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Feasibility of Neutrino Detection in the Muon System of SND@LHC

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Abstract. Detection of ν_μ charged current interactions in the Muon System of the SND@LHC detector is harder due to higher noise from hadronic showers produced in the interactions and lesser granularity of the electronic detectors, when compared to interactions in the Emulsion Target. With a fiducial volume in place, in order to veto events produced by charged particles, two different algorithms were used to assess various parameters such as efficiency and probability that a neutrino neutral current interaction is mislabeled as a charged current event, and the variation in their performance for different parameters, such as energy and interaction location. Furthermore, causes were investigated for the events in which the algorithm mislabeled events in order to probe possible improvements. A baseline of 528 ± 127 muon neutrino detections from interactions in the Muon System is estimated, for a luminosity of 250 fb^{-1} as expected for Run3 of the LHC, utilizing the Hough Transform method, in the absence of background from unassociated neutral particles.

Keywords: Neutrino, LHC, Run3, Detector, Simulation, Efficiency

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.

Figure 1: Photograph of SND@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, permiting the first observations of neutrinos 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 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.

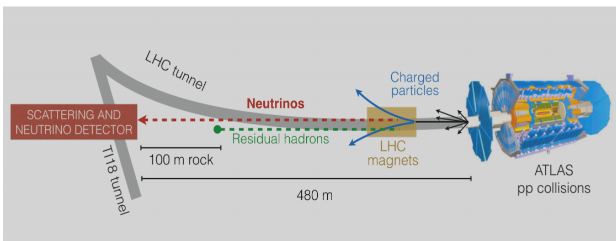

Figure 2: Schematic view of SND@LHC setup and ATLAS collision point.

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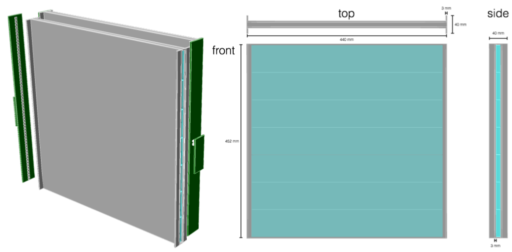

Figure 3: Veto system to detect charged particles.

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. (MS/HC).

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 developed later and give important information regarding the trajectory and nature of the interaction that occurred.

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 9^{th}. The first five planes are called Upstream (US) planes (Fig. 7) and consist of ten horizontal bars which allow to

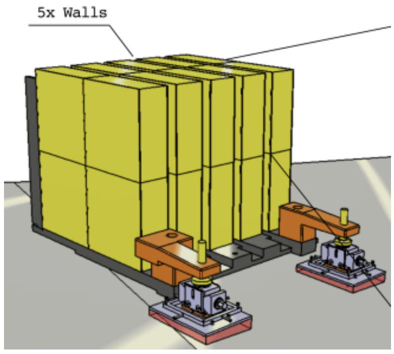

Figure 4: Target System and its emulsion walls.

locate the particles vertically, knowing which bar at which height was triggered. The last three planes are designated as Downstream (DS) planes (Fig. 8) 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. 6.

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

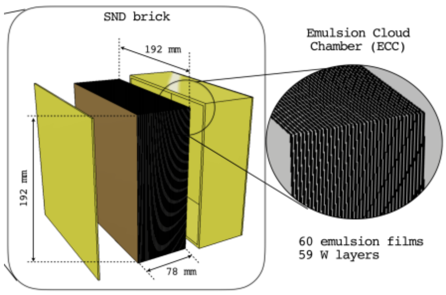

Figure 5: Layers of emulsion film and tungsten inside each wall.

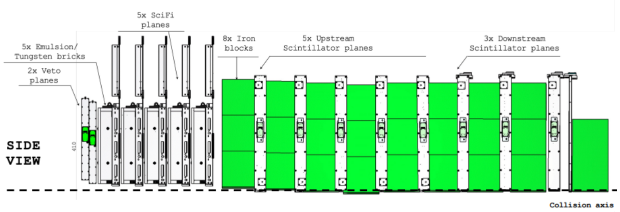

Figure 6: Schematic side view and composition of SND@LHC experiment.

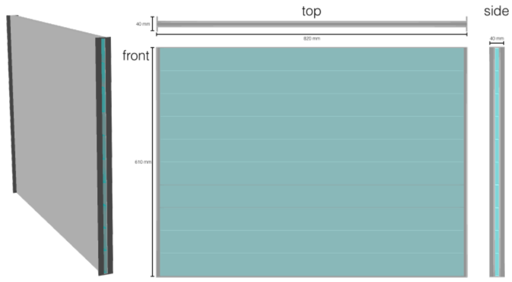

Figure 7: Schematic of an Upstream plane.

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.

1.3.2 Muon neutrinos, ν_μ

When a muon neutrino interacts, there is a probability that a muon will be produced, if this is a CC event. Muons

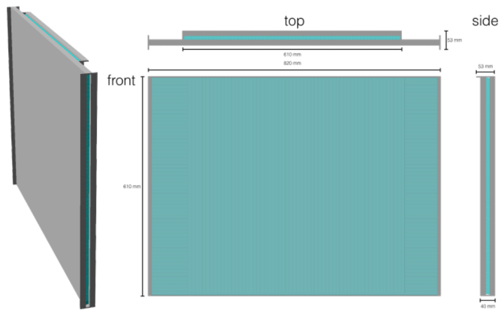

Figure 8: Schematic of a Downstream plane.

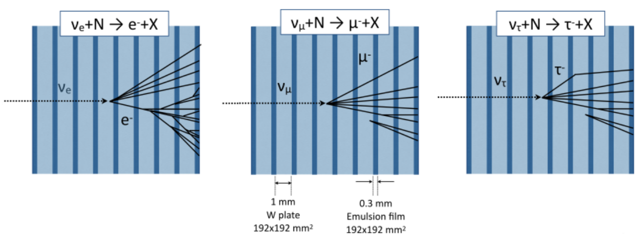

Figure 9: Possible interactions of neutrinos with the three flavors.

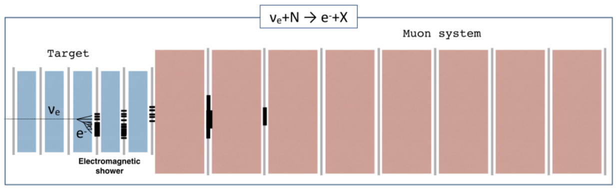

Figure 10: Possible electron neutrino event.

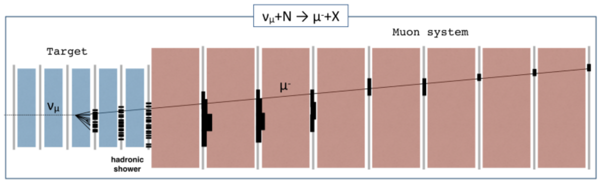

Figure 11: Possible muon neutrino event.

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. This method as well as a new one are also briefly described in section 2.2.)

Muon neutrinos and muon anti-neutrinos will both be denoted by ν_μ 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	$\epsilon_{ds}(\%)$	$\epsilon_{tot}(\%)$
$\tau \to \mu$	82.5 ± 1.6	49.6 ± 1.8
$\tau \to e$	80.8 ± 1.7	48.4 ± 1.8
$\tau \to h$	80.3 ± 1.0	48.4 ± 1.1
$\tau \to 3h$	89.4 ± 1.5	54.0 ± 1.9

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

2 Detection 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 is 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.

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 currently yields the best neutrino flux representation at TI18 originating from the ATLAS 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 10$^{\text{th}}$ of August 2022.

Neutrino events were then generated for muon neutrinos only interacting in the MS/HC with GENIE [3]. For the final step, GEANT4 [4] is employed to propagate the particles through the detector apparatus; 189.000 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 5447 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 Neutrino Detection

As explained in section 1.3, there is a probability that a ν_μ will generate a muon (among other particles) when interacting with the detector. The probability that a ν_μ produces a muon upon interaction was calculated to be 75.7 ± 0.4 %, as expected.

Given this, this study will focus its attention in the ν_μ that hit the MS/HC.

It is important to mention that all the calculated probabilities do not 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. To determine whether or not a muon had been generated, knowledge at the generator level is used. In order to determine whether or not a muon would be seen in a given interaction, algorithms that rely solely on digitized data are used. At the time of writing, there are two algorithms implemented for this task, *Simple Tracking* (ST) and *Hough Transform* (HT).

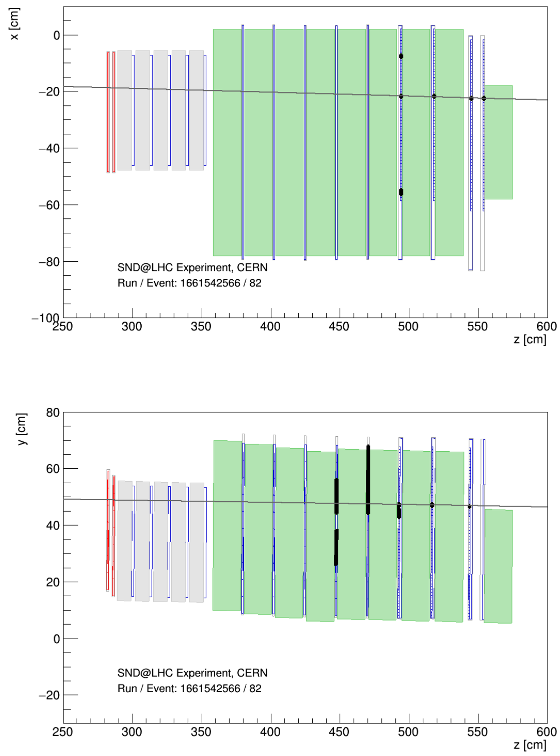

Figure 12: Event display of a muon correctly identified by the ST method, confirming the interaction of a ν_μ in Muon System. Top view showing hits in vertical planes (top); side view showing hits in horizontal planes (bottom).

The ST method tests for the existence of an isolated track in the DS detectors. This method attempts to cluster neighbouring hits together, and implements a criterion which only accepts a track if it contains clusters in at least 3 DS planes. If any of these planes contains any more hits or clusters, then that plane is no longer accepted, thus creating a very aggressive isolation criterion. If the hits (or clusters) fit to a line within certain parameters, then it is considered to be a muon. The HT method also attempts to cluster several hits together, and searches for patterns of clusters which form a line in at least 3 distinct DS planes. This method differs as it does not need such isolation criteria as used with ST as it can search for patterns in more hit dense events.

As the methods rely on the recognition of a muon as proxy to identify a ν_μ, only CC events are identifiable. Consequently, all the efficiency calculation in this study will be in relation to the CC events and not the complete set of events. NC events can sometimes trigger a muon identification for reasons that will be further explored in section 4.4. Out of this set of events, the ones which trigger a muon identification, thus mislabeling it as a CC event will be denominated *False Positives*.

3 Fiducial Volume

In order to improve the ability for detection of ν_μ, as well as having a region where vetoing is possible, a fiducial volume was set.

3.1 Z Restriction

The methods referenced in section 2.2 are applied in the DS trackers; with the ν_μ interaction happening in the first 4 iron blocks of the US, 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. This is further tested, with a more recent version of ST, by evaluating the reliability of the detection algorithm along the Z axis as can be seen in Fig. 13. The red line shows the end of the fourth iron block, where the cut is applied, given that the efficiency dips below 15 % over the next iron block and the expected amount of ν_μ interactions, with a luminosity of 250 fb^{-1} only drops from 1181 to 1031, as can be seen from Table 2. The false positive (FP) rate also shows a peak following this Z cut, especially for the ST method, although this will not be the primary source of background for Run3, but interactions from other particles such as neutral hadrons which cannot be vetted.

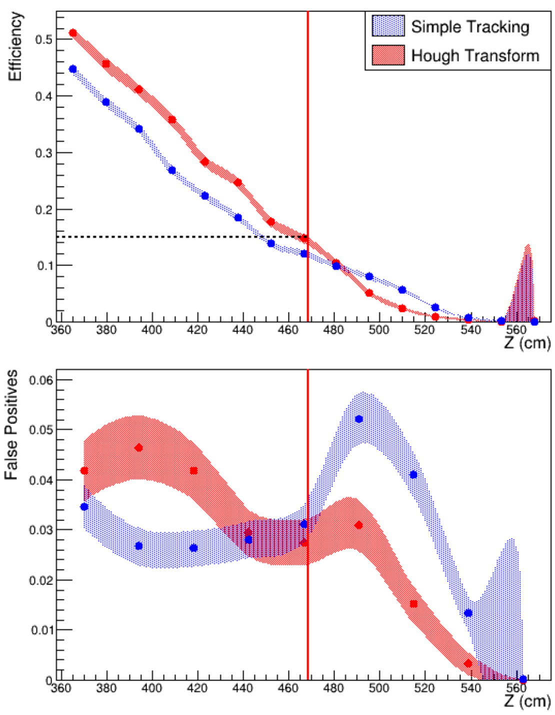

Figure 13: Characteristics for the detection of ν_μ along the z axis without any cuts applied. Variation of the efficiency (top); and variation of the false positive rate (bottom). The red line represents the cut applied in z (end of 4$^{\text{th}}$ iron block), where only values below this threshold are considered.

This reduction in volume to the first 4 iron blocks, allows for the study of 59.0 ± 0.3 % of the ν_μ that interact in the MS. This study will be using this fiducial volume as determined to be favourable in a previous study [5] and further confirmed above.

3.2 X and Y Restrictions

There needs to be a veto that confirms that a particle interacting in the MS is highly likely to be a neutrino. To stress the importance of this veto, the rate at which muons interact with the detector is approximately 5×10^7 higher than that of the neutrino interactions. Therefore, further cuts are applied in the X and Y directions to limit the region of interest to the volume covered by the SciFi of the Target, as shown by the yellow area of Fig. 14.

Table 2 provides the estimates for the general efficiency for detecting ν_μ that interact in the MS within different fiducial volumes. These efficiencies are all in respect to the events in the volume used, thus showing the variation of the algorithms performance within each individual region. As mentioned in section 3.1, the main source of background will not come from FP but from interactions of other particles, which is not taken into consideration during this study. This is important when interpreting the $\overline{N_e}$ values, which will represent the expected amount of ν_μ interactions detected, without any background from other particles other than that of the interacting ν_μ itself. These values are all normalized for a luminosity of 250 fb^{-1}, which is expected for Run3. It is also important to stress that the first 2 lines of the table, without the appropriate cuts to veto charged particles, do not reveal realistic values to establish a baseline on the expected number of interactions. The third line will represent this baseline in an environment where there is no need for background rejection cuts. Given the large number of events simulated to perform this study in relation to the actual expected number of events, by extrapolating the uncertainty to the expected luminosity for Run3, the statistical error is null. Conversely, there is a rather large systematic error to these

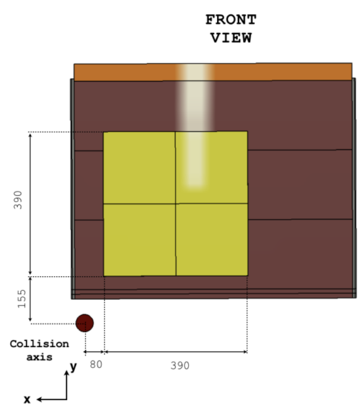

Figure 14: Front view of the SND@LHC Detector. The area in yellow corresponds to the Target and the brown area to the MS, which is behind the Target.

values, originating from the model used to simulate the neutrino fluxes. The model *DPMJET* was used, and the model with the largest discrepancy (*SYBILL*) has a 24 % deviation [6] from this one.

	Int. (%)	Eff. (%)	$\overline{N_e}$	FP (%)
No cuts	100	18.0 ± 0.4	1181	3.1 ± 0.8
Cuts in Z	59.0 ± 0.3	26.7 ± 0.5	1031	2.8 ± 1.0
All cuts	20.7 ± 0.4	30.8 ± 0.8	413	1.7 ± 1.8

Table 2: Effect of cuts applied to the detection of ν_μ with the ST method. Int. refers to the percentage of interactions kept after the cuts; Eff. stands for the detection efficiency; $\overline{N_e}$ refers to the expected amount of ν_μ interactions detected, without any background from other particles, with a luminosity of 250 fb^{-1}; FP refers to the percentage of false positives. "All cuts" refers to the cuts in all 3 directions mentioned.

By applying the final cuts in the X and Y directions, the interactions available decrease close to a third of the initial value, although as mentioned before this is a necessary cut to allow for the veto of charged particles. The FP rate appears to diminish by applying the cuts, nevertheless the result is inconclusive due to the large uncertainty resulting from the small rate of false positive events.

4 Efficiencies for MS/HC

For the following analysis, only the events where the ν_μ hit the region of interest were used, as this is required in order to control the background. The probability of false positives and its efficiency were calculated in order to test the detection capability of the available algorithms and search for possible ways to improve them. There is a caveat to these efficiencies which is explained in appendix A.

4.1 Comparing Different Methods

The general detection capability of both methods mentioned are present in Table 3 as well as their combination. Comparing to ST, the HT method is 1.3 times more efficient, but has a higher FP rate, which was expected due to its less aggressive isolation criteria. Given this, and that the FP rate does not vary considerably, HT reveals to be a preferable method.

Both methods are combined in two different ways to analyse how disjoint the sets of identified muons are, correctly or not. The *Both OR* combination considers a track if any of the methods identifies a track, thus increasing efficiency. The *Both AND* combination considers a track if both methods identify a track, thus increasing purity.

Figure 15 shows that the *Both OR* combination yields only a slightly improved efficiency over the HT method, revealing that both HT and ST create very similar sets of identified muons. This is further proven by the *Both AND* combination, yielding only a slightly worse efficiency than the ST method. The marginally improved efficiency of

	Eff. (%)	$\overline{N_e}$	FP (%)	$\overline{N_{FP}}$
ST	30.8 ± 0.8	413	1.7 ± 1.8	8
HT	39.6 ± 0.8	528	3.9 ± 1.8	16
Both OR	41.2 ± 1.1	545	5.6 ± 2.5	20
Both AND	30.1 ± 1.2	398	1.0 ± 2.6	4

Table 3: General detection capability of both methods mentioned, as well as their combinations, with cuts applied to all directions. Eff. stands for the detection efficiency; $\overline{N_e}$ refers to the expected amount of ν_μ interactions detected, without any background from other particles, with a luminosity of 250 fb^{-1}; FP refers to the percentage of false positives; $\overline{N_{FP}}$ refers to the expected amount of false positives with a luminosity of 250 fb^{-1}, without any background from other particles.

Both OR comes at the cost of an increased FP rate, although due to the high uncertainty of the FP rate, it is not possible to compare the similarity between the two. As expected, the already small FP rate of the ST method is further decreased with the use of *Both AND*. Notice that the distinct results of the HT method in Fig. 13 are not incoherent with those of Fig. 15, because the latter has cuts in all directions increasing its efficiency.

The combination of these methods thus appears to have no significant advantage over the use of HT, but the result is inconclusive, and a study with the expected background from other particles should be conducted to further verify these results.

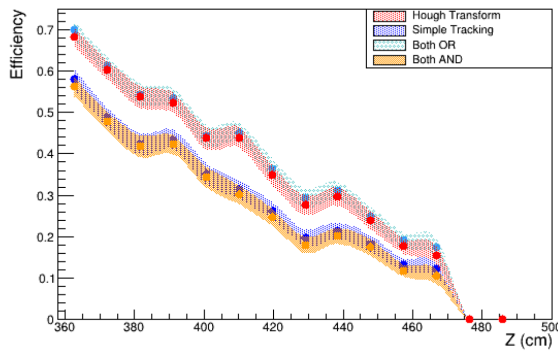

Figure 15: Efficiency variation for the detection of ν_μ along the z axis with cuts applied to all directions. The *Both OR* method considers a track if any of the methods identifies a track. The *Both AND* method considers a track if both methods identify a track.

4.2 Energy Dependence

As shown in Fig. 16, both methods reduce their efficiency for higher energies, although HT generally has a greater efficiency, especially for lower energies. This reduction can be explained by the more penetrating hadronic showers resulting from their high energy, thus hindering the clear detection of a muon. For energies close to 3000 GeV and above, the ST method appears to still be able to detect a few events which the HT cannot, but there is not enough data for a statistically accurate interpretation.

HT has a higher FP rate across the energy spectrum contrasting with its higher efficiency. For energies higher than 2000 GeV both methods appear to have higher FP rate, but the result is inconclusive due to the high uncertainty. This uncertainty arises from the decrease in event quantity for higher energies compounded with a very small FP rate.

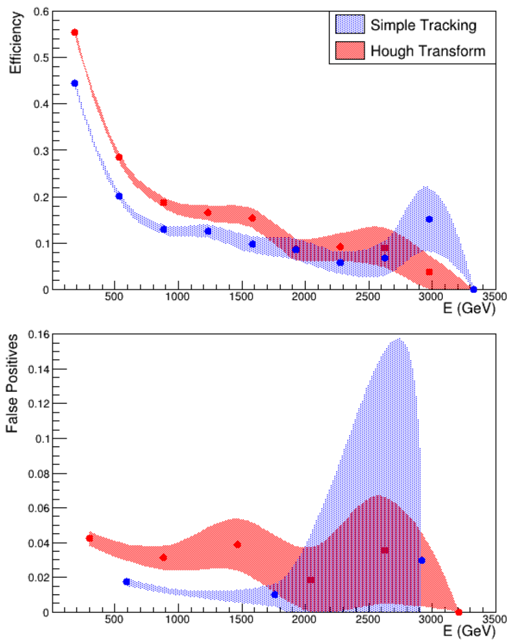

Figure 16: Variation with energy of the detection capability of ν_μ, with cuts applied to all directions. Variation of the efficiency (top); and variation of the false positive rate (bottom).

4.3 Unidentified Muons

Most events where both methods fail to detect a muon, therefore failing to identify a ν_μ, are highly noisy events with a great amount of hits in the downstream detectors, thus clouding the muon track. More event displays regarding this subject are present in appendix D.

As concluded in section 4.1, HT has a higher efficiency and is able to detect noisier events than ST due to its clustering algorithm and less aggressive isolation criteria. Figure 17 shows an event where HT is able to detect a muon, and ST fails to do so. These events tend to be more hit dense than a general event detected by ST (Fig. 12).

4.4 False Positives

Plenty false positives are visibly very ambiguous, with hits in consecutive detector planes connecting an almost perfect line, thus yielding a promising candidate for a muon track. The HT method is especially susceptible to false

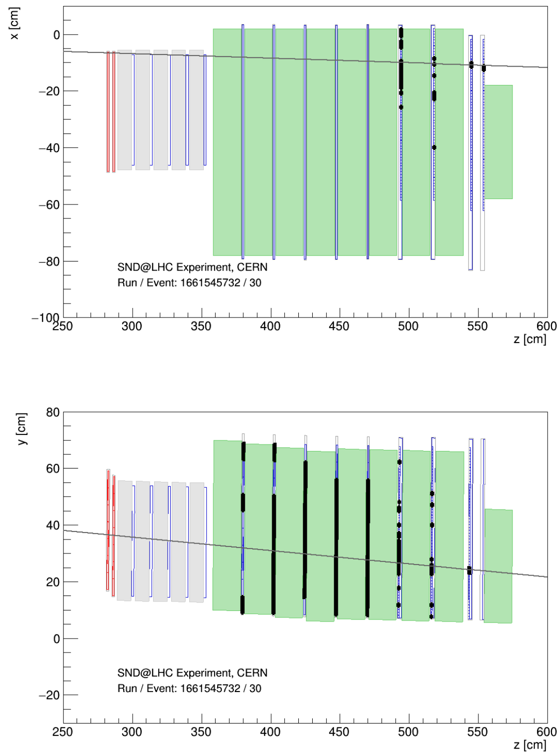

Figure 17: Event display of a ν_μ event, where ST fails to detect a muon, but HT is able to detect it. Top view showing hits in vertical planes (top); side view showing hits in horizontal planes (bottom).

positives mostly due to the same properties which increase its efficiency, namely its less aggressive isolation criteria.

Most false positives result from one of two possibilities. The first results from protons and electrons (mostly, but can also be from different hadrons), being detected in the DS planes, forming hits that appear to form a track, although being uncorrelated. The second results from particles penetrating enough distance to hit the minimum required DS planes, thus creating a track. This mostly happens with charged pions, and sometimes with other hadrons, such as charged Kaons, charged Σ and protons.

Rarer causes for false positives include a muon being generated not from the neutrino but on a later interaction and creating a track, and also a penetrating particle not triggering enough detector planes but an uncorrelated particle creating a hit that appears to form a track.

A considerable, although not very large quantity of the false positives create a track which forms a large angle with the collision axis, not passing through the Target (Fig. 18). This contrasts with the tracks formed by muons stemming from neutrinos, which largely go through the Target (Fig. 12), thus yielding a possible criterion to diminish the FP rate.

Further information regarding false positives can be found in appendix E.

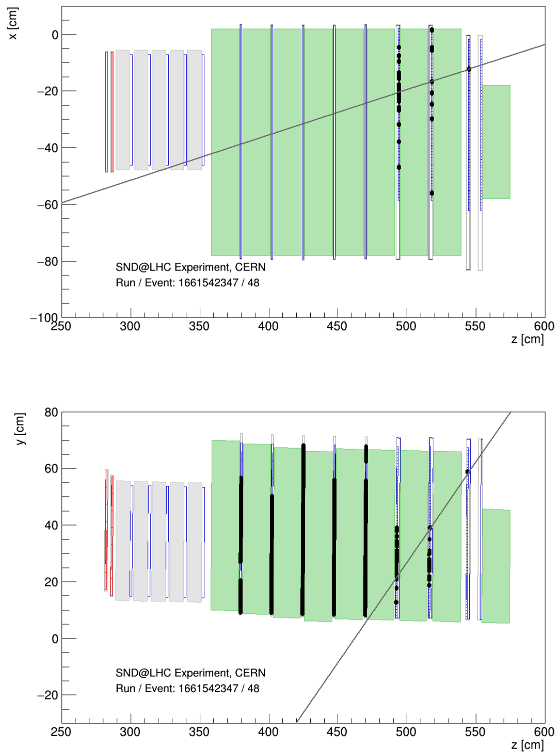

Figure 18: Event display of a ν_μ event, where HT triggers a false positive while ST correctly considers it a NC event. Top view showing hits in vertical planes (top); side view showing hits in horizontal planes (bottom).

5 Conclusions

To sum up, a study regarding the feasibility of muon neutrino detection in the Muon System was carried out. A fiducial volume was set and the Simple Tracking and Hough Transform methods were compared, with the latter showing to be more promising with an increase in efficiency of almost 10 %.

A baseline of 528 ± 127 muon neutrino observations from interactions in the Muon System was established for a luminosity of 250 fb^{-1} as expected for Run3 of the LHC, utilizing the Hough Transform method, without accounting for the background created from other neutral particle interactions.

It was found that both methods sharply decrease their efficiency for higher energies and for interactions further in the Muon System.

Two main causes for false positives were identified as being *Uncorrelated Hits* and *Other Particle Tracks*. An improvement was suggested to reduce the false positive rate, regarding a cut to larger angles of the reconstructed track with the collision axis.

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[10] SND@LHC Collaboration, *Observation of collider muon neutrinos with the SND@LHC experiment* (2023), arXiv:2305.09383 [hep-ex, physics:physics], `http://arxiv.org/abs/2305.09383`

A Caveat to the Efficiencies Displayed

During this study, an event was considered CC when a muon was created directly from the ν_μ. In this case, if the algorithm identified a muon it contributed towards its efficiency. There is, of course, a possible source of error coming from this as it is being assumed that whenever the algorithm allegedly identifies a muon in a CC event, it is indeed a muon and not a false positive.

It was hypothesised that this could be artificially boosting the efficiency, especially for the HT method as it is more permissive. A new restriction was added where the track reconstructed must have 3 hits corresponding to muon hits and the results are displayed in Table 4.

	Eff. (%)	New Eff. (%)
ST	30.8 ± 0.8	29.9 ± 0.9
HT	39.6 ± 0.8	39.2 ± 0.8

Table 4: Comparison of the method used for obtaining efficiency in this paper (Eff.) and with an extra restriction explained above (New Eff.), for the ST and HT methods.

There is a greater efficiency reduction for the ST method, whereas the HT method has only a 0.4% reduction which is within the uncertainty. The HT method shows to be more robust in the identification of muon tracks even with its greater permissiveness. This is further confirmed in Figure 19.

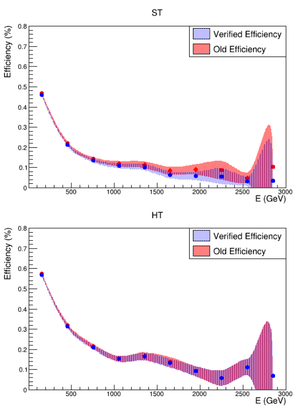

Figure 19. Comparison between the method for obtaining efficiency used in this paper and the method with an extra restriction for the ST and HT methods.

There remains one possibility that could further reduce the efficiencies calculated, which is the lack of verification that the muon identified by the algorithm is the one that originated from the neutrino and not produced in a later interaction.

B More on Z Dependency

Figure 20 shows the FP rate variation for the same conditions as Fig. 15.

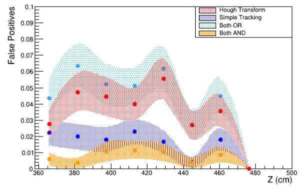

Figure 20. FP rate variation for the detection of ν_μ along the z axis with cuts applied to all directions. The *Both OR* method considers a track if any of the methods identifies a track. The *Both AND* method considers a track if both methods identify a track.

C XY Plane Dependence

The efficiency appears to increase for ν_μ further from the origin, as can be seen from Fig. 21. This is possibly due to geometric effects, but no concrete reason in currently attributed.

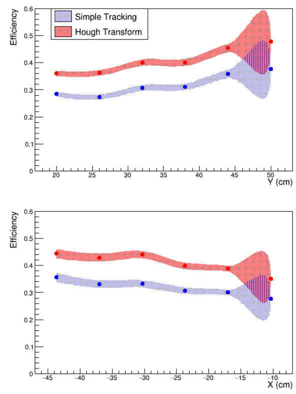

Figure 21. Variation with Y (top) and X (bottom) of the efficiency, with cuts applied to all directions.

D More on Unidentified Muons

Although the HT method has a better capability to detect noisier events than ST, it remains limited for very energetic events with interactions in the Muon System. The event display in Fig. 22 shows an event where both methods failed to detect a muon. Comparing to Fig. 17, a relatively small increase in complexity has caused a failed detection. Figure 23 is an example of a very noisy event, where a muon could not be detected.

E More on False Positives

As mentioned in section 4.4, most false positive events form an almost perfect line, sometimes fairly isolated triggering a FP with both methods, as can be seen on Fig. 24.

Figure 25 shows an event where both ST and HT misidentified a NC event as being CC, but each incorrectly identified different tracks.

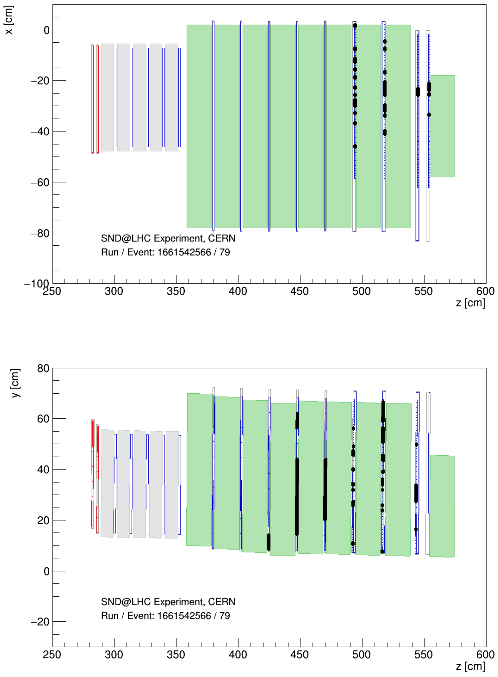

Figure 22: Event display of a ν_μ event, where both methods are unable to detect a muon. Top view showing hits in vertical planes (top); side view showing hits in horizontal planes (bottom).

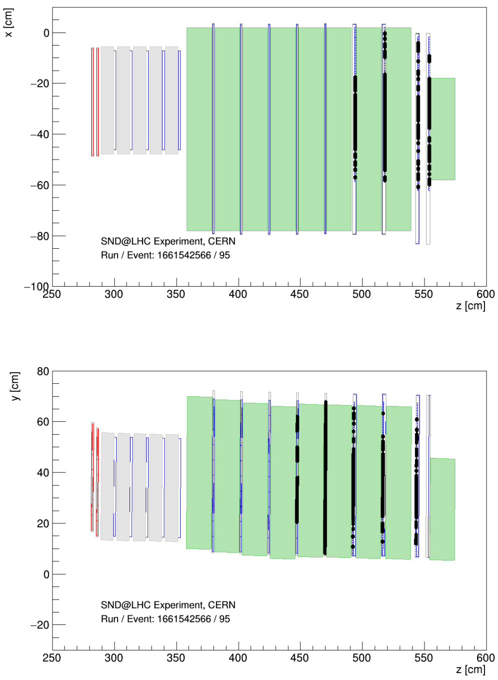

Figure 23: Event display of a very noisy ν_μ event, where both methods are unable to detect a muon. Top view showing hits in vertical planes (top); side view showing hits in horizontal planes (bottom).

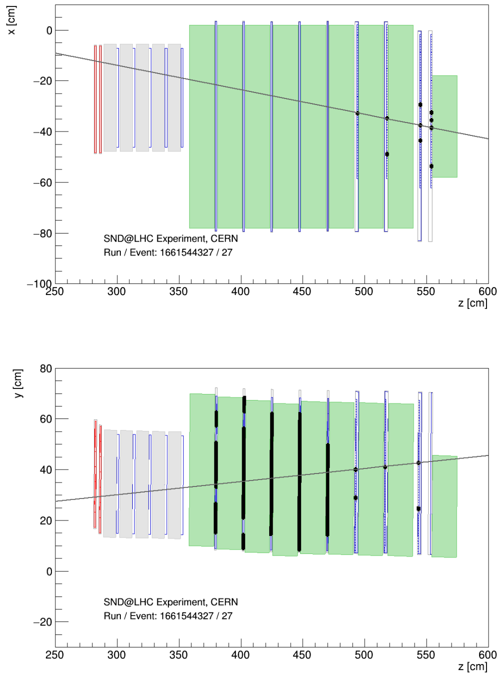

Figure 24: Event display of a ν_μ event, where both methods trigger a false positive. Top view showing hits in vertical planes (top); side view showing hits in horizontal planes (bottom).

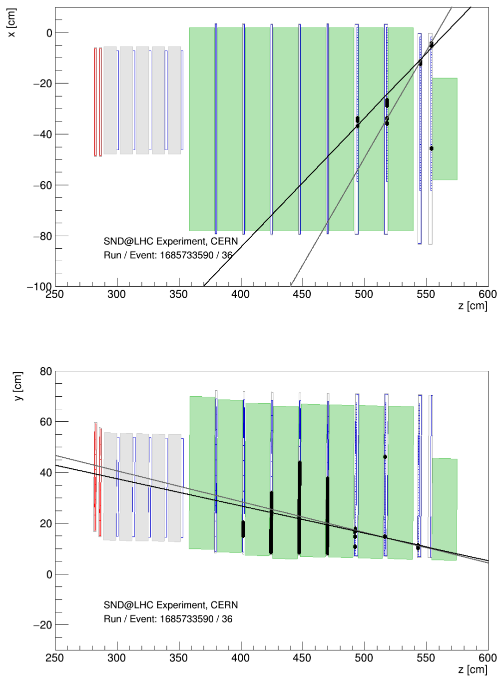

Figure 25: Event display of a false positive ν_μ event, where the ST and HT methods incorrectly identify different tracks. Top view showing hits in vertical planes (top); side view showing hits in horizontal planes (bottom).