Selected spin-physics results from fixed-target experiments

--a mainly European and strange perspective--

Gunar.Schnell @ desy.de
Deep-Inelastic Scattering

use well-known probe to explore hadron structure

inclusive DIS: detect scattered lepton

\[ Q^2_{\text{lab}} = 4EE' \sin^2 \left( \frac{\Theta}{2} \right) \]
\[ \nu_{\text{lab}} = E - E' \]
\[ W^2_{\text{lab}} = M^2 + 2M\nu - Q^2 \]
\[ y_{\text{lab}} = \frac{\nu}{E} \]
\[ x_{\text{lab}} = \frac{Q^2}{2M\nu} \]
Deep-Inelastic Scattering

use well-known probe to explore hadron structure

inclusive DIS: detect scattered lepton
semi-inclusive DIS: detect scattered lepton and some fragments

\[ Q^2_{\text{lab}} = 4EE' \sin^2 \left( \frac{\Theta}{2} \right) \]
\[ \nu_{\text{lab}} = E - E' \]
\[ W^2_{\text{lab}} = M^2 + 2M\nu - Q^2 \]
\[ y_{\text{lab}} = \frac{\nu}{E} \]
\[ x_{\text{lab}} = \frac{Q^2}{2M\nu} \]
\[ z_{\text{lab}} = \frac{E_h}{\nu} \]
Deep-Inelastic Scattering

use well-known probe to explore hadron structure

\[ Q^2 \equiv \frac{4EE' \sin^2(\frac{\Theta}{2})}{2} \]
\[ \nu \equiv E - E' \]
\[ W^2 \equiv M^2 + 2M\nu - Q^2 \]
\[ y \equiv \frac{\nu}{E} \]
\[ x \equiv \frac{Q^2}{2M\nu} \]
\[ z \equiv \frac{E_h}{\nu} \]

Factorization \( \Rightarrow \sigma^{ep \rightarrow ehX} = \sum_q DF^{p \rightarrow q} \otimes \sigma^{eq \rightarrow eq} \otimes FF^{q \rightarrow h} \)

exploit strong correlation between flavor structure of leading hadron and struck quark
Long history of fixed-target DIS

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- polarized (<60%) $e^+/e^-$ beam of 27GeV with both helicity states
- pure gas targets with high transverse (p) and longitudinal (p,d) polarization
- fast spin-flip of target
- excellent hadron PID using dual-radiator RICH
- polarized (<80%) muon beam of 160GeV limited to one helicity state
- NH$_3$ and $^6$LiD targets with transverse and longitudinal polarization, but large dilution
- reversal of target polarization every ~8h (but multiple target cell with opposite P)
- good hadron PID using RICH
Inclusive DIS

vital input to unpolarized PDF sets
Inclusive DIS

$g_1(x,Q^2) = \frac{dF_2}{dx}$

$Q^2 > 1 (GeV/c)^2$

More data from JLAB/EG1a @ low $Q^2$.

B. Badelek (Warsaw)

Nucleon Spin Structure

INPC 2010 13 / 33

Q$^2$ evolution and gluon polarization

- Q$^2$ dependence
- $g_1$ data related to gluon polarization (DGLAP)
- Limited kinematic range (c.f. unpol. HERA)

JINR, Dubna, June 21, 2010

CLAS

G. Mallot
Inclusive DIS

much wider kinematic range needed to test/use evolution

G. Schnell - DESY Zeuthen

JINR, Dubna, June 21, 2010

CLAS

G. Mallot
Inclusive DIS

much wider kinematic range needed to test/use evolution
different targets ☛ non-singlet combination: $g_{1,p}(x)-g_{1,n}(x)$

G. Schnell - DESY Zeuthen
fundamental QCD prediction:

\[ \frac{\Gamma_P(Q^2) - \Gamma_N(Q^2)}{\Delta C_{NS}(\alpha_S(Q^2))} = \frac{1}{6} a_3 \Delta C_{NS}(\alpha_S(Q^2)) \]

from this data: \( g_A/g_V = 1.28 \pm 0.07_{\text{stat}} \pm 0.07_{\text{sys}} \)

need more precise data for both proton and neutron!
High-$x$ behavior of $A_1$

testing (not so fundamental) prediction:

![Graphs showing $A_1$ vs. $x$ with various data points and theoretical curves.]

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*surprises may still await us at large $x$*
Integral of $g_1(x)$

A. Airapetian et al., PRD 75 (2007)

$Q^2 = 5 \text{ GeV}^2$

$\int_x^{0.9} g_1 dx$
Integral of $g_1(x)$

Saturation close to full integral?

\[ \Delta \Sigma = \frac{1}{\Delta C_S} \left[ \frac{9 \Gamma_1^d}{1 - \frac{3}{2} \omega D} - \frac{1}{4} a_8 \Delta C_{NS} \right] \]

A. Airapetian et al., PRD 75 (2007)

\[ \int_x^1 g_1 \, dx \]

$Q^2 = 5 \text{ GeV}^2$

hyperon-decay data

theory

0.05 \pm 0.05

theory

$\Gamma_1^d$

$\Delta C_{NS}$

$\omega D$

$\Delta C_S$

$\Delta \Sigma$

$\MS$

$\Delta \Sigma$

G. Schnell - DESY Zeuthen

INT 10-3, Seattle
Integral of $g_1(x)$

Saturation close to full integral?

$$\Delta \Sigma \overset{\overline{MS}}{=} \frac{1}{\Delta C_S} \left[ \frac{9 \Gamma^d_1}{1 - \frac{3}{2} \omega_D} - \frac{1}{4} a_8 \Delta C_{NS} \right]$$

theory 0.05±0.05

hyperon-decay data

$$\Delta \Sigma \overset{\overline{MS}}{=} 0.330 \pm 0.011_{\text{theory}} \pm 0.025_{\text{exp}} \pm 0.028_{\text{evol}}$$

A. Airapetian et al., PRD 75 (2007)
Integral of $g_1(x)$

Saturation close to full integral?

$$\Delta \Sigma \overline{\text{MS}} = \frac{1}{\Delta C_S} \left[ \frac{9 \Gamma_1^d}{1 - \frac{3}{2} \omega_D} - \frac{1}{4} a_8 \Delta C_{NS} \right]$$

theory 0.05±0.05

hyperon-decay data

$$\Delta \Sigma \overline{\text{MS}} = 0.330 \pm 0.011_{\text{theory}} \pm 0.025_{\text{exp}} \pm 0.028_{\text{evol}}$$

very similar results from COMPASS: 0.33±0.03±0.05
Strange helicity distribution

\[ \Delta s + \Delta \bar{s} \overset{\text{MS}}{=} \frac{1}{\Delta C_S} \left[ \frac{3 \Gamma_1^d}{1 - \frac{3}{2} \omega_D} - \frac{1}{12} a_8 (4 \Delta C_S + \Delta C_{NS}) \right] \]

\[ \Delta s + \Delta \bar{s} \overset{\text{MS}}{=} -0.085 \pm 0.013 \text{theory} \pm 0.008 \text{exp} \pm 0.009 \text{evol} \]

significantly negative using inclusive DIS!

zero from semi-inclusive DIS?
Quark helicity distributions from SIDIS

The spin asymmetries for a deuteron target were evaluated from measurements from HERMES \[14, 26\] (open circles) are shown for comparison to the predictions of the DSSV fit \[1\] at the uncertainty related to the dilution factor, which is small for semi-inclusive asymmetries.

A similar correction to the inclusive asymmetry was evaluated as a fraction of the statistical errors according to the procedure of Ref. \[18\] to the asymmetries of identified hadrons in the COMPASS experiment which measured asymmetries of identified hadron samples where the physical asymmetry cancels out. The asymmetry and each bin of resulting corrections, which do not exceed one fourth of the statistical error, were added in quadrature.

The correlation is larger at small values of the data. The HERMES inclusive \[26\] and the semi-inclusive asymmetries generated by instabilities in the target material \[27\]. These isotopes are both polarised to more than 90% \[28\]. The results of HERMES, the only other experiment which measured asymmetries, except those from HERMES, due to the larger pion multiplicity. The error of the target polarisation measurement and the errors associated with the beam are list in Table 2. The largest correlations \(0.5\%) in the target material \[27\]. The remaining asymmetries made on 23 subsets of data.

The spin asymmetries for a deuteron target were evaluated from measurements from HERMES \[14, 26\] (open circles) are shown for comparison to the predictions of the DSSV fit \[1\] at the uncertainty related to the dilution factor, which is small for semi-inclusive asymmetries.
Quark helicity distributions from SIDIS

![Graphs showing the quark helicity distributions evaluated at various points](image)

The figure displays the quark helicity distributions evaluated at combinations of data points, with the COMPASS acceptance correction. The distributions are shown for both proton and deuteron targets, with error bars indicating the statistical and systematic uncertainties. The graphs compare the distribution at various kinematic points, with solid markers and bands corresponding to PDFs obtained with the DSSV fit and open markers and bands corresponding to PDFs obtained with EMC parameterisations.

G. Schnell - DESY Zeuthen
Quark helicity distributions from SIDIS

![Graphs and plots showing quark helicity distributions](image)

strong dependence on set of FFs used
Quark helicity distributions from SIDIS

\[ \Delta \bar{s}(x)dx \]

EMC: \( R_{SF} = 3.4 \)

DSS: \( R_{SF} = 6.6 \)

KRE: \( R_{SF} = 2.1 \)

Stat. uncert. (incl. DIS)
Stat. uncert. (SIDIS+DSS)
Uncert. due to \( R_{UF} \)

strong dependence on set of FFs used
Strange-quark distributions

- use isoscalar probe and target to extract strange-quark distributions
- only need inclusive asymmetries and $K^+K^-$ asymmetries, i.e., $A_{||,d}(x, Q^2)$ and $A_{||,d}^{K^+K^-}(x, z, Q^2)$, as well as $K^+K^-$ multiplicities on deuteron

\[
S(x) \int D^K_S(z) \, dz \simeq Q(x) \left[ 5 \frac{d^2 N^K(x)}{d^2 N^{DIS}(x)} - \int D^K_Q(z) \, dz \right]
\]

\[
A_{||,d}(x) \frac{d^2 N^{DIS}(x)}{dx \, dQ^2} = \mathcal{K}_{LL}(x, Q^2) \left[ 5 \Delta Q(x) + 2 \Delta S(x) \right]
\]

\[
A_{||,d}^{K^\pm}(x) \frac{d^2 N^K(x)}{dx \, dQ^2} = \mathcal{K}_{LL}(x, Q^2) \left[ \Delta Q(x) \int D^K_Q(z) \, dz + \Delta S(x) \int D^K_S(z) \, dz \right]
\]
Strange-quark distributions

- use isoscalar probe and target to extract strange-quark distributions
- only need inclusive asymmetries and $K^+K^-$ asymmetries, i.e., $A_{||,d}(x, Q^2)$ and $A_{||,d}(x, Q^2)$, as well as $K^+K^-$ multiplicities on deuteron

![Graph showing strange-quark distributions](image)

A. Airapetian et al., PLB 666, 446 (2008)
Strange-quark distributions

- use isoscalar probe and target to extract strange-quark distributions
- only need inclusive asymmetries and $K^+K^-$ asymmetries, i.e., $A_{∥,d}(x, Q^2)$ and $A_{∥,d}^{K^+K^-}(x, z, Q^2)$, as well as $K^+K^-$ multiplicities on deuteron

Strange-quark distribution softer than (maybe) expected

A. Airapetian et al., PLB 666, 446 (2008)
Strange-quark distributions

- use isoscalar probe and target to extract strange-quark distributions
- only need inclusive asymmetries and $K^+K^-$ asymmetries, i.e., $A_{∥,d}(x, Q^2)$ and $A_{∥,d}^{K^+ + K^-}(x, z, Q^2)$, as well as $K^+K^-$ multiplicities on deuteron

Strange-quark distribution softer than (maybe) expected

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G. Schnell - DESY Zeuthen
Strange-quark distributions

- use isoscalar probe and target to extract strange-quark distributions
- only need inclusive asymmetries and $K^+ + K^-$ asymmetries, i.e., $A_{\parallel,d}(x, Q^2)$ and $A_{\parallel,d}^{K^+ + K^-}(x, z, Q^2)$, as well as $K^+ + K^-$ multiplicities on deuteron

Strange-quark distributions softer than (maybe) expected

Strange-quark helicity distribution consistent with zero or slightly positive in contrast to inclusive DIS analyses

A. Airapetian et al., PLB 666, 446 (2008)

G. Schnell - DESY Zeuthen
Towards 3-D pictures of the nucleon
Including transverse momentum

- Quarks are confined in nucleon's volume
- Quarks radiate and absorb gluons
  - Transverse quark momentum $p_T$ can't generally be ignored
  - Consequences, e.g.,
    - $R = \sigma_L / \sigma_T \neq 0$ (2xF1 ≠ F2)
    - More distribution functions (transverse-momentum dependent PDFs)
Spin-Momentum Structure of the Nucleon

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

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

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- Functions in black survive integration over transverse momentum
- Functions in green box are chirally odd
- Functions in red are naive T-odd

Twist-2 TMDs
Spin-Momentum Structure of the Nucleon

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

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

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- functions in black survive integration over transverse momentum
- functions in green box are chirally odd
- functions in red are naive T-odd

Twist-2 TMDs

Sivers

Boer-Mulders

pretzelosity

transversity

worm-gear

helicity

quark pol.
TMDs - Probabilistic interpretation

Proton goes out of the screen/ photon goes into the screen

- nucleon with transverse or longitudinal spin
- parton with transverse or longitudinal spin
- parton transverse momentum

\[ f_1 = \]

\[ g_1 = \]

courtesy A. Bacchetta
TMDs - Probabilistic interpretation

Proton goes out of the screen/ photon goes into the screen

- nucleon with transverse or longitudinal spin
- parton with transverse or longitudinal spin
- parton transverse momentum

\[ f_1 = \]

\[ g_1 = \]

\[ h_1 = \]

courtesy A. Bacchetta
TMDs - Probabilistic interpretation

Proton goes out of the screen/ photon goes into the screen

\[ f_{1T} = \]
\[ h_{1} = \]
\[ g_{1T} = \]
\[ h_{1L} = \]
\[ h_{1T} = \]

nucleon with transverse or longitudinal spin

parton with transverse or longitudinal spin

parton transverse momentum

courtesy A. Bacchetta

G. Schnell - DESY Zeuthen
1-Hadron Production \((ep \rightarrow ehX)\)

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

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

\[
+ S_T \left\{ \sin(\phi - \phi_S) \ d\sigma_{UT}^8 + \sin(\phi + \phi_S) \ d\sigma_{UT}^9 + \sin(3\phi - \phi_S) \ d\sigma_{UT}^{10} \frac{1}{Q} \right.
\]

\[
+ \frac{1}{Q} \left( \sin(2\phi - \phi_S) \ d\sigma_{UT}^{11} + \sin \phi_S \ d\sigma_{UT}^{12} \right)
\]

\[
+ \lambda_e \left[ \cos(\phi - \phi_S) \ d\sigma_{LT}^{13} + \frac{1}{Q} \left( \cos \phi_S \ d\sigma_{LT}^{14} + \cos(2\phi - \phi_S) \ d\sigma_{LT}^{15} \right) \right]\}
\]


Bacchetta et al., JHEP 0702 (2007) 093

1-Hadron Production (ep→ehX)

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

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

\[ + S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^8_{UT} + \sin(\phi + \phi_S) \, d\sigma^9_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \frac{1}{Q} \right\} \]

**Collins Effect:**

sensitive to quark transverse spin
1-Hadron Production (ep→ehX)

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

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

\[+ S_T \left\{ \sin(\phi - \phi_S) \ d\sigma^8_{UT} + \sin(\phi + \phi_S) \ d\sigma^9_{UT} + \sin(3\phi - \phi_S) \ d\sigma^{10}_{UT} \right\} \frac{1}{Q}
\]

**Sivers Effect:**
- correlates hadron's transverse momentum with nucleon spin
- requires orbital angular momentum
Sivers amplitudes for pions

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

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

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

\[ \pi^+ \rightarrow \pi^+ \]

\[ \sum_q e_q^2 f_{1T}^{\perp, u}(x, p_T^2) \otimes W D_{1T}^u(z, k_T^2) \]

\[ \approx - \frac{f_{1T}^{\perp, u}(x, p_T^2) \otimes W D_{1T}^{u \rightarrow \pi^+}(z, k_T^2)}{f_{1T}^u(x, p_T^2) \otimes D_{1T}^{u \rightarrow \pi^+}(z, k_T^2)} \]

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

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

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

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

△ \text{ u-quark Sivers DF < 0}

△ \text{ d-quark Sivers DF > 0}

(cancellation for } \pi^-)
Sivers amplitudes for pions

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

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

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

COMPASS results

Figure 2: Sivers asymmetry as a function of $x$, $z$, and $p_T^h$, for positive (closed points) and negative (open points) hadrons. The bars show the statistical errors. The point-to-point systematic uncertainties have been estimated to be $0.8\sigma_{\text{stat}}$ for positive and $0.4\sigma_{\text{stat}}$ for negative hadrons and are given by the bands. For positive hadrons only, an absolute scale uncertainty of $\pm 0.01$ has also to be taken into account.

Figure 3: Mean values of some kinematic variables in the final data sample. From left to right: mean values of $p_T^h$, $z$ and $Q^2$ as functions of $x$; mean values of $p_T^h$, $x$ and $Q^2$ as functions of $z$; mean values of $x$, $z$ and $Q^2$ as functions of $p_T^h$.

As it is clear from Fig. 1, the Collins asymmetry has a strong $x$ dependence. It is compatible with zero at small $x$ within the small statistical errors and increases in absolute value up to about 0.1 for $x > 0.1$. There, the values agree both in magnitude and in sign with the previous measurements of HERMES [13], which were performed at the considerably lower electron beam energy of 27.5 GeV. Also, the present results agree with the predictions of the global analysis of ref. [19, 20] and thus strongly support the underlying interpretation of the Collins asymmetry in terms of a convolution of the twist-two transversity PDF and the FF of a transversely polarised quark. An important issue is the $Q^2$ dependence of these functions. Our results at large $x$ are compatible with the HERMES data in spite of the higher $Q^2$ values which exceed those of HERMES by a factor 2 to 3 with increasing $x$. This indicates that the possible $Q^2$ dependence should not...
COMPASS results

- similar to HERMES: positive for positive and vanishing for negative hadrons
COMPASS results

- similar to HERMES: positive for positive and vanishing for negative hadrons
- size of amplitudes smaller than at HERMES
COMPASS results

Figure 4: Collins (upper row) and Sivers (lower row) asymmetry as a function of $W$, for positive (left) and negative (right) hadrons. The closed and open points give the values for the "large $x" and the "small $x" samples respectively. The errors are statistical only.

The results for the Sivers asymmetry for negative hadrons exhibit values compatible with zero within the statistical accuracy of the measurement. For positive hadrons, the data indicate small positive values, up to about 3% in the valence region. These values are somewhat smaller than but still compatible with the ones measured by HERMES at smaller $Q^2$.

Figure 5: Mean values of $Q^2$ (left) and $x$ (right) as functions of $W$. The closed and open points give the values for the "large $x" and the "small $x" samples respectively.
**COMPASS results**

Figure 4: Collins (upper row) and Sivers (lower row) asymmetry as a function of $W$, for positive (left) and negative (right) hadrons. The closed and open points give the values for the "large $x" and the "small $x" samples respectively. The errors are statistical only.

The results for the Sivers asymmetry for negative hadrons exhibit values compatible with zero within the statistical accuracy of the measurement. For positive hadrons, the data indicate small positive values, up to about 3% in the valence region. These values are somewhat smaller than but still compatible with the ones measured by HERMES at smaller $Q^2$.

Given the importance of the Sivers function in the present description of the transverse momentum structure of the nucleon, we looked at a possible kinematic dependence of our measurements. In particular, we evaluated the asymmetries as a function of $W$. In particular, we evaluated the asymmetries as a function of $W$.

Is there a $W^2$ dependence?
COMPASS results

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Given the importance of the Sivers function in the present description of the transverse momentum structure of the nucleon, we looked at a possible kinematic dependence of our measurements. In particular, we evaluated the asymmetries as a function of $W$.

is there a $W^2$ dependence?

or rather a hidden $Q^2$ dependence?
The kaon Sivers amplitudes
The kaon Sivers amplitudes

\[ 2 \langle \sin(\phi_S) \rangle_{\text{UT}} \]

\[ \begin{array}{c}
\text{K}^+ \\
\text{K}^- \\
\pi^+ \\
\pi^0 \\
\pi^- \\
\end{array} \]

\[ x, z, P_{h\perp} \text{ [GeV]} \]
The kaon Sivers amplitudes

![Graph showing kaon Sivers amplitudes](image)
\[ \pi^+ / K^+ \text{ production dominated by scattering off } u\text{-quarks: } \sim - \frac{f^\perp_{1T} (x, p_T^2) \otimes \mathcal{W} D^{u \rightarrow \pi^+/K^+}_{1} (z, k_T^2)}{f^u_{1} (x, p_T^2) \otimes D^{u \rightarrow \pi^+/K^+}_{1} (z, k_T^2)} \]
\[ \pi^+ / K^+ \text{ production dominated } \text{by scattering off u-quarks: } \ \varpropto - \] 

\[ \frac{f_{1T}^{\perp u}(x, p_T^2) \otimes \mathcal{W}}{f_1^u(x, p_T^2) \otimes D_1^{u \to \pi^+ / K^+}(z, k_T^2)} \]
The “Kaon Challenge”

\[ \pi^+/K^+ \] production dominated by scattering off \( u \)-quarks:

\[ \pi^+ = |ud\rangle \quad \text{and} \quad K^+ = |u\bar{s}\rangle \]

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

\[ K^+ = |u\bar{s}\rangle \quad \text{and} \quad \pi^+ = |ud\rangle \quad \Rightarrow \text{non-trivial role of sea quarks?} \]
The “Kaon Challenge”

\[ \pi^+ / K^+ \] production dominated by scattering off u-quarks: \( \approx - \frac{x}{f_{1T}^{u}(x, p_{T}^{2}) \otimes \mathcal{W} D_{1}^{u \rightarrow \pi^+/K^+}(z, k_{T}^{2})} \)

- \( K^+ = |u\bar{s}\rangle \) & \( \pi^+ = |ud\rangle \) ➞ non-trivial role of sea quarks?
- convolution integrals depend on \( k_T \) dependence of fragmentation functions
The “Kaon Challenge”

\[ \pi^+ / K^+ \text{ production dominated by scattering off } u\text{-quarks: } \approx - \frac{f_{1T}^u(x, p_T^2) \otimes \mathcal{W} D_{1u \rightarrow \pi^+/K^+}(z, k_T^2)}{f_{1T}^s(x, p_T^2) \otimes \mathcal{W} D_{1u \rightarrow \pi^+/K^+}(z, k_T^2)} \]

- \[ K^+ = |u\bar{s}\rangle \text{ and } \pi^+ = |ud\rangle \] \( \Rightarrow \) non-trivial role of sea quarks?

- convolution integrals depend on \( k_T \) dependence of fragmentation functions

- possible difference in dependences on the kinematics integrated over
Role of sea quarks

[A. Airapetian et al., PLB 666, 446 (2008)]

![Graph showing the role of sea quarks with a fit to HERMES data and the CTEQ6L model.](image)

$2 \langle \sin(\phi - \phi_s)K^+\rangle_{\pi^+} - 2 \langle \sin(\phi - \phi_s)\pi^+\rangle_{\pi^+}$
Role of sea quarks

[A. Airapetian et al., PLB 666, 446 (2008)]

\[ xS(x) \]

\[ \text{Fit} \]

\[ \text{CTEQ6L} \]

\[ x(\bar{u}(x)+\bar{d}(x)) \]

differences biggest in region where strange sea is most different from light sea

\[ K^+ - \pi^+ \]

\[ 2 \langle \sin(\phi-\phi_s) \rangle_{K^+} - 2 \langle \sin(\phi-\phi_s) \rangle_{\pi^+} \]

\[ 10^{-1} \]
Q^2 dependence of amplitudes

- separate each x-bin into two Q^2 bins:
- only in low-Q^2 region significant (>90% c.l.) deviation
dependence of amplitudes

\[ 2 \langle \sin(\phi - \phi_s) \rangle_{\pi^+} \]

\[ Q^2 < \langle Q^2(x_i) \rangle \]

\[ Q^2 \]

\[ \langle Q^2 \rangle \text{ [GeV}^2] \]

\[ x \]

\[ 10^{-1} \]
$Q^2$ dependence of amplitudes

\[ 2 \langle \sin(\phi - \phi_s) \rangle_{ur} \]

\[ \langle Q^2 \rangle [\text{GeV}^2] \]

\[ Q^2 < \langle Q^2(x_i) \rangle \]

\[ Q^2 > \langle Q^2(x_i) \rangle \]
$Q^2$ dependence of amplitudes

\[ 2 \langle \sin(\phi - \phi_S) \rangle_{ur} \]

\begin{align*}
\pi^+ & \quad Q^2 < \langle Q^2(x_i) \rangle \\
& \quad \text{○} \quad Q^2 > \langle Q^2(x_i) \rangle
\end{align*}

\begin{align*}
K^+ & \quad Q^2 < \langle Q^2(x_i) \rangle \\
& \quad \text{○} \quad Q^2 > \langle Q^2(x_i) \rangle
\end{align*}

\[ \langle Q^2 \rangle \text{ [GeV}^2] \]

\[ x \]

\[ 10^{-1} \]

G. Schnell - DESY Zeuthen
$Q^2$ dependence of amplitudes

![Graphs showing $2\langle \sin(\phi - \phi_s) \rangle/\mu r$ vs $Q^2$, with data points for $\pi^+$ and $K^+$, and corresponding $Q^2$ distributions.]

- $Q^2 < \langle Q^2(x_i) \rangle$ for $\pi^+$
- $Q^2 > \langle Q^2(x_i) \rangle$ for $\pi^+$

Hint of $Q^2$ dependence of kaon amplitude

"need larger leverage in $Q^2"
Hunt for transversity
Transversity distribution
(2-hadron fragmentation)

A. Airapetian et al. [HERMES], JHEP 06 (2008) 017
Transversity distribution (2-hadron fragmentation)

A. Airapetian et al. [HERMES], JHEP 06 (2008) 017

First evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS!
Transversity distribution (2-hadron fragmentation)

- First evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS!
- Invariant-mass dependence rules out Jaffe model
Transversity distribution
(2-hadron fragmentation)

A. Airapetian et al. [HERMES], JHEP 06 (2008) 017

G. Schnell - INT 10-3, Seattle
Transversity distribution (2-hadron fragmentation)

A. Airapetian et al. [HERMES], JHEP 06 (2008) 017

G. Schnell - INT 10-3, Seattle
Collins amplitudes

- 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

2005: First evidence from HERMES SIDIS on proton

Non-zero transversity
Non-zero Collins function

Collins amplitudes

- 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

\[ 2 \langle \sin(\phi_S) \rangle_{\pi} \]

[A. Airapetian et al., arXiv:1006.4221]
Collins amplitudes

- leads to various cancellations in SSA observables

\[ A_{\text{Coll}} \]

\[ \sin(\theta_S + \theta_T) \]

\[ x \]

\[ P_{h}^T (\text{GeV/c}) \]

\[ z \]

\[ 10^{-1} \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.5 \]

\[ 1 \]

\[ \pm 0.02 \]

\[ \pm 0.05 \]

\[ \pm 0.08 \]

\[ \pm 0.1 \]

\[ \pm 0.4 \]

\[ \pm 0.6 \]

\[ \pm 0.8 \]

\[ \pm 1 \]

[COMPASS d, HERMES p, and BELLE data are well described in global fits]

[2004 2002 final]

Collins Fragmentation Function
String Model Interpretation (Artru)

transverse spin of struck quark
(polarization component in lepton scattering plane reversed by photoabsorption)
Collins Fragmentation Function
String Model Interpretation (Artru)

transverse spin of struck quark
(polarization component in lepton scattering plane reversed by photoabsorption)

$q\bar{q}$-pair with vacuum quantum numbers ($^3P_0$-state)
**Collins Fragmentation Function**

**String Model Interpretation (Artru)**

transverse spin of struck quark

(polarization component in lepton scattering plane reversed by photoabsorption)

$q\bar{q}$-pair with vacuum quantum numbers ($^3P_0$-state)

outgoing pion/kaon deflected into page

(positive Collins FF)
Collins Fragmentation Function

String Model Interpretation (Artru)

transverse spin of struck quark (polarization component in lepton scattering plane reversed by photoabsorption)

outgoing pion/kaon deflected into page (positive Collins FF)
pion from next string break deflected out of page (negative Collins FF)

$q\bar{q}$-pair with vacuum quantum numbers ($^3P_0$-state)
Collins amplitudes

Results for the transverse asymmetries

- Collins 1–h asymmetries for proton large at $x > 0.1$, consistent with HERMES
- 2–h asymmetry for proton large in the valence region; HERMES sees less.
- Indication of Sivers 1–h asymmetries for $\pi^+$ on proton, $x > 0.032$; similar to HERMES; needs to be cleared.
- COMPASS deuteron data: both Collins and Sivers asymmetries very small.

These data + Hermes + Belle:

$\Delta T_u + \Delta T_d \sim 0$

• First $\Delta T_q$ global analyses performed.

B. Badelek (Warsaw)

Nucleon Spin Structure

INPC 2010 29 / 33

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**Axes:**
- $x$: range $10^{-2}$ to $10^{-1}$
- $z$: range $0.2$ to $0.8$
- $p_T$: range $0.5$ to $1.5$ (GeV/c)

**Legend:**
- Black triangles: positive hadrons
- Red circles: negative hadrons

**Plots:**
- Left: $A_p^{\text{Coll}}$ vs. $x$ for positive and negative hadrons.
- Middle: $A_p^{\text{Coll}}$ vs. $z$ for positive and negative hadrons.
- Right: $A_p^{\text{Coll}}$ vs. $p_T$ for positive and negative hadrons.

**Data Sets:**
- COMPASS 2007 proton data
- HERMES 2002-2005
- Preliminary COMPASS 2007

---

**Contributors:**
- Collins amplitudes
- Preliminary
comparison with predictions from fit to the HERMES proton, COMPASS deuteron, BELLE data

Collins asymmetry - proton

support the assumption of a weak $Q^2$ dependence in the present energy range

Results for the transverse asymmetries

$\rho_{\text{Coll}}$

positive hadrons

negative hadrons

preliminary COMPASS 2007 proton data

COMPASS 2007 transverse proton data

preliminary

$\rho_{\text{Coll}}$

positive hadrons

negative hadrons

HERMES 2002-2005

HERMES 2002-2005

• Collins 1–h asymmetries for proton large at $x > 0.1$, consistent with HERMES

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• COMPASS deuteron data: both Collins and Sivers asymmetries very small.

• First $\Delta T_q$ global analyses performed.

(cf. Anselmino et al., arXiv:0807.0173)
Kaon Collins amplitudes

- significantly non-zero amplitudes also for $K^+$
- larger than for pions
- $K^-$ consistent with zero in contrast to pion case
Kaon Collins amplitudes

- significantly non-zero amplitudes also for $K^+$
- larger than for pions
- $K^-$ consistent with zero in contrast to pion case

Do kaon Collins FF not follow Artru pattern?
Modulations in spin-independent SIDIS cross section

\[
\frac{d^5 \sigma}{dxdydzd\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ A(y) F_{UU,T} + B(y) F_{UU,L} + C(y) \cos \phi_h F_{UU}^{\cos \phi_h} + B(y) \cos 2\phi_h F_{UU}^{\cos 2\phi_h} \right\}
\]

leading twist

\[F_{UU}^{\cos 2\phi_h} \propto C \left( \frac{2(\vec{P}_{h\perp} \cdot \vec{k}_T)(\vec{P}_{h\perp} \cdot \vec{P}_T) - \vec{k}_T \cdot \vec{P}_T}{MM_h} h_1^\perp H_1^\perp \right)\]

next to leading twist

\[F_{UU}^{\cos \phi_h} \propto \frac{2M}{Q} C \left[ \frac{\vec{P}_{h\perp} \cdot \vec{P}_T}{M_h} x h_1^\perp H_1^\perp - \frac{\vec{P}_{h\perp} \cdot \vec{k}_T}{M} x f_1D_1 + \ldots \right] \]

(Implicit sum over quark flavours)
COMPASS results on deuteron

\[
\frac{d\sigma}{dx\, dy\, d\psi\, dz\, d\phi_h\, dP^2_{h\perp}} =  \\
\frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1 - \varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1 + \varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} \\
+ \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1 - \varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} \right\} + \ldots
\]

- Azimuthal distributions fit after correction for apparatus acceptance
- Clear signals for both cosine modulations
- Different for h^+ and h^-: non-negligible contribution of BM term (Cahn term is hadron-flavor blind)
**HERMES extraction of cosine modulations**

- **Fully differential analysis** in \((x, y, z, P_{h\perp}, \phi)\)

- **Multi-dimensional unfolding**: correction for finite acceptance, QED radiation, kinematic smearing, detector resolution

\[
\begin{align*}
n_{\text{EXP}} &= S \cdot n_{\text{BORN}} + n_{\text{Bg}} \\
n_{\text{BORN}} &= S^{-1} \left[ n_{\text{EXP}} - n_{\text{Bg}} \right]
\end{align*}
\]

- Probability that an event generated with a certain kinematics is measured with a different kinematics

- Includes the events smeared into the acceptance
HERMES extraction of cosine modulations

\[
\langle \cos \phi \rangle(x_b) \approx \int_{0.3}^{0.85} dy \int_{0.2}^{0.75} dz \int_{0.05}^{0.75} dP_{h\perp}^2 \sigma^{A\pi}(\omega_{x_i=x_b}) \langle \cos \phi \rangle_{x_i=x_b}
\]
Signs of Boer-Mulders?!

[Graph showingHERMES preliminary results for the process $e p \rightarrow e \pi X$.]

Signs of Boer-Mulders?!

- opposite sign for charged pions (as expected for BM effect?!), with larger magnitude for \( \pi^- \)
- prediction including Cahn effect does not describe data

Cahn effect?

\[ F_{UU}^{\cos \phi_h} \propto 2M C \left( \frac{\mathbf{P}_{h \perp} \cdot \mathbf{P}_T}{M_h} x h_1^+ H_1^+ - \frac{\mathbf{P}_{h \perp} \cdot \mathbf{k}_T}{M} x f_i D_i + \ldots \right) \]

Interaction dependent terms neglected

\[ \text{HERMES preliminary} \]
\* no dependence on hadron charge expected

\* prediction off from data

\* sign of Boer-Mulders in $\cos \phi$ modulation or “real” twist-3?

**G. Schnell - DESY Zeuthen**
Difference of pion amplitudes

\[ \Delta 2(\cos(\phi_h))_{\text{UU}} - 2(\cos(\phi_h))_{\text{UU}} \]

\[ \Delta 2(\cos(2\phi_h))_{\text{UU}} - 2(\cos(2\phi_h))_{\text{UU}} \]

\[ \langle Q^2 \rangle_{\text{[GeV}^2]} \]

- charge-symmetric contributions (e.g., Cahn) cancel
similar behavior for hadrons and pions (not unexpected)

hint of a systematic shift between hadrons and pions
Kaon cosine modulations

- significantly different modulations for kaons for most modulations
- no sign change in BM modulation for $K^+$ vs. $K^-$
Measurement of $A_N$ in $p\,p$-scattering for different center of mass energies:

- $1976$: $4.9$ GeV
- $2002$: $6.6$ GeV
- $1991$: $19.4$ GeV
- $2008$: $62.4$ GeV

Only two models consistently describing the data:

- TMDs (Transverse Momentum Dependent)
- high-twist correlations

Interpretation not yet completely satisfactory

All available models predict $A_N$ goes to zero at high $p_T$ values.

BUT: not yet DATA at such kinematic region

All available data coming from $p\,p$ scattering

**SSA in p-p collision**

**MOTIVATION**

Alejandro López Ruiz
Universiteit Gent
Florence/DIS 10

<table>
<thead>
<tr>
<th>√$s$</th>
<th>$A_N$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.9 GeV</td>
<td>ANL</td>
</tr>
<tr>
<td>6.6 GeV</td>
<td>BNL</td>
</tr>
<tr>
<td>19.4 GeV</td>
<td>FNAL</td>
</tr>
<tr>
<td>62.4 GeV</td>
<td>BRAHMS</td>
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</tbody>
</table>

$\pi^+ p \rightarrow \pi X$
SSA in p-p collision

large $K^-$ asymmetries similar to $K^+$

$p^\uparrow p \rightarrow \pi X$
SSA in p-p collision

large $K^-$ asymmetries similar to $K^+$

large anti-proton asymmetries but vanishing for protons

$p^\uparrow p \rightarrow \pi X$
Inclusive hadron electro-production

\[ ep^\uparrow \rightarrow hX \]

lepton beam going into the page
Inclusive hadron electro-production

- scattered lepton undetected
  ➞ lepton kinematics unknown

\[ ep \uparrow \rightarrow hX \]

lepton beam going into the page
Inclusive hadron electro-production

- scattered lepton undetected
  ➞ lepton kinematics unknown

- dominated by quasi-real photo-production (low $Q^2$)
  ➞ hadronic component of photon relevant?

\[ e p \uparrow \rightarrow h X \]

lepton beam going into the page
Inclusive hadron electro-production

- scattered lepton undetected
  - lepton kinematics unknown
- dominated by quasi-real photo-production (low $Q^2$)
  - hadronic component of photon relevant?
- cross section proportional to $S_N (k \times p_h) \sim \sin \phi$

Diagram:

$$ep^\uparrow \rightarrow hX$$

- Lepton beam going into the page
- $\vec{S_N}$
- $\vec{p_h}$
- $\phi$
Inclusive hadron electro-production

- scattered lepton undetected
  - lepton kinematics unknown

- dominated by quasi-real photo-production (low $Q^2$)
  - hadronic component of photon relevant?

- cross section proportional to $S_N (k \times p_h) \sim \sin \phi$

\[
A_{UT}(p_T, x_F, \phi) = A_{UT}^{\sin \phi}(p_T, x_F) \sin \phi
\]

lepton beam going into the page
	his is what we measure!
Inclusive hadron electro-production

- scattered lepton undetected
  - lepton kinematics unknown
- dominated by quasi-real photo-production (low $Q^2$)
  - hadronic component of photon relevant?
- cross section proportional to $S_N (k \times p_h) \sim \sin \phi$

$$A_{UT}(p_T, x_F, \phi) = A_{UT}^{sin \phi}(p_T, x_F) \sin \phi$$

This is what we measure!

$$A_N \equiv \frac{\int_{-\pi}^{\pi} d\phi \, \sigma_{UT} \sin \phi - \int_0^{\pi} d\phi \, \sigma_{UT} \sin \phi}{\int_{-\pi}^{\pi} d\phi \, \sigma_{UU}}$$

$$= -\frac{2}{\pi} A_{UT}^{sin \phi}$$

---

**Table 1: Binning in the kinematic variables**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Bins</th>
<th>Bin borders</th>
</tr>
</thead>
<tbody>
<tr>
<td>$UU$</td>
<td></td>
<td>$[0.0, 0.27, 0.54, 0.81, 1.08, 1.35, 2.02, 2.29, 2.56, 2.83, \ldots]$</td>
</tr>
</tbody>
</table>
$xf$ dependence of $A_{UT} \sin \phi$ amplitude
**xF dependence of $A_{UT} \sin \phi$ amplitude**

- opposite in sign to pp
- increasing amplitudes
$x_F$ dependence of $A_{UT} \sin \phi$ amplitude

- opposite in sign to pp
- increasing amplitudes

Increasing $p_T$
$p_T$ dependence of $A_{UT} \sin \phi$ amplitude

increasing amplitudes with turnover
p_T dependence of A_{UT} \sin \phi amplitude

Increasing amplitudes with turnover

Sign change
$p_T$ dependence of $A_{UT} \sin \phi$ amplitude

behavior and size similar to SIDIS Sivers
Conclusions

- wealth of data from fixed-target DIS experiment not only give answers but also raise questions
- need precision data in inclusive DIS to check Bjorken SR and to extract gluon polarization via evolution
- quark distribution extraction from SIDIS data still hampered by insufficient knowledge of FFs
- puzzling pattern of kaon results in TMD measurements
- appearing disagreement between HERMES and COMPASS Sivers and 2-hadron results needs clarification
- need a high-lumi, large-acceptance DIS experiment with good particle ID and both polarized leptons and nucleons