Recent and future measurements of transverse momentum distributions in SIDIS

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Transverse structure of the nucleon

Relative position and motion of a parton characterised by

- $x$  Longitudinal momentum fraction
- $k_{\perp}$ Intrinsic transverse momentum
- $b_T$ Transverse position

For a complete understanding of the nucleon structure

- Parton in longitudinal momentum space
  - Parton distribution functions (PDFs)
- Partons in transverse coordinate space
  - Generalized parton distributions (GPDs)
- Partons in transverse momentum space
  - Transverse momentum distributions (TMDs)

→ Could be assessed in Semi-inclusive DIS
Semi-Inclusive deep inelastic scattering

SIDIS: a powerful tool to study quark transverse momenta in the nucleon \((k_\perp)\) and in the fragmentation \((p_\perp)\)

- Assess PDFs/FFs
- Flavor/charge separation
- Wide scale coverage
- Nuclear target provide laboratory for fragmentation in nuclear medium
- Relevant for spin physics kinematic

\[
\frac{d\sigma^{lp\rightarrow l'hX}}{dE_{\ell}' dE_{\ell}} \sim \sum_q e_q^2 f_q(x, Q^2, k_\perp) \otimes \frac{d\sigma^{\ell q\rightarrow \ell q}}{dE_{\ell}' dE_{\ell}} \otimes D^h_q(z, Q^2, p_\perp)
\]

Transverse Momentum Dependent Parton distribution functions

elementary scattering

Transverse Momentum Dependent Fragmentation Functions
Transverse momentum dependence

Transverse momenta of final-state hadron generated by

\[ \Rightarrow \text{quark intrinsic transverse momentum } k_{\perp} \]
Transverse momentum dependence

✧ Transverse momenta of final-state hadron generated by
  ⇒ quark intrinsic transverse momentum $k_\perp$
  ⇒ $p_\perp$ acquired in the quark fragmentation
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✧ A Gaussian ansatz for $k_\perp$ and $p_\perp$ leads to

\[
\langle p_T^2 \rangle = \langle p_\perp^2 \rangle + z^2 \langle k_\perp^2 \rangle
\]
Transverse momentum dependence

- Transverse momenta of final-state hadron generated by
  \( \Rightarrow \) quark intrinsic transverse momentum \( k_\perp \)
  \( \Rightarrow \) \( p_\perp \) acquired in the quark fragmentation

- A Gaussian ansatz for \( k_\perp \) and \( p_\perp \) leads to

\[
< p_T^2 > = < p_\perp^2 > + z^2 < k_\perp^2 >
\]

\[
\text{d}\sigma^{\ell p \to \ell hX} \sim \sum_q e_q^2 f_q(x, Q^2, k_\perp) \otimes \text{d}\sigma^{\ell q \to \ell q} \otimes D_q^h(z, Q^2, p_\perp)
\]

The azimuthal modulations in the unpolarised cross-section result from

- intrinsic \( k_\perp \) of the quarks \( \Rightarrow \) hadron multiplicities, azimuthal asymmetries
- The Boer-Mulders PDF \( \Rightarrow \) azimuthal asymmetries

Combined analysis allows to disentangle the different effects
Hadron Multiplicities are defined as observed number of hadrons in a number of DIS events

\[
\frac{d^2 M^h(x, Q^2, z, p_T^2)}{dz \, dp_T^2} = \frac{d^4 \sigma^h(x, Q^2, z, p_T^2)}{d^2 \sigma(x, Q^2) \, dx \, dQ^2 \, dz \, dp_T^2}
\]

\[
= \frac{\sum_q e_q^2 f_q(x, Q^2, k_{\perp}) D^h_q(z, Q^2, p_{\perp})}{\sum_q e_q^2 f_q(x, Q^2, k_{\perp})}
\]

Experimentally measured multiplicity must be corrected for many effects as

✧ Spectrometer acceptance + detector inefficiencies, bin migration
✧ Radiative effects
✧ Diffractive vector meson (ρ,Φ) production
COMPASS Spectrometer

Excellent discrimination between $\pi$, $K$, $p$ using RICH

For future studies with flavor separation

This analysis:
160 GeV $\mu^+$ beam
1.2 m long polarised $^6$LiD isoscalar target (2006)

- Fixed-target
- Polarised muon beam & polarised targets p&d

NIMA 577 (2007) 455
First analysis to extract $h^\pm$ distributions vs. $p_T^2$ used:

- data collected in 2004
- in the kinematic domain:
  - $1 < Q^2 (\text{GeV}/c)^2 < 10$
  - $W > 5 \text{ GeV}/c^2$
  - $0.1 < y < 0.9$
  - $0.004 < x < 0.12$
  - $0.2 < z < 0.8$
  - $0.01 < p_T^2 < 1.2$

- 4-D binning in $x$, $Q^2$, $z$, $p_T^2$

aimed to study the $x$, $Q^2$ and $z$ kinematic dependences of $\langle p_T^2 \rangle$ assuming Gaussian distribution of quark transverse momentum $k_\perp$ and of the hadron transverse momentum $wrt$ quark direction ($p_\perp$)
$p_T^2$ averaged values

\[ Ae^{-p_T^2/\langle p_T^2 \rangle} \]

\[ \langle x \rangle = 0.015, \langle Q^2 \rangle = 1.92 \]

\[ \langle x \rangle = 0.054, \langle Q^2 \rangle = 7.36 \]
Data collected in 2006

- Larger angular acceptance, higher statistics, wider kinematic range
- First look in a restricted kinematic range: only 3 \((x,Q^2)\) bins, 2 \(z\) bins, extending the \(p_T^2\) range

\(h^\pm\) distributions vs. \(p_T^2\)
**p_T distributions of charged hadrons**

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\(h^\pm\) distributions fitted using

\[ N_1 \exp(-p_T^2/a_1) \quad \text{for} \quad p_T^2 < 0.68 \, (\text{GeV/c})^2 \]

\[ N_1 \exp(-p_T^2/a_1) + N_2 \exp(-p_T^2/a_2) \quad \text{for} \quad p_T^2 < 3 \, (\text{GeV/c})^2 \]

- Need two exponentials to describe the \(p_T^2\) shape of the COMPASS data

- 2nd exp becomes dominant for \(p_T^2 > 0.6 \, (\text{GeV})^2\)

A more complexe curve than one Gaussian is needed to describe the \(p_T\) shape of experimental data
Multiplicities of charged hadron vs. $p_T^2$

- Fully covered kinematic domain used in this analysis:
  - $Q^2 > 1 \text{ (GeV/c)}^2$
  - $W^2 > 5 \text{ (GeV/c)}^2$
  - $0.1 < y < 0.9$
  - $0.003 < x < 0.4$
  - $0.2 < z < 0.8$
  - $0.02 < p_T^2 < 3$

- 4-D binning in $x$, $Q^2$, $z$, $p_T^2$

Graph showing $Q^2 [(\text{GeV/c})^2]$ vs. $p_T^2 (\text{GeV/c})^2$ with regions for $0.2 < z < 0.3$

- $h^+$
- $h^-$
Multiplicities of charged hadron vs. $p_T^2$, cont.

$Q^2 [(GeV/c)^2]$

- **0.3 < z < 0.4**
  - $h^+$
  - $h^-$

- **Larger multiplicities for positive hadrons**
  - at **high x** due to valence $u$-quark dominance
  - at **large z**, where $D_u \pi^+ > D_u \pi^-$

- **Low-$p_T$ range fitted using one exponential**: non-linear $z^2$-dependence of $<p_T^2>$, confirms conclusions of EPJC 73 (2013) 2531

- **Large-$p_T$ shape flattens as x decreases** and $Q^2$ increases, dominated by PGF,...
Multiplicities of charged hadron vs. $p_T^2$, cont.

$Q^2[(GeV/c)^2]$

$0.4 < z < 0.6$

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

- Total: 4918 kinematic bins
- Correction for diffractive vector meson (DVM) production evaluated
- Results available with/without correction for vector meson contribution and radiative effects
- Publication being prepared, expected soon
- Valuable input for TMD analyses and evolution studies
Summary

✧ Transverse momentum dependent multiplicities of charged hadron were measured using 2006 data collected with a deuteron target and 160 GeV $\mu^+$

✧ in a wide kinematic domain
✧ in 4-D kinematic binning in $x$, $Q^2$, $z$ and $p_T^2$

✧ Observations for the low-$p_T^2$ shape confirms 2004 results

✧ Flattening distributions at large-$p_T^2$, at low $x$ (fixed $Q^2$) and at high $Q^2$ (fixed $x$)

✧ Paper expected soon

✧ COMPASS results on hadron multiplicities represent valuable inputs to global QCD analyses of FFs and TMD analyses

✧ Future measurements of hadron multiplicities on proton (LH$_2$) target from 2016-2017 data
Backup
TMD charged hadron multiplicities

$Q^2[(GeV/c)^2]$ vs $p_T^2 (GeV/c)^2$ for $0.6 < z < 0.8$

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