucci, Rosati and Viviani Few-Body Syst. 22(1997)) describing the three-nucleon bound state with an accuracy of about 1 keV

A=3 ground states obtained by KMRV from 2N potential AV18 (Wiringa, Stoks, and Schiavilla, PRC 51 (1995)) + 3N potential Urbana IX (Pieper, Pandharipande, Wiringa,and Carlson,PRC 64 (2001))

The challenge is represented by the final sate interactions (FSIs)

# The Impulse Approximation

A first step:
The (inclusive or exclusive) electron-nucleus x-section is given by a proper folding of the electron-nucleon x-section $\times$ the nucleon momentum distribution (determined by the $^3\mathrm{He}$ wave function, in our case)

A much better approximation:

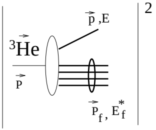
the nucleon *spin-dependent* Spectral Function

that yields the probability distribution to find a nucleon, with given

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

Through the nucleon Spectral Function one takes into account a first contribution by FSIs to the x-section, if i) the relevant em nuclear current can be approximated by only a one-body term and ii) the virtual photon interacts with only the emitted nucleon

The nucleon Spectral Function is a basic quantity needed for describing QE scattering , DIS, SIDIS, DVCS... in Impulse Approximation

$\mathbf{P}^N_{\mathcal{M}\sigma\sigma}(\vec{p},,E) = \sum_f$  $=$



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

- $|\pi_A J_A \mathcal{M}'; \Psi_A\rangle_{S_A} \equiv$ ground state, polarized along the direction $\hat{\mathbf{S}}_A$
- $|\vec{p}, \sigma; \phi_f(E^*_f)\rangle \equiv |\vec{p}, \sigma\rangle \otimes |\phi_f(E^*_f)\rangle$, with $\phi_f(E^*_f)$ is a fully interacting spectator state, with the same interaction adopted for the ground state. For the present case AV18 NN interaction
- 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 removal energy $E = E_{min} + E^*_f$, leaves the nucleus, the recoiling system is left with high excitation energy $E^*_f$ ;
- Extension to heavier nuclei is a very difficult task

## 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)
- Kaptari, Del Dotto, Pace, G.S., S.Scopetta, PRC 89 (2014), spin dependent SF with FSI
- Light-Front SF, preliminary, see, e.g., Scopetta, Del Dotto, Kaptari, Pace, Rinaldi, G.S., Few Body Syst. 56 (2015) 6, 425 and references therein

## Asymmetries in Quasi-elastic inclusive processes

$$\vec{e} + {}^3\vec{\mathrm{He}} \to e + X$$

By orienting the target spin ——— to the momentum transfer **q**, one selects the transverse em response $R^{^3He}_{T'}$, while for $\perp$ one selects $R^{^3He}_{TL'}$.

In PWIA

$$R^{^3He}_{T'}\left(Q^2,\nu\right) = \frac{Q^2}{2qM}\left[2\left(G^p_M(Q^2)\right)^2 \mathcal{H}^p_{T'}(Q^2,\nu) + \left(G^n_M(Q^2)\right)^2 \mathcal{H}^n_{T'}(Q^2,\nu)\right]$$

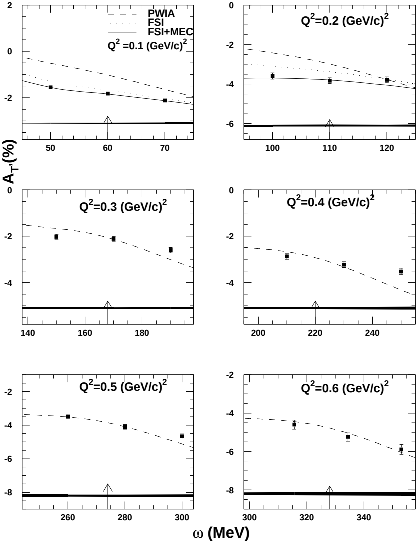
$$R^{^3He}_{TL'}\left(Q^2,\nu\right) = -\sqrt{2}\left[2G^p_E(Q^2)G^p_M(Q^2)\mathcal{H}^p_{TL'}(Q^2,\nu) + G^n_E(Q^2)G^n_M(Q^2)\mathcal{H}^n_{TL'}(Q^2,\nu)\right]$$

$$\mathcal{H}^N_{T'}\left(Q^2,\nu_{peak}\right) = \mathcal{F}^N_{T'}\left[B^N_1, B^N_2\right]$$
$$\mathcal{H}^N_{TL'}\left(Q^2,\nu_{peak}\right) = \mathcal{F}^N_{TL'}\left[B^N_1, B^N_2\right]$$

PWIA is very effective for extracting $G^n_M$ from the asymmetry $R^{^3He}_{T'}/\Sigma_{unpol}$, at the QE peak with $Q^2 \geq 0.3\ (GeV/c)^2$

$$\vec{e} + {}^3\vec{He} \rightarrow e' + X$$

$$A = \frac{\sigma(\uparrow\rightarrow) - \sigma(\uparrow\leftarrow)}{\sigma(\uparrow\rightarrow) + \sigma(\uparrow\leftarrow)} \qquad \theta^* = 0^0 \;\rightarrow\; A_{T'} \rightarrow G_M^n$$




■ ≡ TJLAB data

Solid lines: Bochüm calculations with fully-interacting three-nucleon w.f. + two-body currents, non-relativistic

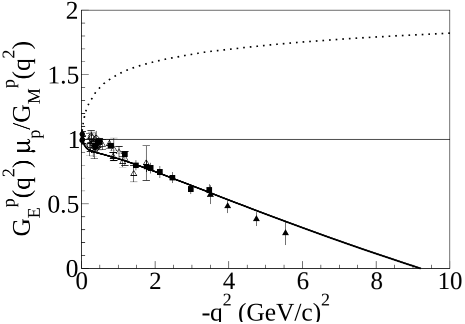
Dashed lines: Rome-Pisa PWIA + relativistic $\sigma_{eN}$ and kinematics (After Xu et al , PRC **67** (2003) 012201)

At low $Q^2$, FSI is relevant! ⇒ low kinetic energy of the struck neutron ($E_{kin}/M_N \leq 0.2$ at the peak).

At the quasielastic peak
$Q^2 = 0.1\ (GeV/c)^2 \rightarrow (1 - PWIA/FSI) \sim 40\%$
$Q^2 = 0.2\ (GeV/c)^2 \rightarrow (1 - PWIA/FSI) \sim 20\%$
$Q^2 = 0.3\ (GeV/c)^2 \rightarrow (1 - PWIA/FSI) \sim 5\%$

*Relativistic quark models for Nucleon EM FFs in Spacelike and Timelike regions*

J.P.B.C. de Melo, et al PLB **671** (2009) 153 ⇒ Only 4 parms, and $m_q = 200$ MeV

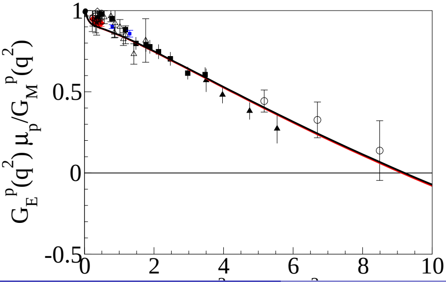



Solid line : full calculation $\equiv \mathcal{F}_\triangle + Z_B\ \mathcal{F}_{bare} + Z_{VM}\ \mathcal{F}_{VMD}$

Dotted line: $\mathcal{F}_\triangle$ (triangle contribution only)

Data: JLAB - Hall A Collab. before 2009

Interference between triangle and Z-diagram contributions, i.e. higher Fock components produces our zero.



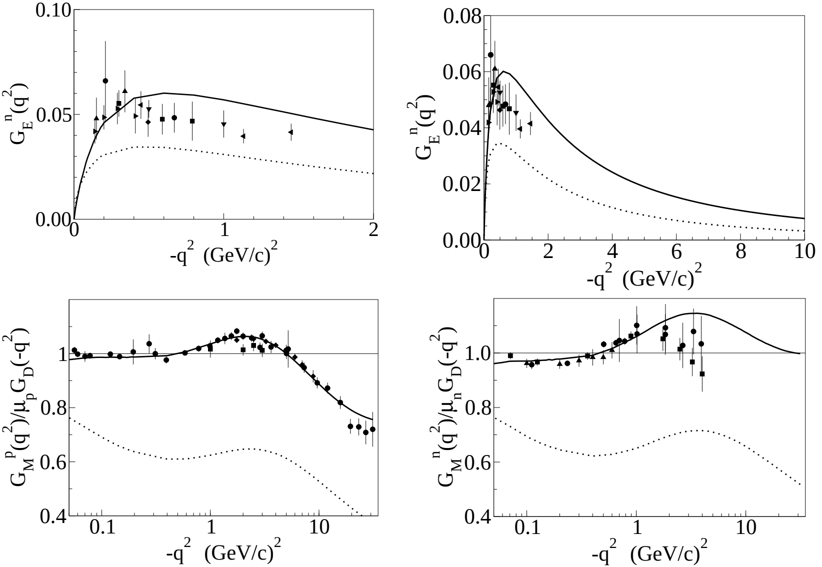

Red line: only $G_E^n$, $G_M^p$ and $G_M^n$ in the fit for fixing the 4 parms

Circles: JLAB - Hall A Collab. PRL **104**, 242301 (2010)

Low-$Q^2$ data: Paolone et al, PRL **105**, 072001 (2010) and Ron et al, PRC **84** 055204 (2011)

The zero is predicted by $G_E^n$, $G_M^p$ and $G_M^n$, within our model !

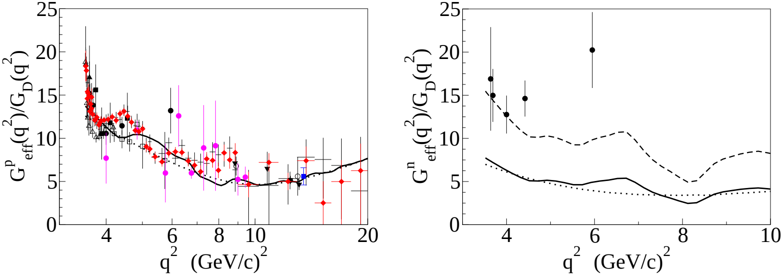
## SL Nucleon form factors: $G_E^n$, $G_M^p$ $G_M^n$




$G_D$ = dipole ff - Solid line: full calculation $\equiv \mathcal{F}_\triangle + Z_B\ \mathcal{F}_{bare} + Z_{VM}\ \mathcal{F}_{VMD}$; Dotted line: $\mathcal{F}_\triangle$

★ Parameter free result ★

Parameter free like the new evaluation of the SL $\mu_p G_E^p / G_M^p$




Solid line: full calculation - Dotted line: bare production (no VM).

Proton: Missing strength at $q^2 = 4.5\ (GeV/c)^2$ and $q^2 = 8\ (GeV/c)^2$

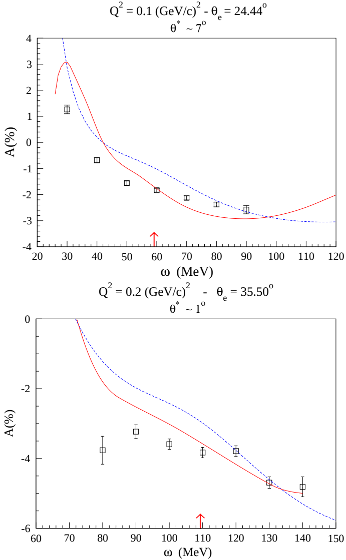
Neutron: Dashed line: solid line arbitrarily $\times$ 2.

$$G_{eff}(q^2) = \sqrt{\frac{2\tau\ |G_M(q^2)|^2\ +\ |G_E(q^2)|^2}{2\tau\ +\ 1}} \qquad (1)$$

## Reactions at low $Q^2$ and FSI

PWIA does not hold for low kinetic energy of the emitted nucleon.

Available numerical solutions only for the fully interacting $|pd\rangle$ (Kievsky, Rosati Viviani FBS 30(2001) 39)




Transverse Asymmetry vs the energy transfer, $\omega$ ($Q^2 = \omega^2 - |\vec{q}|^2$).

$\square$ $\equiv$ TJLAB data, W. Xu et al PRL **85**(2000) 2900

Solid line: full interaction in $\{pd\}$ channel and PWIA in 3-body channel. Dotted line: PWIA calculation, the spectator pair is interacting !

# Inclusive and Exclusive experiments at high $Q^2$

Forthcoming 12 GeV Experiment at TJLAB

- 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 $^3\mathrm{He}$ 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 $^3\mathrm{He}$ Target*

# Neutron structure function $F_2^n$ from DIS on light nuclei

A reliable extraction of the neutron $F_2^n(x)$ for $x < 0.85$ can be achieved from joint measurements of deep inelastic structure functions of deuteron, $^3\mathrm{He}$ and $^3$H (E. Pace, et al PRC 64,,055203 (2001)).

If the nuclear structure effects are properly taken into account, the model dependence in the extraction procedure is quite weak.

FSI not relevant for inclusive reactions at high $Q^2$ !. Then PWIA is ok

The main ingredient is the *light-cone distribution* of the nucleon inside the nuclear target.

$$F_2^A(x) = \int_x^{M_A/M} dz \left[ Z \; F_2^p(x/z) f_p^{unp}(z) + N \; F_2^n(x/z) f_n^{unp}(z) \right]$$

where the light-cone unpolarized nucleon momentum distribution is

$$f_N(z) \propto \int dE \int d\mathbf{p} \; \delta \left( z - \frac{\mathbf{p} \cdot \mathbf{q}}{M\nu} \right) \; Tr \mathbf{P}_N^A(p, E)$$

Within this approach both normalization and momentum sum-rule cannot be simultaneously fulfilled ⇒ a Poincaré covariant approach is needed (in progress)

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

Dynamical nuclear effects in DIS of a longitudinally polarized electron beam by a $^3\vec{\mathrm{He}}$ target have to be evaluated through the spin-dependent spectral function for $^3\vec{\mathrm{He}}$, $\mathbf{P}_{\sigma,\sigma'}(p, E)$.

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

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

$$f_N^{pol}(z) = \tilde{\mathcal{F}}\Big[B_1, B_2\Big]$$

To extract $g_1^n$ one has to get $A_{1n} = 2x g_1^n / F_2^n(x)$, but one measures the inclusive asymmetry with parallel or antiparallel alignements 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 Collaboration for the actual extraction)

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

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

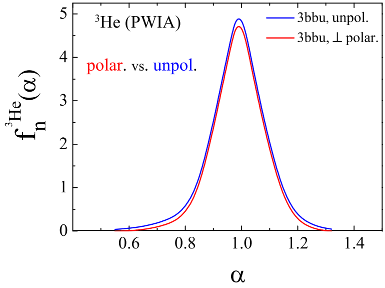
The nuclear effects are hidden in the *effective polarizations* to be evaluated through the spin-dependent SF $P_{\sigma,\sigma'}(\vec{p}, E)$

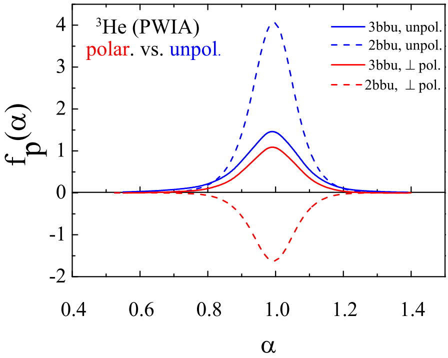
$$p_p = -0.023 \qquad (AV18)$$

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

Let us remind that the very large values of the nucleon kinetic energies involved in DIS lead us to disregard the FSI between the struck nucleon and the spectator pair.

## Light-cone momentum distributions in IA



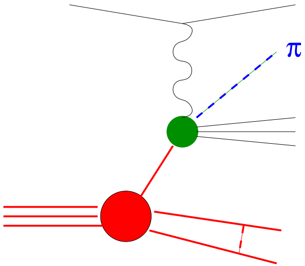




- weak depolarization of the neutron
- strong depolarization of the protons
  (cancellation between contributions in the 2-body and 3-body channels)

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

What happens with SIDIS ?

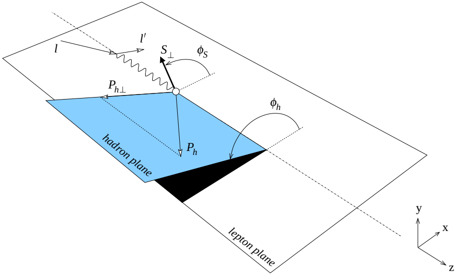
In IA :




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




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

$$d^6\sigma \equiv \frac{d^6\sigma}{dxdydzd\phi_S d^2P_{h\perp}}$$

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

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

The number of emitted hadrons at a given $\phi_h$ 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

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

(SSAs - 2)

SSAs in terms of parton distributions and fragmentation functions:

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

with

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

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

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

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

- 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!

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

in the Bjorken limit and adopting IA $\rightarrow$ no FSI between i) the measured fast, ultrarelativistic $\pi$, ii) the remnant and iii) the two nucleon recoiling system

Aim: to validate an expression, analogous to the one adopted in DIS, in the realm of SIDIS, $\Rightarrow$ the relevant TMDs !

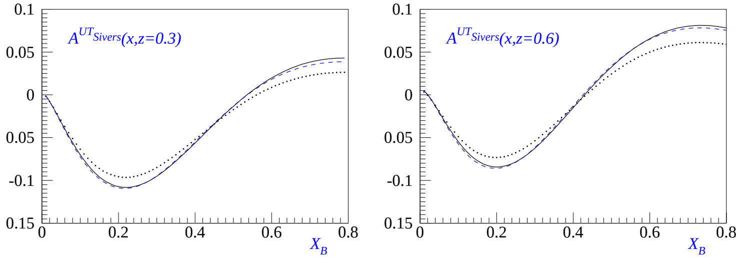
$$A_n \simeq \frac{1}{p_n d_n} \left( A_{3UT}^{exp} - 2 p_p d_p A_p^{model} \right)$$

SSAs for a polarized ${}^3\mathrm{He}$ target involve convolutions of the spin-dependent nuclear spectral function, $\vec{P}(\vec{p}, E)$, with parton distributions AND fragmentation functions (that can be modified by the nuclear environment !) :

$$A_{3UT} \simeq \int d\vec{p}\, dE .... \vec{P}(\vec{p}, E)\; f_{1T}^{\perp q} \left( \frac{Q^2}{2p \cdot q}, \mathbf{k_T^2} \right)\; D_1^{q,h} \left( \frac{p \cdot h}{p \cdot q}, \left( \frac{p \cdot h}{p \cdot q} \kappa_{\mathbf{T}} \right)^2 \right)$$

The nuclear effects on fragmentation functions are new with respect to the DIS case and have to be studied carefully, as well

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



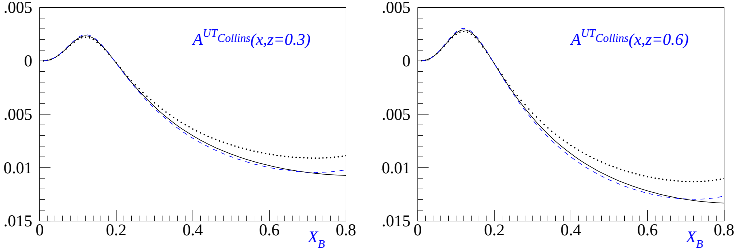

**FULL**: Neutron asymmetry (model: from parametrizations or models of TMDs and FFs)

**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 procedure, successful in DIS, works also in SiDIS, for both the Collins and the Sivers SSAs !

What about FSI effects ?
At work, in view of E12-09-018, A.G. Cates et al., approved with rate A @JLab 12)

**FSI**: Generalized Eikonal Approximation (GEA)
Following C. Ciofi degli Atti L. Kaptari PRC 71, 024005 (2005)

Glauber Approximation

- The NN scattering amplitude, needed to describe the interaction between emitted nucleon and spectator pair, is obtained within the eikonal approximation (to a large extent multiple elastic scattering processes in the forward direction).
- The nucleons of the (A-1) spectator system are stationary during the multiple scattering with the struck nucleon (the *frozen approx.*)
- only perpendicular momentum transfer components in the NN scattering amplitude

Generalized Eikonal Approximation

- the frozen approximation is partly removed, 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 stems out, leading to an additional contribution to the longitudinal component of the missing momentum

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).

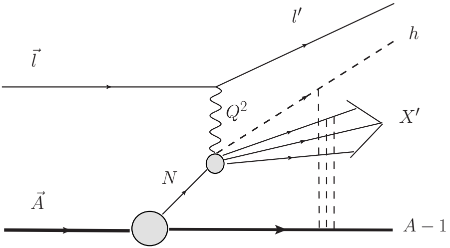
★ From the unpolarized case ($^2$H and $^3$He )

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

★★ ⇒ the polarized $^3$He case

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

## FSI-GEA 1




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

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

where $J^A_\mu \simeq \langle S_A \mathbf{P} | \hat{\mathbf{J}}^{\mathbf{A}}_\mu(\mathbf{0}) | \mathbf{S_X}, \mathbf{S_{A-1}}, \mathbf{P_{A-1}} \mathbf{E^f_{A-1}} \rangle$ with the nucleus ground state $\langle S_A \mathbf{P} | \mathbf{r_1 r_2 r_3} \rangle = \mathbf{\Phi_{^3He}}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) = \mathbf{e^{iPR}} \left[ \mathbf{\Psi_3^{S_A}}(\rho, \mathbf{r}) \right]^*$ and the final state

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

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

$\hat{S}_{Gl}$ = *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 !

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**

## FSI-GEA 3

*Distorted* spin-dependent Spectral Function for a nucleon inside $^3\vec{\mathrm{He}}$ is given in terms of *distorted* overlaps (no more a Cartesian product of a plane-wave and a spectator eigenstate)

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

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

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

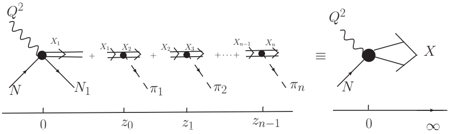
GEA, through $\Gamma(\mathbf{b}_{1i}, z_{1i})$, depends also on the traveled longitudinal distance ($z_{1i}$!) very succesfull in QE. semi-inclusive and exclusive processes off unpolarized $^3\mathrm{He}$
**see, e.g., Alvioli, Ciofi & Kaptari PRC 81 (2010) 02100**

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

*The hadronization model*

$\sigma_{eff}$ 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 $\pi N$...).

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

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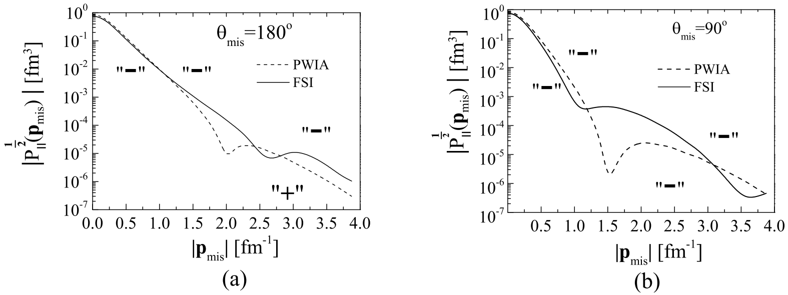



The absolute value $\left|\mathcal{P}_{||}^{\frac{1}{2}}\right| = \mathcal{F}'\left[B_1^{FSI}, B_2^{FSI}\right]$, relevant for $^3\vec{\mathrm{He}}(\vec{e}, e' D)X$, evaluated in the Bjorken limit, vs the missing momentum ($\mathbf{p}_{mis} \equiv \mathbf{P}_D$), in parallel, (left panel), and perpendicular, (right panel) kinematics. Dashed line: PWIA calculations. Solid line: calculations with FSI effects. N.B. $\mathcal{P}_{||}^{\frac{1}{2}}$ with FSI effects remains always negative, while $\mathcal{P}_{||}^{\frac{1}{2}}$ in PWIA changes sign only in parallel kinematics.

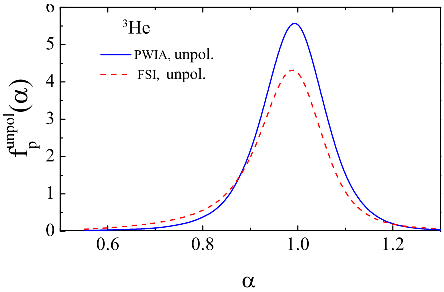
Main message: carefully choose the kinematical region to minimize FSI

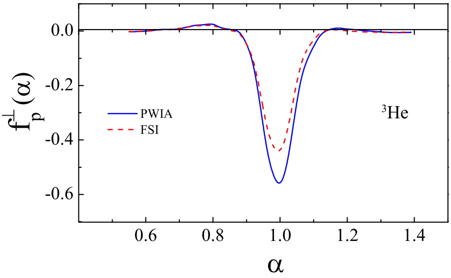
## Second step: FSI also in three-body channels, for evaluating standard SIDIS

**L. Kaptari, A. Del Dotto, E. Pace, G. S., S.Scopetta, in preparation**
A simple example
the distorted light-cone momentum distribution:

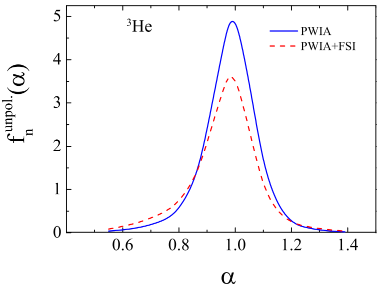
$$f_N^A(\alpha, Q^2, ..) = \int dE \int_{p_m(\alpha,Q^2,..)}^{p_M(\alpha,Q^2,..)} P_N^{A,FSI}(\mathbf{p}, E, \sigma..)\, \delta\left(\alpha - \frac{pq}{m\nu}\right)\, \theta\left(W_x^2 - (M_N + M_\pi)^2\right) d^3\mathbf{p}$$

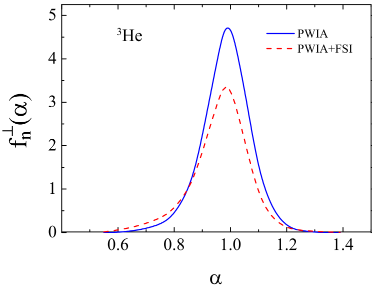
**PROTON @ $E_i$ = 8.8 GeV**



## NEUTRON @ $E_i = 8.8$ GeV




⇒ Effective polarizations change... But also the dilution factors

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

## DILUTION FACTORS

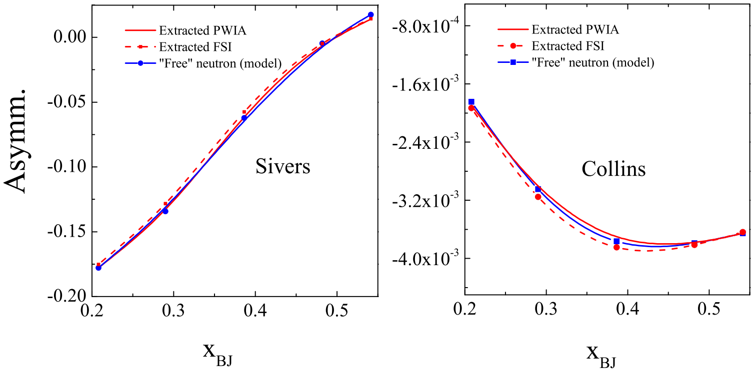
$$A_3^{exp} \simeq \frac{\Delta\vec{\sigma}_3^{exp.}}{\sigma_{unpol.}^{exp.}} \Longrightarrow \frac{\langle\vec{s}_n\rangle\Delta\vec{\sigma}(n) + 2\langle\vec{s}_p\rangle\Delta\vec{\sigma}(p)}{\langle N_n\rangle\sigma_{unpol.}(n) + 2\langle N_p\rangle\sigma_{unpol.}(p)} = \langle\vec{s}_n\rangle f_n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

PWIA:
$$\langle\vec{s}_{n(p)}\rangle = \int dE \int d^3p P_{||}(E,\mathbf{p}) = p_{n(p)};$$
$$\langle N\rangle = \int dE \int d^3p P_{unpol.}(E,\mathbf{p}) = 1.$$
$$\Longrightarrow \quad f_{n,(p)}(x,z) = \frac{\sum_q e_q^2 f_1^{q,n(p)}(x)}{\sum_N \sum_q e_q^2 f_1^{q,N}(x)}$$

FSI:
$$\langle\vec{s}_{n(p)}\rangle = \int dE \int d^3p P_{||}^{FSI}(E,\mathbf{p}) = p^{FSI}_{n(p)};$$
$$\langle N\rangle = \int dE \int d^3p P^{FSI}_{unpol.}(E,\mathbf{p}) < 1.$$
$$\Longrightarrow \quad f^{FSI}_{n,(p)}(x,z) = \frac{\sum_q e_q^2 f_1^{q,n(}}{\sum_N \langle N\rangle \sum_q e_q^2}$$

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

## 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!

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

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## Good *preliminary* news

We are now going to evaluate the SSAs using the Light-front hadronic tensor , to check whether the proposed extraction procedure still holds within the Light-Front 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* |
|---|---|---|---|---|
| $\int dEd\vec{p}\,\frac{1}{2}\,Tr(\mathcal{P})$ | 0.999 | 0.999 | 0.999 | 0.999 |
| $\int dEd\vec{p}\,\frac{1}{2}\,Tr(\mathcal{P}\sigma_z)_{\vec{S}_A=\hat{z}}$ | -0.023 | -0.022 | 0.878 | 0.873 |
| $\int dEd\vec{p}\,\frac{1}{2}\,Tr(\mathcal{P}\sigma_y)_{\vec{S}_A=\hat{y}}$ | -0.023 | -0.023 | 0.878 | 0.875 |

The difference between the effective longitudinal and transverse polarizations is a measure of the **relativistic** content of the system (in a proton, it would correspond to the difference between axial and tensor charges). Notice the NR columns

The extraction procedure should work well within the LF approach as it does in the non relativistic case... BUT WE ARE STILL WORKING...

# 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
- PWIA extraction of $G_M^n$ for $Q^2 \geq 0.3\ (GeV/c)^2$ quite reliable.
- Presently we are focusing on SIDIS for the extraction of relevant neutron TMDs. First Good news: the extraction procedure based on

$$A_n = \frac{1}{p_n f_n}\left(A_{3UT}^{exp} - 2 p_p f_p A_p^{exp}\right)$$

holds also in presence of FSI

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- A Poincaré covariant description of the Nucleon Spectral function is almost completed