Beyond the PWIA approach for SiDIS by polarized ^{3}He: Final state interaction effects and Poincaré covariant description

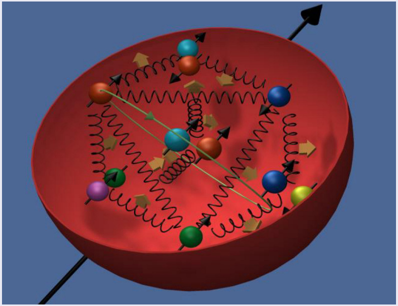
A. Del Dotto
Università di Roma Tre and INFN, Roma 3, Italy
EFB22

In collaboration with
L.P. Kaptari (JINR, Dubna, Russia & Perugia & JLab)
E. Pace (Università di Roma Tor Vergata and INFN, Roma 2, Italy)
G. Salmè (INFN, Roma 1, Italy)
S. Scopetta (Università di Perugia and INFN, Sezione di Perugia, Italy)

10/09/2013

Outline

Nucleon structure



"Spin Crisis" (EMC, '88): only about the 1/3 of the proton spin is carried by the quark helicity Σ

$$\Sigma + L_q + J_g = \frac{1}{2}$$

Goal

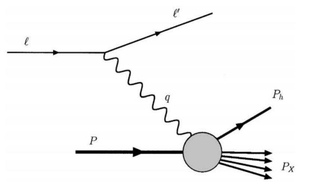
To study the inner structure of the neutron and its spin degrees of freedom.

The neutron structure

The free neutron decays in about 1000 s, therefore we need to use an "effective" neutron target for this scope.

- One can access L_q through non forward processes: SiDIS

Semi-inclusive deep inelastic scattering (SiDIS)



- $\sigma_{SiDIS} \sim TMD(x, p_T^2, Q^2) \otimes \sigma_{\gamma^* q} \otimes FF(z, k_T^2, Q^2)$

TMD: probability density to strike a quark with x fraction of longitudinal momentum and transverse momentum p_T^2
FF: probability density of the struck quark to fragment in an hadron carrying a fraction z of the parton momentum

kinematics variables

- $Q^2 = -q^2$ $(\hat{q} = -\hat{e}_z)$: 4-momentum transferred
- $x = \frac{Q^2}{2P \cdot q}$: longitudinal momentum fraction
- $z = \frac{P \cdot P_h}{P \cdot q}$: energy fraction of the product hadron

Transverse momenta

- $\vec{p}_T$: intrinsic (TMDs)
- $\vec{k}_T$: of the hadronizing quark debris (FFs)
- $\vec{P}_{h\perp}$: of the product hadron (FFs)

SiDIS cross section

$$\frac{d^6\sigma}{dxdydzd\phi_S dP_{h\perp}^2} = d^6\sigma_{UU} + d^6\sigma_{LU} + d^6\sigma_{UL} + d^6\sigma_{LL} + d^6\sigma_{UT} + d^6\sigma_{LT}$$

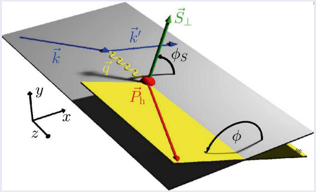
$$A_{UT} \equiv \frac{1}{|S_T|}\frac{d\sigma(\phi,\phi_S) - d\sigma(\phi,\phi_S+\pi)}{d\sigma(\phi,\phi_S) + d\sigma(\phi,\phi_S+\pi)}$$

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

with

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

Angular variables



Collins and Sivers contributions

Transversely polarized target:

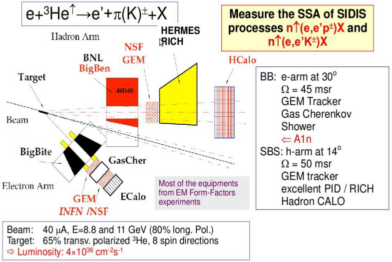
$f_{1T}^{\perp} \rightarrow \text{Ł}_q, \delta q \rightarrow$relativistic effects

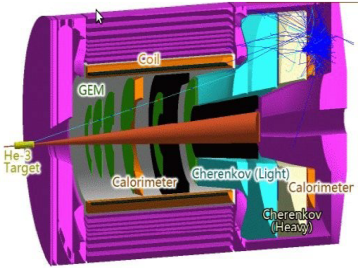
$$F_{UT}^{sin(\phi+\phi_S)} \propto \left[-\frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M}\delta q H_1^{\perp}\right]$$

$$F_{UT}^{sin(\phi-\phi_S)} \propto \left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M} f_{1T}^{\perp} D_1\right]$$

JLab experiments involved in SiDIS investigation by ^{3}He target

<u>12 GeV - SIDIS with SBS (left)</u>:
E12-09-018: Target Single-Spin Asymmetries in Semi-Inclusive Pion and Kaon Electroproduction on a Transversely Polarized 3He Target using Super BigBite and BigBite in Hall A.
Spokespeople: G. Cates, E. Cisbani, G. B. Franklin, A. Puckett, B. Wojtsekhowski
<u>12 GeV – SoLID (right):</u>
E12-10-006: Target Single Spin Asymmetry in Semi-Inclusive Deep-Inelastic (e, e′p±) Reaction on a Transversely Polarized 3He Target at 8.8 and 11 GeV.
Spokespeople: H. Gao, X. Qian, J.-P. Chen, J.-C. Peng
C12-11-008: Target Single Spin Asymmetry in Semi-Inclusive Deep-Inelastic (e, e′p±) Reaction on a Transversely Polarized Proton Target.
Spokespeople: H. Gao, K. Allada, J.-P. Chen, Z.-E. Meziani
E12-11-007: Asymmetries in Semi-Inclusive Deep-Inelastic (e, e'p±) Reactions on a Longitudinally Polarized 3He Target at 8.8 and 11 GeV.
Spokespeople: J.P. Chen, J, Huang, Y. Qiang, W.B. Yan

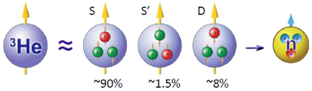




^{3}He polarized target

Motivations and assumptions

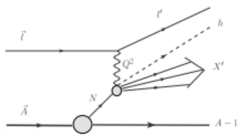
$$^3\vec{He} \simeq \vec{n} \ (87\%)$$



The two protons are mostly in a s=0 wave. The first naive idea is the following:

- The virtual photon interacts with a single nucleon. The FSI among the detected hadron, the nucleon and the spectator nuclear system is disregarded
- The internal structure of the bound nucleon is the same as the free one

The PWIA



(Ciofi degli Atti et al .,PRC48(1993)R968)

$$|P_h, X\rangle^{PWIA} = |P_{A-1}\rangle \otimes |P_h\rangle \otimes |X'\rangle$$

$$A_n \simeq \frac{1}{p_n f_n}(A_3^{exp} - 2p_p f_p A_p^{exp})$$

$$p_p = -0.023 \qquad p_n = 0.878$$

The physical observables through the spectral function

Neutron asymmetry

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

$$p_p = \int dE \int d\vec{p}\, P_{\parallel}^{p}(\vec{p}, E) = -0.023$$

$$p_n = \int dE \int d\vec{p}\, P_{\parallel}^{n}(\vec{p}, E) = 0.878$$

$$f_{p(n)}(x,z) = \frac{\sum_q e_q^2 f_1^{q,p(n)}(x)\, D_1^{q,h}(z)}{\sum_{N=p,n}\sum_q e_q^2 f_1^{q,N}(x) D_1^{q,h}(z)} \simeq 0.2$$

Where the spectral function is obtained through the following overlaps

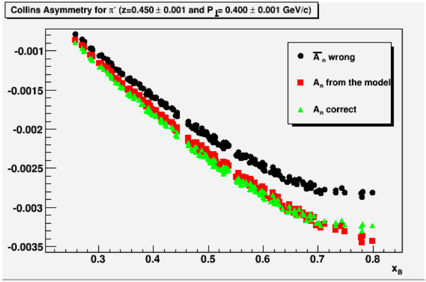
$$\mathcal{O}_{\lambda\lambda'}^{S_A} = \left\langle \{\Psi_{\mathbf{P}_{A-1}}, \lambda, \mathbf{p}_N\} | S_A, P_A \right\rangle \left\langle S_A, P_A | \{\Psi_{\mathbf{P}_{A-1}}, \lambda', \mathbf{p}_N\} \right\rangle$$

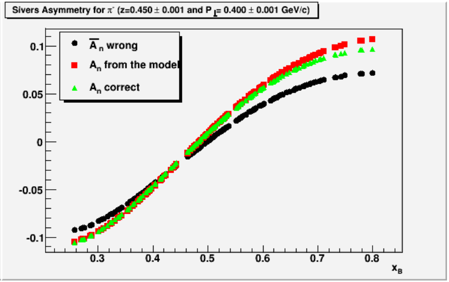
$$\mathcal{P}_{\parallel}^{\hat{\mathbf{S}}_A} = \mathcal{O}_{\frac{1}{2}\frac{1}{2}}^{\hat{\mathbf{S}}_A} - \mathcal{O}_{-\frac{1}{2}-\frac{1}{2}}^{\hat{\mathbf{S}}_A}$$

Extracting A_n from a polarized ^3He target: a first check

SSAs are proportional to a convolution integral of the spin dependent spectral function with the DF and the FF (S.Scopetta, PRD 75 (2007) 054005)

$$A \simeq \int d\vec{p}dEP(\vec{p},E)f_{1T}^{\perp}\left(x,p_T^2\right)D_1(z,k_T^2)$$





Logic chain

i) Neutron asymmetry from the model

ii) Neutron asymmetry from the ^{3}He (with spectral function) with $A_n = \frac{1}{f_n}(A_3^{calc})$

iii) Neutron asymmetry from the ^{3}He (with spectral function) with $A_n = \frac{1}{p_n f_n}(A_3^{calc} - 2p_p f_p A_p^{model})$

Final State interaction through distorted SF

The parallel spectral function is now redefined with the following overlap

$$\mathcal{P}_{||}^{\hat{\mathbf{S}}_A IA(FSI)} = \mathcal{O}^{\hat{\mathbf{S}}_A}_{\frac{1}{2}\frac{1}{2}} - \mathcal{O}^{\hat{\mathbf{S}}_A}_{-\frac{1}{2}-\frac{1}{2}}$$

$$\mathcal{O}^{\hat{\mathbf{S}}_A IA(FSI)}{}_{\lambda\lambda'}(\mathbf{p}_N, E) = \sum\!\!\!\!\!\!\int_{\epsilon^*_{A-1}} \rho\left(\epsilon^*_{A-1}\right) \langle \hat{S}_{Gl}\{\Phi_{\epsilon^*_{A-1}}, \lambda, \mathbf{p}_N\}|S_A, \Phi_A\rangle\langle S_A, \Phi_A|\hat{S}_{Gl}\{\Phi_{\epsilon^*_{A-1}}, \lambda', \mathbf{p}_N\}\rangle \times$$
$$\delta\left(E + M_A - m_N - M^*_{A-1} - T_{A-1}\right)$$

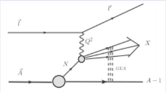
The extended Glauber operator is

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

with the Profile function

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

FSI

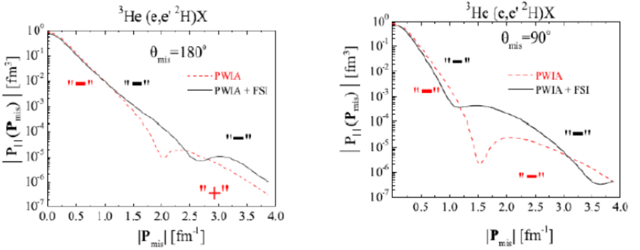


Effective cross section

- The relative energy between the A-1 and the remnant is $\sim GeV \rightarrow$ Eikonal approximation
- $\sigma_{eff}(z_{1i}, x_{Bj}, Q^2) \sim \sigma_{eff}(z_{1i})$ (hadronization mechanism: Kopeliovich, Nemchik, Predazzi, Hayashigaki NPA 2004; σ_{eff} model: Ciofi and Kopeliovich, EPJA 2003)

Beyond the PWIA

FSI in the parallel (along the target polarization) Spin Dependent Spectral function



$$A_n \simeq \frac{1}{p_n^{FSI} f_n}\left(A_3^{exp} - 2p_p^{FSI} f_p A_p^{exp}\right) \qquad p_N^{FSI} = \int P_\parallel^N(\vec{p}_{mis}, E)\, dE\, d^3p_{mis} = p_N^{PWIA} - \delta p_N^{FSI}(Q^2, x_{Bj})$$

$P_\parallel^{PWIA}$ and $P_\parallel^{FSI}$ are different. But the physical observables (SSAs) are obtained through integrals of $P_\parallel$ in the low momenta region, where the difference is not dramatic (about 10-15 %).

Dilution factor

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

PWIA vs FSI

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

$$\longrightarrow \quad f_{n,(p)}(x,z) = \frac{\sum_q e_q^2 f_1^{q,n(p)}(x) D_1^{q,h}(z)}{\sum_N \sum_q e_q^2 f_1^{q,N}(x) D_1^{q,h}(z)}$$

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

$$\longrightarrow \quad f_{n,(p)}^{FSI}(x,z) = \frac{\sum_q e_q^2 f_1^{q,n(p)}(x) D_1^{q,h}(z)}{\sum_N \langle N\rangle \sum_q e_q^2 f_1^{q,N}(x) D_1^{q,h}(z)}$$

Results (preliminary)

1) **PWIA:** $\langle p_n \rangle$= **0.876**, $\langle p_p \rangle$= **-0.0237**, $\theta_e = 30^o$, $\theta_\pi = 14^o$

E_{beam}, GeV	x_{Bj}	ν GeV	p_π GeV/c	$f_n(x,z)$	$\langle p_n \rangle f_n$	$f_p(x,z)$	$\langle p_p \rangle f_p$
8.8	0.21	7.55	3.40	0.304	0.266	0.348	$-8.4\,10^{-3}$
8.8	0.29	7.15	3.19	0.286	0.251	0.357	$-8.5\,10^{-3}$
8.8	0.48	6.36	2.77	0.257	0.225	0.372	$-8.9\,10^{-3}$
11	0.21	9.68	4.29	0.302	0.265	0.349	$-8.3\,10^{-3}$
11	0.29	9.28	4.11	0.285	0.25	0.357	$-8.5\,10^{-3}$

2) **FSI:** $\langle p_n \rangle$= **0.756**, $\langle p_p \rangle$= **-0.0265**,$\langle N_n \rangle = 0.85$,$\langle N_p \rangle = 0.87$, $\langle \sigma_{eff} \rangle = 71\ mb$

E_{beam}, GeV	x_{Bj}	ν GeV	p_π GeV/c	$f_n(x,z)$	$\langle p_n \rangle f_n$	$f_p(x,z)$	$\langle p_p \rangle f_p$
8.8	0.21	7.55	3.40	0.353	0.267	0.405	$-1.1\,10^{-2}$
8.8	0.29	7.15	3.19	0.332	0.251	0.415	$-1.1\,10^{-2}$
8.8	0.48	6.36	2.77	0.298	0.225	0.432	$-1.2\,10^{-2}$
11	0.21	9.68	4.29	0.351	0.266	0.405	$-1.\,10^{-2}$
11	0.29	9.28	4.11	0.331	0.250	0.415	$-1.1\,10^{-2}$

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

The effects of FSI in the dilution factors and in the effective polarizations are found to compensate each other to a large extent. The usual extraction procedure seems to be still solid.

Relativistic description of the process

With the JLab upgrade to 12 GeV, the role of the relativistic effects in the SiDIS description of the ^{3}He could be sizable and has to be investigated.

Relativistic Hamiltonian Dynamics

The RHD (introduced by Dirac in 1949) of an interacting system with a fixed number of on-mass-shell constituents, plus the Bakamijan-Thomas construction allows one to generate a description of SiDIS off ^{3}He which is fully Poincaré covariant and has a fixed number of on-mass-shell constituents.

Possible advantages derived from the Light-Front form of RHD in ^{3}He description are:

- 7 kinematical generators
- separation of the center of mass motion from the intrinsic one
- $P^+ \geq 0$, meaningful Fock expansion
- most natural description of DIS in IMF

The ^{3}He nuclear hadronic tensor

In Impulse Approximation the LF hadronic tensor for the ^{3}He is:

$$\mathcal{W}^{\mu\nu}(Q^2, x_B, z, \tau, \hat{\mathbf{h}}, S_{He}) \propto \sum_{\sigma,\sigma'} \sum_{\tau} \not\sum \int_{\epsilon_S^{min}}^{\epsilon_S^{max}} d\epsilon_S \int_{M_N^2}^{(M_X - M_S)^2} dM_f^2$$
$$\times \int_{\xi_{low}}^{\xi_{up}} \frac{d\xi}{\xi^2(1-\xi)(2\pi)^3} \int_{P_\perp^m}^{P_\perp^M} \frac{dP_\perp}{sin\theta} (P^+ + q^+ - h^+)\, w^{\mu\nu}_{\sigma\sigma'}\left(\tau, \tilde{\mathbf{q}}, \tilde{\mathbf{h}}, \tilde{\mathbf{P}}\right)$$
$$\times \mathcal{P}^{\tau}_{\sigma'\sigma}(\mathbf{k}, \epsilon_S, S_{He})$$

where $\tilde{\mathbf{v}} = \{v^+ = v^0 + v^3, \mathbf{v}_\perp\}$

Convoluted quantities

- $w^{\mu\nu}_{\sigma\sigma'}(\tau, \tilde{\mathbf{q}}, \tilde{\mathbf{h}}, \tilde{\mathbf{P}})$ the nucleonic tensor
- $P^{\tau}_{\sigma'\sigma}(\tilde{\mathbf{k}}, \varepsilon_S, S_{He})$ the spin dependent spectral function

LF spectral function of ^{3}He

The light-front SF is obtained by the instant-form SF trough the following transformation:

$$\mathcal{P}^{\tau}_{\sigma'\sigma}(\mathbf{k}, \epsilon_S, S_{He}) \propto \sum_{\sigma_1\sigma'_1} D^{\frac{1}{2}}[\mathcal{R}^{\dagger}_M(\mathbf{k})]_{\sigma'\sigma'_1} \; \mathcal{S}^{\tau}_{\sigma'_1\sigma_1}(\mathbf{k}, \epsilon_S, S_{He}) \; D^{\frac{1}{2}}[\mathcal{R}_M(\mathbf{k})]_{\sigma_1\sigma}$$

With the two ingredients

- The Melosh rotations

$$D^{\frac{1}{2}}[\mathcal{R}_M(\tilde{\mathbf{k}})] = \frac{m + k^+ - i\sigma \cdot (\hat{z} \times \mathbf{k}_\perp)}{\sqrt{(m+k^+)^2 + |\mathbf{k}_\perp|^2}}$$

- The front-form SF

$$\mathcal{S}^{\tau}_{\sigma'_1\sigma_1}(\tilde{\mathbf{k}}, \epsilon_S, S_{He}) \;=\; \left[B^{\tau}_{0,He}(|\mathbf{k}|, E) \;+\; \boldsymbol{\sigma} \cdot \mathbf{f}^{\tau}_{S_{He}}(\mathbf{k}, E)\right]_{\sigma'_1\sigma_1}$$

$$\mathbf{f}^{\tau}_{S_{He}} = \mathbf{S_A} B^{\tau}_{1,S_{He}}(|\mathbf{k}|, E) + \hat{\mathbf{k}}(\hat{\mathbf{k}} \cdot \mathbf{S_A}) B^{\tau}_{2,S_{He}}(|\mathbf{k}|, E)$$

- The IA spectral function depends on 3 independents function B_0, B_1, B_2 (in the case of IA + FSI there are more independent functions)

Our results (in progress)

- Final state interaction→extended Glauber
  L. Kaptari, A. DD, E. Pace, G. Salmè, S.Scopetta, preprint JLAB-THY-13-1732
- Light-Front (LF) approach at finite Q^2
  S.Scopetta, A. DD, E. Pace, G. Salmè Il Nuovo Cimento C 35 (2012) 101;
  E. Pace, A. DD, M. Rinaldi, G. Salmè, S.Scopetta, Few-Body Systems (2013) - in press

Conclusions

- The results suggest that, in the kinematical range of the planned SiDIS experiments, the amount of FSI is small.
- Nevertheless, we have developed a more realistic model for providing a sound extraction of the neutron single spin asymmetries from a transversely-polarized ^{3}He target.

Possible developments

- We will consolidate those preliminary results also providing new consistency check by using the MC that generates the kinematics of the 12 GeV-SIDIS experiment in combination with the distorted spectral function.
- Relativistic Final State Interaction merged in the RHD framework.