# 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.

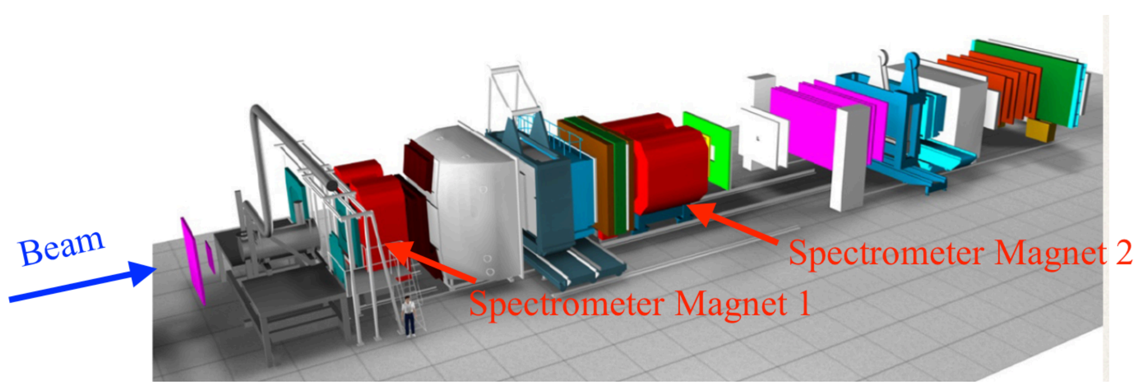


Figure 1.1: A schematic of the 2015 COMPASS setup

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. The Super Proton Synchrotron (SPS) is the second largest accelerator at CERN with 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. 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 100x$10^{11}$ 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 0.6x$10^{8}$ 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

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

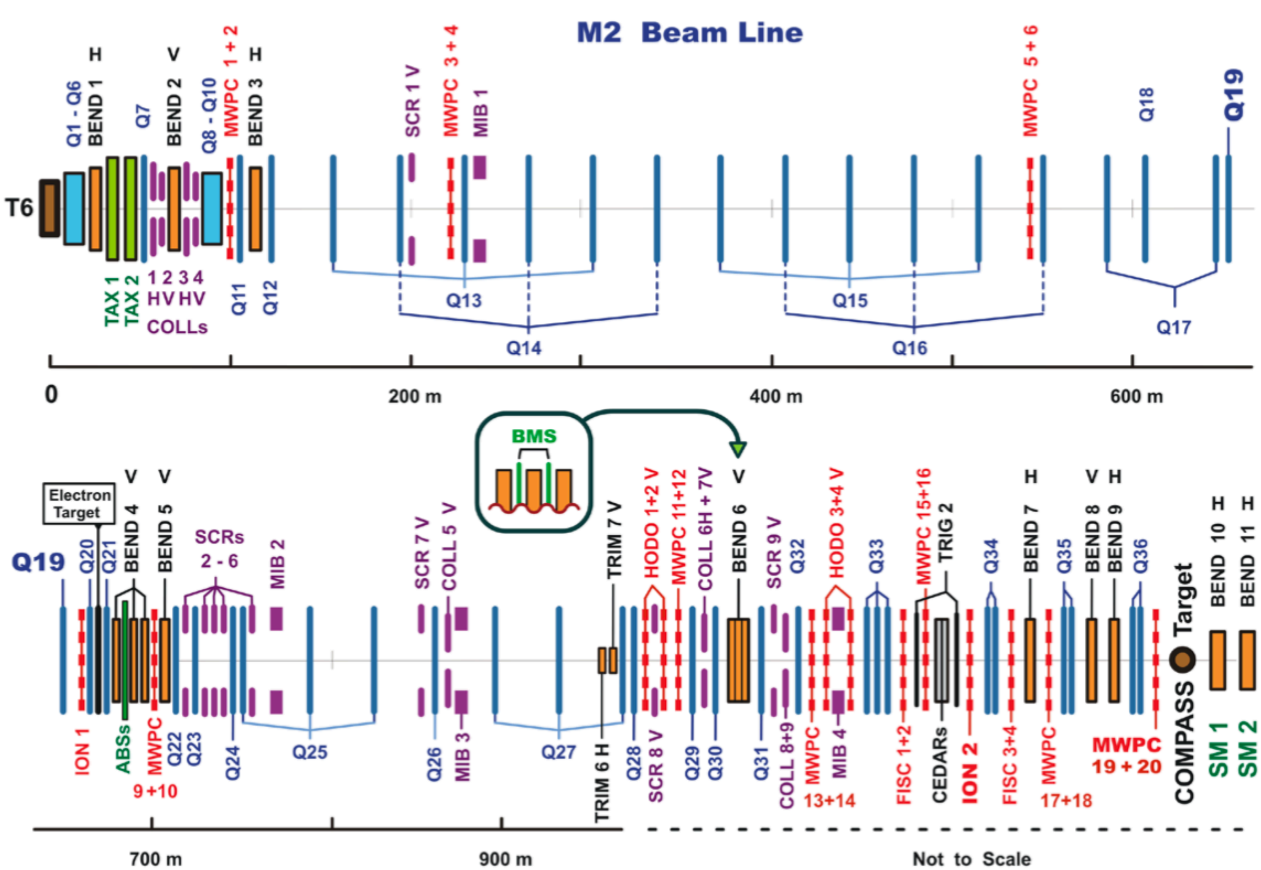

Figure 1.2: The M2 beam line at CERN

and

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

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 $\mu$ 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 % $\pi^-$, 2.5% kaons and 0.5% $\overline{\mathrm{p}}$. 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.

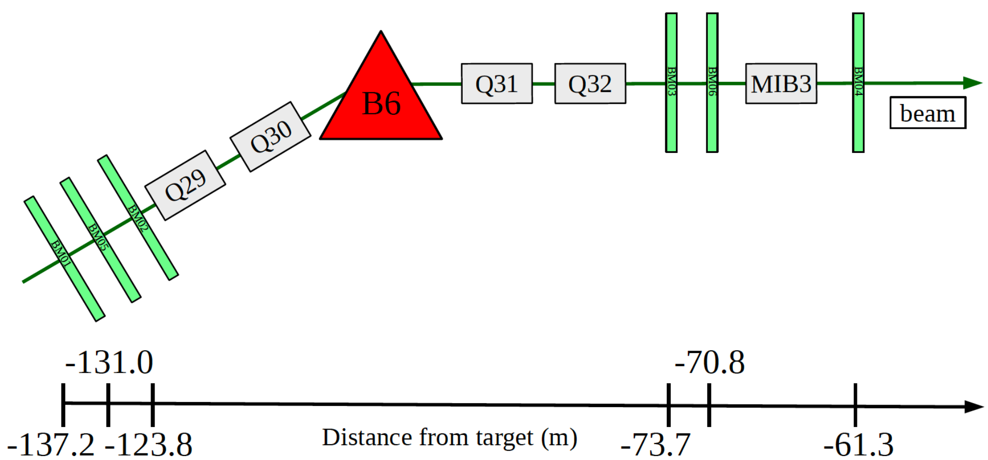


Figure 1.3: Bending the beam to a horizontal position. The BMS detectors are upstream and downstream of the bend 6 magnet.

For the 2015 Drell-Yan setup the $\pi^-$ beam intensity was too high for the BMS station to work properly. For this reason special low intensity, approximately $10^6$ s$^{-1}$, $\pi^-$ 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/$c$.

For years with a transversely polarized target, such as 2015, a chicane system of dipole magnets is setup in front of the target. This is because a beam hitting the target without any angle would then be deflected inside the target to the left or right of the spectrometer. For this reason the chicane gives the beam an angle

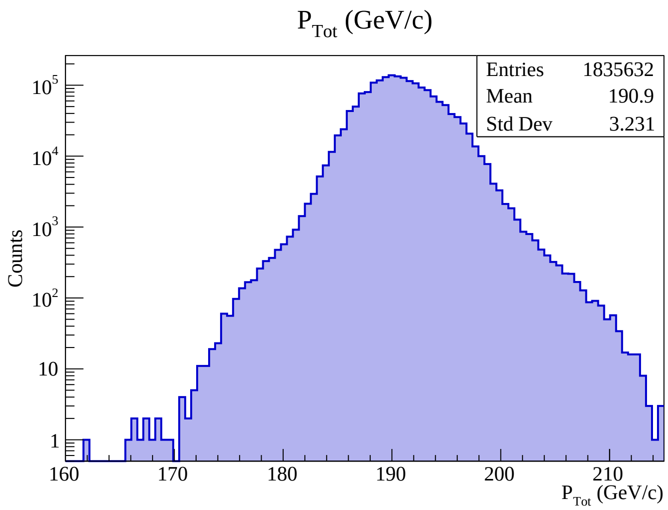


Figure 1.4: The momentum distribution of the $\pi^-$ beam, determined during dedicated low intensity beam times.

before hitting the target such that the non-interacting beam exits the target traveling straight towards the spectrometer.

## 1.2 The Polarized Target

The polarized target at COMPASS is the most complicated and essential component of the spectrometer. It is located upstream of the tracking detectors and spectrometer magnets and downstream of the beam telescope, described in section 1.3, detectors. The target consists of 2 or 3 cylindrical cells and the possible materials are either solid state ammonia ($NH_3$) or deuterated lithium ($^6LiD$) or liquid hydrogen. Fig. 1.5 shows a schematic of the target.

Surrounding the cylindrical cells is a longitudinal super conducting magnet capable of reaching a magnetic field of 2.5T. This longitudinal magnet polarizes the target in the direction of the beam momentum and the target polarization is maintained by keeping the target in a liquid helium bath of approximately 60mK. This is called frozen spin mode where the temperature is maintained by a dilution refrigerator.

The target is polarized through the dynamic nuclear polarization (DNP) method [14]. This process works by first polarizing electrons in the target with the longitudinal magnet in the same longitudinal direction for all target cells while sending electromagnetic radiation in the microwave spectrum into the target. Due to their much lower mass, electrons have a larger magnetic moment and therefore can be polarized at a much faster rate than protons or neutrons. For atoms which have a nuclear spin it is then possible for these atoms to absorb a microwave going to an excited state with the electron spin anti-parallel to the magnet

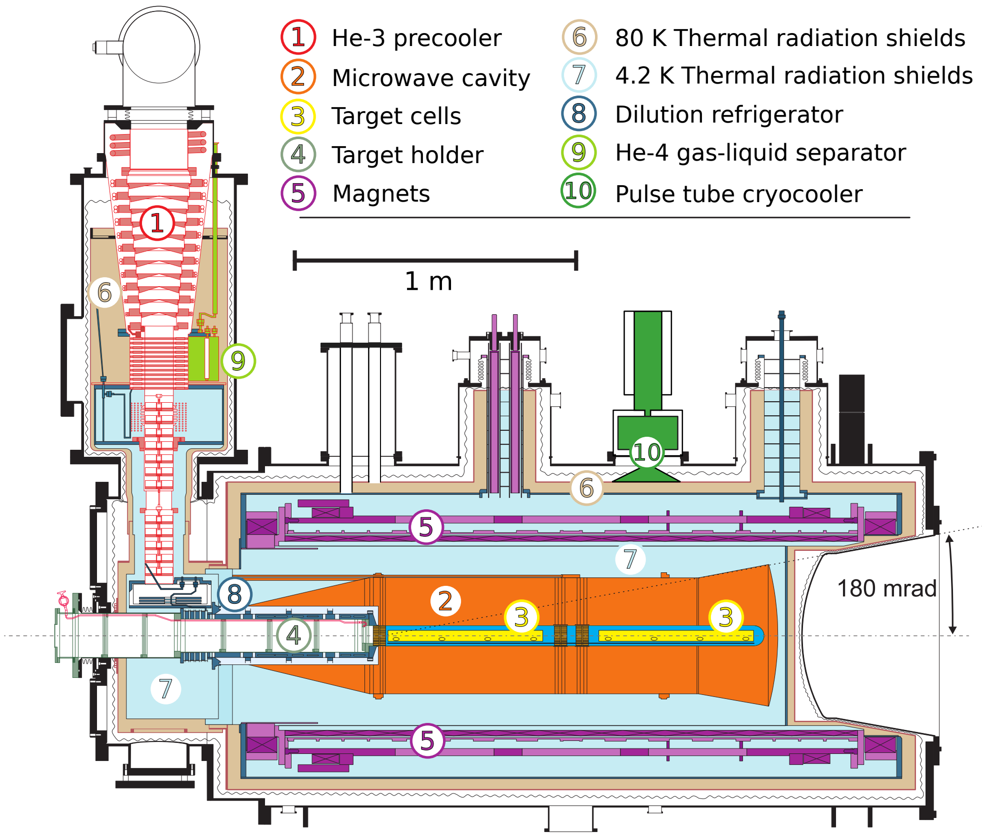


Figure 1.5: The polarized target at COMPASS

and the nuclear spin either parallel or anti-parallel to the magnet depending on the microwave frequency. The electron with the anti-aligned spin will then quickly have its spin realigned while the nucleon will take much longer to lose its polarization due to its smaller magnetic moment. This process can continue in this way resulting in a net nuclear polarization. Using the DNP method the target can achieve a polarization of approximately 90% in three days.

The target also includes a 0.63T transverse dipole magnet to change from longitudinal polarization to transversely polarized. The target must first be longitudinally polarized before the transverse target magnet can change the polarization direction. Once the target is transversely polarized, the target polarization can no longer be increased as microwaves can no longer shine on the target in the polarization direction. Therefore the polarization will decrease exponentially. In 2015 the target was polarized for about half a day between data taking sub-periods and achieved and average polarization of 0.73% which includes the effect of exponential polarization lose with time. The target transverse polarization relaxation time was about 1000 hours in 2015.

The target polarization was measured with 10 NMR coils while in longitudinal magnet mode. In the

2015, each target cell had the most upstream and downstream coils in the center of the target cell and the other three coils on the outside perimeter of the target cells. Due to the fact that the polarization can only be measured with the longitudinal magnet on, the polarization is only measure at the start and finish of a transversely polarized data taking. The intermediate polarization are then determined by exponential interpolating between these two times.

In 2015 the setup was two transversely polarized target cells of 55 cm length and 2 cm in radius, separated by 20 cm and oppositely polarized. The polarization of the target cells was flipped ever two weeks of data taking to reduce systematic effects. Due to the fact that the beam needs to be precisely steered onto the target anytime a beam line magnet is changed and that the chicane magnets upstream of the target are setup for only one transverse target direction, the transverse target magnet only pointed downward in 2015. To achieve a polarization flip the target polarization had to therefore be rotated back to the longitudinal direction and the input microwaves had to be changed to achieve the desired polarization direction.

The target material in 2015 was $NH_3$ where the protons in the three hydrogen atoms were the only nucleons with nuclear spin. Therefore only some fraction of the target was able to be polarized and one would expect that this fraction is 3/17. However to get a more accurate determination of the dilution factor the follow calculation was used

$$f = \frac{n_H \sigma^{DY}_{\pi^- H}}{n_h \sigma^{DY}_{\pi^- H} + \sum_A n_A \sigma^{DY}_{\pi^- A}}, \tag{1.3}$$

where $f$ is the dilution factor, $n_H$ is the number of hydrogen atoms in $NH_3$, $n_A$ is the number of other nucleons in $NH_3$, and $\sigma^{DY}_{\pi^- H}$ and $\sigma^{DY}_{\pi^- A}$ are the Drell-Yan cross-section for pion hydrogen scatter and pion nucleon scattering respectively. The cross-section were determined using a parton-level Monte-Carlo program MCFM [15]. The dilution factor was also further scaled down by studies of reconstruction migration between target cells. The average dilution factor in 2015 was 0.18.

## 1.3 Tracking Detectors

The goal of the tracking detectors is to determine a point in space where a particle traversed. The COMPASS tracking detectors attempt to do this for a wide range of angles, momentums and at different rates. For these reason there are several planar tracking technologies used at COMPASS which can be divided into three categories: very small angle tracker, small angle trackers and large area trackers. As the name suggest very small angle trackers measure tracks with small angle deflections from the beam axis which are essentially beam particles. The small area trackers measure particle tracks with low but non-zero angle have central dead zones. The large area trackers are several meters in height and width and measures the largest deflection angles up to 180 mrad.

All of these trackers are split into stations where each station corresponds to several detectors at roughly the same z-position along the beam line. Each station measures a track position in one or more orientation while most measure tracks in three or more orientations. The coordinate orientations measured are the X and Y coordinates which are the horizontal and vertical directions respectfully and as well the U and V coordinates which are rotated at different angles with respect the X and Y coordinates.

### 1.3.1 Very Small Angle Trackers

The very small angle trackers extend up to 3 cm away from the beam axis. This is the region with the highest number of tracking particles and therefore these detectors must be able to handle the highest rates up to $5\text{x}10^7$ Hz. The two detector types that make up the very small angle trackers are either scintillating fiber detectors (SciFi) or silicon microstrip detectors. These two detector types are complementary to each other as the former have very good timing resolution while the latter have very good spacial resolution.

There are three silicon stations possible at COMPASS with active detecting areas of 5x7 $\text{cm}^2$. The spacial resolution of these detectors is nominally 10 $\mu$m and the timing resolution is nominally 2.5 ns. For the 2015 setup, the beam intensity was too high for the silicon detectors to operate and therefore these detectors were not used in 2015.

There are 10 SciFi stations available at COMPASS with sizes varying from 3.9x3.9 $\text{cm}^2$ to 12.3x12.3 $\text{cm}^2$ planar areas. The fiber diameters vary between detectors and are 0.5 nm, 0.75 nm and 1 nm. Several fibers are bundled together to determine a strip hit position and the resulting nominal spacial resolutions are 130 $\mu$m, 170 $\mu$m and 210 $\mu$m. The nominal timing resolution of these detectors about 400 ps. In 2015 three SciFi stations made up the beam telescope and were placed upstream of the target to measure the beam trajectory and timing information. A fourth SciFi station was place in the LAS section of the spectrometer.

### 1.3.2 Small Angle Trackers

The small angle trackers are small area detectors that detect particles with a non-zero defection angle. They cover 5 cm to 40 cm from the beam axis where the rate drops two orders of magnitude relative to the very small angle trackers to approximate $10^5$ Hz. At COMPASS there are two types of small area tracking detectors: micromesh gaseous structure (micromegas) and gas electron multipliers (GEMs).

There are three micromega stations at COMPASS all location sequentially after each other between the target and the first spectrometer magnet. All three detectors measure four coordinate projections and have an active area of 40x40 $\text{cm}^2$ with a 5 cm diameter dead zone. The micromegas operate by having a conversion region and a smaller amplification region. An ionized particle produced in the conversion region will drift through an electric field too small for amplifaction of around 3.2 kV/cm to the amplification region where the electric field is around 50 kV/cm and is high enough to amplify the sign which is then read out on strips. The conversion and amplification regions are separated by a metallic micromesh material. The electrons pass through the micromesh without resistance and are not rimmed out. The micromegas have good spacial resolution because the thickness of the amplification region is only 100 $\mu$m which is small enough to prevent the electron avalanche from spreading out much transversely between strips. The separation of the larger conversion region from the smaller amplification region with the micromesh prevents electric field lines from being distorted in the conversion region and therefore prevents the primary electrons from drifting slower in the conversion region. This allows micromegas to operate at a higher rate than would be possible otherwise. This principle of operation is illustrated in Fig. 1.6. The strips in the central part of the detector are 360 $\mu$m corresponding to a resolution of about 100 $\mu$m and the strips in the outer region are 460 $\mu$m corresponding to a resolution of about 120 $\mu$m. The nominal timing resolution 9 ns. In 2015 the micromegas were upgraded to include a pixelized section covering much of the dead zone area.

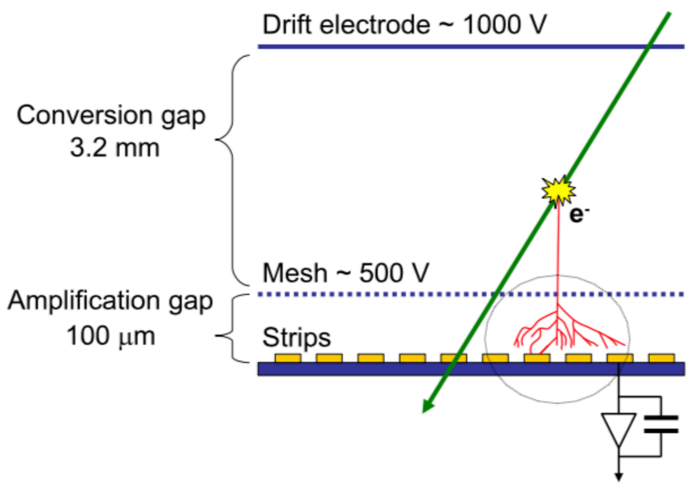


Figure 1.6: Principle of operation for the micromesh gaseous structures (micromegas)

There are eleven GEM detectors located throughout the COMPASS spectrometer starting after the first spectrometer magnet down to the end of the spectrometer. These detectors are close to the beam axis and are mounted on a large area tracker covering the dead zone region of the large area tracker. All eleven detectors have an active area of 31x31 cm$^2$ and a 5 cm diameter dead zone. In times of lower beam intensity the dead zones can be turned on as an active area. The detector is split into four regions separated by a polymide foil (50 $\mu$m thick) clad with copper on both sides with around $10^4$ cm$^{-1}$ drifting holes of 70 $\mu$m diameter. There in an electric potential of a few hundred volts between each foil layer. The GEM detectors speed up the amplification process by splitting the amplification avalanche into three locations there by allowing for a higher rate of operation then would otherwise be possible. The electron amplification occurs around the holes of each of the three foil dividers which therefore speeds up the overall drift time from the ionization location to the strip readout. This principle of operation is shown in Fig. 1.7. The nominal timing and spacial resolution of the GEM detectors is 10 ns and 110 $\mu$m respectively. Two pixelized GEM detectors where also in operation but were not as crucial for the 2015 Drell-Yan measurement.

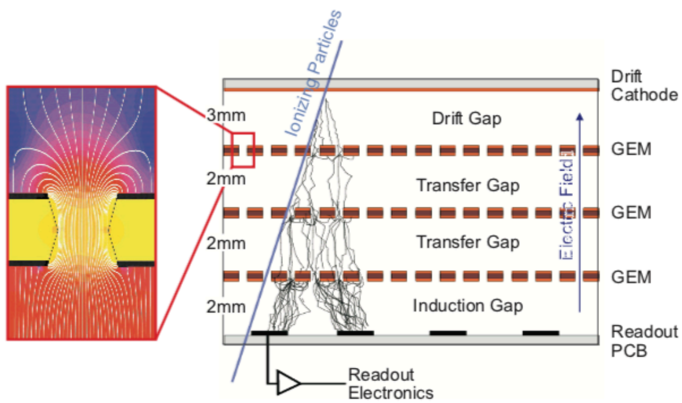


Figure 1.7: The operation principle of the gas electron multiplier (GEM) detectors

### 1.3.3 Large Area Trackers

## 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.

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.

### 1.8.1 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.

# Chapter 2

# References


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