HERMES measurements of charge separated multiplicities for $\pi^\pm$ and $K^\pm$ production in semi-inclusive DIS

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**Definition**

\[
\frac{d^2 M_t^h(Q^2, x, z, p_T)}{dz dp_T} \equiv \frac{dx dQ^2}{d^2 N_t^{DIS}(Q^2, x)} \quad \text{DIS yield } N_t^{DIS}(Q^2, x)
\]

\[
\frac{d^4 N_t^h(Q^2, x, z, p_T)}{dx dQ^2 dz dp_T} \quad \text{SIDIS yield } N_t^h(Q^2, x, z, p_T)
\]
Example: LO Framework

\[
\frac{dM^h_n(Q^2, x, z)}{dz} \approx \frac{\sum_q e_q^2 f_1^q(Q^2, x) D^h_q(Q^2, z)}{\sum_q e_q^2 f_1^q(Q^2, x)}
\]

Assumptions: QPM, LO, leading twist factorized colinear QCD

- Opens access to
  - Fragmentation functions \( D^h_q(Q^2, z) \)
  - Disentangle \( q \) and \( \bar{q} \) contributions
  - Parton distribution functions \( f_1^q(Q^2, x) \)

- Additionally, through the \( p_T \) dependence
  - Fragmentation \( k_T \)
  - Intrinsic quark \( p_T \)
The HERMES Experiment

- 27.6 GeV HERA electron/positron beam
- Pure H and D gas target
- Forward spectrometer
- Very clean lepton-hadron separation
- RICH detector enables very good pion-kaon separation

\[ W^2 > 10 \text{GeV}^2 \]
\[ 0.1 < y < 0.85 \]
\[ Q^2 > 1 \text{GeV}^2 \]
\[ 0.023 < x < 0.6 \]
SIDIS Multiplicities: New HERMES Results

- High statistics
- 3D analysis (in $x$, $z$, $p_T$ and $Q^2$, $z$, $p_T$)
- For identified and charge-separated $\pi^{\pm}$ and $K^{\pm}$
- High precision data require sophisticated analysis:
  - Corrections for detector efficiencies
  - 3D unfolding for smearing and acceptance effects
  - In-depth systematics analysis

High precision 3D data pushes the envelope, enabling:
  - Evaluation of the quality of PDF and FF parametrizations
  - Improvements on the current parametrizations
  - Access to the transverse fragmentation function
  - Tests of the applicability of the usual colinear LO, leading-twist model assumptions in the HERMES kinematic regime
High statistics

3D analysis (in $x$, $z$, $p_T$ and $Q^2$, $z$, $p_T$)

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Unfolding the SIDIS Multiplicities

Relation between true and measured quantities

\[ \nu_i = \mu_{\text{tot}} \sum_{j=1}^{M} \frac{\int_{\text{bin } i} dX \int_{\text{bin } j} dY s(X|Y) \epsilon(Y) f(Y)}{\int_{\text{bin } j} dY f(Y)} \mu_j + \beta_i \]

- Measured quantity \( \nu_i \) in bin \( i \) (eg. differential cross section)
- True quantity \( \mu_j \) in bin \( j \) following the true distribution \( f(Y) \)
- Properties of the experiment:
  - Resolution function \( s(X|Y) \)
    - Experimental resolution
    - Radiative effects
  - Acceptance function \( \epsilon(Y) \)
- Background contributions \( \beta_i \) in bin \( i \)
Unfolding the SIDIS Multiplicities

Relation between true and measured quantities

\[ \nu_i = \mu_{\text{tot}} \sum_{j=1}^{M} \frac{\int_{\text{bin } i} \int_{\text{bin } j} dX \, dY \, s(X|Y) \epsilon(Y) f(Y) \, \mu_j + \beta_i}{\int_{\text{bin } j} dY f(Y)} \]

- Has the shape of a matrix equation

\[ \nu_i = \sum_{j=1}^{M} S_{ij} \mu_j + \beta_i \]

- Smearing matrix \( S \) independent of underlying physics \( f \) if bins small enough
- Extracted from MC simulation
Unfolding the SIDIS Multiplicities

Relation between true and measured quantities

\[ \nu_i = \mu_{\text{tot}} \sum_{j=1}^{M} \frac{\int_{\text{bin}i} \, dX \int_{\text{bin}j} \, dY \, s(X|Y) \epsilon(Y) f(Y)}{\int_{\text{bin}j} \, dY f(Y)} \mu_j + \beta_i \]

- Solve for true data by simple matrix inversion

\[ \mu_j = \sum_{i=1}^{M} S_{ji}^{-1} (\nu_i - \beta_i) \]

- Resulting multiplicity corrected for
  - Limited acceptance
  - Finite detector resolution
  - Radiative smearing
Results: Projections vs $z$

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HERMES SIDIS multiplicities

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Results: Projections vs $zp_T$

- Disentanglement of $z$ and $p_T$
- Access to the transverse intrinsic quark $p_T$ and fragmentation $k_T$. 

\begin{figure}
\centering
\includegraphics[width=\textwidth]{HERMES_multiplicities.png}
\caption{HERMES SIDIS multiplicities}
\end{figure}
Results: Projections vs $zQ^2$

- Disentanglement of $z$ and $Q^2$

![Graph showing projections vs $zQ^2$]
Comparison with Predictions: Projections vs $z$

LO Interpretation
- Good agreement with CTEQ6+DSS for $\pi^+$ and $K^+$
- CTEQ6+Kretzer performs well for pions
- Larger deviations for $\pi^-$
- Agreement with $K^-$ rather poor
- Model uncertainty?
Proton-deuteron multiplicity asymmetry

**definition:**

$$A_{d-p}^h \equiv \frac{M_d^h - M_p^h}{M_d^h + M_p^h}$$

- Reflects different valence quark content
- Improved precision by cancellations in the systematic uncertainty
Proton-deuteron multiplicity asymmetry

**definition:**

\[ A_{h-d-p}^h \equiv \frac{M_{d}^h - M_{p}^h}{M_{d}^h + M_{p}^h} \]

**LO Interpretation:**

- Good agreement with LO model calculations for positive hadrons
- Bigger discrepancy for negative hadrons
- Model uncertainty?
Conclusions

- Unique set of 3D high-precision SIDIS multiplicities for $\pi^\pm$ and $K^\pm$ on $p$ and $d$ are presented.
- By using asymmetries and difference ratios, the precision can be improved even further due to cancellations in the systematic uncertainties.
- High value for NLO fits.
- Data can significantly contribute to knowledge of the quark fragmentation process.
Full Results: Projections vs $z$

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Multiplicity vs $z$

- Proton
- Deuteron
Full Results: Projections vs $z p_T$

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0.2 < z < 0.3
π^+
π^-

0.3 < z < 0.4

0.4 < z < 0.6

0.6 < z < 0.8

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K^+
K^-

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Full Results: Projections vs $ZX$

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- $\pi^+$
- $\pi^-$
- $K^+$
- $K^-$

HerMES SIDIS multiplicities

- Multiplicities
- $0.2 < z < 0.3$
- $0.3 < z < 0.4$
- $0.4 < z < 0.6$
- $0.6 < z < 0.8$

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Full Results: Projections vs $zQ^2$
Full Results: Asymmetries vs $z$

![Graph showing asymmetries vs $z$ for different particles such as $\pi^+$, $\pi^-$, $K^+$, and $K^-$]
Full Results: Asymmetries vs $z p_T$

\[ A_{d,p} \]

\begin{align*}
0.2 < z < 0.3 & & \pi^+ & & \pi^- \\
0.3 < z < 0.4 & & \pi^+ & & \pi^- \\
0.4 < z < 0.6 & & \pi^+ & & \pi^- \\
0.6 < z < 0.8 & & \pi^+ & & \pi^-
\end{align*}

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HERMES SIDIS multiplicities

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Full Results: Asymmetries vs $z\times$
Full Results: Asymmetries vs $zQ^2$
Impact of exclusive VM fractions

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\begin{itemize}
\item \[ \text{proton, excl. VM} \]
\item \[ \text{proton, incl. VM} \]
\end{itemize}
Average $Q^2$ as a function of $x$
SIDIS Multiplicities: Historical

EMC FFs

HERMES multiplicities
1996-97 data