Semi-Inclusive DIS with a longitudinally polarized neutron

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Transverse Momentum Distributions through Semi-Inclusive Deep-Inelastic Scattering

3D description of the nucleon structure in the momentum space → full 3D dynamics of the partons

Transition from hadronic to partonic degrees of freedom → Fragmentation Functions & Hadronization mechanisms

hidden strangeness in the nucleon

Access to quark-gluon-quark correlations through higher-twist observables

Transverse Momentum Dependent PDFs&FFs

8 leading-twist TMDs

They depend on the parton longitudinal fraction $x$ and on its transverse momentum $k_T \rightarrow \textit{full 3D dynamics}$

**Leading Twist TMDs**

<table>
<thead>
<tr>
<th>Nucleon Spin</th>
<th>Quark Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-Polarized (U)</td>
<td>Longitudinally Polarized (L)</td>
</tr>
<tr>
<td>U</td>
<td>$f_i^\perp = \downarrow \rightarrow \uparrow$</td>
</tr>
<tr>
<td>L</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>$f_{1T}^\perp = \uparrow \rightarrow \downarrow$</td>
</tr>
<tr>
<td></td>
<td>$g_{1T}^\perp = \uparrow \rightarrow \downarrow$</td>
</tr>
<tr>
<td></td>
<td>$h_{1T}^\perp = \downarrow \rightarrow \uparrow$</td>
</tr>
</tbody>
</table>

Fragmentation Functions $\rightarrow$ transition from partonic to hadronic degrees of freedom

<table>
<thead>
<tr>
<th>q/H</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>$D_1$</td>
<td></td>
<td>$H_1^+$</td>
</tr>
<tr>
<td>L</td>
<td></td>
<td>$G_{1L}$</td>
<td>$H_{1L}^+$</td>
</tr>
<tr>
<td>T</td>
<td>$H_1^+$</td>
<td>$G_{1T}$</td>
<td>$H_1$, $H_{1T}^+$</td>
</tr>
</tbody>
</table>

- different hadrons in the final state provide information on the hadronization of different flavors
- measurements on DIFFERENT TARGETS are essential to perform flavor separation and access TMDs of individual flavors

Single-hadron SIDIS cross-section

Depending on the degrees of freedom active in the process, various TMD&FF can be accessed:

\[
\frac{d\sigma^h}{dz dy d\phi_S dz d\phi dP_h^2} = \frac{\alpha^2 \gamma^2}{xyQ^2 2(1 - \epsilon)} \left(1 + \frac{\gamma^2}{2x}\right)
\]

\[
\left\{ \begin{aligned}
F_{UU,T} + \epsilon F_{UU,L} \\
+ \sqrt{2\epsilon (1 + \epsilon)} \cos(\phi) F_{UU}^{\cos(\phi)} + \epsilon \cos(2\phi) F_{UU}^{\cos(2\phi)} \\
+ \lambda_l \sqrt{2\epsilon (1 - \epsilon)} \sin(\phi) F_{LU}^{\sin(\phi)} \\
+ \sqrt{2\epsilon (1 + \epsilon)} \sin(\phi) F_{UL}^{\sin(\phi)} + \epsilon \sin(2\phi) F_{UL}^{\sin(2\phi)} \\
+ T \left[ \sin(\phi - \phi_s) \left( F_{UT,T}^{\sin(\phi - \phi_s)} + \epsilon F_{UT,L}^{\sin(\phi - \phi_s)} \right) \\
+ \epsilon \sin(\phi + \phi_s) F_{UT}^{\sin(\phi + \phi_s)} + \epsilon \sin(3\phi - \phi_s) F_{UT}^{\sin(3\phi - \phi_s)} \\
+ \sqrt{2\epsilon (1 + \epsilon)} \sin(\phi_s) F_{UT}^{\sin(\phi_s)} \\
+ \sqrt{2\epsilon (1 + \epsilon)} \sin(2\phi - \phi_s) F_{UT}^{\sin(2\phi - \phi_s)} \right] \\
+ \lambda_l \sqrt{1 - \epsilon^2} \cos(\phi - \phi_s) F_{LT}^{\cos(\phi - \phi_s)} \\
+ \sqrt{2\epsilon (1 - \epsilon)} \cos(\phi_s) F_{LT}^{\cos(\phi_s)} \\
+ \sqrt{2\epsilon (1 - \epsilon)} \cos(2\phi - \phi_s) F_{LT}^{\cos(2\phi - \phi_s)} \right\}
\]

18 structure functions appear in the cross-section

\[F_{ij,K} \propto DF \otimes FF\]

JLab TMD program explored the different terms:

1. Unpolarized contributions (Hall-B, Hall-C)
2. Longitudinally-polarized contributions (Hall-B)
3. Transversely-polarized contributions (Hall-A)
Longitudinal Target-Spin Asymmetry on deuterium

\[ A_1 = A_{LL} \propto \frac{g_1 \otimes D_1}{f_1 \otimes D_1} \]

\[ F_{UL}^{\sin \phi_h} = \left( \frac{2M}{Q} \right) C \left[ -\frac{\hat{h} \cdot k_T}{M_h} \left( x h_L H_1^+ + \frac{M_h}{M} g_{1L} \tilde{G}^- \frac{1}{z} \right) + \frac{\hat{h} \cdot p_T}{M} \left( x f_{1L}^D D_1 - \frac{M_h}{M} h_{1L}^+ \tilde{H} \frac{1}{z} \right) \right] \]

\[ F_{UL}^{\sin 2\phi_h} = C \left[ -\frac{2 (\hat{h} \cdot k_T) (\hat{h} \cdot p_T) - k_T \cdot p_T}{MM_h} h_{1L}^+ H_1^+ \right], \]

- Measurements on deuterium are available from HERMES and COMPASS, need to be (further) extended to VALENCE QUARK region
- low-\(Q^2\) important to test the presence of possible evolution effects on TMDs & FFs
- CLAS12 will allow to explore both pions & kaons channel \(\rightarrow\) see M. Contalbrigo’s contribution
- Combining ND3 and NH3 measurement will allow to perform a flavor separation on the TMDs: compatible precision on hydrogen and deuterium is important to access flavor’s TMDs \(\rightarrow\) see A. Courtoy’s contribution
- many semi-inclusive processes (single-hadron, di-hadron, back-to-back SIDIS), with the specific observables they granted access to, will benefit of additional ND3 days \(\rightarrow\) see H. Avakian’s contribution

Model comparison

- high-$x$ region almost unexplored
- it is the region where models deviate greatly from data
- high-$x$ region on kaon data deviates consistently from models → CLAS12 + RICH + ND3 can provide important constraints
Toward a 5D mapping of the nucleon

Transverse Momentum Dependent and Generalized Parton Distributions are reduction of the Wigner Mother Functions, encoding the 5D structure of the nucleon

TMDs → Semi-Inclusive DIS: $e\, p \rightarrow e\, h\, X$

GPDs → Deeply-Virtual Compton Scattering: $e\, p \rightarrow e\, p\, \gamma$

CLAS12 is the perfect environment to access these two processes

Provide projections in the «5D space» in terms of DVCS variables ($x_B, Q^2, -t, \varphi$) and SIDIS variables ($x_B, Q^2, z, P_T$) in the common electron ($x_B, Q^2$) kinematics

1D PDFs are the common part → to be constrained simultaneously from the two processes

- $r_\perp$: $-t$ from DVCS (at $\xi = 0$)
- $k_\perp$: $P_T$ from SIDIS

Goal: provide a 5D data set
backup
Semi-Inclusive DIS and Transverse Momentum Distributions

\[ F_{UU,T} = C[f_1 D_1], \]

\[ F_{UU,L} = 0, \]

\[ F^{\cos \phi_{h}}_{UU} = \frac{2M}{Q} C \left[ -\frac{\hbar \cdot k_T}{M_h} \left( x h H_1^T + \frac{M_h}{M} f_1 \tilde{D}^T \frac{1}{z} \right) - \frac{\hbar \cdot p_T}{M} \left( x f_1^T D_1 + \frac{M_h}{M} h_1^T \tilde{H} \frac{1}{z} \right) \right], \]

\[ F^{\cos 2\phi_{h}}_{UU} = C \left[ -\frac{2 \left( \frac{\hbar \cdot k_T}{M_h} \left( \frac{\hbar \cdot p_T}{M} - k_T \cdot p_T h_1^T H_1^T \right) \right)}{M M_h} \right], \]

\[ F^{\sin \phi_{h}}_{LU} = \frac{2M}{Q} C \left[ -\frac{\hbar \cdot k_T}{M_h} \left( x c H_1^T + \frac{M_h}{M} f_1 \tilde{G}^T \frac{1}{z} \right) + \frac{\hbar \cdot p_T}{M} \left( x g_1^T D_1 + \frac{M_h}{M} h_1^T \tilde{E} \frac{1}{z} \right) \right], \]

\[ F^{\sin \phi_{h}}_{UL} = \frac{2M}{Q} C \left[ -\frac{\hbar \cdot k_T}{M_h} \left( x h L H_1^T + \frac{M_h}{M} g_{1L} \tilde{G}^T \frac{1}{z} \right) + \frac{\hbar \cdot p_T}{M} \left( x f_1^T D_1 - \frac{M_h}{M} h_1^T \tilde{H} \frac{1}{z} \right) \right], \]

\[ F^{\sin 2\phi_{h}}_{UL} = C \left[ -\frac{2 \left( \frac{\hbar \cdot k_T}{M_h} \left( \frac{\hbar \cdot p_T}{M} - k_T \cdot p_T h_1^T H_1^T \right) \right)}{M M_h} \right], \]

\[ F_{LL} = C[g_{1L} D_1], \]

\[ F^{\cos \phi_{h}}_{LL} = \frac{2M}{Q} C \left[ \frac{\hbar \cdot k_T}{M_h} \left( x c L H_1^T - \frac{M_h}{M} g_{1L} \tilde{D}^T \frac{1}{z} \right) - \frac{\hbar \cdot p_T}{M} \left( x g_1^T D_1 + \frac{M_h}{M} h_1^T \tilde{E} \frac{1}{z} \right) \right] \]
COMPASS measurement (on unidentified hadrons)