Overview of recent HERMES results

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on behalf of the HERMES collaboration

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Spin structure of the nucleon at HERMES

- Longitudinal spin/momentum structure, hadronization
- Transverse spin/momentum structure $\rightarrow$ transversity, TMDs
- DVCS, exclusive meson production $\rightarrow$ GPDs, “nucleon tomography”
- Strange-baryon production
HERA at DESY

Longitudinally polarized electron (positron) beams with both helicities
P=27.57 GeV/c
Internal gas targets:
- Longitudinally polarized $H, D$
- Transversely polarized $H$
- Unpolarized $H, D, ^4He, N, Ne, Kr, Xe$

Forward magnetic spectrometer
- Momentum resolution 1-2%
- Particle identification: $RICH, TRD, H2, calorimeter$
Distribution and fragmentation functions in DIS

\[ \sigma^{e p \rightarrow \gamma^* h X} \propto \sum_q DF(x) \otimes \sigma^{e q \rightarrow e q} \otimes FF^{q \rightarrow h}(z) \]

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

- **Momentum distribution**
  - \( q(x) [f_1^q(x)] \)

- **Helicity distribution**
  - \( \Delta q(x) [g_1^q(x)] \)

- **Transversity distribution**
  - \( \delta q(x) [h_1^q(x)] \)
Transversity

- Chiral-odd: involves quark helicity flip
- Cannot be measured in inclusive DIS
- Needs another chiral-odd partner
and Collins fragmentation function

- Collins fragmentation function $H_{1\perp}$
- Correlation between transverse polarization of fragmenting quark and the transverse momentum $P_{h\perp}$ of the produced (unpolarized) hadron
Single spin asymmetries in semi-inclusive deep inelastic scattering

\[ A_{UT}(\phi, \phi_S) \approx 2\langle \sin(\phi + \phi_S) \rangle_{UT}^h \sin(\phi + \phi_S) + 2\langle \sin(\phi - \phi_S) \rangle_{UT}^h \sin(\phi - \phi_S) + \cdots \]

Collins moment

\[ \propto h_i(x) \otimes H_{1q}^q(z) \]

Transversity DF  
Collins FF

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

- \( \phi \) - angle between the lepton scattering and hadron production planes
- \( \phi_S \) - angle between the target spin direction and the lepton scattering plane
Collins results (pions)

Positive amplitude for $\pi^+$

Large negative amplitude for $\pi^-$

Non-zero transversity and Collins function!

Similar magnitude and opposite sign for favored ($u \rightarrow \pi^+$) and unfavored ($u \rightarrow \pi^-$) FF

Isospin symmetry in $\pi$ fragmentation fulfilled

Information from another process on Collins FF (BELLE) allows extraction of $\delta q$
Collins results (Kaons)


- Collins amplitudes for $K^+$ larger than for $\pi^+$
- No significant non-zero Collins amplitudes for $K^-$
- Collins fragmentation function for Kaons unknown
- Possible non negligible role of the sea quarks

**Details: M. Diefenthaler**
Single spin asymmetries in semi-inclusive deep inelastic scattering

\[ A_{UT}(\phi, \phi_S) \approx 2 \langle \sin(\phi + \phi_S) \rangle_{UT}^h \sin(\phi + \phi_S) + 2 \langle \sin(\phi - \phi_S) \rangle_{UT}^h \sin(\phi - \phi_S) + \cdots \]

Collins moment

\[ \propto h_I(x) \otimes H_{I}^{\perp q}(z) \]

Sivers moment

\[ \propto f_{I T}^{\perp q}(x) \otimes D_{I}^{q}(z) \]

Sivers DF

Unpolarized FF

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

\( \phi \) - angle between the lepton scattering and hadron production planes

\( \phi_S \) - angle between the target spin direction and the lepton scattering plane
Sivers distribution function

- Chiral–even and naive T–odd transverse momentum dependent function
- Allowed due to the final state interaction
- Correlation between intrinsic quark transverse momentum and transverse spin of the nucleon
- Non-zero Sivers DF requires non-vanishing orbital angular momentum of quarks in the nucleon
Sivers asymmetries for pions and Kaons


- Significantly positive for $\pi^+$ and $K^+$
  - Non-zero orbital angular momentum of quarks!
  - Suggests large and negative Sivers function for $u$-quarks

- Consistent with zero for $\pi^-$
  - Requires cancellation effects, opposite sign for $u$- and $d$-quark Sivers functions
Extraction of transversity and Sivers function

\[ A_{UT}^{\sin(\phi - \phi_S)} \propto h_1(x) \otimes H_{1q}^q(z) \]

\[ A_{UT} \propto f_{1T}^r(x) \otimes D_1^q(z) \]

Known

- Anselmino et al. Phys. Rev. D 75 (2007) -

Transverse single-spin asymmetry in inclusive hadron production in pp collisions

Reminder: $p^+ p \rightarrow \pi(K) X$

- Large $A_N$ in $p^+ p \rightarrow \pi(K) X$
- Sivers, Collins, higher twist?
Transverse single-spin asymmetry in inclusive hadron production at HERMES

- First measurement in ep scattering
- High statistics (100 Mil hadrons)
- Inclusive measurements, only hadrons are detected → quasi-real photoproduction

\[ ep^\uparrow \rightarrow hX \]

\[ k \]

\[ P, M \]

\[ W \]

\[ x_F = 2p_L / \sqrt{s} \]

\[ p_T = p \cos \theta \]

\[ \vec{p}_h \]

\[ \phi \]

\[ \vec{s} \]

Front view of HERMES

Target spin vector

Measure \[ A_{UT} = \frac{N_U - N_D}{N_U + N_D} \], acceptance effects cancel (target spin flip every 90s)

Extract amplitude \[ A_{UT}^{\sin \phi} \] of asymmetry \[ A_{UT}(p_T, x_F, \phi) \approx A_{UT}^{\sin \phi}(p_T, x_F) \sin \phi \]
Results on inclusive hadron TSA

- $e^+ p^\uparrow \rightarrow \pi^+ X$: rise at low $p_T$, drop at high $p_T$
- $\pi^-, K^-$: sign change, $K^-$: positive for low $x_F$

New

Details: K. Rith

S. Yaschenko, Overview of recent HERMES results
Results on inclusive hadron TSA

Inclusive hadrons

\[ \text{HERMES preliminary} \]

\[ \langle x_f \rangle \]

\[ A_{\sin^2} \]

\[ 2 \langle \sin(\phi_s) \rangle_{\perp} \]

\[ e^\pm p^\mp \rightarrow \pi^\mp + X \]

\[ p_T [\text{GeV}] \]

Sivers

\[ 2 \langle \sin(\phi_s) \rangle_{\perp} \]

\[ \pi^+ \]

\[ \pi^0 \]

\[ \pi^- \]

Collins

\[ 2 \langle \sin(\phi_s^\perp) \rangle_{\perp} \]

\[ \pi^+ \]

\[ \pi^0 \]

\[ \pi^- \]

\[ P_{h_\perp} [\text{GeV}] \]

\[ P_{h_\perp} [\text{GeV}] \]

\[ A_N \text{ resembles Sivers effect as predicted} \]

M. Anselmino et al., PRD 81(2010) 034007
Generalized Parton Distributions (GPDs)

- Include Form Factors and Parton Distribution Functions as moments and forward limits
- Multidimensional description of nucleon structure
- Access to the quark total angular momentum via Ji relation

\[ \mathcal{J}_q = \lim_{t \to 0} \int_d x \left[ H_q(x, \xi, t) + E_q(x, \xi, t) \right] \]

Access to GPDs via exclusive processes

- Sensitivity of different final states to different GPDs
- For spin-1/2 target 4 chiral-even leading-twist quark GPDs: $H, E, \tilde{H}, \tilde{E}$
- $H, \tilde{H}$ conserve nucleon helicity, $E, \tilde{E}$ involve nucleon helicity flip
- DVCS ($\gamma$) $\rightarrow$ $H, E, \tilde{H}, \tilde{E}$
- Vector mesons ($\rho, \omega, \phi$) $\rightarrow$ $H, E$
- Pseudoscalar mesons ($\pi, \eta$) $\rightarrow$ $\tilde{H}, \tilde{E}$

Details on exclusive mesons: B. Marianski, E. Avetisyan
Deeply virtual Compton scattering (DVCS)

- DVCS and Bethe-Heitler: the same initial and final state
- Bethe-Heitler dominates at HERMES kinematics
- GPDs accessible through cross section differences and azimuthal asymmetries via interference term
DVCS at HERMES

Unique measurements of amplitudes in DVCS at HERMES

- Both beam charges
- Longitudinal beam polarization (both helicities)
- Unpolarized H, D and nuclear targets
- Longitudinally polarized H and D targets
- Transversely polarized H target
- Recoil Detector

$\phi$ - angle between the lepton scattering and real photon production planes

$\phi_S$ - angle between the target spin direction and the lepton scattering plane
Azimuthal asymmetries in DVCS

- Cross section
  \[ \sigma_{LU}(\phi; P_B, C_B) = \sigma_{UU} [1 + P_B^{} A_{LU}^{DVCS} + C_B^{} P_B^{} A_{LU}^l + C_B^{} A_C^{}] \]

- Beam-charge asymmetry
  \[ A_C^{}(\phi) = \left( \frac{\sigma^{\rightarrow + \rightarrow} + \sigma^{\leftarrow + \leftarrow}}{\sigma^{\rightarrow + \leftarrow} + \sigma^{\leftarrow + \rightarrow}} \right) - \left( \frac{\sigma^{\rightarrow \leftarrow} + \sigma^{\leftarrow \rightarrow}}{\sigma^{\rightarrow \rightarrow} + \sigma^{\leftarrow \leftarrow}} \right) = - \frac{1}{D(\phi)} \frac{x_B^{} \sum_{n=0}^{3} c_n^l}{y} \cos(n\phi) \]

- Charge-difference beam-helicity asymmetry
  \[ A_{LU}^{l}(\phi) = \left( \frac{\sigma^{\rightarrow + \rightarrow} - \sigma^{\leftarrow + \leftarrow}}{\sigma^{\rightarrow + \leftarrow} + \sigma^{\leftarrow + \rightarrow}} \right) - \left( \frac{\sigma^{\rightarrow \leftarrow} - \sigma^{\leftarrow \rightarrow}}{\sigma^{\rightarrow \rightarrow} + \sigma^{\leftarrow \leftarrow}} \right) = - \frac{1}{D(\phi)} \frac{x_B^{} \sum_{n=1}^{2} s_n^l}{y} \sin(n\phi) \]

- Charge-averaged beam-helicity asymmetry
  \[ A_{LU}^{DVCS}(\phi) = \left( \frac{\sigma^{\rightarrow + \rightarrow} - \sigma^{\leftarrow + \leftarrow}}{\sigma^{\rightarrow + \leftarrow} + \sigma^{\leftarrow + \rightarrow}} \right) + \left( \frac{\sigma^{\rightarrow \leftarrow} - \sigma^{\leftarrow \rightarrow}}{\sigma^{\rightarrow \rightarrow} + \sigma^{\leftarrow \leftarrow}} \right) = \frac{1}{D(\phi)} \frac{x_B^2 t P_1(\phi) P_2(\phi)}{Q^2} S_{l}^{DVCS} \sin(\phi) \]

- Separation of contributions from DVCS and interference term
  Impossible in case of single-charge beam-helicity asymmetry
  \[ A_{LU}^{}(\phi) = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}} \]
DVCS asymmetries and connections with GPDs

HERMES DVCS

- Beam charge asymmetry
- Beam helicity asymmetry

GPD $H$

$JHEP 11$ (2009) $083$

$JHEP 06$ (2008) $066$
Transverse target spin asymmetry
GPD $E$

$JHEP 06$ (2010) $019$

Longitudinal target spin asymmetry
Double spin asymmetry
GPD $\tilde{H}$
Results on beam-charge and beam-helicity asymmetry amplitudes in DVCS

S. Yaschenko, Overview of recent HERMES results

Comparisons with GPD model, Vanderhaeghen, Guichon, Guidal


Resonance fraction from $ep \rightarrow e\Delta^+\gamma$ is about 12%
Comparison of deuteron and proton data

\[ \begin{align*}
A_{LU, 1} \sin \phi & \quad 0.2 \quad 0 \quad -0.2 \\
A_{LU, 1} \sin(2\phi) & \quad 0.4 \quad 0 \quad -0.2
\end{align*} \]

Amplitudes for proton and deuteron compatible for all leading amplitudes

Details: C. Riedl, 16:30, Location D

S. Yaschenko, Overview of recent HERMES results
New high-statistics results from 2006-2007 data

\[ \phi \cos(CA) \]

\[ \phi \cos(2CA) \]

\[ \phi \cos(3CA) \]

**Details:** M. Düren
Extraction of GPDs

- Postulate GPDs from first principle models
  

- Fit Compton form factors to asymmetry data
  
Pre-Recoil data
- Scattered lepton and photon were detected in the forward spectrometer
- Recoil proton was not detected
- Exclusivity achieved via missing mass technique
- Associated processes were not resolved (12% contribution in the signal)

Recoil data
- Detection of recoil proton
- Suppression of the background to <1% level
DVCS event selection with the Recoil Detector

- Kinematic fitting technique is developed and tested on Monte-Carlo
  - 3 particles detected $\rightarrow$ 4 constraints from energy-momentum conservation
  - Allows to suppress the associated Bethe-Heitler and semi-inclusive background to negligible level

- Applied for data for physics analysis
  - Systematic studies in progress
  - First physics results expected soon

- Missing mass distribution
  - No requirement for Recoil
  - Positively charged Recoil track
  - Kinematic fit probability $>1\%$
  - Kinematic fit probability $<1\%$
Summary and Outlook

- HERMES is actively producing important physics results

- Only selected results presented in this talk
  - Final results on Collins and Sivers asymmetries published
  - New preliminary data on inclusive hadron leptoproduction
  - Unique measurements of asymmetries in DVCS

- Many other interesting results presented in parallel sessions

- Physics analysis is ongoing

- New results will be presented and published soon
Transverse spin/momentum effects:
- Signals for transverse-momentum dependent quark distributions studied at the HERMES experiment, M. Diefenthaler (University of Illinois) for A. Ivanilov (IHEP, Protvino)
- Cosine modulation of the unpolarized pion cross section at HERMES, F. Giordano (DESY)
- Single-spin asymmetries in inclusive hadron electro-production at HERMES, K. Rith (University of Erlangen)
- Measurement of the Proton Spin Structure Function g_2 and Asymmetry A_2 at HERMES, M. Diefenthaler (University of Illinois)
- Transverse Target Moments of SIDIS Vector Meson Production at HERMES, S. Gliske (University of Michigan)
- Search for a two-photon exchange contribution to inclusive deep-inelastic scattering, K. Rith (University of Erlangen) for C. Van Hulse (Gent University)

GPDs:
- Deeply Virtual Compton Scattering off polarised and unpolarised protons at HERMES, M. Düren (Universität Giessen)
- Report on the HERMES Recoil Detector, S. Yaschenko (DESY Zeuthen) for C. Van Hulse (Gent University)
- Helicity Amplitude Ratios in Exclusive Electroproduction of the rho0 meson at HERMES, B. Marianski (Institute for Nuclear Studies)
- Hard exclusive electroproduction of vector mesons at HERMES, E. Avetisyan (DESY)
- DVCS on the deuteron and heavier nuclear targets at HERMES, C. Riedl (DESY)

Strange-baryon production
- Spin Transfer Coefficient D_{LL} to Lambda and anti-Lambda Hyperon in Semi-Inclusive DIS at HERMES, D. Veretennikov (PNPI)
- Measurement of the nuclear-mass dependence of transverse Lambda polarisation in quasi-real photoproduction at HERMES, Yu.Naryshkin (PNPI)
Backup slides
Excellent lepton-hadron separation

Hadron type separation with dual radiator RICH for 2-15 GeV/c
Pion-difference Sivers asymmetry and difference between $K^+$ and $\pi^+$ Sivers asymmetries


Pion-difference asymmetry

\[ A_{UT}^{\pi^+ - \pi^-}(\phi, \phi_S) = \frac{I}{|S_T|} \left( \sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-} \right) - \left( \sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-} \right) \propto \left( f_{IT}^{\perp d} - 4f_{IT}^{\perp u} \right) \]

- Contribution from $\rho^0$ mesons cancels
- Helps to isolate the valence-quark Sivers function
- Assumption of charge-conjugation and isospin symmetry among pion fragmentation

Difference between $K^+$ and $\pi^+$ asymmetries

\[ \pi^+ = |ud\rangle \quad K^+ = |us\rangle \]

- Possible significant role of sea quarks
- Higher-twist effects in kaon production might also contribute
Models for $A_N$
Results on Inclusive hadron leptoproduction
Transverse target spin asymmetry in DVCS

Sensitivity of GPD model predictions to $J_u$ at fixed $J_d=0$