

Investigation on the Trigger Functionality of a 2S Module Prototype for the CMS Phase-2 Upgrade

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1 Introduction

In particle physics, particle accelerators play a crucial role in observing the interactions of matter and in testing the theoretical predictions of the Standard Model. By accelerating particles almost to the speed of light, they can collide with each other with high energies creating optimal conditions for the discovery of new particles. The biggest accomplishment at a particle accelerator in the last decade has been the observation of the Higgs boson [1] at the Large Hadron Collider (LHC) at CERN, the European Organization of Nuclear Research, near Geneva [2].

The LHC is currently the most powerful particle accelerator on earth. This synchrotron focuses on the acceleration of protons and achieves particle collisions with a center-of-mass energy of up to 13 TeV [3]. The particles arising from these collisions are detected by four main detectors installed at different interaction points of the beams, with the CMS (Compact Muon Solenoid) detector representing one of them. The CMS detector is a general purpose detector consisting of different subdetectors that allow the measurement of the particle properties [4].

So far, the LHC has reached an instantaneous luminosity of $2.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in 2018, which already surpasses the original design value. To further expand the research of the Standard Model to rare processes and physics beyond the Standard Model, even higher collision rates are necessary. With this goal in mind, the next major upgrade, the High-Luminosity LHC (HL-LHC), is planned to be installed until 2027. The HL-LHC is expected to reach instantaneous luminosities of $5.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ or even higher. To cope with the new operating conditions of the HL-LHC, the CMS detector has to be upgraded as well. As part of this CMS Phase-2 upgrade the current tracking system will be replaced [5]. Therefore, new types of silicon sensor modules have been developed, with the 2S module being one of them.

The 2S module consists of two silicon strip sensors stacked on top of each other. The module can detect particle tracks with a high transverse momentum, which are an indicator for possibly interesting events, through the correlation of hits in both sensor layers. Parts of these high momentum tracks, the so-called stubs, are reconstructed by the logic of the chips on the 2S module and will be integrated into the event selection process of the CMS detector [5]. Thus, it is of utmost importance that the stubs are correctly identified.

In the framework of this thesis, measurements of cosmic muons with a 2S module prototype of the CMS Phase-2 tracker upgrade were performed in order to investigate and test the stub performance of the module. Measurements with different geometrical configurations and different settings for the stub logic in the readout chip were realized in order to examine various aspects of the stub finding logic. Cosmic muons are suitable for these measurements because they can pass the whole setup due to their minimal energy loss in matter. To detect cosmic muons with the 2S module, a hodoscope of two scintillators was employed with the intention of using the coincidence signal of the scintillators to trigger the readout of the module.

This thesis is structured as follows. In Chapter 2, an overview of the LHC, HL-LHC and the planned CMS Phase-2 tracker upgrade is given. This is followed by a detailed description of the 2S module and an explanation of the stub finding logic in Chapter 3. In Chapter 4 the measurement setup is presented, followed by the analysis of the preparatory measurements in Chapter 5. The measurement of cosmic muons with the 2S module in a horizontal position is examined in Chapter 6. In Chapter 7, the measurements of cosmic muons with a tilted 2S module are described. A summary is provided in Chapter 8.

2 The Large Hadron Collider and the CMS Experiment

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) located at CERN, the European Organization of Nuclear Research, near Geneva is the world's largest and most powerful particle accelerator. The circular synchrotron consists of a 26.7 km long tunnel installed approximately 100 m underground where two counter-rotating beams of protons or heavy ions can be accelerated and collide with each other (pp, PbPb and pPb collisions) [3]. In the beam the protons are arranged in bunches with approximately 3000 bunches per beam, each bunch containing about 10^{11} protons. The bunches have a bunch spacing of 25 ns, corresponding to a bunch crossing frequency of 40 MHz [6]. Before entering the LHC, where the protons are accelerated almost to the speed of light, the protons need to reach a certain speed, which is achieved by using a chain of pre-accelerators. A schematic overview of the LHC and its pre-accelerators is shown in Figure 1.

To further characterize the LHC and its capabilities two important parameters for particle accelerators are introduced: the center-of-mass energy of the colliding particles and the luminosity. The center-of-mass energy $\sqrt{s}$ is the total energy available for the collision and the luminosity relates to the number of potential particle collisions. The instantaneous luminosity describes the rate of potential collisions per unit area and time, while the integrated luminosity describes the rate of potential collisions per unit area for a specific time interval and is therefore used to quantify the number of collected data by the detectors.

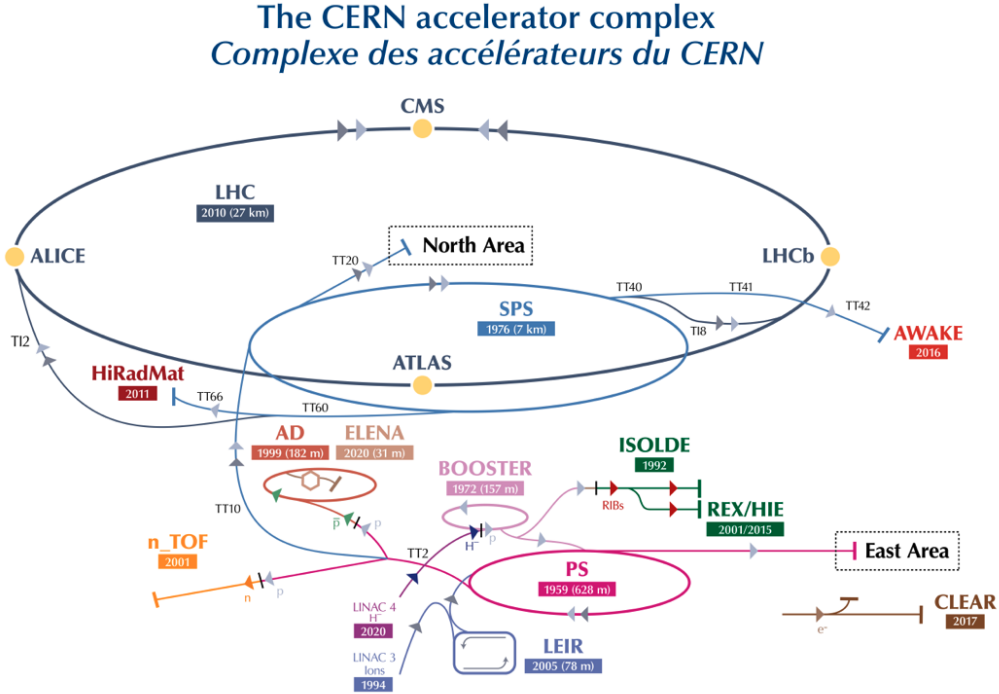


Figure 1: Schematic overview of the LHC and its chain of pre-accelerators [7].

The operating mode of the LHC alternates between running periods for data taking and shutdowns for repair, maintenance and improvement work. Since the start in 2009, the luminosity increased steadily, reaching a peak instantaneous luminosity of $2.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in 2018, which already exceeded the original design value of $1.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ of the LHC [5]. After the last running period from 2015 to 2018, referred to as Run 2, data corresponding to an integrated luminosity of 178 fb^{-1} have been collected in total by the CMS experiment at center-of-mass energies of $\sqrt{s} = 7 \text{ TeV}$, 8 TeV and 13 TeV collectively [8]. The LHC is currently in the Long Shutdown 2 (LS2) until 2022, when Run 3 is set to start. In Run 3 the LHC is expected to operate at an even higher center-of-mass energy of 13.6 TeV . After Run 3 in 2024 the total amount of data is expected to correspond to an integrated luminosity of 300 fb^{-1} [5].

There are four main experiments installed at different beam crossing points around the tunnel to detect the particles arising from the collisions: ALICE (A Large Ion Collider Experiment) [9], ATLAS (A Toroidal LHC ApparatuS) [10], LHCb (Large Hadron Collider beauty) [11] and CMS (Compact Muon Solenoid) [4]. ATLAS and CMS are general purpose detectors studying the Standard Model and looking for new particles such as particles from supersymmetry. While ALICE is a heavy ion detector with focus on the investigation of the quark-gluon plasma, LHCb concentrates on studying collisions where mainly bottom quarks are involved [12, 13].

2.2 The CMS Experiment

The CMS detector is located, as the LHC, approximately 100 m underground in France near the village Cessy at one of the beam interaction points. The detector weighs 14000 t and has a length of 21.6 m and a diameter of 14.6 m. It consists of several subdetectors which are arranged in layers around the collision point [4]. In the middle part of the detector, the so-called barrel, the layers are arranged cylindrical around the beam axis, whereas in the two endcaps, which are closing the barrel on each side, the layers are arranged orthogonal to the beam axis.

Figure 2 shows a schematic overview of the CMS detector and its subdetector layers.

The coordinate system used by the CMS Collaboration is centered at the collision point inside the experiment with the x -axis pointing to the center of the LHC beam ring, the y -axis pointing upwards and the z -axis pointing along the beam in the counterclockwise direction. The azimuthal angle ϕ is measured from the x -axis in the x - y plane and the radial coordinate r is also defined in the x - y plane. The polar angle θ is measured from the z -axis in the r - z plane. The pseudorapidity η is calculated by $\eta = -\ln[\tan(\theta/2)]$ [4].

The innermost layer surrounding the interaction point is the tracking system of the CMS detector with a length of 5.8 m and a diameter of 2.5 m. Its main function is the measurement of the trajectories of charged particles and the reconstruction of primary and secondary vertices. The tracking system is divided into the pixel detector, consisting of 1440 silicon pixel sensors, and the strip detector, consisting of 15148 silicon strip sensors, ensuring a high granularity while covering a pseudorapidity of $|\eta| < 2.5$.

The second layer is made up of two calorimeters, the electromagnetic calorimeter (ECAL) followed by the hadronic calorimeter (HCAL). The ECAL consists of lead tungstate (PbWO_4) crystals which are mounted in the barrel and in both endcaps, measuring the deposited energy of particles like electrons and photons by absorbing them. However, particles that interact via the strong interaction, like neutrons, pass this calorimeter and are therefore measured by the HCAL using mainly brass absorbers and plastic scintillators.

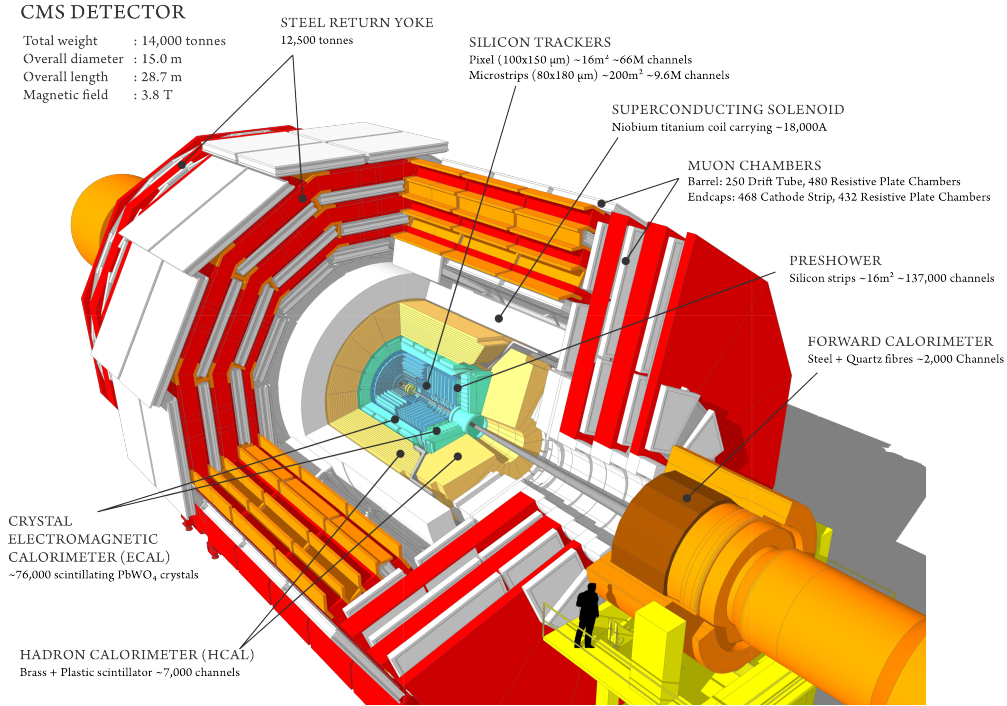


Figure 2: Overview of the CMS detector and its subdetector systems [14].

The tracker and calorimeters are surrounded by a solenoid magnet with a length of 12.5 m and a diameter of 6 m, which is the main feature of the detector giving it its name. It is a superconducting magnet operating at a temperature of 4.5 K, generating a homogeneous magnetic field of 3.8 T inside. The magnetic field forces charged particles on a curved track with a bending angle depending on the transverse momentum p_T of the particle. By measuring the radius of the track, the charge and p_T of the particle can be determined in the tracker.

Outside of the solenoid the muon chambers are located, which are partly embedded in the iron return yoke of the magnet in the barrel and the endcaps. For the muon identification three different types of gaseous detectors are used. Since the return yoke is also magnetized by the magnetic field, the momentum and charge of the muons can also be measured.

Another key element of the CMS detector is the trigger system which is necessary because of the high bunch crossing rate of 40 MHz and a pileup of 20 collisions on average per bunch crossing for an instantaneous luminosity of $1.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. It selects events based on two selection stages to reduce the rate and the amount of data that need to be read out and stored. The first stage is the hardware based Level-1 (L1) Trigger, which reduces the output rate to a maximum of 100 kHz using information from the calorimeters and the muon systems. The second stage is the software based High-Level Trigger (HLT), which performs an offline analysis of the complete data and further reduces the data rate to 1 kHz.

2.3 The High Luminosity LHC

The discovery of the Higgs boson by the ATLAS and CMS Collaborations in 2012 has been the biggest accomplishment of the LHC [1]. Since then the LHC has constantly been improved to achieve higher luminosities and to potentially reach the design center-of-mass energy of 14 TeV. With the intention of using the LHC to its full potential and further examining the Standard Model and its extensions, the next major upgrade, the High-Luminosity LHC (HL-LHC), is planned. The necessary upgrades to the LHC and the detectors are already being developed and will be installed in the Long Shutdown 3 (LS3) after Run 3. From 2027 onwards the LHC is then expected to reach a peak instantaneous luminosity of $5.0 - 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. This results in an estimated integrated luminosity of 300 fb^{-1} per year, so that by its scheduled end in 2035 the LHC will have collected data corresponding to an integrated luminosity of 3000 fb^{-1} , or even up to 4000 fb^{-1} in the case of maximal performance [5]. This will be achieved for example by replacing the inner magnets in the insertion regions. In order to deal with the great challenges that come with the HL-LHC, an upgrade of the subdetector systems of the CMS detector is required, which is called the CMS Phase-2 Upgrade.

2.4 The CMS Phase-2 Tracker Upgrade

In order to maintain the excellent performance under the conditions of the HL-LHC the complete tracker system needs to be replaced. The main aspects of the tracker upgrade include improved radiation tolerance, because of the higher radiation levels due to the increased particle rate of the HL-LHC, a higher detection granularity to cope with the larger pileup of up to 200 interactions per collision, and an improvement of the trigger system to enable acceptable data rates at high luminosities. Therefore new types of silicon sensors are being developed, which are then able to contribute tracking information to the L1 trigger that is currently only receiving information from the calorimeters and the muon systems [5].

The new Phase-2 tracker is divided into the Inner Tracker (IT) using silicon pixel modules and the Outer Tracker (OT) using silicon strip and macro-pixel sensors. For the OT two module types have been developed: the so-called 2S modules, consisting of two strip sensors, and the so-called PS modules, which are built up of a strip and a macro-pixel sensor. In Figure 3 a quarter of the new tracker layout can be seen with the pixel modules in the inner part and the 2S and PS modules in the outer part. The new layout also extends the detector acceptance to a pseudorapidity of $|\eta| < 4$.

The 2S modules consist of two silicon strip sensors stacked on top of each other, which enables the direct measurement of the p_T of the particles based on the track reconstruction through the hits in both sensors. The track information of particles with a high p_T will then be provided to the L1 trigger. In this thesis measurements with a 2S module prototype are being performed, thus a detailed description of this concept and the 2S module will be given in the next chapter.

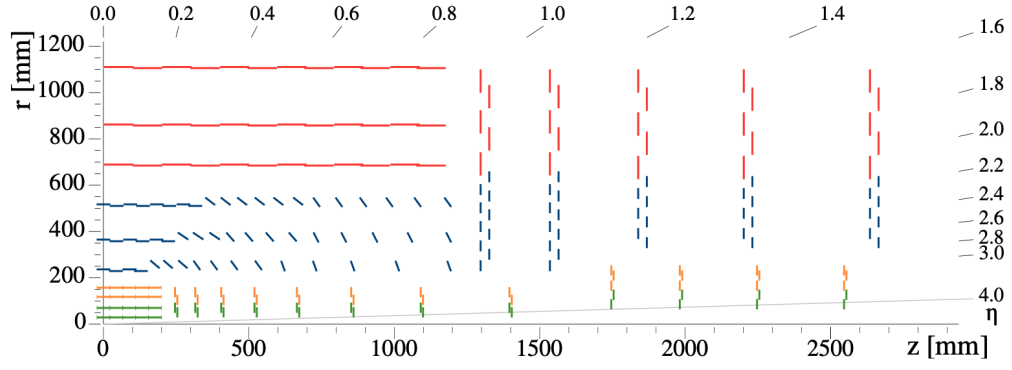


Figure 3: A sketch of the new Phase-2 tracker layout showing a quarter of the tracker in the r - z plane [5]. The pixel modules of the Inner Tracker are shown in green and yellow. The PS modules of the Outer Tracker are shown in blue, while the 2S modules are shown in red.

3 The 2S Module

The 2S and PS module represent a new type of silicon detector, a so-called p_T module, which will be used in the Outer Tracker of the CMS detector. The 2S module consists of two closely spaced n-in-p doped silicon sensors. Each sensor has two rows of 1016 microstrips with each strip having a length of 5 cm and a pitch of $90\ \mu\text{m}$. The sensors have an area of $10 \times 10\ \text{cm}^2$ with an active thickness of $290\ \mu\text{m}$. The two sensors are closely stacked on top of each other so that the rows of strips from the top and bottom sensor are parallel to each other. The spacing between the sensors is either 1.8 mm or 4.0 mm, depending on the position of the module in the detector. It is provided by three Aluminum Carbon Fiber spacers (AlCF bridges) that keep the two sensors apart [5]. Figure 4 shows a CAD drawing of the 2S module. The black lines on the top sensor illustrate the orientation of the silicon strips on the sensor.

The sensor is read out by two front-end hybrids, FEH 0 and FEH 1. Each front-end hybrid is equipped with eight CMS Binary Chips (CBC) and one Concentrator Integrated Circuit (CIC). Each CBC is in total connected to 254 strips, 127 strips of the top and 127 of the bottom sensor. The strips are connected via wire bonds to the front-end hybrids and are read out by the CBCs. The data from the CBCs are then collected by the CIC on each side and send to the so-called service hybrid (SEH). The service hybrid is placed at one side of the sensor and provides the necessary electronics for the power supply and readout of the module. It consists of the Low-Power Gigabit Transceiver (LpGBT) [15] that receives the data from both CICs and sends them to the Versatile TRansceiver plus (VTRx+), which converts the data into an optical signal. Via an optical fiber these signals are transmitted to the back-end. In addition, there are two DC-DC converters [16] placed on the SEH that convert the input voltage of about 11 V to the required voltages of 2.55 V for the VTRx+ and 1.25 V for the CBCs, CICs and the LpGBT [5].

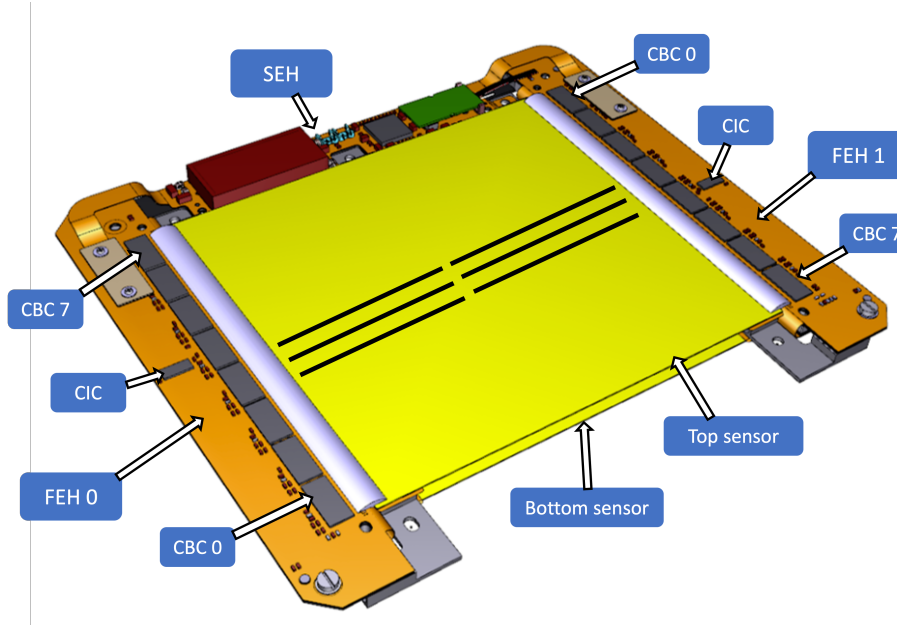


Figure 4: CAD drawing of the 2S module of the Outer Tracker, with major components labeled. The drawing is updated from Ref. [5]. The black lines illustrate the orientation of the silicon strips on the sensor.

3.1 General Concept of the p_T Module

The concept of the 2S module enables the contribution of tracking information of interesting events, namely events containing high p_T tracks, to the L1 trigger. The readout chips of the module can select tracks from charged particles above a certain p_T threshold based on the correlation of hits in the top and bottom sensor of the module. The principle behind this can be described as follows. The trajectories of charged particles are bent when entering the magnetic field of the detector, so that particles with a low transverse momentum have a stronger curved trajectory than particles with a high transverse momentum. When the particles pass through the 2S module, strips are hit in the top as well as in the bottom sensor, creating hit pairs. That way, parts of the particle tracks are reconstructed. Based on the hit in the bottom sensor an acceptance window of strips opens in the top sensor. If the hit in the top sensor is then compatible with this window, the corresponding tracking information, which is a part of a high p_T particle track, is sent out to the L1 trigger as a so-called stub. Particles with a low transverse momentum generate hits outside the window and are therefore rejected by the module, meaning their tracking information will not be provided to the L1 trigger. This mechanism is illustrated in Figure 5, where the left particle track corresponds to an accepted stub while the right particle track is outside of the acceptance window in the top sensor and will therefore be rejected. The size of the acceptance window can be programmed but is limited to a maximum window size corresponding to a p_T -threshold of 2 GeV. This enables to reduce the amount of data that needs to be sent out at 40 MHz under the operating conditions of the HL-LHC. From the stubs tracks are reconstructed offline using powerful electronic boards. The L1 trigger combines the tracking information with the information from the calorimeters and the muon system. When a L1 trigger accept signal is issued, the complete tracking information is read out [5].

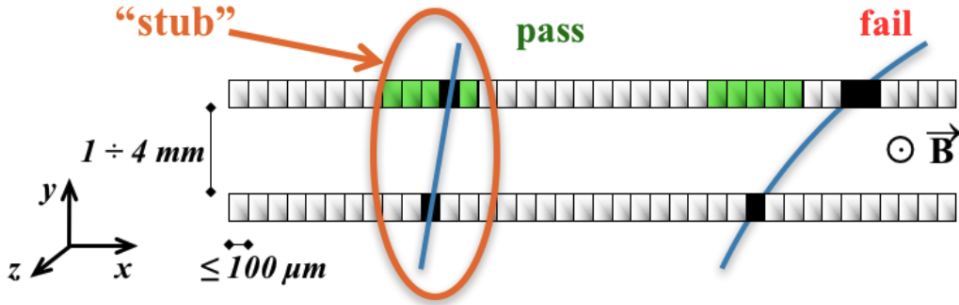


Figure 5: Sectional view of the two sensor layers illustrating the p_T module concept [5]. The acceptance window in the top sensor is depicted in green while the hits of the particles are depicted in black. The left particle track corresponds to an accepted stub while the right particle track is rejected.

3.2 The CMS Binary Chip

The CMS Binary Chip (CBC) is responsible for the readout of the micro-strips of the 2S module. It is bump bonded onto the front-end hybrid and connected to 127 silicon strips of each sensor, resulting in a total of 254 connected strips per CBC. Since each FEH has eight CBCs, one side is connected to a total of 2032 channels. The order of the channel numbers is arranged in such a way that the odd numbered channels are connected to the strips of the top sensor while the even numbered channels are connected to the bottom sensor. A layer swap can be programmed which switches the channel numbering for example for modules that are mounted top down in the detector.

The following paragraph describes the main circuit blocks of the CBC that are important regarding the processing of the hit data, as illustrated in Figure 6. Every channel has a pre- and post-amplifier and a comparator that converts the deposited charge in the silicon strips to binary hit data, meaning it either generates a 'hit' or 'no hit' signal. This happens in the hit detect stage. After that the raw hit data takes two paths. On the first one the hit data directly go into the deep pipeline memory. On the second path the hit data pass through the stub finding logic of the CBC in order to find stubs.

In the first stage of the latter path the chip performs a channel swap if programmed and then adds hits from the neighboring CBCs, so that also particles that produce hits in the border region of two CBCs can be detected as stubs. The second stage is the Cluster Width Discrimination where clusters with more than four strips are rejected. A cluster is the number of neighboring strips with a hit on one sensor. In the next stage a window offset is applied to the acceptance window if programmed. The chip then looks for correlated hits in the acceptance window. In the last stage the stub data, containing the stub address and bend info, are generated. The bend info will be formatted from half strip resolution to whole-number strips. A more detailed explanation of the stub data and the bend formatting is given in the next section. The number of stubs is limited to three per bunch crossing per CBC. When more stubs occur, the ones with the lowest numbered address will be sent out and a stub overflow flag is set. After receiving the stubs from each CBC, the CIC drops the stubs with the highest bend if there are more than 16 stubs per bunch crossing. The stub data is then provided to the L1 trigger. If the chip receives an L1 trigger signal the whole hit data for this event is sent out as triggered data [17]. As a test feature of the CBC the hit data can be read out continuously with the related stub data without receiving an L1 trigger signal. This feature will be used in this thesis so that the raw hit data are constantly read out together with the stub data and can be analyzed as well as the stub data.

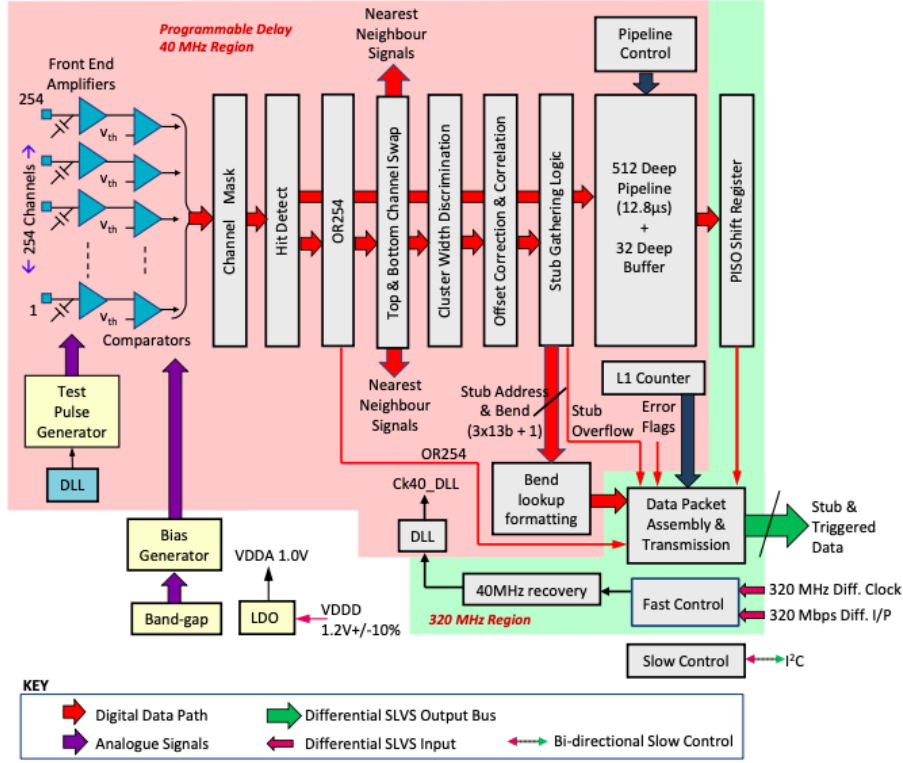


Figure 6: Block diagram of the main circuits of the CBC 3.1 design [17]. In the middle the two paths of the hit data are depicted. The long red arrow illustrates the direct path of the hit data into the pipeline memory while the short red arrows underneath show the processing of the hit data through the different steps for the generation of stubs.

3.3 Principle of the Stub Finding Logic

In the following the principle of the stub finding logic, that is applied to the hit data in the CBC, is described in more detail. Stubs are generated by the CBC out of the correlation of hit pairs. Therefore the CBC builds clusters from the hit data. A cluster is the number of neighboring strips with a hit on one sensor. Large clusters correspond to particles with large bending angle which relates to a low transverse momentum of the particle. Therefore clusters with a cluster size of five strips or more will always be rejected by the CBC. The cluster width can be programmed from 1 to 4 strips. Channels, which are not connected to the CBC because of, for example, broken wire bonds, are not able to detect hits. If a cluster falls across such a disconnected strip, it results in two smaller divided clusters, which then appear to the stub finding logic as two separate clusters. Per default the chip uses the even numbered channels as the seed layer and the odd numbered channels as the correlation layer. This setting can be switched using the layer swap.

At first the logic looks for possible clusters in the seed layer and then tries to match them to a suitable cluster within the acceptance window in the correlation layer. If there is more than one cluster in the acceptance window, the cluster with the least amount of bend is chosen, which corresponds to the particle track with the highest p_T . The acceptance window is programmable up to ± 7 strips in half strip units from the center strip. To account for the fact that the modules are not bowed but flat, the window can be shifted by an offset of up to ± 3 strips in half strip units.

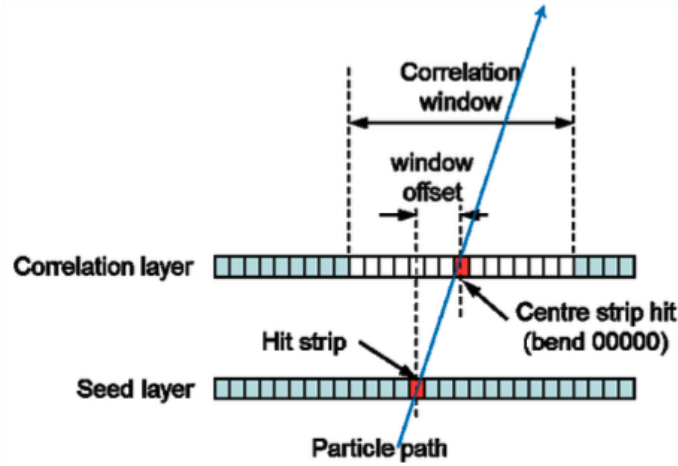


Figure 7: Illustration of the offset correction of the acceptance window in the stub finding logic [17]. If programmed the offset correction is applied to the center of the correlation window in the correlation layer illustrated in red.

This offset correction can be independently adjusted for four different regions per chip. If an offset correction is applied this means that the center strip of the acceptance window will be shifted by the value of the offset in the correlation layer. After this the stub finding logic tries to find suitable hits within the shifted acceptance window in the correlation layer. An illustration of the offset correction can be seen in Figure 7, showing the window offset from the correlation cluster to the seed cluster and the resulting acceptance window, which is shifted by the offset. In the process of finding correlated hit pairs the logic always uses the middle strip of the cluster as the strip position for the stub finding process. One important consequence is that only the middle strip of a cluster needs to be inside the window to be accepted as a suitable correlation cluster for the building of a stub. If the size of the cluster is bigger than one strip then the middle of the cluster will be calculated and serves then as the center strip in the seed layer. For odd cluster sizes there is a definite middle strip, but this is not the case for even cluster sizes. To calculate the middle strip of an even sized cluster, the half strip resolution is needed, so that the position of the middle of an cluster is given in half strip units. This indicates then that the center of the cluster is situated between two strips. Therefore, the acceptance window and offset can also be programmed with half strip resolution.

The information of a stub put out by the CBC contains the position of the center strip of the seed cluster and the so-called bend. The bend is the distance of the center of the cluster in the correlation layer to the center of the cluster in the seed layer in the number of strips. It is calculated with respect to the direction of the particle, meaning that a negative bend corresponds to a strip position of the hit in the correlation layer with a lower channel number than the hit in the seed layer, while a positive bend corresponds to a hit position with a higher channel number than the hit in the seed layer. Since the cluster position is given in half strip resolution, the bend is determined in half strip units inside the CBC logic, but is reduced to whole strip units by the CBC output formatting. The conversion of the bend from half strips to whole-number strips used by the CBC can be seen in Table 1. In conclusion, the bend contains information about the angle of the incoming particle [17].

Output bend with whole-number strip resolution	Calculated bend with half strip resolution
7	6.5, 7
6	5.5, 6
5	4.5, 5
4	3.5, 4
3	2.5, 3
2	1.5, 2
1	0.5, 1
0	0
-1	-0.5, -1
-2	-1.5, -2
-3	-2.5, -3
-4	-3.5, -4
-5	-4.5, -5
-6	-5.5, -6
-7	-6.5, -7

Table 1: Bend formatting table used in the CBC stub finding logic for the conversion of the calculated bend from half strip resolution into whole-number strip resolution.

4 Experimental Setup

4.1 Detection of Cosmic Muons with Semiconductor Particle Detectors

In this thesis, measurements with cosmic muons are used for the investigation of the stub performance of the 2S module. Therefore the following section briefly explains the working principle of silicon strip sensors and how they can detect cosmic muons.

Working Principle of Silicon Strip Sensors

The 2S module sensors consist of p-doped silicon with an active thickness of $290\text{ }\mu\text{m}$. On each sensor, two rows of n-doped capacitively coupled (AC-coupled) strips are located with a pitch of $90\text{ }\mu\text{m}$. At the p-n junction, forming at the border of the strips to the sensor, the holes of the p-doped silicon recombine with the excess electrons of the n-doped silicon producing a depletion region without free charge carriers. By applying a reversed bias voltage to the sensor, the depletion region widens and extends to the whole thickness of the sensor. If a charged particle then crosses the silicon detector it creates electron-hole pairs through ionization. The generated electric field in the silicon sensor leads to the drift of the produced electrons towards the strips creating a voltage pulse which is measured by the readout electronics. An illustration of this principle can be seen in Figure 8. When the particles cross the silicon sensor under an angle, the deposited charge distributes on the adjacent strips so that multiple strips are detecting hits, resulting in the appearance of larger clusters [18].

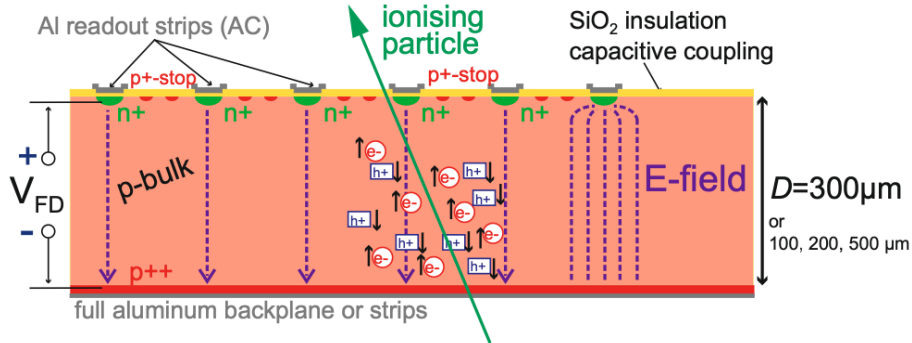


Figure 8: Working principle of a n-in-p doped silicon strip sensor. The n-doped strips are depicted in green with the readout strips in gray, while the p-doped silicon is colored in pink. The ionizing particle is illustrated by the green arrow, the created electron-hole pairs can be seen in red and blue, respectively. V_{FD} is the applied high voltage for the depletion of the silicon sensor [18].

Origin and Detection of Cosmic Muons

Cosmic rays consist mostly of high-energy protons, alpha particles and a small amount of heavier nuclei producing electromagnetic and hadronic particle showers when entering the atmosphere of the earth. These secondary particles are mainly pions that decay into muons and neutrinos. While traveling through the atmosphere, the energy loss of the muons is very low so that 80 % of the charged particles at sea level are composed of cosmic muons. The muon flux at sea level is 1 particle per cm^2 and minute through a horizontal area. The distribution of the zenith angle θ follows a $\cos^2 \theta$ -function [19].

When interacting with matter, the dominating process for charged particles is the energy loss caused by ionization, which is described by the Bethe Bloch formula. Cosmic muons are Minimum Ionizing Particles (MIPs) whose energy loss is described by the minimum of the Bethe Bloch formula. When the muons pass the silicon sensor, electrons are generated by the minimum deposited energy according to this formula [19].

4.2 The 2S Module Prototype

The measurements in this thesis were performed with the 2S module prototype M1805, which can be seen in Figure 9. It has been built by the Physics Institute 1B and 3B at RWTH Aachen University. This prototype has a spacing of 1.8 mm between the sensor layers and uses CBCs of the version 3.1, CICs of the version 2 and an SEH of the version 3.1. The used SEH is equipped with a GBTx and separate Slow Control ASIC (SCA) instead of the LpGBT and a VTRx instead of the VTRx+, but in general it has the same functionalities as described in Section 3.

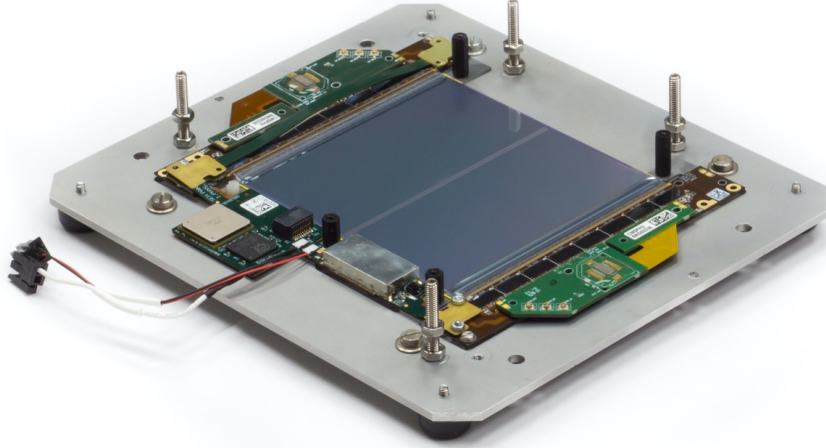


Figure 9: A picture of the used 2S module prototype M1805 [20].

4.3 Setup of the Hodoscope

For the measurement of cosmic muons with the 2S module a hodoscope consisting of two scintillators is used. The 2S module is placed between the two scintillators that are mounted onto a support frame. The module itself is mounted onto a carrier with an acrylic glass plate on top as a protective cover. The carrier with the module then lies directly on top of the lower scintillator. A true to scale sketch of the geometry of the setup next to a side view can be seen in Figure 10. The hodoscope is placed inside an aluminum box in order to shield the setup from light. To prevent condensation on the module the box is provided with a dry air supply. In addition to that an USB ventilator is placed inside the box for the cooling of the DC-DC converters on the SEH. Figure 11 shows a photo of the setup of the hodoscope inside the aluminum box.

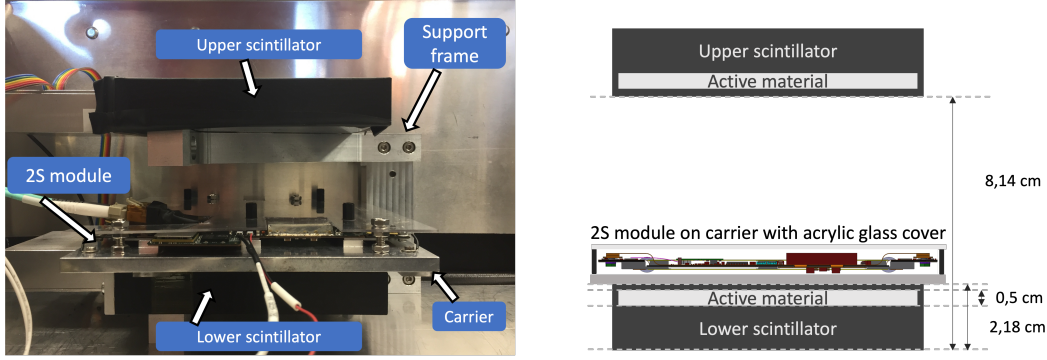


Figure 10: On the left side a photo of the side view of the hodoscope can be seen. The 2S module lies between the two scintillators that are mounted onto a support frame. On the right side a true to scale sketch of the geometry of the setup is depicted.

The power supply system is based on two units. The input voltage of 10 V for the operation of the SEH is provided by the HAMEG HMP4040 Power Supply from Rohde & Schwarz [21]. Based on previous I - V measurements, a depletion voltage of 300 V was used for the measurements to make sure that the silicon sensors of the 2S module are fully depleted. The high voltage for the sensors is provided by a 2410 SourceMeter from Keithley [22]. A picture of both power supplies can be seen on the left in Figure 12. The module is grounded with cables to the carrier. The processing of the signals from the scintillators and the generation of the trigger signal is described in the next section.

4.4 Scintillator Trigger System

For the readout of the 2S module the coincidence signal of the scintillators is used as a trigger signal. The scintillators for the hodoscope and the needed front-end electronics have been built by the Physics Institute 3B at RWTH Aachen University [23]. The scintillators consist of a plastic scintillator with a thickness of 0.5 cm and an area of 10 cm x 10 cm which are enclosed in a light tight cover. The used type is BC-404 from the company Saint-Gobain. For the readout, two silicon photomultipliers (SiPMs) from the company Hamamatsu with an active area of 3 mm x 3 mm are used for each scintillator. An APDPI (Avalanche Photo Diode Power Interface) unit provides the necessary voltage for the SiPMs. In a previous thesis [24] the voltage threshold of the scintillators has been examined and a value of 150 mV has been found as reasonable and will therefore be used for the measurements in this thesis.

For the processing of the signals a NIM crate (Nuclear Instrumentation Module) is used. The signals from both SiPMs are added for each scintillator and converted into NIM signals by a discriminator module from the type LRS-620BL from the company LeCroy [25]. The logic module LRS-622 from LeCroy then forms a coincidence signal out of the NIM signals of the two scintillators, which is used as a trigger for the readout of the module [26]. In addition to that a counter of the type N1145 from CAEN is used in the NIM crate to count the signals of the scintillators separately [27]. The coincidence signal is then converted by a converter module of the type 726 from Philips Scientific into a TTL signal. A picture of the front-end electronics in the NIM crate can be seen on the right in Figure 12.

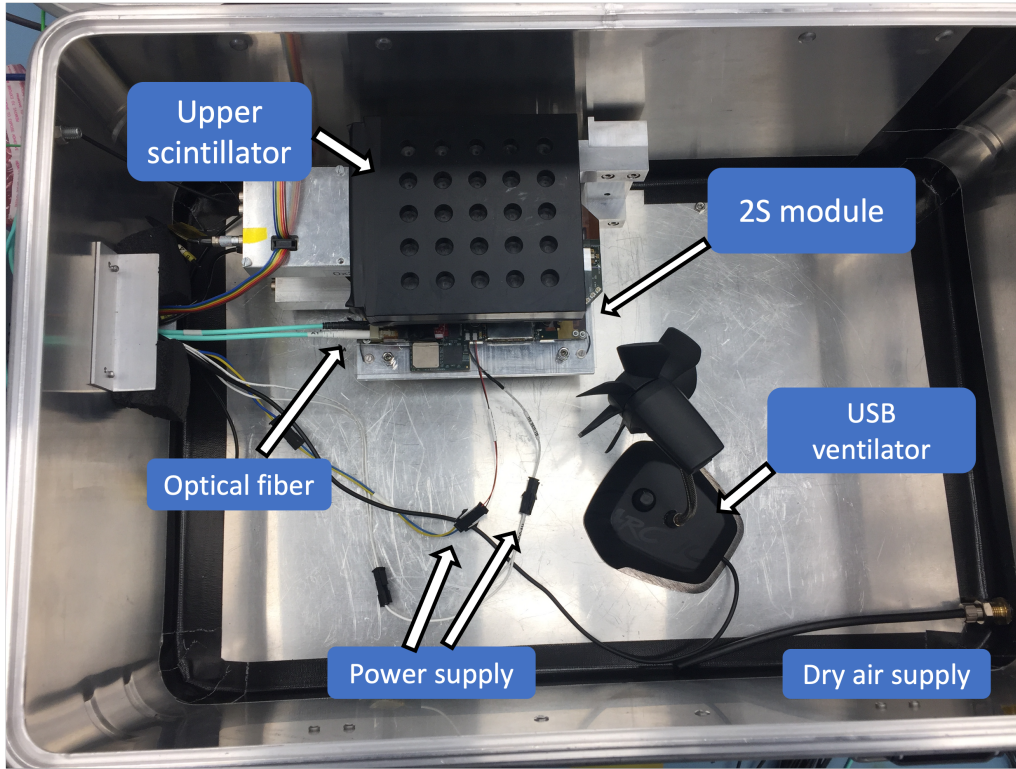


Figure 11: Overview of the setup of the hodoscope in the aluminum box.

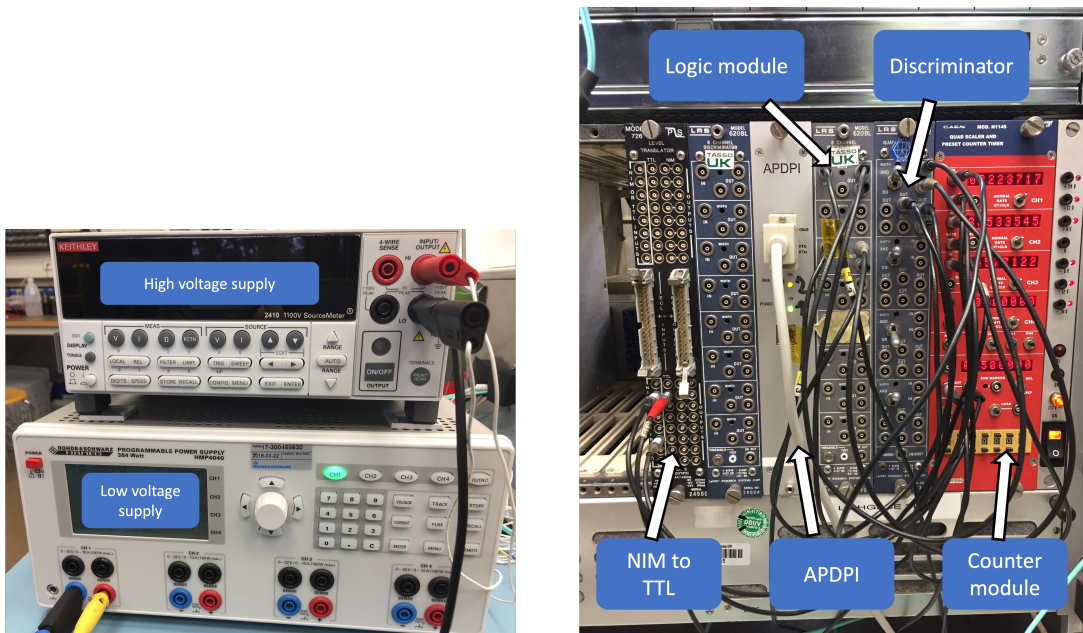


Figure 12: The left side shows a picture of the power supply system. The high voltage supply for the silicon sensors is on top of the low voltage supply that powers the SEH. The right side shows the front-end electronics in the NIM crate that are used for the readout of the scintillator signals.

For the communication and readout of the module an FC7 is used, which is an Advanced Mezzanine Card [28]. The FC7 contains a DIO5 card that receives the TTL signal from the scintillators. It is connected to the SEH of the module via two optical fibers. One fiber receives the measured data from the module and the other fiber is used to send for example the trigger signal of the scintillators to the module. The FC7 is also connected via ethernet to a computer with the readout software.

4.5 DAQ Readout System

For the readout of the module the Phase-2 Acquisition and Control Framework (Ph2 ACF) is used, which is a software framework developed by CERN [29]. For the noise scan of the module the routine "feh_2S_test" was used, while "commission" was used for latency and stub latency scans. The data readout for the actual measurements of cosmic muons is performed with a custom routine based on miniDAQ. This enables the storing of the data for each measurement in a text file. In the further analysis of the measurements the output files are processed with python.

5 Preparatory Measurements

Prior to the main measurements for the analysis in this thesis, a few preparatory measurements are necessary to calibrate the module. A noise scan, a latency scan and a stub latency scan were performed.

5.1 Results of the Noise Scan

In the CBC the deposited charge is converted into binary hit data. Each amplifier has a programmable offset V_{PLUS} to adjust any channel to channel threshold differences. A hit is detected in the comparator stage when the measured voltage pulse of the channel surpasses a defined global chip threshold, the V_{CTH} threshold, producing a digital output. Since the voltage pulse is generated by measuring the electron signal, high V_{CTH} values correspond to low physical thresholds. The voltage pulse is influenced by the Gaussian distributed noise from various sources, for example from the electronics, which can result in the false identification of noise signals as hits or lead to weak signals from particles not passing the threshold. For the useful selection of the threshold value a threshold scan is necessary. The threshold scan measures the occupancy of each channel while increasing the V_{CTH} value. The occupancy is obtained by the ratio of the number of measured noise signals per total number of events. With increasing V_{CTH} values the occupancy also increases because more and more noise signals surpass the threshold until all noise signals exceed the threshold, corresponding to an occupancy of one. The obtained curve, which can be seen in Figure 13 for one channel, can be described as a so-called S-curve and follows an error function. Without Gaussian distributed noise the curve would follow a step function. The pedestal is the threshold value that corresponds to an occupancy of 0.5. The noise is defined as the width of the S-curve and can be derived with the width parameter σ of the derivative of the error function, which is a Gaussian function [30].

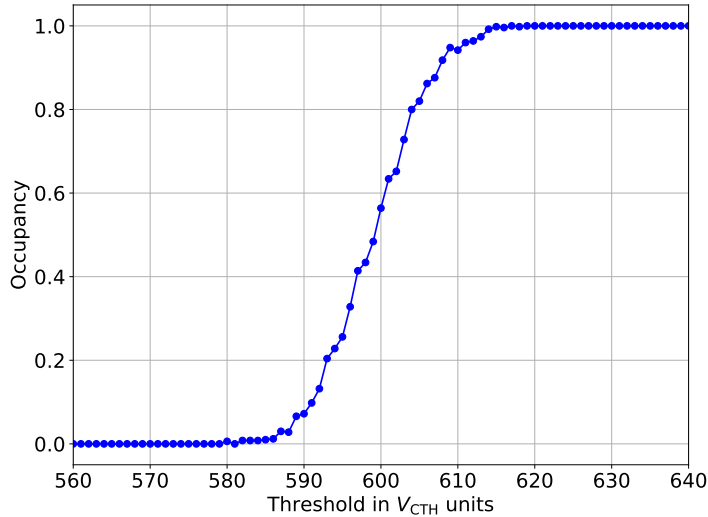


Figure 13: Measurement of a S-curve from one channel on FEH 1 CBC 4.

Before the noise measurement, a calibration routine is used to adjust the offset of each channel so that all channels have the approximately same pedestal value. After the calibration the noise and pedestal of each channel are measured for the used module. A histogram of the obtained pedestal values can be seen in Figure 14, the maximum of the distribution is at $598 V_{\text{CTH}}$ units. In Figure 15 a histogram of the measured noise is shown. The noise distribution has a maximum at approximately $6.2 V_{\text{CTH}}$ units, but there are also some strips that have a noise of 2 to $3 V_{\text{CTH}}$ units. These are strips that are not connected to the CBC anymore due to broken wire bonds, which means that these strips are not able to detect hits. To avoid the detection of noise as hit signals, the selected V_{CTH} value for the threshold should have a sufficient distance to the pedestal. For the measured pedestal of $598 V_{\text{CTH}}$ units with a noise of $6.2 V_{\text{CTH}}$ units, a threshold value of $550 V_{\text{CTH}}$ units would correspond to a distance of 7.7σ to the pedestal. Therefore a V_{CTH} value of 550 has been chosen for the measurements in this thesis.

The noise distribution per strip is shown in Figure 16 with the strips of the top sensor in red and the strips of the bottom sensor in blue. The numbering of the strips in this figure begins with the CBCs of FEH 0, starting at CBC 0 and ending at CBC 7, whose last strip corresponds to the strip number 2031. The numbering then continues with CBC 0 on FEH 1 and ends at CBC 7 on FEH 1. The channels of the bottom sensor generally have a higher noise than those of the top sensor, because of the longer traces on the front-end hybrid for the bottom sensor channels. Most of the strips have a noise of approximately $6 V_{\text{CTH}}$ units, but in the middle region, which corresponds to strips at the end of FEH 0 and the beginning of FEH 1, there are a lot of disconnected strips closely located next to each other.

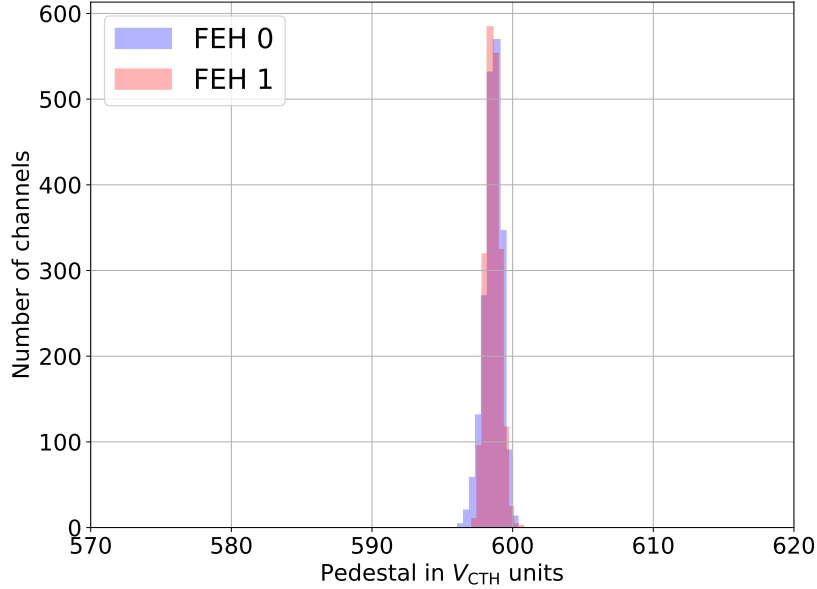


Figure 14: Histogram of the pedestal of all strips from FEH 0 in blue and FEH 1 in red.

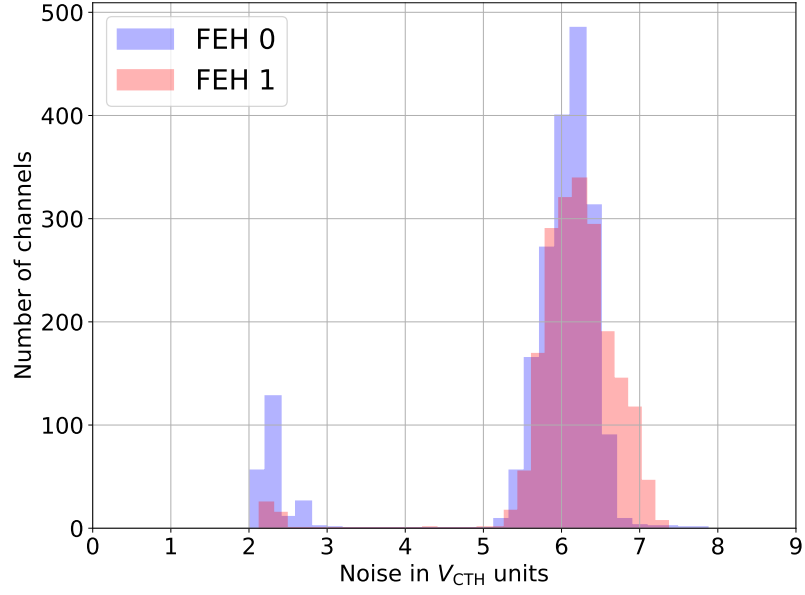


Figure 15: Histogram of the noise of all strips from FEH 0 in blue and FEH 1 in red.

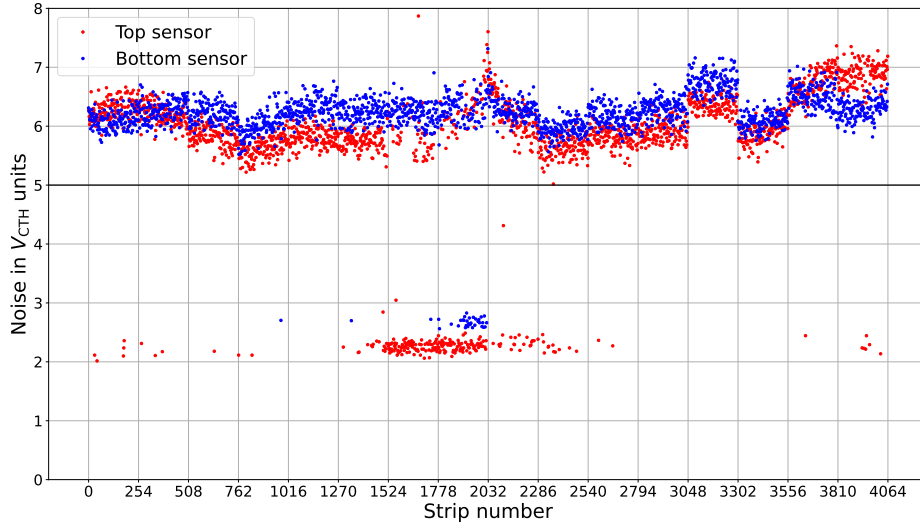


Figure 16: The noise distribution per strip with the strips of the top sensor in red and the bottom sensor in blue. The numbering of the strips begins with the CBCs on FEH 0, in the order from 0 to 7, and then continues with the CBCs on FEH 1 in the same order. Even numbered strips correspond to the bottom sensor while odd numbered strips correspond to the top sensor.

Since stubs contain also the bend information of the particle track, this can lead to a bias in the detection of particles so that only specific tracks given by the location of the remaining connected strips are measured. To prevent this, the percentage of disconnected strips per CBC is calculated using a V_{CTH} value of 5 as the upper limit for the noise of a disconnected strip. The derived percentages of the number of disconnected strips per CBC can be seen in Table 2. CBCs with more than 4% disconnected strips will not be used in the analysis of the stub data. These are the CBC 5, 6 and 7 on FEH 0 and CBC 0 and 1 on FEH 1. This criterium has been applied to the CBCs in this thesis based on the grading system for the pixel modules in the CMS Phase-1 upgrade. In the quality assurance process of this upgrade pixel modules with more than 4% defective pixels were not used for the detector [31].

Percentage of disconnected strips per CBC and FEH		
CBC	FEH 0	FEH 1
0	1.97 %	8.27 %
1	1.18 %	4.33 %
2	0.39 %	0.79 %
3	1.18 %	0 %
4	0 %	0 %
5	6.69 %	0 %
6	34.65 %	0.39 %
7	42.13 %	2.36 %

Table 2: Overview of the percentage of disconnected strips per CBC for both FEHs.

5.2 Results of the Latency and Stub Latency Scan

The module operates at a 40 MHz clock frequency, which matches the bunch crossing frequency. Since the coincidence signal of the scintillators is used as a trigger signal for the measurement of muons with the 2S module, a time delay between the measurement of the muons and the module readout occurs. This delay has to be adjusted relative to the clock cycle so that read out events match the trigger signal. This can be achieved by performing a latency scan [32]. The latency is measured in units of the bunch crossing frequency, 25 ns, and is obtained by measuring the number of hits for a specific number of triggered events over a range of different latency values. The latency value with the largest number of hits can be identified as the correct latency value. The results of the performed latency scan can be seen in Figure 17, where 100 triggered events per latency value were used. The largest number of hits can be measured at a latency value of 94, which will be used as the latency for the following measurements. Considering that we have two data streams, the hit and the stub data, there is also a delay between the received hit data and the stub data, which has to be adjusted so that the read out stubs are matching the hit data. Therefore a stub latency scan was performed as well, which determines the stub latency value by recording the number of stubs for a specific number of triggered events for a range of different stub latency values. The value with the largest number of stubs can be identified as the correct stub latency. The performed stub latency scan can be seen in Figure 18. For this scan 100 triggered events per stub latency value were used.

Since not every triggered event results in a stub, the number of stubs measured at the correct stub latency does not match the number of triggered events. At a stub latency value of 21 the largest number of stubs were measured so that this will be used as the stub latency for the following measurements.

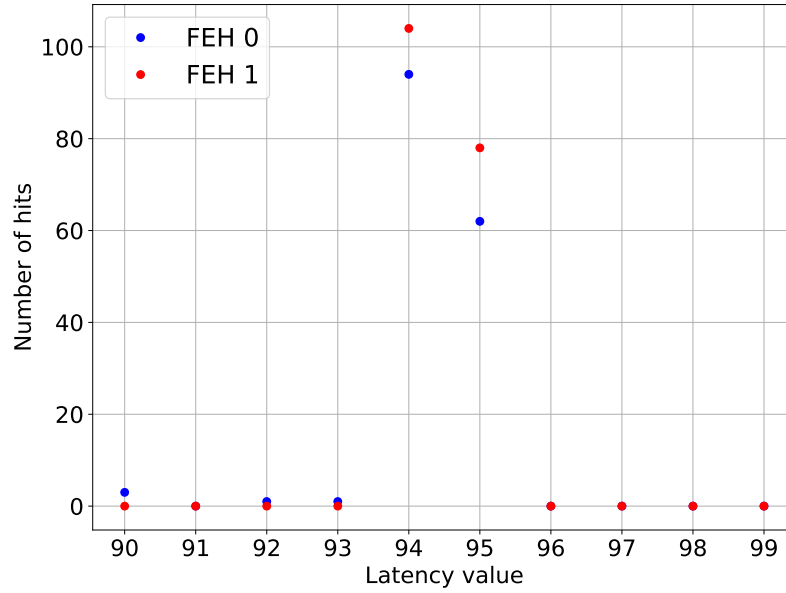


Figure 17: Result of the latency scan for both FEHs.

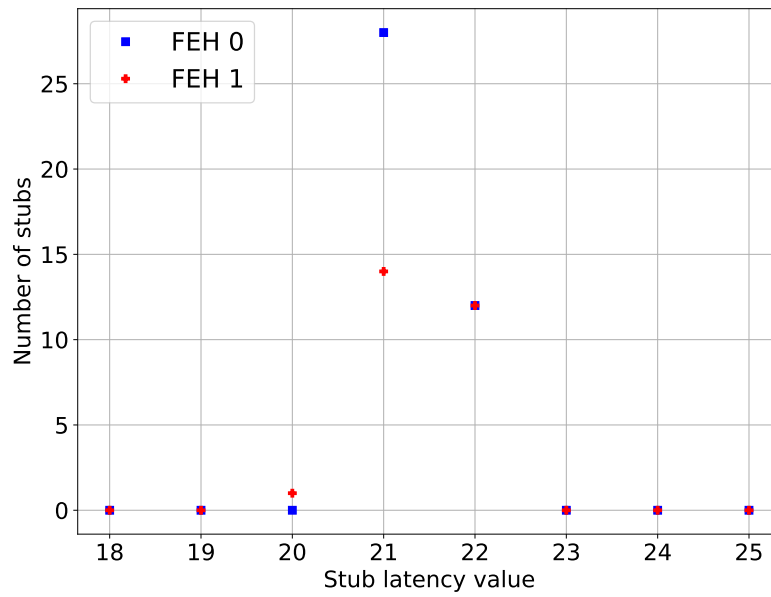


Figure 18: Result of the stub latency scan for both FEHs.

6 Measurements of Cosmic Muons

This chapter begins with an explanation of how the expected zenith angle distribution of the cosmic muons can be determined, taking the strip geometry of the used module type into account. Secondly, the data collected for each measurement are explained. After that, the measurement of cosmic muons with the module in a horizontal position between the scintillators is examined, starting with an analysis of the measured hit data and followed by an analysis of the stub data.

6.1 Expected Zenith Angle Distribution

The bend information of stubs relates to the track angle of the particles. With regard to this, it is important to consider that, depending on the bend, different solid angles are covered by the strips, which is illustrated in Figure 19. This strip detector geometry leads to the measurement of a modulated zenith angle distribution of the cosmic muons, rather than the actual $\cos^2 \theta$ distributed zenith angle.

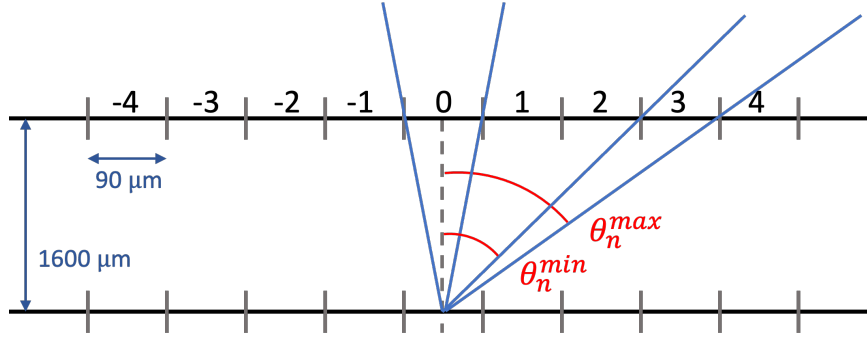


Figure 19: Illustration of the maximum covered angle by each strip. The drawn angles in orange denote the track angles at the strip edges, which are used to determine the maximum covered angle of each strip.

To estimate the expected modulated angle distribution, the following concept is used. For this only particle tracks that pass the bottom sensor in the middle of the strip at zero bend are considered. Based on this, the solid angle that is covered by the strips of each bend can be determined by calculating the minimal and maximal angles from the edges of each strip with the following equations:

$$\theta_n^{\min} = \arctan \left(\frac{(n - 0.5) \cdot 90 \mu\text{m}}{1600 \mu\text{m}} \right) \quad \text{and} \quad \theta_n^{\max} = \arctan \left(\frac{(n + 0.5) \cdot 90 \mu\text{m}}{1600 \mu\text{m}} \right). \quad (1)$$

Hereby n denotes the strip number with a strip width of $90 \mu\text{m}$, while the average distance of $1600 \mu\text{m}$ of both sensor layers is used for the distance between them. To obtain the modulated distribution for the strip geometry of the module, the $\cos^2 \theta$ function is integrated over the solid angle that is covered by each strip respectively:

$$f(n) = \int_{\theta_n^{\min}}^{\theta_n^{\max}} \cos^2(\theta) d\theta. \quad (2)$$

To estimate the modulated angle distribution for the measurements with a tilted module, each angle can be shifted by the tilt angle α of the module:

$$f_{\text{rot}}(n) = \int_{\theta_n^{\min}-\alpha}^{\theta_n^{\max}-\alpha} \cos^2(\theta) d\theta. \quad (3)$$

This angle scale shift is equal to a tilt of the module. To fit the measured data in the analysis the Equation 3 is expanded with a normalization factor β :

$$f(n, \alpha, \beta) = \beta \cdot \int_{\theta_n^{\min}-\alpha}^{\theta_n^{\max}-\alpha} \cos^2(\theta) d\theta. \quad (4)$$

By solving the integral from Equation 4 and simplifying the solution, the following function can be obtained:

$$f(n, \alpha, \beta) = \frac{\beta}{2} \cdot (\sin(\theta_-) \cdot \cos(\theta_+ - 2\alpha) + \theta_-) \quad (5)$$

with $\theta_+ = \theta_n^{\max} + \theta_n^{\min}$ and $\theta_- = \theta_n^{\max} - \theta_n^{\min}$.

This function can be used to fit the measured data, which allows to determine the tilt angle α of the measured distributions.

6.2 Data Taking and Data Format

For each measurement the results are saved in a text file, which contains information of the received trigger signal from the scintillators and the measured hit and stub data. Figure 20 shows an extract of such an output file. The beginning of an event is marked by the information that a trigger signal was received. The next lines in the output file then contain the measured hit data. If there are cluster pairs found by the CBC that fulfill the chosen stub criteria, the stub data is written directly into the next line in the output file. This can be seen in the fourth event in Figure 20 (line 16).

Type	Time	VCTH	TDC	cN	Bunch	FEH	CBC	Strip
Trigger	146.074	-	3	1	42723			
Hit	146.074	550	3	1	42723	0	0	129
Hit	146.074	550	3	1	42723	0	0	144
Trigger	148.268	-	6	2	25460			
Hit	148.268	550	6	2	25460	1	3	97
Hit	148.268	550	6	2	25460	1	3	99
Trigger	149.177	-	0	3	2470			
Hit	149.177	550	0	3	2470	1	0	34
Hit	149.177	550	0	3	2470	1	0	36
Hit	149.177	550	0	3	2470	1	0	51
Trigger	149.761	-	1	4	44471			
Hit	149.761	550	1	4	44471	1	6	42
Hit	149.761	550	1	4	44471	1	6	44
Hit	149.761	550	1	4	44471	1	6	47
Stub	149.761	550	1	4	44471	1	6	45
								0010
Trigger	151.908	-	0	5	50252			
Trigger	157.541	-	5	6	40590			
Hit	157.541	550	5	6	40590	0	4	114
Hit	157.541	550	5	6	40590	0	4	116
Hit	157.541	550	5	6	40590	0	4	141

Figure 20: Extract of an output file of a measurement. The first three events only contain hit data, while the fourth event contains hits and a stub. For the stub the bend code is additionally put out in an extra column. The fifth trigger is directly followed by a trigger signal in the next line because no hits could be measured for this event.

For the hit and stub data the text file contains the following values:

- Time: In this column the amount of time that has passed since the start of the measurement is given in seconds. It has a small offset, since the measurement of the time starts before the first scintillator signal is received.
- VCTH: In this column the threshold value for the measurement is given in V_{CTH} units.
- TDC: The TDC-phase is the phase between the internal clock of the module and the FC7, which has an eight times faster clock cycle than the module. The TDC-phase is therefore given in a range of 0 to 7.
- cN: It counts the number of events starting at 1.
- Bunch: The bunchcrossing-ID is an identification number for each event and allows to differentiate between the events.
- FEH, CBC and Strip: These three parameters denote the location of measured hits or stubs by the number of the FEH (0 or 1), the number of the CBC (0 to 7), and the hit strip number, which lies in a range of 0 to 253 within a CBC. If the strip number is an even number, this corresponds to a strip on the bottom sensor, while an odd strip number corresponds to a strip on the top sensor. For the measured stubs the bend code is additionally put out in an extra column.

For the measured stubs the location denotes the position of the seed cluster on the bottom sensor. The bend information of the stubs decodes the position of the corresponding correlation cluster in relation to the seed cluster within the stub window. This bend information is written out in a binary number and has to be converted to a decimal number, which then corresponds to the bend in units of number of strips. The detailed conversion from bend code in decimal numbers to bend in strip numbers can be found in Table A.1 in the Appendix. With this information the angle of the incoming particle track can be reconstructed. The time, V_{CTH} value, TDC-phase and the cN number are not used for the following analysis in this thesis.

A typical run for a measurement lasts about three days and yields approximately 120 000 received trigger signals. Sometimes the module receives a trigger signal from the scintillators, but does not detect any hits. This case can also be seen in Figure 20 (line 17/18), where two trigger signals are received directly one after another without hit or stub data between them. This happens for approximately 15 % of the trigger signals. The reason for this has not been further examined within this thesis. In the triggered events with hit data there are some events with missing hits in one sensor, although the readout is triggered by the coincidence signal of the scintillator, meaning that the muon passed both the top and bottom scintillator. In addition to that, events with multiple clusters on one sensor occur. The probability that two muons are measured by this setup in the time interval of 25 ns was calculated in a previous thesis [24] and is very small in comparison to the number of events with multiple clusters in the measurements of this thesis. These events with missing hits or multiple clusters appear in approximately 30 % of readout events with hits. The cause for the appearance of these events has not been further investigated in this thesis. To obtain a clean event sample for the stub data analysis, only the events that contain a single cluster in the top sensor and a single cluster in the bottom sensor are used for further analysis. For these remaining events, cluster pairs can be clearly identified.

6.3 Measurements in Horizontal Position

For this measurement, the 2S module was positioned between the two scintillators in a horizontal position, as shown in Figure 10. This will be referred to as the default position in the following.

6.3.1 Analysis of Hit Data

The number of measured hits per strip for all events for FEH 0 and 1 is shown in Figure 21. The numbering of the strips in this figure begins with the CBCs of FEH 0, starting at CBC 0 and ending at CBC 7, whose last strip corresponds to the strip number 2031. The numbering then continues with CBC 0 on FEH 1 and ends at CBC 7 on FEH 1. The figure shows the hits on both the top and bottom sensor, with even numbered strips corresponding to the bottom sensor, while odd numbered strips correspond to the top sensor. In the distribution of the measured hits it can be observed that both sensor layers detect more hits in the middle of the module, while less strips are hit in the outer areas of the module. This is the expected behavior from the geometry of this setup. There are some areas, especially on the outer right of FEH 0, which corresponds to the middle area of Figure 21, where several strips did not detect as many hits as expected. This area corresponds to the CBCs that exhibit several disconnected strips, as already recognized in the noise scan in Figure 16, which is why the strips in this area are not able to detect particles anymore. Also noticeable are a few single peaks in the area of the disconnected strips. These peaks originate from neighboring strips of disconnected ones that measure more hits than connected strips in other areas. This effect could be a result of charge sharing between the strips in areas of disconnected strips, but it has not been explored further within the framework of this thesis.

Only the events with one cluster per sensor layer are further examined. Each event of the hit data is analyzed separately, so that clusters are built offline from the number of adjacent hits. Single hits are represented as a cluster with a cluster size of one. Depending on the size of the cluster, the middle position of each cluster is calculated as specified in Section 3.3.

For these cluster pairs a correlation map is shown in Figure 22. It shows the position of the cluster pair with the position (strip number) of the cluster on the bottom sensor on the x -axis and the position of the cluster in the top sensor on the y -axis. On the left plot a red diagonal line can be seen, which confirms that most of the reconstructed cluster pairs relate to a measurement of actual muons. On the zoom-in on the right plot the number of cluster pairs per position can be observed more clearly. There it can be seen that most particles cross the sensor layers under smaller track angles, which results in the position of the cluster pair being on the diagonal.

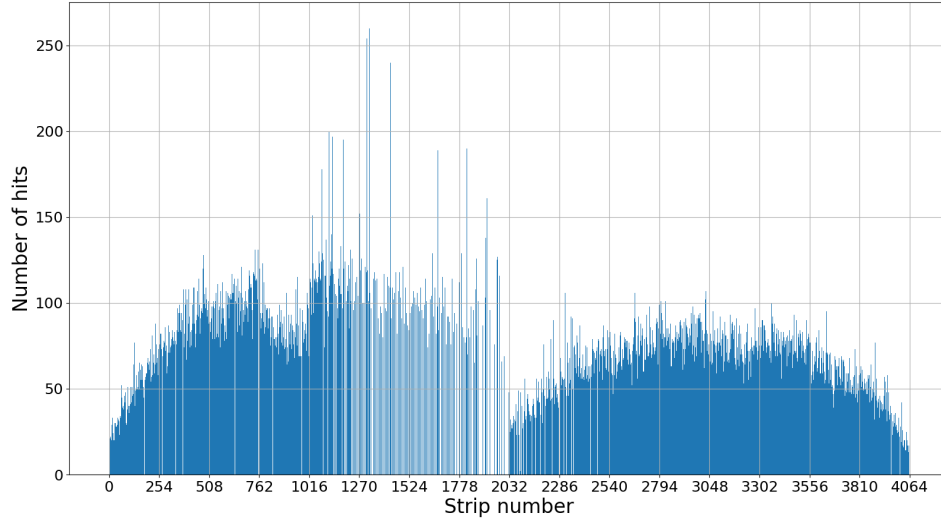


Figure 21: Hit map showing the number of measured hits per strip. The numbering of the strips begins with the CBCs on FEH 0, in the order from 0 to 7, and then continues with the CBCs on FEH 1 in the same order. The even numbered strips correspond to the bottom sensor, while the odd numbered strips correspond to the top sensor. The area between the strips 1270 and 2032 covers the CBCs on FEH 0 with a lot of disconnected strips and therefore detects less hits than the other areas.

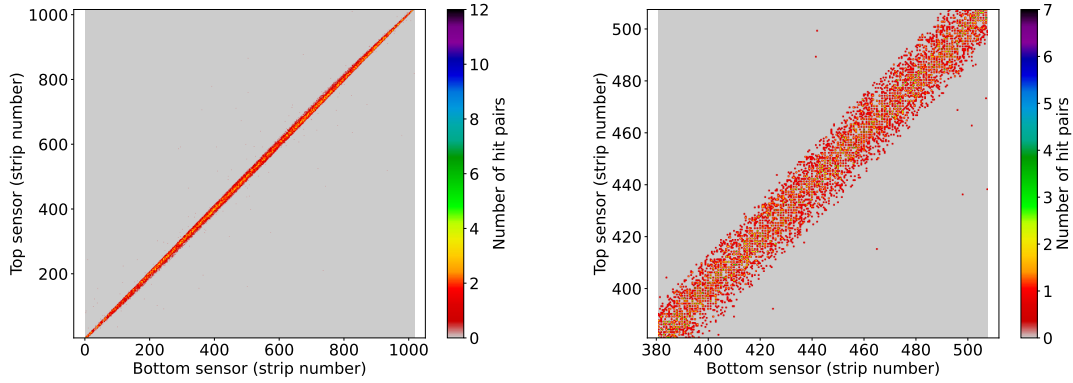


Figure 22: Correlation map of the cluster pairs that are built from events with one cluster per sensor layer for all CBCs on FEH 1 on the left, while a zoom-in on the area covered by CBC 3 of FEH 1 can be seen on the right. The number of cluster pairs per position is color coded via the scale on the right of each map.

6.3.2 Analysis of Cluster Pairs

For the reconstructed cluster pairs in the hit data, the bend between the cluster in the top sensor and the cluster in the bottom sensor can be calculated in half strip units, similar to the bend for stubs. The half-strip resolution for the bend of the cluster pairs is a result of the fact that the cluster positions are calculated in half strip units due to the appearance of cluster with odd and even numbers of hits. This means that if the bend of a cluster pair is given in half strips, it then consists of an odd sized cluster in one layer and an even sized cluster in the other layer. Consequently, a bend in whole-number strips relates to a cluster pair where both clusters are either odd or even sized.

In Figure 23 the bend distribution of the reconstructed cluster pairs in half strip resolution can be seen, showing the number of cluster pairs per bend. Both FEHs are incorporated in this distribution. Since the order of the CBCs of the FEHs is opposite to each other, see Figure 4, the same particle track with a bend of for example +3 strips on FEH 0, would result in a bend of -3 strips on FEH 1. Therefore the sign of the bend orientation from FEH 1 is adjusted, so that it matches the bend orientation of FEH 0. The cluster pairs are divided into four categories of cluster sizes in the bend distribution. Cluster pairs of one strip per cluster are blue, pairs where one cluster is one strip wide, while the other is two strips wide, are orange, pairs where both cluster pairs have a cluster size of two strips are green and lastly cluster pairs with at least one cluster having more than two strips are red.

The bend of the cluster pairs relates to the track angle of the cosmic muons. To prevent a bias in this measurement, the CBCs with a large number of disconnected strips cannot be used for this analysis, as already discussed in Section 5.1. Given that the order of the CBCs of the FEHs is opposite to each other, the excluded CBCs (Table 2) are all located at one end of the module. Only excluding these CBCs from the analysis would result in the fact that some track angles are only covered on one side of the module, while missing on the other, which would lead to another bias in the analysis. Therefore only CBC 3 and 4 from FEH 0 and 1, which are the chips connected to the strips in the middle of the module, will be considered for the examined bend distributions. The main part of the distribution in Figure 23 consists of cluster pairs with a cluster size of one. With larger bends, the cluster size of the cluster pairs increases. This is reasonable, since a larger bend corresponds to a larger track angle, which increases the probability of muons hitting more than one strip while passing the sensors. A sub-distribution, consisting mostly of orange bins, can be seen. It is mainly composed of cluster pairs with a cluster size combination of one and two strips.

Figure 24 shows a histogram of the cluster size for the depicted cluster pairs in the bend distribution with a logarithmic scaled y -axis. The histogram demonstrates that the number of clusters consisting of two strips is much smaller than the number of clusters consisting of one strip. This indicates that cluster pairs that combine two clusters consisting of one strip, happen much more often than cluster pairs with the combination of a cluster consisting of one strip and one consisting of two strips. Since the combination of even and odd sized clusters leads to a bend in half strips, these bins are less populated than those in whole-number strips. The double peak of the sub-distribution at ± 7 strips occurs because the probability of larger cluster sizes increases with a larger angle. After ± 7 strips the sub-distribution lowers to the sides because the general number of muons under large angles decreases.

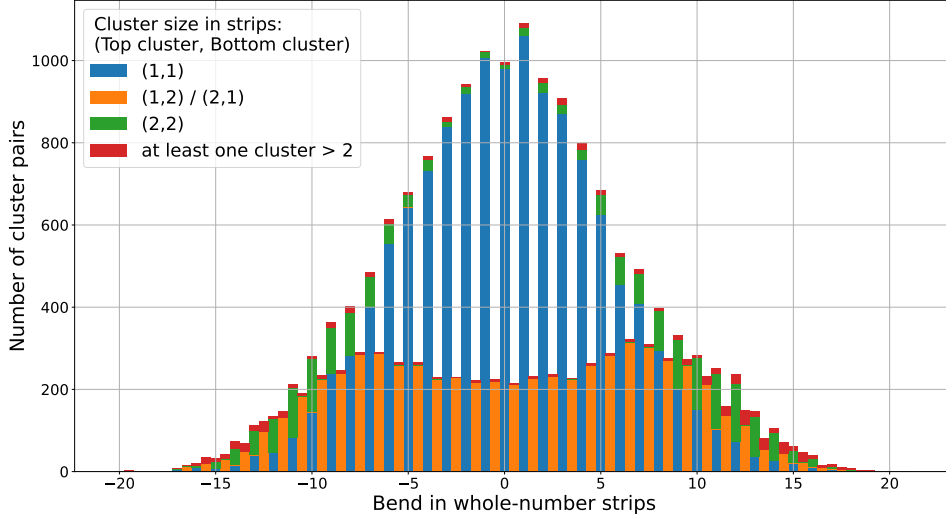


Figure 23: Bend distribution of the cluster pairs from the default measurement in half strip resolution. The colors represent the different cluster sizes of the cluster pairs. The histograms are stacked.

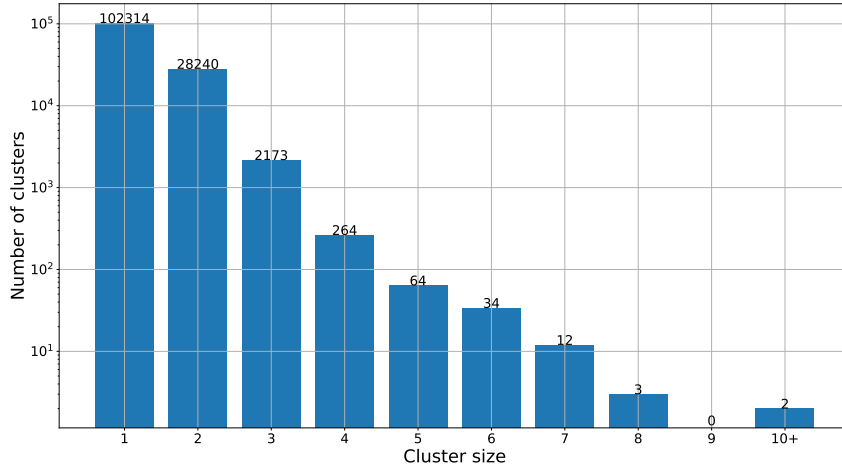


Figure 24: Histogram of the cluster sizes with a logarithmic scaled y -axis.

Figure 25 shows the same bend distribution of cluster pairs in whole-number strip units. For this the bins of the half strips are added onto the whole-number bins, in the same manner like displayed in Table 1. A dip is visible at the bin with zero strip bend, because the conversion from half strips to whole-number strips does not foresee the addition of any half strip bins to the bin at zero strips.

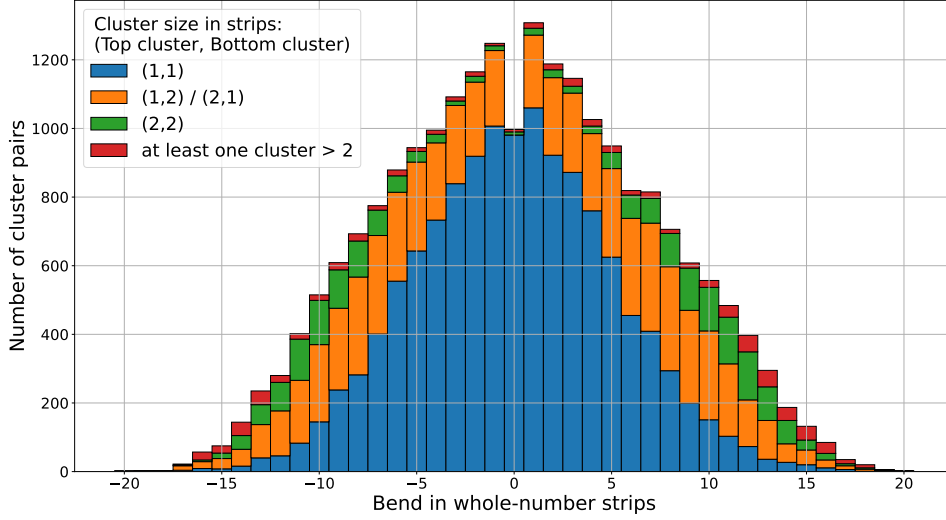


Figure 25: Bend distribution of the cluster pairs from the default measurement in whole-number strip resolution. The bend is converted from half strips to whole-number strips using the bend formatting of the CBC. The colors represent the different cluster sizes of the cluster pairs. The histograms are stacked.

6.3.3 Analysis of Measured Stub Data

In the following sections the measured stub data from the default measurement is analyzed. Beginning with this section, the bend distribution of the measured stubs is examined, followed by an offline reconstruction of stubs out of the measured hit data. This allows to determine the stub efficiency of the CBC stub finding logic by comparing the measured stubs with the offline reconstructed stubs. Lastly, an analysis of the offline reconstructed stubs is performed.

For the default measurement the following settings were used for the stub finding logic of the CBC: a stub window size of ± 7 strips, an offset of zero strips and a cluster width limit of four strips. For the stub analysis, the same criteria are applied to the data as for the analysis of the cluster pairs, meaning that only events with a single cluster on the top and bottom sensor (from CBC 3 and 4 on each side) are considered. As a consequence only one stub per event is possible. The bend of the measured stubs is given in whole-number strips as explained in Section 3.3. Figure 26 shows the number of measured stubs per bend in whole-number strips for both FEHs. Since the data from both FEHs is shown, the bend orientation of FEH 1 is adjusted as in the analysis of cluster pairs. The plot shows in general the expected distribution. The smaller bin at zero strips is again a result of the conversion to whole-number strips of the bend formatting in the CBC. Since the bend information of the stub data corresponds to the track angle of the particle, the function 5 can be fitted to the bend distribution. By determining the value of the parameter α , it can be examined if the data follow the expected modulated zenith angle distribution for a horizontal orientation of the module. The performed fit of the data can be seen in blue in Figure 26. For the fit the statistical uncertainty per bin is considered, which is calculated as the square root of the number of stubs per bin.

For this measurement a tilt of the module of

$$\alpha = (0.65 \pm 0.37 \text{ (stat)})^\circ$$

was determined from the fit to the data. The expectation for an angle of $\alpha = 0^\circ$ was calculated using Equation 4 and can be seen in red in Figure 26. It is normalized using the same parameter β from the fit to the data. In the following analyses the expectation will always be normalized with the same parameter β from the fit, respectively.

The measured bend distribution follows the expectation for a horizontal orientation of the module. In consideration of a small possible unevenness of the setup in the aluminum box, the fitted tilt angle is in agreement with the expectation within the statistical uncertainties. The high χ^2 of the fit is mainly a result of the smaller bin at zero strips, which can be clearly seen in the large variation of the value in the residual plot. The systematic deviation visible in the residual plot can be explained based on the fact that a rather simplified model is used to fit the data. There are numerous aspects, for example the unknown matter distribution of the building above the setup or the trigger acceptance of the two scintillators, that possibly affect the angle distribution of the cosmic muons and have not been taken into account. A consideration of these factors has not been possible, but for the analysis in the framework of this thesis the model of the expected angle distribution provides a useful base.

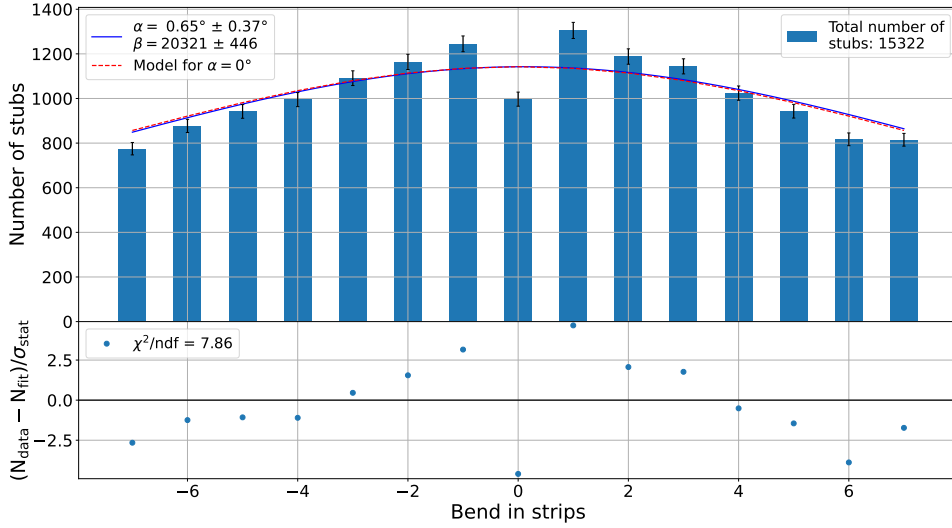


Figure 26: Bend distribution of the measured stubs from the default measurement showing the number of stubs per bend in whole-number strips. The statistical uncertainty per bin is calculated as the square root of the number of stubs per bin. The fit, applied to the data, can be seen in blue with the residual plot below. The dashed red line marks the expected angle distribution.

6.3.4 Stub Efficiency

The stub data are produced by the stub finding logic of the CBC from the measured hit data. In the following the measured stubs are referred to as online stubs. In the CMS detector the stub data are used in the L1 trigger decision, hence it is crucial that the stubs, found by the CBC, are generated correctly. To verify the functionality of the CBC stub finding logic, an algorithm for the offline reconstruction of stubs, based on the measured hit data, was implemented. The offline reconstruction is based on the same principle as the CBC stub logic, which was explained in Section 3.3. By comparing the offline reconstructed stubs, referred to as offline stubs, with the online stubs generated by the CBC, it is possible to determine the stub efficiency.

For the stub efficiency the hit data of events with one cluster per sensor layer of all CBCs from both FEHs were used. By analyzing the hit data event by event, the offline stubs can be assigned to the events by using the bunchcrossing-ID of the event. By comparing the stub position, the bend and the bunchcrossing-ID of the online and offline stubs with each other, the ratio of the online stubs generated by the CBC and the offline stubs can be calculated. This enables to detect specifically if the CBC missed stubs that could be reconstructed offline, or if it created fake stubs that cannot be reconstructed based on the hit data.

For the default measurement the stub efficiency per bend can be seen in Figure 27. It shows that a stub efficiency of 1.0 was determined for each bend. This means that each online stub can be reconstructed based on the measured hits by the applied offline algorithm and no additional offline stubs were found. The stub efficiency of 100% for this measurement indicates that the stub logic of the CBC works correctly for the used settings of stub window size, offset and cluster width for events with one cluster per sensor layer. This is an important result regarding the stub performance of the module in the detector.

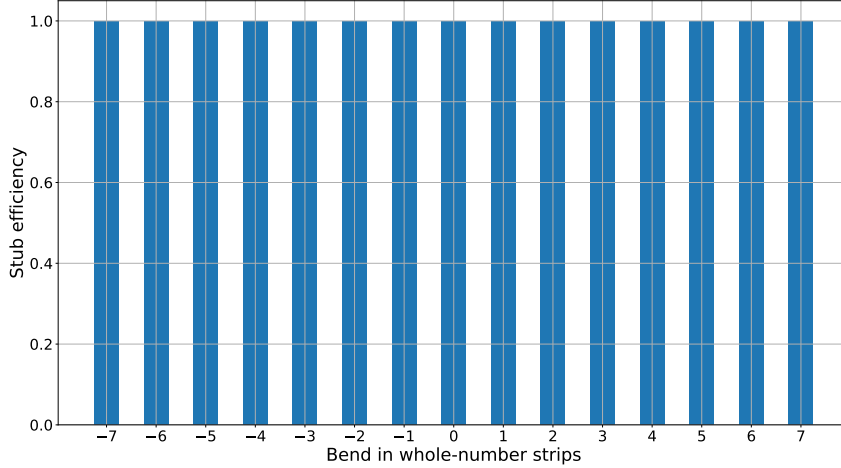


Figure 27: Stub efficiency for the default measurement. It shows the ratio of online to offline stubs per bend. For this measurement a total number of 50 263 stubs have been found online and offline, respectively.

6.3.5 Analysis of Reconstructed Stubs

The offline reconstructed stubs are used to improve the fit of the bend distribution from Section 6.3.3 regarding the smaller bin at a bend of zero. In the offline reconstruction process the bend of the stubs is calculated in half strips at first, before applying the bend formatting used by the CBC stub logic (Table 1) to convert the bend into whole-number strips. Since the smaller bin at a bend of zero is a result of this conversion convention, the offline stubs can be used to improve the fit by re-binning the distribution. For the re-binning the following approach is applied. The bend of the offline stubs is calculated in half strips. The bins at half strip units are then split in half, so that each half is added to its left and right bin, respectively. This approach leads to the correction of the smaller bin at zero bend caused by the original bend formatting method. Now the bin at zero bend is also partly composed of stubs with a bend in half strips. The re-binned bend distribution of the stubs can be seen in Figure 28. The same fit as for the original bend distribution was now applied to this re-binned distribution. Since the bins at ± 7 strips are the outer bins of the stub window, they only receive one half of a bin with a bend in half strips with this method. Therefore these bins are not considered in the applied fit of the re-binned distribution. The fit can be seen in blue in Figure 28, while the expected angle distribution is shown in red. For the re-binned distribution a tilt of

$$\alpha = (0.45 \pm 0.36 \text{ (stat)})^\circ$$

was determined by the fit to the data. This is even better compatible with the expectation of $\alpha = 0^\circ$ within the statistical uncertainties. Lastly it can be clearly seen that the re-binning of the distribution corrects the smaller bin at zero strips and therefore reduces the χ^2 . To conclude, this re-binning method will be used for the analysis of the bend distribution of stubs for the following measurements.

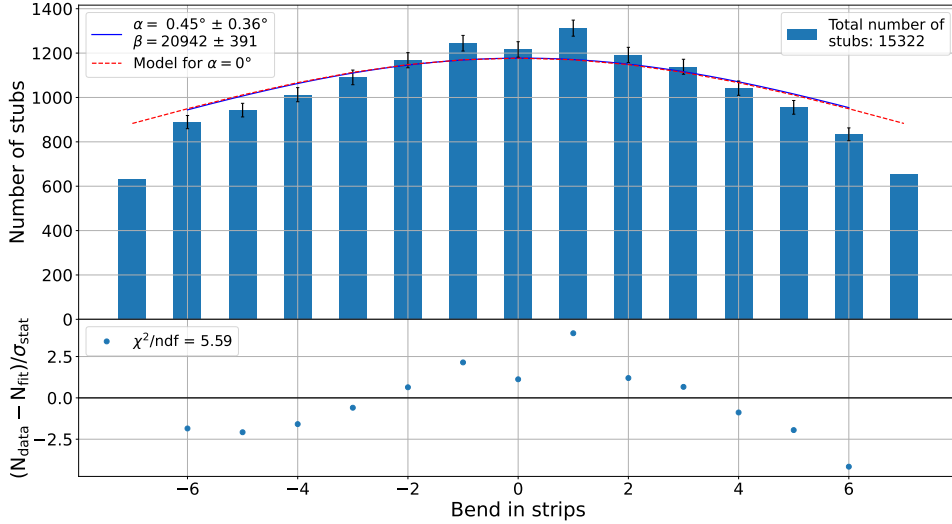


Figure 28: Re-binned bend distribution of the stubs from the default measurement showing the number of stubs per bend in whole-number strips. The statistical uncertainty per bin is calculated as the square root of the number of stubs per bin. The fit, applied to the data, can be seen in blue with the residual plot below. The dashed red line marks the expected angle distribution.

7 Measurements of Cosmic Muons with a Tilted Module

With the measurement presented in the previous Chapter 6, the stub finding logic of the CBC has been examined with regard to two programmable parameters, the acceptance window and the cluster width discrimination. The third programmable parameter within the stub logic, the offset correction, has not been tested so far, as it was set to zero. In the following, measurements with a tilted module in-between the scintillators are analyzed, to examine the functionality of the offset correction in the CBC stub finding logic.

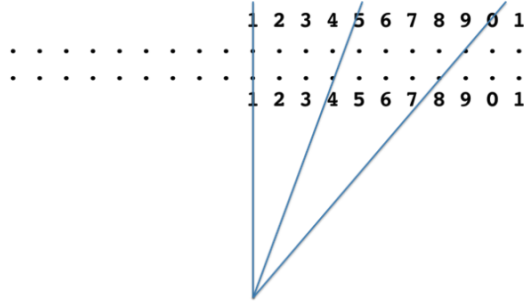


Figure 29: Illustration showing different straight trajectories passing the two sensor layers. It can be seen that the trajectories do not cross the same strips in both sensor layers in general [5].

In the CMS detector the positioning of the 2S modules around the beam axis in the Outer Tracker leads to the effect that straight trajectories do not in general pass the strips directly above each other in the two sensor layers [5]. This is well illustrated in Figure 29, where it can be seen that the outer particle tracks do not cross the same strips in both sensor layers and therefore the clusters have an offset. To account for this effect, the implementation of an offset correction in the stub logic is required, so that the center strip of the stub window can be shifted accordingly. The offset can be corrected by up to ± 3 strips in half strips independently for four different regions per chip [17].

In order to study the offset correction mechanism of the stub finding logic, the following concept is deployed: by tilting the module in-between the scintillators, it is expected that the maximum of the zenith angle distribution of the cosmic muons shifts according to the tilt angle of the module. The offset mechanism of the stub logic can then be applied to correct the shift of the angle distribution of the measured muons. This allows to investigate the offset functionality of the stub finding logic of the 2S module in this thesis within the restrictions of the setup.

At first, measurements with a tilted module are executed without applying an offset in the stub logic of the CBC. These are performed with the purpose of analyzing the effect of the tilt on the bend distribution of the measured stubs. In the following measurement, the shift of the distribution, caused by the tilt of the module, is corrected by setting an offset to the stub window in the CBC. In addition to that, by also implementing an offset correction in the algorithm for the offline reconstruction of stubs, the stub efficiency, for measurements using all three programmable parameters of the CBC stub finding logic, is determined.

7.1 Measurements in Tilted Position

A side view of the setup for the measurements with a tilted module is shown on the left in Figure 30. The tilt of the module is realized by placing the carrier, with the module on top of it, onto a lifting table. The lifting table can be seen on the left in the side view of the setup in Figure 30. The height of the lifting table is adjusted such, that the tilt angle of the module would correspond to a shift of the maximum of the bend distribution of three strips, which is approximately 9.6° . A sketch of this principle can be seen on the right of Figure 30. Therefore the height of the lifting table is calculated by using the formula

$$h = L \cdot \sin(\alpha) \quad \text{and} \quad \alpha = \arctan\left(\frac{3 \cdot 90 \mu\text{m}}{1600 \mu\text{m}}\right), \quad (6)$$

where h denotes the needed height of the lifting table and L the length of the carrier, which was measured to be $L = 15$ cm. For the calculation of the tilt angle, a strip pitch of $90 \mu\text{m}$ and an average distance of $1600 \mu\text{m}$ between the sensor layers was used. As a result, the height of the lifting table has to be adjusted to $h = 2.51$ cm. Since the lifting table is placed on the same level as the lower scintillator, the height of the scintillator has to be added to the calculated height of the lifting table.

In the following sections, two measurements with a tilted module without an offset correction are analyzed. The first measurement was performed with the module in the exact geometrical position as already described on the basis of Figure 30. The second measurement was performed with a tilt in the other direction, meaning that the module was tilted similar to Figure 30, but with an elevation on the right side. For this measurement the same tilt angle was set, which corresponds to an angle of -9.6° in the angle orientation of this setup.

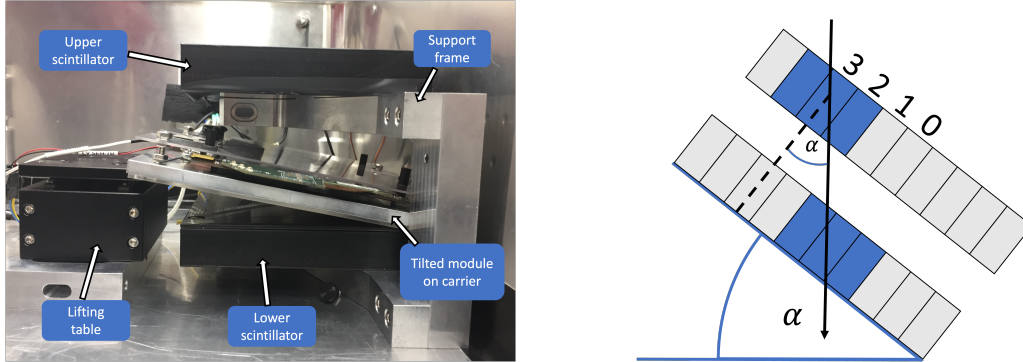


Figure 30: The picture on the left shows a side view of the setup for the measurements with a tilted module. The tilt of the module is realized by placing the carrier on the lifting table on the left. The sketch on the right shows the principle of how the bend is shifted, based on the tilt of the module corresponding to three strips.

7.1.1 Analysis of Cluster Pairs

For the analysis of the cluster pairs of the tilted measurements, only events with a single cluster in each sensor layer are considered, similar to the analysis of the default measurement. Figure 31 shows the bend distribution of the cluster pairs in whole-number strips for the first tilted measurement. Compared to the bend distribution of the cluster pairs from the default measurement in Figure 25, it can clearly be seen that the maximum of the distribution is shifted towards the positive bend direction. This confirms the expected effect of the tilt of the module on the bend distribution. In addition to that, it can be observed that the number of cluster pairs consisting of two clusters with a cluster size of two strips and the cluster pairs consisting of larger clusters are much more prominent on the right side of the distribution than on the left side. This is also an effect of the tilt of the module and emerges from the fact that larger track angles increase the probability of larger cluster sizes. The tilt leads to muons crossing the module under an even larger angle in the lifted area of the module, while the particles on the other side hit the module under a smaller angle. Consequently, the number of larger cluster sizes increases in the lifted area of the module, which corresponds to the area of positive bends in this orientation of the module.

The bend distribution of the cluster pairs for the second tilted measurements, with the tilt in the other direction, can be seen in Figure 32. It shows that the maximum of the bend distribution is shifted into the direction of the lower bends, which is the opposite direction compared to the first measurement. Additionally, the larger cluster sizes are also more prominent on the left side of the distribution. In conclusion, the bend distributions of both measurements verify that the maximum is shifted by the tilted module, which is the expected behavior.

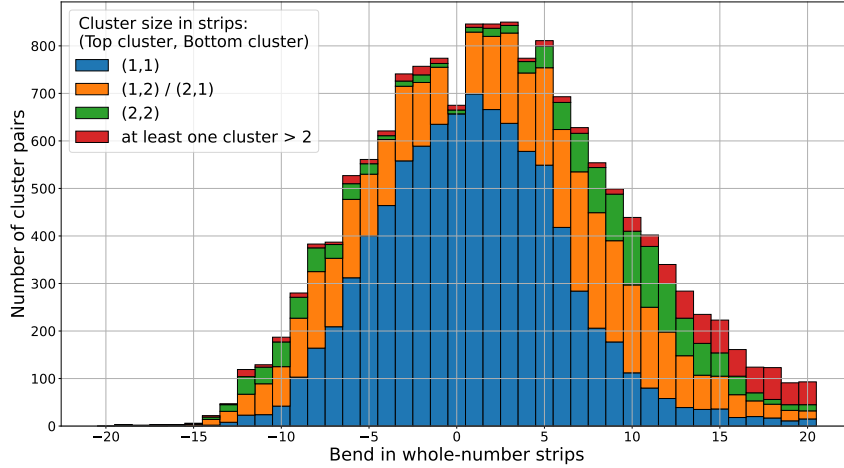


Figure 31: Bend distribution of the cluster pairs for the first tilted measurement with a tilt angle of $\alpha = 9.6^\circ$.

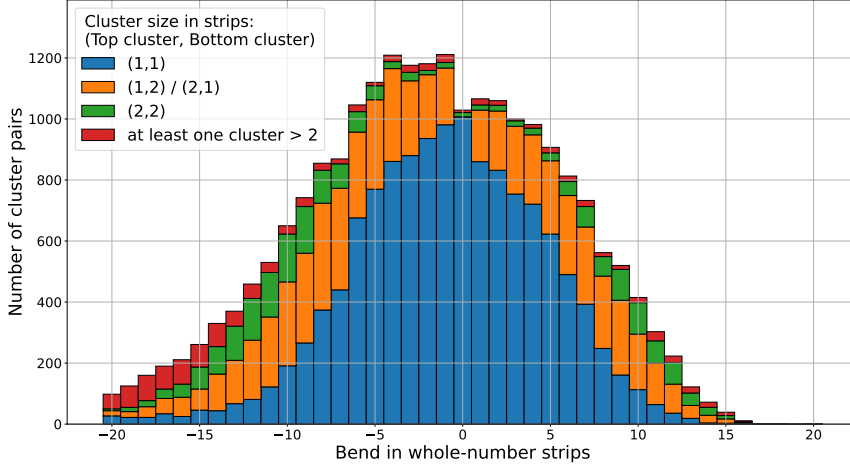


Figure 32: Bend distribution of the cluster pairs for the second tilted measurement with a tilt angle of $\alpha = -9.6^\circ$.

7.1.2 Analysis of Stubs

In order to quantify if the maximum of the measured distribution corresponds to the expectation, based on the tilt angle, the bend distribution of the measured stubs is analyzed for both tilted measurements. Using the function 5 to fit the measured data, it is possible to determine the shift angle of the bend distribution and compare it to the expectation. The bend distribution in whole-number strips for stubs for the first tilted measurement can be seen in Figure 33, using the re-binning method from Section 6.3.5 for the analysis. The fit to the data is shown in blue, while the calculated model for an angle of $\alpha = 9.6^\circ$ is shown in red. Since a tilt of $\alpha_{\text{def}} = (0.45 \pm 0.36 \text{ (stat)})^\circ$ has been determined for the measurement of stubs in the default position, the obtained angle plus its statistical uncertainty will be used as a systematic uncertainty, $\sigma_{\alpha, \text{sys}} = 0.81^\circ$, of the setup for the tilted measurements. For this distribution a tilt of

$$\alpha_1 = (14.43 \pm 0.20 \text{ (stat)} \pm 0.81 \text{ (sys)})^\circ$$

was determined by the fit of the data. Figure 34 shows the bend distribution of stubs for the second tilted measurement. The same fit was applied to this distribution. The fit to the data for this measurement determines a tilt of the distribution of

$$\alpha_2 = -(12.08 \pm 0.14 \text{ (stat)} \pm 0.81 \text{ (sys)})^\circ.$$

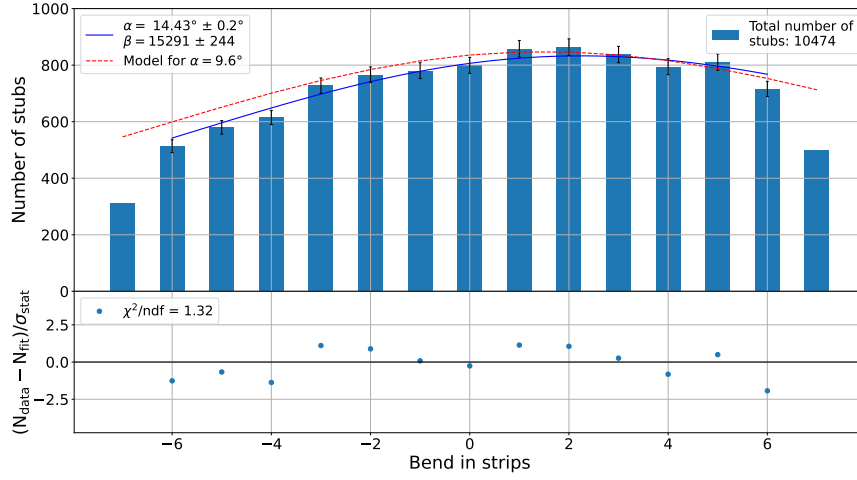


Figure 33: Re-binned bend distribution of the stubs from the first tilted measurement showing the number of stubs per bend in whole-number strips. The tilt angle of the module was adjusted to approximately $\alpha = 9.6^\circ$. The distribution expected for this tilt angle is shown by the dashed red line. The applied fit to the data can be seen in blue with the residual plot below.

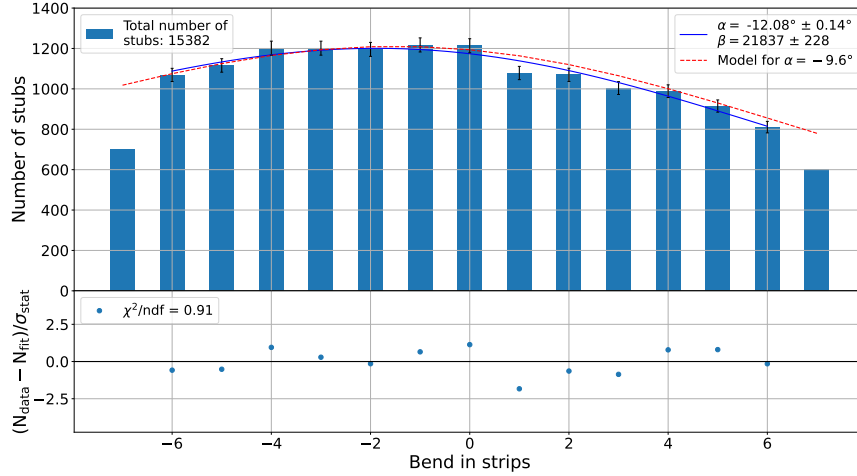


Figure 34: Re-binned bend distribution of the stubs from the second tilted measurement showing the number of stubs per bend in whole-number strips. The tilt angle of the module for this measurement was adjusted to approximately $\alpha = -9.6^\circ$. The distribution expected for this tilt angle is shown by the dashed red line. In blue the applied fit to the data can be seen, with the residual plot below.

To compare the results of both fits with the adjusted tilt angle, an uncertainty for this adjustment has to be considered. Since the tilt angle was realized by calculating the height of the lifting table and the length of the carrier, these are the sources that affect the correct adjustment of the tilt angle. The length itself can be measured very precisely, but as the contact point of the carrier on the lifting table is not located at the exact end of the carrier, it effectively reduces the length, which consequently impacts the tilt angle. Therefore an uncertainty of $\sigma_L = 4$ mm was assumed for the length. In addition to that, an uncertainty of the height was determined in consideration of the fact, that the lifting table is placed on the same level as the lower scintillator. Since the setup is placed in an aluminum box, whose ground is not totally flat, it is difficult to determine how much height has to be added to the calculated height, so that the tilt angle is adjusted correctly. Therefore an uncertainty of $\sigma_h = 5$ mm was assumed for the height. These uncertainties are applied to the tilt angle using gaussian error propagation:

$$\alpha = \arcsin\left(\frac{h}{L}\right) \quad \text{with} \quad \sigma_\alpha = \sqrt{\frac{\sigma_L^2 \cdot \frac{h^2}{L^2} + \sigma_h^2}{L^2 - h^2}}. \quad (7)$$

Based on this formula, a tilt angle of

$$\alpha = (9.63 \pm 1.96)^\circ.$$

was determined as the adjusted angle. When comparing the determined angles α_1 and α_2 from both tilted measurements to the adjusted tilt angle α of the module, it can be concluded that the measured angle α_1 is compatible with the tilt angle α within a two-sigma interval, while α_2 is compatible with the adjusted tilt angle within one standard deviation.

7.2 Measurements with Offset Correction

To test the offset correction mechanism of the CBC stub finding logic, the results from the measurements with a tilted module without offset correction can be used to determine an offset value that can be applied to correct the shift of the bend distribution caused by the tilt of the module. By analyzing the measured bend distribution of stubs with offset correction, it can be verified whether the mechanism is working as expected. The stub efficiency for the measurement with offset correction is calculated.

To determine the offset in strips that corresponds to the tilt angle of the tilted measurements, the maximum of the fit to the bend distributions was calculated. For the first tilted measurement, the maximum of the bend distribution was determined to be at a bend of 2.25 strips, while the maximum of the second tilted measurement lies at a bend of -1.88 strips. The set tilt angle of the module was calculated in such a way, that a shift of the maximum of 3 strips, or respectively -3 strips, was expected. This observation can be described as an effect of the modulation of the $\cos^2\theta$ distributed zenith angle of the cosmic muons based on the strip detector geometry and not a problem of the principle. In a nutshell, it shows that the concept, of the tilt angle corresponding to a shift of three strips of the maximum of the bend distribution, cannot be directly applied to the measurement of cosmic muons in this case.

For the measurement with a tilted module with offset correction, the geometrical configuration of the tilted module that corresponds to a tilt angle of $\alpha = 9.6^\circ$ was used. The maximum of the distribution for the tilted measurement in this configuration lies at a bend of 2.25 strips. In order to correct for this shift of the distribution, an offset value of two strips was chosen for the offset correction, which is the next suitable value, since the offset can only be corrected in half strips. The offset is applied to the stub window by adjusting the settings of the CBC to the desired offset value. The opposite orientation of the CBCs on FEH 0 and 1 has to be taken into account. Since the orientation of FEH 0 is used for the analysis of the bend distribution in this thesis, the offset value for FEH 0 has to be set to 2 strips, while the offset value of FEH 1 has to be -2 strips in the settings of the CBC. Internally, the offset value in the CBC is given in binary numbers. By filling the corresponding decimal number into the offset register in the CBC settings, the offset correction can be programmed. The conversion from the offset value in half strips to the corresponding decimal number can be found in Table A.2 in the Appendix.

7.2.1 Analysis of Cluster Pairs

The bend distribution of the cluster pairs in whole-number strips from the tilted measurement with an offset of two strips can be seen in Figure 35. With regards to the observed cluster sizes, the effect of larger cluster sizes being more prominent in the area of positive bends, similar to the bend distribution of the tilted measurement without offset from Figure 31, can be clearly observed. This is expected, since the offset mechanism only shifts the center of the stub window and does not affect the composition of the measured distribution itself. The effect of the offset can be seen when analyzing the maximum of the distribution. The distribution exhibits a maximum shifted by two strips into the negative bend direction, compared to the tilted distribution without offset. This confirms the expected behavior of the applied offset correction.

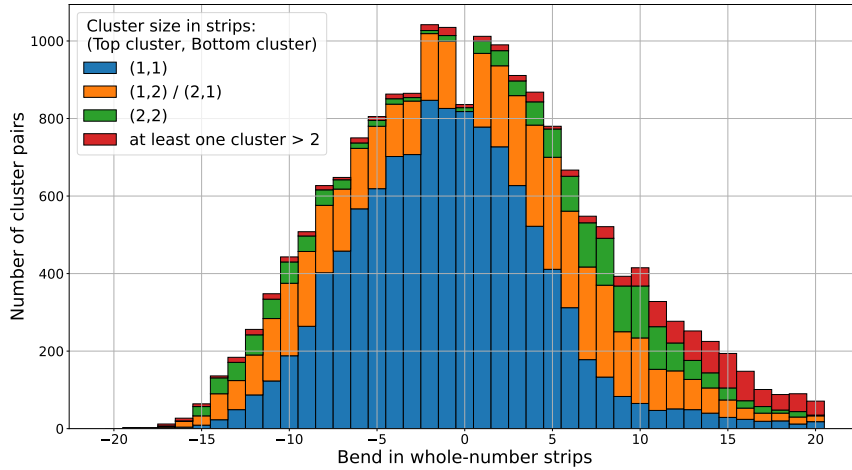


Figure 35: Bend distribution of the cluster pairs in whole-number strips for the measurement with a tilted module with an offset correction of two strips.

7.2.2 Analysis of Stubs

In order to quantify if the shifted maximum of the tilted distribution is fully corrected by the applied offset, the measured stubs are analyzed. Figure 36 shows the bend distribution of the stubs in whole-number strips for the measurement with offset correction. From the fit to the data, a tilt angle of

$$\alpha_{\text{off}} = -(1.83 \pm 0.37 \text{ (stat)})^\circ$$

was determined. Given that the exact maximum of the tilted bend distribution was in-between the possible offset values, the result is compatible with the expected angle of $\alpha = 0^\circ$. Consequently, it can be concluded that the applied offset value of two strips correctly regulates the shifted distribution, caused by the tilt of the module, according to the expectation. This is an important result regarding the use of the offset correction of the CBC in the CMS detector.

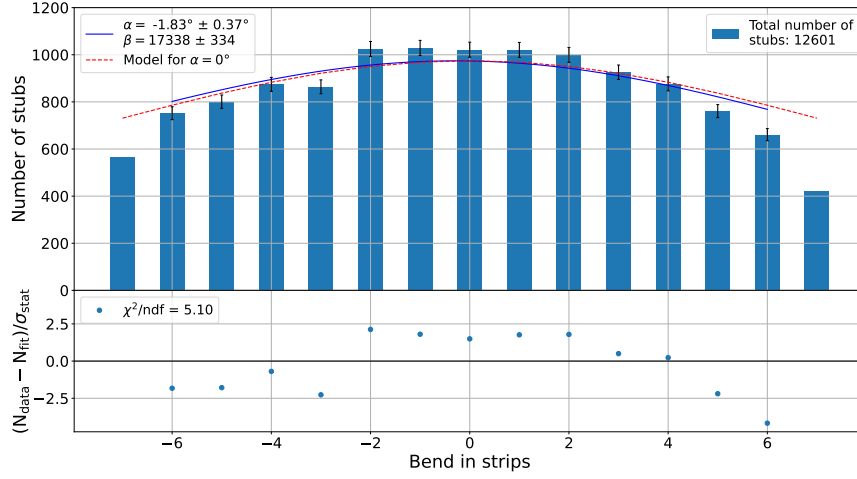


Figure 36: Re-binned bend distribution of the stubs for the tilted measurement with an offset correction of two strips. The fit to the data can be seen in blue with the residual plot below. The dashed red line shows the model for a tilt angle of $\alpha = 0^\circ$.

7.2.3 Stub Efficiency with Offset Correction

To determine a stub efficiency for the measurement with offset correction, the same offset mechanism was implemented in the algorithm for the offline reconstruction of stubs. Based on this, the obtained online and offline stubs are compared with each other, event per event, for all events with one cluster per sensor layer. For the tilted measurement with offset correction, the ratio of the stubs per bend is shown in Figure 37. For each bend, a stub efficiency of 1.0 was determined, which means that a stub efficiency of 100% was obtained for the measurement with offset correction. In accordance with the results for the stub efficiency of the default measurement from Section 6.3.4, the measurement shows that the stub logic of the CBC also works correctly when using all three programmable parameters. Since the offset mechanism will be used to correct the offset of straight trajectories in some areas depending on the position of the module in the Outer Tracker, it can additionally be used to account for any lateral shifts of the two sensor layers of the module to each other. Therefore a stub efficiency of 100%, for the used parameters in this thesis, is an important outcome to ensure a precise p_T measurement of the particles through stubs.

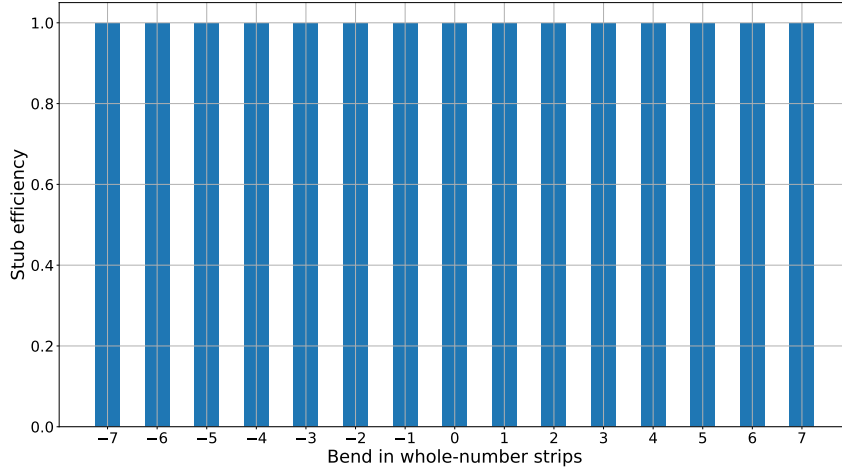


Figure 37: Stub efficiency for the tilted measurement with an offset correction of two strips. It shows the ratio of online to offline stubs per bend. For this measurement a total number of 41 995 stubs have been found online and offline, respectively.

8 Summary

In this thesis, measurements of cosmic muons with a 2S module prototype for the CMS Phase-2 Upgrade were performed. A hodoscope, consisting of two scintillators with the 2S module in-between, was employed, using the coincidence signal of the two scintillators to trigger the readout of the module. The measurements included the collection and analysis of hit and stub data in order to examine the stub performance of the 2S module. To test the stub functionality with regard to all three programmable parameters of the stub finding logic, namely the stub window size, the cluster width and the offset correction, several measurements with different geometrical configurations were performed. In addition to that, an algorithm for the offline reconstruction of stubs, based on the measured hit data, was implemented. The algorithm applies the principle of the CBC stub logic to the measured hit data, so that the stub efficiency can be determined by comparing the online and offline stubs.

The hit data of the measurement in horizontal position showed the expected hit distribution in relation to the geometry of the hodoscope. The areas with missing hits can be assigned to numerous disconnected strips based on the noise scan. For the analysis of cluster pairs and stubs, only events with a single cluster on each sensor layer were considered, because the expected rate of the cosmic muons does not fit to the number of events with multiple clusters. The bend distribution of the measured stubs was examined using a fit model that combines the strip geometry of the module with the expected $\cos^2 \theta$ distributed zenith angle of the cosmic muons. Based on the fit, the tilt angle of the bend distribution of stubs was determined. For the horizontal measurement, the obtained tilt angle was compatible with the expected angle $\alpha = 0^\circ$. By using the offline reconstruction of stubs, a stub efficiency of 100 % was calculated for the horizontal measurement. This enabled the use of offline reconstructed stubs to re-bin the bend distribution in order to correct the dip of the bend at zero strips caused by the bend formatting to whole-number strips of the CBC.

With the measurement in the default position, the stub functionality was examined with regard to a stub window size of ± 7 strips and a cluster width of 4 strips. In order to investigate the offset correction of the stub logic, measurements with a tilted 2S module were performed. For this, the tilt angle was adjusted to approximately 9.6° , which corresponds to a shift of the bend of three strips. The analysis of the tilt angle of the bend distributions of the measured stubs for the tilted measurements showed that the estimated tilt angle is compatible with the adjusted angle within the uncertainties. It was observed that the actual shift of the maximum of the bend distributions was about two strips. This is an effect of the measurement of the $\cos^2 \theta$ distributed zenith angle of the cosmic muons with the strip geometry of the 2S module.

The obtained maximum of the shifted bend distributions from the tilted measurement was used as an offset value in the offset mechanism of the CBC. The tilted measurement with offset correction showed that the applied offset value successfully corrected the shift of the bend distribution, caused by the tilt of the module. Additionally, the offset mechanism was applied in the offline reconstruction of stubs with a resulting stub efficiency of 100% for the measurement with offset correction.

In conclusion, no noticeable problems occurred in the analysis of the performed measurements regarding the stub functionality of the 2S module. For the selected events, a stub efficiency of 100% was determined.

Since the measured stubs of the 2S module will be integrated into the event selection process of the CMS detector, the results are relevant for the future operation of the module in the detector. Nevertheless, since the event selection in the analysis of this thesis limits the number of stubs per event to one, it would be important to test the stub functionality of the 2S module using a source with a higher particle rate, so that events with multiple stubs can be analyzed.

Bibliography

- [1] The CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, in: *Physics Letters B* 716 (2012), pp. 30–61, DOI: 10.1016/j.physletb.2012.08.021.
- [2] CERN, *European Organization of Nuclear Research*, URL: <https://home.cern>.
- [3] Lyndon Evans and Philip Bryant, “LHC Machine”, in: *JINST 3 S08001* (2008), DOI: 10.1088/1748-0221/3/08/s08001.
- [4] The CMS Collaboration, “The CMS experiment at the CERN LHC”, in: *JINST 3 S08004* (2008), DOI: 10.1088/1748-0221/3/08/s08004.
- [5] CMS Collaboration, *The Phase-2 Upgrade of the CMS Tracker*, CERN-LHCC- 2017-014, 2017, URL: <https://cds.cern.ch/record/2272264/files/CMS-TDR-014.pdf>.
- [6] C. Lefevre, *LHC Guide*, URL: <https://cds.cern.ch/record/2255762>.
- [7] Esma Mobs, *The CERN accelerator complex*, CERN, 2019, URL: <https://cds.cern.ch/record/2684277>.
- [8] *CMS Luminosity - Public Results*, URL: https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults#Multi_year_plots.
- [9] The ALICE Collaboration, “The ALICE experiment at the CERN LHC”, in: *JINST 3 S08002* (2008), DOI: 10.1088/1748-0221/3/08/s08002.
- [10] The ATLAS Collaboration, “The ATLAS Experiment at the CERN Large Hadron Collider”, in: *JINST 3 S08003* (2008), DOI: 10.1088/1748-0221/3/08/s08003.
- [11] The LHCb Collaboration, “The LHCb Detector at the LHC”, in: *JINST 3 S08005* (2008), DOI: 10.1088/1748-0221/3/08/s08005.
- [12] CERN, *The ALICE experiment*, URL: <https://home.cern/science/experiments/alice>.
- [13] CERN, *The LHCb experiment*, URL: <https://home.cern/science/experiments/lhcb>.
- [14] *CMS Detector Design*, URL: https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/RetrieveFile?docid=11514&version=1&filename=cms_120918_03.png.
- [15] *LpGBT Main Page*, URL: <http://lpGBT-fpga.web.cern.ch/doc/html/index.html>.
- [16] *DCDC Converter Project Website*, URL: https://espace.cern.ch/project-DCDC-new/_layouts/15/start.aspx#/index/Home.aspx.
- [17] Mark Prydderch, *CBC3.1 User Manual*, Science & Technology Facilities Council, 2019.
- [18] Frank Hartmann, *Evolution of Silicon Sensor Technology in Particle Physics*, Springer International Publishing, 2017, DOI: 10.1007/978-3-319-64436-3.
- [19] Claus Grupen, *Einstieg in die Astroteilchenphysik*, Springer Berlin Heidelberg, 2018, DOI: 10.1007/978-3-662-55271-1.
- [20] Nicolas Röwert, 2021.

- [21] *HMP Series Power Supply Fact Sheet*, URL: https://scdn.rohde-schwarz.com/ur/pws/dl_downloads/dl_common_library/dl_brochures_and_datasheets/pdf_1/Fact_sheet_-_HMP_v2.00.pdf.
- [22] *Model 2410 1100V SourceMeter Service Manual*, URL: https://download.tek.com/manual/2410_902_01B.pdf.
- [23] Simon Weingarten, “Szintillationsdetektoren mit Silizium-Photomultipliern”, PhD thesis, RWTH Aachen, 2018.
- [24] Caspar Mensing, *Messung kosmischer Myonen mit einem 2S-Modul-Prototyp für das CMS Phase-2 Upgrade*, Bachelor thesis, RWTH Aachen, 2020.
- [25] *620BL/BLP Octal Discriminator Manual*, URL: https://wwwusers.ts.infn.it/~rui/univ/Acquisizione_Dati/Manuals/LRS%20620BLP.pdf.
- [26] *NIM Model 622 Quad 2-Fold Logic Unit Manual*, URL: <https://teledynelecroy.com/lrs/dsheets/365al.htm>.
- [27] *Mod. N1145 Technical Information Manual*, URL: <https://crichard.web.cern.ch/pdf/Manual%20%20Datasheet/Caen%20MOD.%20N1145%20Scaler%20Counter%20-%20Manual%20%20Datasheet.pdf>.
- [28] *FC7 Project Home Page*, URL: <https://espace.cern.ch/project-FC7/SitePages/Home.aspx>.
- [29] Fabio Ravera, *Ph2 ACF*, URL: https://gitlab.cern.ch/fravera/Ph2_ACF.
- [30] Nicolas Röwert, *Assembly and Characterization of a First Functional 2S Module for the CMS Phase-2 Upgrade at LHC*, Master Thesis, 2018.
- [31] Martin Lipinski, “System Tests and Qualification of Pixel Modules and DC-DC Converters for the Phase-1 Upgrade of the CMS Pixel Detector”, PhD thesis, RWTH Aachen, 2019.
- [32] Stefan Maier, “Assembly and qualification procedures of 2S modules and high rate tests of the CMS Binary Chip for the Phase 2 Upgrade of the CMS Outer Tracker”, PhD thesis, KIT, 2019.

A Appendix

Bend code	Bend in strips
15	$-6.5, -7$
14	$-5.5, -6$
13	$-4.5, -5$
12	$-3.5, -4$
11	$-2.5, -3$
10	$-1.5, -2$
9	$-0.5, -1$
8	invalid
7	$6.5, 7$
6	$5.5, 6$
5	$4.5, 5$
4	$3.5, 4$
3	$2.5, 3$
2	$1.5, 2$
1	$0.5, 1$
0	0

Table A.1: Conversion of bend code into bend in strips. The bend code for stubs in the output file is given in binary numbers. To obtain the bend in strips, the bend code has to be converted from binary to decimal numbers and can then be converted to the bend in strips via this conversion table. Both values in each line of the right column are assigned to the corresponding bend code in the left column.

Code	Offset in half strips
6	6
5	5
4	4
3	3
2	2
1	1
0	No offset

Code	Offset in half strips
15	-1
14	-2
13	-3
12	-4
11	-5
10	-6

Table A.2: Conversion table for the offset value in half strips to the decimal number, which has to be filled into the offset register in the CBC settings [17].

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