Transversity studies with a polarized ^{3}He target

Sergio Scopetta

Dipartimento di Fisica dell'Università di Perugia
and INFN, Sezione di Perugia, Italy

and

Alessio Del Dotto, Giovanni Salmè

INFN, Sezione di Roma1, Italy

August 30th, 2011

Outline

- **Transversity observables in Semi-inclusive DIS (SiDIS): Sivers (and Collins) Single Spin Asymmetries (SSAs)**

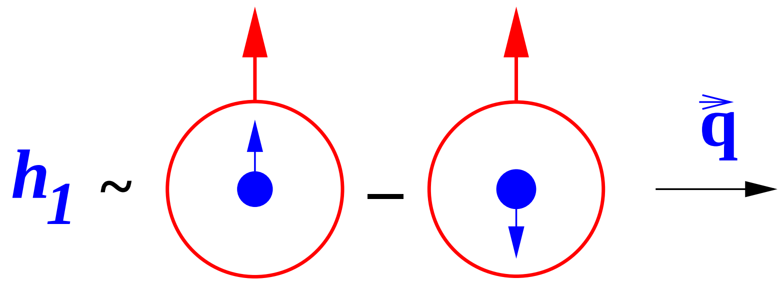
- **Relevance of the neutron information $\longrightarrow {}^3\vec{He}$:**
  An Impulse Approximation approach to SiDIS off ${}^3\vec{He}$; calculation performed in the Bjorken limit
  (S.S., PRD 75 (2007) 054005)

- **A Light-Front approach at finite Q^2**
  (work in progress)
  The LF spectral function and the LF TMDs
  (E. Pace, G. Salmè, S.S, in preparation)

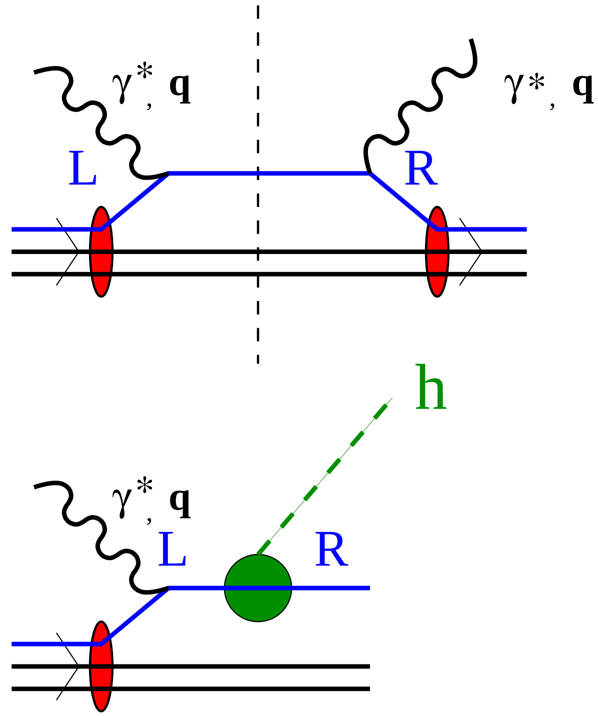
- **Conclusions**

The *Transversity* distribution h_1

How many $\perp$-polarized partons
in a $\perp$-polarized target?
(Bj limit: $Q^2, \nu \to \infty, x \simeq \frac{Q^2}{2M\nu}$ finite)



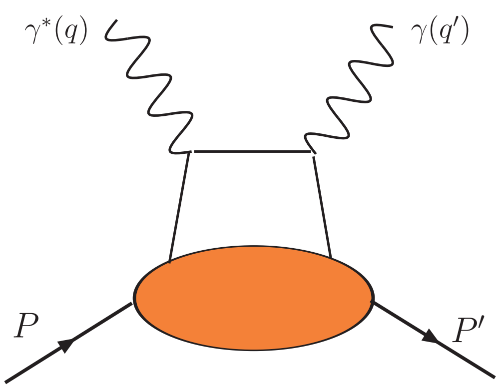
It turns out that h_1 is a twist-2 quantity
(its effects survive the Bj limit),
but it is χ-odd $\longrightarrow$ unseen in DIS:



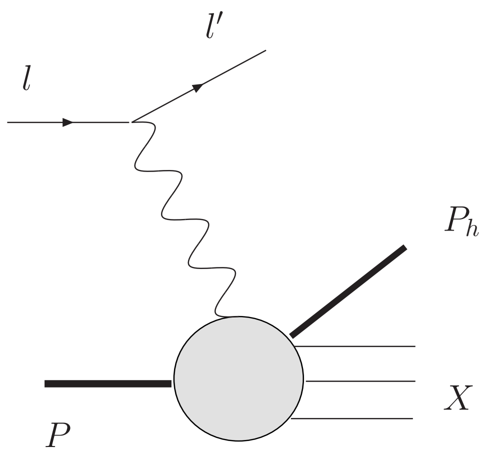
But Ok in SiDIS !

Transversity - why?

- The interest in Transversity is a consequence of the "Spin crisis"(EMC, '88): most of the proton spin NOT carried by the quark helicities Σ
- Spin Sum Rule (Ji): $$\Sigma + L_q + J_g = \frac{1}{2}$$
- OAM (L_q) (and the nucleon wf!) accessed through non forward processes:

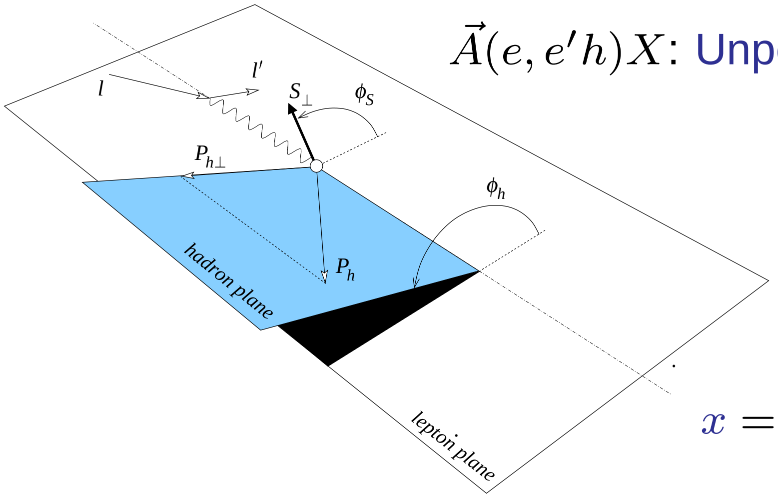


DVCS –> GPDs



SiDIS –> TMDs

Single Spin Asymmetries (SSAs) - 1



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

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

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

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

SSAs due to 2 different mechanisms, which can be distinguished experimentally

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

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 - 2

SSAs in terms of parton distributions and fragmentation functions:

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

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

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

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

If there is good experimental coverage on $\phi_h \pm \phi_s$, simpler $P_{h\perp}$-weighted asymmetries are found, so that

$$N^{Sivers} \propto \sum_q e_q^2 f_{1T}^{\perp q(1)}(x) D_1^{q,h}(z) \qquad N^{Collins} \propto \sum_q e_q^2 h_1^q(x) H_1^{\perp(1)q,h}(z)$$

The neutron information from ^{3}He

First measurements of SSAs:

- 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

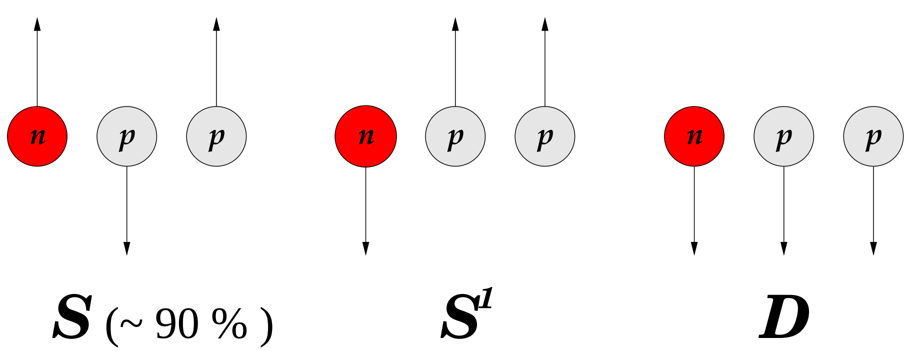
(talks at this workshop)

Importance of the neutron!

Experiments at JLAB on ^{3}He

(X. Qian, PRL 107:072003, 2011; new measurements @ 12 GeV)

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



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

$\vec{n}$ from $^3\vec{He}$: DIS case

... But the bound nucleons in ^{3}He are moving!

Long time ago, a realistic spin-dependent spectral function for $^3\vec{He}$ was used to simulate dynamical nuclear effects in the extraction of the neutron information in inclusive DIS ($^3\vec{H}e(\vec{e},e')X$, C. Ciofi degli Atti et al., PRC 48, R968 (1993)).

It was found that the formula

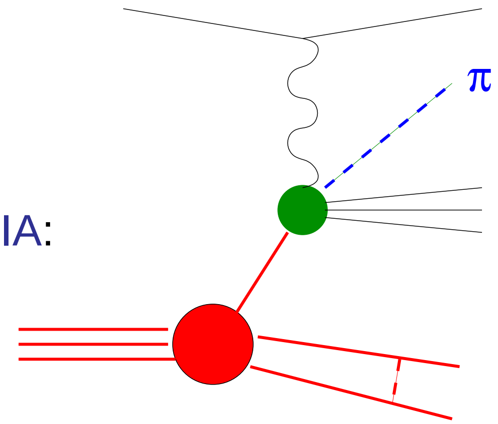
$$A_n \simeq \frac{1}{p_n f_n} \left(A_3^{exp} - 2 p_p f_p A_p^{exp} \right) \ ,$$

where all the nuclear effects are hidden in the "effective polarizations"

$$p_p = -0.024 \quad (Av18) \qquad\qquad p_n = 0.878 \quad (Av18)$$

can be safely used $\longrightarrow$ widely used by experimental collaborations.
Can one use the same formula for extracting the SSAs? In principle NO:
in SiDIS also the fragmentation functions are modified by the nuclear environment!

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



The process ${}^3\vec{H}e(\vec{e}, e'\pi)X$ has been evaluated in IA:
no FSI between the π, the remnant
and the two nucleon recoiling system;
Current fragmentation region;

The obtained expressions for the nuclear SSAs are involved and not reported here (see S.S., PRD 75 (2007) 054005 for details).

In any case SSAs involve convolutions of the spin-dependent nuclear spectral function with parton distributions AND fragmentation functions:

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

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

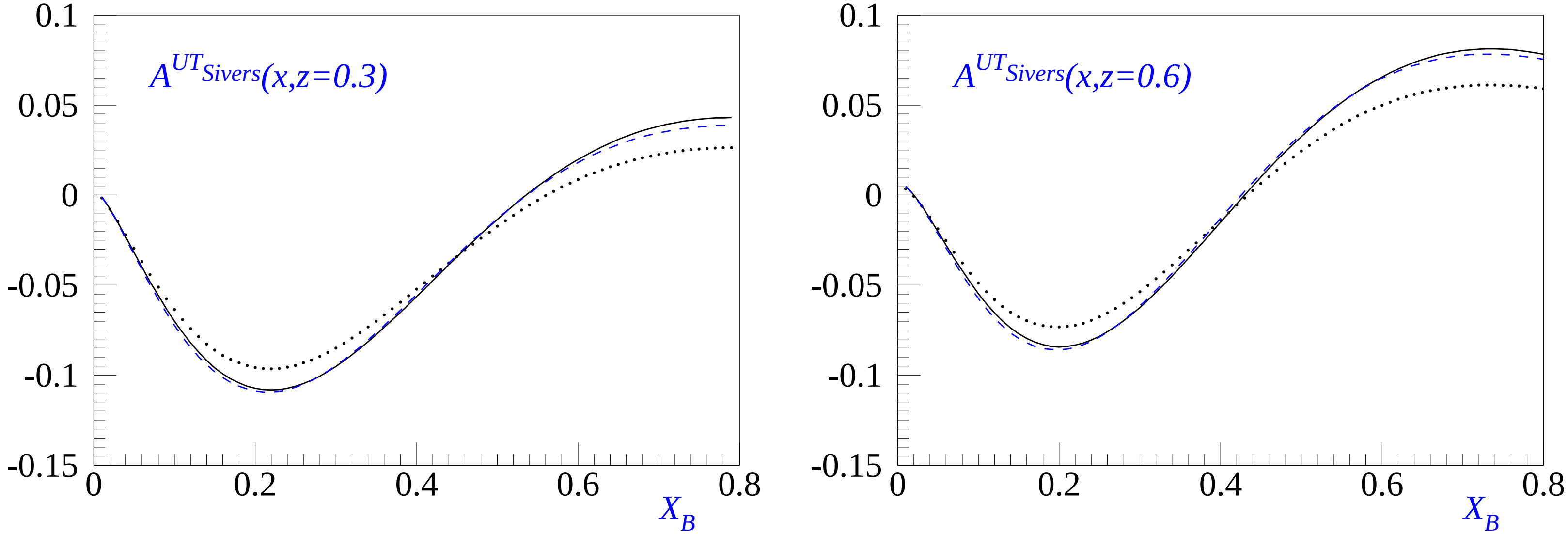
$\vec{n}$ from ${}^3\vec{H}e$: SiDIS case

Ingredients of the calculations:

- A realistic spin-dependent spectral function of ^{3}He (C. Ciofi degli Atti et al., PRC 46 R 1591 (1992); A. Kievsky et al., PRC 56, 64 (1997)) obtained using the AV18 interaction and the wave functions evaluated by the Pisa group (A. Kievsky et al., NPA 577, 511 (1994).)
- Parameterizations of data for pdfs and fragmentation functions whenever available ($f_1^q(x, \mathbf{k_T^2})$, GRV 1998 , $f_{1T}^{\perp q}(x, \mathbf{k_T}^{\mathbf{2}})$, Anselmino et al. 2005, $D_1^{q,h}(z, (z\kappa_{\mathbf{T}})^2)$, Kretzer 2000)
- Models for the unknown pdfs and fragmentation functions. ($h_1^q(x, \mathbf{k_T}^{\mathbf{2}})$, GRVW 2001, $H_1^{\perp q,h}(z, (z\kappa_{\mathbf{T}})^{\mathbf{2}})$ Amrath et al. 2005)

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} , @ JLab



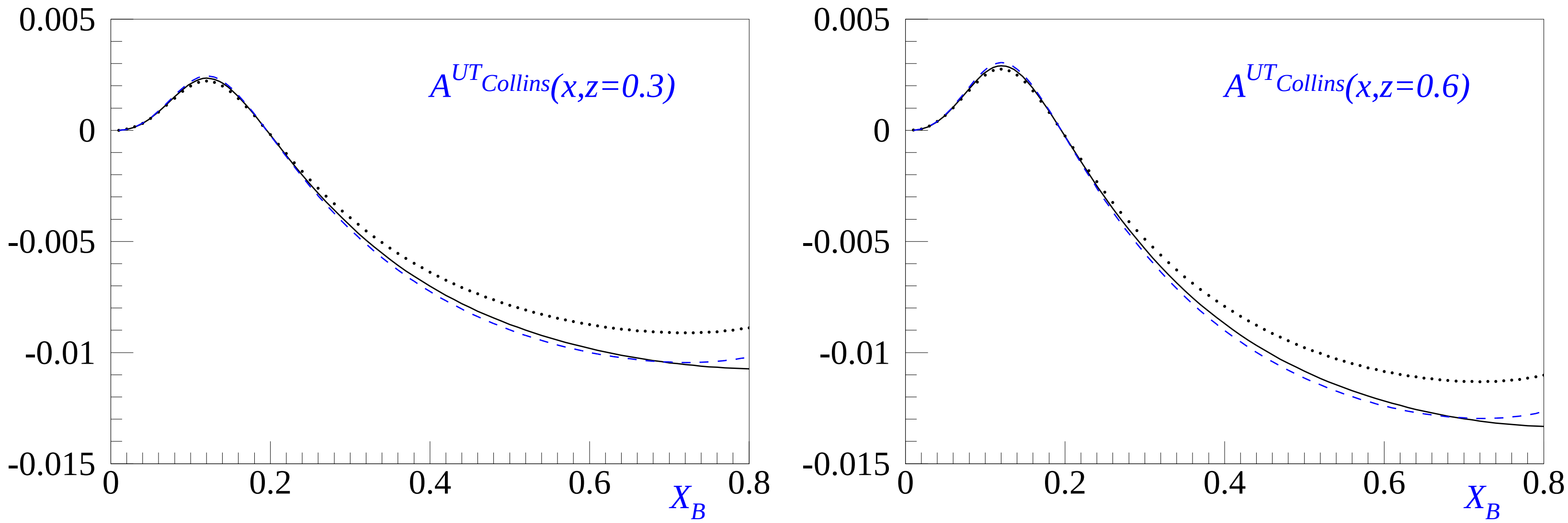
FULL: Neutron (model)

DOTS: Neutron (model) extracted from ^3He (calculation) neglecting the contribution of the proton polarization

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

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

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



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

The calculation has been performed in the Bjorken limit...

What happens in the actual experimental kinematics?

What about relativistic effects?

A LF description of SiDIS off ^{3}He - I

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

- fully Poincarè invariant
- with a fixed number of on-mass-shell constituents
- such that the Clebsch-Gordan coefficients can be used to decompose the wave function (thanks to BT)

Drawback: The description is not explicitely covariant

A LF description of SiDIS off ^{3}He - II

Among the 3 possible forms of RHD, the Light-Front one plays has severale advantages:

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

and a few drawbacks:

- Dinamical transverse LF-rotations but, within BT, one can define a *kinematical*, intrinsic angular momentum.
- As for the other RHD, finite-dimensional Fock space associated to the dynamical description (RFT is infinite dimensional!) of an interacting system. For phenomenological studies, this is enough.

The SiDIS nuclear hadronic tensor in LF

In Impulse Approximation one gets:

$$\mathcal{W}^{\mu\nu}(Q^2, x_B, z, \tau_h f, \hat{\mathbf{h}}, S_{He}) \propto \sum_{\sigma,\sigma'} \sum_{\tau_{hf}} \sum\!\!\!\!\!\!\int_{\epsilon_S^{min}}^{\epsilon_S^{max}} d\epsilon_S \int_{M_N^2}^{(M_X - M_S)^2} dM_f^2$$

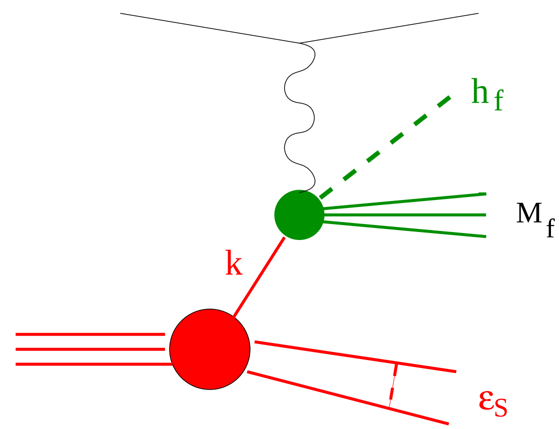
$$\times \int_{\xi_{lo}}^{\xi_{up}} \frac{d\xi}{\xi^2(1-\xi)(2\pi)^3} \int_{P_\perp^{min}}^{P_\perp^{max}} \frac{dP_\perp}{sin\theta} (P^+ + q^+ - h^+)$$

$$\times \; w^{\mu\nu}_{\sigma\sigma'}\left(\tau_{hf}, \tilde{\mathbf{q}}, \tilde{\mathbf{h}}, \tilde{\mathbf{P}}\right) \mathcal{P}^{\tau_{hf}}_{\sigma'\sigma}(\mathbf{k}, \epsilon_S, S_{He})$$

where

$w^{\mu\nu}_{\sigma\sigma'}\left(\tau_{hf}, \tilde{\mathbf{q}}, \tilde{\mathbf{h}}, \tilde{\mathbf{P}}\right)$ is the nucleon hadronic tensor

$\mathcal{P}^{\tau_{hf}}_{\sigma'\sigma}(\mathbf{k}, \epsilon_S, S_{He})$ is the LF nuclear spectral function defined in terms of LF overlaps



The LF Spectral Function

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

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

and the instant-form spectral function

$$\begin{aligned}
\mathcal{S}^{\tau}_{\sigma'_1\sigma_1}(\tilde{\mathbf{k}}, \epsilon_S, S_{He}) &= \sum_{J_S J_{zS} \alpha} \sum_{T_S \tau_S} \langle T_S, \tau_S, \alpha, \epsilon_S J_S J_{zS}; \sigma'_1; \tau, \mathbf{k} | \Psi_0 S_{He} \rangle \\
&\times \langle S_{He}, \Psi_0 | \mathbf{k} \sigma_1 \tau; J_S J_{zS} \epsilon_S, \alpha, T_S, \tau_S \rangle \\
&= B.T. = \left[B^{\tau}_{0,S_{He}}(|\mathbf{k}|, E) + \boldsymbol{\sigma} \cdot \mathbf{f}^{\tau}_{S_{He}}(\mathbf{k}, E) \right]_{\sigma'_1\sigma_1}
\end{aligned}$$

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

NOTICE: $\mathcal{S}^{\tau}_{\sigma'_1\sigma_1}(\tilde{\mathbf{k}}, \epsilon_S, S_{He})$ is given in terms of THREE independent functions $B_{0,1,2}$

LF spectral function and LF TMDs - I

In general, the TMDs for the $J = 1/2$ system are introduced through the q-q correlator

$$\begin{aligned}\Phi(k,P,S) &= \frac{1}{2}\{A_1\,\not P + A_2\,S_L\,\gamma_5\,\not P + A_3\,\not P\,\gamma_5\,\not S_\perp \\ &\quad + \frac{1}{M}\,\widetilde{A}_1\,\vec{k}_\perp\cdot\vec{S}_\perp\,\gamma_5 \not P + \widetilde{A}_1\,\frac{S_L}{M}\,\not P\,\gamma_5\,\not k_\perp \\ &\quad + \frac{1}{M^2}\,\widetilde{A}_1\,\vec{k}_\perp\cdot\vec{S}_\perp\,\not P\,\gamma_5\,\not k_\perp\Big\}\ ,\end{aligned}$$

so that the SIX twist-2 T-even TMDs are identified :

$$\begin{aligned}\frac{1}{2P^+}\,\mathrm{Tr}(\gamma^+\Phi) &= f_1\ ,\\ \frac{1}{2P^+}\,\mathrm{Tr}(\gamma^+\gamma_5\Phi) &= S_L\,g_{1L} + \frac{1}{M}\,\vec{k}_\perp\cdot\vec{S}_\perp\,g_{1T}\ ,\\ \frac{1}{2P^+}\,\mathrm{Tr}(\mathrm{i}\sigma^{\mathrm{i}+}\gamma_5\Phi) &= S^i_\perp\,h_1 + \frac{S_L}{M}\,k^i_\perp\,h^\perp_{1L} - \frac{1}{M^2}\,(k^i_\perp k^j_\perp + \frac{1}{2}k^2_\perp g^{ij}_\perp)S_{\perp,j}\,h^\perp_{1T}\ .\end{aligned}$$

The LF spectral function is the LF equivalent of $\Phi(k,P,S)$.

Let us identify the LF TMDs...

LF spectral function and LF TMDs - II

$$
\begin{aligned}
\frac{1}{2}\mathrm{Tr}(\mathcal{P}I) &= c\, B_0 = f_1^{LF} \\
\frac{1}{2}\mathrm{Tr}(\mathcal{P}\sigma_z) &= S_{Az}\left[a\,(B_1 + B_2\cos^2\theta) + b\cos\theta\frac{|\mathbf{k}_\perp|^2}{k}B_2\right] \\
&+ \mathbf{S_{A}}_\perp\cdot\mathbf{k}_\perp\left[a\;B_2\frac{\cos\theta}{k} + b\,(B_1 + B_2\;\sin^2\theta)\right] \\
&= S_L\;g_{1L}^{LF} + \frac{1}{M}\,\mathbf{S_{A}}_\perp\cdot\mathbf{k}_\perp\;g_{1T}^{LF} \\
\frac{1}{2}\mathrm{Tr}(\mathcal{P}\sigma_y) &= S_{Ay}\left[\left(a + \frac{d}{2}\,|\mathbf{k}_\perp|^2\right)\;B_1 + \frac{1}{2}\left(a - b\frac{k_\perp^2\,\cos\theta}{k}\right)\;B_2\right] \\
&+ S_{Az}k_y\left[a\,\frac{\cos\theta}{k}B_2 - b(B_1 + B_2\cos^2\theta)\right] \\
&+ \left(k_x k_y S_{Ax} - \frac{1}{2}k_\perp^2 S_{Ay}\right)\left[\left(\frac{a}{k^2} - b\,\frac{\cos\theta}{k}\right)B_2 - d\;B_1\right] \\
&= S_{Ay}\;h_1^{LF} + \frac{S_L}{M}\;k_y\;h_{1L}^{\perp LF} + \frac{1}{M^2}\;\left(k_x k_y S_{Ax} - \frac{1}{2}k_\perp^2 S_{Ay}\right)\;h_{1T}^{\perp LF}
\end{aligned}
$$

The SIX TMDs depend actually upon THREE independent functions!

a, b, c, d are *kinematical* factors, *predicted* by the LF procedure!

LF spectral function and LF TMDs - III

Our Analysis shows, from general principles, that, for any spin $1/2$ system as ^{3}He and, in particulare, for the *NUCLEON*:

- **In LF Dynamics (+ BT), the description of SIDIS is *simplified*;**
- **Among the 6 T-even TMDs, 3 relations are found.**
- **These relations are precisely predicted within LF Dynamics, and could be experimentally checked to test the LF description of SiDIS.**

GOOD *preliminary* NEWS for the experiments

What has to be done now is to use the LF hadronic tensor

$$\mathcal{W}^{\mu\nu}(Q^2, x_B, z, \tau_h f, \hat{\mathbf{h}}, S_{He}) \propto \sum_{\sigma,\sigma'} \sum_{\tau_h f} \sum_{\epsilon_S^{min}}^{\epsilon_S^{max}} d\epsilon_S \int_{M_N^2}^{(M_X - M_S)^2} dM_f^2$$
$$\times \int_{\xi_{lo}}^{\xi_{up}} \frac{d\xi}{\xi^2(1-\xi)(2\pi)^3} \int_{P_\perp^{min}}^{P_\perp^{max}} \frac{dP_\perp}{sin\theta} (P^+ + q^+ - h^+)$$
$$\times \; w^{\mu\nu}_{\sigma\sigma'}\left(\tau_h f, \tilde{\mathbf{q}}, \tilde{\mathbf{h}}, \tilde{\mathbf{P}}\right) \mathcal{P}^{\tau_h f}_{\sigma'\sigma}(\mathbf{k}, \epsilon_S, S_{He})$$

to evaluate the SSAs and to figure out whether or not the proposed extraction procedure still holds in the LF analysis.

This information is not available yet BUT we can at least already say that, in the kinematics of the experiment completed at JLab, the effect of considering the integration limits evaluated in the actual JLab kinematics, instead that in the Bjorken limit as previously done, is negligible. The situation will be therefore even better in the experiments planned at 12 GeV.

Conclusions

- **A realistic study of $^3\vec{He}(e,e'\pi)X$ in the Bjorken limit**

  In IA, nuclear effects in the extraction of the neutron information are found to be under control

- **A Light-Front analysis at finite Q^2**

  The spin-dependent LF spectral function has been defined;

  In LF + BT, an intriguing simplification in the theoretical description of SiDIS is found;

  everything could be checked experimentally;

  concerning experiments, work is being done to test the extraction procedure of the neutron information in the new scenario