Polarized Drell-Yan at COMPASS

Riccardo Longo

on behalf of the COMPASS Collaboration
INFN section of Turin and University of Turin

XII Confinement Conference

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Outline

• Introduction
  • TMD PDFs
  • The Drell–Yan process
  • The SIDIS process
  • Drell–Yan SIDIS bridge
• The COMPASS experiment
  • Selected SIDIS results from Phase I
• The COMPASS Polarized DY program
  • Four COMPASS – Drell–Yan mass-ranges
  • COMPASS DY Experimental setup
  • COMPASS Polarized DY Run 2015
• Conclusions
Transverse Momentum Dependent Parton Distribution Functions, TMD PDFs

In the **leading order QCD parton model** nucleon spin-structure can be parametrized in terms of in total 8 twist-2 intrinsic transverse momentum \((k_T)\) dependent TMD PDFs.

<table>
<thead>
<tr>
<th>Nucleon Quark</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>(f_L^q(x,k_T^2))</td>
<td></td>
<td>(f_{1T}^q(x,k_T^2))</td>
</tr>
<tr>
<td></td>
<td>Number density</td>
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<td>Sivers</td>
</tr>
<tr>
<td>L</td>
<td>(g_L^q(x,k_T^2))</td>
<td></td>
<td>(g_{1T}^q(x,k_T^2))</td>
</tr>
<tr>
<td></td>
<td>Helicity</td>
<td></td>
<td>Kotzinian-Mulders or Worm-gear T</td>
</tr>
<tr>
<td>T</td>
<td>(h_L^q(x,k_T^2))</td>
<td>(h_{1L}^q(x,k_T^2))</td>
<td>(h_{1T}^q(x,k_T^2))</td>
</tr>
<tr>
<td></td>
<td>Boer-Mulders</td>
<td>Worm-gear L</td>
<td>Transversity</td>
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</table>
In the leading order QCD parton model nucleon spin-structure can be parametrized in terms of in total 8 twist-2 intrinsic transverse momentum ($k_T$) dependent TMD PDFs.

### TMD PDFs

<table>
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<td></td>
<td>Boer–Mulders</td>
<td>Worm–gear L</td>
<td>Pretzelosity</td>
</tr>
</tbody>
</table>

TMD PDFs can be accessed through measurement of target spin (in)dependent azimuthal asymmetries both in **SIDIS** and **Drell–Yan**

**This talk**
Single Polarized Drell–Yan

General leading order QCD parton model expression of the SP DY cross-section

\[
\frac{d\sigma^{LO}}{d\Omega d^4q} = \left\{ l + D_{[\sin^2 \theta]} \ A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_T \times \left[ A_T^{\sin \varphi_S} \sin \varphi_S \right. \begin{array}{c} \left( A_T^{\sin (2\varphi_{CS}+\varphi_S)} \sin (2\varphi_{CS}+\varphi_S) \\
\left. + A_T^{\sin (2\varphi_{CS}-\varphi_S)} \sin (2\varphi_{CS}-\varphi_S) \right) \right] \right\}
\]

D-factors

\[
D_{[f(\theta)]}^{LO} = \frac{f(\theta)}{1 + \cos^2 \theta}
\]

Azimuthal asymmetries

\[
A^{w(\varphi_{CS}, \varphi_S)}_{U,T} = \frac{F_{U,T}^{w(\varphi_{CS}, \varphi_S)}}{F_U^1 + F_U^2}
\]
Single Polarized Drell–Yan

General leading order QCD parton model expression of the SP DY cross-section

\[
\frac{d\sigma^{LO}}{d\Omega d^4q} \propto \left\{ 1 + D_{[\sin^2\theta]} \right. \\
\left. \left[ A^\cos 2\varphi_{cs} U + A^\sin \varphi_S \sin \varphi_S \right. \\
\left. \times \left( A^\sin (2\varphi_{cs}+\varphi_S) + A^\sin (2\varphi_{cs}-\varphi_S) \right) \right] \right\}
\]

At COMPASS: \( h_a = \pi^- (190 \text{ GeV/c}) \) \( h_b = p^\uparrow \)

- **At LO**
  - 1 *Unpolarized Asymmetry*
  - 3 *Single Spin Asymmetries*

Measurements of these azimuthal asymmetries provide an access to specific convolutions of TMD PDFs of \( h_a \) and \( h_b \)
The SIDIS process

\[
\frac{d\sigma_{\text{SIDIS}}^{\text{LO}}}{dx dy dz dp_T^2 d\phi_h d\psi} = \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{y^2}{2x} \right) \right] \times \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \cos 2\phi_h \left( \varepsilon A_{UU}^{\cos 2\phi_h} \right) \right. \\
\left. + S_T \left[ \sin \left( \phi_h - \phi_S \right) A_{UT}^{\sin \left( \phi_h - \phi_S \right)} \right] + \sin \left( \phi_h + \phi_S \right) \left( \varepsilon A_{UT}^{\sin \left( \phi_h + \phi_S \right)} \right) \right. \\
\left. + \sin (3\phi_h - \phi_S) \left( \varepsilon A_{UT}^{\sin (3\phi_h - \phi_S)} \right) \right\} \\
+ S_T \lambda \left[ \cos \left( \phi_h - \phi_S \right) \left( \sqrt{1 - \varepsilon^2} A_{LT}^{\cos \left( \phi_h - \phi_S \right)} \right) \right] \right\}
\]

\[ A^{w(\phi_h,\phi_\psi)}_{U(L),T} = \frac{F^{w(\phi_h,\phi_\psi)}_{U(L),T}}{F_{UU,T} + \varepsilon F_{UU,L}} ; \gamma = \frac{2Mx}{Q} ; \]
\[ \varepsilon = \frac{l - y - \frac{1}{4} \gamma^2 y^2}{l - y + \frac{1}{2} y^2 + \frac{1}{4} \gamma^2 y^2} ; \]
\[ l' - y - \frac{1}{4} \gamma^2 y^2 \]

- At LO, 1 Unpolarized, 3 Single Spin and 1 Double Spin Asymmetries.
- Measurement of SIDIS azimuthal asymmetries provides an access to specific convolutions of TMD and Fragmentation functions (FFs).
The SIDIS process

\[
\frac{d\sigma^{LO}_{SIDIS}}{dx d\psi} = \left[ \frac{\alpha}{x y Q^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{y^2}{2x}\right) \right] \times \left( F_{UU,T} + \epsilon F_{UU,L} \right) \left\{ 1 + \cos 2\phi_h \left( \epsilon A_{UU}^{\cos 2\phi_h} \right) \right\}
\]

\[
\begin{bmatrix}
\sin (\phi_h - \phi_S) \left( A_{UT}^{\sin (\phi_h - \phi_S)} \right) \\
+ \sin (\phi_h + \phi_S) \left( \epsilon A_{UT}^{\sin (\phi_h + \phi_S)} \right) \\
+ \sin (3\phi_h - \phi_S) \left( \epsilon A_{UT}^{\sin (3\phi_h - \phi_S)} \right)
\end{bmatrix}
\]

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

- At LO, 1 Unpolarized, 3 Single Spin and 1 Double Spin Asymmetries.
- Measurement of SIDIS azimuthal asymmetries provides an access to specific convolutions of TMD and Fragmentation functions (FFs).

\[ A_{UU}^{\cos 2\phi_h} \propto h_{1q} \otimes H_{1q}^{\perp h} \]
\[ A_{UT}^{\sin (\phi_h - \phi_S)} \propto f_{JT}^{\perp q} \otimes D_{1q}^{\perp h} \]
\[ A_{UT}^{\sin (\phi_h + \phi_S)} \propto h_{i}^{q} \otimes H_{1q}^{\perp h} \]
\[ A_{UT}^{\sin (3\phi_h - \phi_S)} \propto h_{IT}^{\perp q} \otimes H_{1q}^{\perp h} \]
\[ A_{LT}^{\cos (\phi_h - \phi_S)} \propto g_{IT}^{q} \otimes D_{1q}^{h} \]
DY-SIDIS Bridge

Single Polarized DY (LO)

COMPASS preliminary
~30% of 2015 Drell-Yan NH$_3$ data

COMPASS preliminary
SIDIS 2010 NH$_3$ proton data

1 September 2016

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DY–SIDIS Bridge

Single Polarized DY (LO)

\[
\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha^2_{em}}{F q^2} F_U^1 \left\{ 1 + \cos^2 \theta + \sin^2 \theta \cos 2\varphi_{CS} A_{CS} \cos 2\varphi_{CS} \right. \\
+ S_T \left[ \left( 1 + \cos^2 \theta \right) \sin \varphi_S A_T^{\sin \varphi_S} \\
+ \sin^2 \theta \left( \sin \left( 2\varphi_{CS} + \varphi_S \right) A_T^{\sin \left( 2\varphi_{CS} + \varphi_S \right)} \\
+ \sin \left( 2\varphi_{CS} - \varphi_S \right) A_T^{\sin \left( 2\varphi_{CS} - \varphi_S \right)} \right) \right\} \right.
\]

Transversely polarized SIDIS (LO)

\[
\frac{d\sigma_{SIDIS}^{LO}}{dx dy dz dp_{l'}^2 d\varphi_{l'} d\psi} = \frac{\alpha}{x y Q^2} \frac{y^2}{2(1 - \varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \\
\times \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \cos 2\varphi_h \left( \varepsilon A_{UU}^{\cos 2\varphi_h} \right) \\
+ S_T \left[ \sin (\varphi_h - \varphi_S) \left( A_{UT}^{\sin (\varphi_h - \varphi_S)} \right) \\
+ \sin (\varphi_h + \varphi_S) \left( \varepsilon A_{UT}^{\sin (\varphi_h + \varphi_S)} \right) \\
+ \sin (3\varphi_h - \varphi_S) \left( \varepsilon A_{UT}^{\sin (3\varphi_h - \varphi_S)} \right) \right] \right\} \\
+ S_T \lambda \left[ \cos (\varphi_h - \varphi_S) \left( \sqrt{1 - \varepsilon^2} A_{LT}^{\cos (\varphi_h - \varphi_S)} \right) \right] \right\} 
\]
DY-SIDIS Bridge

Single Polarized DY (LO)

\[
\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha^2_{em}}{Fq^2} F_U^1 \left\{ 1 + \cos^2 \theta + \sin^2 \theta \cos 2\varphi_{CS} A_U^{\cos 2\varphi_{CS}} \right\}
\]

Transversely polarized SIDIS (LO)

\[
\frac{d\sigma^{LO}_{SIDIS}}{dx dy dz dp^2_{T} d\varphi_{h} d\psi} = \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] 
\times \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \cos 2\varphi_{h} \left( \varepsilon A_{UU}^{\cos 2\varphi_{h}} \right) \right\}
\]

\[
\left[ \sin (\varphi_{h} - \varphi_{S}) \left( A_{UT}^{\sin (\varphi_{h} - \varphi_{S})} \right) \right]
+ S_T \left[ \sin (\varphi_{h} + \varphi_{S}) \left( \varepsilon A_{UT}^{\sin (\varphi_{h} + \varphi_{S})} \right) \right]
+ \left[ \sin (3\varphi_{h} - \varphi_{S}) \left( \varepsilon A_{UT}^{\sin (3\varphi_{h} - \varphi_{S})} \right) \right]
+ S_T \lambda \left[ \cos (\varphi_{h} - \varphi_{S}) \left( \sqrt{1-\varepsilon^2} A_{LT}^{\cos (\varphi_{h} - \varphi_{S})} \right) \right]
\]
**DY-SIDIS Bridge**

**Single Polarized DY (LO)**

\[
\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left\{ 1 + \cos^2 \theta + \sin^2 \theta \cos 2\varphi_{CS} A_{U}^{\cos 2\varphi_{CS}} \right. \\
+ S_T \left[ \begin{array}{c}
(1 + \cos^2 \theta) \sin \varphi_S A_T^{\sin \varphi_S} \\
+ \sin^2 \theta \left( \sin (2\varphi_{CS} + \varphi_S) A_T^{\sin (2\varphi_{CS} + \varphi_S)} \\
+ \sin (2\varphi_{CS} - \varphi_S) A_T^{\sin (2\varphi_{CS} - \varphi_S)} \right) \end{array} \right] \right\}
\]

\[
\frac{d\sigma^{LO}}{dx dy dp_t^2 d\varphi_h d\varphi} = \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)(1+\frac{\gamma^2}{2x})} \left\{ 1 + \cos 2\varphi_h \left( \varepsilon A_{UU}^{\cos 2\phi_h} \right) \right. \\
\times \left( F_{UU,I} + \varepsilon F_{UU,L} \right) \left\{ \begin{array}{c}
\hat{h}^{1q} \otimes \hat{H}_{1q}^{h} \\
+ S_T \begin{array}{c}
\sin (\phi_h - \phi_S) \left( A_{UT}^{\sin (\phi_h - \phi_S)} \right) \\
+ \sin (\phi_h + \phi_S) \left( A_{UT}^{\sin (\phi_h + \phi_S)} \right) \\
+ \sin (3\phi_h - \phi_S) \left( A_{UT}^{\sin (3\phi_h - \phi_S)} \right) \\
+ S_T \lambda \left[ \cos (\phi_h - \phi_S) \left( \sqrt{1-\varepsilon^2} A_{LT}^{\cos (\phi_h - \phi_S)} \right) \right] \end{array} \\
+ \hat{h}^{1q} \otimes \hat{H}_{1q}^{h} \\
\end{array} \right. \right\}
\]

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Within the concept of generalized universality (time-reversal modified process-independence) of TMD PDFs it appears that same parton distribution functions can be accessed both in SIDIS and Drell–Yan

\[ \frac{d\sigma_{SIDIS}^{LO}}{dy} = \left[ \frac{\alpha_{em}}{F_2^2} \right] F_U^1 \left\{ 1 + \cos^2 \theta + \sin^2 \theta \cos 2q_{CS} A_U^{\cos 2q_{CS}} \right. \\
+ S_T \left[ (1 + \cos^2 \theta) \sin q_s A_T^{\sin q_s} \\
+ \sin^2 \theta \left( \sin(2q_{CS} + q_s) A_T^{\sin(2q_{CS} + q_s)} \\
+ \sin(2q_{CS} - q_s) A_T^{\sin(2q_{CS} - q_s)} \right) \right] \right\} \\
\times \left( F_{UU, T} + \epsilon F_{UU, L} \right) \left\{ 1 + \cos 2\phi_h \left( \epsilon A_U^{\cos 2\phi_h} \right) \right\} \\
\sin(\phi_h - \phi_S) \left( A_T^{\sin(\phi_h - \phi_S)} \right) \\
+ \sin(\phi_h + \phi_s) \left( \epsilon A_U^{\sin(\phi_h + \phi_S)} \right) \\
+ \sin(3\phi_h - \phi_S) \left( \epsilon A_U^{\sin(3\phi_h - \phi_S)} \right) \\
+ S_T \lambda \left[ \cos(\phi_h - \phi_S) \left( \sqrt{1 - \epsilon^2} A_U^{\cos(\phi_h - \phi_S)} \right) \right] \} \\
\]

DP – DY only

TMD Universality

Sivers and BM sign change

\[ f_{1T}^{\perp q}\big|_{DY} = - f_{1T}^{\perp q}\big|_{SIDIS} \]

\[ h_{1T}^{\perp q}\big|_{DY} = - h_{1T}^{\perp q}\big|_{SIDIS} \]
Within the concept of generalized universality (time-reversal modified process-independence) of TMD PDFs it appears that same parton distribution functions can be accessed both in SIDIS and Drell-Yan.

**Polarized DY data are needed for the verification!**

**TMD Universality**

Sivers and BM sign change

\[
\begin{align*}
\left. f_{1T}^{\perp q}\right|_{DY} &= - \left. f_{1T}^{\perp q}\right|_{SIDIS} \\
\left. h_1^{q}\right|_{DY} &= - \left. h_1^{q}\right|_{SIDIS}
\end{align*}
\]
The COMPASS collaboration

SPS
LHC
Fixed target experiment
SPS North Area
First data taking in 2002

Phase I
- 2002 – 2011
- Hadron spectroscopy
- Nucleon spin structure studies

G.K. Mallot → Tuesday
M.Mikhasenko → Thursday

Phase II
- 2012 – 2018
- Primakoff + DVCS pilot run (2012)
- Drell-Yan (2015, 2018)

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COMPASS SIDIS experimental setup

- Polarized target
- Large angular acceptance
- Broad kinematic range covered
- Muon and hadron beam
- High tracking power (~350 planes)
- Two stages spectrometer
  - Large Angle Spectrometer (LAS)
    - $35 \text{ mrad} < \theta < 180 \text{ mrad}$
    - SM1 magnet (1 T · m)
  - Small Angle Spectrometer (SAS)
    - $18 \text{ mrad} < \theta < 35 \text{ mrad}$
    - SM2 magnet (4.4 T · m)

<table>
<thead>
<tr>
<th>Target</th>
<th># of cells</th>
<th>Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH$_3$</td>
<td>3</td>
<td>L&amp;T, ~80-90%</td>
</tr>
<tr>
<td>$^6$LiD</td>
<td>2,3</td>
<td>L&amp;T, ~50%</td>
</tr>
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</table>
### COMPASS SIDIS data taking

<table>
<thead>
<tr>
<th>Year</th>
<th>Beam</th>
<th>Target</th>
<th># cells</th>
<th>Polarization</th>
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</thead>
<tbody>
<tr>
<td>2002</td>
<td>μ⁺ @ 160 GeV/c</td>
<td>Deuteron, $^6$LiD</td>
<td>2</td>
<td>L &amp; T, ~ 50%</td>
</tr>
<tr>
<td>2003</td>
<td>μ⁺ @ 160 GeV/c</td>
<td>Deuteron, $^6$LiD</td>
<td>2</td>
<td>L &amp; T, ~ 50%</td>
</tr>
<tr>
<td>2004</td>
<td>μ⁺ @ 160 GeV/c</td>
<td>Deuteron, $^6$LiD</td>
<td>2</td>
<td>L &amp; T, ~ 50%</td>
</tr>
<tr>
<td>2006</td>
<td>μ⁺ @ 160 GeV/c</td>
<td>Deuteron, $^6$LiD</td>
<td>3</td>
<td>L, ~ 50%</td>
</tr>
<tr>
<td>2007</td>
<td>μ⁺ @ 160 GeV/c</td>
<td>Proton, NH₃</td>
<td>3</td>
<td>L &amp; T, ~ 90%</td>
</tr>
<tr>
<td>2010</td>
<td>μ⁺ @ 160 GeV/c</td>
<td>Proton, NH₃</td>
<td>3</td>
<td>T, ~ 90%</td>
</tr>
<tr>
<td>2011</td>
<td>μ⁺ @ 200 GeV/c</td>
<td>Proton, NH₃</td>
<td>3</td>
<td>L, ~ 90%</td>
</tr>
</tbody>
</table>

- During Phase I, the COMPASS collaboration collected a considerable amount of **SIDIS data**, using L&T polarized proton and deuteron targets.
- Many interesting and important **results** and still more to come from several ongoing analysis...

G.K. Mallot → Tuesday

---

2002 – 2004

2006 – 2011

Sivers asymmetry measured in COMPASS is lower than the one from HERMES, for both $\pi^+$ and $K^+$. 
Sivers asymmetry for \( \pi^+ \) and \( K^+ \): COMPASS proton 2010 vs Hermes proton 2002–2005.

Sivers asymmetry measured in COMPASS is lower than the one from HERMES, for both \( \pi^+ \) and \( K^+ \).

Different \( x:Q^2 \) phase spaces.

For given \( x \) COMPASS operates with larger mean \( Q^2 \) values (factor 2–3).

Can the differences in the Sivers amplitude be an evidence of TMD evolution effects?
COMPASS DY ranges

Four $Q^2$ (or mass) ranges

I. $1 < Q^2/(\text{GeV}/c^2) < 4$, "Low mass"
   - Large combinatorial background:
     - Pion and Kaon decays.
     - Open charm (bottom) semi-leptonic decays $D\bar{D}$, $B\bar{B}$
   - Smaller Asymmetries.

II. $4 < Q^2/(\text{GeV}/c^2) < 6.25$, "Intermediate"
    - High DY cross section.
    - Still low signal/background

III. $6.25 < Q^2/(\text{GeV}/c^2) < 16$, "J/ψ"
    - Lower background
    - Difficult to disentangle DY

IV. $16 < Q^2/(\text{GeV}/c^2) < 81$, "High Mass"
    - Beyond J/ψ and ψ' peak.
    - Low background and just in the region $16 < Q^2/(\text{GeV}/c^2) < 25$
    - Valence quark region → Larger asymmetries! But ...
    - Low cross-section
SIDIS results in DY ranges


- COMPASS Proton 2010 data sample divided into the 4 $Q^2$ DY ranges.
- Sivers asymmetry extracted for each $Q^2$ range, using two different $z$-ranges
- Results for the Sivers asymmetry in DY High mass range in SIDIS are already available!
- Only DY part of the puzzle is missing.

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COMPASS Proton 2010 data sample divided into the 4 $Q^2$ DY ranges.
- Sivers asymmetry extracted for each $Q^2$ range, using two different $z$-ranges
- Results for the Sivers asymmetry in DY High mass range in SIDIS are already available!
- Only DY part of the puzzle is missing.
Target material: ammonia beads immersed into liquid helium.
- Oppositely polarized cells.
- Data are collected simultaneously for both target spin orientation.
- Polarization reversal each 7 days, which allows to reduce possible systematics.
- Average polarization per cell $\sim 80\%$.
**COMPASS experimental setup: DY 2015**

- **Beam plug**: made of tungsten, to stop the beam. 120 cm long, $\phi = 9.5 - 8.5$ cm.
- **Additional nuclear target**: Al, 7 cm long, $\phi = 9.5$ cm.
- **Al + W plug** → along with NH$_3$ are another source for unpolarized DY data.
- Higher yield due to density of the materials.
- Lower reconstruction and vertex resolution with respect to NH$_3$.

**Setup for DY, $\pi^- + p \rightarrow \mu^+\mu^- + X$**
- Polarized Target
- Hadron Absorber
- Nuclear Targets

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1 September 2016

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Setup for DY, $\pi^- + p \rightarrow \mu^+\mu^- + X$

- Polarized Target
- Hadron Absorber
- Nuclear Targets

COMPASS experimental setup: DY 2015

Nuclear Targets

Al

W

7 cm 120 cm

190 GeV/c

$\pi^-$

$4 < M_{\mu\mu}/(\text{GeV}/c^2) < 9$

COMPASS preliminary

~30% of 2015 Drell-Yan data

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COMPASS DY run 2015 kinematics: $x_\pi$, $x_N$, $x_F$ and $q_T$
Expected accuracy

- After 2015 DY run, COMPASS expected accuracy for Sivers asymmetry was updated;

Estimated accuracy for COMPASS DY-Run of 2015

- There is a variety of models giving largely spread theoretical predictions.
- Experimental data are the necessary input to constrain the models.
Conclusions

- The DY and SIDIS process are complementary ways to access TMD PDFs.
- The COMPASS Collaboration took a considerable amount of SIDIS data during the Phase I.
- The experiment has taken the first ever polarized DY data in 2015.
- COMPASS is the first experiment that has measured both SIDIS and polarized DY using essentially the same spectrometer!
  - Cross SIDIS-DY studies are already available.
  - Exploration of the same $x:Q^2$ phase space both in SIDIS and DY.
  - First opportunity to test TMD universality and the sign change between SIDIS and DY for Sivers and Boer-Mulders PDFs.
- Analyses are running, new results will be available soon!

Thank you! ευχαριστίες!
COMPASS SIDIS results: Collins

Collins asymmetry: COMPASS proton vs Hermes proton.
- Clear effect at large $x$.
- Collins amplitudes for $\pi^+$ and $\pi$ are mirror symmetric (favoured unfavoured Collins FF).
- Even taking into account different $Q^2$ coverage of the experiments, asymmetries appeared to be compatible.
Asymmetry is small and compatible with zero within statistical accuracy;
It still can provide some information about the PDF;


Riccardo Longo
COMPASS SIDIS results: BM

\[ A_{UU}^{\cos 2\phi_h} \propto -h_1^{\perp q} \otimes H_1^{\perp h} + \left( \frac{M}{Q} \right) f_1^q \otimes D_{1g}^h + \ldots \]

- Large positive amplitudes decreasing with x for both \( h^+/h^- \).
- Clear differences between \( h^+/h^- \)
- Slightly larger amplitude for \( h^- \)
- Similarity between proton and deuteron results for \( A_{UU}^{\cos 2\phi_h} \) has been previously observed at HERMES collaboration.

\[ \sigma_{sys} \approx 2 \cdot \sigma_{stat} \]

\[ \begin{array}{c}
\text{COMPASS deuteron} \\
\text{\( h^+ \)} \\
\text{\( h^- \)}
\end{array} \]

\[ x \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \]

\[ z \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \]

\[ p_T^h \text{ (GeV/c)} \]

1 September 2016

Riccardo Longo
COMPASS SIDIS results: BM

\[ A_{UU}^{\cos2\phi_h} \propto -h_{1q}^\perp \otimes H_{1q}^{\perp h} + \left( \frac{M}{Q} \right)^2 \text{"twist-4" Cahn effect} \]

- Large positive amplitudes decreasing with x for both \( h^+/h^- \).
- Clear differences between \( h^+/h^- \).
- Slightly larger amplitude for \( h^- \).
- Similarity between proton and deuteron results for \( A_{UU}^{\cos2\phi_h} \) has been previously observed at HERMES collaboration.

Available DY data

\[ \nu = 2 A_{UU}^{\cos2\phi} \propto h_{1q}^\perp \otimes h_{1\bar{q}}^\perp \]

- Clear effect in Drell-Yan
- Energy and quark flavour dependence
  - Smaller effect for sea quarks

COMPASS deuteron

\[ \sigma_{\text{sys}} \approx 2 \cdot \sigma_{\text{stat}} \]
COMPASS SIDIS results: BM

\[ A_{UU}^{\cos 2\phi_h} \propto -h_1^{\perp q} \otimes H_1^{\perp h} + \left( \frac{M}{Q} \right) f_1^q \otimes D_1^{h \perp} + \ldots \]

- Large positive amplitudes decreasing with x for both \( h^+/h^- \).
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Available DY data


\[
\frac{d\sigma}{d\Omega} \propto \left( 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \varphi_{CS} + \frac{\nu}{2} \sin^2 \theta \cos 2\varphi_{CS} \right)
\]

Lam Tung relation (collinear LO pQCD)

\( 1 - \lambda - 2\nu = 0 \quad \rightarrow \quad \lambda = 1, \mu = 0, \nu = 0 \)

Violation of L-T relation:
Data from E615 (FNAL) and NA10 (CERN) experiments.

COMPASS is collecting higher precision \( \pi^{-} NH_3, \pi^{-} W, \pi^{-} Al \) data
COMPASS SIDIS results: BM

\[ A_{UU}^{\cos 2\phi_h} \propto -h_{1q}^{\perp} \otimes H_{1q}^{\perp} + \left( \frac{M}{Q} \right)^2 f_1^q \otimes D_{1q}^h + \ldots \]

- Large positive amplitudes decreasing with x for both \( h^+/h^- \).
- Clear differences between \( h^+/h^- \).
- Slightly larger amplitude for \( h^- \).
- Similarity between proton and deuteron results for \( A_{UU}^{\cos 2\phi_h} \) has been previously observed at HERMES collaboration.

Available DY data

E615 (\( \pi^- \) W 252 GeV) PRD 39, 92 (1989)
NA10 (\( \pi^- \) W 194 GeV) Z.Phys.C 31, 513 (1986)

\[ \frac{d\sigma}{d\Omega} \propto \left( 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \varphi_{CS} + \frac{\nu}{2} \sin^2 \theta \cos 2\varphi_{CS} \right) \]

Lam Tung relation (collinear LO pQCD)

\[ 1 - \lambda - 2\nu = 0 \rightarrow \lambda = 1, \mu = 0, \nu = 0 \]

Boer–Mulders PDF's sign-change between SIDIS and Drell–Yan and deep analysis of the LT-relation violation are one of the main issues addressed by COMPASS.