Recent Results on TMDs from HERMES

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(for the HERMES collaboration)
HERMES main research topics:
✓ origin of nucleon spin
   ◐ longitudinal spin/momentum structure
   ◐ transverse spin/momentum structure
✓ hadronization/fragmentation
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✔ nucleon properties (mass, charge, momentum, magnetic moment, spin...) should be explained by its constituents
  ➡ momentum: quarks carry ~ 50% of the proton momentum
  ➡ spin: total quark spin contribution only ~30%
  ➡ study of TMD DFs and GPDs
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✓ isolated quarks have never been observed in nature

✓ fragmentation functions were introduced to describe the hadronization
  ➰ non-pQCD objects
  ➰ universal but not well known functions
  ➡ advantage of lepton-nucleon scattering data ➔ flavour separation of fragmentation functions (FFs)
The HERMES experiment, located at HERA, with its pure gas targets and advanced particle identification ($\pi$, K, p) is well suited for TMD and GPD measurements and for studies of hadronisation process.

- **longitudinal** target polarization (H, D, $^3$He)
- **transverse** target polarization (H)
- **unpolarized** targets: H, D, $^4$He, $^{14}$N, $^{20}$Ne, $^{84}$Kr, $^{131}$Xe
- **unpolarized** H, D targets with **recoil detector**
\[ d^6\sigma \propto \left\{ F_{UU} + \sqrt{2\epsilon(1 + \epsilon)} F_{UU}^{\cos \phi} \cos \phi + \epsilon F_{UU}^{\cos 2\phi} \cos 2\phi \right\} \\
+ \lambda_e \left\{ \sqrt{2\epsilon(1 - \epsilon)} F_{LU}^{\sin \phi} \sin \phi \right\} + S_\parallel \left\{ \ldots \right\} + S_\perp \left\{ \ldots \right\} \]
semi-inclusive DIS cross section and TMDs

\[ \frac{d^6 \sigma}{dx \, dy \, dz \, dP_{h \perp}^2 \, d\phi \, d\phi_s} \propto \left\{ F_{UU} + \sqrt{2\epsilon(1 + \epsilon)} F_{UU}^{\cos \phi} \cos \phi + \epsilon F_{UU}^{\cos 2\phi} \cos 2\phi \right\} 
+ \lambda_\epsilon \left\{ \sqrt{2\epsilon(1 - \epsilon)} F_{UL}^{\sin \phi} \sin \phi \right\} + S_{||} \left\{ \ldots \right\} + S_{\perp} \left\{ \ldots \right\} + \ldots \]

**leading twist TMD DF:**
parameterise the quark-flavour structure of the nucleon

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semi-inclusive DIS cross section and TMDs

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\]

leading twist TMD DF:
parameterise the quark-flavour structure of the nucleon

leading twist TMD FF:
number densities for the conversion of a quark of a certain type to a specific hadron

\[ D_1^q(z, P_{h \perp}^2) \]

\[ F_{UL}^q(z, P_{h \perp}^2) \]

\[ H_1^q(z, P_{h \perp}^2) \]
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leading twist TMD FF:
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semi-inclusive DIS cross section and TMDs

HERMES: access to all TMDs thanks to the polarised beam and target
semi-inclusive DIS cross section and TMDs

\[ \frac{d^6 \sigma}{dx \, dy \, dz \, dP_{h \perp}^2 \, d\phi \, d\phi_s} \]

\[ \propto \left\{ F_{UU} + \sqrt{2\epsilon(1+\epsilon)} F_{UU}^{\cos \phi} \cos \phi + \epsilon F_{UU}^{\cos 2\phi} \cos 2\phi \right\} + \lambda e \left\{ \sqrt{2\epsilon(1-\epsilon)} F_{UL}^{\sin \phi} \sin \phi \right\} + S_{||} \left\{ \ldots \right\} + S_{\perp} \left\{ \ldots \right\} + \ldots \]

leading twist TMD DF:
parameterise the quark-flavour structure of the nucleon

leading twist TMD FF:
number densities for the conversion of a quark of a certain type to a specific hadron

HERMES: access to all TMDs thanks to the polarised beam and target
unpolarised quarks

\[ \sigma_{UU} \propto f_1 \otimes D_1 \]

\[ f_1 = \text{[Diagram]} \]
unpolarised quarks

\[ \sigma_{UU} \propto f_1 \otimes D_1 \]

\[ f_1 = \]

\[ M^h = \frac{d\sigma^h_{SIDIS}(x, Q^2, z, P_{h\perp})}{d\sigma_{DIS}(x, Q^2)} \]
LO interpretation of multiplicity results (integrated over $P_{h\perp}$):

$$M^h \propto \frac{\sum_q e_q^2 \int dx \, f_{1q}(x, Q^2) D_{1q}^h(z, Q^2)}{\sum_q e_q^2 \int dx \, f_{1q}(x, Q^2)}$$

✓ charge-separated multiplicities of pions and kaons sensitive to the individual quark and antiquark flavours in the fragmentation process

$$\sigma_{UU} \propto f_1 \otimes D_1$$

$$f_1 =$$

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unpolarised quarks
unpolarised quarks

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✓ charge-separated multiplicities of pions and kaons sensitive to the individual quark and antiquark flavours in the fragmentation process

$\pi^+$ and $K^+$:
- favoured fragmentation on proton

$\pi^-$:
- increased number of d-quarks in D target and favoured fragmentation on neutron

$K^-$:
- cannot be produced through favoured fragmentation from the nucleon valence quarks

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unpolarised quarks

\[ \sigma_{UU} \propto f_1 \otimes D_1 \]

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\[ \sum \text{calculations using DSS, HNKS and Kretzer FF fits together with CTEQ6L PDFs} \]

proton:

- fair agreement for positive hadrons
- disagreement for negative hadrons

deuteron:

- results are in general in better agreement with the various predictions
unpolarised quarks

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σ_{UU} \propto f_1 \otimes D_1

\checkmark calculations using FFs from HKNS and Kretzer FF fits together with CTEQ6L PDFs

proton:
  - fair agreement for positive hadrons
  - better agreement for negative hadrons

deuteron:
  - results are in general in better agreement with the various predictions

Ami Rostomyan
New global fit DSS+

new data sets since DSS

- Belle, BaBar, Compass, Hermes, Star, Alice

- Rodolfo Sassot -
  Workshop on FFs, Bloomington, December 2013

✓ better agreement for both $\pi^+$ and $\pi^-$
In the absence of experimental constraints, many global QCD fits of PDFs assume

\[ s(x) = s(x) = r[\bar{u}(x) + \bar{d}(x)]/2 \]

- Evaluation of strange quark distribution

\[ S(x) \int \mathcal{D}_S^K(z)dz \simeq Q(x) \left[ 5\frac{d^2N_K(x)}{d^2N_{DIS}(x)} - \int \mathcal{D}_Q^K(z)dz \right] \]

\[
S(x) = s(x) + s(x) \\
Q(x) = u(x) + \bar{u}(x) + d(x) + \bar{d}(x) \\
\mathcal{D}_S^K = D_1^{s\rightarrow K^+} + D_1^{s\rightarrow K^+} + D_1^{s\rightarrow K^-} + D_1^{s\rightarrow K^-} \\
\mathcal{D}_Q^K = D_1^{u\rightarrow K^+} + D_1^{d\rightarrow K^+} + D_1^{d\rightarrow K^+} + D_1^{d\rightarrow K^+} \ldots
\]

**ACKNOWLEDGEMENTS**

\( s(x) = \bar{s}(x) = r[\bar{u}(x) + \bar{d}(x)]/2 \)

- **HERMES Collaboration**
  - Phys. Rev. D89 (2014) 09710

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

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

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

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

- **Fit**
- **CTEQ6L**
- **CTEQ6.5S-0**
- **NNPDF2.3**

\( xS(x) \)

\( 0.02 \) \( 0.1 \) \( 0.6 \)

\( 0 \) \( 0.2 \) \( 0.4 \)

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\( \sqrt{ } \text{ PANIC 2014} \)

- **true** in the absence of experimental constraints, many global QCD fits of PDFs assume

- **true** isoscalar extraction of \( S(x)D_S^K \) based on the multiplicity data of K\(^+\) and K\(^-\) on D

**true** the distribution of S(x) is obtained for a certain value of \( D_S^K \)

**true** the normalization of the data is given by that value

**true** whatever the normalization, the shape is incompatible with the predictions
✓ multi-dimensional analysis allows exploration of new kinematic dependences
✓ broader $P_{h\perp}$ distribution for $K^-$

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beyond the collinear factorisation
flavour-dependent and independent anzatsets

\[ P_T = z \mathbf{k}_\perp + \mathbf{p}_\perp \]

\[ f_{q/p}(x, \mathbf{k}_\perp) = f_{q/p}(x) \frac{e^{-k_z^2/\langle k_z^2 \rangle}}{\pi \langle k_z^2 \rangle} \]

\[ D_{h/q}(z, \mathbf{p}_\perp) = D_{h/q}(z) \frac{e^{-p_z^2/\langle p_z^2 \rangle}}{\pi \langle p_z^2 \rangle} \]

\[ \langle P_{hT,a}^2 \rangle = z^2 \langle k_z^2, a \rangle + \langle P_{\perp, a \rightarrow h}^2 \rangle \]

- different widths for the Gaussian forms of the valence and sea TMD PDFs
- four different Gaussian shapes for TMD FFs

A. Signori, A. Bacchetta, M. Radici and G. Schnell (JHEP, 2013)
no fit on K data:

- the precision and accuracy of the kaon data do not help in constraining the values of the fit parameters.

\[ \langle p_{\perp}^2, \text{fav} \rangle < \langle p_{\perp}^2, \text{unf} \rangle \sim \langle p_{\perp}^2, uK \rangle \]
\[ \langle k_{\perp}^2, d_v \rangle < \langle k_{\perp}^2, u_v \rangle < \langle k_{\perp}^2, \text{sea} \rangle \]

\[ \langle k_{\perp}^2 \rangle = 0.57 \pm 0.08 \text{ GeV}^2, \quad \langle p_{\perp}^2 \rangle = 0.12 \pm 0.01 \text{ GeV}^2 \]

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quarks’ transverse degrees of freedom


Cahn effect

kinematic effect caused by quark intrinsic transverse momentum.


Boer-Mulders effect

correlation between quark transverse momentum and quark transverse spin.

\[
F_{UU}^{\cos 2\phi} = C \left[ -\frac{2(\hat{h} \cdot \vec{k}_T)(\hat{h} \cdot \vec{p}_T) - \vec{k}_T \cdot \vec{p}_T}{MM_h} \right]
\]

\[
F_{UU}^{\cos \phi} = \frac{2M}{Q} C \left[ -\frac{\hat{h} \cdot \vec{p}_T}{M_h} \ x \ h_1^\perp H_1^\perp - \frac{\hat{h} \cdot \vec{k}_T}{M} \ x \ f_1 D_1 + \ldots \right]
\]
quarks’ transverse degrees of freedom

\[ \sigma_{UU} \propto h_1^\perp \otimes H_1^\perp \]

\[ h_1^\perp = \]

\[ = \]
negative asymmetry for $\pi^+$ and positive for $\pi^-$


$H_{1}^{\perp, u \to \pi^+} = -H_{1}^{\perp, u \to \pi^-}$

data support Boer-Mulders DF $h_{1}^{\perp}$ of same sign for $u$ and $d$ quarks

$K^-$ and $K^+$: striking differences w.r.t. pions

role of the sea in DF and FF
negative asymmetries for $\pi^+$ and $\pi$
- larger effect at high $z$
- larger magnitude for $\pi^+$

negative asymmetries for $K^+$
- even larger amplitudes in magnitude than those for $\pi^+$
- suggest a large contribution from the Boer–Mulders effect

compatible with zero asymmetries for $K^-$

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\[ d\sigma = d\sigma^0_{UU} + \cos(2\phi)d\sigma^1_{UU} + \frac{1}{Q} \cos(\phi)d\sigma^2_{UU} + P_l \frac{1}{Q} \sin(\phi)d\sigma^3_{LU} \]
\[ + \quad S_L \left[ \sin(2\phi)d\sigma^4_{UL} + \frac{1}{Q} \sin(\phi)d\sigma^5_{UL} \right] + P_l \left( d\sigma^6_{LL} + \frac{1}{Q} \sin(\phi)d\sigma^7_{LL} \right) \]
\[ + \quad S_T \left[ \sin(\phi - \phi_s)d\sigma^8_{UT} + \sin(\phi + \phi_s)d\sigma^9_{UT} + \sin(3\phi - \phi_s)d\sigma^{10}_{UT} + \frac{1}{Q} \sin(2\phi - \phi_s)d\sigma^{11}_{UT} + \frac{1}{Q} \sin(\phi_s)d\sigma^{12}_{UL} \right] \]
\[ + P_l \left( \cos(\phi - \phi_s)d\sigma^{13}_{LT} + \frac{1}{Q} \cos(\phi_s)d\sigma^{14}_{LT} + \frac{1}{Q} \cos(2\phi - \phi_s)d\sigma^{15}_{LT} \right) \]
\[ d\sigma = d\sigma_U^0 + \cos(2\phi)d\sigma_U^1 + \frac{1}{Q} \cos(\phi)d\sigma_U^2 + P_L \left( d\sigma_L^3 + \frac{1}{Q} \sin(\phi)d\sigma_L^4 \right) \]

+ SL \left[ \sin(2\phi)d\sigma_L^4 + \frac{1}{Q} \sin(\phi)d\sigma_L^5 \right] + P_L \left( d\sigma_L^6 + \frac{1}{Q} \sin(\phi)d\sigma_L^7 \right) \]

+ ST \left[ \sin(\phi - \phi_s)d\sigma_T^8 + \sin(\phi + \phi_s)d\sigma_T^9 + \sin(3\phi - \phi_s)d\sigma_T^{10} + \frac{1}{Q} \sin(2\phi - \phi_s)d\sigma_T^{11} + \frac{1}{Q} \sin(\phi_s)d\sigma_T^{12} \right] \]

+ P_L \left( \cos(\phi - \phi_s)d\sigma_T^{13} + \frac{1}{Q} \cos(\phi_s)d\sigma_T^{14} + \frac{1}{Q} \cos(2\phi - \phi_s)d\sigma_T^{15} \right) \]