Polarized ^{3}He target and final state interactions in SiDIS

Alessio Del Dotto, (INFN, Roma1, Italy & JLab)
Leonid Kaptari (JINR, Dubna, Russia & INFN Perugia)
Emanuele Pace (Università di Roma Tor Vergata and INFN, Roma 2, Italy)
Giovanni Salmè (INFN, Roma 1, Italy)
Sergio Scopetta (Dipartimento di Fisica e Geologia, Università di Perugia and INFN, Sezione di Perugia, Italy)

Aarhus, 12-8-2016

The 23rd European Conference on Few-Body Problems in Physics

Outline

- Context: nucleon structure
- SiDIS off ^{3}He and information on the neutron structure:

  - Recent theoretical developments in SiDIS studies including the final state interaction through a distorted spin dependent spectral function

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

  - Application to the standard SiDIS and to the Sivers (Collins) function extraction in Single Spin Asymmetries measurements

    A.DD., L.P. Kaptari, E. Pace, G. Salmè, S. Scopetta, "ready" for submission

- Conclusions and perspectives

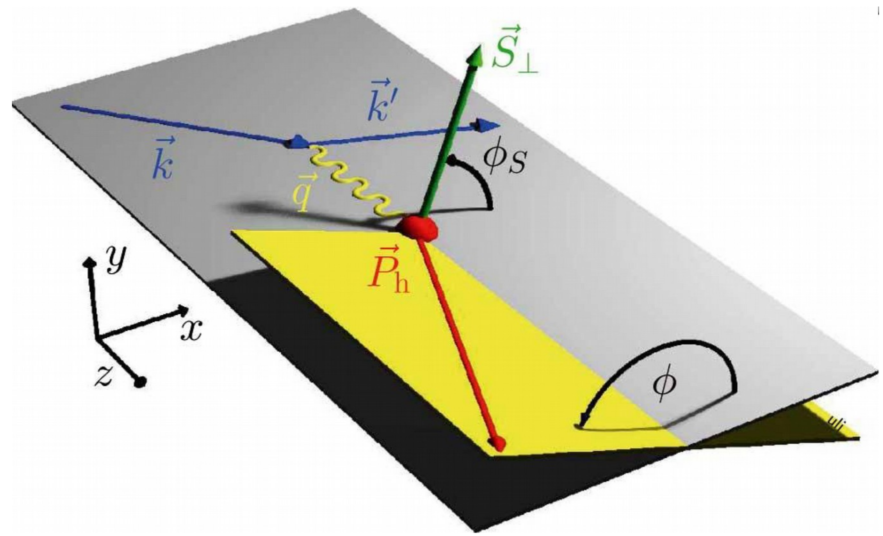
Neutron structure

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

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

- SIDIS on transversely polarized target

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



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

- **TMD**: probability density to strike a quark with $\boldsymbol{x}$ fraction of longitudinal momentum and transverse momentum $\boldsymbol{p_T}$
- **FF**: probability density of the struck quark, with transverse momentum $\boldsymbol{k_T}$ to fragment in an hadron carrying a fraction $\boldsymbol{z}$ of the parton momentum

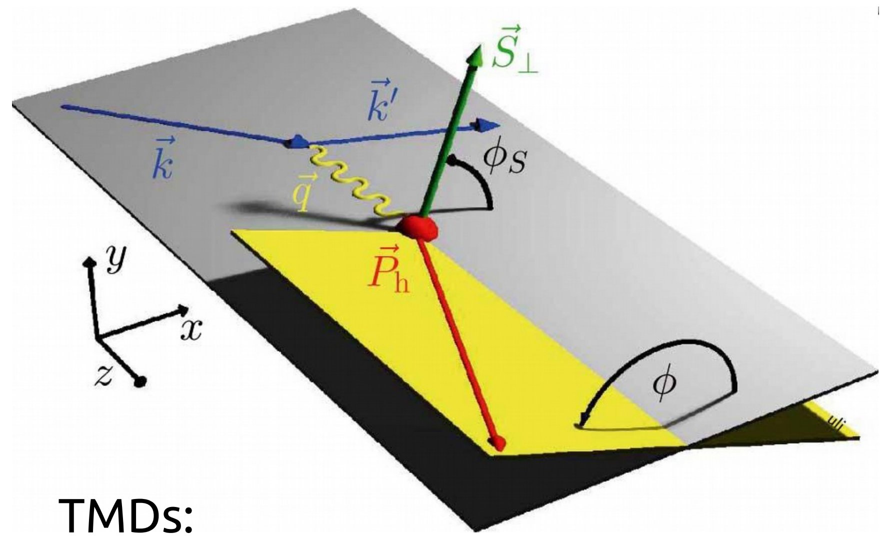
Neutron structure

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

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

- SIDIS on transversely polarized target

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



TMDs:

nucleon		quark U	quark L	quark T
	U	q		$h_1^\perp$
	L		Δq	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	δq, $h_{1T}^\perp$

FFs: $D_1^{q\to h}$ $H_1^{\perp q\to h}$

SiDIS Single Spin Asymmetries

The cross section can be separated into contributions depending on Beam and Target polarization: Unpolarized, Transversely and Longitudinally polarized.

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

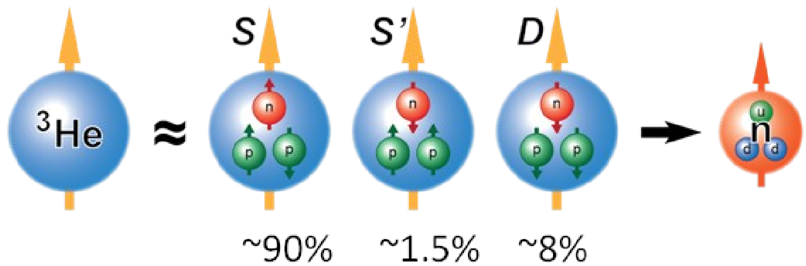
In the case of a transversely polarized target, two important mechanisms can be distinguished.

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

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

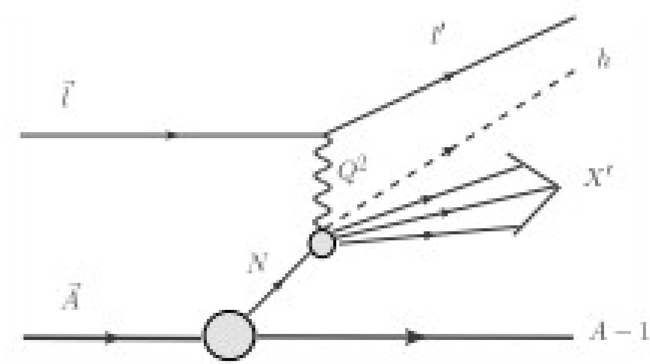
^{3}He polarized target

$$^3\vec{He} \simeq \vec{n}$$



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

---> applied to DiS, first naive extension to SiDIS



The two photons are mostly in a s=0 wave.

The first idea is the following:

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

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

Effective polarizations:

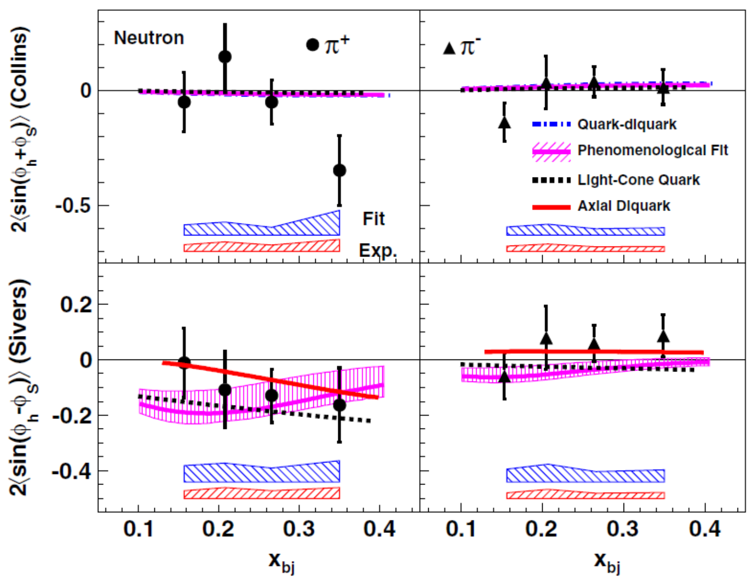
$$p_p = -0.023 \qquad p_n = 0.878$$

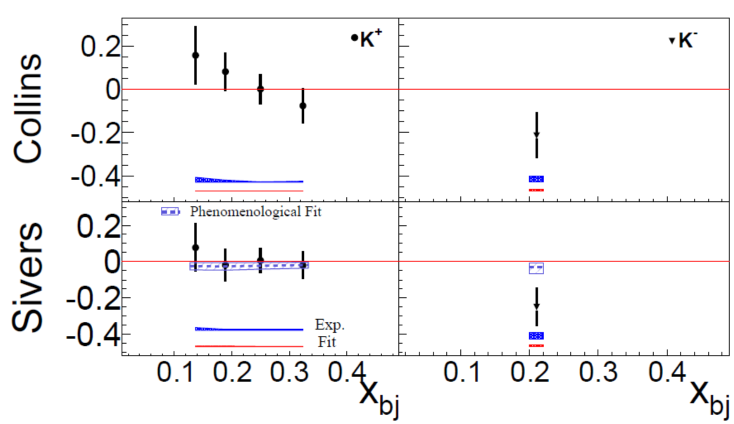
Dilution factor:

$$f_{p(n)} \simeq 0.2$$

The key quantity to obtain the result is the ^{3}He Spectral Function S(p,E) (it appears in several processes i.e. DIS, SIDIS, DVCS)

Existing results on ^{3}He





$$e +^3 \vec{He} \rightarrow e' + \pi(K)^{\pm} + X$$

PRL 107, 072003 (2011) – first results on neutron (^{3}He)

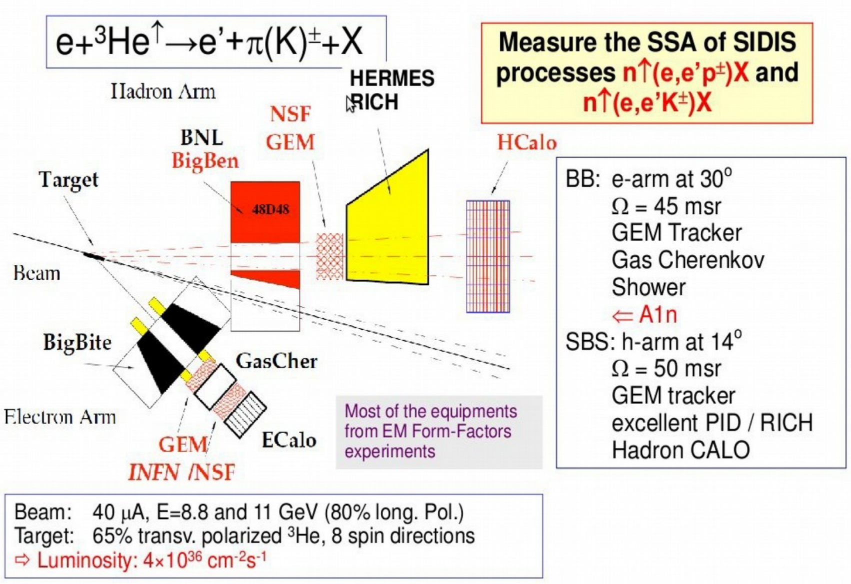
- Results on proton by HERMES and COMPASS collaborations
- Results on deuteron by COMPASS

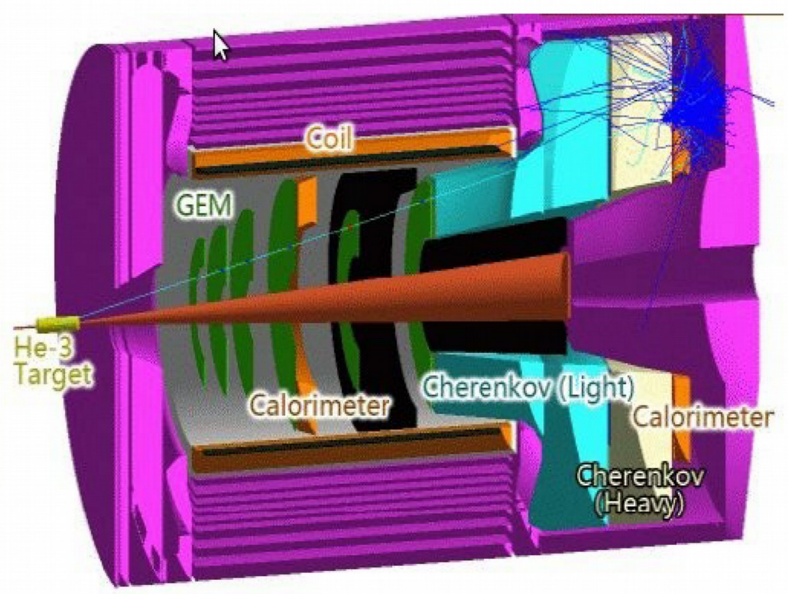
At Jlab12, there will be substantial improvements, SiDIS program, multidimensional binning (x,z,Q^2), valence region

Neutron information crucial for flavor separation!

Planned experiments with ^{3}He target

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





The PWIA and the JLab kinematics

The convolution formula 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:

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

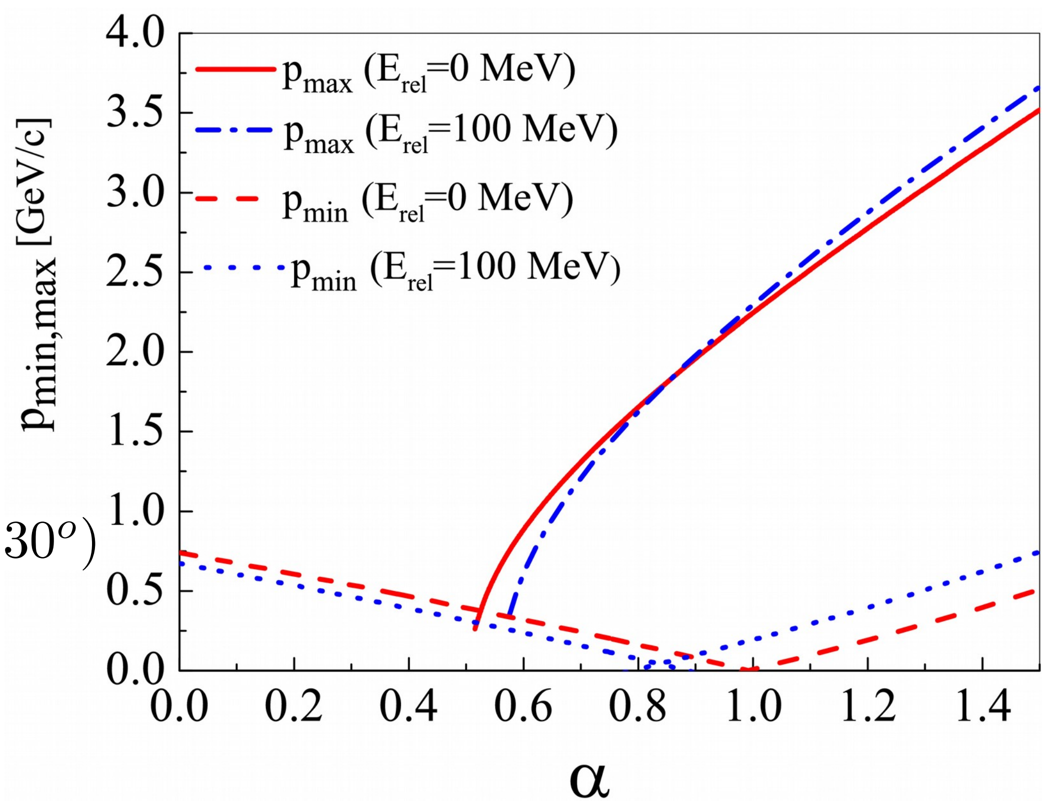
- Bjorken limit:

  $p_{min,max}$ not dependent on Q^2 and x:
  f_N^A depends on α only
  $0 \le \alpha \le A$

- JLab kinematics:

$(E = 8.8\ GeV, E' \simeq 2 \div 3\ \text{GeV}, \theta_e \simeq 30^o)$

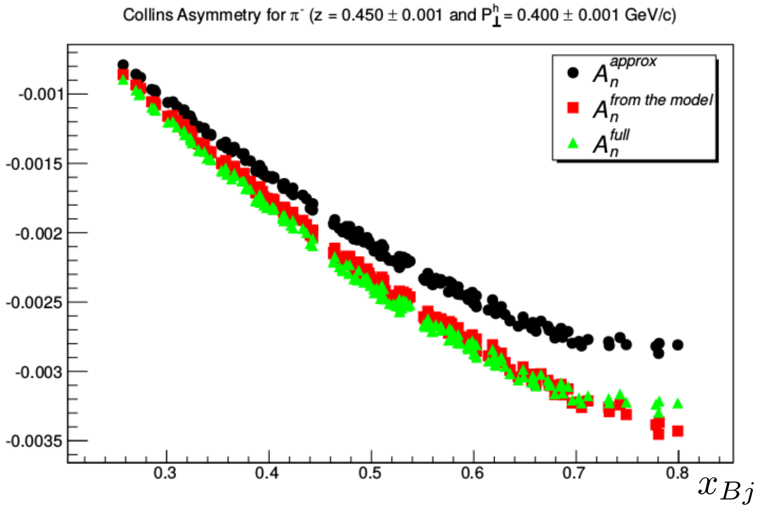
$q \neq \nu$ and $\alpha_{min} \neq 0$

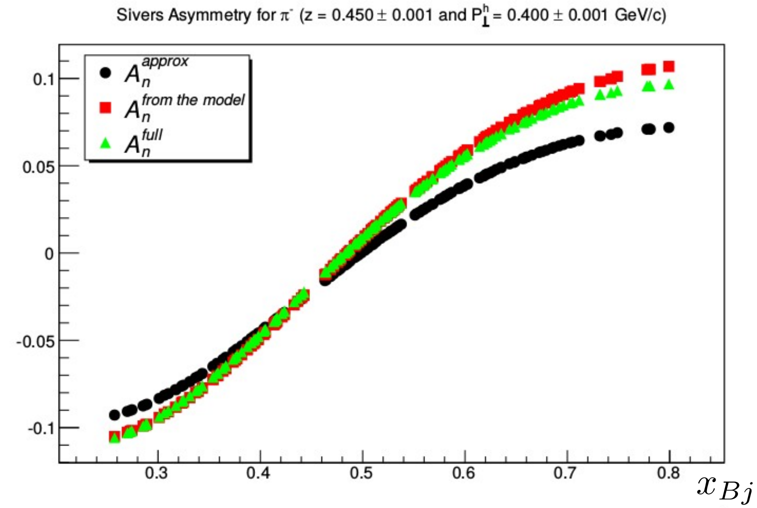


Nuclear effects on the extraction from ^3He

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

$$A \simeq \int d\vec{p}dE P(\vec{p}, E) TMD(x, p_T^2) FF(z, k_T^2)$$





Red: Neutron asymmetry (model: parametrizations or models for TMDs and FFs)
Black: Neutron asymmetry extracted neglecting the proton effective polarization
Green: Extracted using the formula $A_n \simeq \frac{1}{p_n f_n}(A_3^{calc} - 2p_p f_p A_p^{model})$

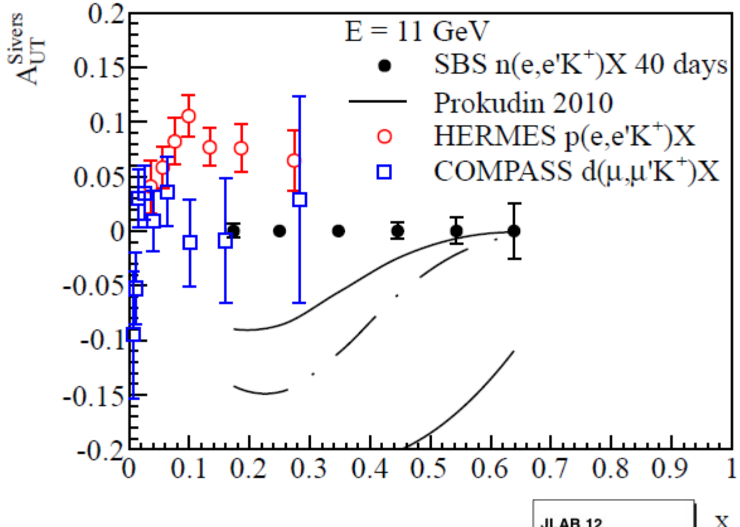
The model has been implemented in a Monte Carlo simulating the phase space of the experiment E12-09-018.

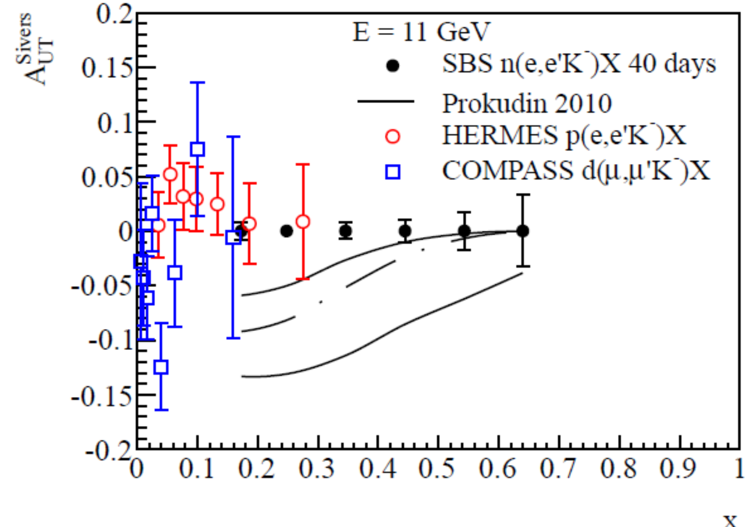
Does nuclear FSI have an effect on the extraction?

11 GeV SIDIS: expected accuracy

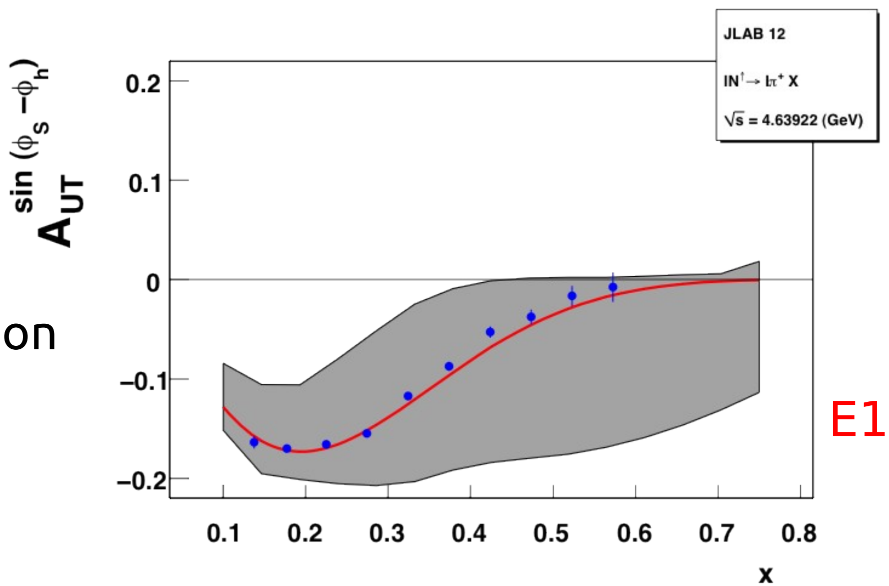
We need to be really confident on our extraction method!
A tremendous reduction of the statistical error is expected!

Kaon

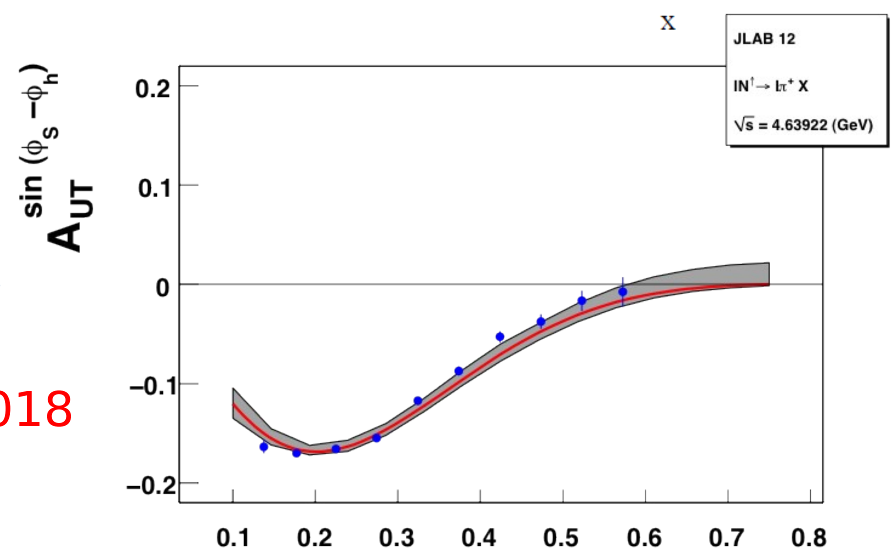




Pion



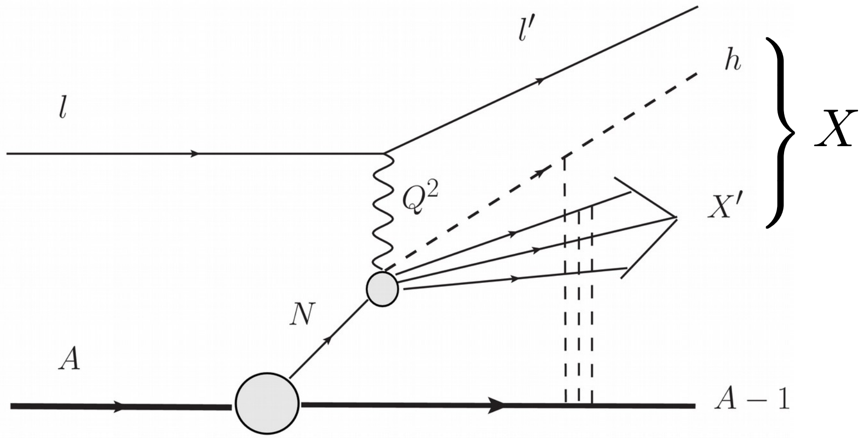
E12-09-018



Does nuclear FSI have an effect on the extraction?

FSI: Generalized Eikonal Approximation (GEA)

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



Relative energy between A-1 and the remnants ~ GeV --> eikonal approximation

$$d\sigma \simeq l^{\mu\nu} W^{A}_{\mu\nu} \qquad W^{A}_{\mu\nu}(S_A) \approx \sum_{S_{A-1}, S_X} J_\mu J_\nu$$

$$J_\mu = \langle\, P_h, X | \hat{J}_\mu | \mathbf{S_A}, P_A \,\rangle = \sum_i \langle\, \Psi^f(1,2,3) | \hat{j}_\mu(i) | \Psi_3^{\mathbf{S}_A}(1,2,3) \,\rangle$$

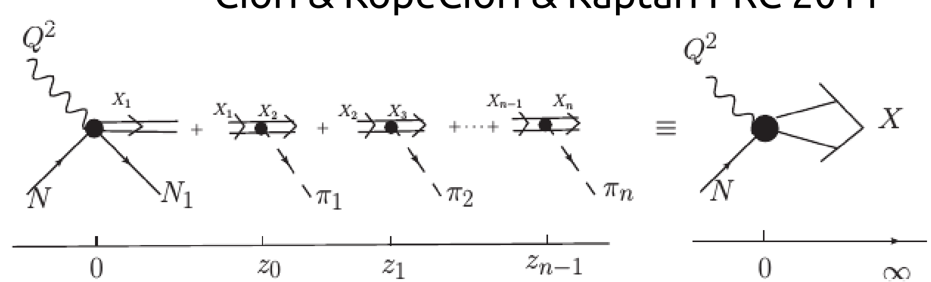
Glauber operator

$$J_\mu(1) = \int d\mathbf{r_1} d\mathbf{r_2} d\mathbf{r_3} \Psi^{*f}_{23}(\mathbf{r_2}, \mathbf{r_3}) e^{-i\mathbf{p}_X \mathbf{r_1}} \chi^+_{\lambda_X} \phi^*(\xi_X) \cdot \hat{S}_{Gl}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) \hat{j}_\mu(\mathbf{r_1}) \Psi_3^{\mathbf{S}_A}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3})$$

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

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

hadronization model: Kopeliovich et al., NPA 2004;
σ_{eff} model: Ciofi & Kopeliovich, EPJA 2003;
succesfull application to unpolarized ^{2}H(e,e'p)X: Ciofi & KopeCiofi & Kaptari PRC 2011



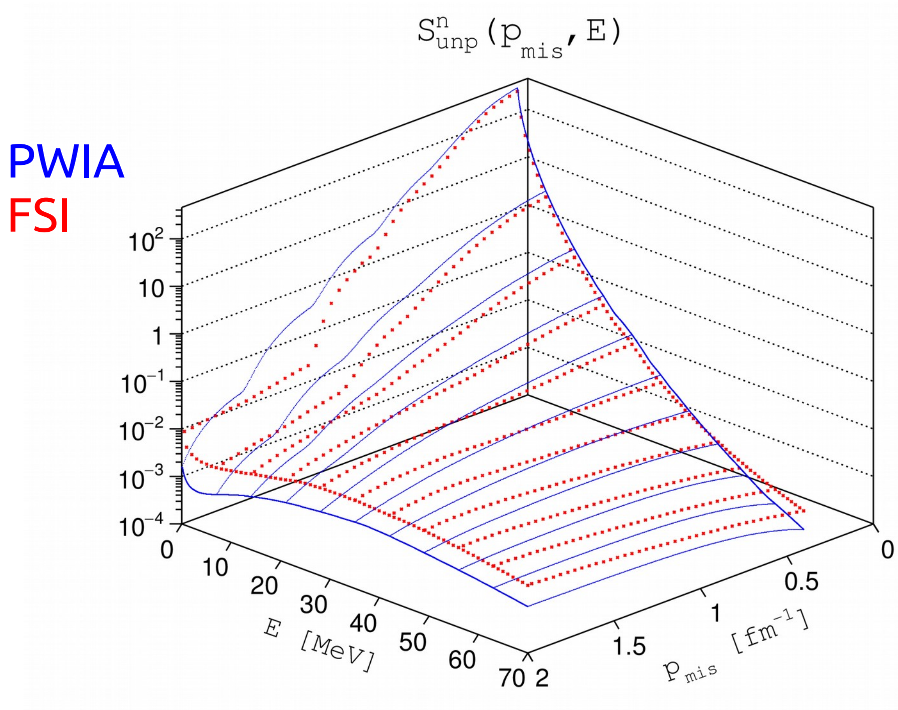
The distorted spin dependent Spectral Function

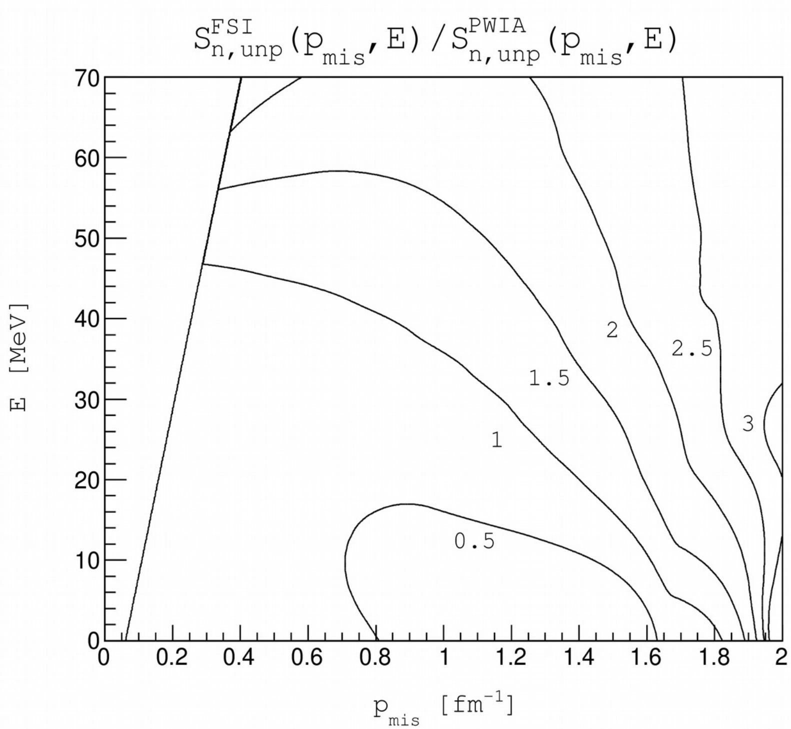
L. Kaptari, A.DD., E. Pace, G. Salmè,S. Scopetta., PRC 89 (2014) 035206

Factorization assumption: $\left[\hat{\mathcal{S}}_{Gl}(\mathbf{r_1},\mathbf{r_2},\mathbf{r_3}),\hat{j}_\mu(\mathbf{r_1})\right]=0$

$$S^{N\,\mathbf{S}_A}_{\lambda\lambda'}(E,\mathbf{p_{mis}})=\sum_{f_{A-1}}\sum\!\!\!\!\!\!\int_{\epsilon^*_{A-1}}\rho\left(\epsilon^*_{A-1}\right)\,\tilde{\mathcal{O}}^{N\,\mathbf{S}_A\,f_{A-1}}_{\lambda\lambda'}(\,\epsilon^*_{A-1},\mathbf{p}_{mis})\,\delta\left(E+M_A-m_N-M^*_{A-1}-T_{A-1}\right)$$

$$W^A_{\mu\nu}(\mathbf{S_A},Q^2,P_h)=\sum_{\lambda\lambda'}\sum_N\int d\mathbf{p}_{mis}\int dE\,\frac{m_N}{E_N}w^{N\,s.i.}_{\mu\nu}(p_{mis},P_h,\lambda\lambda')\mathcal{S}^{N\,\mathbf{S}_A}_{\lambda\lambda'}(\mathbf{p}_{mis},E)$$





The distorted spin dependent Spectral Function

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

- While **P**^{PWIA} is "universal", i.e. depends on groud state properties, **P**^{FSI} is dynamical (hadronizzation eff. cross section) and process dependent
- For each experimental point (x,Q^2,...) a different distorted spectral function has to be evaluated!
- Quantization axis (w.r.t. which polarizations are fixed) and eikonal direction (fixed by the "longitudinal" propagation) are different... States have to be rotated...
- **P**^{FSI} **:** a really cumbersome quantity, a very demanding evaluation (≈ 1 Mega CPU*hours @ "Zefiro" INFN-farm in Pisa, "gruppo 4")

The convolution formula 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:

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

The Collins – Sivers Asymmetries

$$A_3^{Coll.(Siv.)} \equiv \frac{\int d\phi_{S_A} d\phi_h \sin(\phi_h \pm \phi_{S_A}) \left[\sigma(\mathbf{S}_\perp^A, \phi_h, \phi_{S_A}, z) - \sigma(\mathbf{S}_\perp^A, \phi_h, \phi_{S_A} + \pi, z)\right]}{\int d\phi_h \sigma_{unpol}^A (x_{Bj}, Q^2, \mathbf{P}_h)}$$

$$\sigma^A(\mathbf{S}_\perp^A) = \sum_N \int d\mathbf{p}_{mis} \int dE \; \frac{\alpha m_N}{E_N} \left[\sigma^{eN}(\mathbf{s}_\perp^N) \; S^{N\, transverse}(E, \mathbf{p}_{mis}) + \sigma^{eN}(\mathbf{s}_\parallel^N) \; S^{N\, tr-long.}(E, \mathbf{p}_{mis}) \right]$$

This term disappears when weighted with the sinusoidal function, for the properties of the spin-dependent nucleonic tensor

The key quantityes are the *transversely polarized* and the *unpolarized* light-cone momentum distribution

$$A_3^{Coll.(Siv.)} = \frac{\int_{x_{Bj}}^A d\alpha \left[\Delta\sigma^n_{Coll.(Siv.)} \left(x_{Bj}/\alpha, Q^2, \mathbf{S}_\perp^n, z\right) f_n^\perp(\alpha, Q^2) + 2\Delta\sigma^p_{Coll.(Siv.)} \left(x_{Bj}/\alpha, Q^2, \mathbf{S}_\perp^p, z\right) f_p^\perp(\alpha, Q^2)\right]}{\int_{x_{Bj}}^A d\alpha \left[\sigma^n \left(x_{Bj}/\alpha, Q^2, z\right) f_n(\alpha, Q^2) + 2\sigma^p \left(x_{Bj}/\alpha, Q^2, z\right) f_p(\alpha, Q^2)\right]}$$

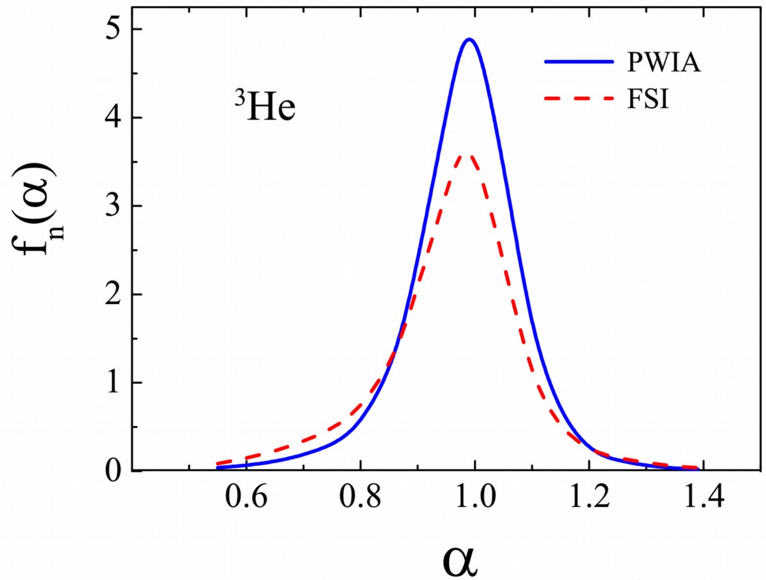
Light-cone momentum distributions, strongly picked around $\alpha = 1$

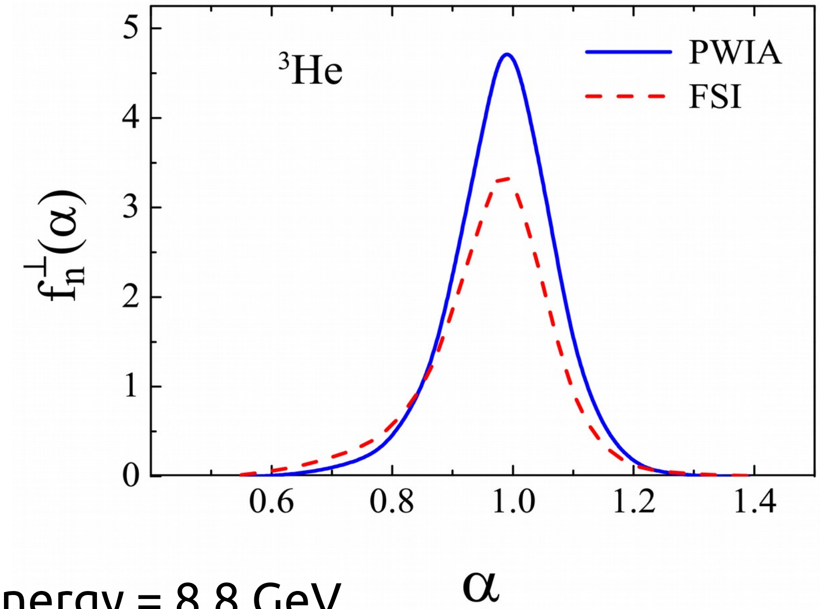
$$A_3^{Coll.(Siv.)} \simeq \frac{\left[\Delta\sigma^n_{Coll.(Siv.)} \left(x_{Bj}, Q^2, \mathbf{S}_\perp^n, z\right) \int_{x_{Bj}}^A d\alpha f_n^\perp(\alpha, Q^2) + 2\Delta\sigma^p_{Coll.(Siv.)} \left(x_{Bj}, Q^2, \mathbf{S}_\perp^p, z\right) \int_{x_{Bj}}^A d\alpha f_p^\perp(\alpha, Q^2)\right]}{\left[\sigma^n \left(x_{Bj}, Q^2, z\right) \int_{x_{Bj}}^A d\alpha f_n(\alpha, Q^2) + 2\sigma^p \left(x_{Bj}, Q^2, z\right) \int_{x_{Bj}}^A d\alpha f_p(\alpha, Q^2)\right]}$$

Light cone momentum distributions

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

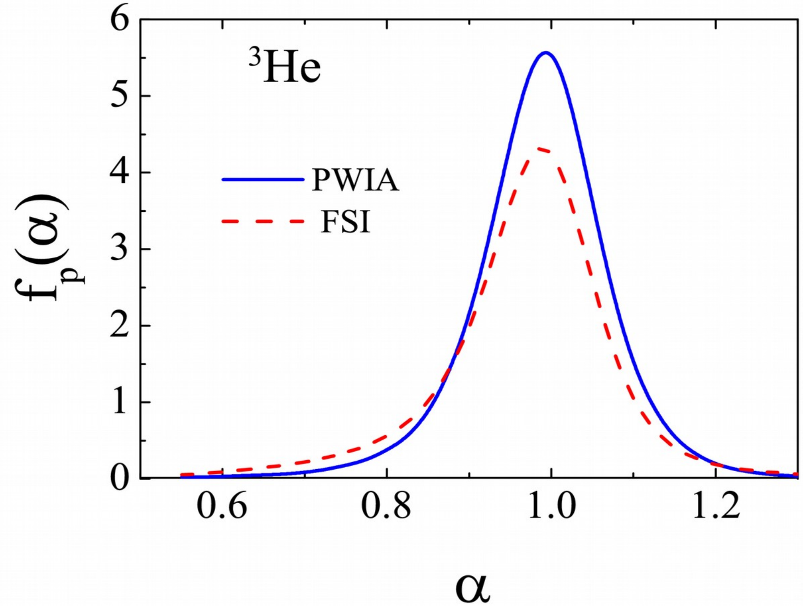
Neutron

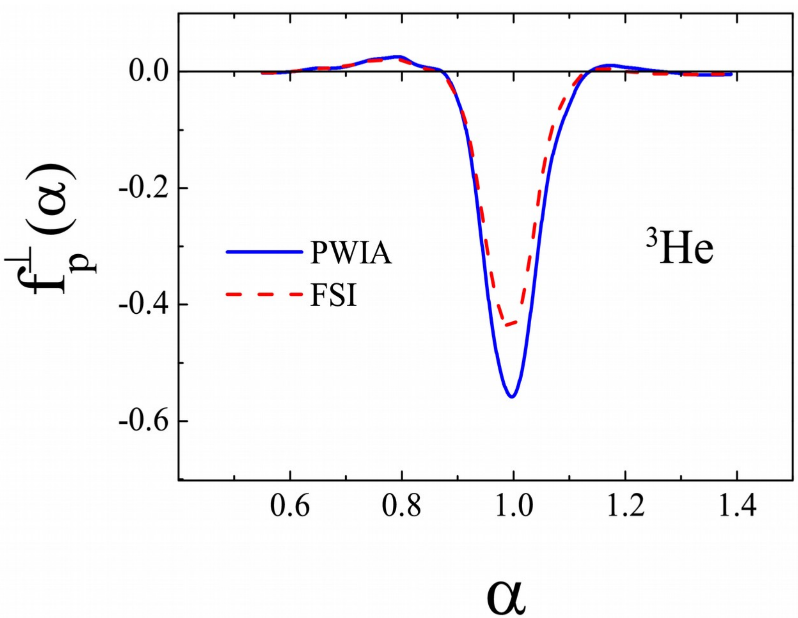




Electron beam energy = 8.8 GeV

Proton





Dilution factors and effective polarizations

$$d_{p(n)}(x,z) = \frac{\sigma^{p(n)}(x_{Bj},Q^2,z)}{\langle N_n\rangle\sigma^n(x_{Bj},Q^2,z) + 2\langle N_p\rangle\sigma^p(x_{Bj},Q^2,z)}$$

$$\langle N_n\rangle = \int d\alpha f_n(\alpha,Q^2) \qquad \langle N_p\rangle = \int d\alpha f_p(\alpha,Q^2)$$

$$p_n = \int d\alpha f_n^{\perp}(\alpha,Q^2) \qquad p_p = \int d\alpha f_p^{\perp}(\alpha,Q^2)$$

Effective polarizations (FSI/PWIA) differ for about 10-15%, but the products with the dilution factors change very little! Therefore:

$$A_n^i \simeq \frac{1}{p_n^{PWIA}d_n^{PWIA}}\left(A_3^{PWIA,i} - 2p_p^{PWIA}d_p^{PWIA}A_p^{exp,i}\right) \simeq \frac{1}{p_n^{FSI}d_n^{FSI}}\left(A_3^{FSI,i} - 2p_p^{FSI}d_p^{FSI}A_p^{exp,i}\right)$$

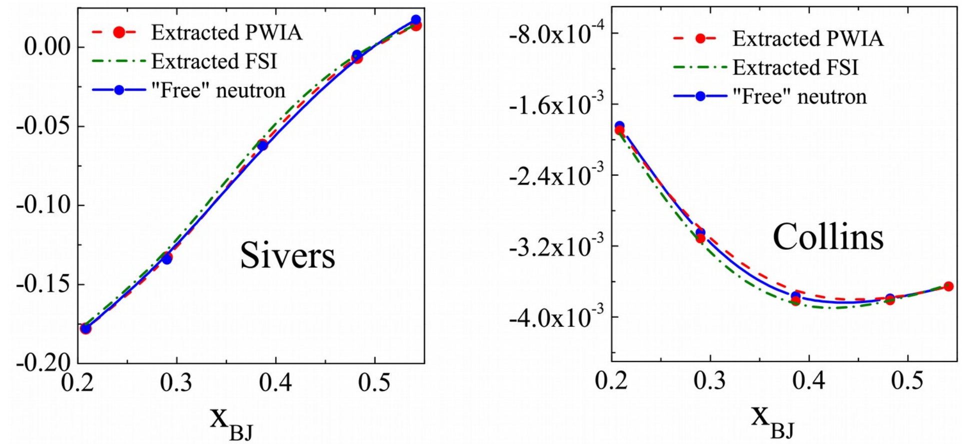
Good news from GEA studies of FSI!

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

E_{beam}, GeV	x_{Bj}	ν GeV	p_π GeV/c	$f_n(x,z)$	$\langle p_n \rangle f_n$	$f_p(x,z)$	$\langle p_p \rangle f_p$
8.8	0.21	7.55	3.40	0.304	0.266	0.348	-8.410^{-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: $\langle p_n \rangle = 0.756$, $\langle p_p \rangle = -0.0265$, $\langle N_n \rangle = 0.85$, $\langle N_p \rangle = 0.87$, $\langle \sigma_{eff} \rangle = 71\ mb$

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}



The usual extraction procedure is safe!

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

- Notice that: at Jlab12 we are dealing with extremely small statistical errors!
- We have the ^{3}He Spectral Function for different typical JLab12 SiDIS kinematics! **A.DD., L.P. Kaptari, E. Pace, G. Salmè, S. Scopetta, "ready" for submission**
- **The extraction procedure can be carefully tested in MC simulating the phase space of the JLab ^{3}He target dedicated experiments (SBS, Solid)**

Conclusions and perspectives

- We are studying SiDIS processes off ^{3}He beyond the NR, PWIA approach.
  We have encouraging results concerning:

  - FSI effects evaluated through the Generalized Eikonal Approximation: a distorted spin dependent spectral function has been studied (still NR);

  - Relativistic effects (in PWIA) through an analysis of the LF spectral function (not presented today)

  E. Pace, A.DD., M. Rinaldi, G. Salmè, S. Scopetta, Few Body Syst. 54 (2013) 1079

- Next steps:

  - relativistic FSI

  - interaction with the JLab12 MonteCarlo comunity to merge the distorted spectral function in the JLab12 SiDIS MC

Backup – n from ^{3}He, SiDIS case

- A realistic spin-dependent spectral function of 3He (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 TMDs and FFs whenever available:

  $f_1^q(x, p_T^2)$ Glueck et al., EPJ C (1998) 461 ,

  $f_{1T}^{\perp q}(x, p_T^2)$ Anselmino et al., PRD 72 (2005) 094007,

  $D_1^{q,h}(z, k_T^2)$ Kretzer, PRD 62 (2000) 054001

- Models for the unknown TMDs and FFs:

  $h_1^q(x, p_T^2)$ Glueck et al., PRD 63 (2001) 094005,

  $H_1^{\perp q,h}(z, k_T^2)$ Amrath et al., PRD 71 (2005) 114018

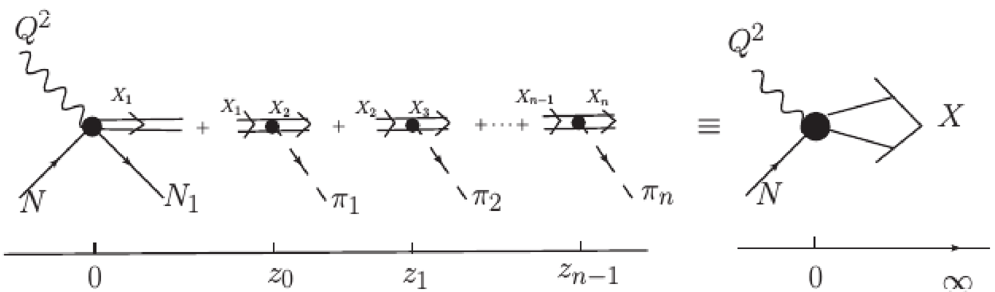
Results will be model dependent. Anyway, the aim for the moment is to study nuclear effects.

Backup – FSI: the hadronization model

Hadronization model (Kopeliovich et al., NPA 2004)

+ σ_{eff} *model* for SiDIS (Ciofi & Kopeliovich, EPJA 2003)

σ_{eff} *GEA + hadronization model* succesfully applied to unpolarized to SiDIS $^{2}H(e,e'p)X$ (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 (i.e. $\sigma_{tot}^{NN} = 40\ mb$ $\sigma_{tot}^{\pi N} = 20\ mb$)