The European Spallation Source Neutrino Super Beam for CP Violation discovery[*]

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Abstract

After measuring the last neutrino mixing angle and founding it to have a relatively large value, neutrino Super Beams became very competitive on discovering a CP violation in the leptonic sector. This large value also, despite the lower statistics, favours the second oscillation maximum for this discovery because of its enhanced sensitivity to the CP violation parameter δ_{CP}. A possible Super Beam operated at the second oscillation maximum could be produced using the very powerful proton linac of the European Spallation Source under construction in Lund, Sweden. Indeed, the 5 MW proton power of this linac could provide enough muon neutrinos to operate the facility at the second oscillation maximum. The performance of this facility on CP violation discovery is presented in this paper. This facility could also produce a copious number of muons, which could be used by other facilities as nuSTORM, the Neutrino Factory or a future muon collider.

INTRODUCTION

The relatively large value of the last neutrino mixing angle θ_{13} opens the door to new discoveries as a possible CP violation in the leptonic sector and the determination of the neutrino mass hierarchy using conventional neutrino facilities. Indeed, neutrino beams produced using the traditional method of hitting a target with a proton beam and producing mesons decaying into neutrinos, can again be used for these researches. The only condition is that the used proton beams must be very powerful compared to the proton drivers already used in neutrino physics. It also comes out that for the measured θ_{13} value, the sensitivity to CP violation is significantly higher at the second oscillation maximum than the first one [1]. The neutrino/antineutrino asymmetry is of the order of $0.3 \sin\delta_{CP}$ on the first oscillation maximum while this value is $0.75 \sin\delta_{CP}$ at the second one. On top of that, at the second oscillation maximum the interference term of the $\nu_\mu \to \nu_e$ oscillation probability is dominant compared to the "solar" and "atmospheric" term [2]. These arguments show that measurements at the second oscillation maximum will be less affected by systematic errors than those done at the first maximum.

To exploite the second oscillation maximum capabilities the baseline between the neutrino production point and the far detector must be relatively large, or the energy of the neutrinos must be relatively low or both. Increasing the distance will necessitate more and more powerful proton beams in order to get enough statistics in relatively short time (less than 10 years of facility operation). Using the European Spallation Source [3] linac under construction (first beam expected by 2019 while a full power and full energy proton beam is expected by 2023) in Lund, Sweden, expected to have a proton power of 5 MW and energy of 2 GeV, enough neutrinos can be obtained placing the far detector at a distance of about 500 km, in order to cover a large fraction of the δ_{CP} values with a confidence level of 5 σ. A full proposal done by the ESSνSB group of how to use the ESS proton beam to add, on top of the neutron facility, a neutrino facility, can be found in [4].

THE NEUTRINO FACILITY AT ESS

Some modifications are necessary in order to add the neutrino facility on top of the neutron one at ESS. These modifications are mainly needed because of the too long proton pulses delivered by the linac for the neutrino facility. Indeed, the proton pulses at the present design are of 2.86 ms, while for the neutrino facility they have to be reduced at the level of few μs, duration affordable by the hadron collector (horn) placed after the neutrino target to collect the charged pions. To reduce the duration of the proton pulses an accumulator ring with a circumference of the order of 400 m has to be added before sending the beam to the target. A fast extraction of the proton beam accumulated in the ring can be performed after.

Not been able to introduce new protons in the accumulator while other protons already circulate in due to space charge effects, H^- ions have to be accelerated in the linac instead of protons. The electrons of the ions can be stripped at the entrance of the accumulator using a classical carbon foil (as done at SNS [5]) or a laser technique.

The adopted target/horn station is the one proposed by the EUROν Design Study in the Super Beam option [6, 7]. In this configuration, in order to mitigate the high power of the proton beam, four target/horn systems are used pulsed alternatively. The pion decay tunnel is relatively short compared to other facilities due to the low pion energy. The length of this tunnel is of the order of 25 m, which can be easily filled with He instead of vacuum in order to avoid a window between the target/horn station and the decay tunnel.

Fig. 1 presents the obtained neutrino (positive horn polarity) and antineutrino (negative horn polarity) beams at a distance of 100 km for 200 days of continues operation. The proton intensity is 1.1×10^{15} protons/pulse. Table I summarizes the obtained neutrino beam composition. The muon neutrino beam is quite pure especially in the neutrino mode. A 0.5% electron neutrino contamination is observed in both modes. Efforts are done to use this contamination to measure the electron neutrino cross-section in a near detector. In case this is possible it will considerably reduce the systematic errors for the CP violation search.

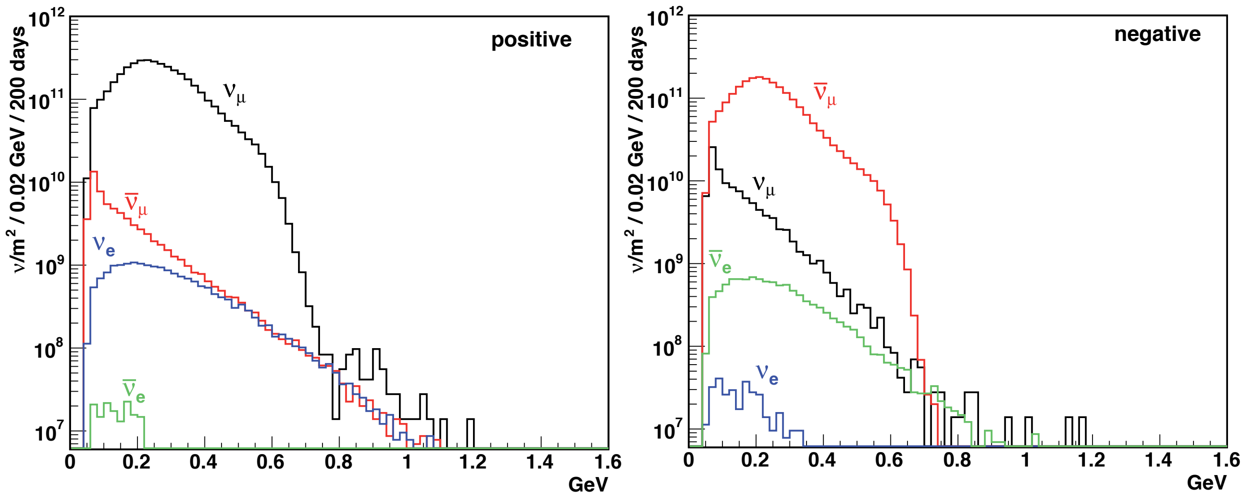

FIG. 1: Neutrino fluence as a function of energy at a distance of 100 km on–axis from the target station, for 2.0 GeV protons and positive (left) and negative (right) horn current polarities, respectively.

TABLE I: Number of neutrinos per m^2 crossing a surface placed on–axis at a distance of 100 km from the target station during 200 days for 2.0 GeV protons and positive and negative horn current polarities.

	positive		negative	
	N_ν $(\times 10^{10})/\mathrm{m}^2$	%	N_ν $(\times 10^{10})/\mathrm{m}^2$	%
ν_μ	396	97.9	11	1.6
$\bar{\nu}_\mu$	6.6	1.6	206	94.5
ν_e	1.9	0.5	0.04	0.01
$\bar{\nu}_e$	0.02	0.005	1.1	0.5

PHYSICS PERFORMANCE

Using the neutrino spectra of Fig. 1 and GLoBES [8, 9] package, the physics performance of the neutrino facility in terms of CP violation discovery has been evaluated. Fig. 2 presents the δ_{CP} fraction coverage versus the distance to the far detector for 3 σ and 5 σ confidence level. This has been extracted assuming the utilization of MEMPHYS Water Cherenkov megaton detector [10, 11] and 5% (10%) systematic error for the signal (background). To estimate this performance several proton energies have been used on top of the default one of 2 GeV since it is possible to upgrade the linac to deliver higher energy protons.

The best performance is obtained for a distance between 350 km to 550 km reaching a maximum of 60% δ_{CP} coverage. An active mine exists at a distance of 540 km at the location of Garpenberg, Sweden, where the far detector can be installed in a depth of more than 1000 m.

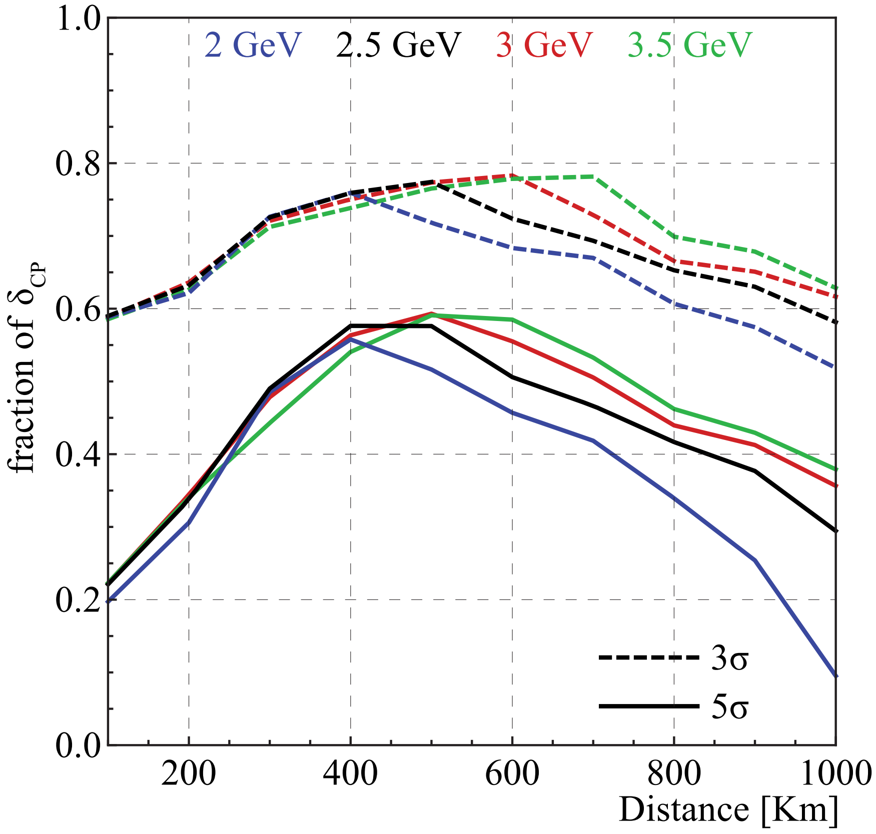

FIG. 2: The fraction of the full δ_{CP} range as function of the baseline. The lower (upper) curves are for CP violation discovery at 5 σ (3 σ) significance.

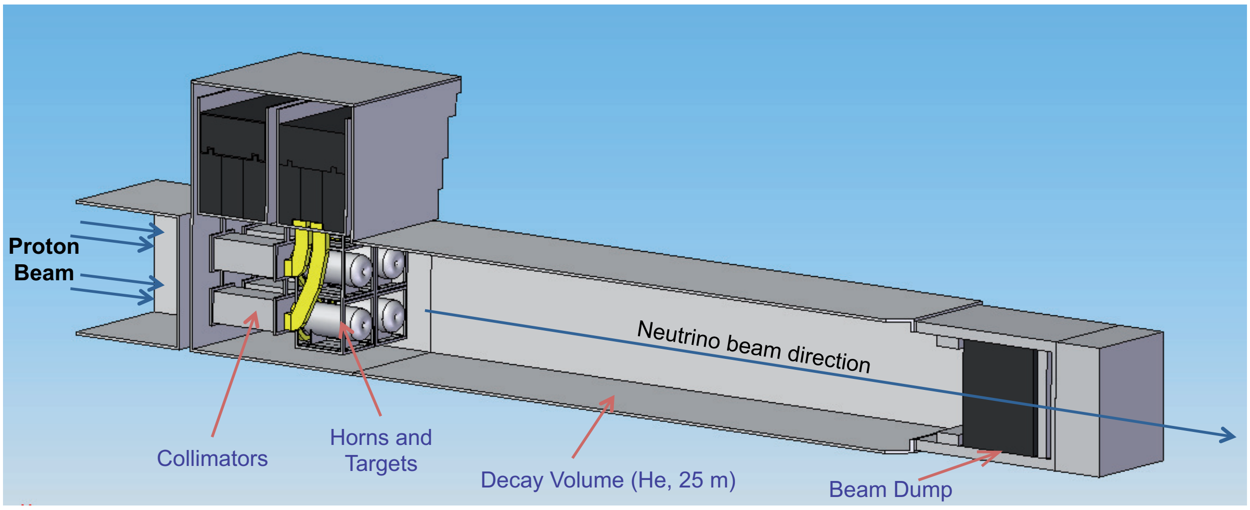

FIG. 3: Schematic view of the target/horn station.

MUON PRODUCTION

The same neutrino facility can be used to produce a copious number of muons. In fact, these muons are produced for free in the decay tunnel together with the muon neutrinos by the decay of pions and could be collected at the level of the neutrino facility beam dump (Fig. 3). These muons could be used by a low energy nuSTORM [12] facility to measure neutrino cross-sections at the energies where this neutrino facility will be operated. They could also be useful for 6D muon cooling experiments and in an ultimate stage they could be used to operate a Neutrino Facility or a muon collider.

A specific device under study could be used to extract these muons and inject them in a beam pipe. Fig. 4 and 5 present the impacts of remaining pions and produced muons at the surface of the beam dump. In the pion distribution one can distinguish four spots induced by the four targets and horns while for the muons coming from the pion decays these spots are more diluted. The big majority of these particles is concentrated in a surface of 2×2 m^2 that constitutes a difficulty for their extraction and injection in a beam pipe. Considering a surface of 1 m^2 centered in the middle of these distributions or centered on one of the pion or muon spots, one could collect about 3.6×10^{20} pions and 4.1×10^{20} muons per year.

The mean value of the momentum of pions and muons is 0.7 GeV and 0.46 GeV, respectively (Fig. 6 and 7). For these energies, the mean free path of pions is of the order of 40 m after which they will decay to give some more muons. The mean free path for the muons is

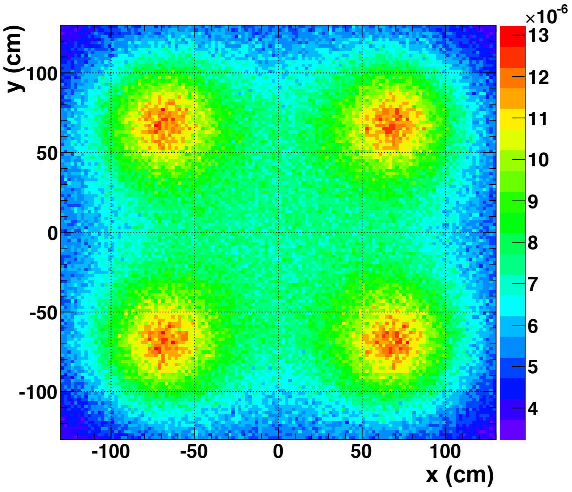

FIG. 4: Impacts of pions on the surface of the beam dump (normalized per proton).

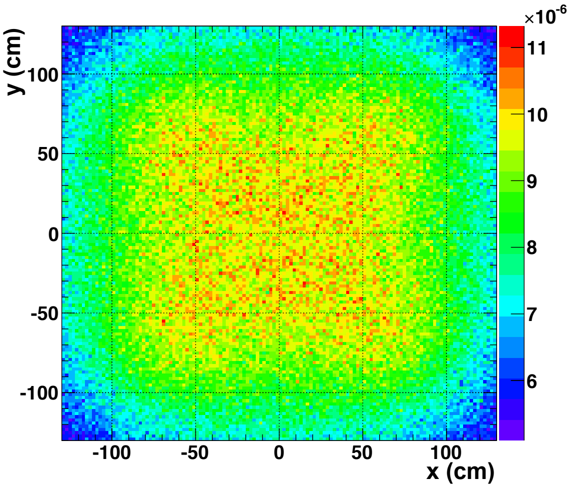

FIG. 5: Impacts of muons on the surface of the beam dump (normalized per proton).

2.9 km which is enough to send them in a ring, as the one foreseen for nuSTORM, where they can decay in straight sections to produce muon and electron neutrinos to be used to measure cross-sections.

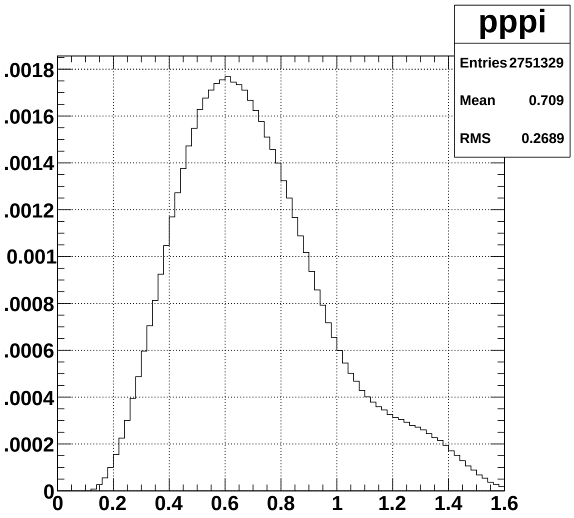

FIG. 6: Momentum of remaining pions at the level the beam dump (normalized per proton).

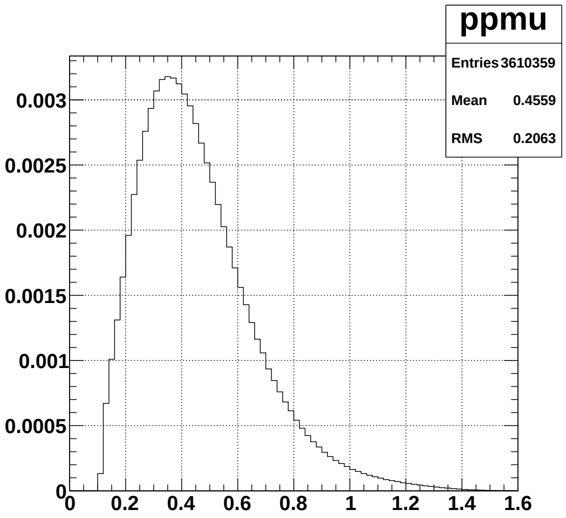

FIG. 7: Muon momentum at the level of the beam dump (normalized per proton).

While for nuSTORM muon beam an iron absorber is needed to lower the muon momentum to a mean value of 400 MeV in order to perform 6D muon cooling experiments (of which success could lead to the construction of a Neutrino Factory and a muon collider), for

ESSnuSB the muon momentum is directly around the required values. nuSTORM plans to collect in the region between 200 MeV/c and 500 MeV/c about 4.3×10^{17} muons per year while the ESSnuSB facility could provide more than 2.5×10^{20} muons per year for the same momentum range.

CONCLUSION

The proposed ESSnuSB neutrino facility operated on the ESS proton linac at the same time than the neutron facility, has very competitive performance in terms of CP violation discovery in the lepton sector. This facility, operated at the second oscillation maximum, can cover up to 60% of the δ_{CP} range with a confidence level of 5 σ. The megaton far Water Cherenkov detector used by this projects also has a rich astroparticle physics program.

A byproduct of this facility is the production of a copious muon number. These muons could be used in a low energy version of nuSTORM to measure neutrino cross-sections at the energies interested by the neutrino oscillation program of the facility. 6D muon cooling experiments could also use these muons for studies which could open the way to the construction of a Neutrino Factory and a muon collider.

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