Table of Contents

Chapter 1

The COMPASS Experiment

The COmmon Muon Proton Apparatus for Structure and Spectroscopy (COMPASS) experiment is a fixed target experiment at located on the French side at CERN. COMPASS started taking data in 2002 in the same hall as earlier Euopean Muon Collaboration (EMC), New Muon Collaboration (NMC) and Spin Muon Collaboration (SMC) experiments. COMPASS has studied hadron structure through (SI)DIS, Drell-Yan and Primakoff reactions and has done hadron spectroscopy measurements.

The COMPASS spectrometer is a two-stage spectrometer. The two stages are in a series and each stage contains various tracking detectors and as well at the end of each stage there is a muon wall filter for distinguishing between muons and other particles. Both stages also contain an electromagnetic and hadron calorimeter. Each stage is centerend around a strong spectrometer magnet used for determining particle momentum. The first stage downstream of the target is the large angle spectrometer (LAS) and it is centered around the SM1 magnet which has an integrated field of 1 Tm. This stage detects tracks with larger polar scattering angles roughly between 26 mrad and 160 mrad. The second stage is the small angle spectrometer (SAS) and it detects particle tracks having a scattering angle between roughly 8 mrad and 45 mrad. This stage is centered around the SM2 magnetic which has an integrated field of 4.4 Tm. A graphic of the 2015 setup is shown in Fig 1.1.

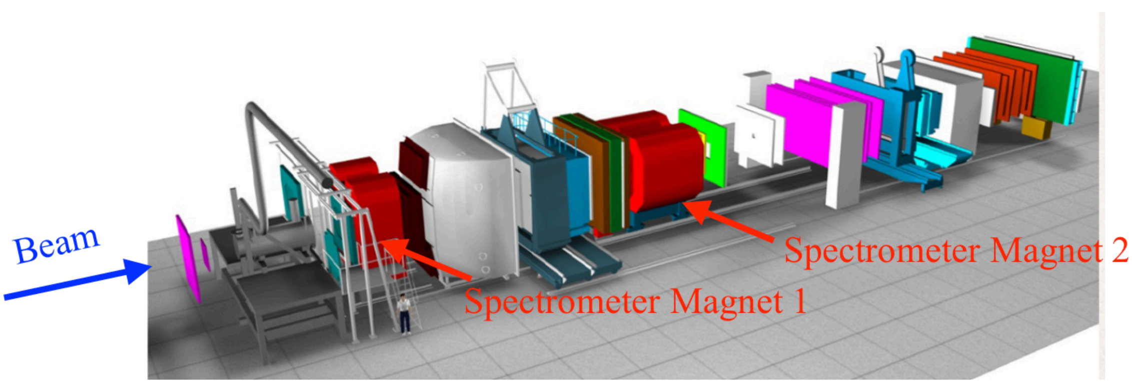

Figure 1.1: A schematic of the 2015 COMPASS setup

This chapter gives an overview of the COMPASS data taking setup with specific interest on the 2015 setup from which the data in this thesis was produced from. For a more thorough review of the spectrometer see reference [12]. This chapter is roughly organized by how the data taking occurs.

1.1 The Beam

The COMPASS spectrometer receives beam from the Super Proton Synchrotron (SPS) along on the M2 beam line. A schematic of the M2 beam line is shown in Fig. 1.2. There are several different beam types and energies available to COMPASS. The most common types used for physics analysis are a tertiary muon beam up to 190 GeV/c and secondary hadron beam with an energy up to 280 GeV/c. Both of these beam types can have a positive or negative charge. As well it is possible to have a lower intensity tertiary electron beam which is manly used for calibrations.

The start of the M2 beam line is the T6 target which is made of beryllium and has an adjustable length. The SPS accelerates primary protons up to 400 GeV/c which impinges on the T6 target to produce a secondary beam. The nominal proton intensity on the T6 target is 100x10^{11} spill^{-}1. The longer the T6 target the higher the secondary intensity where 500mm is the longest and typical target length used for physics data taking. The reaction of the proton beam with the T6 mainly produces secondary protons, pions and kaons. Following this reaction a series of dipole and quadruple magnets are used to select the momentum and charge of interest.

The SPS spill structure varies throughout the data taking year depending mainly on the needs of the Large Hadron Colider (LHC). In 2015 the average intensity provided was 0.6x10^{8} s^{-1} and the typical spill structure was two 4.8 second spills every 36 seconds.

1.1.1 Muon Beam

The muon beam is a tertiary beam which results from a weak decay of the secondary beam. After the initial proton reaction on T6 the resulting secondary particles are momentum and charge selected and sent through a 600m tunnel with focusing and de-focusing (FODO) quadruple magnets. In this tunnel the pion and kaons can decay as

$$\pi^{-(+)} \rightarrow \mu^{-(+)} + \overline{\nu}_{\mu^-}(\nu_{\mu^+}) \tag{1.1}$$

and

$$\kappa^{-(+)} \rightarrow \mu^{-(+)} + \overline{\nu}_{\mu^-}(\nu_{\mu^+}). \tag{1.2}$$

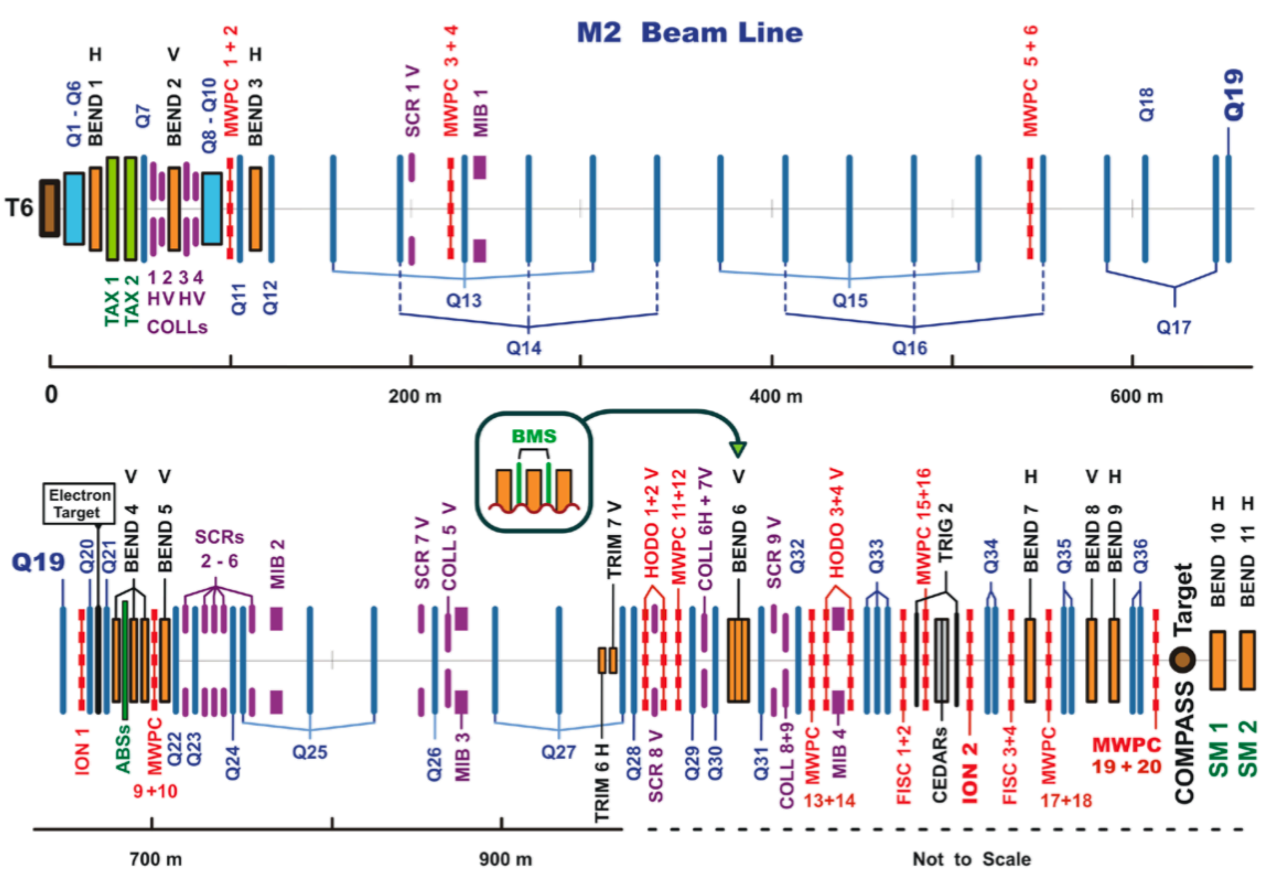

Figure 1.2: The M2 beam line at CERN

At the end of the tunnel a series of nine 1.1m long beryllium absorbers, referred to as the ABS in Fig. 1.2, remove the remaining hadron component of the beam which did not decay. A 172 GeV/c secondary beam is chosen to achieve a 160 GeV/c tertiary μ beam. Due to the fact that the neutrino in the reactions 1.1 and 1.2 is always left handed, the muon will be natural longitudinally polarized. For the muon momentum chosen the muon beam achieves a polarization of 80%.

1.1.2 Hadron Beam

In the case of a hadron beam the ABS absorbers are not used and the decayed muons are removed due to their lower momentum. In the case of a negative hadron beam the composition of the beam is approximately 97 % π^-, 2.5% kaons and 0.5% $\bar{\mathrm{p}}$. The 2015 Drell-Yan data taking used a 190 GeV/c hadron beam.

After the decay tunnel the beam is bent upwards along another FODO tunnel of length 250m before reaching the surface approximately 100m before the COMPASS target. A series of three dipole magnets, called bend 6, then bend the beam to a horizontal position aimed at the COMPASS target. Both upstream and downstream of bend 6 are three tracking detectors (BM01-BM06) that make up the Beam Momentum Station (BMS). The BMS is the upstream most component of the COMPASS spectrometer and is able to determine the beam momentum to better than 1% of the beam momentum with an efficiency of approximately 93%. Bend 6 and the BMS are shown schematically in Fig. 1.3.

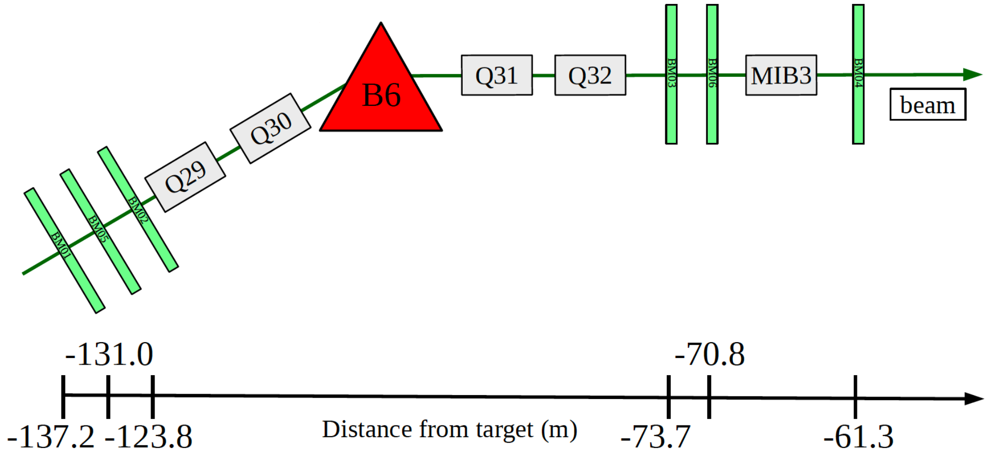

Figure 1.3: Bending the beam to a horizontal position. The BMS detectors are upstream and downstream of the bend 6 magnet.

For the 2015 Drell-Yan setup the π^- beam intensity was too high for the BMS station to work properly. For this reason special low intensity, approximately 10^6 s^{-1}, π^- beams were used in 2014 to determine the momentum distribution for Drell-Yan data taking. The beam momentum distribution is shown in Fig. 1.4 where the average momentum is 190.9 GeV/c with a spread of $\pm$ 3.2 GeV/c.

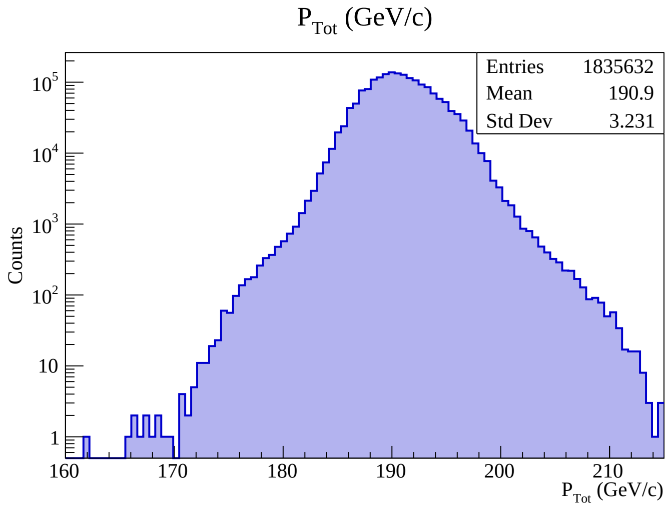

Figure 1.4: The momentum distribution of the π^- beam, determined during dedicated low intensity beam times.

1.2 The Target

1.3 Tracking Detectors

1.4 Particle Identification

1.5 Trigger

1.6 Data Acquisition

1.7 Data Production

1.8 2015 Drell-Yan Setup

This section of the spectrometer covers high Q^2 and high x_b. The target-pointing trigger system in LAS consists of two hodoscopes, one down stream of the last tracker in LAS and the other just after an iron muon filter in front of the second spectrometer magnet.

The trigger in SAS is similar to the LAS trigger but for muons of a lower Q^2 value. The tracking detectors used in both spectrometers are gaseous detectors (drift chambers, straws, multi-wire proportional detectors), micro-megas, and gas electron multiplier (GEM) detectors. The two stages are separated by two spectrometer magnets: SM1, with a magnetic field integral of 1 Tm and SM2, with a magnetic field integral of 4.4 Tm [12].

Both SM1 and SM2 have magnetic fields in the vertical direction meaning charged particles are deflected in the x-z plane and can therefore have their momentum determined. For beam reconstruction there is a beam telescope upstream of the target consisting of eight planes of scifi detectors. To account for the transverse magnetic field in the polarized target a chicane magnet system was added in the beam line. This meant that the beam entered at a slight angle in the beam telescope but exited the target going straight.

1.9 The Beam old

The Super Proton Synchrotron (SPS) is the second largest accelerator at CERN. It has a circumference of almost 7 km and it can accelerate protons up to an energy of 450 GeV. The SPS extracts beam to the Large Hadron Collier and as well sends beam to various experiments in the North Area at CERN. COMPASS is one of these North Area experiments, receiving beam tangent from the SPS on the M2 beam line. In 2015 the SPS was delivering to COMPASS around 100×10^{11} protons over a 4.9 second spill length and a spill was sent approximately twice every 32 seconds. The proton beam extracted from the SPS then would collide with a primary 500 mm long, beryllium target and from there a secondary hadron beam consisting of 97% π^-, 2% $\bar{p}$ and 1% K^- was captured with magneto-optics into a beamline leading to the COMPASS spectrometer. The flux of the secondary hadron beam averaged $0.6 \times 10^8 \frac{\text{hadrons}}{\text{sec}}$ and its momentum was $190\ \frac{\text{GeV}}{\text{c}}$ [11].

1.10 Experimental Setup

The target material used was ammonia (NH_3), where the proton from the hydrogen nucleus was the polarizable nucleon. The average polarization throughout the data taking was 0.73 and a 0.6 T dipole magnet was used to maintain target polarization. With this dipole field and polarization, the spin relaxation time for the target was approximately 1000 hours. The target was separated into two 55 cm cells of radius 2 cm which were in turn separated by 20 cm and oppositely polarized, as shown in figure **??**. In 2015, COMPASS took nine data periods labeled W07-W15. Each data period lasted two weeks and the spin orientation of the targets was reversed after the first week of every period to reduce systematic effects arising from different geometric acceptances and luminosities of up and downstream target cells.

For the 2015 Drell-Yan data taking a hadron absorber, see figure **??**, was placed just downstream of the target cells. This was done to reduce the amount of hadrons and electrons detected in the spectrometer and therefore ensured a cleaner di-muon sample. The absorber material was mostly alumina (Al_2O_3) and concrete and the absorber corresponded to approximately 7.5 interactions lengths of material. Inside the absorber was an aluminum target followed by a tungsten plug, each of radius 2.5 cm, which acted as a beam dump. The aluminum target and tungsten plug served the double purposes as absorbers and also as unpolarized nuclear targets. In addition a thin ^{6}Li absorber was added just downstream of the primary absorber to absorb thermal neutrons produced in the primary absorber. This ^{6}Li absorber was proposed to improve the performance of the first tracking detector downstream of the target.

1.10.1 DAQ and Reconstruction

The data acquisition system (DAQ) was recording events at a rate of approximately 30 kHz with a dead time of 10%. In 2015, COMPASS recorded approximately 750 terabytes of raw data from the nine, two-week periods. Raw data refers solely to individual detector timing and wire or strip positions and does not correspond to physics observables of interest. From this raw information the CORAL reconstruction software at COMPASS is able to determine the trajectory and momentum of charged particles going through the COMPASS spectrometer.

Appendix A

Systematic Error Derivations

A.1 Systematic Error From Acceptance

For an asymmetry defined as

$$\mathrm{A}_\alpha = \frac{1}{\mathrm{P}}\frac{\alpha\sigma_L - \sigma_R}{\alpha\sigma_L + \sigma_R} \tag{A.1}$$

where α is an acceptance ratio. α is assumed to be close to unity therefore let

$$\alpha = 1 \pm 2 * \epsilon, \tag{A.2}$$

where ϵ is a small positive number. The asymmetry can therefore be written

$$\frac{1}{\mathrm{P}}\frac{(1 \pm 2 * \epsilon)\sigma_L - \sigma_R}{(1 \pm 2 * \epsilon)\sigma_L + \sigma_R} = \frac{1}{P}\frac{\sigma_L - \sigma_R \pm 2 * \epsilon * \sigma_L}{(\sigma_L + \sigma_R)(1 \pm \frac{2*\epsilon*\sigma_L}{\sigma_L+\sigma_R})}. \tag{A.3}$$

From there Taylor expand the denominator to get

$$\mathrm{A}_\alpha \approx \frac{1}{\mathrm{P}}\frac{\sigma_L - \sigma_R \pm 2 * \epsilon * \sigma_L}{(\sigma_L + \sigma_R)} * (1 \mp \frac{2 * \epsilon * \sigma_L}{\sigma_L + \sigma_R}) \tag{A.4}$$

$$= \mathrm{A}_\mathrm{N} \pm \frac{1}{\mathrm{P}}\frac{2 * \epsilon * \sigma_L}{\sigma_L + \sigma_R} \mp \mathrm{A}_\mathrm{N} * \frac{2 * \epsilon * \sigma_L}{\sigma_L + \sigma_R} \mp \frac{1}{\mathrm{P}}\Big(\frac{2 * \epsilon * \sigma_L}{\sigma_L + \sigma_R}\Big)^2.$$

Assuming A_N is small and $\sigma_\mathrm{L} \approx \sigma_\mathrm{R}$

$$\mathrm{A}_\alpha \approx \mathrm{A}_\mathrm{N} \pm \frac{\epsilon}{P}. \tag{A.5}$$

The true asymmetry can now be written

$$\mathrm{A}_{\mathrm{N,systematic}} \approx \mathrm{A}_\alpha \mp \frac{\epsilon}{P}. \tag{A.6}$$

Including the $\frac{\epsilon}{P}$ term as an additive error and using standard error propagation the systematic error can be approximated as

$$\delta \mathrm{A}_{\mathrm{N,systematic}} = \frac{\mid \alpha - 1 \mid}{2}\frac{1}{\mathrm{P}} + \frac{\delta_{\frac{|\alpha-1|}{2}}}{\mathrm{P}}. \tag{A.7}$$

A.2 Systematic Error From Left-Right Event Migration

Assuming the fraction of events miss-identified is γ and that the amount of miss-identified events reconstructed left equals the amount of outgoing events reconstructed right

$$\mathrm{A}_{\mathrm{N,measure}} = \frac{1}{\mathrm{P}}\frac{(\mathrm{L} + \frac{\gamma}{2}\mathrm{N}_{\mathrm{total}}) - (\mathrm{R} + \frac{\gamma}{2}\mathrm{N}_{\mathrm{total}})}{(\mathrm{L} + \frac{\gamma}{2}\mathrm{N}_{\mathrm{total}}) + (\mathrm{R} + \frac{\gamma}{2}\mathrm{N}_{\mathrm{total}})} = \frac{1}{\mathrm{P}}\frac{\mathrm{L} - \mathrm{R}}{(\mathrm{L} + \mathrm{R}) * (1 + \gamma * \frac{\mathrm{N}_{\mathrm{total}}}{\mathrm{L}+\mathrm{R}})}, \tag{A.8}$$

where $\mathrm{N}_{\mathrm{total}}$ is the total events measure, L is the true events measured to the left that should be measured left and R is the number of events measure to the right that should be measured to the right.

Assuming γ is a small percentage, the denominator can be Taylor expanded to give

$$\mathrm{A}_{\mathrm{N,measure}} \approx \mathrm{A}_{\mathrm{N}}\Big(1 - \gamma * \frac{\mathrm{N}_{\mathrm{total}}}{\mathrm{L} + \mathrm{R}}\Big). \tag{A.9}$$

Including $\gamma \mathrm{A}_{\mathrm{N,measure}}$ as an additive error and using standard error propagation the systematic error can be approximated as

$$\delta \mathrm{A}_{\mathrm{N,systematic}} = \gamma * \mathrm{A}_{\mathrm{N,measure}} + \gamma * \delta \mathrm{A}_{\mathrm{N,measure}}. \tag{A.10}$$

List of Figures

List of Tables

Chapter 2

References

[1] EMC, A Measurement of the Spin Asymmetry and Determination of the Structure Function g1 in Deep Inelastic Muon-Proton Scatter, Phys. Lett. B 206 (1988) 364.

[2] D. Floria, M. Stratmann and W. Vogelsang, Extraction of spin-dependent parton densities and their uncertainties, Phys. Review D (2009).

[3] J. Collins, Leading twist single transverse-spin asymmetries: Drell-Yan and deep inelastic scattering, Phys. Lett. B 536 (2002) 43.

[4] S. Arnold and A. Metz, Dilepton production from polarized hadron hadron collisions, (2009), arXiv:0809.2262v2[hep-ex].

[5] M. Grosse Perdekamp and F. Yuan, Ann. Rev. Nucl. Part. Sci. 65, 429 (2015), arXiv:1209.2803 [hep-ph].

[6] D. Sivers, Phys. Rev. D41, 83 (1990).

[7] B. Mulders, Phys. Rev. D57 (1998).

[8] I. Kenyon, The Drell-Yan process, Reports on Progress in Physics 45 (1982).

[9] COMPASS Collaboration, COMPASS-II Proposal, (2007).

[10] J. Collins and D. Soper, American Physical Society D16.

[11] COMPASS Collaboration, First measurement of transverse-spin-dependent azimuthal asymmetries in the Drell-Yan process, (2017), arXiv:1704.00488 [hep-ex].

[12] COMPASS Collaboration, The COMPASS Experiment at CERN, (2007), arXiv:0703049 [hep-ex].

[13] V. Blodel, A New Method for the High Precision Alignment of Track Detectors, (2002).