A Poincaré covariant description of a polarized ^{3}He target within the Light-Front Hamiltonian Dynamics

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Outline

- **Motivations and generalities: Poincaré covariance and Few-Nucleon systems**
- **Bakamjian-Thomas construction and the Light-Front Relativistic Hamiltonian Dynamics**
- **The neutron structure from inclusive and Semi-inclusive DIS by a polarized $^3\mathrm{He} \rightarrow$ the spin-dependent Light-Front Spectral Function of the nucleon**
- **A Light-Front approach for Semi-inclusive DIS:**
  $e + {}^3\vec{H}e_\perp \rightarrow e' + h + X$
  (work in progress, and Del Dotto, Pace, Salmè, Scopetta, Il Nuovo Cimento C 35 (2012) 101)
- **Conclusions & Perspectives**

Why a Relativistic description of Few-Nucleon Systems is needed?

- The Standard Model of Few-Nucleon Systems, where nucleon and pion degrees of freedom are taken into account, is already at a very sophisticated stage, and many efforts are presently carried on in order to retain all the general principles compatible with a theory where a fixed number of constituents is acting.

- To achieve a relativistic description, beyond a purely kinematical approach, still with a finite dof, should represent an important step forward in nuclear physics, in view of the fact that, e.g., the extraction of some key quantities for hadronic physics, like the neutron Generalized Parton Distributions and/or Transverse-momentum Distributions, could be affected by relativistic nuclear effects. As a matter of fact, i) nuclear targets are needed (....deuteron, $^3\vec{\mathrm{He}}$) and ii) DIS regime has to be reached. This means that, at least, one has to carefully deal with the boosts of the nuclear states!

- Indeed, even dynamics should be investigated within a relativistic framework, to shed light on some tensions in the description of the Few-nucleon systems (e.g., A_y puzzle?)

Many efforts for Few Nucleons

- Relativistic Mean Field Theory for Few-Nucleon? NO !

- Field theoretical approaches for two-body systems (Bethe-Salpeter Equation, primarily) have a basic role, but difficult to be numerically implemented. NB: in the last two decades, there has been an increasing amount of efforts in implementing different methods for obtaining numerical solutions in both Euclidean and Minkowski space. E.g., Feynman-Schwinger representation of the Green Functions (Tjon and Nieuwenhuis, PRL 77 (1996) 814), the Nakanishi PTIR (Kusaka & William PRD 51 (1995) 7026, Carbonell & Karmanov EPJA 46 (2010) 387 and review in FBS 49 (2011) 205, Frederico et al PRD 85 (2012) 036009, etc. .), or the quasipotential reduction (e.g. Gross-Stadler, review in FBS 49 (2011) 91). They are becoming more and more sophisticated....

- However, for $A \geq 2$, one can exploit phenomenological, but not less rigorous, approaches, like the one based on the Relativistic Hamiltonian Dynamics, proposed by Dirac in 1949 (RMP 21 (1949) 392). RHD's allow one to fulfill the Poincaré covariance, with finite dof, and therefore, they could be seen as falling in between the non relativistic framework and the field theory, in its full glory.

Aim and Tool:

Aim: To describe a Few-Nucleon system through a Poincaré covariant formalism, in order to obtain an approach where both wave functions and operators (e.g. EW current) transform according to the extended Poincaré group (4D translations + Lorentz group + parity and time reversal)

General principles to be implemented

★ Extended Poincaré covariance

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

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

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

★ ★ Macroscopic locality (or macroscopic causality), if we want to take advantage of the study of two-nucleon systems, interacting with short-range forces, when $A \geq 3$ systems are investigated. In a Poincaré covariant framework some issues arise, and can be easily solved through unitary operators called packing operators

Tool: the Dirac Relativistic Hamiltonian Dynamics in Light-front form

Choosing a Relativistic Hamiltonian Dynamics

- 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.
- The investigation of 4D hyper-surfaces (in Minkowski space) with maximal symmetry, under the action of the generators of $\mathcal{G}_P$, lead Dirac to propose the Relativistic form of the Hamiltonian Dynamics.
- A quantum states evolves in time] under the action of Hamiltonian operators that contain the Dynamics. The initial state lives onto a given surface, with its-own symmetries wrt $\mathcal{G}_P$.
  In the non relativistic framework, one has only one choice for the initial hyper-surface : $t = 0$ and any $\{x, y, z\}$. Since any value for the velocity is possible.
- In a relativistic framework, given the existence of a limiting velocity (the speed of the light), one has a set of possibilities. In total 5, but Dirac considered only three surfaces: the ones with maximal symmetry, namely that remain invariant under the action of the maximal number of Poincaré generators.

Dirac presented three forms for the Relativistic Hamiltonian Dynamics:

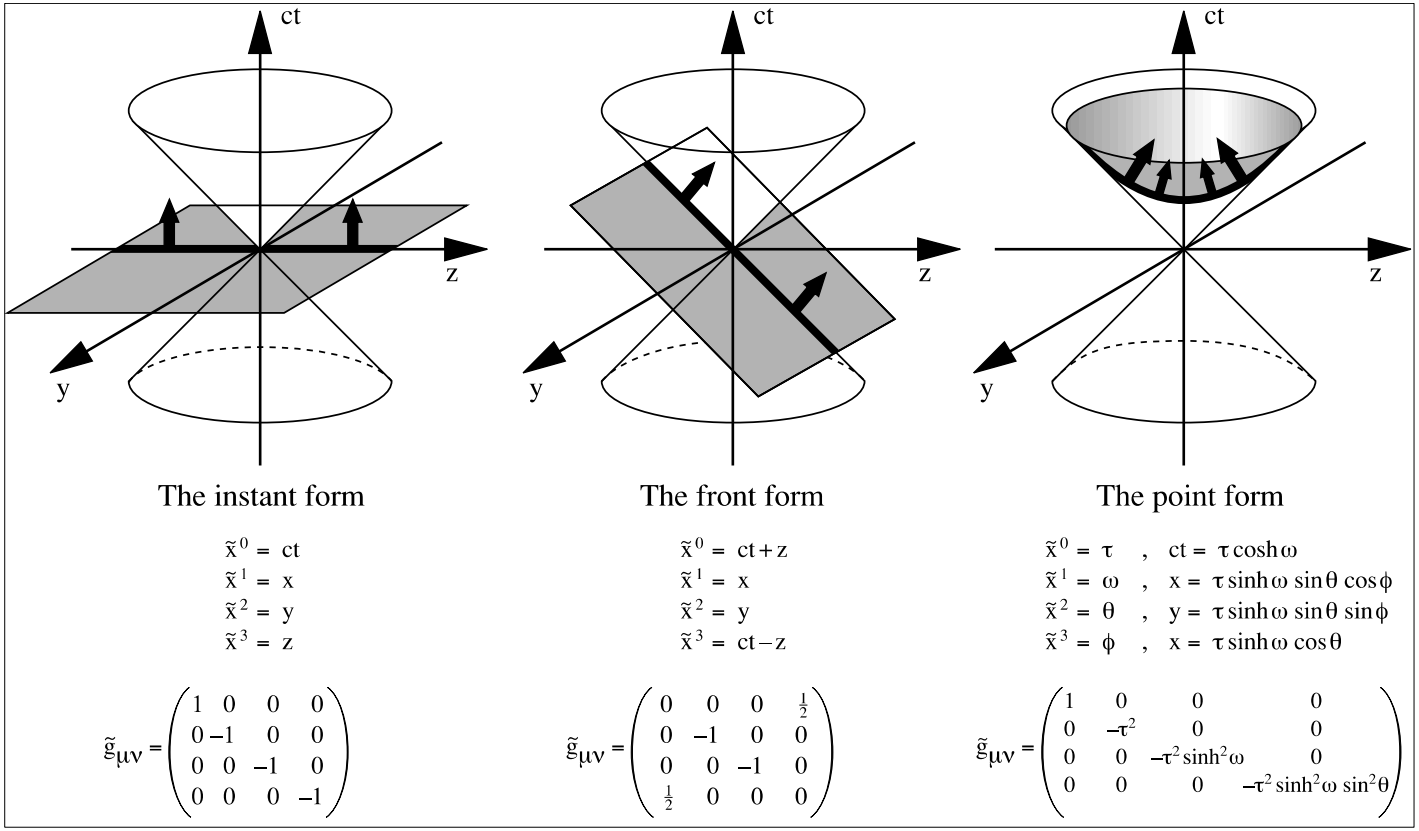
- Instant Form, has as initial surface the most familiar one: $t = 0$, where the time is the standard one. It is invariant wrt to $\vec{P}$ and $\vec{J}$.
- Front Form or Light-Front Form, has an initial surface i) fully "illuminated", at a given $time_{LF} = ct + z$, by an electromagnetic wave and ii) tangent to the light-cone, $\rightarrow$ DIS and SIDIS
- Point Form, has as initial surface, the one invariant for Lorentz transformations. It has a hyperboloid form, since $t^2 - x^2 - y^2 - z^2$ remains invariant.

Notice that the set is completed by two other hyper-surfaces, that have less symmetry properties than the previous ones.

The symmetry properties of the initial surface make a separation among the generators of $\mathcal{G}_P$:

- The ones that leave the initial hyper-surface invariant are called kinematical, since are untouched by the interactions.
- The remaining generators are the dynamical ones. They push the system away from the initial hyper-surface, and therefore they must 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 variable noted as time, 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".

Benefits and problems with LFHD

- 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: $Kz, \vec{E}_\perp$, 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.
- No square roots in the dynamical operator P^-, propagating the state in the LF-time.
- 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.

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Poincaré generators for an interacting system

For finite degrees of freedom, an explicit construction of the 10 Poincaré generators, was given by Bakamjian and Thomas (PR 92 (1953) 1300).
The essential feature of the BT construction is that i) the dynamical generators of $\mathcal{G}_P$ are expressed in terms of the mass operator of the interacting system, and ii) only this contains the interaction (remind 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 (for the other forms one has an analogous procedure, see Keister and Polyzou Adv. NP 20 (1991))

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

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

$[B_{LF}^{-1}]_\nu^\mu$ 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)

- 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 $\{M = M_0 + V, P^+, \vec{P}_\perp, K_3, \vec{E}_\perp, \vec{j}_{0LF}\}$. Then the obtained 10 Poincaré generators, fulfill the correct commutation rules, and contain the interaction.

NB $|\vec{j}_{0LF}|^2$ and the third component of $\vec{j}_{0LF}$ can be used for labeling the states !!

NB NB the BT construction holds for an interacting system with a finite number of dof and it is not unique. In principle, the dependence (in P^- and $\vec{F}_\perp$) upon the interaction could be more general, not only through the mass operator.

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

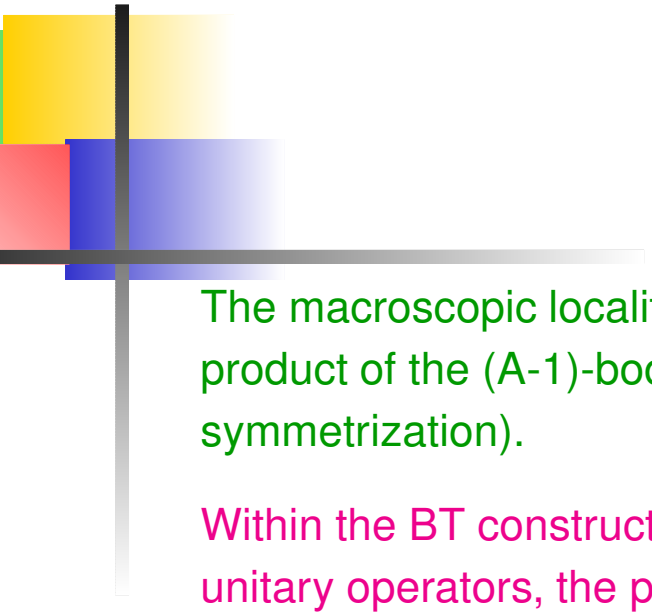
$$\text{For } |r_{12} - r_3| >> \ d \ \Rightarrow \ H(123) = H_{12} + H_3^{free}$$

(the same for the other generators)

NB Spacelike separations are not Lorentz invariant, this leads to a mathematical formulation of the macroscopic locality in terms of 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 we are able to experimentally test) 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 onto free fields.

A first lesson

- BT construction provides a viable tool for obtaining the Poincaré generators for an interacting system, with finite degrees of freedom.

- 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 commutes 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.

- The full theory must fulfills the macroscopic locality, as well. This property can be implemented by using interaction-dependent, unitary operators: the packing operators. Their effects is quite small, and therefore they will be neglected in what follows.

The BT Mass operator for A=3 nuclei - I

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

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) $\vec{p}_\ell$ the Jacobi momentum with respect to the CM of the free pair (ij).
- $V^{BT}_{ij,\ell} = \sqrt{M_0^2(ij) + v^{BT}_{ij} + p_\ell^2} - \sqrt{M_0^2(ij) + p_\ell^2}$ is the two-body interaction in a A=3 system, and v^{BT}_{ij} the two-body interaction in a A=2 system, fulfilling the proper commutation rules.
  The structure of $V^{BT}_{ij,\ell}$, is suggested by the analysis of a two-body interacting system + a free third particle. One can naturally write

$$M_{12,3} = \sqrt{M_0^2(12) + v^{BT}_{ij} + p_3^2} + \sqrt{m^2 + p_3^2} =$$

$$= M_0(123) + \left[\sqrt{M_0^2(12) + v^{BT}_{12} + p_3^2} - \sqrt{M_0^2(12) + p_3^2}\right]$$

- V^{BT}_{123} is a short-range three-body forces

The BT Mass operator for A=3 nuclei - II

Notice that

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

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

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, Analogous elaboration for the Lippmann-Schwinger Eq. (even without approx. on the energies...)

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 the translation invariance, the conservation of the total 3-momentum.

Those properties are similar to the ones in the BT construction. This allows us to consider the standard non relativistic mass operator as a sensible BT mass operator, and 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 a 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 $\tilde{k} \equiv \{k^+, \vec{k}_\perp\}$

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

where $D^{1/2}_{\sigma',\sigma}(R^\dagger_M(\tilde{k}))$ 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 respect to the Instant form, viz

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

Second lesson

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

This does not represent the ultimate response.

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 !

(Instant form calculations of the Faddeev equation for both $n - d$ elastic scattering and breakup, with CD Bonn and TM99 3BF, can be found in Witala et al PRC 83 (2011) 044001.)

The most recent applications

The first application has been the evaluation of the electromagnetic form factors of ^{3}H and ^{3}He, without dynamical two-body currents (Baroncini, Kievsky, Pace and G.S. AIP **1056**, 272 (2008)) $\rightarrow$ Figs.

The second one is given by the spin-dependent nucleon Spectral Function in a nucleus with polarization $\vec{S}_A$

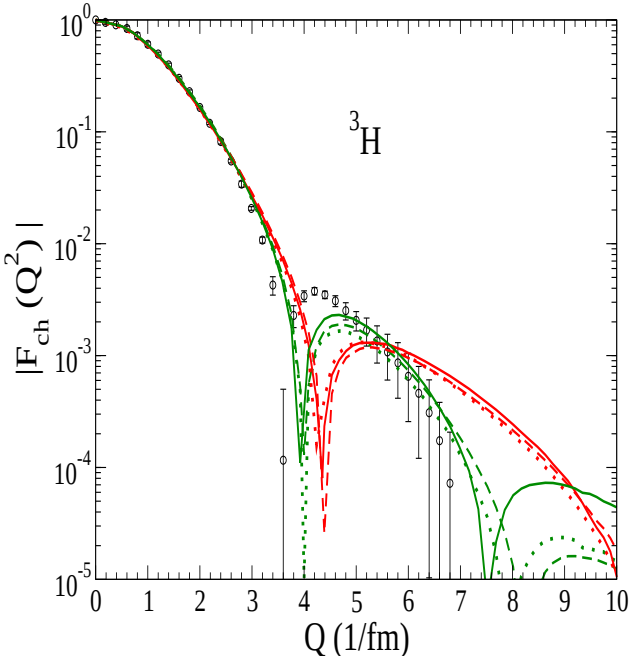
$$\mathbf{P}^N_{\mathcal{M}_A}(k,E) = {}_{S_A}\langle \Psi_A; J_A \mathcal{M}_A \pi_A | a^\dagger_{\vec{k},\mu'}\, \delta(E - H + E_A)\, a_{\vec{k}\mu} | \pi_A J_A \mathcal{M}_A; \Psi_A \rangle_{S_A}$$

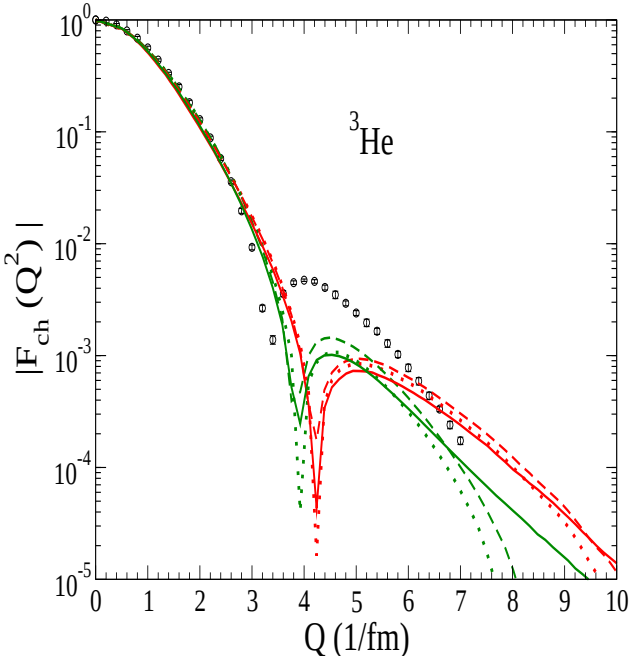
where H is the Hamiltonian of an $(A-1)$ system

The spin-dependent Spectral Function yields the probability distribution to find a nucleon with a given 3-momentum and removal energy E, in a nucleus with the the third component of $\vec{J}_A$ along the polarization $\vec{S}_A$ equal to $\mathcal{M}_A$.

This quantity is relevant for describing the inclusive and semi-inclusive electron scattering from a polarized ^{3}He target.

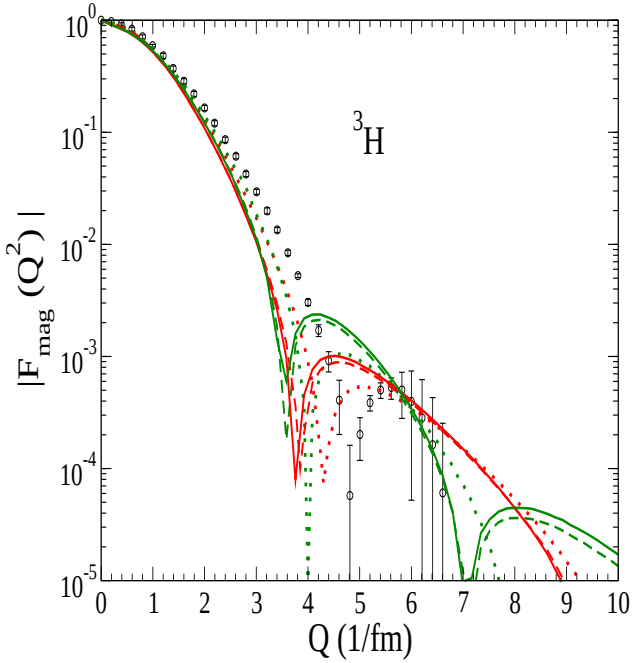
Charge and Magnetic form factors of ^{3}H and ^{3}He in LFHD and AV18

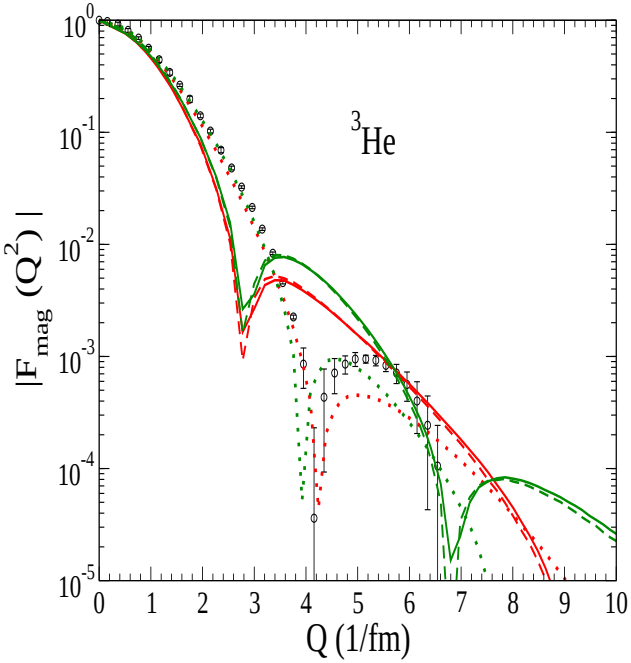




No dynamical 2B currents

Solid line: LF full calculation ($S+S'+P+D$) and LF Nucleon ff's



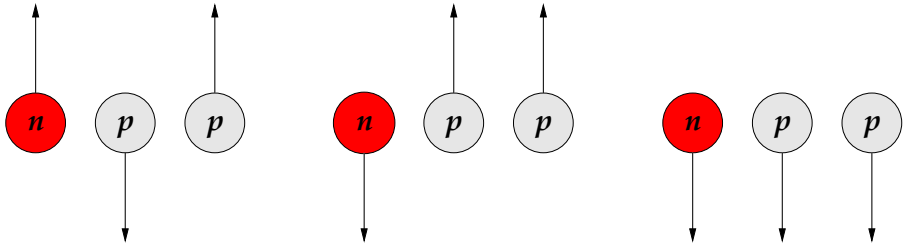


Dashed line: LF full calculation and Gari-Krümpelman ff's. Dotted line: $S+S'$ waves + GK. In Green color, NR calculations

The neutron structure from a polarized ^{3}He target

$^3\vec{\mathrm{He}}$ is the ideal target to study the microscopic structure of the neutron.

Naive picture: in S-wave $^3\vec{\mathrm{He}} = \vec{n}$



S (~ 90 %) **S'** **D**

... A realistic description of the nucleons inside a polarized $^3\mathrm{He}$ leads to modifications, very relevant for an accurate extraction of the neutron properties !

In plane wave impulse approx. (PWIA), an essential ingredient for achieving this goal is the evaluation of a realistic spin-dependent nucleon Spectral-function, that can be written by using a tensor product basis ($|\vec{k}\rangle \otimes |\phi_{f_{A-1}}\rangle$) as

$$\mathbf{P}^N_{\sigma'\sigma\mathcal{M}_A}(k,E) = \sum_{f_{A-1}} \delta(E - E_{A-1} + E_A)$$

$$\underbrace{{}_{S_A}\langle \Psi_A; J_A\mathcal{M}_A\pi_A|\vec{k},\sigma;\phi_{f_{A-1}}\rangle}\ \underbrace{\langle \phi_{f_{A-1}};\sigma'\vec{k}|\pi_A J_A\mathcal{M}_A;\Psi_A\rangle_{S_A}}$$

$\nwarrow$ overlaps $\nearrow$

Example I: the spin structure function of the neutron from DIS

Reaction:

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

In DIS regime, the asymmetry of the inclusive cross section, $d\sigma(\vec{S}_{He}, h)$ (h is the elicity of the incoming electron) is given by

$$A_{\parallel} = \frac{d\sigma(\vec{S}_{He}, h=+) - d\sigma(\vec{S}_{He}, h=-)}{d\sigma(\vec{S}_{He}, h=+) + d\sigma(\vec{S}_{He}, h=-)} = 2x_{Bj}\,\frac{g_1^{He}(x_{Bj})}{F_2^{He}(x_{Bj})}$$

where g_1 and F_2 are spin-dependent and spin-independent structure functions of ^{3}He. If i) one takes into account S, S' and D and ii) Fermi motion + binding effects are considered only for determing the effective nucleon polarization, one can approximate

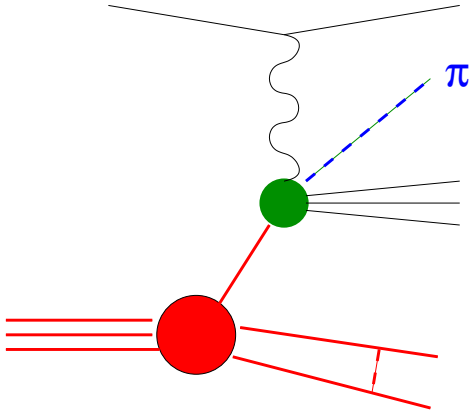
$$g_1^{He}(x_{Bj}) = 2p_p g_1^p(x_{Bj}) + p_n g_1^n(x_{Bj})$$

where p_N is the effective longitudinal polarization of the nucleon, easily evaluated in PWIA from the spin-dependent Spectral Function.

$$p_p = -0.023 \;\; (AV18) \qquad p_n = 0.878 \;\; (AV18)$$

NB This approximation, checked in detail by using the full PWIA expression (Ciofi, Pace, Scopetta, G.S. PRC **48**, 968) is widely adopted.

Example II: neutron Single-Spin Asymmetry from SiDIS



Reaction

$$e + {}^3\vec{\mathrm{He}}_\perp \to e' + \pi + X$$

where $\hat{e}_z \equiv \hat{q}$ with $\vec{q}$ the3-momentum transfer

Aim: to obtain the neutron single-spin asymmetry (wrt to opposite directions of the transverse polarization, $\vec{S}_{\perp He}$), that, in turn, it allows one, e.g., to investigate the T-odd Sivers function, $f_{1T}^{\perp q}(x, k_\perp)$. This is one of the quark transverse-momentum distributions and yields the correlation between the quark transverse-momentum and the transverse polarization of the father nucleon. It provides unique information on the orbital angular momentum content of the nucleon wave function and eventually sheds light on the famous spin-crisis.

Can one use a simple expression, like the one adopted for DIS, to extract the neutron SSA from the ^{3}He SSA?

$$^3\vec{\mathrm{He}}_\perp \to \vec{\mathrm{n}}_\perp$$

The expression to be safely adopted for extracting the neutron SSA (and actually applied to the data by Qian et al., PRL 107 (2011) 072003) is

$$A_3^{exp} = f_n p_{n\perp} A_n^{exp} + 2 f_p p_{p\perp} A_p^{exp}$$

where f_N, is the nucleon dilution factors, and $p_{N\perp}$, the nucleon transverse polarization. In a non relativistic framework the transverse and longitudinal polarizations are equal .

The full calculations (S.Scopetta, PRD 75 (2007) 054005) for checking the reliability of the previous eq. was done in the Bjorken limit and using PWIA (FSI only in the spectator nucleon pair).

$$A_3^{th} \simeq \int d\vec{p}\, dE .... \vec{\mathbf{P}}(\vec{p}, E)\; f_{1T}^{\perp q}\left(\frac{Q^2}{2p\cdot q}, \mathbf{k_T^2}\right)\; D_1^{q,h}\left(\frac{p\cdot h}{p\cdot q}, \left(\frac{p\cdot h}{p\cdot q}\kappa_{\mathbf{T}}\right)^2\right) \simeq$$

$$\simeq p_n A_n^{th} + 2 p_p A_p^{th}$$

For the detailed calculations, one needs again the spin-dependent nuclear spectral function. The function $D_1^{q,h}$, the fragmentation function, describes the hadronization process.

The SiDIS nuclear hadronic tensor in LFHD

In PWIA the LF hadronic tensor for the ^{3}He nucleus is:

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

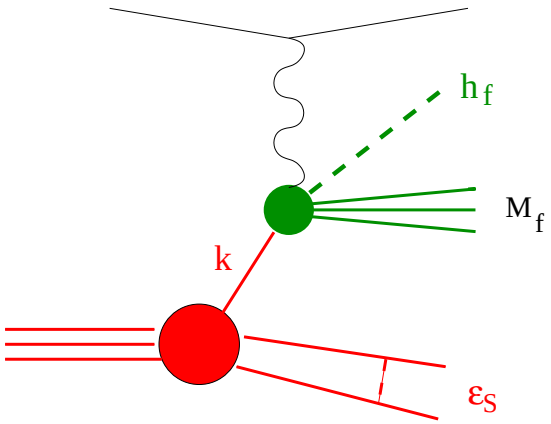
$$\times \int_{\xi_{lo}}^{\xi_{up}} \frac{d\xi}{\xi^2(1-\xi)(2\pi)^3} \int_{P_\perp^{min}}^{P_\perp^{max}} \frac{dP_\perp}{sin\theta} \, (P^+ + q^+ - h^+)$$

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

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

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

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



The ^{3}He spin-dependent Spectral Function in LFHD

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

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

and the instant-form spectral function

$$\mathbf{P}^{\tau}_{\sigma_1'\sigma_1}(\tilde{\mathbf{k}},E,S_{He}) = \sum_{f_{A-1}} \delta(E+E_{f_{A-1}}-E_{He})\ \times$$

$$_{S_{He}}\langle\Psi_{He};J_{He}\mathcal{M}_{He}\pi_{He}|\vec{k}\sigma\tau;\phi_{f_{A-1}}\rangle\ \langle\phi_{f_{A-1}};\tau\sigma'\vec{k}|\pi_{He}J_{He}\mathcal{M}_{He};\Psi_{He}\rangle_{S_{He}} =$$

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

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

NB Only THREE independent functions, $B_{0,1,2}$ are needed, once parity and time-reversal are imposed. Adding FSI between third particle and spectator pair, one could include more terms.

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 at finite values of Q^2.

- LF longitudinal and transverse polarizations show a very little change

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

In the Bjorken limit the extraction procedure works well within the LF approach as it does in the non relativistic case [PRELIMINARY RESULTS].

- The effect of integration limits in the actual JLab kinematics [Qian et al., PRL 107 (2011)] , instead of the ones in the Bjorken limit, is small. The effect will be even smaller in the JLAB planned experiments at 12 GeV [G. Cates et al., E12-09-018].

- We are going to include the FSI between the jet produced from the hadronizing quark and the two nucleon system through a Glauber approach [C. Ciofi degli Atti, L. Kaptari, PRC 83 (2011) 044602] .

Conclusions & Perspectives

- A Poincaré covariant description of an interacting system is proposed. In particular, the Relativistic Hamiltonian Dynamics coupled with the Bakamjian-Thomas construction of the 10 generators appears a viable way to implement the approach.

- The successful phenomenology developed within the non relativistic framework can be embedded in a Poincaré covariant description of the nuclei

- The nucleon spectral function of a polarized ^{3}He, within the Light-Front Hamiltonian Dynamics, has been proposed for the first time. An actual evaluation based on overlaps obtained from the AV18 wave function of the Pisa group is currently adopted for evaluating many quantities, relevant for extracting information on the neutron structure in DIS and SiDIS processes.