HERMES SIDIS multiplicities of charged pions and kaons on the proton and the deuteron

http://www-hermes.desy.de/multiplicities

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Evaluation and improvement of PDFs and FFs

Access to the transverse momentum structure

Precise tests of a leading twist approach at intermediate energies

**Multiplicity: SIDIS cross section normalized to DIS**

\[
M^h(Q^2, x, z, P_{h\perp}) \equiv \frac{d\sigma}{d^2\sigma_{\text{DIS}}(Q^2, x)} \frac{d^4\sigma^h(Q^2, x, z, P_{h\perp})}{dx dQ^2 dz dP_{h\perp}}
\]
Section 1

Measuring SIDIS multiplicities at HERMES
Measuring SIDIS multiplicities at HERMES

- 27.6 GeV HERA $e^\pm$ beam
- Forward spectrometer
  - Pure H and D atomic gas target
  - Clean lepton-hadron identification
  - Very good $\pi - K$ separation with RICH
SIDIS Multiplicities: New HERMES Results

- **High statistics**
- **3D analysis** (in $x$, $z$, $P_{h\perp}$ and $Q^2$, $z$, $P_{h\perp}$)
- For identified and charge-separated $\pi^\pm$ and $K^\pm$
- High statistics data require **sophisticated analysis**:
  - Corrections for trigger inefficiencies
  - Charge-symmetric background correction
  - **RICH unfolding**
  - Correction for the contamination by **exclusive vector mesons** (optional)
  - Multidimensional **smearing-unfolding** for radiative effects, limited acceptance and detector smearing
- Final results corrected to $4\pi$ Born, with well-understood systematics.
Exclusive vector meson contamination

- Diffractive $\rho^0$ and $\phi$ contaminate the SIDIS $\pi$ and $K$ sample
- Correction obtained from tuned PYTHIA
  - Applied at the fully differential level
  - Most of the correction canceled by the corresponding inclusive correction
  - **systematic** $< 1\%$
- **results** available both with and without this correction
- This presentation: with VM correction
Smearing-unfolding in SIDIS

- A raw measurement does not give experiment-independent information:
  - Usually not known if any radiative effects occurred (e.g. ISR and FSR)
  - Detector has less than full $4\pi$ coverage
  - Detector has a finite resolution

Relation between true and measured quantities

\[
\nu_i = \mu_{\text{tot}} \sum_{j=1}^{M} \frac{\int_{\text{bin}_i} dX \int_{\text{bin}_j} dY \int d\bar{Y} f(Y) \rho(\bar{Y}|Y) A(\bar{Y}) M(\bar{Y}|X)}{\int_{\text{bin}_j} dY f(Y)} \mu_j + \beta_i
\]

- Physics distribution $f$
- Background from outside the acceptance $\beta$
Smearing-unfolding in SIDIS

Relation between true and measured quantities

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

- Has the shape of a matrix equation

\[ \nu_i = \sum_{j=1}^{M} S_{ij} \mu_j + \beta_i \]
Smearing-unfolding in SIDIS

Relation between true and measured quantities

\[ \nu_i = \mu_{\text{tot}} \sum_{j=1}^{M} \frac{\int_{\text{bin}_i} dX \int_{\text{bin}_j} dY \int d\bar{Y} f(Y) \rho(\bar{Y}|Y) A(\bar{Y}) M(\bar{Y}|X)}{\int_{\text{bin}_j} dY f(Y)} \mu_j + \beta_i \]

- Has the shape of a matrix equation
- Smearing matrix \( S \) is calculated using two MC simulations
- Solve for true data by simple matrix inversion

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

Relation between true and measured quantities

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

- **Smearing matrix** \( S \) is calculated using **two MC** simulations
- Completely **model-independent if either**:
  - Acceptance function \( A \) is **flat** within each bin
  - Distribution \( f \) is **flat** within each bin
- If this is **not the case**, a **reasonable** (better than 10% level) **model for** \( f \) is required
- This analysis: systematic uncertainty from the \( 1\sigma \) contour in MC parameter space

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Section 2

Fragmentation in collinear DIS
Factorizing the SIDIS cross section

- Separate
  - The proton structure
  - The interaction with the quasi free quarks
  - The hadronization process enforced by confinement

- These results enable:
  - Deeper understanding of the hadronization process
  - Better constrain the FFs
  - Explore the limits of a simple factorized approach

LO SIDIS cross section

$$ \frac{d^3\sigma^h}{dxdQ^2dz}(Q^2, x, z) \propto \sum_q e_q^2 f_1^q(Q^2, x) D_q^h(Q^2, z) $$
Multiplicities: Projected vs $z$

- **$u$-quark dominance**
- Deuteron has less $u$-quarks
- $K^-$ pure sea object
- **Systematic uncertainties** between particles/targets correlated
- **Asymmetries** and difference ratios can increase precision even further

![Graph showing multiplicities projected vs $z$](attachment:image.png)

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One dimensional comparison with LO predictions

- Good agreement CTEQ6+DSS for $\pi^+$ and $K^+$ up to medium $z$
- CTEQ6+Kretzer performs well for pions
- Larger deviations for $\pi^-$ and $K^-$
- Room for improvement at high $z$, and in the disfavored sector
Proton-deuteron multiplicity asymmetry

**Definition:**

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

- Reflects different valence quark content
- **Improved precision by cancellations** in the systematic uncertainty
CTEQ6L+DSS perform very well up to medium $z$

Larger discrepancies at high $z$
$K/\pi$ and strangeness suppression

- **Very good agreement** with the LO prediction
- $u$ dominance: $K^+/\pi^+$ at high $z$ shows the extra cost of producing an $s\bar{s}$ compared to a $d\bar{d}$.

Strangeness suppression larger than current parametrizations suggest

- Also observed during the HERMES MC tuning

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LO parametrizations predict the $\pi/K$ ratio very well up to medium $z$.

At high $z$, LO calculations overshoot the measurement for the entire valence region.
Section 3

Transverse momentum dependence of the multiplicities
Transverse momentum dependence

- The multidimensional results provide leverage in the quest to unfold intrinsic quark $p_T$ and fragmentation $k_T$ from the transverse hadron momentum $P_{h\perp}$
  - Leverage the simultaneous binning in $P_{h\perp}$, $z$ and $x$ (or $Q^2$)
  - Access the shape of the unpolarized TMD
  - Provide a handle on flavor separation
  - Constrain TMD models and calculations

$P_{h\perp}$ dependence in the LO TMD formalism

\[
\frac{d^5 \sigma^h}{dx dQ^2 dz d^2 \vec{P}_{h\perp}} \propto \sum_q e_q^2 \int d^2 \vec{p}_T d^2 \vec{k}_T \delta^2(\vec{P}_{h\perp} - \vec{k}_T - z \vec{p}_T) f_1^q(x, Q^2, p_T) D_h^q(z, Q^2, k_T)
\]
The shape of $P_{h\perp}$ in $z$ slices

- Superficially consistent with the **Gaussian ansatz**
- **Average and width** function of kinematics and hadron type.
\( \langle P_{h\perp} \rangle \) as a function of \( z \)

- Rising function of \( z \)
- \( \langle P_{h\perp} \rangle \) for \( K \) higher than \( \pi \) at larger \( z \)
  - Point-to-point significance of \( 2\sigma \)
  - **Strangeness suppression**: at high \( z \), \( K \) sample contains (relatively) more sea events than \( \pi \)
  - Could hint at higher intrinsic \( \langle p_T \rangle \) for the sea?
\[ \langle P_{h\perp} \rangle \text{ in 2 dimensions} \]

- Slightly falling function of \( x \)
  - Also hints at **higher intrinsic** \( \langle p_T \rangle \) for the sea
Hadron charge asymmetry

- Numerator contains proportionally more valance than the denominator
- Especially at higher $z$
- Ratio encodes information about the shape of the intrinsic $p_T$ distribution

Numerator contains proportionally more valance than the denominator, especially at higher $z$. The ratio encodes information about the shape of the intrinsic $p_T$ distribution.
Applicability of simple LO, leading-twist factorization for high-precision data at intermediate energies
Limits of the Factorization Theorem

- Factorization in $x$ and $z$ not exact, both from theoretical and experimental point-of-view
  
  ▶ **Theoretical:** Reinteraction of final state quarks with the target remnant (higher-twist effects); mass effects
  
  ▶ **Experimental:** Contamination of the current jet with the target jet

- Effect minimized by choosing a lower rapidity limit (described by the Berger Criterion) $\rightarrow$ lower $z$ limit for SIDIS experiments (here: $> 0.2$)

- Need factorization for **universality**!
Probing the limits in a LO, leading twist framework

**LO access (assuming isospin symmetry)**

\[
R^\pi(z) \equiv 2 \frac{\int_{Acc.} dx dQ^2 (\sigma_d^{\pi^+} - \sigma_d^{\pi^-})}{\int_{Acc.} dx dQ^2 (\sigma_p^{\pi^+} - \sigma_p^{\pi^-})} - 1 \approx \frac{\int_{Acc.} dx dQ^2 (u_v - 4d_v)}{\int_{Acc.} dx dQ^2 (d_v - 4u_v)}
\]

\[
\rightarrow \frac{\int_{Acc.} dx dQ^2 d_v}{\int_{Acc.} dx dQ^2 u_v} \approx \frac{4R^\pi + 1}{4 + R^\pi}
\]

- Pushes the experimental precision to a limit
  - A proper treatment of the **correlated systematics** is crucial

- Very **sensitive to theoretical assumptions**
  - Applicability of the LO, leading twist framework
  - Additional assumptions (e.g., isospin symmetry)

- Consequences of interest for future high-precision measurements
Pushing the envelope

\[ R^\pi = 2 \frac{\sigma^\pi_d}{\sigma^\pi_p} - 1 \]

- **Lowest point** > 3σ from the prediction
  - Target remnant or theory?
  - Small isospin violation of the FF (as in DSS) strongly lessens the discrepancy
  - →Probably mix

- **Very good agreement for mid-to-high z**

- Results generally systematics dominated

- CTEQ curve below 0.5 due to the integral over the HERMES acceptance (cfr page 4)
Pushing the envelope

- Discrepancy is a function of $z$
- Lessons
  - More precise knowledge of FF symmetries required
  - Possible target remnant influence should be carefully considered when analyzing data near the low-$z$ limit
  - The framework holds surprisingly well mid-to-high $z$ at intermediate energies

\[ R^\pi = 2 \frac{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}} - 1 \]
Getting the data

arXiv:1212.5407v1 [hep-ex]

http://www-hermes.desy.de/multiplicities
Getting the data: the multiplicity website

- http://www-hermes.desy.de/multiplicities
- Provides all datafiles and available figures.
  - Multiplicities (differential and in various projections)
  - Both with and without the correction for exclusive vector mesons
  - Asymmetries and ratios (Proper handling of the correlated systematics)
Browse the data files

View and download available figures

Use filters for intuitive file selection

Download the final results
Understand what version of the data you have.

Get an overview of what is available.

Detailed description of the different binnings.

File name structure

- **TARGET**: Either proton or deuteron. Blank in case of the target asymmetries.
- **BINNING**: Can be z-3D, zpt-3D, zq2-3D, zx-3D or zpt-3D. The binning codes are defined below in
- **PROJECTION**: Blank in case of the 3D data without projection, or VARIABLE-proj for projected data. For exa
  projection versus z, or zx-proj for a 2D projection versus x in z slices.
- **OPTION**: Results with the vector meson contribution subtracted are labelled *vesub*, results without this correc
  * The covariance matrices for the multiplicities are labelled *covmat_mults*. 
  * Target asymmetry files are labelled *asym PARTICLE* (for example: asymm piplus). 
  * The covariance matrices for the target asymmetries are labelled *covmat_asym*. 

Binning

The smearing unfolding method to correct for QED radiative effects, limited geometric ac
minimum granularity in all variables, allowing us to pursue five different specialized binning
be accommodated.
1. High resolution in z.
2. High resolution in P_{h,\perp} with z slices.
3. High resolution in x with z and P_{h,\perp} slices.
4. High resolution C with x and S slices.
Summary

- Unique set of 3D high-precision SIDIS multiplicities for $\pi^{\pm}$ and $K^{\pm}$ on $p$ and $d$ are presented

- Enabling:
  - Evaluation of the quality of FF (and PDF) parametrizations
  - Input for the next generation of parametrizations
  - Access to the transverse distributions
  - Tests of the applicability of the usual LO, leading-twist model assumptions

- For proper interpretation at this level of precision:
  - Crucial to consider the fully differential case
  - If possible, study the possible correlations in the systematic uncertainties when calculating derived quantities

- Get the data at http://www-hermes.desy.de/multiplicities

http://www-hermes.desy.de/multiplicities

https://www.npl.illinois.edu

http://nsf.gov
BACKUP: Effect of the correction for exclusive VM

![Graph showing the effect of correction for exclusive VM on multiplicity for different particles and z values.]

- **Multiplicity**
  - π⁺ and π⁻ sections display the corrected and uncorrected data points.
  - K⁺ and K⁻ sections also show the corrected and uncorrected data.

- **Ratio**
  - π⁺ and π⁻ sections illustrate the ratio of corrected to uncorrected data.
  - K⁺ and K⁻ sections similarly depict the ratio of corrected to uncorrected data.
EMC FFs

HERMES multiplicities
1996-97 data