Drell-Yan processes at COMPASS

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on behalf of the COMPASS Collaboration

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Outline

- Introduction
- TMD PDFs and Drell-Yan
- DY@COMPASS
- COMPASS spectrometer upgrades
Common Muon Proton Apparatus for Structure and Spectroscopy
The scientific program of COMPASS-II started in 2012. It was approved by the CERN Research board on 1st December 2010.

The research covers three measurements:

- **Primakoff** → started in 2012
- **GPD and SIDIS (2012 and 2016-17)**
- **Drell-Yan** → *starting next year*
The structure of the nucleon at LO

The structure of the nucleon can be described by three parton distribution functions (PDF) at leading order in collinear approximation. When the $k_T$ dependence is taken into account, eight transverse momentum dependent (TMD) parton distribution functions are used to describe it.

- $f_{1T}^\perp(x, k_T^2)$: the Sivers effect is related to the azimuthal asymmetry in the parton intrinsic transverse momentum distribution induced by the nucleon spin.
- $h_{1}^\perp(x, k_T^2)$: the Boer-Mulders function describes the correlation between the transverse spin and the transverse momentum of a quark inside the unpolarised hadron.
- $h_{1T}^\perp(x, k_T^2)$: the Pretzelosity function describes the polarisation of a quark along its intrinsic $k_T$ direction making accessible the orbital angular momentum information.
The Drell-Yan process can be used to access the TMD PDFs of the proton.

The Drell-Yan process is the annihilation of a quark-antiquark pair coming from two hadrons.

It is a simple process, it is well understood, but it has a very small cross-section.

The single polarised Drell-Yan cross-section is (at LO):

\[
\frac{d\sigma}{d^4q d\Omega} = \frac{\alpha^2_{em}}{Fq^2} \hat{\sigma}_U \left\{ \left( 1 + D_{[\sin^2 \theta]} A_{U}^{\cos 2\phi} \cos 2\phi \right) \right.

\left. + |S_T| \left[ A_T^{\sin \phi_S} \sin \phi_S + D_{[\sin^2 \theta]} \left( A_T^{\sin(2\phi + \phi_S)} \sin(2\phi + \phi_S) \right. \right. \right.

\left. \left. + A_T^{\sin(2\phi - \phi_S)} \sin(2\phi - \phi_S) \right) \right]\right\}.
\]

\(D_{[f(\theta)]}\) = depolarisation factors, \(S\) = spin target components, \(F\) = flux of incoming hadrons and \(A\) = the azimuthal asymmetries, \(\hat{\sigma}_U\) = cross section surviving the integration of \(\phi\) and \(\phi_S\), \(\theta\) and \(\phi\) are the polar and azimuthal angle of the lepton in the CS frame, \(\phi_S\) is the spin angle on the nucleon in the TF.
The Drell-Yan process

What can be measured at COMPASS

At COMPASS, it will be possible to measure the asymmetries in single polarised Drell-Yan with the process $\pi^- + p^\uparrow \rightarrow \mu^+ \mu^- + X$

Each asymmetry term in the cross section gives access to two TMD PDFs:

- $A_U^{\cos 2\phi}$: access to the Boer-Mulders functions of both incoming hadron and target nucleon
- $A_T^{\sin \phi_S}$: access to the Sivers function of the target nucleon and unpolarised pdf of beam particle
- $A_T^{\sin(2\phi+\phi_S)}$: access to the Boer-Mulders function of the beam hadron and to the pretzelosity function of the target nucleon
- $A_T^{\sin(2\phi-\phi_S)}$: access to the Boer-Mulders function of the beam hadron and the transversity function of the target nucleon
SIDIS and DY are complementary ways to access the TMD PDFs → it is possible to perform a test of QCD

⇒ QCD expectation is:

\[ f_{1T}^{\perp} (DY) = -f_{1T}^{\perp} (SIDIS) \]
\[ h_{1}^{\perp} (DY) = -h_{1}^{\perp} (SIDIS) \]

This happens because gauge links are present in the cross sections of SIDIS and Drell-Yan processes to provide the gauge invariance. The gauge link provides the possibility of existence of non-zero T-odd TMD PDFs. The Sivers and Boer-Mulders functions are T-odd and they change sign to provide the gauge invariance. This test includes not only the sign change but also the comparisons of the amplitude and the shape of the corresponding TMD PDFs.
Both the Semi-Inclusive DIS and the Drell-Yan measurements allow to extract TMD PDFs.

The phase spaces of the two processes overlap at COMPASS → consistent extraction of TMD PDFs in the same region!
The COMPASS spectrometer

- $\mu, p, \pi, K$ beam
- 50-270 GeV/c momentum
- $\pm 180$ mrad angular acceptance

- NH$_3$ target polarisation $\sim 90$
- dilution factor 0.22 (Drell-Yan)
- three cells target
The main characteristics of the Drell-Yan experiment:

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

- the low Drell-Yan cross section requires a high intensity pion beam in order to obtain a good statistics

- beam intensity up to $10^8 \pi^-$ per second on the thick target ($\sim 1$ interaction length)

- a hadron absorber is needed to stop secondary particles flux and a beam plug to stop the non-interacted beam

- rearrangement of the target area to place the absorber

- new muon trigger in the first stage of the spectrometer

- vertex detector to improve the cell separation of events
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The first stage of the spectrometer has key importance because the main fraction of muons from Drell-Yan process is in its acceptance.
The target platform is modified and moved upstream along the beam line, so the target center will be moved of 230 cm.

The target will be made of two 55 cm long cells spaced by 20 cm.
Structure of the hadron absorber:

- 120 cm tungsten beam plug
- aluminium conical part
- 200 cm alumina (Al₂O₃)
- non-magnetic stainless steel peripheral part
15 minutes after the end of the run

The absorber surrounded by the concrete shield

Also radioprotection rules were considered and they will be respected
A vertex detector has been proposed to:

- improve mass resolution of the virtual photon
- improve resolution on the primary vertex position → better cell separation

Vertex detector specs:

- SciFi detector
- U-X-Y planes
- ~ 1 mm pitch
- ~ 20 × 15 cm²
The COMPASS acceptance covers the valence quark region ($x > 0.1$)

Asymmetries are expected to be significant in the valence quark region, up to $10\%$

The safe mass interval is between $4$ and $9$ GeV/$c^2$
Statistical errors and predictions

Predictions exist for the single spin asymmetry due to the Sivers effect, for the virtual photon mass range 4-9 GeV/c^2 and for the COMPASS kinematics. They are compared with the expected errors (1-2%) coming from a two bin analysis of two years of data taking. There is not TMD evolution in the predictions.

- Efremov et al., PLB612 (2005) 233 (solid and dashed)
- Collins et al., PRD73 (2006) 014021 (dot-dashed)
- Anselmino et al., PRD79 (2009) 054010 (red solid, red dot-dashed)
- Bianconi et al., PRD73 (2006) 114002 (boxes)
- Bacchetta et al., PRD78 (2008) 074010 (green short-dashed)
Predictions for asymmetries: 4-9 GeV/c² @ COMPASS

Sivers

Boer-Mulders

BM ⊗ pretz.

A. N. Sissakian, Phys. Part. Nucl. 41, 64-100 (2010)
In 2007, 2008, 2009 and 2012 important tests were performed at COMPASS. The most recent one was done in the condition of the future measurement, with the hadron absorber. During the short data taking, the feasibility was proved, the J/ψ peak and Drell-Yan events were observed as expected and the two cells were distinguished.

→ target temperature ok!
→ radioprotection limits respected!
→ detector occupancies ok!
→ agreement of simulations and reality!
Time scale

There is much interest in measuring TMD PDFs with the Drell-Yan process.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Type</th>
<th>$s \ (GeV^2)$</th>
<th>Timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPASS</td>
<td>fixed target</td>
<td>$\pi^\pm p^{\uparrow}$</td>
<td>357</td>
</tr>
<tr>
<td>RHIC (STAR, PHENIX)</td>
<td>collider</td>
<td>$p^{\uparrow}p$</td>
<td>$200^2$</td>
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<tr>
<td>Fermilab (SeaQuest)</td>
<td>fixed target</td>
<td>$p^{\uparrow}\Rightarrow H, pH^{\uparrow}\Rightarrow$</td>
<td>234</td>
</tr>
<tr>
<td>J-PARC</td>
<td>fixed target</td>
<td>$pp^{\uparrow}, \pi p^{\uparrow}$</td>
<td>60 – 100</td>
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<tr>
<td>Fair (PAX)</td>
<td>collider</td>
<td>$\bar{p}^{\uparrow}p^{\uparrow}$</td>
<td>200</td>
</tr>
<tr>
<td>NICA</td>
<td>collider</td>
<td>$p^{\uparrow}p^{\uparrow}, d^{\uparrow}d^{\uparrow}$</td>
<td>144, 676</td>
</tr>
</tbody>
</table>

COMPASS has the chance to be the first experiment to collect single polarised Drell-Yan data.
Summary

- the Drell-Yan measurement is part of the COMPASS-II Proposal
- the CERN Research board approved the COMPASS-II Proposal on 1st December 2010
- COMPASS will have first data on single polarised Drell-Yan in 2014
- COMPASS has the possibility to access TMD PDFs with SIDIS and Drell-Yan processes
- a crucial test of TMD PDFs factorization can be done by measuring the change of sign of the Boer-Mulders and the Sivers functions
Thanks for your attention!
Backup
The Collins-Soper frame: virtual photon rest frame, $P_a$ and $P_b$ lie in the $x$-$z$ plane, $z$ axis in the direction of $(P_a - P_b)$. The CS frame is usually chosen to study the Drell-Yan angular distribution

$\theta$ and $\phi$ are the angles defined by the lepton pair w. r. t. the hadrons plane

$\phi_S$ is the azimuthal angle of the target spin vector in the target rest frame (if target is polarised)
Since the $J/\psi$ is a vector particle like the photon and the helicity structure of $\bar{q}q$ ($J/\psi$) and $(\bar{q}q)\gamma^*$ couplings is the same, it is possible to establish an analogy between the two processes:

$$H_aH_b \rightarrow J/\psi X \rightarrow l^+l^-X$$

$$\updownarrow$$

$$H_aH_b \rightarrow \gamma^* X \rightarrow l^+l^-X$$

Studying the $J/\psi$ production will be possible:

- check the duality hypothesis
- dramatically enlarge statistics (for region of mass around $J/\psi$ mass)

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A. Sissakian, O. Shevchenko and O. Ivanov, JETP Lett. 86 (2007) 751
Expression of asymmetries

\[ F_{1}^{LO} \equiv C [ f_a \bar{f}_a ] \]

\[ A_{T}^{\cos 2\phi} \quad \overset{LO}{=} \quad C \left[ \left( 2 (\mathbf{h} \cdot \mathbf{k}_{aT}) \mathbf{h} \cdot \mathbf{k}_{bT} \right) \mathbf{h}_{1T}^\perp \bar{h}_{1T}^\perp \right] / M_a M_b F_{1}^{U} \]

\[ A_{T}^{\sin \phi_S} \quad \overset{LO}{=} \quad \tilde{A}_{T}^{\sin \phi_S} \]

\[ A_{T}^{\sin(2\phi+\phi_S)} \quad \overset{LO}{=} \quad -C \left[ \left( 2 (\mathbf{h} \cdot \mathbf{k}_{bT}) \left[ 2 (\mathbf{h} \cdot \mathbf{k}_{aT}) \mathbf{h} \cdot \mathbf{k}_{bT} \right) - \mathbf{k}_{aT} \cdot \mathbf{k}_{bT} \right] - \mathbf{k}_{bT}^2 (\mathbf{h} \cdot \mathbf{k}_{aT}) \right) \mathbf{h}_{1T}^\perp \bar{h}_{1T}^\perp \right] / 4 M_a M_b^2 F_{1}^{U} \]

\[ A_{T}^{\sin(2\phi-\phi_S)} \quad \overset{LO}{=} \quad -C \left[ \mathbf{h} \cdot \mathbf{k}_{aT} \mathbf{h}_{1T}^\perp \bar{h}_{1}^\perp \right] / 2 M_a F_{1}^{U} \]

where \( \mathbf{h} = q_T / q_T \)
More on acceptances

$x_\pi$ acceptance plot

$x_P$ acceptance plot
Predictions for asymmetries: 2-2.5 GeV/c^2 @ COMPASS

Sivers

Boer-Mulders

BM ⊗ pretz.

BM ⊗ transv.
Predictions for asymmetries: 2.9-3.2 GeV/c^2 @ COMPASS

Sivers

Boer-Mulders

BM $\otimes$ pretz.

BM $\otimes$ transv.
Q^2 vs x mean values

Drell-Yan @ COMPASS (MC)
SIDIS @ COMPASS (2010 proton data)
The unpolarised Drell-Yan angular distribution is:

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

\(\lambda, \mu\) and \(\nu\) as a function of virtual photon transverse momentum

\[\lambda, \mu, \nu\] in CS frame

\[\lambda, \mu, \nu\] in GJ frame

The parameters \(\lambda, \mu\) and \(\nu\) are related by the Lam-Tung sum rule\(^1\):

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

At LO, in collinear approximation:
\(\lambda = 1\) and \(\mu = \nu = 0\)

but

NA10 and E615 showed non-zero values for \(\lambda, \mu, \nu\) and also a \(\cos 2\phi\) modulation