The European Spallation Source neutrino Super Beam plus Project

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28.08.2023 | Vidhya Thara Hariharan (on behalf of the ESSνSB+ collaboration)

Institut für Experimentalphysik, Universität Hamburg

Neutrino Oscillations (Leptonic CP-Violation)

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{31}L}{2}\right)$$

$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}L}{2}\right)$$

$$+\dot{J}\cos\left(\delta_{CP} - \frac{\Delta m_{31}L}{2}\right)\sin\left(\frac{\Delta m_{21}L}{2}\right)\sin\left(\frac{\Delta m_{31}L}{2}\right)$$

where $\dot{J} \equiv \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}$ and $\Delta_{ij} \equiv \Delta m_{ij}^2/2E_\nu$. E_ν is the neutrino energy, L is the source-to-detector distance, the *baseline*.
The sign of δ_{CP} is the opposite for antineutrinos.

→ Important for CPV in leptonic sector

$\boldsymbol{\theta_{13}}$ plays a significant role in evaluating the performance when planning "future" long baseline neutrino experiments
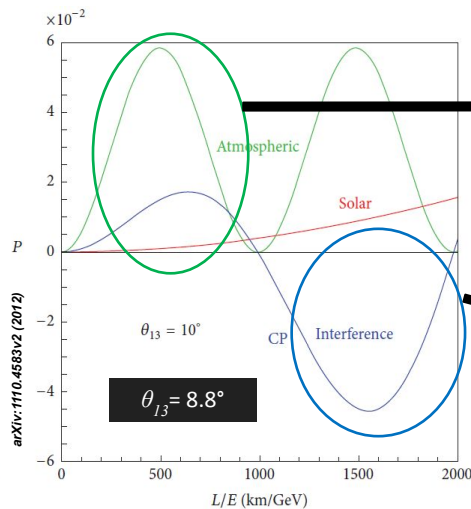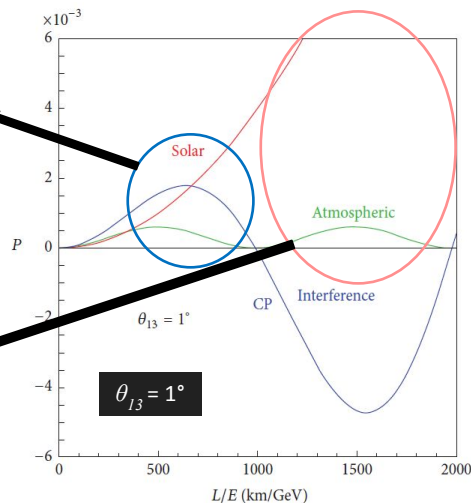

@ 1st oscillation max.

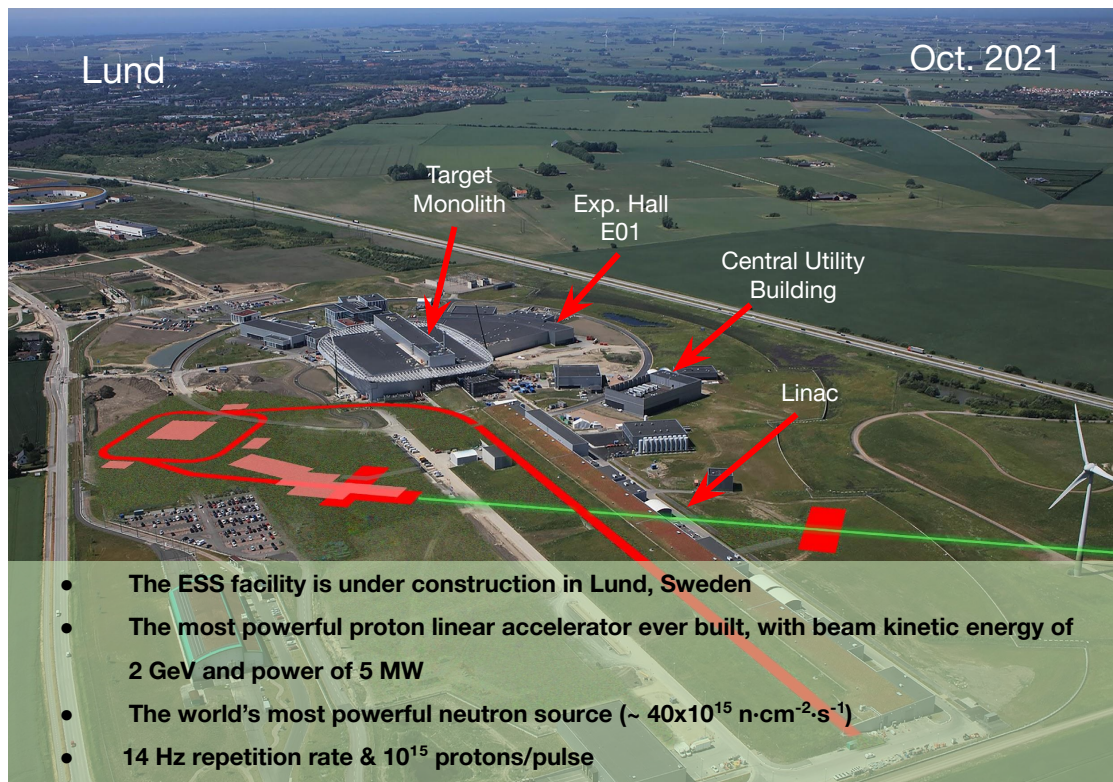CP-interference dominates

@ 2nd oscillation max.

Solar term dominates

@ 1st oscillation max.

Atm. term dominates

@ 2nd oscillation max.

CP-interference dominates
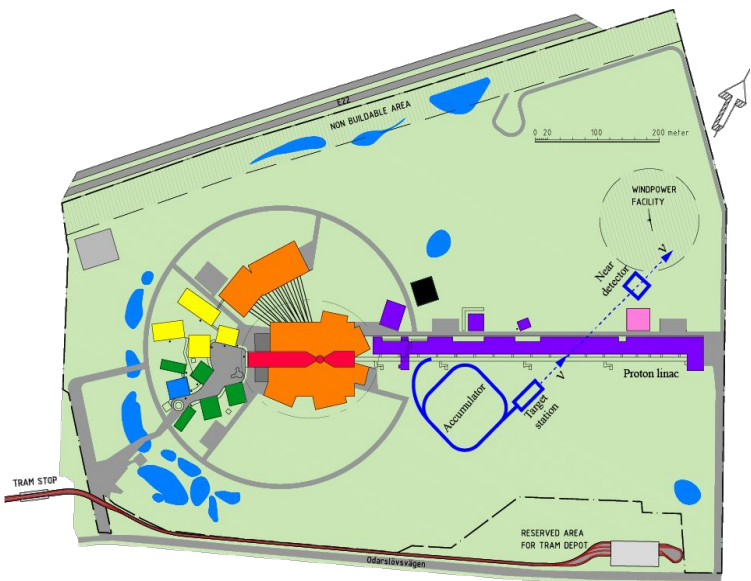
The European Spallation Source (ESS)

Lund — Oct. 2021

- Target Monolith
- Exp. Hall E01
- Central Utility Building
- Linac

- The ESS facility is under construction in Lund, Sweden
- The most powerful proton linear accelerator ever built, with beam kinetic energy of 2 GeV and power of 5 MW
- The world's most powerful neutron source ($\sim 40 \times 10^{15}$ n·cm^{-2}·s^{-1})
- 14 Hz repetition rate & 10^{15} protons/pulse

- Considered baselines to cover 2nd oscillation max.
- 360 km is the chosen baseline

- almost pure ν_μ beam
- small ν_e contamination which could be used to measure ν_e cross-sections in a near detector

Kristineberg
L=1090 km
D=1350 m

Ryhäsalmi
L=1140 km
D=1440 m

SWEDEN

NORWAY

FINLAND

Garpenberg
L=540 km
D=1050 m

Kongsberg
L=500 km
D=1000 m

Zinkgruvan
L=360 km
D=1100 m

ESTONIA

Oskarshamn
L=260 km
D=500 m

DENMARK

LATVIA

LITHUANIA

ESS Lund

POLAND

GERMANY

The European Spallation Source Neutrino Superbeam (ESSνSB)

- Has the benefit of the powerful proton beam of the ESS LINAC to produce intense neutrino beam.

- The neutrino source-to-detector distance, the baseline, is set at the second oscillation maximum.

- Aims at searching and measuring, with precision, for CP-violation in the leptonic sector, at 5σ significance level in more than 70% of the leptonic Dirac CP violating phase range.
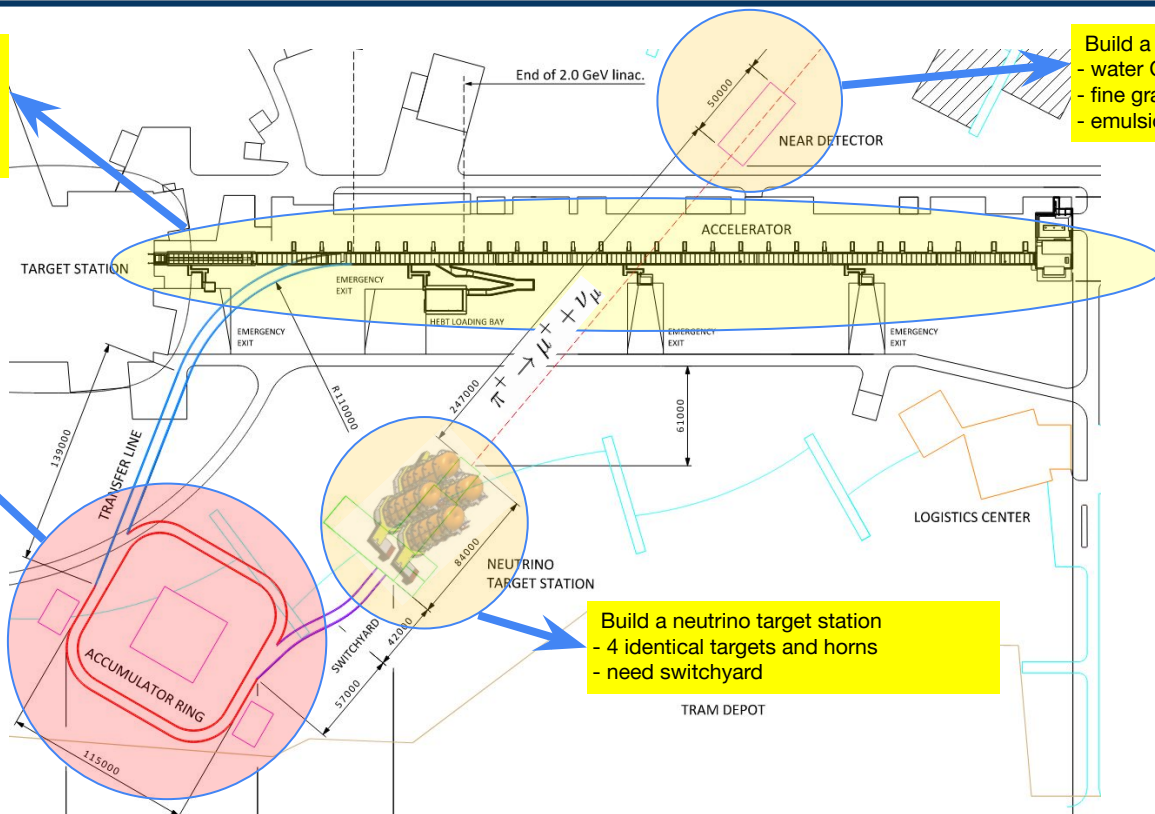
A schematic overview of the main work packages (WP) within the ESSvSB project

Upgrades to the ESS site

Upgrade of the accelerator
- 14 Hz to 28 Hz
  - use H⁻ instead of protons in ESSnuSB cycles
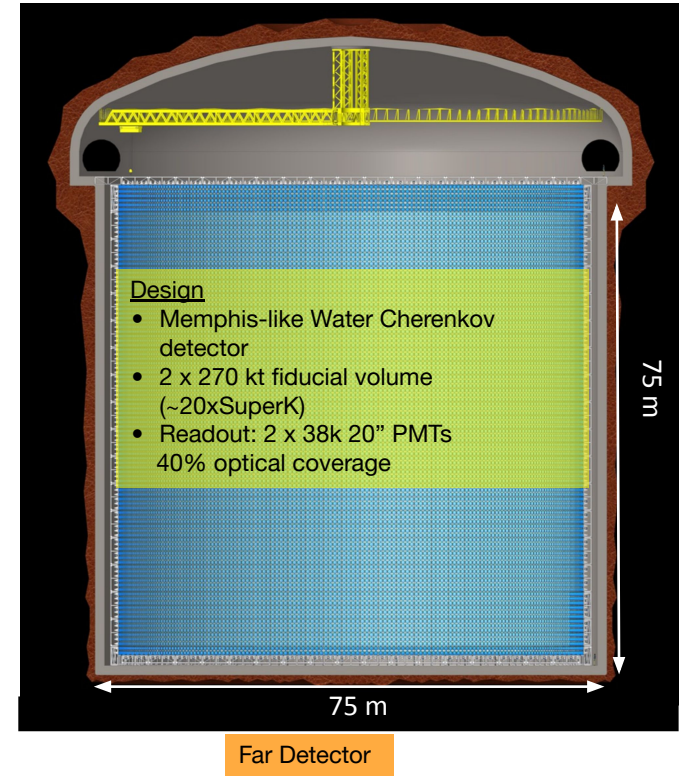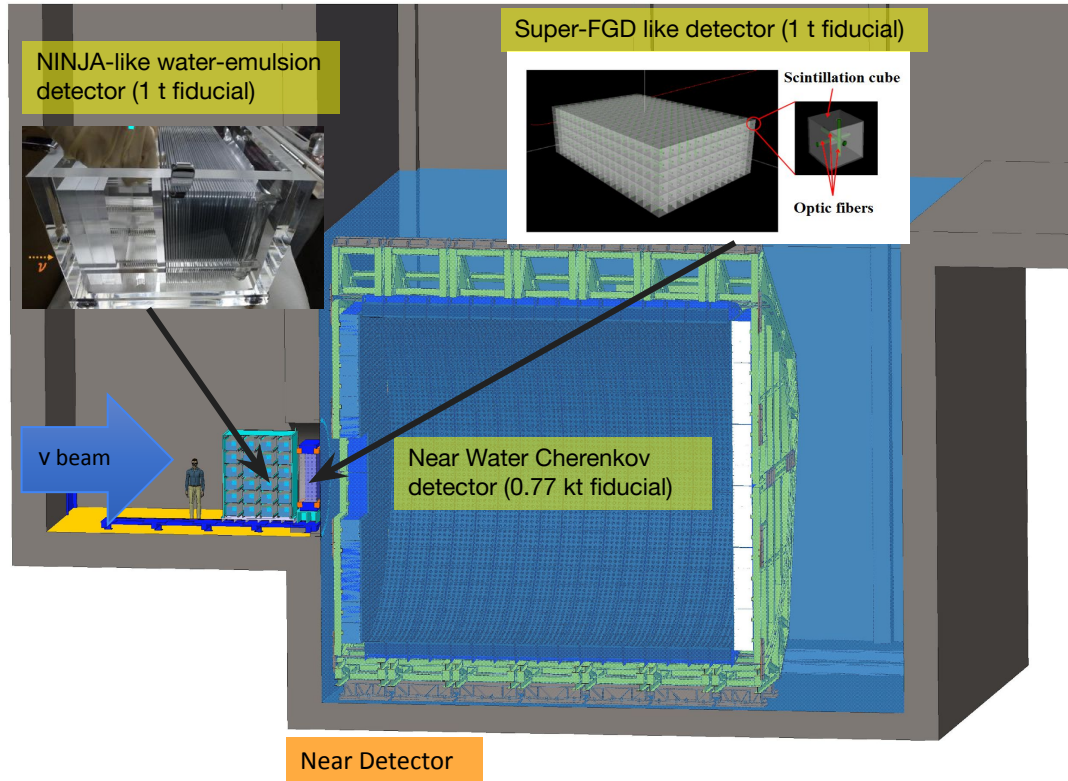 - increase kinetic energy to 2.5 GeV

Build a near detector site
- water Cherenkov detector
- fine grained scintillator
- emulsion detector

Build an accumulator ring
- shorten ESS pulses from 2.86 ms to ≈ 1 µs

Build a neutrino target station
- 4 identical targets and horns
- need switchyard

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

End of 2.0 GeV linac.

NEAR DETECTOR

ACCELERATOR

TARGET STATION

EMERGENCY EXIT

HEBT LOADING BAY

EMERGENCY EXIT

EMERGENCY EXIT

EMERGENCY EXIT

TRANSFER LINE

ACCUMULATOR RING

SWITCHYARD

NEUTRINO TARGET STATION

LOGISTICS CENTER

TRAM DEPOT

ESS*v*SB near and far detectors

NINJA-like water-emulsion detector (1 t fiducial)

Super-FGD like detector (1 t fiducial)

Scintillation cube

Optic fibers

v beam

Near Water Cherenkov detector (0.77 kt fiducial)

Near Detector

Design
- Memphis-like Water Cherenkov detector
- 2 x 270 kt fiducial volume (~20xSuperK)
- Readout: 2 x 38k 20" PMTs 40% optical coverage

75 m

75 m

Far Detector

ESS𝜈SB: Physics Performances

Updated physics performance of the ESS𝜈SB experiment
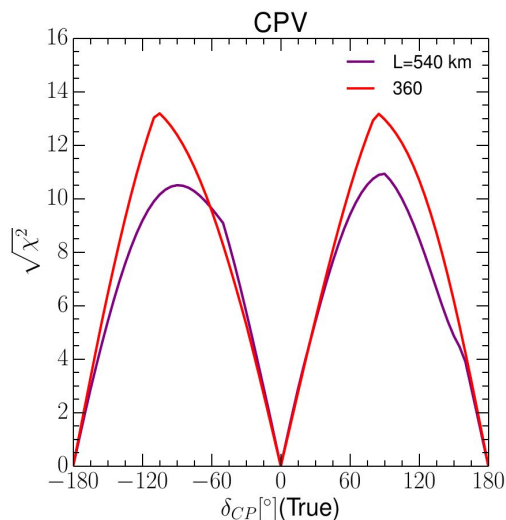
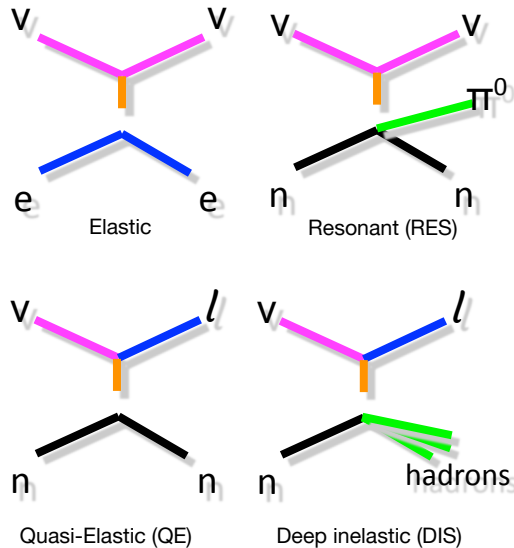Sensitivity for $\delta_{CP} = \pm \pi/2$:
10 σ (540 km)
13 σ (360 km)
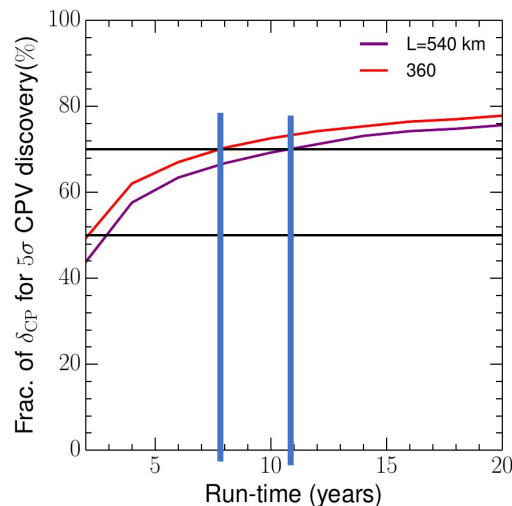
70% δ_{CP} coverage @ 5 σ:
11 years (540 km)
8 years (360 km)
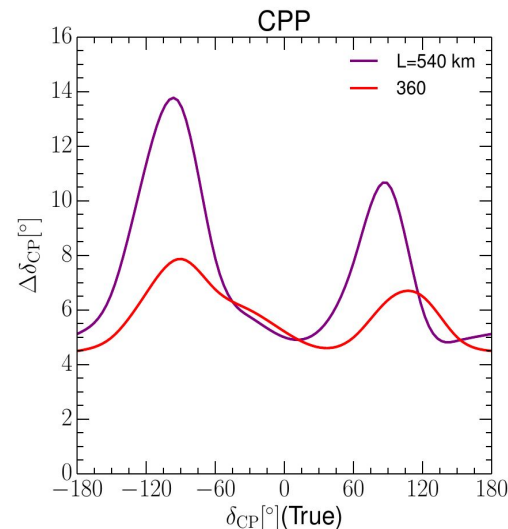
High precision of δ_{CP} measurement

ESSνSB systematic errors

- The influence on δ_{CP} of the systematic errors will be close to three times smaller as compared to other experiments
- Even so, it is of vital importance to measure the neutrino cross-sections in this energy range as precisely as possible for precise measurements of the δ_{CP}, especially since data on neutrino cross-sections in the neutrino energy range of ESSvSB, 0.2-0.6 GeV, is currently very scarce

ν — ν
Elastic

e — e

ν — ν
Resonant (RES)

π^0

n — n

ν — l
Quasi-Elastic (QE)

n — n

ν — l
Deep inelastic (DIS)

n — hadrons

neutrinos
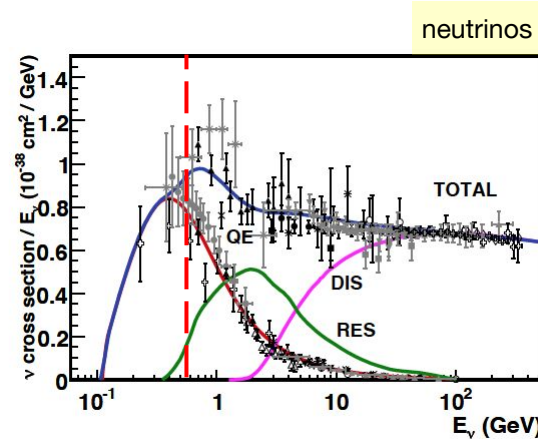
antineutrinos

From eV to EeV: Neutrino cross sections across energy scales, *Rev. Mod. Phys. 84, 1307 – Published 24 September 2012*
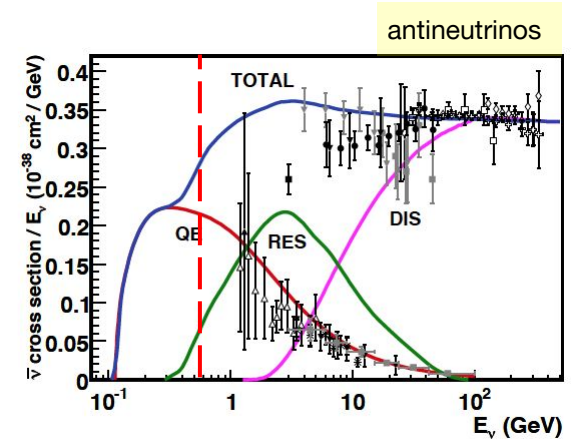
Missing measurements at the ESSvSB region: below 500 MeV

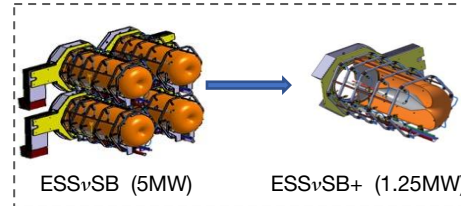# ESSνSB+

A synergic facility based in Europe

ESSνSB+ Superbeam

Cross-section measurements with:

- Low Energy nuSTORM: $\pi \rightarrow \mu \rightarrow e + \nu_\mu + \nu_e$
- Low Energy ENUBET: $\pi \rightarrow \mu + \nu_\mu$

ESSνSB (5MW)   ESSνSB+ (1.25MW)

1. Design a **transfer line** from the ESSνSB accumulator ring to the target

2. Design a **special target facility** that depends on one horn-target system

3. Design a pion **extraction and deflection system**

4. Design an **injection scheme** for the extracted pions to the racetrack storage ring, where the pions will decay to muons

5. Design a **storage ring** for the low energy nuSTROM (for cross section measurements and sterile neutrino searches)

6. Design a **Monitored Neutrino Beam** (low energy ENUBET for cross section measurements)

7. **Optimize the performance** of the ESSvSB detectors
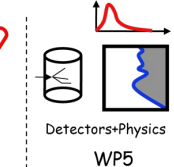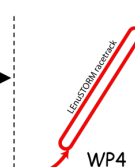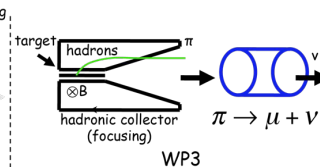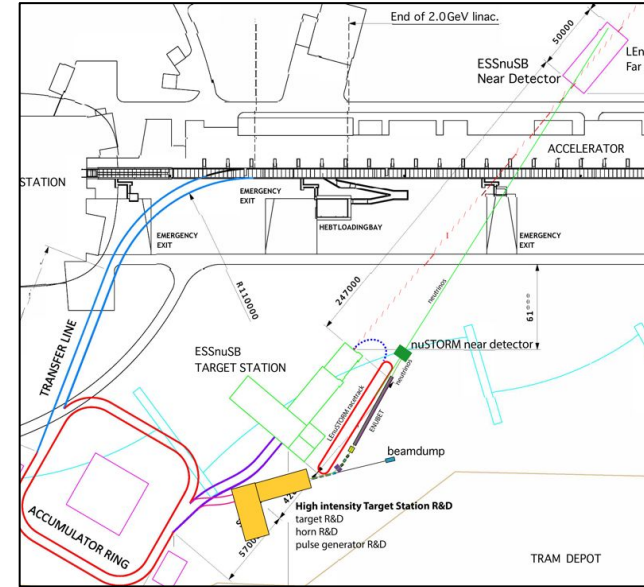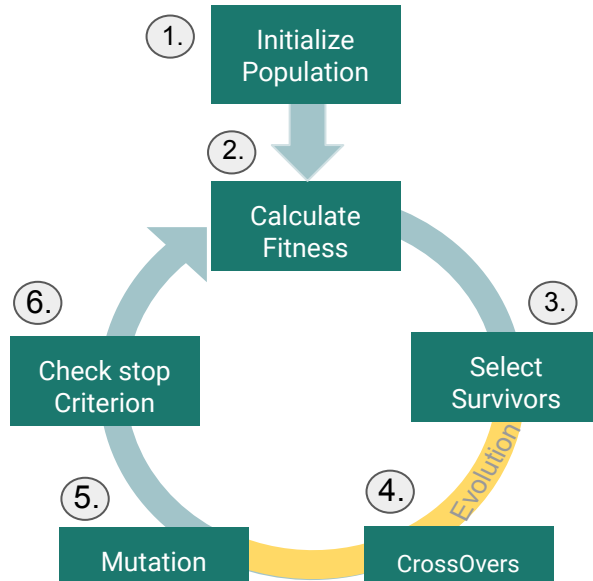
Horn Parameters for study

To obtain a streamlined pion flux the following horn parameters are altered and studied:

1. L1
2. L2
3. L3
4. L4
5. R2
6. R3
7. R4
8. Rdt
9. ztg
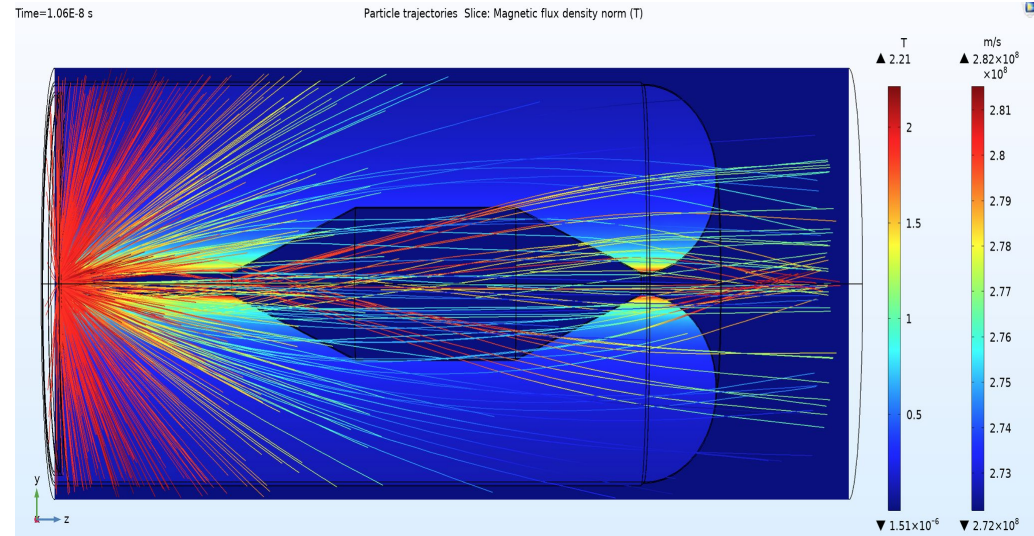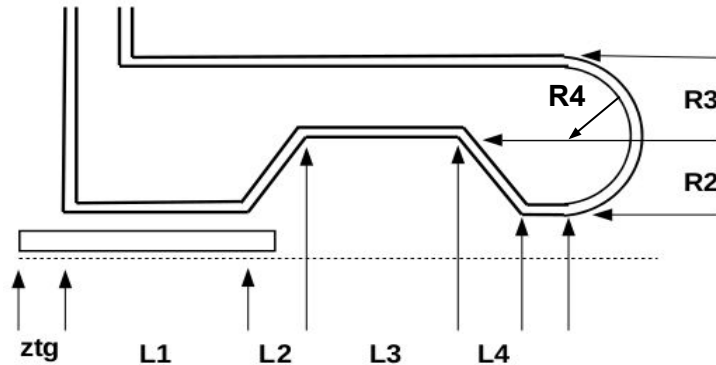
Genetic Algorithm

Workflow of Genetic Algorithm

1. Population: Horn parameter list
   A1: [[60, 15, 80, 78, 51, 68, 87, 2, 26],
   A2: [34, 90, 80, 97, 25, 89, 99, 83, 18],
   A3: [10, 53, 56, 25, 92, 3, 10, 51, 86]]

2. Fitness: Number of π+
   15162, 15005, 15495

3. Fit Individuals: Individuals with highest π+
   A1: [[60, 15, 80, 78, 51, 68, 87, 2, 26],
   A3: [10, 53, 56, 25, 92, 3, 10, 51, 86]]

4. Crossed Over Probability: 0.8882167797500229
   Crossed Offsprings A5: ([60, 53, 56, 25, 51, 68, 87, 51, 86],
   A6: [10, 15, 80, 78, 92, 3, 10, 2, 26])
   Fitness: (15162.0,) (15495.0,)

5. Mutation Probability: 0.235678014576
   Mutant A6: [10, 15, 80, 78, 92, 3, 10, 2, 26]
   Mutated Offspring A7: ([10, 15, 80, 6, 92, 3, 10, 2, 26],)
   Fitness: (15495.0,)

6. Generation 1 - Fit Individuals: A3(15495),
   A6(15495.0),
   A7(15495.0),

Pion distribution
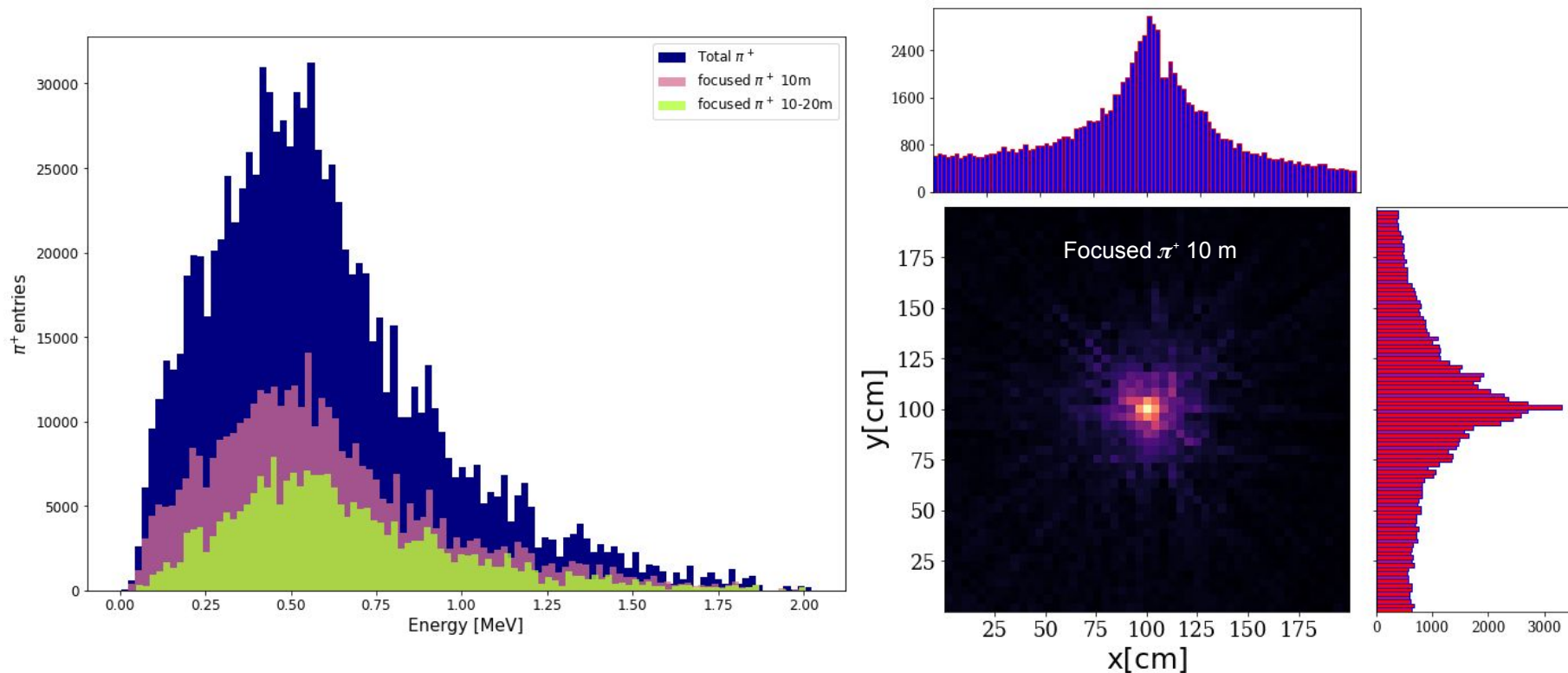
Conclusions

- ESS can also become a neutrino facility, ESSvSB, already proved to have a very high physics performance and potential.

- CPV: 5σ could be reached over 70% of δ_{CP} range by ESSvSB with large physics potential with less than 8° precision.

- Precise neutrino cross-section measurements, sterile neutrino searches and muon studies.

- New application submitted and now approved, and the projected started from 1 Jan., 2023

- This facility offers great opportunity for the community and it is an ideal platform to house R&D activities and other neutrino and muon experiments

Backup

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2nd oscillation max. well covered by the ESS neutrino spectrum
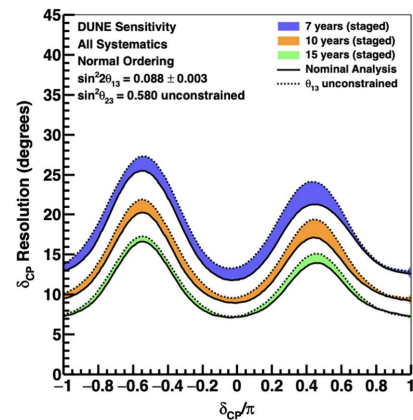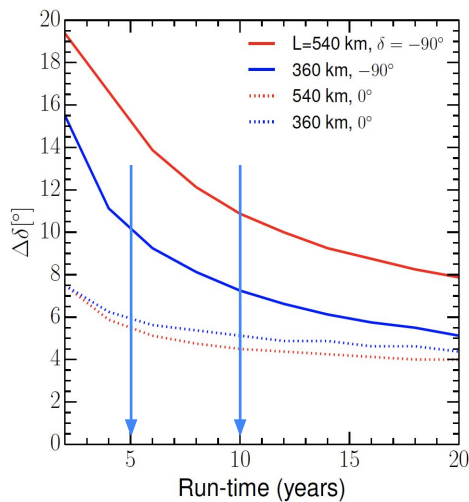
1st oscillation max.
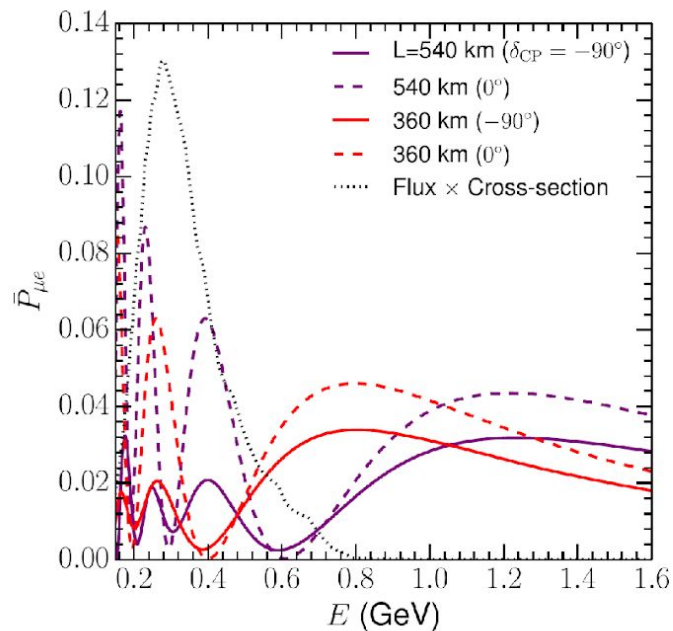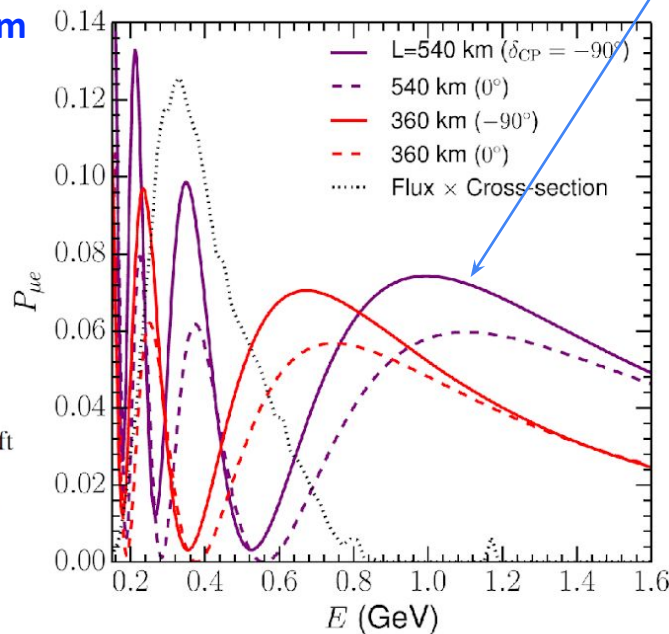
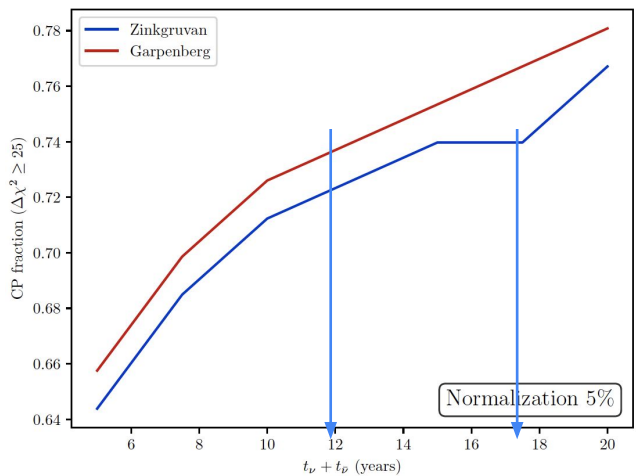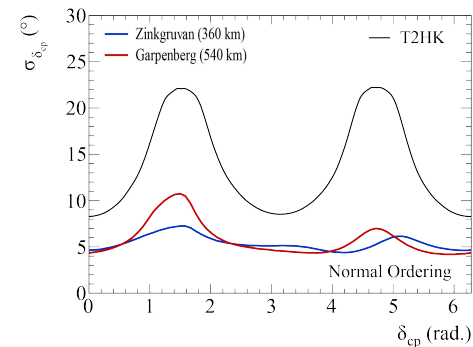**Fig. 1** Appearance channel probability and flux × cross-section vs energy. The left panel is for neutrinos and the right panel is for antineutrinos

Performance Comparison

DUNE

HyperK

Timeline

ESS NEUTRINO SUPER BEAM

ESFRI

2012: inception of the project
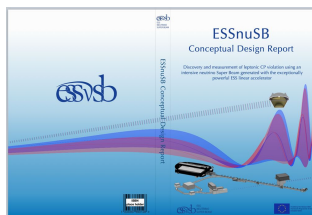
Nucl. Phys. B 885 (2014) 127

2016-2019: beginning of COST Action EuroNuNet

2018: beginning of ESSvSB Design Study (EU-H2020)

2022: End of ESSvSB Design Study, CDR and preliminary costing

arxiv.org/abs/2206.01208
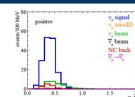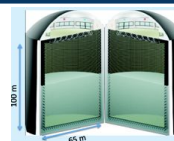
2022-2026: Preparatory Phase, TDR

2026-2028: Preconstruction Phase, International Agreement

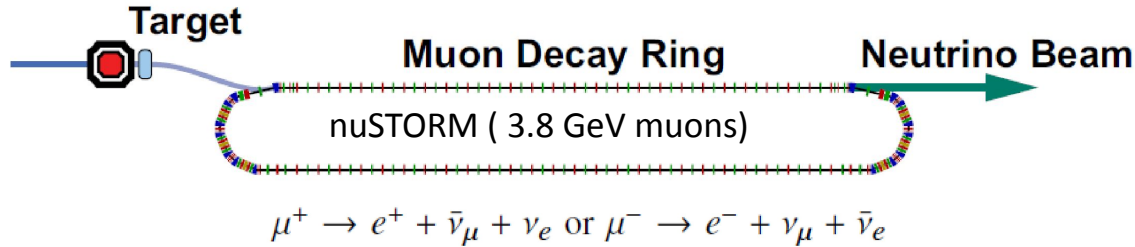**2028-2036**: Construction of the facility and detectors, including commissioning

2037-: Data taking

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Low Energy neutrino Stored Muon facility

Target — **Muon Decay Ring** — **Neutrino Beam**

nuSTORM (3.8 GeV muons)

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \text{ or } \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

The LEnuSTORM facility will take advantage of the extremely high intensity ESS proton beam to:

❖ Serve the future long-baseline ESSnuSB neutrino-oscillation program by providing definitive measurements of (anti)v_e and (anti)v_μN scattering cross sections with percent-level precision;

❖ Allow searches for sterile neutrinos of exquisite sensitivity;

❖ Initiate the development of future muon accelerators (including studying 6D μ ionization cooling).

❖ The facility is unique, it will be capable of storing $\mu^\pm$ beams with momentum of between 1 GeV/c and 6 GeV/c and a momentum spread of ±16%.

❖ At nuSTORM, the flavour composition of the beam and the neutrino-energy spectrum are both precisely known.

❖ The storage-ring instrumentation will allow the neutrino flux to be determined to a precision of 1% or better.

Enhanced NeUtrino BEams from kaon tagging

Proposes a dedicated facility to measure v_μ and v_e cross-sections precisely using a combination of monitored, narrow-band neutrino beams at the GeV energy scale and by instrumenting the meson-decay tunnel with a segmented calorimeter.

- The ENUBET approach is based on monitoring the production of large-angle positrons from $K^+ \to \pi^0 e^+ v_e$ (Ke3) decays in the decay tunnel.
- In addition, ENUBET will monitor muons produced in kaon and pion decays, thus providing a precise measurement of the v_μ flux.
- Due to the optimization of the focusing-and-transport system of the momentum-selected narrow-band beam of the parent mesons, the Ke3 decay represents the main source of electron neutrinos.
- Furthermore, the positron rate may be used to measure the v_e flux directly. Consequently, the monitored v_e beam will lower the uncertainties on the neutrino flux and flavour for a conventional beam from the current level of O(7%-10%) to ~ 1%.
- Similar precision is expected for the v_μ flux, with the bonus that the neutrino energy will be determined with a precision of ~ 10% at the single neutrino level by the "narrow-band off-axis technique", i.e. using only the position of the v_μ interaction vertex.