The relevance of multidimensional binning in SIDIS measurements: COMPASS experience

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AANL, INFN section of Turin and CERN
on behalf of the COMPASS Collaboration

“Science at the Luminosity Frontier: Jefferson Lab at 22 GeV workshop”
23-26 January 2022, JLab, US
Introductory message

- For a better and more complex understanding of the TMD-spin-phenomena, it is important to carry out the extractions, analyses and various corrections in a multi-D approach.

- It is also important to carefully confront experimental data from different experiments.

- Different complex analysis techniques, Monte-Carlo simulations and various corrections (acceptance, VMs, radiative corrections) are being employed by different experimental collaborations.
  - Closer collaboration between different experimental groups would be very beneficial for the field in general.
  - Sharing the tools (MC, generators, analysis techniques), preliminary results, doing cross-analyses, etc.

- Close collaboration between experimentalists on one side and phenomenologists and theorists on the other would also be very beneficial.
  - Flexibility in adapting on the analysis side (in a timely manner) the choice of the observables, phase-space limitations, etc.
  - Ideally a close collaborative work can be organized.
COMPASS collaboration

Common Muon and Proton Apparatus for Structure and Spectroscopy

- 25 institutions from 13 countries
  – nearly 200 physicists

- CERN SPS north area
- Fixed target experiment
- Approved in 1997 (25 years)
- Taking data since 2002 (20 years)

International Workshop on Hadron Structure and Spectroscopy
IWHSS-2022 workshop (anniversary edition)
CERN Globe, August 29-31, 2022

https://indico.cern.ch/e/IWHSS-2022
COMPASS collaboration

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Wide physics program

COMPASS-I
- Data taking 2002-2011
- Muon and hadron beams
- Nucleon spin structure
- Spectroscopy

COMPASS-II
- Data taking 2012-2022
- Primakoff
- DVCS (GPD+SIDIS)
- Polarized Drell-Yan
- Transverse deuteron SIDIS 2022

COMPASS web page: http://wwwcompass.cern.ch
## COMPASS data taking campaigns

<table>
<thead>
<tr>
<th>Beam</th>
<th>Target</th>
<th>year</th>
<th>Physics programme</th>
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<tbody>
<tr>
<td>$\mu^+$</td>
<td>Polarized deuteron (LiD)</td>
<td>2002</td>
<td>80% Longitudinal</td>
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<td>2009</td>
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<td>2011</td>
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<td>LH$_2$</td>
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<td>Pilot DVCS &amp; HEMP &amp; unpolarized SIDIS</td>
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<td>Polarized proton (NH$_3$)</td>
<td>2014</td>
<td>Pilot Drell-Yan</td>
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<td>LH$_2$</td>
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<td>2017</td>
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<td>$\mu^+$</td>
<td>Polarized deuteron (LiD)</td>
<td>2021</td>
<td>Transverse SIDIS</td>
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<td>2022</td>
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COMPASS data taking campaigns

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<th>Beam</th>
<th>Target</th>
<th>year</th>
<th>Physics programme</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ⁻</td>
<td>Polarized deuteron (6LiD)</td>
<td>2002</td>
<td>80% Longitudinal</td>
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<td>2003</td>
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<td>2004</td>
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- Total number of protons delivered on T6: ~5.95×10^{18} (98%) in about 150 days

SPS efficiency: ~ 73%
Spectrometer efficiency: ~ 90%
Physics data collection efficiency: ~ 75%
COMPASS experimental setup

CERN SPS North Area (building 888)
Two-stage spectrometer LAS+SAS
- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)

- Primary beam - 400 GeV $p$ from SPS
  - impinging on Be production target (T6)
- 190 GeV secondary hadron beams
  - $h^-$ beam: 97% $\pi^-$, 2% $K^-$, 1% $p$
  - $h^+$ beam: 75% $p$, 24% $\pi^+$, 1% $K^+$
- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polarized

• Large-acceptance forward spectrometer
  - Precise tracking (350 planes)
    SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon walls
  - PID - CEDARs, RICH, calorimeters, MWs

Various targets:
- Polarized solid-state NH$_3$ or $^6$LiD
- Liquid H$_2$
- Solid-state nuclear targets (e.g. Ni, W, Pb)
COMPASS experimental setup: Phase II (SIDIS programme)

**COrmon Muon Proton Apparatus for Structure and Spectroscopy**

CERN SPS North Area (building 888)

**Two-stage spectrometer LAS+SAS**
- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)

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- impinging on Be production target (T6)

**190 GeV secondary hadron beams**
- \( h^- \) beam: 97% \( \pi^- \), 2% \( K^- \), 1% \( p \)
- \( h^+ \) beam: 75% \( p \), 24% \( \pi^+ \), 1% \( K^+ \)

**160 GeV tertiary muon beams**
- \( \mu^+ \) longitudinally polarized
COMPASS experimental setup: Phase II (DY programme)

**COrmon Muon Proton Apparatus for Structure and Spectroscopy**

CERN SPS North Area (building 888)

- Two-stage spectrometer LAS+SAS
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- 160 GeV tertiary muon beams
  - \( \mu^+ \) longitudinally polarized

- ECAL2 HCAL2
- Muon-filter
- Hadron absorber

- Nuclear target (Al)
- Aluminum cone
- Vertex detector
- Stainless Steel 20 cm
- MM01 25 cm downstream last alumina layer
- Tungsten beam plug

24 January 2023

B. Parsamyan
The COMPASS Experiment at the CERN SPS

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

**Nucleon structure**
- Hard scattering of $\mu^\pm$ and $\pi^-$ off (un)polarized P/D targets
- Study of nucleon spin structure
- Parton distribution functions and fragmentation functions

**Hadron spectroscopy**
- Diffractive $\pi(K)$ dissociation reaction with proton target
- PWA technique employed
- High-precision measurement of light-meson excitation spectrum
- Search for exotic states

**Chiral dynamics**
- Test chiral perturbation theory in $\pi(K)\gamma$ reactions
- $\pi^\pm$ and $K^\pm$ polarizabilities
- Chiral anomaly $F_{3\pi}$
The COMPASS Experiment at the CERN SPS

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Cahn effect in SIDIS

\[
\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \\
\left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2} \right) \right] \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \\
\times \left( 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos \phi_h} \cos \phi_h + \ldots \right)
\]

Cahn effect

R. N. Cahn, **PLB 78** (1978)

\[ k_T \rightarrow \cos \varphi_q \rightarrow \cos \varphi_h \]

The point that there are azimuthal dependences, which arise from the transverse momenta of the partons was clearly stated in this papers:


\[
\hat{u} = -xs \left( 1 - y \right) \left[ 1 - \frac{2k_T}{Q\sqrt{1-y}} \cdot \cos \varphi_q \right] \\
\hat{t} = -Q^2 = -xs, \text{ where } s=(l+P)^2 \\
d\sigma^{lp \rightarrow l'hX} \propto d\sigma^{lq \rightarrow lq} \propto \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}
\]
**Cahn effect in SIDIS**

\[
\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} =
\left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})
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<table>
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\[ f_1^q (x, k_T^2) \]

**Quark number density**

As of 1978 – simplistic kinematic effect:

- Non-zero \( k_T \) induces an azimuthal modulation

As of 2022 – complex SF (twist-2/3 functions)

- Measurements by different experiments

**Significant non-zero effect observed by a number of experiments**

\[
F_{UU}^{\cos\phi_h} = \frac{2M}{Q} C \left\{ \frac{\hat{h} \cdot p_T}{M} \left( xhH_{1q}^{1h} + \frac{M}{f_1^q} \frac{\tilde{D}_{1q}^{1h}}{z} \right) - \frac{\hat{h} \cdot k_T}{M} \left( xf^{1q} D_{1q}^h + \frac{M}{h_{1q}^{1q}} \frac{\tilde{H}_q^h}{z} \right) \right\}
\]

**Significant non-zero effect observed by a number of experiments**

- As of 1978 – simplistic kinematic effect:
  - Non-zero \( k_T \) induces an azimuthal modulation

- As of 2022 – complex SF (twist-2/3 functions)
  - Measurements by different experiments

24 January 2023

B. Parsamyan
Cahn effect in SIDIS

\[ \frac{d\sigma}{dxdydzp_Td\phi_p d\phi_S} = \]

\[ \frac{\alpha}{xyQ^2} \left\{ \frac{y^2}{2(1-\varepsilon)} \left[ 1 + \frac{\gamma^2}{2x} \right] \right\} \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \]

\[ \times ( 1 + \sqrt{2\varepsilon (1+\varepsilon)} A_{UU}^{\phi_h} \cos \phi_h + \ldots ) \]

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\[ f_1^q(x, k_T^2) \]

number density

As of 1978 – simplistic kinematic effect:
- non-zero \( k_T \) induces an azimuthal modulation

As of 2022 – complex SF (twist-2/3 functions)
- Measurements by different experiments

\[ F_{UU}^{\cos \phi_h} = \frac{2M}{Q} C \left\{ -\frac{\hat{h} \cdot p_T}{M_h} \left( xhH_{1q}^{1h} + M_h f_1^q \frac{\tilde{D}_{1q}^{1h}}{z} \right) - \frac{\hat{h} \cdot k_T}{M} \left( xf_{1q}^{1q} \tilde{D}_{1q}^{h} + M_h h_{1q}^{1q} \tilde{H}_{1q}^{h} \right) \right\} \]

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Cahn effect in SIDIS

\[
d\sigma = \frac{d\sigma}{dxdydzdp_T^2d\phi_Hd\phi_S} = \left[ \frac{\alpha}{xyQ^22(1-\varepsilon)} \left(1+\frac{\gamma^2}{2x}\right) \right] \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \times \left( 1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h + \ldots \right)
\]

As of 1978 – simplistic kinematic effect:
- non-zero \( k_T \) induces an azimuthal modulation

As of 2022 – complex SF (twist-2/3 functions)
- Measurements by different experiments
- Complex multi-D kinematic dependences
  - So far, no clear interpretation

Recent COMPASS results (see A. Moretti’s talk)

COMPASS preliminary
Cahn effect in SIDIS

\[
\frac{d\sigma}{dx dy dz d_p^2 d_\phi d_\phi_S} = \\
\left[ \frac{\alpha}{xyQ^2} \left( 1 + \frac{y^2}{2(1 - \epsilon)} \right) \left( F_{U,U,T} + \epsilon F_{U,U,L} \right) \right] \\
\times \left( 1 + \sqrt{2\epsilon(1 + \epsilon)} A_{UU}^{\cos \phi_h \cos \phi} + \ldots \right)
\]

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Recent COMPASS results (see A. Moretti’s talk)

COMPASS preliminary

As of 2022 – complex SF (twist-2/3 functions)

• A set of complex corrections: Acceptance, diffractively produced VMs, radiative corrections, etc.
Cahn effect in SIDIS

\[ \frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} = \left[ \alpha \frac{y^2}{xyQ^2} \frac{1}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \right] \times \left( 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos \phi_h + \ldots \right) \]

Quark | Nucleon
--- | ---
U | U

As of 1978 – simplistic kinematic effect:
• non-zero \( k_T \) induces an azimuthal modulation

As of 2022 – complex SF (twist-2/3 functions)
• Measurements by different experiments
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As of 2022 – complex SF (twist-2/3 functions)
• Measurements by different experiments
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• So far, no clear interpretation

• Strong \( Q^2 \) dependence
Cahn effect in SIDIS

\[
\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \\
\left[ \frac{\alpha}{xyQ^2} \left(1 + \frac{y^2}{2x} \right) \right] \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \\
\times \left( 1 + \sqrt{2\varepsilon (1 + \varepsilon)} A_{UU}^{\cos \phi_h} \cos \phi_h + \ldots \right)
\]

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Recent COMPASS results (see A. Moretti’s talk)

24 January 2023
B. Parsamyan

- Strong \( Q^2 \) dependence
SIDIS x-section and TMDs at twist-2

\[
\frac{d\sigma}{dxdydp_{T}^{2}d\phi_{h}d\phi_{S}} = \frac{\alpha}{xyQ^{2}}\left(1 + \frac{\gamma^{2}}{2x}\right) \left(F_{UU,T} + \varepsilon F_{UU,L}\right)
\]

\[
= 1 + \sqrt{2\varepsilon} (1 + \varepsilon) A_{UU}^{\cos\phi_{h}} \cos \phi_{h} + \varepsilon A_{UU}^{\cos 2\phi_{h}} \cos 2\phi_{h}
\]

\[
+ \lambda \sqrt{2\varepsilon} (1 - \varepsilon) A_{LU}^{\sin\phi_{h}} \sin \phi_{h}
\]

\[
+ S_{L} \left[ \sqrt{2\varepsilon} (1 + \varepsilon) A_{UL}^{\sin\phi_{h}} \sin \phi_{h} + \varepsilon A_{UL}^{\sin 2\phi_{h}} \sin 2\phi_{h} \right]
\]

\[
+ S_{L} \lambda \left[ \sqrt{1 - \varepsilon^{2}} A_{LL} + \sqrt{2\varepsilon} (1 - \varepsilon) A_{LL}^{\cos\phi_{h}} \cos \phi_{h} \right]
\]

\[
\times \left\{ \begin{array}{c}
A_{UT}^{\sin(\phi_{h} - \phi_{S})} \sin(\phi_{h} - \phi_{S}) \\
+ \varepsilon A_{UT}^{\sin(\phi_{h} + \phi_{S})} \sin(\phi_{h} + \phi_{S}) \\
+ \varepsilon A_{UT}^{\sin(3\phi_{h} - \phi_{S})} \sin(3\phi_{h} - \phi_{S}) \\
+ \sqrt{2\varepsilon} (1 + \varepsilon) A_{UT}^{\sin\phi_{h}} \sin \phi_{h} \\
+ \sqrt{2\varepsilon} (1 + \varepsilon) A_{UT}^{\sin 2\phi_{h} - \phi_{S}} \sin(2\phi_{h} - \phi_{S}) \\
+ \sqrt{(1 - \varepsilon^{2})} A_{LT}^{\cos(\phi_{h} - \phi_{S})} \cos(\phi_{h} - \phi_{S}) \\
+ \varepsilon A_{LT}^{\cos\phi_{h}} \cos \phi_{h} \\
+ \varepsilon A_{LT}^{\cos(2\phi_{h} - \phi_{S})} \cos(2\phi_{h} - \phi_{S})
\end{array} \right\}
\]

All measured by COMPASS
$d\sigma \over dx dy dz dp_t^2 d\phi_t d\phi_s = \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left(F_{UU,T} + \varepsilon F_{UU,L}\right) \right]$ 

$= \left(1 + \sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h + \varepsilon A_{UU}^{\cos2\phi_h}\cos2\phi_h + \lambda \sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h\right)$ 

$+ S_L \left[ \sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h + \varepsilon A_{UL}^{\sin2\phi_h}\sin2\phi_h \right]$ 

$+ S_L \lambda \left[ \sqrt{1-\varepsilon^2}A_{LL}\cos\phi_h\cos\phi_h + \sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h \right]$ 

$\times \left[ A_{UT}^{\sin(\phi_h-\phi_s)}\sin(\phi_h-\phi_s) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_s)}\sin(\phi_h+\phi_s) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_s)}\sin(3\phi_h-\phi_s) + \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_s}\sin\phi_s + \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_s)}\sin(2\phi_h-\phi_s) \right]$ 

$+ S_T \left[ \sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_s)}\cos(\phi_h-\phi_s) + \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_s}\cos\phi_s + \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_s)}\cos(2\phi_h-\phi_s) \right]"}
SIDIS TSAs: Sivers effect

\[ \frac{d\sigma}{dx dy dz dp_t^2} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \ldots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) \ldots \right\} \]

- Measured on proton and deuteron
- Expected to change sign between SIDIS and Drell-Yan

HERMES, JHEP 12 (2020) 010
SIDIS \[ \frac{d\sigma^\text{LO}}{dx dy dz dp^2 d\phi_n d\phi_s} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \]

\[
\left. \begin{array}{c}
1 + \varepsilon A_{UU}^{\cos \phi_h} \cos 2\phi_h \\
+ S_L \varepsilon A_{UL}^{\sin \phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL} \\
+ S_T \left[ A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\
+ \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\
+ \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \right] \\
+ S_T \lambda \left[ \sqrt{1 - \varepsilon^2} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \right]
\end{array} \right\} \\
\times \left[ \begin{array}{c}
A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\
+ \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\
+ \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \\
\end{array} \right]
\]

DY \[ \frac{d\sigma^\text{LO}}{dq^4 d\Omega} \propto F_U^1 \left( 1 + \cos^2 \theta_{cs} \right) \]

\[
\left. \begin{array}{c}
1 + D_{[\sin^2 \theta_{cs}]} A_{U}^{\cos 2\phi_{cs}} \cos 2\phi_{cs} \\
+ S_L \sin^2 \theta_{cs} A_{L}^{\sin 2\phi_{cs}} \sin 2\phi_{cs} \\
\times \left[ A_{T}^{\sin \phi_s} \sin \phi_s \\
+ S_T \left[ A_{T}^{\sin(2\phi_{cs} - \phi_s)} \sin(2\phi_{cs} - \phi_s) \\
+ D_{[\sin^2 \theta_{cs}]} \left( A_{T}^{\sin(2\phi_{cs} - \phi_s)} + A_{T}^{\sin(2\phi_{cs} + \phi_s)} \sin(2\phi_{cs} + \phi_s) \right) \right] \right]
\end{array} \right\}
\]

where \( D_{[\sin^2 \theta_{cs}]} = \sin^2 \theta_{cs} \left( 1 + \cos^2 \theta_{cs} \right) \)
**SIDIS and single-polarized DY x-sections at twist-2 (LO)**

\[
\frac{d\sigma^{LO}}{dx dy dz dp^2_1 d\phi_n d\phi_S} \propto \left( F_{UU, T} + \varepsilon F_{UU, L} \right) + S_L \varepsilon A_{UU}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL}^{\sin 2\phi_h} \sin 2\phi_h
\]

\[
+ S_T \varepsilon A_{UL}^{\sin (\phi_h - \phi_S)} \sin (\phi_h - \phi_S)
+ \varepsilon A_{UT}^{\sin (\phi_h + \phi_S)} \sin (\phi_h + \phi_S)
+ \varepsilon A_{UT}^{\sin (3\phi_h - \phi_S)} \sin (3\phi_h - \phi_S)
\]

\[
+ S_T \lambda \left[ \sqrt{1 - \varepsilon^2} A_{LT}^{\cos (\phi_h - \phi_S)} \cos (\phi_h - \phi_S) \right]
\]

\[
1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h
\]

\[
1 + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL}^{\sin 2\phi_h} \sin 2\phi_h
\]

\[
\times
\]

\[
1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\phi_S} \cos 2\phi_S
\]

\[
+ S_L \sin^2 \theta_{CS} A_L^{\sin 2\phi_S} \sin 2\phi_S
\]

\[
+ S_T \left[ A_T^{\sin \phi_S} \sin \phi_S
+ D_{[\sin^2 \theta_{CS}]} \left( A_T^{\sin (2\phi_S - \phi_S)} \sin (2\phi_S - \phi_S)
+ A_T^{\sin (2\phi_S + \phi_S)} \sin (2\phi_S + \phi_S) \right) \right]
\]

where \( D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} \left( 1 + \cos^2 \theta_{CS} \right) \)

**Complementary information from two different channels:**

- **SIDIS-DY bridging of nucleon TMD PDFs; Universality studies;**
- **Sign-change of T-odd Sivers and Boer-Mulders TMD PDFs;**
- **Multiple access to Collins FF \( H_{1q}^{\perp h} \) and pion Boer-Mulders PDF \( h_{1q}^{\perp q} \)**
Single-polarized DY measurements at COMPASS

- **1.0 < M/(GeV/c^2) < 2.0** “Low mass”
  - Large background contamination, combinatorial, Open-charm (B) D\( \bar{D} \), B\( \bar{B} \), π, K decays
- **2.0 < M/(GeV/c^2) < 2.5** “Intermediate mass”
  - High DY-cross section
  - Still low DY-signal/background ratio
- **2.5 < M/(GeV/c^2) < 4.3** “Charmonia mass”
  - Strong J/ψ-signal → study of J/ψ physics
  - Good signal/background
- **4.3 < M/(GeV/c^2) < 8.5** “High mass”
  - Low DY cross-section
  - Beyond charmonium region, background < 3%
  - Valence region → largest asymmetries

\[
\frac{d\sigma^{LO}}{dq^4d\Omega} \propto F_U^1 \left(1 + \cos^2 \theta_{CS}\right)
\]

\[
\left\{\begin{array}{l}
1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\
+ S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\
+ D_{[\sin^2 \theta_{CS}]} \left(A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S)\right)
\end{array}\right.
\]

\[
D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} l \left(1 + \cos^2 \theta_{CS}\right)
\]
Single-polarized DY measurements at COMPASS

\[ \frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left( 1 + \cos^2 \theta_{CS} \right) \]

\[ D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \]

\[ + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \]

\[ \times \left\{ 1 + D_{[\sin^2 \theta_{CS}]} \left( A_T^{\sin (2\varphi_{CS} - \varphi_S)} \sin (2\varphi_{CS} - \varphi_S) + A_T^{\sin (2\varphi_{CS} + \varphi_S)} \sin (2\varphi_{CS} + \varphi_S) \right) \right\} \]

\[ D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} \left( 1 + \cos^2 \theta_{CS} \right) \]

HM events are in the valence quark range

\[ \langle x_{\pi} \rangle = 0.50 \]
\[ \langle x_N \rangle = 0.17 \]

4.3 < \( M_{\mu\mu}/(\text{GeV}/c^2) \) < 8.5 “High mass” range

Beyond charmonium region, background < 3%
Valence region → largest asymmetries

\[ \langle M \rangle = 5.3 \text{ GeV}/c^2 \]

COMPASS 2015 \( M_{\mu\mu} \) data
Drell-Yan \( Q^2 \) distribution

\[ dN/dx_N/dQ^2 \text{ (rescaled)} \]

\[ x_N \]

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

\[ M_{\mu\mu} \text{ (GeV}/c^2) \]
\[ \frac{d\sigma^{LO}}{dx dy dz dp^2 d\phi_n d\phi_S} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \]

**SIDIS**

\[ 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL} \]

\[ + S_T \left[ A_{UT}^{\sin (\phi_h - \phi_S)} \sin (\phi_h - \phi_S) + \varepsilon A_{UT}^{\sin (\phi_h + \phi_S)} \sin (\phi_h + \phi_S) + \varepsilon A_{UT}^{\sin (3\phi_h - \phi_S)} \sin (3\phi_h - \phi_S) \right] \]

\[ + S_T \lambda \left[ \sqrt{1 - \varepsilon^2} A_{LT}^{\cos (\phi_h - \phi_S)} \cos (\phi_h - \phi_S) \right] \]

**DY**

\[ \frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left( 1 + \cos^2 \theta_{CS} \right) \]

\[ 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS} + S_L \sin^2 \theta_{CS} A_L^{\sin 2\phi_{CS}} \sin 2\phi_{CS} \]

\[ + S_T \left[ A_T^{\sin \phi_S} \sin \phi_S + D_{[\sin^2 \theta_{CS}]} \left( A_T^{\sin (2\phi_{CS} - \phi_S)} \sin (2\phi_{CS} - \phi_S) + A_T^{\sin (2\phi_{CS} + \phi_S)} \sin (2\phi_{CS} + \phi_S) \right) \right] \]

where \( D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} \left( 1 + \cos^2 \theta_{CS} \right) \)

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**Comparable x:Q^2 coverage – minimization of possible Q^2-evolution effects**
SIDIS and single-polarized DY x-sections at twist-2 (LO)
\[
\frac{d\sigma^{LO}}{dx dy dz dp^2 d\phi_h d\phi_S} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \\
+ \varepsilon A_{UU} \cos^2 \phi_h \cos 2\phi_h \\
+ S_L \varepsilon A_{UL} \sin^2 \phi_h \sin 2\phi_h \\
+ S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL} \\
\times \left\{ A_{UT} \sin(\phi_h - \phi_S) \sin(\phi_h - \phi_S) \\
+ S_T \varepsilon A_{UT} \sin(\phi_h + \phi_S) \sin(\phi_h + \phi_S) \\
+ S_T \lambda \left[ \sqrt{1 - \varepsilon^2} A_{LT} \cos(\phi_h - \phi_S) \cos(\phi_h - \phi_S) \right] \right\}
\]
DY TSAs at COMPASS (high-mass range)

Theory curves based on S. Bastami et al. JHEP 02, (2021), 166

- General agreement with available theory predictions
COMPASS Multi-D TSA analyses

\[
\frac{d\sigma}{dx dy dz dp_T d\phi_h d\phi_S} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \ldots + S_T A^\sin(\phi_h - \phi_S) \sin(\phi_h - \phi_S) + S_T \varepsilon A^\sin(\phi_h + \phi_S) \sin(\phi_h + \phi_S) \right\}
\]

\[
F^\sin(\phi_h - \phi_S)_{UT,T} = C \left\{ -\hat{h} \cdot k_T M f^\perp_{UL} \right\}, F^\sin(\phi_h - \phi_S)_{UT,L} = 0
\]

\[
F^\sin(\phi_h + \phi_S)_{UT} = C \left\{ - \hat{p}_T M_h h^\perp_{UL} \right\}
\]

3D $x:Q^2:z$ or $x:Q^2:p_T$ $x:z:p_T$

- No clear $Q^2$-dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?
**Sivers asymmetry: 3D x-z-Q^2 dependence**

- In several x-bins some hints for possible Q^2-dependence for positive hadrons (decrease) **more evident at large z**.
- At low z effect for h^+ is smaller in general.
- No clear picture for negative hadrons.

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**24 January 2023**

B. Parsamyan
**Sivers asymmetry: 3D $Q^2$-z-x dependence**

- Positive amplitude for $h^+$ (increasing with $x$ and $z$)
- Positive $h^-$ amplitude at relatively large $x$ (>0.032) and $Q^2$ (>7) at intermediate and large $z$
- Some hint for a possible negative $h^-$ amplitude at low $x$ (<0.032) and $Q^2$ (<7) at intermediate and large $z$
COMPASS Multi-D TSA analyses

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \ldots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \ldots \right\}$$

$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left( -\hat{h} \cdot k_T \frac{f_{1T}^{Lq} D_{1q}^h}{M} \right), F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

HERMES, JHEP 12 (2020) 010

B. Parsamyan (for COMPASS) [arXiv:1504.01599 [hep-ex] (SPIN-2014)]
SIDIS TSAs: Kotzinian-Mulders asymmetry

\[
\frac{d\sigma}{dx dy dz dp_t^2 d\phi_h d\phi_S} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \ldots + \lambda S_T \sqrt{1 - \varepsilon^2} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) + \ldots \right\}
\]

\[
F_{LT}^{\cos(\phi_h - \phi_S)} = C \left[ \frac{\hat{h} \cdot k_T}{M} g_{1T}^q D_{1q}^{h} \right]
\]

COMPASS/HERMES/CLAS6 results

- Only “twist-2” ingredients
- Sizable non-zero effect for \( h^+ \)
- Similar effect at HERMES


HERMES, JHEP 12 (2020) 010
SIDIS TSAs: Kotzinian-Mulders asymmetry

\[ \frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \lambda_S \sqrt{1 - \varepsilon^2} A_{LT}^{\cos(\phi_h - \phi_S)} \right\} \cos(\phi_h - \phi_S) + \ldots \]

\[ F_{LT}^{\cos(\phi_h - \phi_S)} = C \left[ \frac{\hat{h} \cdot k_T}{M} \right] \left( 8 b_{1q} D_{1q}^h \right) \]

M. Horstmann, A. Schafer and A. Vladimirov

First global QCD analysis of the $g_{1T}$ TMD PDF using SIDIS data

PRD 105 (2022) 3, 034007
COMPASS 2022 run: new unique deuteron data to come

Pavia group fits

Bacchetta, Delcarro, Pisano, Radici, in preparation

analysis of statistical error with replica method (200)

68% confidence level

Q^2 \geq 1.4 \text{ GeV}^2, \quad 0.2 \leq z \leq 0.7

P_{ht} < \text{min}[0.2Q, 0.7Qz] + 0.5 \text{ GeV}

300 data points \rightarrow 118 \text{ data fitted}

14 free parameters

\chi^2/\text{d.o.f.} = 1.06 \pm 0.10

JAM Collaboration, PRD 106 (2022) 3, 034014

S. Bhattacharya, Z. B. Kang, A. Metz, G. Penn and D. Pitonyak
PRD 105 (2022) 3, 034007

COMPASS 2022 deuteron run
“Nature”

Raphael “Madonna del Prato”

“1D”

Salvador Dali “Maximum Speed of Raphael’s Madonna”
“Nature”

“multi-D” with available statistics

Raphael “Madonna del Prato”

Raphael “Madonna del Prato” (poor resolution)
Conclusions

• For a better and more complex understanding of the TMD-spin-phenomena, it is important to carry out the extractions, analyses and various corrections in a multi-D approach.
• It is also important to carefully confront experimental data from different experiments.
• Different complex analysis techniques, Monte-Carlo simulations and various corrections (acceptance, VMs, radiative corrections) are being employed by different experimental collaborations.
  o Closer collaboration between different experimental groups would be very beneficial for the field in general.
  o Sharing the tools (MC, generators, analysis techniques), preliminary results, doing cross-analyses, etc.
• Close collaboration between experimentalists on one side and phenomenologists and theorists on the other would also be very beneficial.
  o Flexibility in adapting on the analysis side (in a timely manner) the choice of the observables, phase-space limitations, etc.
  o Ideally a close collaborative work can be organized.

Thank You!
• Spare slides
SIDIS TSAs: Collins effect and Transversity

\[ \frac{d\sigma}{dxdydzdp_t^2d\phi_hd\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \ldots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \ldots \right\} \]

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?
- Extensive phenomenological studies and various global fits by different groups

[Addendum to the COMPASS-II Proposal]
Projected uncertainties for Collins asymmetry

COMPASS-II (2022)
- Deuteron measurement being repeated
- Will be crucial to constrain the transversity TMD PDF for the d-quark
**Sivers asymmetry: 4D Q^2-p_T-x dependence at z>0.2**

- Positive amplitude for h^+ (increasing with x and z and p_T)
- Positive h^- amplitude at relatively large x (>0.032) and Q^2 (>7) at intermediate and large z (all p_T)
- Some hint for a possible negative h^- amplitude at low x (<0.032) and Q^2 (<7) at intermediate and large z (all p_T)
Sivers asymmetry: 4D $Q^2$-$p_T$-$x$ dependence at $0.1<z<0.2$

- Positive amplitude for $h^+$ (increasing with $x$ and $z$ and $p_T$)
- Positive $h^-$ amplitude at relatively large $x$ (>0.032) and $Q^2$ (>7) at intermediate and large $z$ (all $p_T$)
- Some hint for a possible negative $h^-$ amplitude at low $x$ (<0.032) and $Q^2$ (<7) at intermediate and large $z$ (all $p_T$)
Drell-Yan TSAs – Transversity

\[
\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \ldots + S_T \left[ D_{\sin^2 \theta_{CS}} A_T^\sin(2\varphi_{CS} - \varphi_S) \sin(2\varphi_{CS} - \varphi_S) + \ldots \right]
\]

Collins SIDIS TSA
\[
A_{UT}^{\sin(\phi_h + \phi_s)} \propto h^q_1 \otimes H_{1q}^{1h}
\]

Transversity DY TSA
\[
A_T^{\sin(2\varphi_{CS} - \varphi_S)} \propto h^q_{1,\pi} \otimes h^q_{1,p}
\]
Drell-Yan TSAs – Sivers

\[
\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \ldots + S_T \left[ A_T^{\sin \phi_S} \sin \phi_S + \ldots \right]
\]

Sivers DY TSA
\[ A_T^{\sin \phi_S} \propto f_{1q}^{q^T} \otimes f_{1T,p}^{q^T} \]

Sivers SIDIS TSA
\[ A_{UT}^{\sin (\phi_h - \phi_s)} \propto f_{1T}^{q^T} \otimes D_{1q}^{h} \]

COMPASS
PLB 770 (2017) 138
SIDIS: target longitudinal spin dependent asymmetries

\[ \frac{d\sigma}{dxdydzdp^2_Td\phi_h d\phi_S} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + ... + S_L \sqrt{2\varepsilon (1+\varepsilon)} A_{UL}^{\sin \phi_h} \sin \phi_h + ... \right\} \]

\[ F_{UL}^{\sin \phi_h} = \frac{2M}{Q} \left\{ -\hat{h} \cdot p_T \left( x h_L^q H_{1q}^h + \frac{M_h}{M} g_{1L}^q \tilde{G}_{1q}^h \right) \right\} + \frac{\hat{h} \cdot k_T}{M} \left( x f_L^q D_{1q}^h - \frac{M_h}{M} h_{1L}^q \tilde{H}_{1q}^h \right) \]

B. Parsamyan (for COMPASS)
arXiv:1801.01488 [hep-ex]

Zhuo Lu

- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- **Strong non-zero effect for h^+, h^- compatible with zero, clear z-dependence**