Latest results on transverse momentum dependent distribution functions

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for the hermes collaboration

- HERMES overview
- Transverse single-spin asymmetries in semi-inclusive DIS
  - Sivers effect (final results: PRL 103 (2009) 152002)
- Transverse target single-spin asymmetries in inclusive hadron production in DIS (new preliminary results)
• forward acceptance spectrometer: $40 \, \text{mrad} \leq \Theta \leq 220 \, \text{mrad}$
• kinematic coverage: $0.02 \leq x_{\text{Bj}} \leq 0.8$ for $Q^2 > 1 \, \text{GeV}^2$ and $W > 2 \, \text{GeV}$
• tracking: $\delta P/P = 0.7\% - 2.5\%$, $\delta \Theta \leq 1 \, \text{mrad}$
• PID: TRD, Preshower, Calorimeter, RICH
Particle Identification

excellent lepton/hadron separation

RICH: two radiators allow hadron separation between 2-15 GeV

Aerogel; n=1.03
C$_4$F$_{10}$; n=1.0014
Transverse target single-spin asymmetries in semi-inclusive DIS
DIS: probing the nucleon structure

\(e^+ \gamma @ 27.6 \text{ GeV} \quad \text{(HERA)}\)

\[Q^2 = -q^2 = -(k - k')^2\]
\[\nu \equiv \frac{E - E'}{2M\nu}\]
\[x = \frac{Q^2}{2M\nu}\]
\[z \equiv \frac{E_{\text{had}}}{\nu}\]

Target:
\(H: <P_{\text{trans}}> \sim 72.5 \pm 5.3\%\)

Cross section contains Distribution Functions and Fragmentation Functions:

\[\sigma^{ep \rightarrow ehX} \sim \sum_q \text{DF}^{p \rightarrow q} \otimes \sigma^{eq \rightarrow eq} \otimes \text{FF}^{q \rightarrow h}\]

DF: distribution of quarks in the nucleon
FF: fragmentation of (struck) quark into hadronic final state
Distribution functions

Leading twist:

3 DFs survive integration over transverse quark momenta

- momentum distribution: $q(x)$
- helicity distribution: $\Delta q(x)$
- transversity distribution: $\delta q(x)$

Beam

helicity basis

basis of transv. spin eigenstates

all three DFs needed for complete description of the nucleon!
Transversity $\delta q$

- $\delta q$: helicity-flip of the quark $\Rightarrow$ chiral-odd

\[ q(x) \quad \delta q(x) \Rightarrow \Delta q(x) \]
Transversity $\delta q$

- $\delta q$: helicity-flip of the quark $\Rightarrow$ chiral-odd

- Collins-FF $H_{1\perp}$ describes correlation between transverse polarisation of fragmenting quark and the transverse momentum $P_{h\perp}$ of the produced (unpolarised) hadron
Azimuthal Asymmetries

Measurement of cross-section asymmetries depending on the azimuthal angles $\Phi$ and $\Phi_S$

\[
A_{UT}(\phi, \phi_S, \ldots) = \frac{1}{S_{\perp}} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}
\]

\[
\sim \ldots \sin(\phi + \phi_S) \frac{\sum_q e_q^2 I \left[ \ldots \delta q(x, \vec{p}_T^2) \cdot H_1^{\perp q}(z, \vec{k}_T^2) \right]}{\sum_q e_q^2 q(x) \cdot D_1^q(z)}
\]

\[
+ \ldots \sin(\phi - \phi_S) \frac{\sum_q e_q^2 I \left[ \ldots f_{1T}^{\perp q}(x, \vec{p}_T^2) \cdot D_1^q(z, \vec{k}_T^2) \right]}{\sum_q e_q^2 q(x) \cdot D_1^q(z)}
\]

$\mathcal{I} \ldots$ convolution integral over initial ($p_T$) and final ($k_T$) quark transverse momenta
Azimuthal Asymmetries

Measurement of cross-section asymmetries depending on the azimuthal angles $\Phi$ and $\Phi_S$

$$A_{UT}(\phi, \phi_S, \ldots) = \frac{1}{S_\perp} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

Collins Amplitude

$$\sim ... \sin(\phi + \phi_S) \frac{\sum_q e_q^2 I [\ldots \delta q(x, \vec{p}_T^2) \cdot H_{1q}^1(z, \vec{k}_T^2)]}{\sum_q e_q^2 q(x) \cdot D_{1q}^q(z)} + ... \sin(\phi - \phi_S) \frac{\sum_q e_q^2 I [\ldots f_{1T}^{1q}(x, \vec{p}_T^2) \cdot D_{1q}^q(z, \vec{k}_T^2)]}{\sum_q e_q^2 q(x) \cdot D_{1q}^q(z)}$$

$I[\ldots]$ convolution integral over initial ($p_T$) and final ($k_T$) quark transverse momenta
Collins Amplitudes for Pions

\[ A_C \propto \delta q \otimes H_1^\perp \]

- positive amplitudes for \( \pi^+ \)
- large negative \( \pi^- \) amplitude

\[ u \rightarrow \pi^+ \Rightarrow H_1^\perp,\text{fav} \]

\[ u \rightarrow \pi^- \Rightarrow H_1^\perp,\text{unfav} \]

\[ \Rightarrow H_1^\perp,\text{fav} \approx -H_1^\perp,\text{unfav} \]

- \( \pi^0 \) consistent with zero (isospin symmetry)
- information from another process on Collins FF (BELLE) allows extraction of \( \delta q \) (eg. Anselmino et. al. Phys.Rev.D75:054032,2007)

\[ 2 \langle \sin(\phi_S^+ + \phi_S^-) \rangle_U^\pi \]

\[ \begin{array}{c|c|c|c|c|c|c|c}
\text{X} & 0.1 & 0.4 & 0.6 & 0.9 & 1 \\
\hline
\text{Z} & 0.2 & 0.4 & 0.6 & 0.8 & 1 \\
\end{array} \]

\[ \begin{array}{c}
\text{P}_{h\perp} \text{[GeV]} \\
0.5 & 1 \\
\end{array} \]

Collins Amplitudes for Kaons

- Collins amplitudes for $K^+$ larger than for $\pi^+$
- Collins fragmentation function for kaons unknown
- Collins amplitudes for $K^-$ consistent with zero
- Sea quark transversity expected to be small

\[ A_C \propto \delta q \otimes H_1^\perp \]

Azimuthal Asymmetries

Measurement of cross-section asymmetries depending on the azimuthal angles $\Phi$ and $\Phi_S$

$$A_{UT}(\phi, \phi_S, \ldots) = \frac{1}{S_\perp} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

Collins Amplitude

$$\sim \ldots \sin(\phi + \phi_S) \frac{\sum_q e_q^2 I \left[ \ldots \delta q(x, \vec{p}_T^2) \cdot H_1^{\perp q}(z, \vec{k}_T^2) \right]}{\sum_q e_q^2 q(x) \cdot D_1^q(z)}$$

$$+ \ldots \sin(\phi - \phi_S) \frac{\sum_q e_q^2 I \left[ \ldots f_{1T}^{\perp q}(x, \vec{p}_T^2) \cdot D_1^q(z, \vec{k}_T^2) \right]}{\sum_q e_q^2 q(x) \cdot D_1^q(z)}$$

$\mathcal{I} [\ldots]$ convolution integral over initial ($p_T$) and final ($k_T$) quark transverse momenta
Azimuthal Asymmetries

Measurement of cross-section asymmetries depending on the azimuthal angles \( \Phi \) and \( \Phi_S \)

\[
A_{UT}(\phi, \phi_S, \ldots) = \frac{1}{S_{\perp}} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}
\]

Collins Amplitude

\[
\sim \ldots \sin(\phi + \phi_S)
\]

\[
\sum_q e^2_q \, I \left[ \ldots \delta q(x, \vec{p}_{T}^2) \cdot H_{1}^{\perp q}(z, \vec{k}_{T}^2) \right]
\]

Sivers Amplitude

\[
+ \ldots \sin(\phi - \phi_S)
\]

\[
+ \ldots
\]

\[
\sum_q e^2_q \, I \left[ \ldots f_{1T}^{\perp q}(x, \vec{p}_{T}^2) \cdot D_{1}^{q}(z, \vec{k}_{T}^2) \right]
\]

\[
\sum_q e^2_q \, q(x) \cdot D_{1}^{q}(z)
\]

\[I[\ldots]\text{ convolution integral over initial (}p_T\text{) and final (}k_T\text{) quark transverse momenta}\]
Sivers function

- describes correlation between intrinsic transverse quark momentum ($p_T$) and transverse nucleon spin
- chiral-even function
- T-odd functions allowed due to final state interactions (FSI): quark rescattering via a soft gluon
- non-zero Sivers function requires non-vanishing orbital angular momentum in the nucleon wave function (can contribute to nucleon spin!)
Sivers Amplitudes for Pions

\[ A_S \propto f_{1T}^\perp \otimes D_1^q \]

- significantly positive for \( \pi^+ \)
- rise with low \( p_{h\perp} \), plateau at high \( p_{h\perp} \)
- implies non-zero orbital angular momentum of quarks
- slightly positive for \( \pi^- \)
- isospin symmetry of \( \pi \) mesons fulfilled
Sivers Amplitudes for Kaons

\[ A_S \propto f_{1T}^{\perp} \otimes D_{1}^{q} \]

- significantly positive for \( K^+ \)
- implies non-zero orbital angular momentum of quarks
- slightly positive for \( K^- \)
- \( K^+ \) amplitude larger than \( \pi^+ \) amplitude

Sea quark contribution to Sivers mechanism may be important

\[ \pi^+ = |ud\rangle \quad K^+ = |u\bar{s}\rangle \]
Transverse target single-spin asymmetries in inclusive hadron production in DIS
Transverse single-spin asymmetry of inclusive hadrons (I)

- reminder: clear non-zero left-right asymmetry $A_N$ measured in inclusive pion production in $p^+ p$ collisions:

- two models for two approaches:
  - TMD approach: both Sivers and Collins can contribute
  - collinear (high-$p_T$) approach: Sivers-like and Collins-like
Transverse single-spin asymmetry of inclusive hadrons (II)

- so far: all available data from $p^+ p$ collisions
- HERMES data:
  - first data on leptoproduction $lp^+$ (scattered lepton not detected $\Rightarrow$ quasi-real photoproduction)
  - high statistics ($\sim 100$ Million hadrons)
  - complimentary to $p^+ p$, cleaner channel (one $p$ quark field)
  - target spin $S$ reversed every 90s (cancelation of systematic effects)

$$A_{UT}(x, Q^2, \phi) \approx A_{UT}^{\sin \phi}(x, Q^2) \sin(\phi)$$

- prediction: $A_{UT} \rightarrow 0$ for high $p_T$ and for $p_T \rightarrow 0$
**$A_{UT}$ of incl hadrons vs $x_F$**

- **π**: similar to $p^\uparrow p$
- **K**: $p^\uparrow p$ (Brahms): $K^+$ and $K^-$ same size and same sign

![Graph](image)
A\textsubscript{UT} of incl hadrons vs p\textsubscript{T} 

- positive for \( \pi^+ \) and \( K^+ \)
- small/zero for negative hadrons
- decrease at high p\textsubscript{T}
$A_{UT}$ of incl hadrons: 2D

- $e^\pm p^\uparrow \rightarrow \pi^\pm + X$
- $e^\pm p^\uparrow \rightarrow \pi^- + X$
- $e^\pm p^\uparrow \rightarrow K^+ + X$
- $e^\pm p^\uparrow \rightarrow K^- + X$

**HERMES preliminary**

- $0.20 < x_F < 1.00$
- 8.8% scale uncertainty

**$\pi^-$: sign change**

**$K^-$: positive for small $x_F$**

$F$

$A_{UT}$ vs $p_T$ [GeV]
\( A_{UT} \) of incl pions vs \( p_t \)

**A\(_N\)**

**Sivers**

**Collins**

A\(_N\) resembles Sivers effect

as predicted in M. Anselmino et al., PRD 81(2010) 034007

\( e^\pm p^\uparrow \rightarrow \pi^\pm + X \) HERMES preliminary

\( e^\pm p^\uparrow \rightarrow \pi^0 + X \)

\( \langle \chi^2 \rangle \)
Conclusions

• final results on Collins amplitudes published
  ‣ significant Collins amplitudes for charged pions and $K^+$
    ⇒ enables quantitative extraction of transversity distribution

• significant Sivers amplitudes for $\pi^+$ and $K^+$ mesons
  ⇒ clear (and first) evidence of naive T-odd parton distribution
  ⇒ enables quantitative extraction of the Sivers function

• new preliminary results on transverse target single-spin asymmetries in inclusive hadron production
  ‣ large asymmetry for $\pi^+$ and $K^+$
  ‣ no good theoretical understanding yet of inclusive TTSA
Backup
HERMES @ HERA

- Fixed target experiment
  ➡ only using HERA lepton ($e^+/e^-$) beam
- HERA lepton beam self-polarizing
  ➡ cross section asymmetry in synchrotron radiation emission leads to build-up of transverse polarization (Sokolov-Ternov effect)
- Spin-rotators ➡ longitudinal polarization at HERMES interaction region
- Beam polarization measured by two independent polarimeters

Comparison of rise time curves

$<P_B>$ up to 55%
The HERMES Target

Gaseous target in storage cell aligned with lepton beam

Features:

• Pure target (no dilution)
• Unpolarized targets:
  - variety of nuclear targets
    - H, D, He, Ne, Kr, ...
• Polarized targets:
  - Longitudinal pol. (<=2000)
    - H, D, He
  - Transverse pol. (2002-2005)
    - H
  - Rapid reversal of polarization direction within 0.5s (every 90s)

Polarization:

  - Longitudinal: ~85%
  - Transversal: ~75%