Optimisation of the scattering and neutrino detector for the SHiP experiment

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I. SHIP EXPERIMENT

A. Physics motivation

SHiP is a new proposed fixed target experiment at CERN SPS. Scientific programme at SHiP implies searching for HS (hidden sector) particles which are very weakly interacting particles with masses below the Fermi scale and studying the τ-neutrino physics [3, 4]. SHIP experiment is aimed to investigate the intensity frontier which still remains an unexplored area since such feeble interactions are not accessible at the LHC experiments. The HS can be ascertained through the interaction with SM particles. Depending on the type of the coupling various possibilities for new physics particles are available (vector portal, scalar portal, neutrino portal, etc.). SHiP is expected to be sensitive to all these portals and moreover it should be able to reveal Light Dark Matter scattering on the detector material [3].

One of the SHiP challenges is searching for heavy neutral leptons in the mass range predicted by the νMSM model. This model represents a Standard Model complemented with three Heavy Neutral Leptons (HNL) — right-handed partners of the active neutrinos [5]. In this way neutrino masses and oscillations, baryogenesis and dark matter can be explained. Another part of the declared program is focused on direct measurement of τ-neutrino interactions. In this sense SHIP can provide an unique opportunity to study ν_τ and $\bar{\nu_\tau}$ separately and with large statistics.

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B. Experimental facility

The layout of the SHiP facility within the latest design version can be seen from the figure 1. It includes two basic detectors: the Scattering and Neutrino Detector (SND) and the Hidden Sector (HS) spectrometer. The first one studies neutrino physics and performs LDM search while the second one is aimed at searching for new exotic long lived particles. The experiment is proposed to be housed at new SPS Beam Dump Facility located at the North Area of SPS. The engaged proton beam will have the energy around 400 GeV and annual yield of 4×10^{19} protons. For more detailed study see [4, 6].

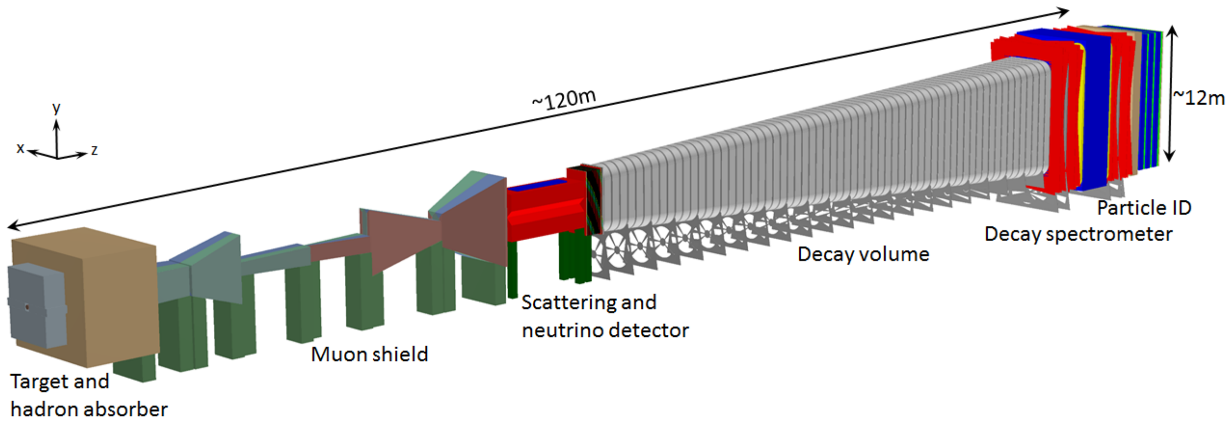


Figure 1: Overview of the SHiP experiment facility.

The target will produce a large number of charm and beauty hadrons as well as photons. After protons interaction with the target material the hadronic and electromagentic components of the flux will be absorbed in the following hadron absorber. Neutrinos and muons from the decays of pions, kaons and other short-lived resonances are the only particles left over downstream of the absorber. The required absorption power is obtained with a hybrid target consisting of blocks of titanium-zirconium doped molybdenum alloy in the core of the proton shower followed by blocks of pure tungsten for a total of 12 interaction lengths.

The proton target is followed by a 5 m long hadron stopper. The iron of the hadron stopper has been magnetised over a length of 4 m with the help of a magnetic coil integrated into the shielding in order to separate positive and negative muons. The muon shield is designed to reduce the flux of muons by six orders of magnitude in the detector acceptance. It represents a free-standing system of six magnets of complex form, each of ~ 5 m length, separated by 10 cm gaps [2].

Further downstream the Scattering and Neutrino Detector (SND) stands which receives the remaining neutrino flux. It is intended for the measurement of the neutrinos spectrum of all flavours and elastic LDM scattering on the electrons of the SND target material. I will describe its structure apart in the next chapter.

The anticipated long-lived HS particles decay in the following 50 m of the decay volume. However except of the registered muons (and neutrinos passed without interaction) there should be background events caused by deep inelastic neutrino-nucleon scattering as well as muon interactions in the decay vessel. In order to suppress this background the system is kept at a pressure of 1 mbar. The mentioned interactions mainly occur in the vessel walls, where they can be easily rejected.

The Decay Spectrometer is designed for precise measurement of charged particles produced in the decay of hidden particles. A particle identification and a momentum spectrometer are used. Basic components of the detector are: the Surrounding Background Tagger (SBT), the Spectrometer Straw Tracker (SST) coupled with the large spectrometer magnet, the Timing Detector (TD), the Electromagnetic Calorimeter and the downstream muon system. The measurement of the track parameters and momentum of charged particles and the suppression of background events are performed by the SST. It consists of a large aperture dipole magnet and two tracking stations on each side of the magnet. The tracking stations are based on sophisticated configuration of ultra-thin straw drift tubes oriented horizontally. The processing signal should be synchronised with the TD timing information.

C. Scattering and neutrino detector

The design of the Scattering and Neutrino Detector (SND) consists of an emulsion target combined with the target tracker system placed inside a magnetised region which is followed by the muon identification system. The schematic picture of the detector is given in figure 2. The host magnet represents an iron yoke with a coil of 7 m long which produces the uniform magnetic field of 1.25 T in limited volume. Coils will be made. of copper. Due to the regulations on the emulsion temperatures range the magnet is accompanied by active cooling system.

The emulsion target has a complex structure of 19 emulsion brick walls interleaved with 19 Target Tracker planes. Each wall consists of Emulsion Cloud Chamber (ECC) followed

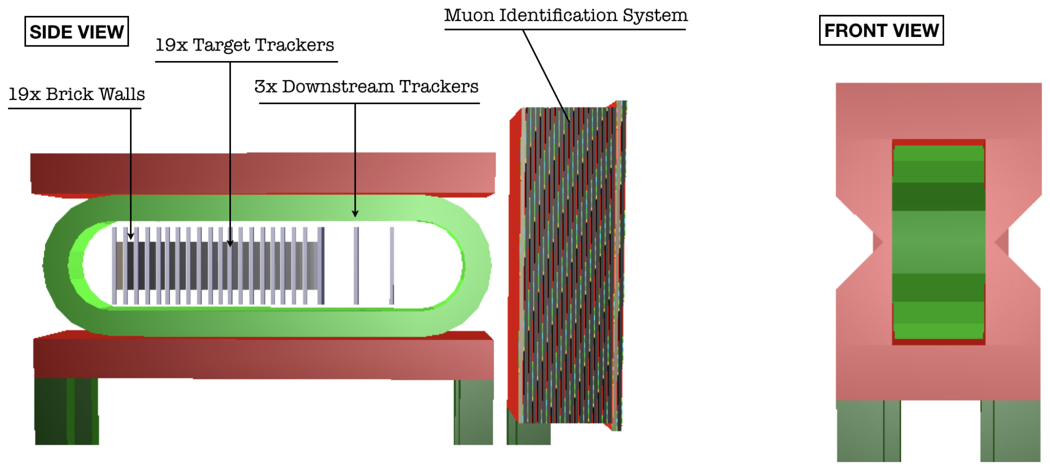


Figure 2: Layout of the SND detector.

by a Compact Emulsion Spectrometer (CES). In the transverse plane the walls are divided into 2×2 cells, each with a transverse size of $40 \times 40\text{cm}^2$ (see figure 3). In turn each ECC cell (also named as brick) has a modular structure: it is made of 57 nuclear emulsion films interleaved with 1 mm thick lead layers.

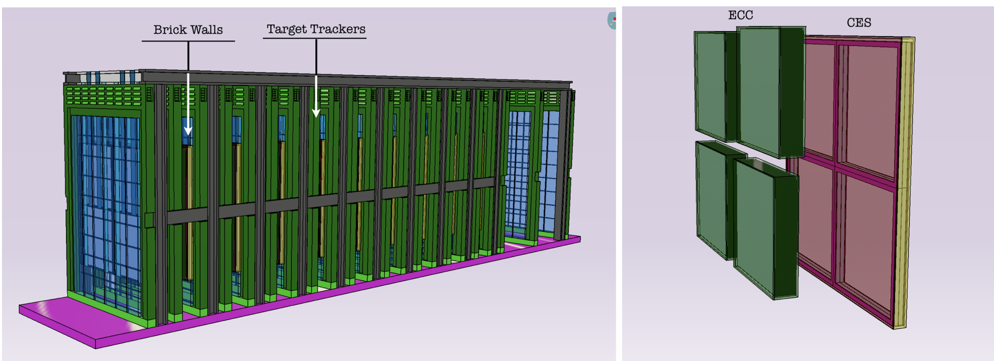


Figure 3: Layout of the emulsion target and closeup view of the ECC brick and CES.

ECC technology was largely demonstrated by the OPERA experiment [1]. Particles passing through the bricks necessarily loose energy due to the multiple scattering or hadronic and electromagnetic showers in the lead. In case of LDM passing one can expect the measurement of the elastic scattering off electrons in the absorber [7]. Eventually the ECC ensures the effective tracking device with high spatial and angular resolution which enables to extract the production and decay vertexes including τ leptons and charmed hadrons.

The Compact Emulsion Spectrometer (CES) is made of three emulsion films separated by air gaps and has a length ~ 3 cm. CES focuses on measuring the electric charge and the momentum of hadrons produced in τ lepton decays and soft muons going at large angles and escaping the Downstream Trackers. The reasonable momentum range in this case is considered to be below 10 GeV.

Each emulsion target wall is complemented by the Target Tracker station which provides the time stamping for the tracks. The same stations are used for Downstream Tracker system. The latest consists of $3 \div 5$ planes separated by air gaps. The DTs are intended for the measurement of high momentum tracks, mostly muons, which are awkward to be measured in CES. The underlying technology for the tracker planes is a subject of ongoing research. Two options are available for this purpose: μ-RWELL detector and Scintillating Fibre (SciFi) Tracker developed at LHCb.

The muon identification system should identify the final muons. In the current design it comprises 13 iron filters, 10 cm thick, interleaved with 12 tracking planes instrumented with RPCs. The last two planes cover the whole decay vessel entrance window in order to tag neutrino interactions in the muon system which may give rise to potential background events in the downstream HS Decay Spectrometer.

II. MY ESTIMATIONS

One of the basic SND's challenges is to measure the inelastic and quasi elastic interactions producing a muon in the final state. In this regard my work was devoted to reconstruction of muon tracks. The main studies to be performed are the momentum resolution of reconstructed tracks and estimation of the detector efficiency. An important aspect is to compare the measurements in Downstream Trackers and in Compact Emulsion Spectrometers and find out the acceptable momentum range for each of them.

The SHiP physics is performed on the basis of the official simulation and reconstruction package, called FairShip. The software contains a full Geant4 performance of the material and detectors geometry. The core of FairShip is FairRoot package. FairShip simulation appeals to underlying Root and Pythia tools.

The neutrino interactions are generated with Genie (neutrino Monte Carlo generator)

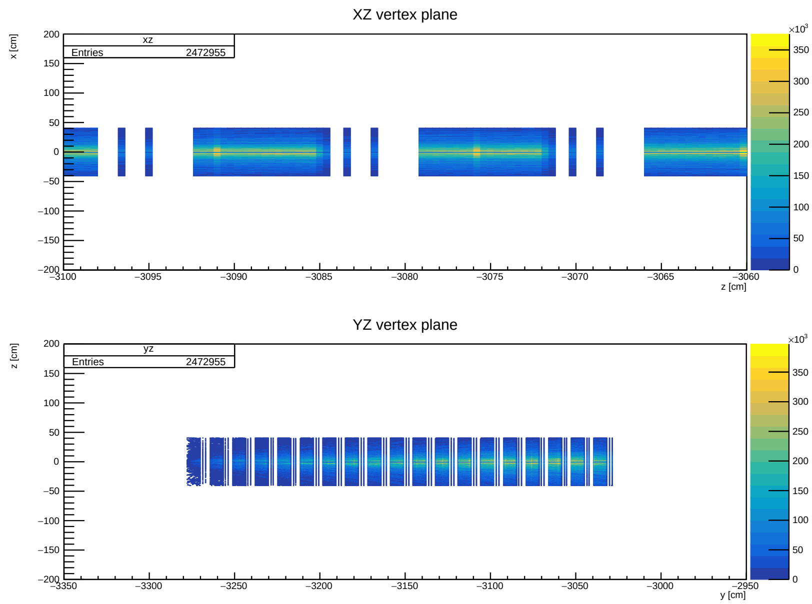
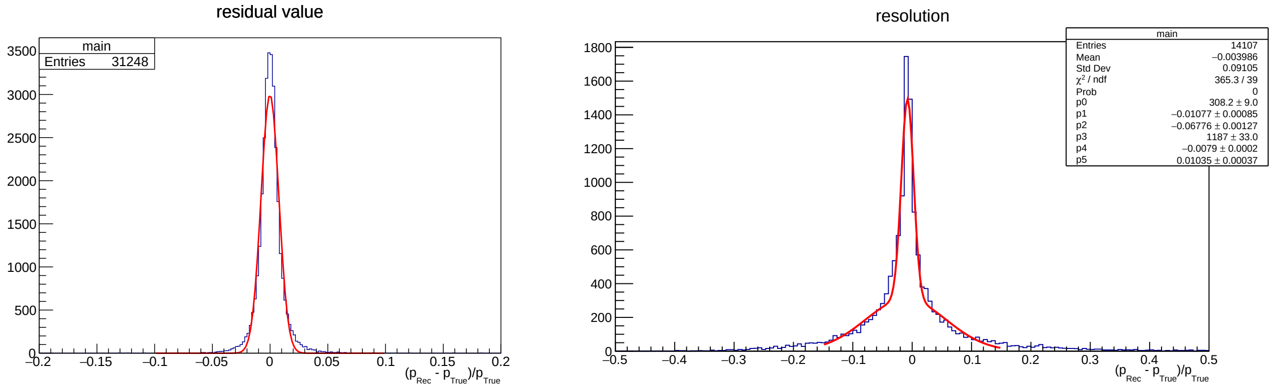


Figure 4: Position of the ν_μ interaction vertex in the emulsion target.

which takes the input neutrino fluxes produced in proton interactions with the upstream target. These neutrinos are further propagated through the detector structure within the FairShip framework. By using Genie and FairShip software I have produced the simulation suitable for analysis. It was limited to 100K events of each ν_μ, ν_e, ν_τ interactions in the emulsion target of SND. Picture 4 shows the distribution in the XZ and YZ views of the primary vertex of ν_μ interaction.

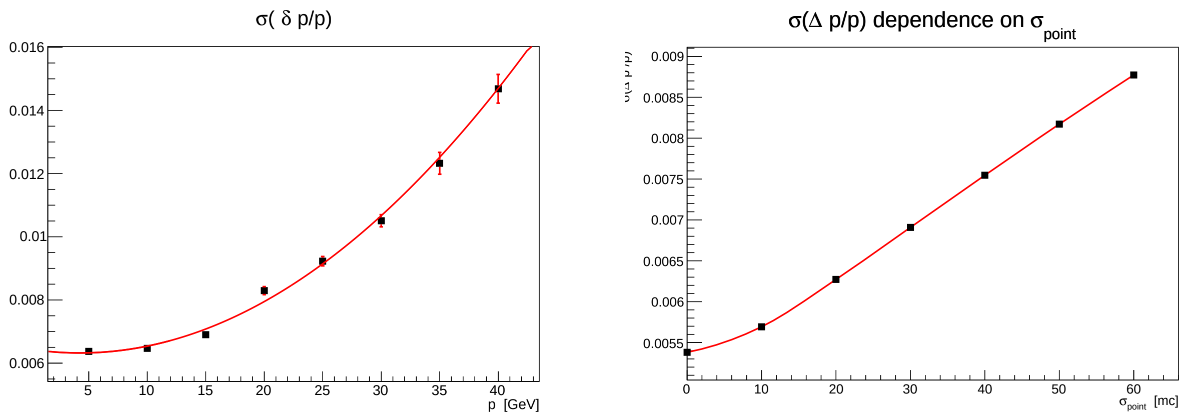
The reconstruction of momentum was done with so-called sagitta method: bending of the charged particle track can be defined at three hits. This bending can be easily interpreted as momentum magnitude. The comparison of reconstructed and Monte Carlo truth momentum was studied with regard to the key features of the detector: coordinate resolution and geometry configuration.

Let us focus on the momentum reconstruction at DTs system. In the current configuration it consists of 5 stations separated by 50 cm gaps. The number of stations could be reduced to 3. However it would lead to the lower efficiency in case of hit inefficiency. The tracker's coordinate resolution is the main source of the error for momentum. For my analysis it was fixed at $\sigma_x = \sigma_y = 60$ μm. This value stays as an approximate since $30 \div 50$ μm is expected in case of SciFi trackers and $50 \div 100$ μm in case of μ-RWELL trackers. The picture 5 (a) shows the gaussian peak for the momentum resolution.



a) b)

Figure 5: Momentum resolution peak: a) gaussian fit for DTs, b) sum of two gaussian fits for CESs.

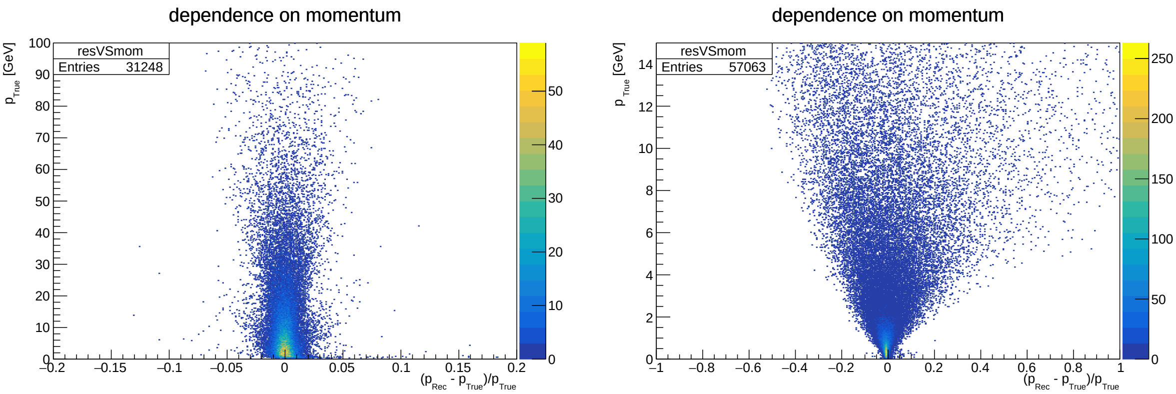


a) b)

Figure 6: Dependence of $\sigma(\Delta p/p)$ for DTs on: a) momentum, b) coordinate resolution.

To verify the reconstruction procedure one can examine the behaviour of standard deviation $\sigma(\Delta p/p)$. I have examined its dependence on momentum and point resolution. The corresponding graphs properly show the linear and parabolic increase (see the picture 6). Another plot providing an important information is shown at figure 7 (a). One can see that momentum resolution is less than 5% up to 100 GeV.

Momentum measurement at CES is supposed to provide less accuracy since a shorter part of a track curve is engaged. The latest tested CES prototype has a design of 3 emulsion films interleaved with 1.5 cm air gaps. The coordinate resolution of emulsion film is approximately



a) b)

Figure 7: Momentum resolution dependence on momentum for: a) DTs, b) CESs.

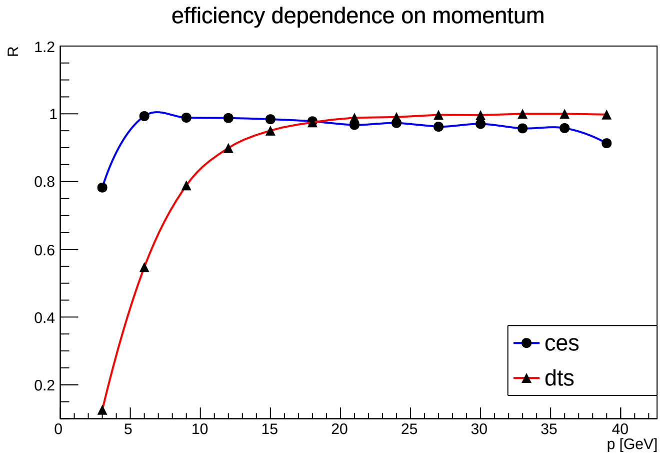


Figure 8: Efficiency for muon identification at SND.

$\sigma \approx 1\ \mu$m. The muon track propagation should be inspected through the hits in the brick emulsions as well. While crossing the bricks muon loses up to 10% of its initial energy. The peak for momentum resolution at CESs is shown at figure 5 (b). However it does not have a clear gaussian shape as in the case of DTs. Though it was fitted with two gaussian fit. CESs are designed for measurement at low momentum range which is consistent with the major part of muon flux (see picture 7 (b)). At $p \sim 10$ GeV the error for momentum reconstruction is $\sim 40\%$.

The second part of the project was the subject of estimation of the detector's efficiency. The analysis for the fraction of reconstructed muons was done. The result is shown at the picture 8, where only geometrical acceptance is accounted. Finally I got for integral values:

$R_{CES} = 91\%$, $R_{DTs} = 41\%$, $R_{combined} = 92\%$. This means that 92% of the muon tracks can be measured by combining both CES and DT detectors. This is only the geometrical acceptance. However the total efficiency should include also the efficiency of charge identification.

III. CONCLUSIONS

SHiP is a proposed project of a new experiment at CERN SPS aiming to search for the exotic long lived particles. Another SHiPs challenge is studying the neutrino physics of all flavours at SND. At the current stage of R&D it is important to get the knowledge about the muon reconstruction at SND. My work covered the simulation of neutrino interactions in the emulsion target and the following analysis of daughter muons reconstruction within the FairShip software. I managed to obtain results concerning the momentum resolution features and estimate the geometrical acceptance of both CES and DT detectors to muon tracks. These results will be used in further development of the software and optimisation of the detectors configuration.

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