

First studies with SND@LHC

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Abstract.

SND@LHC is the most recent experiment at CERN and studies neutrinos produced at the LHC. We simulated muon neutrino interactions in the Muon System in order to estimate the contribution of these events to the neutrino precision studies, and calculated the detection efficiency of muon neutrinos interacting within the first 4 iron walls. The detector has an upcoming testbeam designed to improve the energy calibration of the hadronic showers in the Muon System. This test will be performed with recently built spare planes for both the Upstream and Downstream sections of the detector. The planned design and configurations of the detector for this testbeam were implemented in the SND@LHC software with GEANT4.

KEYWORDS: LHC, Neutrino, Simulation, Geometry, Detector, GEANT4

1 Introduction

Neutrinos are particles of the Standard Model and categorize as leptons. They are very light, feebly interacting and thus extremely difficult to detect and study without specialized setups. The SND@LHC is a novel detector at the LHC, dedicated to the study of neutrinos and other feebly interacting particles. It has been approved, built and installed in 2021, and initiated data taking in 2022 with Run3 of the LHC.

1.1 Neutrinos at the LHC

The Scattering and Neutrino detector at the LHC is the latest approved experiment at CERN and allows the detection and study of neutrinos. This will be the first time that neutrinos are observed at a particle collider. This is possible due to the high energy neutrinos produced by the LHC collisions and the high luminosity and resulting neutrino flux. The detectors that are more commonly installed closer to a collision point receive too much background activity to be able to detect neutrinos, given their low interaction rate and peculiar signal with relation to the remaining particles. Studying neutrinos became possible with SND@LHC given the amount of filtering done to stop the remaining particles from reaching the detector or, in case they do, to be able to easily identify them.

1.2 The Detector

The detector is located at 480 meters from the ATLAS detector (Fig. 2) and is approximately co-linear (though slightly off-axis) with the direction of the beam at the collision point. This also allows the study of a region unavailable to the ATLAS or CMS detectors, which cannot detect the products of the collision co-linear with the beam (high pseudo-rapidity). While the proton beams are steered around the LHC tunnel, the LHC magnets deflect



Figure 1: Photograph of SND@LHC.

other charged particles produced in the collisions, and as a result most particles propagating in the SND@LHC direction are neutral. But most of those – except for the neutrinos – also get blocked by about 100 meters of underground rock, before they could arrive to the SND@LHC detector.

The SND@LHC apparatus, shown in Fig. 1, consists of three main subsystems: The Veto System, the Emulsion Target, and the Muon System/Hadronic Calorimeter.

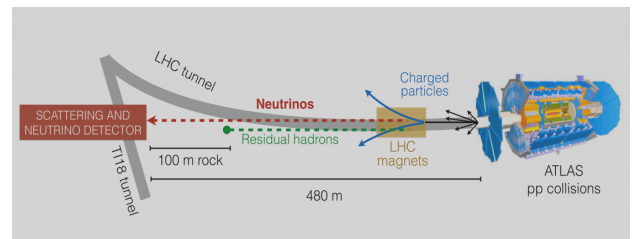


Figure 2: Schematic view of SND@LHC setup and ATLAS collision point.

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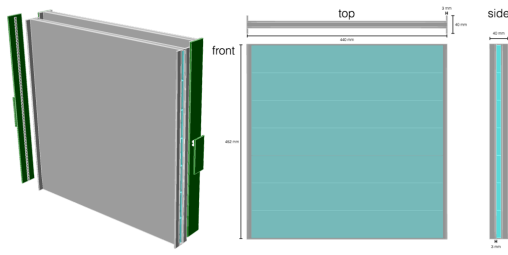


Figure 3: Veto system to detect charged particles.

1.2.1 Veto System

The Veto System is located at the front of the detector and is used to detect charged particles. Neutrinos have no charge, so none of the charged particles are signal. These particles may interact in the rest of the detector, so the Veto is used to determine whether these interactions came from charged or neutral particles.

It consists of scintillating bars read out by silicon photomultipliers. The bars are wrapped in aluminium foil to avoid light loss and to isolate each one. After an event, the trajectory of a particle can be traced back to see its origin. If the origin can be traced back to the Veto System, it is background from a charged particle (see Technical proposal at chapter 4, starting at page 25 [1]).

1.2.2 Emulsion Target

The Emulsion Target is located downstream of the Veto System and is composed of five emulsion brick walls (Fig. 4). Each wall is made of four emulsion bricks, consisting of 60 emulsions films interleaved with 59 layers of 1 mm tungsten plates, as can be seen in Fig. 5. Tungsten was chosen because it is a very dense material and therefore ideal to interact with particles and induce events.

When charged particles go through the emulsion films, they leave a track that records its position. The films can be revealed later and give important information regarding the trajectory and nature of the interaction that occurred.

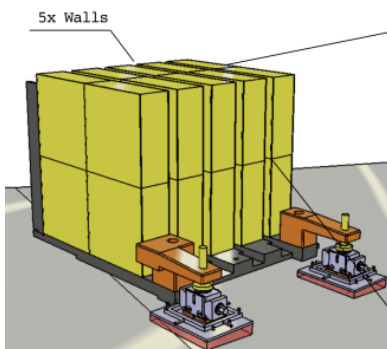


Figure 4: Target System and its emulsion walls.

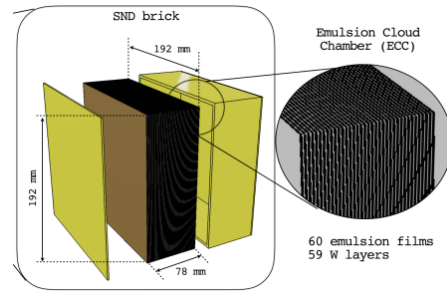


Figure 5: Layers of emulsion film and tungsten inside each wall.

1.2.3 Muon System

The Muon System is located downstream of the Emulsion Target. It has two purposes, from which the trivial one is to identify muons, which are essential to identifying muon neutrino interactions. It also works as an Hadronic Calorimeter, being able to measure the energy of hadronic showers.

The Muon System is made of eight scintillating planes interleaved with iron slabs 20 cm thick, and a last simpler 9th. The first five planes are called Upstream (US) planes (Fig. 6) and consist of ten horizontal bars which allow to locate the particles vertically, knowing which bar at which height was triggered. The last three planes are designated as Downstream (DS) planes (Fig. 7) and consist of two layers of much thinner bars: one layer arranged horizontally and one arranged vertically. This allows for much greater spatial resolution and makes it possible to locate a particle in the entire two-dimensional plane more precisely. Apart from these, there is a fourth downstream plane, albeit with just a vertical layer and without an iron slab prior to it.

A schematic of the detector subsystems is shown in Fig. 8.

Three spare planes of the Muon System were recently produced at LIP, two upstream and one downstream. These will be used in the next testbeam, around the Fall of 2022 or the Winter of 2023, depending on the availability of the place and personnel.

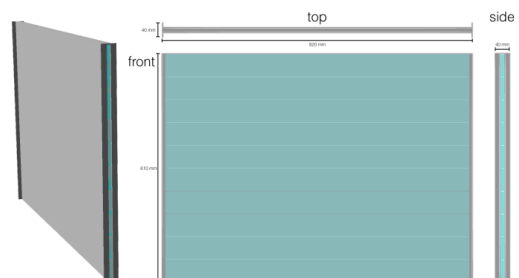


Figure 6: Schematic of an Upstream plane.

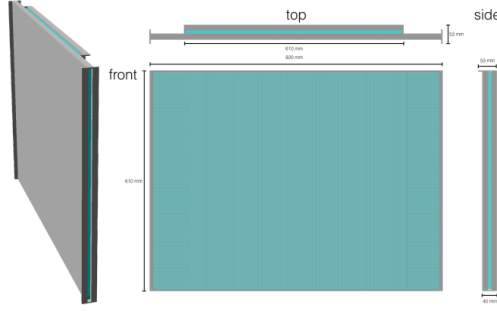


Figure 7: Schematic of a Downstream plane.

1.3 How to detect neutrinos and their interactions

The neutrino flavor can be identified if the interaction is a Charged Current (CC) one, meaning that a charged lepton is produced. If no charged lepton is produced, the interaction is said to be a Neutral Current (NC) one. In this case, it is not possible to distinguish the flavor of the neutrino because only a hadronic shower is produced, which happens in both types of interactions. In this scenario, one can only try to understand whether the original particle was neutral or charged.

Therefore, the following criteria only apply to Charged Current events.

1.3.1 Electron neutrinos, ν_e

If an electron neutrino interacts, a product of the interaction will be an electron, which is a very common particle and will itself interact with other materials easily. This resulting interaction will form smaller electromagnetic showers that can be identified and traced back to study the initial neutrino.

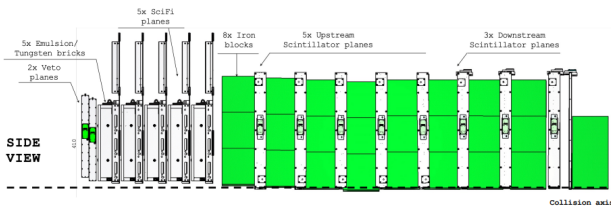


Figure 8: Schematic side view and composition of SND@LHC experiment.

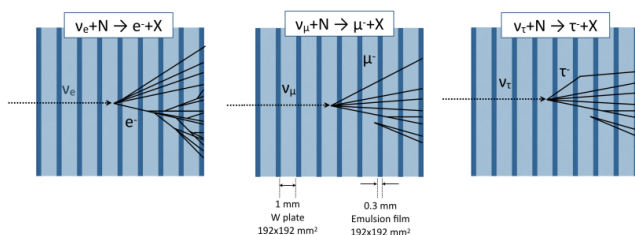


Figure 9: Possible interactions of neutrinos with the three flavors.

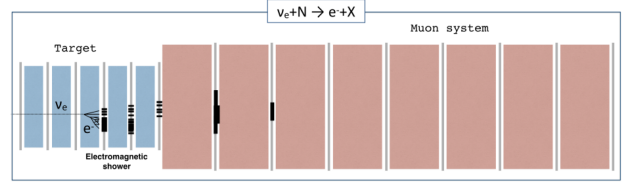


Figure 10: Possible electron neutrino event.

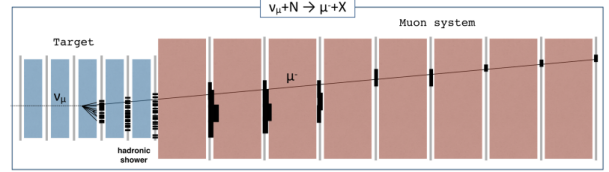


Figure 11: Possible muon neutrino event.

1.3.2 Muon neutrinos, ν_μ

When a muon neutrino interacts, there's a probability that a muon will be produced, if this is a CC event. Muons are very penetrating particles, so if there is a trajectory of a particle that crossed through the entire detector, or more specifically the Muon System (1.2.3), it is very likely to be a muon. The criteria used to identify a muon candidate are related to the detection of an isolated track on the Downstream planes. (The exact criteria can be found on chapter 12, section 4.1 of the Technical Proposal [1], under Muon identification.)

Muon neutrinos and muon anti-neutrinos will be denoted by ν_μ and $\bar{\nu}_\mu$, respectively, from now on.

1.3.3 Tau neutrinos, ν_τ

Identifying tau neutrinos is not as simple as their peers. The criteria are "purely topological", as stated under Tau identification of chapter 12, 4.1 of the Technical Proposal. Due to taus being more massive particles, they can decay into less massive ones, such as electrons or muons.

Table 1 lists possible tau decays and some efficiencies related to those decays (ϵ_{ds} stands for decay search efficiency and ϵ_{tot} stands for total efficiency, which is a combination of geometrical, decay search and other efficiencies). This topic is explained in depth in chapter 12, section 4.1 of the Technical Proposal [1].

Decay Channel	$\epsilon_{ds}(\%)$	$\epsilon_{tot}(\%)$
$\tau \rightarrow \mu$	82.5 ± 1.6	49.6 ± 1.8
$\tau \rightarrow e$	80.8 ± 1.7	48.4 ± 1.8
$\tau \rightarrow h$	80.3 ± 1.0	48.4 ± 1.1
$\tau \rightarrow 3h$	89.4 ± 1.5	54.0 ± 1.9

Table 1: Tau decays and some efficiencies, taken from [1].

1.4 Geometry Simulation

The aforementioned upcoming testbeam will try to characterize hadronic showers produced in a target that emulates the emulsion target, in order to better calibrate the energy reconstruction of the Muon System.

The entire Muon System uses at least eight planes of scintillating bars, but only the recently produced 3 spare ones will be available for the upcoming testbeam. In order to cover the entire detector and collect a complete set of data, it is necessary to implement a new disposition (a geometry) for the three detector parts that were produced in such a way as to cover the entire detector.

2 Interaction of Muon Neutrinos in the Muon System

Neutrino interactions occur throughout the whole detector and not just the Emulsion Target. This means that a lot more neutrino events can be retrieved if we are able to identify neutrino interactions in the Muon System, and further cross-checking studies can be performed.

The area of interest for this study will be the MS/HC. This part of the detector has less precision than the target region, therefore methods involving the emulsion reconstructions cannot be used to correctly identify the ν interactions.

Among these, correctly identifying ν_μ CC events are a priority. This is harder when the ν_μ interaction happens in the Muon System because the hadronic showers will muddle the isolation of muons in the DS layers, when compared with interactions in the Emulsion Target, where the hadronic showers cannot reach as deep into the MS.

Thus, the goal is to estimate efficiencies for the identification and distinction between ν_μ CC and NC events.

2.1 Neutrino Simulation

To simulate the neutrinos, first it was needed to create a flux of neutrinos using FLUKA [2], which is a package that allows for particle physics simulations using Monte Carlo techniques. This was already created by specialists and is the best neutrino flux representation at TI18 provenient from the ALTAS collision point and represents what is expected for Run3.

A geometry file for the detector was also needed and there was one available with its configuration in the tunnel TI18 as of 10th of August 2022.

Neutrino events were then generated for muon neutrinos only interacting in the MS/HC with GENIE [3].

For the final step in simulating, using GENIE and GEANT4 [4] to propagate the particles through the detector apparatus, 18,000 muon neutrino events were simulated with the given geometry and configurations giving the full description of particles created from a single muon neutrino and their products. This corresponds to a luminosity of approximately 500 fb⁻¹.

After the simulation is performed, all data is digitized. This is a practice used with the real data to transform analog signals into digital signals and, besides allowing the

use of code already built, also allows for consistency between simulation and reality.

2.2 Interaction Vertices

For the sake of conciseness, from now on, ν_μ should be understood as representing both particle and anti-particle.

To properly study the efficiencies of the SND@LHC detector for ν_μ it should first be known where the neutrinos themselves interact with the detector.

The following three plots (12, 13, 14) represent the interaction vertex of neutrinos in the MS/HC of SND@LHC from different perspectives. These were created with the data from the aforementioned simulations.

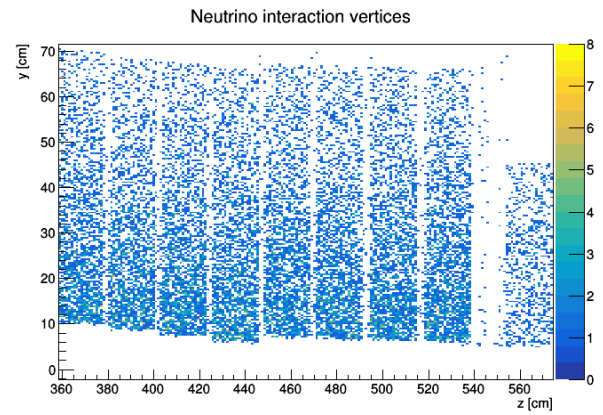


Figure 12: Simulation of the ν_μ interaction vertex in the MS/HC of SND@LHC (side view).

Both figures 12 and 13 show white pseudo-lines, meaning areas of less ν_μ interactions, which correspond to the scintillator planes, while the more densely populated rectangles correspond to the iron bricks.

In Fig. 12, the tilt of the detector is obvious through the iron blocks positioning.

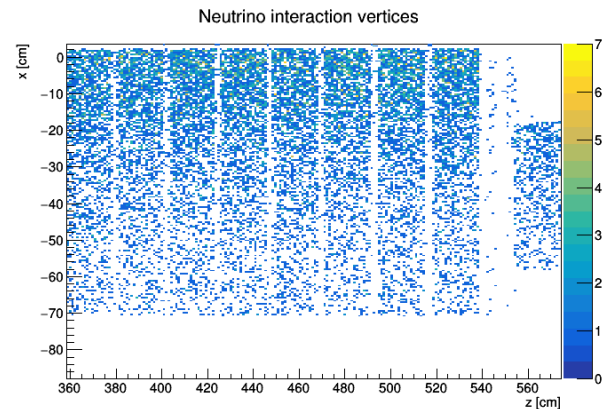


Figure 13: Simulation of the ν_μ interaction vertex in the MS/HC of SND@LHC (top view).

Thus, it can be concluded that most interactions occur in the iron blocks, as expected. This implies that we will

not be able to reconstruct the interaction vertices for the neutrinos interactions.

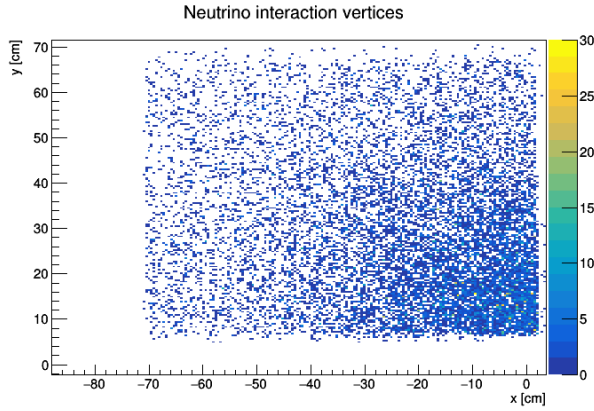


Figure 14: Simulation of the ν_μ interaction vertex in the MS/HC of SND@LHC (front view).

The front view plot in Fig. 14 shows that the neutrino distribution is heavily dependent on the radial proximity to the center of the beam, which is placed at $(x, y) = (0, 0)$ cm in these plots.

With a quick glance, it can also be seen that the density of ν_μ interactions quickly decreases with the distance to the center of the beam.

2.3 Efficiencies for MS/HC

As explained in section 1.3, there's a probability that a ν_μ will generate a muon (among other particles) when interacting with the detector. This is a specific behaviour to this flavour of neutrinos so it constitutes a criterion to test if the flavour of the neutrino was muon or not. Given this criterion, this study will focus its attention in the ν_μ that hit the MS/HC within the first 4 iron blocks as displayed between the two red lines in Fig. 15.

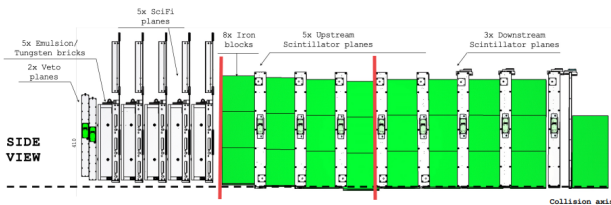


Figure 15: Region of interest for ν_μ interactions.

It's important to mention that all the calculated probabilities don't simply use the number of events in a certain condition but also take in consideration the probability of that event itself happening, thus rarer events have a lower weight.

Within the MS/HC the probability that a ν_μ interacts in the region of interest is $57.9 \pm 1.0 \%$. The probability that a ν_μ produces a muon upon interaction was calculated to be $75.9 \pm 1.0\%$.

For the following calculations, only the events where the ν_μ hit the region of interest were used.

To determine whether or not a muon had been generated, knowledge at the generator level was used. In order to determine whether or not a muon would be seen in a given interaction, an algorithm that relies solely on digitized data was used. This algorithm tests for the existence of an isolated track in downstream by trying to fit the points of detection in the downstream scintillator planes to a line. If these fit within certain parameters, which include an isolation criterion, then it is considered to be a muon.

This is done in the DS trackers, with the ν_μ interaction happening in the first 4 iron blocks of the US since this was the region deemed to be of low enough background from the hadronic showers [5]. These showers will mostly die out before reaching the DS layers leaving a much more distinct track to be interpreted as a muon which is much more penetrating.

To test the reliability of this algorithm and to estimate the relation between number of CC events and NC events, the probability of false positives and its efficiency were calculated. The amount of charged current events that can be correctly identified were calculated to be $23.7 \pm 1.0 \%$ giving an estimate for the efficiency of the algorithm. From the neutral current events, $7.5 \pm 1.0 \%$ were misidentified as being a CC event. This also stems from the fact that the timings of the detector weren't taken in consideration when applying the algorithm. Thus the algorithm may be correctly identifying a muon but these were produced in later interactions and not as a first product of the ν_μ .

Figure 16 shows the reliability of the GENIE generator, as the probability of a muon being generated agrees with the experimental results. As the value has stabilized, generating more events does not change the properties of the sample significantly.

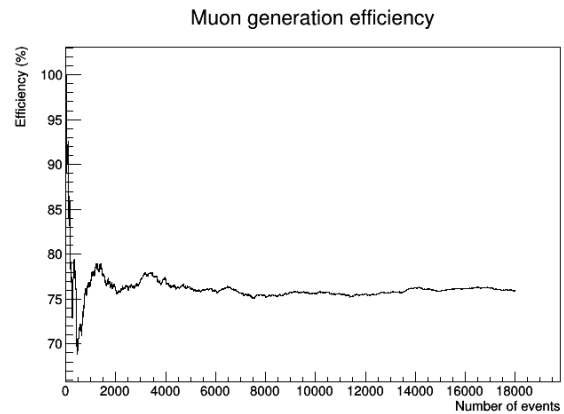


Figure 16: Variation of the probability of a muon being generated upon the interaction of a ν_μ with the number of events. The range of events goes from 1 to 18.576.

3 New Geometry

The detector has a design, translated into the SND@LHC software as a geometry, that was already explained briefly throughout the paper, namely on section 1.2. There is an upcoming third testbeam for SND@LHC, but only three planes will be available for the Muon System: two Upstream and one Downstream.

There is the need to implement a new geometry in order to cover the detector in its entirety and compare the results with the data that we will see after the testbeam. Moreover, to try to understand the behavior of hadronic showers in the Muon System. It is also important to replicate the conditions of previous runs of September and October 2021 for future simulations that are not included in this study.

To achieve these goals, the chosen geometry consists of a standard pattern of two US planes interleaved with an iron block, then two consecutive iron blocks and finally the DS plane. This structure is simply moved to start at three distinct places on the detector (given that in the DS zone is always one and only one DS plane). In this way, it is possible to cover the entire detector with the only three planes that will be available, as can be seen in Fig. 17. Keeping the same standard structure, it is also possible to compare data between configurations.

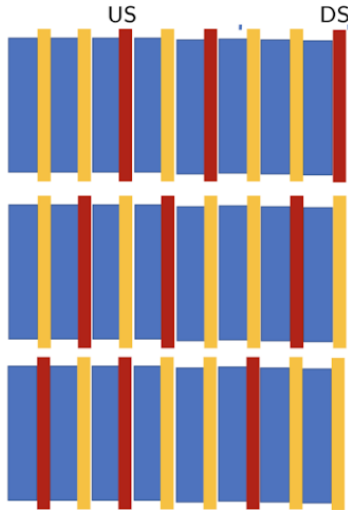


Figure 17: Three configurations chosen to implement the new geometry.

In Fig. 17, red stripes represent the placed planes, the yellow stripes represent the lack of planes in that slot and the blue stripes represent the iron blocks. Configuration 1 starts with an US plane on position 1, then another on position 3 and a DS on slot 6; The second configuration has US planes at position 2 and 4, and a DS plane at slot 7; The third one, consists of an US plane at slot 3, another on slot 5 and the DS plane on position 8.

3.1 Methods

The code used to implement the new geometry is present in the SND@LHC software that can be found in the GitHub Repository [6]. There are scripts in the code that can be modified in order to change the geometry, which is built in GEANT4 [4]. The most important files and its directories to this particular study are the following:

1. `sndsw/geometry/sndLHC_H6geom_config.py`
2. `sndsw/shipLHC/run_simSND.py`
3. `sndsw/macro/getGeoInformation.py`

File number 1 is used to define the geometry of the detector. It is possible to define components and choose their dimensions and quantity, among other properties. Due to the structure of the code itself, any changes made to this file require a subsequent compilation of the entire code to take effect. To define the new geometry, the quantity of components was altered, some components were removed, others "moved" and defined in their new locations.

File number 2 is used to create a simulation. It is important to simulate some events after making changes to the geometry and check if the new geometry is as expected. In this case, the number of events does not matter much, in fact, if the number is small, the computation time will be less and the process will go faster. The sole purpose is to "generate the detector" and see if it is built correctly. The code below is an example of a command to run a simulation of 10 pions on beamline H6:

```
python run_simSND.py --PG --pID 211 --H6 1 -n 10
```

Since there is no documentation of the code, Table 2 was made to explain some of the arguments.

Keywords	Arguments	Functionality
--PG	-	Use particle gun
--pID	int	id of particle used by gun (default 22)
--H6	int	Use geometry of H8/H6 testbeam setup (default 0)
-n/ --nEvents	int	Number of events to generate (default 100)
--Estart	float	start of energy range of PG (default 10 GeV)
--Eend	float	end of energy range of PG (default 100)
--EVx	float	particle gun x-position (default 0)
--EVy	float	particle gun y-position (default 0)
--EVz	float	particle gun z-position (default 0)

Table 2: Brief description of arguments used to run simulations.

The particle's ID can be found in the Monte Carlo particle numbering scheme [7]. On the third page, under the section "Light Mesons", the number 211 corresponds to the pion. The full argument description can be found in file number 2, `run_simSND.py`.

File number 3 gives output about the detectors geometry. After simulating, a geometry file is generated and can be accessed using the file number 3, and the command below:

```
python getGeoInformation.py -g <filename> -l 2
```

For example, regarding a simulation with a particle gun and pions, the name of the geometry file would be *geofile_full.PG_211-TGeant4.root*. Option *-l* indicates the level of detail of the output information, with 2 being more detailed than 1.

To sum up, the usual procedure would be to make the desired changes in *sndLHC_H6geom_config.py*, then compile everything, create a simulation using *run_simSND.py* and checking the new geometry with *getGeoInformation.py*.

3.2 Results

First, the conditions of previous testbeams were replicated by removing the Veto detector (1.2.1). To create a structure to originate events, the Emulsion Target (1.2.2) was replaced by an Iron Block similar to those used in the Muon System (1.2.3).

The priority was to define the planes in their correct locations. Three of the five US planes and two of the three DS planes were removed. The remaining two US planes were placed in their new locations, as well as the third DS plane.

The detector apparatus starts at position $z = 0$ cm, which is on the most upstream side, and goes up to $z = 276.9$ cm, depending on the adopted geometry. A way to locate the components in space is by looking at their z middle point by running *getGeoInformation.py*. The next few Tables (3,4,5) show the positions of the planes in each configuration.

Planes	Z Mid Position (cm)
US 1	104.2
US 3	149.2
DS 1	218.2

Table 3: First Configuration.

Planes	Z Mid Position (cm)
US 2	126.7
US 4	171.7
DS 2	242.1

Table 4: Second Configuration.

Planes	Z Mid Position (cm)
US 3	149.2
US 5	194.2
DS 3	268.1

Table 5: Third Configuration.

The positions of the iron blocks are listed in the next table. The first iron block is the iron target added to replace the Target(1.2.2).

Iron Blocks	Z Mid Position (cm)
volFeTarget_1	48.2
volFeBlock_0	93.0
volFeBlock_1	115.5
volFeBlock_2	138.0
volFeBlock_3	160.5
volFeBlock_4	183.0
volFeBlock_5	205.5
volFeBlock_6	229.4
volFeBlock_7	253.4

Table 6: Iron block positions.

Since there is the need to compile every time a change is made, the code was altered in order to compile the three plane configurations at the same time. Then, the user decides which one to use at the time, when running *run_simSND.py*.

3.3 Discussion

The planes are in their correct locations according to the geometry configurations. However, the placement of the iron blocks presented a bigger problem. Due to the nature of the class with the Muon System Code, the iron blocks were associated with the planes: the number of iron blocks was dependent on the number of planes. In every try, 3 blocks were always placed. Either they were in their correct locations (related to the plane that was placed), but were not enough to fill the entire detector, or they were placed from the beginning of the detector all the way to the back, but since there are only 3, the last places were not filled. To solve this, the number was changed directly in the class and the parts related to the iron block placement were separated from the code of the planes. Apparently, the problem was solved, but we can only be certain once the geometry is properly tested. Perhaps this can be fixed by separating the code related to the creation of the blocks from the code that creates the planes on a deeper level. This should be the next step before testing.

There is no need for the user to change and compile the geometry code in order to use the different configurations. Once compiled, the configuration can be chosen each time the user runs the code. One can simply run the simulation without worrying about geometry code. This allows for an easier and faster experience.

On the one hand, the study had the duration of two months, of which 3 weeks were dedicated to introduction and tutorials, to create CERN accounts and gain computer access. On the other hand, since the experiment is fairly recent, there is no documentation of the code which makes it more difficult to get to know and use.

In the future, it is important to start to write some documentation on the code to make the whole process easier from the beginning.

4 Conclusions

To sum up, two projects were carried out: The study of ν_μ interactions in the Muon System and the implementation of a new geometry for the detector.

In the Muon System, the neutrinos interact almost exclusively in the Iron Blocks. The amount of charged current events that can be correctly identified are $23.7 \pm 1.0 \%$. From the neutral current events, $7.5 \pm 1.0 \%$ were misidentified as a charged current event.

The planned configurations of the new geometry were implemented, covering the entire detector for the upcoming testbeam. There are still adjustments that can be made in the future to improve the quality of the chosen solutions. The next steps would be to make those adjustments, simulate events with the new configurations and analyse the results.

Acknowledgements

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