Simulation of the Drell-Yan process in hadronic interactions
in the COMPASS experiment

António de Valladares Pacheco

Under supervision of Maria Paula Frazao Bordalo e Sa

Dep. Physics, IST, Lisbon, Portugal

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Abstract

The focus of this thesis is the Monte Carlo simulation study of the COMPASS experiments Drell-Yan physics program as proposed in 2010, for the future of the experiment. This is a fixed target experiment, and uses a \( \pi^- \) beam and a \( \text{NH}_3 \) Ammonia polarized target, in order to measure T-Odd transverse momentum dependent (TMD) PDFs, which can describe the single spin asymmetries measured in the past, in Drell-Yan experiments.

**Keywords:** COMPASS, Monte Carlo, Drell-Yan, Sivers Function, Transverse Momentum Dependent (TMD) PDF.

1 Introduction

The Drell-Yan process consists of an electromagnetic interaction between a quark and an antiquark belonging to two hadrons, that annihilate to produce a virtual photon, or a Z-Boson, who then decays into a lepton pair. It was observed that the collision between hadrons resulted in a continuum of lepton pairs with opposite charge, with a mass spectrum that can be explained by the parton model. The process is electromagnetic and can be exactly calculated. Structure Functions are used to describe the internal structure of hadrons, and in the quark parton model they can be described through Parton Distribution Functions (PDF) that can be interpreted as the probability distribution of longitudinal momentum for each flavor of quark possible, in a collinear approximation. The Drell-Yan model can account for most experimental findings for the continuum measured in various experiments, but discrepancies were found in the cross
section calculation, the dimuon transverse momentum, and the angular distribution in the Collins Soper [1] reference frame. The total cross section is underestimated of a factor of 2 in reference to the experimental result, the mean transverse momentum measured was elevated in regard to the theoretical prediction, and measurements of a violation of the Lam-Tung Sum Rule [2] in the angular distribution of the dimuon have put in question the validity of the collinear approach for the description of the nucleons structure.

In 2008 Boers suggested [3] that the discrepancies in the angular distribution measured in NA10 [4] experiment could be accounted for as single spin asymmetries resulting from Transverse Momentum Dependent PDFs (TMDs). These TMD take into account the intrinsic transverse momentum of the quarks $k_T$ with a natural coupling with the spin of the nucleon.

1.1 The Drell-Yan process at COMPASS

COMPASS (COmmon Muon Proton Apparatus for Structure and Spectroscopy) is a CERN experiment that was born in 1998. The physics program proposed in the beginning was extensive and it will finish in the next year (2011). However the collaboration proposed a new physics program [5] for the next years. This proposal includes the study of the polarized Drell-Yan process to measure the transverse momentum dependent parton distribution functions of the nucleon.

1.2 The COMPASS Spectrometer

The spectrometer is divided in three zones. The first one includes the detectors upstream of the target, that measure the beam particles. The second and third zones are located downstream of the target and have a combined length of 50 m length. The second zone is called the Large Angle Spectrometer (LAS) and the third is called the Small Angle Spectrometer (SAS). The combination of these two spectrometers gives us a broad momentum range and a high angular acceptance. Each spectrometer is constructed around one of two magnets (SM1 and SM2) that are preceded and followed by trackers and completed by two calorimeters, one hadronic and another electromagnetic; both spectrometers also have a muon filter station (MW1 and MW2) to identify muons. In addition the LAS contains a RICH, which consists of a Cherenkov identification detector. For the Drell-Yan measurements it is very important to introduce a hadron absorber with a beam plug, in order to absorb the hadrons and to stop the beam that doesn’t interact in the target. The absorber is located immediately after the target.

This work will focus on the simulation of the COMPASS Proposal II [5]. The spectrometer setup simulated in the proposal uses an absorber formed by 150 cm of aluminum oxide, and 60 cm of steel. The beam plug is made of tungsten, designed in a conical shape and it is in the center of the absorber. For the Drell-Yan process analysis, one of the most important detectors are the muon filters.
The first Muon Filter (MF1) is located downstream of the LAS, next to the SM2. The wall of the MF1 is made of iron with 60 cm of thickness and a hole in the center. The second muon filter is located in the final part of the SAS. It has a wall of concrete with 2.4 m thickness and a central hole. These muon walls are preceded and followed by tracking detectors, called Muon Wall Stations. MF1 is associated with MW1 and MF2 with MW2. These stations allow us to identify which is the good sample of muons, since the absorber design covers the acceptance of these stations.

2 Monte Carlo Simulations

2.1 Monte Carlo Simulation of the DY Process

The simulation chain is composed of the fundamental steps. First, the physical process simulation, that allows us to understand what type of by-products we expect from the primary interaction, and its characteristics; for this purpose PYTHIA 6 was used. The program was tuned to simulate a \( q\bar{q} \) annihilation into a \( \gamma^* \) followed by a dimuon decay. In order to understand the total cross section of the DY process the branching ratio was calculated for the mass range \( 4 < M_{\mu\mu} < 9 \text{ GeV}/c^2 \), and for \( M_{\mu\mu} > 3.5 \text{ GeV}/c^2 \) taking into account all other possible decay channels. The mass range \( 4 < M_{\mu\mu} < 9 \text{ GeV}/c^2 \) of the dimuon mass spectrum allows for a DY process measurement without conflicting contributions from other processes, and therefore the data was restricted to that mass range in the analysis. The intrinsic transverse momentum distribution of quarks used was a Gaussian function with a width of 0.9 GeV/c and a cut-off at 3 GeV/c. These values are the ones that best fit the experimental transverse momentum distributions of the dimuon obtained by NA10 [4] collaboration, with a mean transverse momenta of 1.2 GeV/c consistent with the experimental findings of the NA10 [4] collaboration. Finally the reaction was defined as a beam of \( \pi^- \) with a 190 GeV/c momentum colliding with a target of protons.

2.1.1 Angular Distribution predictions

The Drell-Yan model predicts a simple angular distribution for the decay of the dilepton in its rest frame. This angular dependence comes from the resulting virtual photons spin, which is aligned with the beam axis in a collinear annihilation of the \( q\bar{q} \) pair, which integrated over azimuth gives

\[
\frac{dN}{d\theta} = 1 + \cos^2 \theta
\]  

The generated \( \cos(\theta_{CS}) \) distribution was fitted to a \( p_0(1 + p_1 \cos^2(\theta_{CS})) \) function with free parameters \( p_0 \) and \( p_1 \) in order to measure the validity of the \( (1 + \cos^2(\theta_{CS})) \) tendency expected. The \( \cos(\theta_{CS}) \) distribution has the appropriate tendency, with a fitted value of 0.78. The results support that the DY process is well simulated for the phase space we are interested in.
2.2 COMPASS II Proposal Setup Simulation

Afterwards we must simulate the propagation of the particles through the detector. For this purpose a GEANT 3 based program was used called COMGEANT, specifically made for the COMPASS spectrometer, that has as input, the PYTHIA simulation output. In order to simulate the setup intended the implementation of the COMPASS polarized target was necessary with two $NH_3$ target cells inside a 2.61 meters long solenoid that allows a transverse polarization of the ammonia cells. The two target cells are 55 cm long, spaced by 20 cm, with a 2 cm radius each, centered at $Z = -260$ cm, in the laboratory reference frame.

2.2.1 Probability of Interaction in Target Cells

The probability of interaction in each cell was also implemented in COMGEANT according to

$$\frac{N}{N_0} = \exp\left(-\frac{x}{\lambda_{int}}\right)$$  \hspace{1cm} (2)

If we take $x$ as the length of target crossed in the $NH_3$, we can take $N/N_0$ as the probability of non interaction and thus the probability of interaction $P_{int}$ as

$$P_{int} = 1 - \frac{N}{N_0} = 1 - e^{-x/\lambda_{int}}$$  \hspace{1cm} (3)

We therefore reach the conclusion that 22.3 % of all beam particles are going to interact in the first cell, and 17.3 % are going to interact in the second one. To have the most efficient simulation possible all beam pions interact with the target, and we renormalized the interaction probability in each cell in order to have a mean interaction probability in both targets of 100 %. This means that of the 39.6 % of events that have an interaction in either cell (22.3 % in the first and 17.3 % in the second), 56.3 % interact in the first cell, and 43.7 % in the second one.

2.2.2 Hadron Absorber and Beamplug Implementation

The hadron absorber and beamplug required the reimplementation of the material properties of the Alumina and steel, and a study of the loss of energy and multiple scattering of a muon that crosses the absorber from the primary DY interaction. The absorber has a total length of 2.1 m, with 1.5 m of Alumina ($Al_2O_3$) and a final segment with 60 cm of steel. Its transverse dimensions are 80 $\times$ 80 cm, and it was placed 5 cm after the solenoid-target system. This absorber is designed to stop the hadron production of the main interaction.

Inside the absorber a beamplug made out of tungsten, designed to stop the non-interacted beam was implemented, divided into 9 discs, with varied transverse dimensions covering a constant angular range of $\pm15$ mrad, which matches the SAS hole. The first disc of tungsten starts 30 cm inside the Hadron Absorber. The mean momenta of a reconstructed muon from a DY interaction is of about 48 GeV/$c$, and suffers a loss of about 2.5 GeV in
the hadron absorber, crossing 55 radiation lengths.

2.3 Reconstruction of the Monte Carlo Simulated Events

The next step of the simulation is running the events through a program called CORAL (COmpass Reconstruction ALgorithm) that reconstructs them based on the information produced by COMGEANT. The last program used in the simulation is PHAST (PHysics Analysis Software Tools), the analysis program that allows the study of generated and reconstructed events. With this tool we are able to study the acceptances and resolutions for individual muon tracks, and for events with a muon pair resulting in a dimuon. This is done also for positive and negative muons, and dividing LAS and SAS as individual spectrometers.

2.3.1 Acceptance Analysis

The acceptance is calculated as the number of accepted events divided by the number of generated events. The results for the acceptances are consistent with the ones from the COMPASS DY Proposal II, and point to a good geometrical description of the setup. We see a global acceptance of 36 % for accepted dimuon events in the $4 < M_{\mu\mu} < 9 \text{ GeV}/c^2$ mass range where the DY process study is more suitable. The LAS accepts 61 % of these events, and the SAS only 4%. An important contribution is made by events with larger symmetry where one muon is accepted in SAS and one and LAS. It accounts for 40 % of the events, with one muon scattered at a small angle, and the other at a large angle, with a high mean dimuon momenta. We can see that the tendency of the spectrometer to accept events in function of dimuon mass is uniform. When looking at events from LAS we see a slight increase in the acceptance for high dimuon mass, and a slight decrease in events accepted in both SAS, and with one muon in LAS and one in SAS. The acceptance is also uniform as a function of $p_T$. There is a slight increase in acceptance with both muons in SAS for small $p_T$ which may account for very symmetrical muon pairs, that due to their small angles increase the acceptance in the small $p_T$ range, but overall, in every spectrometer the acceptance is almost completely uniform, although there is a very slight tendency for the LAS to increase its acceptance for $p_T$ above 2 $\text{ GeV}/c^2$, and the SAS to decrease at the same range.

If we now turn to the acceptances as a function of momentum, the SAS accepts more events as the dimuon momentum rises, while LAS accepts more events as the dimuon momentum falls. Although the latter consist of a very small contribution for the overall acceptance, we can see, that for LAS + SAS events we have the same tendency, with high momentum muon pairs being detected one in each spectrometer. This can be explained by a tendency for high momentum dimuons being more asymmetrical and therefore at least one of the muons to “escape” the LAS and be detected in the SAS.

An analysis of the tendency of individual muons within the $M_{\mu\mu} > 3.5 \text{ GeV}/c^2$ to be accepted in dif-
different zones leads to the conclusion that the spectrometer is asymmetric and accepts more negative muons than positive ones in all zones of the spectrometer with a larger effect on the SAS. This is due to the past SIDIS (Semi Inclusive Deep Inelastic Scattering) COMPASS program setup. This program did not have a beam plug implemented. Therefore the spectrometer is asymmetric in order to follow the beams trajectory through the spectrometer, due to the magnetic fields from both magnets. The global acceptance for individual muons is 63 % with 70 % of these muons in the LAS, and around 30 % in the SAS. Events detected in both spectrometers account for a very small percentage of around 3% of the total accepted events, and tend to be muons scattered at small angles with low momenta, that are deflected inside the acceptance of the SAS after being detected in LAS.

2.3.2 Reconstruction Analysis

The reconstruction efficiencies are analyzed for single muons in the $M_{\mu\mu} > 3.5 \text{ GeV/c}^2$ mass range, and for events with dimuon reconstruction in the $4 < M_{\mu\mu} < 9 \text{ GeV/c}^2$. The reconstruction efficiencies for the individual muons, and divided in both negative and positive ones, is of around 86 %. We see that the best reconstruction efficiency is in SAS consistently, and we also see that the spectrometer reconstructs more negative muons over positive ones. This could be due to the shift of the detector planes towards the negative particles direction, that would result in a larger probability of positive muons to have fewer hits as the distance to the primary vertex increases, and the deflection of the track becomes greater. The LAS has a reconstruction efficiency of 77 % of its accepted tracks, and reconstructs 69 % of all reconstructed tracks. The SAS reconstructs almost 80% of its accepted tracks, and accounts for 31 % of the total reconstructed tracks.

The dimuon events have a reconstruction efficiency of 73 % with 63 % reconstructed in LAS, only 2 % in the SAS, and 37 % in events with one muon in LAS and one in SAS. These efficiencies are not exclusive since we are neglecting events that are detected in both spectrometers, and therefore are accounted for more than once. The reconstruction efficiency of the LAS is 66 %. SAS has a 31 % reconstruction efficiency, and LAS + SAS events take a value influenced by both, with 60 %.

Finally we studied the quality of our reconstruction, looking at the resolutions achieved. We see that we have a global resolution for individual muon momenta of $\Delta p_{\mu} = p_{\mu\text{rec}} - p_{\mu\text{gen}}$ of 484 GeV/c with a large bias that is not expected. This result is explained by the nature of the material maps used to describe the energy loss in the absorber material. The resolution for the angle of the individual muons in reference to the beam axis of the laboratory reference frame, calculated as before is of 3 mrad. This leads to a mass resolution of 323 MeV/c$^2$, with a bias of 140 MeV/c$^2$. This bias is explained as a consequence of the bias observed in the individual muons momenta resolu-
tion. The resolution in the position of the primary vertex is of about 10 cm, which is smaller than the space between the two cells. This allows for an identification of the cell where the interaction took place. The $p_\mu$ resolution for individual muons is better for SAS with 325 GeV/c for negative muons and 336 GeV/c for positive muons, compared with the resolution in LAS. LAS has a resolution in momenta for individual muons of 530 GeV/c for negative muons, and about 520 GeV/c for positive muons. This feature, in addition to the better reconstruction efficiency for SAS, is explained by the number of tracking stations in SAS compared with the ones in LAS. We see a better resolution in $\theta_{\text{Lab}}$ for SAS than for LAS, which is expected due to the angular range covered by both spectrometers. The SAS accepts small angles and that allows for a better resolution. The opposite effect is felt in the position of the primary vertex resolution, where the small angular range of the SAS in addition with the large distances to the primary vertex results in worst resolutions than for LAS.

3 Beam Momentum Analysis

A possible improvement to the proposed setup and experiment is the modification of the beam momentum in order to achieve a higher Drell-Yan cross section, which is very small. A study of the consequences of either increasing or decreasing the beam momentum is presented comparing three beam momenta: 160 GeV/c, 190 GeV/c and 280 GeV/c. A higher beam momentum would increase the Drell-Yan cross section, while at the same time could possibly lead to an increase in acceptance, and have a large effect in increasing the number of events measured per unit of time. We will also take into account that the setup was designed for a 190 GeV/c beam momentum, and therefore the deflection in the magnetic fields, and the distances from detector planes are not setup for different beam momenta. This is taken into account as we run the complete Monte Carlo chain for the 3 beam momenta configurations. One must also take into account the effect of the increase in beam momenta in the phase-space covered. An important systematic contribution for a measurement of the primary interaction between the $\pi^-$ beam and the target proton, is the probability of the interaction being from a valence or sea quark. This is described by the Parton Distribution Function of the nucleon. PDFs are a function of both $x$ and $Q^2$, where $Q^2$ stands for the squared transfer of energy in the primary interaction. In our DY case we have used the leading order GRV98 for the proton, with $x \equiv x_2$ and $Q^2$ as equivalent to the dimuon mass.

The focus of the experiment is in the valence quarks of the nucleon, therefore the probability of probing a sea quark for low $x_2$ implies that the experimental data will be cut in that variable. The difference in phase space covered for each beam momentum leads to a different $x_2$ distribution for low $x_2$ and a different number of events inside the sample after the quality cut. We are therefore in-
interested in the probability of probing the sea or the valence quarks for a given $x_2$ value, and $Q^2$. If we take in consideration that for a proton the probability of finding a up quark is twice the one for finding a down quark; and also that we have a beam with a $\bar{u}$ valence quark, we expect that most of the interaction will take place with up quarks of the proton, and therefore we now assume this to be the best approximation in order to try and study the PDF structure. In order to have a quantitative idea of the balance of sea and valence in the PDF we take $u_s(x)/u(x)$ as a measure of the probability of probing a sea quark over a valence quark. As stated earlier the PDF is a function of the $Q^2$, and we should try and understand the evolution of the PDF set over the mass range we are going to use in our reconstruction ($4 < M_{\mu\mu} < 9 \text{ GeV}/c^2$).

Studies of the GRV98 leading order PDF set for the higher mass value of $9 \text{ GeV}/c^2$, broken down in sea and valence contributions for up and down quark lead to the conclusion that the ratio $u_s(x)/u(x)$ has a very small dependence on $Q^2$. Also evident is that, as expected, for low $x$ we will have a high probability of interacting with sea. And for $x = 0.05$ there is already a higher then 30% probability of interacting with the valence up quarks. Using this ratio we can try and understand what consequences this has for our different beam momenta.

In order to compare qualitatively the gain in cross section $\sigma$, the luminosity $L$ of our experiment, the spectrometer acceptance $A$, and the efficiency factor for the acquisition. Radioprotection issues only allow for a beam intensity of $6 \times 10^7$ pions per second. This means that we can neglect the $L$ factor as it is constant for each configuration. We then have

$$ N \propto A\sigma_{DY} $$ (4)

If we take the efficiency of the data acquisition term $\epsilon$ as proportional to the statistics inside the $x_2$ cut applied, we can assume $\epsilon = \epsilon_{x_2}\epsilon'$ with

$$ \epsilon_{x_2} = \frac{N_{\text{Entries in Clean Sample}}}{N_{\text{Total Entries}}} $$ (5)

We also know that the error associated with the amplitude for the single spin asymmetry we are interested in is proportional to $1/N$, and therefore we can write a proportional term

$$ \delta A_p = \frac{1}{\sqrt{A\sigma_{DY}\epsilon_{x_2}}} $$ (6)

Taking into account the differences in the beam momenta simulated, this proportional term to the error we will account for the quality of the measurement taking into account the number of events obtained.

In order to have a grasp on the event quality for each $x_2$ distribution, each bin of the $x_2$ distribution for each beam momenta distribution was weighed by the mean value of the ratio $\langle u_s(x)/u(x) \rangle$ for that bin. The integral for various $x_2$ cuts were compared
with the acceptance, the proportional term $\delta A_p$ for the measurement uncertainty and also $\epsilon_{x_2}$.

$$E_C \equiv \sum_{\text{bins}} (N_i \times \langle u_s(x)/u(x) \rangle) / N_{\text{Sample}}$$

(7)

With these proportional terms a balance was made between the various effects mentioned, seen in table 1. This balance was done taking into account the whole COMPASS spectrometer, and only the Large Angle Spectrometer. The motivation to study the LAS as an individual spectrometer arose as the implementation of the beamplug would have a shadowing effect over the SAS.

We can see that for the COMPASS spectrometer the best statistical precision is obtained with $p_{\text{Beam}} = 280 \, GeV/c$ for all $x_2$ cuts. Although the contamination factor is higher for this beam momentum. Nevertheless, the gain in cross section and acceptance outweighs the loss in statistics inside the $x_2$ cut. With $x_2 > 0.1$ the contamination are below 8% for all beam momenta simulated.

The conclusion reached with this study is that the best option is applying a $x_2 > 0.1$ cuts on the sample of reconstructed events with a 280 $GeV/c$ beam momentum which, although loses considerable statistics from this $x_2$ cut, compensates this loss with the gain in cross section and acceptance.

4 Conclusions

The COMPASS Proposal II setup was simulated, and an analysis of the acceptances in the various zones of the spectrometer allowed for an understanding of the physical mechanisms that produce the total acceptance in the spectrometer taking into account the introduction of a hadron absorber. The reconstruction algorithm efficiency was also analyzed for each spectrometer zone concluding that in addition to a tendency to accept more negative muons than positive ones, the reconstruction algorithm also favors negative muon reconstruction. This leads to the conclusion that a symmetrization of the spectrometer is needed for the DY program, for which studies are already underway. The resolutions for the measurements were calculated for all zones and significant variables, we are able to conclude that the $\Delta Z_{\text{Primary Vertex}}$ is enough for an identification of the target cell of origin, which allows for the simultaneous opposite polarization of both cell. The momenta resolutions for individual muons has an unexpected bias, of 400 $MeV/c$ that might be a result of the material map calculation of the energy loss for the hadron absorber, which takes into account only mean values for a great deal of matter crossed.

A study of a possible improvement of the statistical precision of the spin asymmetry measurement through different beam momenta was made, concluding that a configuration of 280 $GeV/c$ beam with a $x_2 > 0.1$ should be the most favorable taking into account the probability of interacting with the quark sea, and the number of events obtained as the cross section increases, and the phase space becomes less favorable for a clean sample of events, within the $x_2$ cut.
References


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<th>$p_{Beam}$ (GeV/c)</th>
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$x_2 > 0.10$

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$x_2 > 0.15$

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Table 1: Balance of the effects for different beam momenta for 160, 190 and 280 GeV/c, in the COMPASS spectrometer, and LAS taking into account different low $x_2$ cuts.