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Calibrating the SHiP μ-flux using NA61/SHINE

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Abstract

A major concern for the design of the SHiP experiment is the lack of a precise knowledge of the muon flux. This is a proposal to measure the expected muon flux in the SHiP experiment by installing a replica of the SHiP target in a 400 GeV proton beam in front of the NA61/SHINE spectrometer. We propose to do a first measurement in 2017.

Contents

1 Introduction

The SHiP experiment [1] requires 4×10^{13} protons on target (POT) per SPS spill. The target is composed of a mixture of Mo, W and Ta [2] to increase the charm cross-section relative to the total cross-section and reduce the probability that long lived hadrons decay. SHiP used Pythia and Geant to simulate the muon rate produced in the target. The fraction of protons which produce charm in Pythia is an order of magnitude below what has been measured, and hence SHiP corrects this to be $\chi(pp \to c\bar{c}) = 1.7 \times 10^{-3}$ for a 400 GeV/c proton beam colliding on a molybdenum target. This χ fraction does not take into account that the target is several interactions length long, and secondaries produced in the initial pN collision can produce heavy flavour in a subsequent interaction. This is also taken into account in the SHiP simulation [3]. Figure 1 shows the expected phase-space of the produced muons. The figure has been obtained by generating $\sim 10^{10}$ pp interactions,

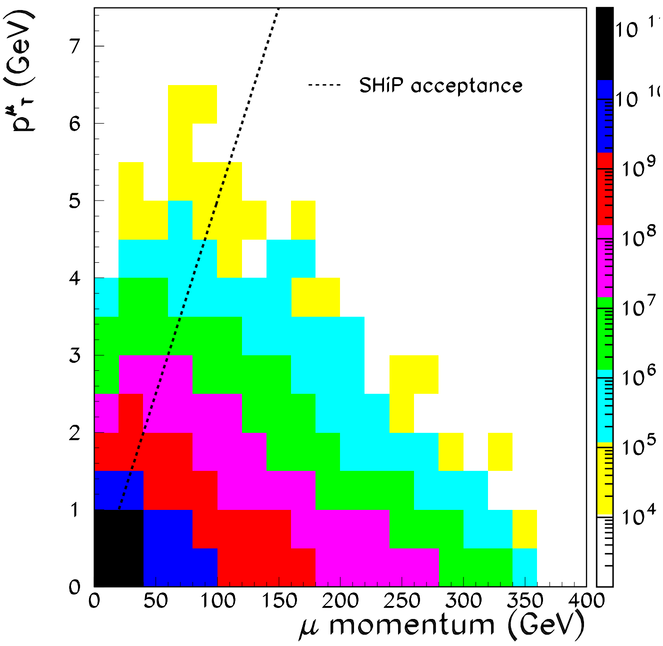


Figure 1: The expected momentum and transverse momentum (p_{T}^{μ}) distribution corresponding to one SPS spill of 4×10^{13} POT. The SHiP acceptance is 50 mrad.

which took several months running on a large CPU farm. Based on this simulation it is expected that $\sim 2.6 \times 10^{10}$ muons will be in the acceptance of SHiP per spill, of which $\sim 4 \times 10^{8}$ muons with a momentum larger than 100 GeV.

SHiP uses a series of shielding magnets to reduce the muon-flux inside the experiment by several orders of magnitude. The design of this shield relies on the muon phase-space to be expected, and in particular on the muons with a larger momentum and larger p_{T}^{μ} as they can escape the shield and end up in the detector acceptance. In the above simulation we obtain 166 muons with a momentum larger than 100 GeV and $p_{\mathrm{T}}^{\mu} > 3$ GeV, which corresponds to a flux in SHiP of $\sim 0.6 \times 10^6$ Hz. A few hundred muons is too small an amount to be the basis of a reliable optimization of the magnetic shield. If these muons would all be the decay products of charmed hadrons, one could increase the equivalent amount of simulated POT by an order of magnitude using the mechanism described in [3]. However, as is shown in Figure 2, the muons at large momentum and p_{T}^{μ} predominantly do not originate from charm decay. For the largest momenta the predominant source is ω

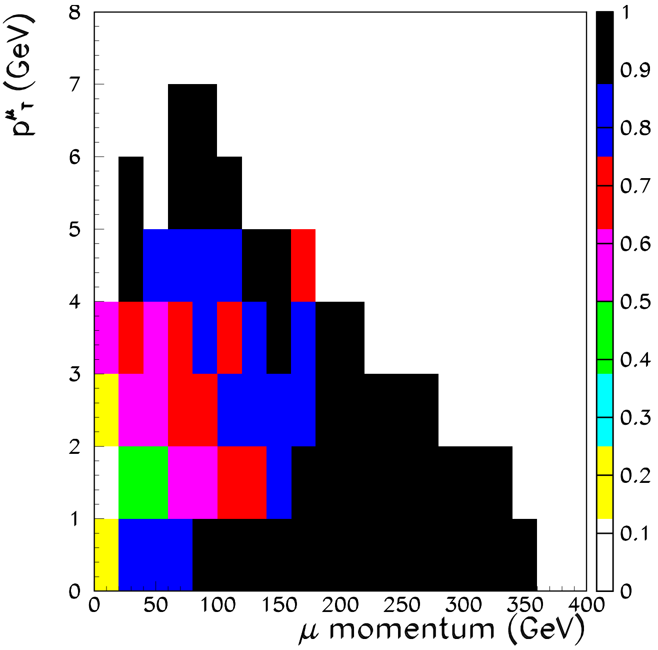


Figure 2: The fraction of muons which do not originate from charm decay as a function of their momentum and p_{T}^{μ}.

and ρ production, while for the largest p_{T}^{μ} the sources are Υ and J/ψ.

As was shown in section 5.1.1 of the SHiP TP [1], the muon flux simulation agrees rather well with what has been measured by the CHARM experiment. However, this does not address the few % of muons at the periphery of phase-space, which drive the design of the magnetic shielding. Hence, the proposal to measure the flux and phase-space of these muons before the construction of the shield commences. The next section will show the proposed layout of an experiment aimed at measuring the flux using the NA61/SHINE spectrometer and the requirements of the SPS proton beam. This is followed by the result of a simulation showing how the trigger selects the muons of interest and its performance.

The proposal is to accumulate $\sim 10^{11}$ 400 GeV POT in NA61/SHINE during a run at the end of 2017 using the actual NA61/SHINE FE electronics of the TPC system [4]. If the readout time is decreased by an order of magnitude during LS2, the request is to accumulate $\sim 10^{13}$ POT during a year of running after LS2.

2 Experimental set-up

The proposal is to place a replica of the SHiP target followed by the 5 m long Fe hadron-stopper in the free area in front of the NA61/SHINE target between the BDP-2 station and the NA61/SHINE target (see Figure 3). The available space is shown in Figure 4.

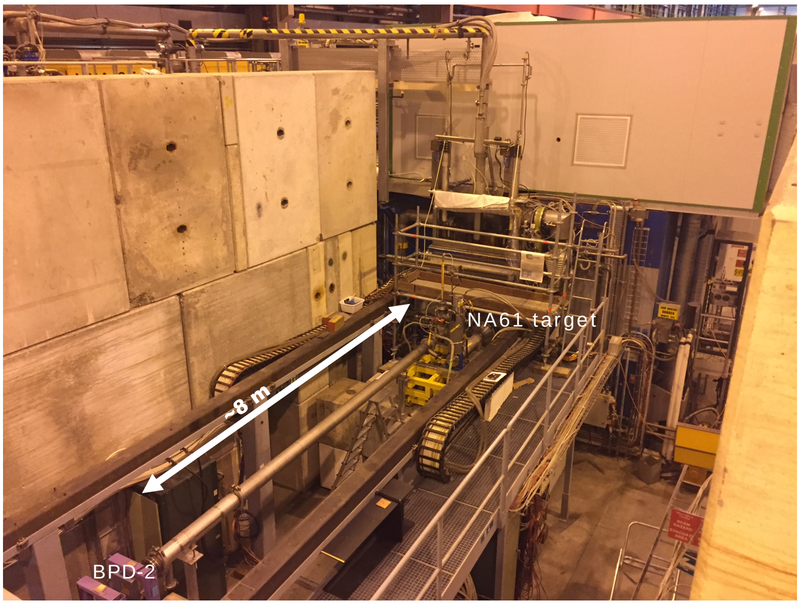


Figure 3: Target area of NA61/SHINE

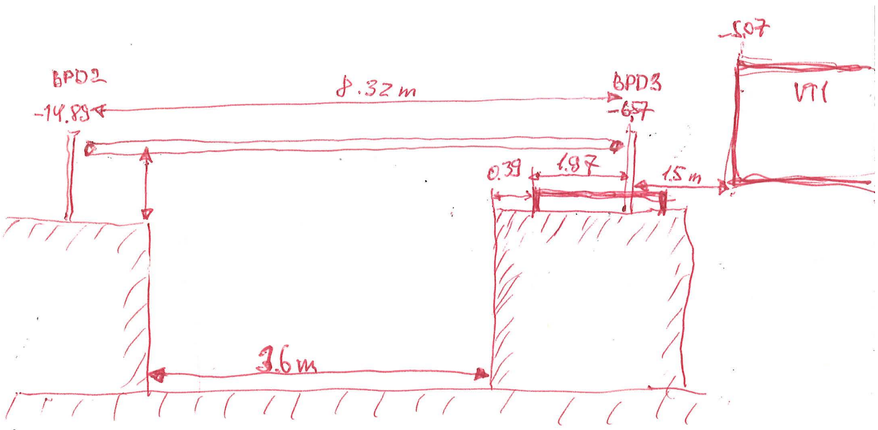


Figure 4: Sketch in y-z of the available space in front of NA61/SHINE

Apart from removing the section of the beam pipe before the NA61/SHINE target, the NA61/SHINE spectrometer remains unchanged.

The following sections describe details of the SHiP target, the NA61/SHINE geometry and the implementation in the SHiP simulation (FairShip).

2.1 The SHiP target

The SHiP target has the dimensions $30 \times 30 \times 116$ cm^3 and consists of 58 cm Molybdenum slabs followed by the same length of Tungsten slabs. To avoid corrosion due to water cooling, the Molybdenum and Tungsten slabs will be Tantalum-cladded (1 or 2 mm on both sides). The peak power during the spill amounts to 2.56 MW. For this reason, the design of the target relies on energy dilution thorugh an Archimedean spiral and a large beam spot (see [2]). The target is followed by a 5 m long iron hadron absorber (see Figure 5 and Figure 6).

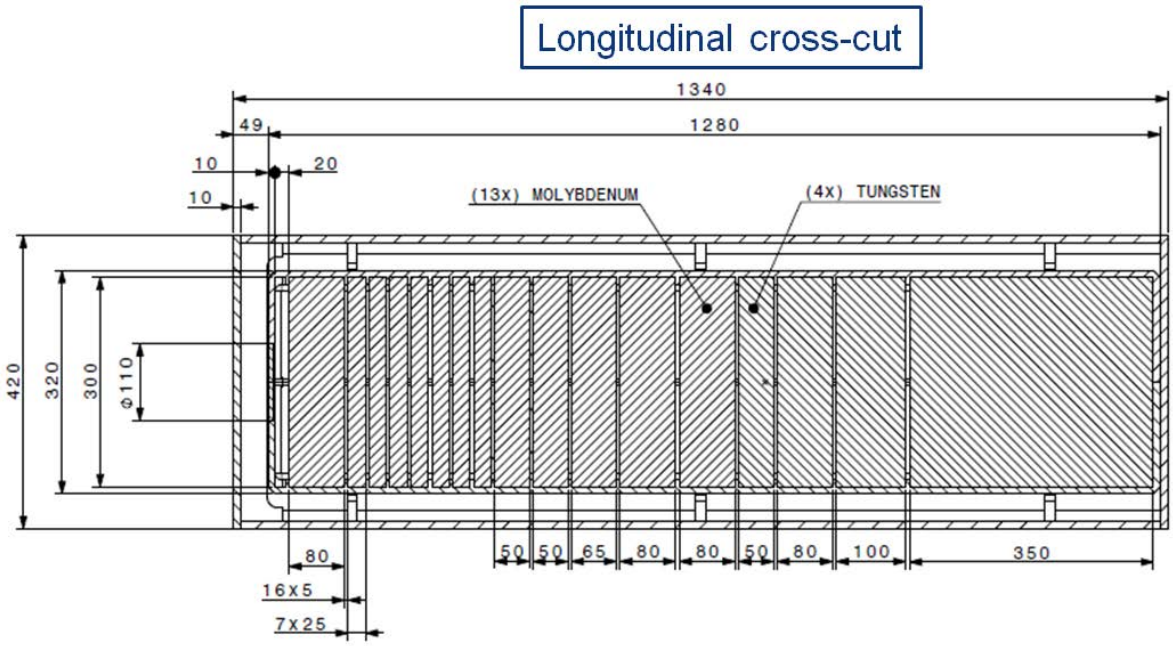


Figure 5: Longitudinal layout of the SHiP target

We propose to place a $10 \times 10 \times 116$ cm^3 replica of the SHiP target with exactly the same Mo, W and Ta distribution in front of NA61/SHINE. Since there is no need to cool the target, the Ta will be added without the cladding to reduce the cost. Similarly, at the SPS intensity of 10^6 POT there is no need to "spiral" the beam. Assuming a beam size with $\sigma = 1$ cm the muons' radial position inside the target is shown in Figure 7. All produced muons "fit" within 10×10 cm^2.

2.2 NA61/SHINE layout

The current experimental setup of NA61/SHINE [5] is shown in Figure 8.

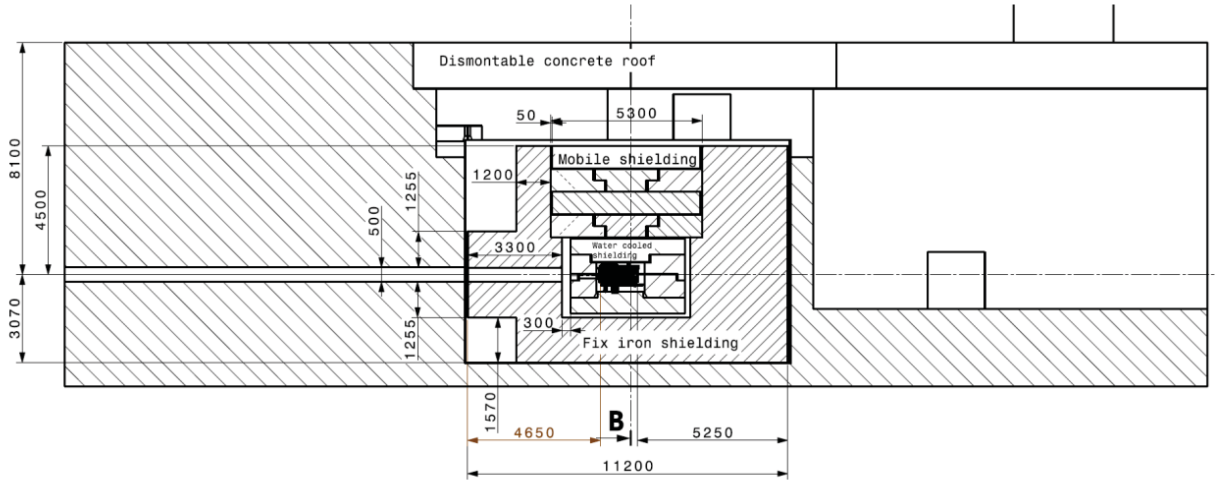


Figure 6: Vertical cross-section of the SHiP target bunker. The SPS beam comes in from the left, and SHiP is located on the right side of the Fix-iron-shielding.

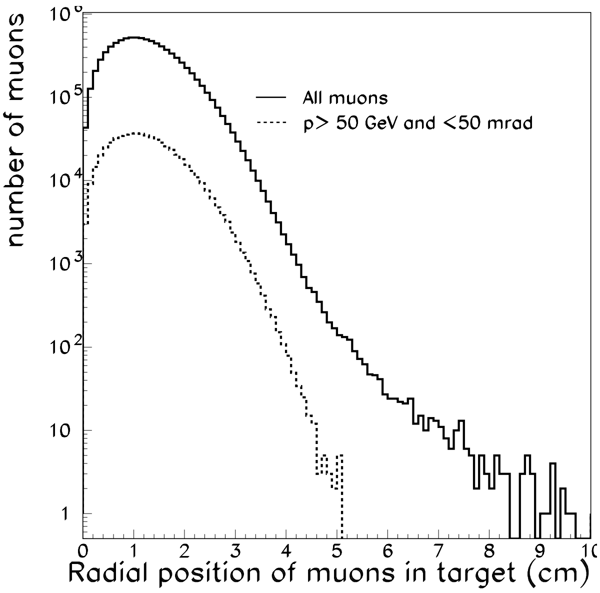


Figure 7: The radial position of muons inside the target with a $\sigma_{\mathrm{beam}} = 1$ cm.

Figure 9 shows xz and yz hitmaps. They show that the fiducial volume (i.e. the volume where hits can be recorded) of the TPCs is smaller than their geometrical dimensions, with an asymmetry in y. This is explained by the presence of electronics on top of the chamber. The $E \times B$ effect and electrostatic distortions cause an asymmetry in the horizontal plane of the order of a few cm. For our simulations (using FairShip) we have taken the fiducial dimensions of the TPCs.

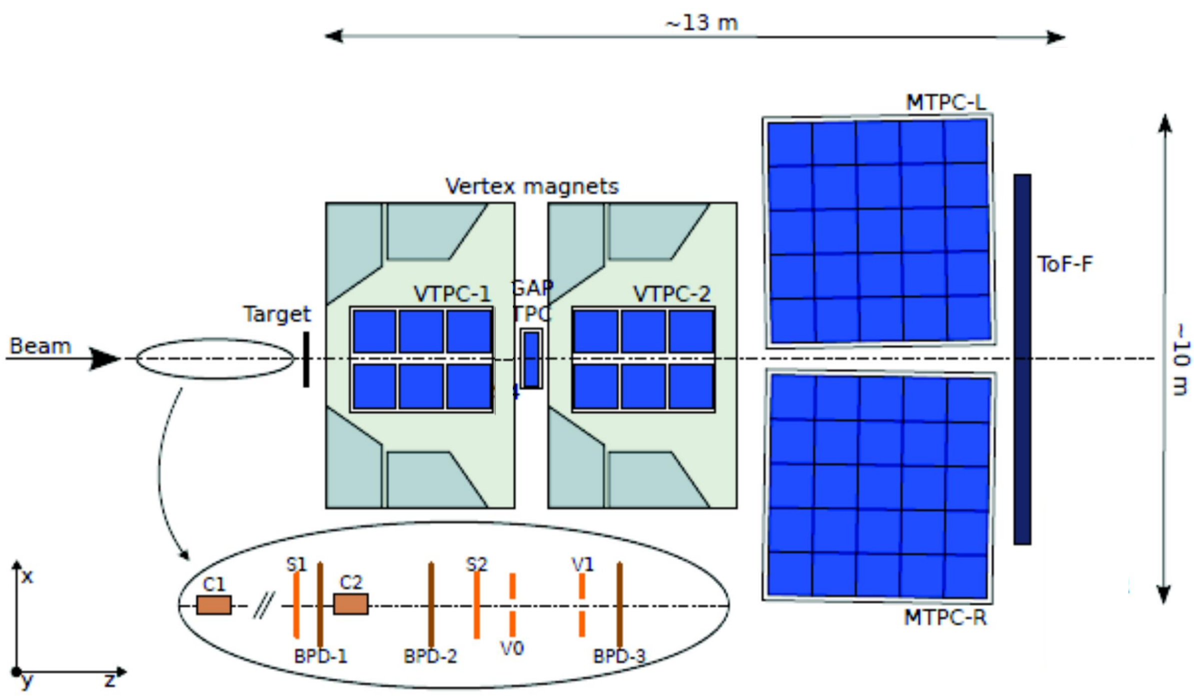


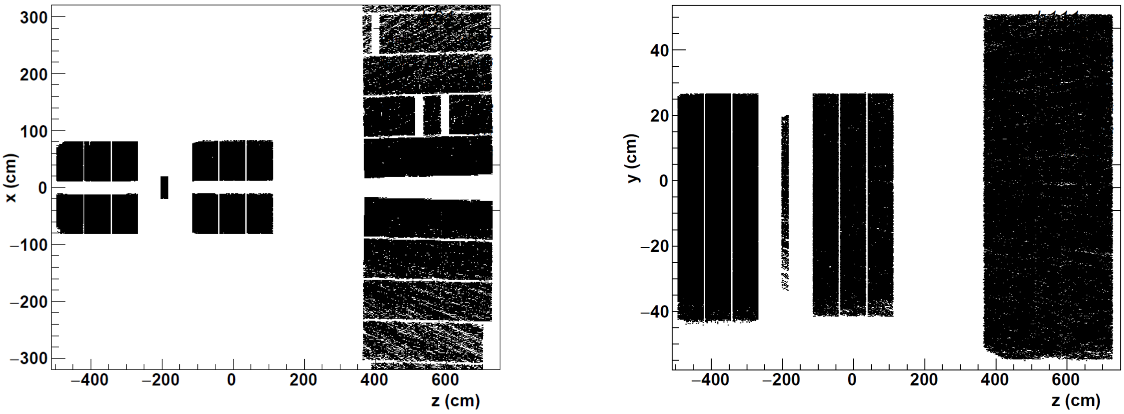
Figure 8: The setup of the NA61/SHINE detector.

The unbiased beam trigger (S1 and S2 in Figure 8) is recorded for normalization purposes (see Section 3 in [6] for details).

2.3 Implementation in FairShip

The implemented version of the NA61/SHINE geometry in FairShip is shown in Figure 10:

- The figure shows the target and the 5 m long iron hadron absorber; the lateral size of Fe is reduced compared to the SHiP target bunker to fit in the space in front of NA61/SHINE.
- The fiducial volumes of the TPCs are implemented by scoring planes at the entrance and exit of the TPCs, and an additional plane in the center of VTPC1,2 and MTPC.
- For triggering purposes we include a scintillator station SA; we will also use the existing NA61/SHINE detector ToF-F (see Figure 11).
- SA consists of 11 scintillators of 6 cm (0.5 cm overlap) wide and 50 cm high after the hadron-stopper, which corresponds to the acceptance of SHiP.



(a) xz hitmap (b) yz hitmap

Figure 9: NA61/SHINE hit maps from the pilot run of NA61/SHINE in 2007

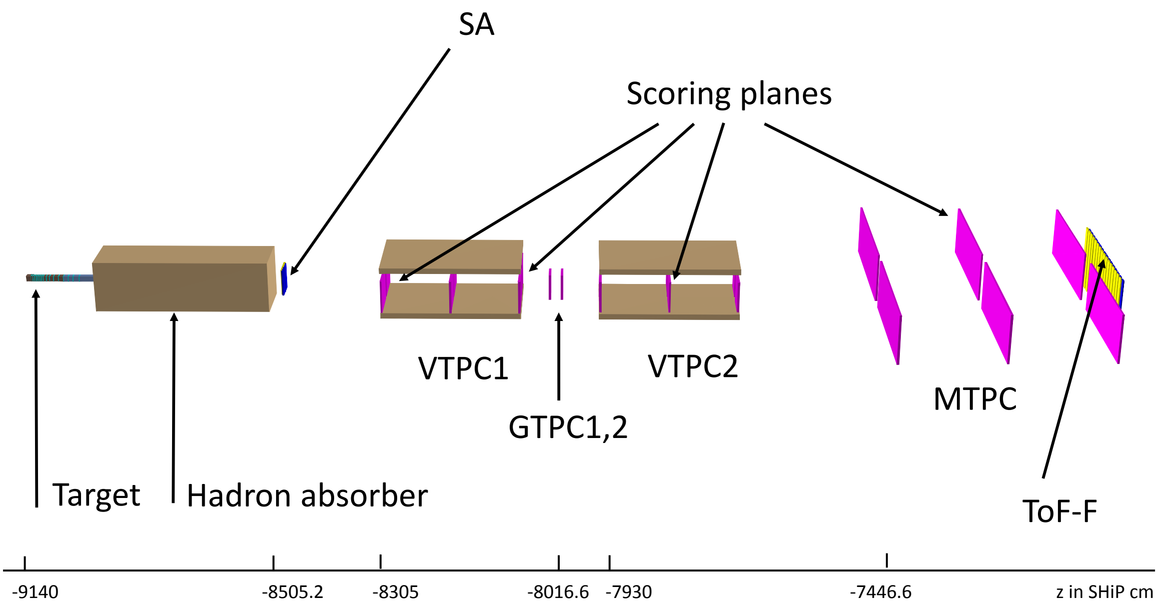


Figure 10: Experimental setup (yz or side view) of NA61/SHINE as implemented in FairShip

- From the ToF-F we will use the central 32 scintillators of 10 cm (0.5 cm overlap) wide and 120 cm high located downstream of MTPC (implemented in FairShip as shown in Figure 12).

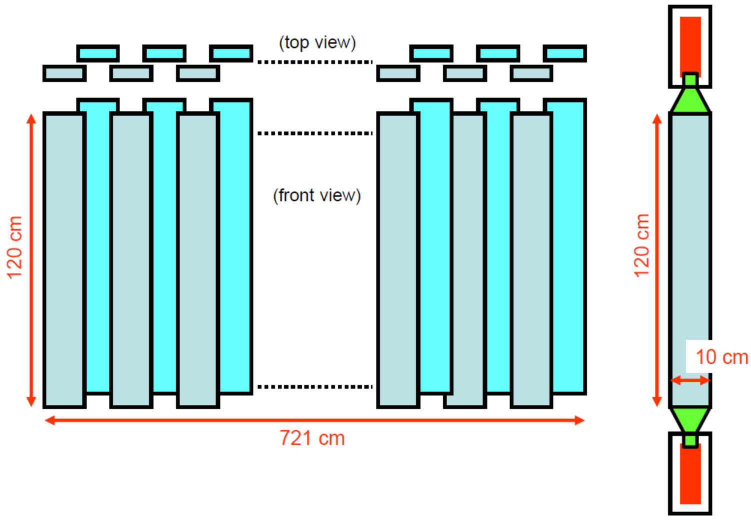


Figure 11: The schematic layout of scintillators in the NA61/SHINE ToF-F detector

- Iron sheets above and below VTPC1 and 2 represent the material there.
- The NA61/SHINE magnetic field map is included and the field along the beam-line is shown in Figure 13.

A sketch of the resulting experimental layout is shown in Figure 10.

3 Simulation

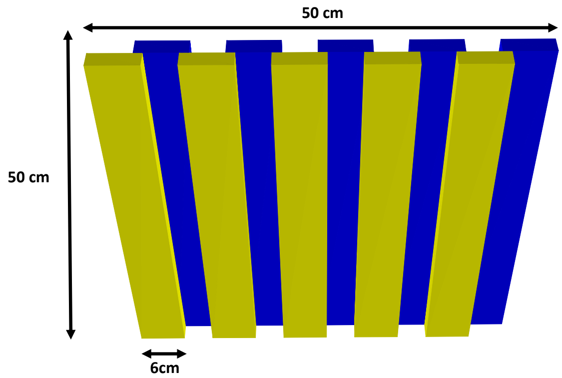
With the NA61/SHINE geometry implemented in FairShip as described in Sec. 2 we did two simulations. The files we used for our simulation can be found in the directory `/eos/ship/data/Mbias/` and `/eos/ship/data/na61/`.

The first one using 17.7 M background muons generated with Pythia as described in Section 1 to estimate the rates. To enhance the statistics in the "dangerous" muon (p_{T}, p) domain, we applied 100 random momentum rotations around the beam-line for muons with $\sqrt{(p_T/3)^2 + (p/200)^2} > 1$ and corrected their weights accordingly.

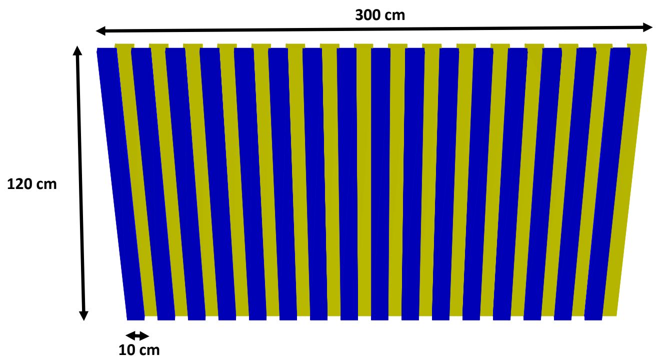
These muons were traced through the SHiP-NA61/SHINE detector with Geant4.

The second simulation used a particle gun to obtain the trigger acceptance with enough statistics over the whole (p_{T}, p) plane.

We generated 1 M μ^- and 1 M μ^+ in the momentum range $(0 - 400$ GeV$)$. These were randomly generated with the azimuth angle ϕ in the range $(0 - 2\pi)$ rad and the polar angle θ in the range $(0 - 0.1)$ rad.



(a) SA closeup



(b) ToF-F closeup

Figure 12: Closeup of SA and ToF-F as implemented in FairShip

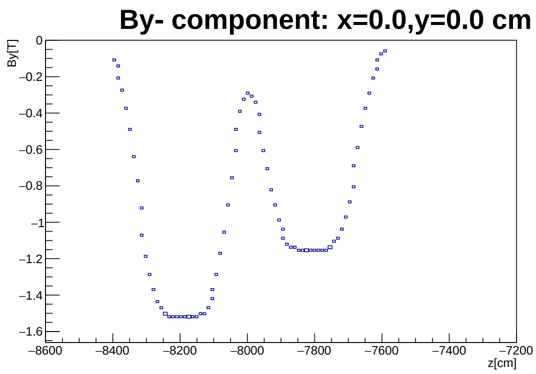


Figure 13: The B_y (vertical) component of the NA61/SHINE magnetic field

4 Trigger and Performance

A SPS spill of 10^6 POT over 5 s gives $\sim$ 130 Hz of muons after the hadron absorber within the $\sim$ 50 mrad SHiP acceptance; as triggered by SA.

Due to the 12 ms read-out time of the NA61/SHINE TPC system, this results in a larger than 60 % dead-time, as is shown in Figure 14.

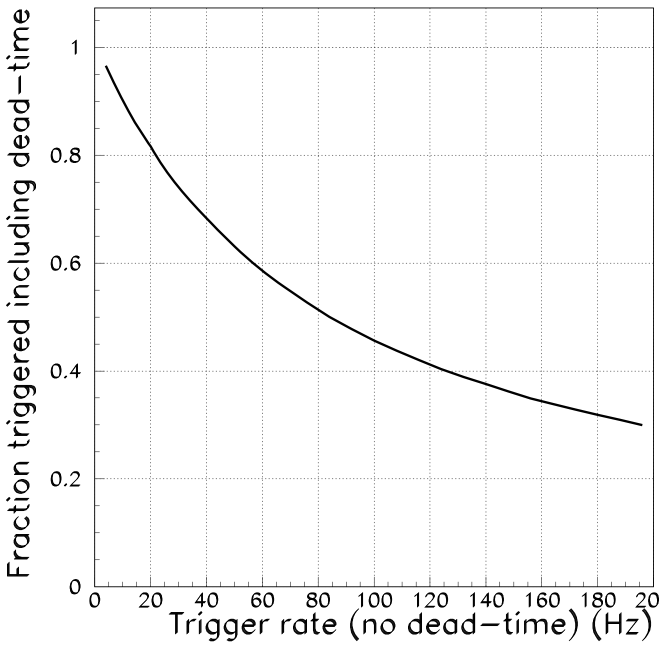


Figure 14: Acceptance including the dead-time due to the 12 ms readout time of the TPCs as a function of the trigger rate not corrected for dead-time.

Figure 15 shows in the left plot the acceptance of muons triggered by SA as a function of their momentum and p_{T}^{μ} corrected for dead-time and requiring that a muon traverses at least the fiducial volume of one of the TPCs.

The NA61/SHINE magnets provide a p_{T} kick of $\sim$ 2.2 GeV. As a result the x-position of the muons before and after the magnet allows one to select a certain area in the (p, p_{T}) plane, as is illustrated in Figure 16.

To reduce the dead-time it is proposed to reduce the trigger efficiency for low momentum and accept only those muons which traverse a certain correlation between scintillators SA and ToF-F. The corresponding look-up-table (LUT) is indicated in black in Figure 16. This reduces the trigger rate to $\sim$ 3 Hz, and hence reduces the dead-time and increases the efficiency as is shown in the right plot of Figure 15. The efficiency is good for all large p_{T} while keeping a good coverage of the entire (p, p_{T}) plane as can be seen from the yields in the (p, p_{T}) plane after 10^{11} POT (appr. 2 weeks of running at the SPS, see Figure 17). If more POT can be delivered by changing the SPS intensity or spill length, the trigger

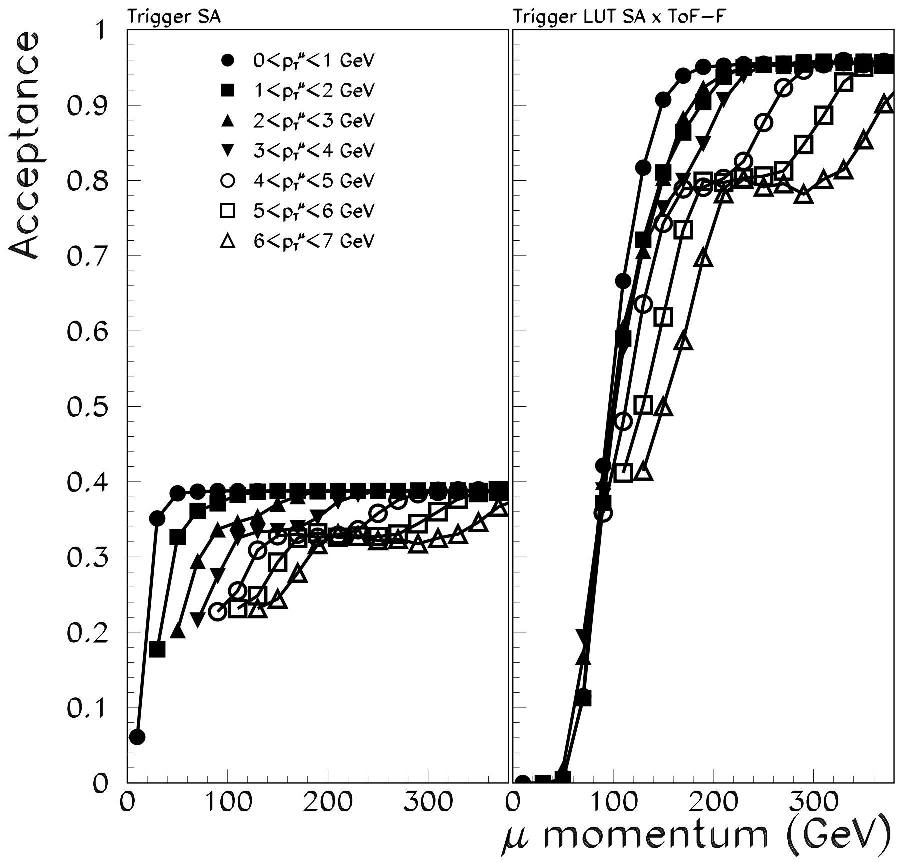


Figure 15: Acceptance of muons as a function of their momentum and p_{T}^{μ} including the loss due to dead-time. The muons traverse at least one of the TPCs. Left plot as triggered by SA. The right plot uses a trigger which correlates SA and ToF-F using a LUT, as explained in the text.

system LUT which correlates SA and ToF-F can be adapted to still limit the dead-time while maintaining a high efficiency for large (p, p_{T}) muons.

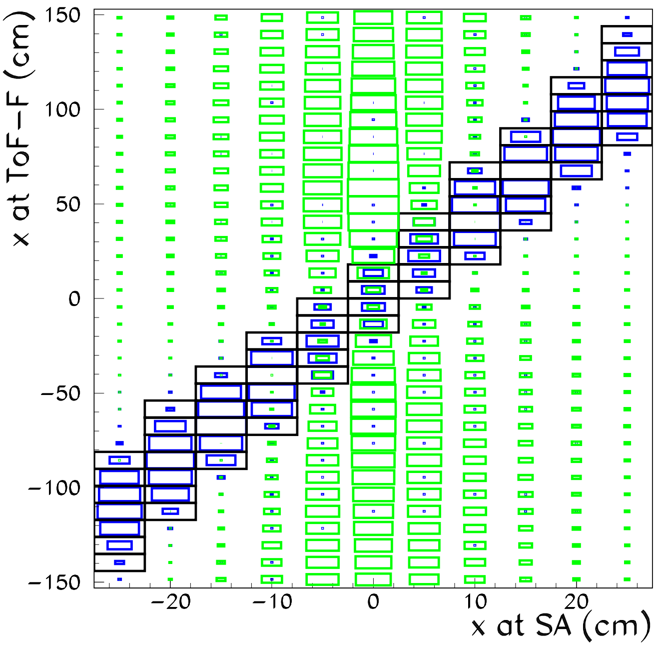


Figure 16: The position of muons at scintillators SA and ToF-F. Muons with $p_{\mathrm{T}}^{\mu} < 2$ GeV as generated with Pythia are shown in green. The blue boxes are from muons with $p_{\mathrm{T}}^{\mu} > 7$ GeV, which is generated with the particle gun. The black boxes give the correlation between the scintillators in SA and ToF-F which are used in the trigger.

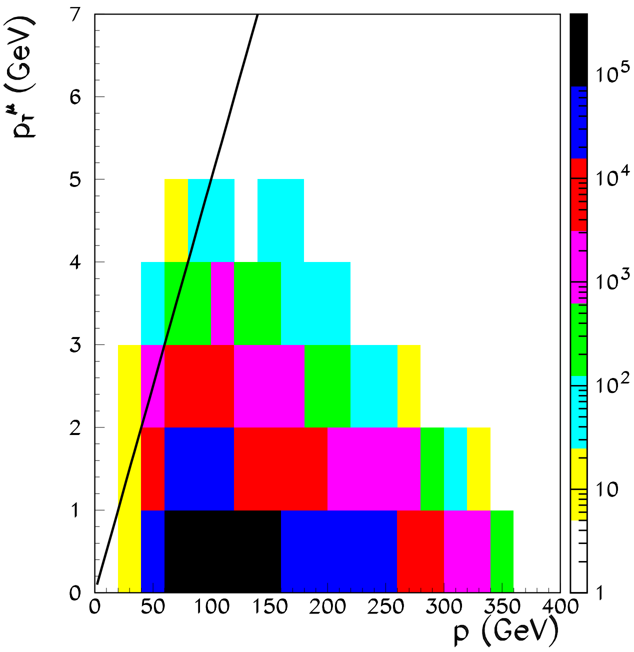


Figure 17: Expected yields in (p, p_{T}) for 10^{11} POT.

5 Schedule and Requested SPS beam time in NA61/SHINE

We require approximatively 1 week to set up the the target area and the trigger.

We require 14 days of running time of the SPS with a 400 GeV primary proton beam in front of NA61/SHINE.

We require a 4.85 s spill length with a uniform extraction of 10^6 (10^7 if possible) protons per spill (like the current spill profile in H2, see Figure 18).

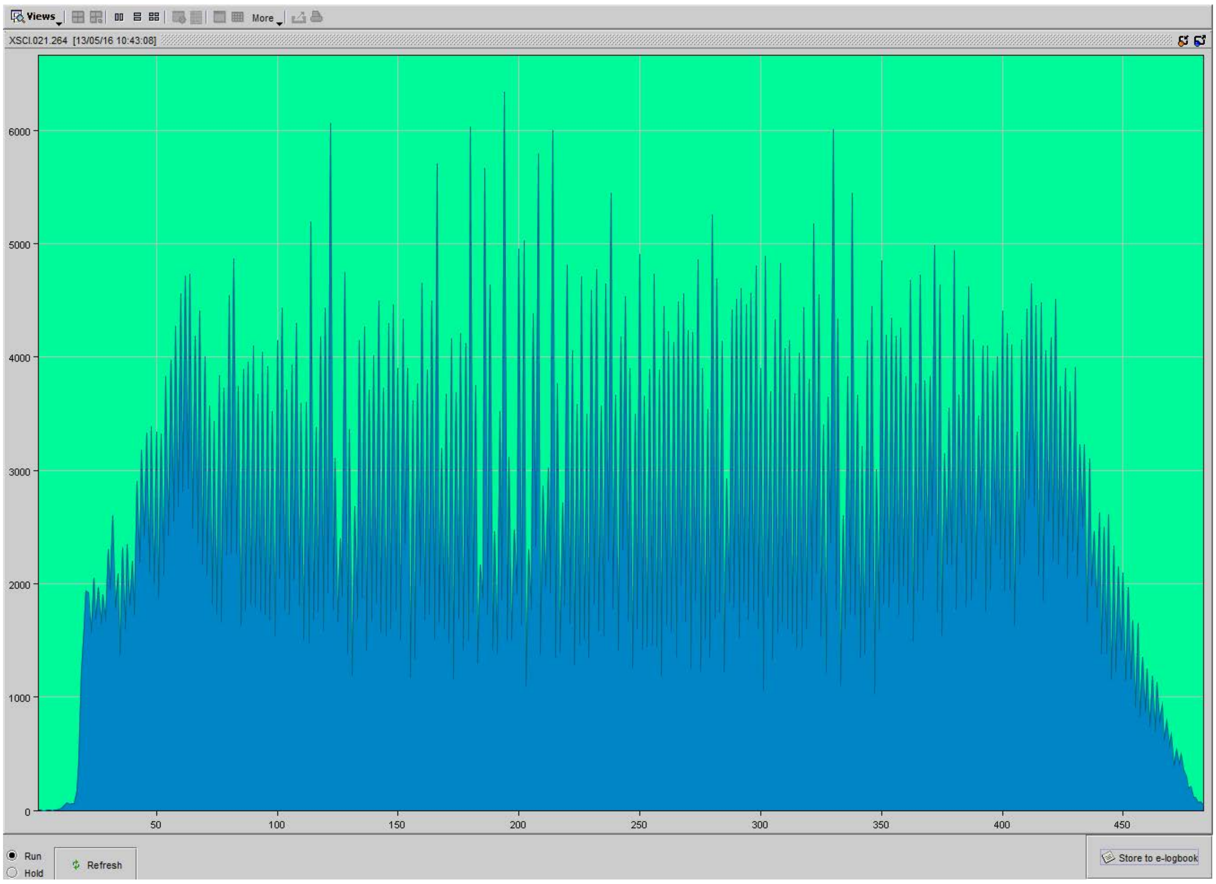


Figure 18: Required SPS spill profile

We do not need a "spiralling" beam; we require a beam size with $\sigma < 1$ cm, enabling us to reduce the transerverse dimensions of the SHiP target to $10 \times\ 10$ cm (see Section 2.1).

If we see a significant discrepance between the generated and measured muon flux, we will request a long run.

6 Summary

It is of key importance for the proposed SHiP experiment to have a good knowledge of the muon flux. The uncertainty of Pythia at large momentum phase space and the impracticality of generating sufficient Monte Carlo statistics make a measurement imperative before the start of construction of the SHiP detector.

We propose a short run at the SPS at the end of 2017 using the NA61/SHINE detector augmented by a scintillator based trigger to do this measurement.

A replica of the SHiP target area could be ready by the middle of 2017.

Based on the results obtained in this test we will consider if a longer run with larger beam intensity will be requested after LS2 to obtain a sample equivalent to the expected POT per spill in SHiP.

References

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