Funded by the Horizon 2020 Framework Programme of the European Union

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

ESS NEUTRINO SUPER BEAM

The ESSnuSB/HIFI Design Study

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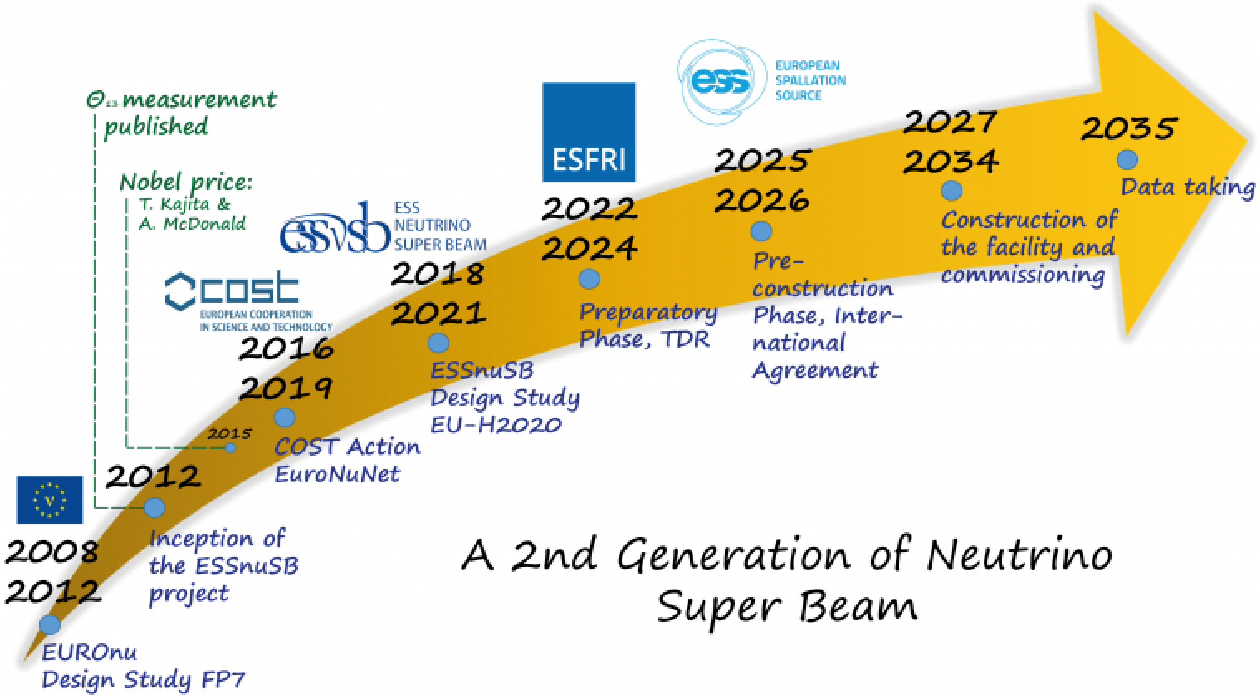
EPS-HEP, Hamburg (Germany), 26-30.07.2021

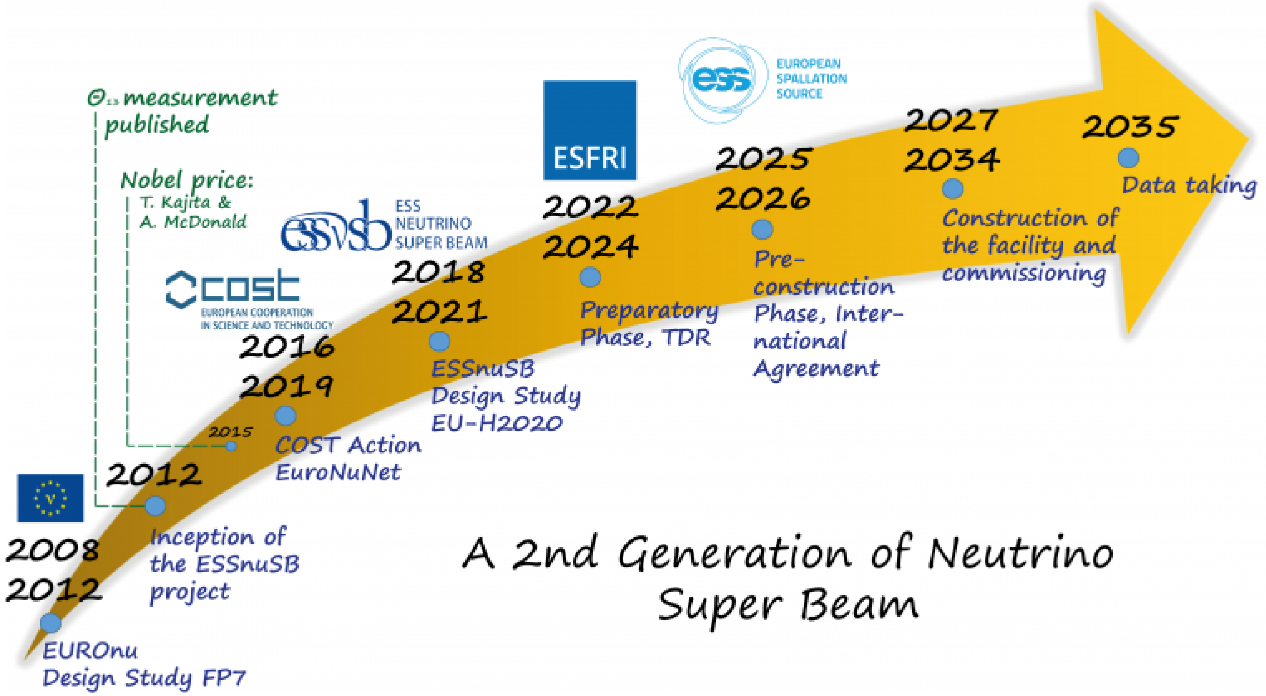
The ESSνSB Proposal for a European Neutrino Super Beam

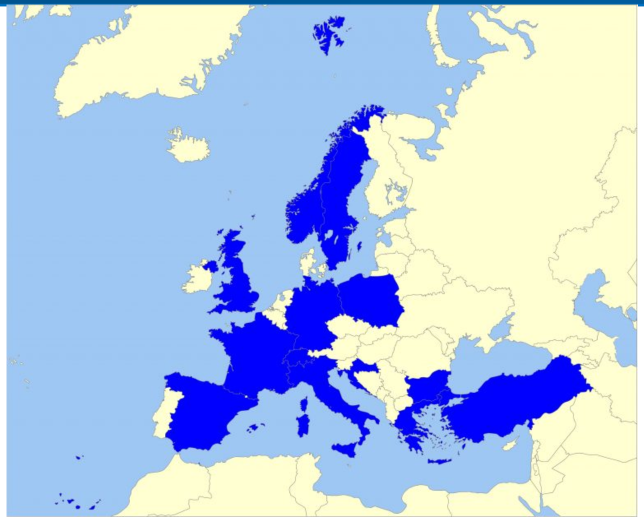


- The ESSνSB project follows the results of the EUROnu design study [1]. In the framework of the EUROnu project, three possible solution for the production of a neutrino beam have been investigated: Beta Beam, Super Beam and Neutrino Factory.
- The measurement of a relatively large θ_{13} oscillation parameter, proved that a Super Beam could be used for the measurement of the CP-violating neutrino oscillation phase δ_{CP} .
- The ESS linac, already approved at that time, can provide the necessary power for this neutrino Super Beam.

[1] T. R. Edgecock et al., Phys. Rev. ST Accel. Beams 16, 021002 (2013) [arXiv:1305.4067 [physics.acc-ph]].

The ESSνSB Proposal for a European Neutrino Super Beam





- Inception of the ESSνSB project: E. Baussan *et al.*, Nucl. Phys. **B885** (2014) 127
  - The ESS linac proposed as proton source (5 MW, 2 GeV, 14 Hz rep. rate)
- EuroNuNet: *Combining forces for a novel European facility for neutrino-antineutrino symmetry violation discovery*
  - Networking project (Action) funded by COST application CA15139 (2016-2020).
- 13 Participating countries.

The ESSνSB Proposal for a European Neutrino Super Beam

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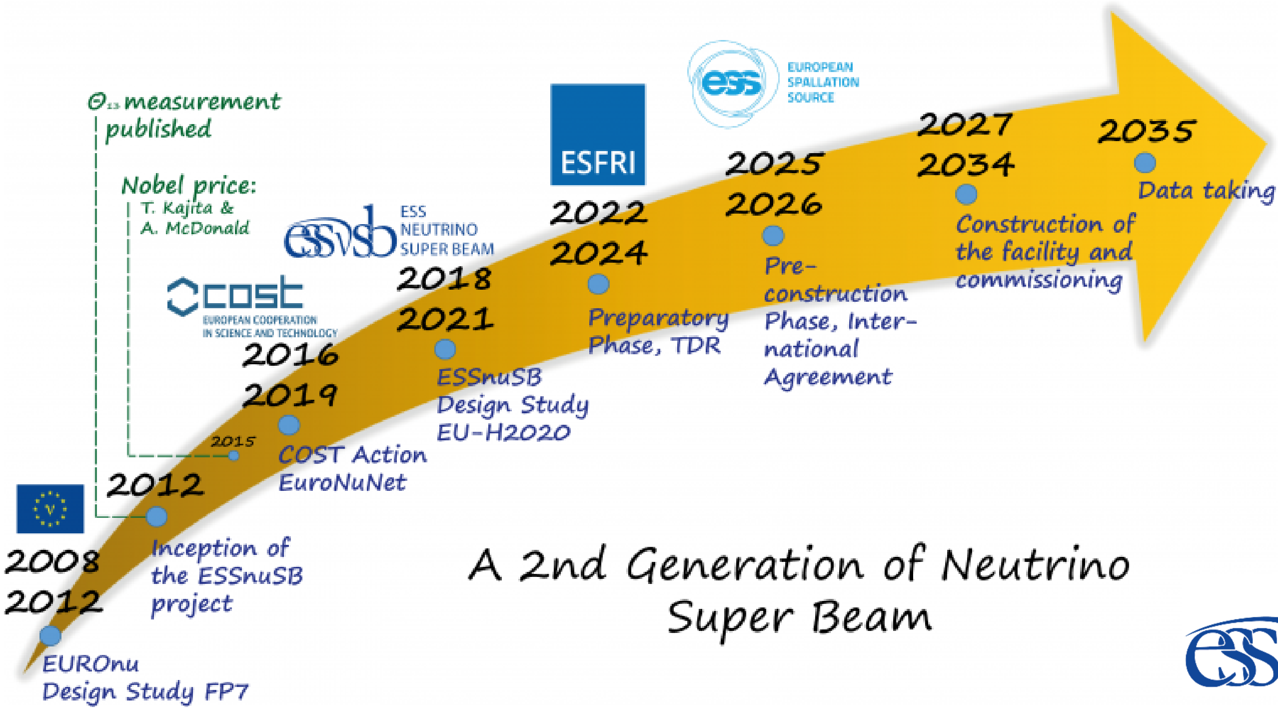

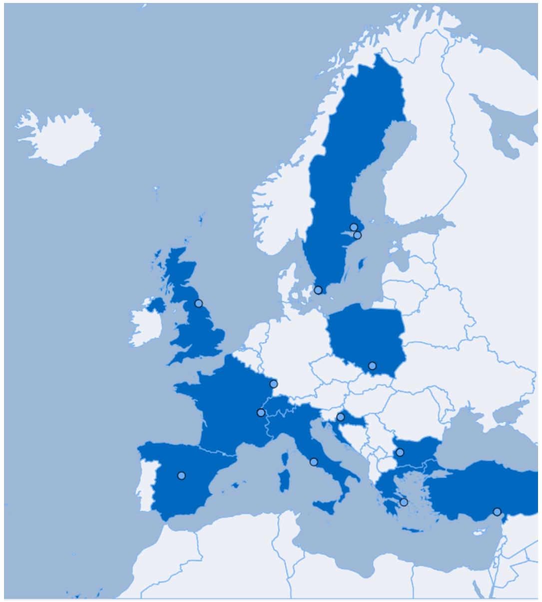

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- ESSνSB (2018-2021): *Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator*
  - A H2020 EU Design Study (Call INFRADEV-01-2017).
- Total cost: 4.7 M€ (2018-2021)
  - EU budget: 3 M€
- 15 participating institutes from 11 European countries including CERN and ESS.

ESSnuSB public report at https://essnusb.eu/DocDB/public/ShowDocument?docid=706
ESSnuSB video film available at https://youtu.be/PwzNzLQh-Dw.

The ESSνSB Proposal for a European Neutrino Super Beam

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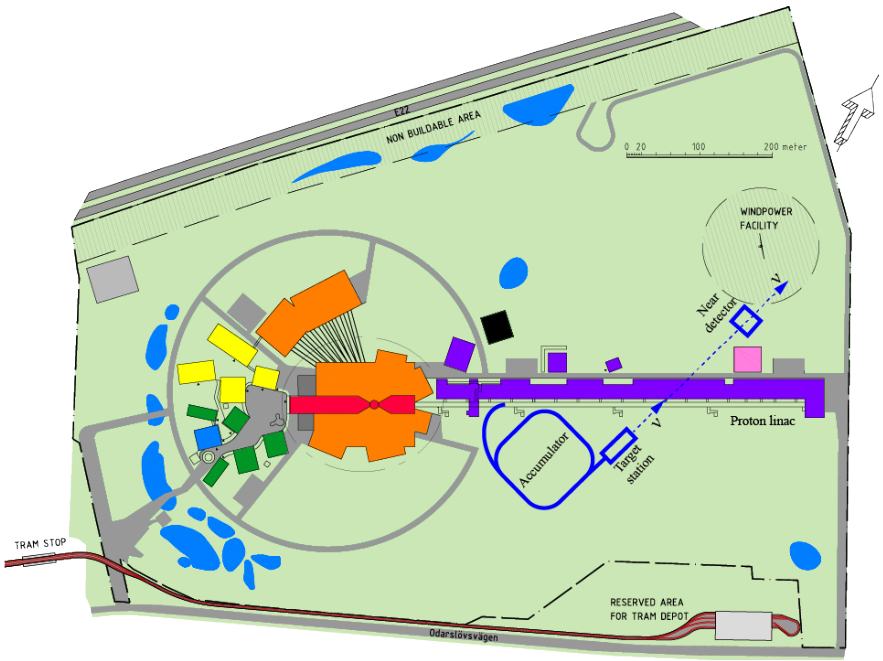
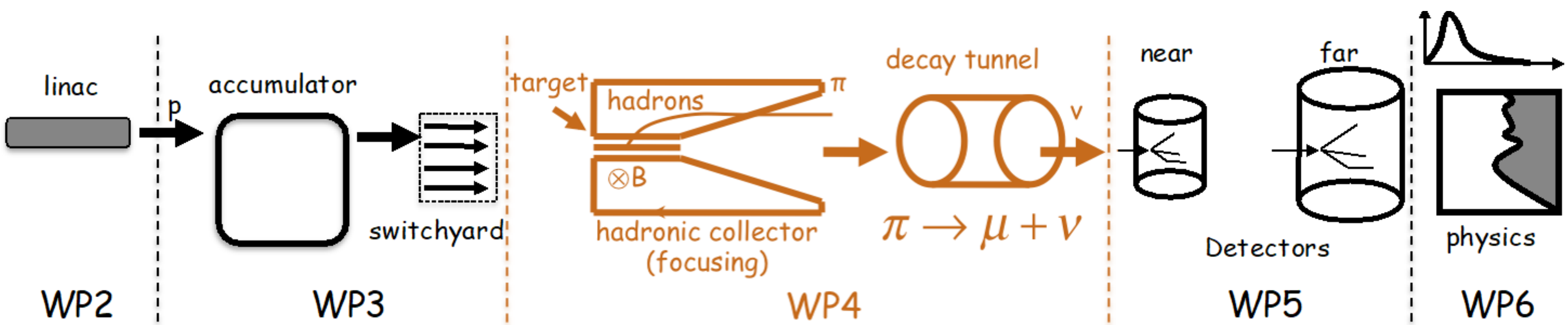
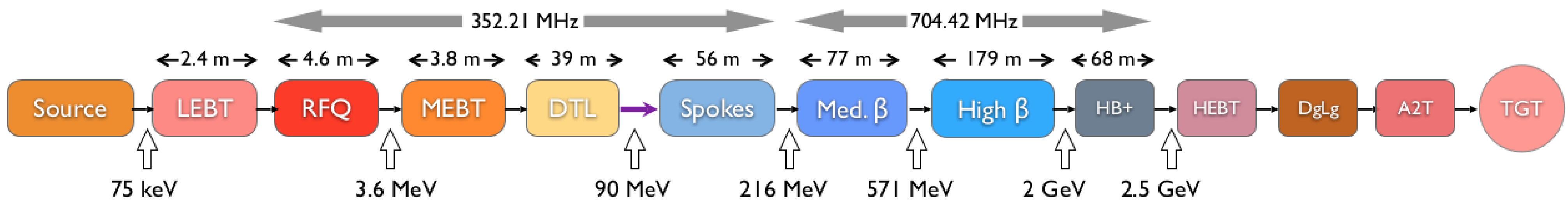
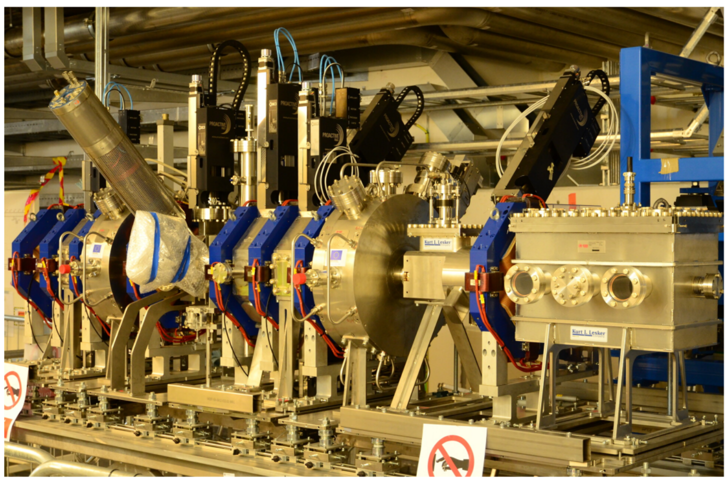


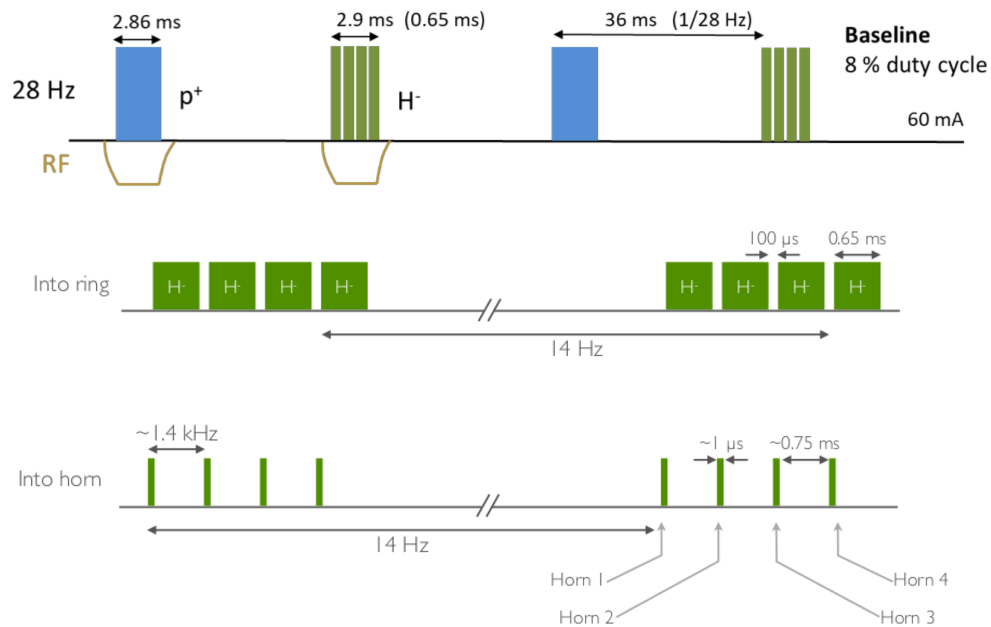
- Required modifications of the ESS current layout:
  - Doubled repetition rate: 14 Hz → 28 Hz
    - To not interfere with the neutron science of ESS
  - H⁻ ion source (extraction of the electrons in the accumulator ring using stripping foils)
  - Upgraded proton kinetic energy: 2 GeV → 2.5 GeV
    - To reduce the space charge effects
  - Reduction of the proton pulse: 2.86 ms → 1.5 μs
    - To reduce current pulse duration in the horn and atmospheric neutrino background
  - Proton pulse split in 4 sub-pulses
    - To reduce heat load on target

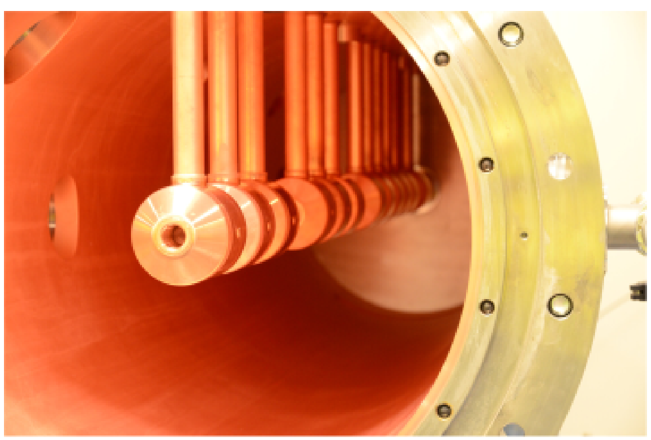


A Dedicated Proton Beam from the ESS Linac



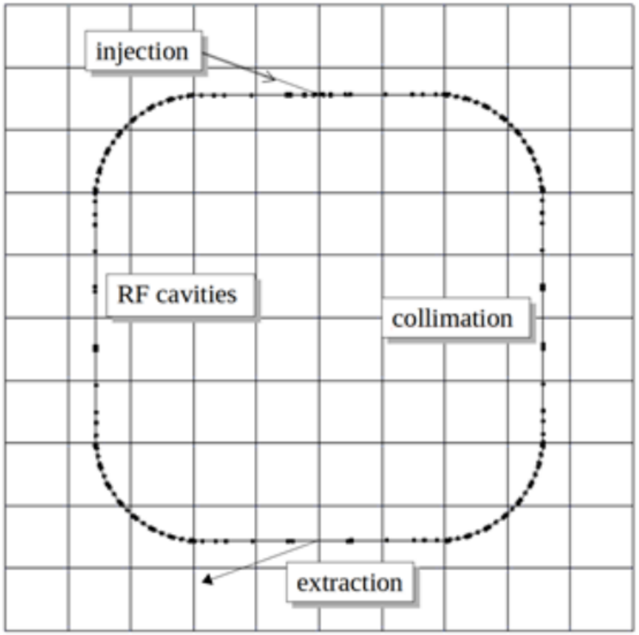






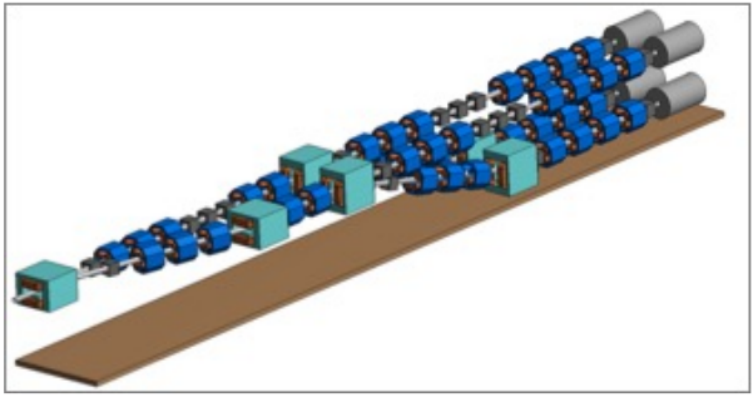
- RFQ installed in the tunnel
- MEBT installed in the tunnel
- DTL assembled on site
- Spoke CM tested in FREIA

The Accumulator Ring and the Switchyard

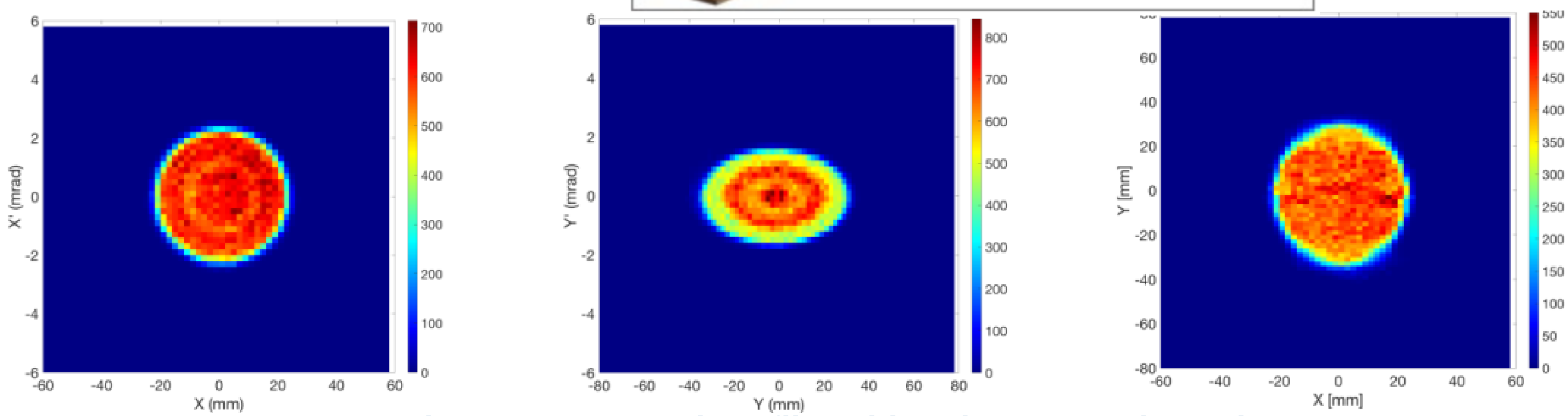


Accumulator ring

- A 384 m circumference (4 arcs, 4 straight sections).
- H- stripping using foil.
- Laser-assisted stripping also considered.
- Correlated and anticorrelated painting of the beam.
- Geom emittance at the switchyard: 70 π mm mrad.



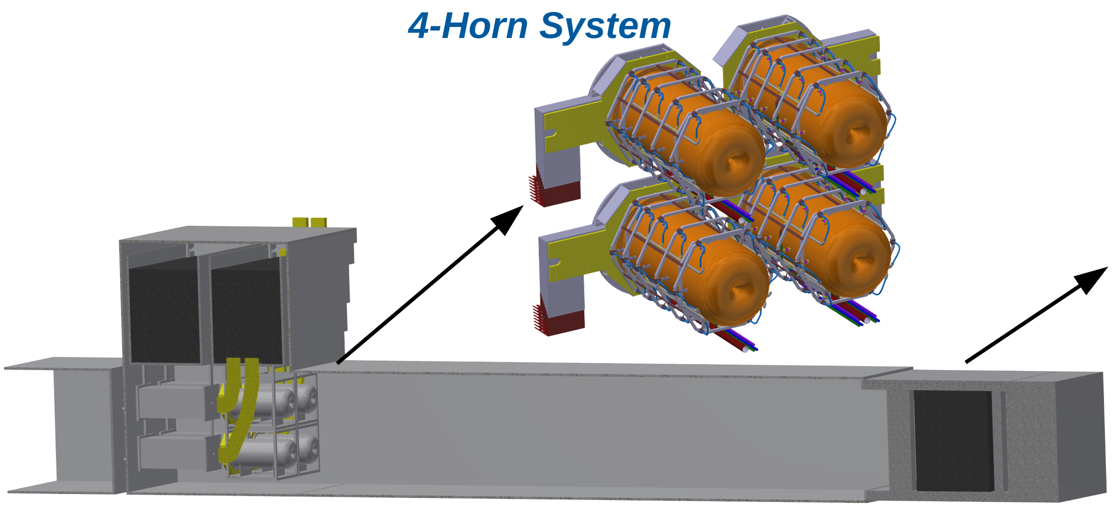
Switchyard layout



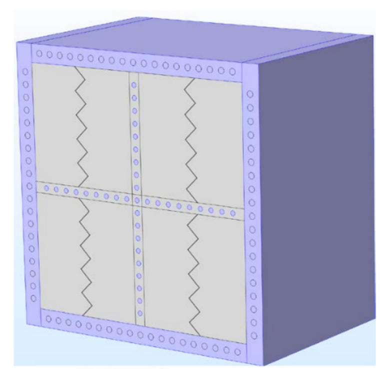
Proton beam transversal profile exiting the accumulator ring

- Main components of the Target Station:
  - A 4-target/horn system for hadron production/collection.
    - Each target consists of a packed bed of titanium spheres. The total radius and length of the proposed target is 1.5 cm and 78 cm, respectively.
    - Each horn has a MiniBooNE-like shape of of about 60 cm radius and 2.5 m length each, before optimization.
    - The magnetic field is generated by a 350 kA half sinusoidal current pulse in the horn.
  - Pions produced and collected are let to decay in flight in a decay tunnel.
  - The hadrons and muons are then absorbed by a beam dump at the end of the decay tunnel.

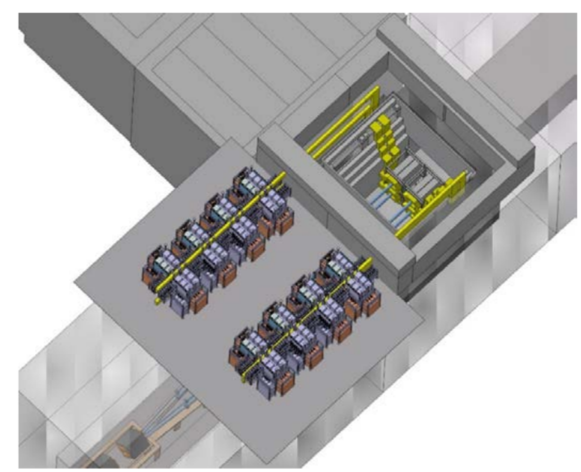
4-Horn System



Decay Tunnel



Beam Dump



PSU Layout

The Target Station for the Neutrino Beam Production

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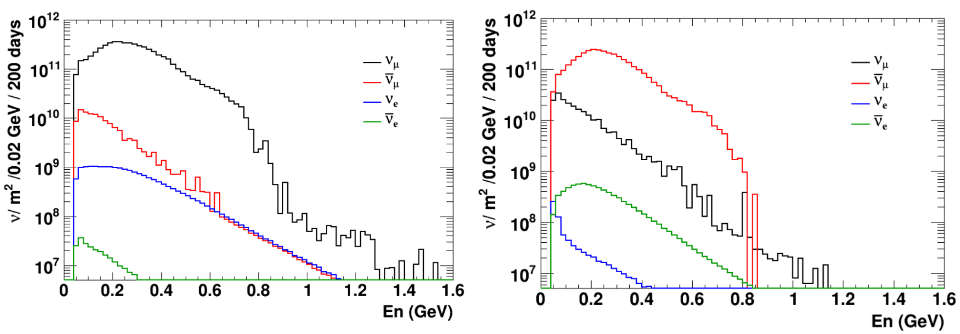
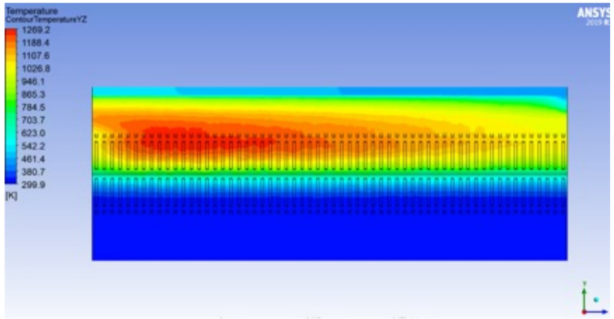
- High purity of the neutrino beam (>90% ν_μ from right sign pions and <1% contribution from electron (anti)neutrino).
- Thermal and mechanical stresses currently under investigation for target, horn and beam dump.
- On-going energy deposition, activation and shielding studies for the whole target station.

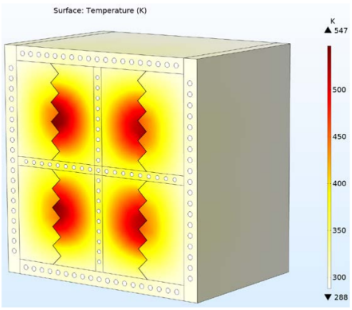


Neutrino flux at 100 km from TS for neutrino (left) and antineutrino (right) mode

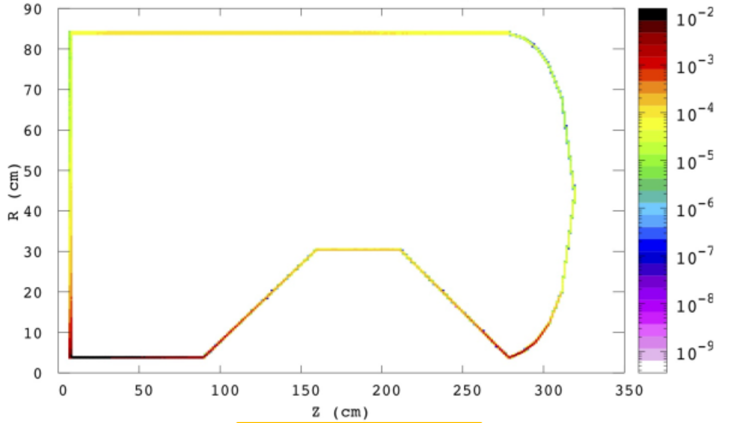
Cooling of target with He

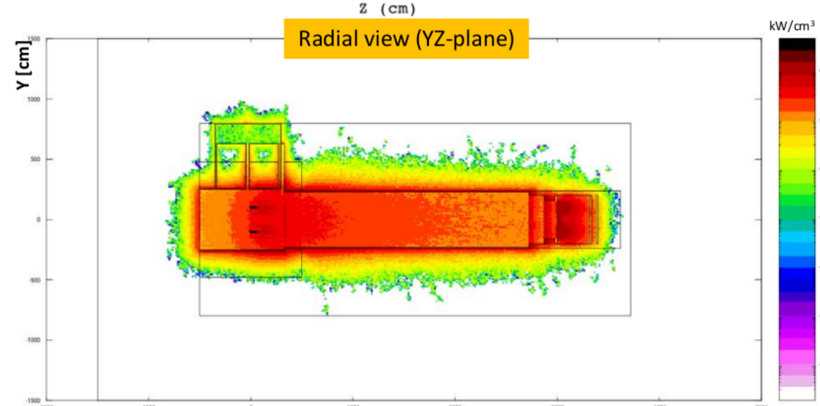


BD Surface temperature



ED in the horn (kW/cm³)

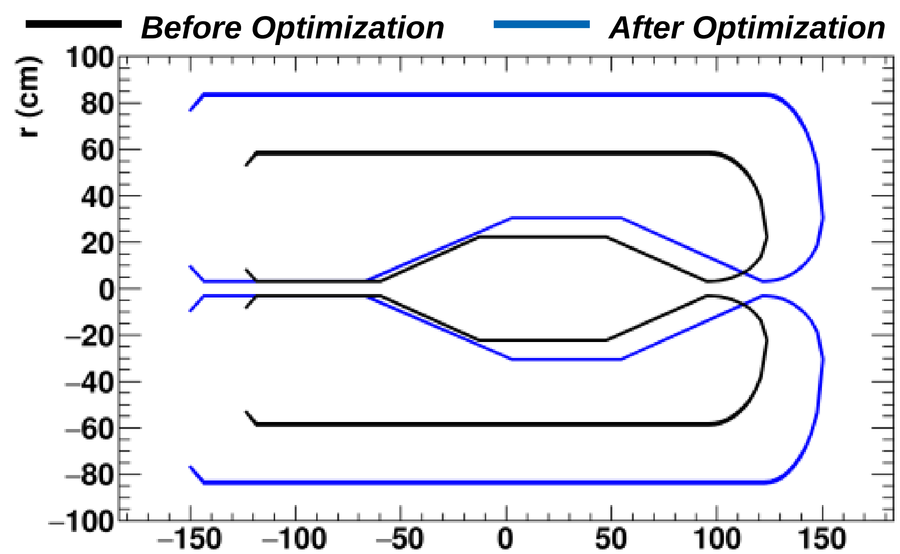




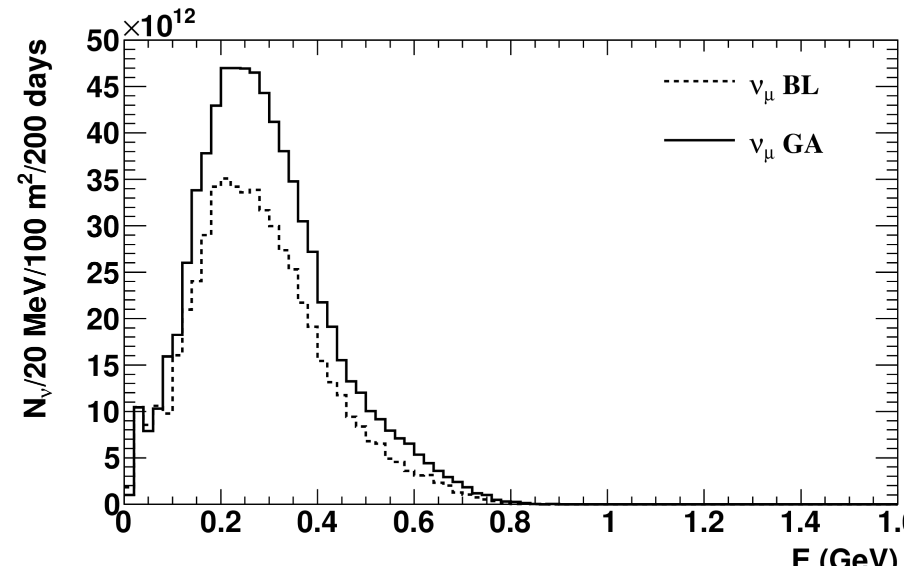
ED in the target station

Optimization of the Neutrino Beam Production Using the Genetic Algorithm

- An optimization study has been carried out, based on FLUKA simulations with different configurations of the magnetic horn and decay tunnel geometry [1,2].
- After the optimization study, it has been proposed to increase the length of the decay tunnel from 25 m to 50 m.
- The new geometry provides higher statistics in the neutrino beam and a consequent better performance of the experiment.
- Studies are currently on-going to verify the feasibility of the new horn in terms of thermo-mechanical stresses.



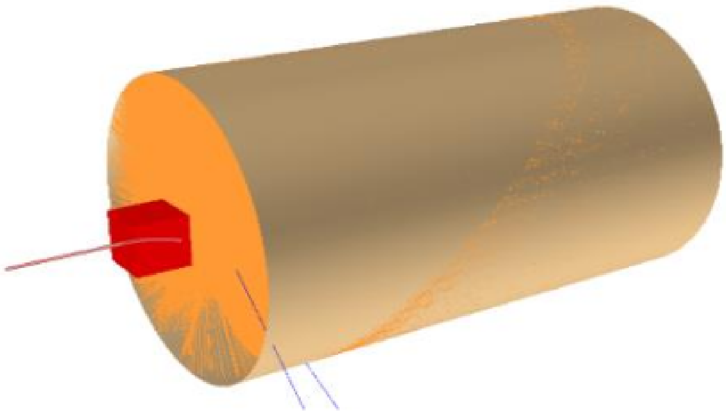
Magnetic horn profile



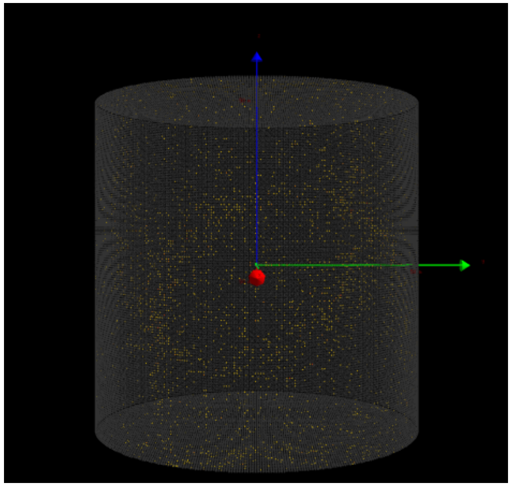
ν_μ flux before (dashed line) and after (continuous line) optimization

[1] L. D'Alessi *et al.* [ESSνSB], "Optimization of the Target Station for the ESSνSB Project Using the Genetic Algorithm", NeuTel Conference 2021.
[2] L. D'Alessi *et al.* [ESSνSB], "Neutrino Beam Optimization for the ESSνSB Experiment", International Research Network - Neutrino 2021.

The Near and Far Detectors



- **Near Detector**:
  - A magnetized Super Fine Grained Detector (SFGD) for cross-section measurements.
  - 1 kton WC detector for event rate measurements, flux normalization and event reconstruction comparison with FD.
  - Emulsion setup, similar to NINJA experiment [1], upstram of the SFGD, for cross-section measurements.



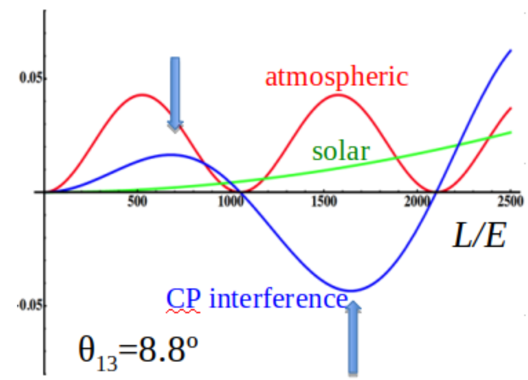
- **Far Detector**:
  - 538 kt fiducial volume (~10 x SuperK).
  - Readout: 20" PMTs (40% optical coverage).
  - Event reconstruction with fiTQun [2,3].
  - New migration matrices obtained.
  - Significant improvements in the reconstruction efficiency (more details in future publication).

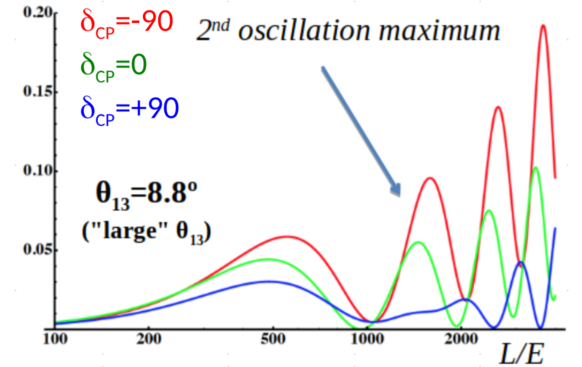
For further information on near detector, see in this conference:

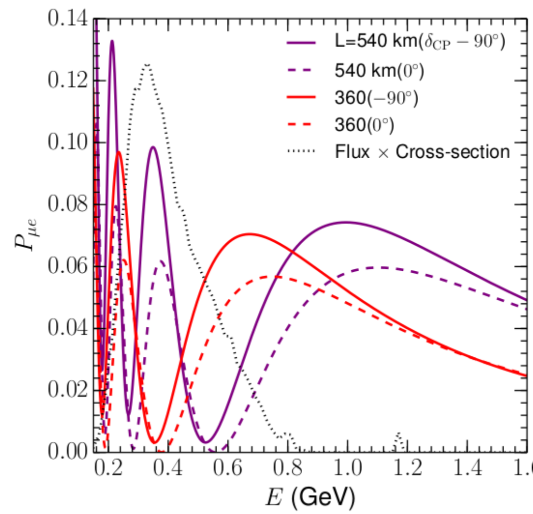
- A. Burgman: *The ESS Neutrino Super-Beam Near Detector* (26.07).
- K. Krhac: *Constraining ESSnuSB neutrino flux by observing elastic scattering of neutrinos on electrons* (Poster).

[1] A. Hiramoto et al., Phys. Rev. D 102, 072006 (2020), arXiv:2008.03895.
[2] T2K Collaboration, A. D. Missert, J. Phys. Conf. Ser. 888 (2017), no. 1 012066
[3] Super-Kamiokande Collaboration, M. Jiang et al., PTEP 2019 (2019), no. 5 053F01, [arXiv:1901.03230].

Probing the 2nd Oscillation Maximum







$$A = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

1st Osc Max: $A = 0.3 \sin \delta_{CP}$

2nd Osc Max: $A = 0.75 \sin \delta_{CP}$

- Neutrino detection at the 2nd Oscillation Maximum.
  - Less statistics than 1st oscillation maximum, but less contribution from systematics.
  - 2 FD locations under consideration: Garpenberg (540 km, current baseline) and Zinkgruvan (360 km).

Physics Performance of the Experiment

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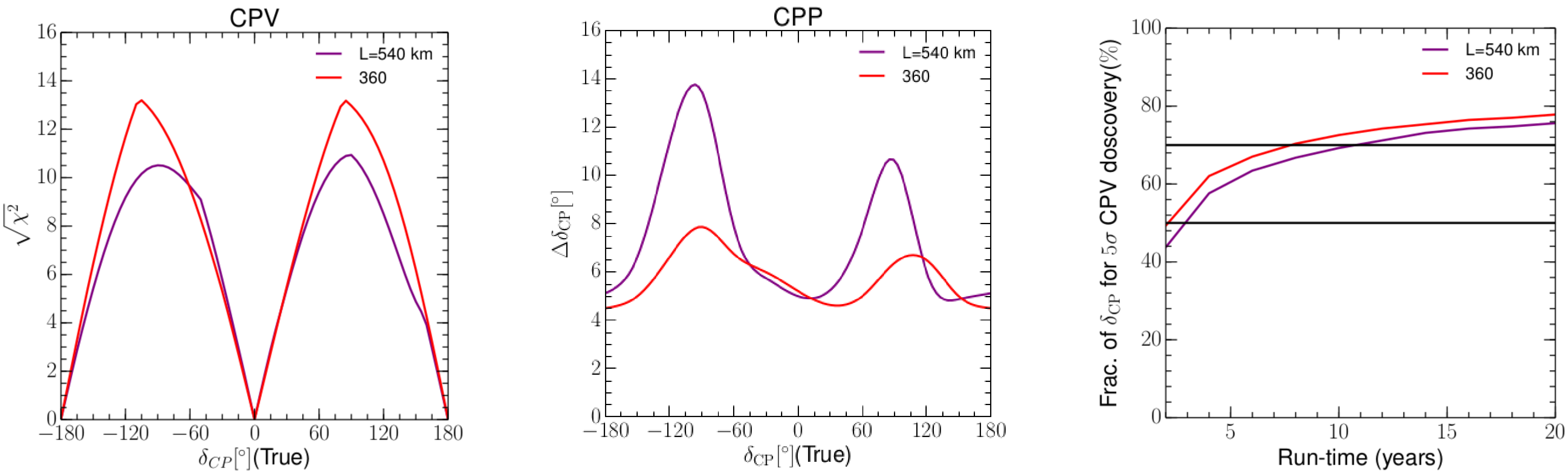
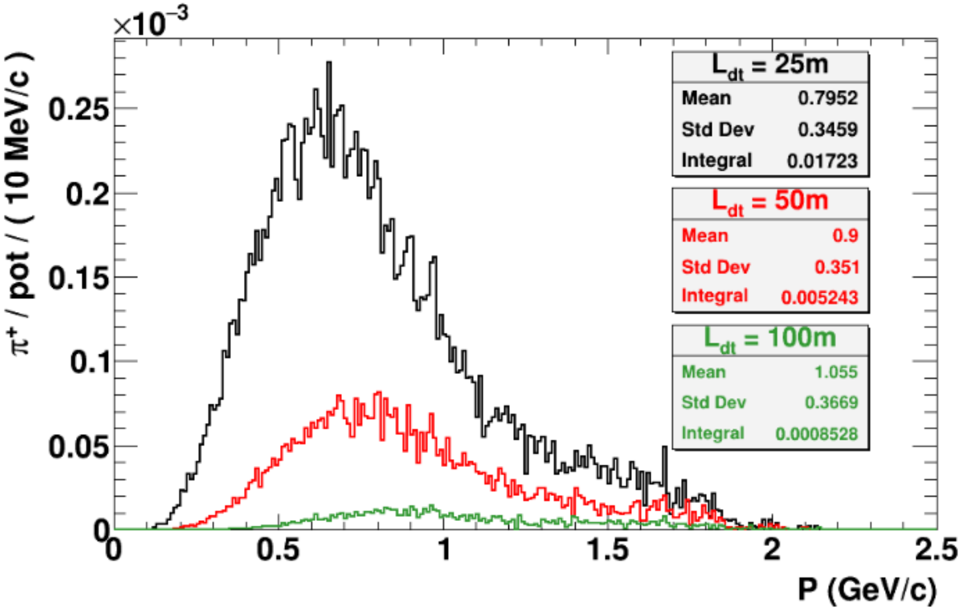
- The optimized geometry of the Target Station and the improved efficiency in the event reconstruction at the FD, lead to an unprecedented precision which can be achieved in the measurement of the δ_{CP} oscillation parameter [1]. Under a conservative estimate of the systematic errors signal/background of **5/10%** , respectively, we observe that:
  - More than 12σ C.L. for δ_{CP}=-90° can be achieved for the location of the FD at 360 km (Zinkgruvan).
  - ~8° uncertainty on δ_{CP} measurement for δ_{CP}=-90° for the same location.
  - More than 70% coverage of δ_{CP} values covered at 5σ in 10 years running time (5 years in neutrino mode + 5 years in antineutrino mode).

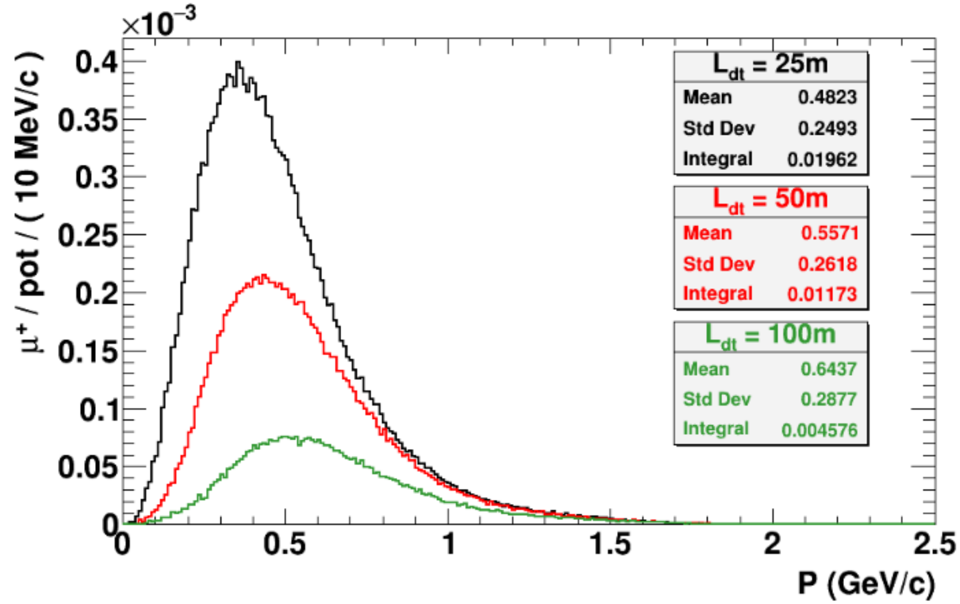


[1] ESSnuSB Collaboration, E. Baussan et al., arXiv:2107.07585 [hep-ex].

Muon and Pions reaching the Beam Dump

Pions and Muons at the Beam Dump (4m x 4m acceptance)





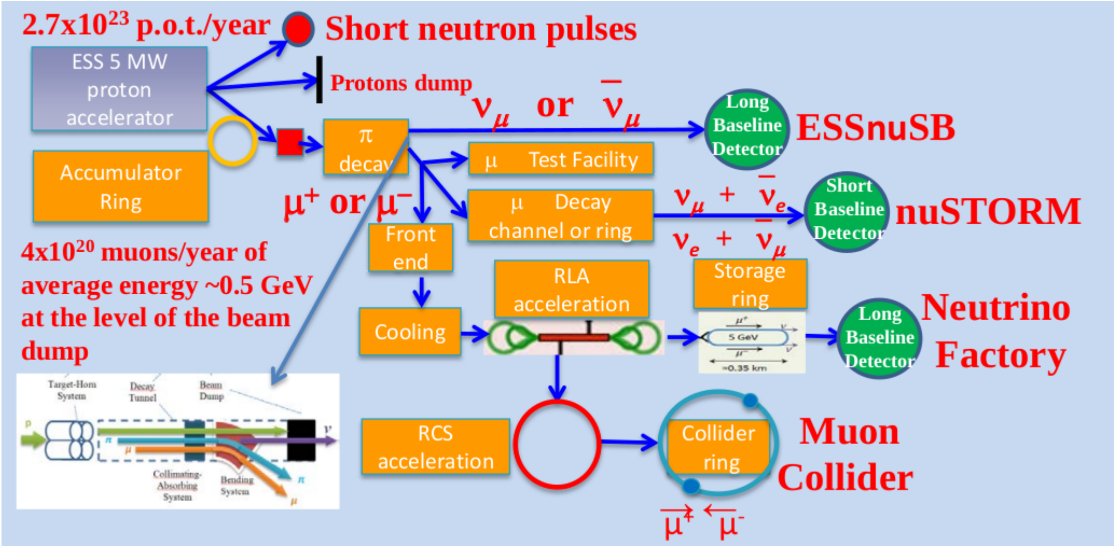
$L_{dt}\,(m)$	$N_\pi\ (\pi^+/pot)$	$N_\pi\ (\pi^+/s)$	$N_\pi\ (\pi^+/200d)$	$\langle P_\pi \rangle\,(GeV/c)$
25	0.017	2.1×10^{14}	3.7×10^{21}	0.79
50	5×10^{-3}	0.6×10^{14}	1.1×10^{21}	0.9
100	8.5×10^{-4}	0.1×10^{14}	0.2×10^{21}	1.06

$L_{dt}\,(m)$	$N_\mu\ (\mu^+/pot)$	$N_\mu\ (\mu^+/s)$	$N_\mu\ (\mu^+/200d)$	$\langle P_\mu \rangle\,(GeV/c)$
25	0.02	2.5×10^{14}	4.3×10^{21}	0.48
50	0.01	1.2×10^{14}	2.1×10^{21}	0.56
100	4.5×10^{-3}	0.6×10^{14}	1.0×10^{21}	0.64

The HIFI Initiative

- The high power proton pulse from ESS, the neutrino beam and the muons which can be obtained, allow to extend the particle Physics program of ESS.

- Several proposals have been discussed during the first HIFI (High Intensity Frontier Initiative) workshop held in Uppsala (02-03.03.2020):
  - ESSνSB
  - Muon Collider R&D
  - Short-pulse Neutron Physics
  - nuSTORM
  - Neutrino Factory
  - Neutrinos from Decay at Rest
  - Coherent Elastic Neutrino Nucleus Scattering (CEνNS)



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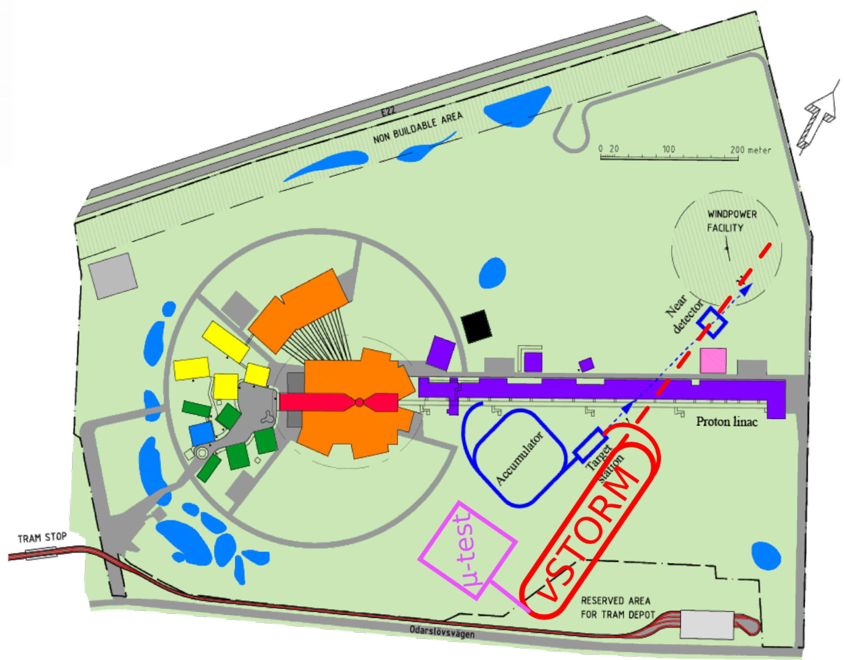
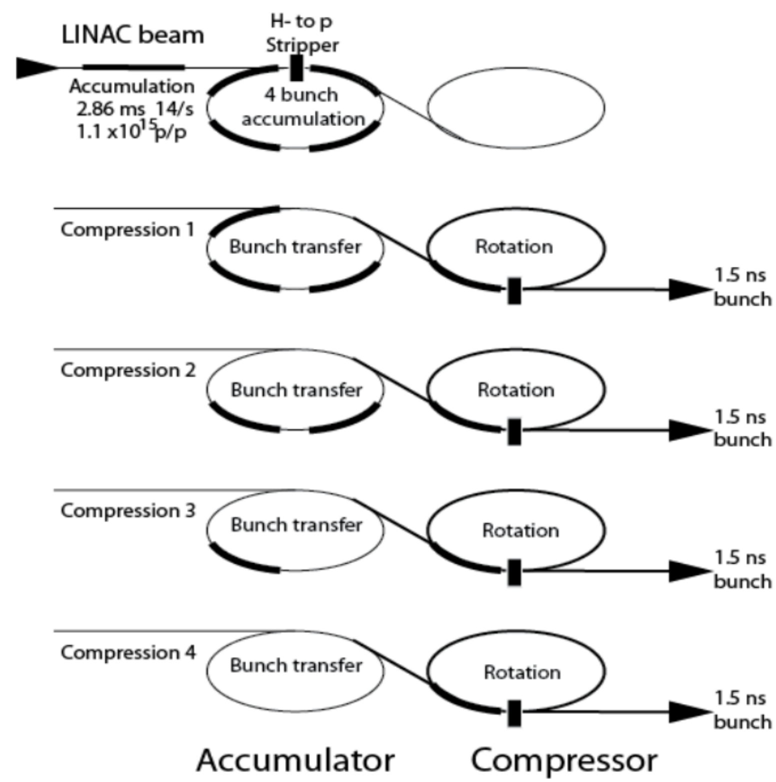
- During the recent community meetings organized by the International Muon Collider Community (IMCC), it has been discussed the possibility to exploit the unique characteristics of the ESS linac proton pulse, to design a muon test facility and/or low energy νSTORM, to modify the design of proton pulses by adding a compressor along with the accumulator ring of ESSνSB to short further the proton pulse up to the level of ns pulses [1].

International MUON Collider Collaboration





More details in T. Ekelof's talks: *Muon Cooling Test Facility at ESS*, Workshop on Muon Collider Testing Opportunities (24-25.03.2021) and *Proposal for a design study of a test facility for the Muon Collider Proton Complex based on the ESS linac and the ESSnuSB accumulator and target station*, 2nd Muon Community Meeting (12-14.07.2021) and references therein.

Conclusions

- ESSνSB aims at constructing a European neutrino beam facility with unprecedented intensity of neutrino flux.
- In this talk, an overview of the current results of the work done by the ESSνSB collaboration for the design of the experiment has been presented.
- The results of optimization design and new reconstruction algorithms of the events at the Far Detector show the high precision which can be achieved by ESSνSB in the measurement of the δ_{CP} oscillation parameter.
- The results of the design of the whole experiment will be published in a CDR by the end of 2021.
- Some outcomes of the design study:
  - In particular, the unique power of the ESS proton beam and the potential neutrino and muon beams open new and exciting opportunities for the design of the next generation of high intensity particle beam facilities.

Acknowledgement

The ESSνSB project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 777419.

Thank You for Your Attention!