Flavor separation of quark transverse momentum

Polarized light-ion physics with an EIC

Ghent - February 5th, 2018

Gunar.Schnell @ DESY.de
Deep-inelastic scattering

\[ \gamma^* (E, p) \rightarrow q (E', p') \]

inclusive

\[ e \rightarrow \text{inclusive} \]

Factorization:

Parton distributions
Deep-inelastic scattering

\[(E, p) \rightarrow (E', p')\]

\[e \rightarrow \gamma^* \rightarrow q\]

Parton distributions

Fragmentation functions

Semi-inclusive

Factorization:
Experimental Prerequisites

- Polarized lepton beam
- Polarized target
- Large acceptance spectrometer
- Good Particle IDentification (PID)
Experimental Prerequisites

- Polarized lepton beam
- Polarized target targets
- Large acceptance spectrometer
- Good Particle IDentification (PID)
The COMPASS experiment @ CERN

- COMPASS 2002-03 data
- Trigger Hodoscopes
- ECALs & HCALs
- MWPCs
- SM1
- RICH
- Straws
- SM2
- GEMs
- Filters/Walls

- ~ 350 planes
- 180 mrad acceptance
- π, K, p separation (from 2, 9, 17 GeV up to ~ 50 GeV)
HERMES Experiment (†2007) @ DESY

27.6 GeV polarized $e^+/e^-$ beam scattered off ...

unpolarized (H, D, He,..., Xe) as well as **transversely (H)**
and longitudinally (H, D, He) polarized (pure) gas targets
6GeV e⁻ @ Jefferson Lab

- 6GeV polarized electron beam now,
  will upgrade to 12 GeV in 2013.
- Continuous beam to three experiment halls.

Hall A: two HRS'  
Hall B: CLAS  
Hall C: HMS+SOS

NH₃ & ND₂ targets

NH₃ & ND₃ targets
Inclusive DIS

$\gamma^*$

$(E, p)$

$(E', p')$

$q$

$h$

$n$

$u$

$d$

$u$
Inclusive DIS (one-photon exchange)

\[
\frac{d^2 \sigma(s, S')}{dx \ dQ^2} = \frac{2\pi \alpha^2 y^2}{Q^6} L_{\mu\nu}(s) W^{\mu\nu}(S)
\]
Inclusive DIS (one-photon exchange)

\[
\frac{d^2 \sigma(s, S')}{dx \ dQ^2} = \frac{2\pi\alpha^2 y^2}{Q^6} L_{\mu\nu}(s) W^{\mu\nu}(S)
\]

Lepton Tensor

Spin Plane

Scattering Plane

\( \vec{k}, \vec{S}_i \)

\( \vec{S}_N \)

\( \alpha \)

\( \theta \)

\( \phi \)
Inclusive DIS (one-photon exchange)

\[
\frac{d^2 \sigma(s, S)}{dx \, dQ^2} = \frac{2\pi\alpha^2 y^2}{Q^6} L_{\mu\nu}(s) W^{\mu\nu}(S)
\]

Lepton Tensor

Hadron Tensor

parametrized in terms of

Structure Functions

\( \vec{k}, \vec{S}_i \)

\( \vec{k}', \vec{S}_N \)

Spin Plane

Scattering Plane
Inclusive DIS (one-photon exchange)

\[
\frac{d^2 \sigma(s, S)}{dx \, dQ^2} = \frac{2\pi \alpha^2 y^2}{Q^6} L_{\mu \nu}(s) W_{\mu \nu}(S)
\]

\[
\frac{d^3 \sigma}{dx dy d\phi} \propto \frac{y}{2} F_1(x, Q^2) + \frac{1 - y - \gamma^2 y^2/4}{2xy} F_2(x, Q^2) - S_l S_N \cos \alpha \left[ \left(1 - \frac{y}{2} - \frac{\gamma^2 y^2}{4}\right) g_1(x, Q^2) - \frac{\gamma^2 y}{2} g_2(x, Q^2) \right] + S_l S_N \sin \alpha \cos \phi \gamma \sqrt{1 - y - \frac{\gamma^2 y^2}{4}} \left( \frac{y}{2} g_1(x, Q^2) + g_2(x, Q^2) \right)
\]
Check the details!

Two-photon exchange can be important!

[PRC 68, 034325 (2003)]

\[
\frac{\mu_{p}G_{E}/G_{M}}{x_{F}}
\]
Two-photon exchange

- Candidate to explain discrepancy in form-factor measurements
- Interference between one- and two-photon exchange amplitudes leads to SSAs in inclusive DIS off transversely polarized targets
- Cross section proportional to $S(kxk')$ -> either measure left-right asymmetries or sine modulation
- Sensitive to beam charge due to odd number of e.m. couplings to beam
Signatures of two-photon exchange

A. Airapetian et al., PLB 682 (2010) 350

consistent with zero for both $e^+/e^-$ in case of protons
Signatures of two-photon exchange

According to their statistical uncertainties. The proton dilution was calculated separately for each trigger type and combined determined by combining the T1 and T6 results according to $\delta \phi_5 \times 10^{-3}$ between 0.75 and 0.82, with uncertainties of 0.02 for the T1 and T6 triggers using the yields from unpolarized hydrogen.

Consistent with each other. The final dilutions, which varied from 0.02 to 0.03, were measured for the T1 and T6 triggers using the yields available and the phase space of this measurement is limited. Correction was made on the asymmetries since the radiative background contamination, the largest of which is from pair-production.

The elastic fraction $Q^2$ scale uncertainty was 10% for BigBite, $Q^2$ scale uncertainty for electron and positron beams is 6.6% for the electron sample. Also, polarization which amounts to 9.3% (6.6%) for the electron (positron) sample. Also, the uncertainties associated with backgrounds in case of protons were measured with an electron trigger.

In conclusion, single-spin asymmetries were measured in inclusive semi-inclusive deep-inelastic scattering at HERA-B. A transverse single-spin asymmetry amplitude $A_{UT}^\sin(\phi_5)$ is the effective elastic fraction $Q^2$ for BigBite, $Q^2 > 1$ GeV.

**Figure:**
- Graph showing $A_{UT}^\sin(\phi_5)$ for $e^-$ and $e^+$ with $Q^2 < 1$ GeV$^2$ and $Q^2 > 1$ GeV$^2$.
- Graph showing $A_{UT}^\sin(\phi_5)$ for $e^+$ and $e^-$ with $Q^2 < 1$ GeV$^2$ and $Q^2 > 1$ GeV$^2$.
- Graph showing the elastic fraction $Q^2$ as a function of $x_B$.
- Graph showing the elastic fraction $x_B$ as a function of $Q^2$.

**Table:**

<table>
<thead>
<tr>
<th>Beam</th>
<th>$A_{UT}^\sin(\phi_5) \times 10^{-3}$</th>
<th>$\delta A_{UT}^\sin(\phi_5)$ (stat.) $\times 10^{-3}$</th>
<th>$\delta A_{UT}^\sin(\phi_5)$ (syst.) $\times 10^{-3}$</th>
<th>$\langle x_B \rangle$</th>
<th>$\langle Q^2 \rangle$ [GeV$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+$</td>
<td>-0.61</td>
<td>3.97</td>
<td>0.63</td>
<td>0.02</td>
<td>0.68</td>
</tr>
<tr>
<td>$e^-$</td>
<td>-6.55</td>
<td>3.40</td>
<td>0.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e^+$</td>
<td>-0.60</td>
<td>1.70</td>
<td>0.29</td>
<td>0.14</td>
<td>2.40</td>
</tr>
<tr>
<td>$e^-$</td>
<td>-0.85</td>
<td>1.50</td>
<td>0.29</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
- The dotted curve near zero (positive) is the LHRS data with combined statistical and systematic uncertainties.
- The square point is the LHRS data with combined statistical and systematic uncertainties indicated by the lower solid band.
- The transverse single-spin asymmetry amplitudes are consistent with zero for both $e^+/e^-$ in case of protons, non-zero for neutrons!
... the other polarized SF ...
$A_2$ and $xg_2$ on the proton

- latest HERMES data consistent with (sparse) world data
- rather low beam polarization during HERA II $\Rightarrow$ small f.o.m.
$A_2$ and $xg_2^w$ on the proton

\begin{align*}
\int_{0.023}^{0.9} g_2(x, Q^2) \, dx &= \left\{ \begin{array}{l}
0.006 \pm 0.024_{\text{stat}} \pm 0.017_{\text{syst}} \\
-0.042 \pm 0.008
\end{array} \right. \\
\int_{0}^{1} x^2 \bar{g}_2(x, Q^2) \, dx &= \left\{ \begin{array}{l}
0.0148 \pm 0.0096_{\text{stat}} \pm 0.0048_{\text{syst}} \\
0.0032 \pm 0.0017
\end{array} \right.
\end{align*}

Gunar Schnell

A. Airapetian et al., EPJ C72 (2012) 1921
... the neutron case

Panel a)

$\frac{g_2}{x}$ vs. $x$ for proton and deuteron.

Panel b)

$\frac{g_2}{x}$ vs. $x$ for $^{3}\text{He}$.

[M. Posik et al., PRL 113, 022002 (2014)]
... the neutron case

- \( d_2 \) sizable at lower energies
- opposite sign compared to proton case (and SLAC measurements) (expected, e.g., by M. Burkardt, PRD 88, 114502 (2013) due to “instantaneous transverse color force”)
- desirable to have more precise large-\( Q^2 \) data covering wide \( x \) range

**Diagram:**

- Data points from different experiments and models, including Lattice QCD, Sum Rules, Chiral Soliton, Bag Models, RSS (Resonance), and Elastic Contribution (CN).
- Graph showing \( d_2 \) vs. \( Q^2 \) with error bars.

[M. Posik et al., PRL 113, 022002 (2014)]
Semi-inclusive DIS

\[(E, p) \rightarrow \gamma^* \rightarrow (E', p') \]

\[e \quad \rightarrow \quad q \quad \gamma^* \quad \rightarrow \quad (E', p') \]

Particles:
- u
- d
- \(h\)
- K
- \(\pi\)
Spin-momentum structure of the nucleon

\[ \frac{1}{2} \text{Tr} \left[ (\gamma^+ + \lambda \gamma^+ \gamma_5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T}^\perp + \lambda \Lambda g_1 + \lambda S^i k^i \frac{1}{m} g_{1T} \right] \]

\[ \frac{1}{2} \text{Tr} \left[ (\gamma^+ - s^j i \sigma^{+j} \gamma_5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T}^\perp + s^i \epsilon^{ij} k^j \frac{1}{m} h_1^\perp + s^i S^i h_1 \right. \]

\[ \left. + s^i (2k^i k^j - k^2 \delta^{ij}) S^j \frac{1}{2m^2} h_{1T}^\perp + \Lambda s^i k^i \frac{1}{m} h_{1L}^\perp \right] \]

<table>
<thead>
<tr>
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- each TMD describes a particular spin-momentum correlation
- functions in black survive integration over transverse momentum
- functions in green box are chirally odd
- functions in red are naive T-odd
Spin-momentum structure of the nucleon

\[ \frac{1}{2} \text{Tr} \left[ (\gamma^+ + \lambda \gamma^+ \gamma_5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T} + \lambda \Lambda g_1 + \lambda S^i k^i \frac{1}{m} g_{1T} \right] \]

\[ \frac{1}{2} \text{Tr} \left[ (\gamma^+ - s^j i \sigma^{+j} \gamma_5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T} + s^i \epsilon^{ij} k^j \frac{1}{m} h_1^+ + s^i S^i h_1 \right. \]

\[ + s^i (2k^i k^j - k^2 \delta^{ij}) S^j \frac{1}{2m^2} h_{1T}^+ + \Lambda s^i k^i \frac{1}{m} h_{1L}^+ \]

<table>
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- **Boer-Mulders**
  - functions in black survive integration over transverse momentum
  - functions in red are naive T-odd

- **Sivers**
  - pretzelosity
  - functions in green box are chirally odd

- **worm-gear**
  - transversity

- **Twist-2 TMDs** describe a particular spin-momentum correlation
Quark polarimetry

- unpolarized quarks: easy - “just” hit them (and count)
- longitudinally polarized quarks: use polarized beam
Quark polarimetry

- unpolarized quarks: easy - “just” hit them (and count)
- longitudinally polarized quarks: use polarized beam
- transversely polarized quarks: need final-state polarimetry, e.g.
TMD fragmentation functions

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### TMD Fragmentation Functions

#### Quark Polarization

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*relevant for unpolarized final state*
### TMD fragmentation functions

#### Quark polarization

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- Relevant for unpolarized final state

#### Collins FF:

$$H_{1L}^\perp, q \rightarrow h$$

#### Ordinary FF:

$$D_{1}^q \rightarrow h$$
Probing TMDs in semi-inclusive DIS

**Twist-2 TMDs**

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in SIDIS*) couple PDFs to:

*) semi-inclusive DIS with unpolarized final state
Probing TMDs in semi-inclusive DIS

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in SIDIS*) couple PDFs to:

Collins FF: $H_{1\perp}^\perp, q \rightarrow h$

*) semi-inclusive DIS with unpolarized final state
Probing TMDs in semi-inclusive DIS

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in SIDIS*) couple PDFs to:

Collins FF: $H_{1L}^\perp$, $q \rightarrow h$

ordinary FF: $D_{1}^{q \rightarrow h}$

*) semi-inclusive DIS with unpolarized final state
Probing TMDs in semi-inclusive DIS

in SIDIS*) couple PDFs to:

Collins FF: $H_1^{⊥},q→h$

ordinary FF: $D_1^q→h$

give rise to characteristic azimuthal dependences

*) semi-inclusive DIS with unpolarized final state
**1-Hadron production** \((ep \rightarrow ehX)\)

\[
d\sigma = d\sigma^0_{UU} + \cos 2\phi \ d\sigma^1_{UU} + \frac{1}{Q} \cos \phi \ d\sigma^2_{UU} + \lambda_e \frac{1}{Q} \sin \phi \ d\sigma^3_{LU} \\
+S_L \left\{ \sin 2\phi \ d\sigma^4_{UL} + \frac{1}{Q} \sin \phi \ d\sigma^5_{UL} + \lambda_e \left[ d\sigma^6_{LL} + \frac{1}{Q} \cos \phi \ d\sigma^7_{LL} \right] \right\} \\
+S_T \left\{ \sin(\phi - \phi_S) \ d\sigma^8_{UT} + \sin(\phi + \phi_S) \ d\sigma^9_{UT} + \sin(3\phi - \phi_S) \ d\sigma^{10}_{UT} \frac{1}{Q} \right. \\
\left. + \frac{1}{Q} \left( \sin(2\phi - \phi_S) \ d\sigma^{11}_{UT} + \sin \phi_S \ d\sigma^{12}_{UT} \right) \right\} \\
+\lambda_e \left[ \cos(\phi - \phi_S) \ d\sigma^{13}_{LT} + \frac{1}{Q} \left( \cos \phi_S \ d\sigma^{14}_{LT} + \cos(2\phi - \phi_S) \ d\sigma^{15}_{LT} \right) \right] \right\}
\]


Bacchetta et al., JHEP 0702 (2007) 093

$1\text{-Hadron production (ep}$ $\rightarrow$ $\text{ehX})$

\[
d\sigma = d\sigma_{UU}^0 + \cos 2\phi d\sigma_{UU}^1 + \frac{1}{Q} \cos \phi d\sigma_{UU}^2 + \lambda_e \frac{1}{Q} \sin \phi d\sigma_{LU}^3
\]

\[
+S_L \left\{ \sin 2\phi d\sigma_{UL}^4 + \frac{1}{Q} \sin \phi d\sigma_{UL}^5 + \lambda_e \left[ d\sigma_{LL}^6 + \frac{1}{Q} \cos \phi d\sigma_{LL}^7 \right] \right\}
\]

\[
+S_T \left\{ \sin(\phi - \phi_S) d\sigma_{UT}^8 + \sin(\phi + \phi_S) d\sigma_{UT}^9 + \sin(3\phi - \phi_S) d\sigma_{UT}^{10} + \frac{1}{Q} \left( \sin(2\phi - \phi_S) d\sigma_{UT}^{11} + \sin \phi_S d\sigma_{UT}^{12} \right) + \lambda_e \left[ \cos(\phi - \phi_S) d\sigma_{LT}^{13} + \frac{1}{Q} \left( \cos \phi_S d\sigma_{LT}^{14} + \cos(2\phi - \phi_S) d\sigma_{LT}^{15} \right) \right] \right\}
\]

Bacchetta et al., JHEP 0702 (2007) 093
1-Hadron production (ep \xrightarrow{} ehX)

\[
d\sigma = d\sigma_{UU}^0 + \cos 2\phi \, d\sigma_{UU}^1 + \frac{1}{Q} \cos \phi \, d\sigma_{UU}^2 + \lambda_e \frac{1}{Q} \sin \phi \, d\sigma_{LU}^3 \\
+ S_L \left\{ \sin 2\phi \, d\sigma_{UL}^4 + \frac{1}{Q} \sin \phi \, d\sigma_{UL}^5 + \lambda_e \left[ d\sigma_{LL}^6 + \frac{1}{Q} \cos \phi \, d\sigma_{LL}^7 \right] \right\} \\
+ S_T \left\{ \sin(\phi - \phi_S) \, d\sigma_{UT}^8 + \sin(\phi + \phi_S) \, d\sigma_{UT}^9 + \sin(3\phi - \phi_S) \, d\sigma_{UT}^{10} \\
+ \frac{1}{Q} \left( \sin(2\phi - \phi_S) \, d\sigma_{UT}^{11} + \sin \phi_S \, d\sigma_{UT}^{12} \right) \right\} \\
+ \lambda_e \left[ \cos(\phi - \phi_S) \, d\sigma_{LT}^{13} + \frac{1}{Q} \left( \cos \phi_S \, d\sigma_{LT}^{14} + \cos(2\phi - \phi_S) \, d\sigma_{LT}^{15} \right) \right] \right\}
\]

Bacchetta et al., JHEP 0702 (2007) 093
... back to results ...
flavor separation of LO quark-helicity distribution using H and D DIS data
Helicity density

\[ R_{SF} = \frac{\int D_{\frac{K^+}{s}}^{K^+}(z) \, dz}{\int D_{\frac{K^+}{u}}^{K^+}(z) \, dz} \]

caveat: potentially large dependences on knowledge of FFs!
caveat: potentially large dependences on knowledge of FFs!

global analysis of DIS, pp, and e^+e^- data
polarized light ions?

- case for iso-scalar target as less (& more convenient?) FFs involved:

\[
A_K^{\pm}(x) \frac{d^2N_K(x)}{dx dQ^2} = \mathcal{K}_{LL}(x, Q^2) \left[ \Delta Q(x) \int D^K_Q(z) dz + \Delta S(x) \int D^K_S(z) dz \right]
\]

- measure strange helicity distribution using polarized D (unpolarized D can be used to constrain strangeness and fragmentation functions involved)

\[
\mathcal{D}_S^K = D_{1s}^{s \rightarrow K^+} + D_{1s}^{s \rightarrow K^+} + D_{1s}^{s \rightarrow K^-} + D_{1s}^{s \rightarrow K^-} \\
\mathcal{D}_Q^K = 4D_{1u}^{u \rightarrow K^+} + 4D_{1u}^{u \rightarrow K^+} + D_{1d}^{d \rightarrow K^+} + D_{1d}^{d \rightarrow K^+} + \ldots
\]
### Helicity density

<table>
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[Avakian et al. [CLAS], PRL 105, 262002 (2010)]

**CLAS data hints at width \( \mu_2 \) of \( g_1 \) that is less than the width \( \mu_0 \) of \( f_1 \)**

\[
\begin{align*}
    f_1^q(x, k_T) &= f_1(x) \frac{1}{\pi \mu_0^2} \exp \left( -\frac{k_T^2}{\mu_0^2} \right) \\
    g_1^q(x, k_T) &= g_1(x) \frac{1}{\pi \mu_2^2} \exp \left( -\frac{k_T^2}{\mu_2^2} \right)
\end{align*}
\]
CLAS data hints at width $\mu_2$ of $g_1$ that is less than the width $\mu_0$ of $f_1$

\[
f_1^q(x, k_T) = f_1(x) \frac{1}{\pi \mu_0^2} \exp \left( -\frac{k_T^2}{\mu_0^2} \right)
\]

\[
g_1^q(x, k_T) = g_1(x) \frac{1}{\pi \mu_2^2} \exp \left( -\frac{k_T^2}{\mu_2^2} \right)
\]

no significant $P_{h\perp}$ dependences seen at HERMES and COMPASS
The quest for transversity
Transversity
(Collins fragmentation)

- **significant in size and opposite in sign for charged pions**
- **disfavored Collins FF large and opposite in sign to favored one**
- leads to various cancellations in SSA observables

<table>
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<tr>
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<tr>
<td>$f_1$</td>
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2005: First evidence from HERMES SIDIS on proton

Non-zero transversity
Non-zero Collins function
since those early days, a wealth of new results:

- **COMPASS**

- **HERMES**
  [PLB 693 (2010) 11]

- **Jefferson Lab**
  [PRL 107 (2011) 072003]
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<td>$g_{1T}$</td>
<td>$h_1^{\perp}, h_{1T}^{\perp}$</td>
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since those early days, a wealth of new results:

- **COMPASS**

- **HERMES**
  [PLB 693 (2010) 11]

- **Jefferson Lab**
  [PRL 107 (2011) 072003]

excellent agreement of various proton data, also with neutron results
since those early days, a wealth of new results:

**COMPASS**

**HERMES**
[PLB 693 (2010) 11]

**Jefferson Lab**
[PRL 107 (2011) 072003]

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**Collins amplitudes**

![Collins asymmetries for charged pions](image1)
![Collins asymmetries for charged kaons](image2)
![Collins asymmetries for neutral kaons](image3)

since those early days, a wealth of new results:

- **COMPASS**

- **HERMES**
  [PLB 693 (2010) 11]

- **Jefferson Lab**
  [PRL 107 (2011) 072003]

- ![Collins asymmetries](image)

  cancelation of (unfavored) u and d fragmentation (opposite signs of up and down transversity)?
Collins amplitudes

since those early days, a wealth of new results:

COMPASS

HERMES
[PLB 693 (2010) 11]

Jefferson Lab


but relatively large K⁻ asymmetry on³He?
A Closer Look at Collins Asymmetries II

express asymmetries in terms of flavor ratios:

\[
\tilde{A}_C^{\pi^+} = \mathcal{K}(x, z) \frac{4 + \delta r \mathcal{H}}{4 + r \mathcal{D}}
\]

\[
\tilde{A}_C^{\pi^-} = \mathcal{K}(x, z) \frac{4 \mathcal{H} + \delta r}{4 \mathcal{D} + r}
\]

\[
\tilde{A}_C^{\pi^0} = \mathcal{K}(x, z) \frac{(4 + \delta r)(1 + \mathcal{H})}{(4 + r)(1 + \mathcal{D})}
\]

<table>
<thead>
<tr>
<th>Polarized Objects</th>
<th>Unpolarized Objects</th>
<th>Mixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mathcal{H}) = (\frac{H_d}{H_f})</td>
<td>(\mathcal{D} = \frac{D_d}{D_f})</td>
<td>(\mathcal{K} = \frac{(\delta u + \frac{1}{4}\delta d)zH_f}{(u + \frac{1}{4}d)D_f})</td>
</tr>
<tr>
<td>(\delta r = \frac{\delta d + 4\delta \bar{u}}{\delta u + \frac{1}{4}\delta d})</td>
<td>(r = \frac{d + 4\bar{u}}{u + \frac{1}{4}d})</td>
<td></td>
</tr>
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\(\Rightarrow 3\) constraints and 3 unknowns!

e.g., CTEQ6,R1990 and Kretzer et al.
express asymmetries in terms of flavor ratios:

\[
\tilde{A}_C^{\pi^+} = K(x, z) \frac{4 + \delta r H}{4 + r D}
\]

\[
\tilde{A}_C^{\pi^-} = K(x, z) \frac{4H + \delta r}{4D + r}
\]

\[
\tilde{A}_C^{\pi^0} = K(x, z) \frac{(4 + \delta r)(1 + H)}{(4 + r)(1 + D)}
\]

The three asymmetries are not independent (\( C(x, z) \equiv \frac{r(x) + 4D(z)}{r(x)D(z) + 4} \)):

\[
\tilde{A}_C^{\pi^+}(x, z) + C(x, z)\tilde{A}_C^{\pi^-}(x, z) - (1 + C(x, z))\tilde{A}_C^{\pi^0}(x, z) = 0
\]

e.g., CTEQ6,R1990 and Kretzer et al.

⇒ 3 constraints and 3 unknowns!
A Closer Look at Collins Asymmetries II

Express asymmetries in terms of flavor ratios:

\[
\begin{align*}
\tilde{A}_C^{\pi^+} &= K(x, z) \frac{4 + \delta r \mathcal{H}}{4 + r \mathcal{D}} \\
\tilde{A}_C^{\pi^-} &= K(x, z) \frac{4 \mathcal{H} + \delta r}{4 \mathcal{D} + r} \\
\tilde{A}_C^{\pi^0} &= K(x, z) \frac{(4 + \delta r)(1 + \mathcal{H})}{(4 + r)(1 + \mathcal{D})}
\end{align*}
\]

The three asymmetries are not independent \((C(x, z) \equiv \frac{r(x) + 4 \mathcal{D}(z)}{r(x) \mathcal{D}(z) + 4})\):

\[
\tilde{A}_C^{\pi^+} (x, z) + C(x, z) \tilde{A}_C^{\pi^-} (x, z) - (1 + C(x, z)) \tilde{A}_C^{\pi^0} (x, z) = 0
\]

E.g., CTEQ6.1, R1990 and Kretzer et al.

\(\Rightarrow 8\) constraints and 3 unknowns!
eliminate $\mathcal{K}$ and relate $\mathcal{H}$ to $\delta r$

$\Rightarrow$ scan solution space for $\mathcal{H}$ and $\delta r$ by sampling set of $(\tilde{A}_C^{\pi^+}, \tilde{A}_C^{\pi^-}, \tilde{A}_C^{\pi^0})$

(around measured values according to statistical uncertainty)
eliminate $\mathcal{K}$ and relate $\mathcal{H}$ to $\delta r$

$\Rightarrow$ scan solution space for $\mathcal{H}$ and $\delta r$ by sampling set of $(\tilde{A}_C^{\pi^+}, \tilde{A}_C^{\pi^-}, \tilde{A}_C^{\pi^0})$

(around measured values according to statistical uncertainty)
\[ \delta r \approx \delta d/\delta u \quad \text{from } \chi_{\text{QSM}} \]

Limits on Transversity and Collins FF

look at slice of distribution:

strong hint for \( H_d/H_f \) negative
Limits on Transversity and Collins FF

\[ \delta r \approx \delta d / \delta u \text{ from } \chi_{QSM} \]

look at slice of distribution:

but transversity ratio hardly constrained

strong hint for \[ H_d / H_f \text{ negative} \]
the “Collins trap”

\[ H_{1,\text{fav}} \approx -H_{1,\text{dis}} \]

thus

\[ \langle \sin(\phi + \phi_S) \rangle^\pi_{UT} \sim (4h_u^u - h_d^d) H_{1,\text{fav}} \]

\[ \langle \sin(\phi + \phi_S) \rangle^\pi_{UT} \sim -(4h_u^u - h_d^d) H_{1,\text{fav}} \]

clearly need precise data from “neutron” target(s)

(valid for all chiral-odd TMDs)
Transversity's friends
first direct evidence on:

- $^3$He target at JLab
- H target at COMPASS & HERMES

References:

- [PRL 108 (2012) 052001]

PLIP 2018, Gent
\[
2\langle \sin(\phi - \phi_S) \rangle_{\text{UT}} = -\frac{\sum_q e_q^2 f_{1T}^q(x, p_T^2) \otimes W D_1^q(z, k_T^2)}{\sum_q e_q^2 f_1^q(x, p_T^2) \otimes D_1^q(z, k_T^2)}
\]

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### Graph

**7.3% scale uncertainty**

[PRL 103 (2009) 152002]
### Sivers amplitudes for pions

\[
2\langle \sin (\phi - \phi_S) \rangle_{\text{UT}} = -\frac{\sum_q e_q^2 f_{1T}^q(x, p_T^2) \otimes W D_1^q(z, k_T^2)}{\sum_q e_q^2 f^q_1(x, p_T^2) \otimes D_1^q(z, k_T^2)}
\]

- $\pi^+$ dominated by u-quark scattering:
  \[
  \sim - \frac{f_{1T}^u(x, p_T^2) \otimes W D_1^{u\to\pi^+}(z, k_T^2)}{f_1^u(x, p_T^2) \otimes D_1^{u\to\pi^+}(z, k_T^2)}
  \]
- u-quark Sivers DF $< 0$

- 7.3% scale uncertainty

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**Graph:**

- $\pi^+$
- $\pi^0$
- $\pi^-$

**Figure:**

- [PRL 103 (2009) 152002]
Sivers amplitudes for pions

\[ 2 \langle \sin (\phi - \phi_S) \rangle_{\text{UT}} = - \frac{\sum_q e_q^2 f_{1T}^q(x, p_T^2) \otimes W D_1^q(z, k_{T}^2)}{\sum_q e_q^2 f_{1T}^q(x, p_T^2) \otimes D_1^q(z, k_{T}^2)} \]

\[ \pi^+ \text{ dominated by u-quark scattering:} \]

\[ \sim - \frac{f_{1T}^u(x, p_T^2) \otimes W D_1^{u \to \pi^+}(z, k_{T}^2)}{f_{1T}^u(x, p_T^2) \otimes D_1^{u \to \pi^+}(z, k_{T}^2)} \]

\[ \text{u-quark Sivers DF } < 0 \]

\[ \text{d-quark Sivers DF } > 0 \]

(cancellation for \( \pi^- \))
cancelation for D target supports opposite signs of up and down Sivers
Sivers amplitudes

- There is a cancellation for D target, which suggests opposite signs of up and down Sivers.
- Newer results from JLab using $^3$He target and from COMPASS for proton target (also multi-d).

Gunar Schnell

PLIP 2018, Gent
Sivers amplitudes
pions vs. kaons

somewhat unexpected if dominated by scattering off u-quarks:

\[ \langle 2 \sin(\phi - \phi_S) \rangle_{^1U^T} \]
Sivers amplitudes pions vs. kaons

somewhat unexpected if dominated by scattering off u-quarks:

$$\frac{\left| f_{1T}^u(x, p_T^2) \otimes \mathcal{W} \right| D_{1}^{u \rightarrow \pi^+ / K^+}(z, k_T^2)}{f_{1}^u(x, p_T^2) \otimes D_{1}^{u \rightarrow \pi^+ / K^+}(z, k_T^2)}$$

larger amplitudes seen also by COMPASS

[PLB 744 (2015) 250]
Sivers amplitudes
pions vs. kaons

somewhat unexpected if dominated by scattering off u-quarks:

\[
\frac{1}{2} = \frac{\int f_{1T}^u(x, p_T^2) \otimes W D_1^{u\rightarrow\pi^+/K^+}(z, k_T^2) - \int f_{1T}^u(x, p_T^2) \otimes D_1^{u\rightarrow\pi^+/K^+}(z, k_T^2))}{f_{1T}^u(x, p_T^2) \otimes W D_1^{u\rightarrow\pi^+/K^+}(z, k_T^2)}
\]

surprisingly large $K^-$ asymmetry for $^3$He target (but zero for $K^+$?!)
first round of SIDIS measurements coming to an end

various indications of flavor-dependent transverse momentum

transversity is non-zero and quite sizable

can be measured, e.g., via Collins effect

d-quark transversity difficult to access with only proton targets

Sivers function also clearly non-zero

opposite sign for up and down quarks in line with their contributions to the nucleon’s anomalous magnetic moment

precision measurements at ongoing and future SIDIS facilities needed to fully map TMD landscape

in particular, several intriguing results for neutron targets motivate program with polarized D and $^3$He