COMPASS DRELL-YAN PROGRAM

Riccardo Longo
on behalf of the COMPASS Collaboration
7th March 2022
OUTLINE

• Introduction
• COMPASS Experimental apparatus
• COMPASS Drell-Yan measurements
• COMPASS Drell-Yan Transverse Spin Asymmetries results
  [NEW RESULTS - 2015+2018 FULL DATA SET]
• COMPASS alternative ways to investigate Sivers: $A_N$ and $q_T$-weighted Transverse Spin Asymmetries results
• COMPASS Drell-Yan Unpolarized Asymmetries results
• Summary
THE COMPASS COLLABORATION

- Fixed target experiment
- CERN SPS North-Area (M2 beam-line)
- First data taking in 2002
- 2022 run approaching!

Phase I
- 2002 - 2011
- Hadron Spectroscopy
- Nucleon spin structure (L/T p/D Targets)

See talk by A. Martin

Phase II
- 2012 - 2022
- Primakoff + DVCS pilot run (2012)
- **Drell-Yan (2015, 2018)** → This talk
- DVCS + Unpolarized SIDIS (2016-2017)
- Transversely polarized SIDIS on D target (2021-2022)

See talks by A. Moretti, C. Riedl,
In the leading order QCD parton model, nucleon spin-structure can be parametrized in terms of 8 twist-2 quark intrinsic transverse momentum ($k_T$) dependent TMD PDFs.

<table>
<thead>
<tr>
<th>Nucleon Polarisation</th>
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<tr>
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<td>$f_1^q(x, k_T^2)$</td>
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<td>Pretzelosity</td>
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TMD PDFs can be accessed through measurement of target spin (in)dependent azimuthal asymmetries both in SIDIS and Drell-Yan
TRANSVERSELY POLARIZED SIDIS CROSS-SECTION

\[
\frac{d\sigma^{LO}}{dx dy dz dp_T^2 d\phi_h d\psi} \propto \begin{cases} 
1 + \cos(2\phi_h)\varepsilon A_{UU}^{\cos(2\phi_h)} \\
+ S_T \left[ \sin(\phi_h - \phi_S)A_{UT}^{\sin(\phi_h - \phi_S)} \\
+ \sin(\phi_h + \phi_S)A_{UT}^{\sin(\phi_h + \phi_S)} \\
+ \sin(3\phi_h - \phi_S)A_{UT}^{\sin(3\phi_h - \phi_S)} \right] \end{cases}
\]

SIDIS on transversely polarized nucleons

\[ \mu + p^\uparrow \rightarrow \mu' + h + X \]

COMPASS 2007, 2010

\[ A_{SIDIS} \propto PDF_p \otimes FF \]

1 Unpolarized Asymmetry

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

3 Single Spin Asymmetries

\[ A_{UT}^{\sin(\phi_h - \phi_S)} \propto f_{1T}^q(x, k_{T}^2) \otimes D_{1q}^h \]

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

\[ A_{UT}^{\sin(3\phi_h - \phi_S)} \propto h_{1T,p}^\perp \otimes H_{1q}^\perp \]

Nucleon Polarization

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<tr>
<td></td>
<td>f_{1T}^q(x, k_{T}^2)</td>
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<tr>
<td>Number Density</td>
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Riccardo Longo 5 03/07/2022
COMPASS SETUP (PHASE I)

- Two-stage spectrometer
  - Large Angle Spectrometer (LAS)
    - SM1 magnet (1 T · m), $\Theta$ up to ±180 mrad
  - Small Angle Spectrometer (SAS)
    - SM2 magnet (4.4 T · m), $\Theta$ up to ±30 mrad

- Data were collected simultaneously for the two target spin orientation
- For transverse program, the polarization was reversed after each 4-5 days

### Solid state transversely polarized target (2007, 2010)

<table>
<thead>
<tr>
<th>Target</th>
<th># of cells</th>
<th>Polarization</th>
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<tbody>
<tr>
<td>NH$_3$</td>
<td>3</td>
<td>T, ~80-90%</td>
</tr>
</tbody>
</table>

- High tracking power: ~350 planes (GEMs, SciFis, DCs, MWPCs, MicroMegas, Straws)
- PID via RICH and Calorimetric measurements

**μ$^+$ beam**
- $P_{μ^+}$: 160 GeV/c, intensity $2 \cdot 10^8 μ^+/4.8$ s

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Riccardo Longo

03/07/2022
SINGLE POLARIZED DRELL-YAN PROCESS

Leading order QCD parton model expression of the Single Polarized DY cross-section

\[
\frac{d\sigma^{LO}}{d\Omega dq} \propto \left\{ 1 + D_{[\sin^2 \theta]} \cos(2\varphi_{CS}) A_{U}^{\cos 2\varphi_{CS}} \right. \\
+ S_T \left. \left[ \sin \varphi_{S} A_{T}^{\sin \varphi_{S}} + D_{[\sin^2 \theta]} \left( \sin(2\varphi_{CS} + \varphi_{S}) A_{T}^{\sin(2\varphi_{CS} + \varphi_{S})} \right) \right. \right. \\
\left. \left. \left. + \sin(2\varphi_{CS} - \varphi_{S}) A_{T}^{\sin(2\varphi_{CS} - \varphi_{S})} \right) \right] \right\}
\]

Pion induced polarized Drell-Yan

\[\pi^- + p^\uparrow \rightarrow \mu^+ \mu^- + X\]

**COMPASS 2015, 2018**

**D-factors**

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

Azimuthal asymmetries

\[A_{U,T}^{w(\varphi_{CS}, \varphi_{S})} = \frac{F_{U,T}^{w(\varphi_{CS}, \varphi_{S})}}{F_{U}^1 + F_{U}^2}\]
Leading order QCD parton model expression of the Single Polarized DY cross-section:

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

\[A_{DY} \propto PDF_\pi \otimes PDF_p\]

1 Unpolarized Asymmetry

\[A^\cos(2\varphi_{CS})_U \propto h^{1,q}_{1,\pi} \otimes h^{1,q}_{1,p}\]

\[A^{\sin \varphi_S}_T \propto f^{q}_{1,\pi} \otimes f^{1,q}_{1T,p}\]

\[A^{\sin(2\varphi_{CS} + \varphi_S)}_T \propto h^{1,q}_{1,\pi} \otimes h^{1,q}_{1T,p}\]

\[A^{\sin(2\varphi_{CS} - \varphi_S)}_T \propto h^{1,q}_{1,\pi} \otimes h^{q}_{1,p}\]

3 Single Spin Asymmetries

- **Quark Polarization**
  - **U**
    - \[f^{q}_{1T}(x, k^2_T)\]
    - Number Density
    - \([-]-\]
  - **L**
    - \[g^{q}_{1}(x, k^2_T)\]
    - Helicity
    - \([-]-\]
  - **T**
    - \[h^{q}_{1T}(x, k^2_T)\]
    - Worm-Gear T
    - \([-]-\]
    - \[h^{1+}_{1T}(x, k^2_T)\]
    - Transversity
    - \([-]-\]
    - \[h^{-1+}_{1}(x, k^2_T)\]
    - Boer-Mulders
    - \([-]-\]
    - \[h^{-1+}_{1}(x, k^2_T)\]
    - Pretzelosity
    - \([-]-\]

**Nucleon Polarization**

- **U**
  - \([-]-\]
  - \[f^{q}_{1T}(x, k^2_T)\]
  - Sivers

- **L**
  - \([+]\)
  - \[g^{q}_{1}(x, k^2_T)\]
  - Helicity

- **T**
  - \([+]\)
  - \[h^{q}_{1T}(x, k^2_T)\]
  - Worm-Gear T
COMPASS SETUP (DY)

- Enforced LAS tracking (DC05, PixelMicroMegas), new DAQ ...

- Polarized DY Data takings:
  - 2015 run ~4 months;
  - 2018 run ~6 months;
- The polarization was reversed after each week;

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<tr>
<td>NH₃</td>
<td>2</td>
<td>T, ~73 %</td>
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π⁻ beam
- $P_{\pi^-} : 190$ GeV/c, intensity $10^8 \pi^-$/s
DY AND SIDIS CROSS-SECTIONS @ LO

**SIDIS on transversely polarized nucleons**

**COMPASS 2007, 2010**

$\mu + p^\uparrow \rightarrow \mu' + h + X$

$$\frac{d\sigma^{LO}}{dxdydp_T^2d\varphi_h d\psi} \propto \begin{cases} 1 + \cos(2\phi_h)\varepsilon A_{UU}^{\cos(2\phi_h)} \\ \sin(\phi_h - \phi_S) A_{UT}^{\sin(\phi_h - \phi_S)} \\ + \sin(\phi_h + \phi_S) A_{UT}^{\sin(\phi_h + \phi_S)} \\ + \sin(3\phi_h - \phi_S) A_{UT}^{\sin(3\phi_h - \phi_S)} \end{cases} + S_T$$

$$A_{SIDIS} \propto PDF_p \otimes FF$$

**Pion induced polarized Drell-Yan**

**COMPASS 2015, 2018**

$\pi^- + p^\uparrow \rightarrow \mu^- + \mu^- + X$

$$\frac{d\sigma^{LO}}{d\Omega d^4q} \propto \begin{cases} 1 + D_{[\sin^2 \theta]}^{\cos(2\varphi_{CS})} A_U^{\cos(2\varphi_{CS})} \\ \sin \varphi_S A_T^{\sin(\varphi_S)} \\ + S_T \\ + D_{[\sin^2 \theta]}^{\sin(2\varphi_{CS})} A_T^{\sin(2\varphi_{CS})} \\ + D_{[\sin^2 \theta]}^{\sin(2\varphi_{CS} - \varphi_S)} A_T^{\sin(2\varphi_{CS} - \varphi_S)} \end{cases}$$

$$A_{DY} \propto PDF_\pi \otimes PDF_p$$

- **Boer-Mulders**
- **Sivers**
- **Pretzelosity**
- **Transversity**

**Universality in the TMD-QCD parton model approach**

- **Transversity** and **Pretzelosity** TMD PDFs "genuinely" universal (no sign change between SIDIS and DY)

- **Boer Mulders** and **Sivers** TMD PDFs "conditionally" universal (sign change between SIDIS and DY)

$h_{1,p}^{\perp} |_{SIDIS} = h_{1,p}^{\perp} |_{DY}$

$h_{1T,p}^{\perp} |_{SIDIS} = h_{1T,p}^{\perp} |_{DY}$

$f_{1T,p}^{q} |_{SIDIS} = -f_{1T,p}^{q} |_{DY}$

$h_{1,p}^{q} |_{SIDIS} = -h_{1,p}^{q} |_{DY}$
**COMPASS SIDIS-DY BRIDGE**

**SIDIS on transversely polarized nucleons**

**COMPASS 2007, 2010** 

\[ \mu + p^\uparrow \rightarrow \mu' + h + X \]

**Pion induced polarized Drell-Yan**

**COMPASS 2015, 2018** 

\[ \pi^- + p^\uparrow \rightarrow \mu^+ \mu^- + X \]

Comparable x:Q^2 kinematic coverage

minimization of possible Q^2 evolution effects

**Unique experimental environment to test the TMD universality and the sign change of Sivers and Boer-Mulders!**
DRELL-YAN MEASUREMENTS AT COMPASS

I. \[ 1 < M_{\mu\mu}/(GeV/c^2) < 2, \text{ "Low mass"} \]
   - Large background contamination

II. \[ 2 < M_{\mu\mu}/(GeV/c^2) < 2.5, \text{ "Intermediate mass"} \]
   - High DY cross section.
   - Still low DY-signal/background ratio.

III. \[ 2.5 < M_{\mu\mu}/(GeV/c^2) < 4.3, \text{ "Charmonia mass"} \]
    - Good signal/background.

IV. \[ 4.3 < M_{\mu\mu}/(GeV/c^2) < 8.5, \text{ "High mass"} \]
    - Beyond J/ψ and ψ’ peak, background < 4%.
    - Valence quark region \(\rightarrow\) u-quark dominance
    - Low DY cross-section
DRELL-YAN MEASUREMENTS AT COMPASS

I. $1 < M_{\mu\mu}/(\text{GeV}/c^2) < 2$, “Low mass”
   - Large background contamination

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III. $2.5 < M_{\mu\mu}/(\text{GeV}/c^2) < 4.3$, “Charmonia mass”
   - Strong $J/\psi$ signal $\rightarrow$ Studies of $J/\psi$ physics.
   - Good signal/background.

IV. $4.3 < M_{\mu\mu}/(\text{GeV}/c^2) < 8.5$, “High mass”
   - Beyond $J/\psi$ and $\psi'$ peak, background < 4%.
   - Valence quark region $\rightarrow$ u-quark dominance
   - Low DY cross-section

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

HM events are in the valence quark region

\[ \langle x_\pi \rangle = 0.5 \]
\[ \langle x_N \rangle = 0.17 \]
I. $1 < M_{\mu\mu}/(\text{GeV}/c^2) < 2$, “Low mass”
   • Large background contamination
II. $2 < M_{\mu\mu}/(\text{GeV}/c^2) < 2.5$, “Intermediate mass”
   • High DY cross section.
   • Still low DY-signal/background ratio.
III. $2.5 < M_{\mu\mu}/(\text{GeV}/c^2) < 4.3$, “Charmonia mass”
   • Strong J/$\psi$ signal → Studies of J/$\psi$ physics.
   • Good signal/background.
IV. $4.3 < M_{\mu\mu}/(\text{GeV}/c^2) < 8.5$, “High mass”
   • Beyond J/$\psi$ and $\psi'$ peak, background < 4%.
   • Valence quark region → u-quark dominance
   • Low DY cross-section

$\langle x_F \rangle = 0.33$
$q_T > 0.4 \text{ GeV}/c$
$\langle q_T \rangle = 1.17 \text{ GeV}/c$

$\langle M \rangle = 5.3 \text{ GeV}/c^2$
Same kinematic coverage of 2015 and 2018 data!
• Dedicated analysis performed by COMPASS dividing Proton 2010 data into the 4 DY $Q^2$ ranges;
• SIDIS TSAs extracted for each $Q^2$ range;
• Sivers in HM range shows a non-zero signal for $h^+$;
DY HM TSA RESULTS: SIVERS

\[ A_T^\sin\varphi_S \propto f_1^{q,\pi} \otimes f_{1T,p}^{\perp q} \]

DY - HM range

**NEW RESULTS! FIRST SHOWN TODAY!**

- COMPASS, 2015 + 2018 Full Data Sample

**Curves from JHEP 02, 166 (2021)**

- COMPASS preliminary
- Drell-Yan, NH$_3$
- 2015+2018 data

4.3 $< M_{\mu\mu}/(\text{GeV}/c^2) < 8.5$

Sivers TSA in SIDIS, HM range

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

COMPASS, **PLB 770 (2017) 138**
DY HM TSA RESULTS: SIVERS

\[ A_T^\sin\phi_s \propto f_{1,\pi}^q \otimes f_{1T,p}^q \]

DY - HM range

NEW RESULTS! FIRST SHOWN TODAY!

- COMPASS, 2015 + 2018 Full Data Sample

Curves from JHEP 02, 166 (2021)

COMPASS HM DY result for Sivers asymmetry is consistent with the predicted change of sign for the Sivers function hypothesis

COMPASS, 2015+2018 data

Drell-Yan, NH\textsubscript{3} 2015+2018 data

4.3 < M_{\mu\mu}/(GeV/c^2) < 8.5

\begin{align*}
\text{COMPASS preliminary} & \\
\text{LFCQM} & \\
\text{SPM} & \\
\text{JAM20} & \\
\text{Torino} & 
\end{align*}

COMPASS HM DY result for Sivers asymmetry is consistent with the predicted change of sign for the Sivers function hypothesis

\begin{align*}
\text{sign change} \\
\text{no sign change}
\end{align*}
DY HM TSA RESULTS: TRANSVERSITY

$A_T^{\sin(2\phi_{CS} - \phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q$  \hspace{1cm} \text{DY - HM range}

\text{NEW RESULTS! FIRST SHOWN TODAY!}
- COMPASS, 2015 + 2018 Full Data Sample

Curves from JHEP 02, 166 (2021)

COMPASS preliminary

Drell-Yan, NH$_3$
2015+2018 data

4.3 < $M_{\mu\mu}$(GeV/c$^2$) < 8.5

Collins TSA in SIDIS, HM range

COMPASS, PLB 770 (2017) 138
DY HM TSA RESULTS: TRANSVERSIY

\[ A_T^{\sin(2\phi_{CS}-\phi_S)} \propto h_{1,\pi}^{1q} \otimes h_{1,p}^{q} \]

**DY - HM range**

**NEW RESULTS! FIRST SHOWN TODAY!**
- COMPASS, 2015 + 2018 Full Data Sample

Curves from JHEP 02, 166 (2021)

COMPASS preliminary Drell-Yan, NH\textsubscript{3} 2015+2018 data

4.3 < \( M_{\mu\mu} \) (GeV/c\textsuperscript{2}) < 8.5

COMPASS HM DY result for Transversity asymmetry found to be below zero about 1.5 \( \sigma \) (stat.+syst.)
DY HM TSA RESULTS: PRETZELOSITY

\[ A_T^{\sin(2\phi_{CS} + \phi_S)} \propto h_{1,T}^{\perp q} \otimes h_{1T,p}^{\perp q} \quad \text{DY - HM range} \]

NEW RESULTS! FIRST SHOWN TODAY!
- COMPASS, 2015 + 2018 Full Data Sample

Curves from JHEP 02, 166 (2021)

COMPASS preliminary

Drell-Yan, NH
2015+2018 data

4.3 < M_{\mu\mu}/(\text{GeV}/c^2) < 8.5

\[ A_T^{\sin(2\phi_{CS} + \phi_S)} \]

10^{-2} 10^{-1} 1 10^{-1} 0 0.2 0.4 0.6 0.8 1 1.5 2 3 4 5 6 7 8

\( x_N \quad x_\pi \quad x_F \quad q_T \quad M_{\mu\mu} \)

Pretzelsosity TSA in SIDIS, HM range

\[ A_T^{\sin(3\phi_h - \phi_S)} \propto h_{1,T}^{\perp q} \otimes H_{1q}^{\perp h} \]

16<Q^2/(\text{GeV}/c^2)<81

COMPASS, PLB 770 (2017) 138
\[ A_T^{\sin(2\varphi_{CS} + \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q} \]

**DY - HM range**

NEW RESULTS! FIRST SHOWN TODAY!
- COMPASS, 2015 + 2018 Full Data Sample

Curves from JHEP 02, 166 (2021)

- COMPASS preliminary
- Drell-Yan, NH, 2015+2018 data
- \( 4.3 < M_{\mu\mu}/(\text{GeV}/\text{c}^2) < 8.5 \)

 COMPASS HM DY result for Pretzelosity asymmetry found to be compatible with zero

Riccardo Longo

03/07/2022
Two higher twist asymmetries
Extracted simultaneously together with the other three TSAs;
• Full 2015+2018 combined Drell-Yan TSA data analysis is now completed!
  - Sivers found to be positive, ~1 σ away from zero
  - Transversity found to be negative, ~1.5 σ away from zero
  - Pretzelosity found to be compatible with zero

• COMPASS SIDIS and Drell-Yan TSAs measurements represent a unique experimental input to study the universality of TMD PDFs
DY HM BONUS TRACK: $A_N$

- Alternative way to investigate the Sivers effect
- Acceptance cancellation implemented and understood in different way compared to TSAs extraction
- Receives contributions from all the amplitudes $\sin(n\phi_S)$
- Also studied in $J/\psi$ region where it can provide information on the resonance production mechanism

$$A_{\ell r} = \frac{1}{|S_T|} \frac{N_{\ell} - N_{r}}{N_{\ell} + N_{r}}$$

$$\frac{d\sigma}{d^4q d\phi_S} \propto \hat{\sigma}_U (1 + |S_T| A_N \sin(\phi_S))$$

$$A_{\ell r} = 1 \frac{\int_0^\pi \frac{d\sigma}{d^4q d\phi_S} d\phi_S - \int_{-\pi}^0 \frac{d\sigma}{d^4q d\phi_S} d\phi_S}{|S_T| \int_0^\pi \frac{d\sigma}{d^4q d\phi_S} d\phi_S + \int_{-\pi}^0 \frac{d\sigma}{d^4q d\phi_S} d\phi_S} = \frac{2A_N}{\pi}$$

![Graph showing COMPASS Drell-Yan preliminary results](graph.png)

NEW RESULTS!
FIRST SHOWN TODAY!
TESTING SIVERS SIGN CHANGE W/ WEIGHTED TSA

- General formalism firstly developed for SIDIS [A. Kotzinian & P. Mulders, PLB 406 (1997) 373];
- It allows to avoid assumptions on $k_T$ (e.g. gaussian);
- Already measured in SIDIS by COMPASS, NPB 940 (2019) 34;
- Complementary way to test the Sivers sign-change!

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<tr>
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<th>SIDIS</th>
<th>Drell-Yan</th>
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<td><strong>TSA</strong></td>
<td>$A_{UT}^{\sin(\phi_h - \phi_S)} \propto f_{1T}^q \otimes D_{1q}^h$</td>
<td>$A_T^{\sin \phi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^q$</td>
</tr>
<tr>
<td><strong>wTSA</strong></td>
<td>$A_{UT}^{\sin(\phi_h - \phi_S)} \frac{P_T}{Z_M} \propto f_{1T}^q(1) \times D_{1q}^h$</td>
<td>$A_T^{\sin \phi_S \frac{q_T}{M_N}} \propto f_{1,\pi}^q \times f_{1T,p}^q(1)$</td>
</tr>
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</table>

See talk by A.Martin

Assuming:
- $u$ quark dominance
- No $Q^2$ evolution for Sivers
- Sivers sign-change

$\mathcal{f}_{1T,p}^q \big|_{SIDIS} = -\mathcal{f}_{1T,p}^q \big|_{DY}$

$1^{st} k_T^2$ moment of the Sivers function from SIDIS data at $Q^2 = Q^2_{SIDIS}(x)$

Results to be updated with the analysis of the full 2018 sample (same as standard TSAs)
DY UNPOLARIZED CROSS-SECTION

- General expression for the unpolarized part of the DY cross-section:

\[
\frac{dN}{d\Omega} = \frac{3}{4\pi} \frac{1}{\lambda + 3} \left[ 1 + \lambda \cos^2 \theta_{CS} + \mu \sin 2\theta_{CS} \cos \varphi_{CS} + \frac{\nu}{2} \sin^2 \theta_{CS} \cos 2\varphi_{CS} \right]
\]

3 Unpolarized Asymmetries (UAs)

\[
\lambda = A_U^1, \quad \mu = A_U^{\cos \varphi_{CS}}, \quad \nu = 2A_U^{\cos 2\varphi_{CS}}
\]

- Values of \(\lambda\), \(\mu\) and \(\nu\) depends on the reference frame definition.
- At LO of Drell-Yan process, the virtual photon is produced purely by the electromagnetic \(q + \bar{q}\) annihilation.

\[
\lambda = 1, \quad \mu = \nu = 0
\]

- Lam-Tung relation [PRD 18(1978) 2447]:

\[
1 - \lambda = 2\nu
\]

- Reflects the spin 1/2 nature of the quarks;
- Analogous of Callan-Gross relation in DIS;

Collins-Soper Frame

Lam-Tung relation

Reflects the spin 1/2 nature of the quarks;
Analogous of Callan-Gross relation in DIS;

FNAL E772 Data
E615, $\pi^-(252 \text{ GeV}) + W$, PRD 39, 92 (1989)

E866/NuSea, $p(800 \text{ GeV}) + d$, Phys. Rev. Lett. 99, 082301


• Sizable $\nu$ asymmetry strongly dependent on $q_T$ measured by different experiments in $\pi^-$ induced DY.

• Can be explained in terms of non-perturbative Boer-Mulders effect;

$$A_{UU}^{\cos 2\phi} = \frac{\nu}{2} \propto h_1^\perp q(p) \otimes h_1^\perp q(\pi^-)$$

• Lam-Tung relation found to be violated in $\pi^-$ induced DY!
• Sizable $v$ asymmetry strongly dependent on $q_T$ also measured by different experiments at colliders (CMS, CDF)
• Room for explanation in terms of NLO and NNLO effects
• Still room for non-perturbative Boer-Mulders effect?

CMS, PLB 750 (2015)

CDF, PRL 106 (2011)

M.Lambertsen and W.Vogelsang
PRD 93 (2016)
• Sizable $\nu$ asymmetry strongly dependent on $q_T$ also measured by different experiments at colliders (CMS, CDF)
• Room for explanation in terms of NLO and NNLO effects
• Still room for non-perturbative Boer-Mulders effect?
• At lower energies - and much lower $<q_T>$ - the picture is far to be clear - more data are needed!

M.Lambertsen and W.Vogelsang
PRD 93 (2016)

W.Chang,
R. McClellan,
J.C.Peng,
O.Teryaev
PRD 99,
014032
(2019)
NLO pQCD prediction for COMPASS
W.Chang, R. McClellan, J.C. Peng, O. Teryaev
PRD 99, 014032 (2019)

COMPASS $\pi^{-} + W$ at 190 GeV

- $\pi^{-} (190 \text{ GeV}) + \text{NH}_3$: analysis ongoing
- $\pi^{-} (190 \text{ GeV}) + W$: preliminary results
  - 70% of 2018 data
  - "reduced" HM range due lower mass resolution for events in $W$,
    $4.7 < M_{\mu\mu}/(\text{GeV}/c^2) < 8.5$
  - First 20 cm of $W$ to minimize effects of reinteraction of secondaries

COMPASS preliminary
Drell-Yan 2018 data (~50%)
$4.3 < M_{\mu\mu}/(\text{GeV}/c^2) < 8.5$
• Angular distribution of unpolarized Drell-Yan event corrected for acceptance making use of Monte Carlo (MC)

• Good MC/data agreement achieved for all the MC distributions related to the W target
DYNNLO pQCD calculation not enough to well describe the $\nu$-dependence measured by COMPASS

- Room for a non-zero TMD Boer-Mulders effect
- DY input to study sign-change of the Boer-Mulders function

$\lambda, \mu, \nu$ preliminary results from COMPASS indicate a possible violation of Lam-Tung relation

- Consistent with results obtained by previous pion-induced DY experiments
TSAs & $A_N$ in J/Ψ range

I. $1 < M_{μμ}/(GeV/c^2) < 2$, "Low mass"
   - Large background contamination

II. $2 < M_{μμ}/(GeV/c^2) < 2.5$, "Intermediate mass"
   - High DY cross section.
   - Still low DY-signal/background ratio.

III. $2.5 < M_{μμ}/(GeV/c^2) < 4.3$, "Charmonia mass"
   - Strong J/Ψ signal → Studies of J/Ψ physics.
   - Good signal/background.

IV. $4.3 < M_{μμ}/(GeV/c^2) < 8.5$, "High mass"
   - Beyond J/Ψ and ψ' peak, background < 4%.
   - Valence quark region → Largest asymmetries!
   - Low DY cross-section


Riccardo Longo

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03/07/2022
I. $1 < M_{\mu\mu}/(\text{GeV}/c^2) < 2$, "Low mass"
   • Large background contamination
II. $2 < M_{\mu\mu}/(\text{GeV}/c^2) < 2.5$, "Intermediate mass"
   • High DY cross section.
   • Still low DY-signal/background ratio.
III. $2.5 < M_{\mu\mu}/(\text{GeV}/c^2) < 4.3$, "Charmonia mass"
   • Strong $J/\psi$ signal ➔ Studies of $J/\psi$ physics.
   • Good signal/background.
IV. $4.3 < M_{\mu\mu}/(\text{GeV}/c^2)$
   • Beyond $J/\psi$ and $\psi'$ peak, background < 4%.
   • Valence quark region ➔ Largest asymmetries!
   • Low DY cross-section.

TSAs & $A_N$ in $J/\psi$ Range @ DIS!

Results currently being finalized
Release expected for DIS 2022!

SUMMARY

- COMPASS successfully collected polarized Drell-Yan data in 2015 and 2018
- Full 2015+2018 combined Drell-Yan TSA data analysis is now completed! **FIRST SHOWN TODAY!**
  - Sivers found to be positive, ~1 $\sigma$ away from zero
  - Transversity found to be negative, ~1.5 $\sigma$ away from zero
  - Pretzelosity found to be small and compatible with zero

- COMPASS SIDIS and Drell-Yan TSAs measurements represent a **unique experimental input** to study the universality of TMD PDFs

- COMPASS is investigating the TMD PDFs also using weighted asymmetries in SIDIS and Drell-Yan and the $A_N$ in Drell-Yan
- **TSAs and $A_N$ in $J/\psi$ region will be presented at DIS 2022**
- COMPASS is also extracting the unpolarized asymmetries of the Drell-Yan cross section. First results from the analysis of 2018 W data already available, and more to come in the future!
THANKS FOR YOUR ATTENTION!
\[
\frac{d\sigma}{d\Omega} \propto \left( F_U^1 + F_U^2 \right) \left( 1 + A_U^1 \cos^2 \theta_{CS} \right)
\]

\[
D[f(\theta_{CS})] = \frac{f(\theta_{CS})}{1 + A_U^1 \cos^2 \theta_{CS}}
\]

- All five DY TSAs are extracted simultaneously using an extended Unbinned Maximum Likelihood estimator;
- Depolarization factors are evaluated under assumption \( A_U^1 = 1 \);
- Possible scenarios with \( A_U^1 \neq 1 \) were evaluated, leading to a normalization uncertainty of at most 5%.
• Thanks to a simultaneous measurement of $A_{UU}^{\cos 2\phi}$ and $A_{UT}^{\sin(2\phi-\phi_S)}$, COMPASS DY TSAs results can also be used to test sign change of the proton Boer-Mulders function - as discussed in JHEP 02, 166 (2021)
  
• Transversity sign is positive, as well as the first $k_T$ moment of the pion Boer-Mulders

• Neglecting sea quark effects, the asymmetry is dominated by

$$A_{UU}^{\cos 2\phi} \propto h_{1,\pi^-}^{(1)}(x_\pi) h_{1,p}^{(1)}(x_p)$$

• With the indication of the positive sign for the pion Boer-Mulders function from the COMPASS data on $A_{UT}^{\sin(2\phi-\phi_S)}$ and from the $q_T$ weighted analysis, one can conclude a positive sign also for the proton $u$ quark Boer-Mulders function in DY, which is opposite to the sign of Boer-Mulders extracted in SIDIS analyses and hence in agreement with the sign change prediction

$$A_{UT}^{\sin(2\phi-\phi_S)} \propto -h_{1,\pi^-}^{(1)}(x_\pi) h_{1,p}^{u}(x_p)$$
COMPASS: FROM SIDIS TO DY

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

- Compatible results
  COMPASS/HERMES for Collins effect
- No $Q^2$ evolution effects?

- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results
- $Q^2$ evolution effects?

Global fit of HERMES - COMPASS - BELLE data

Anselmino et al., JHEP 1704 (2017)046
Anselmino et al., PRD 86 (2012) 014028
DY WEIGHTED TSAs

- General formalism firstly developed for SIDIS \([A. \text{ Kotzinian} \& P. \text{ Mulders, PLB 406 (1997) 373}]\);
- It allows to avoid assumptions on \(k_T\) (e.g. gaussian);
- Already measured in SIDIS by COMPASS: complementary way to test the Sivers sign-change!

- Preliminary analysis using only \(~50\% of 2018 data\)
COMPASS, NPB 940 (2019) 34

- COMPASS has also measured the $p_T$ weighted TSAs in SIDIS;
- Alternative way to compare TMD PDFs from SIDIS and DY;

- Sivers TSA in SIDIS
- Sivers wTSA in SIDIS

$A_{UT} \sin(h - \phi_S) \propto f_{1T}q \otimes D_1^h$

$A_{UT} \sin(h - \phi_S) \frac{p_T}{2M} \propto f_{1T}^{q(1)} \otimes D_1^h$

COMPASS 2010, preliminary

- SIDIS, $h^–$
- SIDIS, $h^+$

CTEQ 5D PDFs at $Q^2(x)$ of COMPASS 2010

$xf_{1T}^{q(1)}(x) = a_q x^b (1 - x)^c q$

DSS 07 LO integrated over $z$, at $Q^2(x)$

1st $k_T^2$ -moment of the Sivers function at $Q^2 = Q^2_{SIDIS}(x)$
WEIGHTED ASYMMETRIES: FROM SIDIS TO DY

Assuming:

- $u$ quark dominance

$$A_T \sin \varphi_S \frac{q_T}{M_N} \sim \frac{f_{1T,p}^{\perp u}(1)}{f_{1,p}^{u}}$$

- No $Q^2$ evolution for Sivers
- Sivers sign-change

$$f_{1T,p}^{\perp u} \big|_{SIDIS} = - f_{1T,p}^{\perp u} \big|_{DY}$$

1st $k_T^2$-moment of the Sivers function from SIDIS data at $Q^2 = Q^2_{SIDIS}(x)$

- Preliminary 2015 results, full data sample;
- Preliminary 2018 results, 50% of the sample;
- Analysis will be repeated with the full 2018 sample (same as standard TSAs)
WEIGHTED ASYMMETRIES: FROM SIDIS TO DY

\[ A_T^{\sin(2\varphi_\Delta - \varphi_\Delta)} \frac{q_T}{M_\pi}(x_\pi, x_N) \approx -2 \frac{h_{1,\pi}^{(1)}(\bar{u}(x_\pi), h_{1,p}^u(x_N))}{f_{1\pi}(x_\pi) f_{1,p}^u(x_N)} \]

GRV-PI pion PDF at \( Q^2 = 25 \text{ (GeV/c}^2)^2 \)

CTEQ proton PDF at \( Q^2 = 25 \text{ (GeV/c}^2)^2 \)

- Different pion PDFs tested (GRV-Pi, JAM);
- Transversity from different asymmetries (Collins, Dihadron);

Assuming:
- u quark dominance
- no \( Q^2 \) evolution
UA_s VS X_F

COMPASS, π⁻ 190 GeV/c, W, preliminary
4.7 < M_{μμ}/(GeV/c²) < 8.5

DYNNLO
DILUTION FACTOR

\[ f = \frac{n_H \sigma_{\pi-H}^{DY}}{n_H \sigma_{\pi-H}^{DY} + \sum A n_A \sigma_{\pi-A}^{DY}} \]

- The dilution factor accounts for the fraction of polarizable material inside the target volume.
- It is corrected to account for the migration of events from one cell to the other (obtained with MC simulation);
COMPASS: FROM SIDIS TO DY

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

- Compatible results COMPASS/HERMES for Collins effect
- No Q^2 evolution effects?

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

- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results
- Q^2 evolution effects?

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Global fit of HERMES - COMPASS - BELLE data

Anselmino et al., JHEP 1704 (2017)046

Anselmino et al., PRD 86 (2012) 014028
NLO ISSUES AT LOW $q_T$

Vogelsang and Lambertsen
PRD 93 (2016)
• Unpolarized data-sets from NH3 (summing over polarization states), Al (low statistics) and W targets open possibilities for further DY studies:
  • Absolute DY cross-section measurement:
  • Input for $p_T$ dependence fit of the DY cross-section in global extraction of TMD PDFs (e.g. Bacchetta et al., JHEP 06 (2017) 081)
  • Input for the extraction of the pion PDF (e.g. JAM 2018, PRL 121, 152001)
  • Comparison with DY cross-section simulations and previous experiments
    • Statistical uncertainties recently in 2020
    • **W data**: projected statistical uncertainties vs DYNNLO simulation and E615 data (after energy rescaling) in same bins of $\sqrt{\tau}$
    • **NH3 data**: projected statistical uncertainties vs DYNNLO simulation
ABSOLUTE DY CROSS-SECTION MEASUREMENT

- Unpolarized data-sets from NH3 (summing over polarization states), Al (low statistics) and W targets open possibilities for further DY studies:
  - Absolute DY cross-section measurement:
    - Input for $p_T$ dependence fit of the DY cross-section in global extraction of TMD PDFs (e.g. Bacchetta et al., JHEP 06 (2017) 081)
    - Input for the extraction of the pion PDF (e.g. JAM 2018, PRL 121, 152001)
  - Comparison with DY cross-section simulations and previous experiments
    - Statistical uncertainties recently in 2020
    - **W data**: projected statistical uncertainties vs DYNNLO simulation and E615 data (after energy rescaling) in same bins of $\sqrt{s}$
    - **NH$_3$ data**: projected statistical uncertainties vs DYNNLO simulation

![Graphs showing projected statistical uncertainties vs DYNNLO simulation and E615 data](image)

![Graphs showing absolute DY cross-section measurement](image)
NUCLEAR DEPENDENCE OF DY PROCESS

- Unpolarized data-sets from NH3 (summing over polarization states), Al (low statistics) and W targets open possibilities for further DY studies:
  - Absolute DY cross-section measurement
  - Nuclear dependence of the DY process:
    - Energy loss of the pion quarks when crossing cold nuclear matter
    - Cronin effect: dilepton $p_T$ broadening in cold nuclear matter
COMPASS: FROM SIDIS TO DY

- Compatible results COMPASS/HERMES for Collins effect
- No $Q^2$ evolution effects?

- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results
- $Q^2$ evolution effects?

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

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