Selected Results and Future Perspectives for TMD Observables at CERN with COMPASS

COMPASS at CERN: unique capability of measuring TMD observables with lepton beams (SIDIS) and hadron beams (Drell-Yan)

Transverse Momentum Dependent PDFs

Single Spin Asymmetries in SIDIS from COMPASS
Constraining Boer Mulders-, Sivers- and Transversity-distributions

Drell-Yan at COMPASS
  Set-up
  Data taking in 2014 and 2015
  Plans for 2016-2018
  First Steps towards the future: COMPASS 2020
COMPASS at the CERN SPS

Common Muon Proton Apparatus for Structure and Spectroscopy

Broad physics program between COMPASS I and II
Studies of nucleon spin structure with longitudinally and transversely polarized $^6\text{LiD}$ and NH$_3$ targets in DIS, SIDIS and Drell-Yan processes.
SIDIS and exclusive reactions with $lq$ hydrogen targets.
Hadron Spectroscopy and Primakov Reactions with hadron beams and unpolarized targets.
COMPASS Collaboration

~250 physicists from 24 institutions in 13 countries
Two staged large acceptance spectrometers with high rate capability:

1. Large Angle Spectrometer (LAS)
2. Small Angle Spectrometer (SAS)

1. Muon, electron or hadron secondary beams with the momentum range 20-250 GeV and intensities up to $10^8$ particles per second.

2. Solid state polarized targets, NH$_3$ or $^6$LiD, as well as liquid hydrogen target and nuclear targets.


COMPASS – Important Instrumentation Features

- 3He – 4He dilution refrigerator (T~50mK)
- Solenoid: 2.5T
- Dipole magnet: 0.6T
- He – 4He dilution refrigerator (T~50mK)
- d (LiD) 50% 40%
- p (NH3) 90% 16%

Opposite polarization in different target segments reversed frequently.
Transverse Momentum Dependent Quark Distribution Functions at Leading Twist

from Acardi et al. arXiv:1212.1701

<table>
<thead>
<tr>
<th>Nucleon polarization</th>
<th>Quark polarization</th>
<th>Unpolarized ((U))</th>
<th>Longitudinally polarized ((L))</th>
<th>Transversely polarized ((T))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(U)</td>
<td>(f_1 = )</td>
<td></td>
<td></td>
<td>(h_1^\perp = )</td>
</tr>
<tr>
<td>(L)</td>
<td>(g_1 = ) Helicity</td>
<td></td>
<td></td>
<td>(h_{1L}^\perp = )</td>
</tr>
<tr>
<td>(T)</td>
<td>(f_{1T} = ) Sivers</td>
<td>(g_{1T} = )</td>
<td></td>
<td>(h_{1T}^\perp = )</td>
</tr>
</tbody>
</table>

similar for gluons
TMD Modulations in the SIDIS and Drell-Yan Cross Sections

**SIDIS:**

\[
\frac{d\sigma}{dxdydzd\phi_h dp_{hT}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \sigma_U \left\{ 1 + \varepsilon \cos(2\phi_h) A_{UU}^{\cos(2\phi_h)} \\
+ S_T \left[ \sin(\phi_h - \phi_S) A_{UT}^{\sin(\phi_h - \phi_S)} + \varepsilon \sin(\phi_h + \phi_S) A_{UT}^{\sin(\phi_h + \phi_S)} \right] \\
+ \varepsilon \sin(3\phi_h - \phi_S) A_{UT}^{\sin(3\phi_h - \phi_S)} \right\} \\
+ S_T P_I \left[ \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) A_{LT}^{\cos(\phi_h - \phi_S)} \right]\]

**DY:**

\[
\frac{d\sigma}{d^4qd\Omega} = \frac{\alpha^2}{\Phi q^2} \hat{\sigma}_U \left\{ \left( 1 + \cos^2(\theta) + \sin^2(\theta) A_{UU}^{\cos(2\phi)} \right) \cos(2\phi) \right\} \\
+ S_T \left[ (1 + \cos(\theta)) A_{UT}^{\sin(\phi_S)} \sin(\phi_S) \right. \\
+ \sin^2(\theta) \left( A_{UT}^{\sin(2\phi + \phi_S)} \sin(2\phi + \phi_S) + A_{UT}^{\sin(2\phi - \phi_S)} \sin(2\phi - \phi_S) \right) \right\} \]
Modulation Amplitudes vs TMDs

SIDIS:

\[ A_{UU}^{\cos(2\phi_h)} \propto h_1^{\perp q} \otimes H_1^{\perp h} \]
\[ A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_1^{h} \]
\[ A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1^{q} \otimes H_1^{\perp h} \]

DY:

\[ A_{UU}^{\cos(2\phi_{CS})} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q} \text{ Boer-Mulders} \]
\[ A_{UT}^{\sin(\phi_S)} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q} \text{ Sivers} \]
\[ A_{UT}^{\sin(2\phi_{CS}-\phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_1^{q} \text{ Transversity} \]
Kinematic Coverage: SIDIS vs Drell-Yan

The phase space for Drell-Yan and SIDIS processes partially overlap in the $x-Q^2$ plane.

In the region of overlap in $x$, the average $Q^2$ in Drell-Yan is about two times larger compared to SIDIS.
Transverse Momentum Dependence in the Unpolarized Cross Section

- The cross-section dependence on transverse hadron momentum, $P_{hT}$, results from:
  - intrinsic $k_\perp$ of the quarks
  - $p_\perp$ generated in the quark fragmentation
  - A Gaussian ansatz for $k_\perp$ and $p_\perp$ leads to
  - $\langle P_{hT}^2 \rangle = z^2 \langle k_{\perp}^2 \rangle + \langle p_{\perp}^2 \rangle$

- The azimuthal modulations in the unpolarized cross-sections originate from:
  - Intrinsic $k_\perp$ of the quarks
  - The Boer-Mulders PDF

Challenge: requires correction for apparatus acceptance!
Hadron Multiplicities
vs x,Q^2, z and p_{hT}

\[ M^h(x, z, P_{hT}^2; Q^2) = \frac{d^5\sigma^h/dx dQ^2 dz d^2\vec{p}_T}{d^2\sigma^{DIS}/dx dQ^2} \]

0.2<z<0.3

2005 \textsuperscript{6}LiD data, COMPASS preliminary at Spin 2014
Boer-Mulders and Cahn: $A_{UU}^{\cos 2\phi_h}$


2004 $^6$LiD target data

\[
\frac{d\sigma}{p_T^h dp_T^h dx dy dz d\phi_h} = \sigma_0 \left( 1 + \epsilon_1 A_{\cos \phi_h}^{UU} \cos \phi_h + \epsilon_2 A_{\cos 2\phi_h}^{UU} \cos 2\phi_h + \lambda \epsilon_3 A_{\sin \phi_h}^{LU} \sin \phi_h \right)
\]
Boer-Mulders and Cahn: $A^{UU \cos \phi_h}$


2004 $^6$LiD target data

\[
\frac{d\sigma}{p_T^h d\sigma_T^h dx dy dz d\phi_h} = \sigma_0 \left( 1 + \epsilon_1 A^{UU \cos \phi_h} \cos \phi_h + \epsilon_2 A^{UU \cos 2\phi_h} \cos 2\phi_h + \lambda \epsilon_3 A^{LU \sin \phi_h} \sin \phi_h \right)
\]
Towards a Global Analysis of $A_{UU}^{\cos 2\phi_h}$, $A_{UU}^{\cos 2\phi_{CS}}$ in SIDIS and $A_{UU}^{\cos 2\phi_h}$, $A_{UU}^{\cos 2\phi_{CS}}$ in Drell-Yan

Data at different $Q^2$ (and from Drell-Yan) will help to isolate BM contributions

- Cahn effect (Twist-4) comparable to BM effect
- Same sign of Cahn contribution for positive and negative pion
- Different average transverse momenta are preferred
- BM contribution opposite in sign for positive and negative pions

Data at different $Q^2$ (and from Drell-Yan) will help to isolate BM contributions
Extraction of Transversity Distributions and Determination of the Tensor Charge

**SIDIS**
\[ \sim \delta q(x) \times CFF(z) \]
\[ \sim \delta q(x) \times IFF(z) \]

**COMPASS**

**Transversity, \( \delta q(x) \)**

**Theory**

Lattice QCD: Tensor Charge = \[ \sum_{q=u,d} \int_0^1 \delta q(x) dx \]

**e^+e^-**
\[ \sim CFF(z_1) \times CFF(z_2) \]
\[ \sim IFF(z_1) \times IFF(z_2) \]

**pp \rightarrow jets**
\[ \sim G(x_1) \times \delta q(x_2) \times CFF(z) \]

**pp \rightarrow h^+ + h^- + X**
\[ \sim G(x_1) \times \delta q(x_2) \times IFF(z) \]

**\pi p \rightarrow l^+ + l^- + X** Drell-Yan
\[ \sim h_{1}^{\perp}(x_1) \times \delta q(x_2) \]
Collins Asymmetries for Pions on Proton Targets

Selected TMD Results from COMPASS


Combined 2007 and 2010 proton data samples analyzed.
Transversity & Tensor Charge Extracted with TMD Evolution and Recent Data Sets


Data sets from SIDIS (HERMES, JLab, COMPASS) and $e^+e^-$ (Belle, BaBar)

Fit describes data sets well!
Transversity and the Tensor Charge Extracted Using TMD Evolution and Recent Data Sets


Results given at $Q^2 = 2.4, 10$ and $1000$ GeV$^2$

Favored and unfavored Collins FF

up and down transversity distributions

Selected TMD Results from COMPASS
Transversity and the Tensor Charge Extracted Using TMD Evolution and Recent Data Sets


up and down contributions to tensor charge

Integrals in data region

\[ \delta u_{[0.0065,0.35]} = +0.30^{+0.04}_{-0.07} \]
\[ \delta d_{[0.0065,0.35]} = -0.20^{+0.12}_{-0.07} \]

Integrals in [0,1]

\[ \delta u_{[0,1]} = +0.39^{+0.07}_{-0.11} \]
\[ \delta d_{[0,1]} = -0.22^{+0.14}_{-0.08} \]
Combined 2007 and 2010 proton data samples analyzed. Good agreement to prediction based on fit to Collins data.
Sivers Asymmetries for $\pi$, $K$ and $K^0$

Combined 2007 and 2010 proton data samples analyzed.

Selected TMD Results from COMPASS
Sivers Asymmetries for $\pi^+ \text{ vs } K^+$

Kaon asymmetries slightly larger Compared to pion? Evidence for sea contribution?

Combined 2007 and 2010 proton data samples analyzed.
COMPASS and HERMES Sivers Asymmetries for $\pi^+ \text{ vs } K^+$

Combined 2007 and 2010 COMPASS proton data samples analyzed.
Sivers – Global Analysis of HERMES & COMPASS Data


Leading order analysis

Full QCD analysis including TMD evolution

Still significant errors, no data for x>0.35 \(\Rightarrow\) J-Lab 12 GeV

Sign Change \(\Rightarrow\) COMPASS Drell-Yan (NSAC Milestone . . .)

Selected TMD Results from COMPASS
Sivers Asymmetries on $^6$LiD and NH$_3$ for Gluons

Krzysztof Kurek and Adam Szabelski for the COMPASS collaboration

COMPASS preliminary

\[
A_{Siv} = R_{PGF}A_{Siv}^{PGF} + R_{QCD}A_{Siv}^{QCD} + R_{LP}A_{Siv}^{LP}
\]

01/09/16

Selected TMD Results from COMPASS
Sign Change of Sivers- and Boer-Mulders Functions Between SIDIS and DY

Sivers: \[ f_{1T}^{+}(x, k_T) \big|_{SIDIS} = -f_{1T}^{+}(x, k_T) \big|_{DY} \]

Boer-Mulders: \[ h_1^{+}(x, k_T) \big|_{SIDIS} = -h_1^{+}(x, k_T) \big|_{DY} \]

Direction of the gauge-link integrals of $k_T$ dep. pdfs is process-dependent and changes its sign between SIDIS and DY.

Need to confirm sign reversal in polarized Drell-Yan!

NSAC performance Milestone HP13 for 2015

TEST “modified” universality of TMD pdfs!
Instrumentation Updates for Drell-Yan Physics

Polarized Target

- Two cells of NH$_3$
- Polarisation $\sim 80\%$
- Dilution factor $\sim 22\%$

Hadron beam
190 GeV/c $\pi$ beam (small contamination of $K$ and $\bar{p}$)

Hadron Absorber

- Due to small cross-section, measurement requires high luminosity
- Hadron absorber downstream of target
  - Stops hadrons and non interacting beam
  - Degrade resolutions, two target cells, vertex detector
- Nuclear targets: Al and W $\Rightarrow$ unpolarised DY studies

June-2-2016

Selected TMD Results from COMPASS
2014 Drell-Yan Pilot Run: Di-Muon Mass Spectrum

- Short Pilot Run in 2014 (~2 weeks of stable data taking)
- No polarization
- Beam intensity up to $8 \times 10^7 / s$
- No vertex detector
2014 Drell-Yan Pilot Run: Vertex Distribution

Z-coordinates vertex distribution, \( M_{\mu\mu} > 4 \text{ GeV} \)
(1) Study of nuclear effects based on Al and W-targets will improve precision of existing information on EMC effect.

(2) Improve precision on testing the Lam Tung sum rule.
First Polarized Drell-Yan Run - 2015

- NH$_3$ polarised target (plus Al and W targets)
- $I_{beam} \sim 10^8 \pi / s$ - very high intensity
- Four months of stable data taking are being analysed
  $\Rightarrow$ One period already produced
- $M_{\mu^+\mu^-} > 4 \text{ GeV}/c^2 \sim 80000 \mu^+\mu^-$ pairs expected from polarised target
- $\delta A_{UT}^{\sin(\phi_S)} \sim 2.8\% \Rightarrow$ Models predict $A_{UT}^{\sin(\phi_S)}$ from 5% to 10%

Sivers asym: $A_{UT}^{\sin(\phi_S)} = A_{UT}(\phi_\gamma - \phi_S) = -A_N$, the same pion PDF is used (PRD 45 (1992) 2349)

P. Sun and F. Yuan, PRD 88 (2013) 114012, $x_F = x_\pi - x_p$, $p_T < 2 \text{ GeV}/c$

Echevarria et al, PRD 89 (2014) 074013, $x_F = x_p - x_\pi$, $p_T < 1 \text{ GeV}/c$
COMPASS Run Plan and Planning for Future Physics and Upgrades

1. 2016-2017 – Two years of exclusive physics with muon beams on liquid hydrogen targets

2. 2018 – Drell-Yan with transversely polarized target NH$_3$

2016 – use series of workshops to formulate physics program for 2020 and beyond:

(1) COMPASS Workshop: Beyond 2020, March 21-22, 2016 at CERN
Initial survey of ideas for SIDIS, exclusive physics, hadron spectroscopy and Drell-Yan.

(2) COMPASS Internal Study Groups.

(3) Physics Beyond Colliders, September 6-7, 2016, CERN.
First ideas were formulated for a document submitted to the European Strategy Preparatory Group in 2012. This document will be updated with ideas and result of the present workshops and study groups.

<table>
<thead>
<tr>
<th>Physics item</th>
<th>Key aspects of the measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadron spectroscopy</td>
<td>280 GeV beam, higher intensity, $\pi$, $K$ and $\bar{p}$ separation</td>
</tr>
<tr>
<td>GPD $E$</td>
<td>Transversely polarized proton target</td>
</tr>
<tr>
<td>SIDIS $h_1^T$ with same accuracy as $h_1^{\perp}$ $f_1^T$ evolution</td>
<td>Transversely polarized deuteron target, 100 GeV and transversely polarized proton target</td>
</tr>
<tr>
<td>DY universality of TMD PDFs flavor separation test of the Lam-Tung relation EMC effect in DY</td>
<td>Higher statistics with transversely polarized proton target, transversely polarized deuteron target, hydrogen target, different nuclear targets</td>
</tr>
</tbody>
</table>
A Speculative Example: Physics with RF Separated Pion, Kaon and Anti-Proton Beams?

Kaon and Anti-Protons Flux possibly reaching $10^7$ p./s

<table>
<thead>
<tr>
<th>Particle type</th>
<th>From CKM beam</th>
<th>Antiproton beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam momentum (GeV/c)</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>Momentum spread (%)</td>
<td>±1</td>
<td>±2</td>
</tr>
<tr>
<td>Angular emittance $H,V$ (mrad)</td>
<td>±3.5, ±2.5</td>
<td>±3.5, ±2.5</td>
</tr>
<tr>
<td>Solid angle ($\mu$sterad)</td>
<td>10-12$\pi$</td>
<td>10-12$\pi$</td>
</tr>
<tr>
<td>% wanted particles lost on dump</td>
<td>37</td>
<td>20</td>
</tr>
</tbody>
</table>

Selected TMD Results from COMPASS

June-2-2016
Pion and Kaon Structure from Drell-Yan Using a Hydrogen Target

Use anti—proton beam and CPT to get p-BMF,

Use pion and kaon beams to study meson structure! Unpolarized
Or first comparison of Meson and Baryon BMF and first comparison of BMF for different mass mesons.

June-2-2016

Selected TMD Results from COMPASS
Consider Possible Addition of a Recoil Detector to the Polarized Target for Exclusive Physics

Initial ideas and first work by Dubna (I. Savin), Munich (J. Friedrich) and at CERN (F. Gautheron and A. Magnon)

Ideas and Suggestion Will be Welcome!
Summary:
COMPASS continues massive data taking for Drell-Yan and exclusive physics through 2018. Analyses of SIDIS, exclusive processes, Drell-Yan Data and hadron spectroscopy is in full swing.

For the next 10 years
• before any collider is available,
• and complementary to Jlab 12 GeV

COMPASS@CERN aims to continue as a major player in QCD physics using its unique high energy
• hadron- and muon beams.

Looking even further... a polarized lepton-nucleon collider appears to be a mandatory tool for achieving further progress!

June-2-2016
Selected TMD Results from COMPASS