COMPASS unpolarised SIDIS results: TMDs
When we consider the transverse momentum of the quark in the calculation of the cross section Transverse Momentum Dependent parton distribution (TMDs)

The unpolarised number density of the quarks gains a dependence from the intrinsic transverse momentum $k_\perp$

$$f_1^q(x, k_\perp)$$

New parton densities arise: the Boer-Mulders functions $h_{1\perp q}(x, k_\perp)$, describing the correlation between the intrinsic quark transverse momentum and the spin of the quark in an unpolarised nucleon

$$f_q^\uparrow(x, k_\perp, \vec{s}) = f_1^q(x, k_\perp) - \frac{1}{M} h_{1\perp q}(x, k_\perp) \vec{s} \cdot (\hat{p} \times \vec{k}_\perp)$$
Intrinsic transverse motion; an old story

- Cross section for SIDIS process expected to be
  \[ d\sigma \sim \sigma_0 [1 + A \cos \phi_h + B \cos 2\phi_h] \]


- R.N. Cahn [1978]: same modulations can arise due to the quark intrinsic motion \( k_\perp \) [Phys. Lett. B 78 (1978) 269]
The cross-section is \( d\sigma_{lp \to l' h^X} = \sum_q f_q(x, Q^2) \otimes d\sigma_{lq \to l' q} \otimes D^h_q(z, Q^2) \) with the partonic process is given by \( d\sigma_{lq \to l' q} = \hat{s}^2 + \hat{u}^2 \)

\[ \hat{s} := (\ell + k)^2 \sim 2\ell \cdot k \]
\[ \hat{u} := (\ell - k)^2 \sim -2\ell \cdot k \]

\[ k = xP + k_\perp \]

In collinear PM \( d\sigma_{lq \to l' q} = \hat{s}^2 + \hat{u}^2 = x[1 + (1 - y)^2] \), i.e. no \( \phi_h \) dependence.
Unpolarised Azimuthal Modulation

When $k_{\perp}$ is taken into account:

$$k \approx (xP, k_{\perp} \cos \phi, k_{\perp} \sin \phi, xP)$$

$$k_{\perp} \approx (0, k_{\perp} \cos \phi, k_{\perp} \sin \phi, 0)$$

$$\hat{s} = sx \left[ 1 - \frac{2k_{\perp}}{Q} \sqrt{1 - y \cos \phi} \right] + \sigma \left( \frac{k_{1}^{2}}{Q} \right) \hat{u} = sx (1 - y) \left[ 1 - \frac{2k_{\perp}}{Q \sqrt{1-y}} \cos \phi \right] + \sigma \left( \frac{k_{1}^{2}}{Q} \right)$$

and

$$d\sigma^{\ell q \to \ell' q} \propto \hat{s}^{2} + \hat{u}^{2} \propto \left[ 1 - \frac{2k_{\perp}}{Q} \sqrt{1 - y \cos \phi} \right]^{2} + (1 - y)^{2} \left[ 1 - \frac{2k_{\perp}}{Q \sqrt{1-y}} \cos \phi \right]^{2},$$

Resulting in the $\cos \phi_{h}$ and $\cos 2\phi_{h}$ modulations observed in the azimuthal distributions.
These effects can be estimated by adopting a model for the transverse momentum distribution of partons in a hadron and for the transverse momentum given to hadrons in the quark decay. Suppose that both these distributions are gaussian:

\[ f(x, p_\perp) \propto e^{-ap_\perp^2}, \quad D(z, p_\perp) \propto e^{-bp_\perp^2}, \quad (16a, b) \]

where \( f \) represents the quark distribution and \( D \) the fragmentation function. Let the \( z \)-direction be defined as in fig. 1. Then the longitudinal momentum of the struck parton is \( xP \) and that of the observed hadron is \( zxP \). If the transverse momentum of the struck parton is \( p_{1\perp} \) and that of the observed hadron is \( p_\perp \), then the momentum of the observed hadron transverse to the parton direction is (for \( zxP \gg |p_{1\perp}|, |p_\perp| \)) just \( p_\perp - zp_{1\perp} \).
The account of the transverse motion of the quark result in the following general form of the unpolarised semi-inclusive deep inelastic cross-section

\[
\frac{d^5\sigma}{dxdydzdP_{hT}^2d\phi_h} = \frac{\alpha^2}{xyQ^2}\left[(1 - y) + \frac{y^2}{2}\right]F_2(x, Q^2) \times \left\{M_{UU}^h \left[1 + \frac{2(2 - y)\sqrt{1 - y}}{1 + (1 - y)^2}A_{UU}^{\cos \phi_h} \cos \phi_h + \frac{2(1 - y)}{1 + (1 - y)^2}A_{UU}^{\cos 2\phi_h} \cos 2\phi_h\right]\right\}
\]

Where we have introduced the amplitude of the azimuthal asymmetries as

\[
A_{UU}^{\cos x\phi_h}(x, z, P_{hT}^2; Q^2) = \frac{F_{UU}^{\cos x\phi_h}(x, z, P_{hT}^2; Q^2)}{F_{UU}^h(x, z, P_{hT}^2; Q^2)}
\]

And the angular independent ratio

\[
M_{UU}^h(x, z, P_{hT}^2; Q^2) = \frac{F_{UU}^h(x, z, P_{hT}^2; Q^2)}{F_2(x, Q^2)}
\]

Experimentally these are more difficult measurements than spin asymmetries, since we have to correct for the apparatus acceptance.
When looking at the content of the structure functions/modulations in terms of TMD PDFs for the \( \cos \phi_h \) and \( \cos 2\phi_h \) we can write:

\[
F_{UU}^{\cos \phi_h} = -\frac{2M}{Q} C \left[ \frac{\hat{h} \cdot \vec{k}_\perp}{M} f_1 D_1 - \frac{p_\perp k_\perp}{M} \frac{\vec{P}_{hT} - z(\hat{h} \cdot \vec{k}_\perp)}{zM_hM} h_{1}^\perp H_{1}^\perp \right] + \text{twists} > 3
\]

\[
F_{UU}^{\cos 2\phi_h} = C \left[ \frac{(\hat{h} \cdot \vec{k}_\perp)(\hat{h} \cdot \vec{p}_\perp) - \vec{p}_\perp \cdot \vec{k}_\perp}{MM_h} h_{1}^\perp H_{1}^\perp \right] + \text{twists} > 3
\]

In the \( \cos 2\phi_h \) Cahn effects enters only at twist4

\[
F_{Cahn}^{\cos 2\phi_h} \approx \frac{2}{Q^2} C \left[ \left\{ 2(\hat{h} \cdot \vec{k}_\perp)^2 - k_\perp^2 \right\} f_1 D_1 \right]
\]
1D vs multi D

• The asymmetries are:

\[ A_{UU}^w(\phi_h)(x, z, P_{hT}^2; Q^2) = \frac{F_{UU}^w(\phi_h)}{F_2(x, Q^2)} \]

• When we measure on 1D, i.e. as a function of \( x \), we integrate over the phase space of the other variables

\[ A_{UU}^w(\phi_h)(x) = \frac{\int_{Q_{min}^2}^{Q_{max}^2} dQ^2 \int_{z_{min}}^{z_{max}} dz \int_{pT_{min}}^{pT_{max}} dp_{hT}^2 F_{UU}^w(\phi_h)}{\int_{Q_{min}^2}^{Q_{max}^2} dQ^2 \int_{z_{min}}^{z_{max}} dz \int_{pT_{min}}^{pT_{max}} dp_{hT}^2 (F_2(x, Q^2))} \]
Covered Results


• Contribution of exclusive diffractive processes to the measured azimuthal asymmetries in SIDIS, *Nuclear Physics B* 956 (2020) 115039

• Preliminary results from 2016 with a proton target
1st publication on $P_{hT}$ distributions;
Improved binning

TABLE I. Bin limits for the four-dimensional binning in $x$, $Q^2$, $z$ and $p_{T}^2$.

<table>
<thead>
<tr>
<th></th>
<th>Bin limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>0.003</td>
</tr>
<tr>
<td>$Q^2$ (GeV/c)$^2$</td>
<td>1.0</td>
</tr>
<tr>
<td>$z$</td>
<td>0.2</td>
</tr>
<tr>
<td>$p_{T}^2$ (GeV/c)$^2$</td>
<td>0.02</td>
</tr>
<tr>
<td>$z$</td>
<td>0.76</td>
</tr>
<tr>
<td>$p_{T}^2$ (GeV/c)$^2$</td>
<td>2.05</td>
</tr>
</tbody>
</table>

Subtraction of Diffractive Vector Mesons
2nd publication on $P_{hT}$ distributions;
2nd publication on $P_{hT}$ distributions;
Positive vs Negative charged hadrons ($^6$LiD)

$$F_{UU}^h(x, z, P_{hT}^2; Q^2) = x \sum_q e_q^2 \int d^2 k_\perp d^2 \vec{p}_\perp \delta(\vec{p}_\perp + z\vec{k}_\perp - \vec{P}_{hT}) f_1^q(x, k_\perp^2; Q^2) D_1^{q\to h}(z, p_\perp^2; Q^2)$$

$$\langle Q^2 \rangle = 9.78 \text{ (GeV/c)}^2 \text{ and } \langle x \rangle = 0.149$$
Positive vs Negative charged hadrons (LH$_2$)

COMPASS preliminary

$Q^2 (\text{GeV/c})^2$

$0.60 < z < 0.80$

$\bullet h^-$

$\circ h^+$

$P_T^2 (\text{GeV/c})^2$

$P_T^2 (\text{GeV/c})^2$

$P_T^2 (\text{GeV/c})^2$
Comparison with the publish deuteron

\[ Q^2 (\text{GeV/c})^2 \]

\[ P_T^2 (\text{GeV/c})^2 \]

\[ x \]

COMPASS preliminary

\( h^- \)
- \( 0.20 < z < 0.30 \)
- \( 0.30 < z < 0.40 \)
- \( 0.40 < z < 0.60 \)
- \( 0.60 < z < 0.80 \)

(\text{deuteron, \textit{PRD}67(2018)})
$q_T$ distributions

$Q^2(\text{GeV/c})^2$

- $h^-$
  - $0.20 < z < 0.30$
  - $0.30 < z < 0.40$
  - $0.40 < z < 0.60$
  - $0.60 < z < 0.80$
  - from $P_T^2$ dist.

COMPASS preliminary
A Gaussian ansatz for $k_\perp$ and $p_\perp$ leads to

$$\langle P_{hT}^2 \rangle = z^2 \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle$$

COMPASS preliminary
Phenomenological fits

Azimuthal modulations on $^{6}$LiD
Azimuthal modulations on $^6$LiD
VM subtraction from $^6$LiD
Azimuthal modulations on $(LH_2) - 3D$
Contamination on \((LH_2) - 3D\)
$Q^2$ behavior

COMPASS preliminary

\[ Q_A^{\cos \phi_h} \]

- 0.008 < $x$ < 0.013
- 0.013 < $x$ < 0.020
- 0.020 < $x$ < 0.032

- 0.032 < $x$ < 0.050
- 0.050 < $x$ < 0.080
- 0.080 < $x$ < 0.130

\[ Q^2 \ (\text{GeV/c})^2 \]
Outlook

- An impressing amount of results
- In the study of unpolarized multiplicities and azimuthal asymmetries we are able already today to obtain precise multidimensional results, allowing the start for the transition from “exploratory/consolidation” to the “maturity” era that will arrive with the EIC
- It also offers the glimpse on the challenges that this “precision” will bring for both the experimentalist and the theoreticians
Contamination of hadrons from $\rho^0$ and $\phi$ produced in exclusive reactions

The diffractive $\rho^0$ production and decay.
Azimuthal modulations on (LH$_2$) – 1D
Contamination on \((\text{LH}_2) - 1\text{D}\)

- Determined from \(z_1 + z_2 > 0.95\)
- Selecting \(\rho^0, \omega\) and \(\phi\)

The diffractive \(\rho^0\) production and decay.

COMPASS preliminary

\[
\begin{align*}
\frac{dN}{dp} & \quad \text{visible exclusive, } \mu^+ \\
\frac{dN}{dp} & \quad h^+ \\
\frac{dN}{dp} & \quad h^- \\
\end{align*}
\]
$P_{hT}$ distributions vs W

$R = \frac{dN/dP_T^2 (W>12\text{GeV}/c^2)}{dN/dP_T^2 (W<12\text{GeV}/c^2)}$

$0.30 < z < 0.40$

- $h^+$
- $h^-$