Recent HERMES Results in Exclusive $\rho$ and $\phi$ Transverse Target Spin Asymmetries

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Outline

I. Background and Motivation
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II. Exclusive $\rho^0$
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III. Exclusive $\phi$
   ▶ Analysis & Results

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I. Background and Motivation
Exclusive Reactions and GPDs

GPDs offer most complete description available of quark-gluon structure of hadrons

GPDs
- orbital angular momentum
- transverse localisation
- form factors
- wide angle Compton scattering
- deep inelastic scattering
- PDFs
- exclusive meson production
- deep virtual / large t
- timelike Compton scattering
- \( p\bar{p} \) annihilation\( \gamma\gamma \rightarrow \pi\pi, \ldots \)

Nucleon Helicity:

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + \Delta G + L_g
\]

\( J_q \) Sum Rule:

\[
J_q = \frac{1}{2} \Delta \Sigma + L_q
\]

\[\text{Ji Sum Rule: } J_q = \frac{1}{2} \lim_{t \rightarrow 0} \int_{-1}^{1} x (H_q(x, \xi, t) + E_q(x, \xi, t)) \, dx\]

- \( \Delta \Sigma = 0.330 \pm 0.011^{(\text{theo.})} \pm 0.025^{(\text{exp.})} \pm 0.028^{(\text{evol.})} \) [hep-ex/0609039]
- \( \Delta G = \text{small (??)} \)
- Measure \( J_q = \frac{1}{2} \Delta \Sigma + L_q \)
**Vector Mesons and GPDs**

- Soft hadronization process given by meson form factor $\Phi$
- Factorization Theorem for Vector Meson production proven only for longitudinal photons.
  
  *Collins, Frankfurt, Strikman

- Approximate $s$-channel helicity conservation (SCHC):
  
  $\rho$ SCHC at $96.4 \pm 1.6\%$**; similar for $\phi$***.

- Assume exact SCHC
- $\rho^0_L/\rho^0_T$ & $\phi_L/\phi_T$ separation can be mapped into $\gamma^*_L/\gamma^*_T$ separation
- Meson production sensitive to flavor dependencies of GPDs

  **(HERMES $\rho$ SDMEs, arXiv:hep-ex/0002016)

  *** (HERMES $\phi$ SDMEs, arXiv:0808.0669)
For $ep \rightarrow e'p'h, h \rightarrow h'^+h'^-$, the cross-section is proportional to

$$d\sigma(\phi, \phi_s, \varphi) \propto \sigma_{UU} [1 + A_{UU}(\phi, \vartheta) + P_{TA_{UT}}(\phi, \phi_s, \vartheta) + \ldots]$$

- $L$–$T$ separation

$$1 + A_{UU}(P_T, \phi, \vartheta) + P_{TA_{UT}}(\phi, \phi_s, \vartheta) \propto$$

$$\left[ \cos^2 \vartheta \quad r_{00}^{04} \quad \left(1 + A_{UU,L}(\phi) + P_{TA_{UT,L}}(\phi, \phi_s)\right) \right]$$

$$+ \frac{1}{2} \sin^2 \vartheta (1 - r_{00}^{04}) \left(1 + A_{UU,T}(\phi) + P_{TA_{UT,T}}(\phi, \phi_s)\right)$$

[M. Diehl, arXiv:0704.1565]
Transverse Target Spin Asymmetry

Transverse Target Spin Asymmetry defined as
\[
\frac{1}{P_T} \frac{d\sigma(\phi, \phi_s) - d\sigma(\phi, \phi_s + \pi)}{d\sigma(\phi, \phi_s) + d\sigma(\phi, \phi_s + \pi)} = \frac{A_{UT}(\phi, \phi_s, \vartheta)}{1 + A_{UU}(\phi, \vartheta)}
\]

Instead, extract \(A_{UT}(\phi, \phi_s, \vartheta)\) using MLE

Fix \(A_{UU}(\phi, \vartheta)\) using SDME values

\(A_{UT,L}\) and \(A_{UT,T}\) parametrized as
\[
A_{UT,X}(\phi, \phi_s) = A_{UT,X}^{\sin(\phi - \phi_s)} \sin(\phi - \phi_s) + \text{five other terms.}
\]

Note:
\[
A_{UT,L}^{\sin(\phi - \phi_s)} = \frac{\sqrt{t_0 - t}}{m_p} \frac{\sqrt{1 - \xi^2 \text{Im}(E_V^*H_V)}}{(1 - \xi^2)|H_V|^2 - (t/(4m_p^2) + \xi^2)|E_V|^2 - 2\xi^2 \text{Re}(E_V^*H_V)}
\]
\[
\approx \frac{\sqrt{t_0 - t}}{m_p} \left| \frac{E_V}{H_V} \right| \sin \delta_V
\]

Assume \(E_V \ll H_V\) in above approximation

GPD \(E\) not suppressed in exclusive meson production, as it is in DVCS & other processes

*arXiv:0708.1121*
Exclusive $\rho^0$: Analysis and Results
Hard Exclusive $\rho^0_L$ Production

- Exclusive events determined by $\Delta E < 0.6$ GeV
- $\rho^0$ identified by peak in the mass of two-pion system distribution.
- Note: subtle difference between defining angles w.r.t. virtual photon or incident electron

$$P_{TAe_{UT}} = S_T(\theta_\gamma, \phi_s)A_{UT}^\gamma + S_L(\theta_\gamma, \phi_s)A_{UL}^\gamma$$

$$|S_L/S_T| < 0.15 \implies P_{TAe_{UT}} \sim S_T(\theta_\gamma, \phi_s)A_{UT}^\gamma$$ at HERMES

Results with Ellinghaus, et al., Model

\[ A_{UT} \sin(\phi - \phi_s) \propto \frac{\mathcal{E}}{\mathcal{H}} \propto \frac{\mathcal{E}_q + \mathcal{E}_g}{\mathcal{H}_q + \mathcal{H}_g} \]

\[ A_{UT} \sin(\phi - \phi_s) \]

\[ \begin{array}{c}
\text{HERMES PRELIMINARY} \\
e^+ p^0 \rightarrow e^+ p^0 \end{array} \]

\[ A_{UT} \sin(\phi - \phi_s) \]

\[ \begin{array}{c}
\text{HERMES PRELIMINARY} \\
e^+ p^0 \rightarrow e^+ p^0 \end{array} \]

- Uses all transverse data, 2002-2005!
- Assume \( J_d = 0 \) for above plots
- Constraint on \( J_u, J_d \) in progress
Results with Diehl/Kugler Model

\[ A_{UT}^{\sin (\phi - \phi_s)} \]

\[ e p^0 \rightarrow e^' \rho^0 p \]

\[ \langle Q^2 \rangle = 2.0 \text{ GeV}^2 \]

\[ \langle -t' \rangle = 0.14 \text{ GeV}^2 \]

Model 2 slightly preferred; Model params. yield \( J_u \approx 0.2, J_d \approx 0 \)
Results with Goloskokov/Kroll Model

- $A_{UT}^\sin(\phi - \phi_s)$

$H$ taken from previous electro-production cross-sections
$E$ taken computed with double distributions, constrained by Pauli nucleon form factors, positivity bounds and sum rules.
Four variants on the model parameters considered
Agreement between data and model within uncertainties
Exclusive $\phi$:
Analysis and Results
Hard Exclusive $\phi_L$ Production

- Identify exclusive $\phi$ in similar manner as identified exclusive $\rho^0$
- $\Delta E$ cut now placed at 1.0 GeV.
- Note: $\phi$ is $s\bar{s}$ pair, while $\rho^0$ is $(u\bar{u} - d\bar{d})/\sqrt{2}$ combination
- Predicted that $\phi A_{UT}$ sensitive to gluon GPDs

$$A_{UT}^{\sin(\phi - \phi_s)} \propto \frac{\mathcal{E}_q + \mathcal{E}_g}{\mathcal{H}_q + \mathcal{H}_g}$$
Results

\[ \text{HERMES Preliminary} \]

\[ <x> = 0.0874 \]
\[ <-t'> = 0.132 \text{ GeV}^2 \]
\[ <Q^2> = 1.89 \text{ GeV}^2 \]

\[ \sin(\phi+\phi_s) \]
\[ \sin(\phi-\phi_s) \]

- Only fully integrated moments shown, as limited statistics
- Newer approach using Kernel Density Estimation may allow extraction of kinematic dependencies
- Model prediction by Diehl/Kugler
  \textit{arXiv:0708.1121}
- First theoretical treatment for excl. \( \phi A_{UT} \)
- Model at higher \( Q^2 \) and \(-t'\)
- Uncertainty on extracted value too large to make strong conclusions
IV. Conclusion and Outlook
Kernel Density Estimation

Given:
- Data set $\mathbf{X} = \{x^{(i)}\}_{i=1}^N$ in $D$ dimensions
- Normalized, centered kernel function $K$
- Bandwidth Matrix $H$

The Kernel Density Estimate (KDE) of the probability density function (PDF) is

$$\hat{p}(x | \mathbf{X}) = \frac{1}{N} \sum_{i=1}^N K \left( H^{-1} (x - x^{(i)}) \right)$$

KDEs are non-parametric, continuous density estimators
- Optimal asymptotic convergence $\rightarrow$ minimal information loss
  - More accurate and precise than histograms for given statistics
  - Scales better with small statistics and/or high dimensions
- No more extracting parameters per kinematic bin! (No more bins!)
- Can yield continuous, non-parametric estimates of $A_{UT}$ moments

Clara Kernel:
$$K \propto \prod_{k=1}^D \left[ 1 - \left( \frac{x_k - x_{k}^{(i)}}{h_k} \right)^2 \right] \gamma \Theta(\cdot)$$
Conclusion

- $A_{UT}$ for exclusive $\rho_L^0$
  - Successful $\rho_L^0/\rho_T^0$ separation
  - Possible constraint on $J_u, J_d$
  - Many recent
  - Great progress on paper draft

- $A_{UT}$ for exclusive $\phi$
  - First theoretical paper including exclusive $\phi$ $A_{UT}$ in August, 2007
  - $A_{UT} \phi_L/\phi_T$ separated moments released
  - High uncertainty currently limits interpretation

- KDEs under investigation for many analyses:
  - Exclusive $\pi^+$ paper—may be able to resolve existence of node
  - Color Transparency—need both $l_c$ and $Q^2$ dependence
  - Kinematic dependencies with low statistics
    - Exclusive $\phi$ and Exclusive $\omega$ $A_{UT}$
  - Unfolding Acceptance and Smearing effects
    - SIDIS $A_{UU}, A_{UT}, A_{LT}$ moments
    - Exclusive $\phi$ and Exclusive $\omega$ $A_{UT}$