COMPASS Drell-Yan measurements: testing the universality of TMD PDFs

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on behalf of the COMPASS Collaboration

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Outline

1. Introduction
2. Drell-Yan and Semi-inclusive DIS processes
3. Spectrometer
4. Unique experimental opportunities
5. Transverse Spin Asymmetries
6. Lam-Tung relation
7. Conclusions and perspectives
A complicated QCD object

How is the mass described dynamically?

How are quarks and gluons confined?

How are they distributed?

How do they contribute to the nucleon spin?

Figure taken from arXiv:1212.1701 [nucl-ex]
Nucleon tomography

General description of nucleon structure

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

\[ \int d\vec{b}_\perp \quad \int d\vec{k}_\perp \]

**Wigner Distributions**

**Momentum tomography**

**Spatial tomography**

**TMDs**

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

\[ \int d\vec{k}_\perp \quad \int d\vec{b}_\perp \]

**GPDs**

\[ H(x, \vec{b}_\perp) \]

\[ \int dx \]

**Longitudinal momentum density**

**Spatial density**

**PDFs**

\[ f(x) \]

\[ 1D \]

**Form Factors**

\[ F(\vec{b}_\perp) \]

\[ x: \text{fraction of longitudinal momentum} \]

\[ k_\perp: \text{Parton transverse momentum} \]

\[ b_\perp: \text{Impact parameter} \]

1D picture is relatively well known, …

… efforts are focusing on the 3D picture
Nucleon structure at leading order QCD is described with **8 Tranverse momentum dependent PDFs**:

- \( f_1 \), \( g_1 \) and \( h_1 \) survive \( k_T \) integration
- Other distributions describe correlations among quark’s \( k_T \), nucleon’s spin and quark’s spin
- Accessible at COMPASS via Semi-inclusive DIS and Drell-Yan processes
Drell-Yan and Semi-inclusive DIS processes

SIDIS:

\[ Q^2 = -M_{\gamma*}^2 \]
\[ x = \frac{Q^2}{2p \cdot q} \]
\[ z = \frac{E_h}{E_{\gamma*}} \]

Variables:

DY:

\[ Q^2 = M_{l^+ l^-}^2 \]
\[ x_{1,2} = \frac{Q^2}{2p_{1,2} \cdot q} \]
\[ q_T = \text{virtual photon transverse momentum} \]
Drell-Yan and SIDIS cross-section modulations

SIDIS:

\[
\frac{d\sigma}{dxdydzd\phi_Sd\phi_hd\phiTd\phi} = \frac{\alpha^2}{xyQ^2} \left(1 + \frac{y^2}{2(1-x)}\right) \sigma_U \left\{1 + \epsilon A_{UU}^{\cos(2\phi_h)} \cos(2\phi_h)\right. \\
+ S_T \left[ A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \epsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h - \phi_S) \right] \\
+ \epsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \right\} \\
+ S_T P_l \left[ \sqrt{1 - \epsilon^2} \cos(\phi_h - \phi_S) A_{LT}^{\cos(\phi_h - \phi_S)} \right]
\]

DY:

\[
\frac{d\sigma}{d^4q_d\Omega} = \frac{\alpha^2}{Fq^2} \sigma_U \left\{\left(1 + \cos^2(\theta) + \sin^2(\theta) A_{UU}^{\cos(2\phi)} \cos(2\phi)\right) \right. \\
+ S_T \left[ (1 + \cos^2(\theta)) A_{UT}^{\sin(\phi_S)} \sin(\phi_S) \right] \\
+ \sin^2(\theta) \left[ A_{UT}^{\sin(2\phi + \phi_S)} \sin(2\phi + \phi_S) + A_{UT}^{\sin(2\phi - \phi_S)} \sin(2\phi - \phi_S) \right]\} 
\]
Modulation amplitudes

<table>
<thead>
<tr>
<th>DY:</th>
<th>SIDIS:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{UU}^{\cos(2\phi)} \propto h_{1,\pi} \otimes h_{1,p}^\perp$</td>
<td>$A_{UU}^{\cos(2\phi_h)} \propto h_{1,p} \otimes H_{1q}^\perp$</td>
</tr>
<tr>
<td>$A_{UT}^{\sin(\phi_S)} \propto f_{1,\pi}^q \otimes f_{1T,p}^\perp$</td>
<td>$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T,p}^q \otimes D_{1q}^h$</td>
</tr>
<tr>
<td>$A_{UT}^{\sin(2\phi-\phi_S)} \propto h_{1,\pi} \otimes h_{1,p}^\perp$</td>
<td>$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_{1,p}^q \otimes H_{1q}^\perp$</td>
</tr>
<tr>
<td>$A_{UT}^{\sin(2\phi+\phi_S)} \propto h_{1,\pi} \otimes h_{1T,p}^\perp$</td>
<td>$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T,p}^\perp \otimes H_{1q}^\perp$</td>
</tr>
</tbody>
</table>

TMD PDFs are **universal** but

final state interaction (SIDIS) vs. initial state interaction (DY) $\rightarrow$ **Sign flip** for naive T-odd TMD PDFs

$$f_{1T,p}^q \mid_{\text{SIDIS}} = -f_{1T,p}^q \mid_{\text{DY}}$$

$$h_{1,p}^\perp \mid_{\text{SIDIS}} = -h_{1,p}^\perp \mid_{\text{DY}}$$

Crucial test of TMD framework in QCD
**COMPASS-I SIDIS setup**

- **Polarised $\mu^+$ beam** from CERN SPS
  - 200 GeV/160 GeV
  - $l_\mu \sim 5 \cdot 10^7 s^{-1}$
  - $P_\mu \sim 80\%$

- **RICH**:  
  - Hadron identification  
  - $(K^\pm, \pi^\pm, \ldots)$

- **Polarised target** of 1.2 m length in a superconducting solenoid
  - NH$_3$
  - $^6$LiD

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COMPASS-II Drell-Yan setup

Almost the same tracking, except for a new Drift Chamber detector in the first stage spectrometer.

- $\pi^-$ beam from CERN SPS
  - 190 GeV
  - $I_\pi \sim 6 \cdot 10^7 \text{s}^{-1}$

- Hadron absorber + nuclear targets

- Polarised target of 1.1 m length
  - in a superconducting solenoid
  - NH$_3$
Polarised target and hadron absorber

**Polarised target**
- Two cells of NH$_3$
- Polarisation $\sim$80%
- Dilution factor $f \sim$22%

$\Rightarrow$ Two spin states recorded simultaneously: minimisation of systematic effects

**Hadron absorber**
- Due to small cross-section and high luminosity
- Improve resolutions $\rightarrow$ Vertex detector
- Used as nuclear targets: Al & W

**Primary vertex distribution**

- COMPASS preliminary ~30% of 2015 Drell-Yan data
- $4 < M_{\mu\mu}(\text{GeV}/c^2) < 9$
COMPASS data taking with polarised target

<table>
<thead>
<tr>
<th>Year</th>
<th>Beam</th>
<th>Target</th>
<th>Polarisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>$\mu$</td>
<td>$^6\text{LiD}$</td>
<td>L &amp; T $\sim$50%</td>
</tr>
<tr>
<td>2003</td>
<td>$\mu$</td>
<td>$^6\text{LiD}$</td>
<td>L &amp; T $\sim$50%</td>
</tr>
<tr>
<td>2004</td>
<td>$\mu$</td>
<td>$^6\text{LiD}$</td>
<td>L &amp; T $\sim$50%</td>
</tr>
<tr>
<td>2006</td>
<td>$\mu$</td>
<td>$^6\text{LiD}$</td>
<td>L $\sim$50%</td>
</tr>
<tr>
<td>2007</td>
<td>$\mu$</td>
<td>$\text{NH}_3$</td>
<td>L &amp; T $\sim$80%</td>
</tr>
<tr>
<td>2010</td>
<td>$\mu$</td>
<td>$\text{NH}_3$</td>
<td>T $\sim$80%</td>
</tr>
<tr>
<td>2011</td>
<td>$\mu$</td>
<td>$\text{NH}_3$</td>
<td>L $\sim$80%</td>
</tr>
<tr>
<td>2014</td>
<td>$\pi$</td>
<td>$\text{NH}_3$</td>
<td>unpol.</td>
</tr>
<tr>
<td>2015</td>
<td>$\pi$</td>
<td>$\text{NH}_3$</td>
<td>T $\sim$80%</td>
</tr>
</tbody>
</table>

→ PLB 744 (2015) 250

First unpolarised DY data
First ever polarised DY data

Focus in this talk on Boer-Mulders and Sivers related measurements.
Many other COMPASS results available!
COMPASS acceptance high where $f_{1T}^{\perp}$ is expected to be large

High acceptance: 40% to be compared to previous experiments ≤ 10% (e.g. NA10, NA50 at CERN, E615 at FNAL)

Acceptance flat in $q_T$
Evolution effects

- COMPASS Sivers asymmetries found significantly smaller than HERMES $A_{Siv}^p$
- Non-trivial $Q^2$-dependence

COMPASS kinematics

SIDIS

DY

Same experiment:

- \( \approx \) Same acceptance
- \( \approx \) Same kinematics
- \( \approx \) Same systematic effects

→ **minimisation** of \( Q^2 \) evolution effects and **systematics effects** in the comparison of the two processes
Intermediate mass: 
\[ 2 < M_{\mu\mu}/(\text{GeV}/c^2) < 2.5 \]
- High Drell-Yan cross-section
- Low DY-signal/background ratio

\( J/\psi \) mass: \[ 2.5 < M_{\mu\mu}/(\text{GeV}/c^2) < 4 \]
- Strong \( J/\psi \) signal
- Lower background

High mass: \[ 4 < M_{\mu\mu}/(\text{GeV}/c^2) \]
- Low DY cross-section
- Low background
SIDIS Transversity in DY $Q^2$ ranges

$h^q_{1,p}$: correlation between transversely polarised quark in a transversely polarised nucleon

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

- Sizable in all $Q^2$ range
- Azymuthal modulation have opposite sign for $h^+$ & $h^-$
Projection for DY transversity in COMPASS

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

- Estimated uncertainties for 2015 DY run
- Expect a sizable DY asymmetry based on SIDIS results
SIDIS Sivers in DY $Q^2$ ranges

$f_{1T, p}^\perp q$ : Correlation between quark transverse momentum and transverse nucleon spin

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

- Sizable in all $Q^2$ ranges for $h^+$
- Asymmetry becomes positive with $Q^2$ for $h^-$

[Graphs showing the asymmetry $A_{UT}^{\sin(\phi_h - \phi_S)}$ for different $Q^2$ ranges]
**Projection for DY Sivers in COMPASS**

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

- **COMPASS preliminary**
  - \( \sim 30\% \) of 2015 Drell-Yan \( \mathrm{NH}_3 \) data
  - Estimated uncertainty
  - \( 4 < M_{\mu\mu}/(\text{GeV}/c^2) < 9 \)

- Estimated uncertainties for 2015 DY run
- Expect a sizable DY asymmetry based on SIDIS results
- Many models exist, experimental data are necessary: COMPASS results awaited
SIDIS and projected DY TSA in COMPASS

- Except for Pretzelosity, all LO TSA common between SIDIS and DY are sizable in SIDIS
- Estimated uncertainties for 2015 DY run
- Another polarised DY run is scheduled for 2018
Unpolarised Drell-Yan angular dependencies

\[ \frac{dN}{d\Omega} = \frac{3}{4\pi} \frac{1}{\lambda + 3} \left( 1 + \lambda \cos^2(\theta) + \mu \sin(2\theta) \cos(\phi) + \frac{\nu}{2} \sin^2(\theta) \cos(2\phi) \right) \]

In naive Drell-Yan model, no $k_T$ and no QCD processes involving gluons:

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

The Lam-Tung relation, derived from the fermionic nature of quarks, predicts:

\[ 1 - \lambda - 2\nu = 0 \]

Analog of DIS Callan-Gross relation for Drell-Yan

Lam-Tung relation

Data:

- Clear departure from $\nu = 0$ and violation of Lam-Tung
- Boer Mulders effects: $\nu = 2A_{UT}^\cos(2\phi)$

E615 PRD 39, 92 (1989)

CMS PLB 750, 154 (2015)
Lam-Tung relation

Data and QCD radiative effects:

E615 PRD 39, 92 (1989)

- Recent interpretations in terms of QCD radiative effects describe pretty well the data
  - J.-C. Peng et al. PLB 758, 384 (2016)
  - M. Lambertsen and W. Vogelsang PRD93, 114013 (2016)
- Boer-Mulders effects are not excluded
- Better precision for fixed target regime would be appreciated

Lambertsen et al. PRD 93 (114013)

CMS PLB 750, 154 (2015)
Estimated uncertainties for 2015 DY run

Sizable asymmetry expected from QCD radiative effect

Positive signal also seen in SIDIS at COMPASS and HERMES with \(^6\)LiD, D and H target

COMPASS preliminary

~30% of 2015 Drell-Yan NH\(_3\) data

Estimated uncertainty

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

- COMPASS is the only experiment able to measure TSA in SIDIS and in DY
  - Direct comparison between SIDIS and DY Sivers without TMD evolution
  - Minimisation of experimental systematic effect between SIDIS and DY

- SIDIS proton TSAs within DY mass ranges are measured
  - Sizable Sivers and Transversity
  - Prezelosity SIDIS TSA is found compatible with zero

- Estimated DY statistical uncertainties would allow a discriminating power between models and a possible verification of the sign change

- Ongoing analysis, results will be available soon!
COMPASS future plans

- 2016-2017: Exclusive physics with muon beams on liquid hydrogen target
- 2018: Drell-Yan with transversely polarised NH$_3$ target

- 2017: Preparation for a possible physics program for 2020 and beyond
RF separated $\bar{p}/K$ beam would provide a unique opportunity for future fixed target COMPASS-like program at CERN

Existing muon/hadron beam allows to extend current COMPASS program by doing unique or first class measurements of exclusive processes, SIDIS and Drell-Yan
## Physics at the SPS M2 beam line at CERN beyond 2020

Non exhaustive list:

<table>
<thead>
<tr>
<th>Physics item</th>
<th>Key aspects of the measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>DY Flavour separation</td>
<td>transversely pol. $^6\text{LiD}$ target</td>
</tr>
<tr>
<td>EMC effect</td>
<td>$\bar{p}$ with transversely pol. $\text{NH}_3$ target</td>
</tr>
<tr>
<td>Universality of TMD PDFs</td>
<td>For $K$ and $\bar{p}$ beam</td>
</tr>
<tr>
<td>Model free TMD PDFs</td>
<td>$\pi$ and $K$ beams</td>
</tr>
<tr>
<td>Lam-Tung</td>
<td>$\bar{p}$ beam</td>
</tr>
<tr>
<td>Meson structure</td>
<td></td>
</tr>
<tr>
<td>GPD E</td>
<td>Transversely pol. $\text{NH}_3$ target with RPD</td>
</tr>
<tr>
<td>SIDIS Precision $h_1^d$</td>
<td>Transversely pol. $^6\text{LiD}$ target</td>
</tr>
<tr>
<td>$f_1$ evolution</td>
<td>$100$ GeV beam with transversely pol. $\text{NH}_3$ target</td>
</tr>
<tr>
<td>Hadron Spectroscopy</td>
<td>High intensity $\pi$, $K$ and $\bar{p}$ beams</td>
</tr>
</tbody>
</table>

New collaborators are welcome
The workshop occurs when a community of physicists is exploring hadron physics opportunities for fixed-target experiments at CERN beyond 2020 (CERN Long Shutdown 2 2019-2020). These discussions already started with the workshop COMPASS beyond 2020 in March 2016 and the workshop Physics Beyond Collider organized by CERN in September 2016. The physics discussed at the Workshop will mainly be related to the most recent results, open issues and short and long future programs on Spectroscopy, Drell-Yan, DVCS and SIDIS, remaining open-minded to new possible programs.

**Physics topics:**

- Longitudinal and Transverse Spin Structure of the Nucleon
- Fragmentation Functions
- Meson Spectroscopy
- Search for Glueballs, Hybrid Mesons and Multiquark States
- TMDs, GPDs and GTMDs
- New opportunities for physics beyond collider
- Cosmic rays and accelerator physics
RF separated beam

Current hadron beam composition:

- 97% $\pi \rightarrow I_{\text{beam}} = 10^7 \text{ s}^{-1}$
- 2.5% $K \rightarrow I_{\text{beam}} = 2 \times 10^6 \text{ s}^{-1}$
- 0.5% $\bar{p} \rightarrow I_{\text{beam}} = 5 \times 10^5 \text{ s}^{-1}$

RF-separated beam composition:

$$\Delta \Phi = 2\pi \left( \frac{L f}{c} \right) (\beta_1^{-1} - \beta_2^{-1}) \text{ with } \beta_1^{-1} - \beta_2^{-1} = \frac{(m_1^2 - m_2^2)}{2p^2}$$

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## Current and to come Drell-Yan experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Particles</th>
<th>Energy</th>
<th>$x_t$</th>
<th>Luminosity</th>
<th>$P_b/P_t$</th>
<th>rFOM</th>
<th>Timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPASS</td>
<td>$\pi^- p^\uparrow$</td>
<td>190 Gev</td>
<td>$x_t = 0.1-0.3$</td>
<td>$2 \times 10^{33}$</td>
<td>0.14</td>
<td>$P_t = 80%$</td>
<td>$1.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>PANDA</td>
<td>$\bar{p} p^\uparrow$</td>
<td>15 GeV</td>
<td>$x_t = 0.2-0.4$</td>
<td>$2 \times 10^{32}$</td>
<td>0.07</td>
<td>$P_t = 90%$</td>
<td>$1.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>AFTER</td>
<td>$p^\uparrow p$</td>
<td>7 TeV</td>
<td>$x_b = 0.1-0.9$</td>
<td>$2 \times 10^{32}$</td>
<td>0.06</td>
<td>$P_t = 100%?$</td>
<td>$2.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>NICA</td>
<td>$p^\uparrow p$</td>
<td>collider</td>
<td>$x_b = 0.1-0.8$</td>
<td>$1 \times 10^{32}$</td>
<td>0.04</td>
<td>$P_t = 70%$</td>
<td>$6.8 \times 10^{-5}$</td>
</tr>
<tr>
<td>PHENIX/STAR</td>
<td>$p^\uparrow p^\uparrow$</td>
<td>collider</td>
<td>$x_b = 0.05-0.1$</td>
<td>$2 \times 10^{32}$</td>
<td>0.08</td>
<td>$P_b = 60%$</td>
<td>$1.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>fsPHENIX</td>
<td>$p^\uparrow p^\uparrow$</td>
<td>collider</td>
<td>$x_b = 0.05-0.6$</td>
<td>$6 \times 10^{32}$</td>
<td>0.08</td>
<td>$P_b = 50%$</td>
<td>$2.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>SeaQuest</td>
<td>$p p$</td>
<td>120 GeV</td>
<td>$x_t = 0.1-0.45$</td>
<td>$3.4 \times 10^{35}$</td>
<td>3.4</td>
<td>$P_t = 85%$?</td>
<td>$0.15$</td>
</tr>
<tr>
<td>E1039</td>
<td>$p p^\uparrow$</td>
<td>120 GeV</td>
<td>$x_b = 0.1-0.45$</td>
<td>$4.4 \times 10^{35}$</td>
<td>0-0.2*</td>
<td>$P_t = 85%$?</td>
<td>$0.15$</td>
</tr>
</tbody>
</table>