Vol. 5 (2012) *Acta Physica Polonica B Proceedings Supplement* No 4

STUDY OF THE NUCLEON SPIN STRUCTURE BY THE DRELL–YAN PROCESS IN THE COMPASS-II EXPERIMENT*

Márcia Quaresma

on behalf of the COMPASS Collaboration

LIP — Laboratório de Instrumentação e Física Experimental de Partículas
Av. Elias Garcia 14–1, 1000-149 Lisbon, Portugal

(Received September 4, 2012)

The Parton Distribution Functions (PDFs) and the spin structure of the nucleon are important topics studied by the COMPASS experiment. The Drell–Yan (DY) process will be used in the future COMPASS-II measurements to access the Transverse Momentum Dependent PDFs (TMD PDFs). Studying the angular distributions of dimuons from the DY reactions with a negative pion beam with 190 GeV/c momentum and a transversely polarised proton target, we will be able to extract the azimuthal spin asymmetries and to access the various TMD PDFs, such as Sivers and Boer–Mulders functions. The start of the COMPASS DY experiment is scheduled for 2014. Three beam tests have been already performed, one of them in 2009 using a prototype hadron absorber downstream of the target, to understand the background reduction factors and the spectrometer response, and also to verify our results from Monte Carlo simulations. COMPASS aims at performing the first DY experiment with a transversely polarised target.

DOI:10.5506/APhysPolBSupp.5.1163
PACS numbers: 12.38.Qk, 13.20.Gd

1. Introduction to the Drell–Yan process

The Drell–Yan (DY) process is a quark–antiquark electromagnetic annihilation with the lepton pair production in the final state. In COMPASS we are interested in the $\mu^+\mu^-$ channel, the so-called dimuon channel. In order to exclude the contamination from the two main background sources, *i.e.* open charm production ($D0$-mesons decays in semi-leptonic mode) and secondary pion/kaons decays (combinatorial background), we will stick to the high mass region of he DY lepton pair $4 < M_{\mu\mu} < 9\,\mathrm{GeV}/c^2$.

* Presented at the Workshop "Excited QCD 2012", Peniche, Portugal, May 6–12, 2012.

The DY process has been measured and studied by several experiments since the 80s. The angular dependence of the DY cross section can be written as

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

where θ and ϕ are the polar and azimuthal angles of one of the produced leptons in a dilepton rest frame. In the assumption that the quarks do not have intrinsic transverse momentum (collinear hypothesis), one expects $\lambda = 1$, $\mu = 0$ and $\nu = 0$. This hypothesis was shown to be violated by two experiments, NA10 at CERN [1] and E615 at Fermilab [2]. They measured a modulation of $\cos 2\phi$ up to 30%, which leads to the conclusion that we cannot neglect the intrinsic transverse momentum of quarks (k_{T}) inside the hadrons.

2. Goals of the Drell–Yan measurement at COMPASS

COMPASS means Common Muon Proton Apparatus for Structure and Spectroscopy. It is a CERN experiment located in the M2 SPS beam line, which provides either muon or hadron beams, in a momentum range from 50 to 280 GeV/c. For the DY program, a negative pion beam with 190 GeV/c momentum will be used. COMPASS is a fixed target experiment with a two stage spectrometer: the large angle (LAS) and the small angle (SAS) spectrometers, which provide a large acceptance range in angles and momenta. Each spectrometer has a dipole magnet preceded and followed by several tracking detectors, as well as an electromagnetic and a hadronic calorimeters. In the LAS, there is a Ring Imaging Cherenkov detector to identify charged particles. Additionally, there is an active muon filter at the end of each spectrometer made by a thick absorber wall and a tracking detectors. Upstream of the polarised target there is a beam telescope made of scintillating fibre detectors for the tracking of the beam particles. The protons of the polarised target material (NH_3 — ammonia) will be transversely polarised with respect to the beam direction. For the DY program we will also use a hadron absorber downstream of the target to absorb the secondary hadrons produced in the target. It includes in its center, along the beam line, a beam plug to stop the non-interacting beam. A complete description of the COMPASS setup can be found in [4].

The nucleon structure is described at leading twist by 3 Parton Distribution Functions (PDFs) assuming the collinear hypothesis, namely unpolarised (f), helicity (g) and transversity (h) that do not depend on k_{T}. To take into account the quark intrinsic transverse momentum 8 PDFs are necessary to describe the nucleon structure, the transverse momentum dependent (TMD) PDFs. In the DY COMPASS program we will be able to access 4 of these TMD PDFs, namely transversity h_1, Boer–Mulders $h_1^{\perp}$, Sivers $f_{1T}^{\perp}$ and pretzelosity $h_{1T}^{\perp}$.

Arnold *et al.* [3] derived the full expression of the DY cross section ($\sigma_{\rm DY}$), for arbitrarily polarised beam and target. In COMPASS we have the opportunity to use an unpolarised beam and a transversely polarised target and in these conditions the $\sigma_{\rm DY}$ in LO can be written as

$$\frac{d\sigma}{d^4q d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U \left\{ \left(1 + D_{[\sin^2\theta]} \boxed{A_U^{\cos 2\phi}} \cos 2\phi \right) + \left|\vec{S}_{\rm T}\right| \left[\boxed{A_{\rm T}^{\sin\phi_{\rm S}}} \sin\phi_{\rm S} \right.\right.$$
$$\left.\left. + D_{[\sin^2\theta]} \left(\boxed{A_{\rm T}^{\sin(2\phi+\phi_{\rm S})}} \sin(2\phi+\phi_{\rm S}) + \boxed{A_{\rm T}^{\sin(2\phi-\phi_{\rm S})}} \sin(2\phi-\phi_{\rm S}) \right) \right] \right\} ,$$

where θ and ϕ are respectively the polar and azimuthal angles in the Collins–Soper reference frame, $\phi_{\rm S}$ is the angle between the transverse spin of the target nucleon and the transverse momentum of the γ^*. F is given by $F = 4\sqrt{(P_\pi \cdot P_p)^2 - M_\pi^2 M_p^2}$. q is the γ^* four-momentum, $\hat{\sigma}_U$ is the part of the cross section surviving the integration over the angles ϕ and $\phi_{\rm S}$, $|\vec{S}_{\rm T}|$ is the target polarization value and $D_{[\sin^2\theta]}$ is the virtual photon depolarisation factor.

The boxes in the above formula correspond to the 4 asymmetries we will measure. These azimuthal asymmetries contain a convolution of 2 PDFs of the target and beam hadrons:

- $\boxed{A_U^{\cos 2\phi}}$ gives access to the Boer–Mulders functions of both hadrons.
- $\boxed{A_{\rm T}^{\sin\phi_{\rm S}}}$ gives access to the unpolarised PDF of beam hadron and the Sivers function of the target nucleon.
- $\boxed{A_{\rm T}^{\sin(2\phi+\phi_{\rm S})}}$ gives access to the Boer–Mulders function of the beam hadron and to the pretzelosity function of the target nucleon.
- $\boxed{A_{\rm T}^{\sin(2\phi-\phi_{\rm S})}}$ gives access to the Boer–Mulders function of the beam hadron and to the transversity function of the target nucleon.

The Sivers ($f_{1T}^{\perp}$) and the Boer–Mulders ($h_1^{\perp}$) functions are naïve time-reversal odd functions, which leads to the prediction that they must change sign when accessed from DY or Semi-Inclusive Deep Inelastic Scattering

(SIDIS) [6]. The experimental confirmation of this sign change is considered a crucial test of non-perturbative QCD. We will have the unique opportunity to access these TMD PDFs from both processes in the same experiment.

We will also check the J/ψ–DY duality, which results from the possible analogy in the production mechanisms of both J/ψ ($q\bar{q} \rightarrow J/\psi + X$) and γ^*. Studying the charmonium mass region in the dimuon decay channel, it is possible to check the duality hypothesis. And if this hypothesis is confirmed then one can possibly access the PDFs from the J/ψ events, which implies much more statistics available.

3. Feasibility of the measurement

In 2007, 2008 and 2009, short DY beam tests were performed, to check the feasibility of the DY COMPASS measurement.

In 2007, an open spectrometer configuration (without hadron absorber) was used. With a negative pion beam with 160 GeV/c momentum and 4×10^6 π/s intensity off an unpolarised proton target (NH_3) $\simeq$ 90000 dimuons were collected in $\lesssim$ 12 hours. The J/ψ yields expected from extrapolation using past experiments measured cross sections were confirmed.

In 2008, also using an open spectrometer and increasing the beam intensity up to 6.5×10^6 π/s, a high occupancy of the detectors closer to the target region was observed. This was, in fact, expected and confirmed that the use of a hadron absorber is mandatory.

These two tests were important to verify the spectrometer response and the radiation conditions in the experimental hall. The control of the radiation doses is mandatory because COMPASS is a ground level experiment and the protection of both humans and detectors is a priority.

In 2009, the most important test was performed, using a prototype hadron absorber. A negative pion beam with 190 GeV/c was used, with two target cells of polyethylene with 40 cm length and 5 cm diameter each, spaced by 20 cm. The absorber prototype was made of two blocks of concrete and stainless steel, 100 cm length each, and $80 \times 80\,\mathrm{cm}^2$ in transverse dimensions. Inside the central part of the absorber, there was a beam plug made of tungsten and steel disks. This absorber had 66 radiation lengths and 6.7 pion interaction lengths. A good absorber is one with a number of radiation lengths as low as possible in order to avoid high multiple scattering of the muons and a number of interaction lengths as high as possible in order to absorb the produced hadrons in target.

The 2009 DY beam test had a duration of only three days. It was not expected to have a high DY statistics in a such short time, thus our monitoring signal was a J/ψ and the expected and measured yields for this channel were found in a good agreement.

The proposal setup [5] was meanwhile optimised. The current version of the planned absorber is made of alumina 236 cm long, the plug inside the absorber is made of 6 disks of W, 20 cm long each and 20 cm of alumina in the most downstream part (total of 140 cm). This absorber had 33.5 radiation lengths and 7.3 pion interaction lengths. Comparing these values with the ones for the 2009 test absorber, this is much better. From MC simulations and using this configuration we get a z vertex resolution of 6 cm in HMR. As the target will be made of two cells transversely polarised with respect to the beam direction, with opposite polarisations, it is important to know the contamination level in each, *i.e.* the number of events generated in one cell but attributed to the other due to smearing. The level of contamination is estimated as 0.3% in the upstream cell and 1.2% in the downstream one. The dimuon mass resolution is around 180 MeV/c^2 in HMR.

4. Acceptances, event rates and statistical errors

The dimuons acceptance in the HMR is 39%, 22% of which is with both muons in LAS, 2% with both muons in SAS and 18% with one muon in LAS and the other in SAS.

Assuming a negative pion beam with 190 GeV/c momentum, an intensity of $6 \times 10^7\, \pi^-$/s and a luminosity of $1.2 \times 10^{32}\, \mathrm{cm}^{-2}\mathrm{s}^{-1}$, a DY event rate of 900 events/day is expected in the HMR.

In two years of data taking (280 days), the statistical errors in the azimuthal asymmetries expected are presented in Table I.

TABLE I

Statistical uncertainty for the azimuthal asymmetries in the HMR.

Asymmetry	Uncertainty in HMR
$\delta A_U^{\cos 2\phi}$	0.0043
$\delta A_{\mathrm{T}}^{\sin \phi_{\mathrm{S}}}$	0.0134
$\delta A_{\mathrm{T}}^{\sin(2\phi+\phi_{\mathrm{S}})}$	0.0270
$\delta A_{\mathrm{T}}^{\sin(2\phi-\phi_{\mathrm{S}})}$	0.0270

With the COMPASS DY program we will access the 4 asymmetries, shown in Fig. 1. The total precision (statistical and systematic) expected for two years of data taking, dividing the statistics in a number of equipopulated x_F bins is shown as an error bars. The theoretical prediction for three of these asymmetries is also plotted. These theoretical predictions which were available in 2010, can be found in [7–9]. It was recently discussed in [10] that the Q^2 evolution of the TMDs is not properly taken into account in the existing predictions. The topic needs further theoretical investigation.

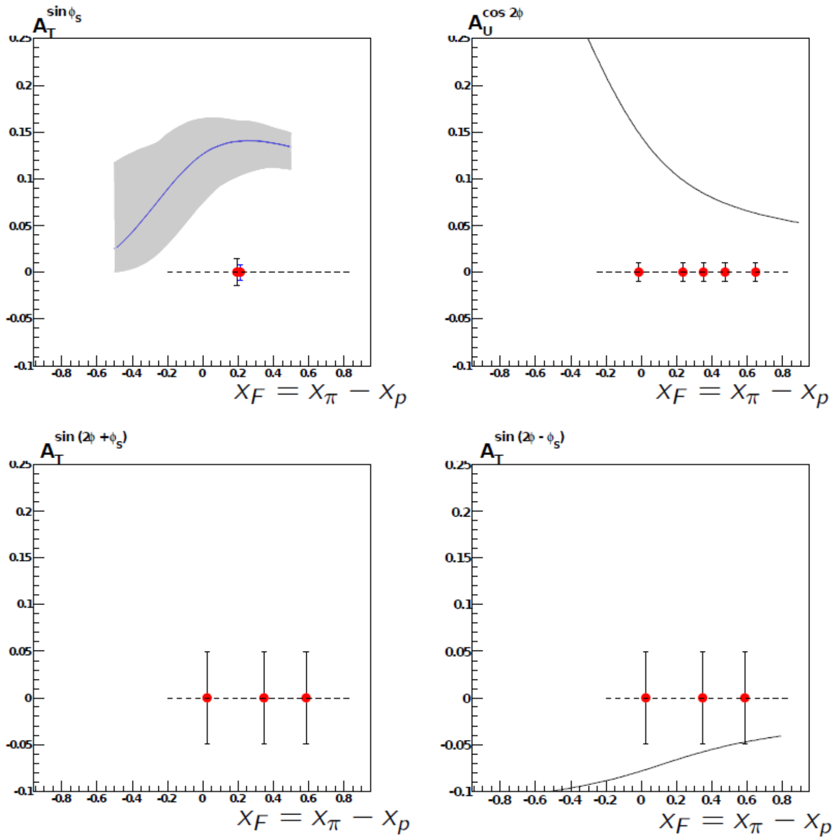

Fig. 1. $A_{\mathrm{T}}^{\sin\phi_{\mathrm{S}}}$ correspond to unpolarised PDF (beam) ⊗ Sivers (target) [7]. $A_U^{\cos 2\phi}$ correspond to Boer–Mulders (beam) ⊗ Boer–Mulders (target) [8]. $A_{\mathrm{T}}^{\sin(2\phi+\phi_{\mathrm{S}})}$ correspond to Boer–Mulders (beam) ⊗ pretzelosity (target). $A_{\mathrm{T}}^{\sin(2\phi-\phi_{\mathrm{S}})}$ correspond to Boer–Mulders (beam) ⊗ transversity (target) [9].

5. Summary

The opportunity to study in the same experiment the TMD PDFs from both SIDIS and DY processes is unique at COMPASS. The sign change in Sivers and Boer–Mulders functions when accessed from DY or SIDIS will be tested. The feasibility of the polarised DY measurement was proved by three past beam tests. The COMPASS II Proposal was approved by CERN for a first period of 3 years including 1 year for DY. This DY data taking will start in 2014, and the possibility to have a second year of data taking in 2017 is foreseen.

REFERENCES

[1] S. Falciano *et al.* [NA10 Collaboration], *Z. Phys.* **C31**, 513 (1986).

[2] J.S. Conway *et al.* [E615 Collaboration], *Phys. Rev.* **D39**, 92 (1989).

[3] S. Arnold *et al.*, *Phys. Rev.* **D79**, 034005 (2009).

[4] P. Abbon *et al.* [COMPASS Collaboration], *Nucl. Instrum. Meth.* **A577**, 455 (2007).

[5] COMPASS Collaboration, COMPASS-II proposal, CERN-SPSC-2010-014, SPSC-P-340, May 17, 2010.

[6] J.C. Collins, *Phys. Lett.* **B536**, 43 (2002); J.C. Collins, talk at LIGHT CONE 2008.

[7] M. Anselmino *et al.*, *Phys. Rev.* **D79**, 054010 (2009).

[8] B. Zhang *et al.*, *Phys. Rev.* **D77**, 054011 (2008).

[9] A.N. Sissakian *et al.*, *Phys. Part. Nucl.* **41**, 64 (2010).

[10] M. Aybat, T. Rogers, *Phys. Rev.* **D83**, 114042 (2011).