PROCEEDINGS OF SCIENCE

The European Spallation Source neutrino Super Beam and muon synergies

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The European Spallation Source neutrino Super Beam has been proposed to observe and measure CP Violation in the leptonic sector using the 5 MW-power ESS proton linac. It has already been proved that such a project has a very high physics performance to make this discovery, but also to measure precisely the CP violating parameter. On top of the very intense neutrino beam produced by this project, a huge number of muons is also produced at the same time, which can be used for other physics subjects related to neutrino physics or not. The synergies between the neutrino project and muon utilisation are described in this paper.

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1. Introduction

The European Spallation Source (ESS[1]), under construction in Lund (Sweden) is a neutron facility using a 5 MW-power proton linac. The duty cycle of this linac being only 4%, it has been proposed to double the 14 Hz pulse rate in order to produce another 5 MW proton beam to be used by a neutrino facility operated at the same time than the neutron one. The European Spallation Source neutrino Super Beam (ESSνSB[2]) proposes to use this second proton beam to produce a very intense neutrino beam to discover CP violation in the leptonic sector. This, under some assumptions, would help to understand the matter-antimatter asymmetry observed in the Universe.

In order to maximise the physics performance of this project and thanks to the high power proton beam, it is proposed to operate the neutrino facility near the second oscillation maximum on which the CP violation sensitivity is significantly higher than the one expected at the first oscillation maximum [3–5].

2. Description of the project

In order to add a performant neutrino facility on top of the ESS neutron one some modifications are needed with the condition that the neutron users would not be disturbed. If possible, synergies with the neutron facility and other physics projects should also be exploited.

The frequency of the ESS proton linac can be doubled to have one pulse for neutron production and one for the neutrino facility. The ESS duration of the proton pulses of ~3 ms is too large for the ESSνSB project because, on one hand, of the large background of atmospheric neutrinos interacting in the large Cherenkov far detector and, on the other hand, because of the too large current pulses needed to be sent in the hadron collector (horn) necessary to focus charged pions decaying to neutrinos and muons.

To reduce the proton pulse duration an accumulation ring is needed. The main constrain on this ring is the size which has to fit in the ESS allocated area. For this, a proton accumulator with a circumference of 384 m has been chosen providing at the exit proton pulses with a duration of 1.3 μs. For the injection into the accumulator, H^- ions are needed to be accelerated in the linac, necessitating the installation of an H^- source. The H^- electrons are stripped during the injection into the accumulator.

As at this moment it is not possible to send a proton beam with a power of 5 MW on a single target (too intense beam with many cooling issues), the beam at the exit of the accumulator will be split in four with the help of a switchyard. The four pulses will be send alternatively on a four target/horn system. The proposed target is made of TiO_2 spheres located in a canister cooled by gas helium. Due to the relatively low proton energy, the target is located inside the horn, inducing extra power dissipation issues.

The particles coming out of the target and focused by the magnetic horn are mainly pions decaying in a 30 m tunnel to produce muons and the neutrino beam. The obtained neutrino beam is composed by more than 97% of muon neutrinos. A small contamination of the order of 0.3% of electron neutrinos, composing the main source of background in the far detector, could be used to measure the ν_e cross-sections in a near detector at the neutrino energy range relevant to this project.

A near detector, for beam monitoring and neutrino cross-section measurements, is placed at a distance of 250 m away from the target station. A far water Cherenkov detector, 540 ktons fiducial volume, is planed to be placed in Zinkgruvan mine, in Sweden, at a distance of 360 km from Lund. This detector, by its own, can also participate to proton decay searches and have a rich astroparticle physics program by detecting cosmological neutrinos as those emitted during supernovae explosions.

Fig. 1 presents the neutrino facility implementation on top of the ESS neutron facility. All new installations necessary for the neutrino facility remain in the already allocated ESS area.

3. Physics performance

After designing and optimising the main parameters of the whole neutrino facility, the physics performance to discover CP violation in lepton sector and precisely measure the violating parameter δ_{CP}, has been evaluated. Fig. 2 presents the expected CP violation discovery significance (left-axis) versus δ_{CP}. More than 70% of δ_{CP} space is covered with a significance higher than 5 σ for a data taking period of 10 years. The same figure presents on the right-axis the expected precision on δ_{CP}. It can be seen that this precision is lower than 8° for all δ_{CP} values. It has been assumed a systematic error on the signal of 5% and 10% for the background.

After 10 years data taking the reached physics performance will still be dominated by the statistical errors. If by then more precision is needed, no upgrades of the facility will be required, but just continue taking more data.

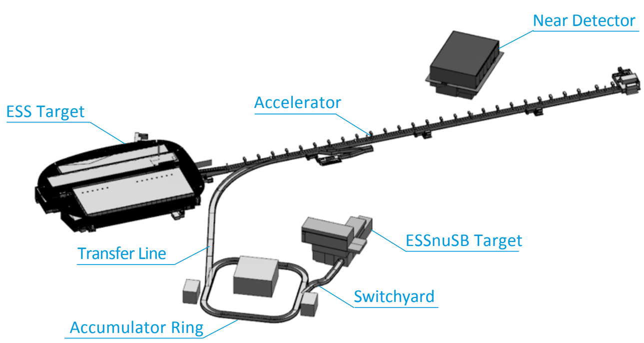

Figure 1: Layout of the neutrino facility in the ESS site.

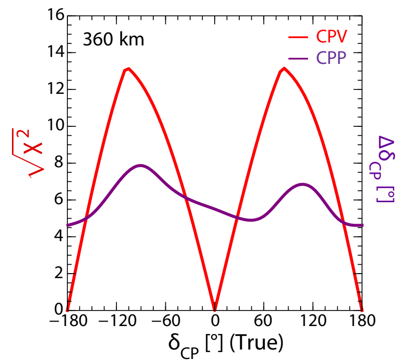

Figure 2: CP violation discovery significance (left-axis) and δ_{CP} precision (right-axis) versus δ_{CP} value, achieved after 10-years data taking.

All details about the proposed neutrino facility can be found in the already published Conceptual Design Report [6].

4. Muon potentialities

Together with the neutrino production, a tremendous amount of muons coming from pion decays is also produced. Fig. 3 presents the muon momentum distribution per proton on the target at 25 m, 50 m and 100 m from the magnetic horn. The muon energy average is around 0.5 GeV, which slightly depends on the extraction distance because of the muon lifetime.

At a distance of 25 m, more than 4.3×10^{21} muons per year can be collected and used for other physics projects and R&D. These synergetic projects could be 6D muon cooling R&D (see, e.g., [7] and references in), low energy nuSTORM[8], Neutrino Factory [9] and Muon Collider[10].

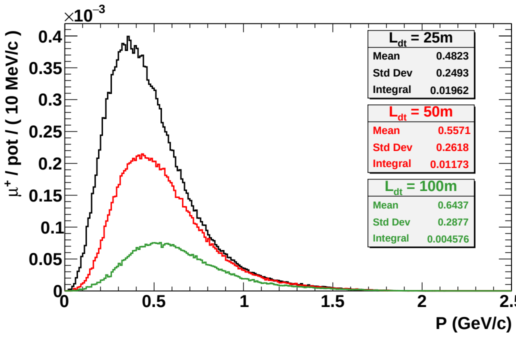

Figure 3: Muon momentum distribution per proton on the target at three distances from the ESSνSB magnetic horn.

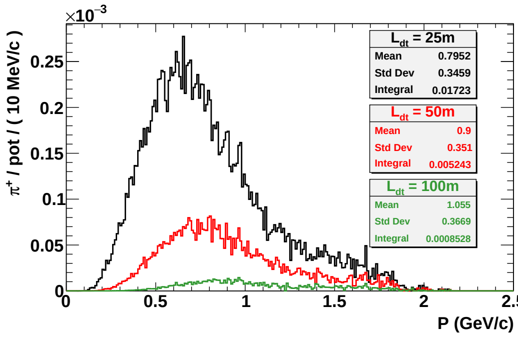

Figure 4: Pion momentum distribution per proton on the target at three distances from the ESSνSB magnetic horn.

In order to go in the muon direction, a new European project has been submitted and approved including a low energy nuSTORM (LEnuSTORM). For this purpose, only 1/4 of the proton beam power will be used sent on a reduced size target station having only one target and one horn. The produced pions and muons will be deviated at the exit of the horn to be sent into the LEnuSTORM decay ring. The constraint on the LEnuSTORM decay ring is that it has to be compact fitting in a specific location in ESS area and having short circular sections to avoid too many muon decays in these sections compared to the useful decays in the straight sections.

LEnuSTORM can be used for neutrino cross-section measurements and for sterile neutrino searches. For this purpose, the near detector placed at 250 m from the target station for CP violation searches can be used as far detector by LEnuSTORM (Fig. 5), while a new near detector very closed to one of the muon decay ring straight sections has to be designed.

The pions can also be used by a low energy version of ENUBET[11], called Low Energy Monitored Neutrino Beam (LEMNB), producing a well controlled neutrino beam. For this purpose, an instrumented decay tunnel to tag the leptons produced by pion decays is used, contrarily to the relatively high energy ENUBET version where kaon decays are used. The neutrino detector could be the same than the near detector of LEnuSTORM (Fig. 5). LEMNB, as LEnuSTORM, can be used for neutrino cross–section measurements in the region of 300 MeV where no measurements exist up to now.

Probably, for LEMNB, not needing a too intense proton beam to avoid pileup in the instrumented tunnel, the present proton pulse duration of 3 ms could be acceptable. In this case, the accumulation ring will not be needed allowing LEMNB to start operation before all other parts of the neutrino facility.

This new EU project, called ESSνSB+, has started beginning of 2023 and will finish end of 2026. At the end of this period a new Conceptual Design Report including costing will be produced.

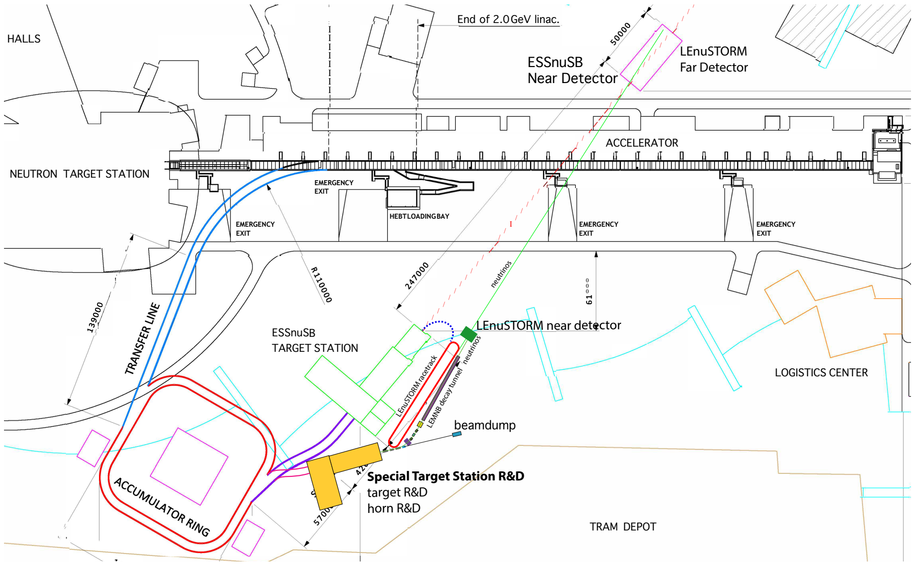

Figure 5: Implementation of the single target/horn target station (yellow), LEnuSTORM (racetrack storage ring in red), and LEMNB (instrumented tunnel in purple) in ESS site.

5. Conclusion

The European Spallation Source under construction in Lund can be upgraded in a later stage to a very performant neutrino facility. The European Spallation Source neutrino Super Beam Design Study, financed by EU under the framework of Horizon 2020 and Horizon Europe, already produced a Conceptual Design Report summarising all feasibility studies done during the first phase between 2018 and 2022.

Not only ESSνSB proved the feasibility of the production of a very intense neutrino beam using the 5 MW ESS proton beam, but also that the physics performance obtained, operating the facility at the second oscillation maximum, surpasses all expectations. Indeed, in ten years data taking, this project can reach, for CP violation discovery, a δ_{CP} coverage of more than 70% with a significance higher than 5 σ. The project can also reach a δ_{CP} precision lower than 8° for all δ_{CP} values.

Strong of this success, a second phase of the project, ESSνBS+, has been submitted and approved by EU, with the aim to enhance even more the possibilities and potentiality of ESSνBS. This second project includes the feasibility study of adding in the project a low energy nuSTORM for neutrino interaction cross–section measurements and sterile neutrino searches using neutrinos from pion and muon decays. It also includes a low energy ENUBET study for neutrino cross–section measurements using a monitored neutrino beam.

6. Acknowledgements

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References

[1] The European Spallation Source, http://europeanspallationsource.se/, ESS TDR, Release 1.0, Nov. 2012.

[2] "A Very Intense Neutrino Super Beam Experiment for Leptonic CP Violation Discovery based on the European Spallation Source Linac", Nuclear Physics B, **885** (2014) 127.

[3] H. Nunokawa, S. J. Parke and J. W. F. Valle, "CP Violation and Neutrino Oscillations," Prog. Part. Nucl. Phys. **60** (2008) 338.

[4] P. Coloma and E. Fernandez-Martinez, "Optimization of neutrino oscillation facilities for large θ_{13}," JHEP **1204** (2012) 089.

[5] S. Parke, "Neutrinos: Theory and Phenomenology", Phys. Scripta T, **158** (2013) 014013, [arXiv:1310.5992 [hep-ph]].

[6] A. Alekou, E. Baussan, A. K. Bhattacharyya, N. Blaskovic Kraljevic, M. Blennow, M. Bogomilov, B. Bolling, E. Bouquerel, O. Buchan and A. Burgman, *et al.* Eur. Phys. J. ST **231** (2022) no.21, 3779-3955 doi:10.1140/epjs/s11734-022-00664-w [arXiv:2206.01208 [hep-ex]].

[7] C. Rogers. "A demonstrator for muon ionisation cooling". *Physical Sciences Forum*, 8(1), 2023.

[8] D. Adey *et al.* [nuSTORM], "nuSTORM - Neutrinos from STORed Muons: Proposal to the Fermilab PAC," [arXiv:1308.6822 [physics.acc-ph]].

[9] T. R. Edgecock *et al.*, "The EUROnu Project", Phys. Rev. ST Accel. Beams **16**, 021002 (2013).

[10] C. Rubbia, "Further searches of the Higgs scalar sector at the ESS," arXiv:1908.05664 [physics.acc-ph].

[11] A. Longhin *et al.*, "Enhanced NeUtrino BEams from kaon Tagging (ENUBET)," [arXiv:2203.08319 [hep-ex]].