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3D Tracking at SND@LHC

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Summer Student Project Report

SND@LHC Collaboration

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Abstract

The goal of this project is to reconstruct a new type of object in the SND@LHC detector, namely a 3 dimensional (3D) track. Due to readout constraints, the muon tracking inside of the SND@LHC detector is performed by splitting the recorded hits in two separate sets based on the inclination of the detector bar recording the hit. The hits are projected onto two perpendicular planes and the tracking is performed on the two projections separately. The position of the hit along the direction perpendicular to the plane of projection, that is to say along the detector bar, is unknown.

These two 2 dimensional (2D) tracks can be combined into one 3D track, but not in case of multi-track events.

To perform true 3D tracking, the missing third coordinate of the hits has to be retrieved. This can only be done for systems which have readout on two opposite sides. The difference between the time at which the signal reaches each of the ends of the detector bar is used for this purpose. Once the set of 3D coordinates is completed, the same set of hits can be projected onto the two perpendicular planes and the tracking performed as was done before. The result of the track reconstruction is now a 3D track.

The performance of the 3D tracking is studied on Partition 9 of Run 4705. The line equations of the reconstructed tracks are computed using Hough transform for pattern recognition. When only allowing one reconstructed track per event, the tracking efficiency achieved by the new 3D tracking scheme is $(75.6 \pm 0.1)\%$. Its efficiency compared to the previous 2D scheme is $(79.4 \pm 0.1)\%$.

When allowing multiple reconstructed tracks per event, the total amount of reconstructed tracks is higher with the 3D tracking than with the 2D scheme, with (1.125 ± 0.001) times more tracks with the 3D algorithm.

Contents

1 Introduction and project goal

In the SND@LHC (Scattering and Neutrino Detector at the LHC) experiment, the track reconstruction is performed in two systems, the Scintillating Fibre (SciFi) system and the DownStream muon system (DS). Both of these tracking systems are made of planar detectors, arranged in series and interleaved with passive layers. The constituents of the DS detector planes are scintillating bars. The latter are either stacked one of top of each other or one next to each other to make up the plane. These two inclinations are called horizontal and vertical respectively. The DS bars are as wide or as high as the detector itself in the respective inclination. Their base is 1 cm^2 wide.

When a particle goes through the detector and triggers the detector planes, the identity of the triggered bar in the plane is known. Out of this information, two out of three spatial coordinates of the hit are known: x and z in the case of a so-called vertical hit (z being the direction of flight of the particles); y and z in the horizontal case.[1]

In both cases, only two out of three coordinates are collected and the hits are considered separately, based on their inclination. They are projected in the xz or yz plane, depending on which coordinates are known, and the tracking is performed independently in those two planes, with two distinct sets of hits.

The goal of this work is to devise an algorithm to complement the information provided by these two separate 2D tracks with a new object, namely a coherent 3D track. This can be achieved by making use of the fact that DS horizontal bars are equipped with readout systems at each end of the detector bar, denoted left and right. In contrast, the vertical inclination only leaves room for readout systems on the top of the planes. Thus, only horizontal hits are used for 3D tracking, the vertical ones are discarded. The SciFi planes are only equipped with readout systems on one edge as well.

Using the difference between the times at which the signal reaches the readout systems at both ends of the detector bar, together with the known speed of light in the medium, it is possible to infer the x corrdinate of the horizontal hits. This completes the 3D coordinates set and the 3D tracking can be performed.

[1] It is assumed that the hits follow a continuous uniform distribution along both known axes.

2 The SND@LHC experiment

2.0.1 Overview

The SND@LHC detector is an experiment at CERN dedicated to studying neutrinos in the pseudo-rapidity range $7.2 < \eta < 8.4$ [1]. The studied neutrinos originate from LHC pp collisions at the ATLAS interaction point (IP1). The SND@LHC experiment is located in the T118 tunnel, 480 m downstream from IP1, as pictured in Fig. 1, so that the neutrino flux from IP1 in the pseudo-rapidity range of interest reaches the detector while all other less penetrating particles get absorbed in the rock they cross on their path to the T118 tunnel. Muon background is expected to reach the detector as well.[2]

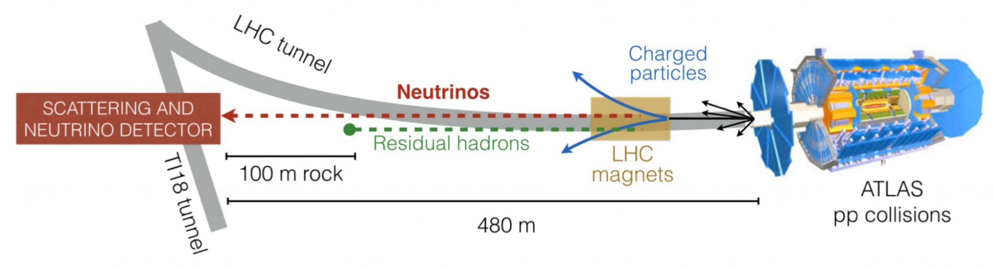

Figure 1: Schematic location of the SND@LHC experiment [3].

2.0.2 Physics goals

One of the two major goals of the SND@LHC experiment is to study neutrino physics. In this scope, different tasks are performed and detailed below [4].

Firstly, the experiment should allow to probe charmed-hadron production in LHC pp collisions. Indeed, in the given pseudo-rapidity range, electron type neutrinos are preferentially produced by ground-state charmed hadrons (D^0, D, D_s, Λ_c) decays. The decaying hadrons are themselves produced in pp collisions in the ATLAS interaction point. This production channel not only allows to probe charmed-hadron production at the LHC but can be generalized into an open-charm ($c\bar{c}$) production measurement. Since the $c\bar{c}$ pairs can be produced by two gluons scattering with fractional momentum x as small as 10^{-6}, it allows for the extraction of the parton distribution functions of the gluon at these small x values.

Secondly, lepton universality can be probed as an internal consistency check, knowing the similarities among the production channels of the three flavours of neutrinos in the studied pseudo-rapidity range. Indeed, muonic neutrinos are produced by charmed-hadron channels, with equivalent branching ratios to ν_e, and tau neutrinos originate from D_s decays. Accounting for charm hadronisation fractions, for branching ratios and for uncertainties due to π and K presence, whose decay can also produce muonic neutrinos, SND@LHC should give reasonable ν_e/ν_τ and ν_e/ν_μ measurements.

The other mission of SND@LHC is the search for feebly interacting particles (FIPs). The experiment allows model independent searches for FIPs, such as light dark matter particles, Heavy Neutral Leptons, dark scalars or dark photons.

The detector is capable of distinguishing between FIP and neutrino events based on their time of flight. The more massive the FIP is, the more significant is this difference, due to the light mass of the neutrinos.

[2]Sections 2.0.1, 2.0.2 and 2.0.3 are taken from a previous report of the same author [2].

2.0.3 Detector layout

The SND@LHC detector is pictured on Fig. 2. It consists of the following building pieces: a veto system, a target region composed of emulsion targets and Scintillating Fibre (SciFi) planes as target trackers, a hadronic calorimeter, a muon identification system and a cold box [1].

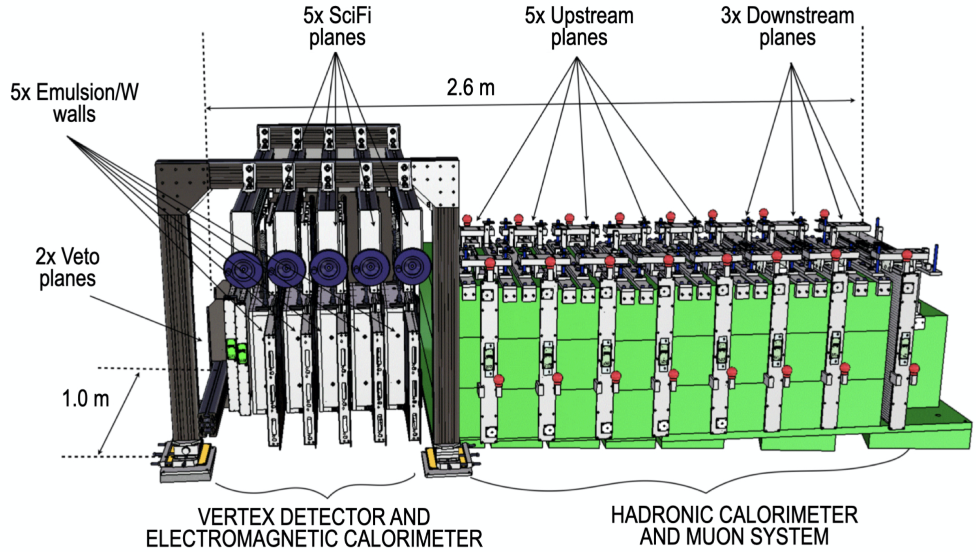

Figure 2: Schematic representation of the SND@LHC detector layout [1].

The veto system is composed of three planes of scintillator bars (the drawing in Fig. 2 corresponds to a previous version of the detector), that are able to detect incoming charged particles (mainly muons in this case). Those particles are tagged and not considered as neutrino events. The detector is instrumented to measure neutrino interactions inside of the target region. The latter is made of tungsten (830 kg in total) to increase the density and hence the probability of a neutrino-nucleon interaction. The high energy range of the studied neutrinos also increases the probability of interaction. The target region is structured layer by layer, alternating between five emulsion cloud chambers (ECC) and five SciFi planes. Their role is to precisely detect the vertex position (precisely enough to observe the presence of a τ lepton before its decay) and to act as a timestamp for the reconstructed events respectively. The whole target region acts as an electromagnetic calorimeter, covering a total of 85 radiation lengths X_0, so that the electromagnetic shower can be expected to have been absorbed by the end of this region.
The hadronic calorimeter also has a layered structure, with iron slabs as passive layers and stations of staggered scintillating bars as active ones. It is long enough to retrace 9.5 interaction lengths λ_{int}, 11 λ_{int} in total when accounting for the fact that the hadronic shower already starts in the electromagnetic calorimeter. The first five stations of scintillator bars are called the UpStream (US) stations, while the last three, acting as a muon identification system, are called DownStream (DS) stations.
The cold box surrounds the veto planes and the target region and prevents the passing through of low energy background neutrons. In addition, it allows for temperature and humidity calibration to assure a good environment for the emulsion films inside the ECCs.

2.0.4 Current tracking scheme

Once the DS hits are projected onto two planes as explained in Section 1, the track reconstruction is performed in two consecutive steps. First, pattern recognition is implemented in order to find straight lines along the hits in the detector. The Hough transform is chosen as a tool for this purpose. This operation associates to every point in Cartesian space a straight line in the slope-intercept parameter space. This straight line represents the infinity of slope-intercept pairs parametrising an affine function in Cartesian space that goes through the point that is undergoing Hough transformation. This operation is done for all DS hits. If these hits are aligned on a straight track in Cartesian space, their associated curves in the Hough parameter space all cross at one point. This intersection point gives the slope and intercept of the track. The Cartesian and parameter space are pictured in Fig. 3.

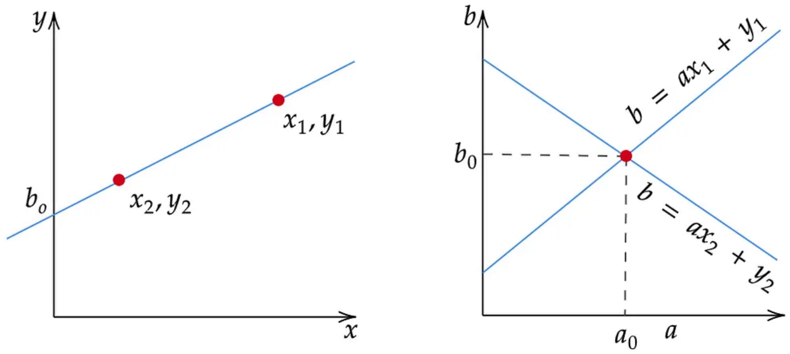

Figure 3: Hough transform of the points (x_1, y_1) and (x_2, y_2) from Cartesian to slope-intercept parameter space [5].

The second step of the track reconstruction is performed only when the pattern recognition is able to find a straight line inside of the DS. If applicable, the hits that are found to be along the straight line are put together in a `genfit::Track` [6] [7], that is then fed to a Kalman filter. The filter perfoms dynamical fitting on the track. If the fit converges, the track is saved.

3 3D tracking

3.1 Third coordinate computation

As mentioned in Section 1, the x coordinate of the horizontal hits is computed to complete the set of 3D coordinates associated to the hits. The x coordinate is inferred from the time difference between the readout systems on both sides of the bar

$$\Delta t = t_0 - t_1 = \frac{x_1 - x_0}{v} \ ,$$

where v is the speed of light in the scintillating bar medium. As pictured in Fig. 4, the indices 0 and 1 refer to the position and time with respect to the readout systems on the left and right of the bar respectively. It is approximated that the photons released by the charged particle passage in the scintillating medium propagate to the readout systems along a straight path.
The total length of the bar is $L = x_0 + x_1$. From the length and the time difference, it is straightforward to solve for x_0, giving

$$x_0 = \frac{1}{2}\left(L + \Delta t \cdot v\right) \ .$$

The final x position of the hit is found by using the known x position of the readout systems (a and b in Fig. 4). It is chosen to use the left

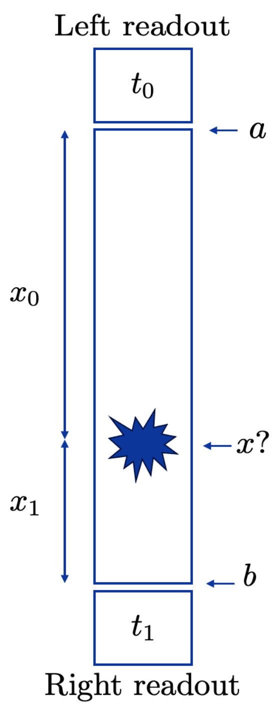

Figure 4: Sketch of one horizontal DS detector bar.

readout system as a reference, with $x = a - x_0$. The expected resolution for x with the above computation is 1.6 cm.

All three DS horizontal detector planes are associated with their vertical counterpart inside of the detector, meaning that each of the DS stations pictured in Fig. 2 is made of one horizontal plane next to a vertical one[3]. Hence, the x positions obtained with the above computation can be compared as a cross-check with the x positions of the vertical hits recorded at approximately the same z position. The agreement is considered satisfactory enough to pursue with the initial objective.

The x coordinate computation is implemented in the track reconstruction script of a local version of the SND@LHC software. A few other minor changes have to be made so that the new tracking scheme is compatible with the Kalman filter used in the second step of the reconstruction. First, the old tracking scheme is slightly modified so that only horizontal DS hits are considered, both for the fitting in the xz plane and the yz plane[4]. Then, the type of the measurement object used to construct the `genfit::Track` is modified to account for the fact that the x coordinate is now pointlike (and not an interval as long as the bar itself anymore): the object type is changed from `WireMeasurement` to `PlanarMeasurment` [8].

3.2 Event displays

Once the tracking scheme is implemented, the event display picturing the two projected tracks together with the recorded hits and the detector geometry can be used as a debugging tool. The former script in the software again only has to be slightly modified. A display example is given in Fig. 5.

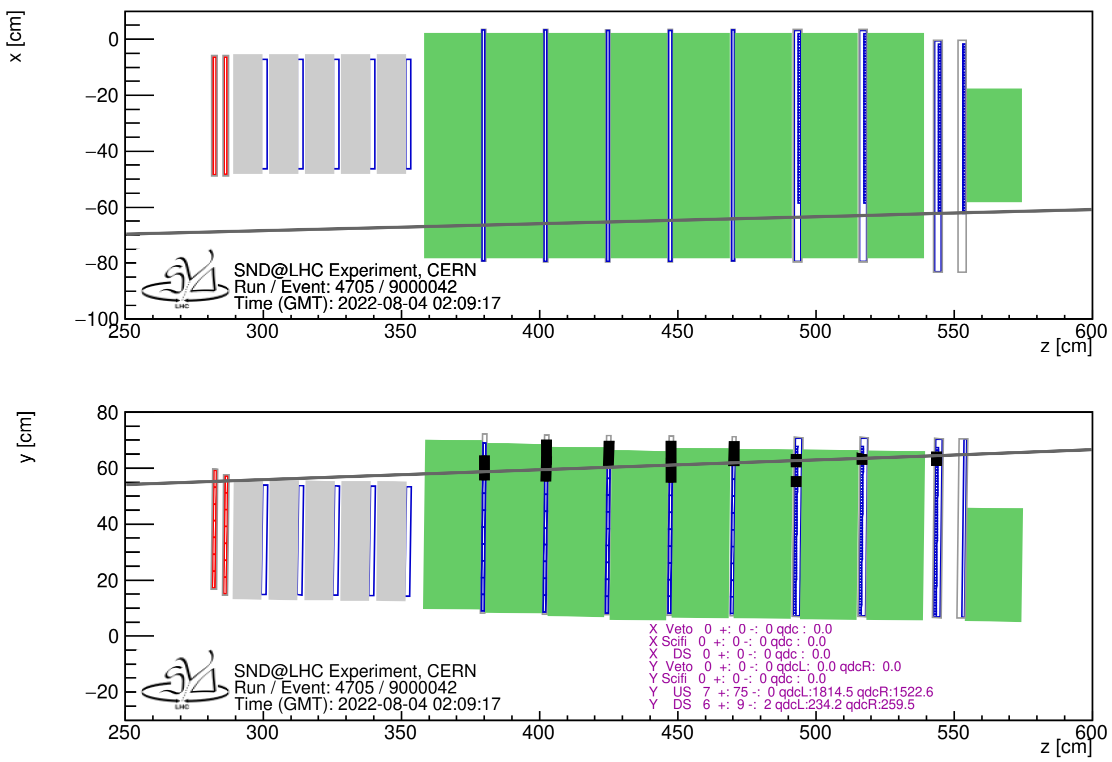

Figure 5: 2D event display with a 3D Hough track[5] for Event 42 in Partition 9 of Run 4705.

[3]There is a fourth single vertical plane located downstream of the first three DS planes not pictured in Fig. 2.

[4]It should be stressed here that while the hits are still projected in two separate planes to perform the track fitting, the track is 3D since the same set of hits is projected in the two planes, and not two independent sets anymore. The projection is kept out of convenience and for readability of the event displays.

Another type of display is implemented for the track fitting, namely the `genfit` event display. It allows the user to study the Kalman fitting part of the reconstruction process in more details. The display is shown in an interactive window, as the one pictured in Fig. 6.

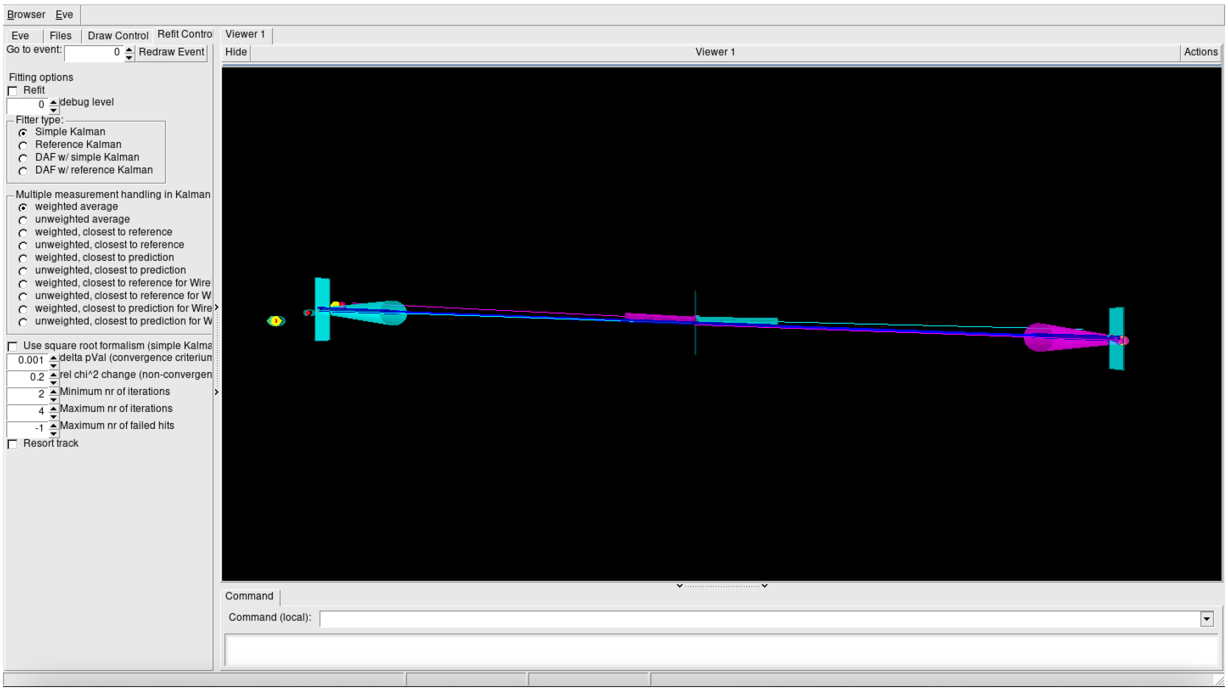

Figure 6: Example of a `genfit` [6] [7] display interactive window for a successful Kalman fit.

3.3 Performance study

The performance of the newly implemented 3D tracking scheme is studied both compared to the previous 2D tracking algorithm and standalone. For all of the studies performed below, the full 9th partition of Run 4705 is used (one million events). A Gaussian smoothing [9] is performed on the Hough space, with smoothing parameters `sigma` = 3 and `truncate` = 4.
In this section, only one track reconstruction per event is allowed (see Section 3.4 for the multi-track case).
The studies were first performed considering the fully reconstructed tracks, with both the Hough transform and the Kalman filter part of the reconstruction successful. It appeared that in most cases, only the Hough transform part of the reconstruction was successful and not the Kalman filter step. It was decided as a temporary solution that the only requirement for a 3D track to be considered reconstructed would be the achievement of the pattern recognition. This solution is only temporary and the low efficiency of the Kalman fitting needs to be addressed in the future.
To evaluate the efficiency of the 3D tracking compared to the 2D scheme, the events are considered one by one. Each event in which a track is reconstructed in 2D is considered as eligible. For each eligible event, a track is searched for with the 3D tracking scheme. The efficiency is then computed as the number of 3D tracks obtained over the number of eligible events (since only one track reconstruction per event is allowed).
The average efficiency obtained for the 3D tracking when comparing to the 2D algorithm is $(79.4 \pm 0.1)\%$. The efficiency is also plotted as a function of the number of DS hits in the event of interest, as pictured in Fig. 7. The statistical uncertainties in the efficiency are computed using

[5] Track reconstructed with Hough transform only (without Kalman fitting), see Section 3.3.

the Clopper-Pearson statistics with a 90% confidence level. The binning among the number of DS hits is a quantile binning[6].

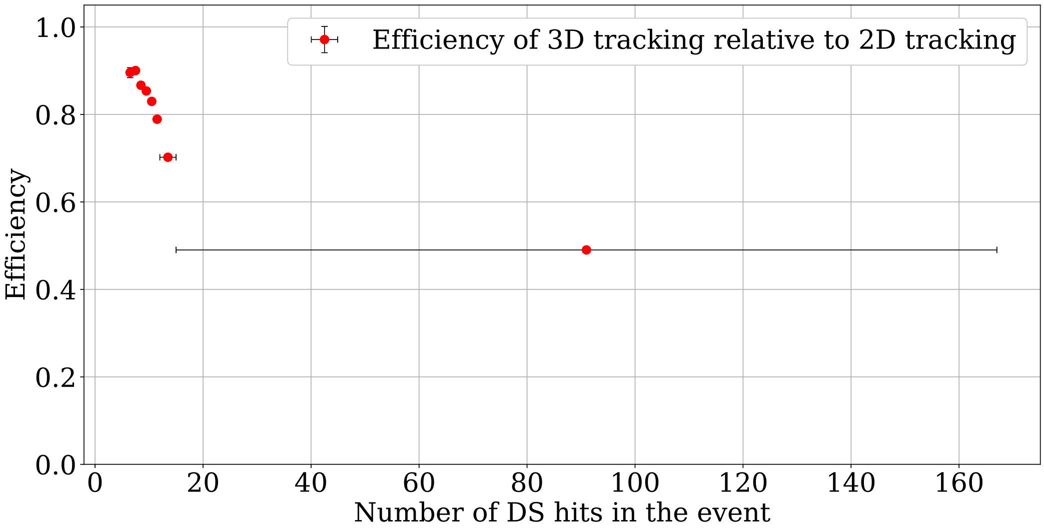

Figure 7: Efficiency of the 3D tracking scheme event by event compared to the 2D algorithm.

Similarly, the efficiency of the 3D tracking is computed as such. Again, the events are considered one by one but here the eligible events are not the ones with a reconstructed 2D track but the events for which a 3D track is reconstructible. The only requirement for a 3D track to be reconstructible is that at least three different horizontal DS detector planes should record a hit in the event. This time, the average efficiency is $(75.6 \pm 0.1)\%$. The corresponding plot can be found in Fig. 8.

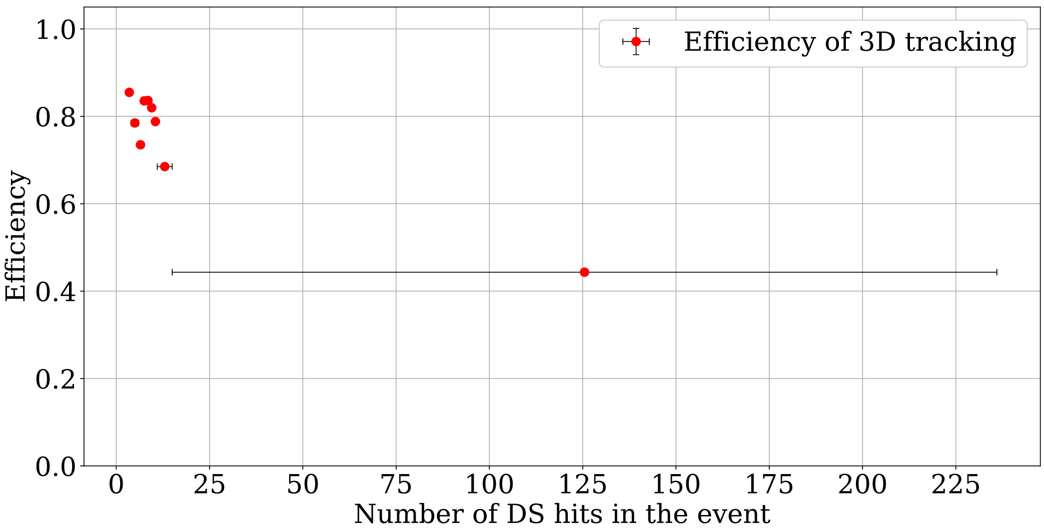

Figure 8: Efficiency of the 3D tracking considering reconstructible events one by one.

Finally, a last case is investigated, namely the events that are reconstructible in 3D but do not fulfill the 2D tracking scheme requirements. These are events that trigger at least three horizontal DS detector planes but less than three vertical DS detector planes. The study is

[6]The uncertainties and the binning are computed in the same way for all result plots in Section 3.

made in the same manner as both previous ones, with the events reconstructible in 3D only as the eligible set. The average efficiency in this case is $(70.5 \pm 0.2)\%$. The associated plot is displayed in Fig. 9.

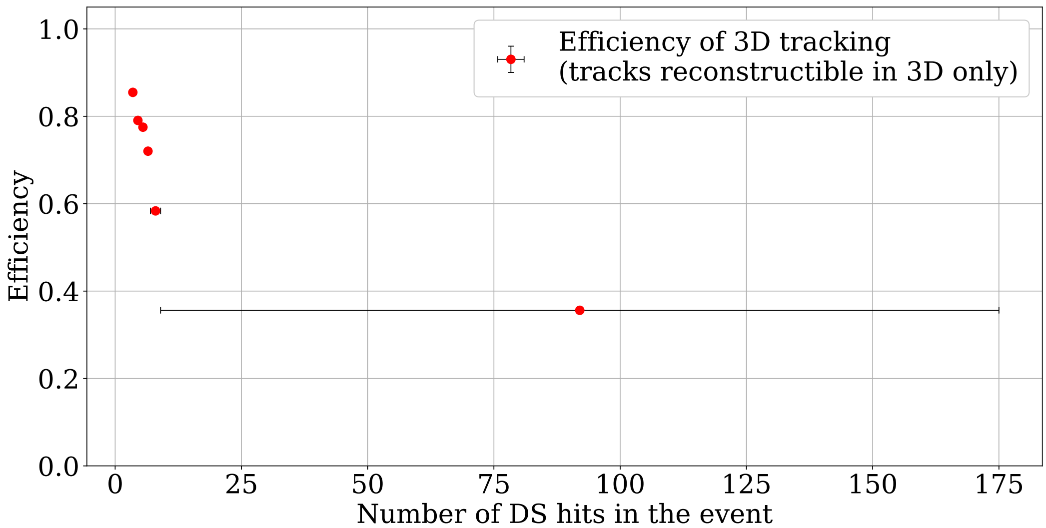

Figure 9: Efficiency of the 3D tracking algorithm considering events that are only reconstructible in 3D (and not in 2D).

Results show that for the moment the 3D DS tracking cannot fully replace the 2D tracking. However, it can complement it and successfully reconstruct tracks where information is insufficient in the vertical DS planes, but the muon hit all horizontal DS ones.

3.4 Multi-muon events

The performance of the 3D tracking scheme is finally studied when allowing reconstruction of multiple tracks per event. Partition 9 of Run 4705 is used again. The ratio in the number of tracks reconstructed with the two tracking schemes is computed. On average, the 3D scheme allows to reconstruct (1.125 ± 0.001) times more tracks than the 2D algorithm. The ratio is pictured as a function of the number of DS hits in the corresponding event in Fig. 10.

3.5 Discussion

All efficiencies obtained in Section 3.3 are between 70% and 80%, which is an encouraging result to further develop and improve the 3D tracking scheme. A good amount of other studies and corrections can already be imagined as a next step in the algorithm development.
First of all, the focus should be set to the Kalman filter part of the track reconstruction. The 3D tracks must ultimately be fully reconstructed and considering only the Hough track for the performance study was only a temporary solution.
Then, the accuracy of the reconstructed 3D tracks has to be computed. This could be done for instance by computing the resolution of the track along x and y in the detector. The question of the resolution computation itself has to be addressed first. Indeed, since the tracks are fitted on only three DS hits, the option of leaving one of the points out to compute the residuals is not feasible. The resolution should especially be of concern because, in some event displays, the reconstructed vertical track is parallel to the vertical hits population. While the vertical track intercept seems problematic in some cases, the slope of the track seems to mostly agree

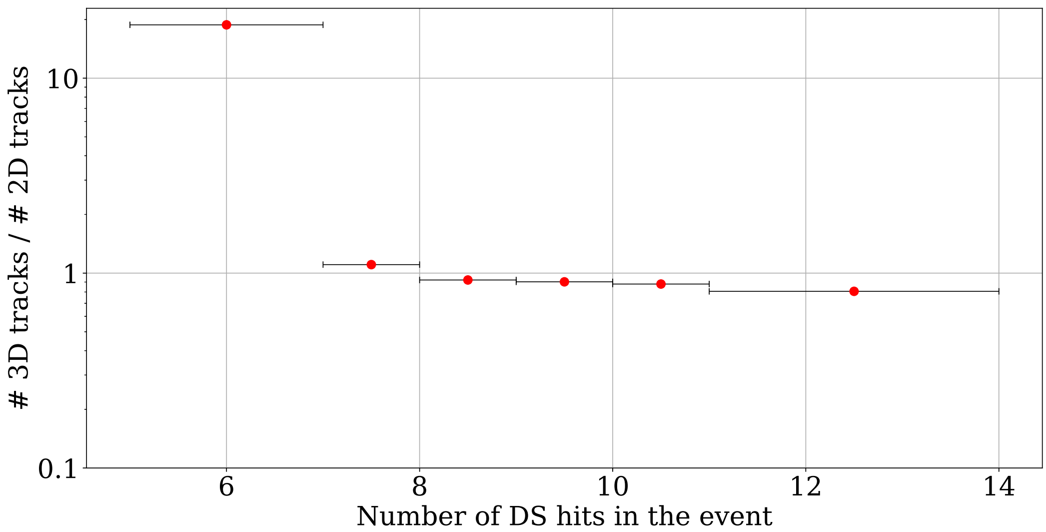

Figure 10: Ratio in the number of tracks reconstructed with the 3D and 2D tracking scheme. The rightmost bin is not displayed here for readability of the plot.

with the vertical hits population.
Finally, the tracking can be further tuned to give better results when using the 3D scheme. Some of the Hough parameters, namely the `sigma` and `truncate` variables used for the Gaussian smoothing are already set to the best possible values but this can be extended to some more quantities, such as the Hough space binning.

4 Conclusion

In this experimental work, a 3D tracking scheme was implemented for the SND@LHC experiment. The obtained 3D tracks should complement the information provided by the current 2D tracking scheme. The latter constructs two 2D tracks associated to two separate sets of hits, according to the detector geometry.
The tracking is performed in two steps: a straight line is found with the help of a Hough transform and then dynamically fitted using a Kalman filter. While the Kalman fitting part of the reconstruction still needs to be improved, the Hough transform already gives promising results. Considering the Hough transform only, the achieved 3D tracking efficiency is $(75.6 \pm 0.1)\%$, $(79.4 \pm 0.1)\%$ when compared to the 2D tracking scheme.
The 3D tracking should ultimately be added to the experiment software. It should be an especially useful tool when studying multi-muon events. The 3D tracking will indeed allow to perform a matching between the multiple tracks in both projections and should help to discard ghost and clone tracks for those events.

References

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