Charged-hadron lepto-production off unpolarized protons and deuterons at HERMES

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Why study SIDIS from unpolarized targets?

- Semi-inclusive DIS provides information on both hadron structure and formation

\[
\begin{align*}
\gamma^* &\rightarrow q \rightarrow (E, p) \\
\rightarrow &\rightarrow (E', p') \\
\rightarrow &\rightarrow h, K, \pi
\end{align*}
\]
Why study SIDIS from unpolarized targets?

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- $f_1$ is one of the leading-twist PDFs
- (probably) easiest one to study facets of hadron structure, even in 3D
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- In semi-inclusive DIS, $f_1$ couples to $D_1$ fragmentation function.
- Both are ingredients of basically every (spin) asymmetry.
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- Both are ingredients of basically every (spin) asymmetry.
- May probe quark flavors less accessible in inclusive DIS.
- Complimentary info on FFs to $e^+e^-$ (e.g., charge separation).
Polarization-averaged cross section

\[
\frac{d^5 \sigma}{dx dy dz d\phi_h dP_{h\perp}^2} \propto \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \epsilon F_{UU,L} \right\} + \sqrt{2\epsilon(1 - \epsilon)} F_{UU}^{\cos \phi_h} \cos \phi_h + \epsilon F_{UU}^{\cos 2\phi_h} \cos 2\phi_h \]

where \( tions \) [28] we define the azimuthal angle \( \phi \) for semi-inclusive DIS at small transverse momentum and given in \([27]\). The ratio for forward [10, 11], updating past results for one-…

\[
\gamma = \frac{2Mx}{Q} \]

\[
\epsilon = \frac{1 - y - \frac{1}{4} \gamma^2 y^2}{1 - y + \frac{1}{2} y^2 + \frac{1}{4} \gamma^2 y^2} \]

[see, e.g., Bacchetta et al., JHEP 0702 (2007) 093]
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Some experimental challenges ...

- pureness of targets
- large kinematic acceptance
- excellent particle identification
- no spin asymmetry \(\rightarrow\) worry more about systematics, e.g.,
  - efficiencies
  - absolute luminosity
  - acceptance
  - smearing
The HERMES Experiment

27.5 GeV $e^+/e^-$ beam of HERA
The HERMES Experiment

- pure gas targets
- internal to lepton ring
- unpolarized ($^1$H ... Xe)
- long. polarized: $^1$H, $^2$H, $^3$He
- transversely polarized: $^1$H
Particle ID detectors allow for
- lepton/hadron separation
- RICH: pion/kaon/proton
discrimination 2GeV<p<15GeV
accessing the various terms

\[
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hadron multiplicity:
normalize to inclusive DIS cross section

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\[ \frac{d^4 M^h(x, y, z, P_{h\perp}^2)}{dx dy dz dP_{h\perp}^2} \propto \left( 1 + \frac{\gamma^2}{2x} \right) \frac{F_{UU,T} + \epsilon F_{UU,L}}{F_T + \epsilon F_L} \]

\[ \approx \frac{\sum_q e_q^2 f_1^q(x, p_T^2) \otimes D_1^q(h, K_{T}^2)}{\sum_q e_q^2 f_1^q(x)} \]
accessing the various terms

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moments:
normalize to azimuth-independent cross-section
hadron multiplicity: normalize to inclusive DIS cross section

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2\langle \cos 2\phi \rangle_{UU} \equiv 2 \int d\phi_h \cos 2\phi \frac{d\sigma}{d\phi_h d\sigma} = \frac{\epsilon F_{UU}^{\cos 2\phi}}{F_{UU,T} + \epsilon F_{UU,L}}
\]

moments: normalize to azimuth-independent cross-section

\[
\approx \sum_q \epsilon_q^2 f_q^q(x, p_T^2) \otimes D_{q\rightarrow h}^q(z, K_T^2)
\]

\[
= \sum_q \epsilon_q^2 f_q^q(x)
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accessing the various terms
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moments:
normalize to azimuth-independent cross-section

\[
\approx \frac{\sum_q e_q^2 h_{1,q}^+ (x, p_T^2) \otimes_{\text{BM}} H_{1,q}^{\to h} (z, K_T^2)}{\sum_q e_q^2 f_1^q (x, p_T^2) \otimes D_1^{q \to h} (z, K_T^2)}
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\]

this talk
Figure 6.7: Difference between two $\phi$'s which evaluated with and without the detector smearing effects. Note this result is independent of the QED radiative effect.

Figure 6.8: Schematic illustration of event migration.

[courtesy of H. Tanaka]
... event migration ...

- migration correlates yields in different bins
- can’t be corrected properly in bin-by-bin approach
... event migration -> unfolding

\[ \mathcal{Y}^{\exp}(\Omega_i) \propto \sum_{j=1}^{N} S_{ij} \int d\Omega \, d\sigma(\Omega) + B(\Omega_i) \]
... event migration -> unfolding

\[ \mathcal{Y}_{\text{exp}}(\Omega_i) \propto \sum_{j=1}^{N} S_{ij} \int_{j} d\Omega \, d\sigma(\Omega) + B(\Omega_i) \]

- experimental yield in \( i^{\text{th}} \) bin depends on all Born bins \( j \) ...
... event migration \(\rightarrow\) unfolding

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- ... and on BG entering kinematic range from outside region
... event migration $\rightarrow$ unfolding

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- smearing matrix \(S_{ij}\) embeds information on migration

- determined from Monte Carlo - independent of physics model in limit of infinitesimally small bins and/or flat acceptance/cross-section in every bin
- in real life: dependence on BG and physics model due to finite bin sizes
... event migration -> unfolding

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- in real life: dependence on BG and physics model due to finite bin sizes
- inversion of relation gives Born cross section from measured yields
Neglecting to unfold in z changes x dependence dramatically. 1D unfolding clearly insufficient.
The Born-level multiplicities, i.e., the multiplicities with kinematic and geometric acceptance effects, and smearing which take into account the charge-symmetric background, are extracted. A function of desired, and from measured multiplicities binned in three dimensions: radiative effects and detector resolution, are extracted no limitations in geometric acceptance and corrected for due to radiative effects. After all corrections and unfolding due to the strong correlation of marches to yield the semi-inclusive cross section of the hadron yield h when they are to be given as a dependence of the unpolarized semi-inclusive h; ~ DIS processes, like the ... pairs, can produce a signature indistinguishable from that of DIS events. This background is most significant at low... produced off a...
Influence from exclusive VM

for instance: $ep \rightarrow ep \rho^0 \rightarrow ep \pi^+ \pi^-$

partially large contribution from exclusive VM production, in particular at high $z$ -> (optionally) subtracted from both numerator and denominator
Influence from exclusive VM

for instance: \( ep \rightarrow ep \rho^0 \rightarrow ep \pi^+ \pi^- \)

multiplicities before and after subtraction of contributions from exclusively produced VMs

[Airapetian et al., PRD 87 (2013) 074029]
Multiplicities: $z$ projection

Most exhaustive data set on $(P_{h\perp}$-integrated) electro-production of charged identified mesons on nucleons

[Airapetian et al., PRD 87 (2013) 074029]

Slight differences between proton and deuteron targets: reflection of valence structure of target and produced meson, e.g.

$u/d \to \pi^+ / \pi^-$

$p = |uud\rangle$ and $n = |u\bar{d}\rangle$
Multiplicities: z projection

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  - \(p = |uud\rangle\) and \(n = |udd\rangle\)

- \(K^-\) pure "sea object" hence suppressed and hardly any difference for proton and deuteron
Multiplicities: $z$ projection

proton target: (deuteron similar)

positive hadrons in general better described than negative ones

➡ better understanding of favored fragmentation?

➡ best described by HERMES Jetset tune and DSS FF set

kaons best described by DSS FF set, though all with problems in describing $K^-$

[Airapetian et al., PRD 87 (2013) 074029]
Multiplicity ratio: \( z \) projection

[http://www-hermes.desy.de/multiplicities]
Multiplicity ratio: z projection

at large z mainly favored fragmentation:

- dominated by up quarks
- kaon requires strangeness production
- strangeness suppression of about 0.3 (apparently stronger than modeled in DSS FF set)
- in rough agreement with typical ansatz of 1/3

[http://www-hermes.desy.de/multiplicities]
Multiplicities: x-z projection

\[ \sum_q \frac{e^2 q f^q_1(x)}{\sum_{q'} e^2 q' f^q_{1'}(x)} D^{q \rightarrow \pi}_1 (z) \]
Multiplicities: $x$-$z$ projection

$\sum_{q} \frac{e_{q}^{2} f_{q}^{1}(x)}{\sum_{q'} e_{q'}^{2} f_{q'}^{1}(x)} D_{1}^{q \rightarrow \pi}(z)$

$\Rightarrow$ weaker dependence on $x$

[Airapetian et al., PRD 87 (2013) 074029]
Multiplicities: x-z projection

[Airapetian et al., PRD 87 (2013) 074029]

\[ \sum_q \frac{e^2 f^q_1(x)}{\sum_{q'} e^2 f^q'_1(x)} D^{q \rightarrow \pi}_1(z) \]

- weaker dependence on x
- remaining dependence from \( f_1 - D_1 \) convolution over quark flavors
Strange-quark distribution

- use isoscalar probe and target to extract (here at LO!) strange-quark distribution
- only need $K^+K^-$ multiplicities on deuteron

\[
S(x) \int D^K_S(z) \, dz \simeq Q(x) \left[ 5 \frac{d^2N^K(x)}{d^2N_{DIS}(x)} - \int D^K_Q(z) \, dz \right]
\]

[Airapetian et al., PRD 89 (2014) 097101]

\[
S(x) = s(x) + \bar{s}(x)
\]
\[
Q(x) = u(x) + \bar{u}(x) + d(x) + \bar{d}(x)
\]
\[
D^K_S = D^s_1 \rightarrow K^+ + D^s_1 \rightarrow K^+ + D^s_1 \rightarrow K^- + D^s_1 \rightarrow K^-
\]
\[
D^K_Q = 4D^u_1 \rightarrow K^+ + 4D^u_1 \rightarrow K^+ + D^d_1 \rightarrow K^+ + D^{\bar{d}}_1 \rightarrow K^+ + \ldots
\]
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- assume vanishing strangeness at high $x$ to extract non-strange fragmentation

\[ S(x) = s(x) + \bar{s}(x) \]
\[ Q(x) = u(x) + \bar{u}(x) + d(x) + \bar{d}(x) \]
\[ D_S^K = D_1^{s \to K^+} + D_1^{\bar{s} \to K^+} + D_1^{s \to K^-} + D_1^{\bar{s} \to K^-} \]
\[ D_Q^K = 4D_1^{u \to K^+} + 4D_1^{\bar{u} \to K^+} + D_1^{d \to K^+} + D_1^{\bar{d} \to K^+} + \ldots \]

[Airapetian et al., PRD 89 (2014) 097101]
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[Airapetian et al., PRD 89 (2014) 097101]

\[ \langle Q^2 \rangle = 2.5 \text{ GeV}^2 \]

\[ \text{Hermes with } \int D_S^K(z,Q^2) \, dz = 1.27 \]

\[ \text{Fit} \quad \text{CTEQ6L} \quad \text{x}(u(x)+d(x)) \quad \text{CTEQ6.5S-0} \quad \text{NNPDF2.3} \]

Strange-quark distribution softer than (maybe) expected
Transverse momentum dependence

- multi-dimensional analysis allows going beyond collinear factorization
- flavor information on transverse momenta via target variation and hadron ID

[Airapetian et al., PRD 87 (2013) 074029]
Transverse momentum dependence

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[Airapetian et al., PRD 87 (2013) 074029]
caveats
the HERMES multiplicity database
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- all the data available at [http://hermes.desy.de/multiplicities](http://hermes.desy.de/multiplicities)
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- when using the data base, please read carefully the “Important information”, in particular,
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  - multiplicities are integrated quantities, where both numerator and denominator are integrated separately over the full space within each kinematic bin
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- important consequences
  - comparison to calculations best done performing the same integration over phase space
  - average multiplicity is not multiplicity at average kinematics
\[ \langle M(Q^2) \rangle_{Q^2} \neq M(\langle Q^2 \rangle) \]
MULTIPLECTIES OF CHARGED PIONS AND KAONS

Fig. 8 (color online). Multiplicities of pions (left panels) and kaons (right panels) for the proton and the deuteron as a function of $0.4 < z < 0.6$.

$\langle M(Q^2) \rangle_{Q^2 \neq 0} \neq \langle M(Q^2) \rangle_{Q^2 = 0}$
\( \langle M(Q^2) \rangle_{Q^2} \neq M(\langle Q^2 \rangle) \)
even though having similar average kinematics, multiplicities in the two projections are different
\[ \langle M(Q^2) \rangle_{Q^2} \neq M(\langle Q^2 \rangle) \]
\[ \langle \mathcal{M}(Q^2) \rangle_{Q^2} \neq \mathcal{M}(\langle Q^2 \rangle) \]

- the average along the valley will be smaller than the average along the gradient
\[ \langle M(Q^2) \rangle_{Q^2} \neq M(\langle Q^2 \rangle) \]

- the average along the valley will be smaller than the average along the gradient
- still the **average kinematics** can be the same
integrating vs. using average kinematics

- (by now old)
  DSS07 FF fit to z-Q^2 projection

- z-x “prediction” reasonable well when using integration over phase-space limits (red lines)

[R. Sassot, private communication]
integrating vs. using average kinematics

(by now old)
DSS07 FF fit to z-Q\(^2\) projection

z-x “prediction” reasonable well when using integration over phase-space limits (red lines)

significant changes when using average kinematics

[R. Sassot, private communication]
... anticipating the COMPASS talk

\[
M^{\pi^\pm} = \int \langle M^{\pi^\pm}(x, y, z) \rangle_y \, dz \quad \text{(COMPASS)}
\]
COMPASS vs. HERMES

\[ M_{\pi^\pm} = \int \langle M_{\pi^\pm} (x, y, z) \rangle_y dz \]

• not clear that indeed we compare the same here, needs more thinking

• averaging over different regions in y gives different answers [see, e.g., talk by R. Sassot at QCD-N'16]
not all can (yet) be extracted from data

e.g., observables that rely on perfect cancelations of large quantities in order to access inherently small quantities

it was suggested to look at a different combination of multiplicities than in the isoscalar extraction of $s(x)$ to test the latter

involves difference of multiplicities, which emphasizes small corrections that might be needed to perfectly describe multiplicities:

$$\frac{dN^{K'}}{dN^{\text{DIS}}} = \frac{5Q+2S}{Q} \frac{dN^K}{dN^{\text{DIS}}} - \frac{5Q+2S}{u_v + d_v} \frac{dN^{K_{\text{diff}}}}{dN^{\text{DIS}}}$$

$$\text{LO}_{s=\tilde{s}} \equiv 8D^K_{\bar{u}} + 2D^K_d + \frac{S}{Q} D^K_S$$
not all can (yet) be extracted from data

- large spread both from (limited) knowledge of PDFs (left) and FFs (right)
- no high-\(x\) limit to be used to constrain disfavored kaon FFs

\[
\frac{dN^{K'}}{dN^{\text{DIS}}} \equiv \frac{5Q + 2S}{Q} \frac{dN^K}{dN^{\text{DIS}}} - \frac{5Q + 2S}{u_v + d_v} \frac{dN^{K\text{diff}}}{dN^{\text{DIS}}}
\]

\[
\text{LO, } s = \bar{s} \equiv 8D_{u}^{K^+} + 2D_{d}^{K^+} + \frac{S}{Q} D_{S}^{K^+}
\]
not all can (yet) be extracted from data

similar problem when look at just the (“scaled”) difference multiplicity

\[
\frac{dN^{K^{\text{diff}}}}{dN^{\text{DIS}}} \equiv \frac{d(N^{K^+} - N^{K^-})}{dN^{\text{DIS}}}
\]

\[
\text{LO, } s=\bar{s} \left( u_v + d_v \right) \left( 4D_u^{K^+} - 4D_{\bar{u}}^{K^+} + D_d^{K^+} - D_{\bar{d}}^{K^+} \right)
\]

\[
\frac{5Q + 2S}{4(u_v + d_v)}
\]
Conclusions

- HERMES managed step from spin-asymmetry experiment to unpolarized-target experiment
- Most comprehensive data set on charged-separated identified meson lepto-production on both proton and deuterons
- Multi-dimensional analysis and various targets allow study of correlations and flavor dependences
- Analysis of averages requires careful consideration of kinematic ranges averaged over
- Transverse-momentum dependence -> TMD Session VII
backup slides
COMPASS kinematics

Data selection

- $Q^2 > 1 \text{ (GeV/c)^2}$
- $W > 5 \text{ GeV/c}$
- $0.1 < y < 0.9$
- $0.20 < x < 0.7$
- $0.125 < z < 0.85$

3-dim. binning in $x$, $y$, $z$ used

$\theta_{\mu} = 70 \text{ mrad}$
COMPASS multi-D binning

\[ \frac{dM^{\pi^+}}{dz} \]

Curves: COMPASS LO fit

- \( 0.50 < y < 0.70 \)
- \( 0.30 < y < 0.50 \)
- \( 0.20 < y < 0.30 \)
- \( 0.15 < y < 0.20 \)
- \( 0.10 < y < 0.15 \)