Sivers Asymmetry

for the proton and the neutron (^{3}He)

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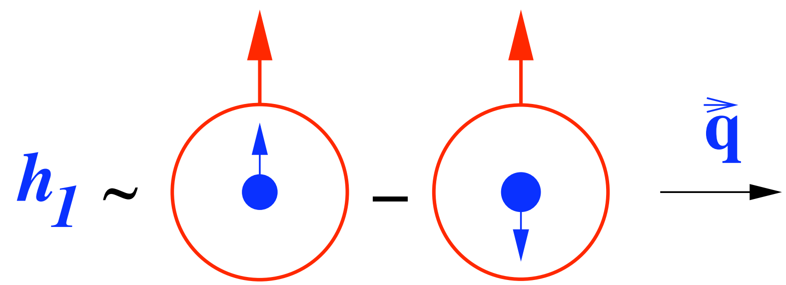
May 15, 2008

Outline

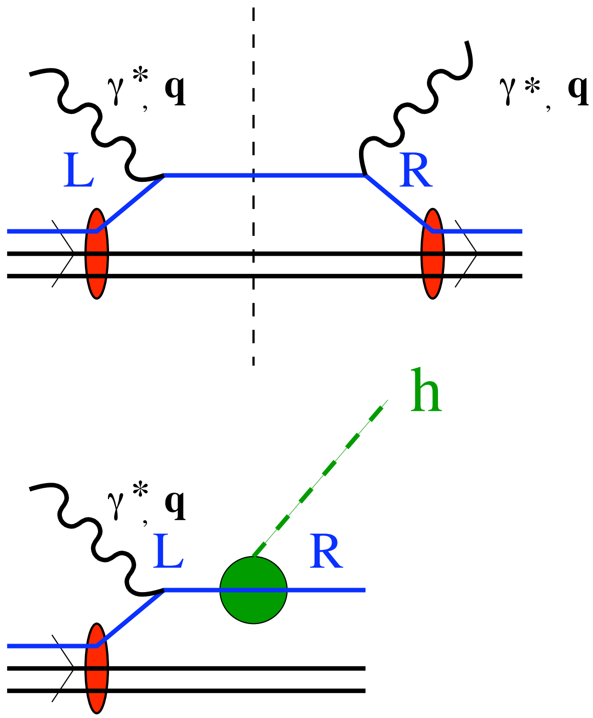
- Transversity observables in Semi-inclusive DIS (SiDIS): Sivers (and Collins) Single Spin Asymmetries (SSAs)
- A quark model calculation of the Sivers function
  (A. Courtoy, F. Fratini, S.S. and V. Vento, arXiv:0801.4347 [hep-ph])
- Relevance of the neutron information $\longrightarrow {}^3\vec{He}$:
  An Impulse Approximation approach to SiDIS off ${}^3\vec{He}$
  (S.S., PRD 75 (2007) 054005)
- Conclusions

The *Transversity* distribution h_1

How many $\perp$-polarized partons
in a $\perp$-polarized target?
(Bj limit: $Q^2, \nu \to \infty$)



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



But Ok in SiDIS !

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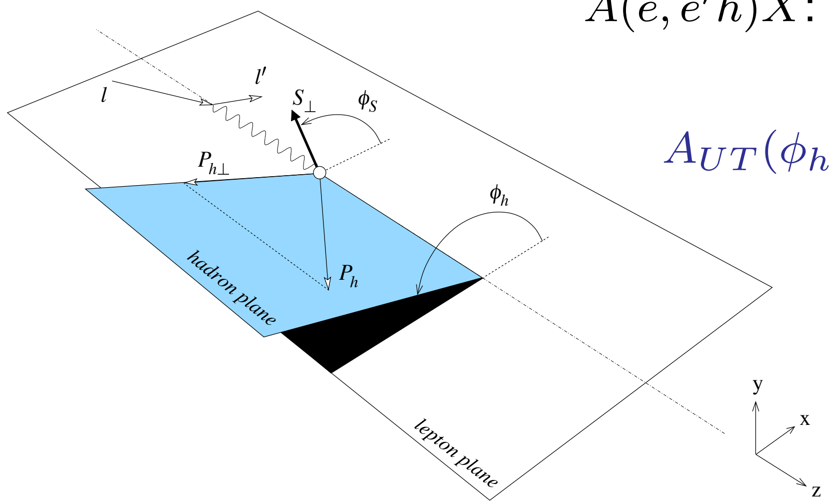
Single Spin Asymmetries (SSAs) - 1



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

$$A_{UT}(\phi_h,\phi_S) \equiv \frac{d\sigma(\phi_h,\phi_S) - d\sigma(\phi_h,\phi_S+\pi)}{d\sigma(\phi_h,\phi_S) + d\sigma(\phi_h,\phi_S+\pi)} \equiv \frac{d^6\sigma_{UT}}{d^6\sigma_{UU}}$$

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

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

- Sivers: correlations between $\mathbf{k}_\perp$ of the parton and $\vec{S}_\perp$ $\rightarrow$ parton OAM !

.

$$A_{UT}^{Sivers} = \frac{\int d\phi_S d\phi_h \sin(\phi_h - \phi_S) d^6\sigma_{UT}}{\int d\phi_S d\phi_h d^6\sigma_{UU}}$$

- Collins: due to FSI

$$A_{UT}^{Collins} = \frac{\int d\phi_S d\phi_h \sin(\phi_h + \phi_s) d^6\sigma_{UT}}{\int d\phi_S d\phi_h d^6\sigma_{UU}}$$

SSAs - 2

SSAs in terms of parton distributions and fragmentation functions:

- $A_{UT}^{Sivers} = \frac{1-y}{1-y+y^2/2}|\mathbf{S_T}|N^{Sivers}/D$
- $A_{UT}^{Collins} = \frac{1-y}{1-y+y^2/2}|\mathbf{S_T}|N^{Collins}/D$

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

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

$$D = \sum_q e_q^2 \int d\phi_S d\phi_h d^2\kappa_{\mathbf{T}} d^2\mathbf{k_T} \delta^2(\mathbf{k_T} + \mathbf{q_T} - \kappa_{\mathbf{T}}) f_1^q(x, \mathbf{k_T^2}) D_1^{q,h}(z, (z\kappa_{\mathbf{T}})^2)$$

$$x = \frac{Q^2}{2P \cdot q} \qquad y = \frac{P \cdot q}{P \cdot l} \qquad z = \frac{P \cdot h}{P \cdot q}$$

Sivers function - Definition

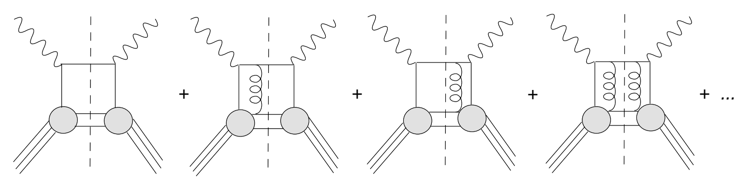
A Transverse Momentum Dependent (TMD) Parton Distribution (PD).
Asymmetry of unpolarized partons with given k_T in a transversely polarized target:

$$f_{1T}^{\perp Q}(x,k_T) = -\frac{M}{4k_x}\int \frac{d\xi^- d^2\vec{\xi}_T}{(2\pi)^3} e^{-i(x\xi^- P^+ - \vec{\xi}_T\cdot\vec{k}_T)} \times \{ \langle PS_y = 1|\hat{O}_Q|PS_y = 1\rangle - \langle PS_y = -1|\hat{O}_Q|PS_y = -1\rangle \} .$$

where $\hat{O}_Q = \bar{\psi}_Q(0,\xi^-,\vec{\xi}_T)\mathcal{L}^\dagger_{\vec{\xi}_T}(\infty,\xi^-)\gamma^+\mathcal{L}_0(\infty,0)\psi_Q(0,0,0)$,
and the gauge link:

$$\mathcal{L}_{\vec{\xi}_T}(\infty,\xi^-) = P\exp\left(-ig\int_{\xi^-}^{\infty} A^+(\eta^-,\vec{\xi}_T)d\eta^-\right)$$

$\simeq$



No gauge link (i.e., no FSI @ leading twist) $\longrightarrow$ $f_{1T}^{\perp q}(x,k_T) = 0$

S. Brodsky, D. Hwang, I Schmidt, PLB 530 (2002) 99; J. Collins NPB 396, (1993) 161
A.V. Belitsky, X. Ji, F. Yuan NPB 656 (2003) 165.

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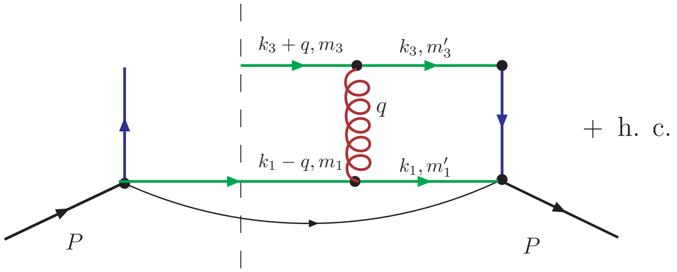
Sivers function - present knowledge

- Theory
  - A t-odd quantity? (P. Mulders, D. Boer, O. Teryaev, J. Collins, A. Drago...)
  - Relation with GPDs (?) and OAM (M. Burkardt, S. Brodsky...)
    Burkardt Sum Rule (M. Burkardt, PRD 69 (2004) 091501)
- Experiment
  - 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)
- Extraction from data
  - W. Vogelsang and F. Yuan, PRD 72, 054028 (2005)
  - M. Anselmino et al., PRD 72, 094007 (2005)
  - J.C. Collins et al., PRD 73, 014021 (2006)
- Model calculations
  - MIT: F. Yuan PLB 575, 45 (2003); I.O. Cherdnikov et al. PLB, 39 (2006).
  - quark-diquark model, A. Bacchetta et al., PLB 578, 109 (2004)...
  - HERE: a 3B - Constituent Quark Model (CQM) calculation

Sivers function in a CQM

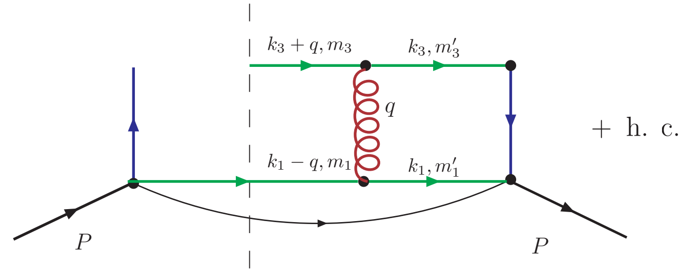
In a helicity basis, to the first non-vanishing order:



$$
\begin{aligned}
f_{1T}^{\perp Q}(x, k_T) \quad = \quad & \Im\left\{ \frac{M}{2k_x} \int \frac{d\xi^- d^2\vec{\xi}_T}{(2\pi)^3} e^{-i(x\xi^- P^+ - \vec{\xi}_T \cdot \vec{k}_T)} \langle P r S_z = 1 | \right. \\
\times \quad & \bar{\psi}_{Qi}(0, \xi^-, \vec{\xi}_T)\,(ig) \int_{\xi^-}^{\infty} A_a^+(0, \eta^-, \vec{\xi}_T) d\eta^- T_{ij}^a\, \gamma^+ \psi_{Qj}(0,0,0) \\
\times \quad & \left. |P S_z = -1\rangle + \text{h.c.} \right\}
\end{aligned}
$$

Sivers function in a CQM

In a helicity basis, to the first non-vanishing order:



$$
\begin{aligned}
f_{1T}^{\perp Q}(x,k_T) &= \Im\left\{ \frac{M}{2k_x} \int \frac{d\xi^- d^2\vec{\xi}_T}{(2\pi)^3} e^{-i(x\xi^- P^+ - \vec{\xi}_T\cdot\vec{k}_T)} \langle PrS_z = 1| \right. \\
&\times \quad \bar{\psi}_{Qi}(0,\xi^-,\vec{\xi}_T)(ig)\int_{\xi^-}^{\infty} A_a^+(0,\eta^-,\vec{\xi}_T)d\eta^- T_{ij}^a \gamma^+ \psi_{Qj}(0,0,0) \\
&\times \quad \left. |PS_z = -1\rangle + \text{h.c.} \right\}
\end{aligned}
$$

By expanding the quark fields and by properly inserting complete sets of free states (A. Courtoy, F. Fratini, S.S. and V. Vento, arXiv:0801.4347 [hep-ph])

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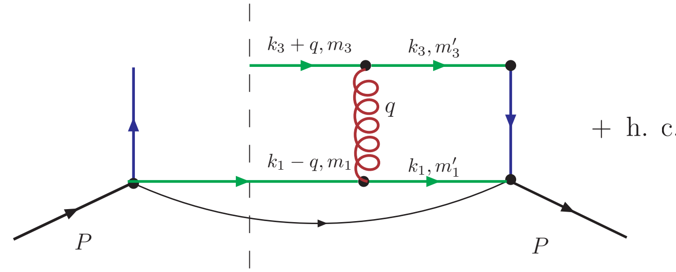
Sivers function in a CQM

In a helicity basis, to the first non-vanishing order:



$$
\begin{aligned}
f_{1T}^{\perp Q}(x, k_T) \;&=\; \Im\Bigg\{ \frac{M}{2k_x} \int \frac{d\xi^- d^2\vec{\xi}_T}{(2\pi)^3} e^{-i(x\xi^- P^+ - \vec{\xi}_T\cdot\vec{k}_T)} \langle P r S_z = 1| \\
&\times \int d\tilde{k}_3 \sum_{m_3} b^{\mathcal{Q}\dagger}_{m_3 i}(\tilde{k}_3) e^{ik_3^+\xi^- - i\vec{k}_{3T}\cdot\vec{\xi}_T} \bar{u}_{m_3}(\vec{k}_3) \\
&\times \sum_{l_n, l_1} \int d\tilde{k}_n \int d\tilde{k}_1 |\tilde{k}_1 l_1\rangle |\tilde{k}_n l_n\rangle \langle \tilde{k}_n l_n| \langle \tilde{k}_1 l_1| \\
&\times (ig) \int_{\xi^-}^{\infty} A_a^+(0, \eta^-, \vec{\xi}_T) d\eta^- T^a_{ij} \\
&\times \sum_{l'_n, l'_1} \int d\tilde{k}'_n \int d\tilde{k}'_1 |\tilde{k}'_1 l'_1\rangle |\tilde{k}'_n l'_n\rangle \langle \tilde{k}'_n l'_n| \langle \tilde{k}'_1 l'_1| \gamma^+ \\
&\times \sum_{m'_3} \int d\tilde{k}'_3\, b^{\mathcal{Q}}_{m'_3 j}(\tilde{k}'_3) u_{m'_3}(\vec{k}'_3) \,|P r S_z = -1\rangle + h.c. \Bigg\}
\end{aligned}
$$

Sivers function in CQM - 2

After some technical steps, using translational invariance:

$$
\begin{aligned}
f_{1T}^{\perp Q}(x, k_T) &= \Im\Big\{ i g^2 \frac{M}{2k_x} \int d\tilde{k}_1 d\tilde{k}_3 \frac{d^4 q}{(2\pi)^3} \delta(q^+)(2\pi)\delta(q_0) \\
&\times \delta(k_3^+ + q^+ - xP^+)\delta(\vec{k}_{3T} + \vec{q}_T - \vec{k}_T) \sum_{\mathcal{F}_1,\{m_i\}\{c_i\}} \\
&\times \Psi^{\dagger}_{r\, S_z=1}\left(\tilde{k}_3\{m_3, i, Q\};\, \tilde{k}_1\{m_1, c_1, \mathcal{F}_1\};\, \tilde{P} - \tilde{k}_3 - \tilde{k}_1, l_n\right) \\
&\times T^a_{ij} T^a_{c_1 c_1'} V(\vec{k}_1, \vec{k}_3, \vec{q}) \\
&\times \Psi_{r\, S_z=-1}\left(\tilde{k}_3 + \tilde{q}, \{m_3', j, Q\};\, \tilde{k}_1 - \tilde{q}, \{m_1', c_1', \mathcal{F}_1\};\, \tilde{P} - \tilde{k}_3 - \tilde{k}_1, l_n\right)\Big\}
\end{aligned}
$$

with the interaction given by:

$$
V(\vec{k}_1, \vec{k}_3, \vec{q}) = \frac{1}{q^2} \bar{u}_{m_3}(\vec{k}_3)\gamma^+ u_{m_3'}(\vec{k}_3 + \vec{q})\bar{u}_{m_1}(\vec{k}_1)\gamma^+ u_{m_1'}(\vec{k}_1 - \vec{q})
$$

Sivers function in a NR CQM

In a NR CQM the Sivers function becomes

$$
\begin{aligned}
f_{1T}^{\perp u(d)}(x, k_T) &= \Im\Big\{ -2ig^2 \frac{M^2}{k_x} \int d\vec{k}_1 d\vec{k}_3 \frac{d^2 \vec{q}_T}{(2\pi)^2} \delta(k_3^+ - xP^+) \delta(\vec{k}_{3T} + \vec{q}_T - \vec{k}_T) \\
&\times \sum_{m_i} \Phi^\dagger_{sf, S_z=1} \left(\vec{k}_3, m_3; \vec{k}_1, m_1; -\vec{k}_3 - \vec{k}_1, m_n \right) \frac{1 \pm \tau_3(3)}{2} \\
&\times V_{NR}(\vec{k}_1, \vec{k}_3, \vec{q}) \Phi_{sf, S_z=-1} \left(\vec{k}_3 + \vec{q}, m_3'; \vec{k}_1 - \vec{q}, m_1'; -\vec{k}_3 - \vec{k}_1, m_n \right) \Big\}
\end{aligned}
$$

with the interaction reduced to a potential

$$
\begin{aligned}
V_{NR}(\vec{k}_1, \vec{k}_3, \vec{q}) &= \frac{1}{2q^2} \left\{ 1 + \frac{k_3^z}{m} + \frac{\vec{q} \cdot \vec{k}_3}{4m^2} + i \frac{(\vec{q} \wedge \vec{\sigma}_3)_z}{2m} + i \frac{\vec{\sigma}_3 \cdot (\vec{k}_3 \wedge \vec{q})_z}{4m^2} \right\} \\
&\times \left\{ 1 + \frac{k_1^z}{m} - \frac{\vec{q} \cdot \vec{k}_1}{4m^2} - i \frac{(\vec{q} \wedge \vec{\sigma}_1)_z}{2m} - i \frac{\vec{\sigma}_1 \cdot (\vec{k}_1 \wedge \vec{q})_z}{4m^2} \right\}
\end{aligned}
$$

The Sivers function can be now evaluated in any NR 3-body model

Example: the Isgur-Karl (IK) CQM

IK is a well known model based on an ONE GLUON EXCHANGE (OGE) correction to the H.O., generating a hyperfine interaction which breaks SU(6). Nucleon state:

$$|N\rangle = a|^2S_{1/2}\rangle_S + b|^2S'_{1/2}\rangle_S + c|^2S_{1/2}\rangle_M + d|^4D_{1/2}\rangle_M$$

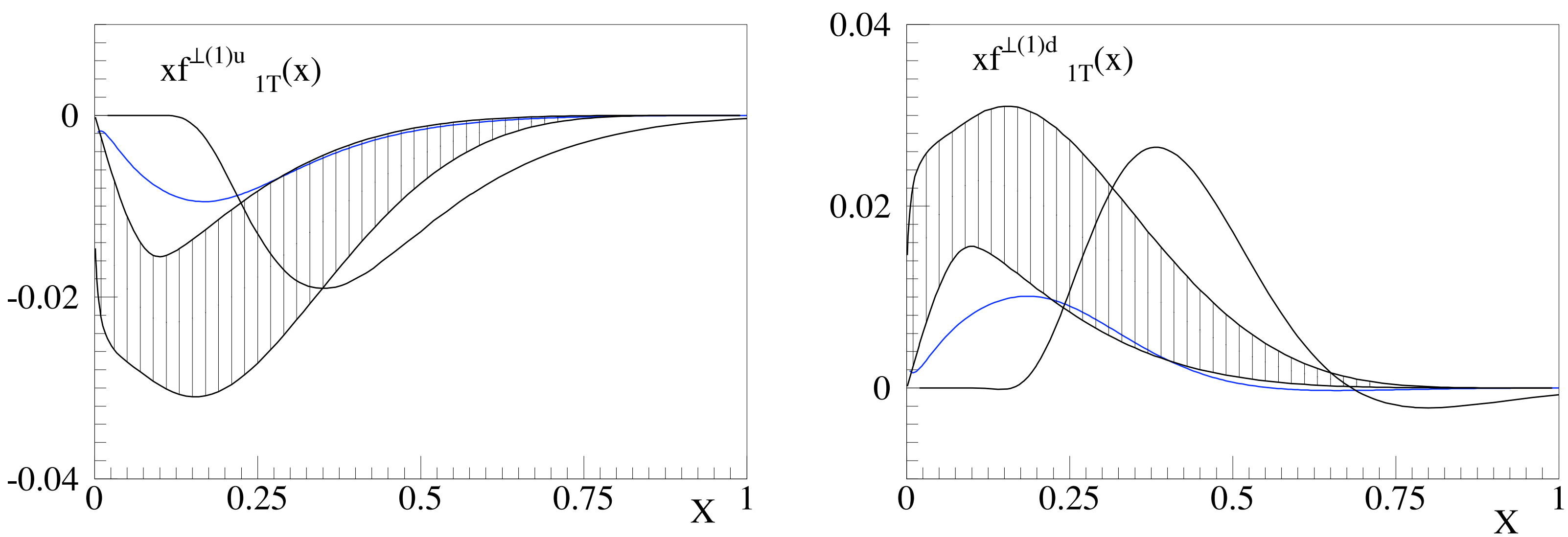
Notation: $|^{2S+1}X_J\rangle_t$; $t = A, M, S$ = symmetry type
From spectroscopy: $a = 0.931$, $b = -0.274$, $c = -0.233$, $d = -0.067$

Suitable framework fo the calculation of the Sivers function:

- Gross features of the standard PDs are well reproduced;
- Based on a OGE mechanism, the same generating the FSI in the definition of the Sivers function.

Nevertheless: the model results are related to a low momentum scale (hadronic scale, μ_o^2). Since there are only valence quarks, the scale has to be very low (around 0.1 GeV^2 according to NLO pQCD). Data are taken in DIS kinematics, high momentum scale Q^2.
QCD evolution needed!
QCD evolution largely unknown for the Sivers function and all the TMDs!

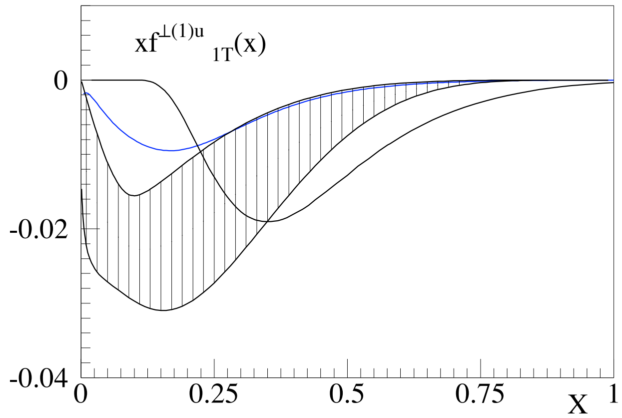
Results for $f_{1T}^{\perp(1)q}(x) = \int d^2\vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp q}(x, k_T)$.

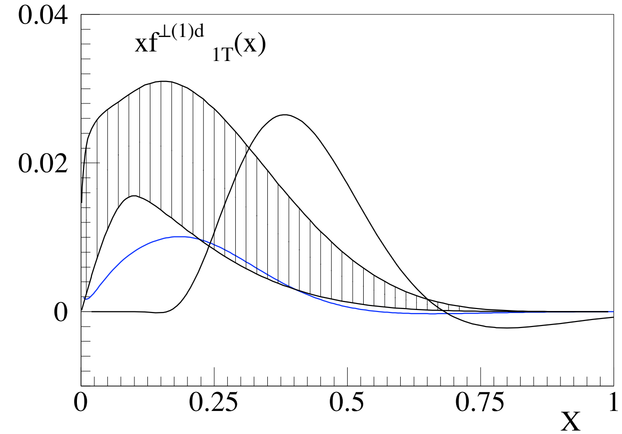


- shaded area: $1 - \sigma$ region of the best fit of the Sivers function extracted from HERMES data, at $Q^2 = 2.5$ GeV^2 (J.C. Collins et al., PRD 73 (2006) 014021);
- full: results at the hadronic scale $\mu_o^2 = 0.1$ GeV^2;
- Blue: results after NLO-*standard* evolution to $Q^2 = 2.5$ GeV^2;

Sivers in CQM: discussion of results

- Evolution needed!
- *Correct* Evolution missing.
- Difference in sign, and little difference in size between u and d consistent with results of Impact Parameter Dependent PDs calculated in IK;
- Burkardt Sum Rule, $u \simeq -d$, confirmed to a large extent.
- Encouraging agreement: (at least) not worse than the results of other calculations.
- Importance of "small" components: relevance of further analysis with other (relativistic) models.





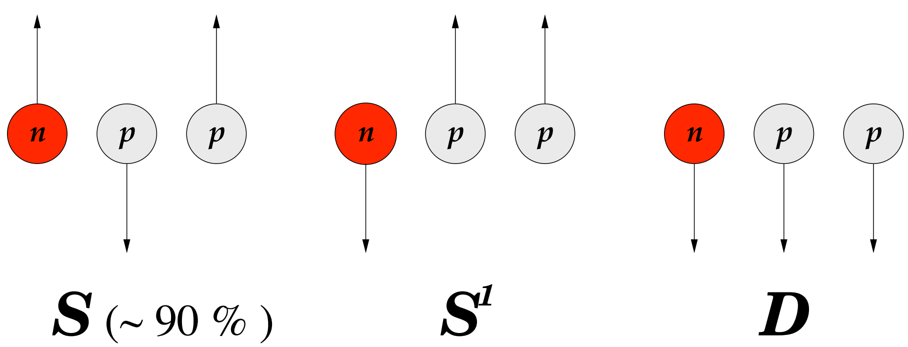
SSAs - experimental knowledge

- 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)

Importance of the neutron!

2 experiments planned at JLAB on ^{3}He
(E-06-010 Chen - Peng; E-06-011 Cisbani - Gao)

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



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

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

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

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

It was found that the formula

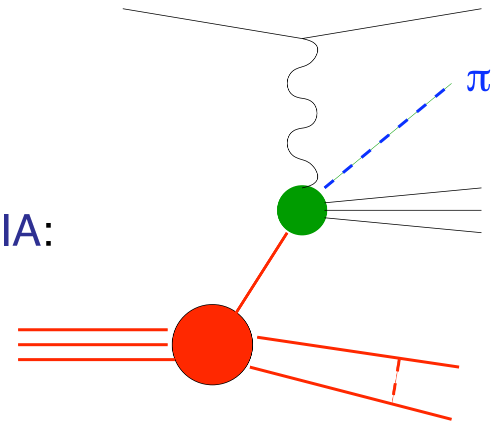
$$A_n \simeq \frac{1}{p_n f_n}\left(A_3^{exp} - 2 p_p f_p A_p^{exp}\right) \; ,$$

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

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

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

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



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

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

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

$$A \simeq \int d\vec{p}\, dE \ldots\, \vec{P}(\vec{p}, E)\ f_1^q \left(\frac{Q^2}{2p \cdot q}, \mathbf{k_T^2} \right)\ D_1^{q,h} \left(\frac{p \cdot h}{p \cdot q}, \left(\frac{p \cdot h}{p \cdot q} \kappa_\mathbf{T} \right)^2 \right)$$

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

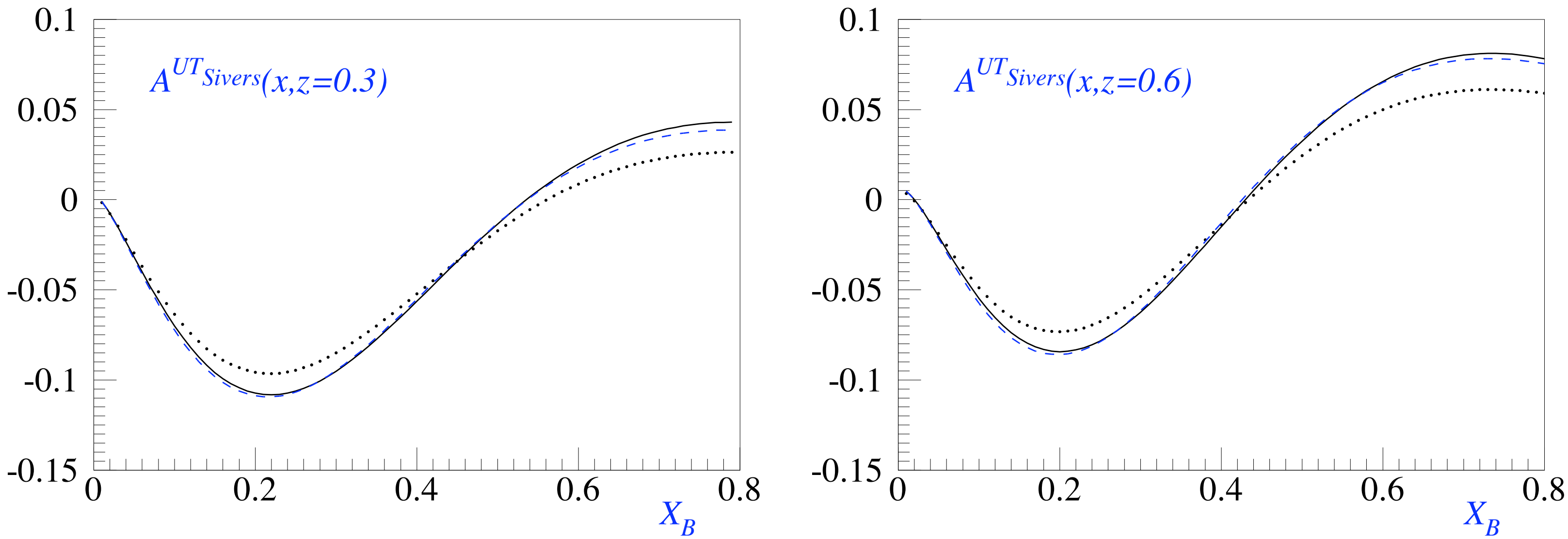
$\vec{n}$ from $^3\vec{He}$: SiDIS case

Ingredients of the calculations:

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

The aim is to study nuclear effects, not to obtain realistic figures: any reasonable input for the nucleon structure is ok.

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



FULL: Neutron (model)

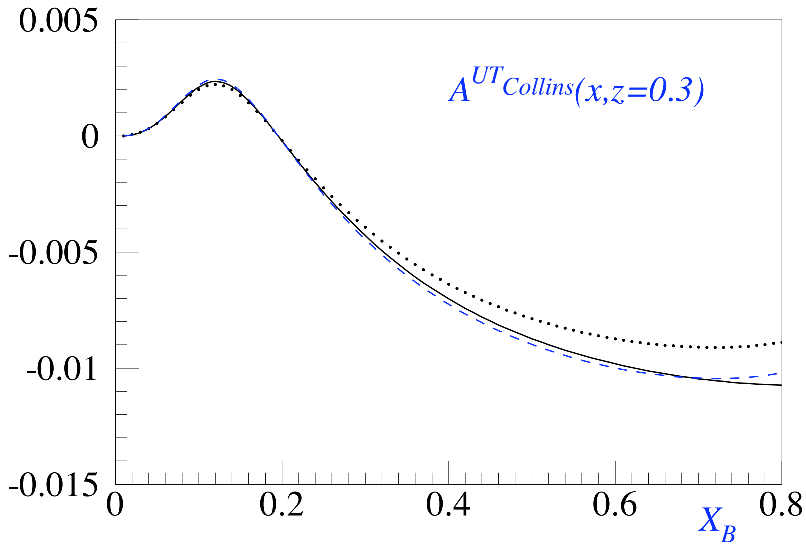
DOTS: Neutron (model) extracted from ^3He (calculation) neglecting any nuclear structure effects

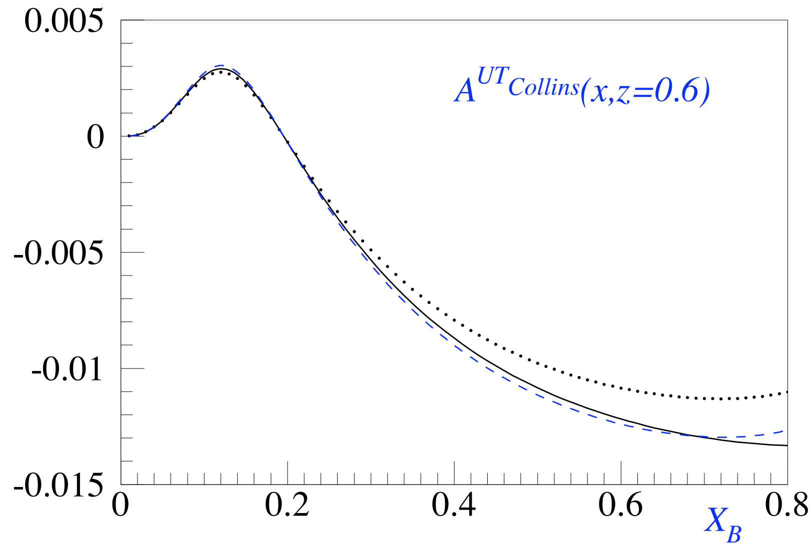
DASHED : Neutron (model) extracted from ^3He (calculation) taking into account nuclear structure effects through the formula:

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

May 15, 2008

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





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

Results: SSAs for $\vec{n}$ from $^3\vec{H}e$ @ JLab

Our findings are easily explained: in JLab kinematics one has

$$E_i \simeq 6\,GeV \qquad 0.13 \leq x \leq 0.41$$
$$z \simeq 0.5 \rightarrow E_\pi \simeq 3\,GeV \simeq p_\pi \rightarrow current\ fragmentation$$

and the π emitted forward, $\theta_{qh} \leq 16^o$, so that $\theta_{ph} \simeq \theta_{pq}$; therefore

$$\frac{p \cdot h}{p \cdot q} \simeq \frac{E_h\,(p_0 - p\cos\theta_{ph})}{\nu\,(p_0 - p\cos\theta_{pq})} \simeq \frac{E_h}{\nu} = z\ ,$$

so that:

$$D_1^{q,h}\left(\frac{p \cdot h}{p \cdot q}, \left(\frac{p \cdot h}{p \cdot q}\kappa_{\mathbf{T}}\right)^2\right) \longrightarrow D_1^{q,h}(z, (z\kappa_{\mathbf{T}})^2)$$

Only negligible nuclear effects in the fragmentation functions!

The same results as in the DIS case, in Impulse Approximation, is found.

Conclusions

- My results:

  An analysis of the Sivers function in a 3-Body model:
  reasonable agreement with data and with the theoretical wisdom;
  Evolution needed!

  A realistic study of $^3\vec{H}e(e,e'\pi)X$ @ JLab kinematics:
  In IA, nuclear effects in the extraction of the neutron information are under control

- To go beyond:

  for the proton target:
  Calculation of the Sivers function in other (relativistic) models;
  proper QCD evolution

  for ^{3}He:
  Estimate of effects beyond IA and beyond JLab kinematics:
  study of FSI for the propagation of the π in the nuclear medium, crucial for other studies: Color Transparency, Deeply Virtual Meson Production...

IPDPDs

$$\rho_q(\vec{b}) = \int dx \, \rho_q(x, \xi = 0, \vec{b})$$