Recent HERMES results from inclusive and semi-inclusive hadron production with a transversely polarised target

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Outline

• Dihadron ($\pi\pi$ and KK) production in TMD semi-inclusive DIS on a transversely polarized proton target

• Transverse target single-spin asymmetry in inclusive electroproduction of charged pions and kaons

• Transverse polarization of $\Lambda$ hyperons from quasi-real photoproduction on nuclei
Dihadron production in semi-inclusive DIS
Dihadron production

\[ \vec{R} = \frac{1}{2}(\vec{P}_1 - \vec{P}_2) \]
\[ \vec{P}_h = \vec{P}_1 + \vec{P}_2 \]
\[ \vec{R}_T = \vec{R} - \frac{\vec{R} \cdot \vec{P}_h}{|\vec{P}_h|^2} \vec{P}_h \]

\[ \phi_R = \text{signum}[(\vec{n} \times \vec{R}_T) \cdot \vec{P}_h] \arccos \frac{\vec{n} \cdot \vec{R}_T}{|\vec{n}| |\vec{R}_T|}, \]

with \( \vec{n} \perp \vec{P}_h \) and \((\vec{P}_h \times \vec{n}) \cdot (\vec{q} \times \vec{k}) > 0 \)

\( x, y, z, P_{h\perp} \)
\( \phi_h, \phi_R \)

dihadron mass \( M_{hh} \)
New convention for (di)hadron fragmentation functions (*)

- new convention for FFs:
  - FFs entirely defined by quark spin $\chi, \chi'$
  - final-state polarisation of (di-)hadrons $|l_1, m_1>, |l_2, m_2>$ contained in partial-wave expansion

- exactly 2 FFs:
  - unpolarised FF $D_1$ with $\chi=\chi'$
  - polarised (Collins) FF $H_1^\perp$ with $\chi \neq \chi$

Partial-wave expansion

- direct sum base $|l, m>$ rather than direct product base $|l_1, m_1>, |l_2, m_2$

\[
\frac{1}{2} \otimes \frac{1}{2} \otimes \frac{1}{2} \otimes \frac{1}{2} = \left( \frac{1}{2} \otimes \frac{1}{2} \right) \otimes \left( \frac{1}{2} \otimes \frac{1}{2} \right) = (1 \oplus 0) \otimes (1 \oplus 0),
\]

\[
= 2 \oplus 1 \oplus 1 \oplus 1 \oplus 0 \oplus 0.
\]

experimentally

- partial wave

\[
D_1 = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} P_{\ell,m}(\cos \vartheta) e^{im(\phi_R-\phi_k)} D_1^{\ell,m}(z, M_h, |k_T|),
\]

\[
H_1^\perp = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} P_{\ell,m}(\cos \vartheta) e^{im(\phi_R-\phi_k)} H_1^{\perp \ell,m}(z, M_h, |k_T|)
\]
Cross section

\[ d\sigma_{UT} = \frac{\alpha^2 M_h P_{h\perp}}{2\pi xy Q^2} \left(1 + \frac{\gamma^2}{2x}\right) |S_\perp| \]

\[
\times \sum_{\ell=0}^{2} \sum_{m=-\ell}^{\ell} \left\{ A(x, y) \left[ P_{\ell,m} \sin((m+1)\phi_h - m\phi_R - \phi_S) \right] \right.
\times \left( F_{UT,T}^{\ell,m} \sin((m+1)\phi_h - m\phi_R - \phi_S) + \epsilon F_{UT,L}^{\ell,m} \sin((m+1)\phi_h - m\phi_R - \phi_S) \right) \right.
\]

\[
+ B(x, y) \left[ P_{\ell,m} \sin((1-m)\phi_h + m\phi_R + \phi_S) F_{UT}^{\ell,m} \sin((1-m)\phi_h + m\phi_R + \phi_S) \right] \right.
\]

\[
+ P_{\ell,m} \sin((3-m)\phi_h + m\phi_R - \phi_S) F_{UT}^{\ell,m} \sin((3-m)\phi_h + m\phi_R - \phi_S) \right\} \right. \}

\text{and analogously for } d\sigma_{UU}, d\sigma_{UL}, d\sigma_{LU}, d\sigma_{LL}, d\sigma_{LT}
Structure functions at leading twist

\[ F_{UT,L}^{p, m \sin((m+1)\phi_h - m\phi_R - \phi_S)} = 0 \]

\[ F_{UT,T}^{p, m \sin((m+1)\phi_h - m\phi_R - \phi_S)} = -\mathcal{I} \left[ \frac{|p_T|}{M} \cos((m+1)\phi_h - \phi_p - m\phi_k) \right. \]
\[ \times \left( f_{1T}^{\perp} D_1^{\ell,m} + \text{signum}[m] g_{1T} D_1^{\ell,m} \right) \],

\[ F_{UT}^{p, (1-m)\phi_h + m\phi_R + \phi_S} = -\mathcal{I} \left[ \frac{|k_T|}{M_h} \cos((m-1)\phi_h - \phi_p - m\phi_k) h_1 H_1^{\perp,\ell,m} \right], \]

\[ F_{UT}^{p, (3-m)\phi_h + m\phi_R - \phi_S} = \mathcal{I} \left[ \frac{|p_T|^2 |k_T|}{M^2 M_h} \cos((m-3)\phi_h + 2\phi_p - (m-1)\phi_k) \right. \]
\[ \times \left. h_{1T}^{\perp} H_1^{\perp,\ell,m} \right] . \]

"Sivers"

"Collins"

"pretzelocity"

usual IFF related to \( H_1^{\perp,1,1} \)

\( \vec{p}_T, \phi_p \) struck quark

\( \vec{k}_T, \phi_k \) fragmenting quark
Results

- Collins moments for $\pi^+\pi^-, \pi^+\pi^0, \pi^-\pi^0$
- Collins and Sivers moments for $K^+K^-$ in $\phi$ resonance region
- Collins, Sivers and pretzelosity for $|0, 0>$ moments for $K^+K^-$ outside $\phi$ resonance region since $l > 0, m > 0$ are zero (as expected)
$|1, 1 >$ Collins moments for $\pi\pi$

allows collinear access to transversity
Collins moments for $\pi\pi$
$|2, \pm 2 > \textbf{Collins moments for } \pi\pi$

$|2, \pm 2 >= |1, \pm 1 > |1 \pm 1 >$

\[ \begin{align*}
A_{UT}^{(2, \pm 2)} & \quad \text{HERMES Preliminary} \\
\text{\bullet } \pi^+\pi^0 & \quad \text{\triangle } \pi^+\pi^- & \quad \text{\square } \pi^-\pi^0
\end{align*} \]

$|2, -2 >$

consistent with zero

$|2, +2 >$

- no signal outside resonance region
- hint of negative signal for $\pi^\pm\pi^0$ in $\rho^\pm$ region
- no signal in $\rho^0$ region
Collins moments for $K K^{-}$ in $\phi$ resonance region

sensitive to transversity $s$-quark distribution

no indication for different signal in and outside $\phi$-resonance region
Sivers moments for $K K^-$ in $\phi$ resonance region

no indication for different signal in and outside $\phi$-resonance region
Moments for $K^+K^-K^+K^-$ outside $\phi$ resonance region @ leading twist

- consistent with small positive value

\[ A_{LT} \]

\[ \sin(\theta_{LT}) \]

HERMES Preliminary

7.3% Scale Uncertainty

\[ e^+ p' \to e^+ K^+K^- X \]

\[ \cos(\theta_{LT}) \]

\[ 7.3\% \text{ Scale Uncertainty} \]
Moments for $K K$ outside $\phi$ resonance region @ leading twist

• consistent with zero
Moments for $K K$ outside $\phi$ resonance region @ sub-leading twist

- consistent with zero
$A_{UT}$ inclusive
Transverse target single-spin asymmetry in inclusive electroproduction of pions and kaons

- various polarized pp scattering experiments consistently observe since 35 years large $A_N$ asymmetries, with $\sqrt{s}$ from 5 to 200 GeV

- not interpretable in leading-twist based on collinear factorisation
Transverse target single-spin asymmetry in inclusive electroproduction of pions and kaons

- various polarized pp scattering experiments consistently observe since 35 years large $A_N$ asymmetries, with $\sqrt{s}$ from 5 to 200 GeV

- not interpretable in leading-twist based on collinear factorisation

- HERMES measurement of inclusive transverse target spin asymmetry $A_{UT}^{\sin(\psi)}$:

$$d\sigma = d\sigma_{UU}[1 + s_\perp A_{UT}^{\sin(\psi)} \sin(\psi)]$$

- $A_{UT}^{\sin(\psi)} = \frac{\pi}{2} A_N$

- @ HERMES

$$\sin(\psi) \sim \sin(\phi - \phi_S)$$
Results: $x_F$ dependence

$x_F = 2P_L/\sqrt{s}$

$\pi^+$
- positive, increase linearly with $x_F$

$\pi^-$
- negative, decrease linearly with $x_F$

$x_F$ behavior of pions similar to what observed in hadron-hadron collisions

$K^+$
- positive, $\sim$constant with $x_F$

$K^-$
- compatible with zero, with small variations over $x_F$
Results: disentangle $x_F$ and $P_T$ dependence

$\pi^+$
- increase with $P_T$ up to $P_T \approx 0.8 \text{ GeV}$
- $P_T$ dependence independent of $x_F$
- $x_F$ increase from $P_T$ dependence

$\pi^-$
- small amplitudes,
  varyingly positive and negative with $P_T$
- decrease with increasing $x_F$
Results: disentangle $x_F$ and $P_T$ dependence

$K^+$
- increase with $P_T$ up to $P_T \approx 0.8$ GeV
- increase with increasing $x_F$

$K^-$
- small amplitudes
- decrease with increasing $x_F$
Contribution of various sub-samples

3 sub samples:

- anti-tagged: no $e^\pm$ detected (mostly $Q^2 \approx 0$)
- DIS with $0.2 < z < 0.7$
- DIS with $z > 0.7$

- anti-tagged results ~ overall results, majority of statistics
- $0.2 < z < 0.7$ results: similar to Sivers amplitudes
- $z > 0.7$ results: large asymmetries
Transverse $\Lambda$ polarization in inclusive measurement
Figure 1: $pp \rightarrow \Lambda^\uparrow X$

Figure 4: $p_p \rightarrow \Lambda^\uparrow X$

$\sqrt{s} = 62$ GeV corresponds $\Lambda^\uparrow$ production.

$\Lambda^\uparrow$ production at $1 \text{ GeV}/c$.

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$\Lambda^\uparrow$ production at $1 \text{ GeV}/c$.
\(pp \rightarrow \Lambda^\uparrow X\)

\(ep \rightarrow \Lambda^\uparrow X\)

- in SIDIS (large \(Q^2\)) proportional to polarizing FF \(D_{1T}^{\perp}\) (naive T-odd, chiral even)
- in twist-3 factorization, opposite sign to \(pp\)

[Y. Koike, hep-ph/0210434]
the other inclusive SSA

• clearly positive for light target nuclei
• consistent with zero for heavy targets

[HERMES, arXiv:1406.3236]
the other inclusive SSA

[HERMES, arXiv:1406.3236]

- larger in backward direction w.r.t. incoming lepton

- consistent with $x_F$ dependence of twist-3 calculation (opposite sign conventions for $x_F$!)

$\zeta \equiv (E_\Lambda + p_{z\Lambda})/(E_e + p_e)$
the other inclusive SSA

• larger in backward direction w.r.t. incoming lepton

• distinct $p_T$ dependences in forward and backward directions: rising with $p_T$ in backward direction as in $pp$
Summary

- SIDIS dihadron moments (in new partial wave expansion) provide potentially rich information on various distribution and fragmentation functions.

- Inclusive $A_{UT}$ provides information that can contribute to understanding of $A_N$ in pp data.

- Inclusive production of $\Lambda$ in ep can provide complementary information to pp data on the mechanism to generate $\Lambda$ polarization.