Study of the Drell-Yan process in pion-proton interactions at COMPASS

Márcia Quaresma

Under supervision of Prof.ª Doutora Paula Bordalo

Dep. Physics, IST, Lisbon, Portugal

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Abstract

The Drell-Yan (DY) process was measured in several experiments over the last decades, but with unpolarized beam and target. COMPASS is going to be the first experiment that will take data on polarized DY, using a polarized target, the main aim of which is to determine the transversity PDF and Parton Distribution Functions (PDFs) Transverse Momentum Dependent (TMD). To prepare the future experiment a data taking test was carried out, with a duration of 3 days. It's objective was to determine the quality conditions of the spectrometer in relation with the DY process analysis. This work is based on the Monte-Carlo simulation of the 2009 test. Firstly an introduction to the DY process is given, that explains the main features and shows the purpose of the measurement of the DY process at COMPASS. The origin of the collaboration and the experiment are presented along with the COMPASS spectrometer features. The simulation done is discussed, and in the end the studies done are reported.

Keywords: Drell-Yan, COMPASS experiment, Monte-Carlo Simulation, Angular distribution.

1 The Drell-Yan process

1.1 Historical overview

The Drell-Yan process is an electromagnetic interaction of a quark and an antiquark belonging to two hadrons, that annihilate to give a virtual photon, which then decays in a lepton pair. The process is electromagnetic and exactly calculable. The Drell-Yan model predictions are in agreement with almost all the features of the continuum measured in some experiments, except the high transverse momentum, and the underestimated cross section value by a factor of approximately 2. To account for these differences it is necessary that the simple Drell-Yan model suffers modifications arising from Quantum Cromodynamics (QCD), namely allowing gluon emission and absorption by quarks. This way the cross section value increases and this mechanism naturally provide transverse momentum to the dileptons. By considering the first order Feynman diagrams in QCD, Altarelli, Ellis and Martinelli (1979) [1] and Parisi (1980) [2] computed the cross section value and obtained $\sigma = K\sigma_0$ where K is a constant and σ_0 is the naive DY cross section. The next order was also fully calculated. The actual theoretical value of K is around 1.8, and therefore close to the experimental result, but it is not the same, so the problem is not yet solved.

1.2 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 programme proposed in the beginning was extensive and it will be finished in the next year (2011). However the Collaboration proposed a new physics programme [3] 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.

2 The COMPASS spectrometer

The spectrometer is divided in three parts. The first one includes the detectors upstream and downstream of the target, that measure the beam particles. The second and third parts are located downstream of the target and they have in total 50 m length. The second is called the Large Area Spectrometer (LAS) and the third is called the Small Area Spectrometer (SAS). The use of these two parts gives us a broad momentum range and a high angular acceptance. Each spectrometer is constructed around one magnet (SM1 and SM2) that is preceded and followed by trackers and completed by two calorimeters, one hadronic and other electromagnetic; both spectrometers have also a muon filter station (MW1 and MW2) to identify muons. In addition the LAS contains a RICH, a detector to identify particles. For the Drell-Yan measurements it is very important to introduce another component, an absorber with a beam plug, to absorb the hadrons and to "kill" the beam that doesn't interact in the target. The absorber is located immediately after the target. In the 2009 test, whose setup I will simulate in this work, the absorber is formed by 100 cm of concrete and 100 cm of stainless steel. The beam plug is made of tungsten and stainless steel. It has a conical shape and it is in the centre of the absorber.

For the Drell-Yan study, one of the most important spectrometer components are the muon filters, because we want to measure the dimuon produced by the virtual photon. The design principle for a muon filter is an absorber wall preceded and followed by tracking detectors. 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 centre. 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.

3 2009 beam test with π^- beam

3.1 Simulation

We start by discussing the simulation sequence. First we generate the Drell-Yan process with the *Monte-Carlo* generator PYTHIA, where we need to indicate what is the physical process to generate (the annihilation of two quarks into a virtual photon) and then the possible virtual photon decays that we can use. In this case only the decay in two opposite sign muons (i.e. dimuon) is allowed. A kinematic cut on the mass of the dimuon ($M_{\mu\mu}$) was used, with a lower limit of 3.3 GeV/c^2. Even though this cut was applied, it was verified that there were dimuons with a mass lower than 3.3 GeV/c^2, this problem was solved with the option *parton shower* off, which doesn't allow the possibility of gluon emission by the quarks. 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 obtained by NA3 and NA10 Collaborations. Finally the reaction was defined as a beam of π^- with a 190 GeV/c momentum colliding with a target of protons. The next step is to run COMGEANT using as input the PYTHIA generated events in order to simulate the particles interaction with the spectrometer. COMGEANT is a program based on GEANT, specific to COMPASS. In my case the objective is to have the same geometry as the one of the 2009 test. Thus it is necessary to describe the target and the absorber. The target is made of two cylindrical cells of polyethylene, each 40 cm long and with 5 cm in diameter, spaced by 20 cm. The absorber is made from two blocks of matter, one of concrete and the other of stainless steel, both 100 cm long, 80 cm wide and 80 cm high. In its centre there is a beam plug with conical shape. In the first 40 cm there is no matter; the next 120 cm are filled with tungsten and the last 40 cm with stainless steel. 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.

3.2 Kinematic Drell-Yan distributions

3.2.1 Distributions that characterize the Drell-Yan process

These distributions were obtained in the end of the simulation. Figure 1 shows the z vertex distribution.

We can determine the reconstruction efficiency through values in figure 1; it is simply the ratio between the number of reconstructed events and

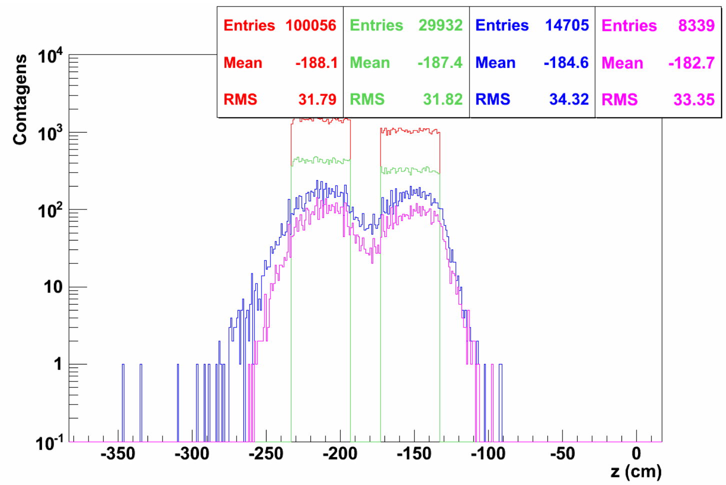

Figure 1: z initial vertex distribution for the muon pair production. We can see four distributions: red to generate events, green for geometrical accepted events, blue for reconstructed events and pink for reconstructed events in the mass region $4 < M_{\mu\mu} < 9\ GeV/c^2$.

the number of accepted events, that is, 49%. We want only to analyse the mass region $4 < M_{\mu\mu} < 9\ GeV/c^2$ because for lower masses there is a lot of background related with the ψ and ψ' resonances, combinatorial background from pion and kaon decays and physical background from semi-leptonic D meson decays. The region $4 < M_{\mu\mu} < 9\ GeV/c^2$ is the cleanest. For higher masses the cross section is very small. The Feynman x, x_F, distribution shows that all the accepted and reconstructed muons go forward, as expected, because COMPASS is a fixed target experiment. For the momentum we can extract that the lower dimuon reconstructed and accepted momentum is around $20\ GeV/c$, because lower momentum dimuons are expelled by the magnets to outside of the geometrical acceptance. The transverse momentum distribution has a mean value around $1.2\ GeV/c$, as expected for the mass region in study. The angular geometrical acceptance is around $\pm 120\ mrad$ so the distribution of the angle between the two muons in the laboratory frame cannot be larger than $240\ mrad$, as we can observe in the corresponding thesis plot.

3.2.2 Angular distribution of the muon pair

The DY model provides the leptons' angular distribution in the virtual photon rest frame, more specifically in the Collins-Soper (CS) frame. The θ and ϕ distributions for one of the muons in the CS frame are shown in the thesis. In first order QCD, the DY angular distribution is:

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

There is a sum rule, the Lam-Tung sum rule relating the magnitudes from equation 1:

$$1 - \lambda - 2\nu = 0 \quad (2)$$

In the collinear approximation $\lambda = 1$ and $\mu = \nu = 0$, so in the naive parton model it is expected that the θ distribution obeys the expression:

$$\frac{dN}{d\theta} = 1 + \alpha\cos^2\theta \quad (3)$$

where α is equal to unity and there is no dependence on ϕ.

We fit the $\cos(\theta_{CS})$ distribution for the generated events and we obtain for α a value 0.86 ± 0.03, near unity. We also did a bi-dimensional fit ($\cos(\theta_{CS})$, ϕ_{CS}) to the data from PYTHIA and the results seem to suggest that the model was adjusted to the existing experimental data.

4 Studies about the hadron absorber

4.1 Proposal and 2009 test absorbers

In experiments with high intensity beams, to study the DY process it is necessary to use an hadron absorber between the target and the spectrometer because the hadronic and DY cross sections differ by $> 10^6$ orders of magnitude and we only want to measure final state muons. Preliminary studies have shown that from the options considered, the best absorber was one made of 150 cm long alumina and 60 cm long iron and this is the proposal's absorber; however the work of optimization is still ongoing. For the 2009 test we decided not to use alumina because of the long manufacturing time and its high cost; and also because the test absorber was meant to be only a prototype.

4.2 Study of the transverse dimensions of the absorber

The transverse dimensions of the absorber were determined to cover the whole MW1 acceptance, so that all accepted muons in MW1 pass by the absorber, thus being in the same conditions. The resulting minimum transverse dimensions are $78.38 \times 67.12\ cm^2$, to be compared to the absorber dimensions of $80 \times 80\ cm^2$.

4.3 Interaction probability in the absorber plug

The beam plug role is to absorb all the beam that doesn't interact in the target. So we calculate the interaction probability of the beam with the beam plug. The result is 0.99997; it is high, but not enough to stop all of the beam (given its intensity), so the beam plug optimization is important to the future experiment.

4.4 Energy losses and multiple scattering

A study was made to understand the energy losses and the multiple scattering in the COMPASS setup. The calculation was made for the absorber, the muon filter 1 (MF1), the muon filter 2 (MF2) and the beam plug, and these were compared with the values extracted from COMGEANT at the passage of particles in these volumes. The results are in agreement, taking into account all the approximations, in both energy losses and multiple scattering. The mean energy lost in the absorber is 2.2 GeV; in MF1 it is 1 GeV; in MF2 it is 1.2 GeV; and in the beam plug it is 5.5 GeV. So we can conclude that we understand how the energy losses and multiple scattering are calculated in COMGEANT.

5 Results of the optimization studies

5.1 Interaction probability in each of the target cells

The calculation of the beam interaction probability in each of the target cells was computed by hand, using both the GEANT Manual's expressions (0.584 for the first cell and 0.416 for the second); and also using the PDG tabulated values (0.585 for the first cell and 0.415 for the second). The results are very similar, the difference being probably related with approximation factors.

5.2 Study of the vertices distribution along the spectrometer

To understand the absorber impact, a study of the secondary vertices distribution along the spectrometer was done. We use several geometries: without absorber; with absorber but without beam plug (beam plug region filled with air); only with the beam plug and without absorber; with absorber and plug (the last two plug discs filled with tungsten); and with the absorber and the plug used in 2009 test. Our interest is to observe the vertices number downstream of the absorber. For 1000 generated events, without absorber we have 89717 vertices; while for the geometries with absorber this number is smaller. The best is the 2009 test geometry, where the number of vertices is lowest downstream of the absorber.

5.3 Geometrical acceptance

The geometrical acceptance is the number of accepted events divided by the number of generated events. It is determined in two ways. First, considering only the geometrical dimensions of the detectors that have the function to identify muons, that are the MW1, the MW2 and MWPC-Bs. So we compute the angles covered by these detectors with respect to the centre of target and ignoring the SM1 and SM2 magnetic fields; this is an approximated calculation. The result is that these detectors cover the domain $[5, 120]$ $mrad$ of polar angle, leading to an acceptance of 33.95%. The second way to calculate the acceptance is by taking into account the number of hits in MW1, MW2 and MWPC-B detectors, as given by the spectrometer simulation. We calculate also the acceptance per region of the spectrometer. We consider that an event is accepted in LAS if both muons are accepted there; in SAS if both muons are accepted there; and the third hypothesis is if one is accepted in LAS and the other in SAS. Being accepted in LAS implies that a muon has more than 4 hits in the second part of MW1; accepted in SAS implies that a muon has more than 6 hits in MW2 or more than 3 hits in the MWPC-Bs. These criteria mean that more than half of the planes of the detectors have hits. We use two mass regions: the total generated mass region ($M_{\mu\mu} > 3.3\ GeV/c^2$) and the mass region of interest for DY studies, $4 < M_{\mu\mu} < 9\ GeV/c^2$. For the total mass region we obtain an acceptance of 33.86% and with the mass cut we have 33.87%; they are very close to the approximated values computed. The results in the different spectrometer areas are presented in table 1.

5.4 Dimuon resolutions

We calculate the mass, z vertex, transverse momentum and θ resolutions. The resolutions are very important values to obtain in a Monte-Carlo simulation because they are related with the error introduced by the reconstruction. When we use real data we know that the results are uncertain by values of this order, due to the smearing induced by the spectrometer components. The resolution is given by:

$$R_i = \frac{i_{rec} - i_{gen}}{i_{gen}} \tag{4}$$

where i is the studied variable, rec and gen refer to the reconstructed and generated samples. The variables' dispersion is defined as:

$$\Delta_i = i_{rec} - i_{gen} \tag{5}$$

where i, rec and gen have the same meaning as in the case of the resolution.

In table 2 the resolution results are shown. We can see that $R_M \sim R_z$ and $R_{p_T} \sim R_\theta$, as expected.

In table 3 we can see the dispersion values for several variables. The results are similar in ΔM for both cells. With respect to the Δz result, we can observe that, the distance between the target cells being 20 cm and assuming a Gaussian distribution of events originated in each cell, with a σ of 9 cm, the 20 cm correspond to 2.5σ. If the event was generated in the end of the first cell, the probability to wrongly consider that it was generated in the second is around 2%. This means that we can distinguish where the particle was generated with a small error.

6 Conclusion

The main aim of COMPASS is the measurement of the polarized Drell-Yan process to obtain the Transverse Momentum Dependent Parton Distribution Functions (TMD PDFs), using a π^- beam

Region	LAS (%)	LAS + SAS (%)	SAS (%)
Without restriction	62.12	34.95	2.93
[4, 9] GeV/c^2	65.81	31.99	2.20

Table 1: Acceptance in several regions of spectrometer and for two domains of mass.

R_M	R_z	R_{p_T}	R_θ
4.7	4.7	11.7	11.7

Table 2: Resolutions (in %).

and a transversely polarized target. To prepare the future experiment and write the experimental proposal three beam tests were performed. The objective of the tests is to conclude which points must be improved. This thesis is based on the 2009 beam test.

The simulation was done using a set of programs, a Monte-Carlo generator, PYTHIA; a package that simulates the experimental setup, COMGEANT; the reconstruction program, CORAL; and at the end a package that allows us to access the events and to do the analysis, PHAST.

It was concluded that it is necessary the use of an absorber in the future experiment. The absorber used on the 2009 test was a prototype, for the future it is necessary to optimize it. Many studies were done about the 2009 absorber that allow us to conclude what is important to modify.

The reconstruction efficiency is 49%, not very good, probably meaning that the reconstruction program CORAL needs some modifications for the Drell-Yan process studies, because the program was created for DIS reconstruction.

For the analysis we used the dimuon mass region $4 < M_{\mu\mu} < 9$ GeV/c^2, because it is the cleanest region from background.

The geometrical acceptance was computed in two ways, and the results were seen to be in agreement. The acceptance is 33.86% for the whole mass region and 33.87% for the mass region of $4 < M_{\mu\mu} < 9$ GeV/c^2.

The resolutions were computed and the results are summarized above. The resolutions are very important results because they show the uncertainty introduced by the reconstruction.

The data taking start is expected for 2013. Until them, many optimizations of the setup must be done.

$\Delta\ M_{1cell}\ (GeV/c^2)$	$\Delta\ M_{2cell}\ (GeV/c^2)$	$\Delta\ z\ (cm)$	$\Delta\ p_T\ (GeV/c)$	$\Delta\ P\ (GeV/c)$	$\Delta\ \theta\ (mrad)$
0.221 ± 0.003	0.222 ± 0.003	9.0 ± 0.1	0.160 ± 0.003	1.69 ± 0.03	1.54 ± 0.03

Table 3: Dispersions.

This thesis was very enriching for me because it allowed me to understand and collaborate in a big experiment, that probably will obtain new and highly important results in Particle Physics in the near future.

References

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