Polarized Drell-Yan measurement at COMPASS-II

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on behalf of the COMPASS Collaboration

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Outline

• Brief introduction of TMD PDFs
• Polarized Drell-Yan process
• Polarized Drell-Yan experiment in COMPASS-II
• Beam Test Results
• Expected Precision
• Time Schedule
• Summary
quantum phase-space “tomography” of the nucleon

Wigner functions: \( W^q(k, b) \)

probability to find a quark in a nucleon with a certain polarization in a position \( b \) and momentum \( k \)

\[ q(x, k_T) \]

Transverse Momentum Dependent (TMDs) distribution functions

- Drell-Yan measurements
- semi-inclusive measurements

\[ f^q(x) \]

Parton Distribution Functions (PDFs)

- inclusive measurements

\[ H(x, \xi, t) \]

Generalized Parton Distributions (GPDs)

- exclusive measurements

\[ d^2 k_T \ d b \]

center of momentum

\[ R_{\perp} = \sum x_i r_{\perp, i} \]

- space dependent distribution functions

\[ d^3 b \]

Ami Rostomyan for HERMES


PRC 72, Hamburg, 2011
Nucleon Structure at Leading Order (LO)

At LO, the nucleon structure are described by 8 Transverse Momentum Dependent Parton Distribution Functions (TMD PDFs), when the quark intrinsic transverse momentum ($k_T$) is taken into account.

\[ f_{1T}(x,k_T^2) \]  \textbf{Sivers function}  
the correlation between the transverse spin of the nucleon and the transverse momentum of the quark.

\[ h_{1T}(x,k_T^2) \]  \textbf{Boer-Mulders function}  
the correlation between the transverse spin and the transverse momentum of a quark in unpolarized nucleon.

\[ h_{1T}^\perp(x,k_T^2) \]  \textbf{Pretzelosity function}  
the polarization of a quark along its $k_T$ direction, making accessible to the orbital angular momentum information.

<table>
<thead>
<tr>
<th>Quark polarization</th>
<th>Nucleon polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>unpol.</td>
<td>$f_1$ (unpol.)</td>
</tr>
<tr>
<td>long. pol.</td>
<td>$g_1$ (long. pol.)</td>
</tr>
<tr>
<td>transv. pol.</td>
<td>$h_1$ (transv. pol.)</td>
</tr>
</tbody>
</table>

- $f_1$: Number Density
- $f_{1T}$: Sivers
- $g_1$: Helicity
- $g_{1T}$: Worm Gear
- $h_1$: Boer-Mulders
- $h_{1T}$: Transversity
- $h_{1T}^\perp$: Pretzelosity
Single transversely-polarized Drell-Yan (DY) cross-section in LO QCD Parton Model

\[ \frac{d\sigma^{LO}}{d^4 q d\Omega} = \frac{\alpha_{em}^2}{F q^2} \hat{\sigma}_U^{LO} \left\{ \left( 1 + D^{LO}_{[\sin^2 \theta]} \right) A_U^{\cos 2\varphi} \cos 2\varphi \right. \\
+ \left| \vec{S}_T \right| \left[ A_T^{\sin \varphi_S} \sin \varphi_S \\
+ D^{LO}_{[\sin^2 \theta]} \left( A_T^{\sin (2\varphi + \varphi_S)} \sin (2\varphi + \varphi_S) \\
+ A_T^{\sin (2\varphi - \varphi_S)} \sin (2\varphi - \varphi_S) \right) \right] \right\} \]

Clean access to 4 azimuthal modulations (no Fragmentation Functions are involved)

- \( A_U^{\cos 2\varphi} \propto \text{BM}(h_1^\perp) \mid_\pi \otimes \text{BM}(h_1^\perp) \mid_p \)
- \( A_T^{\sin \varphi_S} \propto \text{Density}(f_1) \mid_\pi \otimes \text{Sivers}(f_{1T}^\perp) \mid_p \)
- \( A_T^{\sin (2\varphi + \varphi_S)} \propto \text{BM}(h_1^\perp) \mid_\pi \otimes \text{pretzelosity}(h_{1T}^\perp) \mid_p \)
- \( A_T^{\sin (2\varphi - \varphi_S)} \propto \text{BM}(h_1^\perp) \mid_\pi \otimes \text{transversity}(h_1) \mid_p \)

A : azimuthal asymmetry
D : depolarization factor
S_T : transverse target spin
F : flux of incoming hadrons
\( \sigma_U \) : cross section surviving integration over \( \varphi \) and \( \varphi_S \)
\( \varphi_S \) : azimuthal angle of \( S_T \) in the target rest frame
\( \theta, \varphi \) : polar and azimuthal angle of the lepton in the Collins-Soper frame
Sign Change of Sivers & Boer-Mulders Functions


\[ f_{iT}^{\perp}|_{\text{DY}} = - f_{iT}^{\perp}|_{\text{SIDIS}} \]
\[ h_{I}^{\perp}|_{\text{DY}} = - h_{I}^{\perp}|_{\text{SIDIS}} \]

- QCD gluon gauge link in the initial state (DY) vs. final state interactions (SIDIS).

- **Experimental confirmation of the sign change will be a crucial test of perturbative QCD and TMD physics.**
In COMPASS, we have the opportunity to access these TMD PDFs from both DY and SIDIS processes.

There is a phase space overlap between the two measurements.

Kinematics compatibility between DY and SIDIS
DY experiment

High Mass Region \((4 \leq M_{\mu\mu} \leq 9 \text{ GeV/c}^2)\)
- Clean DY signal
- Small Production Cross section

Intermediate Mass Region \((2 \leq M_{\mu\mu} \leq 2.5 \text{ GeV/c}^2)\)
- Combinatorial background

- High intensity beam
  → and also the Detectors and Data Acquisition System (DAQ) designed to stand high particle fluxes.
- Hadron absorber
- Large angular acceptance spectrometer
- Transversely polarized solid state proton target
- Dedicated muon trigger system.

COMPASS-II fulfills all the conditions.

* Combinatorial and physics backgrounds are different from COMPASS-II DY.
COMPASS-II facility at CERN

COmmon Muon Proton Apparatus for Structure and Spectroscopy
COMPASS-II facility

Target Region

Large Angle Spectrometer (LAS)
- SM1
- ECAL & HCAL
- RICH
- straw

Small Angle Spectrometer (SAS)
- SM2
- ECAL & HCAL
- μ Filter

Powerful tracking system: 350 planes
PID: μ-Walls, Calorimeters, RICH

Beam:
- Polarized lepton beam: μ⁺, μ⁻ 50-280 GeV/c
- Hadron beam: π⁺, π⁻, K⁺, K⁻, p

Target:
- Polarized proton and deuteron target
- Liquid hydrogen target
- Nuclear target

Various Combinations of Beam & Target
Key Elements in DY@COMPASS-II

**Polarized NH$_3$ target**
- Materials: $p$(NH$_3$)
- Dilution factor: 0.22
- Polarization: > 90%

**Target**
- Target spin reversal every few days

**Magnet**
- Solenoid: 2.5 T
- Dipole: 0.5 T

**Vertex Detector**
- Improvement of
  - Mass/Angle Resolution of the virtual photon
  - Vertex Position Resolution

**Hadron Absorber**
- Large Stopping Power for hadrons
- Small Multiple Scattering for leptons
- Radiation Shielding

**Beam**
- 190 GeV/c $\pi^-$
- Intensity: $10^8$ particles/s
- Spill extraction length: 9.6 sec
  - SPS cycle: 33.6 sec

**Materials**:
- Tungsten Plug
- Stainless Steel
- Alumina (Al$_2$O$_3$)
- Dilution factor: 0.22
- Polarization: > 90%

**Beam Target spin reversal**

Target spin reversal every few days
Kinematics/Acceptance

\[ \pi p \rightarrow \mu^+ \mu^- X \quad 4 \leq M_{\mu \mu} \leq 9 \text{ GeV/c}^2 \]

- The COMPASS acceptance covers the valence quark region
- \( \langle p_T \rangle \sim 1\text{ GeV} \) – TMDs induced effects expected to be dominant with respect to the higher QCD corrections

Large angular acceptance spectrometer (approx. 10 times larger acceptance compare to the typical past DY experiments) provides a “flat” acceptance for \( p_T \)

Beam Test 2009

- 160 GeV/c π- beam
- 2 cells polyethylene target
- Hadron Absorber and Beam Plug (not final ver.)
- 3 days of data taking

Reasonable Z-vertex separation, allowing to distinguish the 2 target cells and the absorber.

Invariant mass spectrum of μ⁺ μ⁻ pairs from Monte-Carlo simulation:
- expected J/Ψ : 3600±600
- expected DY : 110±22
Theoretical Predictions vs. Expected Precision

Luminosity: $1.2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$  
(Beam Intensity: $6 \times 10^{7} \text{ particles/sec}$)

280 days of data-taking $\rightarrow$ 2.5 x 10^5 DY events in $4 \leq M_{\mu\mu} \leq 9 \text{ GeV/c}^2$ region
1.4 x 10^6 DY events in $2 \leq M_{\mu\mu} \leq 2.5 \text{ GeV/c}^2$ region

$2 \leq M_{\mu\mu} \leq 2.5 \text{ GeV/c}^2$

4 x 10^6 events

$4 \leq M_{\mu\mu} \leq 9 \text{ GeV/c}^2$

1.4 x 10^6 events

Possibility of extended setup

CEDAR
(CErenkov Differential counter with Achromatic Ring focus)

$h^+$ beam: $p$ (75%) / $\pi^+$ (24%)
$h^-$ beam: $\pi^-$ (97%) / $K^-$ (2.4%)

In parallel with the “normal” DY exp.
- Flavor dependency of EMC effect
- Structure of the $\pi$ and $K$
- Strange quark in nucleon

Beam Particle Identification

p(NH$_3$) target (polarized)
(Unpolarized) Nuclear Target(s)
Tungsten Plug

Nuclear Target(s)
Time Schedule

• The first-ever polarised DY experiment will be started in the mid-October 2014, with a short beam test. Physics data taking will take place over the whole 2015. A second year of DY data-taking is planned, in case of LS2 delay, in 2018.

• Medium term future program ($^6$LiD and LH$_2$ targets): 2020-2024 ?

• Long term future program (Kaon & Anti-proton high intensity): 2025- ?

A lots of new unique data is just behind the corner !!
Summary

- Transverse spin effect has triggered the investigation of $k_T$-dependence (TMD) PDFs via SIDIS and Drell-Yan processes.

- The Drell-Yan process offers a clean testing ground for extracting the Sivers and Boer-Mulders functions without the complication of fragmentation.

- A successful measurement of Sivers and Boer-Mulders functions in the polarized COMPASS-II DY experiment will mark a milestone of perturbative QCD and TMD physics.
backup
## Planned Polarized Drell-Yan Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Particles</th>
<th>Energy</th>
<th>$x_1$ or $x_2$</th>
<th>Luminosity</th>
<th>Timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPASS (CERN)</td>
<td>$\pi^\pm + p^\uparrow$</td>
<td>190 GeV $\sqrt{s} = 19$ GeV</td>
<td>$x_2 = 0.2 - 0.3$ $x_2 \sim 0.05$ (low mass)</td>
<td>$2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$</td>
<td>2014</td>
</tr>
<tr>
<td>pol. SeaQuest (FNAL)</td>
<td>$p^\uparrow + p$ / $p + p^\uparrow$</td>
<td>120 GeV $\sqrt{s} = 15$ GeV</td>
<td>$x_1 = 0.3 - 0.9$</td>
<td>$1 \times 10^{36}$ cm$^{-2}$ s$^{-1}$</td>
<td>$&gt;2014$</td>
</tr>
<tr>
<td>NICA (JINR)</td>
<td>$p^\uparrow + p$</td>
<td>collider $\sqrt{s} = 20$ GeV</td>
<td>$x_1 = 0.1 - 0.8$</td>
<td>$1 \times 10^{30}$ cm$^{-2}$ s$^{-1}$</td>
<td>$&gt;2014$</td>
</tr>
<tr>
<td>J-PARC</td>
<td>$p^\uparrow + p$</td>
<td>50 GeV $\sqrt{s} = 10$ GeV</td>
<td>$x_1 = 0.5 - 0.9$</td>
<td>$1 \times 10^{35}$ cm$^{-2}$ s$^{-1}$</td>
<td>$&gt;2015 ?$</td>
</tr>
<tr>
<td>PANDA (GSI)</td>
<td>$\bar{p} + p^\uparrow$</td>
<td>15 GeV $\sqrt{s} = 5.5$ GeV</td>
<td>$x_2 = 0.2 - 0.4$</td>
<td>$2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$</td>
<td>$&gt;2016$</td>
</tr>
<tr>
<td>PAX (GSI)</td>
<td>$p^\uparrow + \bar{p}$</td>
<td>collider $\sqrt{s} = 14$ GeV</td>
<td>$x_1 = 0.1 - 0.9$</td>
<td>$2 \times 10^{30}$ cm$^{-2}$ s$^{-1}$</td>
<td>$&gt;2017$</td>
</tr>
<tr>
<td>PHENIX (RHIC)</td>
<td>$p^\uparrow + p$</td>
<td>collider $\sqrt{s} = 500$ GeV</td>
<td>$x_1 = 0.05 - 0.1$</td>
<td>$2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$</td>
<td>$&gt;2018$</td>
</tr>
<tr>
<td>RHIC internal target phase-1</td>
<td>$p^\uparrow + p$</td>
<td>250 GeV $\sqrt{s} = 22$ GeV</td>
<td>$x_1 = 0.25 - 0.4$</td>
<td>$2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$</td>
<td>$&gt;2018$</td>
</tr>
<tr>
<td>RHIC internal target phase-2</td>
<td>$p^\uparrow + p$</td>
<td>250 GeV $\sqrt{s} = 22$ GeV</td>
<td>$x_1 = 0.25 - 0.4$</td>
<td>$6 \times 10^{34}$ cm$^{-2}$ s$^{-1}$</td>
<td>$&gt;2018$</td>
</tr>
<tr>
<td>A$_v$DY RHIC (IP-2)</td>
<td>$p^\uparrow + p$</td>
<td>500 GeV $\sqrt{s} = 32$ GeV</td>
<td>$x_1 = ?$</td>
<td>$? \text{ cm}^{-2} \text{ s}^{-1}$</td>
<td>?</td>
</tr>
</tbody>
</table>
FIG. 12: Predictions for the Sivers single spin asymmetry for the Drell-Yan process at COMPASS, with $\pi^-$ beam of 190GeV, as function of $x_P$. We have chosen the average $x_\pi \approx 0.55$ and integrate transverse momentum up to 2GeV.