TMD Measurements at Hermes

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Outline

- Inclusive hadron electroproduction in DIS
- Single hadron production in TMD Semi-inclusive DIS
- Dihadron production in TMD Semi-inclusive DIS
Inclusive hadron electroproduction in DIS
Semi-Inclusive vs. Inclusive DIS

**Semi-Inclusive**

- Hadron detected in coincidence with lepton
- DIS regime $Q^2 > 1 \text{ GeV}^2$
- Hard scales: $Q^2, P_{h\perp} \text{ (w.r.t. } \gamma^\ast\text{)}$
- Factorization valid for $P_{h\perp} \ll Q^2$

**Inclusive**

- No $Q^2$ information
- Data dominated by $Q^2 \approx 0$
- Hard scale: $P_T \text{ (w.r.t. incident } l)$
- Main variables $x_F = 2\frac{P_L}{\sqrt{s}}, P_T$
- Events selected with at least one $\pi^\pm$ or $K^\pm$, regardless of any detected leptons.

<table>
<thead>
<tr>
<th>Hadron yields for UT data</th>
<th>$\pi^+$</th>
<th>$\pi^-$</th>
<th>$K^+$</th>
<th>$K^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIDDIS</td>
<td>7.3 M</td>
<td>5.4 M</td>
<td>131 K</td>
<td>54 K</td>
</tr>
<tr>
<td>Incl. h</td>
<td>60 M</td>
<td>50 M</td>
<td>5.1 M</td>
<td>2.8 M</td>
</tr>
</tbody>
</table>
**Angles Semi-Inclusive vs. Inclusive DIS**

**Semi-Inclusive**

\[
d\sigma \propto F_{UU,T} + \epsilon F_{UU,L} + \\
\sqrt{2\epsilon(1 + \epsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \epsilon \cos 2\phi_h F_{UU}^{\cos \phi_h} + \\
S_T \left[ \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) + \\
\epsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \\
\epsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} + \\
\sqrt{2\epsilon(1 + \epsilon)} \sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \\
\sqrt{2\epsilon(1 + \epsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \right] + \ldots
\]

**Inclusive**

\[
d\sigma = d\sigma_{UU} \left[ 1 + S_\perp A_{UT}^{\sin \psi} \sin \psi \right].
\]

- Cross section
- \(A_{UT}^{\sin \psi}\) includes contributions from Sivers, Collins, & higher twist
- HERMES kinematics implies \(\sin \psi \approx \phi_h - \phi_S\)

**Cross Section**
**Angles Semi-Inclusive vs. Inclusive DIS**

**Semi-Inclusive**

- Cross Section
  - Same general form, but polarization in the final state

**Inclusive**

- Cross section
  \[ d\sigma = d\sigma_{UU} \left[ 1 + S_{UT} A_{sin \psi} \sin \psi \right]. \]
  - \( A_{sin \psi} \) includes contributions from Sivers, Collins, & higher twist
  - HERMES kinematics implies \( \sin \psi \approx \phi_h - \phi_s \)
For an ideal detector with full $2\pi$ coverage in $\psi$:

$$A_{UT}^{\sin \psi} = -\frac{\pi}{2} \int_0^\pi d\psi \sin \psi d\sigma_{UT} = -\frac{\pi}{2} A_N$$

- $pp A_N$ results mirror symmetric for $\pi^\pm$ vs $x_F$
- Reproduced by various experiments over 35 years over wide energy range ($\sqrt{s}$ from 5 to 200 GeV)
- Cannot be interpreted using standard leading-twist framework based on collinear factorization.
HERMES Results vs. $x_F$

- $\pi^+$ amplitude rises fairly linearly with $x_F$ up to a magnitude of 10%
- $\pi^-$ amplitude is negative, also fairly linearly, but smaller magnitude
  - Pion results vs $x_F$ have comparable features as $A_N$ in $pp$ scattering
- $K^+$ amplitude is quite constant, around 7%
- $K^-$ amplitude is also quite constant, but consistent with zero.
  - Significant flavor dependence
No $pp^\uparrow$ scattering data with sufficient coverage in $p_T$ with high enough $|x_F|$

- Expectation is linear rise from zero at small $P_T$ and $1/P_T$ scaling at large $P_T$ with minimal constraints on behavior at intermediate $P_T$

- $\pi^+$ and $K^+$ rise linearly from zero, as might be expected from $A_N$ in $pp$.
  - Clear node in $\pi^+$ results, suggested node in $K^+$ results
  - Node in both cases around $P_T \approx 1.3$ GeV

- Negative mesons have much smaller amplitude, except one $\pi^-$ point
Results generally quite flat with $x_F$

Shape versus $p_T$ persists even in limited $x_F$ bins
Inclusive HERMES Results, Interpretation

- Results include mixtures of various contributions with different kinematic dependencies
  - Makes interpretation of the underlying physics quite difficult
- More insight can be gained through separating different contributing processes
- Overall, anti-tagged events constitute 98% of the statistics

![Diagram of inclusive hadron production](image-url)
Anti-tagged events look much like overall results, as they dominate the statistics.

Exclusive-like events: very large asymmetries!
- Pions have contributions from exclusive $\rho$ decays
- Large $\pi^-$ could be from $d$-quark Sivers and favored $D_1$ distribution function.

SIDIS-like events: $\pi^\pm$ are larger and the magnitudes increase fairly linearly with $P_T$.
- In this regime, $Q^2 > P_T^2$ and TMDs can contribute without $P_T$-suppression.
Single Hadron SIDIS
The Boer-Mulders Moment

\[
\frac{d\sigma^h}{dx \, dy \, d\phi \, dz \, d\phi \, dP^2_{h\perp}} = \frac{\alpha^2}{x y Q^2} \frac{y^2}{2 (1 - \varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left( F_{UU,T} + \epsilon F_{UU,L} \right) + \sqrt{2\epsilon (1 + \epsilon)} \cos (\phi) F_{UU}^{\cos(\phi)} + \epsilon \cos (2\phi) F_{UU}^{\cos(2\phi)} \\
+ \lambda_l \left[ \sqrt{2\epsilon (1 - \epsilon)} \sin (\phi) F_{LU}^{\sin(\phi)} \right] \\
+ S_L \left[ \sqrt{2\epsilon (1 + \epsilon)} \sin (\phi) F_{UL}^{\sin(\phi)} + \sin (2\phi) F_{UL}^{\sin(2\phi)} \right] \\
+ S_L \lambda_l \left[ \sqrt{1 - \epsilon^2} F_{LL} + \sqrt{2\epsilon (1 - \epsilon)} \cos (\phi) F_{LL}^{\cos(\phi)} \right] \\
+ S_T \lambda_l \left[ \sin (\phi - \phi_s) \left( F_{UT,T}^{\sin(\phi - \phi_s)} + \epsilon F_{UT,L}^{\sin(\phi - \phi_s)} \right) \\
+ \epsilon \sin (\phi + \phi_s) F_{UT}^{\sin(\phi + \phi_s)} + \sin (3\phi - \phi_s) F_{UT}^{\sin(3\phi - \phi_s)} \right] \\
+ \sqrt{2\epsilon (1 + \epsilon)} \sin (\phi - \phi_s) F_{UT}^{\sin(\phi - \phi_s)} \\
+ \sqrt{2\epsilon (1 + \epsilon)} \sin (2\phi - \phi_s) F_{UT}^{\sin(2\phi - \phi_s)} \right] \}
\]

Naive-T-odd & Chiral-odd
Describes correlation between quark transverse momentum and transverse spin in unpolarized nucleon

\[ \propto h_1^+ \otimes H_1^+ + \frac{1}{Q^2} [f_1 \otimes D_1 + \ldots] \]

B-M effect
[PRD 57 (1998)]

Cahn effect
[PLB 78 (1978)]

\[ \propto h_1^+ \otimes H_1^+ + \frac{1}{Q} [h_1^+ \otimes H_1^+ + f_1 \otimes D_1 \ldots] \]

Interaction dependent terms

Boer-Mulders Moment Results

- **Pion Results:**
  - Similar results for $H$ and $D$ indicate $h_1^{\perp, u} \approx h_1^{\perp, d}$.
  - Opposite sign for $\pi^\pm$ consistent with opposite signs of fav./unfav. Collins function.

- **Kaon Results:**
  - Kaon results are larger magnitude than pions and have different kinematic dependencies.
  - $K^+$ generally positive, $K^-$ generally consistent with zero.
  - Suggests significant flavor dependence in Collin’s fragmentation.

- Preform your own projections of the 5D results
The Collins Moment

\[
\frac{d\sigma^h}{dx \, dy \, d\phi_S \, dz \, d\phi \, dP_{h\perp}^2} = \frac{\alpha^2}{x y Q^2} \frac{y^2}{2 (1 - \varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right)
\]

\[
\begin{align*}
&\left\{ \right. \\
&\quad \left[ F_{UU,T} + \varepsilon F_{UU,L} \right. \\
&\quad + \sqrt{2\varepsilon (1 + \varepsilon)} \cos(\phi) F_{UU}^\cos(\phi) + \varepsilon \cos(2\phi) F_{UU}^\cos(2\phi) \bigg] \\
&\quad + \lambda_I \left[ \sqrt{2\varepsilon (1 - \varepsilon)} \sin(\phi) F_{LU}^\sin(\phi) \right] \\
&\quad + S_L \left[ \sqrt{2\varepsilon (1 + \varepsilon)} \sin(\phi) F_{UL}^\sin(\phi) + \varepsilon \sin(2\phi) F_{UL}^\sin(2\phi) \right] \\
&\quad + S_L \lambda_I \left[ \sqrt{1 - \varepsilon^2} F_{LL} + \sqrt{2\varepsilon (1 - \varepsilon)} \cos(\phi) F_{LL}^\cos(\phi) \right] \\
&\quad + S_T \lambda_I \left[ \sin(\phi - \phi_S) \left( F_{UT,T}^\sin(\phi - \phi_S) + \varepsilon F_{UT,L}^\sin(\phi - \phi_S) \right) \\
&\quad + \varepsilon \sin(\phi + \phi_S) F_{UT}^\sin(\phi + \phi_S) + \varepsilon \sin(3\phi - \phi_S) F_{UT}^\sin(3\phi - \phi_S) \\
&\quad + \sqrt{2\varepsilon (1 + \varepsilon)} \sin(\phi S) F_{UT}^\sin(\phi S) \\
&\quad + \sqrt{2\varepsilon (1 + \varepsilon)} \sin(2\phi - \phi_S) F_{UT}^\sin(2\phi - \phi_S) \right] \\
&\quad + S_T \lambda_I \left[ \sqrt{1 - \varepsilon^2} \cos(\phi - \phi_S) F_{LT}^\cos(\phi - \phi_S) \\
&\quad + \sqrt{2\varepsilon (1 - \varepsilon)} \cos(\phi S) F_{LT}^\cos(\phi S) \\
&\quad + \sqrt{2\varepsilon (1 - \varepsilon)} \cos(2\phi - \phi_S) F_{LT}^\cos(2\phi - \phi_S) \right] \\
&\left. \right\}
\]

\[\propto h_1 \otimes H_1^\perp\]

Collins effect
The Collins Moment Results

▶ Results high magnitude and opposite sign for $\pi^\pm$
▶ Results consistent with zero for $\pi^0$
▶ $u$-quark dominance suggests opposite signs of fav./unfav. Collins function.
▶ $K^+$ results positive with higher magnitude than $\pi^+$
▶ $K^-$ results consistent with zero.
▶ Exist TMD transversity extraction using these results, along with Compass and Belle
The Sivers Moment

\[
\frac{d\sigma^h}{dx dy d\phi_S d\phi dP^2_{h\perp}} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1 - \varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \\
\left\{ \begin{array}{l}
F_{UU,T} + \varepsilon F_{UU,L} \\
p \sqrt{2\varepsilon (1 + \varepsilon)} \cos(\phi) F_{UU}^{\cos(\phi)} + \varepsilon \cos(2\phi) F_{UU}^{\cos(2\phi)} \\
+ \lambda_l \left[ \sqrt{2\varepsilon (1 - \varepsilon)} \sin(\phi) F_{LU}^{\sin(\phi)} \right] \\
+ S_L \left[ \sqrt{2\varepsilon (1 + \varepsilon)} \sin(\phi) F_{UL}^{\sin(\phi)} + \varepsilon \sin(2\phi) F_{UL}^{\sin(2\phi)} \right] \\
+ S_L \lambda_l \left[ \sqrt{1 - \varepsilon^2} F_{LL} + \sqrt{2\varepsilon (1 - \varepsilon)} \cos(\phi) F_{LL}^{\cos(\phi)} \right] \\
+ S_T \left[ \sin(\phi - \phi_S) \left( F_{UT,T}^{\sin(\phi - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi - \phi_S)} \right) \\
+ \varepsilon \sin(\phi + \phi_S) F_{UT}^{\sin(\phi + \phi_S)} + \varepsilon \sin(3\phi - \phi_S) F_{UT}^{\sin(3\phi - \phi_S)} \\
+ \sqrt{2\varepsilon (1 + \varepsilon)} \sin(\phi) F_{UT}^{\sin(\phi)} \\
+ \sqrt{2\varepsilon (1 + \varepsilon)} \sin(2\phi - \phi_S) F_{UT}^{\sin(2\phi - \phi_S)} \right] \\
+ S_T \lambda_l \left[ \sqrt{1 - \varepsilon^2} \cos(\phi - \phi_S) F_{LT}^{\cos(\phi - \phi_S)} \\
+ \sqrt{2\varepsilon (1 - \varepsilon)} \cos(\phi_S) F_{LT}^{\cos(\phi_S)} \\
+ \sqrt{2\varepsilon (1 - \varepsilon)} \cos(2\phi - \phi_S) F_{LT}^{\cos(2\phi - \phi_S)} \right] \end{array} \right\}
\]
The Sivers Moment Results

- Results significantly positive for $\pi^+$
- Results consistent with zero for $\pi^-$
- $\pi^0$ results appear as average of $\pi^+$, $\pi^-$
- $K^+$ results positive with higher magnitude than $\pi^+$
- $K^-$ results slightly positive
- Further studies hints that $K^+$, $\pi^+$ difference may be due to higher twist effects for kaons
Dihadron SIDIS
Why SIDIS TMD Dihadrons?

- Dihadron cross section similar to single hadron cross section
  - Involves identical distribution functions but different factorization functions.
  - Dihadrons also access different flavor combinations.
    - Dihadrons give a wealth of flavor-dependent information
  - Different distribution functions also occur in the collinear cross section.
    - Collinear access to transversity

- Lund/Artru string fragmentation model predicts sign change in the Collins function between single hadron and the corresponding transversely polarized vector meson.

- Siver’s function in $\phi$-meson production may be related to gluon orbital angular momentum.
Fragmentation Functions and Spin/Polarization

- Leading twist Fragmentation functions are related to number densities
  - Amplitudes squared rather than amplitudes
- Difficult to relate Artru/Lund prediction with published notation and cross section.
- Propose new convention for fragmentation functions
  - Functions entirely identified by the polarization states of the quarks, $\chi$ and $\chi'$
  - Any final-state polarization, i.e. $|\ell_1, m_1\rangle|\ell_2, m_2\rangle$, contained within partial wave expansion of fragmentation functions
- Exists exactly two fragmentation functions
  - $D_1$, the unpolarized fragmentation function ($\chi = \chi'$)
  - $H_{1,1}^\perp$, the polarized (Collins) fragmentation function ($\chi \neq \chi'$)
- New partial waves analysis proposed, using direct sum basis $|\ell, m\rangle$ rather than the direct product basis $|\ell_1, m_1\rangle|\ell_2, m_2\rangle$.

$$H_{1,1}^\perp = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} P_{\ell,m}(\cos \vartheta) e^{im(\phi_R - \phi_k)} H_{1,1}^\perp |\ell,m\rangle (z, M_h, |k_T|),$$
Dihadron Twist-2 and Twist-3 Cross Section

\[
d\sigma_{UU} = \frac{\alpha^2 M_h P_{h\perp}}{2\pi x y Q^2} \left( 1 + \frac{\gamma^2}{2x} \right) \times \sum_{\ell=0}^2 \left\{ A(x, y) \sum_{m=0}^{\ell} \left[ P_{\ell, m} \cos(m(\phi_h - \phi_R)) \left( F_{UU,T} P_{\ell, m} \cos(m(\phi_h - \phi_R)) + \epsilon F_{UU,L} P_{\ell, m} \cos(m(\phi_h - \phi_R)) \right) \right] \right.
\]

\[
+ B(x, y) \sum_{m=-\ell}^{\ell} P_{\ell, m} \cos((2-m)\phi_h + m\phi_R) F_{UU} P_{\ell, m} \cos((2-m)\phi_h + m\phi_R)
\]

\[
+ V(x, y) \sum_{m=-\ell}^{\ell} P_{\ell, m} \cos((1-m)\phi_h + m\phi_R) F_{UU} P_{\ell, m} \cos((1-m)\phi_h + m\phi_R) \}
\]

\[
d\sigma_{UT} = \frac{\alpha^2 M_h P_{h\perp}}{2\pi x y Q^2} \left( 1 + \frac{\gamma^2}{2x} \right) |S_\perp| \sum_{\ell=0}^{2} \sum_{m=-\ell}^{\ell} \left\{ A(x, y) \left[ P_{\ell, m} \sin((m+1)\phi_h - m\phi_R - \phi_S) \right. \right.
\]

\[
	\times \left( F_{UT,T} P_{\ell, m} \sin((m+1)\phi_h - m\phi_R - \phi_S) + \epsilon F_{UT,L} P_{\ell, m} \sin((m+1)\phi_h - m\phi_R - \phi_S) \right) \right. \right.
\]

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

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

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

\[
+ P_{\ell, m} \sin((2-m)\phi_h + m\phi_R - \phi_S) F_{UT} P_{\ell, m} \sin((2-m)\phi_h + m\phi_R - \phi_S) \right\}.
\]
Twist-2 Structure Functions, Transverse Target

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

\[
F_{UT,T}^{P,\ell,m} \sin((m+1)\phi_h - m\phi_R - \phi_S) = -\mathcal{J} \left[ \frac{|p_T|}{M} \cos ((m + 1)\phi_h - \phi_p - m\phi_k) \right.

\times \left( f_{1T}^\perp \left( D_1^{\ell,m} + D_1^{\ell,-m} \right) \right) + \chi(m) g_{1T} \left( D_1^{\ell,m} - D_1^{\ell,-m} \right) \biggr) \right],
\]

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

\[
F_{UT}^{P,\ell,m} \sin((3-m)\phi_h + m\phi_R - \phi_S) = \mathcal{J} \left[ \frac{|p_T|^2 |k_T|}{M^2 M_h} \cos ((m - 3)\phi_h + 2\phi_p - (m - 1)\phi_k) \right. \left. h_1 H_1^{\perp |\ell,m}\right].
\]

- Can test Lund/Artru model with \( F_{UT}^{\sin^2 \vartheta \sin(-\phi_h + 2\phi_R + \phi_S)} \) and \( F_{UT}^{\sin^2 \vartheta \sin(3\phi_h - 2\phi_R + \phi_S)} \) via transversity.

- In theory, could also test Lund/Artru and gluon radiation models with \( F_{UT}^{\sin^2 \vartheta \sin(\phi_h + 2\phi_R - \phi_S)} \) and \( F_{UT}^{\sin^2 \vartheta \sin(5\phi_h - 2\phi_R - \phi_S)} \) via pretzelocity.

- Data from SIDIS pseudo-scalar production indicate pretzelocity very small or possibly zero.
Where is “the Collins function?”

- Consider direct sum vs. direct product basis

\[
\begin{pmatrix}
\frac{1}{2} \\
\frac{1}{2} \\
\frac{1}{2} \\
\frac{1}{2}
\end{pmatrix} \otimes 
\begin{pmatrix}
\frac{1}{2} \\
\frac{1}{2} \\
\frac{1}{2} \\
\frac{1}{2}
\end{pmatrix} = \left( \begin{pmatrix}
\frac{1}{2} \\
\frac{1}{2} \\
\frac{1}{2} \\
\frac{1}{2}
\end{pmatrix} \otimes \begin{pmatrix}
\frac{1}{2} \\
\frac{1}{2} \\
\frac{1}{2} \\
\frac{1}{2}
\end{pmatrix} \right),
\]

= \left( 1 \oplus 0 \right) \otimes \left( 1 \oplus 0 \right),

= 2 \oplus 1 \oplus 1 \oplus 1 \oplus 0 \oplus 0.

- The three \( \ell = 1 \) cannot be separated experimentally
  - Note: the usual IFF, related to \( H^{1|1,1}_1 \) is not pure \( sp \), but also includes \( pp \) interference.

- Longitudinal vector meson state \( |1, 0\rangle|1, 0\rangle \) is a mixture of \( |2, 0\rangle \) and \( |0, 0\rangle \)
  - \( |2, 0\rangle \) partial waves affected very strongly by \( \cos \vartheta \) acceptance

- Transverse vector meson states \( |1, \pm 1\rangle|1, \pm 1\rangle \) are exactly \( |2, \pm 2\rangle \)
  - Models predict dihadron \( H^{2|1,1}_1 \) has opposite sign as pseudo-scalar \( H^{1}_1 \).
  - Cross section has direct access to \( H^{2|2,\pm 2}_1 \)

- Using symmetry, can calculate cross section for any polarized final state from the scalar final state cross section
Dihadrons considered in this talk: $\pi^\pm \pi^0 (\rho^\pm)$, $\pi^+ \pi^- (\rho^0)$, $K^+ K^- (\phi)$

$K^+ K^-$ near the $\phi$-peak ($M_{KK} < 1.05 \text{ GeV}^2$) analyzed separately than non-resonant region ($1.05 \text{ GeV}^2 < M_{KK} < 2.5 \text{ GeV}^2$)

Both TMDGen and Pythia were used as Monte Carlo generators for systematic studies

- TMDGen was also used in the acceptance correction

- TMDGen uses a new TMD spectator model for the unpolarized dihadron fragmentation function $D_1^{(0,0)}$
  - Different tunes of the model are used for each dihadron type and region.

Acceptance effects are corrected by inverting the smearing matrix in the parameter space.

- As no $p$-wave signal was found in the non-resonant $K^+ K^-$ region, only the $\ell = 0$ sector is used in the fitting functions.
|1, 1⟩ Moment for $\pi\pi$ Dihadrons

Published $\pi^+\pi^-$ Results

- Signs of moments are consistent for all $\pi\pi$ dihadron species.
- Statistics are much more limited for $\pi^\pm\pi^0$ dihadrons.
- Despite uncertainties, may still help constrain global fits.

New $\pi^\pm\pi^0$ Results
|2, ±2⟩ Moments for ππ Dihadrons

- |2, −2⟩ moment very consistent with zero for all flavors
- Results for |2, 2⟩ are consistent with expectations
  - No indication of any signal outside the ρ-mass bin
  - Suggests negative moments for ρ±, very small ρ0 moments
  - Results are sufficiently suggestive to merit measurements at current experiments.
Exists rotation in $SU(3)$ space, so no direct testing of Lund/Artru

No obvious change within $\phi$-meson peak (middle bin) vs. sidebands within available statistics for any partial waves.

Collinear access to transversity: $s$-flavor of either transversity or Collins is small
Again, no obvious change within $\phi$-meson peak vs. sidebands within available statistics

The $|0, 0\rangle$ partial wave may suggest difference between strange and other sea flavors of Sivers function
Results consistent with small positive value

Note: single hadron $K^+$ results positive and $K^-$ are consistent with zero
Results consistent with small positive value

Note: single hadron $K^+$ results also large and positive and $K^-$ results small and slightly positive
$K^+K^-$, Non-Res. Region, Pretzel Velocity Moment

- Consistent with zero, as expected
Higher twist moments also mostly consistent with zero
Conclusions

- HERMES inclusive hadron electroproduction reveal interesting features, common with $A_N$ in $pp$ and the Sivers effect in SIDIS.

- SIDIS single and dihadron results provide rich details regarding flavor separation for many distribution functions and both fragmentation functions.
  - DFs: $h_1^\perp$, $h_1$, $f_{1T}^\perp$, $h_{1T}^\perp$, …
  - FFs: Single and dihadron $D_1^{[\ell,m]}$, $H_1^{\perp[\ell,m]}$.

- The HERMES experiment has played a pioneering role in TMD studies, and there is still more to come…