



A Light-Front approach to the 3He Spectral Function

Sergio Scopetta

**Dipartimento di Fisica e Geologia, Università di Perugia
and INFN, Sezione di Perugia, Italy**

in collaboration with

Alessio Del Dotto – Università di Roma Tre and INFN, Roma 3, Italy

Leonid Kaptari – JINR, Dubna, Russia & Perugia

Emanuele Pace – Università di Roma “Tor Vergata” and INFN, Roma 2, Italy

Matteo Rinaldi – Università di Perugia and INFN, Sezione di Perugia, Italy

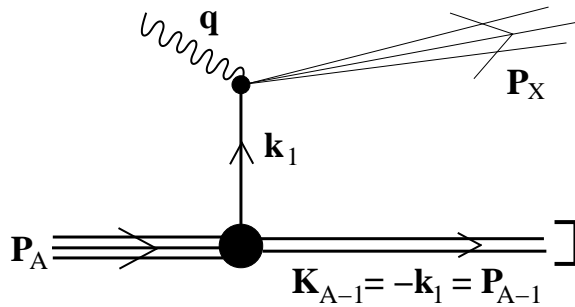
Giovanni Salmè – INFN, Roma 1, Italy



March 9th, 2015

This is an exciting Workshop for me...

We studied the process $A(e, e'(A-1))X$ many years ago



An old idea (Claudio among the first):
in this process, in IA,

$$d^2\sigma_A \propto F_2^N(x)$$

there is no convolution! (nucl-th/9609062)
Example: through ${}^3\text{He}(e, e'd)X$, check
of the reaction mechanism (EMC effect);
measuring ${}^3\text{H}(e, e'd)X$, direct
access to the **neutron!**

new perspectives
(loi to the JLab PAC,
already in November 2010)

Eur. Phys. J. A 5, 191-207 (1999)

THE EUROPEAN
PHYSICAL JOURNAL A
© Springer-Verlag 1999

Semi-inclusive deep inelastic lepton scattering off complex nuclei

C. Ciofi degli Atti¹, L.P. Kaptari^{1,*}, S. Scopetta²

¹ Department of Physics, University of Perugia, and Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Via. A. Pascoli, I-06100 Perugia, Italy

² Departament de Física Teòrica, Universitat de València, E-46100 Burjassot, València, Spain

Received: 4 March 1999
Communicated by B. Povh

Abstract. It is shown that in semi-inclusive deep inelastic scattering (DIS) of electrons off complex nuclei, the detection, in coincidence with the scattered electron, of a nucleus ($A-1$) in the ground state, as well as of a nucleon and a nucleus ($A-2$), also in the ground state, may provide unique information on several long standing problems, such as: i) the nature and the relevance of the final state interaction in DIS; ii) the validity of the spectator mechanism in DIS; iii) the medium induced modifications of the nucleon structure function; iv) the origin of the EMC effect.

PACS. 13.40.-f Electromagnetic processes and properties - 21.60.-n Nuclear-structure models and methods - 24.85.+p Quarks, gluons, and QCD in nuclei and nuclear processes - 25.60.Gc Breakup and momentum distributions

Semi-inclusive Deep Inelastic Scattering from Light Nuclei by Tagging Low Momentum Spectators

R. Dupré, K. Hafidi, and X. Zhan
Argonne National Laboratory, Argonne, Illinois 60439, USA

S. Dhamija
Indiana University, Bloomington, Indiana 47405, USA

S. Stepanyan
Thomas Jefferson National Accelerator Facility,
Newport News, Virginia 23606, USA

(Dated: November 24, 2010)

Abstract

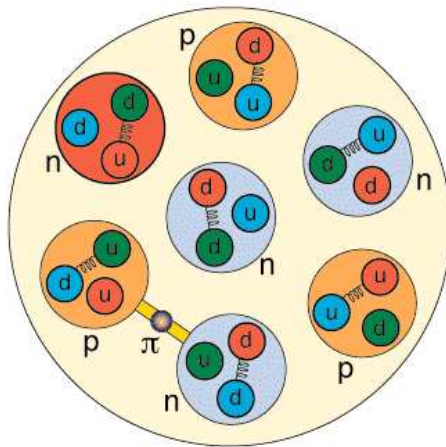
We propose to measure the semi-inclusive deep inelastic scattering from light nuclei ($D, {}^3\text{He}, {}^4\text{He}$). The detection of the low energy recoil nucleus in the final state will provide unique information about the nature of nuclear EMC effect and will permit to investigate the modifications of the nucleon structure functions in the nucleus. We propose to measure a set of observable by using the future 11 GeV electron beam in Hall B CLAS12. The baseline CLAS12 detector is suitable to detect electrons in the valence region, and a new low energy recoil detector with good performance is required to achieve the proposed physics goals.



This is an exciting Workshop for me...

Later, I studied nuclear GPDs...

Which of these pictures is more similar to a nuclear section?

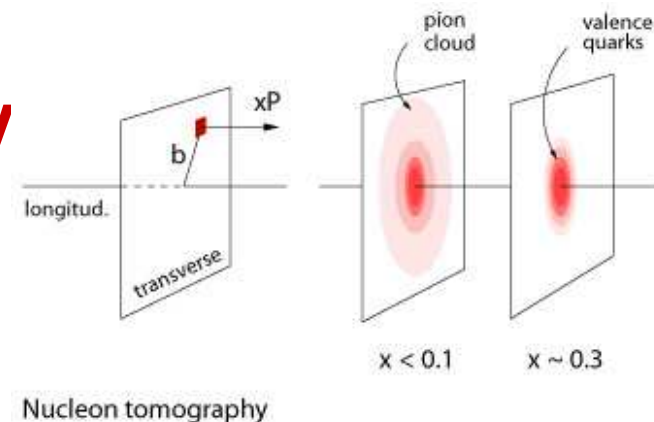


We should perform a **tomography**

It is possible!

Coherent DVCS & GPDs

Slow nuclear recoil detection is necessary...



Nucleon tomography



March 9th, 2015

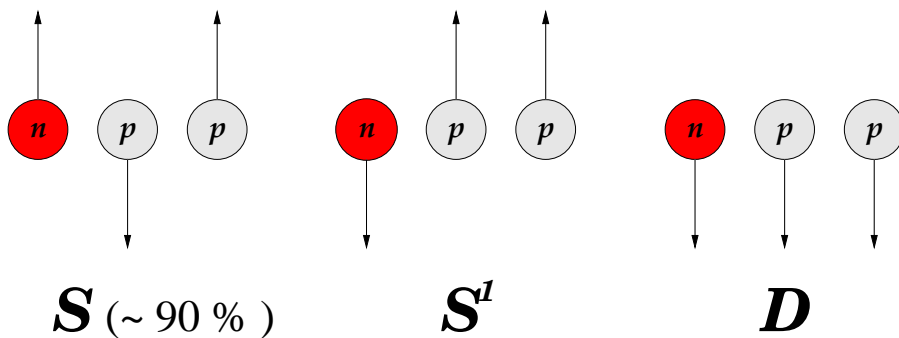
Outline

- Importance of the ^3He nucleus for fundamental studies in Hadronic Physics.
In particular: the **neutron** information from ^3He .
- **Crucial quantity: the (distorted) spectral function**
Recent theoretical developments in DVCS
(M. Rinaldi, S.S. PRC 85, 062201(R) (2012); PRC 87, 035208 (2013))
and SiDIS studies
(L. Kaptari, A. Del Dotto, E. Pace, G. Salmè, S.S., PRC 89 (2014) 035206)
Importance of a relativistic treatment for the description
of the JLab program @ 12 GeV
- **The LF spectral function of ^3He**
(E. Pace, A. Del Dotto, M. Rinaldi, G. Salmè, S.S., Few Body Syst. 54 (2013) 1079)
(work in progress): preliminary results
- Conclusions



Importance of ^3He for DIS structure studies

- ^3He is **theoretically well known**. Even a **relativistic treatment** may be implemented.
- ^3He has been used extensively as an **effective neutron target**, especially to unveil the **spin content** of the **free neutron**, due to its peculiar spin structure:



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

^3He always **promising** when the **neutron polarization properties** have to be studied.

- To this aim, ^3He is **unique** and its **spectral function arises in**

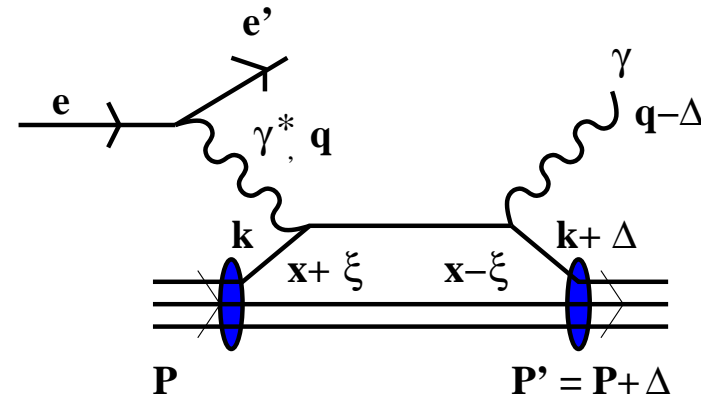
- * DIS, together with ^3H , for the extraction of F_2^n (Marathon experiment, JLab);
- * polarized DIS, for the extraction of the SSF g_1^n ;
- * polarized **SiDIS**, for the extraction of **neutron transversity** and related observables;
- * **DVCS**, for the extraction of **neutron GPDs**



Example 1: DVCS off ${}^3\text{He}$

For a $J = \frac{1}{2}$ target,
in a hard-exclusive process,
($Q^2, \nu \rightarrow \infty$)
such as (coherent) DVCS

(Definition of GPDs from X. Ji PRL 78 (97) 610):



- $\Delta = P' - P$, $q^\mu = (q_0, \vec{q})$, and $\bar{P} = (P + P')^\mu / 2$
- $x = k^+ / P^+$; $\xi = \text{"skewness"} = -\Delta^+ / (2\bar{P}^+)$
- $x \leq -\xi \rightarrow$ GPDs describe *antiquarks*;
 $-\xi \leq x \leq \xi \rightarrow$ GPDs describe $q\bar{q}$ *pairs*; $x \geq \xi \rightarrow$ GPDs describe *quarks*

the GPDs $H_q(x, \xi, \Delta^2)$ and $E_q(x, \xi, \Delta^2)$ are introduced:

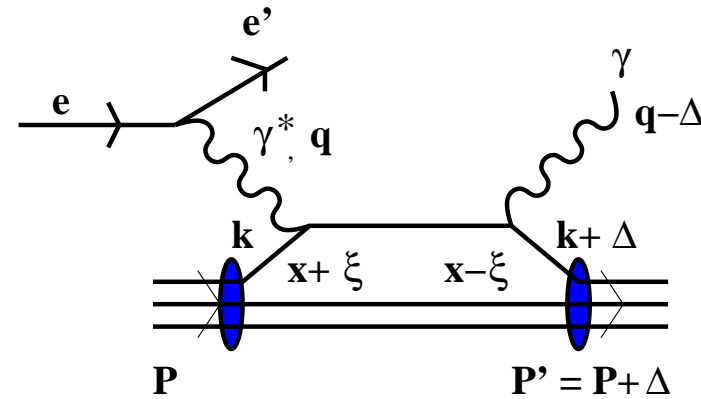
$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P' | \bar{\psi}_q(-\lambda n/2) \gamma^\mu \psi_q(\lambda n/2) | P \rangle = H_q(x, \xi, \Delta^2) \bar{U}(P') \gamma^\mu U(P) + E_q(x, \xi, \Delta^2) \bar{U}(P') \frac{i\sigma^{\mu\nu} \Delta_\nu}{2M} U(P) + \dots$$



Example 1: DVCS off ${}^3\text{He}$

For a $J = \frac{1}{2}$ target,
in a hard-exclusive process,
($Q^2, \nu \rightarrow \infty$)
such as (coherent) DVCS

(Definition of GPDs from X. Ji PRL 78 (97) 610):



- $\Delta = P' - P$, $q^\mu = (q_0, \vec{q})$, and $\bar{P} = (P + P')^\mu / 2$
- $x = k^+ / P^+$; $\xi = \text{"skewness"} = -\Delta^+ / (2\bar{P}^+)$
- $x \leq -\xi \rightarrow$ GPDs describe *antiquarks*;
 $-\xi \leq x \leq \xi \rightarrow$ GPDs describe $q\bar{q}$ *pairs*; $x \geq \xi \rightarrow$ GPDs describe *quarks*

and the helicity dependent ones, $\tilde{H}_q(x, \xi, \Delta^2)$ and $\tilde{E}_q(x, \xi, \Delta^2)$, obtained as follows:

$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P' | \bar{\psi}_q(-\lambda n/2) \gamma^\mu \gamma_5 \psi_q(\lambda n/2) | P \rangle = \tilde{H}_q(x, \xi, \Delta^2) \bar{U}(P') \gamma^\mu U(P) + \tilde{E}_q(x, \xi, \Delta^2) \bar{U}(P') \frac{\gamma_5 \Delta^\mu}{2M} U(P) + \dots$$

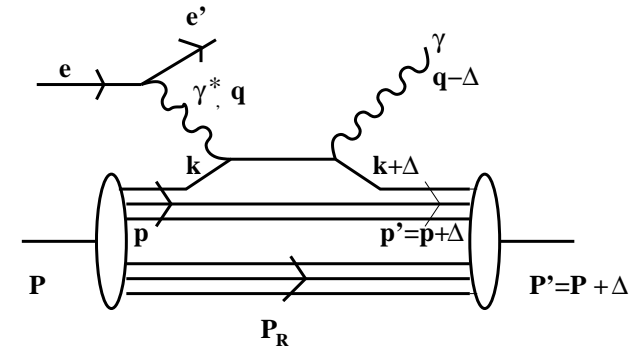


GPDs of ^3He : the Impulse Approximation

coherent DVCS in I.A.

(^3He does not break-up, $\Delta^2 \ll M^2, \xi^2 \ll 1$,):

In a symmetric frame ($\bar{p} = (p + p')/2$) :



$$k^+ = (x + \xi)\bar{P}^+ = (x' + \xi')\bar{p}^+,$$

$$(k + \Delta)^+ = (x - \xi)\bar{P}^+ = (x' - \xi')\bar{p}^+,$$

one has, for a given GPD, $H_q, \tilde{G}_M^q = H_q + E_q$, or \tilde{H}_q

$$GPD_q(x, \xi, \Delta^2) \simeq \sum_N \int \frac{dz^-}{4\pi} e^{ix\bar{P}^+ z^-} {}_A \langle P' S' | \hat{O}_q^{\mu, N} | P S \rangle_A |_{z^+=0, z_\perp=0}.$$

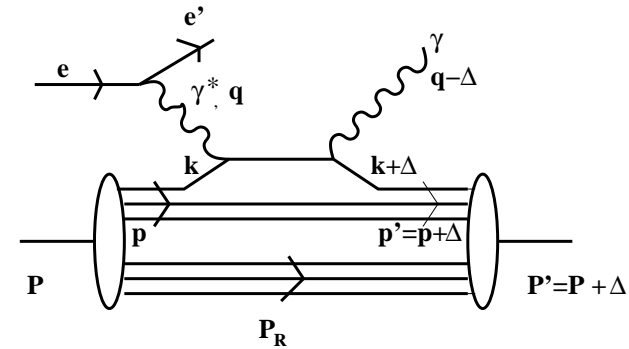


GPDs of ^3He : the Impulse Approximation

coherent DVCS in I.A.

(^3He does not break-up, $\Delta^2 \ll M^2, \xi^2 \ll 1$,):

In a symmetric frame ($\bar{p} = (p + p')/2$) :



$$k^+ = (x + \xi)\bar{P}^+ = (x' + \xi')\bar{p}^+,$$

$$(k + \Delta)^+ = (x - \xi)\bar{P}^+ = (x' - \xi')\bar{p}^+,$$

one has, for a given GPD, $H_q, \tilde{G}_M^q = H_q + E_q$, or \tilde{H}_q

$$GPD_q(x, \xi, \Delta^2) \simeq \sum_N \int \frac{dz^-}{4\pi} e^{ix\bar{P}^+z^-} {}_A \langle P' S' | \hat{O}_q^{\mu, N} | P S \rangle_A |_{z^+=0, z_\perp=0}.$$

By properly inserting a tensor product complete basis for the nucleon (PW) and the fully interacting recoiling system :

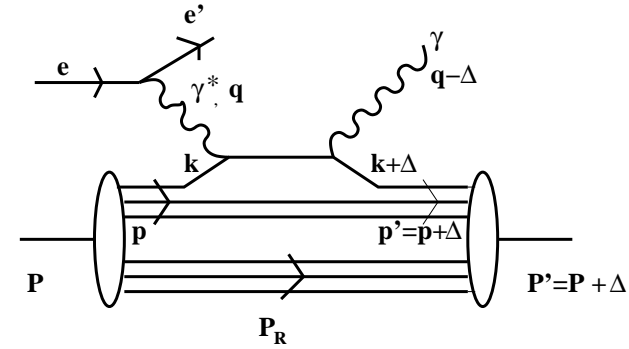


GPDs of ^3He : the Impulse Approximation

coherent DVCS in I.A.

(^3He does not break-up, $\Delta^2 \ll M^2, \xi^2 \ll 1$,):

In a symmetric frame ($\bar{p} = (p + p')/2$) :



$$\begin{aligned} k^+ &= (x + \xi)\bar{P}^+ = (x' + \xi')\bar{p}^+ , \\ (k + \Delta)^+ &= (x - \xi)\bar{P}^+ = (x' - \xi')\bar{p}^+ , \end{aligned}$$

one has, for a given GPD, $H_q, \tilde{G}_M^q = H_q + E_q$, or \tilde{H}_q

$$GPD_q(x, \xi, \Delta^2) \simeq \sum_N \int \frac{dz^-}{4\pi} e^{ix'\bar{p}^+ z^-} \langle P' S' | \sum_{\vec{P}'_R, f'_{A-1}, \vec{p}', s'} \{ |P'_R, \Phi_{A-1}^{f'} \rangle \otimes |p' s' \rangle \}$$

$$\langle P'_R, \Phi_{A-1}^{f'} | \otimes \langle p' s' | \hat{O}_q^{\mu, N} \sum_{\vec{P}_R, f_{A-1}, \vec{p}, s} \{ |P_R, \Phi_{A-1}^f \rangle \otimes |ps \rangle \} \{ \langle P_R, \Phi_{A-1}^f | \otimes \langle ps | \} | PS \rangle ,$$

and, since $\{ \langle P_R, \Phi_{A-1}^f | \otimes \langle ps | \} | PS \rangle = (2\pi)^3 \delta^3(\vec{P} - \vec{P}_R - \vec{p}) \langle \Phi_{A-1}^f, ps | PS \rangle ,$

(NR! Separation of the global motion from the intrinsic one!)



GPDs of ^3He in IA: the spectral function

H_q^A can be obtained in terms of H_q^N (S.S. PRC 70, 015205 (2004), PRC 79, 025207 (2009)):

$$H_q^A(x, \xi, \Delta^2) = \sum_N \int dE \int d\vec{p} \overline{\sum_{\mathcal{M}}} \sum_s P_{\mathcal{M}\mathcal{M},ss}^N(\vec{p}, \vec{p}', E) \frac{\xi'}{\xi} H_q^N(x', \Delta^2, \xi'),$$

$\tilde{G}_M^{3,q}$ in terms of $\tilde{G}_M^{N,q}$ (M. Rinaldi, S.S. PRC 85, 062201(R) (2012); PRC 87, 035208 (2013)):

$$\tilde{G}_M^{3,q}(x, \Delta^2, \xi) = \sum_N \int dE \int d\vec{p} \left[P_{+-,+ -}^N - P_{+-,- +}^N \right] (\vec{p}, \vec{p}', E) \frac{\xi'}{\xi} \tilde{G}_M^{N,q}(x', \Delta^2, \xi'),$$

and \tilde{H}_q^A can be obtained in terms of \tilde{H}_q^N :

$$\tilde{H}_q^A(x, \xi, \Delta^2) = \sum_N \int dE \int d\vec{p} \left[P_{++;++}^N - P_{++,- -}^N \right] (\vec{p}, \vec{p}', E) \frac{\xi'}{\xi} \tilde{H}_q^N(x', \Delta^2, \xi'),$$



GPDs of ${}^3\text{He}$ in IA: the spectral function

H_q^A can be obtained in terms of H_q^N (S.S. PRC 70, 015205 (2004), PRC 79, 025207 (2009)):

$$H_q^A(x, \xi, \Delta^2) = \sum_N \int dE \int d\vec{p} \overline{\sum_{\mathcal{M}}} \sum_s P_{\mathcal{M}\mathcal{M},ss}^N(\vec{p}, \vec{p}', E) \frac{\xi'}{\xi} H_q^N(x', \Delta^2, \xi'),$$

$\tilde{G}_M^{3,q}$ in terms of $\tilde{G}_M^{N,q}$ (M. Rinaldi, S.S. PRC 85, 062201(R) (2012); PRC 87, 035208 (2013)):

$$\tilde{G}_M^{3,q}(x, \Delta^2, \xi) = \sum_N \int dE \int d\vec{p} \left[P_{+-,+ -}^N - P_{+-,- +}^N \right] (\vec{p}, \vec{p}', E) \frac{\xi'}{\xi} \tilde{G}_M^{N,q}(x', \Delta^2, \xi'),$$

where $P_{\mathcal{M}'\mathcal{M},s's}^N(\vec{p}, \vec{p}', E)$ is the one-body, spin-dependent, off-diagonal **spectral function** for the nucleon N in the nucleus,

$$\mathbf{P}_{\mathcal{M}'\mathcal{M}\sigma'\sigma}^N(\vec{p}, \vec{p}', E) = \sum_{f_{A-1}} \delta(E - E_{A-1} + E_A) \underbrace{S_A \langle \Psi_A; J_A \mathcal{M} \pi_A | \vec{p}, \sigma; \phi_{f_{A-1}} \rangle}_{\text{intrinsic overlaps}} \underbrace{\langle \phi_{f_{A-1}}; \sigma' \vec{p}' | \pi_A J_A \mathcal{M}'; \Psi_A \rangle S_A}_{\text{intrinsic overlaps}}$$

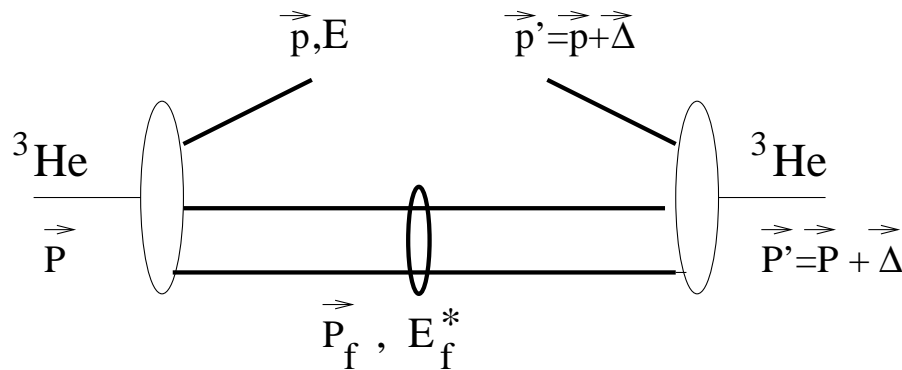
↖ intrinsic overlaps ↗



The spectral function: a few words more

$$\mathbf{P}_{\mathcal{M}'\mathcal{M}\sigma'\sigma}^N(\vec{p}, \vec{p}', E) = \sum_f \delta(E - E_{min} - E_f^*)$$

$$S_A \langle \Psi_A; J_A \mathcal{M} \pi_A | \vec{p}, \sigma; \phi_f(E_f^*) \rangle \langle \phi_f(E_f^*); \sigma' \vec{p}' | \pi_A J_A \mathcal{M}'; \Psi_A \rangle S_A$$



- 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^* ;
- the three-body bound state and the two-body bound or scattering state are evaluated within the same interaction (in our case, **Av18**, from the **Pisa** group (Kievsky, Viviani): the extension of the treatment to heavier nuclei would be very difficult



GPDs of ${}^3\text{He}$: importance of relativity

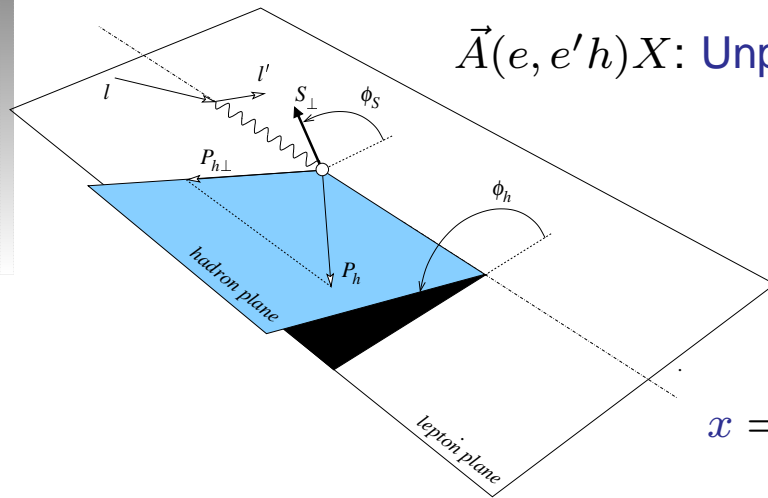
- What we have:
 - * An instant form, I.A. calculation of $H^3, \tilde{G}_M^3, \tilde{H}^3$, within AV18;
 - * the neutron contribution dominates \tilde{G}_M^3 and \tilde{H}^3 at low Δ^2 ;
 - * an extraction procedure of the neutron information, able to take into account all the nuclear effects encoded in an IA analysis;
- What we can do now: to estimate X-sections (DVCS, BH, Interference)
→ a proposal of coherent DVCS off ${}^3\text{He}$ at JLab@12 GeV?

BUT

- In case experiments are performed at higher Δ^2 :
 - * a RELATIVISTIC TREATMENT is mandatory:
a sizable difference in momentum between the initial and final states requires proper boosting
 - * The fulfillment of polynomiality requires covariance;
In NR calculations, number of particle sum rule, momentum sum rule, (slightly) violated.
- A relativistic extension of the ${}^3\text{He}$ spectral function definition is necessary



Example II: Single Spin Asymmetries (SSAs)



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

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

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

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

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

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



SSAs \rightarrow the neutron \rightarrow ^3He


SSAs in terms of parton distributions and fragmentation functions:


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

$$N^{Sivers} \propto \sum_q e_q^2 \int d^2\kappa_T d^2\mathbf{k}_T \delta^2(\mathbf{k}_T + \mathbf{q}_T - \kappa_T) \frac{\hat{\mathbf{P}}_{h\perp} \cdot \mathbf{k}_T}{M} f_{1T}^{\perp q}(x, \mathbf{k}_T^2) D_1^{q,h}(z, (z\kappa_T)^2)$$

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

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

 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)

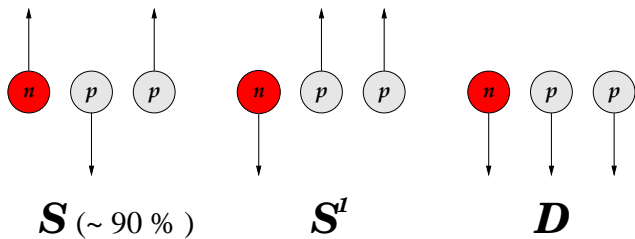
A strong flavor dependence confirmed by recent data

Importance of the neutron for flavor decomposition!



The neutron information from ${}^3\text{He}$

As we have seen already ${}^3\text{He}$ is the ideal target to study the polarized neutron:



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

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

Dynamical nuclear effects in inclusive DIS (${}^3\vec{H}e(e, e')X$) were evaluated with a realistic spin-dependent spectral function for ${}^3\vec{H}e$, $P_{\sigma, \sigma'}^{\mathcal{M}}(\vec{p}, E)$. It was found that the formula

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

(f_p, f_n dilution factors)

can be safely used \longrightarrow widely used by experimental collaborations.

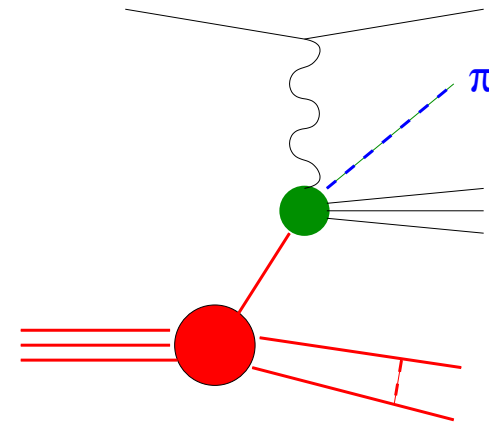
The nuclear effects are hidden in the “effective polarizations”

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



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

Can one use the same formula to extract the SSAs ?
 in SiDIS also the fragmentation functions can be modified
 by the nuclear environment !



The process ${}^3\vec{H}e(e, e'\pi)X$ has been evaluated :

in IA \rightarrow no FSI between the measured fast, ultrarelativistic π
 the remnant and the two nucleon recoiling system

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

SSAs involve convolutions of the transverse spin-dependent nuclear spectral function, $P_\perp(\vec{p}, E)$, with parton distributions AND fragmentation functions [S.Scopetta, PRD 75 (2007) 054005] :

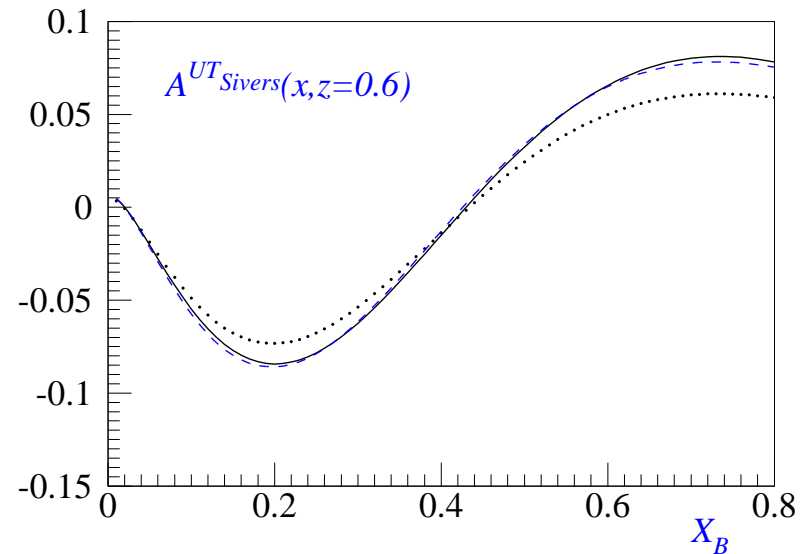
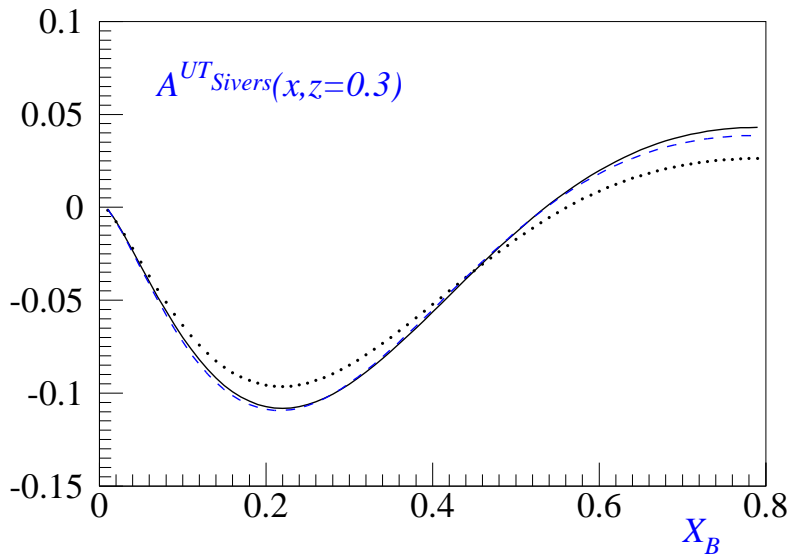
$$A \simeq \int d\vec{p} dE \dots P_\perp(\vec{p}, E) f_{1T}^{\perp q} \left(\frac{Q^2}{2p \cdot q}, \mathbf{k}_T^2 \right) D_1^{q,h} \left(\frac{p \cdot h}{p \cdot q}, \left(\frac{p \cdot h}{p \cdot q} \kappa_T \right)^2 \right)$$

The nuclear effects on fragmentation functions are new with respect to the DIS case and have been studied carefully, using models for $f_{1T}^{\perp q}$, $D_1^{q,h}$... and the Av18 (Pisa group w.f.) spectral function.

March 9th, 2015



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



FULL: Neutron asymmetry (model)

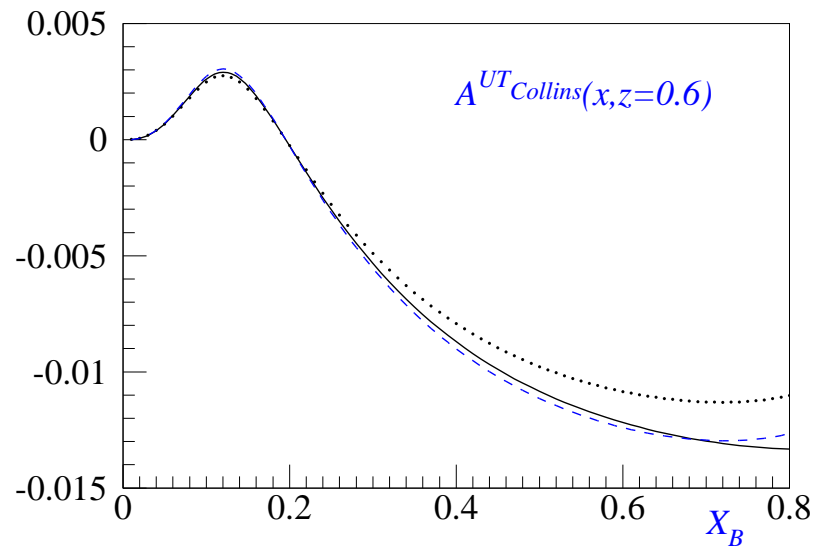
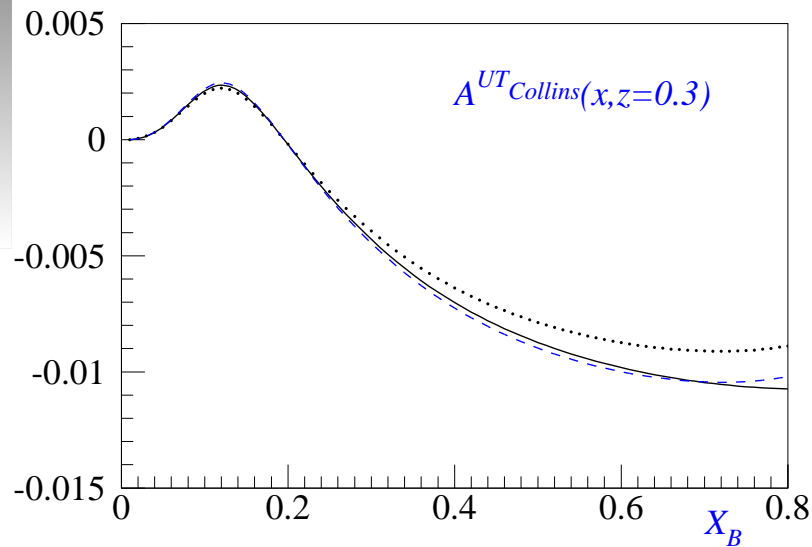
DOTS: Neutron asymmetry extracted from 3He (calculation) neglecting the contribution of the proton polarization $\bar{A}_n \simeq \frac{1}{f_n} A_3^{calc}$

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

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



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



The extraction procedure successful in **DIS**

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

1 - **What about FSI effects ? A pion is detected, now...**

2 - **What about relativistic effects @ 12 GeV JLab?**

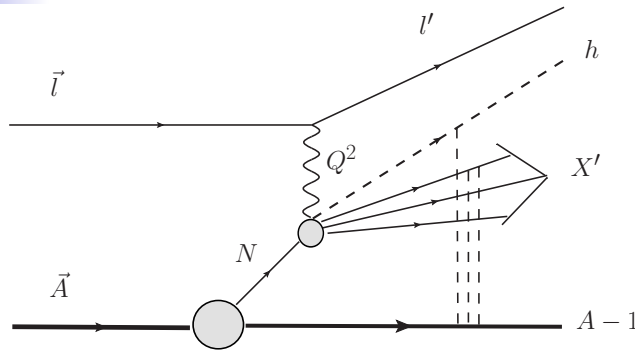
E12-09-018 experiment, approved with rate A, G. Cates et al.



March 9th, 2015

FSI: distorted spin-dependent spectral function of ${}^3\text{He}$

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



Relative energy between $A - 1$ and the remnants: a few GeV
 → **eikonal** approximation.

Relevant part of the (**distorted**) spin dependent spectral function:

$$\mathcal{P}_{||}^{IA(FSI)} = \mathcal{O}_{\frac{1}{2}\frac{1}{2}}^{IA(FSI)} - \mathcal{O}_{-\frac{1}{2}-\frac{1}{2}}^{IA(FSI)}; \quad \text{with:}$$

$$\mathcal{O}_{\lambda\lambda'}^{IA(FSI)}(p_N, E) = \sum_{\epsilon_{A-1}^*} \rho(\epsilon_{A-1}^*) \langle S_A, \mathbf{P}_A | (\hat{S}_{GI}) \{ \Phi_{\epsilon_{A-1}^*}, \lambda', \mathbf{p}_N \} \rangle \times \\ \langle (\hat{S}_{GI}) \{ \Phi_{\epsilon_{A-1}^*}, \lambda, \mathbf{p}_N \} | S_A, \mathbf{P}_A \rangle \delta(E - B_A - \epsilon_{A-1}^*).$$

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

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

(hadronization model: Kopeliovich et al., NPA 2004; σ_{eff} model: Ciofi & Kopeliovich, EPJA 2003)

GEA = Generalized Eikonal Approximation

(succesfull application to unpolarized ${}^2H(e, e'p)X$: Ciofi & Kaptari PRC 2011)



Recoil detection in ${}^3\text{He}(e, e'D)X$, ${}^3\vec{\text{H}}e(\vec{e}, e'D)X$

FSI have been included into the scheme in the unpolarized case;

(Ciofi and Kaptari, PRC 83 (2011) 044602)

Everything has been extended to the spin-dependent case

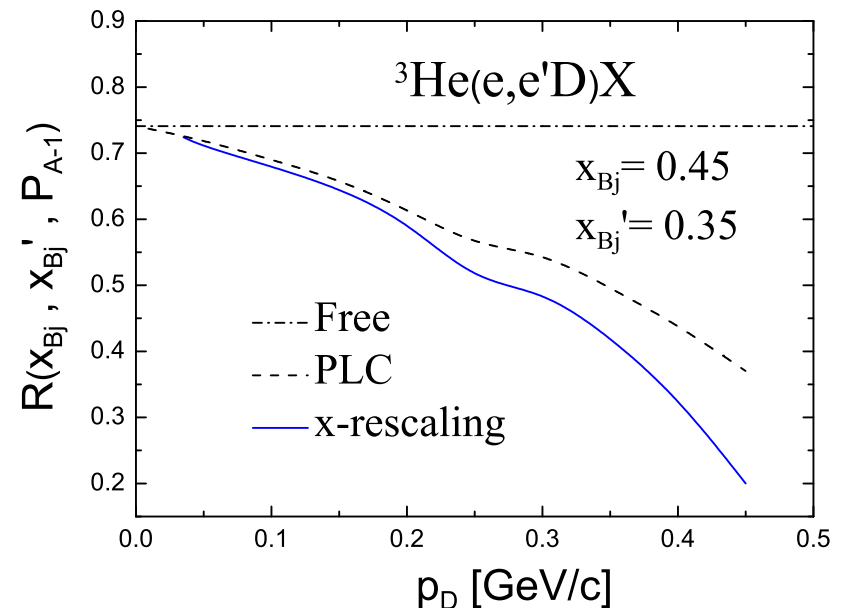
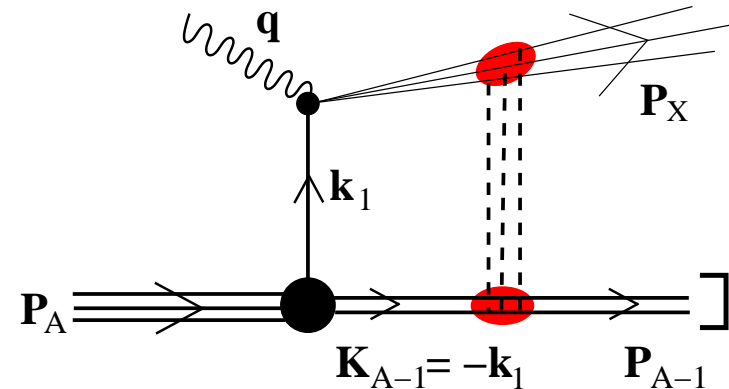
(Kaptari, Del Dotto, Pace, Salmè, S.S.

PRC 89 (2014) - 035206)

Properly defined observables can distinguish among different descriptions of the EMC effect.

In the polarized case, convenient kinematical regions have been addressed to access either the structure of the bound proton (tagged EMC effect)

or details of the hadronization mechanism

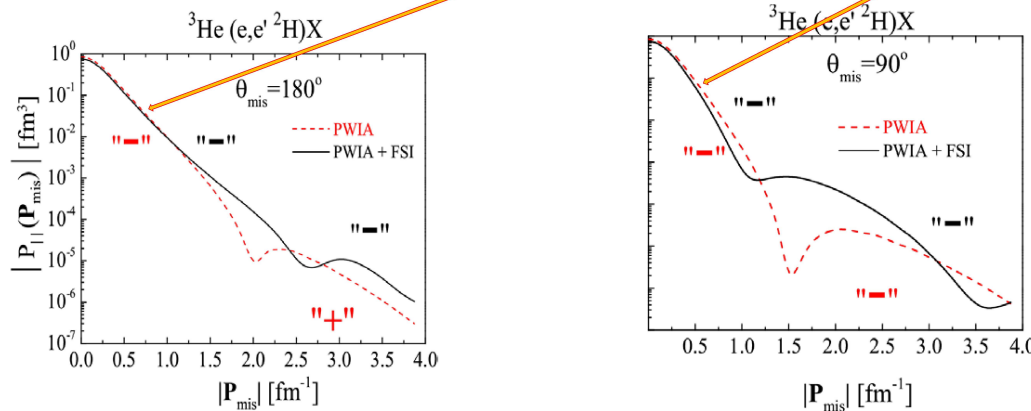


(preliminary) FSI effects on ${}^3\text{He} \uparrow (\vec{e}, e'h)X$

FSI in the Parallel (along the target polarization) Spin Dependent Spectral Function $P_{\parallel}(\mathbf{p}_{\text{mis}}, \theta_{\text{mis}})$

$$\mathcal{F}^A(x, \{\alpha\}) \simeq \int_x^A \mathcal{F}^N(\xi/x, \{\alpha\}) f^A(\xi) d\xi; \quad f^A(\xi) = \int dE \int_{\mathbf{p}_{\text{min}}}^{\mathbf{p}_{\text{max}}} P^A(\mathbf{p}, E) \delta\left(\xi - \frac{pq}{m\nu}\right) d^3\mathbf{p}$$

$\mathbf{p} = \mathbf{p}_{\text{min}} \rightarrow |\cos \theta_{\mathbf{p}}| = 1$ (FSI minimized, Spectral Function maximized !!!)



$$\mathbf{A}_n \simeq \frac{1}{\mathbf{p}_n^{\text{FSI}} f_n} \left(\mathbf{A}_3^{\text{exp}} - 2\mathbf{p}_p^{\text{FSI}} f_p \mathbf{A}_p^{\text{exp}} \right)$$

$$\mathbf{p}_N^{\text{FSI}} = \int P_{\parallel}^N(\vec{p}_{\text{mis}}, E) dE d^3 p_{\text{mis}} = \mathbf{p}_N^{\text{PWIA}} - \delta \mathbf{p}_N^{\text{FSI}}(Q^2, x_{\text{Bj}}) \quad \text{Preliminary } \delta \mathbf{p}_N^{\text{FSI}}(Q^2, x_{\text{Bj}}) \sim 10 - 15 \%$$

$\mathcal{P}_{\parallel}^{\text{PWIA}}$ and $\mathcal{P}_{\parallel}^{\text{FSI}}$ can be very different: but observables evaluated in IA (GEA) are obtained through their integrals, dominated by the low momentum region, where they are rather close – not dramatic differences: e.g., $p_p(n)$ differ by 10-15 %.

Is this the effect in the extraction of the neutron information?

March 9th, 2015



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

DILUTION FACTORS

$$A_3^{exp} \simeq \frac{\Delta \vec{\sigma}_3^{exp.}}{\sigma_{unpol.}^{exp.}} \Rightarrow \frac{\langle \vec{s}_n \rangle \Delta \vec{\sigma}(\mathbf{n}) + 2 \langle \vec{s}_p \rangle \Delta \vec{\sigma}(\mathbf{p})}{\langle \mathbf{N}_n \rangle \sigma_{unpol.}(\mathbf{n}) + 2 \langle \mathbf{N}_p \rangle \sigma_{unpol.}(\mathbf{p})} = \langle \vec{s}_n \rangle \mathbf{f}_n A_n + 2 \langle \vec{s}_p \rangle \mathbf{f}_p A_p$$

PWIA:

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

$$\langle N \rangle = \int dE \int d^3p P_{unpol.}(E, \mathbf{p}) = 1.$$



$$\mathbf{f}_{n,(p)}(\mathbf{x}, \mathbf{z}) = \frac{\sum_q e_q^2 \mathbf{f}_1^{q,n(p)}(\mathbf{x}) D_1^{q,h}(\mathbf{z})}{\sum_N \sum_q e_q^2 \mathbf{f}_1^{q,N}(\mathbf{x}) D_1^{q,h}(\mathbf{z})}$$

FSI:

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

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



$$\mathbf{f}_{n,(p)}^{FSI}(\mathbf{x}, \mathbf{z}) = \frac{\sum_q e_q^2 \mathbf{f}_1^{q,n(p)}(\mathbf{x}) D_1^{q,h}(\mathbf{z})}{\sum_N \langle \mathbf{N} \rangle \sum_q e_q^2 \mathbf{f}_1^{q,N}(\mathbf{x}) D_1^{q,h}(\mathbf{z})}$$



Good news from preliminary GEA studies of FSI!

Results (Preliminary)

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

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	-8.410^{-3}
8.8	0.29	7.15	3.19	0.286	0.251	0.357	-8.510^{-3}
8.8	0.48	6.36	2.77	0.257	0.225	0.372	-8.910^{-3}
11	0.21	9.68	4.29	0.302	0.265	0.349	-8.310^{-3}
11	0.29	9.28	4.11	0.285	0.25	0.357	-8.510^{-3}

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

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	-1.110^{-2}
8.8	0.29	7.15	3.19	0.332	0.251	0.415	-1.110^{-2}
8.8	0.48	6.36	2.77	0.298	0.225	0.432	-1.210^{-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	-1.110^{-2}

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

3

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** seems to be safe!

What about **Relativity**?

March 9th, 2015



Relativity for Few Nucleon Systems: many efforts

- Relativistic Mean Field Theory for Few-Nucleon Systems? NO !
- Field theoretical approaches for two-body system (Bethe-Salpeter Equation, primarily): very important, difficult to be numerically implemented
- However, for $A \geq 2$, Relativistic Hamiltonian Dynamics (RHD), devised by Dirac in 1949 (RMP 21 (1949) 392), allow one to fulfill the Poincaré covariance, with finite dof, and therefore they fall in between the NR framework and the field theory, in its full glory.

The Few-Nucleon system has to be described through a Poincaré covariant formalism, where both wave functions and operators transform according to the extended Poincaré group \mathcal{G}_P (4D translations + Lorentz group + parity and time reversal)

This represents a reasonable compromise: i) fulfilling Poincaré covariance in a non perturbative way; ii) embedding the whole successful non relativistic phenomenology; iii) affordable numerical calculations; iv) fixed number of constituents; v) large class of allowed interactions.



Choosing a Relativistic Hamiltonian Dynamics

- DIRAC: A quantum states evolves in **time** under the action of Hamiltonian operators that contain the Dynamics. The initial state lives onto a given hyper-surface in the Minkowski space, with its-own symmmetries wrt \mathcal{G}_P . In the non relativistic framework, since any value for the velocity is possible, one has only one choice for the initial hyper-surface : $t = 0$ and any $\{x, y, z\}$,
- In a relativistic framework, given the existence of a limiting velocity (the speed of the light), one has a set of possibilities: **Forms of Dynamics:**

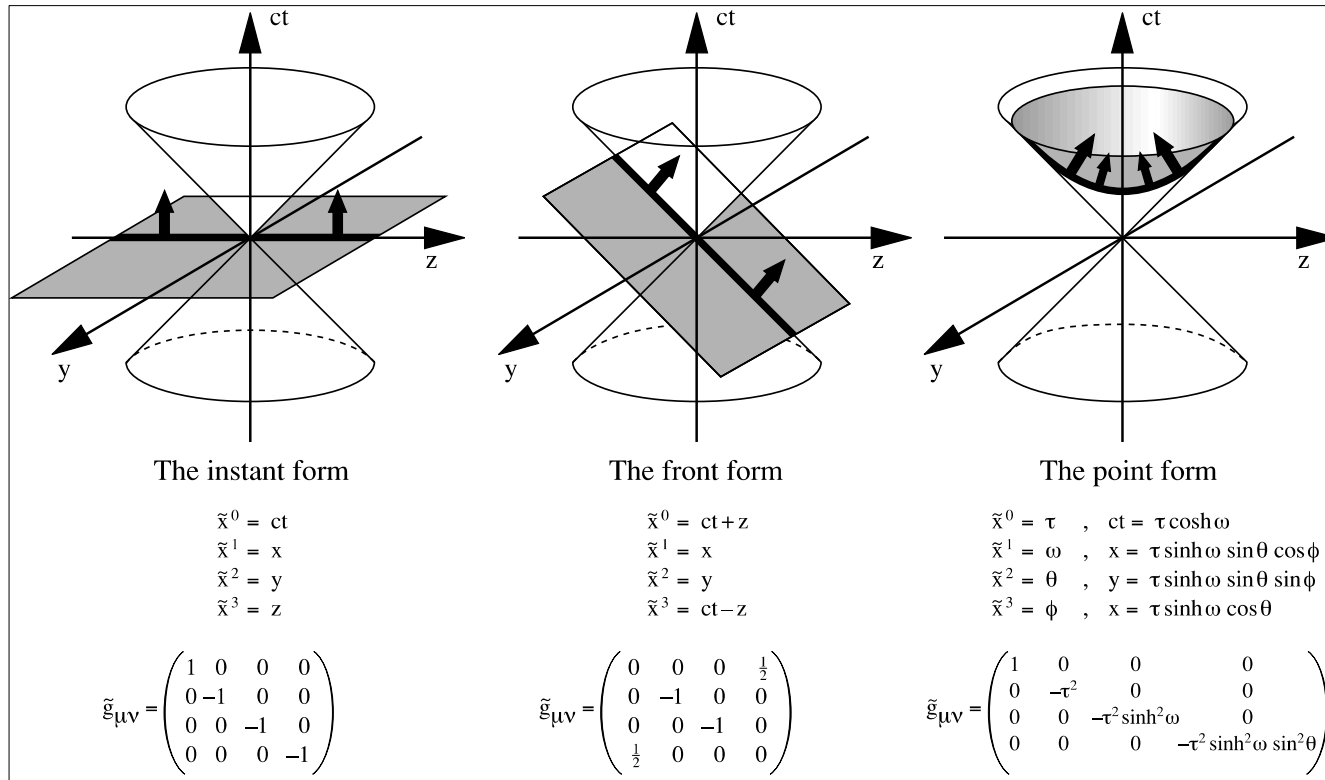
- **Instant Form**; familiar surface $t = 0$, invariant wrt to \vec{P} and \vec{J} .
- **Front Form** or **Light-Front Form**, initial surface i) fully "illuminated", at a given $time_{LF} = ct + z$, by an electromagnetic wave and ii) tangent to the light-cone, natural for DIS and SIDIS
- **Point Form**, $t^2 - x^2 - y^2 - z^2$ invariant for Lorentz transformations.

The symmetry properties of the initial surface distinguish the generators of \mathcal{G}_P :

- The ones that leave the initial hypersurface invariant are called **kinematical**, since are untouched by the interactions.
- The remaining generators are **dynamical**: they push the system away from the inital hypersurface, and therefore they contain the interaction, that governs the evolution. They are also called **Hamiltonians**.



4D surfaces with maximal symmetry under \mathcal{G}_P



After S.J. Brodsky, H.C. Pauli and S.S Pinsky, Phys. Rep. 301, 299 (1998).

The thick arrows indicate the flow of the time variable, that labels the states reached by the interacting system under the action of the generators containing the Dynamics.

Summarizing: different forms of HD \rightarrow different form of the variable "time".



Choosing LFHD: benefits and problems

- + In LFHD, one has the maximal set of kinematical generators. They are 7 $P^+ = P^0 + P_z, \vec{P}_\perp, J_z, K_z, \vec{E}_\perp$. The two generators $\{E_x, = K_x + J_y, E_y = K_y - J_x\}$ are the transverse LF boosts.
- + The LF boosts: K_z, \vec{E}_\perp , given their kinematical nature, produce trivial transformation rules for boosting quantum states, and allows one to separate the intrinsic motion from the global motion, in complete analogy with the non relativistic case.
- + $P^+ \geq 0$ leads to a meaningful Fock expansion.
- + The IMF description of DIS is easily included.
- + The dynamical set is composed by only 3 generators: $P^- = P^0 - P_z$ and $F_x = K_x - J_y, F_y = K_y + J_x$. The last two generators are the transverse LF rotations.
- Although one can define a **kinematical, intrinsic angular momentum** in a particular construction of the generators, as discussed below, the transverse LF-rotations are dynamical.



Poincaré generators for an interacting system

Finite number of dof: an explicit construction of the 10 Poincaré generators given by Bakamjian and Thomas (BT) (PR 92 (1953) 1300).

Essential feature of the BT construction: i) the dynamical generators of \mathcal{G}_P are expressed in terms of the mass operator of the interacting system, and ii) only the latter contains the interaction (remember that the mass operator is one of the Casimir of \mathcal{G}_P)

For the LFHD, the BT construction is implemented through the following steps (see Keister and Polyzou Adv. NP 20 (1991))

- First step: construct the 10 generators, $\{P_0^-, J_3, \vec{F}_{0\perp}, P^+, \vec{P}_\perp, K_3, \vec{E}_\perp\}$ for the **non interacting system**
- Second step: choose 10 auxiliary operators, $\{M_0, \vec{j}_{0LF}, P^+, \vec{P}_\perp, K_3, \vec{E}_\perp, \}$. The non interacting mass, M_0 , and the angular momentum, \vec{j}_{0LF} in the LF intrinsic frame, are given by

$$M_0^2 = P_0^- P^+ - |\vec{P}_\perp|^2 \quad (0, \vec{j}_{0LF}) = \left[B_{LF}^{-1} \left(\frac{P_0}{M_0} \right) \right]^\mu_\nu \frac{W_0^\nu}{M_0}$$

$[B_{LF}^{-1}]^\mu_\nu$ is a LF boost, and W_0^ν is the Pauli-Lubanski 4-vector ($W_0^2 = M_0^2 |\vec{j}_{0LF}|^2$)

NB the commutation rules of the Poincaré generators imply the ones of the auxiliary operators (and viceversa)



Poincaré generators for an interacting system

- Third step: add to M_0 an interaction V that commutes with $\{P^+, \vec{P}_\perp, K_3, \vec{E}_\perp, \vec{j}_{0LF}\}$. Then, the set $\{M = M_0 + V, P^+, \vec{P}_\perp, K_3, \vec{E}_\perp, \vec{j}_{0LF}\}$ have the same commutation rules of the non interacting set (i.e. the one with M_0).
- Fourth step: invert the second step, starting from $\{M = M_0 + V, P^+, \vec{P}_\perp, K_3, \vec{E}_\perp, \vec{j}_{0LF}\}$ and obtaining 10 Poincaré generators, that fulfill the correct commutation rules, and contain the interaction.

A first lesson:

- The key ingredient is the **mass operator**, Casimir of \mathcal{G}_P , that contains the interaction, and generates the dependence upon the interaction of the dynamical generators, P^- and the LF transverse rotations \vec{F}_\perp , in LFHD.
- The interaction, V , must commute with all the kinematical generators, and in addition with the non interacting spin. These constraints lead to the independence upon the global (CM) motion, as in the non relativistic case and the property to **conserve the BT angular momentum**. \longrightarrow NB $|\vec{j}_{0LF}|^2$ and the third component of \vec{j}_{0LF} can be used for labelling the states !!!
- NB NB the BT construction holds for an interacting system with a finite number of dof and it is not unique.



The BT Mass operator for A=3 nuclei - I

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

where

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

is the free mass operator, with i) $\vec{k}_1 + \vec{k}_2 + \vec{k}_3 = 0$, and ii) \vec{p}_ℓ the Jacobi momentum with respect to the CM of the free pair (ij) .

● $V_{ij,\ell}^{BT} = \sqrt{M_0^2(ij) + v_{ij}^{BT} + p_\ell^2} - \sqrt{M_0^2(ij) + p_\ell^2}$ is the two-body interaction in a A=3 system, and v_{ij}^{BT} the two-body interaction in a A=2 system, fulfilling the proper commutation rules.

The structure of $V_{ij,\ell}^{BT}$, is suggested by the analysis of a two-body interacting system + a free third particle. One can naturally write

$$\begin{aligned} M_{12,3} &= \sqrt{M_0^2(12) + v_{12}^{BT} + p_3^2} + \sqrt{m^2 + p_3^2} = \\ &= M_0(123) + \left[\sqrt{M_0^2(12) + v_{12}^{BT} + p_3^2} - \sqrt{M_0^2(12) + p_3^2} \right] \end{aligned}$$

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



The BT Mass operator for A=3 nuclei - II

Notice that

$$V_{12,3}^{BT} = \frac{v_{12}^{BT}}{\sqrt{M_0^2(12) + v_{12}^{BT} + p_3^2} + \sqrt{M_0^2(12) + p_3^2}} \sim$$

$$\frac{4mV_{12}^{NR}}{\sqrt{M_0^2(12) + v_{12}^{BT} + p_3^2} + \sqrt{M_0^2(12) + p_3^2}} \rightarrow V_{12}^{NR}$$

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



The BT Mass operator for A=3 nuclei - III

In the non relativistic framework, it is not taken into account the changes in the two-body interaction when we move from the two-body CM to the three-body CM

The NR mass operator is written as

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

NB The operators describing the two- and three-body forces must obey to the commutation rules proper of the Galilean group, leading to the well-known properties like translational invariance (conservation of total 3-momentum).

Those properties are similar to the ones in the BT construction. This allows us to consider the standard non relativistic mass operators a sensible BT mass operator, and embedding it in a Poincaré covariant approach.

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

As a consequence, the standard eigensolutions of M^{NR} can be eligible for a Poincaré covariant description of the A=3 nuclei.



The BT Mass operator for A=3 nuclei - IV

To complete the matter:

- within the LFHD, the LF boosts are kinematical and therefore their action result in simple phases
- Coupling intrinsic spins and orbital angular momenta is easily accomplished within the Instant form of RHD: it amounts to the usual non relativistic machinery (Clebsch-Gordan coefficients)
- 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 $\tilde{k} \equiv \{k^+, \vec{k}_\perp\}$

$$|s, \sigma'\rangle_{LF} = \sum_{\sigma} D_{\sigma', \sigma}^{1/2}(R_M^\dagger(\tilde{k})) |s, \sigma\rangle_c$$

where $D_{\sigma', \sigma}^{1/2}(R_M^\dagger(\tilde{k}))$ is the standard Wigner function for the $J = 1/2$ case

- for the nucleon quantities, like the density distribution or the Spectral Function, the Melosh rotations does not produce an extra algebraic burden with respect to the Instant form, viz

$$O_{\sigma''', \sigma}^{LF} = \sum_{\sigma'', \sigma'} D_{\sigma''', \sigma''}^{1/2}(R_M^\dagger) O_{\sigma'', \sigma'}^{IF} D_{\sigma', \sigma}^{1/2}(R_M)$$



Second lesson

What has been done till now, within a non relativistic framework, can be re-used in a Poincaré covariant framework NB:

$$V_{12,3}^{BT} = \frac{v_{12}^{BT}}{\sqrt{M_0^2(12) + v_{12}^{BT} + p_3^2} + \sqrt{M_0^2(12) + p_3^2}}$$

and v_{12}^{BT} is the two-body interaction that must describe the whole two-nucleon phenomenology (bound + scattering states), in the A=2 CM !

We are now (almost) ready for phenomenology!



Example: The SiDIS nuclear hadronic tensor in LF

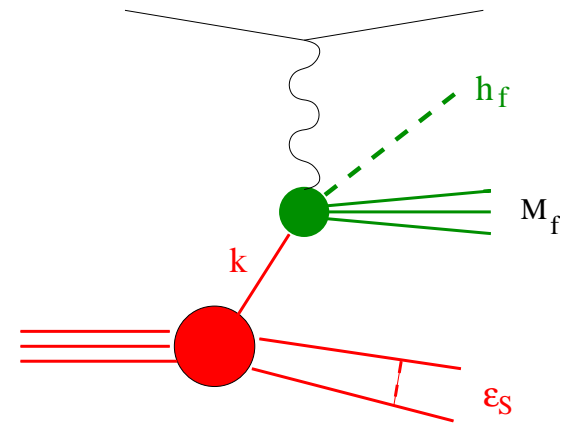
In **Impulse Approximation** the LF hadronic tensor for the ${}^3\text{He}$ nucleus is:

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

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

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

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



The ${}^3\text{He}$ LF Spectral Function

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

is obtained through the unitary **Melosh Rotations**: $D^{\frac{1}{2}}[\mathcal{R}_M(\tilde{\mathbf{k}})] = \frac{m+k^+ - i\boldsymbol{\sigma}\cdot(\hat{z}\times\mathbf{k}_\perp)}{\sqrt{(m+k^+)^2 + |\mathbf{k}_\perp|^2}}$
and the **instant-form spectral function**

$$\begin{aligned} \mathcal{S}_{\sigma'_1\sigma_1}^\tau(\tilde{\mathbf{k}}, \epsilon_S, S_{He}) &= \sum_{J_S J_z S \alpha} \sum_{T_S \tau_S} \langle T_S, \tau_S, \alpha, \epsilon_S J_S J_z S; \sigma'_1; \tau, \mathbf{k} | \Psi_0 S_{He} \rangle \\ &\times \langle S_{He}, \Psi_0 | \mathbf{k} \sigma_1 \tau; J_S J_z S \epsilon_S, \alpha, T_S, \tau_S \rangle \\ &= \left[B_{0,S_{He}}^\tau(|\mathbf{k}|, E) + \boldsymbol{\sigma} \cdot \mathbf{f}_{S_{He}}^\tau(\mathbf{k}, E) \right]_{\sigma'_1\sigma_1} \end{aligned}$$

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

NOTICE: $\mathcal{S}_{\sigma'_1\sigma_1}^\tau(\tilde{\mathbf{k}}, \epsilon_S, S_{He})$ is given in terms of **THREE independent functions**, $B_{0,1,2}$, once parity and t-reversal are imposed. Adding FSI, more terms could be included.



GOOD preliminary NEWS

We are now evaluating 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:

	<i>proton NR</i>	<i>proton LF</i>	<i>neutron NR</i>	<i>neutron LF</i>
$\int dE d\vec{p} \frac{1}{2} \text{Tr}(\mathcal{P}\sigma_z) \vec{S}_A = \hat{z}$	-0.02263	-0.02231	0.87805	0.87248
$\int dE d\vec{p} \frac{1}{2} \text{Tr}(\mathcal{P}\sigma_y) \vec{S}_A = \hat{y}$	-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** (in a proton, it would correspond to the difference between **axial** and **tensor** charges).

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



LF spectral function and LF TMDs - I

The LF spectral function for a $J = 1/2$ system of three spin 1/2 constituents can be used to find relations among the SIX T-even TMDs, A_i, \tilde{A}_i ($i = 1, 3$), at the leading twist for the quarks inside a nucleon with momentum P and spin S .

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

$$\begin{aligned} \Phi(k, P, S) &= \int d^4z e^{ik \cdot z} \langle PS | \bar{\psi}_q(0) \psi_q(z) | PS \rangle \\ &= \frac{1}{2} \left\{ A_1 \not{P} + A_2 S_L \gamma_5 \not{P} + A_3 \not{P} \gamma_5 \not{S}_\perp \right. \\ &\quad \left. + \frac{1}{M} \tilde{A}_1 \vec{k}_\perp \cdot \vec{S}_\perp \gamma_5 \not{P} + \tilde{A}_2 \frac{S_L}{M} \not{P} \gamma_5 \not{k}_\perp + \frac{1}{M^2} \tilde{A}_3 \vec{k}_\perp \cdot \vec{S}_\perp \not{P} \gamma_5 \not{k}_\perp \right\}, \end{aligned}$$

so that particular combinations of the SIX twist-2 TMDs can be obtained by proper traces of $\Phi(k, P, S)$ (instead of A_i, \tilde{A}_i , the “Amsterdam” notation can be used for the TMDs), :

$$\begin{aligned} \frac{1}{2P^+} \text{Tr}(\gamma^+ \Phi) &= A_1, \\ \frac{1}{2P^+} \text{Tr}(\gamma^+ \gamma_5 \Phi) &= S_L A_2 + \frac{1}{M} \vec{k}_\perp \cdot \vec{S}_\perp \tilde{A}_1, \\ \frac{1}{2P^+} \text{Tr}(i\sigma^{i+} \gamma_5 \Phi) &= S_\perp^i A_3 + \frac{S_L}{M} k_\perp^i \tilde{A}_2 + \frac{1}{M^2} \vec{k}_\perp \cdot \vec{S}_\perp k_\perp^i \tilde{A}_3. \end{aligned}$$



LF spectral function and LF TMDs - II

Actually, in LF one has on-mass shell quarks. Let us consider therefore the contribution to the **correlation function** from on-mass-shell fermions

$$\begin{aligned}\Phi_p(k, P, S) &= \frac{(k_{on} + m)}{2m} \Phi(k, P, S) \frac{(k_{on} + m)}{2m} = \\ &= \sum_{\sigma} \sum_{\sigma'} u_{LF}(\tilde{k}, \sigma') \bar{u}_{LF}(\tilde{k}, \sigma') \Phi(k, P, S) u_{LF}(\tilde{k}, \sigma) \bar{u}_{LF}(\tilde{k}, \sigma)\end{aligned}$$

and let us identify $\bar{u}_{LF}(\tilde{k}, \sigma') \Phi(k, P, S) u_{LF}(\tilde{k}, \sigma)$ with the LF nucleon spectral function

$$\bar{u}_{LF}(\tilde{k}, \sigma') \Phi(k, P, S) u_{LF}(\tilde{k}, \sigma) = \mathcal{P}_{\sigma'\sigma}(\tilde{\mathbf{k}}, \epsilon_S, S)$$

In a reference frame where $\mathbf{P}_{\perp} = 0$, the following relation holds between k^{-} and the spectator diquark energy ϵ_S :

$$k^{-} = \frac{M^2}{P^{+}} - \frac{(\epsilon_S + m) 4m + |\mathbf{k}_{\perp}|^2}{P^{+} - k^{+}}$$



LF spectral function and LF TMDs - III

The contributions of on-mass-shell fermions to the traces previously introduced in terms of the TMD's, A_i, \tilde{A}_i ($i = 1, 3$), are

$$\frac{1}{2P^+} \text{Tr} [\gamma^+ \Phi_p(k, P, S)] = \frac{k_{on} \cdot P}{2m^2} \frac{k^+}{P^+} A_1$$

$$\begin{aligned} \frac{1}{2P^+} \text{Tr} [\gamma^+ \gamma_5 \Phi_p(k, P, S)] &= \left(\frac{1}{2} - \frac{k_{on} \cdot P}{4m^2} \frac{k^+}{P^+} \right) \left[A_2 \lambda_N + \frac{1}{M} \tilde{A}_1 \mathbf{k}_\perp \cdot \mathbf{S}_\perp \right] + \\ &+ \frac{1}{2m} \left[A_3 \mathbf{k}_\perp \cdot \mathbf{S}_\perp + \tilde{A}_2 \frac{\lambda_N}{M} |\mathbf{k}_\perp|^2 + \frac{1}{M^2} \tilde{A}_3 \mathbf{k}_\perp \cdot \mathbf{S}_\perp |\mathbf{k}_\perp|^2 \right] \end{aligned}$$

$$\begin{aligned} \frac{1}{2P^+} \text{Tr} [k_\perp \gamma^+ \gamma_5 \Phi_p(k, P, S)] &= \frac{1}{2m} |\mathbf{k}_\perp|^2 \left[A_2 \lambda_N + \frac{1}{M} \tilde{A}_1 \mathbf{k}_\perp \cdot \mathbf{S}_\perp \right] + \\ &+ \left(\frac{k^+}{P^+} \frac{k_{on} \cdot P}{4m^2} - \frac{|\mathbf{k}_\perp|^2}{4m^2} \right) \left[A_3 \mathbf{k}_\perp \cdot \mathbf{S}_\perp + \tilde{A}_2 \frac{\lambda_N}{M} |\mathbf{k}_\perp|^2 + \frac{1}{M^2} \tilde{A}_3 \mathbf{k}_\perp \cdot \mathbf{S}_\perp |\mathbf{k}_\perp|^2 \right] \end{aligned}$$



LF spectral function and LF TMDs - IV

However these same contributions can be also expressed through the LF spectral function

$$\begin{aligned}
 & \frac{1}{2P^+} \text{Tr} [\gamma^+ \Phi_p(k, P, S)] = \\
 & = \frac{1}{2P^+} \sum_{\sigma \sigma'} \bar{u}_{LF}(\tilde{\mathbf{k}}, \sigma) \gamma^+ u_{LF}(\tilde{\mathbf{k}}, \sigma') \bar{u}_{LF}(\tilde{\mathbf{k}}, \sigma') \Phi(k, P, S) u_{LF}(\tilde{\mathbf{k}}, \sigma) = \\
 & = \frac{1}{2P^+} \sum_{\sigma \sigma'} \bar{u}_{LF}(\tilde{\mathbf{k}}, \sigma) \gamma^+ u_{LF}(\tilde{\mathbf{k}}, \sigma') \mathcal{P}_{\sigma'\sigma}(\tilde{\mathbf{k}}, \epsilon_S, S) = \frac{k^+}{2mP^+} \text{Tr} [\mathcal{P}_{\sigma'\sigma}(\tilde{\mathbf{k}}, \epsilon_S, S)]
 \end{aligned}$$

$$\begin{aligned}
 & \frac{1}{2P^+} \text{Tr} [\gamma^+ \gamma_5 \Phi_p(k, P, S)] = \sum_{\sigma \sigma'} \bar{u}_{LF}(\tilde{\mathbf{k}}, \sigma) \gamma^+ \gamma_5 u_{LF}(\tilde{\mathbf{k}}, \sigma') \mathcal{P}_{\sigma'\sigma}(\tilde{\mathbf{k}}, \epsilon_S, S) = \\
 & = \frac{k^+}{2mP^+} \sum_{\sigma \sigma'} \chi_{\sigma}^{\dagger} \sigma_z \chi_{\sigma'} \mathcal{P}_{\sigma'\sigma}(\tilde{\mathbf{k}}, \epsilon_S, S) = \frac{k^+}{2mP^+} \text{Tr} [\sigma_z \mathcal{P}(\tilde{\mathbf{k}}, \epsilon_S, S)]
 \end{aligned}$$

$$\begin{aligned}
 & \frac{1}{2P^+} \text{Tr} [\mathbf{k}_{\perp} \gamma^+ \gamma_5 \Phi_p(k, P, S)] = \frac{1}{2P^+} \sum_{\sigma \sigma'} \bar{u}_{LF}(\tilde{\mathbf{k}}, \sigma) \mathbf{k}_{\perp} \gamma^+ \gamma_5 u_{LF}(\tilde{\mathbf{k}}, \sigma') \mathcal{P}_{\sigma'\sigma}(\tilde{\mathbf{k}}, \epsilon_S, S) = \\
 & = \frac{k^+}{2mP^+} \sum_{\sigma \sigma'} \chi_{\sigma}^{\dagger} \mathbf{k}_{\perp} \cdot \boldsymbol{\sigma} \chi_{\sigma'} \mathcal{P}_{\sigma'\sigma}(\tilde{\mathbf{k}}, \epsilon_S, S) = \frac{k^+}{2mP^+} \text{Tr} [\mathbf{k}_{\perp} \cdot \boldsymbol{\sigma} \mathcal{P}(\tilde{\mathbf{k}}, \epsilon_S, S)]
 \end{aligned}$$



LF spectral function and LF TMDs - V

$$\begin{aligned}
 \frac{1}{2} \text{Tr}(\mathcal{P}I) &= c B_0 \\
 \frac{1}{2} \text{Tr}(\mathcal{P}\sigma_z) &= S_{Az} \left[a (B_1 + B_2 \cos^2 \theta) + b \cos \theta \frac{|\mathbf{k}_\perp|^2}{k} B_2 \right] \\
 &+ \mathbf{S}_{A_\perp} \cdot \mathbf{k}_\perp \left[a B_2 \frac{\cos \theta}{k} + b (B_1 + B_2 \sin^2 \theta) \right] \\
 \frac{1}{2} \text{Tr}(\mathcal{P}\sigma_y) &= S_{Ay} [(a + d |\mathbf{k}_\perp|^2) B_1] \\
 &+ S_{Az} k_y \left[a \frac{\cos \theta}{k} B_2 - b (B_1 + B_2 \cos^2 \theta) \right] \\
 &+ k_y \mathbf{S}_{A_\perp} \cdot \mathbf{k}_\perp \left[\left(\frac{a}{k^2} - b \frac{\cos \theta}{k} \right) B_2 - d B_1 \right]
 \end{aligned}$$

The SIX TMDs can be expressed in terms of the 3 independent functions B_0, B_1, B_2 !
 a, b, c, d are kinematical factors, predicted by the LF procedure!

In the LF approach only THREE of the SIX A_i, \tilde{A}_i ($i = 1, 3$) distributions are independent!



Help from ^3He for *proton* studies?

^3He is a spin 1/2 system with 3 spin 1/2 constituents. The same as the *proton*, in the valence region \Rightarrow they have the same symmetries.

One could investigate the analogy:

proton	\Leftrightarrow	^3He
<i>Valence quark contribution</i>	\Leftrightarrow	<i>nucleon contribution</i>
<i>twist - 2 Approximation</i>	\Leftrightarrow	<i>Impulse Approximation</i>
<i>SiDIS</i>	\Leftrightarrow	<i>(e, e' p) at high Q^2</i>
<i>6 independent asymmetries</i>	\Leftrightarrow	<i>6 independent Response functions</i>
<i>6 independent TMDS @ twist - 2</i>	\Leftrightarrow	<i>6 independent momentum distributions</i>

A one-to-one correspondence can be obtained \Rightarrow check of the 3 relations found in RHD among the TMDS looking at ^3He data (may be, in part, available)
 \Rightarrow test of RHD! Hint for TMDs data analysis?



Conclusions

We are studying **DIS processes off ^3He beyond** the realistic, **NR**, **IA** approach.
We have encouraging results concerning:

- **FSI effects** evaluated through the **GEA**:
a **distorted spin dependent spectral function is studied**
- **An analysis of a LF spectral function** (in IA); besides, within LF dynamics only 3 of the 6 T-even TMDs are independent. The relations among them are precisely predicted within LF Dynamics, and could be experimentally checked to test the LF description of SiDIS.

Next steps:

- **complete this program!**
- **apply the LF spectral function to other processes (e.g., DVCS);**
- **relativistic FSI?**

^3He : an effective neutron AND a LAB for Light-Front studies



Nuclear DIS: Workshop at ECT*!!!

Applications Places System 10:56 AM

New Directions in Nuclear Deep Inelastic Scattering | ECT* - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://www.ectstar.eu/node/1221

Most Visited CentOS Support

New Directions in Nuclea...

Home

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

ABOUT US WORKSHOPS TRAINING SEMINARS & COLLOQUIA PUBLICATIONS PEOPLE ASSOCIATES

Home

New Directions in Nuclear Deep Inelastic Scattering

From Monday, 8 June, 2015 - 09:00 to Friday, 12 June, 2015 - 17:00

Location: ECT* Conference room

Abstract:
Recent experimental and theoretical ideas are laying the ground for a new era in nuclear deep inelastic scattering. Novel coincidence measurements at high luminosity facilities, such as Jefferson Lab (JLab), have become possible, pointing out the nucleus as a laboratory for QCD studies, in a top-down approach. Issues like the extraction of the neutron information from light nuclei, the measurement of nuclear parton distributions, mandatory for the analysis of nucleus-nucleus scattering aimed at producing quark-gluon plasma, or the phenomenon of in-medium fragmentation, crucial to unveil the dynamics of hadronization, will be investigated with unprecedented accuracy. Besides, the detection of multiple parton collisions in proton-nucleus scattering at the LHC could unveil the three-dimensional proton structure. The new exciting scenario is completed by the nice perspectives within lattice QCD, facing nuclear structure in a bottom-up approach. The Workshop is aimed at improving collaborations between theorists and experimentalists, working with electroweak and strong probes. Besides the presentation of recent results, an emphasis will be put on the preparation of experiments at JLab, CERN and at a future electron-ion collider.

Registration period: 06 Apr 2015 to 24 May 2015

Organizer: Sergio Scopetta, Raphael Dupre'

SECRETARIAT
Gian Maria Ziglio
ziglio@ectstar.eu
+39 0461 314725

© 2012 ECT* | Strada delle Tabarelle, 286 | I-38123 Villazzano TRENTO (TN) | Phone: +39 0461 314721 | +39 0461 314722 | e-mail: ectweb@ectstar.eu Login Grafica Netwise

Done

New Directions in Nuclear Deep Inelastic Scattering | ECT* - Mozilla Firefox

Please come and help us to *boost* our Physics in Europe!

March 9th, 2015



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

Ingredients of the calculations :

- A realistic **spin-dependent spectral function** of ${}^3\text{He}$ (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,
 $D_1^{q,h}(z, (z\kappa_T)^2)$, 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,
 $H_1^{\perp q,h}(z, (z\kappa_T)^2)$ Amrath et al., PRD 71 (2005) 114018

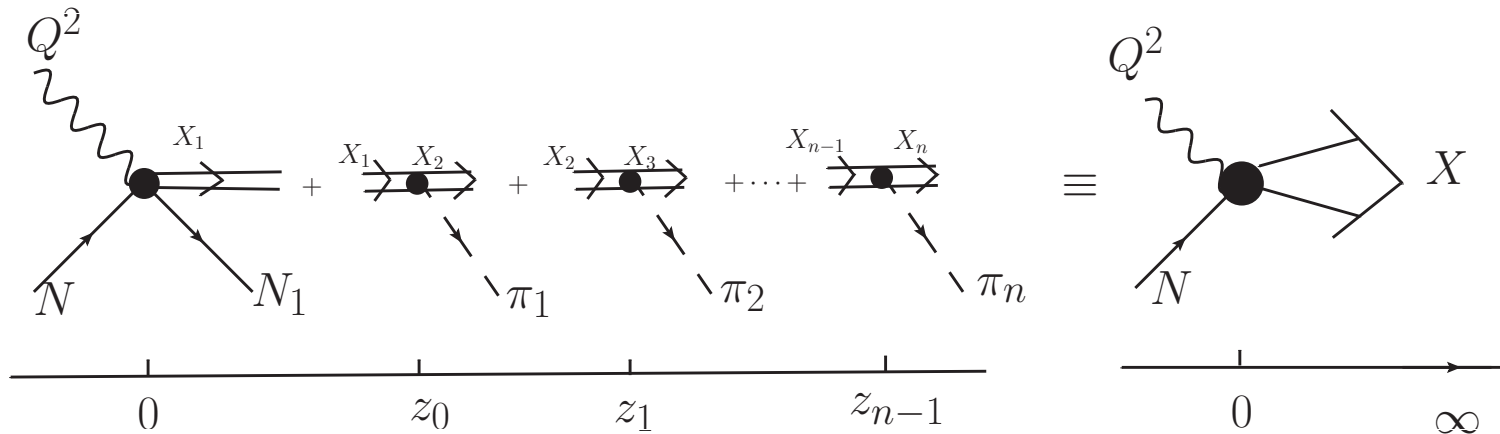
Results will be model dependent. Anyway, the aim for the moment is **to study nuclear effects**.



backup: the hadronization model

hadronization model: Kopeliovich et al., Predazzi, Hayashigaki, NPA 2004;

σ_{eff} model: Ciofi & Kopeliovich, EPJA 2003)



At the interaction point, a color string, denoted X_1 , and a nucleon N_1 , arising from target fragmentation, are formed; the color string propagates and gluon radiation begins. The first π is created at $z_0 = 0.6$ by the breaking of the color string, and pion production continues until it stops at a maximum value of $z = z_{max}$, when energy conservation does not allow further pions to be created, and the number of pions remains constant. Once the total effective cross section has been obtained, the elastic slope b_0 and the ratio α of the real to the imaginary parts of the elastic amplitude remain to be determined.



Macroscopic locality

Macroscopic locality meets our physical intuition

For instance, if the spacelike distance increases, and the interaction dies, one should expect two completely isolated subsystems, for which the Hamiltonian clusterizes as follows

$$\text{For } |r_{12} - r_3| \gg d \Rightarrow H(123) = H_{12} + H_3^{free}$$

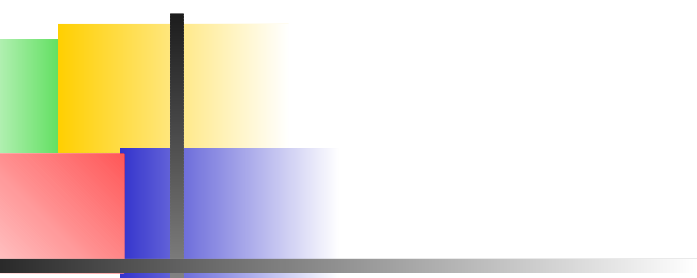
(the same for the other generators)

NB Spacelike separations are not Lorentz invariant, this leads to a mathematical formulation of the macroscopic locality given for infinitely large spacelike separations: $d \rightarrow \infty$.

Imposing macroscopic locality means that all the properties valid for a system must hold for any subsystem in isolation.

Then, e.g., the two-body interaction extracted from the study of NN systems can be adopted in the description of many-nucleon systems (modulo the presence of many-body interactions).





The macroscopic locality can be easily implemented if one takes as a basis the tensor product of the (A-1)-body interacting states and the single particle states (with the proper symmetrization). Within the BT construction, the macrolocality cannot be implemented, but there are unitary operators, the packing operators, that relate the states obtained in the BT approach and the one related to the tensor-product approach

The packing operators, fortunately give very small effects, and therefore one can adopt the BT framework safely (Coester-Polyzou PRD 26, 1348 (1982) and Keister-Polyzou PRC 86 (2012)014002).

The macroscopic locality (the only property that can be experimentally tested) can be seen as a weak counterpart of the microscopic locality (or microcausality): one of the basic axioms of the Local Field Theory. In this case the constraint is imposed at arbitrarily short spacelike distances to free fields.



March 9th, 2015