Simulação do processo Drell-Yan em interações hadrónicas na experiência COMPASS
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Resumo

Esta tese foca-se no estudo da simulação Monte Carlo do programa Drell-Yan para o futuro da experiência COMPASS como proposto em 2010. Trata-se de uma experiência de alvo fixo que usa um feixe de $\pi^-$ para interagir com um alvo polarizado de Amônia NH$_3$, de forma a medir PDFs dependentes do momento transverso (TMD), que podem descrever as simetrias de spin medidas no passado.

Introduz-se o processo Drell-Yan, a sua cinemática, características principais e discrepâncias experimentais. É então apresentada a origem da colaboração, motivação para uma medida do processo Drell-Yan, e uma descrição do espectrômetro COMPASS. No capítulo seguinte apresenta-se uma explicação da cadeia de simulação Monte Carlo e os seus resultados são descritos, tal como as implementações necessárias executadas sobre o software de simulação. De seguida um estudo sobre os efeitos que diferentes momentos de feixe podem ter sobre a precisão estatística da medida das assimetrias de spin pretendidas é apresentado. Finalmente um resumo e discussão dos resultados são apresentados.

Palavras-chave: COMPASS, Monte Carlo, Drell-Yan, Sivers, TMD PDF.
Abstract

The focus of this thesis is the Monte Carlo simulation study of the Drell-Yan physics program for the future of the COMPASS experiment, as proposed in 2010. This is a fixed target experiment, and uses a negative pion beam and an 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.

The thesis begins with an introduction to the Drell-Yan process, its kinematics, main characteristics and experimental discrepancies. It is then presented the collaborations origin and motivation for a Drell-Yan measurement, and a description of the COMPASS spectrometer. In the next chapter the Monte Carlo simulation chain is explained and results of the simulation are described, as are the implementation of needed features into the simulation software. Next, a study of the possible effects that different beam momenta could have in the statistical precision of the single spin asymmetry measurements intended is presented. Finally a summary and discussion of the results is shown.

Keywords: COMPASS, Monte Carlo, Drell-Yan, Sivers Function, Transverse Momentum Dependent (TMD) PDF.
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Chapter 1

The Drell-Yan Process

This chapter deals with the introduction of the Drell-Yan process (DY). We shall discuss its historical context and main characteristics. Although previous experimental efforts measured the unpolarized DY process, we will discuss the motivation behind the COMPASS experiment measurement of the polarized DY using a transversely polarized target. It will be the first measurement of this process using such polarization, and will be able to provide new information within the study of transversity and the T-Odd Transverse Momentum Dependent (TMD) Parton Distribution Functions (PDF).

1.1 Historical Context

The Drell-Yan process consists of an electromagnetic interaction between two quarks, that annihilate to produce a virtual photon, or a Z-Boson, which then will decay into a lepton pair. It was first observed in hadron-hadron scattering by J. H. Christensen et al (1970) in proton collisions with uranium nuclei at CERN (This was a different approach to the study of the internal structure of hadrons, which up until this point was centered in lepton-hadron collisions, using Deep Inelastic Scattering (DIS)).

Figure 1.1: Dimuon invariant mass spectrum, not corrected for acceptance, for Pb-Pb collisions at 158 GeV/c incident momentum. Data collected in 1996 in the NA50 Experiment at CERN (2001).
In this experiment and in others that followed, it was observed that the collision between the hadrons resulted in a continuum of lepton pairs with opposite charge, with a mass spectrum as shown in figure 1.1. This figure shows the results produced by the NA50 experiment at CERN [3] (2001), with Pb-Pb interactions at 158 GeV/c per nucleon. In this spectrum we can observe the resonance signatures of the $\psi$ and $\Upsilon$ families as discovered by Aubert et al (1974) [4], Augustin et al (1974) [5], Herb et al (1977) [6] and Ines et al (1977) [7].

Later in 1970 and in 1971, after the results from J.H.Christesen et al [2], Drell and Yan [8] proposed an interpretation of the dilepton pair continuum observed based on the parton model, using the process shown in figure 1.2. As we can see, one of the quarks(antiquarks) from the beam hadron will interact with one of the target antiquarks(quarks), annihilating into a virtual photon. This virtual photon will then decay into a lepton pair ($e^+e^-,\mu^+\mu^-,...$), with opposite charges. The process is electromagnetic and can be easily calculated. The propagator for the virtual photon comes with a $M^{-4}$ factor, which accounts for the rapid decrease of the cross section with mass, as observed in the experimental dilepton mass spectrum previously shown.

Figure 1.2: Feynman Diagram for the Drell-Yan process, as Sidney D. Drell and Tung-Mow Yan proposed in [8] (1970,1971).

When one computes the differential cross-section for such a process, with a resulting dimuon

$$A + B \rightarrow \mu^+ + \mu^- + X$$

one can see that the process depends on the momentum distribution of the quarks within the hadrons (A and B). Structure Functions are used to describe the internal structure of A and B, 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.

The Drell-Yan model predictions are in agreement with most of the experimental observations of the DY continuum to date in hadron-hadron collisions except for an underestimation by a factor 2 in the cross section and a high mean transverse momentum of the dilepton. It is therefore necessary to go beyond the simple electromagnetic DY process, and include Quantum Chromodynamics (QCD) into the process model. We will discuss this evolution of the model further ahead in this thesis.

**Kinematics of the process**

In order to describe the process we will begin by defining kinematic variables that will be useful in our discussion.

Feynman $x_F$ describes the fraction of the maximum possible momentum the virtual photon can carry. It is consequently defined as the longitudinal momentum normalized to the maximum allowed longitudinal momentum for the interaction's available CM energy ($\sqrt{s}$). In the high energy limit of the parton model, if we neglect the transverse momentum ($p_T \approx 0$) and the reduced mass of the hadrons from the interaction ($M = \frac{M_A M_B}{M_A + M_B}$) to be much smaller than $\sqrt{s}$, we can simplify the variable as:
\[ x_F = \frac{p_L}{p_L \text{ max}} \approx 2p_L \sqrt{\frac{1}{s} \left( 1 + \frac{p_L^2}{M^2} \right)} \]  
(1.1)

with a kinematic region from \(-1\) to \(1\). Also useful for our discussion is the definition of rapidity \(y\) defined as

\[ y = \frac{1}{2} \ln \left( \frac{E + p_L}{E - p_L} \right). \]  
(1.2)

We begin by describing the simple electromagnetic model proposed in 1970 and 1971 by Drell and Yan [8]. Just as we described earlier we have

\[ A + B \rightarrow \mu^+ + \mu^- + X \]  
(1.3)

The kinematic variables for the outgoing dimuon are also directly correlated to the parents \(q\) and \(\bar{q}\) longitudinal momentum, described by the Bjorken \(x_B\) variable, where this value translates the fraction of longitudinal momenta the quark carries from the parent hadron. We then have a beam hadron, with a corresponding quark (or antiquark) with a fraction of momentum \(x_1\) from its parent, and a target hadron with an antiquark (or quark) with a fraction \(x_2\) of its momentum.

With this in mind, in the hadronic CM reference frame, neglecting the sea quarks \((p_s L \approx 0)\), each of the annihilated quarks have a longitudinal momentum of \(x_1 \sqrt{s}/2\) and \(-x_2 \sqrt{s}/2\) respectively. Computing for the dilepton

\[ E = (x_1 + x_2) \sqrt{s}/2 \]  
(1.4)

and

\[ p_L = (x_1 - x_2) \sqrt{s}/2 \]  
(1.5)

and thus we get the invariant squared mass

\[ M^2 = E^2 - p_L^2 = s x_1 x_2 \]  
(1.6)

which allows us to define

\[ \tau = \frac{M^2}{s} = x_1 x_2 \]  
(1.7)

and also relate \(x_F\) with the hadron’s variables using

\[ x_F = \frac{2p_L}{\sqrt{s}} = x_1 - x_2. \]  
(1.8)

In the DY case we have a time-like photon, with a single amplitude needed to describe it, much as in \(e^- e^+\) annihilation. This is different for Deep Inelastic Scattering (DIS), where the virtual photon is space-like. Therefore if we take the virtual photon four-momentum as \(q\), for DIS we have a negative \(q^2\) whereas for Drell-Yan we have a positive \(q^2\).

In both the DIS and the DY cases, the partonic model dictates the total cross section computation takes into account the same quark and antiquark momentum probability distributions. These distributions are a function of longitudinal momentum, and therefore in this collinear approach are integrated over all transverse variables. This feature will be discussed further ahead as it is essential for the evolution from regular PDFs to Transverse Momentum Dependent (TMD) PDFs.

**The Drell-Yan Formalism**

We now have the basis to analyze the process and its formalism [1]. Figure 1.3 shows the diagram originating the dilepton continuum experimentally observed by Christensen et al [2]. We therefore have
\( q + \bar{q} \rightarrow \mu^+ \mu^- \) \hspace{1cm} (1.9)

which has the same cross-section as any annihilation of point-like fermions in QED, and analogous to the \( e^+e^- \) annihilation

\[
\sigma = 4\pi\alpha^2 \frac{Q^2}{3q^2} \tag{1.10}
\]

\( \alpha \) being the fine structure constant, \( Q^2 \) the charge of the quark, and \( q^2 \) the four-momentum of the virtual photon. This \( q^{-2} \) factor comes from the propagator factor in the amplitude, where in this case we can obviously see that \( q^2 = M^2 \) giving us

\[
\sigma = 4\pi\alpha^2 \frac{Q^2}{3M^2} \tag{1.11}
\]

We must convolute \( \sigma \) with the probability that the beam quark carries a fraction \( x_1 \) of the parent momentum, and with the probability that the target quark carries a fraction \( x_2 \), for each flavor of quarks available. Taking also into account that the antiquark can be associated either with the beam hadron or the target hadron, and consequently so is the quark. We obtain

\[
d^2\sigma = 4\pi\alpha^2 \frac{Q^2}{3M^2} (q_1(x_1)\bar{q}_2(x_2) + \bar{q}_1(x_1)q_2(x_2)) \, dx_1 dx_2 \tag{1.12}
\]

summing over all flavors, and divided by a factor 3 due to the fact that the quark and antiquark flavor must match

\[
\frac{d^2\sigma}{dx_1 dx_2} = 4\pi\alpha^2 \frac{Q^2}{9M^2} \sum Q^2 (q_1(x_1)\bar{q}_2(x_2) + \bar{q}_1(x_1)q_2(x_2)) \tag{1.13}
\]

with \( q_1 \) related to the beam hadron’s quark, and \( q_2 \) related to the target quark.

An equivalent form is also possible if we change to our dilepton variables (\( M \) and \( x_F \)), this will allow an analysis of the model predictions in the next section.

\[
\frac{d^2\sigma}{dM^2 dx_F} = 4\pi\alpha^2 \frac{x_1 x_2}{9M^4} \left( \frac{x_1 x_2}{x_1 + x_2} \right) \sum Q^2 (q_1(x_1)\bar{q}_2(x_2) + \bar{q}_1(x_1)q_2(x_2)) \tag{1.14}
\]

where

\[
\begin{align*}
x_1 &= \frac{1}{2} \left( x_F + \sqrt{x_F^2 + 4\tau} \right) \\
x_2 &= \frac{1}{2} \left( -x_F + \sqrt{x_F^2 + 4\tau} \right)
\end{align*} \tag{1.15}
\]

We can also retrieve the cross section as a function of rapidity \( y \), using

\[
dy = \frac{dp_L}{E} = \frac{dx_F}{(x_1 + x_2)} \tag{1.16}
\]
\[
\frac{d^2\sigma}{dMdy} = \frac{8\pi\alpha^2}{9\sqrt{s}} \sum Q^2 (q_1(x_1)q_2(x_2) + \bar{q}_1(x_1)\bar{q}_2(x_2))
\]  \tag{1.17}

As was previously mentioned, not taking into account the transverse momentum of the partons, allows us to describe the kinematics of this process through the simple relations.

\[
\begin{aligned}
\tau &= x_1x_2 \\
x_F &= x_1 - x_2
\end{aligned}
\]  \tag{1.18}

1.2 The Simple Drell-Yan Model Predictions and Results

Further experimental efforts have since 1971 brought light to the consistency of the Drell-Yan proposed model and its predictions. As mentioned in section 1.1 there is a good agreement between the experimental findings and the theory, except for the overall cross-section observed, and the transverse momentum distribution of the dilepton. Examples of consistency between the model and the experimental findings are shown, regarding the scaling test of the model, and the angular distributions observed; then, in next section 1.3 we will address the discrepancies concerning the transverse momentum distribution and total cross-section, as well as the possible QCD corrections to the model and their consequences.

Scaling

For \( x_F = 0 \) we have \( x_1 = x_2 = \sqrt{\tau} \), and the cross section can be simplified to

\[
\left. \frac{d^2\sigma}{dM^2dx_F} \right|_{x_F=0} = \frac{2\pi\alpha^2\sqrt{\tau}}{9\sqrt{s}} \sum Q^2 (q_1(\sqrt{\tau})\bar{q}_2(\sqrt{\tau}) + \bar{q}_1(\sqrt{\tau})q_2(\sqrt{\tau}))
\]  \tag{1.19}

\[
\left. \frac{d^2\sigma}{dMdy} \right|_{y=0} = \frac{8\pi\alpha^2}{9\sqrt{s}} \sum Q^2 (q_1(\sqrt{\tau})\bar{q}_2(\sqrt{\tau}) + \bar{q}_1(\sqrt{\tau})q_2(\sqrt{\tau}))
\]  \tag{1.20}

As was mentioned in section 1.1 the \( M^{-4} \) behavior due to the propagator of the intermediate photon accounts for the rapid fall of the cross section with increasing mass. One obtains

\[
M_3 \frac{d^2\sigma}{dMdx_F} = F_{12}(x_F, \tau)
\]  \tag{1.21}

where \( F_{12} \) depends only on the beam and target nature, and therefore should be independent of energy if measured at equal values of \( x_F \) and \( \tau \). Therefore \( \tau \) proves to be a good scaling measurable variable, that can test the Drell-Yan process theory. There is some simplification at \( x_F = 0 \), so taking then the cross section in \( y \) we get

\[
M_3 \frac{d^2\sigma}{dMdy} \bigg|_{y=0} = \tau^2 \left( s \frac{d^2\sigma}{d\sqrt{s}dy} \right) \bigg|_{y=0} \Leftrightarrow \tau^2 \left( s \frac{d^2\sigma}{d\sqrt{s}dy} \right) \bigg|_{y=0} = \frac{8\pi\alpha^2}{9} \sum Q^2 (q_1(\sqrt{\tau})\bar{q}_2(\sqrt{\tau}) + \bar{q}_1(\sqrt{\tau})q_2(\sqrt{\tau}))
\]  \tag{1.22}

where this cross section is only dependent on the PDFs at \( x_{1/2} = \sqrt{\tau} \). It is also clear that the total cross-section at a given value of \( \tau \) must be constant. We can define

\[
\begin{aligned}
F_{12}(\sqrt{\tau}) &\equiv M_3 \frac{d\sigma}{dMdy} \bigg|_{y=0} \\
G_{12}(\tau) &\equiv M_3 \frac{d\sigma}{d\tau}
\end{aligned}
\]  \tag{1.24}

This results in a model prediction of a constant behavior of the DY cross section for a given value of \( \sqrt{\tau} \), allows for a test of the model validity with the measurement of the cross section at equal values of \( \sqrt{\tau} \) at different beam energies.
Figure 1.4: Scaling form of the cross section for 200, 300, and 400 GeV data from the Fermilab CFS experiment in 1980 [9]. The dotted line is an exponential fit, while the solid line is the Drell-Yan model fit to the data.

Figure 1.4, taken from the work of Ito et al [9] (1980) at Fermilab, shows very good consistency between the experimental results and the theoretical expectations. The experimental data was obtained using a proton beam at three different energies, 400, 300 and 200 GeV, interacting with 4 different nuclear targets, covering a range of $\sqrt{s}$ between 20 and 28.2 GeV. The data was taken with $y = 0.2$ over the range in $\tau$ from 0.15 – 0.5.

Angular Distribution of the Drell-Yan Process

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 photon spin, which is aligned with the beam axis in a collinear annihilation of the $q \bar{q}$ pair. This photon decay amplitude into the lepton pair is then obtained with the possible spin alignments of the leptons

$$A(\theta, \phi) = \uparrow \uparrow Y_0^1(\theta, \phi) + \uparrow \downarrow Y_1^1(\theta, \phi)$$  \hspace{1cm} (1.25)$$

where the up arrow matches a parallel spin allignment with the beam, the down arrow the antiparallel, and $Y$ are the spherical harmonic functions with respect to the beam axis. The angular distribution is

$$\frac{dN}{d\Omega} \propto |A(\theta, \phi)|^2$$  \hspace{1cm} (1.26)$$

which integrated over the azimuth angle gives

$$\frac{dN}{d\theta} \propto 1 + \cos^2 \theta$$  \hspace{1cm} (1.27)$$

Table 1.1 shows data from several collaborations (Kourkoumelis et al [11] (1980), Antreasyan et al [12] (1980), and Badier et al [10] (1979) ) fitted with a function

$$\frac{dN}{d\theta} = 1 + \alpha \cos^2 \theta$$  \hspace{1cm} (1.28)$$

Although the experimental errors are large, the overall data is consistent with the simple Drell-Yan prediction that $\alpha$ should equal unity. A relevant factor for this analysis is that the alignment axis of the virtual photon changes in an event by event basis, and becomes uncertain by an angle of the order of $p_T/p_L$. Several choices of the reference axis in the rest frame of the lepton pair have been employed in attempts to minimize this problem. These are the u channel, the t channel and Collins-Soper [14] (1977) choices. The u-channel
choice has the polar axis pointing opposite to the incident target nucleon direction, and the t-channel choice has the polar axis along the incident beam particle direction and is known as Gottfried-Jackson reference frame. Collins and Soper take a direction midway in angle between the u and t-channel polar axes as the polar axis. Then if the two parent partons contribute equally, on average, to the transverse momentum, the Collins-Soper choice will minimize the distortion of the decay angular distribution.

![Figure 1.5: Definition of the azimuthal φ_{CS} and polar angle θ_{CS} in the Collins-Soper reference frame](image)

### 1.3 The Drell-Yan process in QCD

As was shown in the previous section there is good agreement between the Drell-Yan electromagnetic model and the experimental findings posterior to the proposal of Drell and Yan in 1971. One experimental downfall of this simple model is the discrepancy with the total cross section measured (σ_{exp}). This experimental measurement was found to be a factor $K$ above the expected value ($σ_0$). This, in addition to the discrepancies of the mean value of the $p_T$ distributions of dileptons was what motivated a QCD correction to the simple QED based process.

#### K-Factor

In table 1.2 we can see a summary of experimental efforts and the values of $K$ measured which is of the order of 2 or greater. This means experiments measure 2 times the cross section predicted.

$$σ_0 = Kσ_{exp}$$ (1.29)

---

1 The reference frame axis chosen for the dilepton reference-frame is important for the interpretation of the data, and therefore must be included in the table.
Table 1.2: Measurements of the K factor by which the experimental dilepton cross sections exceed the simple Drell-Yan formulae prediction.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Beam - Target</th>
<th>$E_{CM}(GeV)$</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA51 [15]</td>
<td>$p-p$</td>
<td>29.1</td>
<td>2.27 ±0.06 ± 0.16</td>
</tr>
<tr>
<td>E288</td>
<td>$p-Pt$</td>
<td>27.4</td>
<td>1.7</td>
</tr>
<tr>
<td>E439</td>
<td>$p-W$</td>
<td>27.4</td>
<td>1.6 ±0.3</td>
</tr>
<tr>
<td>CHEMNP</td>
<td>$p-p$</td>
<td>44.6</td>
<td>1.6 ±0.2</td>
</tr>
<tr>
<td>AABCSY</td>
<td>$p-p$</td>
<td>44.6</td>
<td>1.7</td>
</tr>
<tr>
<td>NA3</td>
<td>$p-Pt$</td>
<td>27.4</td>
<td>3.1 ±0.5 ± 0.3</td>
</tr>
<tr>
<td>E537</td>
<td>$p-W$</td>
<td>15.3</td>
<td>2.45 ±0.12 ± 0.20</td>
</tr>
<tr>
<td>NA3</td>
<td>$p,p-Pt$</td>
<td>16.8</td>
<td>2.3 ±0.4</td>
</tr>
<tr>
<td></td>
<td>$\pi-Pt$</td>
<td>16.8</td>
<td>2.49 ±0.37</td>
</tr>
<tr>
<td></td>
<td>$\pi-Pt$</td>
<td>22.9</td>
<td>2.22 ±0.33</td>
</tr>
<tr>
<td>E326</td>
<td>$\pi-W$</td>
<td>20.6</td>
<td>2.70 ±0.08 ± 0.40</td>
</tr>
<tr>
<td>NA10</td>
<td>$\pi-W$</td>
<td>19.1</td>
<td>2.8 ±0.1</td>
</tr>
<tr>
<td>Goliath</td>
<td>$\pi-Be$</td>
<td>16.8,18.1</td>
<td>2.5</td>
</tr>
<tr>
<td>Omega</td>
<td>$\pi-W$</td>
<td>8.7</td>
<td>2.6 ±0.5</td>
</tr>
</tbody>
</table>

Transverse Momentum Distributions

Another expectation from the simple Drell-Yan model was that the transverse momentum distribution of Drell-Yan events should be simply the vector sum of the transverse momentum of the $q\bar{q}$ pair. In this case we should expect the dimuon $p_T$ to be 0, but experimental findings have showed this not to be true, and considering these results one can try to infer the intrinsic transverse momentum $k_T$ distribution of the quarks. If we take a gaussian $k_T$ distribution with

$$h \left( k_T^2 \right) = \frac{b}{\pi} e^{-\frac{b^2 k_T^2}{2}}$$  (1.30)

we should expect an exponential decrease with increasing $k_T$. Looking at experimental data in figure 1.6, one finds that at small $p_T$ the distribution is very well described; however there is an excess of events at large transverse momentum. This is an evidence that QCD perturbative contributions gain importance for $p_T \approx M$.

Actually it is possible to identify different regime zones in the $p_T$ distribution. At low $p_T$ the gaussian $k_T$ regime and parametrization are evident, while at high $p_T$ a pure QCD perturbative region describes the distribution.

Figure 1.6: Dilepton transverse momentum distribution from Ito et al [9] compared with a Gaussian intrinsic $k_T$ distribution for the annihilating partons.
QCD first order corrections

The simple Drell-Yan model doesn’t take into account the interaction between the quarks within the hadrons as described in QCD, which can be exactly the kind of mechanism that can explain a higher mean value for the $p_T$ distribution. Thus considering the first order processes shown in figure 1.7 which amount to take the first term in the perturbative expansion on the coupling constant, we can achieve

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2f) \ln(Q^2/\Lambda^2)}$$

(1.31)

where $f$ corresponds to the number of possible quark flavors and $\Lambda$ ($200 \text{MeV}$) to the interaction scale. With $Q$ set to the value of typical dimuon masses, the value of $\alpha_s$ is small (of the order of 0.2) so that a perturbative expansion is not unreasonable.

The diagrams include the Born Drell-Yan diagram 1.7 (a), and the vertex corrections in (b). 1.7 (c) and (d) involve gluon emission, and are called annihilation diagrams. 1.7 (e) and (f) show a quark from one hadron scattering off a gluon from the other hadron. These are the QCD Compton diagrams, so named by analogy with the similar electromagnetic process. The amplitudes for the annihilation and Compton diagrams are copies of the QED amplitudes with colour factors added. Altarelli, Ellis and Martinelli [16] (1979) and Parisi [17] (1980) calculated explicitly the cross section using these diagrams and presented that

$$\sigma = K_{Theo}\sigma_0$$

(1.32)

where $\sigma_0$ is the QED simple cross section. These calculations lead to $K_{Theo} \approx 1.6$ for $\alpha_s \approx 0.3$. The corrections of higher orders are of very hard computation, due to the number of Feynman diagrams needed. Although this is true, it has been found that the perturbative series for the dominant vertex correction will exponentiate at

$$K_{Theo} \to \exp \left( \frac{2\pi \alpha_s}{3} \right) = 1.8$$

(1.33)

This means that most of the discrepancy between the experimental measurements of the cross section and the theoretical calculations can be explained by the QCD first order corrections but not completely. The problem still remains, and a higher order corrections could show a better answer.
In the case of the transverse momentum distributions some difficulties arise in the QCD calculations because of the existence of two energy scales, namely $p_T$ and the dilepton mass $M$. Only when both are large compared with the QCD energy scale set by $\Lambda$ it is reasonable to expect the simple perturbation expansion to apply. Calculations of this sort have been made by many authors. Also there is the problem of introducing the contribution of the intrinsic transverse momentum of quarks ($k_T$). This can be the factor that explains the constant term at small $p_T$, and theoretical predictions by Altarelli et al. [16] (1979) were remarkably close to the experimental data available. Other efforts for different kinematic regions of $p_T$ lead also to good agreement with the experimental data, and so different versions of the QCD calculations gave different degrees of success in fitting the $p_T$, and although no attempt stands out, it seems to be an indicator that the QCD approach can explain the discrepancies observed.

**Lam-Tung Sum Rule**

This first order QCD correction will also have consequences on the angular distributions expected by the model. The angular distributions become

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

(1.34)

And in Lam and Tung (1980) [18,19] proposed a sum rule defined as

$$1 - \lambda - 2\nu = 0$$

(1.35)

where $\lambda$, $\mu$ and $\nu$ are the amplitudes of the angular distribution. If we take a collinear approach, in the parton model, we have that $\lambda = 1$, $\mu = \nu = 0$.

However past experiments, such as NA10 and E615, have measured differences up to 30% in the modulation of $\cos(2\phi)$, as we can see in figure 1.8 from the NA10 collaboration [13] (1986).

In the late 90’s, Boer pointed out in [20] that the $\cos(2\phi)$ angular dependences observed in NA10 and other experiments could be due to transverse spin asymmetries resulting from a $k_T$ dependent parton distribution function (TMD) $h_1^T (x, k_T^2)$, the Boer-Mulder function. Model calculations for the nucleon and pion Boer-Mulders functions have been carried out and can describe the $\nu$ behavioral and account for the $\cos(2\phi)$ asymmetries observed in figure 1.8.
1.4 Structure of the Nucleon

As we discussed in section 1.3, the intrinsic transverse momentum of partons is a necessary part of the understanding of the 3-dimensional structure of the nucleon. The experimental results lead to the conclusion that the collinear approach of Drell-Yan falls short to describe the inner structure of both the neutron and the proton. A collinear approach based model can describe the quark structure of the nucleon with only three PDFs, which describe the structure functions of the nucleon as the coherent sum of the probability distributions for each type of quark, as functions of longitudinal momentum, integrated over the intrinsic momentum of the quark ($k_T$).

- $f_1(x)$ - Unpolarized distribution function describing the probability of finding a quark with a fraction $x$ of the longitudinal momentum of the parent hadron regardless of its spin orientation.
- $g_1(x)$ - Helicity distribution describing the difference between the number densities of quarks with spin parallel and anti parallel to the spin of the longitudinally polarized parent hadron.
- $h_1(x)$ - Transversity, a function similar to $g_1(x)$ but for transversely polarized hadrons.

However when $k_T$ is taken into account, several new Transverse Momentum Dependent functions arise, each one describing a different physical mechanism. Transverse spin, in fact, couples naturally to intrinsic transverse momentum, and the resulting correlations are encoded in various transverse-momentum-dependent parton distribution and fragmentation function [22] [21]. These properties result in spin asymmetries which are experimentally measurable.

When considering non-zero quark transverse momentum $k_T$ with respect to the hadron momentum, the nucleon structure is described at leading twist by eight PDFs:

![Diagram of 8 TMD PDFs](image.png)

Figure 1.9: The 8 TMD PDFs needed to describe the internal structure of the nucleon.

The distributions $f_1(x, k_T^2)$, $g_{1L}(x, k_T^2)$, $h_1(x, k_T^2)$, when integrated over $k_T^2$, yield $f_1(x)$, $g_1(x)$ and $h_1(x)$, respectively. $h_1^\perp(x, k_T^2)$ and $f_{1T}^\perp(x, k_T^2)$ are T-odd PDFs, which means that the distributions change sign with a naive time reversal transformation.

The Boer–Mulders function $h_1^\perp(x, k_T^2)$ describes the correlation between transverse spin and transverse momentum of the quark in an unpolarized nucleon. The Sivers function $f_{1T}^\perp(x, k_T^2)$ describes the influence of the transverse spin of the nucleon onto the quark transverse momentum distribution. A correlation between $k_T$ and the transverse polarization of a parton/hadron is intuitively possible only for non-vanishing orbital angular momentum of the quarks themselves. Hence, determinations of $h_1^\perp$ and $f_{1T}^\perp$, as well as of $h_1$ are of great interest to further reveal the partonic (spin) structure of hadrons.

The Drell-Yan quark-antiquark annihilation process is an excellent tool to study transversity and $k_T$-dependent T-odd PDFs, for there exists no fragmentation process in DY.
Chapter 2

The COMPASS Experiment

More than 10 years ago, the COMPASS experiment was conceived as “COmmon Muon and Proton apparatus for Structure and Spectroscopy” at CERN, capable of addressing a large variety of open problems in both hadron structure and spectroscopy. As such, it can be considered as a “QCD experiment”. By now, an impressive list of results has been published concerning nucleon structure, while the physics harvest of the recent two years of hadron spectroscopy data taking is just in its beginnings. The COMPASS apparatus has been proven to be very versatile, so that it offers the unique chance to address in the future another large variety of newly opened QCD-related challenges in both nucleon structure and hadron spectroscopy, at very moderate upgrade costs.

2.1 Origin and Motivation

What is COMPASS?

The COMPASS experiment was established in 1998, as two different physics groups, the CHEOPS (Charm Experiment with Omni-Purpose Setup) group and the HMC (Hadron Muon Collaboration) group, with different physics programs merged, in order to take advantage of the fact that the experimental requirements to achieve their physical measurements were very similar. Using the unique CERN SPS M2 beam line that delivers hadron or naturally polarised $\mu^\pm$ beams in the energy range between 50 GeV and 280 GeV, COMPASS addresses major physical programs, the muon program and the hadronic program. One result of the merger of these two groups is that the COMPASS spectrometer was designed to be very versatile in order to be able to satisfy the needs of the hadron and the muon programs, and therefore created a very large potential for future programs.

Building of the apparatus began, after the approval by CERN, in October 1998, and was followed by a technical run in 2001. The muon beam program started data taking in 2002, until 2006 (2007) with a polarised $^6$LiD target (NH$_3$), interrupting during 2005 for the LHC preparation at CERN, reserving a 2 week pilot run with a hadron beam and profiting from this time to upgrade spectrometer. In 2008 and 2009 the hadron beam program took place. In 2010-2011 the muon program with the NH$_3$ target was completed. Meanwhile in 2010 the COMPASS-II proposal was presented to CERN detailing what will be the future of the experiment, and within this future resides the use of the Drell-Yan process to study the Structure of the Nucleon.

Drell-Yan Physics at COMPASS

Much attention in the recent years has been devoted to the Sivers function originally proposed to explain the single-spin asymmetries observed in DIS scattering, that from $T$-invariance arguments, for a long time was believed to be zero. One of the main theoretical achievements of the recent years was the interpretation that the structure of parton distributions implies that the $T$-odd distributions measured in SIDIS and the same
distributions measured in DY exhibit an opposite sign. The Sivers function can be different from zero but
must have opposite sign in SIDIS and DY. There is a keen interest in the community to test this prediction
which is rooted in fundamental aspects of QCD, and many groups at different world laboratories are planning
experiments just to test it. The Sivers function was recently measured by HERMES and COMPASS in SIDIS
off transversely polarised targets and shown to be different from zero and measurable. In order to test its
sign change, DY experiments with transversely polarised hadrons are required, but none were performed so
far. The main goal of the COMPASS-II DY program is to measure, for the first time, on a transversely
distinguishable target, the process $\pi^- p^\uparrow \rightarrow \mu^+ \mu^- X$. In two years of data taking with a 190 GeV/c $\pi^-$ beam and
the COMPASS spectrometer with the NH$_3$ transversely polarised target, the fundamental prediction for the
sign of the $u$ quark Sivers function can be tested for the first time.

2.2 Experimental Apparatus

The COMPASS physics program imposed specific requirements to the experimental setup in order to ac-
commodate both hadron and muon beam programs. They were: large angle and momentum acceptance,
including the request to track particles scattered at extremely small angles, precise kinematic reconstruction
of the events together with efficient PID and good mass resolution. Operation at high luminosity imposes
capabilities of high beam intensity, and huge data flows.

The basic layout of the COMPASS spectrometer, as it was used in 2010, is shown below in figure 2.2
1, and a detailed description can be found in Abbon et al 23 (2007). Three parts can be distinguished.
The first part includes the detectors upstream of the target, which measures the incoming beam particles.
The second and the third part of the setup are located downstream of the target, and extend over a total
length of 50 m. These are the large angle spectrometer (LAS) and the small angle spectrometer (SAS),
respectively. The use of two spectrometers for the outgoing particles is a consequence of the large momentum
range and the large angular acceptance requirements. Each of the two spectrometers is built around an
analyzing magnet, preceded and followed by telescopes of trackers and completed by an electromagnetic
and hadronic calorimeter set, and by a muon filter station for muon identification. A RICH detector for hadron
identification is part of LAS. An overview of the detectors and their most important characteristics is shown
in the three following tables hereafter.

---

1With the exception of the Beam Momenta Spectrometer (BMS) described in section 2.2.
Figure 2.2: Top view of the 2010 Compass spectrometer setup.

<table>
<thead>
<tr>
<th>Station</th>
<th># dets.</th>
<th>Planes/det.</th>
<th># of ch./det.</th>
<th>Active (X \times Y) (cm(^2))</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Angle Spectrometer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SciFi 3,4</td>
<td>2</td>
<td>XYU</td>
<td>384</td>
<td>(5.3 \times 5.3)</td>
<td>(\sigma_s = 130\mu m, \sigma_t = 0.4) ns</td>
</tr>
<tr>
<td>Micromegas</td>
<td>12</td>
<td>X/Y/U/V</td>
<td>1024</td>
<td>(40 \times 40)</td>
<td>(\sigma_s = 90\mu m, \sigma_t = 9) ns</td>
</tr>
<tr>
<td>DC</td>
<td>3</td>
<td>XYUV</td>
<td>1408</td>
<td>(180 \times 127)</td>
<td>(\sigma_s = 190\mu m)</td>
</tr>
<tr>
<td>Straw</td>
<td>9</td>
<td>X/Y/U/V</td>
<td>892</td>
<td>(323 \times 280)</td>
<td>(\sigma_s = 190\mu m)</td>
</tr>
<tr>
<td>GEM 1-4</td>
<td>8</td>
<td>XY/UV</td>
<td>1536</td>
<td>((Y:704))</td>
<td>(\sigma_s = 70\mu m, \sigma_t = 12) ns</td>
</tr>
<tr>
<td>SciFi 5</td>
<td>1</td>
<td>XY</td>
<td>320</td>
<td>(8.4 \times 8.4)</td>
<td>(\sigma_s = 170\mu m, \sigma_t = 0.4) ns</td>
</tr>
<tr>
<td>RICH(_1)</td>
<td>8</td>
<td>1(pads)</td>
<td>10368</td>
<td>(60 \times 120)</td>
<td>(\sigma_{ph} = 1.2) mrad</td>
</tr>
<tr>
<td>MWPC A*</td>
<td>1</td>
<td>XUVY</td>
<td>2768</td>
<td>(178 \times 120)</td>
<td>(\sigma_s = 1.6) mm</td>
</tr>
<tr>
<td>HCAL 1</td>
<td>1</td>
<td>1</td>
<td>480</td>
<td>(420 \times 300)</td>
<td>(\Delta E/E = 0.596) mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(\sqrt{E/GeV} \oplus 0.08)</td>
</tr>
<tr>
<td>MW1</td>
<td>8</td>
<td>X/Y</td>
<td>1184/928</td>
<td>(473 \times 405)</td>
<td>(\sigma_s = 3) mm</td>
</tr>
<tr>
<td>Small Angle Spectrometer</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GEM 5-11</td>
<td>14</td>
<td>XY/UV</td>
<td>1536</td>
<td>(31 \times 31)</td>
<td>(\sigma_s = 70\mu m, \sigma_t = 12) ns</td>
</tr>
<tr>
<td>MWPC A</td>
<td>7</td>
<td>XUV</td>
<td>2256</td>
<td>(178 \times 120)</td>
<td>(\sigma_s = 1.6) mm</td>
</tr>
<tr>
<td>SciFi 6</td>
<td>1</td>
<td>XYU</td>
<td>462</td>
<td>(10 \times 10)</td>
<td>(\sigma_s = 210\mu m, \sigma_t = 0.4) ns</td>
</tr>
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<td>XY</td>
<td>286</td>
<td>(10 \times 10)</td>
<td>(\sigma_s = 210\mu m, \sigma_t = 0.4) ns</td>
</tr>
<tr>
<td>SciFi 5</td>
<td>1</td>
<td>XY</td>
<td>352</td>
<td>(12.3 \times 12.3)</td>
<td>(\sigma_s = 210\mu m, \sigma_t = 0.4) ns</td>
</tr>
<tr>
<td>Straw</td>
<td>6</td>
<td>X/Y/U/V</td>
<td>892</td>
<td>((Y:704))</td>
<td>(\sigma_s = 190\mu m)</td>
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<tr>
<td>Large Area DC</td>
<td>6</td>
<td>XY/XV/XU</td>
<td>390/548/548</td>
<td>(500 \times 250)</td>
<td>(\sigma_s = 0.5) mm</td>
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<td></td>
<td></td>
<td>YV/YU</td>
<td>418/418</td>
<td></td>
<td></td>
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<td>ECAL 2</td>
<td>1</td>
<td>1</td>
<td>2972</td>
<td>(245 \times 184)</td>
<td>(\Delta E/E = 0.06) mm</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(\sqrt{E/GeV} \oplus 0.02)</td>
</tr>
<tr>
<td>HCAL 2</td>
<td>1</td>
<td>1</td>
<td>216</td>
<td>(440 \times 200)</td>
<td>(\Delta E/E = 0.66) mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(\sqrt{E/GeV} \oplus 0.05)</td>
</tr>
<tr>
<td>MWPC B</td>
<td>6</td>
<td>XU/XV</td>
<td>1504</td>
<td>(178 \times 90)</td>
<td>(\sigma_s = 1.6) mm</td>
</tr>
<tr>
<td>MW2</td>
<td>2</td>
<td>XYV</td>
<td>840</td>
<td>(447 \times 202)</td>
<td>(\sigma_s = 0.6 - 0.9) mm</td>
</tr>
</tbody>
</table>

Table 2.1: Overview of detectors used in COMPASS, together with their respective main parameters, grouped according to their geometrical positions along the beam line (stations) and functions in the spectrometer.\(^2\)
Table 2.2: Overview of Beam detectors used in COMPASS, together with their respective main parameters, grouped according to their geometrical positions along the beam line (stations).²

<table>
<thead>
<tr>
<th>Station</th>
<th># dets.</th>
<th>Planes/det.</th>
<th># of ch./det.</th>
<th>Active X × Y (cm²)</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM01-04</td>
<td>4</td>
<td>Y</td>
<td>64</td>
<td>6 × 12 × 9 − 23</td>
<td>σₚ = 1.3 − 2.5 mm, σₜ = 0.3 ns</td>
</tr>
<tr>
<td>BM05</td>
<td>2</td>
<td>Y</td>
<td>64</td>
<td>12 × 16</td>
<td>σₚ = 0.7 mm, σₜ = 0.5 ns</td>
</tr>
<tr>
<td>BM06</td>
<td>2</td>
<td>Y</td>
<td>128</td>
<td>12 × 16</td>
<td>σₚ = 0.7 mm, σₜ = 0.5 ns</td>
</tr>
<tr>
<td>SciFi 1,2</td>
<td>2</td>
<td>XY</td>
<td>192</td>
<td>3.9 × 3.9</td>
<td>σₛ = 130µm, σₚ = 0.4 ns</td>
</tr>
<tr>
<td>Silicons</td>
<td>6</td>
<td>XY/UV</td>
<td>2304</td>
<td>5 × 7</td>
<td>σₛ = 8 − 11µm, σₚ = 2.5 ns</td>
</tr>
</tbody>
</table>

Beam Spectrometer

The first part of the experimental setup is the Beam Spectrometer. The momentum of the beam is measured only for the muon type of beam. In the muon program, in order to measure the momentum of the beam muon that will interact in Deep Inelastic Scattering with the target, the Beam Momentum Spectrometer (BMS) is used. It is located upstream from the target, and consists of a bending dipole magnet and trajectory telescopes, which measure the incident and scattered muons momentum from the DIS interaction. In hadron beam runs the BMS isn’t used to measure the beam momentum due to the possible interaction of the beam with the BMS detectors, instead the value taken into account is the one given by the CERN beamline.

In order to determine the beam position, scintillating fiber detectors (SciFi) and Silicon detectors (Silicons) are used. Also used are anti-trigger hodoscopes (Vetos), as a way of identifying which particles belong to the collimated beam, and which don’t, and therefore are halo, and will contaminate the data.

Finally Cherenkov differential detectors (Cedars) are used in the hadron program to identify the beam particles, since the π⁻ beam is not pure. It is 95% π⁻, 4% K⁻ and 1% ¯p⁻.

Large Angle Spectrometer

LAS was designed in order to ensure an angular acceptance of ±180 mrad, matching the target solenoid magnets opening. It is constructed around the SM1 dipolar magnet, with tracking telescopes upstream and downstream from its position. SM1 is 110 cm long with a central opening of 229 × 152cm². The main component of the field is in the vertical direction, with a field integral of 1 T.m which means a deflection of 300 mrad for particles with momentum of 1 GeV/c. Due to this deflection power the LAS detectors positioned downstream must have an angular acceptance of ±250 mrad in the horizontal plane.

The SM1 magnet is followed by the RICH detector, used to identify charged hadrons with momentum ranging between a few GeV/c to 43 GeV/c. It has large enough transverse dimensions to cover the LAS acceptance requisits. Downstream from the RICH detector stands ECAL1, an electromagnetic calorimeter, used in the detection of neutrals, namely π⁰ and photons, and HCAL1 a hadronic calorimeter with a central opening that covers the acceptance of the SAS. HCAL1 detects hadrons produced and is used in triggering events. Finally LAS has a Muon Filter.

Small Angle Spectrometer

SAS is used to detect particles with small angles regarding the beam axis, with a maximum of 60 mrad, and therefore high momentum. It is also built around a magnet, the SM2, which is 4 meters long and also surrounded by tracking telescopes.

² The first column shows the naming convention for the respective stations. The second column gives the number of detectors making up these stations, while the third column specifies the coordinates measured by the detectors. Here, e.g. XY means that both projections are measured by each detector, while X/Y means that only one of two coordinates X or Y is measured by one of the detectors. Typical values for resolutions of one detector at standard COMPASS muon beam conditions are given, where appropriate, in the sixth column. These numbers correspond to an average over all detectors of this kind in the experiment, and hence may include contributions from pile-up, magnetic fringe fields, or reconstruction inefficiencies. Here, σₛ denotes the r.m.s. spatial resolution along one coordinate, σₚ the r.m.s. time resolution, σₚₗ the single photon resolution, σᵣingen the ring resolution.
<table>
<thead>
<tr>
<th>Det. name</th>
<th># dets.</th>
<th>Planes/det.</th>
<th># of ch./det.</th>
<th>Active $X \times Y (cm^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trigger Hodoscopes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner</td>
<td>1</td>
<td>X</td>
<td>64</td>
<td>17.3 $\times$ 32</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>X</td>
<td>64</td>
<td>35.3 $\times$ 51</td>
</tr>
<tr>
<td>Ladder</td>
<td>1</td>
<td>X</td>
<td>32</td>
<td>128.2 $\times$ 40</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>X</td>
<td>32</td>
<td>168.2 $\times$ 47.5</td>
</tr>
<tr>
<td>Middle</td>
<td>1</td>
<td>XY</td>
<td>40/32</td>
<td>120 $\times$ 102</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>XY</td>
<td>40/32</td>
<td>150 $\times$ 120</td>
</tr>
<tr>
<td>Outer</td>
<td>1</td>
<td>Y</td>
<td>16</td>
<td>200 $\times$ 100</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Y</td>
<td>32</td>
<td>480 $\times$ 225</td>
</tr>
<tr>
<td>Veto 1</td>
<td>1</td>
<td></td>
<td>34</td>
<td>250 $\times$ 320</td>
</tr>
<tr>
<td>Veto 2</td>
<td>1</td>
<td></td>
<td>4</td>
<td>30 $\times$ 30</td>
</tr>
<tr>
<td>Veto BL</td>
<td>1</td>
<td></td>
<td>4</td>
<td>50 $\times$ 50</td>
</tr>
</tbody>
</table>

Table 2.3: Overview of the Trigger detectors used in COMPASS, together with their respective main parameters, grouped according to their geometrical positions along the beam line (stations).

SM2 is a dipole magnet of rectangular shape and an opening of $2 \times 1 \, m^2$, and a field integral of 4.4 T.m for a nominal current of 4000, or 5000 A. Depending on the beam particle momentum the current is set to a higher or lower current. For beam momentum of about 200 GeV/c the 5000 A current setting is used, and for a beam momentum of 160 GeV/c a 4000 A configuration is used. As with SM1 the main component of the field is in the vertical direction. It was used in past experiments, and its field map has been measured and is well known.

Downstream from SAS stands ECAL2, an electromagnetic calorimeter, and a hadronic calorimeter HCAL2. Further downstream a second Muon Filter completes the SAS.

**Trackers**

The particle flux per unit of transverse area varies by more than 5 orders of magnitude in the different acceptance regions of the spectrometer. Along the beam line and near the target, the detectors should combine an ability to withstand a high particle rate (up to some MHz/ch.) a very good spatial resolution ($< 100 \, \mu m$). The amount of material along the trajectory of the beam has to be reduced in order to avoid secondary interactions. These requisites are particularly harsh upstream from the SM1 magnet, where the incoming flux of particles is higher due to the amount of secondary, low energy particles coming from the target region.

Away from the beam the resolution constraints can be relaxed, but large areas must be covered. Thus, different detectors were employed at different distances from the beam line, in order to satisfy the constraints in flux, time, and spatial resolution. Different types of large gaseous detectors, based on amplifying drift wires are used in the regions further from the beam, with its central regions deactivated, so the radiation level is not exceeded. The beam region and close to it, is covered by very fast silicon scintillating, and gaseous detectors, with active areas that cover the deactivated areas of the larger detectors, in order to ensure good efficiency in track reconstruction and relative alignment.

The tracking detectors are grouped as:

- **VSAT** (Very Small Area Trackers) - small in size, must combine the ability to withstand high particle flux, with good spatial and time resolutions. The beam region, upstream and downstream of the target is covered by 8 scintillating fiber detector (SciFi) stations, and upstream there are 3 silicon microstrip (Silicon) detectors. Their transverse dimensions vary between 4 and 12 cm, so the beam divergence can be taken into account, along the beam line position of the detectors.

- **SAT** (Small Area Trackers) - In the region up to 2.5 cm away from the beam line, medium sized detectors are used, with high spatial resolution and a low amount of material used. 3 Micromegas stations and
11 Gas Electron Multiplier (GEM) stations. The 3 Micromegas stations are located between the target and SM1, and the 11 GEM stations are covering the region downstream from SM1 until the end of the spectrometer. Both devices possess central regions of 5 cm diameter, deactivated.

- LAT (Large Area Trackers) - At large angles these detectors have a good spatial resolution and cover the acceptance of the spectrometer. LAS has 3 Drift Chambers (DC), 2 of them located upstream of the SM1, and the other one immediately downstream. All of them have a deactivated central area with 30 cm of diameter in which the micromegas are inserted. They are followed by 2 drift chambers, of the straw drift type, upstream from the RICH, each with a deactivated central area of $20 \times 20 \text{cm}^2$. Downstream of the RICH detector until the end of the spectrometer the scattered particles at large angles are detected by 14 Multi Wire Proportional Chamber (MWPC) stations, with a deactivated central area that opens along the beam line from 16 cm to 22 cm. The section downstream from the SM2 magnet is covered by an additional straw drift tube station with the same characteristics described above, and by 6 large area drift chambers (W45) with a deactivated central area with diameters of 50 or 100 cm.

### Muon Filters

The muon identification is performed by two detector systems, one in LAS and one in the SAS part. Both systems are made of a set of tracking stations, a hadron absorber, and a second set of tracking stations. Such a structure allows to discriminate muons from track segments induced by the typical backgrounds like hadronic punch through from the hadron calorimeters. In this case these detecting stations are Muon Walls, and have a moderate spatial resolution. Muons are identified when the particles trajectory is reconstructed before and after the Muon Filter, in the Muon Wall.

The muon filtering system in LAS consists of two stations MW1, separated by a 60 cm thick iron absorber (Muon Filter 1) located in the final section of LAS before SM2. The basic element of the MW1 system is a gaseous wire detector called mini drift tube (MDT). A modified version of the MDTs with fully metallic cathodes was produced for the COMPASS experiment. Each station has four detectors with two planes of MDTs on both sides. Vertical and horizontal tubes provide the X and Y coordinates, respectively. The outer surface of each station is covered with thin (1 mm thick) aluminium sheets for mechanical, electrostatic and noise protection. All frames have a rectangular shape in the XY plane and a hole in their centre matching the acceptance of the SM2.

The active areas are $4845 \times 4050 \text{mm}^2$ (hole $1445 \times 880 \text{mm}^2$) and $4730 \times 4165 \text{mm}^2$ (hole $1475 \times 765 \text{mm}^2$) for the X and the Y planes, respectively in order to cover the transverse area of the Muon Filter 1. This way any track that crosses the absorbing material is detected. The MW1 system provides a measurement of up to eight points per track in each projection with the coordinate accuracy of $10/\sqrt{12}$ mm typical for the 10 mm wire pitch.

In SAS the tracking downstream from SM2 is used in combination with a 2.4 m thick concrete absorber (Muon Filter 2) followed by two stations of MW2 and three MWPC stations at the end of SAS. Muon Wall 2 (MW2) consists of two identical stations of layers of drift tubes. Each of the two stations consists of six layers with an active area of $447 \times 202 \text{cm}^2$ grouped into double layers, each mounted to a separate steel frame. A rectangular hole in each plane of the detector with a size of $1 \times 0.8 \text{m}^2$ around the beam is realised using properly shortened tubes. The hole is covered by the MWPC stations, which partly overlap with the sensitive area of MW2.

### 2.3 COMPASS II Proposal Setup

This thesis is focused on a Monte Carlo simulation study of the COMPASS II Proposal Drell-Yan Setup, and a study of its features and possible improvements. A discussion of the hardware upgrades to the 2010 spectrometer described above follows. In this sense, except otherwise noted, all hardware upgrades described in this thesis refer to the set-up used in 2010 with the muon beam and the polarised NH$_3$ target. The 2010 spectrometer is shown in Fig. 2.2 and a detailed discussion of most of the components can be found in Ref. [23].
Transversely Polarised Target

The proposed experiment requires a transversely polarised proton target. The existing COMPASS polarised-target system can be used for this purpose.

The polarisation of the target is obtained by the Dynamic Nuclear Polarisation (DNP) method, with a high-cooling-power dilution refrigerator, a 2.5 T solenoid magnet and two microwave systems of about 70 GHz corresponding to the Zeeman splitting for electrons. The polarisation value is measured by NMR techniques from the integral of the NMR absorption signal which is proportional to the polarisation. The spin can be oriented perpendicular to the beam direction by using a 0.6 T dipole magnet. Under this magnetic condition the polarisation can not be enhanced by the DNP method but can be maintained at a lattice temperature below 100 mK. As time passes, the polarisation decreases by the spin relaxation which depends on the magnetic field, the lattice temperature and the target material (frozen spin mode).

Ammonia (NH$_3$) as polarised proton material is well suited for the Drell–Yan measurements. It reaches a polarisation of 80% after one day and a maximum of 90% after three days. A spin relaxation time of about 4000 hours was measured at 0.6 T and 60 mK in 2007.

Due to multiple scattering in the hadron absorber, which is located downstream from the target, the vertex resolution is expected to be worse than in previous COMPASS measurements. Thus it should be more difficult to associate the target cell where each event originated. A distance of 20 cm between them appears necessary. This would result in a maximum length of 55 cm for each target cell.

The effects of the hadron beam and backscattering from the absorber to the target material and the cryogenic system have to be controlled. The total heat input into the mixing chamber caused by the pion beam is expected to be about 2 mW, which will not affect the spin relaxation time because the refrigerator has a cooling power of 5 mW at 70 mK. Therefore, no modifications of the refrigerator are required.

The radiation load to the sensitive elements of the cryogenic system was calculated using FLUKA simulations. The results appear to be far below the limits.

Absorber for Drell-Yan Measurements

The introduction of a hadron absorber is a necessity of a spectrometer design for any Drell-Yan measurement in the muon decay channel. After the 2007 and 2008 Drell–Yan beam tests, the introduction of a hadron absorber was proposed for the Drell-Yan measurement. In fact the installation of the hadron absorber will strongly reduce the high secondary particle flux produced by the interaction of the pion beam in the target and, consequently, the tracking detector occupancies. This allows the use of a high intensity pion beam. Various possibilities were analyzed, and different configurations were taken into account.

The hadron absorber design proposed in the COMPASS-II Proposal is shown in figure 2.3 although the Monte Carlo studies that were undertaken for the proposal took into account a different, simpler absorber. The absorber implemented in our Monte Carlo studies is the same used for the studies made for the Proposal. A detailed description of the implemented absorber is shown in section 3.3 in chapter 3.

The choice of materials for the absorber must follow two main criteria: to maximize the number of interaction lengths crossed by the hadrons produced in the collision in order to stop them while minimizing the radiation length in order to have energy loss and multiple scattering of the muons as small as possible.

Table 2.4 shows the basic characteristics of the various hadron absorbers used in CERN Drell-Yan experiments so far.

The best absorber configuration was found in the NA50 experiment for protons at an intensity of 10$^9$ particles/s, achieving a particle reduction factor of $I/I_0 = 1.74 \times 10^{-6}$. A NA50-like absorber was selected for the COMPASS-II Proposal design, taking into account the lower beam intensity of the COMPASS Drell–Yan experiment, which will be $6 \times 10^7$ particles/s, 16.7 times less than for NA50. As the background increases quadratically with the beam intensity, the particle reduction factor $I/I_0$ could be increased by a factor of 16.7$^2$ in COMPASS with respect to NA50, $I/I_0 = 4.85 \times 10^{-4}$, leading to a number of interaction lengths of $L/\lambda_{int} = 7.6$.

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$^2$FLUKA is a fully integrated particle physics MonteCarlo simulation package. It has many applications in high energy experimental physics and engineering, shielding, detector and telescope design, cosmic ray studies, dosimetry, medical physics and radio-biology.
Figure 2.3: Drawing of the hadron absorber proposed. The two NH$_3$ target cells of 55 cm length and 4 cm radius each, are also shown. They are spaced by 20 cm and placed 30 cm upstream of the absorber.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam mom. (GeV/c)</td>
<td>$\pi, p$ 200</td>
<td>$\pi, p, 200$</td>
<td>$p, 400$</td>
<td>$\pi, 150–200$</td>
</tr>
<tr>
<td>Intensity (p/s)</td>
<td>$4 \times 10^7$</td>
<td>$6 \times 10^8$</td>
<td>$1 \times 10^9$</td>
<td>$6 \times 10^7$</td>
</tr>
<tr>
<td>Absorber length (m)</td>
<td>1.5 (Fe)</td>
<td>4.8 (C+Fe)</td>
<td>5.4 (Al+C+Fe)</td>
<td>1.5 $\text{Al}_2\text{O}_3 + 0.65 \text{Fe}$</td>
</tr>
<tr>
<td>Beam dump (m)</td>
<td>1.5 (W)</td>
<td>4. (W+U)</td>
<td>4. (W+U)</td>
<td>1.8 (W)</td>
</tr>
<tr>
<td>Number of $\lambda_{\text{int}}$</td>
<td>7</td>
<td>13</td>
<td>13</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Table 2.4: Information relevant for the absorber design from past CERN Drell–Yan experiments as compared to the proposed COMPASS DY experiment.

The configuration for the future, is an absorber of aluminum oxide ($\text{Al}_2\text{O}_3$) with a total length of 150 cm, followed by a 65 cm long stainless steel absorber, corresponding to a total number of interaction lengths of $L/\lambda_{\text{int}} = 7.5$ (This is not the design for the absorber used in the Monte Carlo studies). For our implementation of the hadron absorber we used a similar absorber, with aluminum oxide ($\text{Al}_2\text{O}_3$) with a total length of 150 cm, but followed by 60 cm of stainless steel, instead of the above mentioned 65 cm, allowing for a $L/\lambda_{\text{int}} = 7.3$ as described in section 3.3 in chapter 3.

The two blocks of absorber materials have a central hole, centered with respect to the beam line, for the installation of the beam dump (plug), made of tungsten. The first 30 cm inside the aluminum oxide absorber are left empty (filled with air), in order to minimize back-scattering of particles produced by the beam interacting in the beginning of the plug. The plug itself is made of tungsten rods of increasing radius, covering a constant angle; it has to be optimized in order to stop the incoming beam particles and, on the other hand, to limit shadowing of the second spectrometer (SAS). The maximum transverse dimension of the absorber must match the maximum acceptance of the spectrometer, namely of the Muon Wall 1 detector (140 mrad).

This feature is the same as the one implemented in our Monte Carlo simulation, and on the Monte Carlo studies undertaken for the proposal.

An additional cone-shaped aluminum oxide piece is included in the proposal absorber, plugged into the target solenoid with a 2 cm gap before the absorber itself for a possible installation of vertex detectors (This feature was not taken into account in the present Monte Carlo Simulation performed in this thesis). A concrete shielding will be placed around the whole structure to reduce the dose rate diffused to the environment.
Trigger for Drell-Yan measurements

A trigger on muon pairs is needed for LAS plus a trigger on a single muon in the LAS and a single muon in the SAS. At the moment, there is no trigger system for muon pairs only a single muon trigger for SAS, which should be incorporated in a new trigger system. This system will use pairs of hodoscopes in order to be able to identify muon pairs in the LAS, single muon in LAS and single muon in SAS. There is not much need for a muon pair in SAS, for as will be seen in the third chapter events with 2 muons in the SAS account for a very small part of the events detected. In this work a criteria for accepted muons will be discussed in the chapter 3.

Radioprotection

Radiation aspects of the COMPASS facility were presented for the first time in the Radiation Protection Committee (RPC) meeting on March 18, 1999. At that time, the facility was approved for muon and hadron beam operation with the following limitations: $2 \times 10^8$ muons at 190 GeV/c per SPS supercycle of 16.8 seconds for the muon beam, and $1 \times 10^8$ hadrons at 190 GeV/c per SPS supercycle of 16.8 seconds for the hadron beam. The maximum amount of material in the beam line had to be limited to about 5% of a nuclear interaction length during hadron beam operation.

In the DY part of the proposal a beam intensity up to $6 \times 10^8$ hadrons per SPS supercycle (48 seconds) and a considerable longer target are requested. The hadron absorber will be placed immediately forward of the target to stop the forward component of the secondary particle’s flux. These are major changes with respect to the configuration approved in 1999 and require new estimations of radiation levels in accessible areas around the facility, especially at unshielded or weakly shielded locations.

For the 2009 DY beam test performed at a beam intensity up to $1.5 \times 10^8$ pions per spill the shielding requirements were determined again with FLUKA and excellent agreement between measurement and calculation was once more confirmed. The radiation level in the test with the hadron absorber was found low, $\leq 0.5 \mu$Sv/hour (the limit in the area of permanent occupancy is $\leq 3 \mu$Sv/hour).

The shielding configuration for future Drell–Yan data taking (pion beam intensity is $6 \times 10^8$ pions per spill) is under study. Sufficient shielding will be installed around the absorber and the target in order to stay below the radiation limits allowed in the accessible areas of the experimental hall during beam operation.
Chapter 3

Monte Carlo Simulation Study

In this chapter, a description of the simulation chain is presented, including the software used and the most important parameters that were defined throughout the Monte Carlo study. The results will also be presented, at each step, for the physics generated by the simulation.

3.1 Overview

The simulation chain is composed of four fundamental steps. The physical process simulation, that allows us to understand what type of by-products we expect from the primary interaction, as its characteristics, and distributions; for this purpose PYTHIA 6 \cite{26} was used. Afterwards we must simulate the behavior of the detector in such a physical situation, which means simulating the propagation of the particles through the detector and understanding how will we “see” the physics generated. For this purpose a GEANT \cite{27} based program was used called COMGEANT, developed for the COMPASS spectrometer, and then tuned for the specific setup. It receives the kinematical variables generated from PYTHIA as input and returns the information the detector would return under the simulated conditions. The COmpass Reconstruction Algorithm, or CORAL, is then applied to the COMGEANT output in order to reconstruct the information the detector supplies, similarly to the real data, but with the obvious advantage of knowing exactly what were the initial physical mechanisms present. Finally PHAST software is used, as a data analysis framework, that allows us to access both the simulated physics coming from PYTHIA, as well as the reconstructed information.

3.2 Monte Carlo Simulation of the DY Process

In order to simulate a Drell-Yan event from a $\pi^- p$ collision, PYTHIA 6 version 6.4.24 was used. This is a multipurpose generator for high energy physics processes, and results from a combination of QCD based calculations, analytical results, and experimental data. It requires initial conditions that define the basic interaction according to specific tuning parameters. It is programmed in Fortran using a variety of libraries and other packages, in order to ensure control over the possible physical parameters the user needs for his simulation. In this work a C++ class, TPythia6, was used to link to the PYTHIA libraries.
Generation Parameters

In order to fine tune PYTHIA for this particular simulation, one needs to set the generation parameters. A wide range of possible options can be used. The generation conditions were defined with:

- SetMRPY(1, Random Integer) - Determines the random number generator seed for the job, which in this work was determined by the current time from the computer clock.
- SetMSEL(0) - Configures the program to have a physical process determined by the user instead of using a generic predefined one.
- SetMSUB(1,1) and SetMSTP(43,1) - These options determine the main process to be generated. In MSUB(1,1), we set the process with a PYTHIA internal code equal to 1, as true by the option 1. The process is the quark antiquark annihilation, \( q\bar{q} \rightarrow \gamma^*/Z^0 \). Afterwards we limit the process of \( q\bar{q} \) pair annihilation into only \( \gamma^* \), with the option MSTP(43,1). This option is allowed to be turned on in the case because the center of mass (CM) energy is not enough for \( Z^0 \) production.
- SetMDME(184,1) - This defines the decays for the \( \gamma^* \) from \( q\bar{q} \) annihilation as \( \gamma^* \rightarrow \mu^+ + \mu^- \), this way the generated physical sample will always have a dimuon associated with each event, and forces the branching ratio of the dimuon decay to 100 %. This allows us to study the physics of interest to our work, although the virtual photon can decay into any lepton pair, neutrinos, or \( q\bar{q} \) pairs. With this in mind we also generated a sample in the same conditions with all the possible decays of the \( \gamma^* \), in order to calculate the branching ratio for the dimuon decay. This was done with SetMDME([174 - 189],[1]).
- Pyinit("FIXT","pi-","p",Beam momentum) - Finally we define the type of experiment being simulated as fixed target, with a \( \pi^- \) beam with momentum of 190 \( GeV/c \), interacting with a proton.

With these generation parameters we will simulate the DY physics, although not yet tuned for the works purpose. Because we are interested in the Drell-Yan process with decay into a dimuon, first we must choose the mass range for the \( \gamma^* \) that allows this study. Figure 1.1 shows the dimuon mass spectrum, and for the \([2.5, 4]\) \( GeV/c^2 \) mass range we see a substantial background contribution from the \( \psi \) and \( \psi' \) resonances, while for \( M_{\mu\mu} < 2.5 \) \( GeV/c^2 \) there is a large combinatorial background from muon pairs coming from \( \pi \) and \( K \) decays, and muon pairs coming from \( D \) meson semi-leptonic decays. Taking into account that for \( M_{\mu\mu} > 9 \) \( GeV/c^2 \) we have the contribution from the \( Y \) family, the conclusion is that the best mass range for the DY process study is the \([4, 9]\) \( GeV/c^2 \) high mass range. We therefore set the lower limit for virtual photon mass as 3.5 \( GeV/c^2 \), using SetCKIN(1,3,5), with the upper limit as the PYTHIA default being limited by the available energy \( \sqrt{s} \) of the reaction in order to include the desired mass range. After the reconstruction process the mass range will be cut to the desired \([4, 9]\) \( GeV/c^2 \).

After this cut was applied the existence of a small distribution of events below the lower mass region limit was observed. This was due to a default PYTHIA option allowing for the generation of parton showers from the primary interaction. This was corrected by not allowing initial gluon emission that results in parton showers from the quarks, by setting SetMSTJ(41,0).

The COMPASS experiment will measure single spin asymmetries caused by TMDs, and therefore are a function of the intrinsic transverse momentum \( (k_T) \) of the quarks of a polarised target as described in 1.4. Results from the NA10 [28] Collaboration were used in order to tune the \( k_T \) distribution in order to obtain the measured mean value of the transverse momentum of the dimuon \( p_T \) in these experiments, for high mass Drell-Yan events in pion induced interactions. For this purpose the default gaussian distribution defined by PYTHIA was tuned to an upper cutoff limit of 3 \( GeV/c \) with SetPARP(93,3.), and a \( \sigma \) of 0.9 \( GeV/c \) with SetPARP(91,0,9).

It is also important to define which Parton Distribution Functions set we want to use. In this case we chose the leading order GRV98 for the proton, and the leading order GRVPI for the incoming pions, using a package that is linked with the PYTHIA program libraries, called LHAPDF. We initialize the library in the program and define in PYTHIA the use of an external PDF library for the protons with SetMSTP(52,2) and adding a dummy value for the choice of a proton PDF with SetMSTP(51, Dummy Value). Then we follow the same procedure for the pion libraries with SetMSTP(53, Dummy Value) and SetMSTP(54,2). We call the LHAPDF class routine that initializes the PDFs for proton and pion: initPDFSetByName(80060,"GRV98lo",LHGRID),
and initPDFSetByName(252,"GRVPI0",LHGRID). And finally we link the C++ program with a Fortran PYTHIA subroutine that gives an output format which is compatible with a COMGEANT input, in order to make sure the information is well transferred from one software package to the other.

With these generation conditions, the branching ratio into muons and total cross section of the Drell-Yan process was calculated for all possible decays for the virtual photon, and only dimuon decay.

- For $4 < M_{\mu\mu} < 9 \text{ GeV/c}^2$ : a total cross section $\sigma_{\text{Total}} = 0.89 \text{ nb}$ and a dimuon decay cross section of $\sigma_{\gamma^* \rightarrow \mu\mu} = 0.14 \text{ nb}$, with a branching ratio into muons of $\sigma_{\gamma^* \rightarrow \mu\mu}/\sigma_{\text{Total}} = 15.7 \%$.
- For $M_{\mu\mu} > 3.5 \text{ GeV/c}^2$ a total cross section of $\sigma_{\text{Total}} = 1.42 \text{ nb}$ was reached, and a dimuon decay cross section of $\sigma_{\gamma^* \rightarrow \mu\mu} = 0.23 \text{ nb}$, with a branching ratio into muons of $\sigma_{\gamma^* \rightarrow \mu\mu}/\sigma_{\text{Total}} = 16.4 \%$.

After these calculations, a new generation of 100 K events was done with only muon decays allowed, for the main purpose of the work, with $M_{\mu\mu} > 3.5 \text{ GeV/c}^2$.

![Graphs](image.png)

(a) Mass distribution  
(b) $x_F$ distribution  
(c) $x_2$ versus $x_1$  
(d) $p_T$ distribution

Figure 3.1: Physical distributions for generated events with dimuon masses above 3.5 $\text{ GeV/c}^2$. Were mass is the invariant mass of the virtual photon, $x_1$ the fraction of longitudinal momentum of the beam quark, $x_2$ the fraction of longitudinal momentum of the target quark, and $p_T$ the transverse momentum of the dimuon.

We can observe in figure 3.1 that the transverse momentum of the virtual photon has a mean value as required, which means that, within the QCD models applied, we have a $k_T$ distribution that allows for a $p_T\mu\mu$ distribution coherent with the experimental results described.

25
Collins-Soper Reference Frame Transformation

As discussed in section 1.2, the choice of a reference frame for a measurement of angular distributions is paramount for the understanding of the single spin asymmetries we are interested in. In order to be able to measure these distributions, we now discuss the transformation from the laboratory reference frame to the Collins-Soper reference frame, with the polar axes defined as the bisector angle between the u and t-channel polar axes.

First we must transform from the laboratory reference frame to the hadronic CM rest frame, using

$$\beta = \frac{p}{E} = \frac{p_{\text{Beam}}}{E_{\text{Beam}} + M_{\text{Target}}}$$

and also

$$\gamma = \frac{E_{\text{Beam}} + E_{\text{Target}}}{E_{\text{CM}}} = \frac{p_{\text{Beam}}}{E_{\text{Beam}} + M_{\text{Target}}}.$$  \hspace{1cm} (3.2)

if we take into account that $p_{T\text{Lab}} = p_{T\text{CM}}$, we have a transformation in the direction of the longitudinal component of the dimuon with

$$\begin{pmatrix} E \\ p_L \end{pmatrix}_{\text{CM}} = \begin{pmatrix} \gamma & -\beta \gamma \\ -\beta \gamma & \gamma \end{pmatrix} \begin{pmatrix} E \\ p_L \end{pmatrix}_{\text{Lab}}.$$  \hspace{1cm} (3.3)

Now we must rotate the axes in order to have a $xx$ axis coincident to the dimuon $p_{T\mu\mu}$, with the $zz$ axis still along the dimuon $zz$ axis. This is a medium step that must be taken, and the resulting 4-vector will be $(p_{T\gamma*}, 0, p_{z\gamma*}, E_{\gamma*})$. For this transformation from the CM reference from to this CM’ reference frame we have

$$\begin{pmatrix} p_x \\ p_y \end{pmatrix}_{\text{CM'}} = \begin{pmatrix} \cos(\delta) & -\sin(\delta) \\ \sin(\delta) & \cos(\delta) \end{pmatrix} \begin{pmatrix} p_x \\ p_y \end{pmatrix}_{\text{CM}}$$

with $\delta$ being the angle between the CM $xx$ axis, and the transverse momentum of the dimuon. With this in mind is easy to understand that

$$\begin{cases} \cos(\delta) = p_{x\gamma*}/p_{T\gamma*} \\ \sin(\delta) = p_{y\gamma*}/p_{T\gamma*} \end{cases}$$  \hspace{1cm} (3.5)

Finally we transform from this CM’ reference frame to the Collins-Soper frame. Using the variables

$$\rho = \frac{p_{T\gamma*}}{q_{\gamma*}}$$

$$\sin(\alpha) = \frac{\rho}{\sqrt{1 + \rho^2}}$$

$$\cos(\alpha) = \frac{1}{\sqrt{1 + \rho^2}}$$

we write the transformation matrix as

$$\begin{pmatrix} E \\ p_x \\ p_y \\ p_z \end{pmatrix}_{CS} = \frac{1}{q_{\gamma*}} \begin{pmatrix} E_{\gamma*} \\ -\sin(\alpha)E_{\gamma*} \frac{q_{\gamma*}}{\cos(\alpha)} \\ 0 \\ -\cos(\alpha)p_{L\gamma*} \end{pmatrix} \begin{pmatrix} E \\ p_x \\ p_y \\ p_z \end{pmatrix}_{\text{CM'}}$$  \hspace{1cm} (3.9)

Now from figure 1.5 one may write

$$\cos(\theta_{CS}) = \frac{p_{z\mu}}{p_{\mu}}$$

and

26
\[ \phi_{CS} = \arccos \left( \frac{p_{x\mu}}{p_{T\mu}} \right). \]  \hfill (3.11)

Plotting the histograms for these two variables we have

![Histograms of \( \cos(\theta_{CS}) \) and \( \phi_{CS} \) distributions.](image)

(a) \( \cos(\theta_{CS}) \) distribution

(b) \( \phi_{CS} \) distribution

Figure 3.2: Histograms of the resulting distributions of \( \cos(\theta_{CS}) \) and \( \phi_{CS} \) in the Collins-Soper Reference frame for positive muons. \( \cos(\theta_{CS}) \) is fitted with a \( p_0(1 + p_1 \cos^2(\theta_{CS})) \) function.

The fit function tries to evaluate the validity of the \( (1 + \cos^2(\theta_{CS})) \) behavior expected in first order QCD predictions described. So we fitted the distribution to a \( p_0(1 + p_1 \cos^2(\theta_{CS})) \) function with free parameters \( p_0 \) and \( p_1 \), a normalization factor for that should be a function of the number of events, and we should expect value of \( p_1 \) close to unity, according to the predictions of equation 1.27 shown in section 1.2.

The value of \( p_1 \) is \( 0.78 \pm 0.02 \), which is smaller than the expected. Although this is not exactly what is expected on a theoretical level, various simulations with different parameters lead to the conclusion that PYTHIA seems to take into account the previous measurements of the angular distributions from the NA3 [10] and NA10 [13] experiments, as described in section 1.3. Since compatible values for the Lam-Tung sum rule violation measurement are also verified, this leads to the conclusion that PYTHIA makes use of the experimental data available which can account for the deviation from the expected value for the \( \cos(\theta_{CS}) \) distribution.

### 3.3 COMPASS II Proposal Setup Simulation

For the simulation, through the spectrometer, of the propagation of the physics generated as described in the above section, a Geant 3 based program called COMGEANT was used. This program is designed to simulate in detail the COMPASS spectrometer, and to permit the tuning of the program in order to achieve a simulation specific to the COMPASS II Proposal [22], the object of this work. Therefore we modified the geometry definition files, in order to achieve a configuration consistent with the proposed one.

The program works with a wide range of different possible input formats for the physics to propagate, from a ASCII file with the coded nature of the particle, the momentum, and initial point for propagation, to a dedicated PYTHIA output file. The latter was used in the simulation, for it was the best possible way to transfer the largest amount of information to COMGEANT, in a controlled way.

Along with this input file, other input files must also be introduced into the program. These files are called free format read files (*.ffr), they are formatted for the COMGEANT software, and contain the information for the geometry of the detectors, material definitions, magnetic fields, and everything needed for the spectrometer definition. These cards obey a hierarchy, with a base of files that define the fundamental characteristics of the detectors, which than can be redefined and tuned by more specific files for small changes for each type of setup.
Geometry Implementation and Simulation Parameters

For the simulation of the setup in question, we started by including in the COMGEANT input the general settings and definitions for the COMPASS spectrometer, called "geom_general.ffr". Afterwards, it is a question of modifying a specific setup, until we reach the proposal setup. With this in mind we introduced first the 2007 muon beam run setup ("geomMuon2007.ffr"), and changed the beam properties and detector positions in a separate ffr file, in order to achieve the wanted configuration.

The main changes to the 2007 setup were:

- Implementation of a new polarised target, and hadron absorber with a beamplug, as will be shown in section 3.3, centered at $Z = -260$ cm, instead of $Z = 0$.
- Moving all the detectors between RICH and SM2 about 3 meters upstream.
- SciFi 1, and Silicons moved upstream in order to accommodate the absorber and the target solenoid.
- Two Vetos VI02 and VO01 also moved upstream.

Also included are particle tables with their definitions, coding and properties, and the magnetic field maps: "SM1M.map.172.data" and "SM2.map.5000.dat" for SM1 and SM2 respectively at the working currents suitable for a 190 GeV beam. Also included is a field map for the target dipole "OD_dipole.fieldmap".

After the appropriate geometry files have been added, one must include the main parameters of the simulation. This is done through another *.ffr file, that controls namely:

- Number of events to simulate.
- Beam and Halo input files, which in this case are turned off.
- Which types of output are to be created.
- If the simulation determines that in each event there is always an interaction between the target and the beam.
- Physical cuts one might want to implement.
- Physical processes to simulate in the propagation of the particles through the detector materials.

The final item listed above is the most important in understanding how the simulation is taking into account the interaction of particles with matter namely the loss of energy. The options selected were:

1. ANNI = 1 $\rightarrow e^+ e^-$ annihilation with photon emission.
2. BREM = 1 $\rightarrow$ Bremsstrahlung with an emitted $\gamma$.
3. COMP = 1 $\rightarrow$ Compton scattering (with electron production).
4. DCAY = 1 $\rightarrow$ In flight decay with secondary particle emission.
5. DRAY = 1 $\rightarrow$ Delta ray emission with electron generation.
6. HADR = 1 $\rightarrow$ Hadronic interaction with secondary particle emission.
7. LOSS = 2 $\rightarrow$ Continuous loss of energy without generation of $\delta$ rays and full Landau-Vavilov-Gauss fluctuations.
8. MULS = 1 $\rightarrow$ Molière multiple scattering.
9. MUNU = 1 $\rightarrow$ Muon nucleus interaction with secondary particle emission.
10. PAIR = 1 $\rightarrow e^+ e^-$ pair production.
11. PFIS = 1 $\rightarrow$ Photon induced nuclear fission with secondary particle emission.
12. PHOT = 1 $\rightarrow$ Photoelectric effect with electron emission.
13. RAYL = 1 $\rightarrow$ Rayleigh effect.
Polarised Target Implementation

A polarised target was implemented with two $NH_3$ target cells inside a 2.61 meters long solenoid that gives a transverse polarisation of the target. The target dipole field was introduced into the COMGEANT software through "OD_Dipole.fieldmap". The two target cells are cylindrical, 55 cm long, spaced by 20 cm, with a 2 cm radius each, centered at $Z = -260$ cm, in the laboratory reference frame. The first cell is centered at $Z = -297.5$ cm, and the second one at $Z = -222.5$ cm.

![Solenoid and target system, and hadron absorber as simulated, plotted with interactive COMGEANT.](image)

We can describe the interaction probability between the beam and the target as the $\pi^-$ crosses the target cells, as a function of the length traveled in pion interaction lengths ($\lambda_{int}$) for the NH$_3$ material. COMGEANT, in the simulation calculation for the beam-target interaction, takes a mean value for the probability of interaction in each cell. In this work we implemented this description in the COMGEANT code, in order for the interaction to follow the expected probability in each point of the target consistently. To achieve this effect we begin by stating that the fraction of beam particles $N/N_0$ which survive after crossing $x/\lambda_{int}$ interaction lengths is

$$\frac{N}{N_0} = \exp\left(-\frac{x}{\lambda_{int}}\right) \quad (3.12)$$

So the interaction probability is

$$P_{int} = 1 - \frac{N}{N_0} = 1 - e^{-x/\lambda_{int}} . \quad (3.13)$$

Taking this into account we obtain the following mean values for the interaction in each cell: 77.7 % of beam particles cross the 55 cm of each target cell without interacting, which means 22.3 % of all beam particles interact in the first cell, and 17.3 % interact in the second one. To have the most efficient simulation possible all beam pions are forced to interact with the target, and we renormalize the interaction probability in each cell in order to have a total interaction probability of 100 % in both targets. 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.
We then inserted equation 3.13 in the source code of COMGEANT, and recompiled. This forced the program to generate a probability of interaction and then associate it with the Z position of the primary vertex, instead of taking a mean value for each cell. The results are shown in figure 3.4.

As we can see, for each cell, the vertex distribution along the target material follows the expected tendency. We observe 56,190 entries in the first cell, which amounts to 56% of the interacting events, as expected, and we have 43,800 entries in the second cell completing the 44% of the events used. This way we can see that the probability interaction in each cell has become the renormalized probability for all beam pion interaction. Both fits have deviations from the expected value for \( \lambda_{int} \) shown in table 3.1, with \( p_1 = \lambda_{int} \), this is due to the fact that the calculation used in the simulation software takes into account the specific mixture of the ammonia target, and its packing factor, which are not taken into account in this work's calculation, and also due to the small value of \( \lambda_{int} \) in 3.13, that reflects a slow decreasing tendency and might imply a larger statistical sample is needed for a more precise measurement.

**Figure 3.4:** Z of primary vertex distribution at COMGEANT level. The function is fitted for each target cell according to 3.13, where \( \lambda_{int} = p_1 \) and \( p_0 \) is a free normalizing parameter.

**Hadron Absorber Implementation**

Finally we finish the geometry modifications with the introduction of a hadron absorber. Its total length is 2.1 m, with a first segment of 1.5 m of Alumina (\( \text{Al}_2\text{O}_3 \)) and a final segment with 60 cm of steel. Its transverse dimensions are 80 × 80 cm, and it was placed immediately after the solenoid-target system, spaced by only 5 cm. This absorber is designed to stop the hadrons produced in the main interaction, and therefore allows for a clean detection of the muon pair emitted.

For the implementation of the materials of the hadron absorber and of the polarised target, we must calculate the properties of the specific materials in each volume that are not predefined in COMGEANT. For the NH\(_3\) target implementation, it was necessary to calculate the \( X_0 \) and the \( \lambda_{int} \) of the ammonia at the temperature, and pressure conditions in which it will operate inside the target cell, and of the Alumina implemented for the hadron absorber. Taking the stoichiometry of the molecule we can calculate the effective \( A \) and \( Z \) exactly as it is done in COMGEANT. As explained in the COMGEANT manual, we have

30
\[
\begin{align*}
A_{mol} &= \sum n_i A_i \\
Z_{mol} &= \sum n_i Z_i 
\end{align*}
\] (3.14)

where \( n_i \) is the number of atoms of the \( i^{th} \) component of the molecule. Then we calculate the weight \( p_i \) for each element,

\[
p_i = \frac{n_i A_i}{A_{mol}}
\] (3.15)
in order to calculate the effective

\[
A_{eff} = \sum_i p_i A_i
\] (3.16)

\[
Z_{eff} = \sum_i p_i Z_i .
\] (3.17)

With these values one uses the S. Carrol et al \[29\] parametrization for the pion interaction cross section,

\[
\sigma_i = \sigma_0 A^\alpha
\] (3.18)

with \( \alpha = 0.759 \) and \( \sigma_0 = 26.17 \) mb in order to calculate the pion cross section \( \sigma_i \) for the specific material, for each atomic component. Taking the density \( \rho \) of the NH\(_3\) used (0.58 g/cm\(^3\)), we compute

\[
\lambda_i = \frac{A_i}{\sigma_i N_v}
\] (3.19)

Adding over all the elements, we obtain the interaction length:

\[
\frac{1}{\lambda_{int}} = \sum_i \frac{p_i}{\lambda_i} .
\] (3.20)

For the radiation length \( X_{0i} \), we compute

\[
\frac{1}{\rho X_{0i}} = 4\alpha r_0^2 N_v Z A (Z + \xi(Z)) \ln \left( \frac{183}{Z^{4/3} - F_c(Z)} \right)
\] (3.21)

where \( \alpha \) is the fine structure constant, \( r \) the classical electron radius, \( N_v \) the Avogadros number, and \( F_c(Z) \) is the Coulomb correction function

\[
F_c(Z) = (\alpha Z)^2 \left[ \frac{1}{1 + (\alpha Z)^2} + 0.20206 - 0.0369(\alpha Z)^2 + 0.0083(\alpha Z)^4 - 0.0020(\alpha Z)^6 \right]
\] (3.22)

with

\[
\xi(Z) = \ln \left( \frac{1440}{Z^{4/3} - F_c(Z)} \right)
\] (3.23)

Finally we can compute

\[
\frac{1}{\rho X_0} = \sum_i \frac{p_i}{\rho_i X_{0i}}
\] (3.24)

The material properties are shown in table [3.1]. The tungsten and steel used for the hadron absorber values presented were taken from the COMGEANT material definitions, in order to know exactly what kind of densities and material properties were being simulated. The alumina values were calculated and implemented in COMGEANT, while the ammonia values presented are calculated, but the values implemented took into account the real target packing factor and mixture. Therefore, although the density is the true density implemented, \( \lambda_{int} \) and \( X_0 \) are approximate values.
Table 3.1: Target, absorber and beamplug constituent material properties, density $\rho$, $\pi$ interaction length $\lambda_{int}$ and radiation length $X_0$.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho$ (g/cm$^3$)</th>
<th>$\lambda_{int}$ (cm)</th>
<th>$X_0$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amonia $NH_3$</td>
<td>0.58</td>
<td>218.13</td>
<td>75.08</td>
</tr>
<tr>
<td>Alumina $Al_2O_3$</td>
<td>3.80</td>
<td>34.03</td>
<td>7.35</td>
</tr>
<tr>
<td>Steel</td>
<td>8.00</td>
<td>20.92</td>
<td>1.71</td>
</tr>
<tr>
<td>Tungsten $W$</td>
<td>19.30</td>
<td>11.33</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Inside the absorber a beamplug made of tungsten, designed to stop the non-interacting beam was implemented, with material properties reported in Table 3.1. It is divided into 9 discs, with different transverse dimensions, as shown in Table 3.2. The beamplug was designed in order to stop the non-interacting beam, but taking also into account the shadowing effect it casts on the SAS at small angles in the laboratory reference frame. Thus a design covering a constant angular range was chosen, with $\pm 15$ mrad, which matches the SAS hole (i.e. the Muon Wall 2 dead zone). The first disc of tungsten starts 30 cm inside the Hadron Absorber, which means $Z = -90$ cm. All the discs have a length of 20 cm, and start 30 cm downstream from the start of the absorber until the end covering the 1.8 m. Their transverse dimensions are summarized in Table 3.2 and were designed to fit the angular range mentioned.

Table 3.2: Tungsten beamplug discs transverse dimensions, length and position.

<table>
<thead>
<tr>
<th>Disc</th>
<th>$Z$ (cm)</th>
<th>Length (cm)</th>
<th>Radius (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-90</td>
<td>20</td>
<td>1.70</td>
</tr>
<tr>
<td>2</td>
<td>-70</td>
<td>20</td>
<td>2.00</td>
</tr>
<tr>
<td>3</td>
<td>-50</td>
<td>20</td>
<td>2.30</td>
</tr>
<tr>
<td>4</td>
<td>-30</td>
<td>20</td>
<td>2.65</td>
</tr>
<tr>
<td>5</td>
<td>-10</td>
<td>20</td>
<td>2.95</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>20</td>
<td>3.30</td>
</tr>
<tr>
<td>7</td>
<td>30</td>
<td>20</td>
<td>3.60</td>
</tr>
<tr>
<td>8</td>
<td>50</td>
<td>20</td>
<td>3.90</td>
</tr>
<tr>
<td>9</td>
<td>-90</td>
<td>20</td>
<td>4.25</td>
</tr>
</tbody>
</table>

The final result of the simulation in COMGEANT, of the DY COMPASS II proposal setup is shown in Figure 3.5.
3.4 Multiple Scattering and Energy Loss in Hadron Absorber

Taking into account the different volumes added to the setup for this simulation it was also necessary to produce new material maps for the target and hadron absorber. This is done in COMGEANT, and basically one simulates the multiple scattering and continuous energy loss of a sample of Monte Carlo through the volumes added, divided into cells. This way, either in cylindrical or cartesian coordinates, COMGEANT maps the energy loss in each cell, and allows the reconstruction process to understand how to assess the energy loss for tracks that cross these material volumes.

In our case we used cylindrical coordinates to propagate muons through the absorber and target materials, resulting from a simulation of DY events from a 190 GeV/c π− beam, and produced a material map for energy loss and one for multiple scattering.

Most of the detectors that constitute this spectrometer are very thin the energy loss in these detectors is negligible. However the multiple scattering that they suffer as they cross these materials will determine the error associated with their momentum measurement. As the absorber and beamplug are introduced immediately after the target, one must understand how this will affect the multiple scattering, as it is proportional to radiation lengths crossed by muons. A summary of the radiation lengths crossed by the muons in these volumes is shown in table 3.3. Therefore, the number of radiation lengths crossed using the new material map should match the ones calculated below, as should also the energy loss lost inside the absorber material, taking into account the muon generated ⟨pμ⟩ of around 45 GeV/c.

<table>
<thead>
<tr>
<th>Volume</th>
<th>Material</th>
<th>ρ (g/cm³)</th>
<th>Length (cm)</th>
<th>X0 (cm)</th>
<th>X/X0</th>
<th>dE/dx(MeVcm²/g)</th>
<th>∆E (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>Alumina</td>
<td>3.80</td>
<td>150</td>
<td>7.35</td>
<td>20.41</td>
<td>55.58</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>Steel</td>
<td>8.00</td>
<td>60</td>
<td>1.71</td>
<td>34.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beamplug</td>
<td>Tungsten</td>
<td>19.30</td>
<td>180</td>
<td>0.35</td>
<td>514.29</td>
<td></td>
<td>2.16</td>
</tr>
</tbody>
</table>

Table 3.3: Calculation of the mean energy loss, and radiation lengths that a muon is expected to cross in the hadron absorber and beamplug implemented.

We can conclude that a muon that crosses the beamplug must cross a minimum of 500 radiation lengths losing about 7.5 GeV, while a muon that crosses that whole absorber must cross at least 50 radiation lengths with a loss of about 2.5 GeV. This is illustrated in figure 3.6 where the selected events from the reconstructed sample are shown. This figure allows us to verify the implementation of the material map in the CORAL software, which is described below in section 3.5. We see that the muons that cross the absorber lose about 2.6 GeV as they cross about 55 radiation lengths X/X0 of the Alumina + Steel absorber. Also figure 3.6 shows that there are events that cross the beamplug, with a distribution around 500 radiation lengths crossed.
Reconstruction of the Monte Carlo Simulated Events

Now that we have the simulated response of the detector, tuned for the desired setup, the next step is to treat this data as experimental results, and reconstruct the information using the COMPASS Reconstruction Algorithm Software (CORAL). As the input of CORAL, is the output of the COMGEANT software, which consists of two files: one describing the geometry simulated; and the second the data for the propagation of the Monte Carlo events through the spectrometer. The first is called "detectors.dat", and the latter is a *.fz format file. It contains all the information from the physics that was introduced in COMGEANT, and the information for the propagation through the detectors.

The algorithm works from the downstream end of the spectrometer to the point where the primary interaction occurred, the primary vertex, associating various hits in different detectors into tracks, and then associating the track segments to one another, until finally reaching a vertexing process. The detectors are divided into zones with borders determined by the target, the magnets and the last Muon Wall. These zones were redefined for the different setup simulated in COMGEANT.

- Zone 0 → Before the target.
- Zone 1 → After the target and before the first magnet SM1.
- Zone 2 → After SM1 and before the second magnet SM2.
- Zone 3 → After SM2 and before the second Muon Wall MW2.
- Zone 4 → After MW2.

Between each zone we have one or more large volumes, with high density materials, which correspond to different material maps. These were changed to the ones described in section 3.4 as well as additional material maps for other large volumes for which the $X/X_0$ crossed is significant. The material maps included, account for the multiple scattering in the whole spectrometer, with an additional material map that accounts for the energy loss in the target region, where the absorber implementation implies a energy loss before any momentum measurement. This means that this energy loss is not negligible, and therefore, as described in section 3.4, a material map was produced.

After producing association of hits to tracks the algorithm tries to associate the track produced with more hits of the same zone until reaching the end of that zone. Then starts the bridging process, where different track segments from two neighboring zones are joined into a bigger track. Finally when all zones in a tracks trajectory have been crossed, we reach the target region, where the vertexing process takes place. For each event, this process uses the beam track to try and assess if there is a vertex with each reconstructed track, and therefore a primary vertex is reconstructed.

This program is tuned with *.opt files, that allow for the parameters of the reconstruction to be modified for different beam energies, beam charge, different reconstruction requirements and many other technical possibilities. Again, the use of a previous reconstruction option file was the base for modifications to the different conditions we have simulated. Changes in this step include the beam particle charge and momentum, and reconstruction parameters for vertexing and bridging that were found to be unsuited. The beam reference plane was redefined before the beam detectors upstream of the target ($Z = -8$ m), and the reference plane for the target area to after the hadron absorber ($Z \approx 1$ m). The criteria for an accepted reconstructed track was modified in order to accept muons with momentum as high as the beam, and finally the zones for the detectors were defined to the new positions taking into account the 3 meter shift upstream for the proposal setup: Muon Wall 1 redefined to $Z_{MW1} = 1.4$ m, Muon Wall 2 as $Z_{MW2} = 3.8$ m, the first Hadron Calorimeter to $Z_{HCAL1} = 1.3$ m, the second Hadron Calorimeter to $Z_{HCAL2} = 3.6$ m, and finally the second Electromagnetic Calorimeter to $Z_{ECAL2} = 3.3$ m.

The output is a data file called a mDST ( miniDataSummaryTape ), which contains all information from the Monte Carlo simulation, and the reconstruction information of the processed data.
3.6 Data Analysis

Finally we have all the information in a data file, so the next step is to analyse it. For this purpose we use the PHAST package. PHAST is a data analysis environment that processes the mDST file, with a set of C++ classes that allow the treatment of the information. The output is stored in a *.root file as a Tree object, and can be manipulated to analyse most aspects of the reconstruction process.

Functional ”Trigger-like” Criteria

Since a trigger system for Drell-Yan has not yet been designed, the Monte Carlo tracks we analyse with PHAST have no information on whether they were or not triggered as muons. Therefore a condition was implemented in the analysis, analogous to the one used for the DY COMPASS II Proposal we intend to simulate. The criteria used in the COMPASS II Proposal \cite{22} take a minimum of 5 hits on the furthest part of the Muon Wall 1 for a particle to be triggered within the Large Angle Spectrometer (LAS), and either 7 hits on any plane of Muon Wall 2 or 5 hits on the Multi Wire Proportional Chambers (PB) of the Small Angle Spectrometer to determine a trigger on the SAS. These criteria determine that the particle detected is of interest if it has fired in the Muon Walls. Since the absorber covers the Muon Walls acceptance, if the primary vertex is inside the target cells, then it should have crossed the hadron absorber, and should be a accepted muon. It is also important to note that there should be a presence of punch through particles from the interaction with the absorber.

This way when looking at the Monte Carlo information in the data analysis we can divide the results into different spectrometer zones, either the LAS or the SAS, and understand the acceptances for each part, as well as study the different resolutions for the measured variables in the different zones.

Acceptances

Single Muons

We will now study the performance of the spectrometer in each of its parts, LAS and SAS. As a first step we try to understand the acceptance of the spectrometer in the detection of individual muons in the whole mass range generated with $M_{\mu\mu} > 3.5$ GeV/c$^2$. The acceptance of single muons in the spectrometer is 63.1%. The sum of the percentage of accepted events in the different spectrometer parts does not equal one, but rather the sum of the LAS and SAS events subtracting the events that are detected in both. This is due to the fact that the criteria applied were not exclusive, a muon that was detected in LAS can also be detected again in SAS. This allows an analysis of the spectrometer parts as independent individual spectrometers, where

$$A_X = \frac{N_X(\text{Accepted Events})}{N_X(\text{Generated Events})}. \quad (3.25)$$

<table>
<thead>
<tr>
<th></th>
<th>Average Acceptance (%)</th>
<th>LAS (%)</th>
<th>SAS (%)</th>
<th>LAS &amp; SAS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Muons</td>
<td>63.1 ± 0.1</td>
<td>71.9 ± 0.1</td>
<td>31.4 ± 0.1</td>
<td>3.3 ± 0.1</td>
</tr>
<tr>
<td>Positive Muons</td>
<td>62.3 ± 0.2</td>
<td>72.6 ± 0.2</td>
<td>30.9 ± 0.2</td>
<td>3.5 ± 0.1</td>
</tr>
<tr>
<td>Negative Muons</td>
<td>63.8 ± 0.2</td>
<td>72.9 ± 0.2</td>
<td>32.8 ± 0.2</td>
<td>3.2 ± 0.1</td>
</tr>
</tbody>
</table>

Table 3.4: Acceptance in the spectrometer for the detection of individual muons, $\mu^+$, $\mu^-$, and the ratio of accepted events in LAS, SAS, or in both.

The results allow us to see that there is a slightly higher acceptance of negative muons than for positive muons in the spectrometer. This is due to the fact that the COMPASS spectrometer was previously used for a SIDIS (Semi Inclusive Deep Inelastic Scattering) program. This program focused on the detection of scattered muons, and therefore the spectrometer is asymmetric in order to follow the non-interacted beam trajectory through the spectrometer due to the magnetic fields from both magnets. This results in a spectrometer that
favors negative charged muons over positive, although solutions are being studied towards the symmetrization of the spectrometer.

Figure 3.7: $p_\mu$ and $\theta_{Lab}$ distributions for muons accepted in the whole spectrometer, in the LAS, in the SAS, or detected in both.

Figure 3.8: Acceptances as a function of muon momentum in the whole spectrometer, in the LAS, in the SAS, or detected in both.
The distributions of figure 3.7 show that the SAS favors small angles in the laboratory reference frame, with high momentum, while the LAS will favor large angles with smaller overall momentum. Events that are detected in both spectrometers have an angular distribution above the inner angular limit of the LAS, and the below the outer angular limit of the SAS. Because they must geometrically match, these events have small momentum but also large enough angles for them to be detected in LAS, but sufficiently small for the magnetic field to deviate the trajectory enough in order for the particle to be detected in SAS.

The results in figure 3.8 show that the acceptance in the whole spectrometer is quite uniform for muons of momentum above 35 GeV/c. This is due to the combination of SAS, for high momentum muons, and LAS for small momentum muons. We can see that LAS favors low momentum muons, with a maximum around 85 % at 35 GeV/c, and than decreases for high momentum muons. In the meanwhile SAS has a positive tendency, it accepts more muons as the momentum rises. There are very few accepted muons with momentum below 25 GeV/c, this is due to the fact that these muons are swept away by the magnetic field, and therefore are not detected.

As observed in figure 3.9 we can see that muons detected in SAS will have a small angular distribution, associated with large momentum, while low momentum will favor larger angles and the LAS. This is very intuitive, and these acceptances allow us to understand that the SAS acceptance, in the laboratory reference frame, increases with smaller angles and larger momentum, and the LAS with smaller momentum and larger angles.
Dimuon Events

We now show the acceptances for dimuon events in the spectrometer as a whole, and separately for Large and Small Angle Spectrometer. These results are taken in a Mass Range of $4 < M_{\mu\mu} < 9$ GeV/c$^2$, and can be compared with the ones quoted in COMPASS II shown in table 3.5. A more detailed understanding of how the acceptance in a specific spectrometer evolves as a function of a physical variable can be also seen in figure 3.10. Events labeled as LAS are events that have a dimuon associated, coming from two muons, both of them detected in LAS. The same procedure is done for SAS, while LAS + SAS means that the dimuon comes from a muon detected in LAS and one detected in the SAS. The condition was applied disregarding muons detected in both spectrometers since we have seen that they are a very small percentage of the events accepted.

<table>
<thead>
<tr>
<th>This Works Results</th>
<th>Acceptance (%)</th>
<th>LAS (%)</th>
<th>SAS (%)</th>
<th>LAS + SAS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPASS II Proposal</td>
<td>35.9 ± 0.2</td>
<td>61.4 ± 0.3</td>
<td>3.8 ± 0.1</td>
<td>41.7 ± 0.3</td>
</tr>
</tbody>
</table>

Table 3.5: Global acceptance for Dimuon masses in the $4 < M_{\mu\mu} < 9$ GeV/c$^2$ range in the COMPASS spectrometer, and ratio of events accepted in LAS, accepted in SAS, and accepted with one muon in LAS and one in SAS, compared with COMPASS II Proposal.

Figure 3.10: Invariant mass $M_{\mu\mu}$, momentum $p_{\mu\mu}$, and transverse momentum $p_{T\mu\mu}$ distribution for events with muons accepted in the whole spectrometer, with both muons in LAS, with both muons in SAS, and with one muon in LAS and another in SAS.

We notice that the global acceptance is consistent with the Proposal one, which is to expect given it is the same simulated setup. The acceptance is affected by the geometry of the detector, and since we simulated the same geometry these values should be consistent, with the ones published by the proposal.

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Events with both muons in LAS are the main contribution with 61.4% of the accepted events. They account for muons from the primary interaction with large angles in the laboratory reference frame. Events with both muons in SAS have a much smaller acceptance, only 4% of the accepted events, since they account for a smaller angular window. These muons have a tendency to be more symmetrical, since both muons are detected in SAS, and thus result in a tendency of SAS to accept low $p_{T\mu\mu}$ events as shown in figure 3.13.

It is very important to notice the contribution of events with one muon detected in LAS and one in SAS (LAS + SAS). These events account for 40% of the global acceptance, and reflect larger dimuon momentum, and therefore imply at least one muon of the pair detected at low angle, with a large momentum, and a second one, with smaller but still high momentum detected in the LAS.

From figure 3.10 we see that LAS tends to accept events with higher mass than SAS. This can be best understood looking at the acceptance in figure 3.11. Also the tendency for events accepted in LAS + SAS is of high dimuon momentum, and therefore of a vectorial sum of both muons larger than in LAS. This points to the conclusion that events with largest dimuon momentum are detected in SAS, and the LAS + SAS events account for high momentum muons.

![Figure 3.11: Acceptances as a function of dimuon mass in the whole spectrometer, with both muons in LAS, with both muons in SAS, and with one muon in LAS and another in SAS. The whole spectrometer acceptance is fitted to a uniform distribution with one free parameter $p_0$.](image)

The overall acceptance in the whole spectrometer is almost uniform as a function of $M_{\mu\mu}$, an uniform fit with a free parameter giving $p_0 = 0.36 \pm 0.002$, which accounts for the expected 36% of global acceptance. This global acceptance is the result of the sum between the acceptance in LAS, which is almost uniform with a slight increase as the dimuon mass rises, accounting for 60% of the total acceptance, and the LAS + SAS events, and SAS events, that have a tendency to decrease as the mass rises, accounting for the remaining 40% of the total acceptance. If we now turn the attention to the acceptances in momentum, we can see in figure 3.12 the tendency that was already clear in figure 3.10. The SAS accepts more events as the dimuon momentum rises, while LAS...
Figure 3.12: Acceptances as a function of $p_{\mu \mu}$ in the whole spectrometer, with both muons in LAS, with both muons in SAS, and with one muon in LAS and another in SAS.

accepts more events as the dimuon momentum falls. Although the latter consists of a very small contribution for the overall acceptance, one notices that for LAS + SAS events the same tendency is present, with high momentum muon pairs being detected one in each spectrometer. This can be explained by high momentum asymmetrical dimuons where at least one of the muons ”escapes” the LAS and is detected in the SAS.

Finally from figure 3.13 that the spectrometer accepts uniformly dimuons 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.

**Track Reconstruction**

**Quality Cuts**

We now analyze the reconstructed tracks. To do so, we start by studying the pairs of tracks that CORAL was able to reconstruct out of the accepted tracks in the mass range \((4 < M_{\mu \mu} < 9 \text{ GeV/c}^2)\). We can then study the criteria one can apply in order to obtain a clean sample of events. This will allow us to get a sample of controlled events and understand the efficiency reconstruction, and what kind of performance the algorithm had during this analysis.

If we look at every Drell-Yan event obtained, in figure 3.14 the tracks from a vertex inside the target cells \((i.e.\ a\ primary\ vertex)\), identified as a muon by CORAL, we can see that the position of the first detection of
Figure 3.13: Acceptances as a function of $p_{T\mu\mu}$ in the whole spectrometer, with both muons in LAS, with both muons in SAS, and with one muon in LAS and another in SAS.

Figure 3.14: Z position of first detected hit without quality cuts for Drell-Yan events in the $4 < M_{\mu\mu} < 9 \text{ GeV}/c^2$ region.
about 1% tracks occurred after the first magnet, centered at $Z = 363.7$ cm in the laboratory reference frame. These events were cut in order to assure the quality of the sample, since for these we have no momentum measurement in LAS.

Figure 3.15: Radiation lengths crossed by the muons from the first detected hit $Z$ position to the primary vertex after $Z_{First}$ cut, for Drell-Yan events in the $4 < M_{\mu\mu} < 9$ GeV/c$^2$ region.

![Graph showing radiation lengths crossed by muons](image)

Figure 3.16: Z position of reconstructed primary vertex (a), and of the Monte Carlo generated one (b), for Drell-Yan events in the $4 < M_{\mu\mu} < 9$ GeV/c$^2$ region after quality cuts, and with associated Monte Carlo track.

![Graph showing reconstructed and generated primary vertex positions](image)

After cleaning these events, we now look at the number of interaction lengths crossed by the tracks in figure 3.14. The particle identification system uses the number of radiation lengths crossed by a particle in order to ensure that the particle crossed both muon filters, and therefore is a muon. This is a good way to clean our sample from particles that do not come from the DY primary interaction. With the introduction of the absorber an extension of the concept can be applied and ensure that the reconstructed tracks cross the whole absorber, this way we should eliminate particles that do not cross the whole absorber, and could be punch through particles. We can see that about 16% of the reconstructed events have crossed less than 50 $X/X_0$, as seen in table 3.3. This means we cannot be sure whether they are or not muons from the DY interaction. Since the absorber covers the Muon Wall 1 acceptance, if the muons do not cross the whole
(absorber they should be outside of the spectrometer acceptance altogether. This way we eliminate such events, and see that all of the tracks are detected before the first detector telescope, positioned upstream from the first magnet, and at the same time we have confidence that all of them have crossed the hadron absorber implemented, and are therefore muons from our primary DY interaction.

After applying these quality cuts, with the help of figure 3.16 we can study the events that are associated with a Monte Carlo track, and thus allow for a comparison with the true value information for the track. One notes that since we eliminate events that do not cross the absorber, the decrease of events produced on the first cell is larger than the decrease in the second one. This is due to the fact that the cell closest to the absorber is more likely to have events crossing the whole absorber. In what concerns the reconstructed $Z$ position distribution, the difference between these distributions describes the $Z_{\text{Primary Vertex}}$ resolution and will be discussed in the final section of this chapter.

**Dimuon Events**

![Figures 3.17](image)

Figure 3.17: Comparison between the generated Monte Carlo events in the $4 < M_{\mu\mu} < 9 \text{ GeV}/c^2$ region, the accepted and reconstructed events, for $M_{\mu\mu}$ and $x_F$ distributions.

Shown in figure 3.17 are the distributions for the dimuon mass and $x_F$ in the range mentioned ($4 < M_{\mu\mu} < 9 \text{ GeV}/c^2$), as well as the ratio between the number of reconstructed events and the number of accepted events. The global reconstruction efficiency seems independent of $M_{\mu\mu}$, and we seem to have a higher reconstruction rate for positive $x_F$. This is also apparent in figure 3.18, where we can clearly see that the reconstruction increases with momentum, and seems to be independent of $p_T^{\mu\mu}$. In fact, as a consequence, the mean value
of the $p_{\mu\mu}$ distribution increases almost 7 GeV/c in momentum from the accepted events to the reconstructed ones. While the mean $p_{T\mu\mu}$ of the dimuon remains almost the same, around 1.2 GeV/c, as generated in the $4 < M_{\mu\mu} < 9$ GeV/c² mass region of interest.

![Graphs showing distributions](image)

Figure 3.18: Comparison between the generated Monte Carlo events in the $4 < M_{\mu\mu} < 9$ GeV/c² region, the accepted and reconstructed events, for $p_{\mu\mu}$ and $p_{T\mu\mu}$ distributions.

Shown in figure 3.19 are the angular distributions for the Collins-Soper angles. As expected, we have no dependence of the reconstruction yield for these variables.

**Reconstruction Efficiencies**

We now summarise the number of tracks reconstructed and accepted in each zone of the spectrometer in tables 3.6 and 3.7. The reconstruction efficiencies ($\epsilon$) are given relative to the total number of accepted tracks, and relative to the number of accepted tracks in that given spectrometer, with

\[
\epsilon_{\text{Absolute}} = \frac{N_{\text{Reconstructed Tracks}}}{N_{\text{Reconstructed Tracks All Spectrometer}}} \tag{3.26}
\]

\[
\epsilon_{\text{Relative}} = \frac{N_{\text{Reconstructed Tracks}}}{N_{\text{Accepted Tracks}}} \tag{3.27}
\]
Figure 3.19: Comparison between the generated Monte Carlo events in the $4 < M_{\mu\mu} < 9$ GeV/$c^2$ region, the accepted and reconstructed events for the Collins-Soper reference frame angular variables $\cos(\theta_{CS})$ and $\phi_{CS}$.

**Single Muons**

For the complete mass range of the Monte Carlo sample ($M_{\mu\mu} > 3.5$ GeV/$c^2$), we now study the individual muons reconstruction efficiencies. In order to identify which tracks were reconstructed in LAS or in SAS, or both, we used the same criteria applied to the accepted events in the reconstructed events. The global number of reconstructed tracks is therefore not the sum of the tracks reconstructed in LAS and SAS subtracted the ones that are reconstructed in both, because the criteria used does not include all the reconstructed tracks, just the ones that have the minimum amount of hits in the Muon Walls. These tracks account for more than 90 % of the total number of reconstructed tracks.

<table>
<thead>
<tr>
<th></th>
<th>Accepted Tracks</th>
<th>Reconstructed Tracks</th>
<th>$\epsilon_{\text{Absolute}}(%)$</th>
<th>$\epsilon_{\text{Relative}}(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COMPASS Spectrometer</td>
<td>126227</td>
<td>107883</td>
<td>85.5 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>LAS</td>
<td>90839</td>
<td>70078</td>
<td>69.7 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>SAS</td>
<td>39607</td>
<td>31486</td>
<td>31.3 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>LAS &amp; SAS</td>
<td>4219</td>
<td>1014</td>
<td>1.0 ± 0.0</td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>COMPASS Spectrometer</td>
<td>63926</td>
<td>55004</td>
<td>86.2 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>LAS</td>
<td>45594</td>
<td>35247</td>
<td>68.8 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>SAS</td>
<td>20371</td>
<td>16445</td>
<td>32.1 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>LAS &amp; SAS</td>
<td>2039</td>
<td>480</td>
<td>0.9 ± 0.2</td>
</tr>
<tr>
<td>$\mu^+$</td>
<td>COMPASS Spectrometer</td>
<td>62301</td>
<td>52879</td>
<td>84.9 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>LAS</td>
<td>45245</td>
<td>34831</td>
<td>70.6 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>SAS</td>
<td>19236</td>
<td>15041</td>
<td>30.5 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>LAS &amp; SAS</td>
<td>2180</td>
<td>534</td>
<td>1.1 ± 0.0</td>
</tr>
</tbody>
</table>

Table 3.6: Number of muon tracks accepted and reconstructed per spectrometer, for $\mu^{+/-}$, $\mu^+$ and $\mu^-$.

We see in table 3.6 that the global reconstruction efficiency for muons in the COMPASS spectrometer is 86 %, with 70 % being reconstructed in the LAS and 31 % in the SAS, with a very small percentage of tracks that are detected in both spectrometers, 1 %. It is also clear that SAS has a better reconstruction efficiency for individual muons, either positive or negative. This is due to the amount of tracking stations in SAS, which is greater than the one in LAS, and allows SAS to have a higher efficiency in the reconstruction process. The LAS reconstructs 77 % of the accepted muons, while the SAS reconstructs almost 80%.

Also of interest is that, as discussed previously in section 3.6, we can observe that the spectrometer
Let us now restrict ourselves to the reconstructed dimuon events, Dimuon events
that SAS would suffer a bigger effect than LAS due to its position. This is because the deflection of the track becomes greater. This would imply that the shift of the planes towards one side might 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. This would imply that SAS would suffer a bigger effect than LAS due to its position.

**Dimuon events**

Let us now restrict ourselves to the reconstructed dimuon events, *i.e.* the events where two reconstructed muons come from a primary vertex, and are identified as muons, with the quality cuts previously presented, in the dimuon mass range $4 < \mu_{\mu} < 9 \text{ GeV}/c^2$. We now analyse the reconstruction efficiency of CORAL to deal with dimuon events accepted from our Monte Carlo. Once again we use the same criteria to determine where the track is reconstructed.

<table>
<thead>
<tr>
<th></th>
<th>Accepted Tracks</th>
<th>Reconstructed Tracks</th>
<th>$\epsilon_{\text{absolute}}$(%)</th>
<th>$\epsilon_{\text{relative}}$(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPASS Spectrometer</td>
<td>21853</td>
<td>158656</td>
<td>72.6 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>LAS</td>
<td>13423</td>
<td>8868</td>
<td>62.7 ± 0.4</td>
<td>66.1 ± 0.4</td>
</tr>
<tr>
<td>SAS</td>
<td>827</td>
<td>225</td>
<td>1.8 ± 0.1</td>
<td>30.8 ± 1.6</td>
</tr>
<tr>
<td>LAS+SAS</td>
<td>9114</td>
<td>5308</td>
<td>37.5 ± 0.4</td>
<td>58.2 ± 0.5</td>
</tr>
</tbody>
</table>

Table 3.7: Reconstruction efficiencies for the whole spectrometer, detected with both muons in LAS, in SAS, and one muon in LAS and one in SAS.

We notice that the number of total reconstructed tracks allows for a 73 % reconstruction efficiency. Applying the criteria for a reconstructed event to have both muons in LAS, or in SAS we can see that taking into account only the LAS, we are able to account for 63 % of the tracks reconstructed within this criteria, while the SAS reconstructs 2 %. Events that have one muon in each spectrometer account for 42 % of the accepted events as seen in table 3.5, and we are able to account for 38 % of the reconstructed tracks.

Individually, we can see that LAS is the most efficient detector, reconstructing 66% of the dimuon events within its acceptance criteria, followed by events with one muon in each detector, that give a 58 % recon-
struction efficiency. SAS has an efficiency of 31%, although it accounts for a very small percentage of accepted events.

This feature was not expected, since SAS has the greater reconstruction efficiency for individual muons, but this is not the case for events with two muons reconstructed in the SAS.

We can see in figure 3.21 that CORAL reconstructs higher mass values with both muons in LAS than with both muons in SAS, as expected from figure 3.10. Because the global acceptance as a function of \( M_{\mu\mu} \) is uniform, this effect should be a product of the slight increase in acceptance with mass for the LAS, and the decrease in SAS, that should bias the values of the reconstructed events according to the acceptance distribution in each spectrometer.

We notice a tendency for SAS to reconstruct lower \( p_{\mu\mu} \) events which can also be related to the acceptance distribution. Since the events accepted in this spectrometer must be very symmetric and therefore the \( p_{\mu\mu} \) values for the events accepted should be smaller than the LAS ones. At the same time the combination of two muons, one in each spectrometer, allows for very asymmetric events, and therefore higher \( p_{\mu\mu} \) mean values of the accepted muons, and thus for the reconstructed ones.

### Efficiency Analysis

For a more thorough analysis of the reconstruction algorithm applied, how the physical cuts affected the sample, and efficiency obtained, we now turn to individual muons, and try and understand what is happening to the missing Monte Carlo tracks that weren’t reconstructed. After applying all the previously explained cuts, we turned to the study of which tracks failed to be identified by the reconstruction program, and why they weren’t included in the results. Figure 3.22 shows that the Z position in the laboratory reference frame for the unidentified tracks, where the last detection occurred. It is apparent that a majority of these tracks
stopped being reconstructed before either Muon Wall 1 \(Z \approx 1420\) cm, or Muon Wall 2 \(Z \approx 4250\) cm. This is irregular since there is no clear reason for this to happen.

These distributions were identified with last hits in the Drift Wire Chamber 06 (DW06), the Straw Tube Chamber 03 (ST03), and the Rich Wall. And the tracks were extrapolated to their respective \(Z\) position. This way we can see where in the detectors exactly were the hits detected. Afterwards an extrapolation of the same track towards the associated Muon Wall 1 or 2 was undertaken, showing whether there was a reason to expect the tracks to be inside the spectrometers acceptance, or not. For the hits in the DW06 we can see that the momentum distribution of the muons is low for a track in SAS, which should have about 70 GeV/c, and see almost half of that value. After observing the position of the hits we can account for most of the hits in the DW06 as tracks that although hit the DW06, are swept outside of the SAS by the magnetic field due to their low momentum, and do not hit the Muon Wall 2.

After a similar study performed for the Straw and Rich Wall distributions the conclusion was not the same. Since almost all tracks seem to be inside the Muon Wall 1 acceptance, we restricted these two peaks to the only ones with Monte Carlo associated tracks with hits in Muon Wall 1. This removed almost half of the tracks, corresponding to tracks that were not inside the spectrometer, and therefore the hits in the Muon Wall 1 shown were not expected.

Since the other half of the tracks are in fact supposed to have hits in the first Muon Wall, and the extrapolation to its position tells us that a hit should have occurred, it seems that there was an inefficiency in the bridging process through the Muon Filter 1. In support of this conclusion is the fact that for the initial trial runs of CORAL this situation was also identified, and two scenarios were hypothesized. The first was a problem in associating hits with tracks in the reconstruction process, and the other the above mentioned bridging issues. In order to rule out the first the association parameters that define the association between track and hit were changed to a more loose setting. This allows us to rule out that possibility.

We thus understand what are most of the reasons for CORAL not to identify these particles. Either a bridging problem occurred, or the tracks seem to come from low momenta low angle muons that cause hits in LAS but are swept either inside the hole, or outside the acceptance of SAS.

**Resolutions**

The quality of the reconstruction process can be analysed through the resolutions of the physical variables to be measured. Since this is a Monte Carlo simulation study, we can use the generated physics to understand, for each track reconstructed, what physical measurements were undertaken and compare them with the generated "true" value of the associated muon.
Single Muon Events

Taking into account all the reconstructed muons from the $M_{\mu\mu} > 3.5 \text{ GeV/c}^2$ sample associated with a Monte Carlo track from which we can retrieve the Monte Carlo information we can calculate the resolutions for the individual muon momentum ($\Delta p_\mu$), for the polar angle in regard to the laboratory reference frame beam axis ($\Delta \theta_{\text{Lab}}$) and finally for the primary vertex $Z$ position $\Delta Z_{\text{Primary Vertex}}$:

$$\Delta p_\mu = p_\mu \text{ Reconstructed} - p_\mu \text{ Generated}$$  \hspace{1cm} (3.28)

$$\Delta \theta_{\text{Lab}} = \theta_{\text{Lab}} \text{ Reconstructed} - \theta_{\text{Lab}} \text{ Generated}$$  \hspace{1cm} (3.29)

$$\Delta Z_{\text{Primary Vertex}} = Z_{\text{Primary Vertex}} \text{ Reconstructed} - Z_{\text{Primary Vertex}} \text{ Generated}$$  \hspace{1cm} (3.30)

Figures 3.23 and 3.24 show the $\Delta p_\mu$, and $\Delta \theta_{\text{Lab}}$ distributions for positive and negative muons. The dimuon mass is a very important measurement in order to understand the mass range of the events, and therefore the type of physics process one is probing in a real data acquisition situation. The single muon momenta and $\theta_{\text{Lab}}$ polar angle in the laboratory reference frame, are the two measurements that provide access to the dimuon mass information.

The resolution distribution was fitted with a gaussian, where its mean value represents a bias of the data, and its $\sigma$ the resolution of the distribution and of the measurement. We can see that the momentum measurement has a resolution of 485 $MeV/c$ for negative muons and 448 $MeV/c$ for positive muons. Also important is the presence of a large bias in the momentum measurement, of 436 $MeV/c$ for the negative muons and 327 $MeV/c$ for positive muons. This might be explained by the introduction of the hadron absorber and the description of its material properties for energy loss through the volume. The material maps are constructed with specific conditions and therefore translate mean values for energy loss in the materials. The introduction of a large and dense material volume as the hadron absorber that each reconstructed track must cross can be the source of an overestimation of the momenta measurement, and therefore create such a positive bias.

The resolution for the $\theta_{\text{Lab}}$ polar angles (see 3.24) show a resolution of about 3 mrad for both positive and negative muons, with very small positive biases. We can therefore be confident in a very precise angular measurement of the muons angular distribution in the laboratory reference frame.

Figure 3.25 shows the resolution for the primary vertex $Z_{\text{Primary Vertex}}$ distribution that enables us to understand the quality of the vertexing process. A resolution of about 14 cm is extracted, which allows for a distinction between both polarised target cells with a wrong assignment of about $\approx 10 \%$, since they are spaced 20 cm. This is a very important result since each cell has a different polarisation, and therefore the
wrong identification of the originating target cell would bias the spin asymmetry analysis of the data. We can also see a small positive bias of 2 cm, for both positive and negative muons.

We can now divide the spectrometer into the different parts already discussed in the previous sections and summarize in Table 3.8 the resolutions for muons reconstructed in LAS, in SAS or in the whole spectrometer. The resolutions for $\Delta p_\mu$, $\Delta \theta_{Lab}$ and $\Delta Z_{Primary \, Vertex}$ are present in the appendix A.

Table 3.8 shows that the resolution in the COMPASS spectrometer is influenced by the individual spectrometers, so that its overall value is between the individual ones. The best momentum resolution is in SAS due to the number of tracking detectors this spectrometer has, and the small angular distribution it accepts. This way a momentum measurement is favored in the SAS, while a $Z_{Primary \, Vertex}$ measurement is favored in the LAS, since the angular distribution accepted is wider (allowing for more precise back extrapolations to define the vertex). There seems to be no effect of the asymmetry of the detector on the resolutions, the accepted and reconstructed muon tracks have good quality, although there are fewer positive tracks than negative.

We notice that the bias observed for the global resolution over the whole COMPASS spectrometer, is also observed in LAS and in SAS.
<table>
<thead>
<tr>
<th></th>
<th>$\Delta p_\mu$</th>
<th>$\Delta Z_{\text{Primary Vertex}}$ (cm)</th>
<th>$\Delta \theta_{\text{Lab}}$ (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^-$</td>
<td>$\sigma$ (MeV/c)</td>
<td>Bias (MeV/c)</td>
<td>$\sigma$ (cm)</td>
</tr>
<tr>
<td>COMPASS Spectrometer</td>
<td>484.6 ± 4.1</td>
<td>436.4 ± 3.6</td>
<td>13.7 ± 0.1</td>
</tr>
<tr>
<td>LAS</td>
<td>530.8 ± 5.7</td>
<td>356.0 ± 4.6</td>
<td>13.0 ± 0.1</td>
</tr>
<tr>
<td>SAS</td>
<td>325.1 ± 4.6</td>
<td>609.1 ± 5.0</td>
<td>17.6 ± 0.2</td>
</tr>
<tr>
<td>$\mu^+$</td>
<td>$\sigma$ (MeV/c)</td>
<td>Bias (MeV/c)</td>
<td>$\sigma$ (cm)</td>
</tr>
<tr>
<td>COMPASS Spectrometer</td>
<td>447.9 ± 4.4</td>
<td>326.8 ± 3.6</td>
<td>14.1 ± 0.1</td>
</tr>
<tr>
<td>LAS</td>
<td>518.9 ± 6.2</td>
<td>349.4 ± 5.2</td>
<td>13.4 ± 0.1</td>
</tr>
<tr>
<td>SAS</td>
<td>335.5 ± 5.2</td>
<td>306.9 ± 5.1</td>
<td>17.0 ± 0.3</td>
</tr>
</tbody>
</table>

Table 3.8: Summary of resolutions in $p_\mu$, $\theta_{\text{Lab}}$ and $Z_{\text{Primary Vertex}}$ for $\mu^+$ and $\mu^-$, divided in tracks reconstructed in LAS, SAS or in the whole COMPASS spectrometer.

Dimuon Events

![M_\mu resolution](image1)

(a) $M_\mu\mu$ resolution.

![p_\mu resolution](image2)

(b) $p_\mu\mu$ resolution.

Figure 3.26: Dimuon mass and momenta resolution for a mass range of $4 < M_\mu\mu < 9$ GeV/c².

Taking into account the mass range $4 < M_\mu\mu < 9$ GeV/c² of Drell-Yan events reconstructed with associated Monte Carlo tracks from which to retrieve information we can use we calculate the resolutions $\Delta M_\mu\mu$, $\Delta p_\mu\mu$, and $Z_{\text{Primary Vertex}}$.

$$\Delta M_\mu\mu = M_\mu\mu \text{ Reconstructed} - M_\mu\mu \text{ Generated} \tag{3.31}$$

$$\Delta p_\mu\mu = p_\mu\mu \text{ Reconstructed} - p_\mu\mu \text{ Generated} \tag{3.32}$$

$$\Delta Z_{\text{Primary Vertex}} = Z_{\text{Primary Vertex Reconstructed}} - Z_{\text{Primary Vertex Generated}} \tag{3.33}$$

From figure 3.26 (a) we can see that the dimuon mass resolution is about 324 MeV/c². Also important is the existence of a bias of 141 MeV/c². Figure 3.26 (b), we note that the dimuon momentum resolution of the spectrometer is of about 1.2 GeV/c, with a bias of about 530 MeV/c. The positive bias tendency was expected if one takes into account the individual muons momentum resolutions, where large positive biases were also found. These biases are related to the hadron absorber and target material map for energy loss, as explained in the previous section.

In figure 3.27 we observe a resolution in the $Z$ position of the primary vertex of 11 cm, with a bias of about 3 cm.
Figure 3.27: Dimuon Z position of the primary vertex resolution as defined in equation 3.28, for a mass range of $4 < M_{\mu\mu} < 9\, GeV/c^2$.

After achieving these results for the whole spectrometer, the same calculations are undertaken for Drell-Yan events that were detected in LAS, in SAS or with one muon in LAS and one in SAS. Their $M_{\mu\mu}$, $p_{\mu\mu}$ and $Z_{\text{Primary Vertex}}$ distributions are shown in appendix B for events with both muons reconstructed in LAS, in SAS, or with one muon in LAS and the other in SAS. A summary of these resolutions is shown in table 3.9.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta M_{\mu\mu}$</th>
<th>$\Delta p_{\mu\mu}$</th>
<th>$\Delta Z_{\text{Primary Vertex}}$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma$ (MeV/c$^2$)</td>
<td>Bias $\sigma$ (MeV/c$^2$)</td>
<td>Bias (GeV/c)</td>
</tr>
<tr>
<td>COMPASS Spectrometer</td>
<td>323.8 ±2.7</td>
<td>140.9 ±3.2</td>
<td>1.21 ±0.02</td>
</tr>
<tr>
<td>LAS</td>
<td>295.5 ±2.8</td>
<td>130.1 ±3.5</td>
<td>1.32 ±0.02</td>
</tr>
<tr>
<td>SAS</td>
<td>328.7 ±22.6</td>
<td>-200.0 ±24.5</td>
<td>1.09 ±0.12</td>
</tr>
<tr>
<td>LAS + SAS</td>
<td>354.5 ±6.8</td>
<td>180.8 ±8.0</td>
<td>0.97 ±0.25</td>
</tr>
</tbody>
</table>

Table 3.9: Summary of resolutions in $M_{\mu\mu}$, $p_{\mu\mu}$ and $Z_{\text{Primary Vertex}}$ for dimuon events with 2 muons reconstructed in LAS, SAS, with one in LAS and one in SAS, or in the whole COMPASS spectrometer.

Analysing the resolutions in table 3.9 it is apparent that the dimuon mass resolution for LAS is of about 296 $MeV/c$, is better than the one for SAS, which goes up to about 330 $MeV/c$. The resolution for events with one muon in LAS and one in SAS is a value between the previous two since it is influenced by both spectrometers of 354 $MeV/c$. The bias of LAS is positive of about 130 $MeV/c$ which is slightly smaller than the bias of the overall resolution for the whole spectrometer. And the LAS+SAS bias is also higher than the one of LAS of about 180 $MeV/c$.

Looking at the $\sigma$ values for the $p_{\mu\mu}$ resolution seen in appendix B figure 3.2, the resolution for LAS is of about 1.32 $GeV/c$ with a bias of 512 $MeV/c$, while SAS has momentum resolution of 1.09 $GeV/c$, with a smaller positive bias almost consistent with zero. LAS + SAS events have about 1 $GeV/c$ resolution with a bias of about 620 $MeV/c$. These biases in the momentum resolution are not expected, and were already seen in table 3.8 for the individual muons momentum resolution.

The resolutions for $Z_{\text{Primary Vertex}}$ (see appendix B figure B.3) are of 10 cm in the LAS, while the SAS has a similar resolution of almost 9.6 cm. LAS + SAS events have a 13.4 cm resolution that result from the convolution of the influences of both spectrometers. The bias is of about 3 cm, positive in all situations, with exception of SAS, which has a 1.6 cm bias, but associated with an error of almost 1 cm.
3.7 Conclusions

The results show that the simulation chain is well implemented. The physics generated is coherent with what was wanted, with a simulation of the Drell-Yan process for a wide mass range of $M_{\mu\mu} > 3.5$ GeV/c$^2$ that was restricted, in the reconstruction process to $4 < M_{\mu\mu} < 9$ GeV/c$^2$. In this range the total DY cross section is 1.42 nb, and the branching ratio for the decay into a muon pair is 16.4 %. The tunning of intrinsic parton transverse momentum $k_T$ was successful with a generated sample of dimuons with a mean transverse momenta of 1.2 GeV/c consistent with the experimental findings of the NA10 Collaboration. Finally the $\cos(\theta_{CS})$ distribution has the appropriate tendency, with a fitted value of $0.78 \pm 0.02$. The results support that the DY process is well simulated for the phase space we are interested in.

The implementation of a polarised target and of a hadron absorber was successful. Results show that the implementation of the interaction probability inside the target cells is coherent with the theoretical prediction, and well implemented inside the Monte Carlo simulation software. The material properties calculated and simulated in the hadron absorber and beamplug have been shown to be also consistent with the expectation. We have measured the expected loss of energy, and number of radiation lengths crossed, for a particle crossing the hadron absorber. The $p_\mu$ of a muon from a DY interaction reconstructed in the spectrometer is of about 48 GeV/c, and suffers a loss of about 2.5 GeV, crossing 55 radiation lengths in the hadron absorber, losing 7.5 GeV and crossing 515 radiation lengths in the beamplug.

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, as intended. We measure a global acceptance of 36 % for accepted dimuon events in the $4 < M_{\mu\mu} < 9$ GeV/c$^2$ mass range where the DY process study is more suitable. LAS accepts 61 % of these events, and SAS only 4%. An important contribution is made by events with larger asymmetry where one muon is accepted in SAS and another in LAS. It accounts for 42 % of the events, with one muon produced at a small angle, and the other at a large angle, with a high dimuon momentum average. We can see the tendency of the two parts of the spectrometer to accept different angular ranges, and we understand the tendency of each part to accept events as a function of dimuon mass, momentum, and $p_T$.

We also analyse the tendency of individual muons within the $M_{\mu\mu} > 3.5$ GeV/c$^2$ to be accepted in different spectrometer parts. We conclude that the spectrometer is asymmetric and accepts more negative muons than positive ones, with a larger effect on SAS. The global acceptance for individual muons is 63 % with 70 % of these muons in LAS, and around 30 % in 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 produced at small angles with low momenta, that are deflected inside the acceptance of SAS after being detected in LAS.

The reconstruction process is studied, and quality cuts analysed in order to clean the sample of events to achieve a subsample of muons coming from a DY interaction inside the target cells. The criteria are checked, and we can observe the resulting distribution for the reconstructed events. The reconstruction efficiencies are analysed for single muons in the $M_{\mu\mu} > 3.5$ GeV/c$^2$ mass range, and for events with dimuon reconstruction in the $4 < M_{\mu\mu} < 9$ GeV/c$^2$ mass range. The reconstruction efficiencies for the individual muons study is of around 86 % for all muons, as well as for both negative and positive ones. 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. 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 global reconstruction efficiency of 73 % with 63 % of which are reconstructed in LAS, 2 % in SAS, and 37 % in events with one muon in LAS and one in SAS. These efficiencies are not exclusive since events detected in both spectrometers are accounted for more than once. LAS reconstructs 66 % of the events accepted, while SAS reconstructs 31 %, and LAS + SAS events with a value influenced by both, reconstructs 60 %.

Finally we studied the quality of our reconstruction, measuring the resolutions achieved. We see that we have a global resolution for individual muon momentum of $\Delta p_\mu = 484 \pm 4$ MeV/c with a large bias that is not expected. This result is explained by the material maps used to describe the energy loss in the absorber material, which use mean values of energy loss for small cells of material taking into account muons with 40 GeV/c momentum.

The polar angle resolution of the individual muons in reference to the beam axis of the laboratory reference
frame is of 3 mrad. This leads to a mass resolution of $324 \pm 3 \text{ MeV}/c^2$, with a bias of $140 \pm 3 \text{ MeV}/c^2$. This bias is explained as a consequence of the bias observed in the individual muons momenta resolution. 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 $325 \pm 5 \text{ GeV}/c$ for negative muons and $336 \pm 5 \text{ GeV}/c$ for positive muons, compared with the resolution in LAS. LAS has a resolution in momenta for individual muons of $531 \pm 6 \text{ GeV}/c$ for negative muons, and $519 \pm 6 \text{ GeV}/c$ for positive muons. We see a better resolution for individual muons in $\theta_{\text{Lab}}$ for SAS than for LAS. These features, 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. The small angular range of the SAS in addition with the large distances to the primary vertex results in worst $Z_{\text{Primary Vertex}}$ resolutions than for LAS.
Chapter 4

Beam Momentum Study

This chapter deals with possible improvements to the proposed experiment. We know that the Drell-Yan cross section is very low, and requires a large luminosity in order to achieve measurements with statistical merit. One possible way to increase the Drell-Yan cross section would be to increase the beam momentum. 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.

4.1 Possible Improvements

As stated, an increase in beam momentum would enhance the Drell-Yan cross section. At the same time one can argue that, being COMPASS a fixed target experiment, this could possibly lead to an increase in acceptance, and therefore have an accumulative effect in increasing the number of events measured per unit of time. On the other hand we should also note 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 optimised for the detection of particles for different beam momentum.

Finally, one must also take into account the effect of different beam momentum in the phase-space covered. Since we are interested in the target valence quarks, in order to annihilate one of them with the $\bar{u}$ antiquark of the $\pi^-$ beam, we now study the behavior of the sea and valence for the GRV98 leading order PDF set used in our Monte Carlo simulation.

4.2 PDFs as a function of $x$

An important systematic contribution for a measurement of the primary interaction between the $\pi^-$ beam and the proton target, is the probability of the interaction being from a valence or sea quark. This is described by the Parton Distribution Functions 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 $Q$ as equivalent to the dimuon mass.

Taking this into account we have

$$
\begin{align*}
\left\{ 
\begin{array}{l}
  u(x, Q^2) = u_v(x, Q^2) + u_s(x, Q^2) \\
  d(x, Q^2) = d_v(x, Q^2) + d_s(x, Q^2)
\end{array}
\right.
\end{align*}
$$

Where the subscript "$s$" stands for sea, and "$v$" for valence. We are interested in understanding what is the probability to probe the sea or the valence for a given $x$ value and given dimuon mass. Figure 4.1 shows the GRV98 leading order PDF set used, for the higher mass value of 9 GeV/c$^2$, separated in sea and valence contributions for up and down quarks.

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, it is expected 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. For a quantitative idea of the balance of sea and valence in the PDF we take $u_s(x)/u(x)$ as a measurement of the probability of probing a sea quark of the nucleon. 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 the reconstruction ($4 < M_{\mu\mu} < 9 \text{ GeV}/c^2$).

Figure 4.2: $u_s(x)/u(x)$ ratio for GRV98 LO PDF, for both limits of the mass range of the analysis, 4 and 9 GeV/$c^2$. 

---

Figure 4.1: GRV98 leading order PDF set for the up and down quark, at $Q^2 = 81 \text{ GeV}/c^2$, decomposed in sea ($s$) and valence ($v$) contributions taken from [31].
Figure 4.2 shows that $u_s(x)/u(x)$ has a very small dependence on $Q^2$, and for low $x$ we have a high probability of interacting with the sea quarks. But also evident is that the probability of interacting with the sea, decreases rapidly as $x$ increases, and for $x = 0.05$ the probability of interacting with the valence up quarks is already 75%. Using this ratio we can try and understand what consequences this has for our studies with different beam momenta.

### 4.3 Simulation of different Beam Energies

With this study in mind, three different beam momentum were used in the Monte Carlo chain: 160, 190 and 280 GeV/c. The mass range generated in PYTHIA was $M_{\mu\mu} > 3.5\text{GeV}/c^2$, and then the same Monte Carlo cut in the mass range of $4 < M_{\mu\mu} < 9 \text{GeV}/c^2$ was also undertaken. For each beam momentum generation, a sample of 100 000 events was simulated. After each mass cut the events within the mass range were 59 179 events for 160 GeV/c beam momentum, 60 822 events for 190 GeV/c beam momentum, and 62 569 events for 280 GeV/c beam momentum.

![Figure 4.3](image-url)

(a) $p_{\mu}$ distribution for generated events at different beam momenta.  
(b) $\theta_{Lab}$ distribution for generated events at different beam momenta.

(c) $x_2$ distribution normalized to the integral of the distribution.

Figure 4.3: $p_{\mu}$, $\theta_{Lab}$ and $x_2$ for the generated events within the mass range of $4 < M_{\mu\mu} < 9 \text{GeV}/c^2$, for 160, 190 and 280 GeV/c, with the $x_2$ distribution normalized to the integral of the corresponding distribution for direct comparison for different beam momenta.

Figure 4.3 shows the different distributions for the physics in the mass range allowed of $4 < M_{\mu\mu}<$
The $x_2$ distribution, \textit{i.e.} the fraction of longitudinal momentum of the proton carried by the struck quark, decreases in mean value as we increase the beam momentum as does the mean polar angle in the laboratory reference frame. On the other hand the mean momentum of muons increases when the beam momentum is increased, from 31 GeV/c for 160 GeV/c of beam momentum, to 35 GeV/c for 190 GeV/c of beam momentum, and 46 GeV/c for 280 GeV/c of beam momentum. The angular distributions decrease from 136.5 mrad for 160 GeV/c, to 127.2 mrad for 190 GeV/c, to 110.1 mrad for 280 GeV/c.

**DY Cross Section and Acceptance for different Beam Energies**

In order to compare qualitatively the gain in cross section $\sigma$ one must first understand how this affects the number of events $N$ obtained. If we take the luminosity $L$ of the experiment, the spectrometer acceptance $A$, and a global efficiency factor $\epsilon$ for the measurement, we know that

$$\sigma = \frac{N}{A \epsilon} \Rightarrow N = A \sigma \epsilon L .$$  \hfill (4.2)

The CERN M2 beam line limits the beam intensity for each beam momentum in such a way that for a higher beam momentum there is a lower beam intensity. As a consequence the luminosity will decrease with beam momentum, proportionally to the beam intensity. As explained in chapter 2 radioprotection issues only allow for a beam intensity of $6 \times 10^7$ pions per second in the experimental hall. Since at 190 GeV/c we can have $I \approx 1.8 \times 10^8$ pions per second as the production limit, we know that the intensity is always forced to the radioprotection limit in the simulations for all beam momenta. This means that we can neglect the $L$ factor as it is constant for each configuration. We then have

$$N \propto A \epsilon x_2 \sigma_{DY\mu\mu} .$$  \hfill (4.3)

Due to the high probability of finding a sea quark for low $x$, the introduction of a $x_2$ cut in the experimental data is needed in order to ensure the DY primary interaction probes the valence quarks. Since for each beam momentum every simulation is produced with the same conditions, we assume the global efficiency of the measurement as proportional to the fraction of events accepted in the cut. Although surely there are other contributions to the efficiency, the statistical cut on the $x_2$ variable is the most directly correlated one to this study. Defining

$$\epsilon_{x_2} = \frac{N_{\text{Accepted Events}}}{N_{\text{Events}}} ,$$  \hfill (4.4)

we can then assume

$$\epsilon = \epsilon_{x_2} \epsilon'$$  \hfill (4.5)

and write

$$N \propto A \epsilon_{x_2} \sigma_{DY\mu\mu} .$$  \hfill (4.6)

The simulated generations at 160 and 280 GeV/c beam momentum, allow to obtain the acceptance, using the same procedure as seen in chapter 3 and the DY cross sections we are interested in.

<table>
<thead>
<tr>
<th>$p_{\text{Beam}}$ (GeV/c)</th>
<th>160</th>
<th>190</th>
<th>280</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$ (%)</td>
<td>31.1</td>
<td>36.0</td>
<td>44.6</td>
</tr>
<tr>
<td>$\sigma_{DY\mu\mu}$ (pb)</td>
<td>121.8</td>
<td>142.0</td>
<td>188.1</td>
</tr>
</tbody>
</table>

Table 4.1: Cross-sections and acceptances for three beam momenta MC simulation, 160, 190 and 280 GeV/c.

Show in table 4.1 is a summary of the cross-sections and acceptances for each simulation. The Drell-Yan cross section and acceptance increases as expected with: 121 pb for 160 GeV/c, 142 pb for 190 GeV/c, and 188 pb for the 280 GeV/c beam momentum, allowing for greater statistics.
**Statistical precision of single spin asymmetry measurements**

We now try and assess the implications of these effects in the statistical merit of the single spin asymmetry measurements. If we take for instance the amplitude of the Sivers single spin asymmetry \[^{20}\] , we observe a dependence on the number of events measured \[^{22}\] :

\[
A^\sin \phi_S (x_1, x_2) = \frac{2}{f|S_T|} \int d\phi_S d\phi \frac{dN(x_1, x_2, \phi, \phi_S)}{d\phi d\phi_S} \sin \phi_S \frac{dN(x_1, x_2)}{N(x_1, x_2)}
\]  

(4.7)

where \(|S_T|\) is the mean target polarization and \(f\) the dilution factor of the NH\(_3\) target. The associated uncertainty of the measurement is

\[
\delta A^\sin \phi_S (x_1, x_2) = \frac{1}{f|S_T|} \frac{\sqrt{2}}{\sqrt{N(x_1, x_2)}}
\]  

(4.8)

which means that

\[
\delta A^\sin \phi_S (x_1, x_2) \propto \frac{1}{\sqrt{N(x_1, x_2)}}
\]  

(4.9)

using equation (4.6)

\[
\delta A^\sin \phi_S (x_1, x_2) \propto \frac{1}{\sqrt{A \epsilon x_2 \sigma_{DY \mu \mu}}}
\]  

(4.10)

If we now define a proportional term \(\delta A_p \propto \delta A^\sin \phi_S\) as

\[
\delta A_p = \frac{1}{\sqrt{A \epsilon x_2 \sigma_{DY \mu \mu}}}
\]  

(4.11)

this term allows us to understand, taking into account the differences in the beam momentum simulated, a proportional term to the error we will have associated to the amplitude of the single spin asymmetry.

**Probability of sea quark interaction**

If we now look at the \(x_2\) distribution for the mass range of interest, inside the spectrometer acceptance, we see that it shifts towards smaller \(x_2\) as the beam momentum increases, as shown in figures (4.4(a) and 4.5(a)). Which means increasing the statistics for the \(x_2\) range with higher probability of sea quark interaction. This means that, although we gain in cross section and in acceptance, we also lose in the statistics due to the cut to be applied for low \(x_2\), and/or in the quality of the events as seen in the plot for the ratio \(u_s(x)/u(x)\) in figure 4.2.

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 momentum distribution was weighted by the mean value of the ratio \(\langle u_s(x)/u(x) \rangle\) for that bin. This is illustrated in figures (4.4(b) and 4.5(b)), which can be interpreted as the distribution of events that interacted with a sea quark.

In figure 4.5 we can see the same distribution of \(x_2\) but taking into account only the LAS.

This analysis allows an intuitive measurement of the quality of the sample, and of the "contamination" of events with interaction with sea quarks, by taking the integral of the "contaminated" events of each sample, and calculating what fraction of the sample it amounts to, using

\[
E_C = \frac{\sum_{\text{bins}} (N_x \times \langle u_s(x)/u(x) \rangle)}{N_{\text{Sample}}}
\]  

(4.12)

\(^1\)This factor translates the fraction of target material that is effectively polarized.
Figure 4.4: $x_2$ distribution inside the spectrometer acceptance (a), and weighted with $\langle u_s(x)/u(x) \rangle$ (b), for the for 160, 190 and 280 GeV/c beam momenta.

Figure 4.5: $x_2$ distribution inside the LAS acceptance (a), and weighted with $\langle u_s(x)/u(x) \rangle$ (b), for the for 160, 190 and 280 GeV/c beam momenta.

Discussion

Summarizing our study in table 4.2 we can now test different $x_2$ cuts and weight the various effects, from the cross section to the single spin asymmetries measurement imprecision. This allows for an evaluation of the various factors discussed. For each $x_2$ cut we take the fraction $E_C$ of the integral of our weighted $x_2$ distribution, allowing us to account for the "contaminated" events of the sample, and the fraction of the total sample of events in the mass cut for each $x_2$ cut ($\epsilon_{x_2}$).

We analyse the behavior of LAS spectrometer individually due to the possible shadowing effect of the beamplug on SAS. This motivated a study of the behavior of LAS independently of SAS, although throughout chapter 3 it has been shown that the acceptance for dimuon events with one muon in LAS and one in SAS represents 42% of the accepted events, and that the reconstruction efficiency in SAS is higher than in LAS.

As expected the acceptance for LAS is smaller in comparison with the whole spectrometer acceptance, and it dilutes the effect of the change in the $x_2$ distribution with increasing beam momentum. Due to the fact that the higher momentum muons are mostly detected in SAS, we see that the $x_2$ distribution in the LAS spectrometer, is less dependent on beam momentum increase, since these muons are outside the LAS.
Table 4.2: Summary of the proportional factors for $\sigma$, acceptance ($A$), sea quark interaction ($E_C$), efficiency and uncertainty of the Sivers amplitude for 160, 190 and 280 GeV/c, in the whole COMPASS spectrometer, and in LAS, taking into account different low $x_2$ cuts.

acceptance. Therefore, as we increase the beam momentum, the high momentum muons for events of small $x_2$, for which the ratio $\langle u_s(x)/u(x) \rangle$ is higher, are not detected, and the fraction of events with sea quark interaction will increase slightly, but not as significantly as when we take into account the whole spectrometer.

We also conclude that the LAS acceptance does not grow with beam momentum reaching its highest value at 190 GeV/c. This is due to the LAS spectrometer hole, and the events that go through the hole into SAS. When we increase the beam momentum, the mean $p_\mu$ of the particles rises and the mean angle in the laboratory reference frame decreases. This implies that more muons enter the LAS acceptance window, but at the same time that more muons, with very small angles, escape through the hole. This means that when we increase the beam momentum from 160 GeV/c to 190 GeV/c, we gain events from outside the angular range of the acceptance, and lose events with small angles that go through the hole, although we note that the balance of these two effects is positive with a slight increase in acceptance from 21.8 % to 22.0 %. On the other hand, that doesn’t occur when we change the beam momentum from 190 to 280 GeV/c. For 190 GeV/c we have an acceptance of 22.0 %, and as we change for 280 GeV/c, what we lose in small angle events of high momenta muons is more than what we gain in increasing the mean angle in the laboratory reference frame, with an acceptance of 20.5 %.

For the whole spectrometer we conclude that, since we have SAS present, what is lost in the spectrometer inner hole is very little when compared with the gain in a higher mean value for the angular distribution in the laboratory reference frame. A steady increase from 31.1 % to 44.6 % for the three energies emerges. Although the latter acceptance seems very high in comparison with the others, the events accepted are also of smaller $x_2$ and therefore prone to higher probability of interaction with the sea quarks.

If we now take into account three possible cuts on the data for low $x_2$, we see that as we increase the minimum value of $x_2$ allowed, we are favoring large angle muons, and therefore losing a great amount of events for high beam momentum configurations. We also note that if we disregard SAS, we are amplifying this effect, and therefore we lose a great amount of statistics in the process. A balance must be reached, in order to ensure the statistical precision, as well as to guarantee the quality of the events in the sample. The
best way of comparing the number of events we are going to be able to analyse is to use the contribution proportional to $\delta A$ that takes into account the acceptance, cross section, and efficiency of the cut. The higher the number of events within acceptance and inside the sample chosen, the smaller the uncertainty of the amplitude measurement.

If we take this value and compare it to the total "contamination" of the sample, i.e. the probability of interaction with a sea quark instead of with valence quarks, we see that taking into account only LAS would pose problems with the acceptance of this spectrometer, and the number of high momentum events detected. It surely would minimize the interaction with sea quarks, but on the other hand the loss of statistics are too great in order to justify using only this spectrometer.

For the whole spectrometer, we can see that a beam momentum of 190 or 280 GeV/c, seem to be the best configuration if we choose a minimum value for the accepted $x_2$ distribution of 0.1, allowing for a sea quark "contamination" below 8 %. For 190 GeV/c, we see that the sample retains 84% of the events and therefore results in a small value for the $\delta A$ estimate. For 280 GeV/c the sample retains a lower fraction of events, only 64 % of events, but the increase in $\sigma_{DY\mu\mu}$ allows for a number of events that lead to a good estimate of the $\delta A$, and therefore a better precision in the Sivers function amplitude measurement, as compared to 190 GeV/c beam momentum.

In order to reach a more informed conclusion on the best solution one should introduce a complete reconstruction study in order to analyse possible effects of the different beam momenta in the reconstruction efficiencies of CORAL.

The conclusion reached in 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. Although it suffers a great deal with the low $x_2$ cut, the gain in cross-section compensates this loss allowing a low value for the asymmetry uncertainty.
Chapter 5

Conclusions

The COMPASS Proposal II DY setup was simulated, with all the modifications needed in order to achieve the proposed setup. New implementations were undertaken of the polarized target and the interaction probability as a function of the interaction point; and of the hadron absorber and its material properties. This simulation leads to an understanding of the behavior of a muon pair when crossing the absorber. A material mapping of the multiple scattering and energy loss in the target and absorber region was also made, thus allowing for the analysis of the reconstruction algorithm and its ability to calculate the physical properties of the generated physics, from the simulated propagation through the spectrometer.

An analysis of the acceptances in the various parts of the spectrometer allowed for an understanding of the overall acceptance. The reconstruction algorithm efficiency was analysed for each spectrometer zone. We concluded that the spectrometer has a left-right asymmetry which leads to a tendency to accept more negative muons than positive ones, as well as a higher reconstruction efficiency for negative muons. 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 spectrometer parts and significant variables, taking into account the introduction of the hadron absorber, a very large amount of matter that was not present in earlier setups. 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 cells. The momenta resolutions for individual muons have an unexpected bias, of about 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. This has a consequence on the dimuon mass resolution that also suffers from such a bias, and results on a $\Delta M_{\mu\mu} = 324$ $MeV/c^2$ with a 141 $MeV/c^2$ bias.

A study of a possible improvement of the statistical precision of the single spin asymmetry measurements through different beam momenta was made, taking into account three beam momenta: 160 $GeV/c$, 190 $GeV/c$ and 280 $GeV/c$. The gain in cross section was weighted with the phase space covered, and acceptance for each beam momenta, concluding that a configuration of 190 $GeV/c$ beam with a $x_2 > 0.1$ should be the most favorable.

This work allowed for a confirmation of some of the COMPASS II proposal predictions, and a study of the setup acceptances, reconstruction efficiencies and resolutions for all parts of the spectrometer. Furthermore a possible improvement on the measurement of single spin asymmetries was studied, allowing to conclude that the choice of a 280 $GeV/c$ beam could improve the statistical precision in this measurement in comparison with a beam momentum of 160 or 190 $GeV/c$. 
Appendix A

Single Muon Resolutions

Positive Muons

Figure A.1: $p_\mu$ resolution for positive muons within the whole Monte Carlo mass range of $M_{\mu\mu} > 3.5$, for muon tracks detected in the COMPASS spectrometer (a), in LAS (b) and in SAS (c).
Figure A.2: $Z_{\text{Primary Vertex}}$ position resolution for positive muons within the whole Monte Carlo mass range of $M_{\mu\mu} > 3.5$, for muon tracks detected in the COMPASS spectrometer (a), in LAS (b) and in SAS (c).
Figure A.3: $\theta_{\text{Lab}}$ resolution for positive muons within the whole Monte Carlo mass range of $M_{\mu\mu} > 3.5$, for muon tracks detected in the COMPASS spectrometer (a), in LAS (b) and in SAS (c).
Negative Muons

Figure A.4: $p_\mu$ resolution for negative muons within the whole Monte Carlo mass range of $M_{\mu\mu} > 3.5$, for muon tracks detected in the COMPASS spectrometer (a), in LAS (b) and in SAS (c).
Figure A.5: $Z_{\text{Primary Vertex}}$ position resolution for negative muons within the whole Monte Carlo mass range of $M_{\mu\mu} > 3.5$, for muon tracks detected in the COMPASS spectrometer (a), in LAS (b) and in SAS (c).
Figure A.6: $\theta_{\text{Lab}}$ resolution for negative muons within the whole Monte Carlo mass range of $M_{\mu\mu} > 3.5$, for muon tracks detected in the COMPASS spectrometer (a), in LAS (b) and in SAS (c).
Appendix B

Dimuon Resolutions

Figure B.1: Dimuon mass resolution for events within the mass range of $4 < M_{\mu\mu} < 9$ GeV/c$^2$, in events detected in different sub spectrometers.
(a) $p_\mu$ resolution for events detected in LAS.

(b) $p_\mu$ resolution for events detected in SAS.

(c) $p_\mu$ resolution for events detected with one muon in LAS and one in SAS.

Figure B.2: $p_\mu$ resolution for events within the mass range of $4 < M_{\mu\mu} < 9 \text{ GeV/c}^2$, in events detected in different sub spectrometers.
Figure B.3: Z position of the primary vertex resolution for events within the mass range of $4 < M_{\mu\mu} < 9 \, GeV/c^2$, in events detected in different sub spectrometers.
Bibliography


