Semi-inclusive DIS off unpolarized targets

--the Hermes perspective--

Gunar.Schnell @ desy.de
Why study SIDIS from unpolarized targets?

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

\[ (E, p) \rightarrow (E', p') \]

\[
\begin{align*}
\gamma^* &\rightarrow q \\
\text{u} &\rightarrow h \\
\text{d} &\rightarrow \pi \\
\end{align*}
\]

parton distribution
fragmentation functions
Why study SIDIS from unpolarized targets?

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  - Both are ingredients of basically every (spin) asymmetry
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- Both are ingredients of basically every (spin) asymmetry.
- Complimentary info on FFs to $e^+e^-$ (e.g., charge separation).
- Nuclear targets provide laboratory for hadronization studies.
Polarization-averaged cross section

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

[see, e.g., Bacchetta et al., JHEP 0702 (2007) 093]
Polarization-averaged cross section

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\]

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

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

- pure targets
- large acceptance
- excellent particle identification
- no spin asymmetry → few systematics cancel
- 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 \ldots \(^{129}\)Xe)
- long. polarized: \(^1\)H, \(^2\)H, \(^3\)He
- transversely polarized: \(^1\)H
two (mirror-symmetric) halves
-> no homogenous azimuthal coverage

Particle ID detectors allow for
- lepton/hadron separation
- RICH: pion/kaon/proton discrimination 2GeV<p<15GeV
\[
\frac{d^5 \sigma}{dxdydzd\phi_h dP_{h\perp}^2} \propto \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1-\epsilon)} F_{UU}^{\cos \phi_h} \cos \phi_h + \epsilon F_{UU}^{\cos 2\phi_h} \cos 2\phi_h \right\}
\]
hadron multiplicity:

normalize to inclusive DIS cross section

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\frac{d^2 \sigma_{\text{incl.DIS}}}{dx dy} \propto F_T + \epsilon F_L
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+ \sqrt{2\epsilon(1-\epsilon)} F_{UU}^{\cos \phi_h} \cos \phi_h + \epsilon F_{UU}^{\cos 2\phi_h} \cos 2\phi_h
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... and solutions ...

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+ \sqrt{2\epsilon(1 - \epsilon)} F_{UU}^{\text{cos } \phi_h} \cos \phi_h + \epsilon F_{UU}^{\text{cos } 2\phi_h} \cos 2\phi_h

moments: normalize to azimuth-independent cross-section

\[
\approx \frac{\sum_q e_q^2 f_q^1(x) \otimes D_q^{h\rightarrow h}(z, K_T^2)}{\sum_q e_q^2 f_q^1(x)}
\]
... and solutions ...

\[
\begin{align*}
\text{hadron multiplicity:} & \quad \text{normalize to inclusive DIS cross section} \\
\frac{d^2\sigma_{\text{incl.DIS}}}{dxdy} & \propto F_T + \epsilon F_L \\
\frac{d^5\sigma}{dxdydzd\phi_h dP_{h\perp}^2} & \propto \left(1 + \frac{\gamma^2}{2x}\right) \{ F_{UU,T} + \epsilon F_{UU,L} \} \\
& \quad + \sqrt{2\epsilon(1-\epsilon)} F_{UU}^{\cos \phi_h} \cos \phi_h + \epsilon F_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\
& \quad + \frac{\epsilon F_{UU}^{\cos 2\phi}}{F_{UU,T} + \epsilon F_{UU,L}} \\
\end{align*}
\]

\[2\langle \cos 2\phi \rangle_{UU} \equiv 2 \int d\phi_h \cos 2\phi d\sigma \quad \frac{\epsilon F_{UU}^{\cos 2\phi}}{F_{UU,T} + \epsilon F_{UU,L}}\]
... and solutions ...

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

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

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

\[
\approx \epsilon \sum_q e_q^2 h_1^{\perp,q}(x, p_T^2) \otimes_{BM} H_1^{\perp,q \rightarrow h}(z, K_T^2) \frac{\sum_q e_q^2 f_1^q(x, p_T^2) \otimes D_1^{q \rightarrow h}(z, K_T^2)}{\sum_q e_q^2 f_1^q(x, p_T^2) \otimes D_1^{q \rightarrow h}(z, K_T^2)}
\]
hadron multiplicity:
normalize to inclusive DIS cross section

\[ \frac{d^2\sigma^{\text{incl.DIS}}}{dx dy} \propto F_T + \epsilon F_L \]

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

\[ \approx \sum_q e_q^2 f_q^2(x, p_T^2) \otimes D_{1,h}^{q \to h}(z, K_T^2) \]

\[ \sum_q e_q^2 f_q^1(x) \]

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

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\[ \sum_q e_q^2 f_q^1(x, p_T^2) \otimes D_{1,h}^{q \to h}(z, K_T^2) \]

moments:
normalize to azimuth-independent cross-section
... and solutions ...

hadron multiplicity: normalize to inclusive DIS cross section

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d^2 \sigma_{\text{incl.DIS}} \frac{d^4 M^h(x, y, z, P_{h\perp}^2)}{dxdydzdP_{h\perp}^2} \propto (1 + \frac{\gamma^2}{2x}) \frac{F_{UU,T} + \epsilon F_{UU,L}}{F_T + \epsilon F_L}
\]

normalize to inclusive DIS cross section

\[
d^5 \sigma \frac{d^5 \sigma}{dxdydzd\phi_h dP_{h\perp}^2} \propto (1 + \frac{\gamma^2}{2x}) \{ F_{UU,U} + \epsilon \} F_{UU,L}
\]

moments: normalize to azimuth-independent cross-section

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\]
... geometric acceptance ...

extract acceptance from Monte Carlo simulation?

$$\epsilon(\phi, \Omega) = \frac{\epsilon(\phi, \Omega) \sigma_{UU}(\phi, \Omega)}{\sigma_{UU}(\phi, \Omega)}$$

$$\Omega = x, y, z, \ldots$$

simulated acceptance

simulated cross section
... geometric acceptance ...

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\[
\Omega = x, y, z, \ldots
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\[
\int d\Omega \sigma_{UU}(\phi, \Omega) \epsilon(\phi, \Omega) \neq \frac{\int d\Omega \sigma_{UU}(\phi, \Omega) \epsilon(\phi, \Omega)}{\int d\Omega \sigma_{UU}(\phi, \Omega)}
\]

"Aus Differenzen und Summen kürzen nur die Dummen."
... geometric acceptance ...

extract acceptance from Monte Carlo simulation?

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$$
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$$

$$
\neq \int d\Omega \epsilon(\phi, \Omega) \equiv \epsilon(\phi)
$$

Cross-section model does NOT CANCEL in general when integrating numerator and denominator over (large) ranges in kinematic variables!

“Aus Differenzen und Summen kürzen nur die Dummen.”

G. Schnell, Universiteit Gent, Jefferson Lab, January 11th, 2008
Figure 6.7: Difference between two φS's which evaluated with and without the detector smearing effects. Note this result is independent of the QED radiative effects.

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

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

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

- experimental yield in \( i^{\text{th}} \) bin depends on all Born bins \( j \) ...
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- ... and on BG entering kinematic range from outside region
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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
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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
Multi-D vs. 1D unfolding at work

Neglecting to unfold in $z$ changes $x$ dependence dramatically

1D unfolding clearly insufficient

[S.J. Joosten, PhD thesis UIUC (2013)]

Figure 4.5: The $x$-dependence of the $K$ multiplicities differs drastically between a proper three-dimensional analysis (red), compared to a simple one-dimensional extraction (blue). This illustrates the large systematic uncertainty introduced by not considering the proper kinematic dependencies during the analysis, in particular the acceptance correction. The points in this figure were extracted from the 2000 proton sample.
Kinematic range at HERMES

- $0.023 < x < 0.6$
- $0.1 < y < 0.85$
- $0.2 < z < 0.8$
- $W^2 > 10 \text{ GeV}^2$
- $Q^2 > 1 \text{ GeV}^2$
Results I:
charged pions and kaons from proton and deuteron targets

http://www-hermes.desy.de/multiplicities
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 \( z \)

[Airapetian et al., PRD 87 (2013) 074029]
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. $u/d \rightarrow \pi^+ / \pi^-$
  - $p = |uud\rangle$ and $n = |udd\rangle$
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$u/d \rightarrow \pi^+ / \pi^-$

$p = |uud\rangle$ 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 $1/3$
Multiplicities: \( x \)-\( z \) projection

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

\[
\sum_q \frac{e_q^2 f_1^q(x)}{\sum_{q'} e_{q'}^2 f_1^{q'}(x)} D_1^{q \rightarrow \pi}(z)
\]
Multiplicities: x-z projection

- weaker dependence on x
- remaining dependence from $f_1 - D_1$ convolution over quark flavors

$$
\sum_q \sum_{q'} e_q^2 f_{q'}^q(x) D_{q \to \pi}^q(z)
$$

- parameterizations generally fail to reproduce shape

[Airapetian et al., PRD 87 (2013) 074029]
Strange-quark distribution

- use isoscalar probe and target to extract strange-quark distribution
- only need $K^+K^-$ multiplicities on deuteron

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

\[
S(x) = s(x) + \bar{s}(x)
\]

\[
Q(x) = u(x) + \bar{u}(x) + d(x) + \bar{d}(x)
\]

\[
D_S^K = D_{s \rightarrow K^+} + D_{s \rightarrow K^-} + D_{s \rightarrow K^+} + D_{s \rightarrow K^-}
\]

\[
D_Q^K = 4D_{u \rightarrow K^+} + 4D_{u \rightarrow K^+} + D_{d \rightarrow K^+} + D_{d \rightarrow K^+} + \ldots
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- assume vanishing strangeness at high $x$ to extract non-strange fragmentation

$S(x) = s(x) + \bar{s}(x)$
$Q(x) = u(x) + \bar{u}(x) + d(x) + \bar{d}(x)$
$D_S^K = D_1^{s \rightarrow K^+} + D_1^{s \rightarrow K^+} + D_1^{s \rightarrow K^-} + D_1^{s \rightarrow K^-}$
$D_Q^K = 4D_1^{u \rightarrow K^+} + 4D_1^{u \rightarrow K^+} + D_1^{d \rightarrow K^+} + D_1^{d \rightarrow K^+} + \ldots$
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- use isoscalar probe and target to extract strange-quark distribution
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S(x) \int D^K_S(z) \, dz \simeq Q(x) \left[ 5 \frac{d^2 N^K(x)}{d^2 N^{DIS}(x)} - \int D^K_Q(z) \, dz \right]
\]

HERMES Preliminary

\[
f(x) = x^{-0.833} e^{-0.0337(1-x)}
\]

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

Strange-quark distribution

softer than (maybe) expected

HERMES Preliminary with $\int D_S(z,Q^2)dz = 1.27$

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

- multi-dimensional analysis allows going beyond collinear factorization
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[Airapetian et al., PRD 87 (2013) 074029]
Results II:

multiplicity ratios - nuclear attenuation

A. Airapetian et al., EPJ A 47 (2011) 113
http://inspirebeta.net/record/918944/
Nuclei: a hadronization laboratory

- Partons in nuclear medium:
  - PDFs modified (e.g., EMC effect)
  - Gluon radiation and rescattering effects

- (Pre)hadron in nuclear medium:
  - Rescattering
  - Absorption
Nuclei: a hadronization laboratory

- **parton**
- **pre-hadron**
- **colorless**
- **quantum numbers of final hadron**
- **final state hadron**

**differences predicted for partonic and (pre-)hadronic interactions**

Formation length $l_c \sim 1-10 \text{ fm}$ (size of nucleon)
Nuclei: a hadronization laboratory

- parton
- pre-hadron
- colorless
- quantum numbers of final hadron
- final state hadron

- differences predicted for partonic and (pre-)hadronic interactions
- depends on formation lengths (1-10 fm) = O(nucleus size)
Multiplicity ratios

$$R^h_A(\nu, Q^2, z, p_t^2) = \frac{\left( \frac{N^h(\nu, Q^2, z, p_t^2)}{N^e(\nu, Q^2)} \right)_A}{\left( \frac{N^h(\nu, Q^2, z, p_t)}{N^e(\nu, Q^2)} \right)_D}$$

- nuclear targets: (He,) Ne, Kr, Xe compared to D
- ratio ➔ approximate cancellation of:
  - QED radiative effects (RADGEN)
  - limited geometric and kinematic acceptance of spectrometer
  - detector resolution
- multi-dimensional extraction
**Nuclear attenuation**

- Strong mass dependence: attenuation mainly increases with $A$
- Quite different behavior for protons

[A. Airapetian et al., NPB 780 (2007) 1-27]
Nuclear attenuation

\[ R_A^h \equiv \frac{M_A^h}{M_d^h} \]

strong $p_T$ dependence of nuclear attenuation (e.g., Cronin effect - enhancement at large $p_T$)

except maybe at large $z$ for pions and kaons (little energy loss dictates few interactions)

larger effect for protons
Nuclear attenuation

- mostly decrease of attenuation with increasing $\nu$
- enhancement of proton multiplicities at low $z$ and high $\nu$
Nuclear attenuation

- strong $z$ dependence of attenuation
- amplified by transverse momentum and target mass (i.e., size)

G. Schnell
Conclusions

- HERMES managed step from spin-asymmetry experiment to unpolarized-target experiment
- largest data set on charged-separated identified meson lepto-production
- multi-dimensional analysis and various targets allow study of correlations and flavor dependences
- large attenuation effects at HERMES energies, mainly increasing with nucleus size (except protons) with correlated kinematic dependences
- nuclear environment can play significant role in TMD effects
- don’t forget longitudinal photons