Spin dependent spectral functions of ^{3}He

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Why? 12 GeV Experiments @JLab, with ^{3}He

- DIS regime, e.g.

  Hall A, $http://hallaweb.jlab.org/12GeV/$
  MARATHON Coll. E12-10-103 (Rating A): MeAsurement of the F_{2n}/F_{2p}, d/u Ratios and A=3 EMC Effect in Deep Inelastic Electron Scattering Off the Tritium and Helium MirrOr Nuclei

  Hall C, $https://www.jlab.org/Hall-C/$
  J. Arrington, et al PR12-10-008 (Rating A$^-$): Detailed studies of the nuclear dependence of F_2 in light nuclei

- SIDIS regime, e.g.

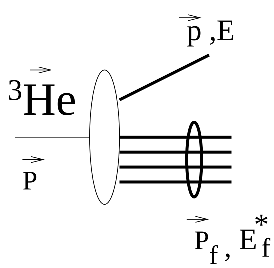
  Hall A, $http://hallaweb.jlab.org/12GeV/$
  H. Gao et al, PR12-09-014 (Rating A): Target Single Spin Asymmetry in Semi-Inclusive Deep-Inelastic $(e, e'\pi^{\pm})$ Reaction on a Transversely Polarized ^{3}He Target
  J.P. Chen et al, PR12-11-007 (Rating A): Asymmetries in Semi-Inclusive Deep-Inelastic $(e, e'\pi^{\pm})$ Reactions on a Longitudinally Polarized ^{3}He Target

- Others? DVCS, spectator tagging...

  In ^{3}He conventional nuclear effects under control... Exotic ones disentangled

The spectral function (Impulse Approximation)

$$\mathbf{P}^N_{\mathcal{M}\sigma\sigma}(\vec{p},, E) = \sum_f \left| \right|^2 =$$



↙ intrinsic overlaps ↘

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

- probability distribution to find a nucleon with given 3-momentum and missing energy in the nucleus. It arises in q.e., DIS, SIDIS, DVCS...
- In general, if spin is involved, a 2x2 matrix, $\mathbf{P}^N_{\mathcal{M}\sigma\sigma'}(\vec{p},, E)$, not a density;
- the two-body recoiling system can be either the deuteron or a scattering state: when a deeply bound nucleon, with high removal energy $E = E_{min} + E_f^*$, leaves the nucleus, the recoling system is left with high excitation energy E_f^* ;
- Realistic Spectral Function: 3-body bound state and 2-body final state evaluated within the same Realistic interaction (in our case, Av18, from the Pisa group **(Kievsky, Viviani)**). Extension to heavier nuclei very difficult

Status (Impulse Approximation and beyond)

	Impulse Approximation		including FSI	
	unpolarized	spin dep.	unpolarized	spin dep.
Non Relativistic	✓	✓	✓	✓
Light-Front	Def: ✓ Calc: 🔧	Def: ✓ Calc: 🔧	⚠ WORK IN PROGRESS	⚠ WORK IN PROGRESS

Selected contributions from Rome-Perugia:

- Ciofi, Pace, Salmè PRC 21 (1980) 505 ...
- Ciofi, Pace, Salmè PRC 46 (1991) 1591: spin dependence
- Pace, Salmè, S.S., Kievsky PRC 64 (2001) 055203, first Av18 calculation
- Ciofi, Kaptari, PRC 66 (2002) 044004, unpolarized with FSI (q.e.)
- S.S. PRC 70 (2004) 015205, non diagonal SF for DVCS
- Kaptari, Del Dotto, Pace, Salmè, S.S., PRC 89 (2014), spin dependent with FSI
- LF, preliminary, see, e.g., S.S., Del Dotto, Kaptari, Pace, Rinaldi, Salmè, Few Body Syst. 56 (2015) 6, 425 and references therein

Outline

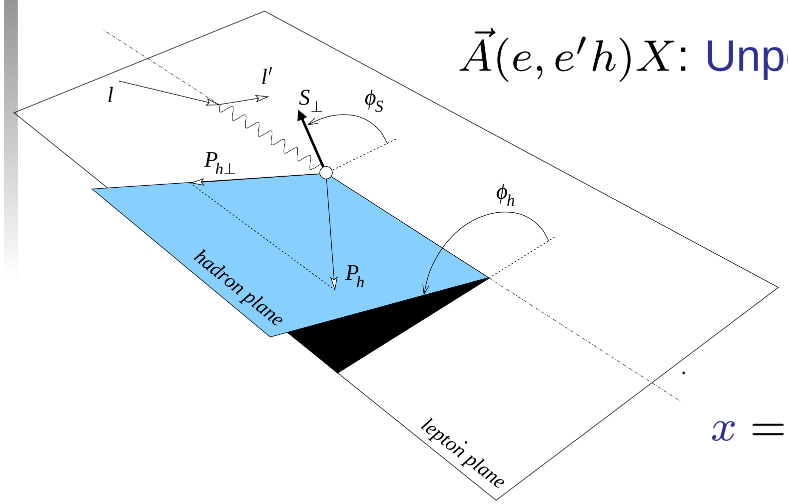
	Impulse Approximation		including FSI	
	unpolarized	spin dep.	unpolarized	spin dep.
Non Relativistic	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
Light-Front	Def: $\checkmark$	Def: $\checkmark$		
	Calc: 	Calc: 		

- Extracting the neutron information from SiDIS off $^3\vec{He}$.
  Basic approach: Impulse Approximation in the Bjorken limit
  (S.S., PRD 75 (2007) 054005)

- **Main topic:**
  - * **Evaluation of Final state interactions (FSI): distorted spectral function and spectator SIDIS**
    (L. Kaptari, A. Del Dotto, E. Pace, G. Salmè, S.S., PRC 89 (2014) 035206)
  - * **Evaluation of FSI: distorted spectral function and full treatment of SIDIS**
    (A. Del Dotto, L. Kaptari, E. Pace, G. Salmè, S.S., “ready” for submission)

- A short Light-Front update & Conclusions

Single Spin Asymmetries (SSAs) - 1



$\vec{A}(e, e'h)X$: 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 $\quad d^6\sigma_{UT} = \frac{1}{2}(d^6\sigma_{U\uparrow} - d^6\sigma_{U\downarrow}) \qquad d^6\sigma_{UU} = \frac{1}{2}(d^6\sigma_{U\uparrow} + d^6\sigma_{U\downarrow})$

SSAs - 2

SSAs in terms of parton distributions and fragmentation functions:

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

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

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

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

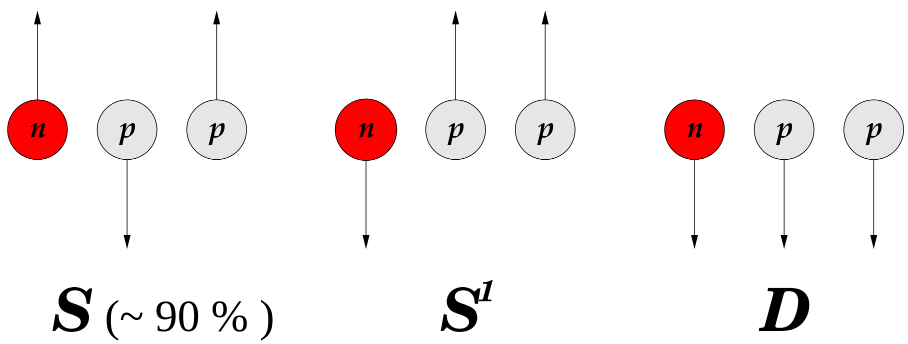
- LARGE A_{UT}^{Sivers} measured in $\vec{p}(e, e'\pi)x$ HERMES PRL 94, 012002 (2005)
- SMALL A_{UT}^{Sivers} measured in $\vec{D}(e, e'\pi)x$; COMPASS PRL 94, 202002 (2005)

A strong flavor dependence

Importance of the neutron for flavor decomposition!

The neutron information from ^{3}He

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



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

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

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

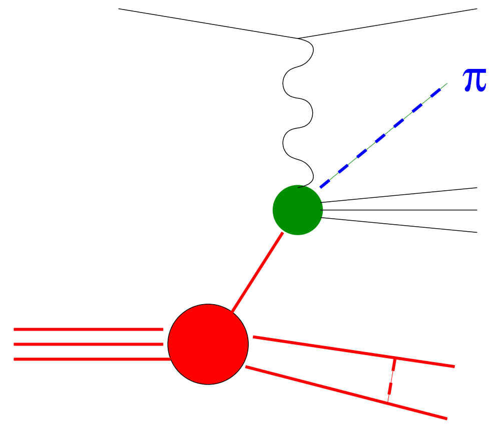
$$A_n \simeq \frac{1}{p_n f_n}\left(A_3^{exp} - 2p_p f_p A_p^{exp}\right), \quad (Ciofi\ degli\ Atti\ et\ al.,\ PRC48(1993)R968)$$

$$(f_p, f_n \quad dilution\, factors)$$

can be safely used $\longrightarrow$ widely used by experimental collaborations.
The nuclear effects are hidden in the "effective polarizations"

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

$\vec{n}$ from $^3\vec{H}e$: SIDIS case, IA



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 the Bjorken limit
in IA $\longrightarrow$ no FSI between the measured fast, ultrarelativistic π
the remnant and the two nucleon recoiling system
$E_\pi \simeq 2.4\ GeV$ in JLAB exp at $6\ GeV$ - Qian et al., PRL 107 (2011) 072003

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

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

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

The IA @ JLab kinematics: a few words more

The convolution formulae for a generic structure function can be cast in the form

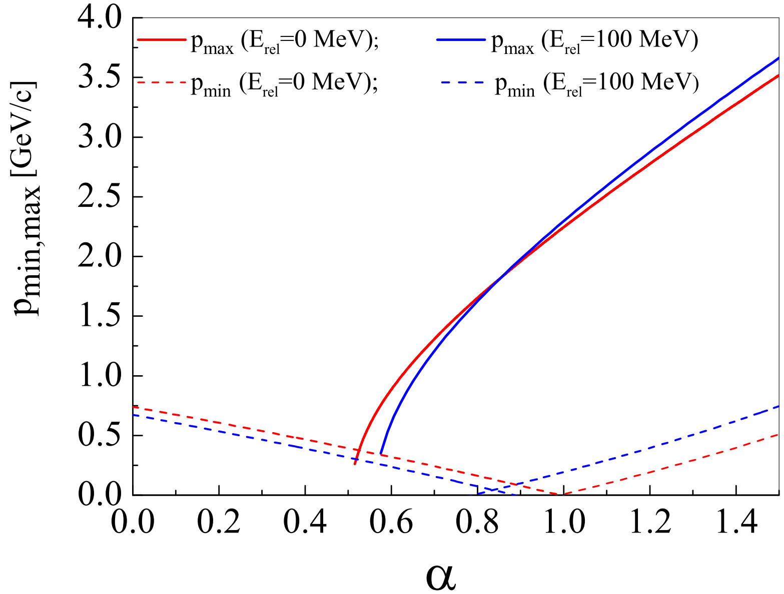
$$\mathcal{F}^A(x_{Bj}, Q^2, ...) = \sum_N \int_{x_{Bj}}^A f_N^A(\alpha, Q^2, ...)\, \mathcal{F}^N(x_{Bj}/\alpha, Q^2, ...)\, d\alpha$$

with the light-cone momentum distribution:

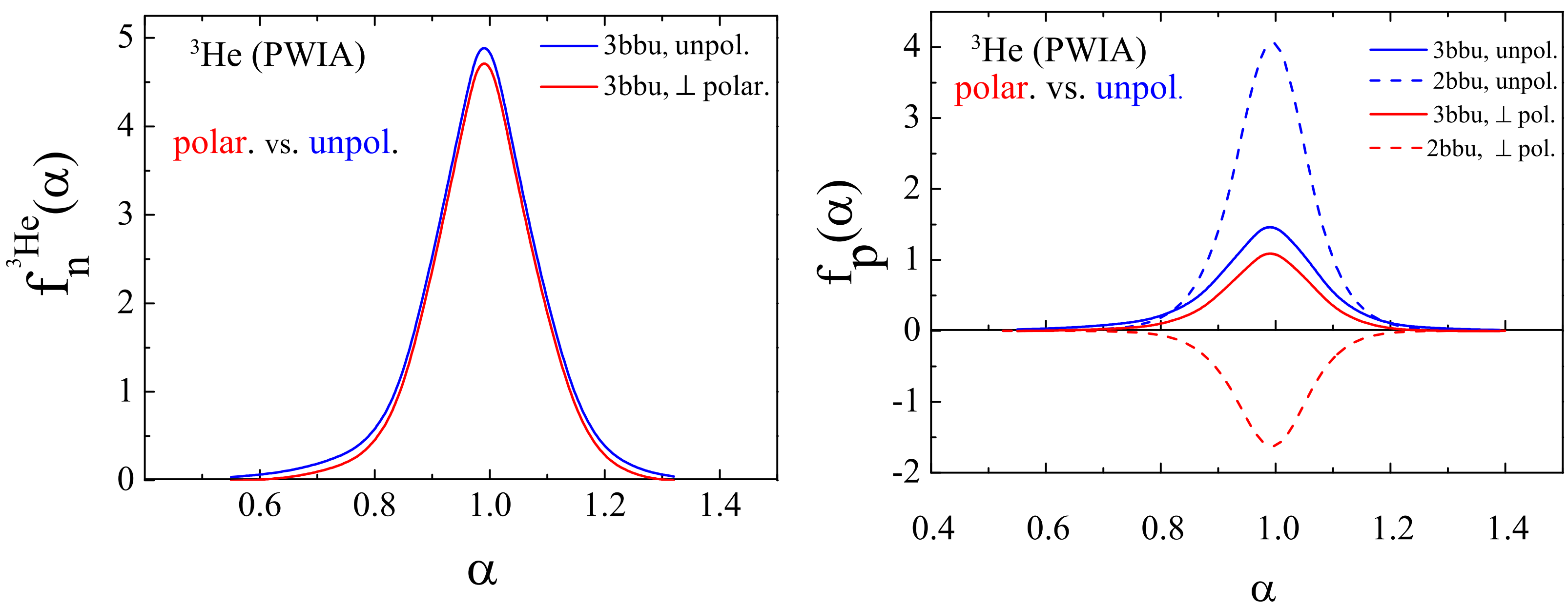
$$f_N^A(\alpha, Q^2, ...) = \int dE \int_{p_{min}(\alpha,Q^2,...)}^{p_{max}(\alpha,Q^2,...)} P_N^A(\mathbf{p}, \mathbf{E})\, \delta\left(\alpha - \frac{\mathbf{pq}}{\mathbf{m}\nu}\right)\, \theta\left(\mathbf{W_x^2} - (\mathbf{M_N} + \mathbf{M}_\pi)^\mathbf{2}\right) \mathbf{d^3p}$$

- Bjorken limit:
  $p_{min,max}$ not dependent on Q^2, x:
  $f_N^A(\alpha)$ depends on α only,
  $0 \leq \alpha \leq A$

- @ JLab kinematics,
  ($E = 8.8$ GeV, $E' \simeq 2 \div 3$ GeV,
  $\theta_e \simeq 30^o$) $q \neq \nu$ and $\alpha_{min} \neq 0$

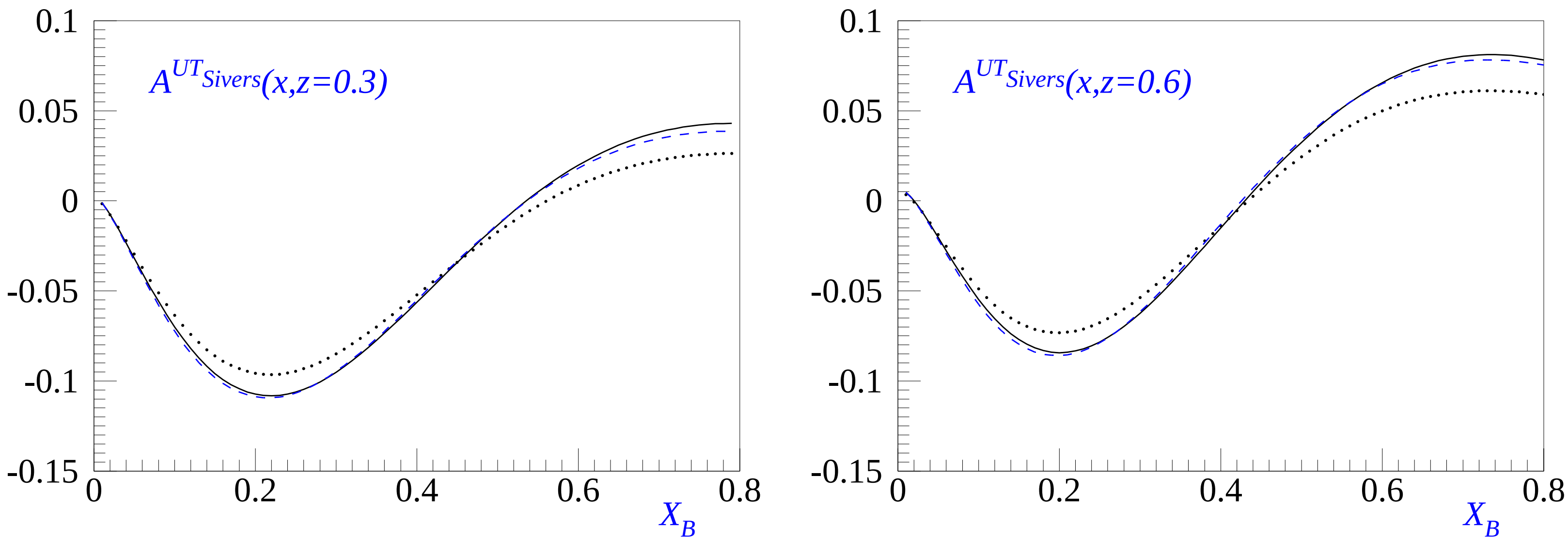


Light-cone momentum distributions in IA



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

Results: $\vec{n}$ from ${}^3\vec{He}$: A_{UT}^{Sivers}, @ JLab, in IA



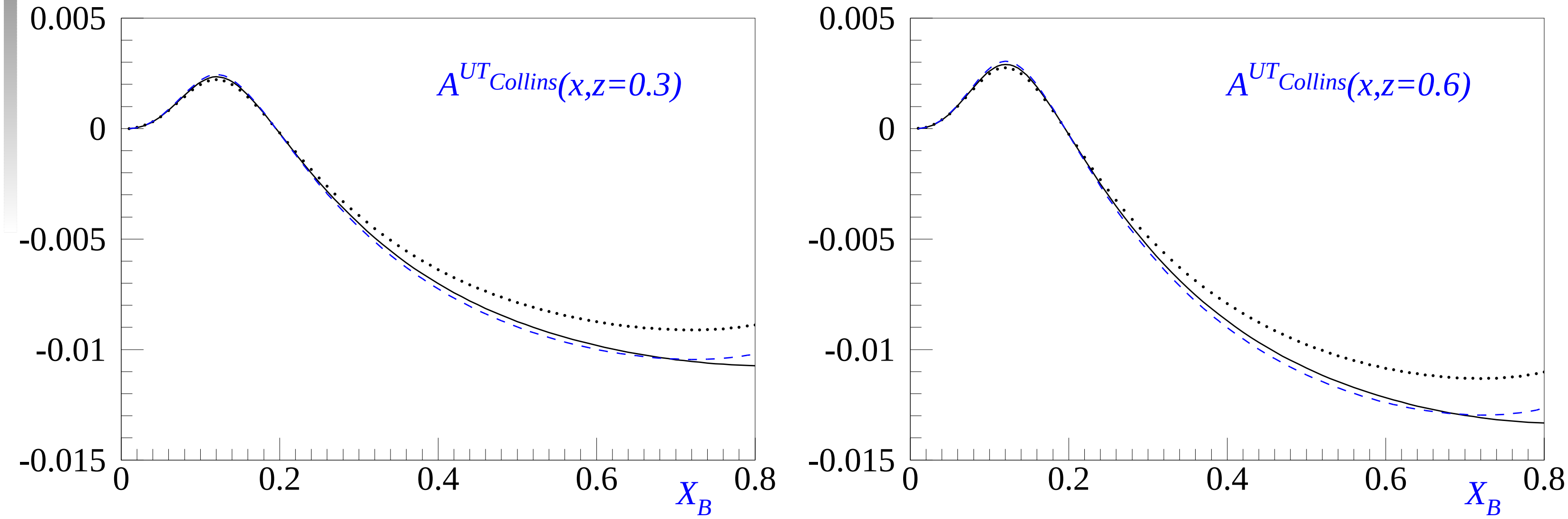
FULL: Neutron asymmetry (model: from parameterizations or models of TMDs and FFs)

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:

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

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



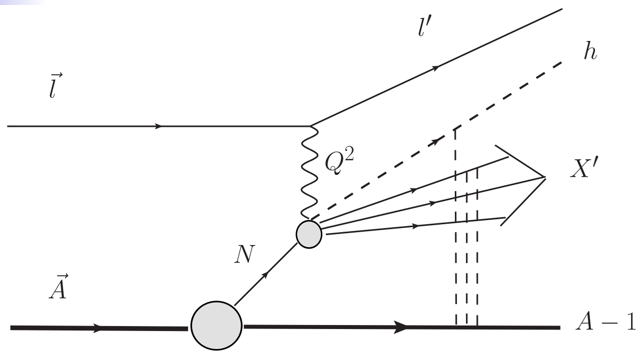
In the Bjorken limit the extraction procedure successful in DIS works also in SiDIS, for both the Collins and the Sivers SSAs !

What about FSI effects ?

(thinking to E12-09-018, A.G. Cates et al., approved with rate A @JLab 12)

FSI: Generalized Eikonal Approximation (GEA)

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
$\longrightarrow$ eikonal approximation.

$$d\sigma \simeq l^{\mu\nu} W^A_{\mu\nu}(S_A)$$

$$W^A_{\mu\nu}(S_A) \approx \sum\nolimits_{S_{A-1},S_X} J^A_\mu J^A_\nu \qquad J^A_\mu \simeq \langle S_A \mathbf{P} | \hat{\mathbf{J}}^{\mathbf{A}}_\mu(\mathbf{0}) | \mathbf{S_X}, \mathbf{S_{A-1}}, \mathbf{P_{A-1} E^f_{A-1}} \rangle$$

$$\langle S_A \mathbf{P} | \mathbf{r_1 r_2 r_3} \rangle = \mathbf{\Phi_{3_{He}}}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) = \mathcal{A}\, \mathbf{e^{iPR}} \mathbf{\Psi_3^{S_A}}(\rho, \mathbf{r})$$

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

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

$$\boxed{\hat{S}_{Gl} = Glauber\ operator}$$

$$J^A_\mu \approx \int d\mathbf{r_1} d\mathbf{r_2} d\mathbf{r_3} \Psi^{*f}_{23}(\mathbf{r_2}, \mathbf{r_3}) e^{-i\mathbf{p}_X \mathbf{r_i}} \chi^+_{S_X} \phi^*(\xi_x) \cdot \hat{S}_{Gl}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) \hat{j}_\mu(\mathbf{r_1}, X) \vec{\Psi}_3^{\mathbf{S}_A}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3})$$

IF ($FACTORIZED$ FSI !) $\left[\hat{S}_{Gl}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3), \hat{j}_\mu(\mathbf{r_1})\right] = 0$ THEN:

$$W^A_{\mu\nu} = \sum_{N,\lambda,\lambda'} \int dE\, d\mathbf{p}\, w^{N,\lambda\lambda'}_{\mu\nu}(\mathbf{p})\, P^{FSI,A,N}_{\lambda\lambda'}(E, \mathbf{p}, ...) \qquad CONVOLUTION!$$

FSI: *distorted* spin-dependent spectral function of ^{3}He

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

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

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

with:

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

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

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

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

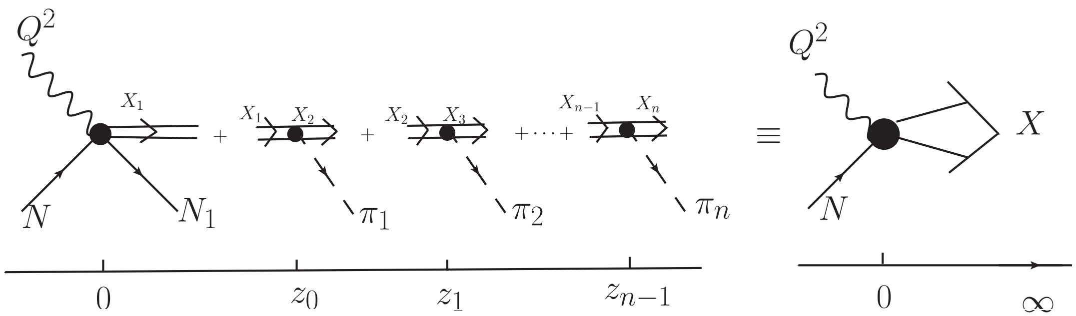
GEA (Γ depends also on the traveled longitudinal distance z_{1i}!) very succesfull in q.e. semi-inclusive and exclusive processes off ^{3}He

see, e.g., Alvioli, Ciofi & Kaptari PRC 81 (2010) 02100

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

FSI: *the hadronization model*

Hadronization model **(Kopeliovich et al., NPA 2004)**
+ σ_{eff} model for SIDIS **(Ciofi & Kopeliovich, EPJA 2003)**
GEA + hadronization model succesfully applied to unpolarized SIDIS $^2H(e,e'p)X$
(Ciofi & Kaptari PRC 2011).



$$\sigma_{eff}(z) = \sigma_{tot}^{NN} + \sigma_{tot}^{\pi N}\,[n_M(z) + n_g(z)]$$

- The hadronization model is phenomenological: parameters are chosen to describe the scenario of JLab experiments (e.g., $\sigma_{NN}^{tot} = 40$ mb, $\sigma_{\pi N}^{tot} = 25$ mb, $\alpha = -0.5$ for both NN and πN...).

FSI: *distorted* spin-dependent spectral function of ^{3}He

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

- While P^{IA} is "static",i.e. depends on groud state properties, P^{FSI} is dynamical ($\propto \sigma_{eff}$) and process dependent;
- For each experimental point (given x, Q^2...), a different spectral function has to be evaluated!
- Quantization axis (w.r.t. which polarizations are fixed) and eikonal direction (fixing the "longitudinal" propagation) are different)... States have to be rotated...
- P^{FSI}: a really cumbersome quantity, a very demanding evaluation ($\approx$ 1 Mega CPU*hours @ "Zefiro" PC-farm, PISA, INFN "gruppo 4").

The convolution formulae for a generic structure function can be cast in the form

$$\mathcal{F}^A(x_{Bj}, Q^2, ...) = \sum_N \int_{x_{Bj}}^A f_N^A(\alpha, Q^2, ...) \, \mathcal{F}^N(x_{Bj}/\alpha, Q^2, ...) \, d\alpha$$

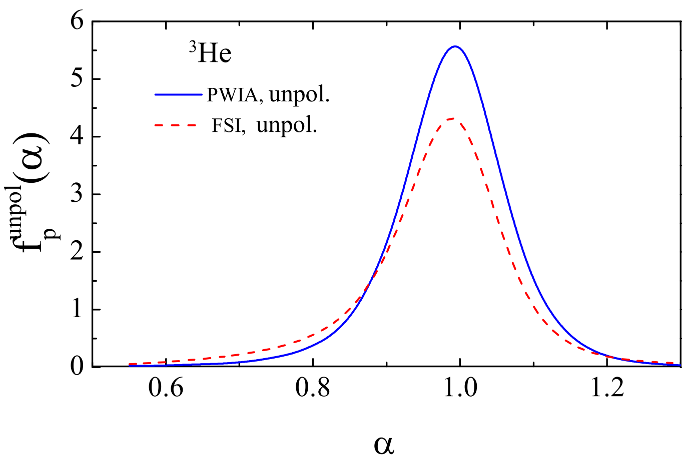
with the distorted light-cone momentum distribution:

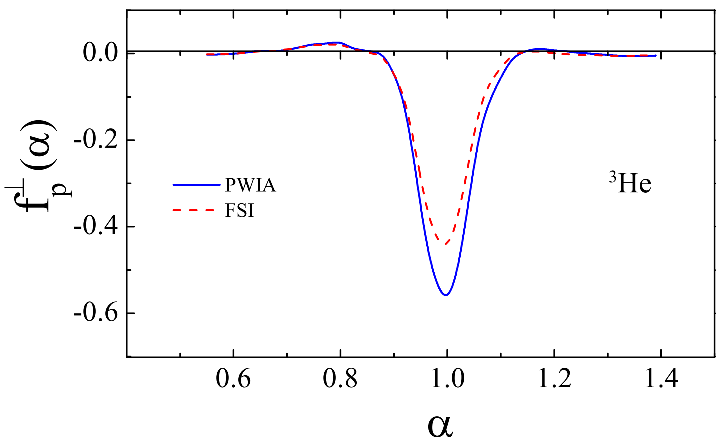
$$f_N^A(\alpha, Q^2, ..) = \int dE \int_{p_m(\alpha, Q^2, ..)}^{p_M(\alpha, Q^2, ..)} P_N^{A,FSI}(\mathbf{p}, E, \sigma..) \, \delta\left(\alpha - \frac{pq}{m\nu}\right) \theta\left(W_x^2 - (M_N + M_\pi)^2\right) d^3\mathbf{p}$$

light-cone momentum distributions with FSI:

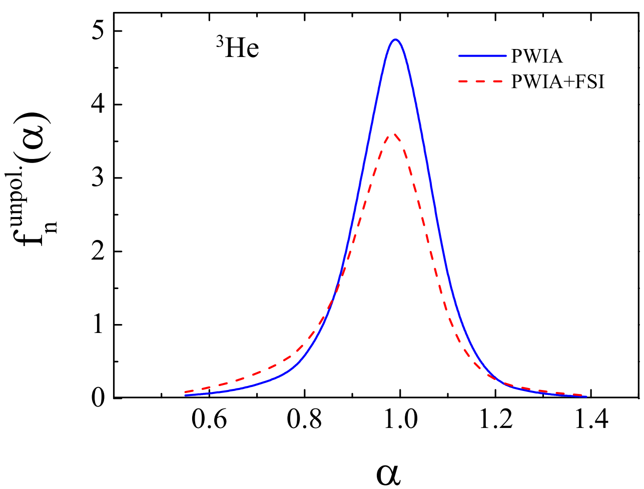
A. Del Dotto, L.P. Kaptari, E. Pace, G. Salmè, S.S., “ready” for submission

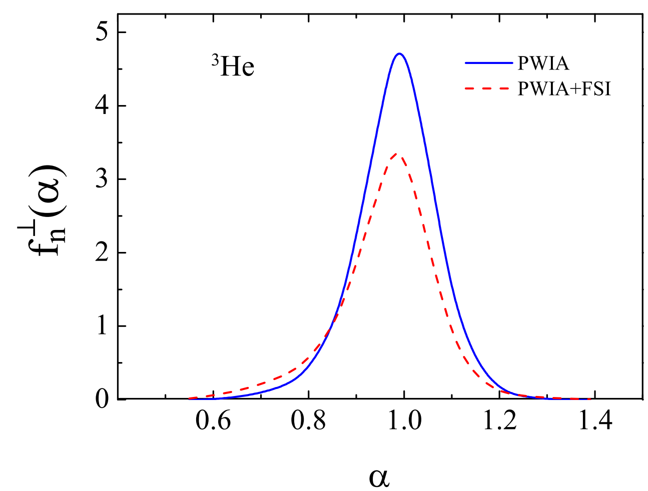
PROTON @ E_i = 8.8 GeV





NEUTRON @ E_i = 8.8 GeV





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

DILUTION FACTORS

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

PWIA:

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

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

FSI:

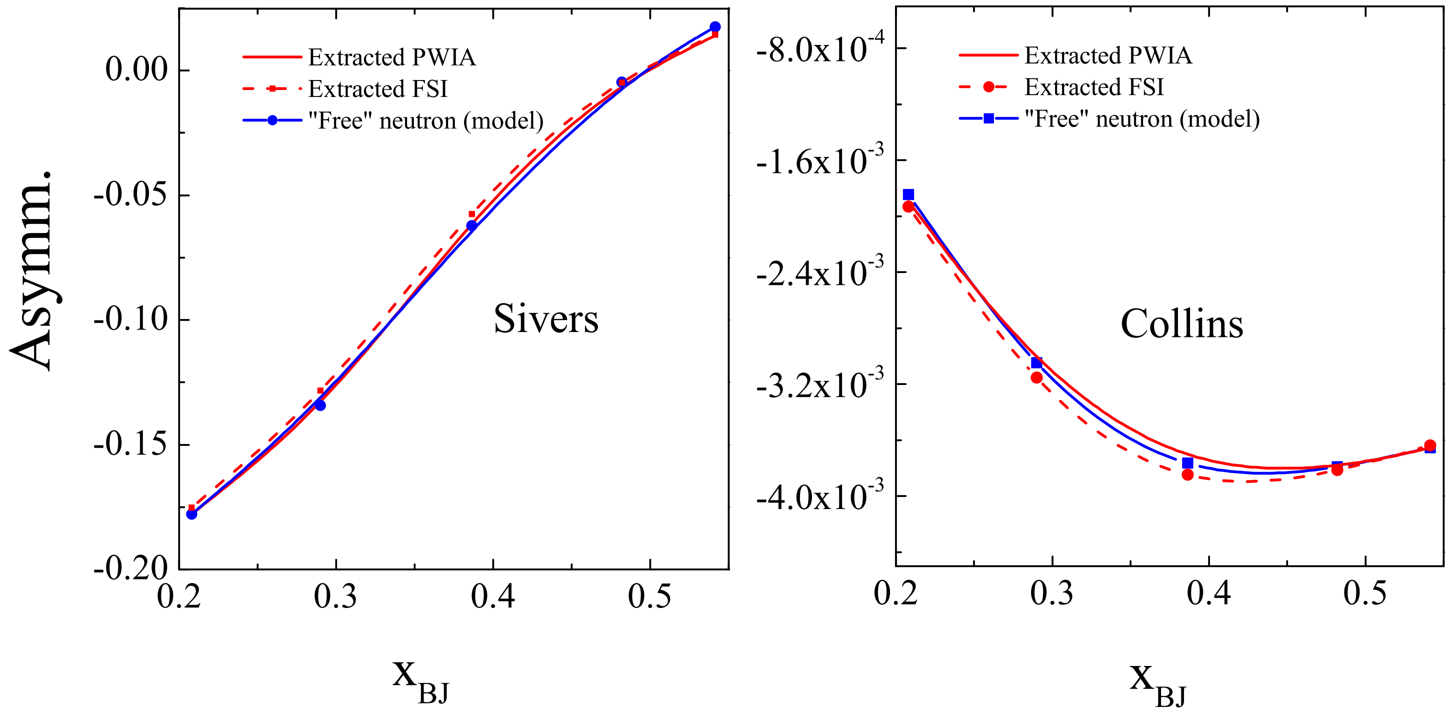
$$\langle \vec{s}_{n(p)}\rangle = \int dE \int d^3p P_{||}^{FSI}(E,\mathbf{p}) = \mathbf{p_{n(p)}^{FSI}};$$
$$\langle N\rangle = \int dE \int d^3p P_{unpol.}^{FSI}(E,\mathbf{p}) < 1.$$

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

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

2

Good news from GEA studies of FSI!



Effects of GEA-FSI (shown at $E_i = 8.8$ GeV) in the dilution factors and in the effective polarizations compensate each other to a large extent: the usual extraction is safe!

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

L. Kaptari, A. Del Dotto, E. Pace, G. Salmè, S.S., “ready” for submission

What about relativity ?

Good *preliminary* news

We are now going to evaluate 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:

	$proton\ NR$	$proton\ LF$	$neutron\ NR$	$neutron\ LF$
$\int dE d\vec{p}\, \frac{1}{2} Tr(\mathcal{P})$	0.999	0.999	0.999	0.999
$\int dE d\vec{p}\, \frac{1}{2} Tr(\mathcal{P}\sigma_z)_{\vec{S}_A=\hat{z}}$	-0.023	-0.022	0.878	0.873
$\int dE d\vec{p}\, \frac{1}{2} Tr(\mathcal{P}\sigma_y)_{\vec{S}_A=\hat{y}}$	-0.023	-0.023	0.878	0.875

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

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

LF Nucleon Spectral Function for ^3He

$$\mathcal{P}^{\tau}_{\sigma'\sigma}(\kappa^+, \boldsymbol{\kappa}_\perp, \epsilon_S, S_{He}) = \rho(\epsilon_S) \sum_{J_S J_{zS} \alpha} \sum_{T_S \tau_S} {}_{LF}\langle \tau_S, T_S, \alpha, \epsilon_S J_S J_{zS}; \tau\sigma', \tilde{\boldsymbol{\kappa}} | \Psi_0 S_{He} \rangle$$
$$\times \langle S_{He}, \Psi_0 | \tilde{\boldsymbol{\kappa}}, \sigma\tau; J_S J_{zS} \epsilon_S, \alpha, T_S, \tau_S \rangle_{LF}$$

- $\kappa^+ = \xi \mathcal{M}_0(1,23)$ and

$$\mathcal{M}_0^2(1,23) = \frac{m^2 + |\boldsymbol{\kappa}_\perp|^2}{\xi} + \frac{M_S^2 + |\boldsymbol{\kappa}_\perp|^2}{(1-\xi)}$$

  $\mathcal{M}_0(1,23)$="free mass", value of the total P^+ in the LF intrinsic frame of the (1,23) cluster, in terms of which the spectral function is defined

- $M_S = 2\sqrt{m^2 + m\epsilon_S}$
- $\rho(\epsilon_S) \equiv$ density of the two-body states (1 for the bound state, and $m\sqrt{m\epsilon_S}/2$ for the excited ones)
- what about the overlap ${}_{LF}\langle \tau_S, T_S, \alpha, \epsilon_S J_{zS} J_S; \tau\sigma', \tilde{\boldsymbol{\kappa}} | \Psi_0 S_{He} \rangle$?

LF overlaps for ^3He from the IF ones

$$_{LF}\langle \tau_S, T_S, \alpha, \epsilon_S J_S J_{zS}; \tau\sigma, \tilde{\boldsymbol{\kappa}} | \Psi_0 S_{He}\rangle =$$

$$= \sum_{\tau_2,\tau_3} \sum_{\sigma'_1} D^{\frac{1}{2}}[\mathcal{R}^{\dagger}_M(\tilde{\boldsymbol{\kappa}})]_{\sigma\sigma'_1} \int d\mathbf{k}_{23} \sum_{\sigma_2,\sigma_3} \sqrt{\frac{\kappa^+ E_{23}}{k^+ E_S}} \sqrt{(2\pi)^3\, k^+ \frac{\partial k_z}{\partial k^+}} \times$$

$$_{IF}\langle \tau_S, T_S, \alpha, \epsilon_S J_S J_{zS} | \mathbf{k}_{23}; \sigma_2, \sigma_3; \tau_2, \tau_3\rangle \langle \tau_3, \tau_2, \tau_1; \sigma_3, \sigma_2, \sigma'_1; \mathbf{k}, \mathbf{k}_{23} | \Psi_0 S_{He}\rangle_{IF}$$

- $\mathbf{k}_\perp = \boldsymbol{\kappa}_\perp$, since the ^3He transverse momentum is $\mathbf{P}_\perp = 0$, by choice
- $k^+ = \xi\; M_0(123) = \kappa^+\; M_0(123)/\mathcal{M}_0(1,23)$

$$\text{with} \qquad M_0^2(123) = \frac{m^2 + |\boldsymbol{\kappa}_\perp|^2}{\xi} + \frac{M_{23}^2 + |\boldsymbol{\kappa}_\perp|^2}{(1-\xi)}$$

and $M_{23}^2 = 4(m^2 + |\mathbf{k}_{23}|^2)$ the mass of the spectator pair without interaction !
Recall that in $\mathcal{M}_0(1,23)$ the spectator pair is interacting, $M_{23} \to M_S$

- $k_z = \frac{1}{2}\left[k^+ - \frac{m^2 + |\boldsymbol{\kappa}_\perp|^2}{k^+}\right]$, $E_{23} = \sqrt{M_{23}^2 + |\mathbf{k}|^2}$ and $E_S = \sqrt{M_S^2 + |\boldsymbol{\kappa}|^2}$
- In the preliminary results, $\mathcal{M}_0(1,23) = M_0(123)$

In the actual calculations, we have identified the IF overlaps with the NR ones

$$\langle \tau_3, \tau_2, \tau_1; \sigma_3, \sigma_2, \sigma_1'; \mathbf{k}, \mathbf{k}_{23} | \Psi_0 S_{He} \rangle_{IF} \Rightarrow \langle \tau_3, \tau_2, \tau_1; \sigma_3, \sigma_2, \sigma_1'; \mathbf{k}, \mathbf{k}_{23} | \Psi_0 S_{He} \rangle_{NR}$$

$$_{IF}\langle \tau_S, T_S, \alpha, \epsilon_S J_S J_{zS} | \mathbf{k}_{23}; \sigma_2, \sigma_3; \tau_2, \tau_3 \rangle \Rightarrow_{NR} \langle \tau_S, T_S, \alpha, \epsilon_S J_S J_{zS} | \mathbf{k}_{23}; \sigma_2, \sigma_3; \tau_2, \tau_3 \rangle$$

- Formally set up **E. Pace, A. Del Dotto, M. Rinaldi, G. Salmè, S.S., Few-Body Systems (2016) Light-Cone Conference 2015, Frascati, Proceedings, in press;**

- (difficult) calculation in progress

Conclusions

We are studying $^3\vec{H}e(e,e'\pi)X$ **beyond** the realistic, NR, IA approach in the Bjorken limit, to check if nuclear effects in the extraction of the neutron information are under control. We have preliminary encouraging results concerning:

- **FSI effects**
  Evaluated through the GEA – a distorted spin dependent spectral function is studied
- **An analysis at finite Q^2 with a LF spectral function** (in IA); (briefly discussed today)
  E. Pace, A. Del Dotto, M. Rinaldi, G. Salmè, S.S., Few-Body Systems 54 (2013) 1079-1082;
  S.S., Del Dotto, Kaptari, Pace, Rinaldi, Salmè, Few Body Syst. 56 (2015) 6, 425 and references there in

Next steps: 1) complete this program! 2) relativistic FSI?
3) Towards 4-body systems: DVCS off ^{4}He (in collaboration with M. Viviani, Pisa), non diagonal spectral function...

BACKUP - $\vec{n}$ from $^3\vec{He}$: SiDIS case

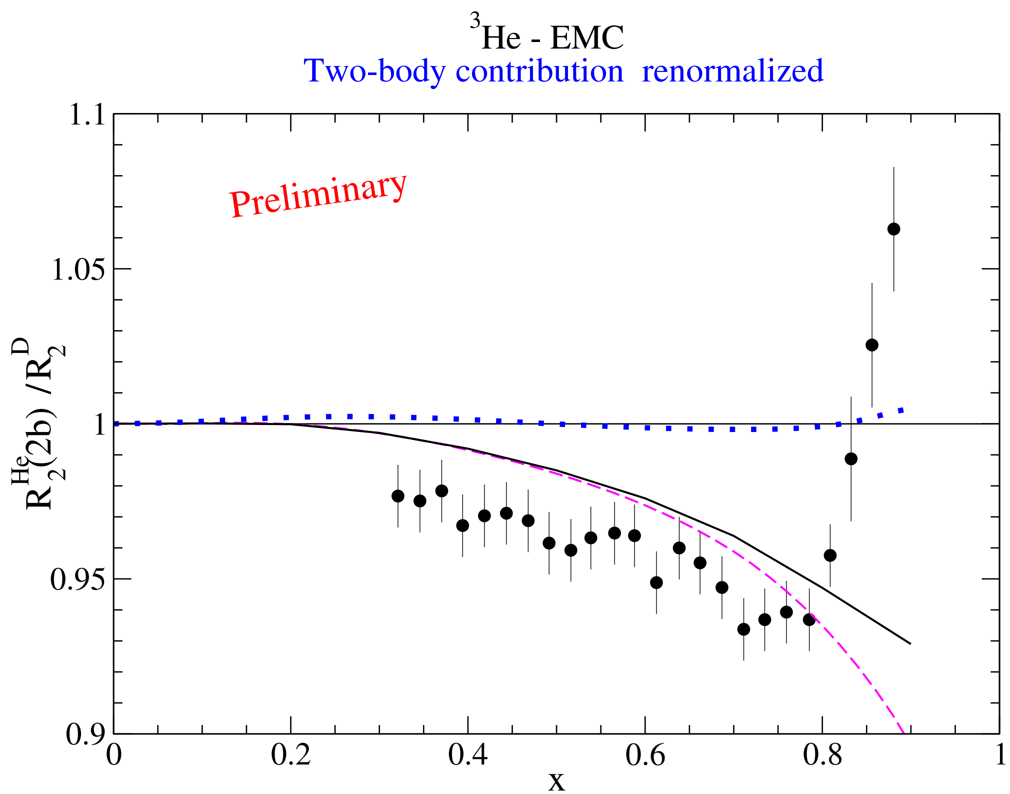
Ingredients of the calculations :

- A realistic spin-dependent spectral function of ^{3}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 ,
  $f_{1T}^{\perp q}(x, \mathbf{k_T}^{\mathbf{2}})$, Anselmino et al., PRD 72 (2005) 094007,
  $D_1^{q,h}(z, (z\kappa_\mathbf{T})^2)$, Kretzer, PRD 62 (2000) 054001
- Models for the unknown pdfs and fragmentation functions:
  $h_1^q(x, \mathbf{k_T}^{\mathbf{2}})$, Glueck et al., PRD 63 (2001) 094005,
  $H_1^{\perp q,h}(z, (z\kappa_\mathbf{T})^{\mathbf{2}})$ Amrath et al., PRD 71 (2005) 114018

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

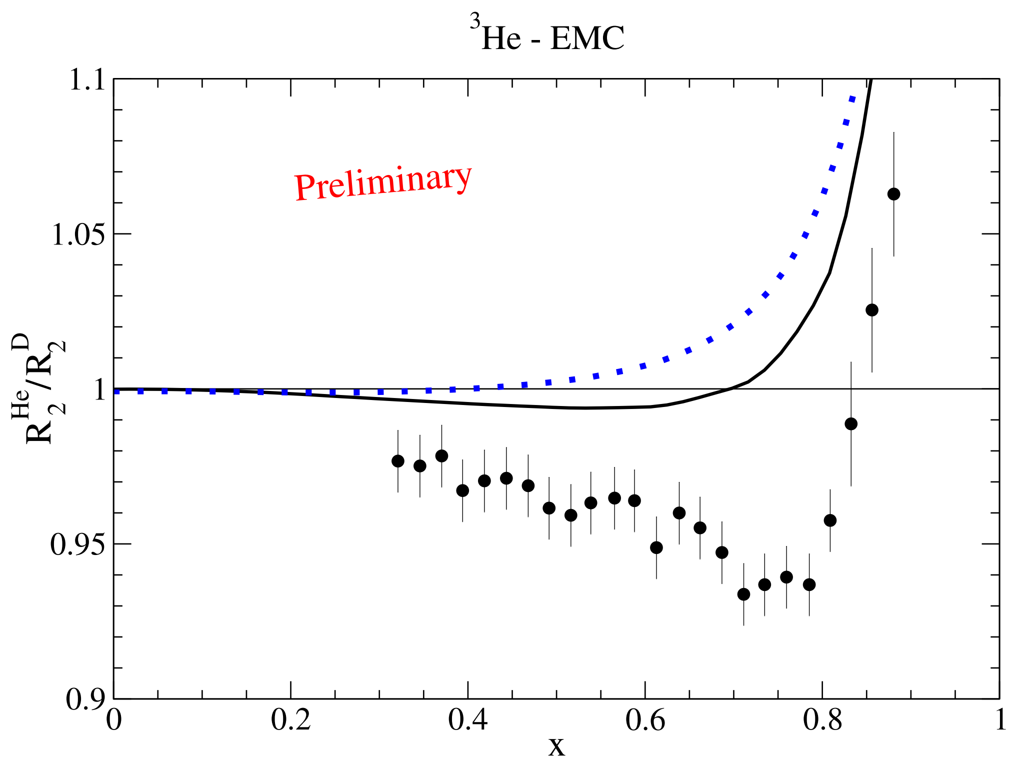
Preliminary Results for ^3He EMC effect

We have first calculated the contribution from the 2B channel, with the spectator pair in a deuteron state



- Solid line: calculation with the LF Spectral Function.
- Dashed line: as the solid line, but with $\sqrt{\bar{k}_{23}^2} = 136.37\ MeV$ for D (AV18).
- Dotted line: LF Momentum Distribution with only two-body contribution

Calculation of $R_2^{He}(x)/R^D(x)$: 2-body and 3-body contributions



- Solid line: LF Spectral Function, with the exact calculation for the 2-body channel, and an average energy in the 3-body contribution: $<\bar{k}_{23}>= \ 113.53\ MeV$ (proton), $<\bar{k}_{23}>= \ 91.27\ MeV$ (neutron).
- Dotted line: LF momentum distribution

Within the LF framework normalization and momentum sum rule are fulfilled automatically.

Big difference from the IF approach !