TMD extractions from COMPASS SIDIS data

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TMD extractions from COMPASS SIDIS data

outlook

- a leading order extraction of the intrinsic transverse momentum
  - transverse momentum distributions in SIDIS
  - the COMPASS and the Belle measurements
  - results for the intrinsic transverse momentum
    ongoing work - COMPASS Transversity group

- extraction of Transversity and Sivers function from SIDIS Transverse Spin Asymmetries (reminder)
transverse momentum distributions in SIDIS

The measurement of the transverse-momentum distributions / cross-sections of hadrons produced in DIS allows to access the transverse momentum of quarks in the nucleon.

\[ \vec{k}_T \] transverse momentum of the initial quark in the GNS

\[ \vec{P}_T \] transverse momentum of the final state hadron in the GNS

\[ \vec{P}_\perp \] transverse momentum acquired by the hadron in the fragmentation process with respect to the quark direction.
the measurement of the transverse-momentum distributions / cross-sections of hadrons produced in DIS allows to access the transverse momentum of quarks in the nucleon

\( \vec{k}_T \) transverse momentum of the initial quark in the GNS
\( \vec{p}_\perp \) transverse momentum acquired by the hadron in the fragmentation process with respect to the quark direction
\( \vec{P}_T \) transverse momentum of the final state hadron in the GNS

at leading order \( \vec{P}_T \simeq z\vec{k}_T + \vec{p}_\perp \) \( \Rightarrow \) \( \langle P_T^2 \rangle \simeq z^2 \langle k_T^2 \rangle + \langle p_\perp^2 \rangle \)

the mean value of \( k_T^2 \) can be obtained from the \( P_T^2 \) distributions

LO approach: on the theory side, a huge effort is ongoing
factorisation, TMD formalism applicability, Next-to-Next-to-Next-to Leading Order, separation of phase space regions …
transverse momentum distributions in SIDIS measured since a long time
and, more recently
• HERMES, Jlab
• COMPASS – charged hadrons in DIS of 160 GeV muons
transverse momentum distributions in SIDIS

measured since a long time


and, more recently

- HERMES, Jlab

- **COMPASS** – charged hadrons in DIS of 160 GeV muons
  - $^6\text{LiD}$ – 2004 data  $0.004 < x < 0.12$  $1 < Q^2 < 10 \text{ GeV}^2$
transverse momentum distributions in SIDIS

measured since a long time


and, more recently

• HERMES, Jlab

• COMPASS – charged hadrons in DIS of 160 GeV muons
  • $^{6}\text{LiD} – 2004$ data $0.004 < x < 0.12$ $1 < Q^2 < 10 \text{ GeV}^2$
  • $^{6}\text{LiD} – 2006$ data $0.003 < x < 0.40$ $1 < Q^2 < 81 \text{ GeV}^2$
transverse momentum distributions in SIDIS

measured since a long time


and, more recently

• HERMES, Jlab

• COMPASS – charged hadrons in DIS of 160 GeV muons
  • $^6$LiD – 2004 data $0.004 < x < 0.12$ $1 < Q^2 < 10$ GeV$^2$
  • $^6$LiD – 2006 data $0.003 < x < 0.40$ $1 < Q^2 < 81$ GeV$^2$

• LH$_2$ – 2016 data $0.003 < x < 0.10$ $1 < Q^2 < 16$ GeV$^2$ NEW $\rightarrow$ A. Moretti

• $4x \times 2Q^2 \times 4z \leftarrow$ used in this work

• $4x \times 2Q^2 \times 7z$
• $4x \times 4Q^2 \times 4z$
• $4x \times 2Q^2 \times 2W \times 4z$
• $4x \times 4Q^2 \times 2W \times 4z$
transverse momentum distributions in SIDIS

COMPASS – charged hadrons, DIS with 160 GeV muons and LH$_2$ target 2016 data

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

$0.20 < z < 0.30$

$h^+$

$h^-$

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

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

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

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

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

$x$
transverse momentum distributions in SIDIS

**COMPASS** – charged hadrons, DIS with 160 GeV muons and LH$_2$ target 2016 data

- $0.2 < z < 0.3$
- $0.3 < z < 0.4$
- $0.4 < z < 0.6$
- $0.6 < z < 0.8$

- strong $z$ dependence
- almost the same shapes for $h^+$ and $h^-$
- clear $Q^2$ dependence

- good quality fits with the sum of two exponentials up to 3 (GeV/c)$^2$
- reasonable fits with one exponential up to 1 (GeV/c)$^2$ - bad $\chi^2$ at low $z$ → $\langle P_T^2 \rangle$

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transverse momentum distributions in SIDIS

**COMPASS** – charged hadrons, DIS with 160 GeV muons and LH$_2$ target 2016 data

\[ \langle P_T^2 \rangle \] from fits with an exponential function up to 1 (GeV/c)$^2$

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

LO expectation: \( \langle P_T^2 \rangle \approx z^2 \langle k_T^2 \rangle + \langle p_{\perp}^2 \rangle \)

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

\[ \langle k_T^2 \rangle \text{ depends on } z \]

information from the recently published Belle data

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transverse momentum distributions in SIDIS

**COMPASS** – charged hadrons, DIS with 160 GeV muons and LH$_2$ target 2016 data

\[ \langle P_T^2 \rangle \] from fits with an exponential function up to 1 (GeV/c)$^2$

![Graph showing the dependence of $\langle P_T^2 \rangle$ on $z^2$](image)

LO expectation: \[ \langle P_T^2 \rangle \approx z^2 \langle k_T^2 \rangle + \langle p_{\perp}^2 \rangle \quad \Rightarrow \quad \langle p_{\perp}^2 \rangle \text{ depends on } z \]

information from the recently published Belle data

this work:

same analysis of the COMPASS and Belle data to extract \( \langle P_T^2 \rangle \) and \( \langle p_{\perp}^2 \rangle \) respectively, and then evaluate \( \langle k_T^2 \rangle \) using the LO expression
transverse momentum distributions in SIDIS

**COMPASS** – charged hadrons, DIS with 160 GeV muons and LH$_2$ target 2016 data

same in SIDIS and $e^+e^-$-annihilation

M. Boglione et al, 2201.12197 [hep-ph]

this work:

same analysis of the COMPASS and Belle data to extract $\langle P_T^2 \rangle$ and $\langle p_{T}^2 \rangle$ respectively, and then evaluate $\langle k_T^2 \rangle$ using the LO expression
the Belle $P_{hT}^2$ cross-sections

“Transverse momentum dependent production cross sections of charged pions, kaons and protons produced in inclusive $e^+e^-$ annihilation at $\sqrt{s}=10.58$ GeV”

in 18 $z$ bins from 0.10 to 1.00 and in 5 bins of the event shape variable $T$

transverse momentum measured with respect to the thrust axis $\sim$ quark direction

$P_{hT}^2 \rightarrow p_{\perp}^2$

the Belle data can be used to extract $\langle p_{\perp}^2 \rangle$

and then $\langle k_{T}^2 \rangle$ from the COMPASS $\langle P_{T}^2 \rangle$

all fragmentation properties in \ldots
the Belle $P_{hT}^2$ cross-sections

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all fragmentation properties in !

main problem when comparing SIDIS and $e^+e^-$ data: the scale $s$ (or $Q^2$) in $e^+e^-$, $Q^2$ and $W$ is SIDIS

$Q_{COMPASS}^2 \ll Q_{Belle}^2$ but $W_{COMPASS} \approx W_{Belle}$ …
the Belle $P_{hT}^2$ cross-sections

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and then $\langle k_T^2 \rangle$ from the COMPASS $\langle P_T^2 \rangle$
all fragmentation properties in !

we added up the cross-sections in all the $T$ bins excluding only 0.95$<T<1.00$
small cross-section and large uncertainties
the Belle $P_{hT}^2$ cross-sections

$\pi^\pm$ integrated over $T$

$\begin{align*}
0.10 < z < 0.15 & \quad 0.15 < z < 0.20 & \quad 0.20 < z < 0.25 & \quad 0.25 < z < 0.30 & \quad 0.30 < z < 0.35 \\
0.35 < z < 0.40 & \quad 0.40 < z < 0.45 & \quad 0.45 < z < 0.50 & \quad 0.50 < z < 0.55 & \quad 0.55 < z < 0.60 \\
0.60 < z < 0.65 & \quad 0.65 < z < 0.70 & \quad 0.70 < z < 0.75 & \quad 0.75 < z < 0.8 & \quad 0.80 < z < 0.85 \\
+ \ldots
\end{align*}$
the Belle $P_{hT}^2$ cross-sections

$\pi^\pm$ integrated over $T$

for $z < 0.40$

the cross-sections are cut because of the Belle fixed energy

$$z = 2 \frac{E_h}{\sqrt{s}} = \frac{E_h}{E_q},$$

$z < z^* \rightarrow P_{hT} < z^* \sqrt{s}/2$

not used
the Belle $P_{hT}^2$ cross-sections

\[ \pi^\pm \text{ integrated over } T \]

for $0.4 < z < 0.80$
the cross-sections look fine, at least up to $P_{hT}^2 = 3 \ (GeV/c)^2$

we summed the cross-sections to obtain the distributions in the bins

$0.40 < z < 0.60$ and $0.60 < z < 0.80$,
the same $z$ bins as in COMPASS
\( \langle P_{hT}^2 \rangle \) from Belle distributions

fits up to 3 \( (\text{GeV}/c)^2 \) with

\[
p_0 \cdot \exp\left(-\frac{P_{hT}^2}{p_1}\right) + p_2 \cdot \exp\left(-\frac{P_{hT}^2}{p_3}\right)
\]

to extract

\[
\langle P_{hT}^2 \rangle = \frac{p_0 p_1^2 + p_2 p_3^2}{p_0 p_1 + p_2 p_3}
\]

\( 0.40 < z < 0.60 \) \( \langle P_{hT}^2 \rangle = 0.389 \) \((\text{GeV}/c)^2\)

\[
\langle p_{\perp}^2 \rangle
\]

\( 0.60 < z < 0.80 \) \( \langle P_{hT}^2 \rangle = 0.398 \) \((\text{GeV}/c)^2\)

good agreement up to 5 \( (\text{GeV}/c)^2 \)

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\[ \langle P_T^2 \rangle \text{ from COMPASS distributions} \]

for consistency with Belle

- we have produced the \( h^+ + h^- \) distributions (almost no difference between \( h^+ \) and \( h^- \))
  in the bins \( 0.40 < z < 0.60 \) (\( \langle z \rangle = 0.48 \)) and \( 0.60 < z < 0.80 \) (\( \langle z \rangle = 0.68 \))

and we have used

- the \( x \) bin \( 0.020 < x < 0.055 \) (statistics) \( \langle x \rangle = 0.037 \)
- the \( Q^2 \) bin \( 3 < Q^2 < 16 \text{ GeV}^2 \)
\[ \langle P_T^2 \rangle \] from COMPASS distributions

for consistency with Belle

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\( 0.40 < z < 0.60 \)

too low \( Q^2 \)

from SIDIS measurements there is evidence that the \( Q^2 \) dependence is stronger at low \( Q^2 \) values
for consistency with Belle

- we have produced the \( h^+ + h^- \) distributions (almost no difference between \( h^+ \) and \( h^- \)) in the bins \( 0.40 < z < 0.60 \) (\( \langle z \rangle = 0.48 \)) and \( 0.60 < z < 0.80 \) (\( \langle z \rangle = 0.68 \))

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- the \( x \) bin \( 0.020 < x < 0.055 \) (statistics) \( \langle x \rangle = 0.037 \)
- the \( Q^2 \) bin \( 3 < Q^2 < 16 \) GeV\(^2\)

**fit up to 3 (GeV/c)\(^2\) with the same function used for the Belle data**

very good \( \chi^2 \)

\[
p_0 \cdot \exp \left( - \frac{P_T^2}{p_1} \right) + p_2 \cdot \exp \left( - \frac{P_T^2}{p_3} \right)
\]

and calculated \( \langle P_T^2 \rangle \) in the same way

\[
\langle P_T^2 \rangle = \frac{p_0 p_1^2 + p_2 p_3^2}{p_0 p_1 + p_2 p_3}
\]

results:

\( 0.40 < z < 0.60 \) \( \langle P_T^2 \rangle = 0.456 \) (GeV/c)\(^2\)
\( 0.60 < z < 0.80 \) \( \langle P_T^2 \rangle = 0.545 \) (GeV/c)\(^2\)
\[ \langle k_T^2 \rangle \] from the \( P_T^2 \) distributions

to summarise

<table>
<thead>
<tr>
<th>( z )</th>
<th>( \langle P_T^2 \rangle ) (GeV/c)^2</th>
<th>( \langle p_{\perp}^2 \rangle ) (GeV/c)^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.48</td>
<td>0.456</td>
<td>0.389</td>
</tr>
<tr>
<td>0.68</td>
<td>0.545</td>
<td>0.398</td>
</tr>
</tbody>
</table>

using \( \langle P_T^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_{\perp}^2 \rangle \) one gets, from the two \( z \) bins,

\[ \langle k_T^2 \rangle = 0.29 \text{ (GeV/c)^2} \quad \text{and} \quad \langle k_T^2 \rangle = 0.32 \text{ (GeV/c)^2} \]

final results: \[ \langle k_T^2 \rangle = 0.31 \text{ (GeV/c)^2} \]

at \( \langle x \rangle = 0.037, \langle Q^2 \rangle = 4.7 \text{ GeV}^2, \langle W \rangle = 11 \text{ GeV/c}^2 \)
check: if the intrinsic transverse momentum has a Gaussian distribution,
and \( \vec{P}_T \approx z\vec{k}_T + \vec{p}_\perp \),
the Belle distributions should be in agreement with the COMPASS distributions
when \( p_{\perp i}^2 \) is scaled by \( \frac{(z^2\langle k_T^2 \rangle + \langle p_{\perp i}^2 \rangle)}{\langle p_{\perp i}^2 \rangle} \)
\begin{align*}
\langle k_T^2 \rangle & = 0.31 \ (\text{GeV/c})^2 \\
\text{at} \quad \langle x \rangle & = 0.037, \quad \langle Q^2 \rangle = 4.7 \text{ GeV}^2, \quad \langle W \rangle = 11 \text{ GeV/c}^2
\end{align*}

this simple, LO extraction of the mean intrinsic transverse momentum looks promising
TMD extractions from COMPASS SIDIS data

direct extraction of Transversity and Sivers function from SIDIS Transverse Spin Asymmetries

important results have been measuring SIDIS with
• high energy muons (160, 190 obtained GeV/c - unique facility, at CERN)
• transversely polarised d (6LiD) and p (NH3) targets

in particular, COMPASS is the only experiment that could measure TSA with p and d targets at the same energy, in the same kinematic region, with the same binning

this gave the opportunity to
directly extract the transversity and Sivers functions
Transversity extraction using

- the $h^+$ and $h^-$ Collins asymmetry in SIDIS off deuteron and protons measured by COMPASS
Transversity extraction

using

- the $h^+$ and $h^-$ Collins asymmetry in SIDIS off deuteron and protons measured by COMPASS
- the corresponding Belle asymmetries
Transversity extraction using

- the $h^+$ and $h^-$ Collins asymmetry in SIDIS off deuteron and protons measured by COMPASS
- the corresponding Belle asymmetries

with the Gaussian ansatz

point by point extraction of $h_1$

A.M., F. Bradamante, V. Barone
PRD91, 014034 (2015)
Transversity extraction

- the $h^+$ and $h^-$ Collins asymmetry in SIDIS off deuteron and protons measured by COMPASS
- the corresponding Belle asymmetries

with the Gaussian ansatz
point by point extraction of $h_1$

main advantage: no Monte Carlo nor parametrisation of PDFs and FFs is needed

done also with 2h asymmetries – similar results

it is possible to include the HERMES results (COMPASS addendum, …)

large statistical uncertainty on d-quark transversity due to missing deuteron data (2022 run!)

A.M., F. Bradamante, V. Barone
PRD91, 014034 (2015)
Sivers function extraction / 1

using

- the charged pion and kaon Sivers asymmetry in SIDIS off proton and deuteron measured by COMPASS

with the Gaussian ansatz

point by point extraction of $f_{1T}^{(1)}$

AM, Bradamante, Barone
PRD 95 (2017) 9, 094024

curves:
Anselmino, Boglione, Melis,
COMPASS has also measured the $P_T$-weighted Sivers asymmetries for charged hadrons produced in SIDIS off protons.
COMPASS has also measured the $P_T$-weighted Sivers asymmetries for charged hadrons produced in SIDIS off protons using these asymmetries the convolution over transverse momenta can be solved → no need for the Gaussian ansatz to extract $f_{1T}^{\perp(1)}$
COMPASS has also measured the $P_T$-weighted Sivers asymmetries for charged hadrons produced in SIDIS off protons.

Using these asymmetries, the convolution over transverse momenta can be solved → no need for the Gaussian ansatz to extract $f_{1T}^{\perp(1)}$.

Assuming the Sivers function to be zero for sea quark (lack of the corresponding deuteron data)

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direct extractions of the transversity PDF and of the Sivers function have been performed using the COMPASS data on TSA, and the Belle data, a different approach with respect to the global fits including also HERMES, JLab and RHIC data.

NEW WORK: the direct comparison of the COMPASS and the Belle measurements of transverse momentum distributions allows for a simple, LO extraction of the mean value of the intrinsic transverse momentum squared, a very reasonable result!
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   a different approach with respect to the global fits including also HERMES, JLab and RHIC data

NEW WORK: the direct comparison of the COMPASS and the Belle measurements of transverse momentum distributions allows for a simple, LO extraction of the mean value of the intrinsic transverse momentum squared
   a very reasonable result!

conclusions

thank you!
check: if the intrinsic transverse momentum has a Gaussian distribution, and \( \vec{p}_T \approx z \vec{k}_T + \vec{p}_\perp \), the Belle distributions should be in agreement with the COMPASS distributions when \( p_{\perp i}^2 \) scaled by \( (z^2 \langle k_T^2 \rangle + \langle p_{\perp}^2 \rangle)/\langle p_{\perp}^2 \rangle \)