Polarised Drell-Yan results from COMPASS

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on behalf of the COMPASS collaboration
COMPASS: Common Muon and Proton Apparatus for Structure and Spectroscopy (fixed target experiment at CERN)

Physics program

- Spin dependent structure function $g_1$
- Quark and gluon helicities
- Transversity and TMDs (via SIDIS and DY processes)
- GPDs
- Fragmentation functions
- Primakoff effect, pion polarisabilities
- Exotics: glueballs, charmed baryons, multiquark states

Taking data since 2002

240 physicists
23 institutes
12 countries + CERN

μ+/μ−
A picture of the QCD fundamental state: the proton

The base element of all matter is a complex QCD object:

Main questions addressed by COMPASS about the structure of the proton:

1) What is the nature of the proton spin?

2) How are the confined partons (quarks and gluons) distributed in the position and in the momentum space?

$S_z^N = \frac{1}{2} \Delta \Sigma + \Delta G + L_{z}^{q,g}$

Main questions addressed by COMPASS on the proton structure:

1) What is the nature of the proton spin?

2) How are the confined partons (quarks and gluons) distributed in the position and in the momentum space?
General description of the proton structure

Wigner Distributions

\[ W(x, \vec{b}_T, \vec{k}_T) \]

Momentum tomography

\[ \int d\vec{b}_T \int d\vec{k}_T \]

Spatial tomography

GPDs

\[ f(x, \vec{k}_T) \]

3D

Longitudinal momentum density

\[ \int \vec{k}_T \]

Spatial density

\[ \int \vec{b}_T \int d\tau \]

TMDs

\[ f(x) \]

1D

PDFs

\[ F( \vec{b}_T) \]

5D

PDF

transverse position

longitudinal momentum

TMD

transverse momentum

partons

GPD

PDF

PDFs: Generalized Parton Distributions

TMDs: Transverse Momentum Dependent PDFs
Nucleon structure in the momentum space

3 PDFs ($x$) & 5 TMDs ($x$, $k_T$):

<table>
<thead>
<tr>
<th>Nucleon</th>
<th>Quark Unpolarised</th>
<th>Longitudinal Polarisation</th>
<th>Transverse Polarisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unpolarised</td>
<td>$f_1$ (Number density)</td>
<td></td>
<td>$h^\perp_1$ (Boer Mulders)</td>
</tr>
<tr>
<td>Longitudinal Polarisation</td>
<td></td>
<td>$g_1$ (Helicity)</td>
<td>$h^\perp_{1L}$ (Worm Gear)</td>
</tr>
<tr>
<td>Transverse Polarisation</td>
<td></td>
<td>$f^\perp_{1T}$ (Sivers)</td>
<td>$g_{1T}$ (Worm Gear)</td>
</tr>
</tbody>
</table>

Contains information about the Orbital Angular Momentum (OAM)

Investigated at COMPASS via measurement of spin asymmetries

Study $\Delta q(x, Q^2)$ and $\Delta g(x, Q^2)$

(Transversity)

Study $\Delta_T q(x, Q^2)$

Surviving $k_T$ integration

$\Phi^{Tw^{-2}}_{Coll}(x) = \frac{1}{2} \left[ q(x) + S_L Y_5 \Delta q(x) + S_L Y_5 \Delta_T \Delta_T q(x) \right]$
The M2 beamline at CERN

Naturally polarised muon beam for SIDIS measurements: \( P_\mu \sim 80\% \)

<table>
<thead>
<tr>
<th>SPS</th>
<th>p (400 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_\mu )</td>
<td>( \pi^+ )</td>
</tr>
</tbody>
</table>

- Beryllium target
- Hadron absorber
- COMPASS target
- Secondary beam:
  - \( \sim 96\% \pi \)
  - 600 m decay pipe

\( (\pi, k)^{+/-}, p \)

\( \mu^{+/-} (160/200 \text{ GeV}) \)

hadrons (190 GeV)

400 m for momentum and beam selection (up to \( 10^8 \) particles/s)

used only for \( \mu \) beams

Naturally polarised muon beam for SIDIS measurements: \( P_\mu \sim 80\% \)
The polarised target of COMPASS

Drell-Yan setup in 2015

- $P_T \sim 73\%$
- $f$ (dilution factor) $\sim 18\%$
- $T \sim 50 \text{ mK } (^3\text{He} / ^4\text{He})$
- Solenoid field $\sim 2.5 \text{ T}$
- Dipole field $\sim 0.6 \text{ T}$

Dynamic Nuclear Polarisation:

- The target is irradiated with a specific microwave frequency for a simultaneous spin flip of the electron–nucleon system.
- The nucleon keeps its spin due to its long relaxation time.

Transversely polarised $\text{NH}_3$ cells

$\pi$ beam $\sim 10^8 / s$
COMPASS spectrometer for the Drell-Yan setup: Double stage spectrometer for large angles (SM1) and small angles (SM2)
The Drell-Yan (DY) and SIDIS cross-sections using a transversely polarised target

\[ d\sigma^{\text{DY}} \propto (1 + \cos^2(\theta) + \sin^2(\theta) A_{UU}^{\cos(2\phi)} \cos(2\phi)) \]
\[ + S_T [(1 + \cos^2(\theta)) A_{UT}^{\sin(\phi_S)} \sin(\phi_S) \]
\[ + \sin^2(\theta) (A_{UT}^{\sin(2\phi - \phi_S)} \sin(2\phi - \phi_S)) \]
\[ + A_{UT}^{\sin(2\phi + \phi_S)} \sin(2\phi + \phi_S)] \]

\[ d\sigma^{\text{SIDIS}} \propto (1 + \epsilon \cos(2\phi_h) A_{UU}^{\cos(2\phi_h)} \]
\[ + S_T [\sin(\phi_h - \phi_S) A_{UT}^{\sin(\phi_h - \phi_S)} \]
\[ + \epsilon \sin(\phi_h + \phi_S) A_{UT}^{\sin(\phi_h + \phi_S)} \]
\[ + \epsilon \sin(3\phi_h - \phi_S) A_{UT}^{\sin(3\phi_h - \phi_S)} \]
Interpretation of azimuthal spin asymmetries

Spin (in)dependent fragmentation functions → (D)H

Pion PDF/TMDs

Proton TMDs

Spin (in)dependent fragmentation functions → (D)H

DY

SIDIS

Boer-Mulders

Sivers

Transversity

Pretzelosity

A_{UU}^{\cos(2 \phi)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}

A_{UT}^{\sin(\phi_S)} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}

A_{UT}^{\sin(2 \phi - \phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}

A_{UT}^{\sin(2 \phi + \phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}

A_{UU}^{\cos(2 \phi_h)} \propto h_{1,p}^{\perp q} \otimes h_{1q}^{\perp h}

A_{UT}^{\sin(\phi_h - \phi_S)} \propto f_{1T,p}^{\perp q} \otimes D_{1q}^{h}

A_{UT}^{\sin(\phi_h + \phi_S)} \propto h_{1,p}^{q} \otimes H_{1q}^{\perp h}

A_{UT}^{\sin(3 \phi_h - \phi_S)} \propto h_{1T,p}^{\perp q} \otimes H_{1q}^{\perp h}
Universality of the TMDs

- The resummation of soft gluons in a $k_T$ dependent PDF is process dependent:

\[ f_{1T,p}^{q}(DY) = -f_{1T,p}^{q}(SIDIS) \quad h_{1,p}^{q}(DY) = -h_{1,p}^{q}(SIDIS) \]

Crucial test of the TMD approach being performed by COMPASS!
35000 DY dimuons are used for the extraction of the transverse spin asymmetries → $M_{\mu\mu} \in [4.3, 8.5] \, \text{GeV/c}^2$ (contamination < 4%)
Kinematic distributions in the high mass range

Valence region where the Sivers TMD is predicted to be large!

\[ x_F = x_\pi - x_N \]

\[ \langle x_\pi \rangle = 0.50 \]
\[ \langle x_N \rangle = 0.17 \]
Extraction of the Twist-2 & Twist-3 Transverse Spin Asymmetries

- A total of 5 TSAs are extracted using an unbinned maximum likelihood method:

\[ d\sigma^{DY} \propto 1 + D_{[\sin(2\theta)]} A_{UU}^{\cos(\phi)} \cos(\phi) + D_{[\sin^2(\theta)]} A_{UU}^{\cos(2\phi)} \cos(2\phi) + S_T[D_{[1 + \cos^2(\theta)]} A_{UT}^{\sin(\phi_S)} \sin(\phi_S)] \\
+ D_{[\sin^2(\theta)]} (A_{UT}^{\sin(2\phi - \phi_S)} \sin(2\phi - \phi_S) + A_{UT}^{\sin(2\phi + \phi_S)} \sin(2\phi + \phi_S)) \\
+ D_{[\sin(2\theta)]} (A_{UT}^{\sin(\phi - \phi_S)} \sin(\phi - \phi_S) + A_{UT}^{\sin(\phi + \phi_S)} \sin(\phi + \phi_S)) \]

The asymmetries are weighted with the dilution factor \( f \) and the depolarisation factors \( D \):

\[ D_{[\sin(2\theta)]} = \frac{\sin(2\theta)}{1 + \lambda \cos^2(\theta)} \quad D_{[1 + \cos^2(\theta)]} = \frac{1 + \cos^2(\theta)}{1 + \lambda \cos^2(\theta)} \quad D_{[\sin^2(\theta)]} = \frac{\sin^2(\theta)}{1 + \lambda \cos^2(\theta)} \quad f = \frac{n_H O_{\pi H}^{DY}}{n_H O_{\pi H}^{DY} + \sum_A n_A O_{\pi A}^{DY}} \]
The dilution and depolarisation factors

The depolarisation factors are evaluated for $\lambda = 1$ (Drell–Yan model with $K_T = 0$).

Other scenarios with $\lambda \neq 1$ lead to a maximum uncertainty of 5%.

Fraction of polarisable material

$\langle f \rangle \sim 0.18$ with an uncertainty of 8%.

Takes into account the migration of events from one target cell to another.
TSA results: DY & SIDIS measurements in the same kinematic region

DY: COMPASS PRL 119, 112002 (2017)

SIDIS: COMPASS PLB 770 (2017) 138

Higher-Twist asymmetries
A closer look to the DY Transversity
(significant asymmetry in SIDIS)

COMPASS PRL 119, 112002 (2017)

The DY data cover the region where the quarks transversity is expected to be significant.
A closer look to the DY Sivers

**DY - COMPASS PRL 119, 112002 (2017)**

![Graph showing COMPASS 2015 data with x_N and x_\pi on the x-axis and sin(\phi_s) on the y-axis, with error bars indicating uncertainty. The data points are plotted in different regions corresponding to 4.3 < M_{\mu\mu} (GeV/c^2) < 8.5.]

**SIDIS - COMPASS PLB 770 (2017) 138**

![Graph showing sin(\phi_s) and A_T for different values of Q^2 and M_{\mu\mu} (GeV/c^2).]

Significantly positive for both hadron charges at high Q^2 (encodes information about the orbital angular momentum of quarks)

What about the Sivers sign change?
Sivers asymmetry in Drell-Yan: **Sign Change is favored**

DGLAP (2016) M. Anselmino et al., arXiv:1612.06413, fit to COMPASS, HERMES and JLab SIDIS data
TMD-1 (2014) M. Echevarria et al., PRD 89 (2014) 074013, fit to COMPASS, HERMES and JLab SIDIS data, 0<p_t<1 and 4<M<9 GeV/c^2
Summary and Outlook

• In 2015 COMPASS performed the first ever polarised Drell-Yan measurement using a pion beam. The main results are:

  • The Pretzelosity asymmetry is compatible with zero (positive with a significance of about 1σ). The two higher-twist asymmetries are also compatible with zero.

  • The Transversity asymmetry is negative with a significance of 2σ

  • The predicted sign change for the Sivers TMD when accessed via SIDIS or DY processes is consistent with the measured asymmetries → First world test to the universality of the T-Odd TMDs (using the γ* channel for the DY lepton pair production)

• A second year of polarised DY data taking will take place in 2018 to improve the experimental uncertainties (for the moment the DY Sivers asymmetry is only 1σ away from zero)