Why EIC with polarized beams? Discussion

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Friday EIC meeting

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Introduction

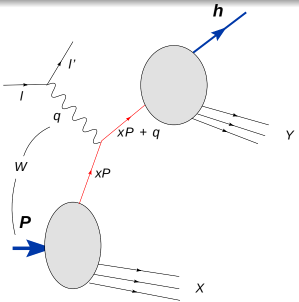
The biggest Single Spin Asymmetries ($\sim 40\%$) were measured in $P^\uparrow P \to \pi X$. They were thought to be *negligible* due to "simple" arguments of helicity conservation in QED and QCD interactions, thus $A_N \sim \alpha_s \frac{m_q}{P_T}$. Nevertheless *experimental* measurements proved this prediction to be wrong.

$\langle cos\phi \rangle$ asymmetry in unpolarised SIDIS was proposed as a *"clean test of perturbative QCD"* and again *experimental* measurements revealed that such an asymmetry carries information on intrinsic motion of partons inside the proton.

Experiments with polarized target and beams were always source of new information about partonic structure of hadrons and frequently changed our understanding of parton dynamics.

Future experimental measurements at EIC will bring us valuable information on the structure of the proton and on the validity of our current theoretical framework.

Semi Inclusive Deep Inelastic Scattering



$l + P \to l' + h + X$

Kinematical variables:

$Q^2 = -q^2$,
$x_{Bj} = \frac{Q^2}{2P \cdot q}$,
$y = \frac{Q^2}{(s - m_p^2) x_{Bj}}$,
$z = \frac{P \cdot h}{P \cdot q}$,
$W^2 = Q^2 \frac{1 - x_{Bj}}{x_{Bj}} + m_p^2$

Cross section

$$d\sigma \equiv \frac{d^5 \sigma^{\ell p \to \ell' h X}}{dx_{Bj} dy dz_h d^2 \mathbf{P}_T} \propto L_{\mu\nu} W^{\mu\nu}$$

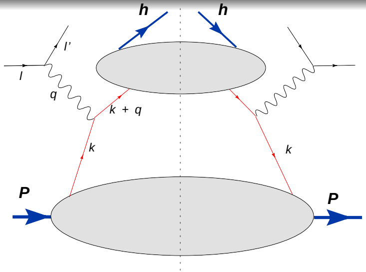
Leptonic tensor

$$L_{\mu\nu} = 2(l_\mu l'_\nu + l'_\nu l_\nu - l \cdot l' g_{\mu\nu}) + 2i\lambda_e \epsilon_{\mu\nu\rho\sigma} l^\rho l'^\sigma$$

Hadronic tensor

$$W^{\mu\nu} \propto \sum_X \int \frac{d^3 \mathbf{P}_X}{2P_X^0} \delta^{(4)}(q + P - P_X - P_h) \langle PS | J^\mu(0) | h, X \rangle \langle h, X | J^\nu(0) | PS \rangle$$

TMD Factorization in Semi Inclusive Deep Inelastic Scattering



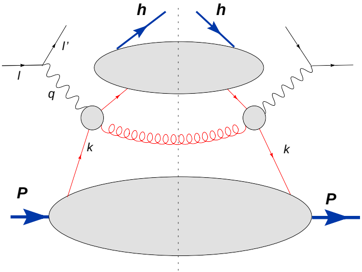
TMD factorization Ji, Ma, Yuan 2005 is valid for soft $P_T \sim \Lambda_{QCD}$ $Q^2 \gg \Lambda^2_{QCD}$ and describes SIDIS cross section as convolution of Transverse Momentum Dependent (TMD) distribution and fragmentation functions.

Cross section

$$d\sigma \propto L_{\mu\nu} W^{\mu\nu} = \sum_q \int d^2\mathbf{k}_\perp d^2\mathbf{p}_\perp f_{q/p}(x, \mathbf{k}_\perp, ...) \otimes \sigma \otimes D_q^h(z, \mathbf{p}_\perp, ...)$$

Intrinsic transverse momenta $\mathbf{k}_\perp$ and $\mathbf{p}_\perp$ are of non perturbative origin. Polarised case is explored in TMD factorization formalism Kotzinian 1995; Mulders, Tangerman 1995; Goeke, Metz, Schlegel 2005, Bacchetta et al 2007

Collinear Factorization in Semi Inclusive Deep Inelastic Scattering



Collinear factorization Collins, Soffer, Sterman 1982, Meng, Olness, Soper 1996 is valid for hard $P_T \sim Q \gg \Lambda_{QCD}$ and describes SIDIS cross section as convolution of usual integrated distribution and fragmentation functions.

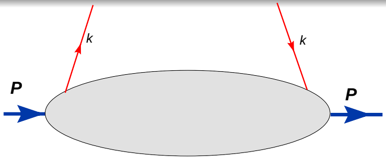
Gluon radiation generates P_T of the produced hadron.

Cross section

$$d\sigma \propto L_{\mu\nu} W^{\mu\nu} = \sum_q \int f_{q/p}(x, ...) \otimes \sigma \otimes D_q^h(z, ...)$$

In polarized case multy-parton correlations play role in collinear factorization formalism Efremov, Teryaev 1982; Qiu, Sterman 1991; Ji, Qui, Vogelsang, Yuan 2006.

Quark-quark Correlator



$$\Phi_{ij}(P,k,S) = \int \frac{d^4\xi}{(2\pi)^4} e^{ik\cdot\xi} \langle P,S|\bar{\psi}_j(0)\mathcal{W}(0,\xi|n_-)\psi_j(\xi)|P,S\rangle$$

Mulders, Tangerman 1995; Goeke, Metz, Schlegel 2005, Bacchetta et al 2007

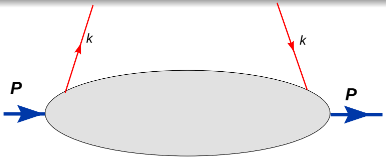
Gauge link $\mathcal{W}(0,\xi|n_-)$ ensures gauge invariance of the correlator.
TMD distribution functions can be found via k^- integration

$$\Phi(P,k_\perp,S) = \int dk^- \Phi(P,k,S)$$

Dirac decomposition is done by

$$\Phi^{[\Gamma]}(P,k_\perp,S) = \frac{1}{2} Tr(\Phi(P,k_\perp,S)\Gamma)$$

Quark-quark Correlator



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Twist-2 decomposition contains 8 functions:

$$\Phi^{[\gamma^+]}(P,k_\perp,S) = f_1(x,k_\perp^2) - \frac{\epsilon_T^{ij} k_{\perp i} S_{Tj}}{M} f_{1T}^\perp(x,k_\perp^2)$$

$$\Phi^{[\gamma^+\gamma_5]}(P,k_\perp,S) = S_L g_{1L}(x,k_\perp^2) - \frac{k_\perp \cdot S_T}{M} g_{1T}^\perp(x,k_\perp^2)$$

$$\Phi^{[i\sigma^{i+}\gamma_5]}(P,k_\perp,S) = S_T^i h_1 + S_L \frac{k_\perp^i}{M} h_{1L}^\perp - \frac{k_\perp^i k_\perp^j - 1/2 k_\perp^2 g_T^{ij}}{M^2} S_{Tj} h_{1T}^\perp - \frac{\epsilon_T^{ij} k_{\perp j}}{M} h_1^\perp$$

"Amsterdam notation" is used for the TMDs

Parton distribution functions

- Collinear Parton Distribution Functions:
  $f_{a/A}(x_a)$, $\underbrace{\Delta q(x_a)}_{g_1}$, $\underbrace{\Delta_T q(x_a)}_{Transversity\ h_1}$
- Transverse Momentum Dependent (TMD) PDFs
  Kotzinian 1995; Mulders, Tangerman 1995; Bacchetta et al 07; Anselmino et al 06

1. Hadron A unpolarized: $\hat{f}_{a/A}(x_a, k_{\perp a})$, $\underbrace{\Delta \hat{f}_{s_y/A}(x_a, \mathbf{k}_{\perp a})}_{\text{Boer-Mulders} \quad h_1^\perp}$
2. Transversely polarised hadron $A^\uparrow$:
   $\underbrace{\Delta \hat{f}_{a/A^\uparrow}(x_a, \mathbf{k}_{\perp a})}_{\text{Sivers} \quad f_{1T}^\perp}$, $\underbrace{\Delta \hat{f}^q_{s_x/A^\uparrow}(x_a, \mathbf{k}_{\perp a}), \Delta^- \hat{f}_{s_y/A^\uparrow}(x_a, \mathbf{k}_{\perp a})}_{\text{Transversity} \quad h_1,\, h_{1T}^\perp}$,
   $\underbrace{\Delta \hat{f}_{s_z/A^\uparrow}(x_a, \mathbf{k}_{\perp a})}_{g_{1T}^\perp}$
3. Longitudinally polarized hadron $A^\rightarrow$:
   $\underbrace{\Delta \hat{f}_{s_z/+}(x_a, \mathbf{k}_{\perp a})}_{\Delta q}$, $\underbrace{\Delta \hat{f}_{s_x/+}(x_a, \mathbf{k}_{\perp a})}_{h_{1L}^\perp}$

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- Electron Ion Collider project is proposed to study Polarized SIDIS at the medium – high energies $200 \leq \sqrt{s} \leq 3000$ GeV^2 thus providing a big span in $1 \leq Q^2 \leq 100$ GeV^2 and $0 \leq P_T \leq 3$ GeV.
- Complete spin and flavour decomposition is possible both in valence and sea-quark region $x \sim 10^{-4}$.
- Possibility of high Q^2 range allows to study twist-2 functions and higher twist content of the nucleon.
- Range of P_T allows to study intermediate region where both TMD and collinear factorizations are valid.
- Changing Q^2 at some fixed x provides information on Q^2 behaviour of the asymmetries and Q^2 evolution of TMDs.

TMDs and Structure functions Unpolarised hadron

$$F_{UU} = f_1 \otimes D_1$$

$$F_{UU}^{\cos\phi_S} = \frac{1}{Q}(f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp} + ...)$$

$$F_{UU}^{\cos 2\phi_S} = \underbrace{h_1^{\perp}}_{Boer-Mulders} \otimes \underbrace{H_1^{\perp}}_{Collins\ FF}$$

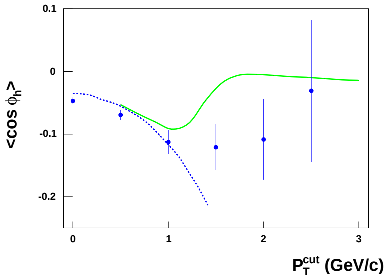
$${F_{AB}}^{\sin(\cos)\phi_X}$$

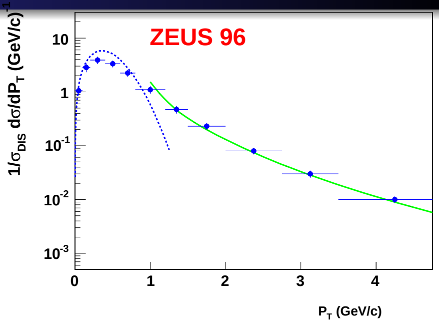
beam polarization $A = U, L$, hadron polarization $B = U, L, T$ and contribution to cross section

$\sigma \propto \sin(\cos)\phi_X \cdot {F_{AB}}^{\sin(\cos)\phi_X}$

Boer-Mulders destribution (Boer and Mulders 1998) describes distribution of transversely polarised quarks in unpolarised hadron.
Measuring F_{UU} we access non perturabtive dynamics of parton motion.
Intermediate P_T region both TMD and Collinear factorizations are valid.
Using a simple gaussian approximation we can obtain values $\langle k_\perp^2 \rangle = 0.25$ GeV^2 $\langle p_\perp^2 \rangle = 0.2$ GeV^2 (Anselmino et al 2007)
Where are some hints that $\langle k_\perp^2 \rangle_u \neq \langle k_\perp^2 \rangle_d$ and on x and z dependence of $\langle k_\perp^2 \rangle$ and $\langle p_\perp^2 \rangle$.

From low to high P_T Anselmino et al 2007





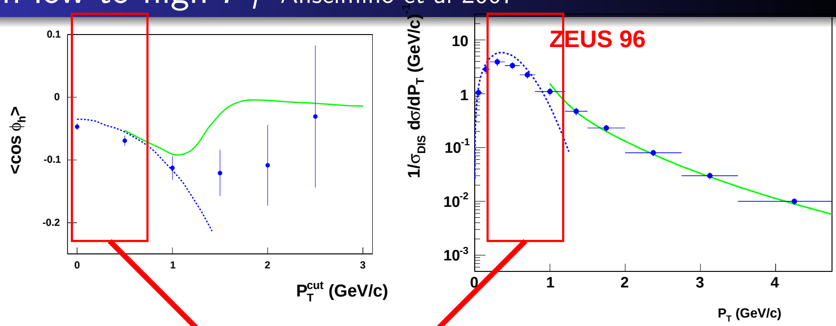
TMD σ_0 and collinear QCD σ_1 cross sections are included:

$$d\sigma \;=\; \alpha_s^0\, d\sigma_0 + \;\alpha_s^1\, d\sigma_1 + \alpha_s^2\, d\sigma_2 \simeq$$
$$\alpha_s^0\, d\sigma_0 \quad + \quad K\alpha_s^1\, d\sigma_1$$

$K \simeq 1.5$, The data are from **ZEUS** and **E665**.

Fermilab E665 Collaboration, M.R. Adams *et al.*, *Phys. Rev.* **D48** (1993) 5057.

M. Derrick *et al*, ZEUS Collaboration, *Z. Phys.* **C70** (1996) 1.



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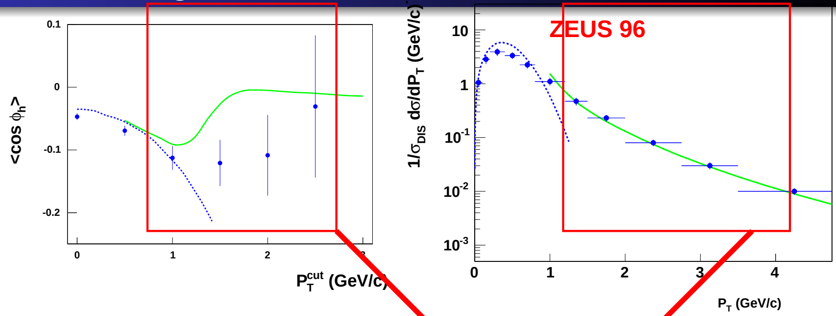
$$
\begin{aligned}
d\sigma &= \alpha_s^0\, d\sigma_0 + \alpha_s^1\, d\sigma_1 + \alpha_s^2\, d\sigma_2 \simeq \\
&\quad \alpha_s^0\, d\sigma_0 + K\alpha_s^1\, d\sigma_1
\end{aligned}
$$

$\langle k_\perp^2 \rangle = 0.25\ \mathrm{GeV}^2$ $\langle p_\perp^2 \rangle = 0.2\ \mathrm{GeV}^2$

in accordance with lattice results Musch et al, 2008



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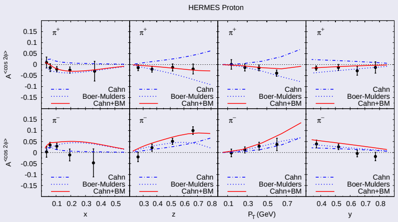
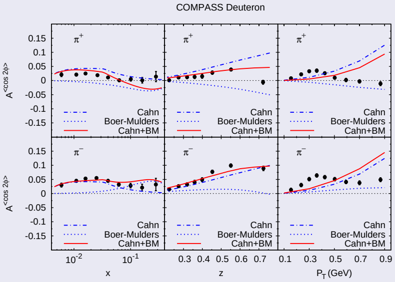
HERMES $A^{\cos 2\phi_h}$



COMPASS $A^{\cos 2\phi_h}$



$$F_{UU}^{\cos 2\phi_S} = h_1^\perp \otimes H_1^\perp + \frac{1}{Q^2} f_1 \otimes D_1$$

Barone, Melis, AP 2009 in preparation

Twist-2 contribution is comparable to higher twist contribution at low Q^2. EIC at high Q^2 allows to measure $h_1^\perp \otimes H_1^\perp$ without higher twists.

TMDs: Longitudinally polarized hadron

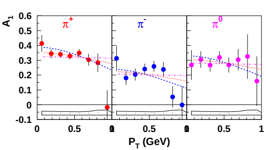
$$F_{LL} = g_{1L} \otimes D_1$$

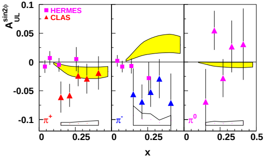
$$F_{UL}^{\sin 2\phi_S} = h_{1L}^{\perp} \otimes H_1^{\perp}$$

$h_{1L}^{\perp}$ describes distribution of transversely polarized quarks in longitudinally polarized hadron.

g_{1L} can be accessed at low x. Study of $k_\perp$ dependence of g_{1L} is possible. Is its $\langle k_\perp^2 \rangle$ equal to that of f_1?

HERMES, JLab and COMPASS measure $F_{UL}^{\sin 2\phi_S}$ and F_{LL}





Jlab CLASS collaboration Avakian et al 2009 preliminary

TMDs: Transversely polarized hadron

$$F_{UT}^{\sin(\phi_h-\phi_S)} = f_{1T}^{\perp} \otimes D_1 \quad \textit{Sivers effect}$$

$$F_{UT}^{\sin(\phi_h+\phi_S)} = h_1 \otimes H_1^{\perp} \quad \textit{Collins effect}$$

$$F_{UT}^{\sin(3\phi_h-\phi_S)} = h_{1T}^{\perp} \otimes H_1^{\perp} \quad F_{LT}^{\cos(\phi_h-\phi_S)} = g_{1T}^{\perp} \otimes D_1$$

Sivers function $f_{1T}^{\perp}$ describes distribution of unpolarised quarks in transversely polarized hadron.

Transversity h_1 describes distribution of transversely polarized quarks in transversely polarized hadron. Survives $k_\perp$ integration.

$h_{1T}^{\perp}$ describes distribution of transversely polarized quarks in transversely polarized hadron, vanishes under $k_\perp$ integration. $h_{1T}^{\perp} = g_1 - h_1$ in some models. Some preliminary data are available from HERMES and COMPASS.

$g_{1T}^{\perp}$ describes distribution of transversely polarized quarks in a longitudinally polarized hadron. *No experimental data are available!*

Sivers effect

The azimuthal asymmetry $A_{UT}^{sin(\phi_h-\phi_S)}$ arises due to Sivers function

$$f_{q/p^\uparrow}(x,\mathbf{k}_\perp) \;=\; f_{q/p}(x,k_\perp)+\frac{1}{2}\,\Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\mathbf{S}_T\cdot(\hat{\mathbf{P}}\times\hat{\mathbf{k}}_\perp)$$

Sivers 90

$$A_{UT}^{sin(\phi_H-\phi_S)} \sim \Delta^N f_{q/p^\uparrow}(x,k_\perp)\otimes\, D_{h/q}(z,p_\perp)$$

$\mathbf{S}_T\cdot(\hat{\mathbf{P}}\times\hat{\mathbf{k}}_\perp)$ – correlation between the spin and angular momentum implies non zero contribution $< L_z^{q,\bar{q}} > \neq 0$

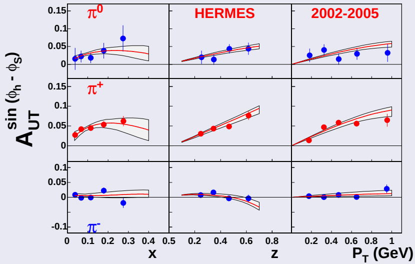
Data are available from HERMES and COMPASS.

First hints on nonzero sea quark Sivers functions.

HERMES and COMPASS DATA

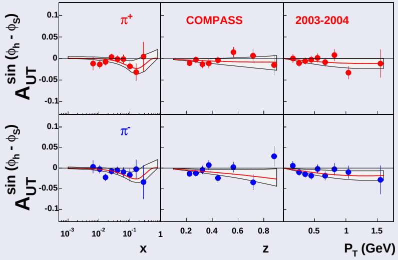
HERMES

$ep \to e\pi X$, $p_{lab} = 27.57$ GeV.



COMPASS

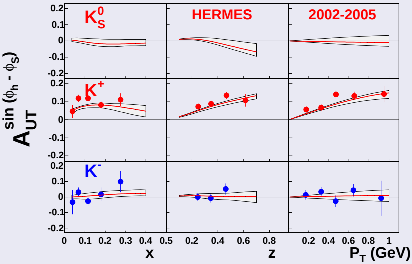
$\mu D \to \mu\pi X$, $p_{lab} = 160$ GeV.



$$lp^\uparrow \to l\pi^+ X \simeq \Delta^N u \otimes D_{u/\pi^+} > 0$$
$$lp^\uparrow \to l\pi^- X \simeq 4\Delta^N u \otimes D_{u/\pi^-} + \Delta^N d \otimes D_{d/\pi^-} \simeq 0$$
$$lD^\uparrow \to l\pi^+ X \simeq (\Delta^N u + \Delta^N d) \otimes D_{u/\pi^+} \simeq 0$$

HERMES

$ep \to eKX$, $p_{lab} = 27.57$ GeV.



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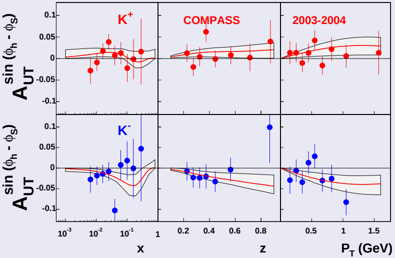
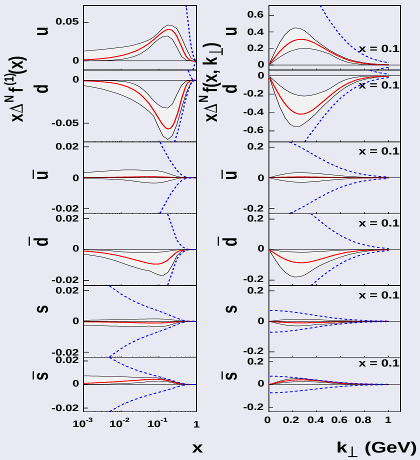


Kaon data allow for light antiquark Sivers function extraction.

M. Anselmino et al 2009

$K^+(u\bar{s})$, $K^-(\bar{u}s)$

$$\Delta^N f_q^{(1)}(x) \equiv \int d^2\,\mathbf{k}_\perp \,\frac{k_\perp}{4m_p}\,\Delta^N f_{q/p^\uparrow}(x,k_\perp) = -f_{1T}^{\perp(1)q}(x)\,.$$



Sivers functions for *u*, *d* and *sea* quarks are extracted from HERMES and COMPASS data.

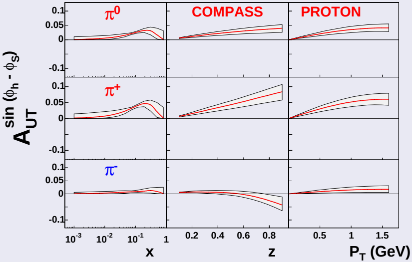
$\Delta^N f_u > 0$, $\Delta^N f_d < 0$, first hints on nonzero sea quark Sivers functions.

EIC will contribute to flavour separation of Sivers functions.

PREDICTIONS

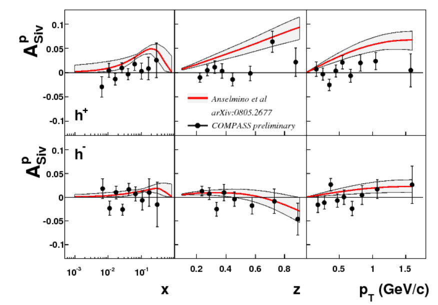
COMPASS on PROTON

$\mu p \to \mu \pi X$, $p_{lab} = 160$ GeV.



Comparison

preliminary COMPASS data arXiv:0808.0086



Mismatch of COMPASS and HERMES results on Sivers asymmetry

COMPASS data $\to$ Q^2 dependence of the asymmetry. Not supported by HERMES data. Wider region of Q^2 at fixed x is needed.

Constraint on Gluon Sivers Function

Burkardt sum rule

$$\sum_a \int dx\, d^2\mathbf{k}_\perp\, \mathbf{k}_\perp\, f_{a/p^\uparrow}(x, \mathbf{k}_\perp) \equiv \sum_a \langle \mathbf{k}_\perp^a \rangle = 0$$

M. Burkardt Phys.Rev.D69:091501,2004

$\langle \mathbf{k}_\perp^a \rangle$ is related to the first moment of the Sivers function.

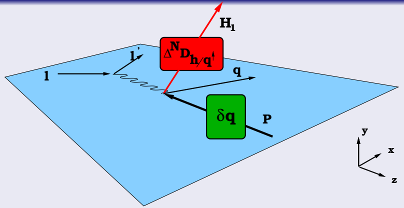
$\langle k_\perp^u \rangle = 96^{+60}_{-28}$ (MeV) $\qquad \langle k_\perp^d \rangle = -113^{+45}_{-51}$ (MeV)
The sum rule is almost saturated by u and d quarks at $Q^2 = 2.4$ GeV^2:
$\langle k_\perp^u \rangle + \langle k_\perp^d \rangle = -17^{+37}_{-55}$ (MeV) $\qquad \langle k_\perp^{\bar u} \rangle + \langle k_\perp^{\bar d} \rangle + \langle k_\perp^s \rangle + \langle k_\perp^{\bar s} \rangle = -14^{+43}_{-66}$ (MeV).

thus leaving little room for the gluon Sivers function
$-10 \leq \langle k_\perp^g \rangle \leq 48$ (MeV)
Agrees with Anselmino et al 06; Brodsky, Gardner 06

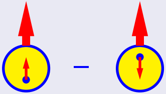
But SIDIS measurements cover restricted region in x: $0.01 \lesssim x \lesssim 0.4$
Still to be investigated... EIC will widen the region of x.

Collins effect: SIDIS and e^+e^- annihilation

SIDIS $lN \to l' H_1 X$



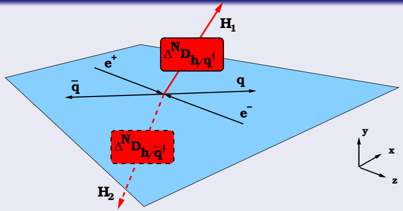
Collins effect gives rise to azimuthal Single Spin Asymmetry

 $= \Delta_T q(x, Q^2)$

 $= \Delta^N D_{h/q^\uparrow}(z, Q^2)$

J. C. Collins, *Nucl. Phys.* **B396** (1993) 161

$e^+e^- \to H_1 H_2 X$



Collins effect gives rise to azimuthal asymmetry, q and $\bar{q}$ Collins functions are present in the process:

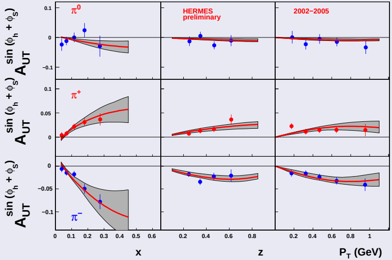
$\Delta^N D_{h/q^\uparrow}(z_1, Q^2)$

$\Delta^N D_{h/\bar{q}^\uparrow}(z_2, Q^2)$

D. Boer, R.Jacob and P. J. Mulders *Nucl. Phys.* **B504** (1997) 345

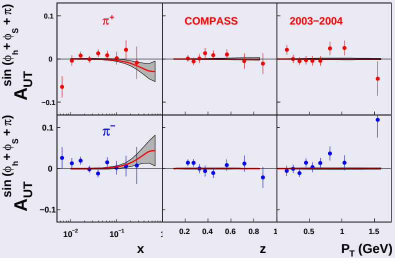
Description of the data

HERMES $A_{UT}^{sin(\phi_h+\phi_S)}$



$ep \to e\pi X$, $p_{lab} = 27.57$ GeV.

COMPASS $A_{UT}^{sin(\phi_h+\phi_S+\pi)}$



$\mu D \to \mu\pi X$, $p_{lab} = 160$ GeV

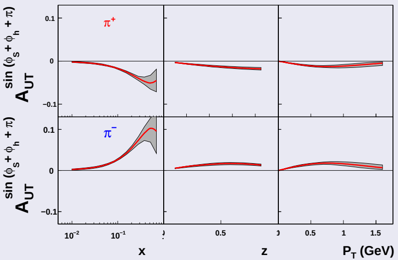
M.Anselmino et al, Nucl.Phys.Proc.Suppl.191:98-107,2009

HERMES, M. Diefenthaler, (2007),arXiv:0706.2242

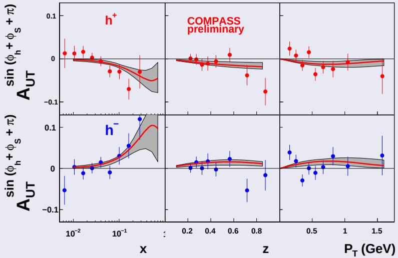
COMPASS, M. Alekseev et al., (2008), Phys.Lett.B673:127-135,2009

Predictions for COMPASS operating on PROTON target

COMPASS $A_{UT}^{sin(\phi_h+\phi_S+\pi)}$



COMPASS $A_{UT}^{sin(\phi_h+\phi_S+\pi)}$

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Comparison with preliminary
COMPASS data arXiv:0808.0086
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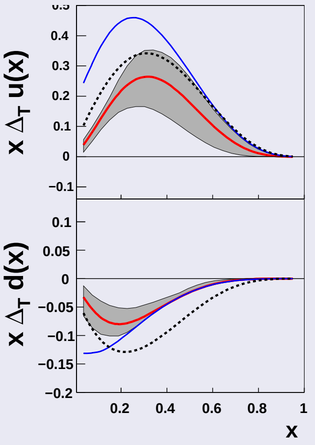
Anselmino et al 2009

Transversity vs. helicity



1. Solid red line – transversity distribution

$$\Delta_T q(x)$$

this analysis at $Q^2 = 2.4$ GeV^2.

2. Solid blue line – Soffer bound

$$\frac{q(x) + \Delta q(x)}{2}$$

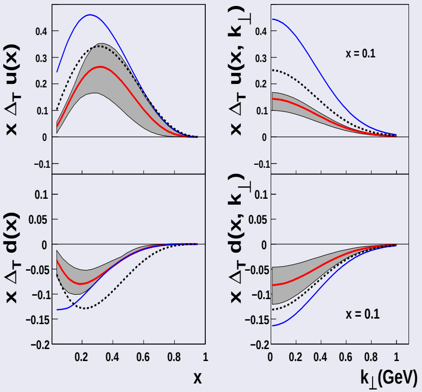
GRV98LO + GRSV98LO

3. Dashed line – helicity distribution

$$\Delta q(x)$$

GRSV98LO

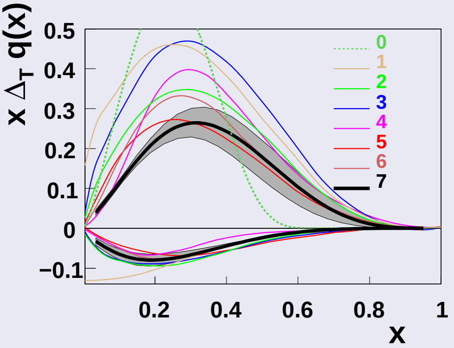
Transversity



- This is the extraction of transversity from existing experimental data. Anselmino et al 2009
- $\Delta_T u(x) > 0$ and $\Delta_T d(x) < 0$
- $|\Delta_T q(x)| < |\Delta q(x)|$.
- EIC will allow study of Q^2 dependence of h_1 and provides wider region of x for tensor charge extraction.

Transversity, comparison with models

New extraction is close to most models.

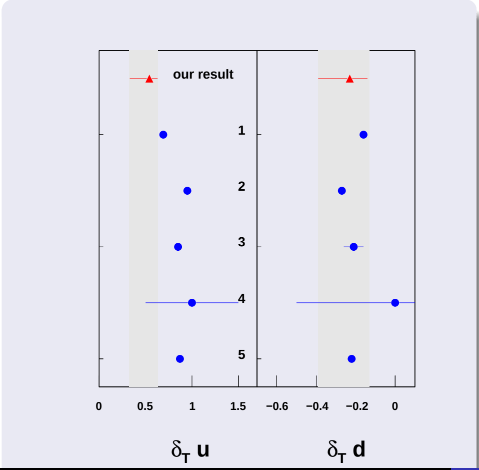


0. Barone, Calarco, Drago PLB 390 287 (97)
1. Soffer et al. PRD 65 (02)
2. Korotkov et al. EPJC 18 (01)
3. Schweitzer et al. PRD 64 (01)
4. Wakamatsu, PLB B653 (07)
5. Pasquini et al., PRD 72 (05)
6. Cloet, Bentz and Thomas PLB 659 (08)
7. Anselmino et al 2009.

Tensor charges

$$\delta q = \int_0^1 dx\,(\Delta_T q - \Delta_T \bar{q}) = \int_0^1 dx\,\Delta_T q$$

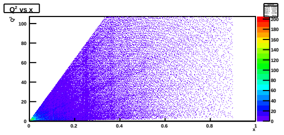
$\Delta_T u = 0.54^{+0.09}_{-0.22}$, $\Delta_T d = -0.23^{+0.09}_{-0.16}$ at $Q^2 = 0.8$ GeV^2

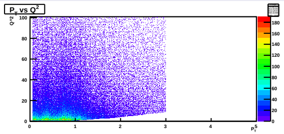


1. Quark-diquark model:
   Cloet, Bentz and Thomas
   PLB **659**, 214 (2008), $Q^2 = 0.4$ GeV^2
2. CQSM:
   M. Wakamatsu, PLB **653** (2007) 398.
   $Q^2 = 0.3$ GeV^2
3. Lattice QCD:
   M. Gockeler et al.,
   Phys.Lett.B627:113-123,2005 ,
   $Q^2 = 4$ GeV^2
4. QCD sum rules:
   Han-xin He, Xiang-Dong Ji,
   PRD 52:2960-2963,1995, $Q^2 \sim 1$ GeV^2
5. Constituent quark model:
   B. Pasquini, M. Pincetti, and
   S. Boffi, PRD72(2005)094029 and
   PRD76(2007)034020, $Q^2 \sim 0.8$ GeV^2

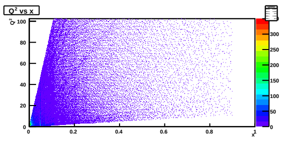
Some snapshots of EIC

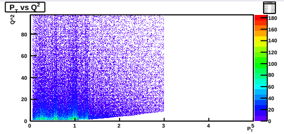
EIC $\sqrt{s} = 20$ GeV





EIC $\sqrt{s} = 35$ GeV





$0.01 < y < 0.8$, $0.1 < z < 1$, No cut on W^2 (should we have one $W^2 > 10$ GeV^2 to avoid resonance region?) Other SIDIS cuts?

CONCLUSIONS

- EIC will be a powerful tool to study parton dynamics and TMDs.
- High Q^2 range will allow to study twist-2 functions and higher twist content of the nucleon.
- Range of P_T will allow to study intermediate region where both TMD and collinear factorizations are applicable.
- Q^2 range at some fixed x will provide information on Q^2 behaviour of the asymmetries and Q^2 evolution of TMDs.
- Full flavour and spin decomposition of TMDs can be attempted at EIC.

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THANK YOU!

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