

ALIGNMENT STUDY OF SCINTILLATING FIBER MODULES OF THE
SND@LHC EXPERIMENT AT CERN

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
PHYSICS

SEPTEMBER 2023

Approval of the thesis:

**ALIGNMENT STUDY OF SCINTILLATING FIBER MODULES OF THE
SND@LHC EXPERIMENT AT CERN**

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ABSTRACT

ALIGNMENT STUDY OF SCINTILLATING FIBER MODULES OF THE SND@LHC EXPERIMENT AT CERN

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September 2023, 92 pages

The Standard Model (SM) of particle physics does not supply any fundamental particles for dark matter and can not explain the baryon-antibaryon asymmetry in the Universe. Therefore new searches with new techniques are essential in high energy physics. With these motivations SND@LHC (Scattering and Neutrino Detector at the Large Hadron Collider) at CERN is proposed to search for feebly interacting particles that can be a dark matter candidate. In this thesis work, spatial alignment of the SciFi (Scintillating Fiber) modules of the SND@LHC detector is studied using the minimization software MINUIT, employing chi-square minimization method. The results of the alignment studies demonstrate that the MINUIT minimization package can be used to align the SND@LHC SciFi modules. In addition, Millepede-II package for linear least squares fits is introduced to further improve the alignment.

Keywords: CERN, SND@LHC Experiment, Chi-square Minimization, SciFi Alignment

ÖZ

CERN SND@LHC DENEYİ SİNTİLATÖR MODÜLLERİNİN HİZALAMA ÇALIŞMALARI

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Eylül 2023 , 92 sayfa

Parçacık fiziğindeki Standart Model (SM) karanlık madde için herhangi bir temel parçacık önermez ve evrendeki baryon-antibaryon asimetrisini açıklayamaz. Bu nedenle, yüksek enerji fiziğinde yeni tekniklerle gerçekleştirilecek yeni arayışlar çok önemlidir. Bu motivasyonlarla, CERN'deki SND@LHC'nin karanlık madde adayı olabilecek zayıf etkileşimli parçacıkları araştırması önerilmiştir. Bu tez çalışmasında, MINUIT minimizasyon yazılım paketi ve chi-kare minimize etme yöntemi kullanılarak SND@LHC dedektörünün SciFi (Sintilatör Fiber) modüllerinin uzamsal hizalanması incelenmiştir. Çalışma sonuçları, MINUIT minimize etme paketinin, SND@LHC SciFi modülleri uzamsal hizalanmasında kullanılabileceğini göstermiştir. Ayrıca, hizalamayı daha da iyileştirmek için doğrusal en küçük kareler yöntemi kullanan Millepede-II paketi tanıtılmıştır.

Anahtar Kelimeler: CERN, SND@LHC Deneyi, Chi-kare Minimizasyonu, Sintilatör Hizalama

To my parents, my sister, and my one true love Giray

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my thesis advisor, Prof. Dr. Ali Murat Güler, for his unwavering support and guidance throughout my academic journey. I am forever grateful for the opportunity he provided to me to be a part of the SND@LHC collaboration, which has been invaluable in shaping my research experience.

I extend my sincere thanks to the entire SND@LHC collaboration since my experience as a part of the collaboration has been incredibly enriching, thanks to the collective efforts of each member. In particular, I want to acknowledge our physics coordinator Antonia Di Crescenzo, software manager Thomas Ruf, and Antonio Iuliano from the collaboration. Antonia, you've been more than a supervisor; you've been a trusted colleague and a dear friend. Your hands-on guidance and wisdom have played a vital role in my growth as a researcher. Thomas, your extensive coding and software expertise, coupled with your willingness to guide me through challenging tasks, helped me significantly to grow as a researcher. Dear Antonio, you were always there whenever I needed help. Thank you so much for being the kindest heart and taking time for my problems.

I also want to thank the members of the METU-SND@LHC team, Onur Durhan and Eda Yaman. Onur, I am thankful for your guidance and patience during the countless errors and debugging challenges I encountered throughout my studies. My dear roommate Eda, you have been by my side throughout my master's journey, and your friendship has given me strength and joy every day. I am filled with gratitude to have you in my life.

On a personal note, my deepest appreciation goes to my dear family - my beautiful mother Şükran, my father and my hero Yavuz, and my little sister Selen. Your unwavering love, encouragement, and patience have been my rock throughout this academic journey. Your support has been my greatest motivation and I cannot thank

you enough. Words cannot describe the depth of my love and appreciation for you.

Most importantly, I want to extend my most heartfelt thanks to my beloved boyfriend Giray Önür. Your exceptional ambition and dedication have not only been an inspiration to me but also a guiding light in my life. Our eight-year journey together has been filled with moments of growth, love, and shared aspirations, and I cherish every single second of it.

In addition, I would like to thank my dear friends from the *paçito* group. Throughout my academic journey and beyond, you have been the unwavering moral support of my life. Your support, whether academic or moral, has been invaluable, and I am deeply grateful for your presence in my life.

Last but not least, I would like to acknowledge TENMAK for supporting our project with grant no. 2022TENMAK(CERN) A5.H3.F2-1, TÜBİTAK 2211 *Yurt İçi Yüksek Lisans Burs Programı* for providing me financial support through my education, and CERN for the subsistence allowance that made it possible for me to attend the SND@LHC emulsion shifts at CERN, and meet the collaboration in person.

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LIST OF ABBREVIATIONS

3D	3 Dimensional
ATLAS	A Toroidal LHC ApparatuS
CERN	The European Organization for Nuclear Research
CPU	Central Process Unit
DPMJET	Multipurpose Generator Based on the Dual Parton Model
DS	Down-stream
ECC	Emulsion Cloud Chamber
EM	Electromagnetic
FEDRA	Frame-work for Emulsion Data Reconstruction and Analysis
FLUKA	FLUktuierende KAskade simulation package
GBL	General Broken Lines
GENFIT	a Generic Track-Fitting Toolkit
GENIE	Generates Events for Neutrino Interaction Experiments
Geant	GEometry ANd Tracking framework
HT	Hough Tracking
IP1	ATLAS Interaction Point-1
LASSO	Large Angle Scanning System for OPERA
LHC	Large Hadron Collider
LFU	Lepton Flavor Universality
LXPLUS	Linux Public Login User Service
MC	Monte Carlo
METU	Middle East Technical University
MP	Millepede
SND@LHC	Scattering and Neutrino Detector at the Large Hadron Collider

SciFi	Scintillating Fiber
SHiP	Search for Hidden Particles
SiPM	Silicon Photo-multiplier
ST	Simple Tracking
TENMAK	Türkiye Enerji, Nükleer ve Maden Araştırma Kurumu
TÜBİTAK	Türkiye Bilimsel ve Teknolojik Araştırma Kurumu
US	Up-stream

CHAPTER 1

INTRODUCTION

SND@LHC is a compact, hybrid detector that can examine both electrical detector and analog emulsion data. It is distinctive among all other detectors at the LHC since it is designed to detect incoming particles with pseudo-rapidities between 7.2 and 8.4. The detector is located in the TI18 tunnel at the LHC, which is 480 *m* downstream of the ATLAS experiment (A Toroidal LHC ApparatuS) interaction point [5].

The hybrid layout of the SND@LHC detector opens a novel door granting the identification of all three flavors of neutrinos. The analog part of the detector consists of target walls that are based on the Emulsion Cloud Chamber (ECC) technique. The target walls contain successive passive tungsten plates and nuclear emulsion films, totaling 830 *kg* of target mass [5]. Each wall is followed by an electronic tracker station of scintillating fiber (SciFi) planes, that provide electromagnetic calorimetry to the detector.

Installation of the SND@LHC in the TI18 tunnel was completed during the LHC Long Shutdown-2 in 2021. The detector started taking data in the 2022 proton-physics run of the LHC and is planning to operate all through the LHC Run-3. The total integrated luminosity of 250 fb^{-1} is aimed to be collected by the SND@LHC detector during the whole LHC Run 3 [22].

For a proper analysis of the data, it is crucial to know the exact positions of each individual detector part. Thus, alignment is an important concept in the particle physics experiments in general. In this thesis work, the spatial alignment of the SciFi modules of the SND@LHC detector is studied. The MINUIT minimization package is utilized, fitting the data using the chi-squared minimization method [29].

In addition to the MINUIT package used in this thesis, a novel study of the SND@LHC SciFi alignment using the Millepede-II [12] package is introduced. The preliminary results suggest that the Millepede algorithm can further improve the alignment of the SND@LHC SciFi modules.

The structure of this thesis is as follows: Physics motivation, the detector structure, and the sub-detectors are explained in detail in the Chapter 2. The software and tools used for analyzing the data collected by the SND@LHC detector, data acquisition, and tracking are explained briefly in the Chapter 3. The alignment method is explained in the Chapter 4. The results of the implemented alignment method are discussed in the Chapter 5. The goals of the suggested alignment using the Millepede Algorithm are explained in the Chapter 6. A summary of the study and conclusions are given in the Chapter 7.

CHAPTER 2

SND@LHC EXPERIMENT

2.1 Physics Motivation

Neutrinos are the elementary particles of the Standard Model (SM) that can be vital to understanding the fundamental nature of matter and the universe. Neutrinos interact with matter strictly through the weak interaction, due to their significantly small mass and lack of electric charge, which makes it incredibly challenging to detect them. Nevertheless, neutrino studies are crucial to test the SM and peek beyond the SM for new physics [34, 9].

Proposed by the SND@LHC Collaboration¹ in August 2020, the SND@LHC experiment is dedicated to pioneering the measurements of high-energy neutrinos produced at the LHC. It can be seen from Figure 2.1 that in the current neutrino cross-section measurements, there is an unexplored region between 350 *GeV* and 10 *TeV* [22].

In the very forward region of the LHC, a notable portion of the neutrinos originate from charmed-hadron decays. SND@LHC detector is designed to investigate the heavy flavor physics within this very forward region of the LHC, and explore lepton universality in the neutrino sector [22]. SND@LHC detector started taking data in July 2022 and planning to continue during the whole LHC Run 3. The detector aims to collect a total integrated luminosity of 250 fb^{-1} in the range $7.2 < \eta < 8.4$, and measure $pp \rightarrow \nu X$ cross-section for all neutrino flavors, ν_e , ν_μ and ν_τ [5].

Proton-proton collisions at the LHC give rise to neutrino production through events such as leptonic W and Z decays, b and c decays, and subsequent pion (π) and

¹ SND@LHC Collaboration Homepage <https://snd-lhc.web.cern.ch/>

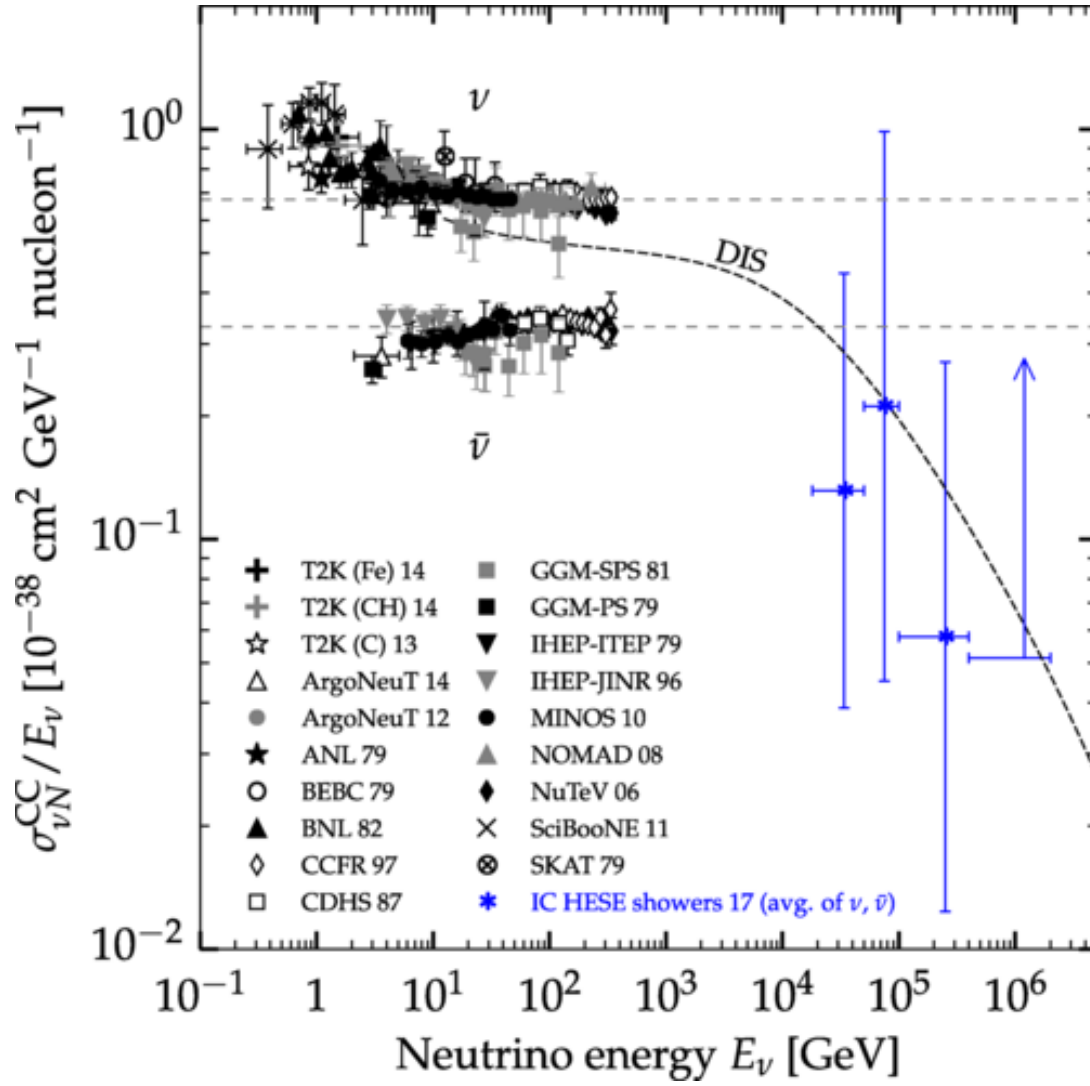


Figure 2.1: ν (and $\bar{\nu}$) - nucleon charged-current cross-section measurements at different energies [13].

kaon (K) decays [5]. Figure 2.2 shows the simulation results of neutrino ν and anti-neutrino $\bar{\nu}$ flux as a function of energy E_ν and pseudo-rapidity η for all three flavors.

In the η range of SND@LHC, an important contribution to ν_μ s and $\bar{\nu}_\mu$ s come from π and K decays, while ν_τ s and $\bar{\nu}_\tau$ s are produced particularly from heavy-hadron decays. The main ν_e s and $\bar{\nu}_e$ s sources are charmed-hadron decays, with a small contamination from low-energy K s [5].

As the LHC reached higher intensity beams, it is expected that now there is a high neutrino flux with high-energy neutrinos. Hence, even a detector that is small in size has the potential to observe neutrino interactions [5].

The main physics goals of the SND@LHC experiment can be categorized under four main headings:

- i.* Charmed-hadron production in proton-proton collisions.
- ii.* Lepton flavor universality tests in neutrino interactions.
- iii.* Measurement of the neutral-current and charged-current interactions ratio (NC/CC).
- iv.* Neutrino-induced charm production. [5, 22]

which are summarized below.

Charmed-Hadron Production in pp Collisions

The study of charmed hadrons is a crucial tool for expanding the current knowledge on the nature of quarks and the strong force. Furthermore, it can be used to test the SM of the particle physics and to search for new physics beyond the Standard Model. In the η range of SND@LHC, ν_e s and $\bar{\nu}_e$ s are primarily produced by charmed-hadron decays. Through the observation of ν_e and $\bar{\nu}_e$, SND@LHC has the potential to indirectly measure charmed-hadron production [18]. Assuming the SM predictions are valid for the deep-inelastic Charged-Current (CC) cross-section for ν_e , it is possible to study charm production using the ν_e s. The energy spectrum of the ν_e needs to be treated since it is affected by instrumental effects such as resolution and reconstruction. This treatment is called unfolding. Apart from this unfolding,

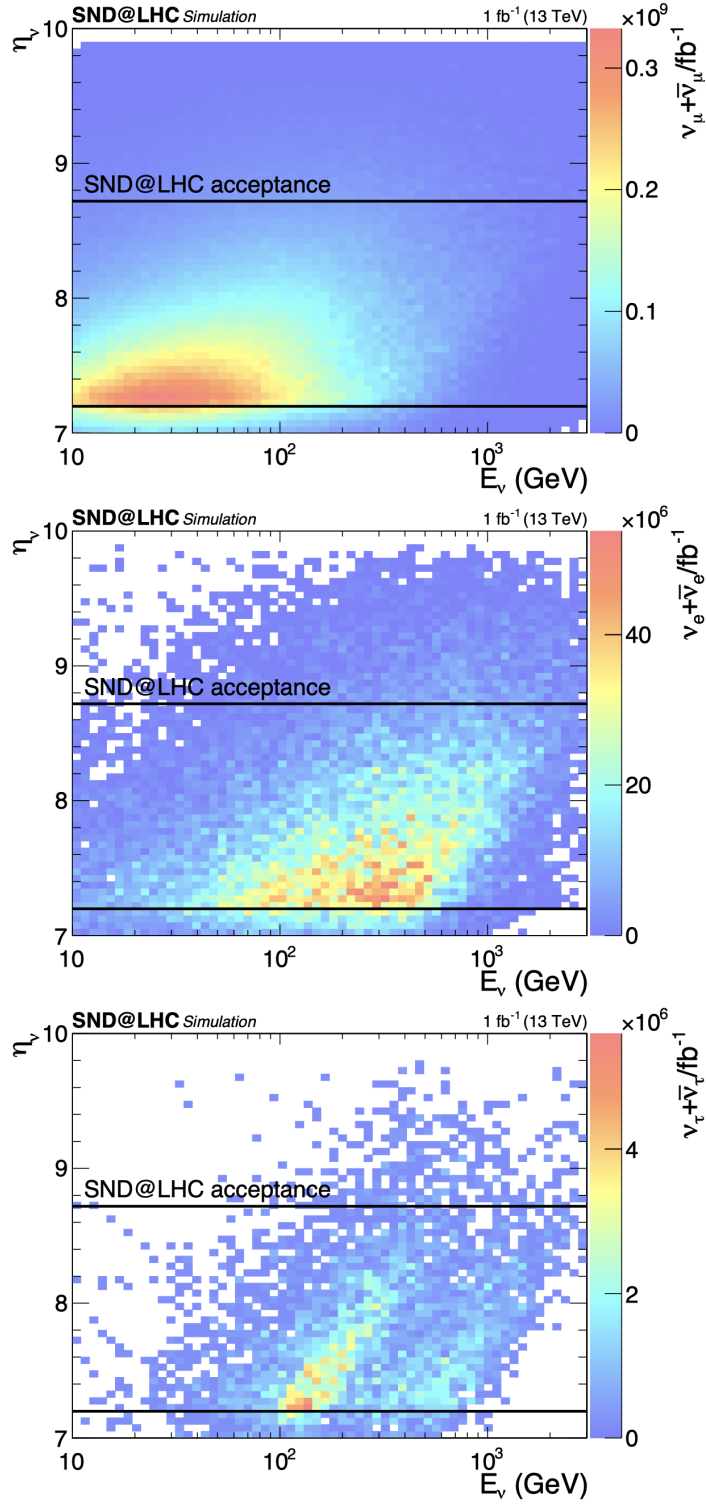


Figure 2.2: $\nu_\mu + \bar{\nu}_\mu$ (top), $\nu_e + \bar{\nu}_e$ (middle), $\nu_\tau + \bar{\nu}_\tau$ (bottom) flux as a function of neutrino energy E_ν and pseudo-rapidity η_ν within the SND@LHC acceptance range [5].

the contribution from K 's needs to be removed to get the contribution from charmed hadrons only. Measurements of $pp \rightarrow \nu_e X$ cross-sections can be performed using the detector data, with 15% accuracy effected by the systematical uncertainty of the unfolding method[5]. Moreover, an additional 20% uncertainty comes as the K contribution is removed. Using a complete simulation method, the charmed-hadron yield in a given η interval is matched with the ν s in the measured η interval, after measuring the $pp \rightarrow \nu_e X$ cross-section. As a result of this method, there is an extra systematic uncertainty of 25% [5, 16].

Table 2.1 summarizes the uncertainties for the charmed-hadron production measurements of SND@LHC.

Table 2.1: Statistical and systematical uncertainties of the $pp \rightarrow \nu_e X$ cross-section and charmed-hadron production in LHC Run 3 proposed by SND@LHC.

Measurement	Approximate Uncertainty	
	Statistical	Systematic
$pp \rightarrow \nu_e X$ cross-section	5%	15%
Charmed-hadron production	5%	35%

Lepton Flavor Universality Tests in Neutrino Interactions

The SM suggests that the electroweak gauge bosons Z and $W^\pm$ interact with all three lepton flavors equally. This implies that the probability of a decay involving different lepton flavors should be the same, apart from differences caused by the phase space and the helicities. This prediction is called the Lepton Flavor Universality (LFU) [35]. Through the measurement of the ratios ν_e/ν_μ and ν_e/ν_τ , it is possible to test LFU in neutrino sector [22]. Due to the location of the SND@LHC detector, ν_τ s are mainly only produced in $D \rightarrow \tau \nu_\tau$ and the subsequent τ decays. Meanwhile, ν_e s can be originated from all charmed-hadrons that are in ground-state, mainly D^0 , D , D_s . Thus, the ratio of ν_e/ν_τ depends only on charm-hadronization and branching fractions. Using several event generators such as PYTHIA6[40], PYTHIA8[41] and HERWIG[11], the systematic uncertainties are studied. Analysis of the results showed that the sys-

tematic uncertainty is mainly due to the uncertainty in the charmed-hadron branching ratios, which is about 22%, with a dominant statistical uncertainty of 30% due to the small size of the ν_τ sample. The uncertainties due to charm quark production cancel out in the calculation of the ratio[22]. Even though ν_μ s are more abundant, at lower energies they are contaminated by the ν_μ s originated from π s and K s decays. However, above 600 GeV the related ν_μ s remain stable with 15% accuracy. Apart from this contamination, the branching fractions for the ν_μ and ν_e produced in charmed-hadron decays are almost equal. Table 2.2 summarizes the uncertainties of the SND@LHC LFU tests.

Table 2.2: Statistical and Systematical Uncertainties of the lepton flavor universality tests in LHC Run 3 proposed by SND@LHC.

LFU Test	Approximate Uncertainty	
	Statistical	Systematic
ν_e/ν_τ	30%	22%
ν_e/ν_μ	10%	10%

Measurement of the Neutral-Current and Charged-Current Interactions Ratio (NC/CC)

While the Neutral-Current (NC) interactions are not sensitive to flavors, for the Charged-Current (CC) interactions, the corresponding charged lepton in the final state is used to determine the neutrino flavor. Moreover, charged leptons of the three flavors need to be identified to distinguish between CC and NC interactions. Since there is no magnet in the SND@LHC detector, charge identification, and hence, differentiation between CC interaction involving ν and $\bar{\nu}$ is not achievable [22]. A significant portion of the interactions of the high-energy LHC neutrinos happen through deep-inelastic scattering mechanism. As a result, it is possible to approximate the scattering off-nuclei by summing over protons and neutrons. Under the assumption of ν and $\bar{\nu}$ flux with respect to E_ν are equal, the observed NC/CC ratio can be written as Equation 2.1:

$$P_{NC/CC} = \frac{\sum_i \sigma_{NC}^{\nu_i} + \sigma_{NC}^{\bar{\nu}_i}}{\sum_i \sigma_{CC}^{\nu_i} + \sigma_{CC}^{\bar{\nu}_i}} \quad (2.1)$$

Being one of the fundamental parameters of the SM, the Weinberg angle θ_w is a probability measure of a neutrino interaction with matter, resulting in a scattered neutrino and the residual components of the matter [20, 43]. The NC and CC cross-section ratios in the limit of deep-inelastic scattering can be defined in terms of the Weinberg, or electro-weak mixing angle (θ_w) [5]:

$$P_{NC/CC} = \frac{1}{2} \left[1 - 2 \sin^2 \theta_w + \frac{20}{9} \sin^4 \theta_w - \lambda (1 - 2 \sin^2 \theta_w) \sin^2 \theta_w \right] \quad (2.2)$$

where the parameter λ in Equation 2.2 originates from the difference in the number of protons and neutrons in the target material, hence is material dependent. For SND@LHC, the target is tungsten with a corresponding λ of 0.04. Table 2.3 summarizes the uncertainties of the NC/CC measurements of SND@LHC.

Table 2.3: Statistical and systematical uncertainties of the NC/CC ratio measurement in LHC Run 3 proposed by SND@LHC.

Measurement	Approximate Uncertainty	
	Statistical	Systematic
NC/CC ratio	5%	10%

Neutrino-Induced Charm Production

Regarding the energy range of SND@LHC, high-energy neutrino interactions result in charmed-hadrons about 10% of the total rate. Interactions of these high-energy neutrinos can be a powerful and unique tool to probe charm physics [5, 19].

Nuclear emulsion, a powerful technology developed by the OPERA experiment² [24], has shown that it can be a powerful tool in the identification of charmed hadrons, allowing the observation of two-vertex topology [22]. The same technology is used in

² The OPERA Experiment Homepage: <http://operaweb.lngs.infn.it/spip.php?rubrique1>

the SND@LHC target walls. Observation of two-vertex topology is the key element in the identification of tau-neutrino interactions [17]. The Feynman diagrams for the charm production in neutrino and anti-neutrino interactions are given in the Figures 2.3a and 2.3b respectively.

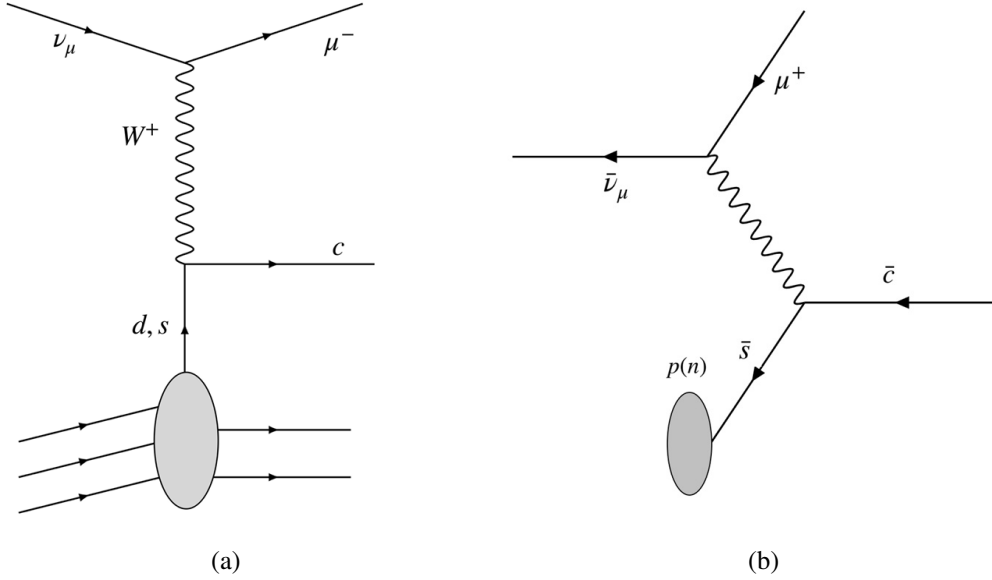


Figure 2.3: Feynman diagrams of charm production in neutrino (a) and anti-neutrino (b) charged-current interactions [17].

Feebly Interacting Particles

The search for Feebly Interacting Particles (FIPs) is an expanding field of research [33, 39]. It is estimated that FIPs are either extremely light particles, or that they have very long lifetimes. Hence, they are expected to rarely interact with matter through extreme weak interactions, meaning the interaction is through weak or gravitational force. The idea of FIPs is a great interest since they can be used to explain many mysteries in the Universe such as the origin of dark matter, matter anti-matter asymmetry, and the origin of cosmological inflation [33]. It is possible that the pp scattering at the LHC interaction point may result in the production of FIPs, which can propagate through and scatter inside the SND@LHC detector. The hybrid structure of the SND@LHC detector can differentiate the scattering of massive FIPs from the neutrino interactions [17].

2.2 Detector Layout

SND@LHC is a hybrid setup that combines the nuclear emulsion with electronic detectors. At the very front of the instrument, a veto system is located for the identification of the charged particles entering the detector from the upstream direction. The veto system is succeeded by the target region consisting of a total of five target walls, each consisting of four emulsion cloud chamber (ECC) bricks, and five scintillating fiber (SciFi) planes, consecutively. Together with the time stamp provided by the SciFi planes, ECC walls provide particle tracking. The target region is followed by the muon identification system, which performs as the hadronic calorimeter of the detector. The schematic layout of the whole detector is given in Figure 2.4.

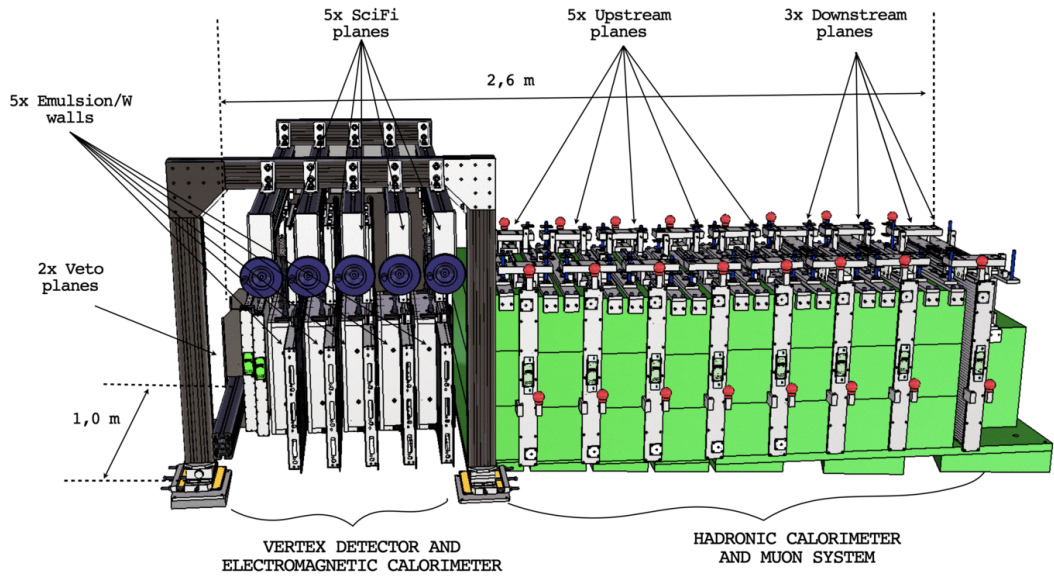


Figure 2.4: Schematic layout of the SND@LHC detector [16].

The detector layout is optimized to meet the requirements to perform the desired physics measurements while compromising environmental constraints such as the tunnel size and slope. In Figure 2.5, the tilted floor of the TI18 tunnel can be seen clearly.

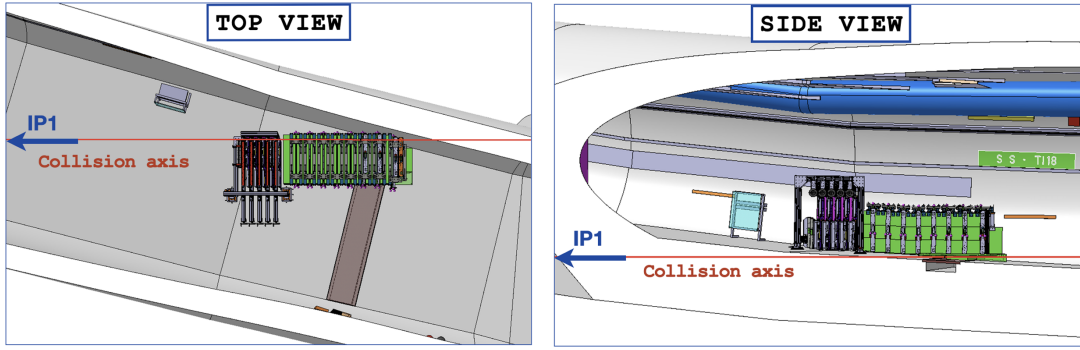


Figure 2.5: Schematic top and side views of the SND@LHC detector in the TI18 tunnel. [5].

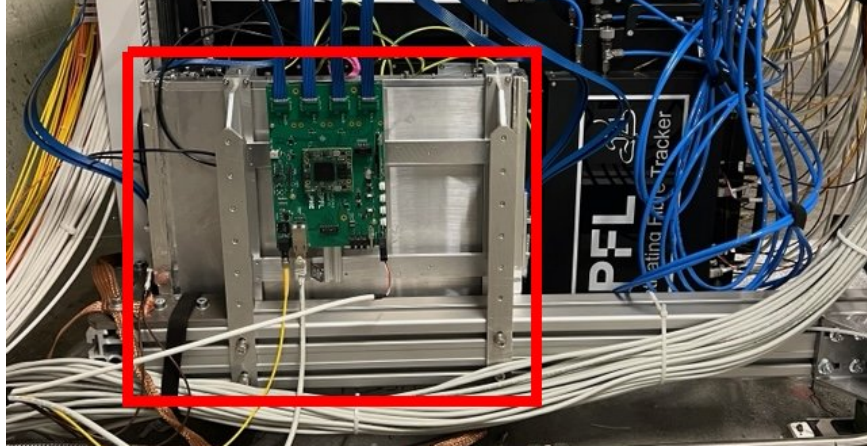
2.2.1 Veto System

In order to identify the charged particles entering into the detector volume, the veto system is located before the target region. The veto system is composed of two parallel planes of scintillating bars, which are isolated from each other so that the light originating from a scintillating bar does not affect the adjacent bars. The light tightness is ensured by wrapping each scintillating bar in a foil of aluminized BoPET (Biaxially-oriented Polyethylene Terephthalate) [7]. Even though BoPET is a strong, flexible, and durable material, it is transparent to light [21]. The aluminum coating makes the foil opaque to light, which prevents light from leaking between the scintillating bars. The installed veto system can be seen in Figures 2.6a and 2.6b.

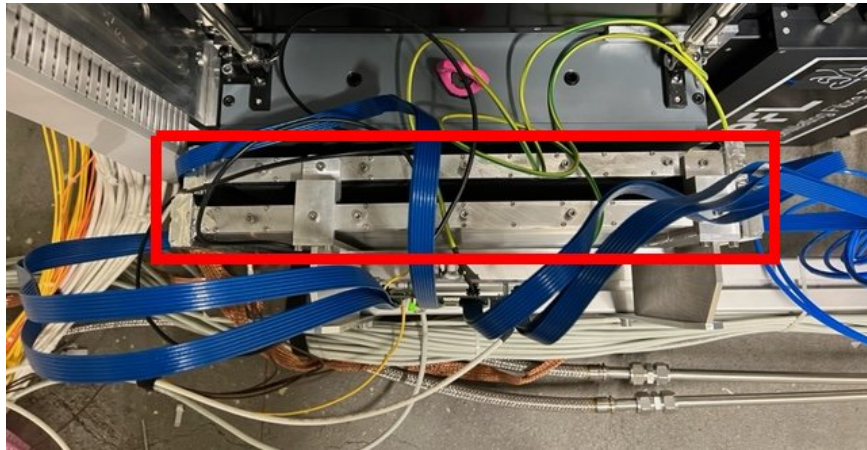
A single veto plane contains seven EJ-200³ scintillator bars, and each bar end is read out by eight Hamamatsu S14160-6050HS SiPMs⁴. The emission spectrum of the EJ-200 bars has its peak at 425 *nm*, which complements the SiPMs' spectral response. There are custom PCBs with the SiPMs on each lateral side of the planes. The whole system is covered by a frame of aluminum to secure light tightness (see Figure 2.7).

³ ELJEN Technology plastic scintillators. <https://eljentechnology.com/products/plastic-scintillators/>

⁴ Hamamatsu optical sensors. <https://www.hamamatsu.com/eu/en/product/optical-sensors/>



(a)



(b)

Figure 2.6: Front (a) and top (b) views of the veto system installed in TI18. Red rectangles represent the area in which veto planes are in [16].

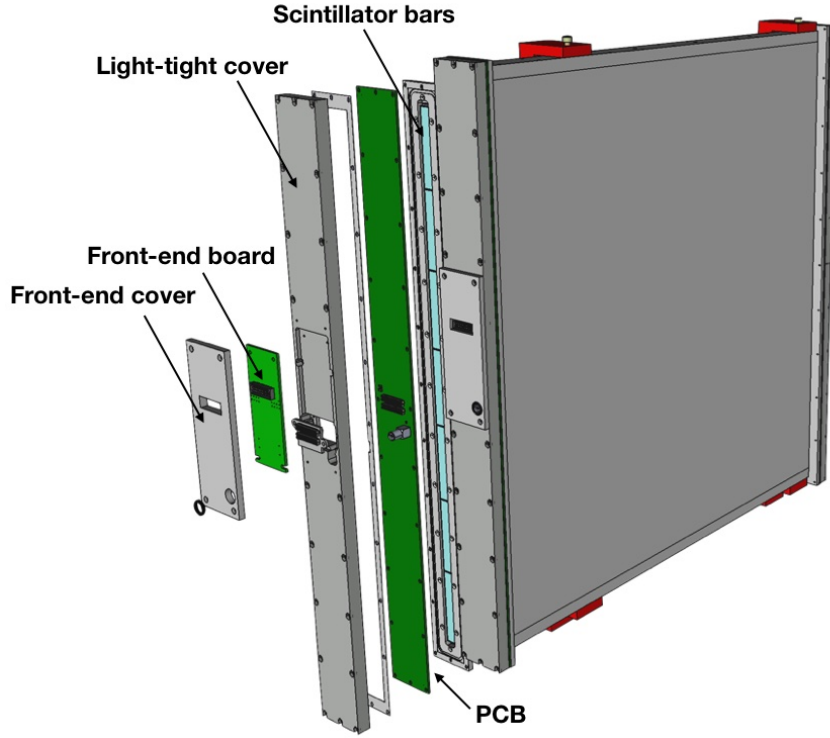


Figure 2.7: Schematic of the SND@LHC veto system [5].

2.2.2 Target and Vertex Detector

The emulsion target of SND@LHC consists of walls of nuclear emulsions based on the Emulsion Cloud Chamber (ECC) technology, developed by the OPERA experiment. The emulsion films are interleaved by passive tungsten plates, creating a tracking detector with sub-micro-metric spatial resolution and milli-radian angular resolution [16]. The structure of the target walls allows for the detection of the τ leptons that are produced in ν_τ CC interactions [4], and short-lived charmed-hadrons [3] through their production and decay vertices, which are demonstrated by the OPERA experiment. Furthermore, it is possible to observe the scattering of FIPs (see Section 2.1) by the electrons or nucleons of the tungsten plates. Thus, the SND@LHC emulsion target fits to study FIPs.

The SND@LHC target detector contains five ECC walls that are assembled in the darkroom of the CERN emulsion facility. As seen in Figure 2.8 and Figure 2.9, a single wall is made up of four units called bricks. Each brick is built with consecutive

emulsion films and 1 *mm* thick tungsten plates, weighing 41.5 *kg* with a size of 192 x 192 x 78 *mm*³. Therefore, the sensitive area of each wall is 384 x 384 *mm*², and the total target mass of five walls is around 830 *kg*.

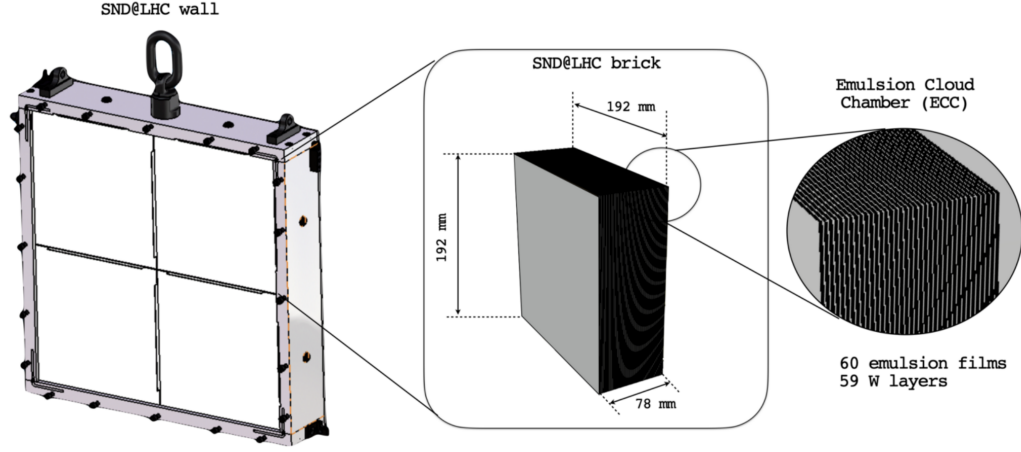


Figure 2.8: Schematic of the SND@LHC target walls. Each wall is made up of four bricks. [5].

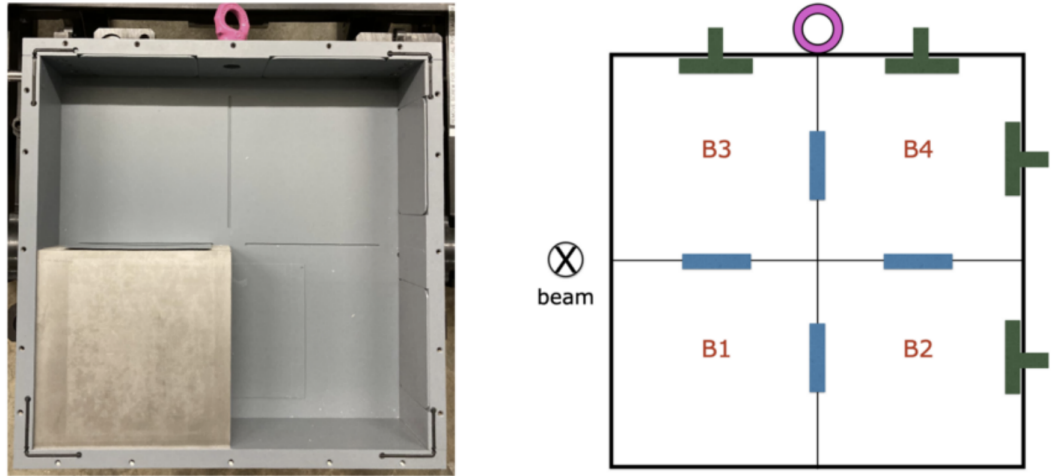
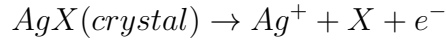


Figure 2.9: Picture of an ECC wall with one brick in place (left), and a schematic showing brick labeling with the beam direction (right)[16].

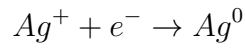
The nuclear films used in SND@LHC target walls are produced in Japan and Russia, by the Nagoya University and Slavich Company respectively [16]. Depending on the emulsion used, each ECC brick contains 60 or 57 films and 59 or 56 tungsten plates. For a whole emulsion run, approximately 1200 emulsion films, covering 44 *m*² are

needed.

An emulsion film has a transparent plastic base in the middle, and two sensitive layers at the top and the bottom surfaces. The sensitive layers are composed of silver halide crystals (AgX), commonly referred as grains. When an ionizing particle passes through the emulsion film, the silver halide crystals absorb energy from the particle, and a series of reactions begins. At first, a free X is produced:



Then, the Ag ion combines with the free electron to form a silver atom:



The resulting Ag^0 atom darkens the film, forming the latent image[10]. Figure 2.10 describes the process. The details of the development and the scanning processes for the emulsion films are given in Chapter 3.4.

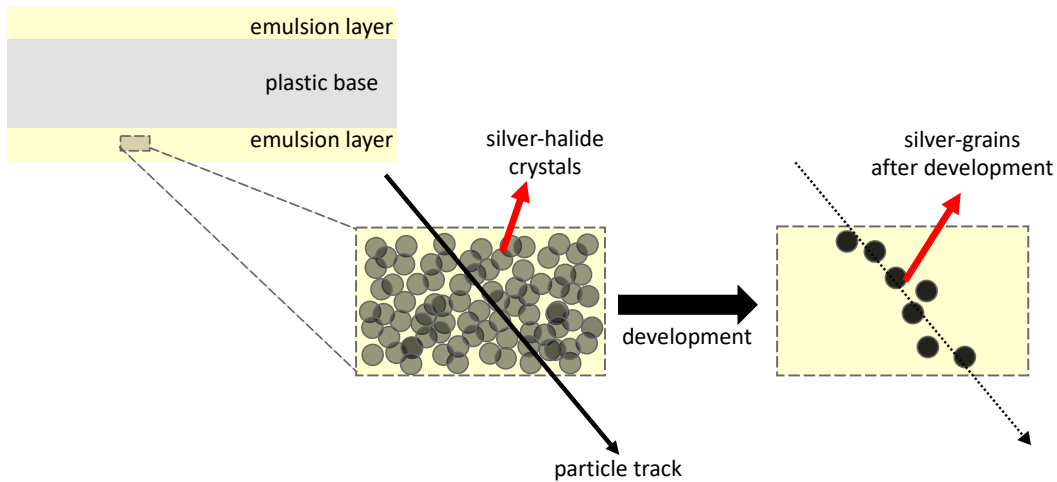


Figure 2.10: Schematic showing the latent image forming in the emulsion films.

A cold box (see, Figure 2.11) made of borated-polyethylene and acrylic walls is placed around the emulsion target for the thermal neutron shielding and temperature controlling. The cooling system for the cold box keeps the temperature of the target at $15 \pm 1^\circ C$, with the relative humidity 40-50% [16].



Figure 2.11: Picture of the cold box, taken from upstream [16].

2.2.3 Target Trackers and Electromagnetic Calorimeter

The target trackers of the SND@LHC contain five stations containing planes made of scintillating fibers (SciFi). Each SciFi station is placed after a target wall. Considering the expected rate of tracks from the ATLAS interaction point (IP1) at peak luminosity is approximately 0.8 hertz per square centimeter [45], the SciFi technology is convenient for large-scale tracking in this low track environment.

The SciFi trackers have two main purposes:

- i.* Provide a timestamp for the interactions reconstructed in ECC walls.
- ii.* Measure the electromagnetic (EM) showers produced in the target region.

In addition, the SciFi modules can be used together with the muon system to measure the energy of the hadronic jets, providing a non-homogeneous hadronic calorimeter to the detector [5].

The center of gravity of the showers reconstructed in the SciFi is connected with the reconstructed tracks in the emulsions to match the events. Due to the large multi-

plicity of tracks and the high density of the muons, track-by-track matching between emulsions and the SciFi is not possible[16].

The scintillating fiber mats and the SiPM photo-detectors of the SND@LHC SciFi modules are developed based on the LHCb SciFi Tracker [15]. The SciFi setup can be seen in Figure 2.12. The active area of a SciFi module is $40 \times 40 \text{ cm}^2$.



Figure 2.12: SND@LHC SciFi tracker with five stations [16].

Each SciFi module consists of one vertical and one horizontal plane, made up of scintillating fibers. Six layers of Kuraray SCSF-78MJ fibers⁵, each has a 0.25 mm diameter, are glued together to form fiber mats, see Figure 2.14a. The Kuraray SCSF-78MJ fibers have a polystyrene core with inner and outer claddings, producing several thousand photons per 1 MeV of deposited energy [25]. The schematic representation of the fibers with light generation is given in Figure 2.14b.

SND@LHC SciFi mats are produced using a winding machine, providing accurate positioning. Each SciFi mat is 1.35 mm thick, with $399 \times 133 \text{ mm}^2$ surface. Three SciFi mats create a SciFi plane with a dead zone of less than $500 \mu\text{m}$. Each SciFi module is enclosed by an opaque Tedlar sheet which is sealed on the Kapton flex that is held by an aluminum frame [16]. As a result, the light tightness of the modules is guaranteed.

⁵ Kuraray Scintillating Fibers. <http://kuraraypsf.jp/psf/sf.html>

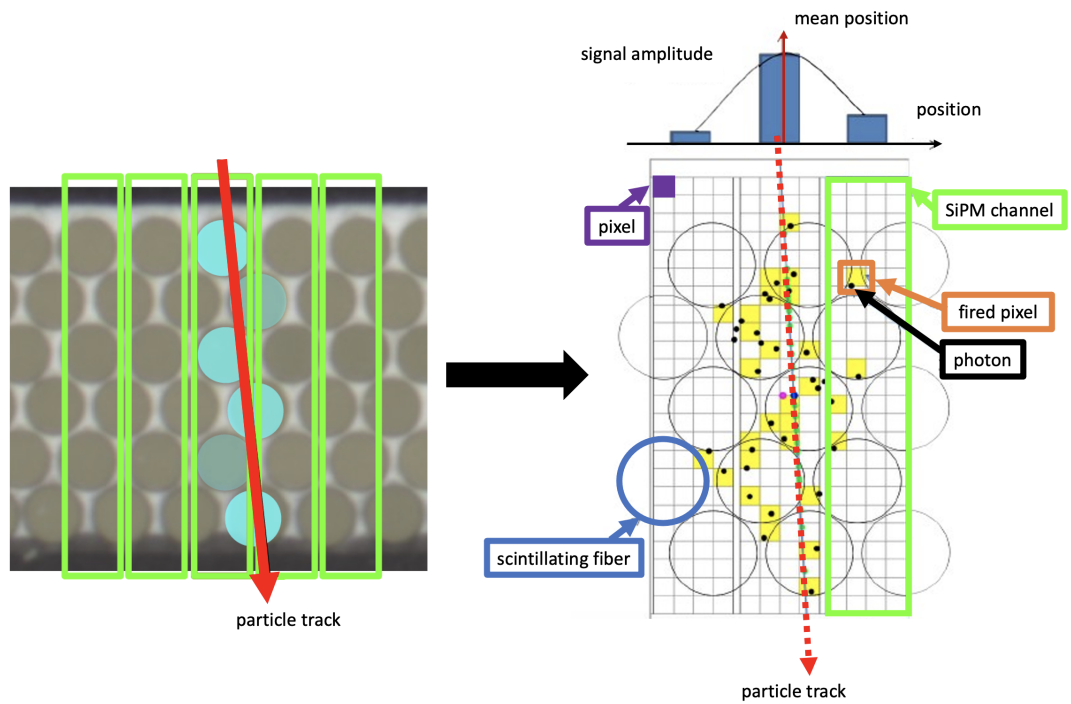


Figure 2.13: Basic schematic showing the principle of the SciFi mats. The effect of a passing particle on the fibers (left) and the records on the multi-channel silicon photo-multipliers (SiPMs) (right) can be seen.

The readout for the SciFi modules is done by multichannel Hamamatsu S13552 SiPM photo-detectors⁶, given in Figure 2.15. The multichannel SiPM array is tuned in order to maximize the detection efficiency with a tolerable noise rate, resulting in approximately 99% efficiency for the SciFi tracker [16]. The basic principle of the scintillating fibers is given in Figure 2.13 while the data acquisition is explained in Chapter 3.2.

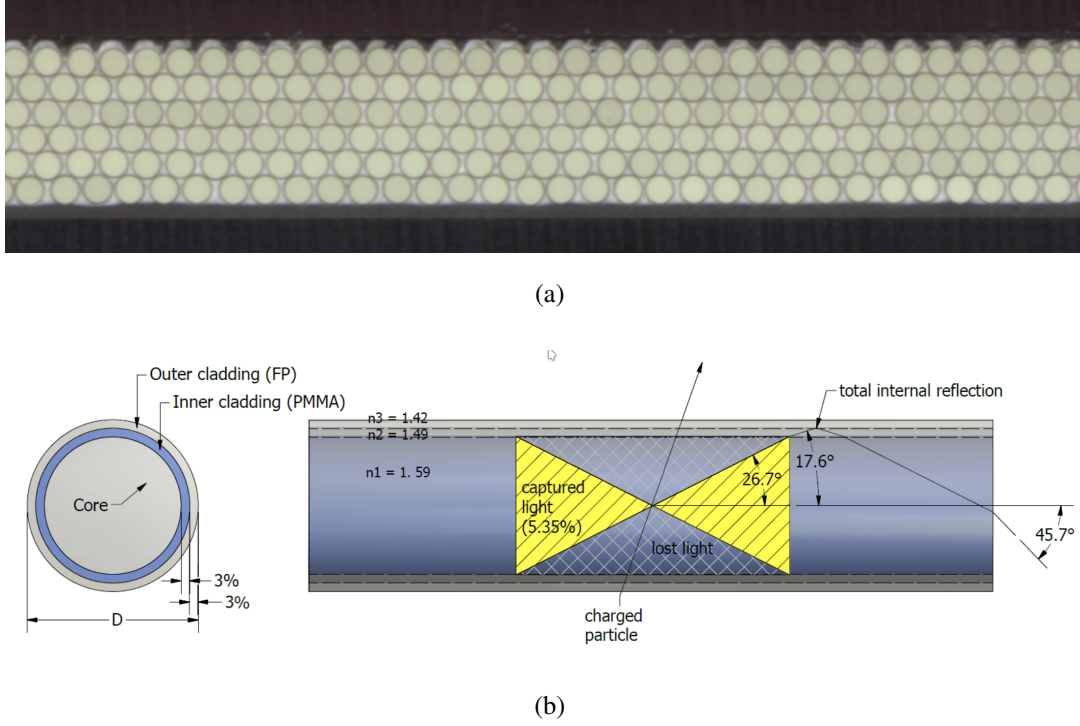


Figure 2.14: (a) Six layers of scintillating fibers glued together, forming a 1.35 mm thick SciFi mat [16]. (b) Transverse (left) and longitudinal (right) cross-sections of Kuraray SCSF-78MJ fibers [25].

The decay time of the scintillating fibers and the number of photons detected restrains the time resolution of the SciFi tracker. Using minimum ionizing particles, the time resolution of a single SciFi plane is measured as 250 ps [16].

The spatial alignment of the SND@LHC SciFi modules is studied in this thesis, with details given in Chapters 4 and 5.

⁶ Hamamatsu optical sensors. <https://www.hamamatsu.com/eu/en/product/optical-sensors/>

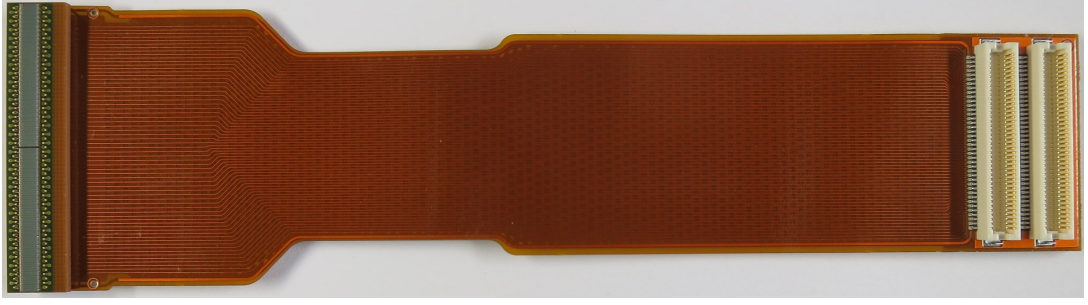


Figure 2.15: SND@LHC SciFi module SiPM arrays [16].

2.2.4 Muon System and Hadronic Calorimeter

Following the target region, a muon identification system is placed at the very downstream of the detector, to classify the muons. In the muon system, there are eight stations with 20 *cm* thick iron walls in between. The total mass of the iron walls is 750 *kg*. The muon system is divided into two parts: the upstream (US) and the downstream (DS) stations, see Figure 2.16.



Figure 2.16: US and DS stations of the SND@LHC muon system [16].

The US contains the first five stations, and each station is made up of 10 horizontal EJ-200 scintillator bars. Similar to the veto system, each bar is wrapped in aluminized BoPET foils. Meanwhile, the DS contains the last three stations which are made of both horizontal and vertical scintillator bars. The bars used in DS are thinner than the bars used in US and veto, hence they provide better granularity. Each station has one vertical and one horizontal plane, that both consist of 60 EJ-200 scintillator bars. Close-up of several bars wrapped in aluminized BoPET, as well as the entire 60 bars of a DS plane, can be seen in Figure 2.17a and 2.17b respectively.

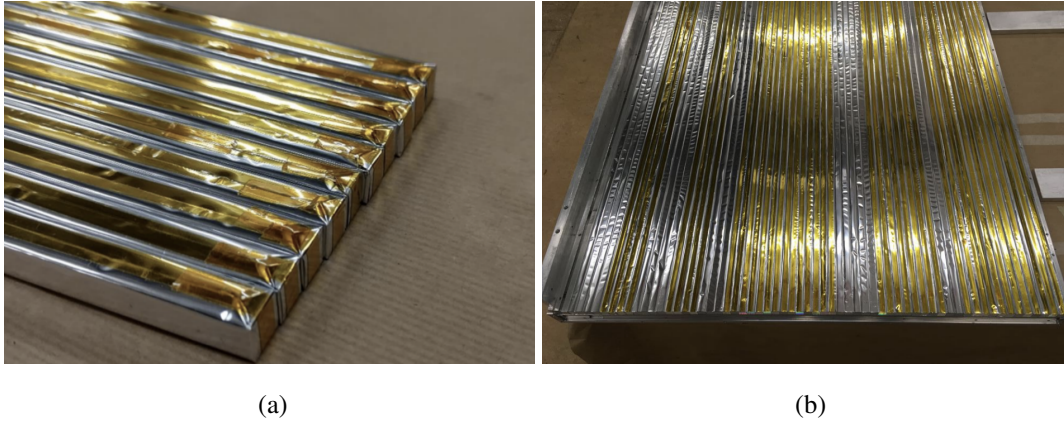


Figure 2.17: Several EJ-200 scintillator bars used in DS planes wrapped in aluminized BoPET foils (a). A DS plane is made of 60 EJ-200 scintillator bars (b) [16].

Together with the SciFi, the muon system provides the measurement of hadronic jets, making the system act as a hadronic calorimeter [5].

2.3 Detector Environment

The SND@LHC detector is constructed at the TI18 service tunnel of the LHC. A schematic top view of the experiment location is given in Figure 2.18. The TI18 tunnel is between the ATLAS interaction point (IP1) and ALICE interaction point (IP2), with a distance of 480 m and more than 2 km to each IP respectively. Apart from being significantly closer, IP1 has a much higher luminosity compared to IP2. Thus, the main source of particles arriving SND@LHC are the beam crossings at IP1 [26]. The LHC magnets between the IP1 and TI18 deflect the charged particles that

originate from the LHC collisions and propagate through the tunnel.

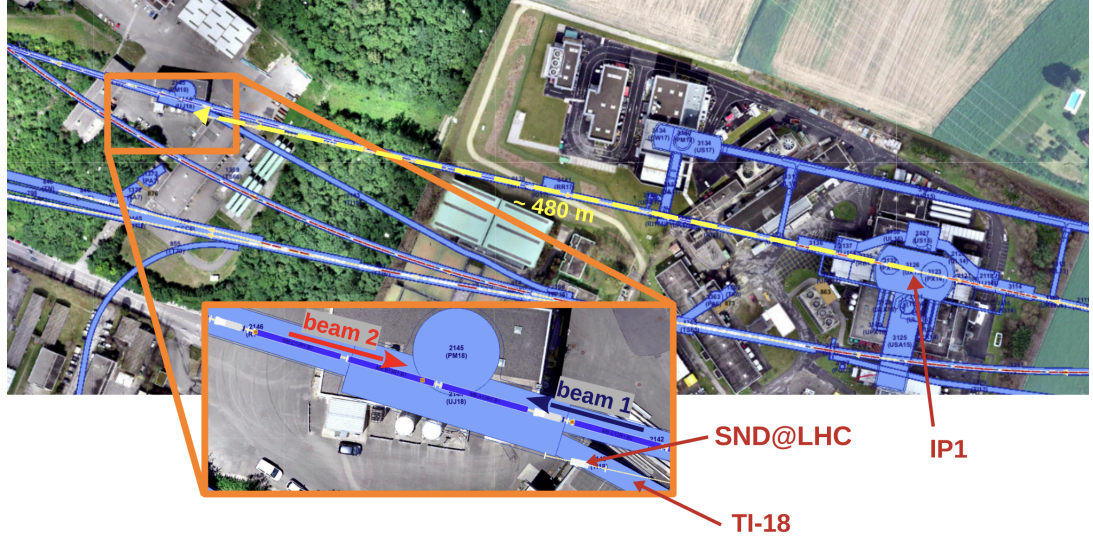


Figure 2.18: Location of the SND@LHC detector in the LHC complex.

The coordinate system used for the SND@LHC is shown in Figure 2.19. The origin of the coordinate system, DCUM480, is located at the point which is at 480 m distance from the IP1 collision axis [26]. Directions of the x , y , and z , axes are given in Table 2.4.

Table 2.4: Directions of the SND@LHC coordinate system axes.

Axis	Direction
x	Pointing away from the LHC center
y	Perpendicular to the LHC plane, points upwards
z	Aligned with beam collision axis, pointing from IP1 towards TI18

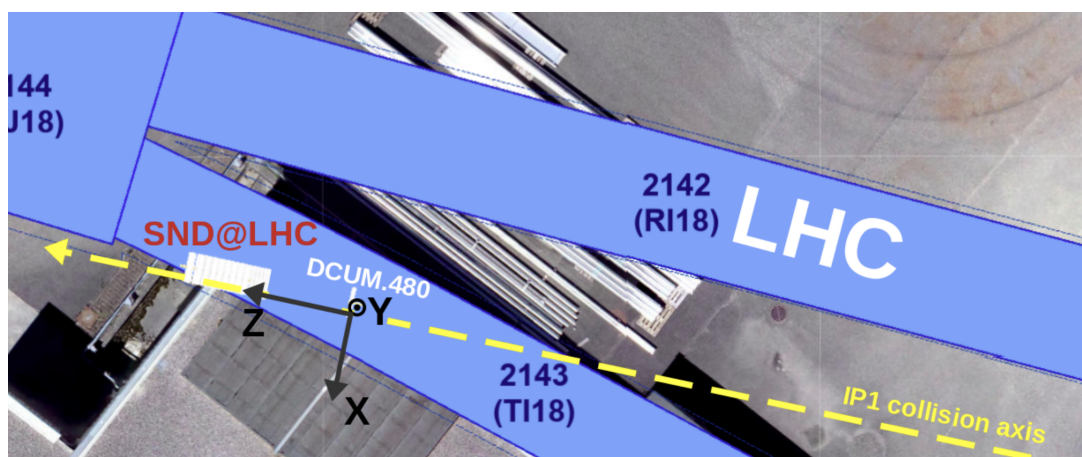


Figure 2.19: Schematic of the SND@LHC coordinate system, with origin at DCUM480.

CHAPTER 3

SOFTWARE AND TRACKING

3.1 Offline Software and Simulations

The offline software for SND@LHC, SNDSW is based on the FairSHiP¹ software developed for the SHiP Experiment², which is based on the FairRoot³ framework. FairRoot is a ROOT⁴ based analysis framework that offers simulation, reconstruction, and data analysis, hence a useful base for different experiments [6].

Table 3.1: Simulation tools used for SND@LHC, with their purpose of usage.

Simulation Tool	Purpose
FLUKA	Simulation of muons from ATLAS IP1
Geant4	Transportation of the FLUKA muons through the detector
Pythia6	Muon Deep-Inelastic Scattering
DPMJET3 / Pythia8	Neutrino production at ATLAS IP1
GENIE	Neutrino interactions in SND@LHC target system

Various simulation packages are used for the SND@LHC experiment. Used simulation tools and their general purpose of usage for the experiment are given in the Table 3.1.

¹ FairSHiP Framework homepage: <http://ship.web.cern.ch/FairShip/default.html>

² Search for Hidden Particles Experiment homepage: <https://ship.web.cern.ch/>

³ FairRoot Framework homepage: <https://fairroot.gsi.de/>

⁴ ROOT Data Analysis Framework homepage: <https://root.cern/>

3.1.1 Detector Geometry

The ROOT geometry package TGeo⁵ is used to create the detector geometry. The electronic detectors as well as the emulsion films are defined as sensitive volumes [16]. Each scintillator bar and scintillating fiber is implemented in the geometric model, which provides good accuracy for the offline analysis and simulations.

3.2 Data Acquisition

SND@LHC detector collects electronic data through its veto, SciFi trackers, and muon systems. For the veto and muon systems scintillator bars, and for the SciFi tracker scintillating fibers form the active sub-systems of the detector [5].

Both scintillator bars and scintillating fibers are read out by silicon photo-multipliers (SiPMs) with the same data acquisition (DAQ) systems. A simple version of the SND@LHC DAQ system is given in Figure 3.1. The Beam Synchronous Timing (BST) system receives the LHC clock and orbit signals and then transmits them to the DAQ boards via the Trigger Timing Control (TTC) [5]. This ensures that all DAQ boards run synchronously.

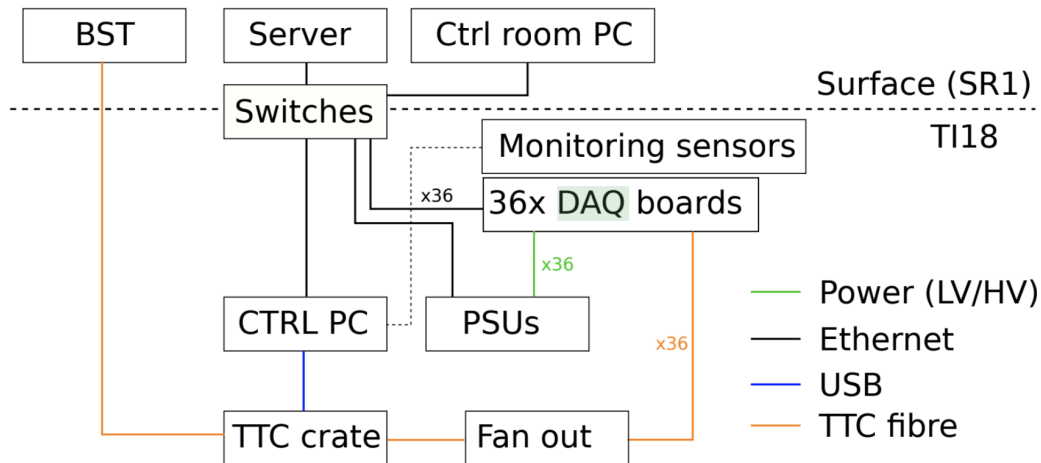


Figure 3.1: A simplified scheme of SND@LHC DAQ [5].

A total of 36 DAQ boards in veto, SciFi trackers, and muon systems read signals from

⁵ ROOT TGeoManager Class Reference <https://root.cern.ch/doc/master/classTGeoManager.html>

the SiPMs, digitize the signals, and send them to the DAQ server. The DAQ server combines signals into events based on the time they are received. The events are then saved into a ROOT file. The DAQ only performs basic online processing including clustering and preliminary track reconstruction. By using online processing, the risk of losing information can be minimized while still allowing for data quality monitoring [5]. Data recorded from DAQ is regularly sent to EOS, CERN's mass storage system, for offline data analysis.

3.3 Tracking

Tracking or track fitting is the method used to determine the kinematic state of a particle using measurements at different points. Track fit provides information on particle's energy, momentum, position, and their respective uncertainties [42].

The SND@LHC electronic detectors achieve tracking in the SciFi and down-stream muon systems individually, whereas the up-stream muon system stations are eliminated due to their large transverse dimension [26]. As muons travel through detector material, they lose energy due to processes like bremsstrahlung, pair-production, ionization, and multiple scattering [14]. The heavy target walls in between electronics may increase the effects of multiple scattering inside the detector volume and change the muon trajectory. It is possible that a muon loses so much of its energy due to multiple scattering, and eventually gets absorbed by the target material that it cannot be detected. Furthermore, these interactions can produce additional hits in the detector, making the tracking a more challenging task.

In SNDSW, two tracking methods are available for finding track candidates [26]:

- i.* Simple Tracking (ST): Custom track-finding method particularly designed for the SND@LHC experiment. Uses clusters, a group of hits that are likely to generate from the same particle.
- ii.* Hough Tracking (HT): Pattern recognition technique that uses the Hough transform. Uses hits, and individual data points.

In both ST and HT, the Kalman Filter method available in the GENFIT [37] package

is implemented for the track fitting process [26]. GENFIT is an open-source toolkit for track fitting. It creates Genfit Track objects that contain measurements and information on the related object [42].

The SciFi planes and vertical DS planes only have two spatial coordinates per hit, so tracking is done separately in the horizontal and vertical planes and then combined to get the final 3D track [26].

3.4 Emulsion Data

The emulsion data of SND@LHC is obtained after the target walls are extracted and the emulsion films are developed, scanned, and analyzed. Considering the expected muon rate of $2 \times 10^4 / \text{cm}^2 / \text{fb}^{-1}$, the target walls need to be replaced every 25 fb^{-1} during the LHC technical stops [5]. Replacing the target walls every 25 fb^{-1} is a compromise between the need to exchange the emulsion target frequently enough to ensure that the data collected is of high quality, and the need to keep the cost of the experiment reasonable.

The assembly and disassembly of target walls are done in the darkroom at the CERN emulsion facility. METU SND@LHC team had the opportunity to participate in target wall replacement activities as well as the emulsion development process.

After disassembling the target walls, the emulsion films need to undergo a chemical development process (see Figure 3.2). Each step of the development process can be summarized as:

- i.* Development: The developer reacts with the silver halide crystals in the emulsion, causing them to develop into visible metallic silver grains.
- ii.* Stopping: The stopper is a solution of acetic acid. Acetic acid is a weak acid that instantly stops the development process by neutralizing the reducing agents in the developer.
- iii.* Fixing: The fixer dissolves all of the remaining silver halide crystals, leaving only the metallic silver grains that make up the image.

- iv. Washing: The wash is a process of rinsing the emulsion with water to remove all of the silver thiosulphate complexes.
- v. Thickening: The thickener is a solution of glycerine and Fujifilm Driwell. Glycerine is a hygroscopic substance that attracts water. Fujifilm Driwell is a hardening agent that helps to prevent the emulsion from shrinking. The thickener re-inflates the emulsion to its original thickness, making it easier to view the image [5].

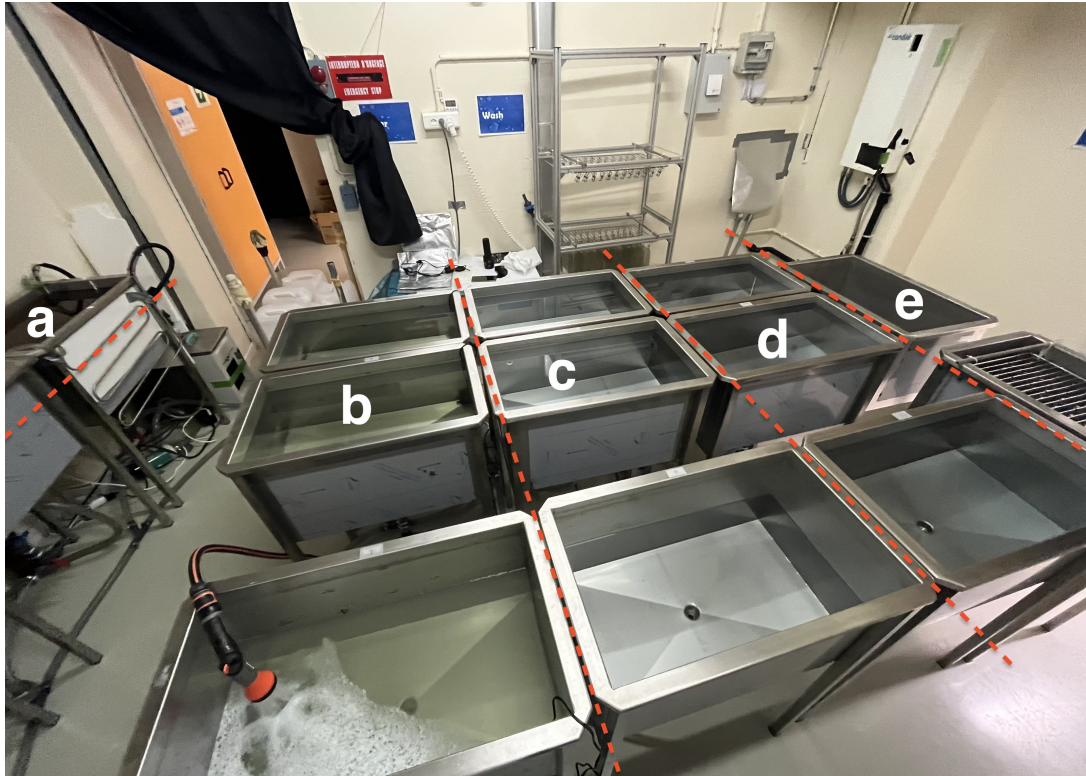
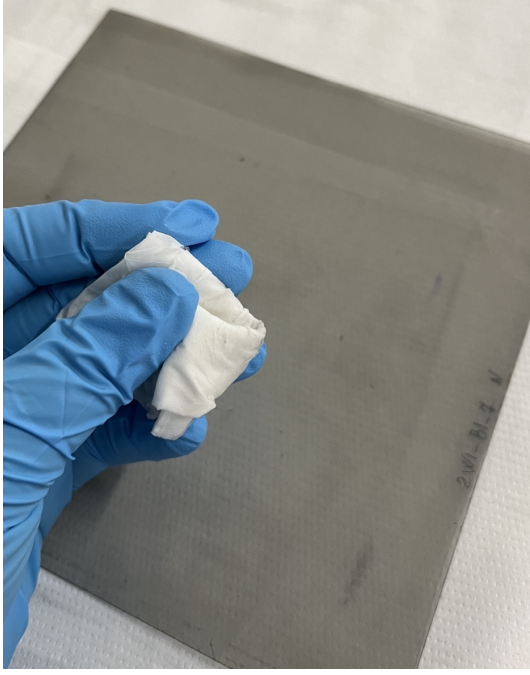
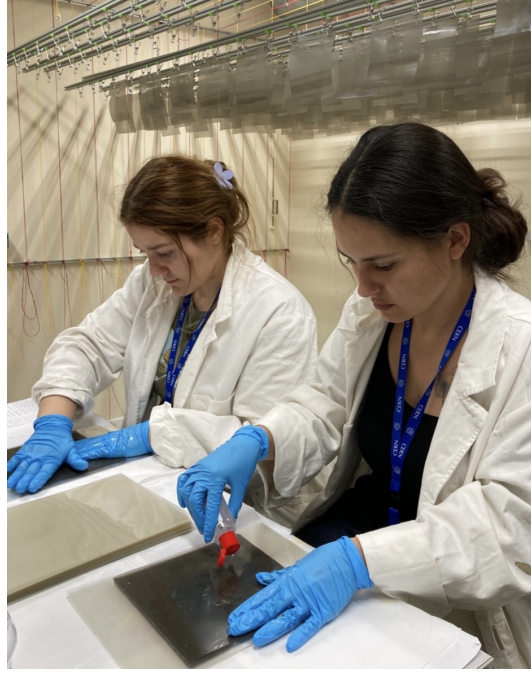


Figure 3.2: Development setup at CERN emulsion facility. The baths in a row (a) are the developer and stopper (steps *i* and *ii*). In row (b), the baths are filled with fixer (step *iii*). Rows (c) and (d) are water baths (step *iv*). The last row (e) is the glycerine bath (the last step *v*).

The developed emulsion films need to be cleaned manually with ethanol to get rid of the silver residuals on the surface (see figure 3.3a). The films are scanned using automated optical microscopes customized for SND@LHC emulsion scanning. The scanning is performed at several laboratories of the collaboration institutes, making it possible to scan different emulsion bricks at the same time. To prevent the films from



(a) Cleaning



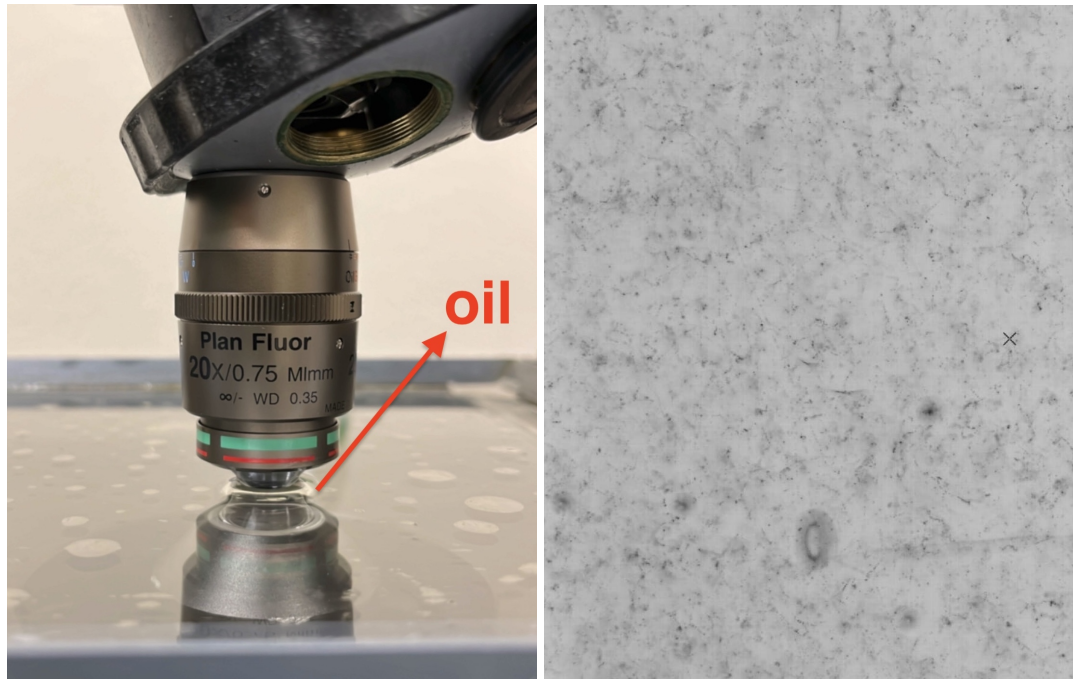
(b) Oiling and packing

Figure 3.3: Preparing the developed emulsion films for transportation and scanning.

getting damaged during transportation, each emulsion is covered with oil and placed between plastic sheets (see figure 3.3b) before being packed.

The emulsion to be scanned is placed on a platform that can move in the xy plane. The microscope lens moves along the z axis, capturing images of the different depths along the film. This structure allows for a 3D scanning of the film, hence 3D particle tracks can be reconstructed. The microscope lens provides a sub-micron resolution, which is crucial in accurate track reconstruction [5]. Close-up of a scanning microscope and a part of a scanned image can be seen in Figure 3.4a and Figure 3.4b respectively.

The LASSO (Large Angle Scanning System for OPERA) scanning system [8] is used for scanning and initial processing. After digitizing the scanned images, several algorithms are used for linking, alignment, and tracking processes. FEDRA (Framework for Emulsion Data Reconstruction and Analysis) [44] is used to develop the offline reconstruction tools used for the SND@LHC emulsion data [5].



(a) Microscope lens

(b) Scanned image

Figure 3.4: (a) Close-up of one of the scanning microscopes at CERN. The emulsion film is on top of the movable platform. An oil with the same refraction index as the emulsion is covering the surface. (b) One of the many images constructed during the scanning.

CHAPTER 4

ALIGNMENT METHOD

4.1 The MINUIT Minimization Package

MINUIT is a package of programs that can be used to solve the problem of finding the smallest value of a function of one or more variables. In particular, by minimizing the discrepancy between theoretical predictions and experimental results, MINUIT can be used to estimate the unknown parameters of a function [29].

The function F that is minimized is described by its value at any point x in the parameter space. Physical limitations may limit the function's parameter space. Additional information on the function may be available, such as the numerical derivatives $\frac{\partial F}{\partial x}$ of the function F at any point x in space. Until a minimum value x_{min} is reached, the function F is repeatedly evaluated at various points x in space chosen by the minimization method [29].

MINUIT package offers various minimization methods that can be used alone or in combination depending on the specific problem. The organization of MINUIT, parameters, and error definitions are described in the following subsections.

4.1.1 Basic Concepts of MINUIT

MINUIT is a low-level, platform-independent package with optimal performance. The function to be minimized, usually called FCN, along with the definitions of the variable parameters of the function, are supplied by the user. The function F is typically a chi-squared or a log-likelihood. Depending on the user demand and chosen method, the trial values of the parameters are determined by MINUIT [27].

4.1.2 Parameter Definitions

Parameters of the function FCN can be defined in different ways: free, single-limited, double-limited, fixed, and constant variable. Since the user determines these parameters, they are the external parameters for MINUIT. Parameters can be defined briefly as follows:

- i.* Free variable: can take any value.
- ii.* Single-limited: can take values between one upper or lower limit specified by the user and is free on the other side.
- iii.* Double-limited: can take values only between upper and lower limits specified by the user.
- iv.* Fixed: can only take on the value when it is fixed. Hence, no longer variable.
- v.* Constant: can only take on the value given by the user [30].

MINUIT subroutines only accept variable parameters that are entirely free. Therefore, instead of passing the user-supplied parameters directly to the minimizing subroutines, MINUIT creates an internal parameter list from the external parameters. The internal parameter list is created by eliminating the parameters that are not variables, and transforming the variable parameters with limits so that they can vary freely. This correlation between the external and internal parameters causes the internal parameter list to be dynamic [30].

4.1.3 Transformations for Limited Parameters

Double-limited parameters are transformed by MINUIT using the non-linear transformation:

$$P_{internal} = \arcsin \left(2 \frac{P_{external} - l}{u - l} - 1 \right) \quad (4.1)$$

$$P_{external} = l + \left(\frac{u - l}{2} \right) (\sin P_{internal} + 1) \quad (4.2)$$

where l represents the lower and u represents the upper limits. The external parameters $P_{external}$ can take only the values between the lower and upper limits, whereas there is no limit on the values that internal parameters $P_{internal}$ can take.

It can be seen from Equation 4.2 and 4.1 that, as the external value gets closer to the lower or upper limit, the effect of non-linearity becomes more significant. Transforming a linear problem into a bounded non-linear one introduces additional numerical uncertainty and slows the computation [2].

In order to avoid additional uncertainties due to having limits on both ends, MINUIT provides single-limited parameters to the user. Single-limited parameters are transformed by MINUIT using:

$$P_{internal} = \pm \sqrt{(P_{external} - l + 1)^2 - 1}$$

$$P_{external} = l - 1 + \sqrt{P_{internal}^2 + 1}$$

and

$$P_{internal} = \pm \sqrt{(u - P_{external} + 1)^2 - 1}$$

$$P_{external} = u + 1 - \sqrt{P_{internal}^2 + 1}$$

for the upper and lower bounds u, l respectively [30].

Even though the single-limited parameter transformation is linear, it may fail to give meaningful results when parameters get extremely close to the limits, where $\frac{\partial P_{external}}{\partial P_{internal}} \approx 0$, since it just provides an approximation.

In the case of a parameter being close to its limit at the function's minimum, it is possible that the actual minimum can be achieved at a limit. At the limits, the partial derivatives of the function with respect to the internal parameters $\frac{\partial F}{\partial P_{int}}$ are zero, making $\frac{\partial F}{\partial P_{ext}}$ also zero:

$$\frac{\partial F}{\partial P_{int}} = \frac{\partial F}{\partial P_{ext}} \frac{\partial P_{ext}}{\partial P_{int}} = \frac{\partial F}{\partial P_{ext}} = 0$$

therefore, the minimizer can become blocked at a limit. Hence, the user should avoid using limited parameters to prevent getting unphysical solutions [30].

In the presence of limited parameters, MINUIT also transforms the parameter error matrix since it gets affected by the transformation of the parameters [30]. The error matrix and error definitions are given in Subsection 4.1.4.

4.1.4 Error Definitions

Parameter errors are a crucial aspect of any minimization study. MINUIT provides the user with several error-analyzing tools, which can be selected depending on the problem.

Independent of the chosen method, the parameter errors will depend on how the function FCN is normalized. If any change affects the scale of the function FCN, the scale of the parameter errors should also be modified in order to maintain the accuracy of the results. Using MINUIT with experimental data requires measurement errors to be known since the parameter errors are directly related to the uncertainty of data [28, 29].

During the minimization routine, MINUIT constructs a second-derivative matrix (see Equation 4.3). The diagonal elements of the second-derivative matrix are the second partial derivatives of the function FCN, with respect to the free parameters of the function. The second derivatives are generally calculated at the function's minimum. The error matrix of the function given in Equation 4.4 is the inverse of this second-derivative matrix [28].

$$\mathbf{D} = \begin{bmatrix} \frac{\partial^2 F}{\partial p_1^2} & \frac{\partial^2 F}{\partial p_1 \partial p_2} & \cdots \\ \frac{\partial^2 F}{\partial p_2 \partial p_1} & \frac{\partial^2 F}{\partial p_2^2} & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix} \quad (4.3)$$

$$\mathbf{E} = \begin{bmatrix} \sigma_1^2 & \rho_{12}\sigma_1\sigma_2 & \cdots \\ \rho_{21}\sigma_1\sigma_2 & \sigma_2^2 & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix} \quad (4.4)$$

In the second-derivative matrix, each element of the diagonals is calculated with respect to a single parameter only. When a matrix is inverted, the resultant matrix is a

weighted sum of the inverses of the individual elements of the matrix. Meaning, each element is multiplied by a weight that depends on the other elements of the matrix. Thus, in the error matrix, the diagonals contain the effects of correlations with all other parameters [28].

4.1.5 Function Normalization

The function FCN to be minimized is generally a chi-square which must be accurately normalized. The χ^2 can be expressed in a general form of:

$$\chi^2(\alpha) = \sum_{i,j} (x_i - y_i(a)) V_{ij} (x_j - y_j(a)) \quad (4.5)$$

where $x_{i,j}$ are the components of the observation vector, each $y_{i,j}(a)$ is the theoretical or the fitted value with the fit parameters a , and V_{ij} form the covariance matrix which is the inverse of the error matrix of the observations.

For a random vector $\mathbf{X} = [X_1, X_2, \dots, X_n]$, the covariance matrix in general can be defined as [23]:

$$\sum_{i,j} = \begin{bmatrix} \sum_{1,1} & \sum_{1,2} & \cdots & \sum_{1,n} \\ \vdots & \vdots & \ddots & \vdots \\ \sum_{n,1} & \sum_{n,2} & \cdots & \sum_{n,n} \end{bmatrix} \quad (4.6)$$

where $\sum_{i,j} = Cov(X_i, X_j)$ is the covariance of X_i and X_j . The covariance of X_i and X_j is defined as:

$$\begin{aligned} Cov(X_i, X_j) &= \mathbb{E}[(X_i - \mu_i)(X_j - \mu_j)] \\ &= \frac{\sum_{n=1}^N (X_i^n - \mu_i)(X_j^n - \mu_j)}{N} \end{aligned}$$

where μ_i and μ_j are the expected values of X_i and X_j , respectively.

The expected value of the product of two variables that are independent of each other is the product of the expected values of the two random variables. In this case, the expected value of X_i is μ_i , the expected value of X_j is μ_j , so the expected value of

the product of X_i and X_j is $\mu_i\mu_j$ [36].

$$\begin{aligned}\text{Cov}(X_i, X_j) &= \mathbb{E}[(X_i - \mu_i)(X_j - \mu_j)] \\ &= \mathbb{E}[X_i X_j] - \mu_i \mu_j \\ &= (\mu_i \mu_j) - \mu_i \mu_j \\ &= 0.\end{aligned}$$

Hence, the covariance of X_i and X_j is zero if X_i and X_j are independent.

Therefore, the covariance matrix in 4.6 becomes a diagonal matrix, in the case of observations being independent of each other since $\text{Cov}(X_i, X_j) = 0$ for all $i \neq j$:

$$\sum_{i,j} = \begin{bmatrix} \sum_{1,1} & 0 & \cdots & 0 \\ 0 & \sum_{2,2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sum_{n,n} \end{bmatrix}$$

For a diagonal covariance matrix, the general form of the χ^2 in Equation 4.5 becomes [23, 28]:

$$\chi^2(\alpha) = \sum_{i=1} \frac{(x_i - y_i(a))^2}{e_i^2} \quad (4.7)$$

where e_i corresponds to the error of the observation x_i .

The minimization of the χ^2 in 4.7 may be referred as the weighted least squares, $\frac{1}{e_i^2}$ being the weights [28].

4.1.6 TMinuit Class

TMinuit is the direct implementation of MINUIT in C++. Fred James initially created the MINUIT package in Fortran¹ around 1975. R.Brun has transformed it into a C++ class called TMinuit². In the ROOT implementation, the MINUIT subroutines are member functions [2].

¹ The Fortran Programming Language. <https://fortran-lang.org/>

² ROOT TMinuit Class Reference. <https://root.cern.ch/doc/master/classTMinuit.html>

4.2 Minimization Methods in MINUIT

It is not possible to use a single algorithm to perform minimization for every problem. The user should choose the most suitable minimization algorithm for the specific problem. MINUIT was one of the first programs that provided users to choose between different algorithms to perform minimization [29]. The available methods of MINUIT are explained in the following sections.

4.2.1 MIGRAD

For almost all functions, the MIGRAD method can be used to minimize the function without a problem. MIGRAD offers the user a metric-based variable method including a line search. Its metric updating system is very stable [30].

MIGRAD has the option to run the method low-level or high-level, depending on the user's priorities. The low-level option provides a faster solution, but the results are less reliable [30]. Thus, for more reliable solutions, running MIGRAD on a high-level option is advised.

To be able to use the MIGRAD method, the user needs to check the accuracy of the first derivatives. If the first derivatives are problematic, the MIGRAD method breaks down. To prevent such cases, MIGRAD allows the first derivatives to be defined and calculated inside the function FCN [30].

4.2.2 SIMPLEX

If the case of inaccurate first derivatives, the user can choose this method to eliminate the usage of the first derivatives overall. The SIMPLEX method can be much faster and safer than the MIGRAD method, in the region that is away from the function's minimum. Nevertheless, it is not reliable in getting the parameter errors or correlations. SIMPLEX simply makes an estimation of a distance to the minimum value, without giving the user the guarantee to converge [30].

4.2.3 MINIMIZE

The MINIMIZE method first calls the MIGRAD method. If for any reason the MIGRAD method breaks, the MINIMIZE method then calls SIMPLEX [30].

The MINIMIZE method is particularly useful for problems where the function being minimized is not well-behaved or where it is difficult to compute the derivatives of the function. If the user is not sure about which method to use, the MINIMIZE method can be a good choice.

4.2.4 SCAN

This method is called SCAN because the function is scanned parameter by parameter by this method. For each scan, the best value of the function is found [30].

The application of the alignment method to SND@LHC SciFi modules is explained in the following chapter.

CHAPTER 5

ALIGNMENT RESULTS AND DISCUSSION

5.1 Implementation of Alignment to SND@LHC SciFi Modules

Following each target replacement, the alignment of the target modules needs to be performed. The SciFi alignment of the SND@LHC detector is done by minimizing the residuals for each fitted muon track. Residuals in general indicate the distance of the closest approach between a track and a hit belonging to the track. In the alignment studies of the SND@LHC SciFi modules, residuals refer to the distance of closest approach between the line given by the cluster end-points and the particle trajectory in 3D¹.

In Figure 5.1a, the cluster end-points are labeled as A and B , C is the point of position, and the particle trajectory is shown with a red dashed line. Define the vector $\vec{d}$ as:

$$\vec{d} = \overrightarrow{CA}$$

and let

$$\vec{u} \times \vec{v} = \overrightarrow{AB} \times \vec{p}$$

where $\vec{p}$ is the momentum vector. Using these definitions, the distance of closest approach (DOCA) shown in Figure 5.1b can be calculated as:

$$DOCA = \vec{d} \cdot \frac{\vec{u} \times \vec{v}}{|\vec{u} \times \vec{v}|} \quad (5.1)$$

To select the events for the alignment process, a minimum of 10 measurements are necessary along with a track fit. The track fit needs to converge, using at least 8 measurements [26].

¹ This definition is retrieved from the presentation titled "First attempt of TI18 SciFi alignment" by Thomas Ruf, which was presented at SND@LHC Software and Physics Meeting on July 5, 2022.

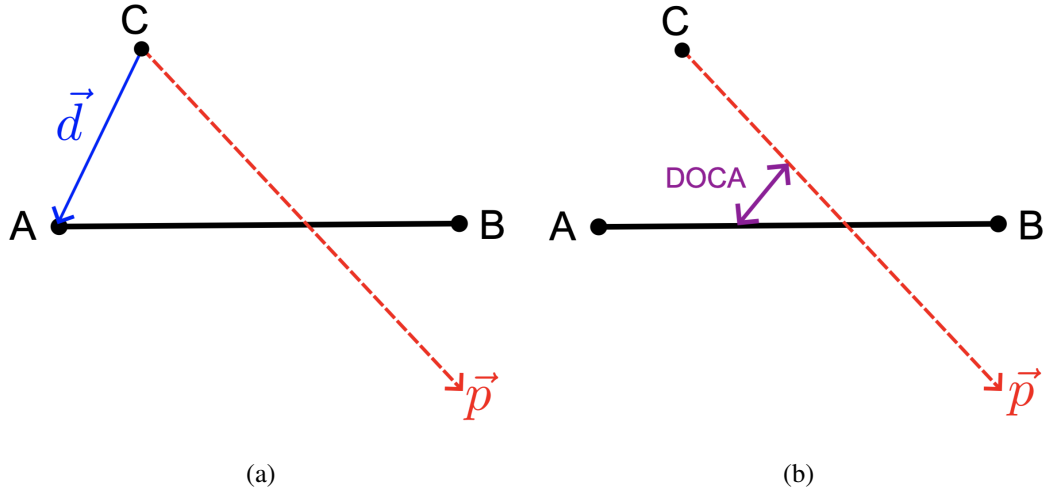


Figure 5.1: Representation of SciFi residual calculation, used in SciFi alignment process.

As explained in Chapter 2, the SciFi detector comprises 5 stations. Each station features one horizontal and one vertical plane, and 3 mats of scintillating fibers make up one plane. The alignment parameters utilized are the relative mat positions within the measured plane, and the rotation angles for the entire plane [26], shown in Figure 5.2.

During the procedure, one mat from each orientation and the rotation of one plane is fixed [26], and the alignment is done locally relative to the fixed modules.

The initial values for the positions are determined by the survey measurements² [26]. Survey measurements are done using special instruments and techniques such as laser trackers and precision levels to measure the position and orientation of each detector component, relative to a well-defined reference frame. These measurements are crucial and must be precise since they are used to calibrate and align the detector.

The alignment procedure uses the initial measurements from the survey data and performs minimization based on the SIMPLEX method provided by the MINUIT minimization package, explained in Chapter 4. The method aims to adjust alignment parameters so that the chi-square value is minimized. This, in turn, minimizes the

² Survey Measurements of SND@LHC. Visible to everyone holding a valid CERN account. <https://edms.cern.ch/document/2882720/1/>

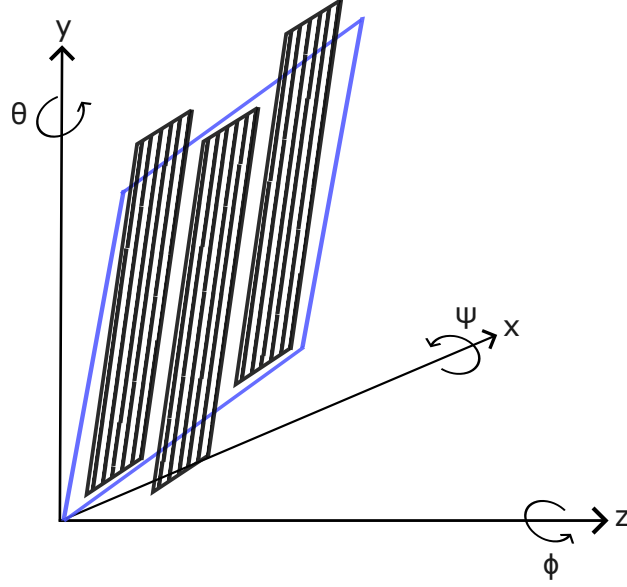


Figure 5.2: Schematic representation showing the spatial alignment of a single SciFi plane. The plane has rotational freedom, whereas individual mats of a plane can move along xy-plane.

discrepancies between the observed value and model prediction, which is the residual value.

For TI18 data, currently, 8 different SND@LHC geometry files are present, each corresponding to a different run period, see Table 5.1. The positions of all SciFi modules along with their planes and mats in each geometry file are calculated using the alignment method described in this thesis.

In Table 5.1, LHC scrubbing runs refer to exposing the inner surface of the chambers to beam-induced electron bombardment [38]. In the course of a scrubbing run, the LHC is run with low-intensity proton beams, operating at energies significantly lower than high-energy collision runs. These low-energy beams are intentionally focused and guided to traverse the beam pipes, essentially cleaning the inner surfaces. The scrubbing process decreases the emission yields of secondary particles resulting from primary collisions [38].

The exposure interval and their corresponding run periods for each target replacement are given in Table 5.2.

Table 5.1: Existing geometry files for SND@LHC TI18 data. The middle column represents the period that the geometry file version corresponds to. The significance of each period is given in the third column. For more information on geometry files, see Chapter 3.1.1.

Geometry File Version	Corresponding Run / Data	Aspect
v0	Survey measurements	Position of detector elements
v1	LHC scrubbing runs	Replaced with v2 as the beam became stable
v2	0 - 4574	First SciFi alignment with 13.6 TeV collisions
v3	4575 - 4618	Added Veto/US/DS shifts with respect to SciFi alignment
v4	4619 - 4574	Valid SciFi alignment for the given run period
v5	4575 - 4855	Improved rotations
v6	4856 - 5171	Valid SciFi alignment for the given run period
v7	5172 - present	Valid SciFi alignment from run 5172 up to now

For this thesis, four runs in total are used; a single run with sufficient statistics from each emulsion run period. The overview of runs used can be seen in Table 5.3. The results of the MINUIT alignment are given and analysis of the results is discussed in Section 5.2.

Preliminary studies with small statistics are performed on the Linux Public Login User Service (LXPLUS)³, which offers remote access to powerful machines with low

³ The LXPLUS Service <https://lxplusdoc.web.cern.ch/>

Table 5.2: Exposure periods of emulsion targets. Each target replacement is referred as a RUN.

Emulsion RUN	Target Exposure Period	Corresponding Runs
RUN0	7 Apr 2022 - 26 Jul 2022	0-4574
RUN1	26 Jul 2022 - 13 Sept 2022	4575 - 4854
RUN2	13 Sept 2022 - 4 Nov 2022	4855 - 5171
RUN3	4 Nov 2022 - present	5172 - present

CPU load.

After making sure the alignment method works properly, alignment studies are performed again, with higher statistics. The CERN batch service⁴, HTCondor⁵, is used to run jobs.

Table 5.3: Overview of the runs used for analysis.

Run	Run Summary		Corresponding Emulsion RUN
	Total Number of Events	Start Time	
4449	12367098	Jul14 17:40:02 2022	RUN0
4769	100788480	Aug 13 14:41:47 2022	RUN1
5036	27611613	Oct 14 00:59:42 2022	RUN2
5377	108345742	Nov 24 05:19:10 2022	RUN3

The alignment studies are performed using the MINUIT SIMPLEX method. The function that is minimized, FCN, is the chi-square function. The results of the MINUIT alignment are presented and discussed in the following section.

⁴ CERN Batch Service User Guide <https://batchdocs.web.cern.ch/index.html>

⁵ HTCondor Version 10.7.1 Manual <https://htcondor.readthedocs.io/en/latest/>

5.2 Alignment Results and Discussion

In this section, the residual distributions before and after the MINUIT alignment will be provided and discussed only for run 4449. For clarity, the results of the rest of the runs are given in Appendix B, C, and D.

Analyses for all runs are performed using 1000000 events, which provides enough statistics while keeping the computing time relatively short.

5.2.1 Before the MINUIT Alignment

The distribution of the SciFi residuals for run 4449 with the misaligned survey geometry is given in Figures 5.3 and 5.4, for horizontal and vertical planes respectively.

For a closer look on the mean offsets and sigma values of the residual distributions, Figure 5.5 for SciFi planes and 5.6 for SciFi mats is provided.

Finally, in Figures 5.7 and 5.8, plots of the extrapolated track positions X and Y versus residuals are provided, showing the misalignment.

5.2.2 After the MINUIT Alignment

Using the alignment parameters calculated by MINUIT, the distribution of the SciFi residuals for run 4449 is given in Figures 5.9 and 5.10, for horizontal and vertical planes respectively.

Similar to before, for a closer look at the mean offsets and sigma values of the residual distributions, Figure 5.11 for SciFi planes and 5.12 for SciFi mats are provided.

Again, in Figures 5.13 and 5.14, plots of the extrapolated track positions X and Y versus residuals are provided, showing the change in alignment.

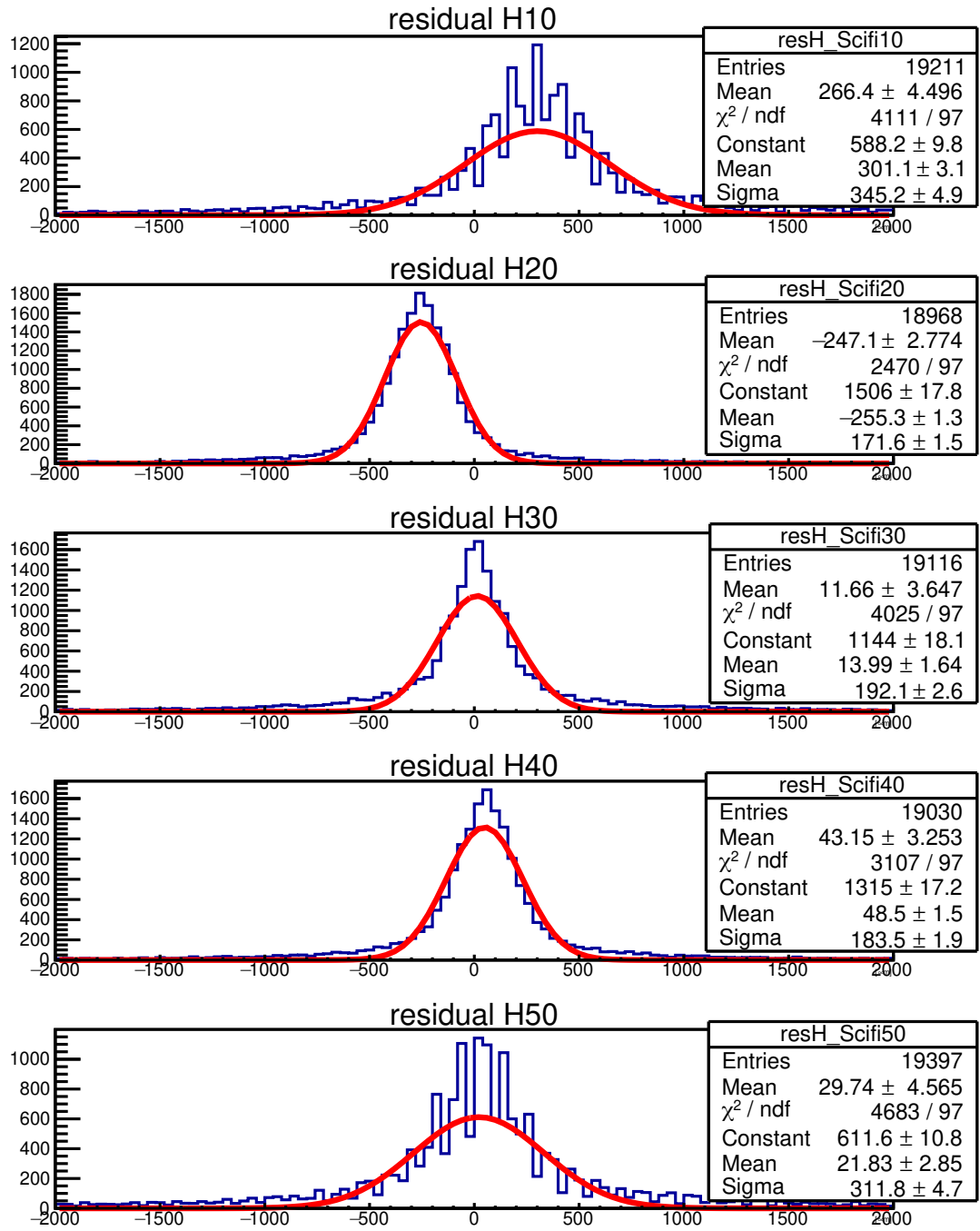


Figure 5.3: Residual distributions for run 4449 with misaligned geometry, horizontal SciFi planes. The horizontal axis is in μm s. The first mean in the legend represents the mean value for the data whereas the second mean represents the mean value of the fit. The constant is the maximum value of the fit.

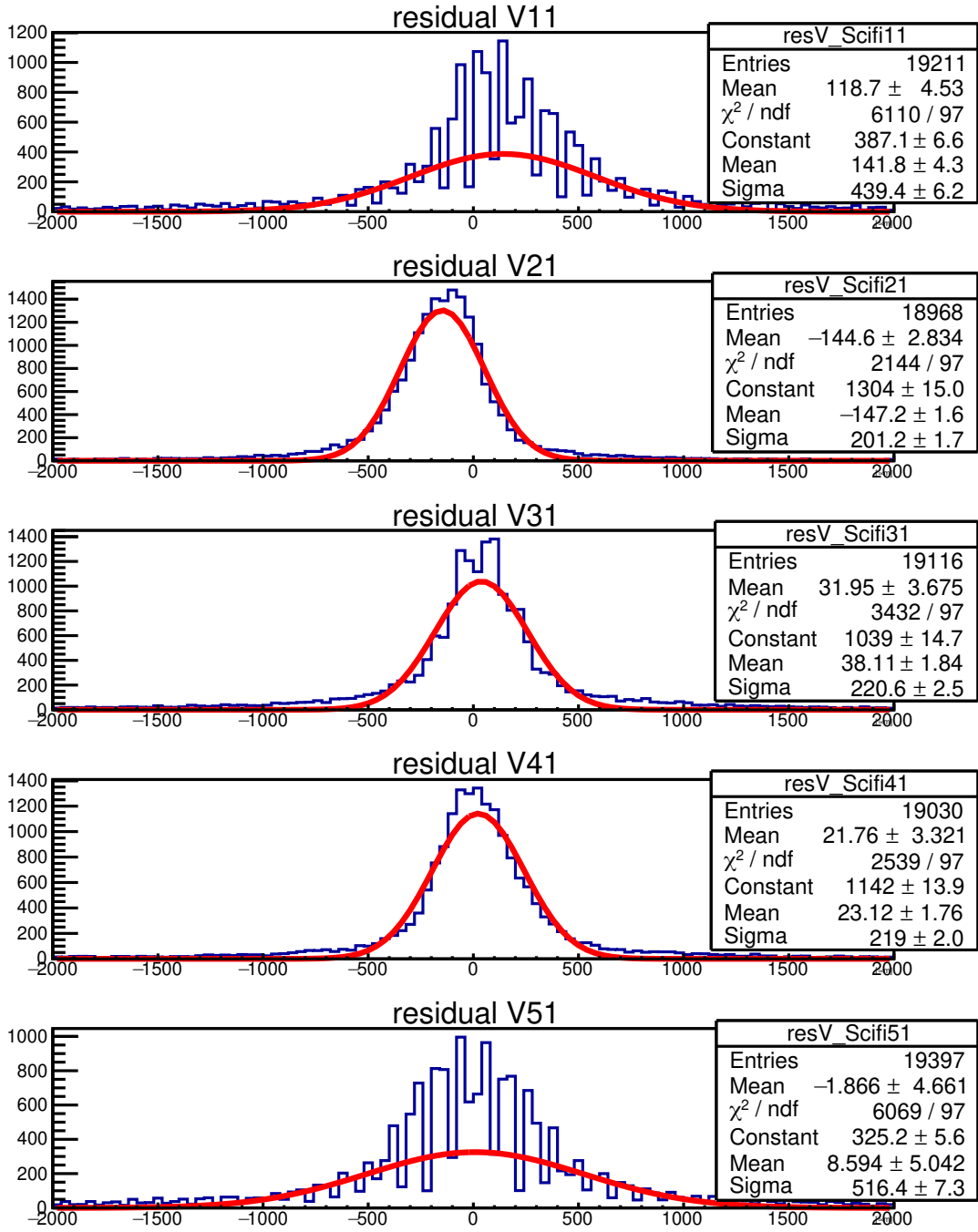


Figure 5.4: Residual distributions for run 4449 with misaligned geometry, vertical SciFi planes. The horizontal axis is in μms . The first mean in the legend represents the mean value for the data whereas the second mean represents the mean value of the fit. The constant is the maximum value of the fit.

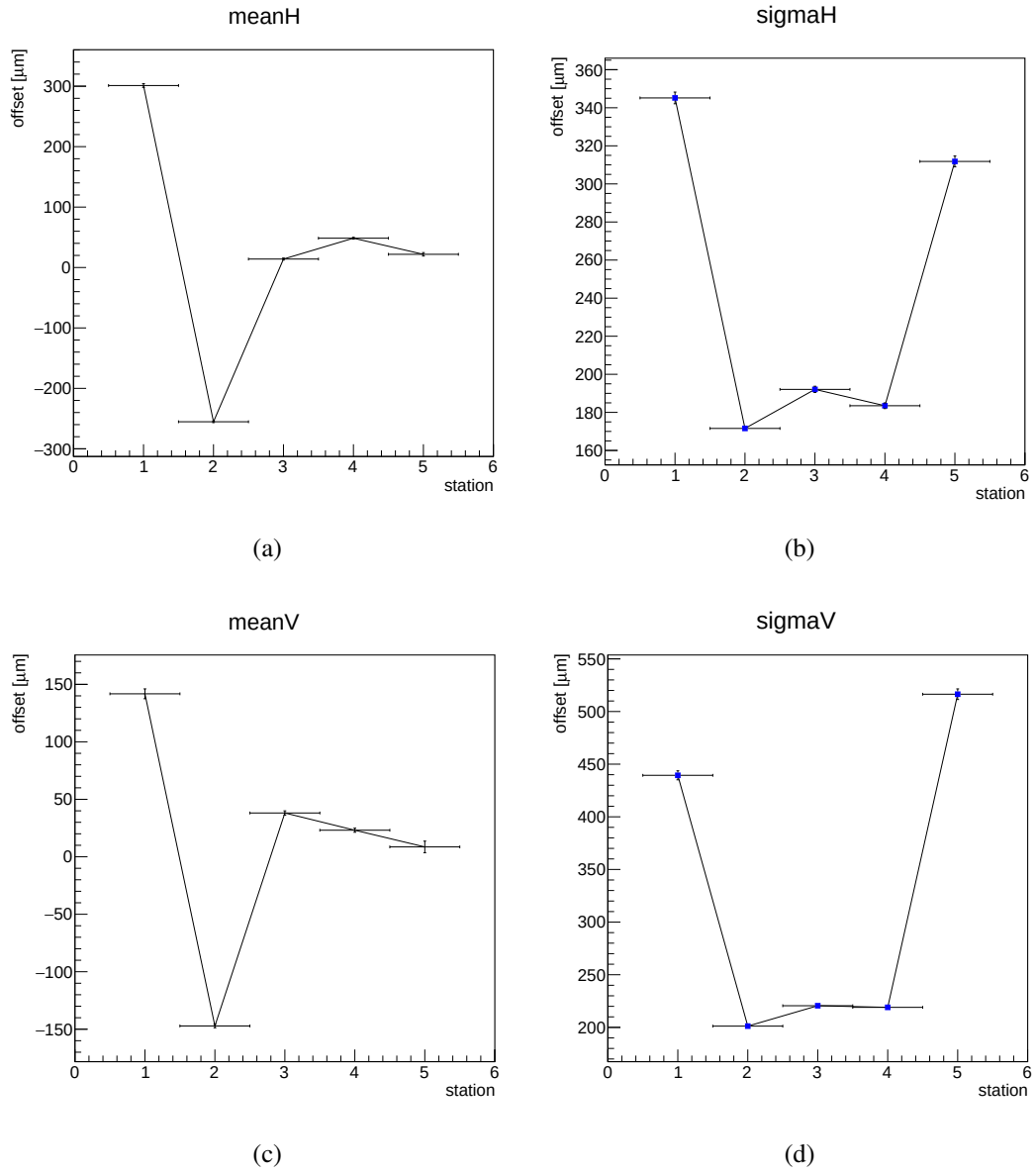
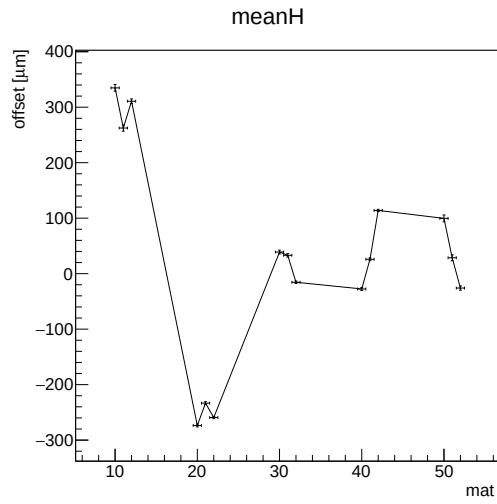
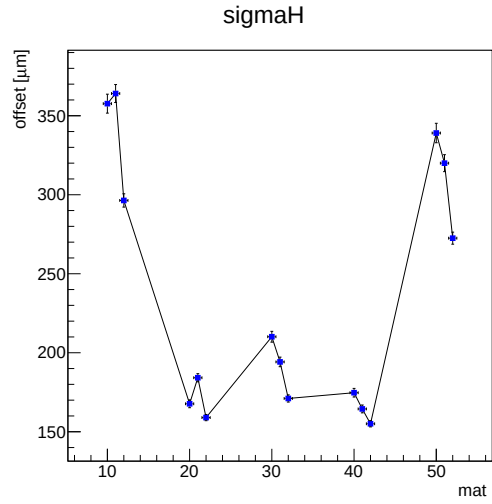


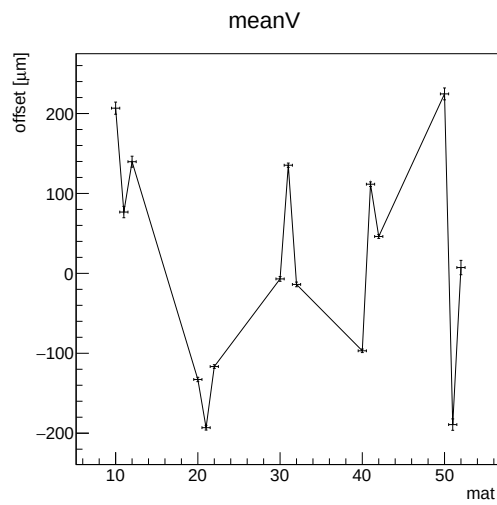
Figure 5.5: Mean offsets for the horizontal (a) and vertical (c) planes before the alignment, with corresponding sigma values (b) and (d) respectively.



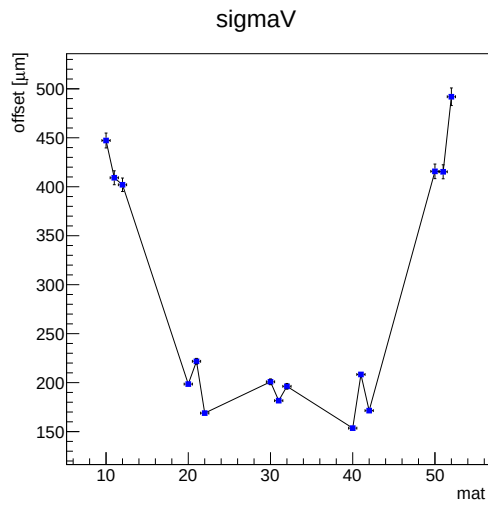
(a)



(b)



(c)



(d)

Figure 5.6: Mean offsets for the horizontal (a) and vertical (c) mats before the alignment, with corresponding sigma values (b) and (d) respectively.

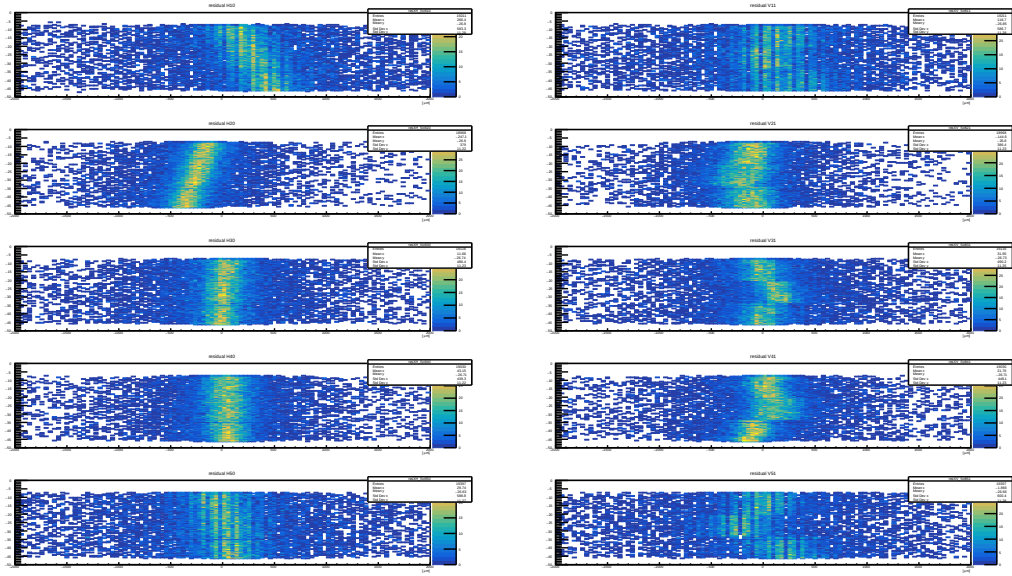


Figure 5.7: Extrapolated track positions X for horizontal (left) and vertical (right) planes versus residuals for run 4449 with misaligned geometry.

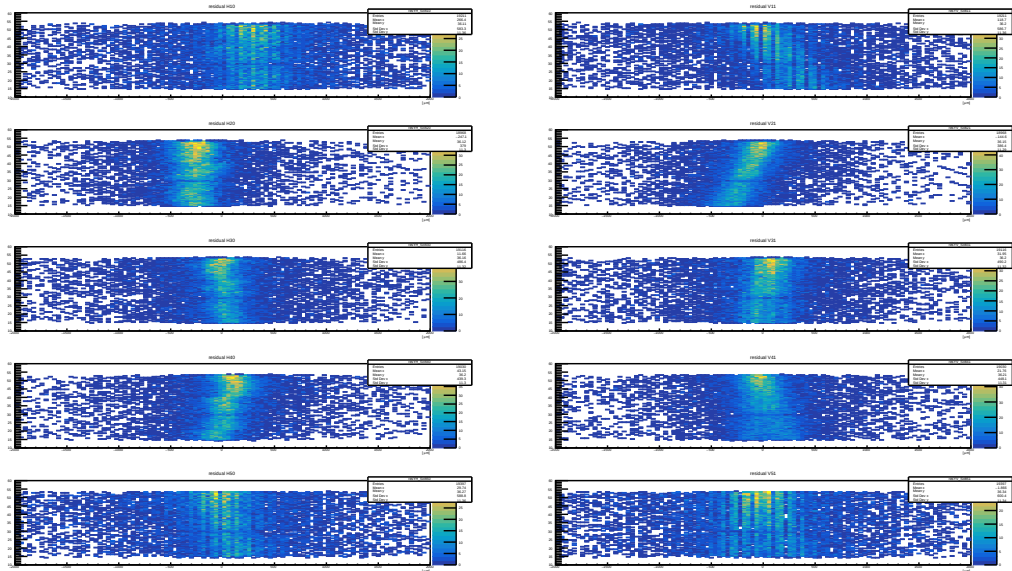


Figure 5.8: Extrapolated track positions Y for horizontal (left) and vertical (right) planes versus residuals for run 4449 with misaligned geometry.

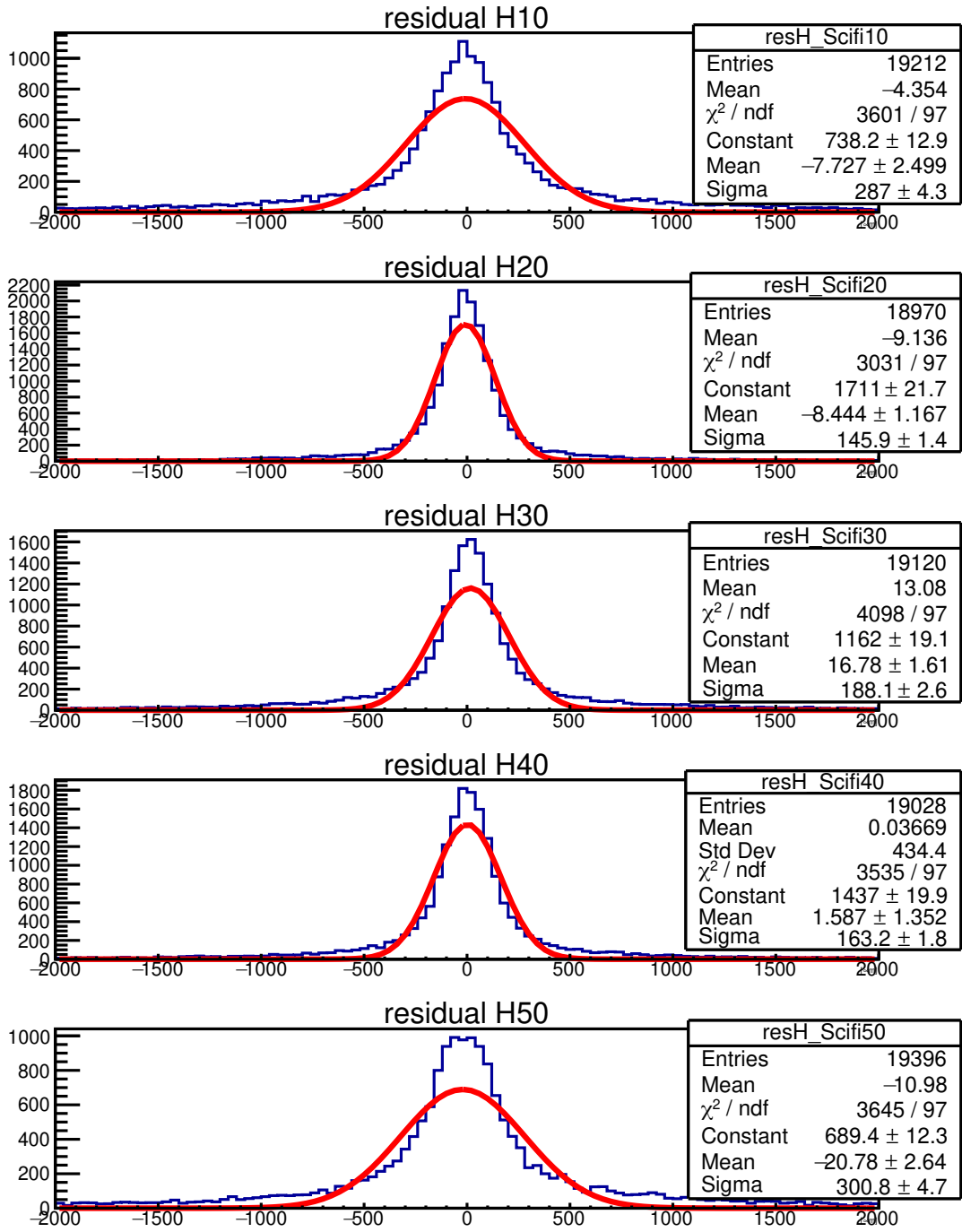


Figure 5.9: Residual distributions for run 4449 with corrected geometry, vertical SciFi planes. The horizontal axis is in μms . The first mean in the legend represents the mean value for the data whereas the second mean represents the mean value of the fit. The constant is the maximum value of the fit.

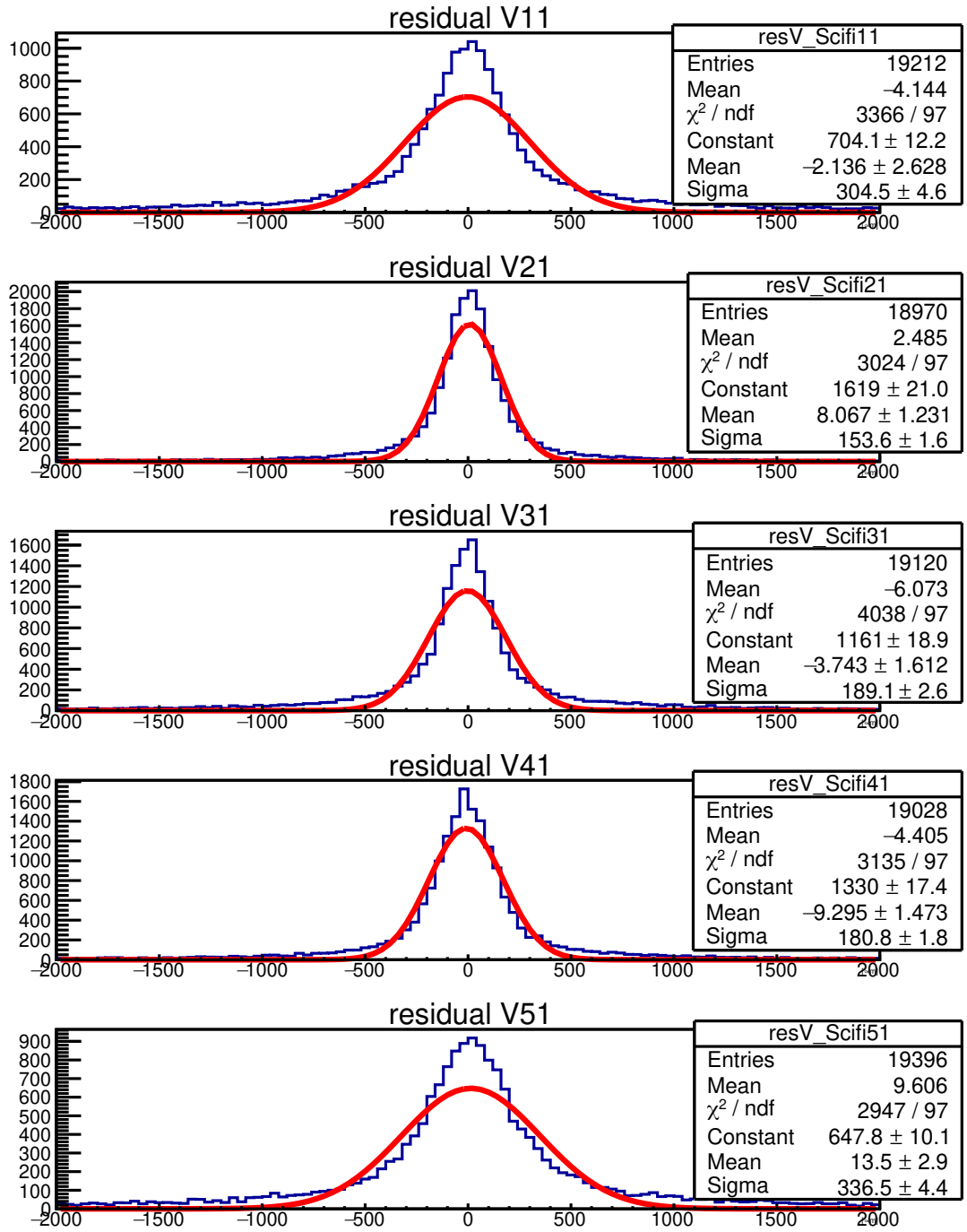


Figure 5.10: Residual distributions for run 4449 with corrected geometry, vertical SciFi planes. The horizontal axis is in μms . The first mean in the legend represents the mean value for the data whereas the second mean represents the mean value of the fit. The constant is the maximum value of the fit.

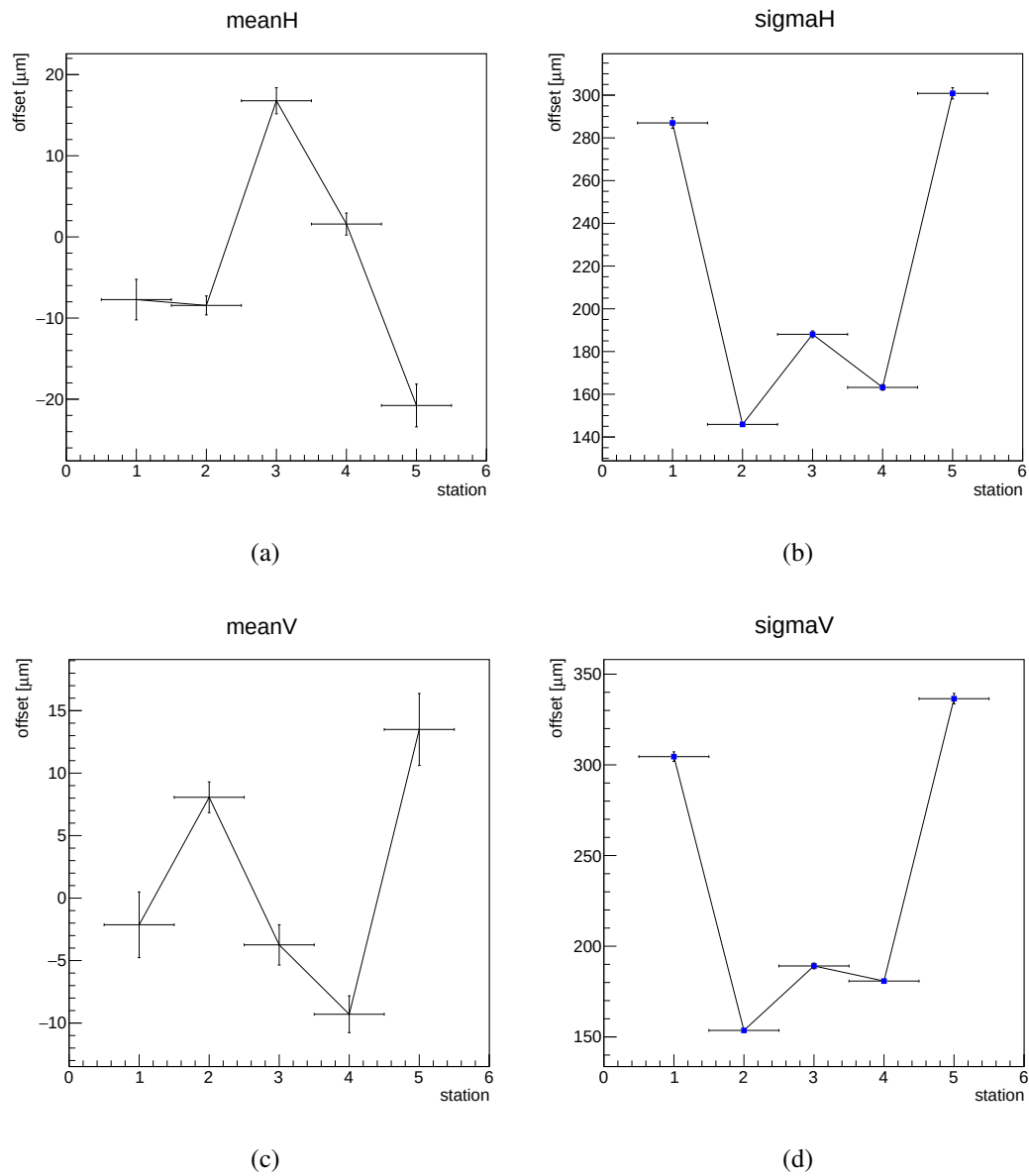


Figure 5.11: Mean offsets for the horizontal (a) and vertical (c) planes after the alignment, with corresponding sigma values (b) and (d) respectively.

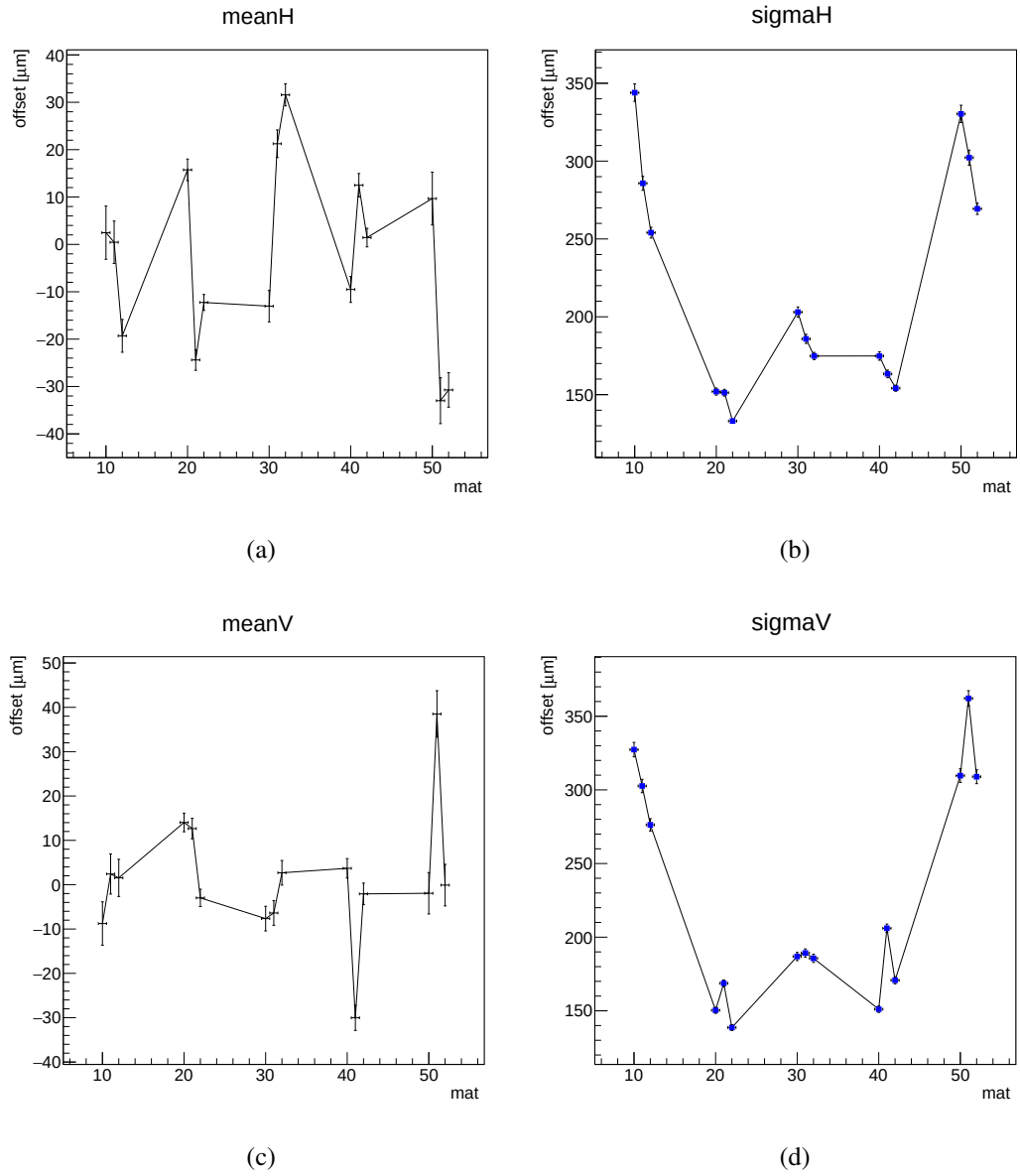


Figure 5.12: Mean offsets for the horizontal (a) and vertical (c) mats after the alignment, with corresponding sigma values (b) and (d) respectively.

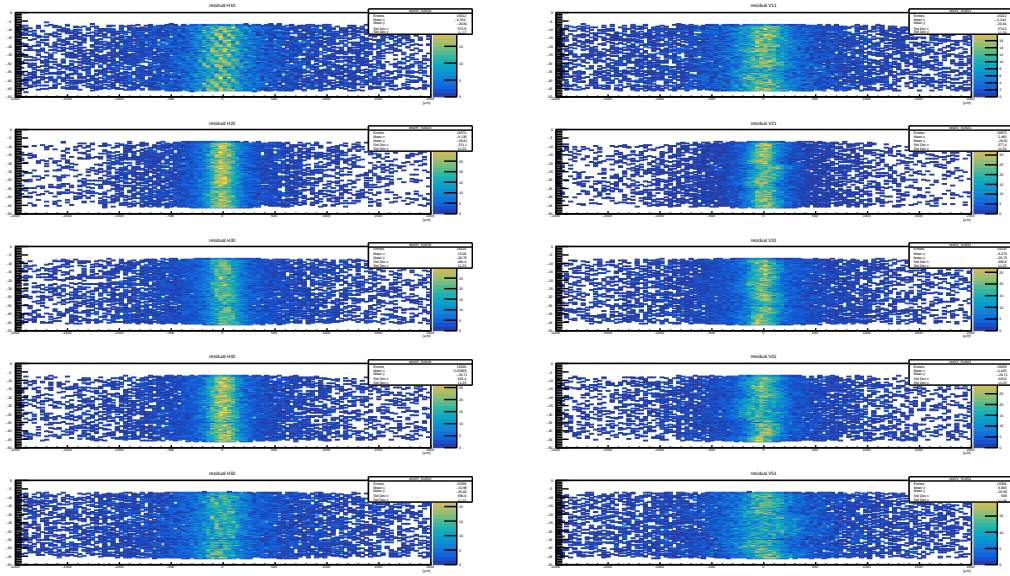


Figure 5.13: Extrapolated track positions X for horizontal (left) and vertical (right) planes versus residuals for run 4449 with corrected geometry.

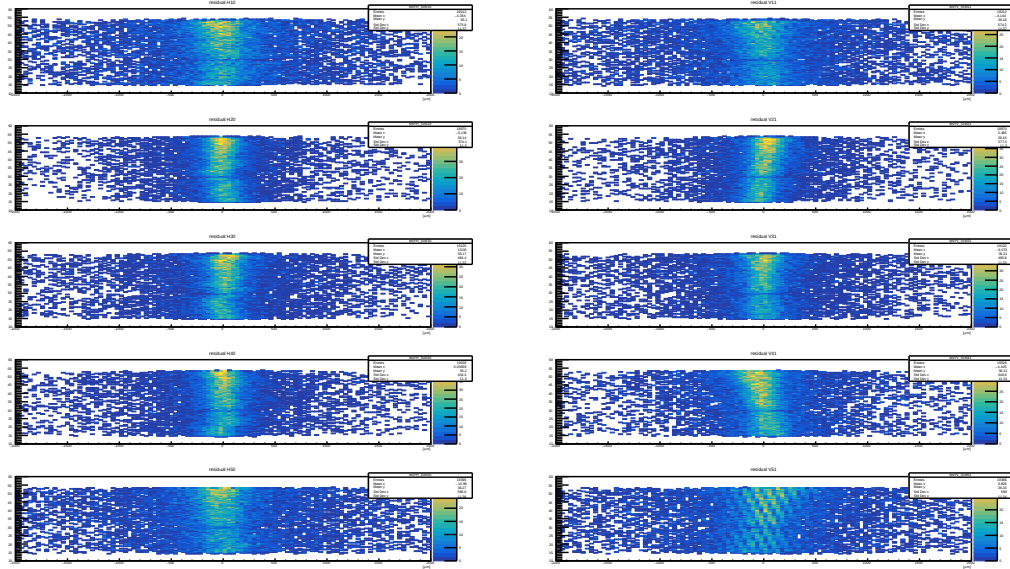


Figure 5.14: Extrapolated track positions Y for horizontal (left) and vertical (right) planes versus residuals for run 4449 with corrected geometry.

5.2.3 Discussion

Table 5.4: Mean of the residual distributions before and after alignment, for horizontal (H) SciFi planes.

SciFi Plane (H)	Mean residual(in μm)	
	Before	After
1	266.4	-4.354
2	-247.1	-9.136
3	11.66	13.08
4	43.15	0.03669
5	29.74	-10.98

Table 5.5: Mean of the residual distributions before and after alignment, for vertical (V) SciFi planes.

SciFi Plane (V)	Mean residual(in μm)	
	Before	After
1	118.7	-4.144
2	-144.6	2.485
3	31.95	-6.073
4	21.76	-4.405
5	-1.866	9.606

Comparison of the means of the residual distributions with the alignment parameters provided by the survey measurements and calculated by MINUIT minimization is given in Tables 5.4 and 5.5 for horizontal and vertical SciFi planes respectively.

It can be seen from the Tables 5.4 and 5.5 that the mean of the residuals for each plane is significantly closer to zero, except from the horizontal plane of station 3 and the vertical plane of station 5. This shows that the MINUIT alignment has indeed improved the accuracy of the track fit. Both horizontal and vertical planes of station 1 have significant differences, indicating that the MINUIT alignment has corrected a large systematic error in track fitting for this station.

On the other hand, for the vertical plane of station 5 and the horizontal plane of station 3, the mean residuals are increased after the alignment. However, since their mean residual values before the alignment are already close to zero, the overall alignment is not significantly affected by it.

Comparing Figures 5.7 with 5.13 and 5.8 with 5.14, the improvement of the alignment can be seen geometrically.

The sigma values for the inner stations 2, 3, and 4 are notably smaller than the outer stations 1 and 5, both before and after MINUIT alignment. This effect can be seen in the residual distributions also. Station 1 and Station 5 have wider residual distri-

butions compared to the rest of the stations, indicating that the residuals for the inner stations are more tightly clustered around the mean, compared to the outer stations.

To conclude, the MINUIT minimization method successfully improved the overall alignment of the SND@LHC SciFi modules. However, it did not significantly reduce the wider residual distributions of the outer SciFi stations, 1 and 5, compared to the inner SciFi stations, 2,3, and 4. This suggests that even though the MINUIT minimization method can be used for the alignment, it may not be the optimal solution and other methods may be tried to achieve a better alignment for all SciFi stations.

A candidate for a different alignment method is the Millepede method, which was suggested by the software team leader of the SND@LHC collaboration, Thomas Ruf. Millepede algorithm and the possible SciFi alignment method are explained in Chapter 6.

CHAPTER 6

FUTURE ALIGNMENT STUDIES: GENERAL BROKEN LINES AND MILLEPEDE-II

6.1 Introduction

The alignment results of the MINUIT method given and discussed in Chapter 5 opened a possibility for a different alignment method for the SND@LHC SciFi modules. Millepede is a method that is used in a variety of high-energy physics experiments and proved its efficiency. The details of the algorithm and the planned alignment method are explained in this chapter.

To reach an optimal solution for the alignment parameters, the global minimum of the χ^2 function has to be calculated with respect to each and every alignment and track parameter of the system. The χ^2 as a sum of squares of residuals over the track measurements and predictions, or fitted values, is:

$$\chi^2 = \sum_{i,j} \frac{r_{ij}^2}{\sigma_{ij}^2} \quad (6.1)$$

where r_{ij} is the residual of a measurement, and σ_{ij} is the corresponding uncertainty. A residual are defined as the difference between individual measurements m_{ij} and the predictions p_{ij} of a track j :

$$r_{ij} = m_{ij} - p_{ij}(\mathbf{a}, \mathbf{q}_j)$$

with alignment parameters $\mathbf{a}$, and predicted track parameters $\mathbf{q}_j$.

Therefore, the global minimization of Equation 6.1 becomes:

$$\frac{d\chi^2(\mathbf{a}, \mathbf{q}_1, \mathbf{q}_2, \dots)}{d(\mathbf{a}, \mathbf{q}_1, \mathbf{q}_2, \dots)} = 0 \quad (6.2)$$

The minimization problem in Equation 6.2 can be linearized and expressed as a matrix equation, given the initial values for the alignment and track parameters. Considering the number of total parameters, the related matrix has a large dimension, n_{tot} :

$$n_{tot} = n_{glo} + (n_{loc}n_{track})$$

where n_{glo} is the number of global parameters of the system, n_{loc} is the number of local parameters for a single track, and n_{track} is the total number of tracks used for the process. The *global parameters* correspond to the alignment parameters to be determined, which affect all measurements, whereas the *local parameters* affect only the track fit.

6.2 Millepede Algorithm

The Millepede algorithm offers a solution for the χ^2 minimization for Equation 6.1 by performing least squares fit with respect to both the alignment (global) and the track (local) parameters, with only approximation being the linearization of the problem [12].

Given some initial values for the global and local parameters, the first order linearization for the χ^2 in Equation 6.1 for small corrections can be expressed as:

$$\chi^2(\Delta \mathbf{a}, \Delta \mathbf{q}_1, \Delta \mathbf{q}_2, \dots) = \sum_{i,j} \left(m_{ij} - p_{ij}(\mathbf{a}_0, \mathbf{q}_0) + \frac{\partial r_{ij}}{\partial \mathbf{a}} \Delta \mathbf{a} + \frac{\partial r_{ij}}{\partial \mathbf{q}_j} \Delta \mathbf{q}_j \right)^2 \frac{1}{\sigma_{ij}^2} \quad (6.3)$$

Minimizing the function 6.3 by 6.2 can be expressed as a linear matrix equation of the form:

$$\begin{bmatrix} \sum \mathbf{G}_{1j} & \dots & \mathbf{M}_j & \dots \\ \vdots & \ddots & 0 & 0 \\ \mathbf{M}_j^T & 0 & \mathbf{\Gamma}_j & 0 \\ \vdots & 0 & 0 & \ddots \end{bmatrix} \cdot \begin{bmatrix} \Delta \mathbf{a} \\ \vdots \\ \Delta \mathbf{q}_j \\ \vdots \end{bmatrix} = \begin{bmatrix} \sum \mathbf{g}_{1j} \\ \vdots \\ \mathbf{L}_j \\ \vdots \end{bmatrix} \quad (6.4)$$

where

$$(\mathbf{G}_{1j})_{kl} = \sum_i \left(\frac{\partial r_{ij}}{\partial a_k} \frac{\partial r_{ij}}{\partial a_l} \frac{1}{\sigma_{ij}^2} \right) \quad (6.5)$$

$$(\mathbf{M}_j)_{kl} = \sum_i \left(\frac{\partial r_{ij}}{\partial a_k} \frac{\partial r_{ij}}{\partial q_{jl}} \frac{1}{\sigma_{ij}^2} \right) \quad (6.6)$$

$$(\mathbf{\Gamma}_j)_{kl} = \sum_i \left(\frac{\partial r_{ij}}{\partial q_{jk}} \frac{\partial r_{ij}}{\partial q_{jl}} \frac{1}{\sigma_{ij}^2} \right) \quad (6.7)$$

$$(\mathbf{g}_{1j})_k = \sum_i \left(\frac{\partial r_{ij}}{\partial a_k} \frac{\partial r_{ij}}{\sigma_{ij}^2} \right) \quad (6.8)$$

$$(\mathbf{L}_j)_k = \sum_i \left(\frac{\partial r_{ij}}{\partial q_{jk}} \frac{\partial r_{ij}}{\sigma_{ij}^2} \right) \quad (6.9)$$

In the left-hand side of the matrix equation 6.4, the $(\mathbf{G}_{1j})_{kl}$ sum depends only on the derivatives with respect to the global parameters, whereas the $(\mathbf{\Gamma}_j)_{kl}$ matrices depend only on the derivatives with respect to the local parameters. The $(\mathbf{M}_j)_{kl}$ terms have contributions from both the local and the global parameters. On the other hand, in the right-hand side of Equation 6.4, the residual for each measurement is multiplied by the related local (Equation 6.9) or global (Equation 6.8) derivatives to ensure a unique solution to the equation [1].

6.2.1 Millepede-II

Millepede-II¹ is the second version of the Millepede program that is developed by V. Blobel. In the second version, Mille and Pede routines are separated. The Mille routine creates binary files with specific data blocks containing the information needed for the actual minimization process. Whereas, Pede is a stand-alone Fortran program that takes the binary input created by Mille and performs the minimization [12].

The user needs to supply the following for each measurement:

1. The track fit prediction and the residual, $m_{ij} - p_{ij}(\mathbf{a}, \mathbf{q}_j)$
2. Uncertainty, σ_{ij}

¹ Millepede II - Draft Manual. V. Blobel, University Hamburg, 2007.
https://www.desy.de/~kleinwrt/MP2/doc/html/draftman_page.html

3. Derivatives of the residuals with respect to the local parameters, $\frac{\partial r_{ij}}{\partial q_j}$
4. Derivatives of the residuals with respect to the global parameters, $\frac{\partial r_{ij}}{\partial a}$

6.3 General Broken Lines Refit

General Broken Lines (GBL) is a track fitting method that takes the Kalman fitted tracks as input, or seed, and performs a refit on the Genfit track objects. The GBL is an advanced tracking method that introduces additional track parameters to describe the multiple scattering, which arises mainly from Coulomb interactions and can affect the position and the momentum of the particles [31]. One of the most important advantages of GBL is that the necessary methods to produce output files for Millepede-II alignment are implemented in the GBL class. The details of the Millepede-II (MP-II) alignment are described in Chapter 6.2.

The GBL method performs a refit for a set of measurements while adding scatterers to the particle trajectory. Scatterers are some additional points on the trajectory regarding the multiple scattering effects. The points on the initial seed need to be ordered by their arc lengths. A local coordinate system (u, v, w) for each point is interpreted with local parameters, $\mathbf{p}_l$. A point-to-point Jacobian, $\frac{\partial \mathbf{p}_{l,i+1}}{\partial \mathbf{p}_{l,i}}$ is needed to define how the track parameter corrections propagate along the initial trajectory.

By interpolating two neighboring points with offsets, the deviation of each point from the initial trajectory can be described [32]. For each scatterer of the trajectory, a so-called kink is defined using the offsets of the scatterer and its two neighboring points. The variance of the kink depends on the angular multiple scattering error that is at the center point. The derivatives of the measurements and the kinks with respect to the fit parameters can be calculated using the point-to-point Jacobian. As a consequence, it is possible to describe the track fit with a linear matrix equation:

$$\mathbf{B}\mathbf{p}_l = \mathbf{m}$$

where $\mathbf{p}_l$ is the vector of track fit parameters, $\mathbf{m}$ is the vector of measurements with kinks, and $\mathbf{B}$ is the matrix that describes the relation between the track fit parameters and the measurements with kinks. The matrix $\mathbf{B}$ has a band structure with a border

of non-zero elements around the main diagonal, hence referred to as a bordered-band matrix [32]. In GBL implementation, measurement refers to an arbitrary linear function depending on the local track parameters, with a prediction $\mathbf{f}_m$ and a covariance matrix $\mathbf{V}_m$. The prediction matrix contains the expected values for the measurements, whereas the covariance matrix describes the uncertainty of the measurements.

The covariance matrix $\mathbf{V}_m$ is diagonalized during the GBL refit and provides scalar measurements m_{ij} and corresponding errors σ_{ij} that will later be used in MP-II alignment. If the user will perform MP-II alignment, one needs to describe how the global derivatives $\partial\mathbf{f}/\partial p$ should be calculated and assign labels for each global derivative. The local derivatives $\partial\mathbf{f}/\partial\mathbf{q}_j$ are calculated internally by GBL. Using the MilleBinary subroutine of GBL, the information of local and global derivatives for each trajectory can be written to a binary file for MP-II [31].

6.3.1 GBL in GENFIT

GBL can be easily accessible from GENFIT, with classes that are designed to handle bordered-band matrix operations, store and manage data associated with independent scalar measurements, information about fit status, construct GBL points and trajectories, and create binary output for Millepede-II alignment. The source code for GBL is provided by the DESY research center, and more information about the method is provided on the GBL homepage² and the related Physics at the Terascale wiki³.

6.4 Implementing Millepede-II to SND@LHC: Progress

The implementation of the Millepede-II to the alignment of SND@LHC SciFi modules is a work in progress. Thus far, the GBL refit method has been successfully implemented and tested with the Genfit tracks produced by the Simple Tracking method. The necessary interface that allows calling Fortran and C++ based MP-II source codes from Python is created. Currently, the binary files produced by the Mille subroutine are being examined.

² General Broken Lines. <https://www.desy.de/kleinwrt/GBL/doc/cpp/html/>

³ Physics at the Terascale Wiki, General Broken Lines. <https://www.terascale.de/wiki/generalbrokenlines>

CHAPTER 7

CONCLUSION

In this thesis, the spatial alignment of the SciFi modules of the SND@LHC detector is studied using the MINUIT minimization software. The alignment parameters utilized are the relative SciFi mat positions within the measured SciFi plane, and the rotation angles for the entire SciFi plane. The alignment parameters correspond to the relative mat positions within the measured plane (one per mat), and the rotation of SciFi planes (one per plane).

The minimization method aims to adjust alignment parameters so that the chi-square value is minimized. As a result, the discrepancies between the observed value and model prediction are minimized. The observed value corresponds to the SciFi residuals, which are calculated as the distance of the closest approach between the line given by the cluster end-points and the particle trajectory in 3D, whereas the model prediction refers to the track fit. Track fit is done using the Simple Tracking method which is developed for the experiment.

During the alignment procedure, one mat from each orientation and the rotation of one plane is fixed, and the alignment is done locally relative to the fixed modules. The alignment procedure uses the initial measurements that are determined by the survey measurements and performs minimization based on the SIMPLEX method provided by the MINUIT minimization package.

For this thesis, a single run from each emulsion run period, a total of four runs are used. Comparison of the means of the residual distributions with the alignment parameters provided by the survey measurements and calculated by MINUIT minimization showed that the mean of the residuals for each plane is significantly closer to zero,

except from the horizontal plane of station 3 and the vertical plane of station 5. This shows that the MINUIT alignment has indeed improved the accuracy of the track fit. However, MINUIT did not significantly reduce the wider residual distributions of the outer SciFi stations compared to the inner SciFi stations. This suggests that even though the MINUIT minimization method can be used for the alignment, it may not be the optimal solution and other methods may be tried to achieve a better alignment for all SciFi stations. As a new possible alignment, the usage of the Millepede algorithm, which is used in a variety of high-energy physics experiments and proved its efficiency, is proposed. The details of the algorithm and the planned alignment method are explained along with the current process, which can further improve the alignment of the SciFi modules.

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Appendix A

VALUES OF THE ALIGNMENT PARAMETERS FOR DIFFERENT RUN PERIODS

After the minimization routine is completed, the corrected values of each alignment parameter are displayed. In the output, there are a total of 40 alignment parameters; 30 corresponding to the relative mat positions within the measured plane (one per mat), and 10 corresponding to the rotation of SciFi planes (one per plane). The positional alignment parameters are labeled with "M", whereas the rotational ones are labeled with "D". The labeling format is:

"SciFi/Loc + M(if spatial) or D(if rotational) + s(number of the SciFi station) + o(0 for horizontal orientation, 1 for vertical orientation) + m(number of the mat)"

For example, "Scifi/LocM310" can be decoded as the "positional alignment parameter for the mat number 0 of the vertical plane in the 3rd SciFi station.

The values of each corrected alignment parameter for the runs 4449, 4769, 5036, and 5377 can be seen in Table A.1. Each run is chosen from one of the four emulsion run periods, thus run 4449 is from emulsion run 0, run 4769 is from emulsion run 1, run 5036 is from emulsion run 2, and run 5377 is from emulsion run 3.

Table A.1: Corrected value of each alignment parameter with errors for different runs.

Alignment Parameter	Run 4449	Run 4769	Run 5036	Run 5377
Scifi/LocD10	-7.73 ± 2.50	20.22 ± 5.85	26.25 ± 4.26	22.43 ± 4.04
Scifi/LocD20	-8.44 ± 1.17	-20.37 ± 2.49	-4.97 ± 2.17	-12.86 ± 2.08
Scifi/LocD30	16.78 ± 1.67	2.63 ± 3.27	-38.20 ± 2.50	-5.97 ± 2.46
Scifi/LocD40	1.59 ± 1.35	4.65 ± 2.52	47.71 ± 2.03	-2.09 ± 2.09
Scifi/LocD50	-20.78 ± 2.64	-2.19 ± 5.87	-19.28 ± 4.30	11.99 ± 4.09
Scifi/LocD11	-2.14 ± 2.63	46.44 ± 5.57	69.10 ± 4.25	22.93 ± 4.23
Scifi/LocD21	8.07 ± 1.23	6.82 ± 2.45	-5.41 ± 1.98	5.89 ± 2.10
Scifi/LocD31	-3.74 ± 1.61	-77.69 ± 3.21	-62.57 ± 2.66	-43.45 ± 2.48
Scifi/LocD41	-9.30 ± 1.47	46.27 ± 2.62	19.73 ± 2.32	27.68 ± 2.30
Scifi/LocD51	13.50 ± 2.88	15.78 ± 6.07	41.91 ± 4.50	3.61 ± 4.56
Scifi/LocM100	2.47 ± 5.62	23.37 ± 10.85	16.88 ± 5.86	40.93 ± 6.74
Scifi/LocM110	0.45 ± 4.47	64.83 ± 10.27	-13.19 ± 7.61	-15.70 ± 7.97
Scifi/LocM120	-19.30 ± 3.46	-15.42 ± 8.97	63.46 ± 6.32	31.94 ± 6.18
Scifi/LocD200	15.74 ± 2.29	-9.49 ± 4.65	17.96 ± 4.11	-10.06 ± 3.73
Continued on next page				

Table A.1 – continued from previous page

Alignment Parameter	Run 4449	Run 4769	Run 5036	Run 5377
Scifi/LocD210	-24.40 ± 2.18	-52.28 ± 4.46	-0.73 ± 3.95	-16.50 ± 3.67
Scifi/LocD220	-12.25 ± 1.68	-1.67 ± 3.75	-23.27 ± 3.24	-11.71 ± 3.35
Scifi/LocM300	-13.04 ± 3.31	-8.97 ± 6.27	-49.01 ± 4.97	-19.37 ± 4.18
Scifi/LocM310	21.25 ± 2.91	7.50 ± 6.60	-11.36 ± 4.83	23.44 ± 4.78
Scifi/LocM320	31.56 ± 2.32	9.64 ± 4.48	-52.18 ± 3.46	-17.60 ± 3.75
Scifi/LocM400	-9.51 ± 2.73	15.85 ± 4.64	37.83 ± 3.94	-20.40 ± 3.57
Scifi/LocD410	12.49 ± 2.47	-6.36 ± 4.43	33.48 ± 3.74	24.23 ± 3.73
Scifi/LocD420	1.44 ± 1.96	4.86 ± 3.99	64.54 ± 2.98	-6.69 ± 3.37
Scifi/LocM500	9.68 ± 5.57	-4.17 ± 9.88	-5.56 ± 8.36	56.014 ± 6.60
Scifi/LocM510	-33.00 ± 4.85	16.12 ± 11.52	-24.19 ± 7.83	-53.16 ± 7.32
Scifi/LocM520	-30.72 ± 3.63	-17.33 ± 8.65	-23.25 ± 6.24	28.80 ± 6.52
Scifi/LocM101	-8.76 ± 4.89	13.36 ± 8.53	-29.25 ± 7.52	24.66 ± 7.57
Scifi/LocM111	2.41 ± 4.53	21.61 ± 10.94	73.78 ± 6.67	13.36 ± 7.46
Scifi/LocM121	1.53 ± 4.19	104.03 ± 9.34	158.62 ± 6.46	33.49 ± 6.32
Continued on next page				

Table A.1 – continued from previous page

Alignment Parameter	Run 4449	Run 4769	Run 5036	Run 5377
Scifi/LocM201	14.03 ± 2.10	-7.13 ± 4.00	7.70 ± 3.44	-7.96 ± 3.58
Scifi/LocD211	12.65 ± 2.31	45.14 ± 4.34	-4.27 ± 3.50	7.19 ± 3.76
Scifi/LocD221	-2.98 ± 1.96	-18.00 ± 4.10	-19.34 ± 3.30	18.79 ± 3.39
Scifi/LocM301	-7.65 ± 2.78	-40.63 ± 5.58	25.59 ± 4.43	-39.73 ± 4.55
Scifi/LocM311	-6.38 ± 2.77	-98.61 ± 5.67	-101.25 ± 4.09	-22.70 ± 3.84
Scifi/LocM321	2.68 ± 2.77	-96.48 ± 5.32	-105.82 ± 3.97	-68.54 ± 4.34
Scifi/LocM401	3.69 ± 2.19	57.96 ± 4.22	5.16 ± 3.71	43.43 ± 3.62
Scifi/LocD411	-30.03 ± 2.85	33.19 ± 4.93	91.84 ± 3.80	-8.676 ± 4.29
Scifi/LocD421	-2.08 ± 2.43	48.30 ± 4.34	-47.95 ± 3.29	51.05 ± 3.59
Scifi/LocM501	-1.94 ± 4.67	-45.09 ± 8.92	-41.26 ± 7.84	-8.19 ± 8.09
Scifi/LocM511	38.51 ± 5.25	60.82 ± 10.50	-16.61 ± 7.35	20.74 ± 8.03
Scifi/LocM521	-0.10 ± 4.69	37.20 ± 10.83	176.07 ± 6.69	-1.13 ± 6.96

Appendix B

RESULTS OF RUN 4769

B.1 Residual distributions with misaligned geometry

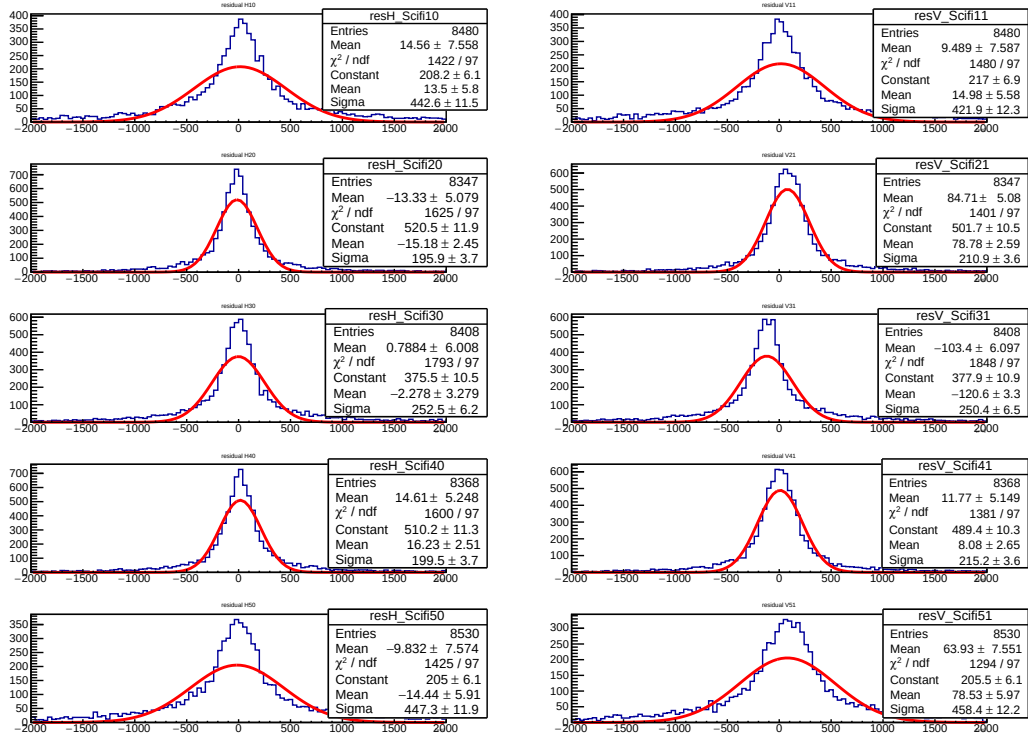


Figure B.1: Residual distributions for run 4769 with misaligned geometry, vertical SciFi planes. The horizontal axis is in μm s. The first mean in the legend represents the mean value for the data whereas the second mean represents the mean value of the fit. The constant is the maximum value of the fit.

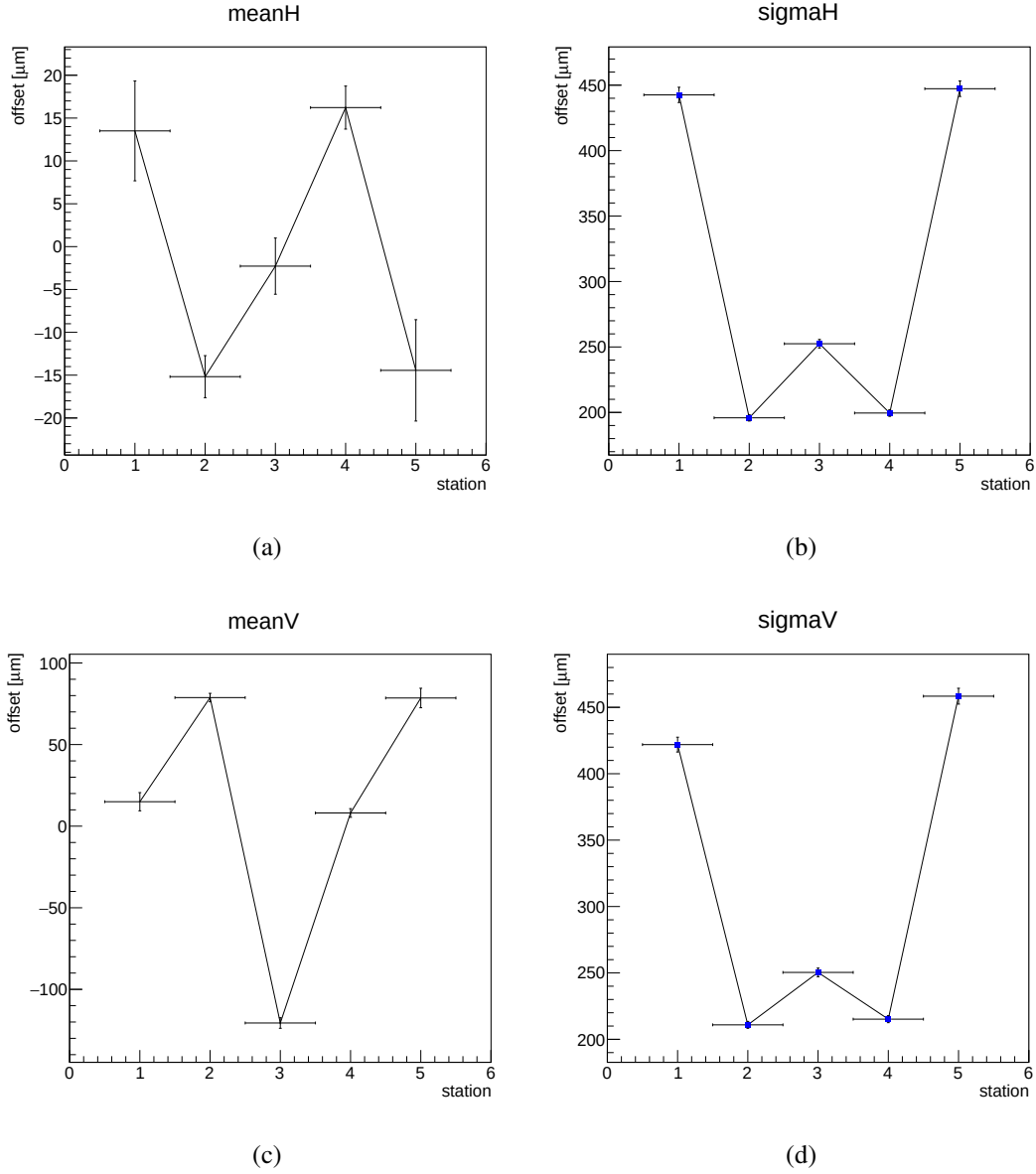


Figure B.2: Mean offsets for the horizontal (a) and vertical (c) planes before the alignment, with corresponding sigma values (b) and (d) respectively.

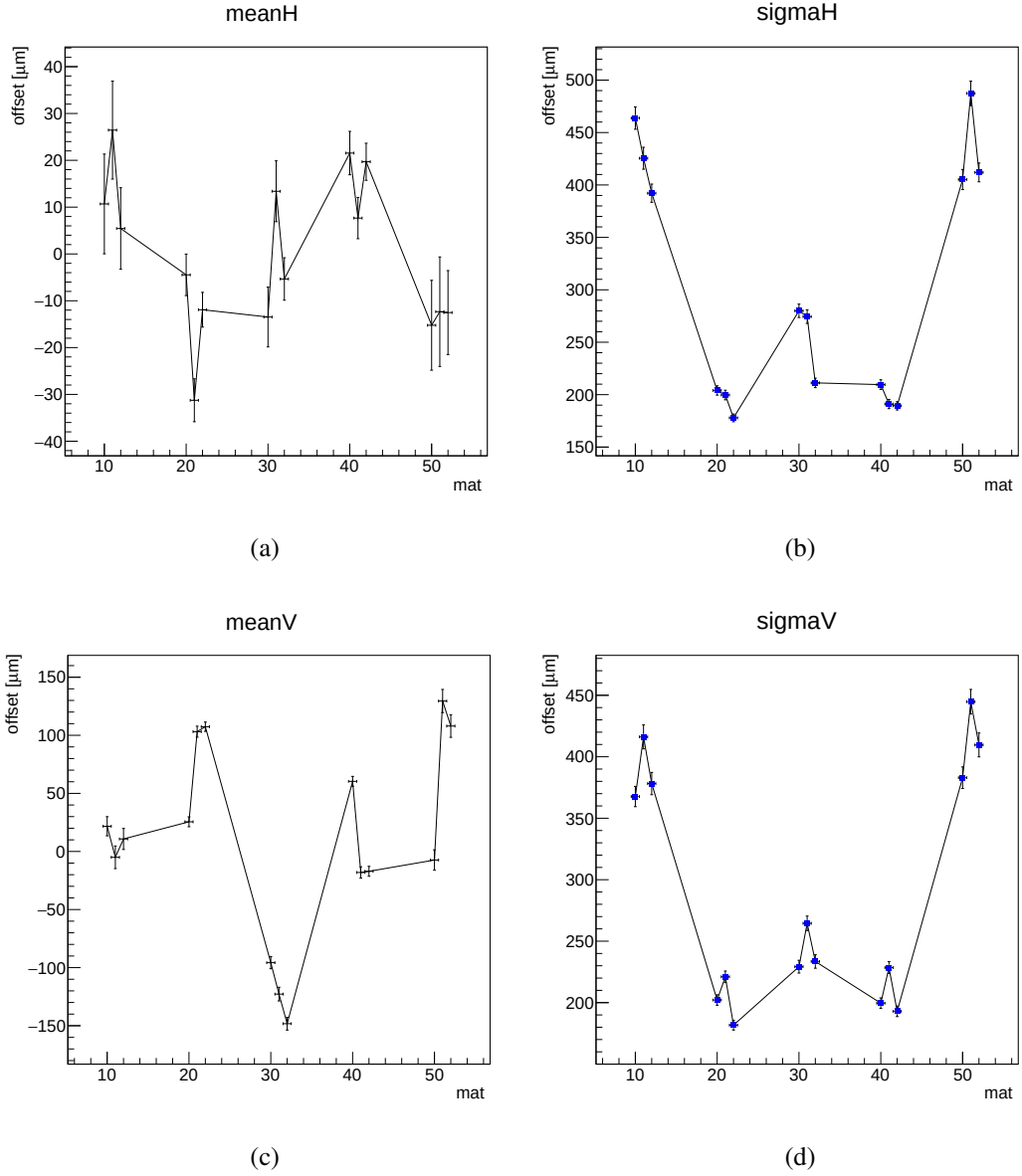


Figure B.3: Mean offsets for the horizontal (a) and vertical (c) mats before the alignment, with corresponding sigma values (b) and (d) respectively.

B.2 Residual distributions after MINUIT alignment

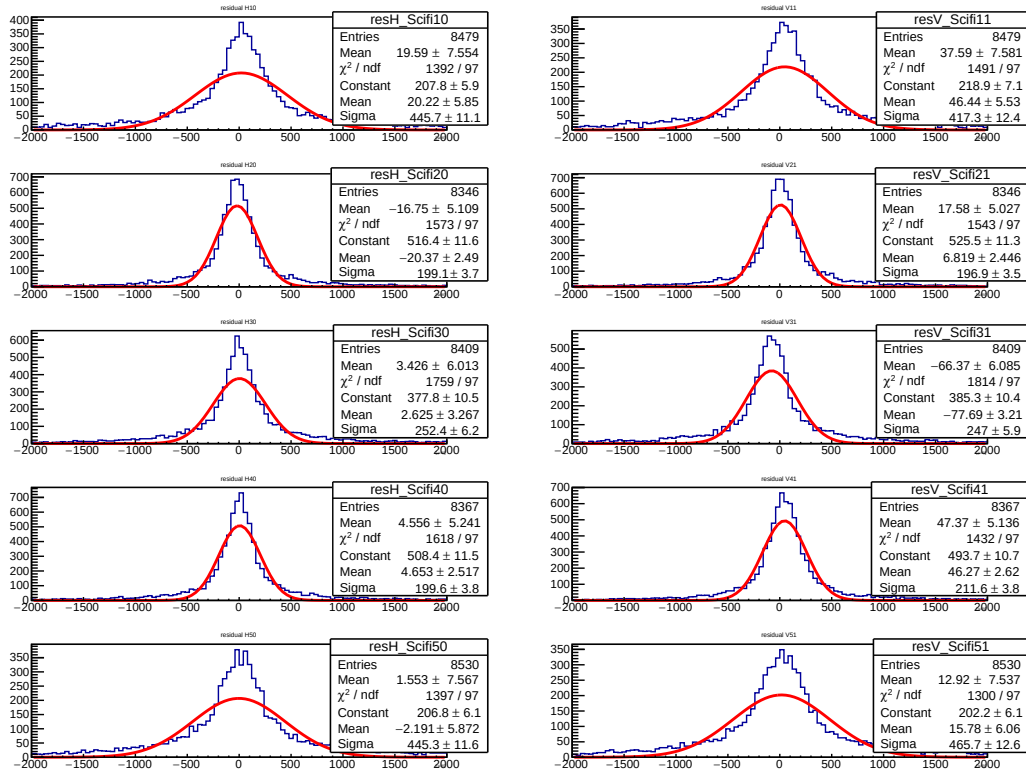


Figure B.4: Residual distributions for run 4769 with corrected geometry, vertical SciFi planes. The horizontal axis is in μm s. The first mean in the legend represents the mean value for the data whereas the second mean represents the mean value of the fit. The constant is the maximum value of the fit.

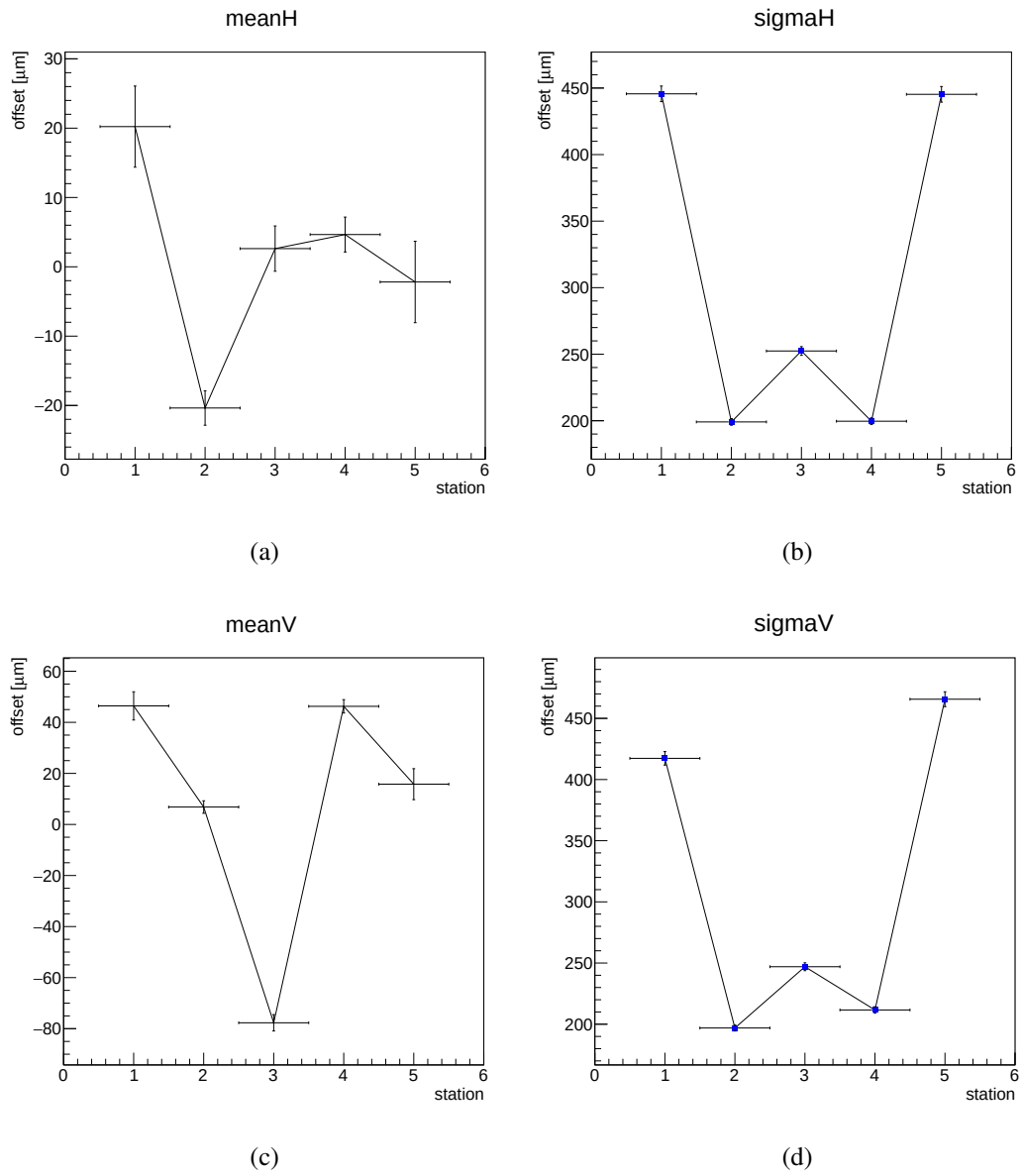
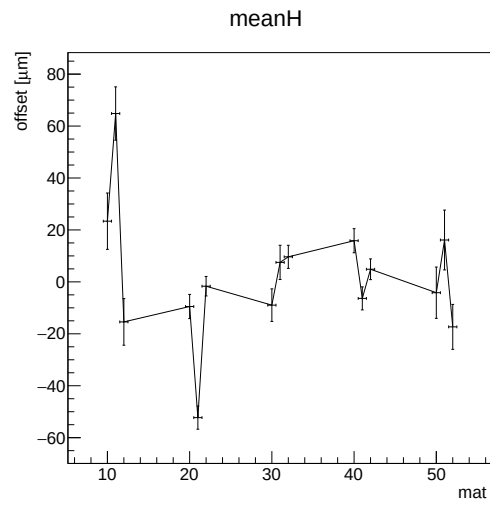
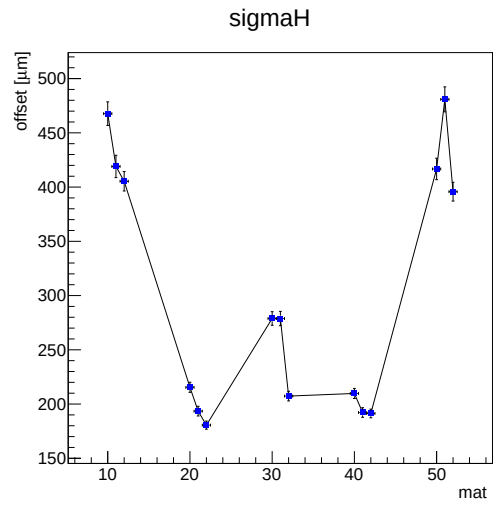


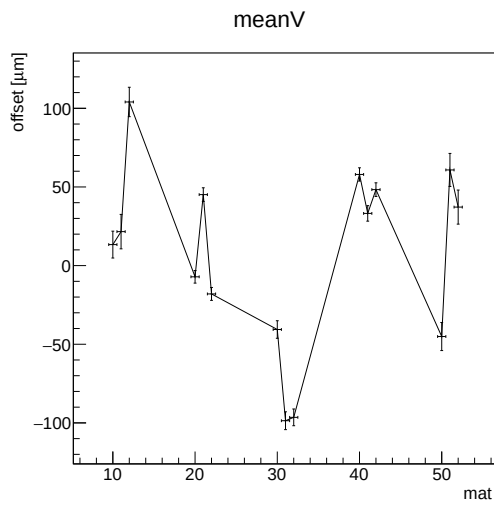
Figure B.5: Mean offsets for the horizontal (a) and vertical (c) planes after the alignment, with corresponding sigma values (b) and (d) respectively.



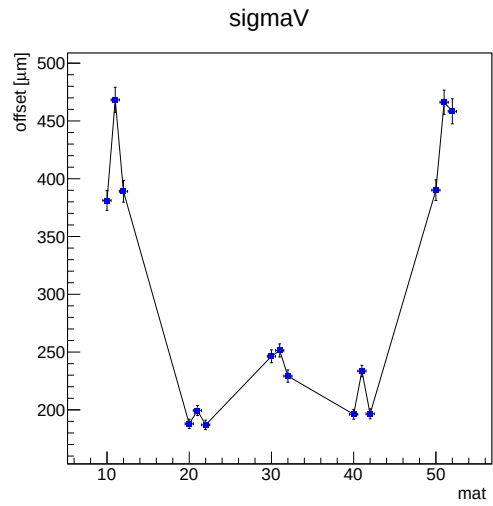
(a)



(b)



(c)



(d)

Figure B.6: Mean offsets for the horizontal (a) and vertical (c) mats after the alignment, with corresponding sigma values (b) and (d) respectively.

Appendix C

RESULTS OF RUN 5036

C.1 Residual distributions with misaligned geometry

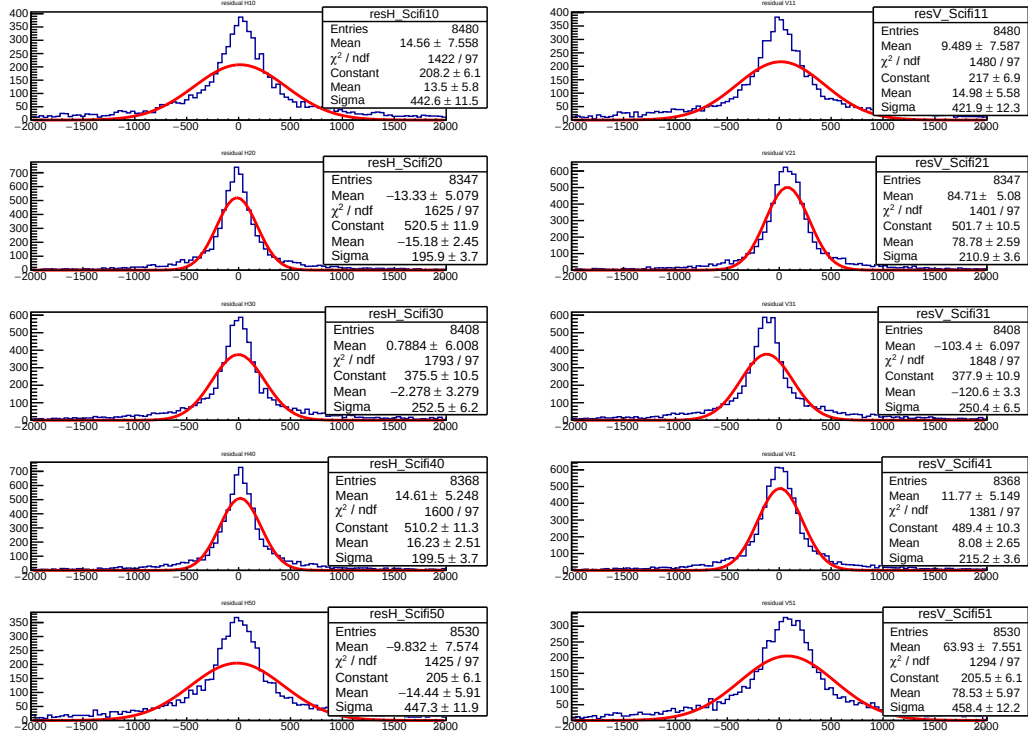


Figure C.1: Residual distributions for run 5036 with misaligned geometry, vertical SciFi planes. The horizontal axis is in μm s. The first mean in the legend represents the mean value for the data whereas the second mean represents the mean value of the fit. The constant is the maximum value of the fit.

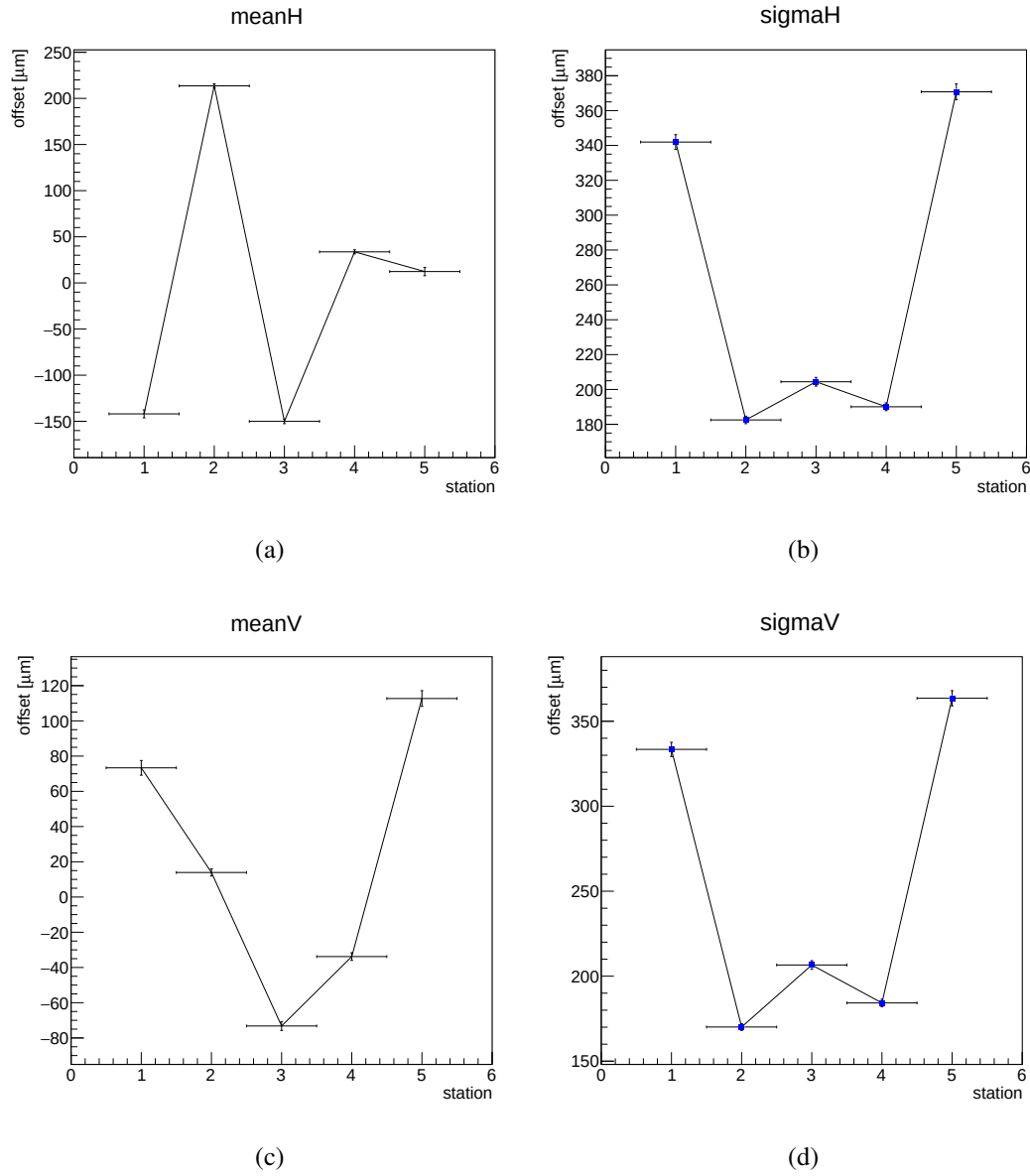


Figure C.2: Mean offsets for the horizontal (a) and vertical (c) planes before the alignment, with corresponding sigma values (b) and (d) respectively.

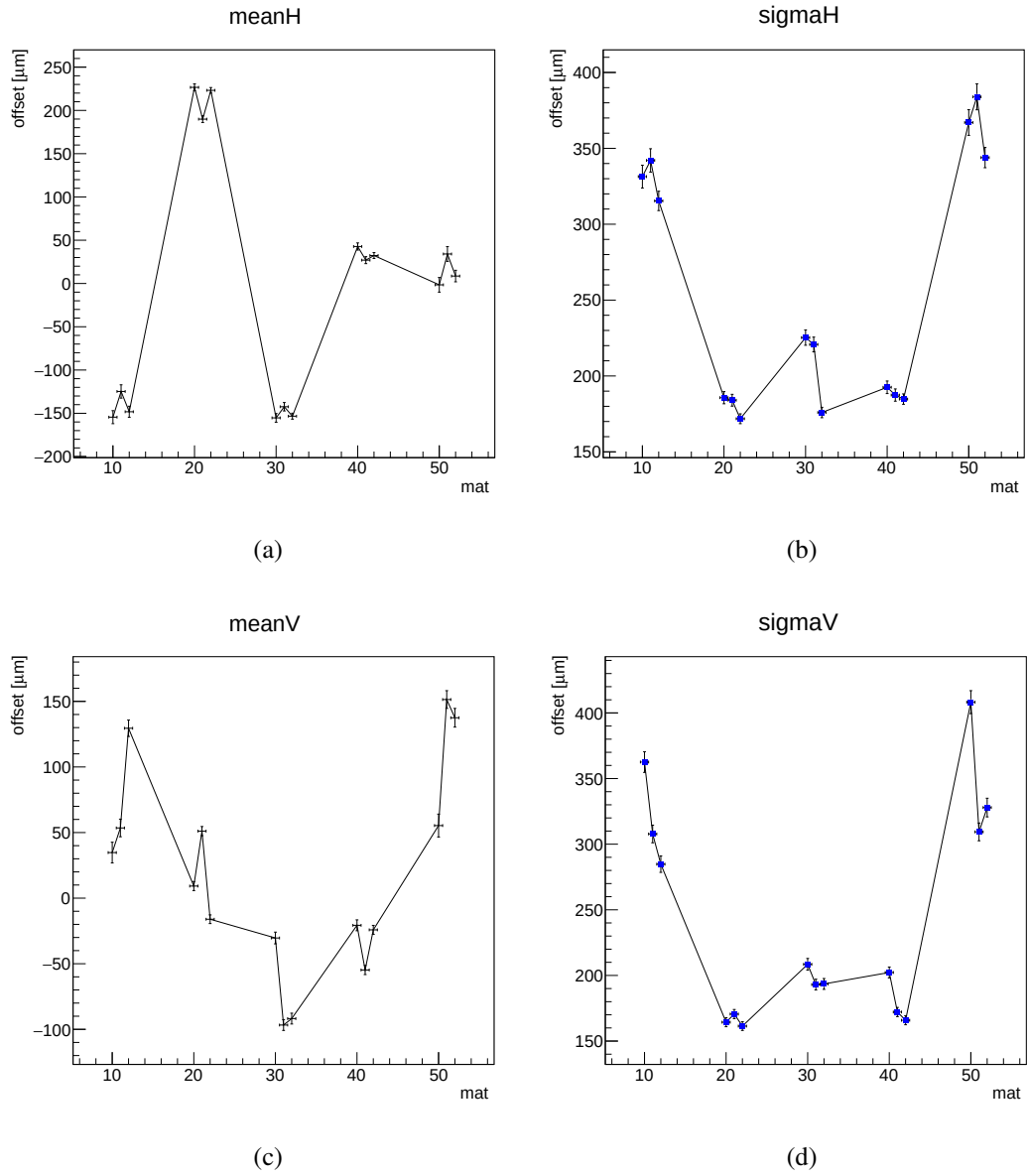


Figure C.3: Mean offsets for the horizontal (a) and vertical (c) mats before the alignment, with corresponding sigma values (b) and (d) respectively.

C.2 Residual distributions after MINUIT alignment

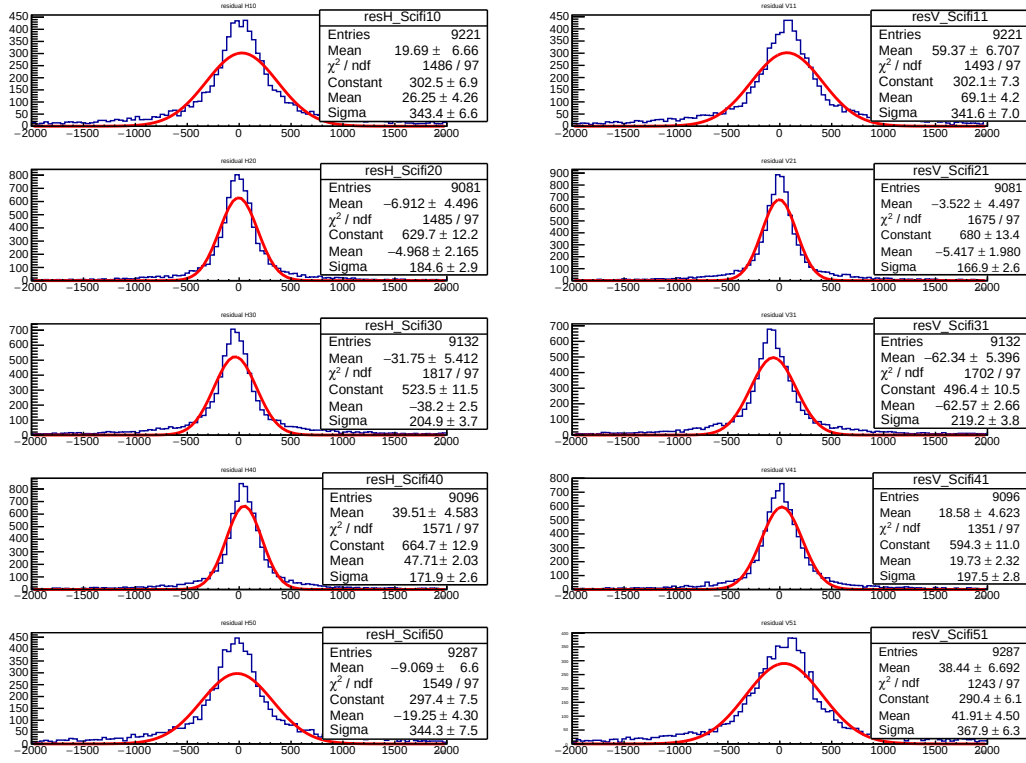


Figure C.4: Residual distributions for run 5036 with corrected geometry, vertical SciFi planes. The horizontal axis is in μms . The first mean in the legend represents the mean value for the data whereas the second mean represents the mean value of the fit. The constant is the maximum value of the fit.

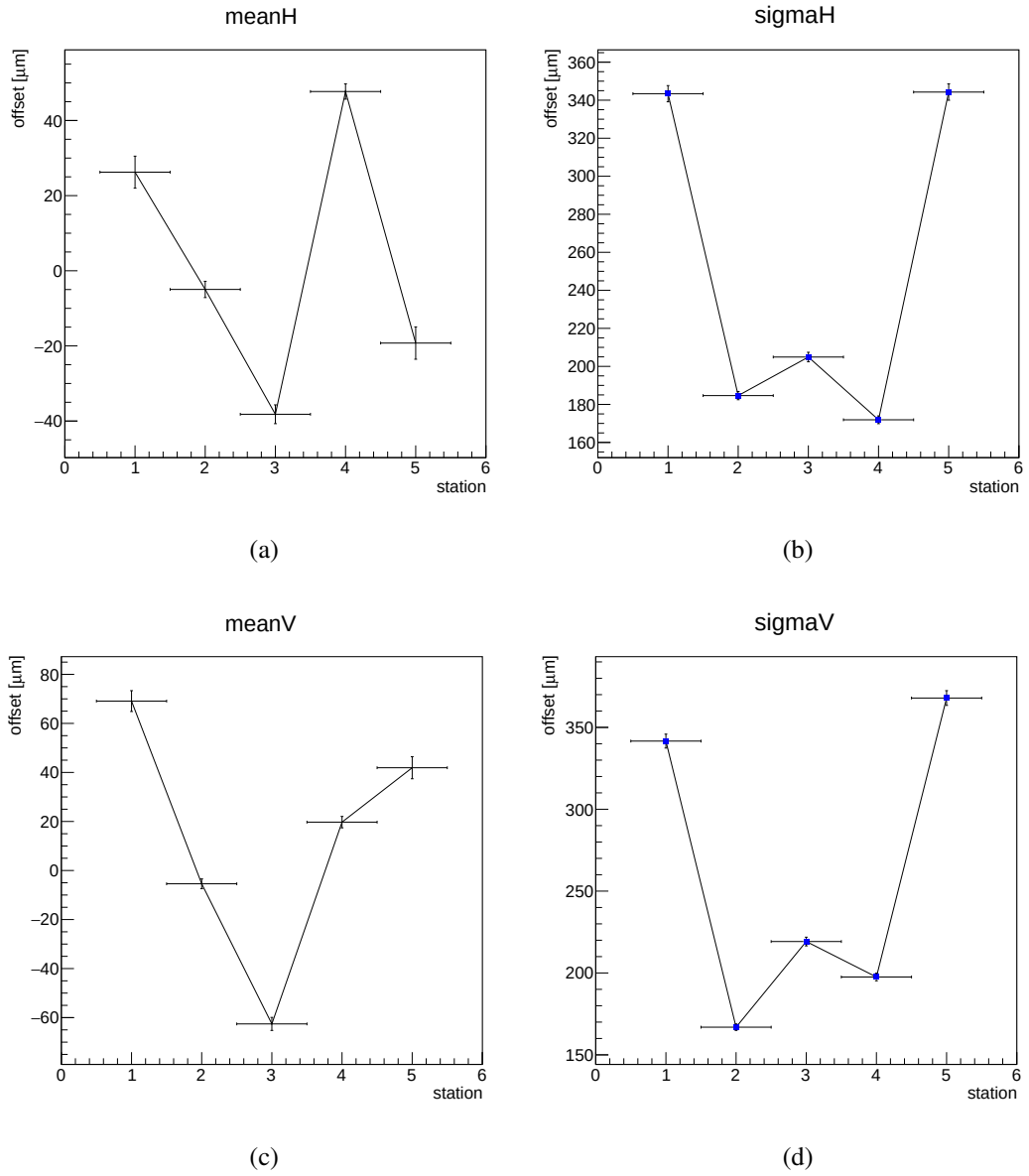


Figure C.5: Mean offsets for the horizontal (a) and vertical (c) planes after the alignment, with corresponding sigma values (b) and (d) respectively.

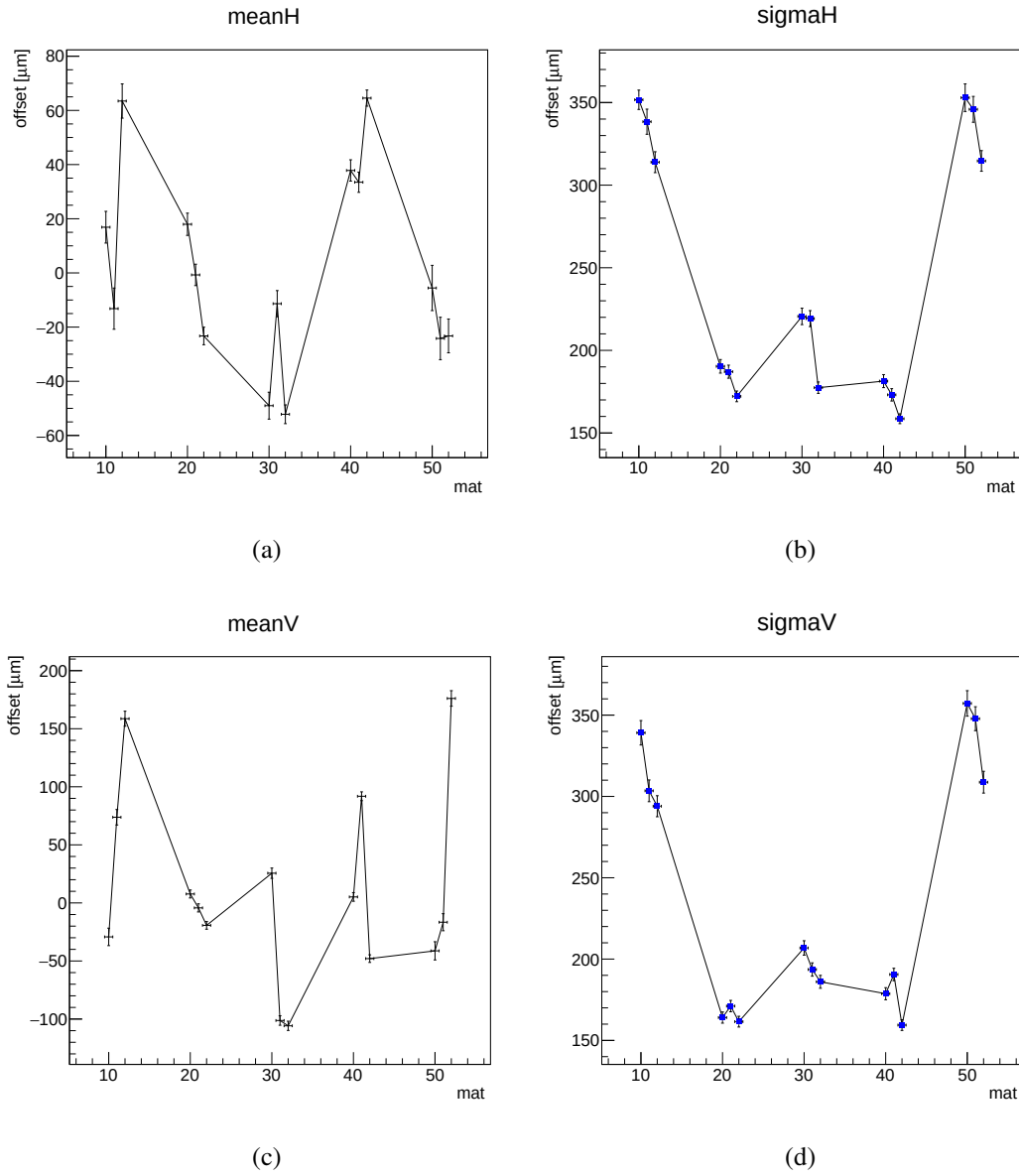


Figure C.6: Mean offsets for the horizontal (a) and vertical (c) mats after the alignment, with corresponding sigma values (b) and (d) respectively.

Appendix D

RESULTS OF RUN 5377

D.1 Residual distributions with misaligned geometry

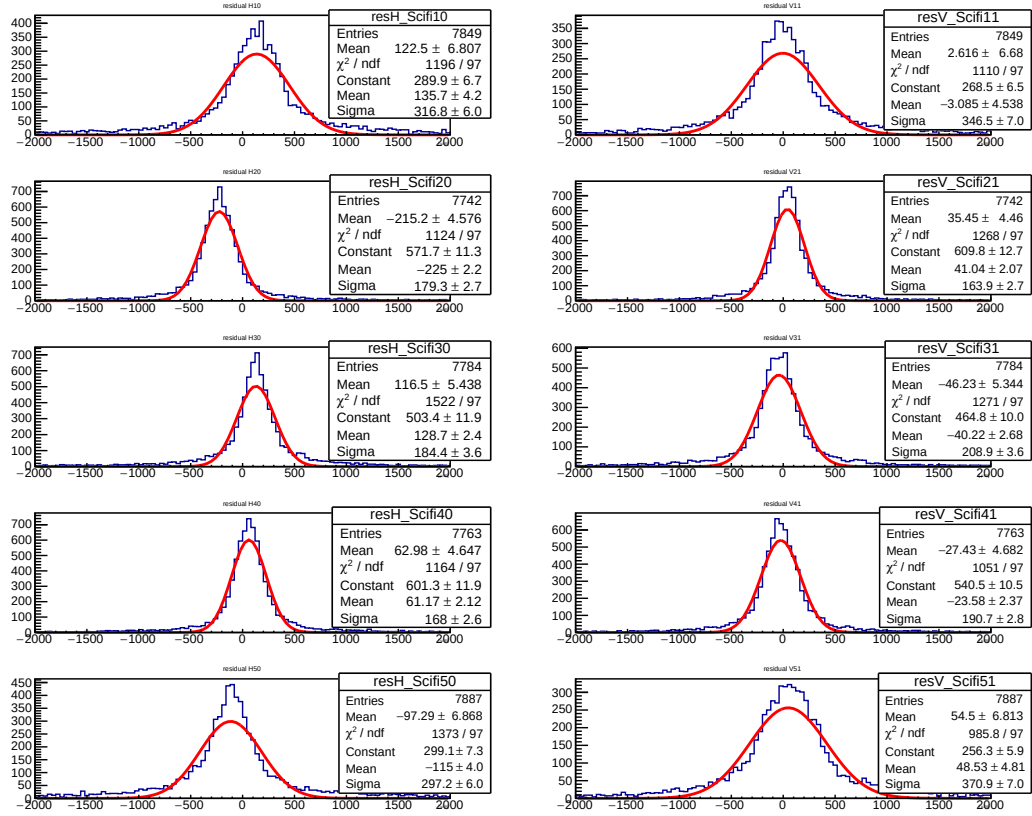


Figure D.1: Residual distributions for run 5377 with misaligned geometry, vertical SciFi planes. The horizontal axis is in μms . The first mean in the legend represents the mean value for the data whereas the second mean represents the mean value of the fit. The constant is the maximum value of the fit.

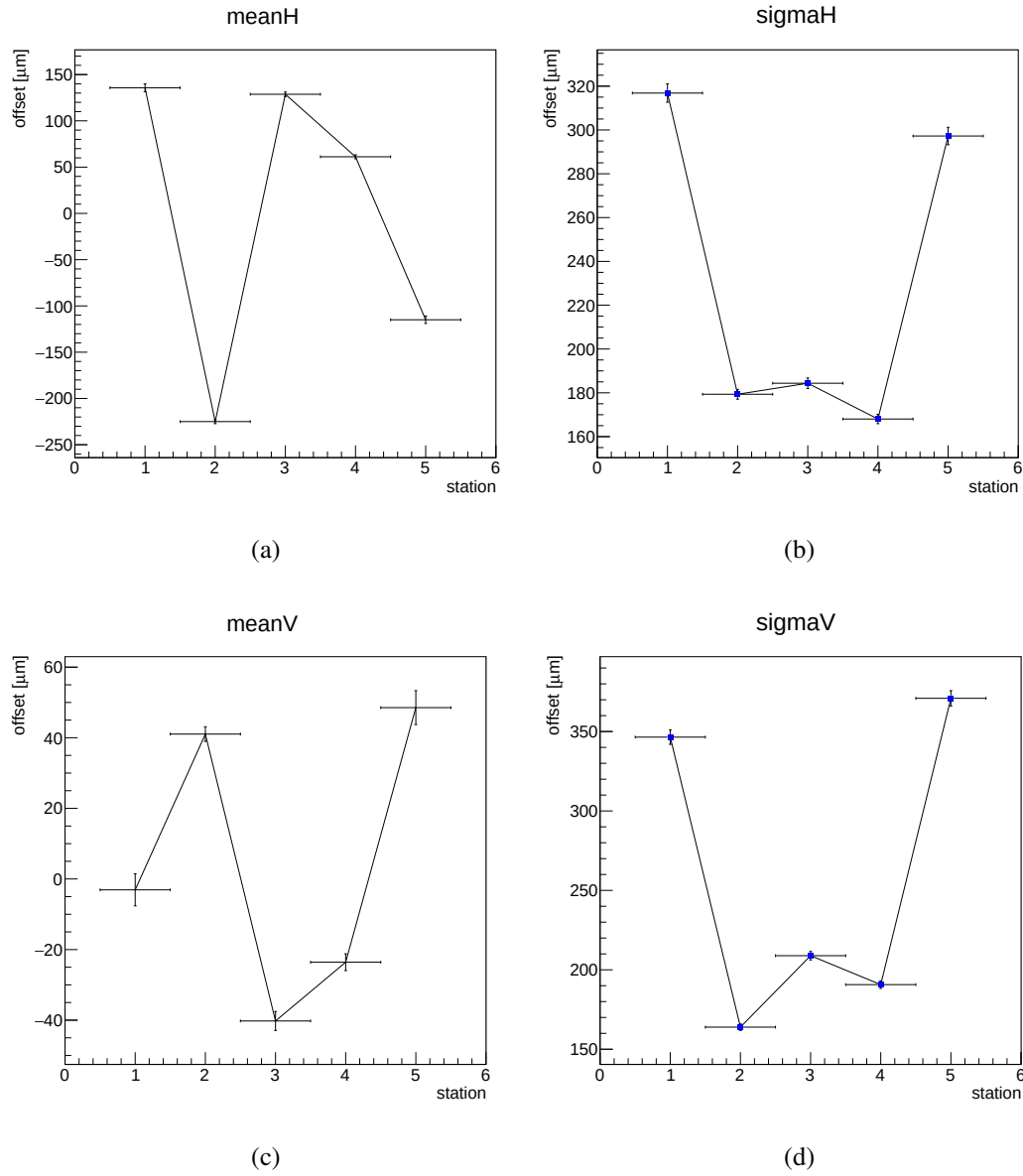


Figure D.2: Mean offsets for the horizontal (a) and vertical (c) planes before the alignment, with corresponding sigma values (b) and (d) respectively.

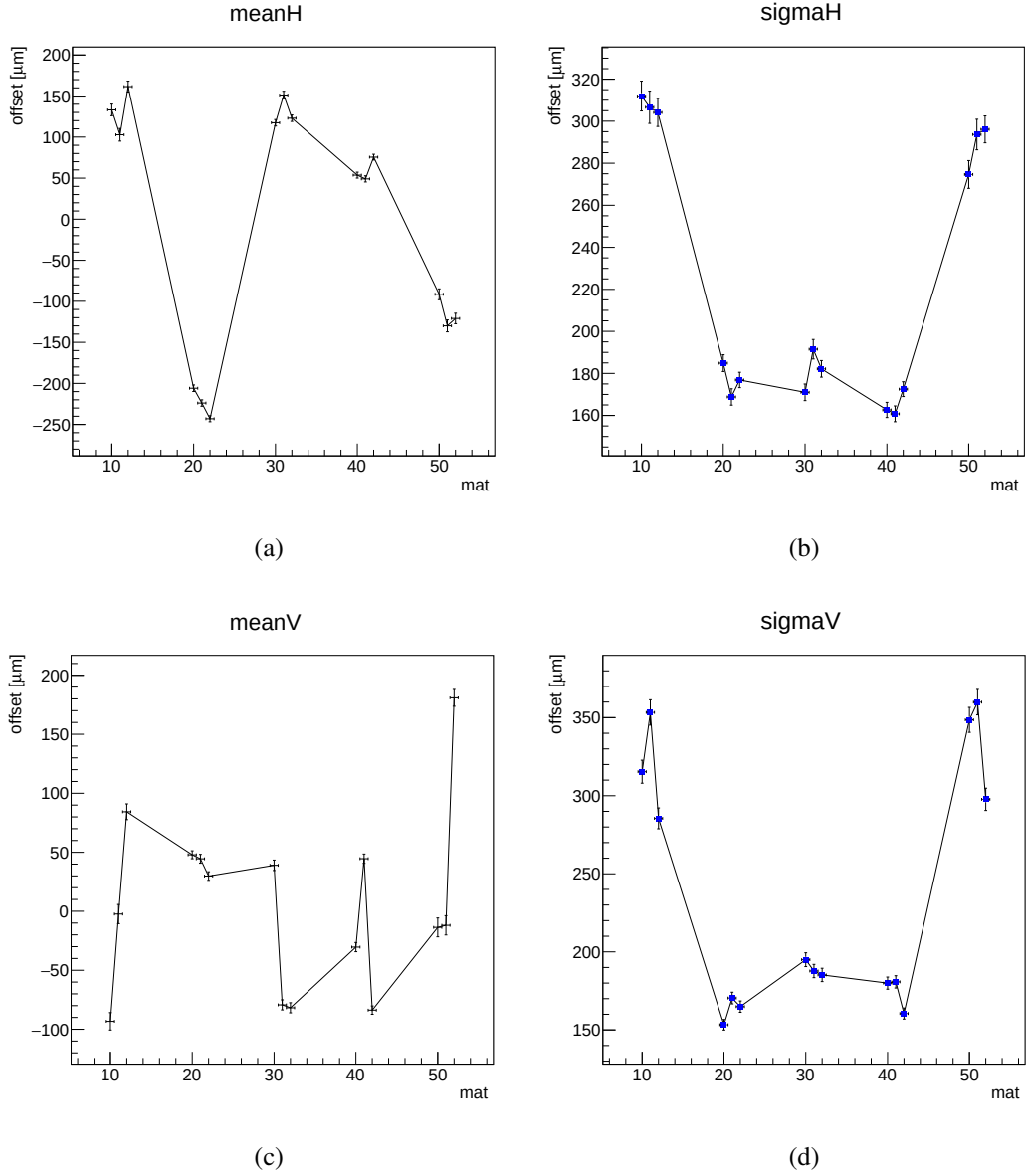


Figure D.3: Mean offsets for the horizontal (a) and vertical (c) mats before the alignment, with corresponding sigma values (b) and (d) respectively.

D.2 Residual distributions after MINUIT alignment

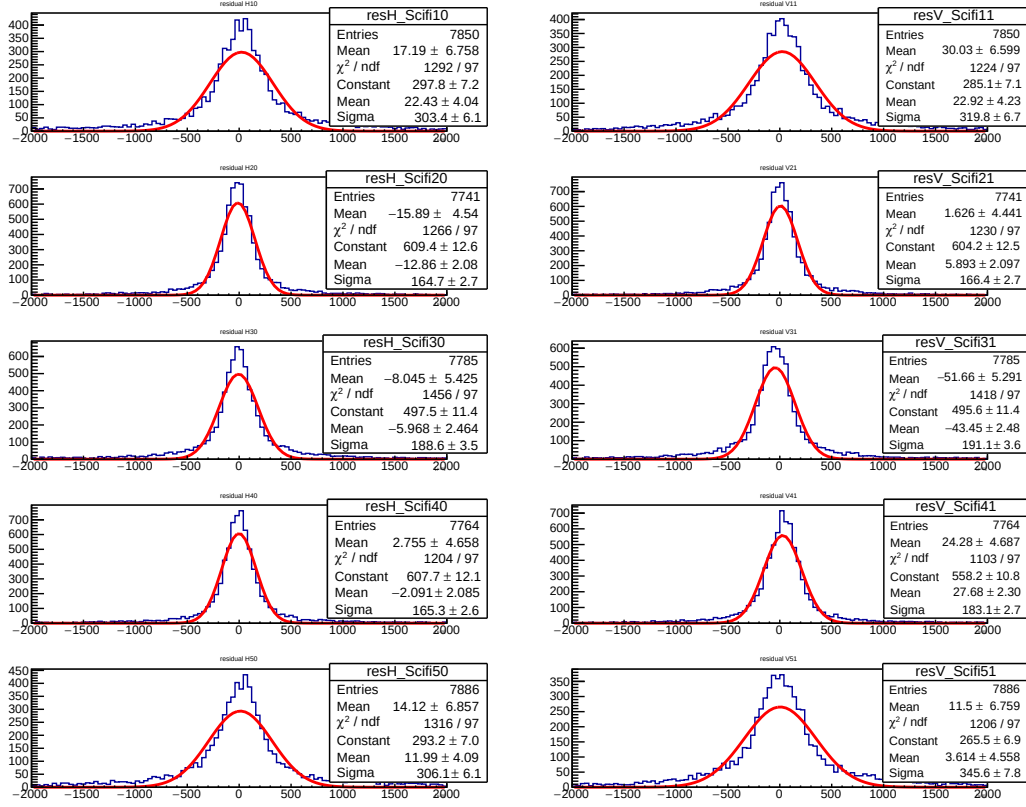


Figure D.4: Residual distributions for run 5377 with corrected geometry, vertical SciFi planes. The horizontal axis is in μms . The first mean in the legend represents the mean value for the data whereas the second mean represents the mean value of the fit. The constant is the maximum value of the fit.

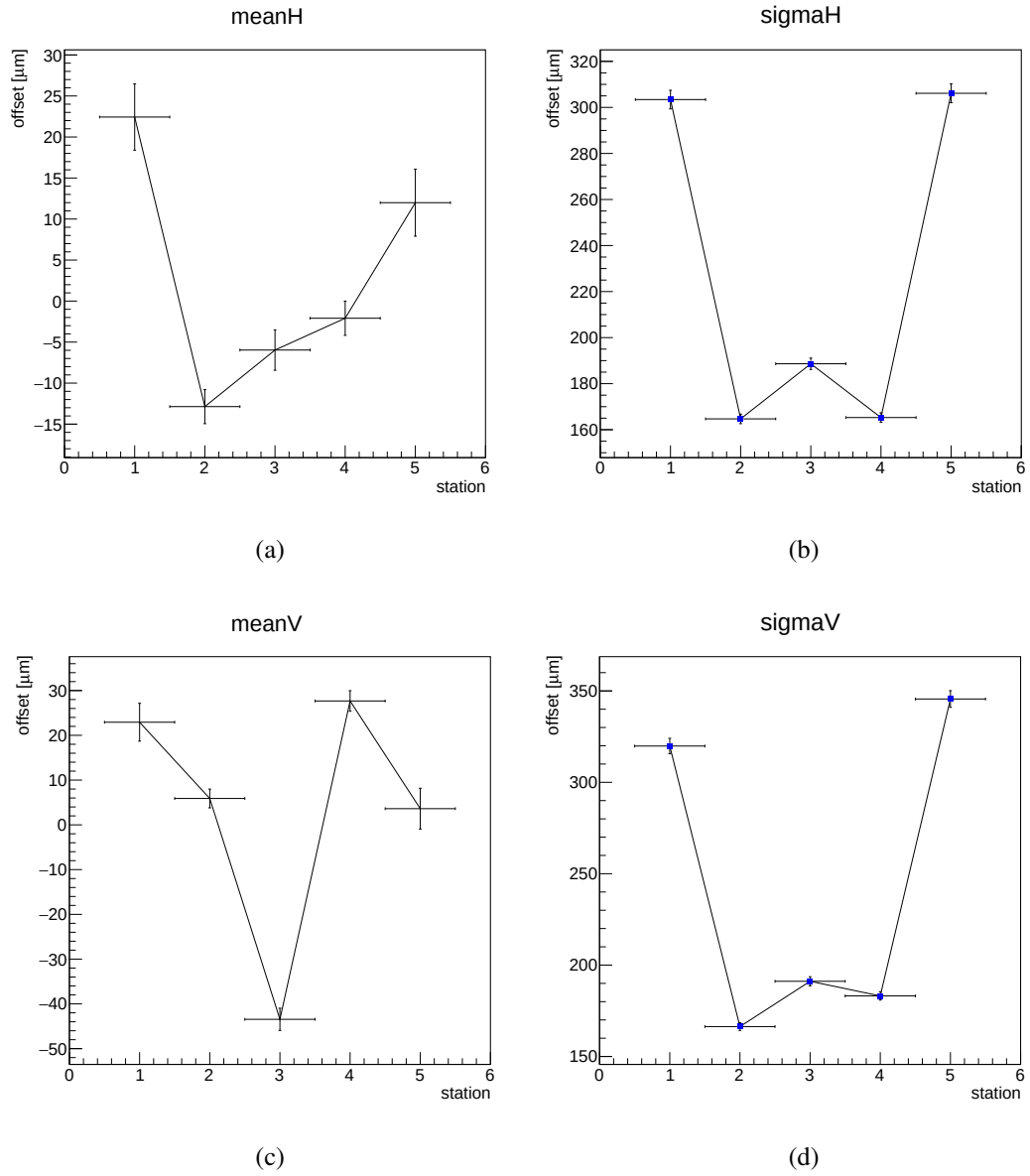


Figure D.5: Mean offsets for the horizontal (a) and vertical (c) planes after the alignment, with corresponding sigma values (b) and (d) respectively.

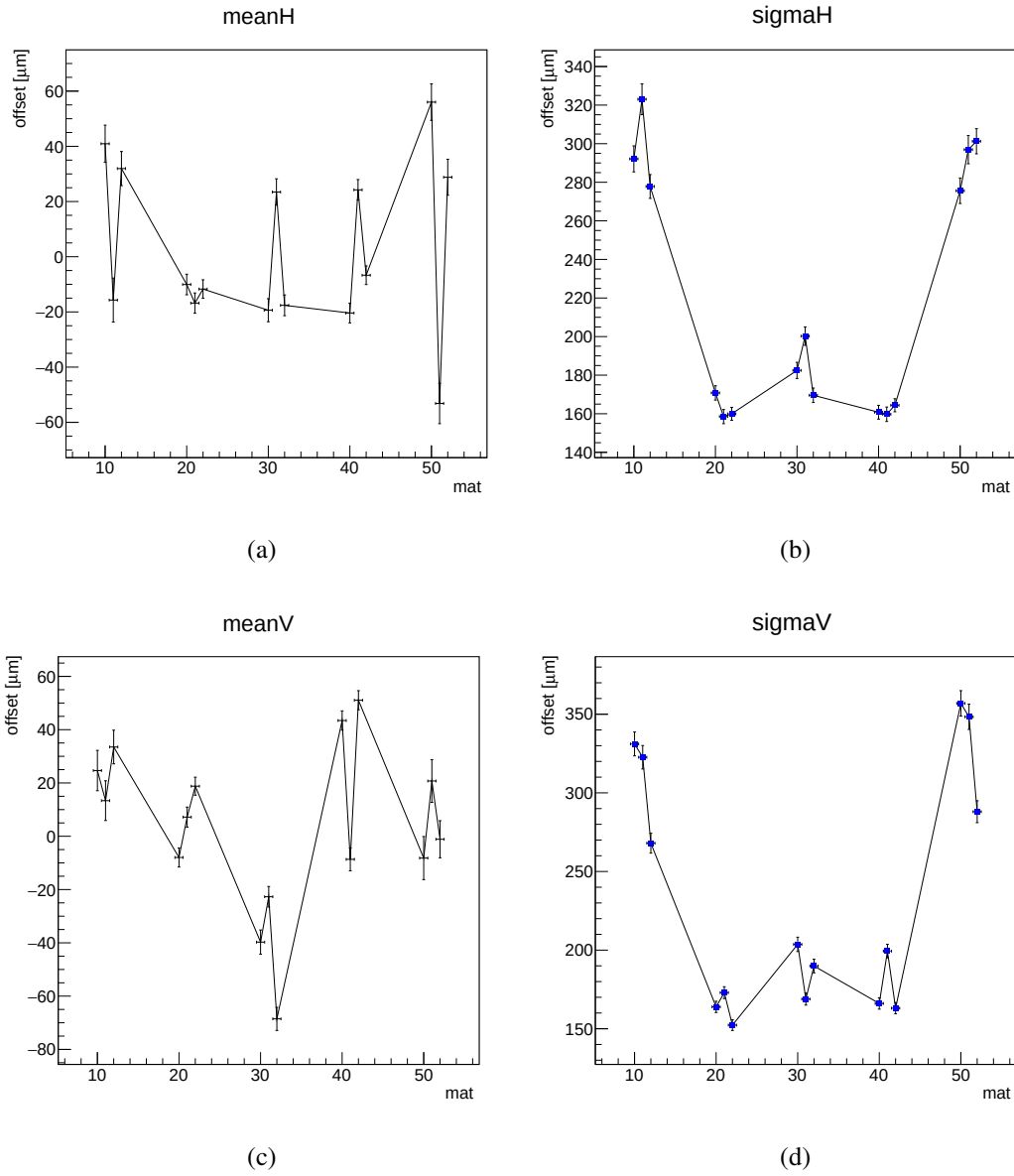


Figure D.6: Mean offsets for the horizontal (a) and vertical (c) mats after the alignment, with corresponding sigma values (b) and (d) respectively.