Physics Drivers for polarized beams

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Beam Polarization and Polarimetry at EIC
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Why we need an EIC

World Data on $F_2^p$

World Data on $g_1^p$

World Data on $h_1^p$

momentum  spin  transverse spin ~ angular momentum
The inclusive deep inelastic scattering double differential cross section $\ell p \rightarrow \ell' X$ can be expressed using two structure functions $F_2$ and $F_1$, or, better, $F_2$ and $F_L$ ($F_L = F_2 - 2xF_1$) which depend from $x$ and mildly by $Q^2$.

$$\frac{d^2\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{2xQ^4} [(1 + (1 - y)^2)F_2(x, Q^2) - y^2 F_L(x, Q^2)]$$

Keeping in mind the transformations:

$$\frac{d^2\sigma}{dxdy} = \frac{2\pi M\nu}{E'} \frac{d^2\sigma}{d\Omega dE'} = x(s - M^2) \frac{d^2\sigma}{dxdQ^2} \approx xs \frac{d^2\sigma}{dxdQ^2}$$

We are able to express the cross section in other variables.
In quark-parton model the structure functions can be written as:

\[ F_2(x, Q^2) = x \sum_q e_q^2 f_1^q (x) \quad \text{and} \quad F_L(x, Q^2) = 0 \]

where \( f_1^q \) is the probability that to find a parton of type \( q = u, \bar{u} \ldots \) with momentum fraction \( p_q = xP \) in the proton.

When including higher orders the structure functions become:

\[ F_2(x, Q^2) = x \sum_{n=0}^{\infty} \frac{\alpha_s^n}{(2\pi)^n} \sum_{i=q,g} \int_0^1 \frac{dz}{z} C_{2,i}^{(n)} (z, Q^2) f_1^i \left( \frac{x}{z} \right) \]

With the Wilson coefficients \( C_{2,i}^{(n)} \) known up to \( N^3\)LO

\[ C_{2,q}^{(0)} = e_q^2 \delta (1 - z) \quad \text{and} \quad C_{2,g}^{(0)} = 0 \]
Impact of the HERA $ep$ Collider

Cross Section vs $Q^2 (\text{GeV}/c)^2$

- HERA NC $e^+p$ 0.4 fb$^{-1}$
- HERA NC $e^+p$ 0.5 fb$^{-1}$

$\sqrt{s} = 318 \text{ GeV}$

- Fixed Target
- HERAPDF2.0 $e^+p$ NLO
- HERAPDF2.0 $e^+p$ NLO

arXiv:1506.06042
Polarized Cross Sections

• For longitudinally polarized beams (either parallel or antiparallel we can express the difference of the parallel to anti-parallel cross sections by mean of two structure functions $g_1$ and $g_2$,

$$\frac{d^2\sigma_{\uparrow\rightarrow}}{dx\,dQ^2} - \frac{d^2\sigma_{\downarrow\rightarrow}}{dx\,dQ^2} = \frac{d^2\Delta\sigma_{\parallel}}{dx\,dQ^2} = \frac{16\pi\alpha^2 y}{Q^4} \left[ \left( 1 - \frac{y}{2} - \frac{\gamma^2 y^2}{4} \right) g_1(x, Q^2) - \frac{\gamma^2 y}{2} g_2(x, Q^2) \right]$$

• And when the proton beam is transversely polarized we have:

$$\frac{d^3\sigma_{\uparrow\rightarrow}}{dx\,dQ^2\,d\phi} - \frac{d^3\sigma_{\downarrow\rightarrow}}{dx\,dQ^2\,d\phi} = \frac{d^3\Delta\sigma_{\perp}}{dx\,dQ^2\,d\phi} = -\cos \phi \frac{8\alpha^2 y}{Q^4} \sqrt{1 - y - \frac{\gamma^2 y^2}{4}} \left[ \frac{y}{2} g_1(x, Q^2) + g_2(x, Q^2) \right]$$

• With $\gamma = \sqrt{Q^2/\nu} \ll 1$
Physics content of the structure functions

- At LO in quark-parton model the structure functions can be written as:

\[ g_1(x, Q^2) = \frac{1}{2} \sum_q [\Delta q(x) - \Delta \bar{q}(x)] \quad \text{and} \quad g_2(x, Q^2) = 0 \]

Where the helicity distribution \( \Delta q(x) = q^+(x) - q^-(x) \) represents the difference between the number of quarks in the proton with the spin parallel \( q^+ \) and antiparallel \( q^- \) to the spin of the proton.

- When including higher orders the structure functions content become, f.i.:

\[ g_1(x, Q^2) = \frac{1}{2} \sum_{k=1}^{n_f} e_f^2 \left[ C_q^S \otimes \Delta \Sigma + 2n_f C_g \otimes \Delta g + C_q^{NS} \otimes \Delta q^{NS} \right] \]

The Wilson coefficients at LO are:

\[ C_q^S = C_q^{NS} = \delta(1 - x) \quad \text{and} \quad C_g = 0 \]
The spin content of the proton: where we stand

Gluons PDF are accessed using DGLAP Equations

\[
\frac{d}{dt} \Delta \Sigma(x, t) = \frac{\alpha_s(t)}{2\pi} \int_x^1 \frac{dy}{y} \left[ P_{qq}^S \left( \frac{x}{y}, \alpha_s(t) \right) \Delta \Sigma(y, t) + 2n_f P_{qg} \left( \frac{x}{y}, \alpha_s(t) \right) \Delta g(y, t) \right]
\]

\[
\frac{d}{dt} \Delta g(x, t) = \frac{\alpha_s(t)}{2\pi} \int_x^1 \frac{dy}{y} \left[ P_{gq} \left( \frac{x}{y}, \alpha_s(t) \right) \Delta \Sigma(y, t) + P_{gg} \left( \frac{x}{y}, \alpha_s(t) \right) \Delta g(y, t) \right]
\]

\[
\frac{d}{dt} \Delta q_{NS}(x, t) = \frac{\alpha_s(t)}{2\pi} \int_x^1 \frac{dy}{y} P_{qq}^{NS} \left( \frac{x}{y}, \alpha_s(t) \right) \Delta q_{NS}(x, t)
\]

With \( t = \ln \frac{Q^2}{\Lambda^2} \), \( \Delta \Sigma(x, t) = \sum_{i=1}^{n_f} \Delta q_i \) and \( \Delta q_{NS}(x, t) = \sum_{i=1}^{n_f} (e_i^2 / \langle e^2 \rangle - 1) \Delta q_i \),

where \( \langle e^2 \rangle = \frac{1}{n_f} \sum_{i=1}^{n_f} e_i^2 \)

A very powerful tool access \( \Delta g \), but limited by the present experimentally available phase space
QCD fits - World data on $g_1^p$ and $g_1^d$

$g_1(x, Q^2)$ as input to global QCD fits for extraction of $\Delta q_f(x)$ and $\Delta g(x)$

$x$ and $Q^2$ coverage not yet sufficient for precise $\Delta g$
Can be improved by constraining from pp data (as DSSV, NNPDF…)

$$\frac{dg_1}{d\ln Q^2} \propto -\Delta g(x, Q^2)$$
Another NLO pQCD fit to $g_1$ DIS world data

- Assumes functional forms for $\Delta \Sigma$, $\Delta G$ and $\Delta q^{NS}$ and SU3 symmetry
- Use DGLAP equations.
- Fit $g_1^p$, $g_1^d$, $g_1^n$ DIS world data

→ Quark spin contribution:
$$\Delta \Sigma = 0.31 \pm 0.05 \text{ at } Q^2 = 3 \text{ (GeV/c)}^2$$

Uncertainties are dominated by the bad knowledge of the functional forms.

→ Gluon spin contribution: $\Delta G$ not well constrained, even the sign, using DIS only

Solution with $\Delta G > 0$ agrees with result from DSSV++ using RHIC pp data

$$\begin{align*}
0.82 \leq \Delta U &\leq 0.85 \\
-0.45 \leq \Delta D &\leq -0.42 \\
-0.11 \leq \Delta S &\leq -0.08
\end{align*}$$
Measurement of the $\Delta G$ at RHIC

\[ \Delta G(x, Q^2 = 10 \text{ GeV}^2/c^2) = 0.20^{+0.6}_{-0.7} \]

DSSV++

\[ \int_{0.05}^{1} dx \Delta g(x, Q^2 = 10 \text{ GeV}^2/c^2) = 0.17 \pm 0.06 \]

NNPDFpol1.1

\[ \int_{0.05}^{0.2} dx \Delta g(x, Q^2 = 10 \text{ GeV}^2/c^2) = 0.5 \pm 0.4 \]

JAM15

\[ \int_{0.001}^{0.8} dx \Delta g(x, Q^2 = 1 \text{ GeV}^2/c^2) = 0.20^{+0.6}_{-0.7} \]

E. Nocera et al.,
NPB 887 (2014) 276

Gluon helicity $\Delta g/g$ from SIDIS

Extraction at LO:

$$\Delta G/G (x = 0.1) = 0.11 \pm 0.04 \pm 0.04$$

Photon Gluon Fusion

EPJC 77 (2017) 209
Summary on nucleon SPIN

\[ \frac{1}{2} = \frac{1}{2} (\Delta u_v + \Delta d_v + \Delta q_s) + \Delta G + L_q + L_g \]

**Quarks** \( \frac{1}{2} \Delta \Sigma \sim 0.15 \) from \( g_1 \) measurements and global analysis at NLO. Largest uncertainty on \( \Delta \Sigma \) due to uncertainty on \( \Delta G \).

**Gluons** \( \Delta G \sim 0.2 \) integrated between \( 0.05 < x < 0.2 \): precise result from RHIC. \( \Delta G/G \) positive at \( x \sim 0.1 \) (from data of \( \gamma g \) fusion process, at LO). Low-\( x \) contribution to integral still unknown. Not enough constrain from \( g_1 \) global analysis at NLO.

**Orbital momenta:** \( L_q + L_{q'} = ? \) Ongoing studies of GPDs.

**Promising results from lattice QCD calculations:**

\( \to \) **The main question raised in ‘Nucleon spin crisis’ is resolved:**

- Quark spin represents a non zero fraction (0.3) of nucleon spin
  *(measurements and lattice QCD calculations)*
- The hypothesis of very large \( \Delta G \) (2 to 3, associated to \( L \sim -2 \div -3 \)) rejected

\( \to \) **Puzzle still pending:** share between \( \Delta G \) and \( L \)
The semi inclusive deep inelastic scattering cross section for a hadron of type $h$ of a given energy fraction $z_h$ is written as:

$$
\frac{d^3\sigma}{dx dy dz_h} = \frac{2\pi \alpha^2}{Q^2} \left[ \frac{(1 + (1 - y)^2)}{xy} F_2^h(x, z_h, Q^2) + \frac{2(1 - y)}{y} F_L^h(x, z_h, Q^2) \right]
$$

Where the structure functions are:

$$
F_2^h(x, z_h, Q^2) = \sum_{q, \bar{q}} e_q^2 \left[ f_1^q(x, Q^2) D_{h/q}(z; Q^2) + \frac{\alpha_s(Q^2)}{2\pi} \right] \quad \text{(QCD improved)}
$$

$$
F_L^h(x, z_h, Q^2) = \sum_{q, \bar{q}} e_{\bar{q}}^2 \left[ \frac{\alpha_s(Q^2)}{2\pi} \right] \quad \text{(QCD improved)}
$$
Collinear Multiplicities

$\frac{dM_{\pi^+}}{dz} + \alpha$

$0.004 < x < 0.01$
- $\alpha = 1.00$
- $\alpha = 0.75$
- $\alpha = 0.50$
- $\alpha = 0.25$
- $\alpha = 0$

$0.01 < x < 0.02$

$0.02 < x < 0.03$

$0.03 < x < 0.04$

$0.04 < x < 0.06$

$0.06 < x < 0.10$

$0.10 < x < 0.14$

$0.14 < x < 0.18$

$0.18 < x < 0.40$

$0.2 < 0.4 < 0.6 < 0.8$

Curves: COMPASS
LO fit

hep-ex/1604.02695
Quark helicities from semi-inclusive DIS

Leading order extraction of quark helicities from spin asymmetries:

- COMPASS
  \[PLB693(2010)227,\] using DSS FFs

- HERMES
  \[PRD71(2005)012003\]
  __ DSSV at NLO

\[l^\pm p^\to \to l^\pm h^\mp X\]

- Full flavour separation \(x \approx 0.004\)
- Sea quark distributions \(\approx 0\)
- Good agreement with global fits

What about \(\Delta s\)? Integral is found negative from \textit{inclusive} data, when imposing SU3 while here from \textit{semi-inclusive} data, \(x > \sim 0.005\) \(\Delta s\) is compatible with zero.

\textbf{NB:}
- The extraction assumes quark Fragmentation Functions known (DSS here)
- No measurement at lower \(x\)

\[Q^2 = 3 \text{ (GeV/c)}^2\]
Transverse structure of the Nucleon

Confinement Scale

Transverse momentum

Transverse position

Longitudinal momentum

Photon Virtuality $Q^2$

Hard Scale

High Energy Probe

$W_p^q (x, \vec{k}_\perp, \vec{b}_T)$
Confined parton motion in a hadron

- **Scattering with a large momentum transfer**
  - Momentum scale of the hard probe $Q > \frac{1}{R} \sim 1 \text{ fm}^{-1} \sim \Lambda_{QCD}$
  - Combined motion $\sim \frac{1}{R}$ is too week to be sensitive to the hard probe
  - Collinear factorization – integrated into PDFs

- **Scattering with multiple momentum scales observed**
  - Two-scale observables (such as low $P_{hT}$ SIDIS, low $p_T$ Drell-Yan) $Q \gg q_T \sim \frac{1}{R} \sim \Lambda_{QCD} \sim 1 \text{ fm}$
  - “Hard” scale $Q$ localizes the probe to see the quark or gluon d.o.f.
  - “Soft” scale $q_T$ could be sensitive to the confined motion
  - TMD factorization: the confined motion is encoded into TMDs
When we consider the transverse momentum of the quark in the calculation of the cross section, Transverse Momentum Dependent parton distribution (TMDs) gain a dependence from the intrinsic transverse momentum $k_{\perp}$.

The unpolarised number density of the quarks gains a dependence from the intrinsic transverse momentum $k_{\perp}$:

$$ f_1^q (x, k_{\perp}) $$

New parton densities arise: the Boer-Mulders functions $h_{1,q}^\perp (x, k_{\perp})$, describing the correlation between the intrinsic quark transverse momentum and the spin of the quark in an unpolarised nucleon:

$$ f_{q^\uparrow} (x, k_{\perp}, \vec{s}) = f_1^q (x, k_{\perp}) - \frac{1}{M} h_{1,q}^\perp (x, k_{\perp}) \vec{s} \cdot (\vec{p} \times \vec{k}_{\perp}) $$
Accessing TMD PDFs and FFs

- TMD factorization works in the domain where there are two observed momenta in the process, such as SIDIS, DY, $e^+e^-$. $Q \gg q_T$: $Q$ is large to ensure the use of pQCD, $q_T$ is much smaller such that it is sensitive to parton’s transverse momentum.

- **SIDIS off polarized p, d, n targets**
  - HERMES
  - COMPASS
  - JLab
  - *future: EIC*

- **polarised Drell-Yan**
  - COMPASS
  - RHIC
  - FNAL
  - *future: FAIR, JPark, NICA*

- $e^+e^- \rightarrow h_1h_2$
  - BaBar
  - Belle
  - Bes III
Azimuthal asymmetries in SIDIS

We look at our events in the Gamma Nucleon System (GNS), i.e. we need a perfectly reconstructed lepton kinematic.
\[
\frac{d^5 \sigma}{dx dy dz dP_{hT} d\phi_h} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1 - \epsilon)} \left(1 + \frac{y^2}{2x}\right) \left\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1 + \epsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \epsilon \cos 2\phi_h F_{UU}^{\cos 2\phi_h} \right. \\
+ \lambda_e \sqrt{2\epsilon(1 + \epsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} + S_{\parallel} \left[ \sqrt{2\epsilon(1 + \epsilon)} \sin \phi_h F_{UL}^{\sin \phi_h} + \epsilon \sin 2\phi_h F_{UL}^{\sin 2\phi_h} \right] \\
+ \lambda_e S_{\parallel} \left[ \sqrt{1 - \epsilon^2} F_{LL} + \sqrt{2\epsilon(1 + \epsilon)} \cos \phi_h F_{LL}^{\cos \phi_h} \right] \\
+ \left| \vec{S}_{\perp} \right| \left( \sin (\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \right) \\
\]

14 independent azimuthal modulations
SIDIS Experiments

SIDIS Experiment must:

• Have large acceptances on all the relevant variables \( x, Q^2, z, P_{hT}, \phi \)

• Use different targets (p, d, n) and identify hadrons to allow flavor separation

• Be at different energies for to cover PDFs from the valence region down to small-\( x \)

• Large luminosity to allow multidimensional results needed by the complexity of TMDs

• **The polarized lepton-nucleon collider is a mandatory tool to reach the level of ordinary PDF**
SIDIS access to TMDs

Factorization (Collins & Soper, Ji, Ma, Yuan, Qiu & Vogelsang, Collins & Metz...)

\[
\sigma(\ell p \rightarrow \ell' hX) \sim \text{TMDs} \otimes \hat{\sigma}^{\gamma q \rightarrow q} \otimes \text{TMD-FFs}
\]

- chiral odd
- T odd

TMDs

\[ (x, \vec{k}_T) \]

Nucleon polarization

<table>
<thead>
<tr>
<th>Parton polarization</th>
<th>U</th>
<th>T</th>
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<tr>
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<td>U</td>
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<td>( h_1, h_{1T} )</td>
<td>( h_{1L} )</td>
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<td>L</td>
<td>( g_{1T} )</td>
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Hadron polarization

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<td>( G_{1L} )</td>
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- NOT directly accessible
- Their extractions require measurements of x-sections and asymmetries in a **large** kinematic domain of \( x, Q^2, z, P_{hT} \)
TMD evolution:

- QCD evolution of TMDs in Fourier space (solution of equation)

\[
F(x, b; Q) \approx C \otimes F(x, c/b^*) \exp \left\{ - \int_{c/b^*}^{Q_f} \frac{d\mu}{d} \left( A \ln \frac{Q_f^2}{\mu^2} + B \right) \right\} \times \exp[-S_{\text{non-pert}}(b, Q)]
\]

Evolution of longitudinal/collinear part

Evolution of transverse part (Sudakov form factor)

Non-perturbative part has to be fitted to experimental data

The key ingredient is spin-independent

- Polarized scattering data comes as ratio: e.g. 
  \[ A_{UT}^{\sin(\Phi_h - \Phi_s)} = \frac{F_{UT}^{\sin(\Phi_h - \Phi_s)}}{F_{UU}} \]

- Unpolarised data is very important to constrain/extract the key ingredient for the non-perturbative part
Transversity PDF

\[ h_1^q(x) = q^\uparrow(x) - q^{\uparrow\downarrow}(x) \]

with \( q = u_V, d_V \) and quarks/antiquarks of the sea

Describes quark with spin parallel to the nucleon spin in a transversely polarized nucleon

- is chiral-odd: decouples from inclusive DIS
- probes the relativistic nature of quark dynamics: in NR limit, boost and rotations commute and we should have \( h_1^q(x) = g_1^q(x) \)
- no contribution from the gluons \( \rightarrow \) simple \( Q^2 \) evolution
- Positivity constrain, i.e.: Soffer bound [Soffer, PRL 74 (1995)]
  \[ 2|h_1^q(x)| \leq f_1^q(x) + \Delta q(x) \]
- first moments: tensor charge
  \[ g_1^q(Q^2) = \int_0^1 dx \left[ h_1^q(x, Q^2) - h_1^\bar{q}(x, Q^2) \right] \]
is chiral-odd:

observable effects are given only by the product of $h_1^q(x)$ and another chiral-odd function

can be measured in SIDIS on a transversely polarized target via “quark polarimetry”

$\ell N^\uparrow \rightarrow \ell' h X$

“Collins” asymmetry
“Collins” Fragmentation Function

$\ell N^\uparrow \rightarrow \ell' h h X$

“two-hadron” asymmetry
“Interference” Fragmentation Function

$\ell N^\uparrow \rightarrow \ell' \Lambda X$

$\Lambda$ polarization
Fragmentation Function of $q^\uparrow \rightarrow \Lambda$
Global Analysis: Transversity

Fragmentation (or hadronization) is the nonperturbative process that brings quarks and gluons to dress into observable hadrons. Fragmentation functions (FFs) describe the probability that a hadron $h$ is produced in the fragmentation process of a quark $q$, taking away a fraction of the quark momentum.

What about the quark spin? The fragmentation of a transversely polarized quark in an unpolarised hadron is described by:

$$ D_{h/q}^{\uparrow}(z, p_{\perp}) = D_{h/q}(z, p_{\perp}) + \frac{\hat{k} \times \vec{p}_{\perp} \cdot \hat{S}_{qT}}{zm_h} H_{1}^{\perp}(z, p_{\perp}) $$

Where $\hat{k}$ is the direction of the fragmenting quark and $\hat{S}_{qT}$ is it’s spin projection in the transverse plane.

In this model, the $q\bar{q}$ pairs at each string breaking are produced in a state that has total orbital angular momentum $L = 1$ and total spin $S = 1$ opposite to the orbital angular momentum such that $J = L + S = 0$.

For a struck quark $q_A$ with spin along $\hat{y}$, the first $q_2\bar{q}_2$ at the string breaking will be polarized along $-\hat{y}$, while the angular momentum $\vec{L}_2$ is along $\hat{y}$. If the initial quark $q_A$ is $u$ then the $^3P_0$ mechanism produces opposite effects for positive and for negative pions.
The full points are Monte Carlo data, scaled by $\lambda \sim \langle h_1^u / f_1^u \rangle \sim 0.055$.

Agreement with the measured Collins asymmetry is quite satisfactory.
Sivers Asymmetry

Sivers: correlates nucleon spin & quark transverse momentum $k_T/T$-ODD at LO:

$$A_{Siv} = \frac{\sum_q e_q^2 f_{1Tq}^{\perp} \otimes D_q^h}{\sum_q e_q^2 q \otimes D_q^h}$$

$$\mu p^\uparrow \to \mu X h^{\pm}$$

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>1992</td>
<td>Sivers proposes $f_{1T}^{\perp}$</td>
</tr>
<tr>
<td>1993</td>
<td>J. Collins proofs $f_{1T}^{\perp} = 0$ for T invariance</td>
</tr>
<tr>
<td>2002</td>
<td>S. Brodsky, Hwang and Schmidt demonstrate that $f_{1Tq}^{\perp}$ may be $\neq 0$ due to FSI</td>
</tr>
<tr>
<td>2002</td>
<td>J. Collins shows that $(f_{1T}^{\perp})<em>{DY} = -(f</em>{1T}^{\perp})_{SIDIS}$</td>
</tr>
<tr>
<td>2004</td>
<td>HERMES on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$</td>
</tr>
<tr>
<td>2004</td>
<td>COMPASS on d: $A_{Siv}^{\pi^+} = 0$ and $A_{Siv}^{\pi^-} = 0$</td>
</tr>
<tr>
<td>2008</td>
<td>COMPASS on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$</td>
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</tbody>
</table>
Sivers asymmetry on p charged pions (and kaons), HERMES and COMPASS
Transverse Spin Asymmetry in Drell-Yan

190 GeV/c $\pi^-$ beam, transversely polarized NH$_3$ target

$A_N^{\pm}$

STAR p-p 500 GeV (L = 25 pb$^{-1}$)

$0.5 < P_T^W < 10$ GeV/c

$W^+ \rightarrow l^+ \nu$

KQ (assuming “sign change”)

Global $\chi^2$/d.o.f. = 7.4 /6

3.4% beam pol. uncertainty not shown

$W^- \rightarrow l^- \bar{\nu}$

KQ (no “sign change”)

Global $\chi^2$/d.o.f. = 19.6 /6

3.4% beam pol. uncertainty not shown

$f_{1T, DY} = -f_{1T, SIDIS}$

PRL119, 112002 (2017)
To conclude

- Many important results both for the spin structure and the internal 3D structure of the nucleon have been provided by experiments at HERA, CERN, RHIC and JLAB; very partial coverage here.

- Before the EIC, JLAB will map the valence region with high precision; COMPASS and RHIC will complete their programs.

- **THE EIC will allow us TO MOVE FROM EXPLORATION TO PRECISION in the KNOWLEDGE of the internal structure of the NUCLEON.**
Thank you
Kinematic coverage
Global analysis of the spin dependent distribution functions

\[ \Delta \Sigma = +0.36 \pm 0.09 \]
\[ \Delta s^+ = -0.03 \pm 0.10 \]

Gluon Spin From Lattice QCD

\[ \Delta \vec{p}_p = (0,0,0) \]

\[ \mu^2 = 10 (\text{GeV}/c)^2 \]

\[ \vec{p}_p = (0,0,p_3) \]

\[ \mu^2 = 10 (\text{GeV}/c)^2 \]

\[ m_\pi = 139 \text{ MeV}/c^2 \]

\[ \Delta G (\mu^2 = 10 (\text{GeV}/c)^2) \approx S_G (\mu^2 = 10 (\text{GeV}/c)^2, |p| \to \infty) = 0.251 \pm 0.047 \pm 0.016 \]

MS scheme

Cahn $A_{UU}^{\cos \phi}$ and Boer-Mulders $A_{UU}^{\cos 2\phi}$ modulation

$$A_{UU}^{\cos \phi}(x, z, P_{hT}^2; Q^2)$$
$$\propto \frac{1}{Q} \sum_q e_q^2 \left[ f_1^q \otimes D_1^q \rightarrow h - h_1^\perp q \otimes H_1^\perp, q \rightarrow h \right]$$

$$A_{UU}^{\cos 2\phi}(x, z, P_{hT}^2; Q^2)$$
$$= -x \sum_q e_q^2 \int d^2 \vec{k} d^2 \vec{p} \frac{2 (\hat{h} \cdot \vec{k}) (\hat{h} \cdot \vec{k}) - \vec{k} \cdot \vec{p}}{M m_h} h_1^\perp q (x, k_\perp^2; Q^2) H_1^\perp, q \rightarrow h (z, p_\perp^2; Q^2)$$
$P_hT$ dependent Multiplicities $M_{UU}^h$

$$M^h(x, z, P_{hT}^2; Q^2) = \frac{d^5 \sigma^h}{dx dQ^2 dz dP_{hT}^2} \frac{d^2 \sigma^{DIS}}{dx dQ^2} \sim F_{UU}^h(x, z, P_{hT}^2; Q^2)$$
Collins asymmetry on proton. Multidimensional
Extraction of TSAs with a Multi-D \((x: Q^2: z: p_T)\) approach

One dense plot out of many
TSA of inclusive jets and $\pi^\pm$ within jets from STAR

COLLINS asymmetries: general agreement between data and predictions from SIDIS consistent with TMD factorization and universality of the Collins function
2h asymmetries on p and $^{3}P_0$ model for FF

$$A^\sin(\phi_R + \phi_S - \pi)_{UT} = \frac{\sum q e_q^2 h_1^q(x) H_{q \rightarrow h_1 h_2}^2(z, M_{h_1 h_2}^2)}{\sum q e_q^2 q(x) D_a^{h_1 h_2}(z, M_{h_1 h_2}^2)}$$

$$a_p^{u \rightarrow h^+ h^-} = \langle \sin(\phi_R + \phi_S - \pi) \rangle \quad \text{and} \quad \vec{R} = \frac{z_2 \vec{P}_{h_1} - z_1 \vec{P}_{h_2}}{z_1 + z_2} \quad \text{and as before} \quad \lambda \sim \langle h_1^u / f_1^u \rangle \sim 0.055$$

6/26/2020 Beam Polarization and Polarimetry at the Electron Ion Collider
Interference fragmentation functions in pp

\[ p^+ p \rightarrow \pi^+ \pi^- X \rightarrow h_1 \cdot H_1^{\alpha} \]

survives in collinear framework

\[ A_{UT} \sin(\phi_{RS}) = \frac{1}{Pol} \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \]

- Significant di-hadron asymmetries both at \( \sqrt{s} = 200\text{GeV} \) and \( \sqrt{s} = 500\text{GeV} \) (arXiv:1710.10215)
- Increasing with \( p_T \)
- Access to transversity with a collinear observable
\( P_{\Lambda(\bar{\Lambda})}(x, z) = \frac{\sum_q e_q^2 h_1^q(x) H_1^{\Lambda(\bar{\Lambda})}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{\Lambda(\bar{\Lambda})}(z)} \)

\[
\frac{dN}{d \cos \theta^*} \propto A(1 + \alpha P_{\Lambda(\bar{\Lambda})} \cos \theta^*)
\]
\( \Lambda \) transverse spin transfer from STAR

\[
D_{TT} = \frac{d\sigma^{p\uparrow p\rightarrow \Lambda\uparrow X} - d\sigma^{p\uparrow p\rightarrow \Lambda\downarrow X}}{d\sigma^{p\uparrow p\rightarrow \Lambda\uparrow X} + d\sigma^{p\uparrow p\rightarrow \Lambda\downarrow X}}
\]

\[
D_{TT} = \frac{1}{\alpha P_B \langle \cos \theta^* \rangle} \left( \sqrt{N_{\uparrow \cos \theta^* N_{\downarrow \cos \theta^*}} - \sqrt{N_{\downarrow \cos \theta^* N_{\uparrow \cos \theta^*}}} \right) \left( \sqrt{N_{\uparrow \cos \theta^* N_{\downarrow \cos \theta^*}} + \sqrt{N_{\downarrow \cos \theta^* N_{\uparrow \cos \theta^*}}} \right)
\]

\[
\frac{dN}{d\cos \theta^*} \propto A \left( 1 + \alpha P_{\Lambda(\bar{\Lambda})} \cos \theta^* \right)
\]

About 60\% of \( \Lambda \) or \( \bar{\Lambda} \) are not primary particles, but are from heavier hyperons decay.

\[
D_{TT}(\Lambda) = +0.031 \pm 0.033_{\text{stat}} \pm 0.008_{\text{sys}}
\]

\[
D_{TT}(\bar{\Lambda}) = -0.034 \pm 0.040_{\text{stat}} \pm 0.009_{\text{sys}}
\]
TSA of inclusive jets and $\pi^\pm$ within jets from STAR

COLLINS LIKE asymmetries: sensitive to linearly polarized gluons in a polarized proton, are found to be small and provide the first constraints on model calculations.
TSSA $A_N$ studies at PHENIX

Described by twist 3 collinear approach (1 scale, high $p_T$)

Suppression in $p^+A$ expected by gluon saturation ($\propto A^{1/3}$)

Hybrid approach: twist-3 and CGC
Sivers Asymmetry for Gluon from SIDIS

\[ A_{PGF}^{Siv,d} = -0.14 \pm 0.15 \text{(stat.)} \pm 0.10 \text{(syst.)} \quad \langle x_g \rangle = 0.13 \]

\[ A_{PGF}^{Siv,p} = -0.26 \pm 0.09 \text{(stat.)} \pm 0.06 \text{(syst.)} \quad \langle x_g \rangle = 0.15 \]