The European Spallation Source neutrino Super Beam (ESSnuSB) Project

Tamer Tolba *(on behalf of the ESSnuSB collaboration)*

Institut für Experimentalphysik, Universität Hamburg, Germany

JUNO – Germany Meeting

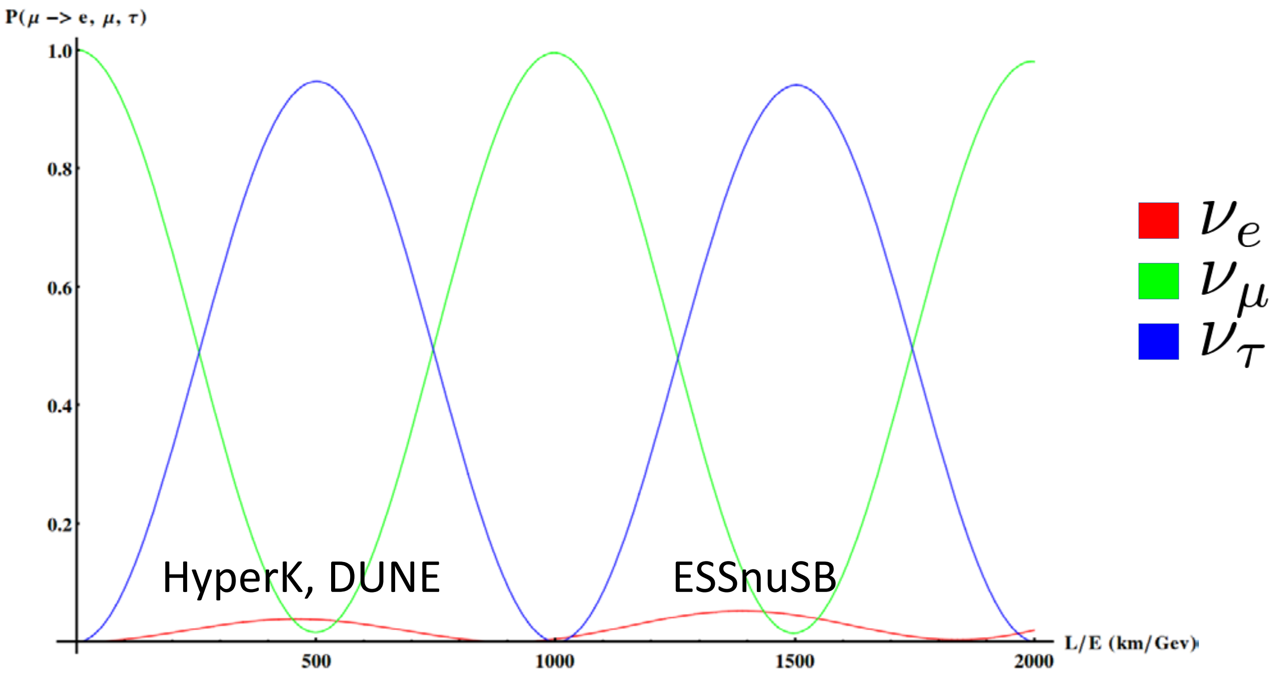
07 October 2025

Hamburg – Germany

ESSnuSB

(European Spallation Source neutrino Super Beam)

A proposed second generation long-baseline experiment based in Europe to measure the **CP violation in the lepton sector** at the ***second neutrino oscillation maximum*** with ***precision***



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ESS neutrino Super Beam plus

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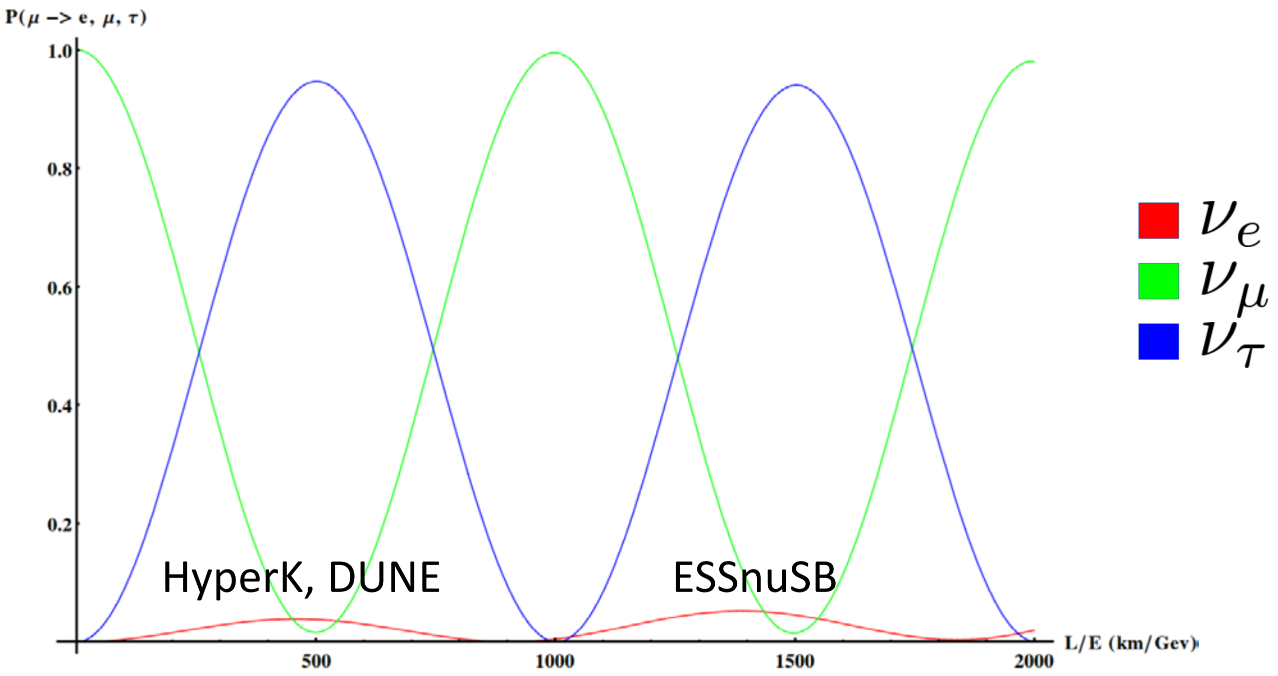
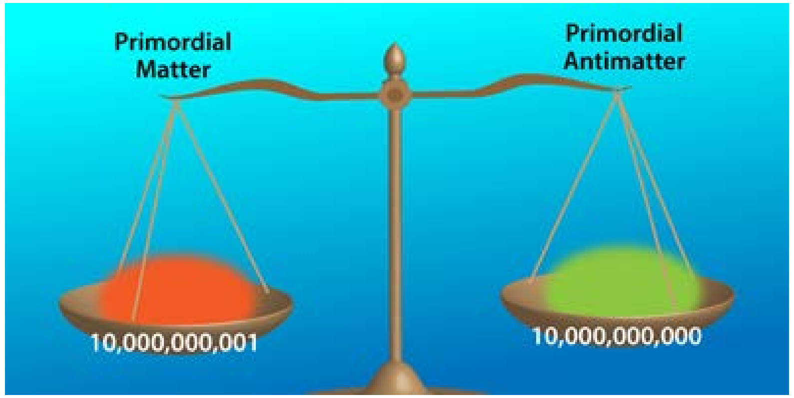


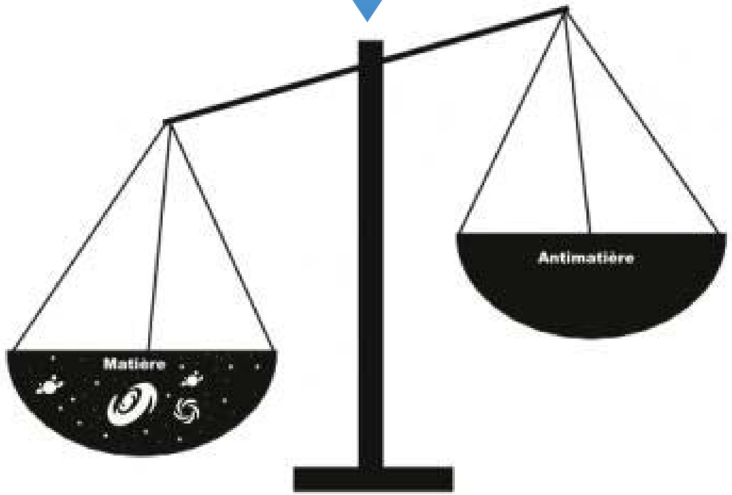
CP-Violation in the Lepton Sector

- Standard Model of Particle Physics assumes that the big bang created equal amounts of matter and antimatter



➔ BUT matter ≠ antimatter in the universe,
i.e. there is a matter/anti-matter Asymmetry (*A*)

- For any theory of the baryon creation, or baryogenesis, to be able to explain the Baryon Asymmetry of Universe (BAU), three (Sakharov) conditions must be fulfilled:
  1. existence of baryon number violation
  2. existence of Charge (C) an Charge-Parity (CP) symmetries violation
  3. departure from thermal equilibrium.



No. of observed baryons
No. of observed light

$$\frac{n_B}{n_\gamma} \simeq 6 \times 10^{-10}$$

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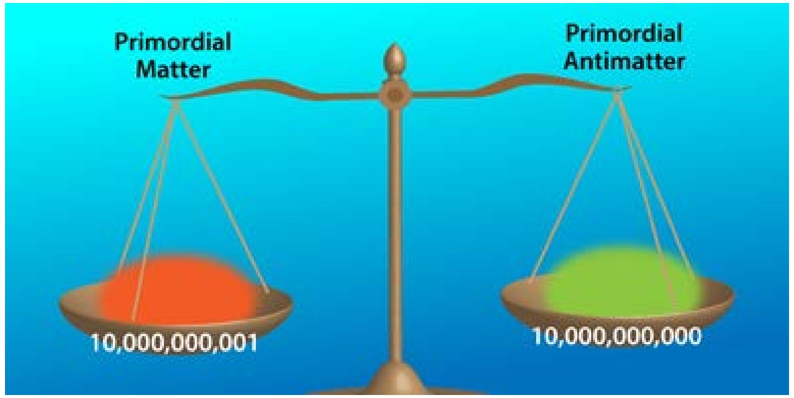

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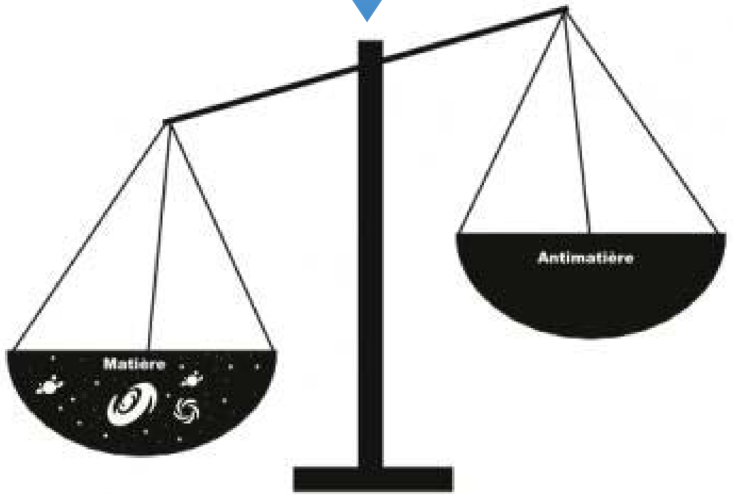


No. of observed baryons → n_B
No. of observed light → n_γ

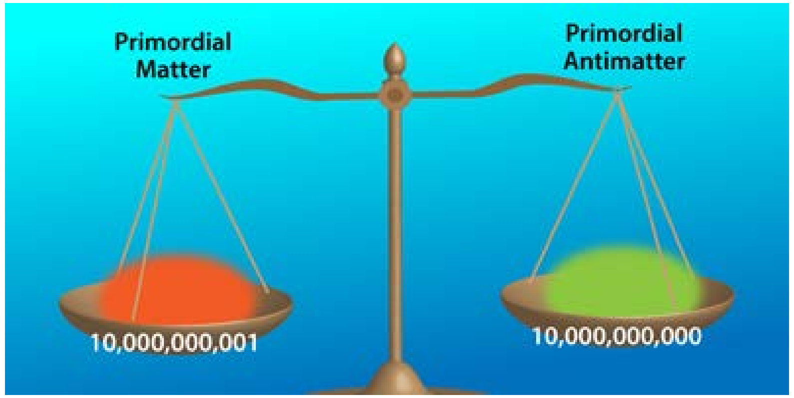
$$\frac{n_B}{n_\gamma} \simeq 6 \times 10^{-10}$$

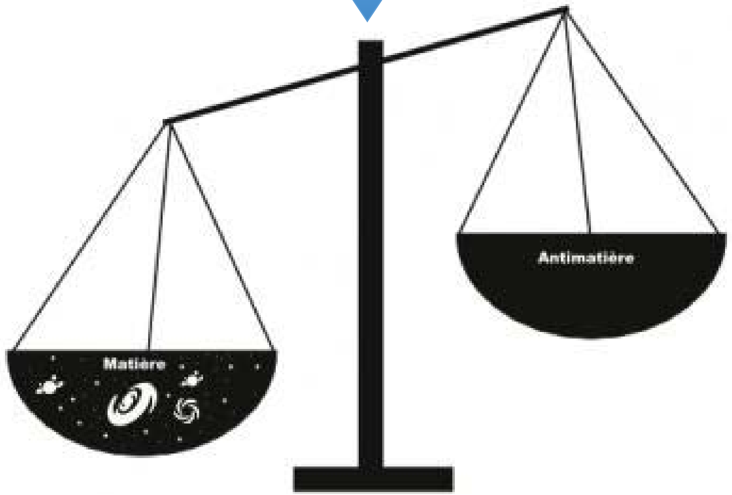
CP-Violation in the Lepton Sector

- In the SM, the size of the CP violation is driven by the Jarlskog invariant

$$A^{CP}_{\alpha\beta} = P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$
$$= J^{max}_{CP} \cdot \sin\delta_{CP}$$

with J^{max}_{CP}, Jarlskog invariant, $= \sin\delta \, \sin2\theta_{13} \, \cos\theta_{13} \, \sin2\theta_{12} \, \sin2\theta_{23}$. ➔ *depends on the CP violation ingredients; the three generation mixing, (12), (23), (13) and the CP-violating phase, δ.*





- CPV has been observed in the hadron sector (in the neutral *K*-meson decay)
  - ➔ In the quark sector, $J^{CKM}_{CP} \sim 3 \times 10^{-5}$ ➔ **is not enough** to explain the CP-violation, even at $\delta_{CP} \sim 70°$!

- In the lepton sector, $J^{PMNS}_{CP} \sim 3 \times 10^{-2}$ ➔ Theoretical models predict that if $|\sin\delta_{CP}| \gtrsim 0.7$ (i.e. 45° < δ_{CP} < 135° or 225° < δ_{CP} < 315°), **this could be enough** to explain the observed matter/anti-matter asymmetry.

(Nucl.Phys.B774:1-52,2007, arXiv:hep-ph/0611338)

CP-Violation in Neutrino Oscillation

Oscillation probability for neutrinos is different than Oscillation probability for anti-neutrinos in vaccum.

probability of oscillation

$$P_{\nu_\alpha \rightarrow \nu_\beta} \neq P_{\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta}$$

neutrino flavour at production

neutrino flavour at detection

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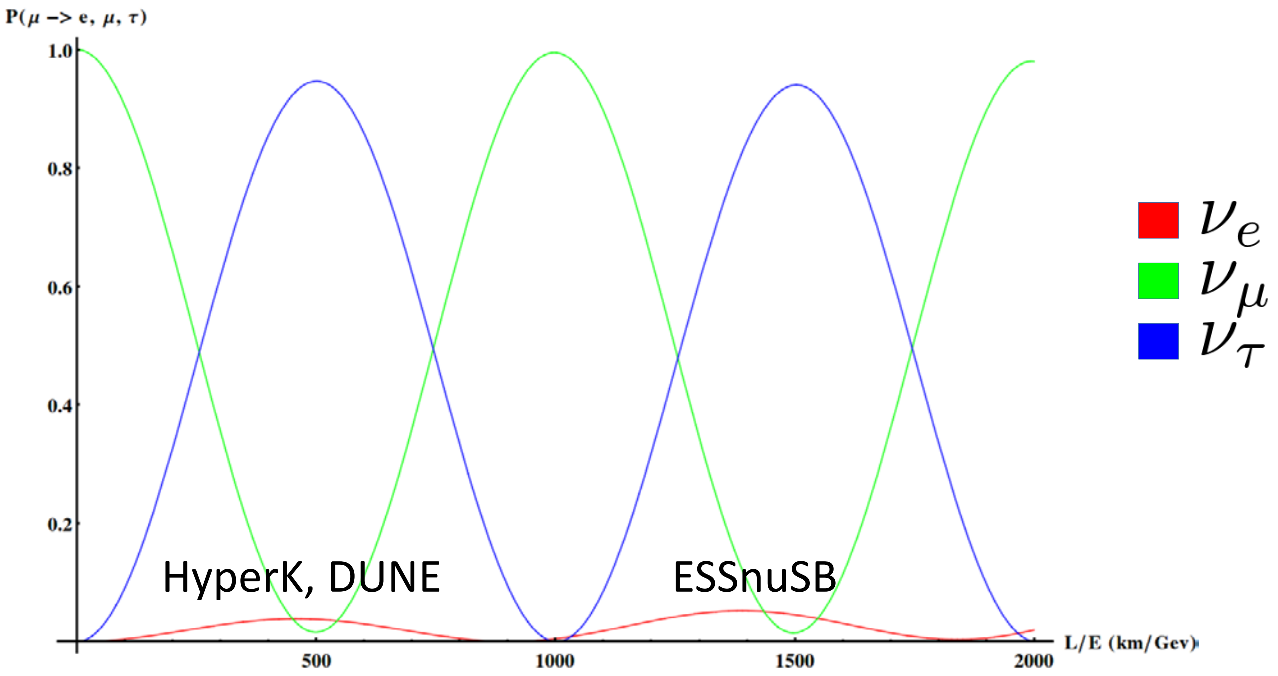


Why 2nd Oscillation Maximum?

$\nu_\mu \rightarrow \nu_e$ oscillation probability:

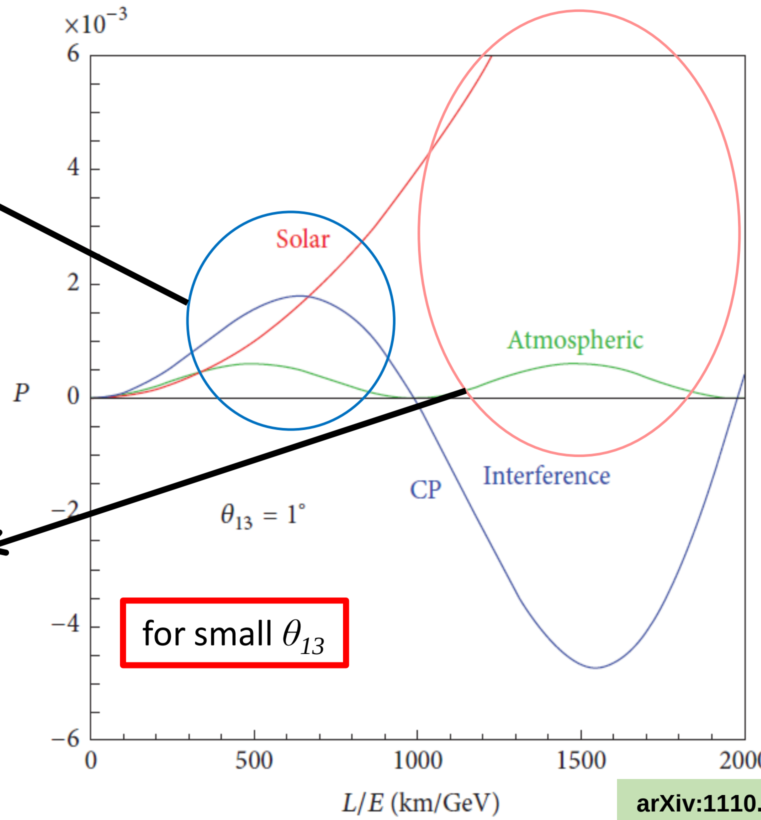
Picture before 2012

$$P(\nu_\mu \rightarrow \nu_e) = sin^2\theta_{23} sin^2 2\theta_{13} sin^2\left(\frac{\Delta m_{31}L}{2}\right)$$
$$+ cos^2\theta_{23} sin^2 2\theta_{12} sin^2\left(\frac{\Delta m_{21}L}{2}\right)$$
$$+ \bar{J} cos\left(\delta_{CP} - \frac{\Delta m_{31}L}{2}\right) sin\left(\frac{\Delta m_{21}L}{2}\right) sin\left(\frac{\Delta m_{31}L}{2}\right)$$

where $\bar{J} \equiv cos\theta_{13} sin2\theta_{12} sin2\theta_{23} sin2\theta_{13}$ and $\Delta_{ij} \equiv \Delta m^2_{ij}/2E_\nu$. E_ν is the neutrino energy, L is the source-to-detector distance, the *baseline, and* the sign of δ_{CP} is the opposite for antineutrinos.
In this plot $cos\left(\delta_{CP} - \frac{\Delta_{31}L}{2}\right) = 1$

Important for CPV in lepton sector

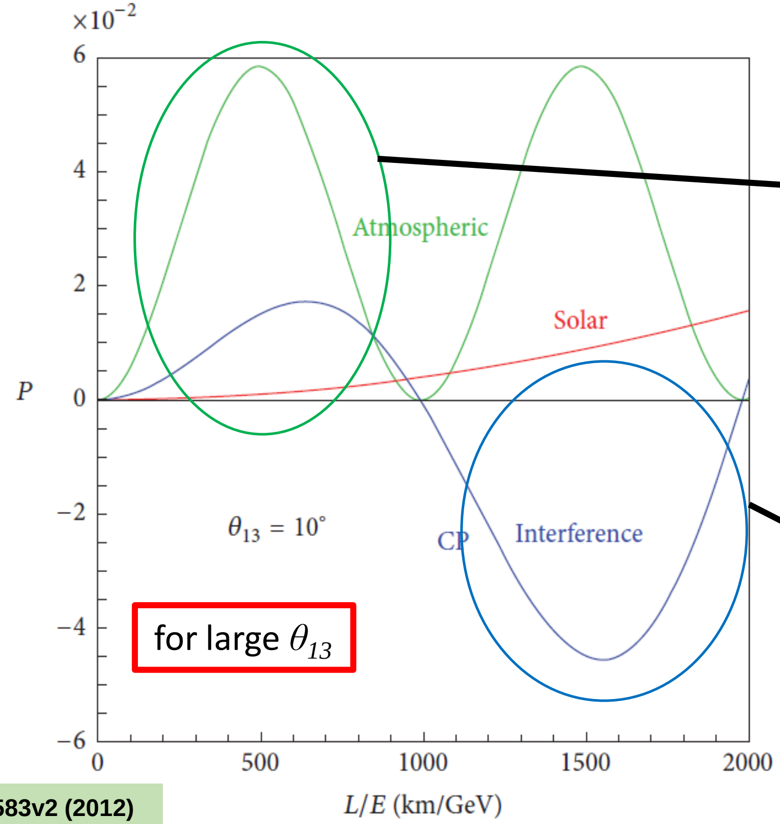
θ_{13} plays a significant role in evaluating the performance when planning "future" long baseline neutrino experiments



@ 1st oscillation max.
CP-interference dominates

@ 2nd oscillation max.
Solar term dominates

for small θ_{13}



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arXiv:1110.4583v2 (2012)

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Picture after 2012

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{31}L}{2}\right) + \cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}L}{2}\right) + \bar{J}\cos\left(\delta_{CP} - \frac{\Delta m_{31}L}{2}\right)\sin\left(\frac{\Delta m_{21}L}{2}\right)\sin\left(\frac{\Delta m_{31}L}{2}\right)$$

where $\bar{J} \equiv \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}$ and $\Delta_{ij} \equiv \Delta m^2_{ij}/2E_\nu$. E_ν is the neutrino energy, L is the source-to-detector distance, the *baseline, and* the sign of δ_{CP} is the opposite for antineutrinos.
In this plot $\cos\left(\delta_{CP} - \frac{\Delta_{31}L}{2}\right) = 1$

θ_{13} found to be at higher values ~ 8.5°
(https://arxiv.org/abs/2007.14792)

CPV is best studied at the 2nd oscillation maximum

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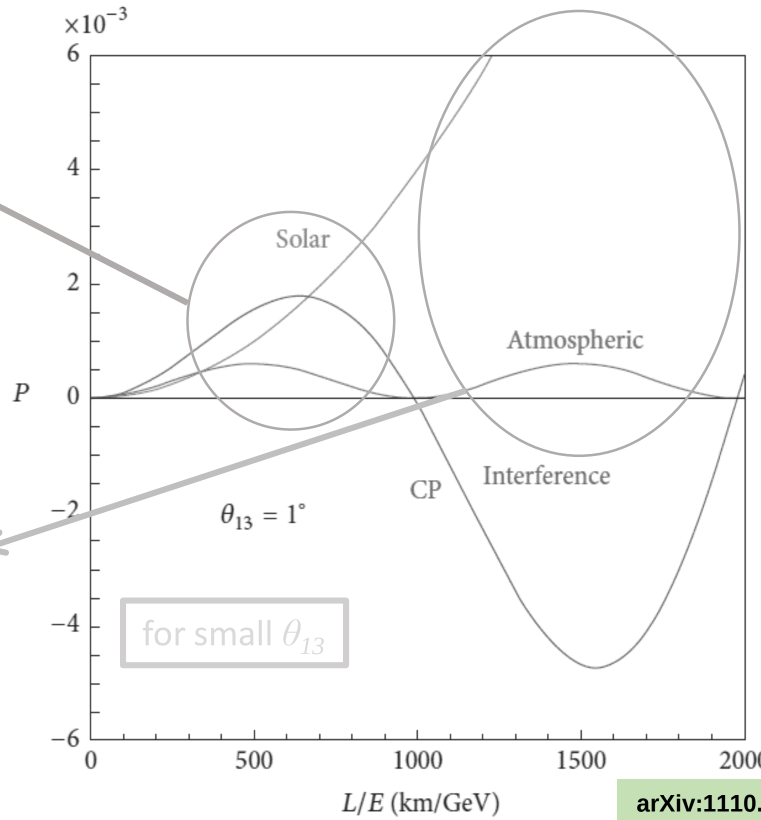

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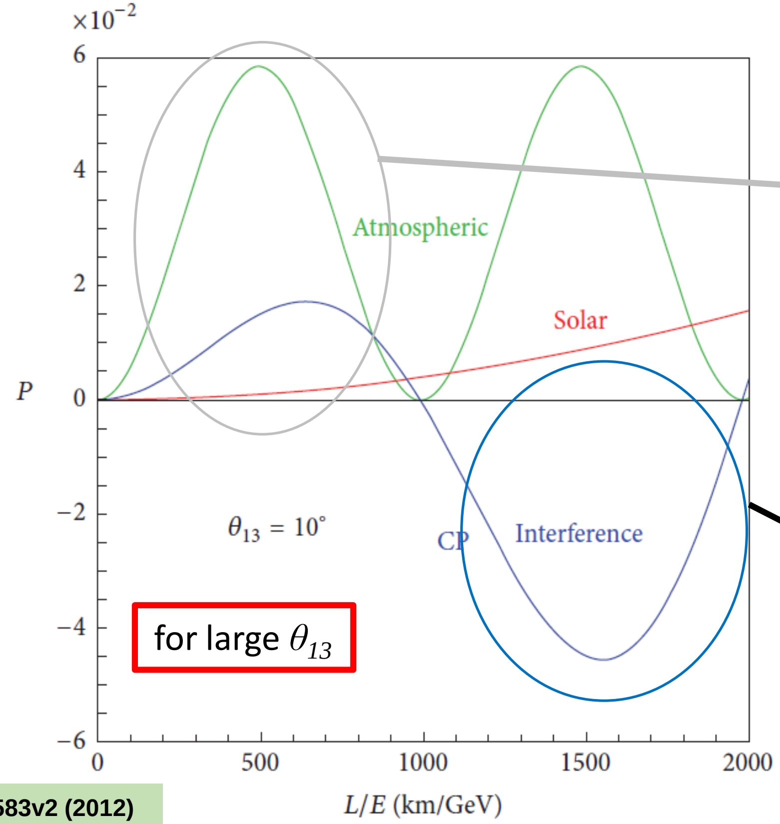

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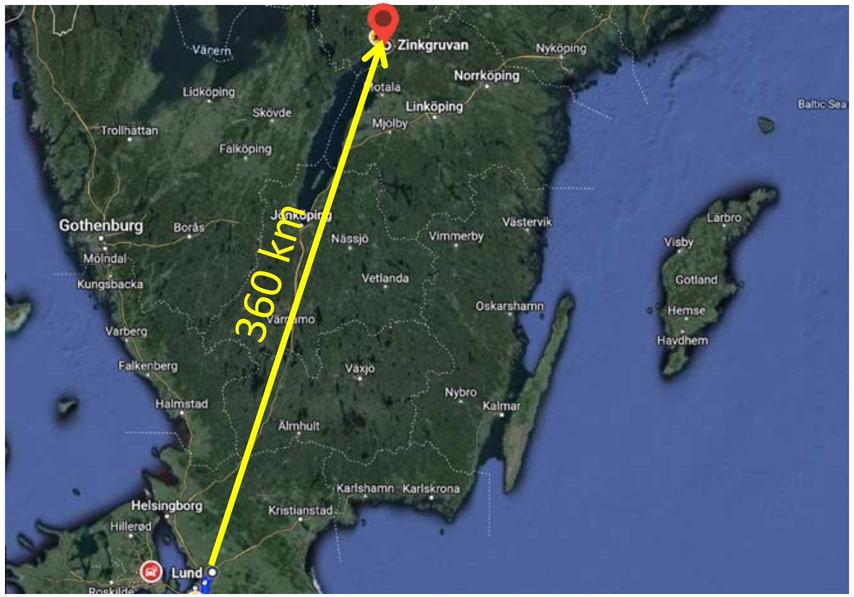
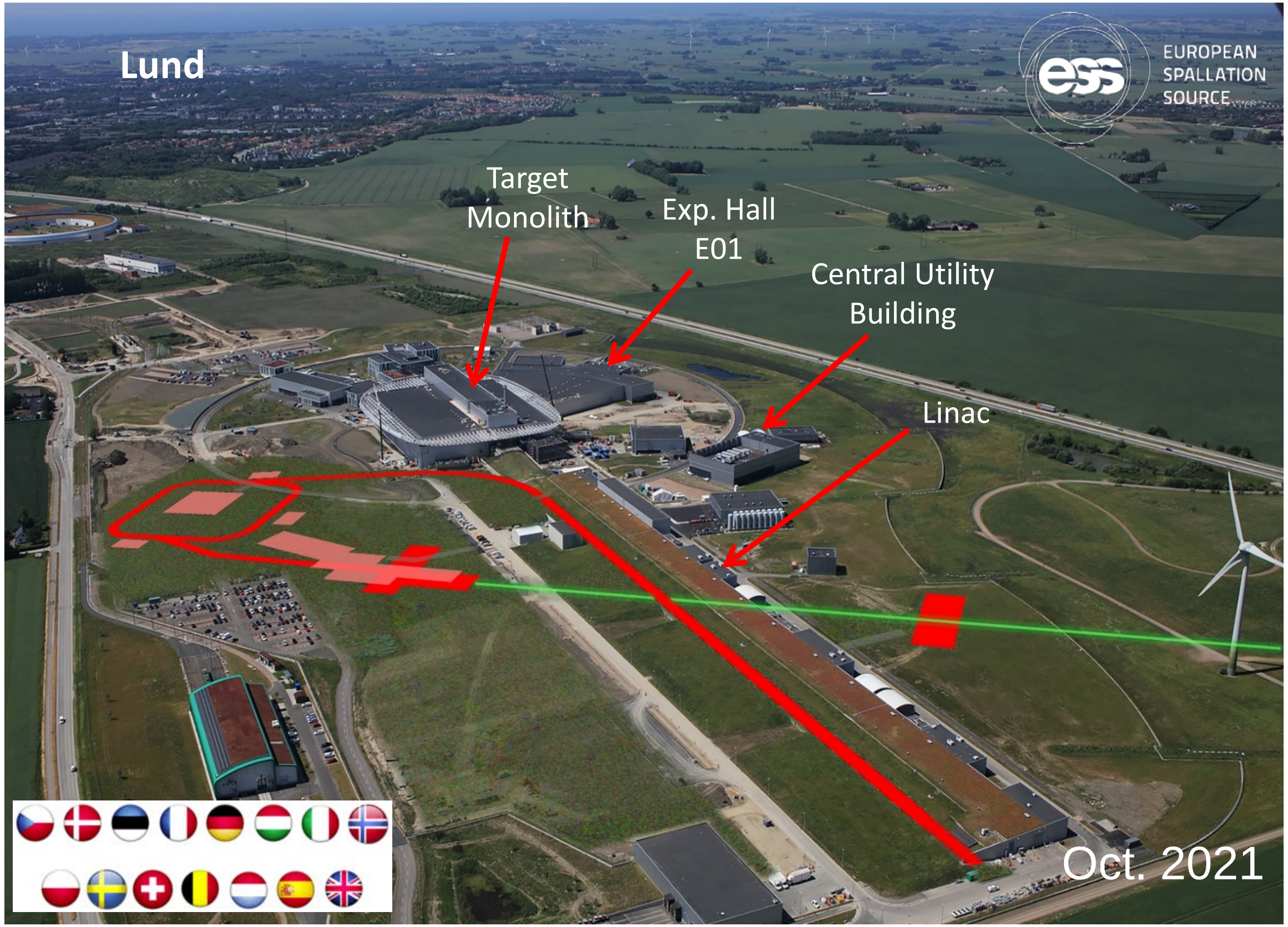
The European Spallation Source (ESS)

- The ESS facility is under construction in Lund, Sweden
- The most powerful proton linear accelerator
- The world's most powerful neutron source
- Designed for $E_{kinetic}$ = 2 GeV and power of 5 MW





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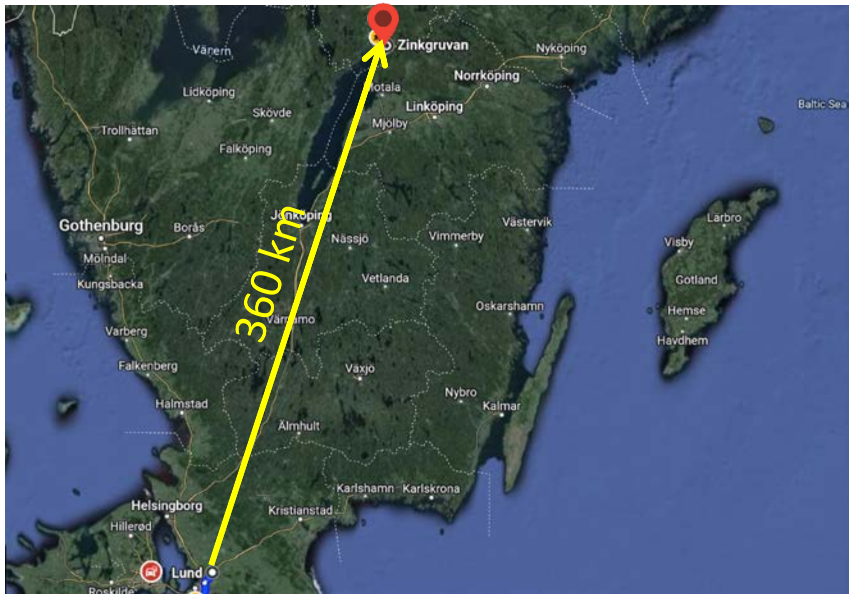

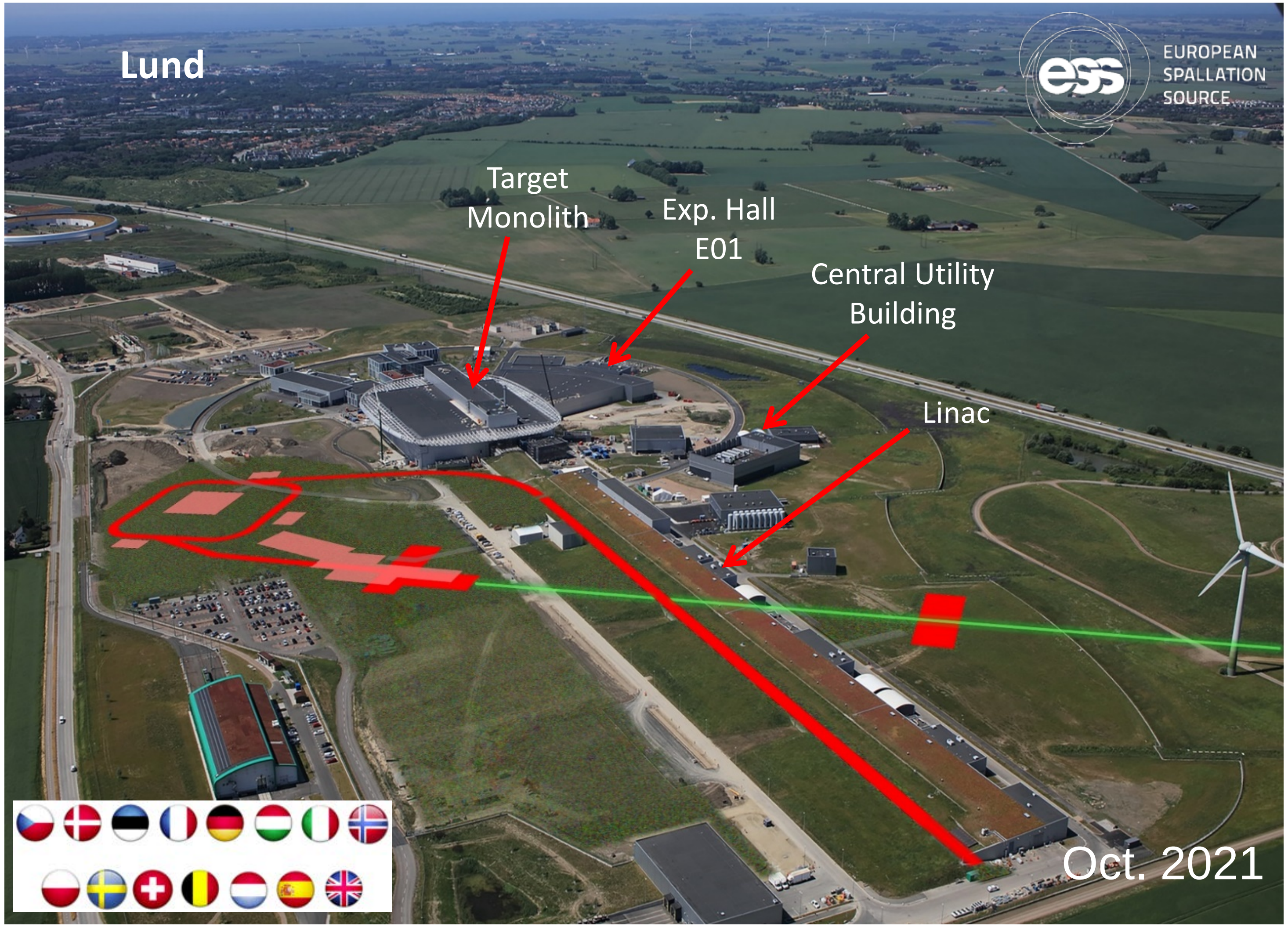

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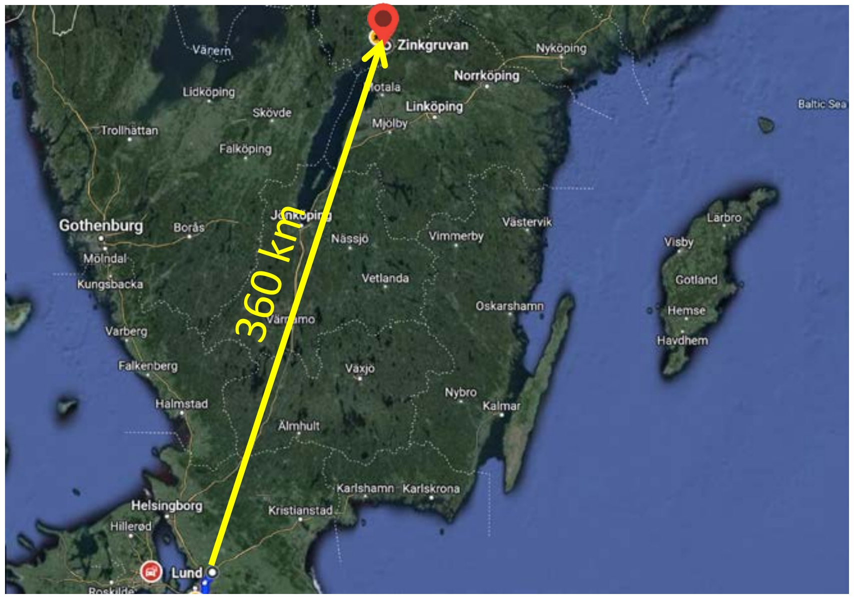
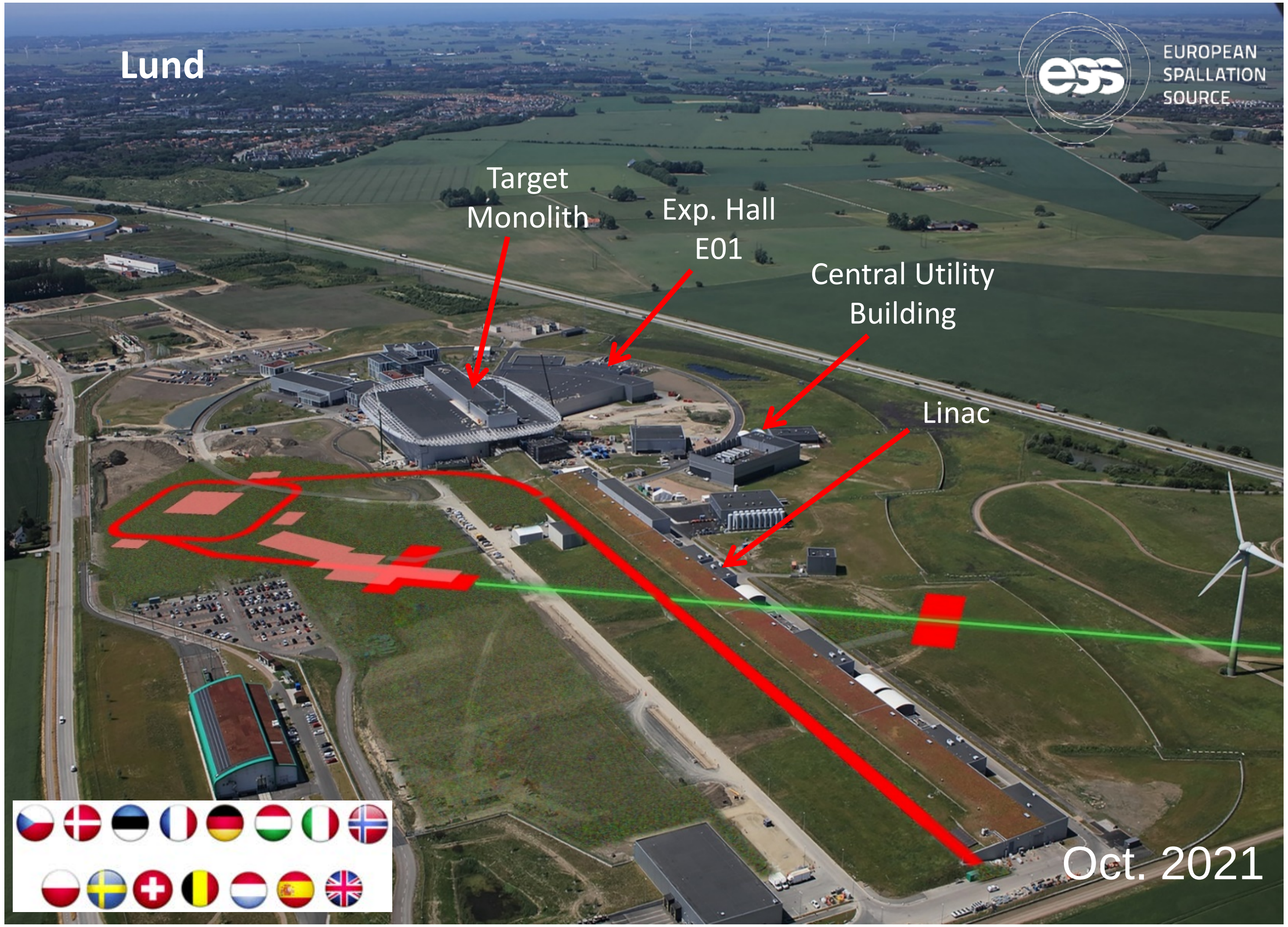
- Designed for $E_{kinetic}$ = 2 GeV and power of 5 MW ➔ **Makes measurements at the 2nd Oscil. maximum possible**





ESSnuSB collaboration

- **94 members**
- **23 Institutes (Incl. CERN and ESS)**
- **13 EU countries (Incl. Japan)**

Participant no.	Participant organisation name	Part. short name	Country
1 (Coordinator)	Centre National de la Recherche Scientifique	CNRS	France
2	Université de Strasbourg	UNISTRA[1]	France
3	Rudjer Boskovic Institute	RBI	Croatia
4	Tokai National Higher Education and Research System, National University Corporation	NU[2]	Japan
5	Uppsala Universitet	UU	Sweden
6	Lunds Universitet	ULUND	Sweden
7	European Spallation Source ERIC	ESS	Sweden
8	Kungliga Tekniska Hoegskolan	KTH	Sweden
9	**Universitaet Hamburg**	**UHH**	**Germany**
10	University of Cukurova	CU	Turkey
11	National Center for Scientific Research "Demokritos"	NCSRD	Greece
12	Aristotelio Panepistimio Thessalonikis	AUTH[1]	Greece
13	Hellenic Open University	HOU[4]	Greece
14	Sofia University St. Kliment Ohridski	UniSofia	Bulgaria
15	Lulea Tekniska Universitet	LTU	Sweden
16	European Organisation for Nuclear Research	CERN	IEIO[3]
17	Universita degli Studi Roma Tre	UNIROMA3	Italy
18	Universita degli Istudi di Milano-Bicocca	UNIMIB	Italy
19	Istituto Nazionale di Fisica Nucleare	INFN	Italy
20	Universita degli Istudi di Padova	UNIPD[1]	Italy
21	Consorcio para la construccion, equipamiento y explotacion de la sede espanola de la fuente Europea de neutrones por espalacion	ESSB	Spain
22	Ghent University	GU[4]	Belgium
23	Akademia Górniczo-Hutnicza University of Krakow	AGH[4]	Poland

[1] Affiliated Partner
[2] Associated Institute
[3] International European Interest Organisation
[4] Associate Partner

ESS neutrino Super Beam plus

Co-funded by the European Union

Collaboration annual meeting – Milos 2025

AGH
UNIVERSITEIT GENT
ESS bilbao
CERN
Luleå University of Technology
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Université de Strasbourg
ess
ROMA TRE UNIVERSITÀ DEGLI STUDI
Università degli Studi di Padova
ARISTOTLE UNIVERSITY OF THESSALONIKI
UPPSALA UNIVERSITET
LUNDS UNIVERSITET
KTH VETENSKAP OCH KONST
HELLENIC OPEN UNIVERSITY
名古屋大学 Nagoya University
IPHC Institut Pluridisciplinaire Hubert Curien Strasbourg
INFN
cnrs

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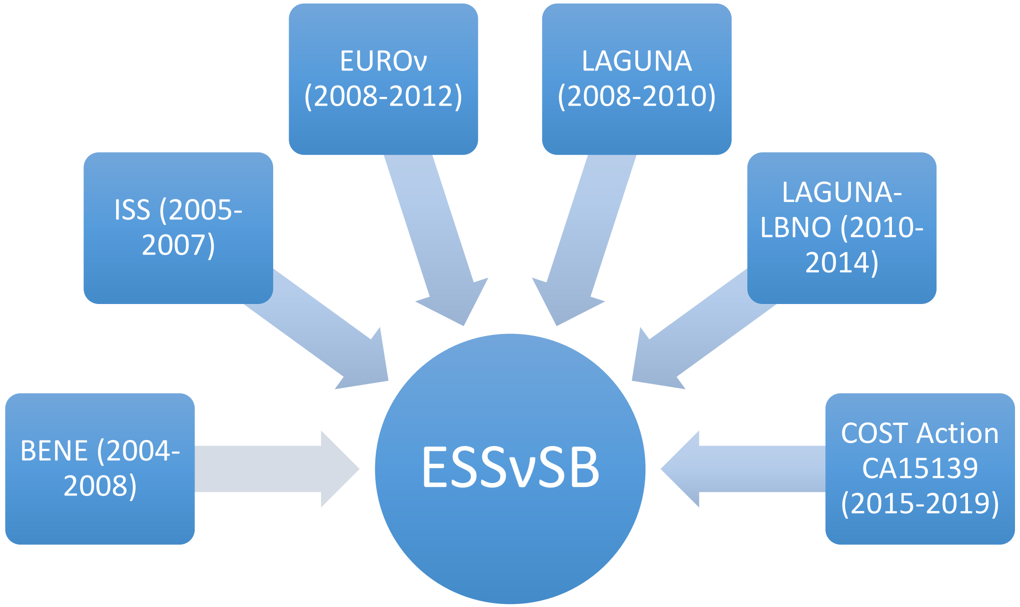
ESSnuSB Design Study Programme

ESS neutrino Super Beam plus

A H2020 EU Design Study (Call INFRADEV-01-2017)

- **Title of Proposal**: *Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator*
- **Duration: 4 years**
- **Total cost: 4.7 M€**
- **Requested budget: 3 M€**
- **15 participating institutes from 11 European countries including CERN and ESS**
- **6 Work Packages**
- **Approved end of August 2017**



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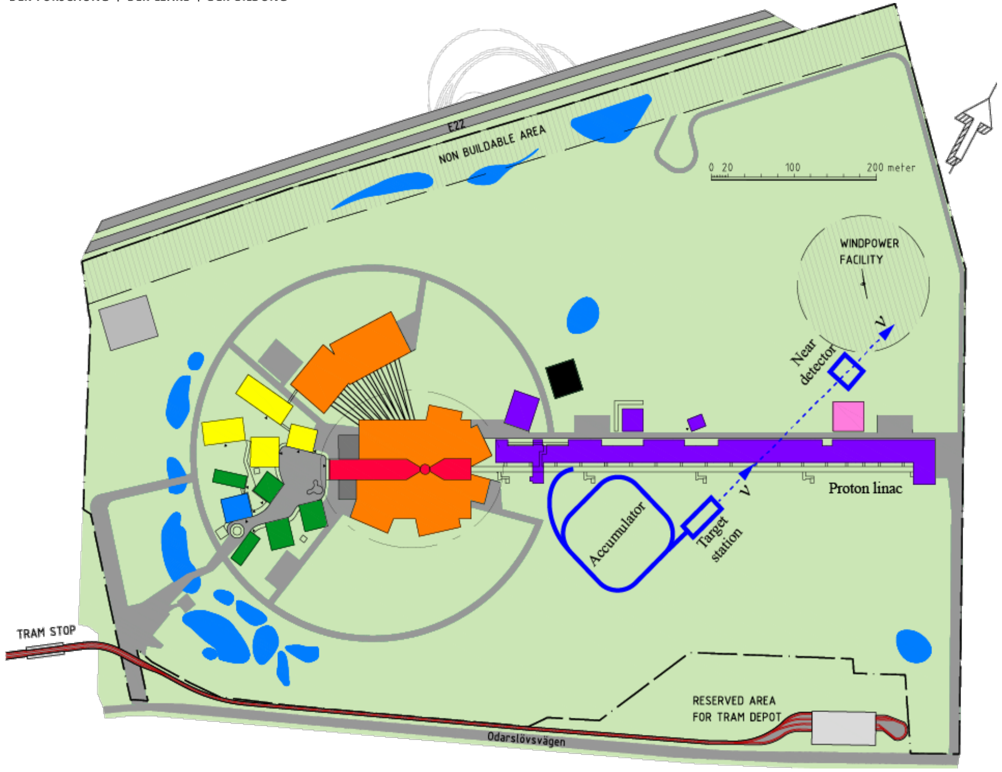
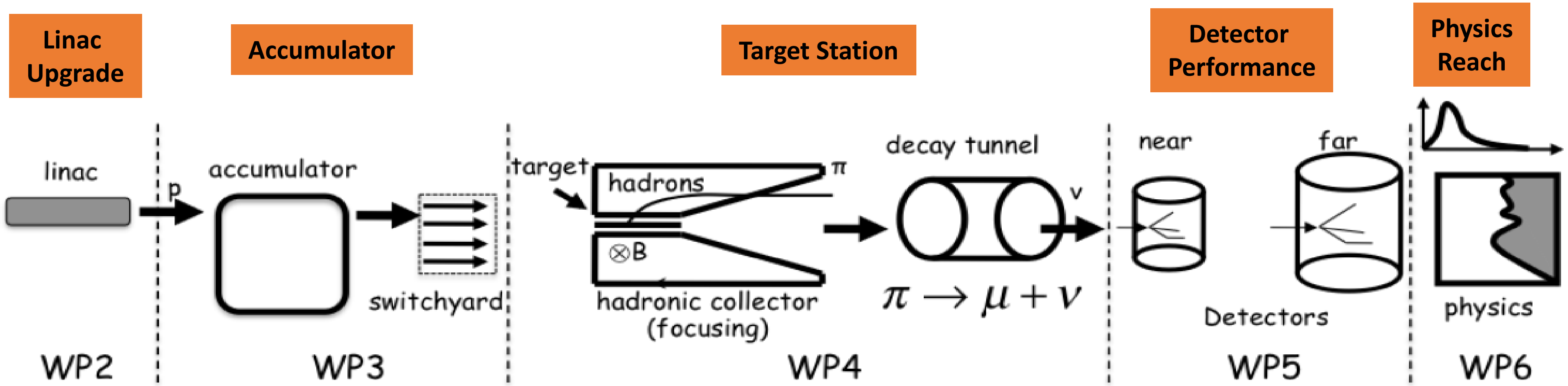


- It will benefit from the powerful proton beam of the ESS LINAC, of ~ 5 MW power and 2 GeV kinetic energy, to produce intense neutrino beam.
- Aims at searching and measuring, with precision, for CP-violation in the lepton sector, at 5σ significance level in more than 70% of the lepton Dirac CP violating phase range, by setting the neutrino source-to-detector distance at the **second oscillation maximum.**
- The far detector will be located ~ 1.2 km below the surface of the earth in the Zinkgruvan mine - Sweden, at ~ 360 km from Lund (ESS).



A schematic overview of the main work packages (WP) within the ESSvSB project

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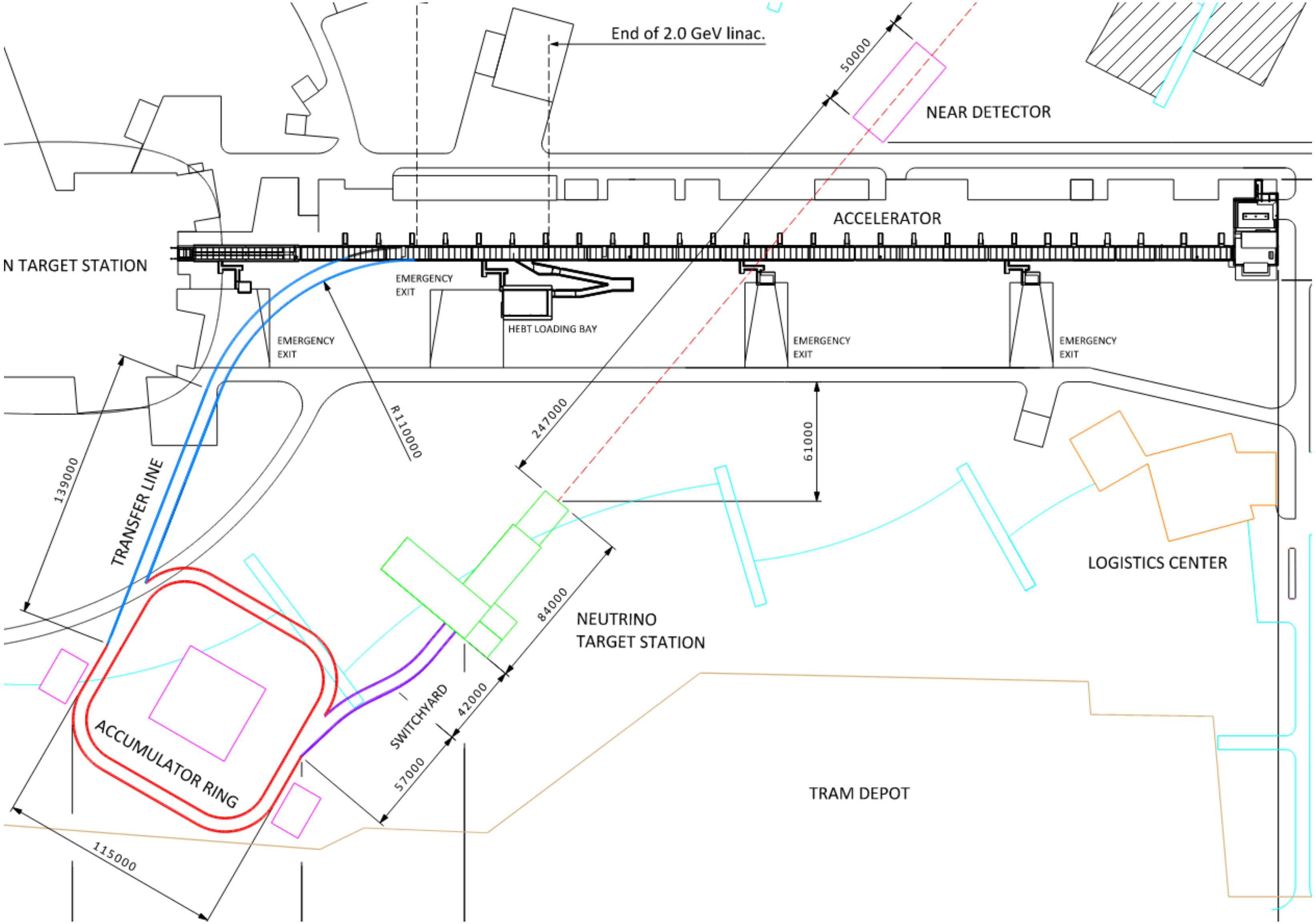
ESS neutrino Super Beam plus

ESS upgrades to host the neutrino experiment



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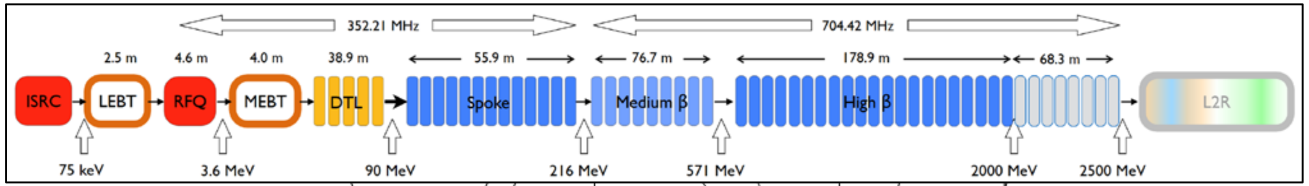
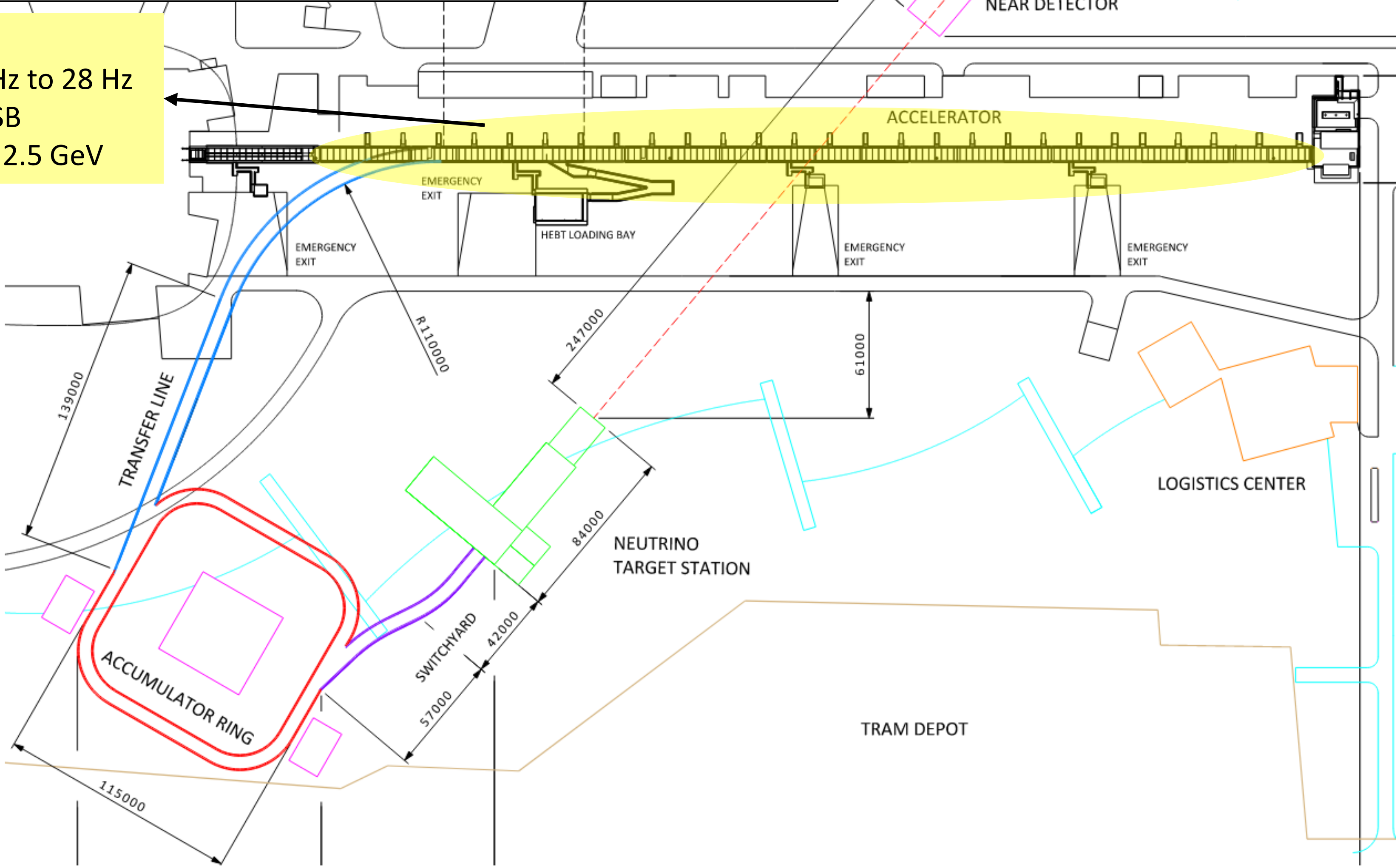


Upgrade of the accelerator
Increase pulse frequency 14 Hz to 28 Hz
Use H^- instead of p for ESSnuSB
Increase $E_{kinetic}$ from 2 GeV to 2.5 GeV



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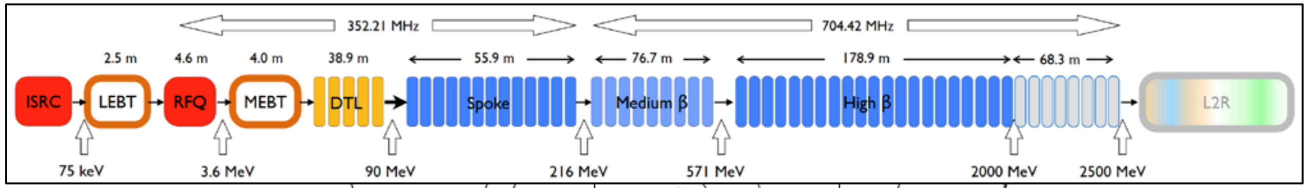

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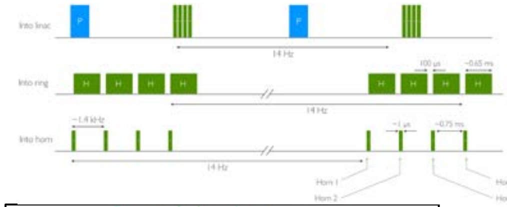
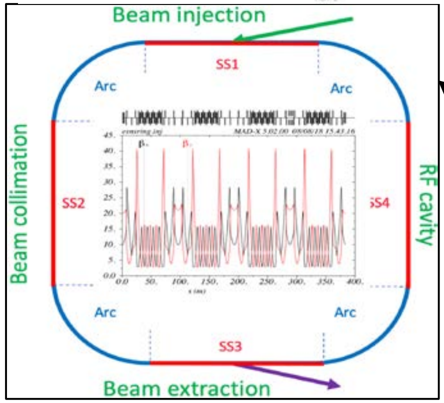
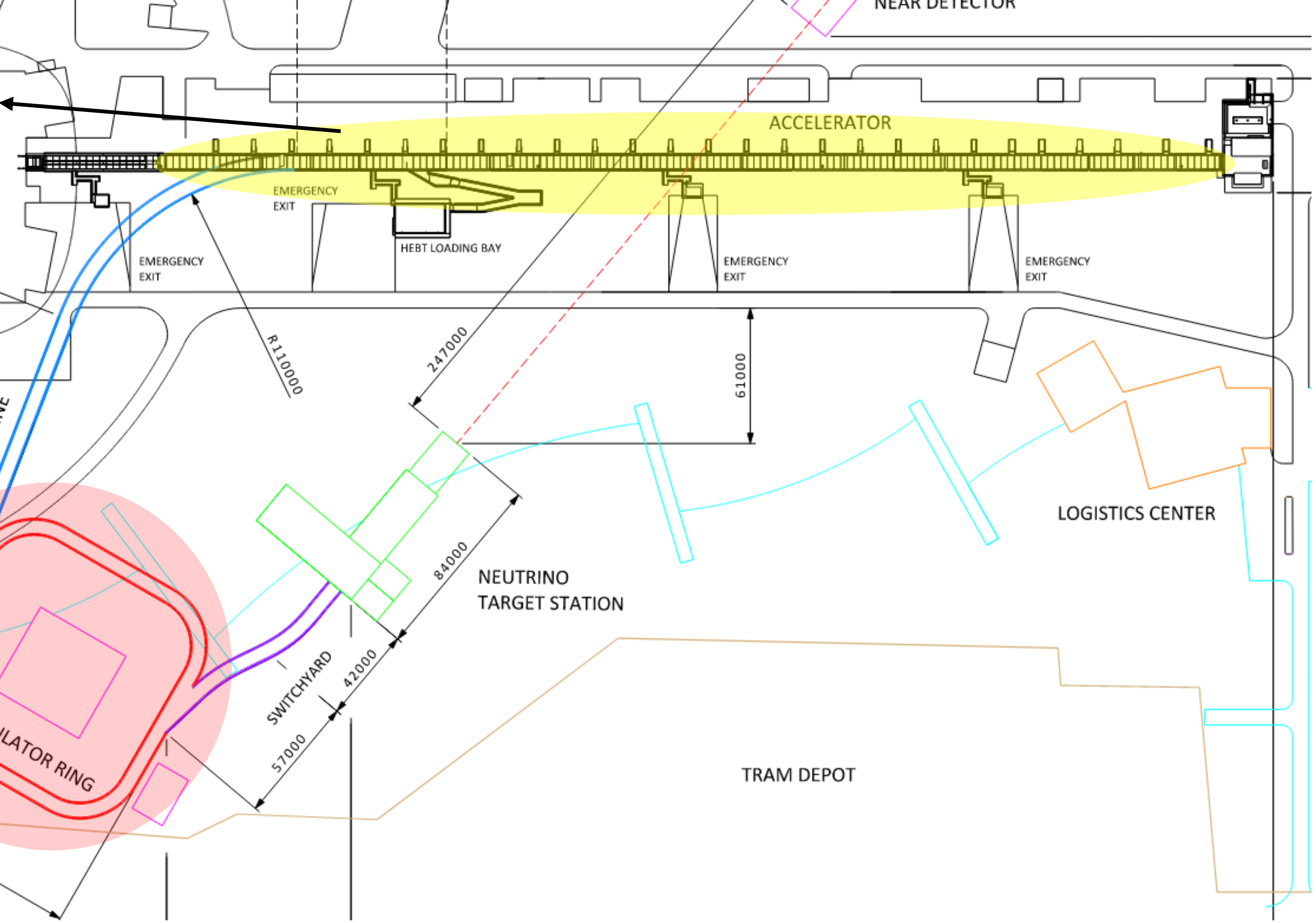
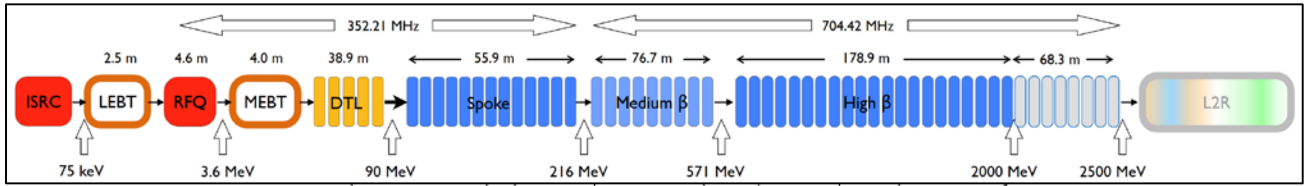


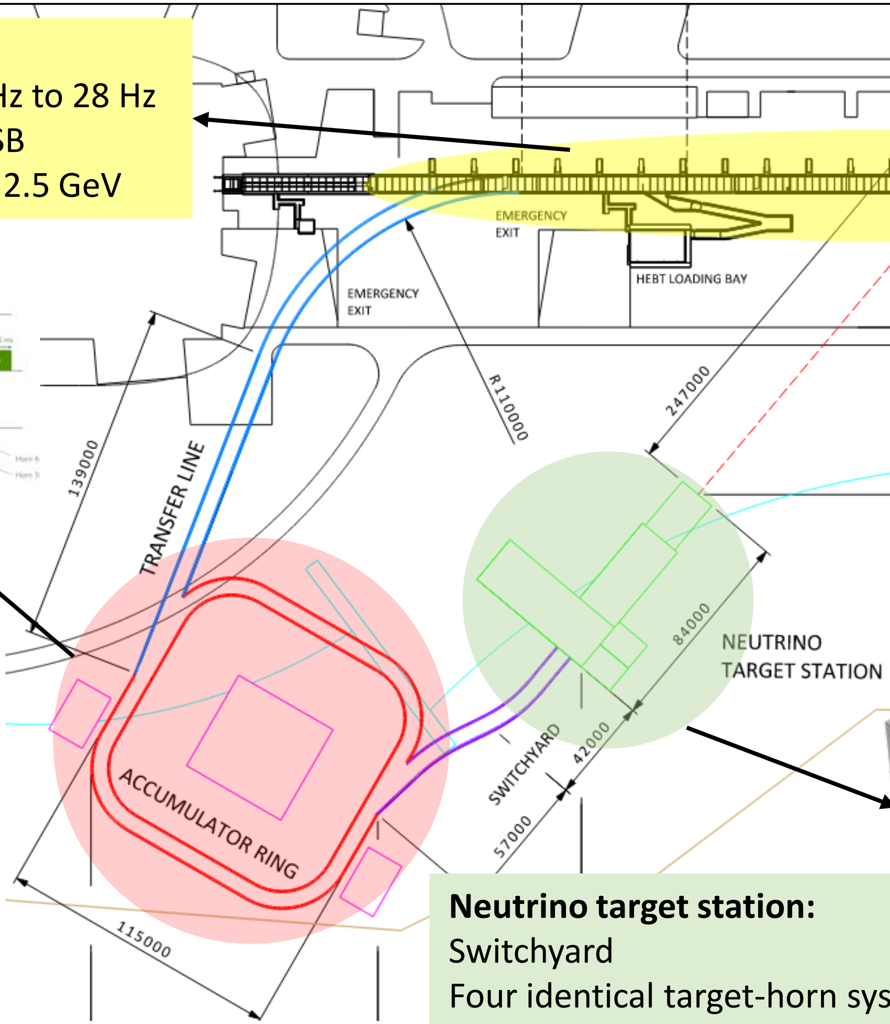




Build an accumulator ring
Compress ESS pulse length from 2.86 ms to 4x 1.2 µs

ESS upgrades to host the neutrino experiment





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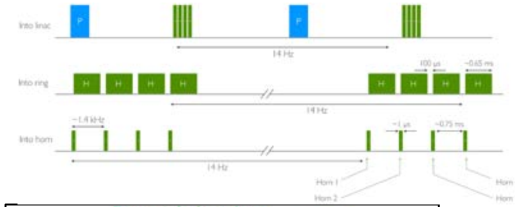

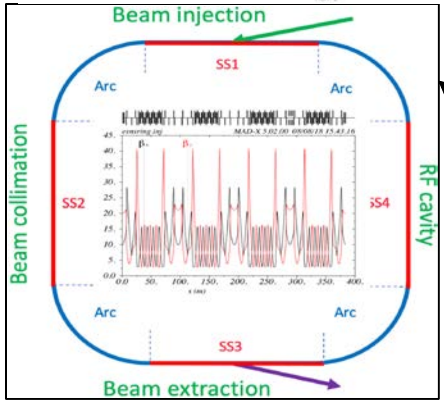

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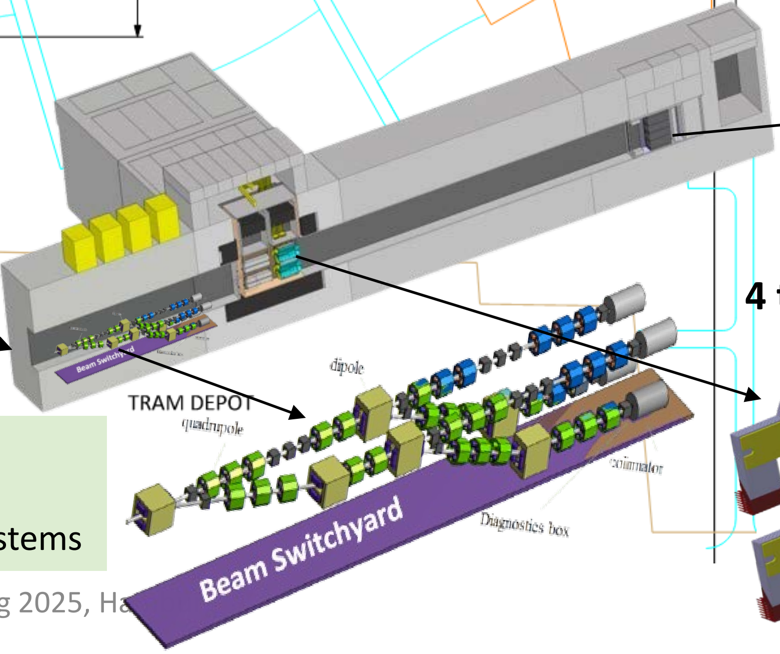
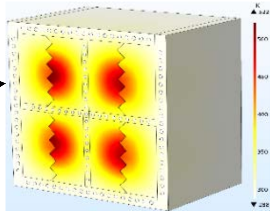
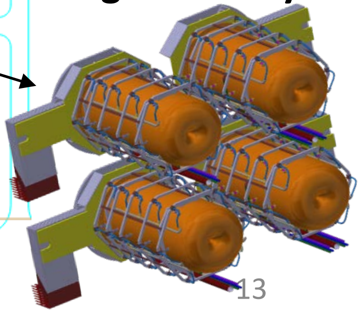
Neutrino target station:
Switchyard
Four identical target-horn systems



Beam dump



4 target-horn systems



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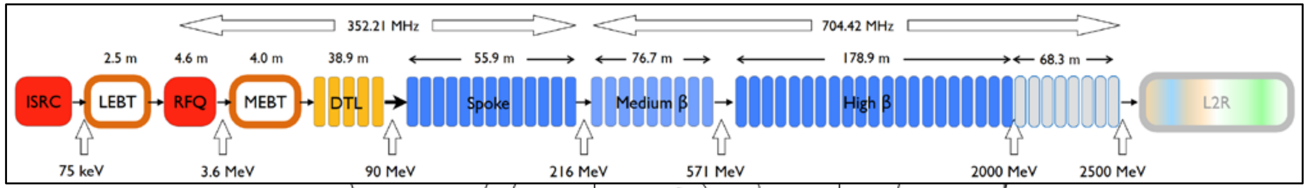

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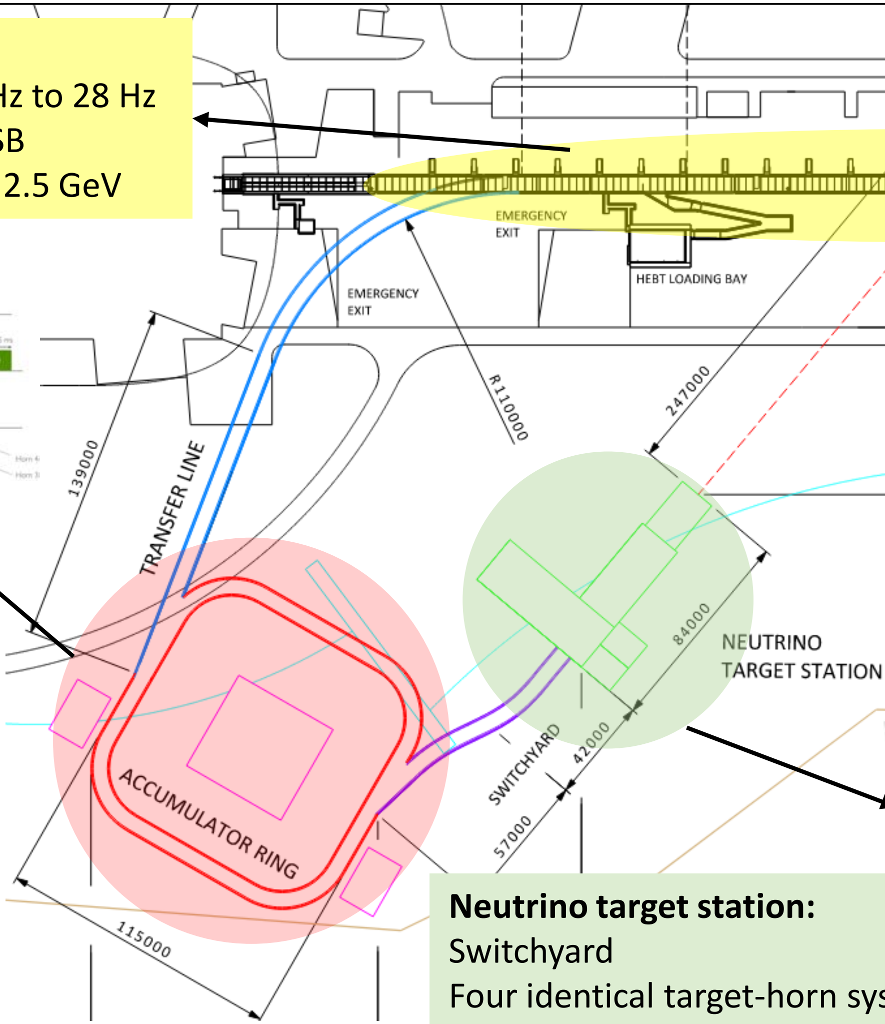
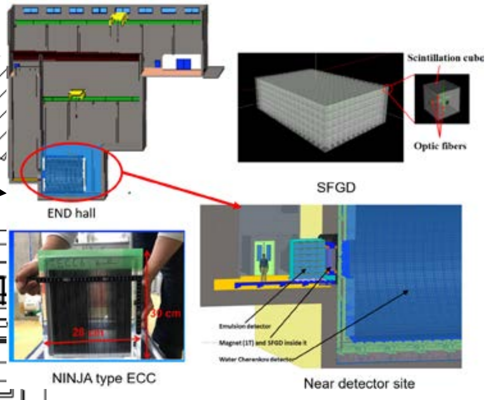




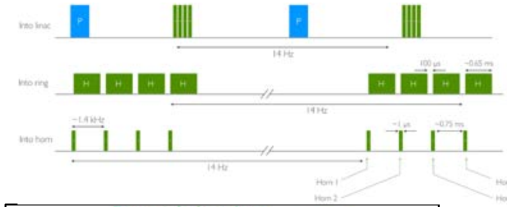
Near detector:

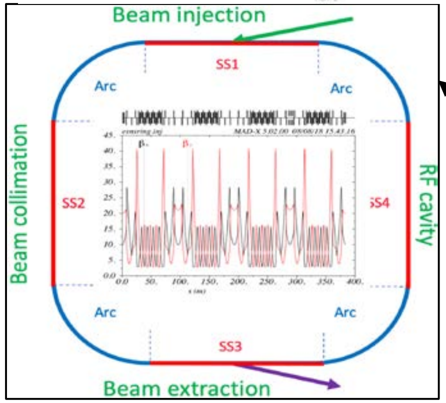
Water Cherenkov detector

Fine grained scintillator

Emulsion detector

Pulsing scheme





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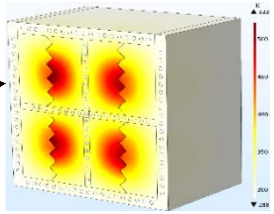
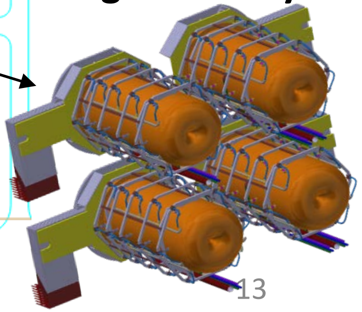
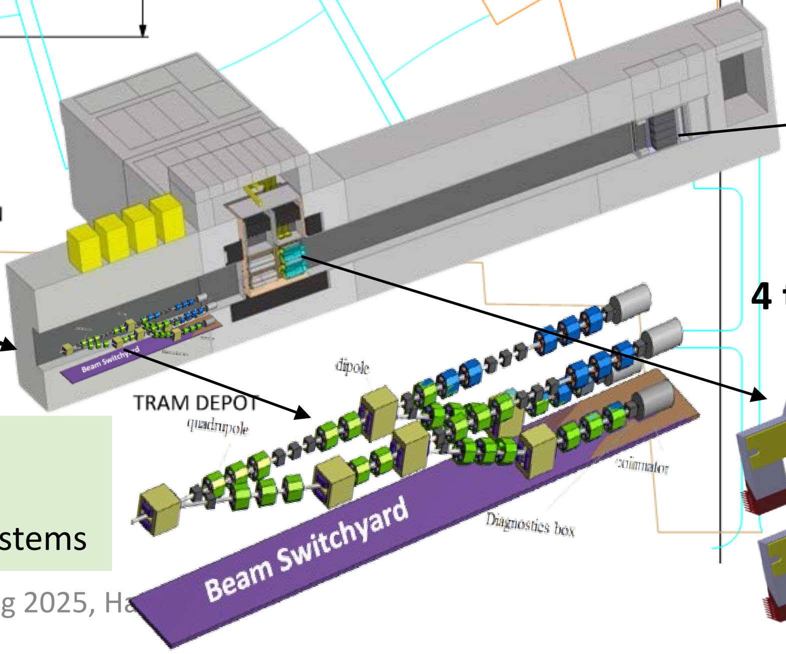
Beam dump



4 target-horn systems



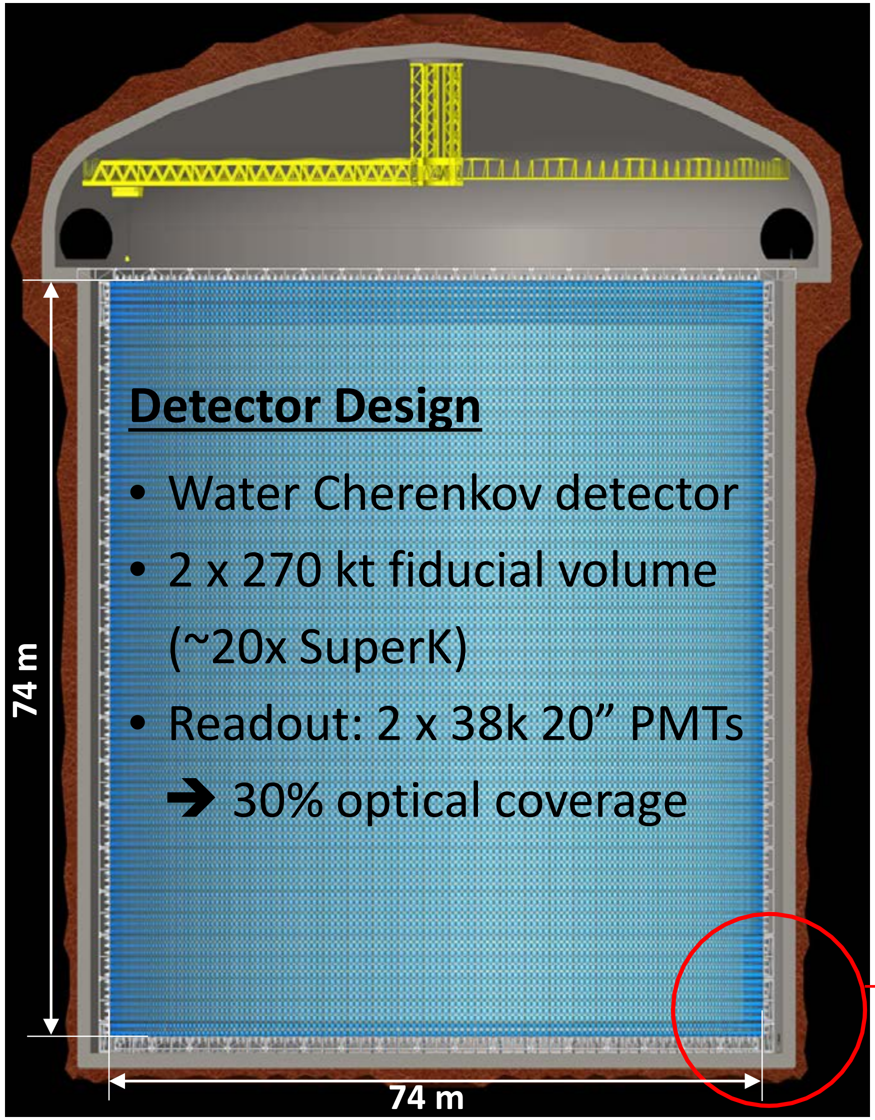


Neutrino target station:

Switchyard

Four identical target-horn systems

ESSnuSB Far Detector



Detector Design

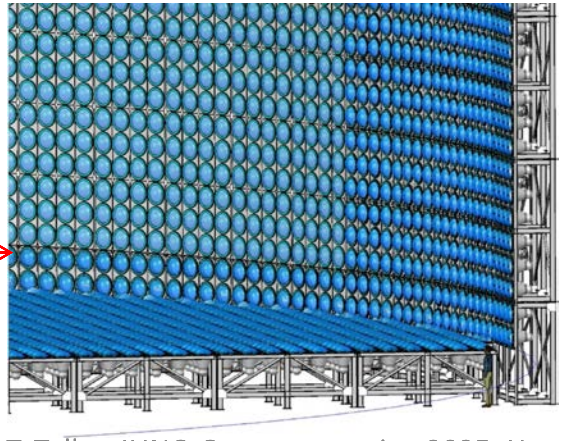
- Water Cherenkov detector
- 2 x 270 kt fiducial volume (~20x SuperK)
- Readout: 2 x 38k 20" PMTs
  ➔ 30% optical coverage

Detector Specifications

- Baseline 360 km
- Detector diameter 74.0 m (Internal)
- Detector height 74.0 m (Internal)
- Depth (w.r.t.) ground level > 1000 m

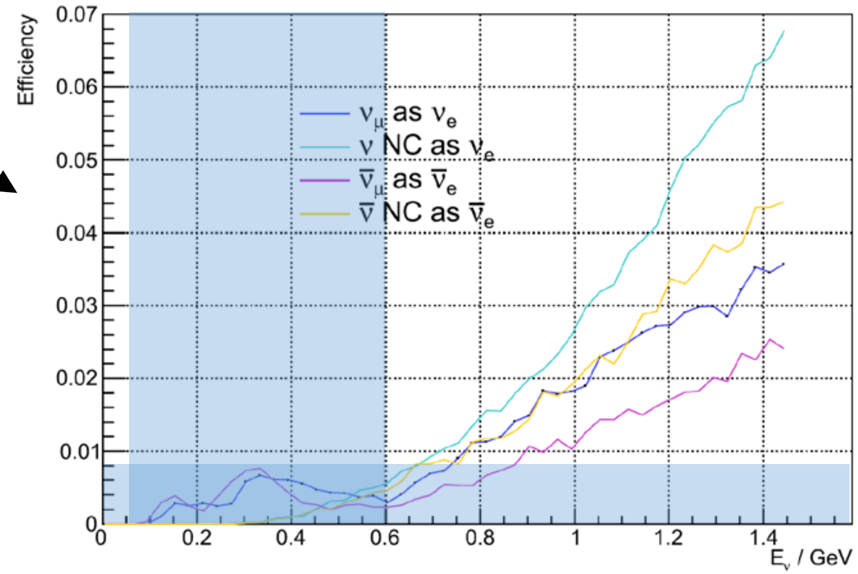
Detector Performance

- Detector efficiency for correctly identifying neutrinos > 85%.
- Flavour misidentification probability < 1%.



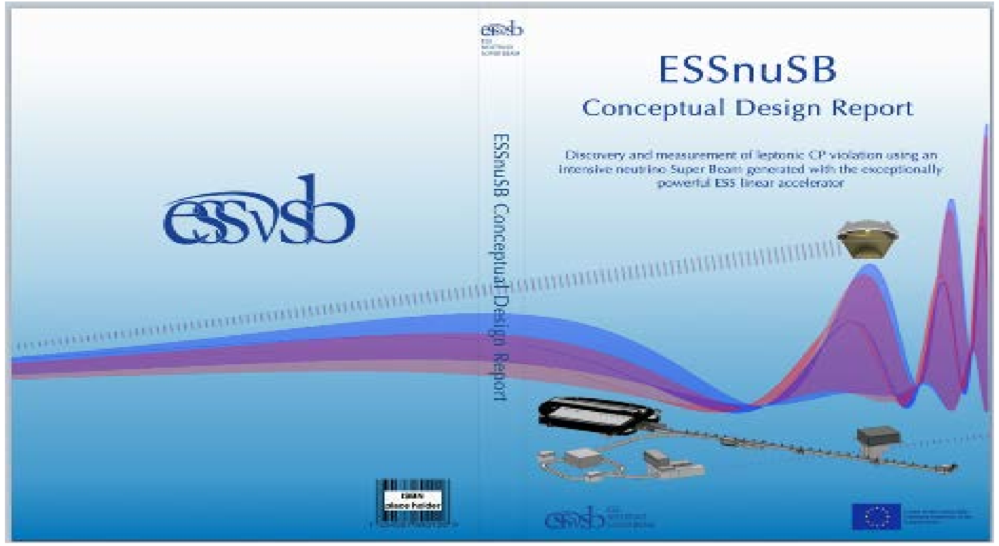
ESSnuSB Particle selection efficiency

fiducial cut



 [Eur. Phys. J. Spec. Top. 231, (2022) 3779–3955]

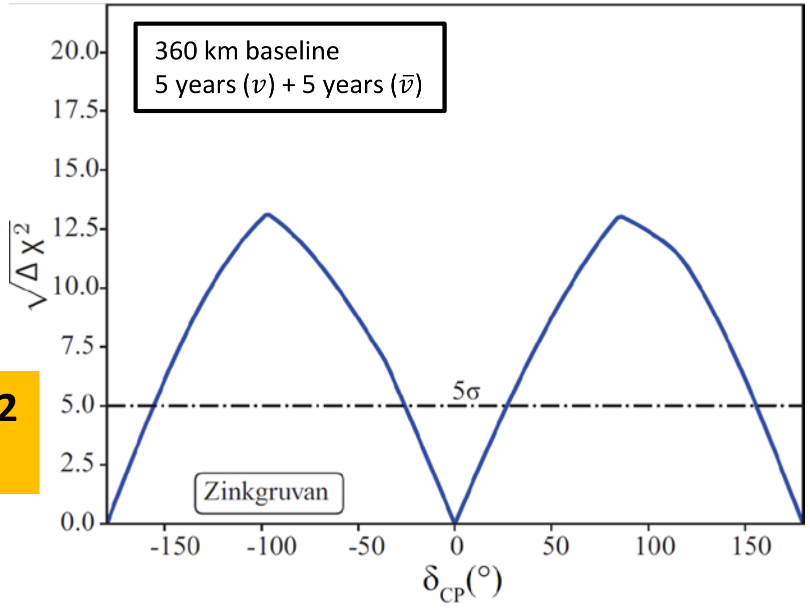
ESSnuSB physics reach



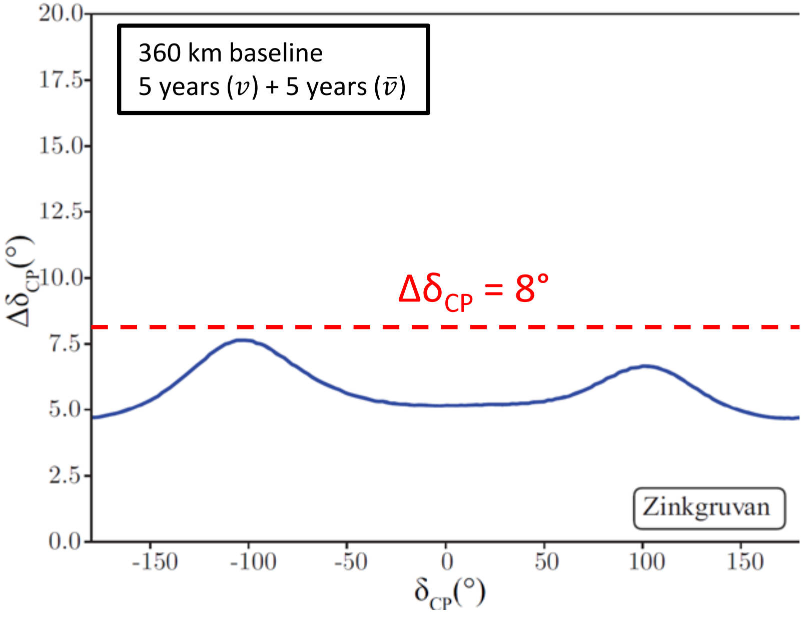
[Eur. Phys. J. ST. 231 (21), (2022) 3779]

https://arxiv.org/abs/2203.08803

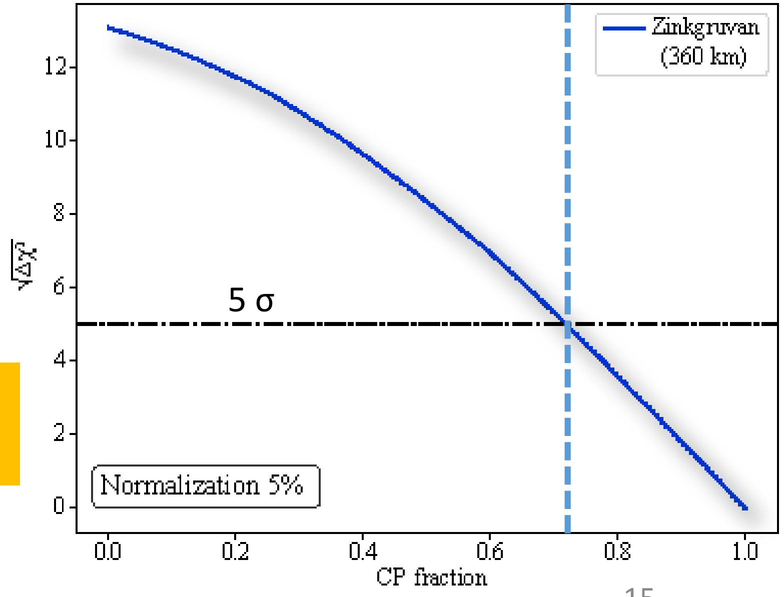
includes cost estimate



Sensitivity for $\delta_{CP} = \pm \pi/2$ ~ 12 σ



$\Delta\delta_{CP} < 8°$ for all δ_{CP} values



Covers 72% of δ_{CP} values in ~ 10 years (@ 5 σ C.L.)

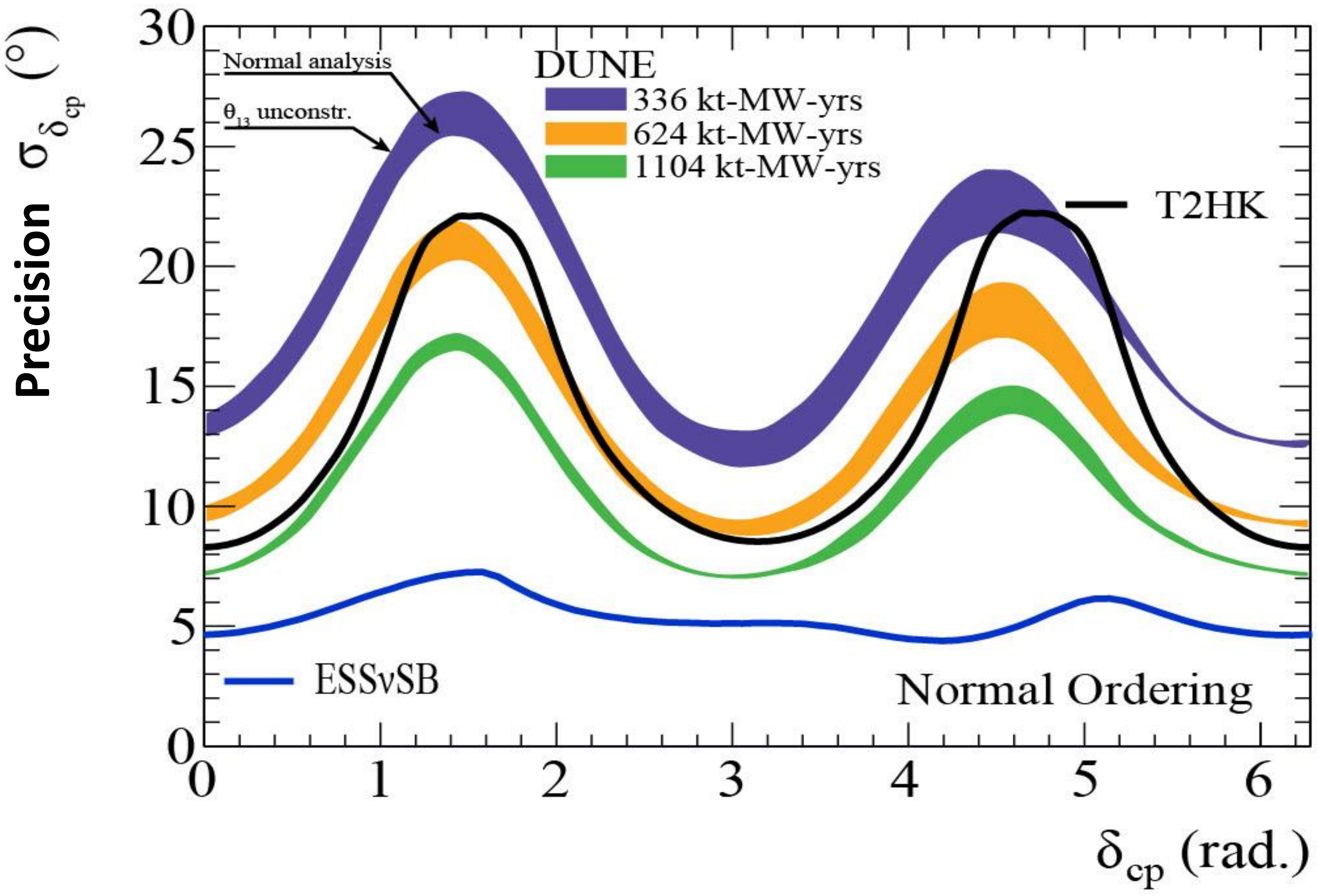
ESSnuSB performance comparison with under construction Experiments

Precision in δ_{CP}

ESSnuSB 10 years
https://arxiv.org/abs/2206.01208 p. 205

DUNE 10 years, **orange** curve
https://arxiv.org/abs/2002.03005 p. 174

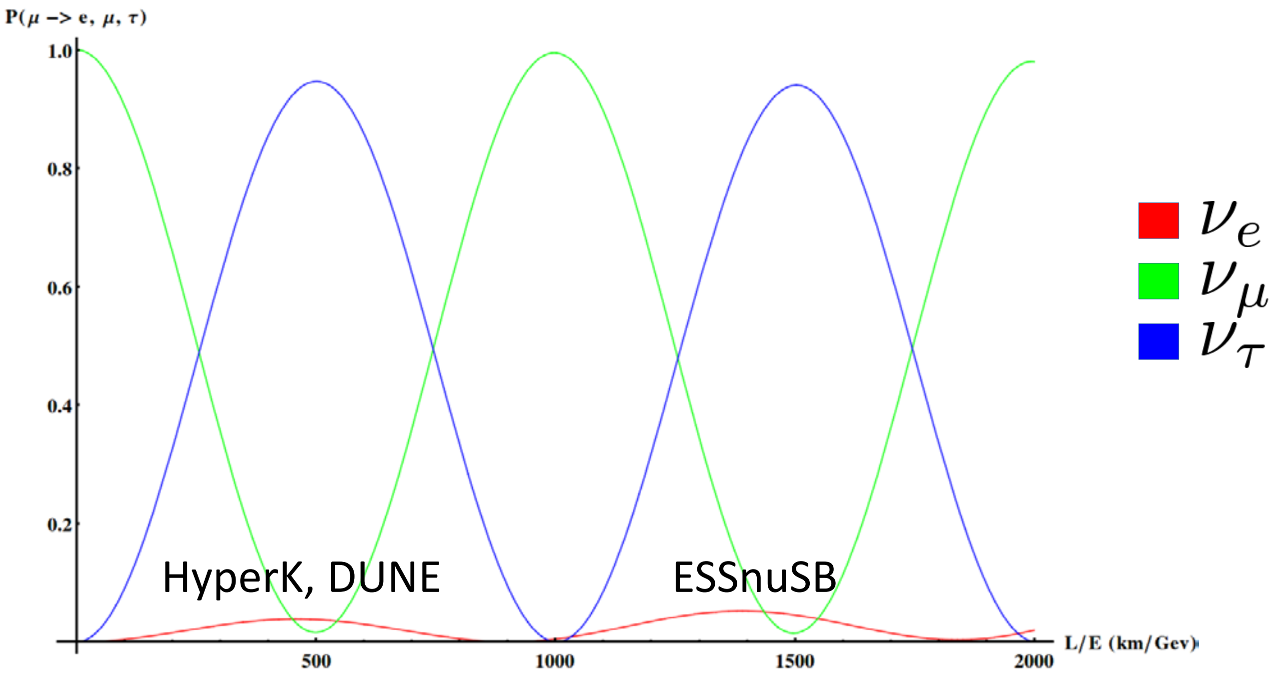
HyperKamiokande 10 years
https://arxiv.org/abs/1611.06118 p. 60



ESSnuSB

(European Spallation Source neutrino Super Beam)

A proposed second generation long-baseline experiment based in Europe to measure the **CP violation in the lepton sector** at the ***second neutrino oscillation maximum*** with ***precision***



Why measuring lepton CPV precisely?

- The observed CPV in the quark sector is too small to explain the observed matter density in the universe.
- Several leptogenesis models, describing the baryon asymmetry, and flavor models, describing the origin of neutrino flavors, cover a wide range of values for the Dirac CP-violating phase (δ_{CP}).
- Prospective (useful / requested) precision:

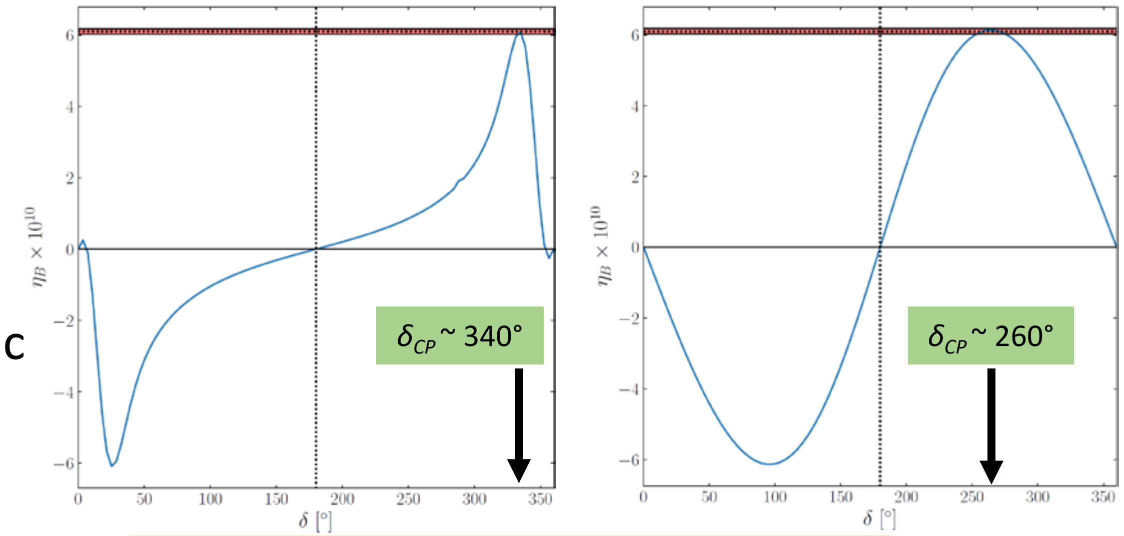
$$\delta(\delta) \leq 12^\circ \text{ at } \delta = 3\pi/2$$

(S.T. Petcov, NPB 2024, IAS, HKUST, Hong Kong 20/02/2024)

➔ **therefore it is essential to measure δ_{CP} with the highest precision in order to confirm or reject these models**

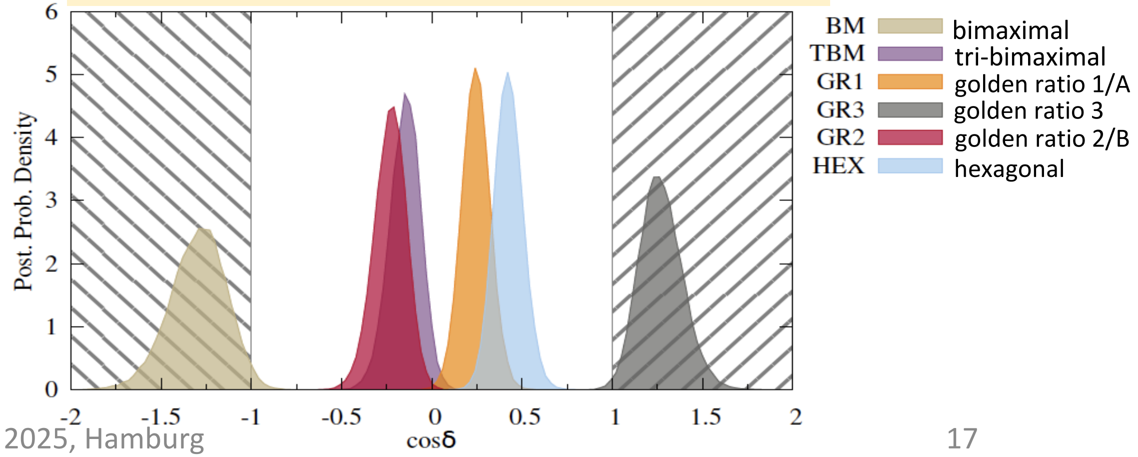
Leptogenesis Theories [K. Moffat et al., arXiv:1809.08251 (2019)]

Low mass flavor regime M_1 (GeV) < 10^9 | **Intermediate mass flavor regime** 10^9 < M_1 (GeV) < 10^{12}



Flavour Theories [P. Ballett *et al.*, JHEP12 (2014) 122]

four different symmetry forms of the neutrino mixing matrix

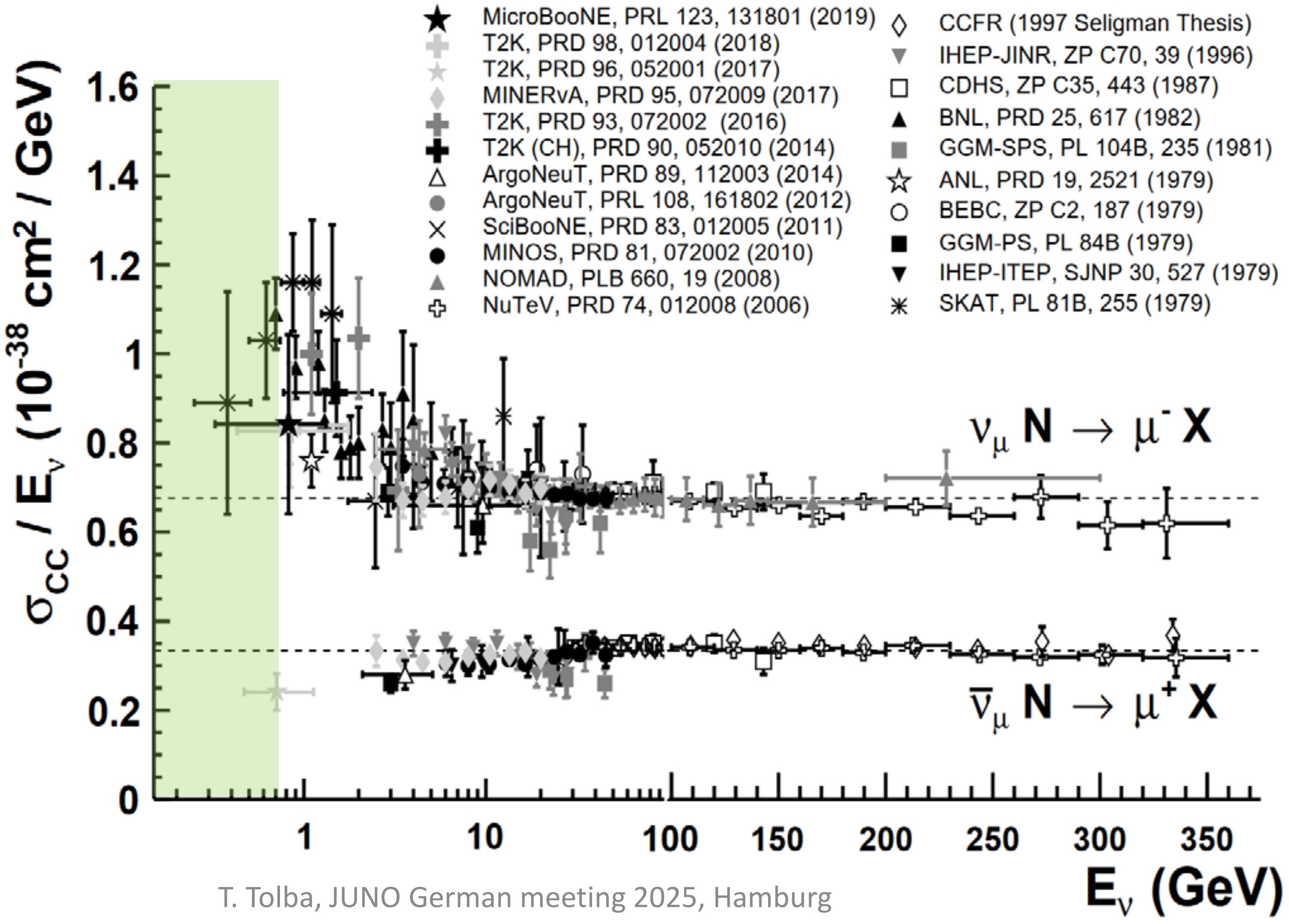


ESSnuSB…systematic uncertainty

The uncertainty in the neutrino-nucleus cross section below 600 MeV is the dominant term of the systematic uncertainty in ESSnuSB.

missing measurements at the ESSnuSB region below 600 MeV

https://pdg.lbl.gov/2022/reviews/rpp2022-rev-nu-cross-sections.pdf



ESSnuSB**plus** Project

(European Spallation Source neutrino Super Beam **plus**)

ESSnuSB**+** aims primarily to measure the neutrino cross sections in the ESSnuSB energy range

APPROVED

Marcos DRACOS
CENTRE NATIONAL DE LA RECHERCHE
SCIENTIFIQUE CNRS
RUE MICHEL ANGE 3
75794 PARIS
FRANCE

3 M€

Started in Jan. 2023 for four years

Subject: **Horizon Europe (HORIZON)**
Call: HORIZON-INFRA-2022-DEV-01
Project: 101094628 — ESSnuSBplus
GAP invitation letter

Dear Applicant,

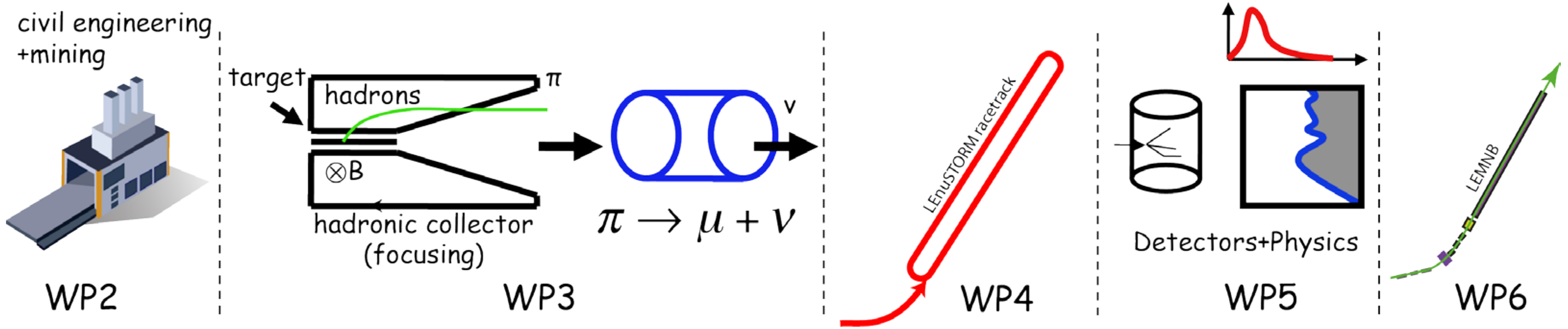
I am writing in connection with your proposal for the above-mentioned call.

Having completed the evaluation, we are pleased to inform you that your proposal has passed this phase and that we would now like to start grant preparation.

Please find enclosed the evaluation summary report (ESR) for your proposal.

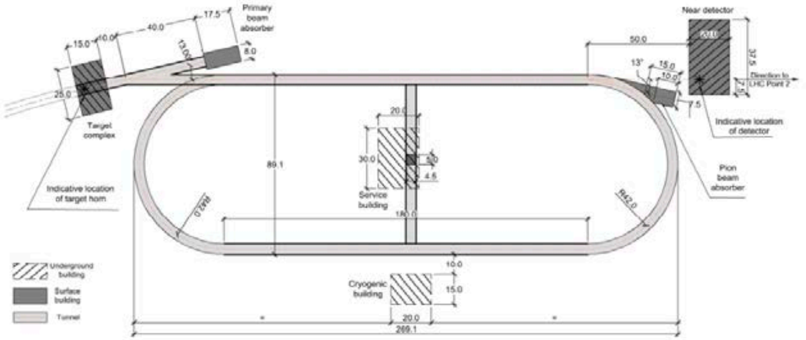
Invitation to grant preparation

ESSnuSBplus (Work-Packages)

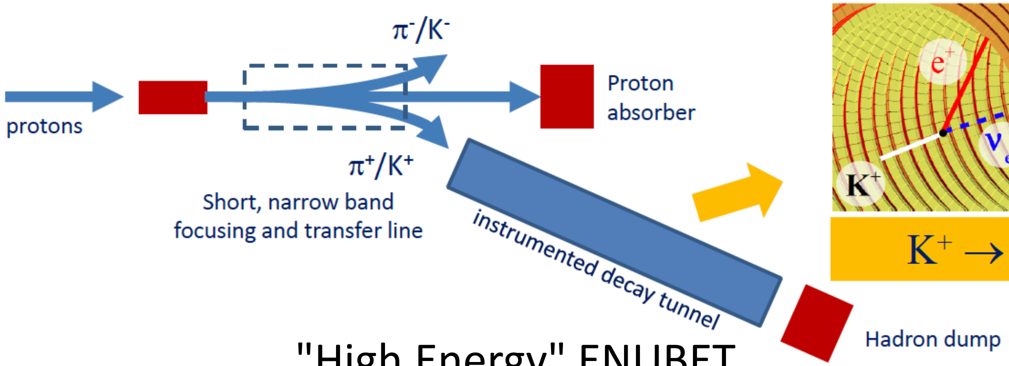


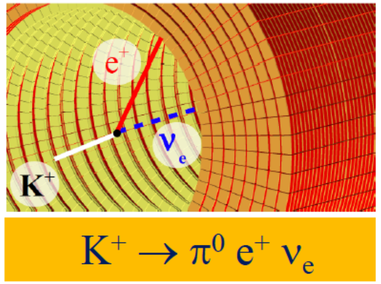
- cross-sections
- sterile neutrinos

- cross-sections



"High Energy" nuSTORM



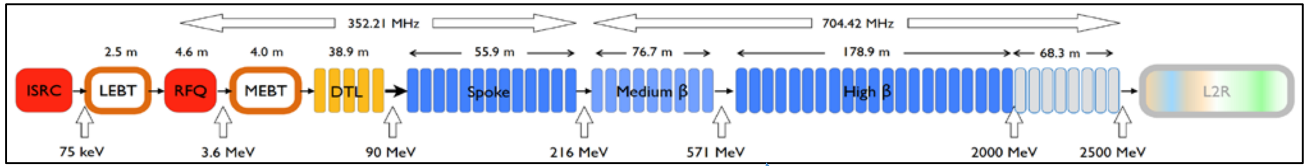


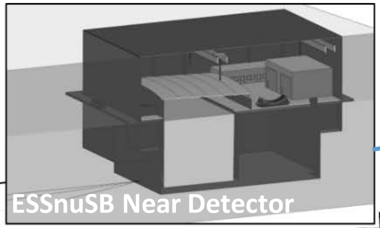
"High Energy" ENUBET

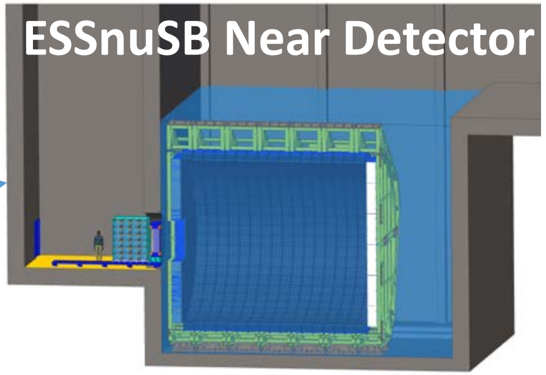
build a "Low Energy" version

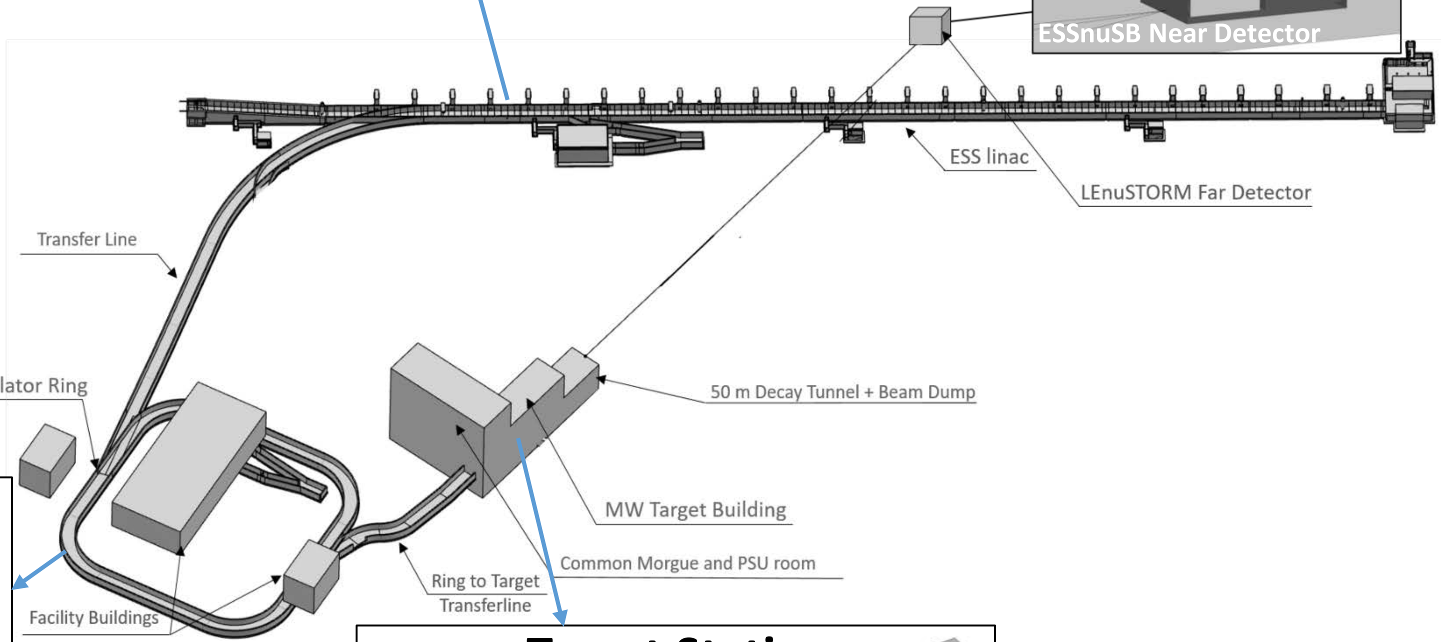
ESS upgrades to host the ESSnuSB+

ESS linac

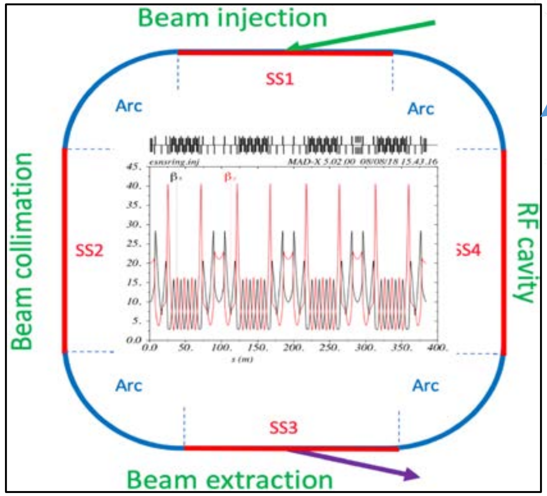




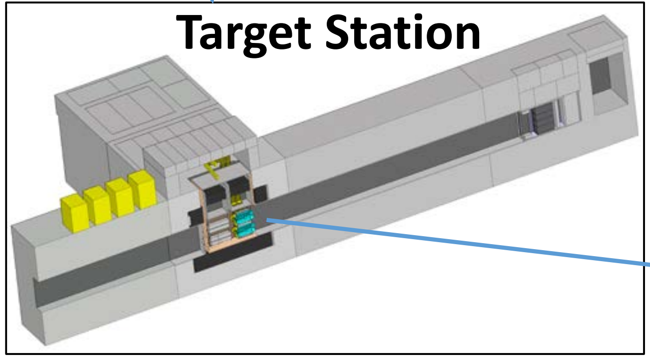


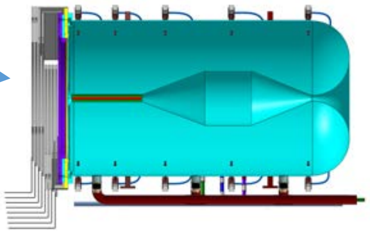


Accumulator Ring



Target Station

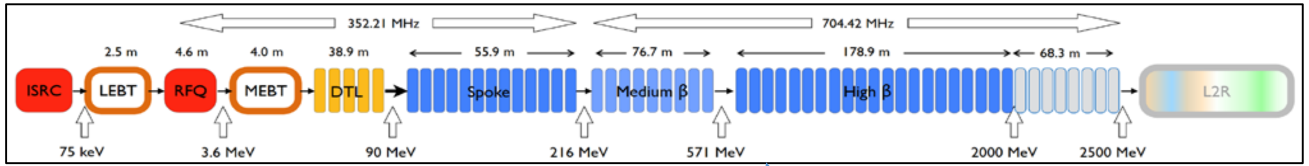




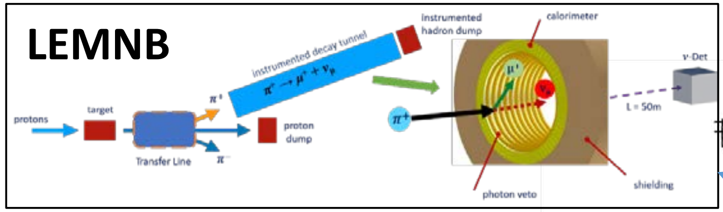
One horn-target system

ESS upgrades to host the ESSnuSB+

ESS linac

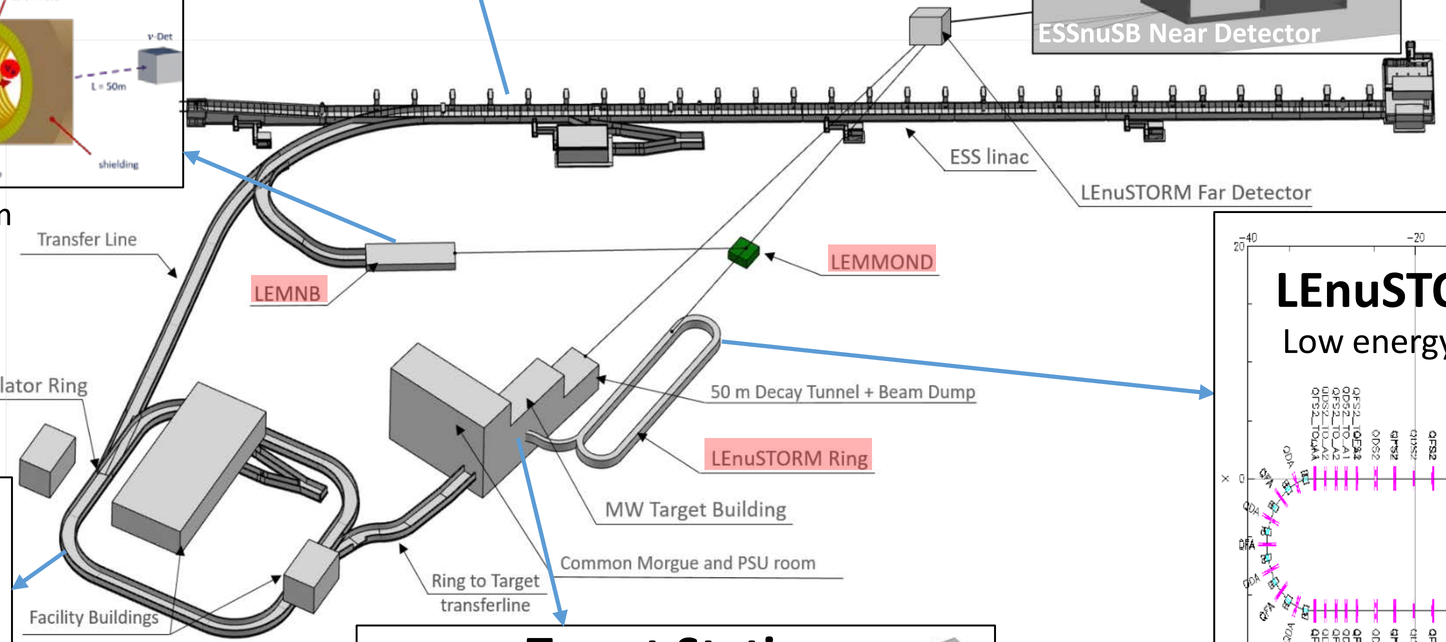


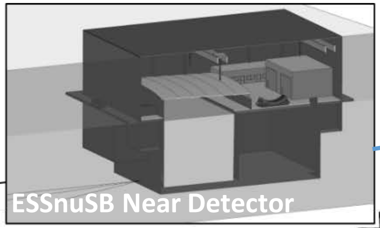
LEMNB

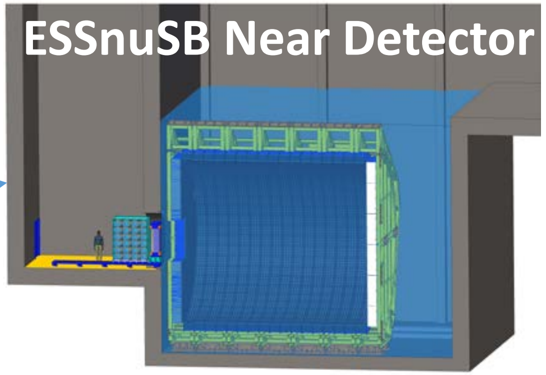


Low Energy Monitored neutrino Beam

$$\pi^{+(-)} \rightarrow \mu^{+(-)} + \overset{(-)}{\nu}_\mu$$

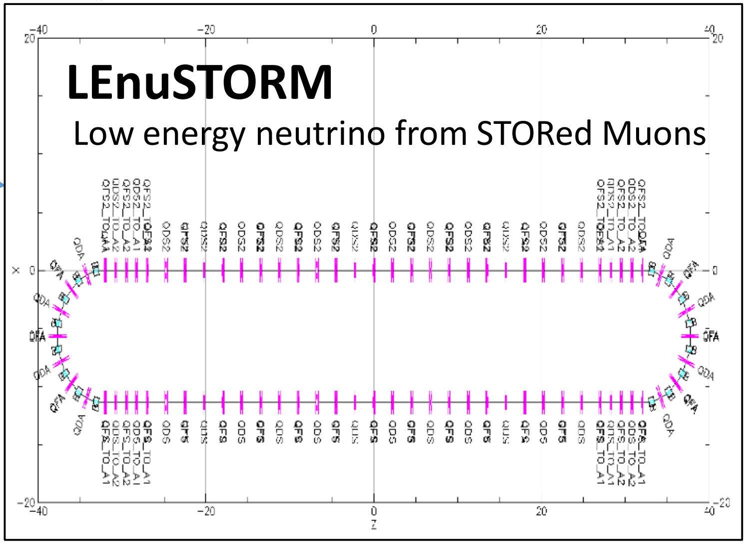






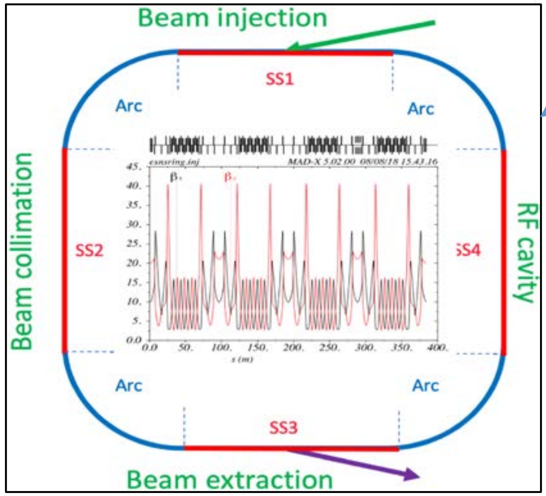
LEnuSTORM

Low energy neutrino from STORed Muons

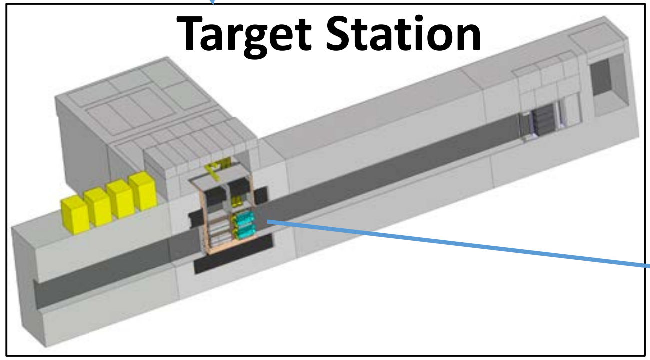


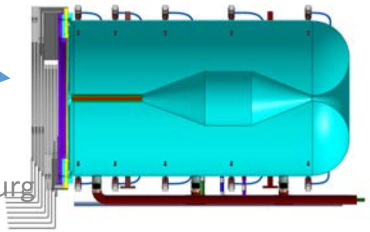
$$\mu^{+(-)} \rightarrow e^{+(-)} + \nu_\mu + \overset{(-)}{\nu}_e$$

Accumulator Ring



Target Station



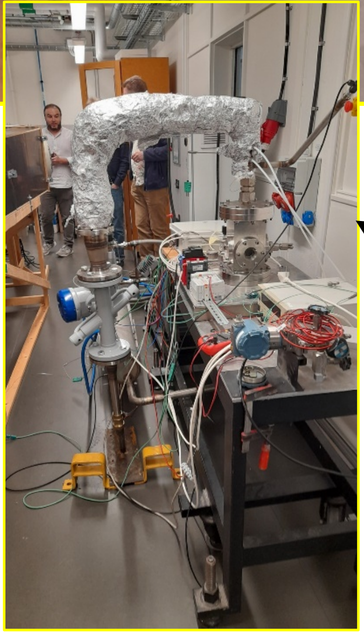


One horn-target system

ESSnuSB Target R&D Test Facility (ETTF)

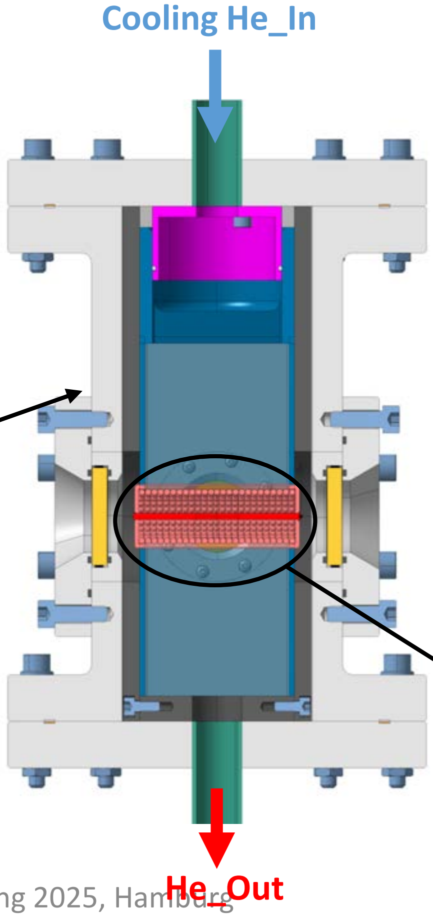
- ESSnuSB adopts a granular target concept of 3 mm titanium spheres in 78 cm Ti Canister, cooled by transverse helium gas.
- A Prototype of 7.8 cm length and a 3 cm diameter will be tested in the ETHEL test facility in ESS.

Mechanical Measurements Lab (MML) @ESS

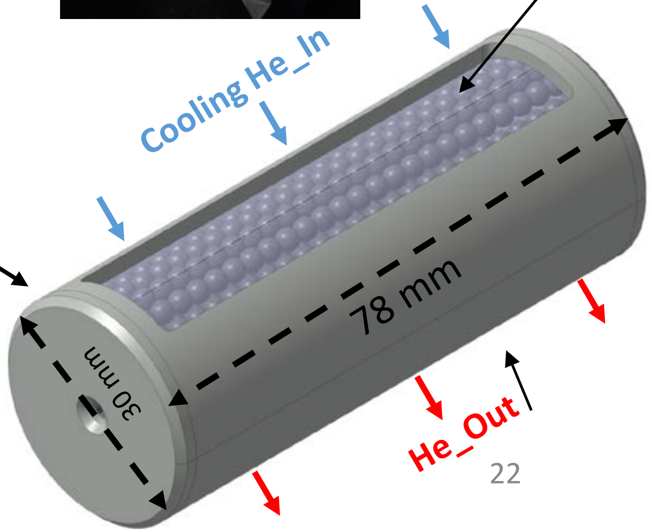


ESS Target Helium Experiments at LTH (ETHEL) @LTH

(https://indico.ess.eu/event/648/attachments/5153/7015/essDocumentDownload_002.pdf)



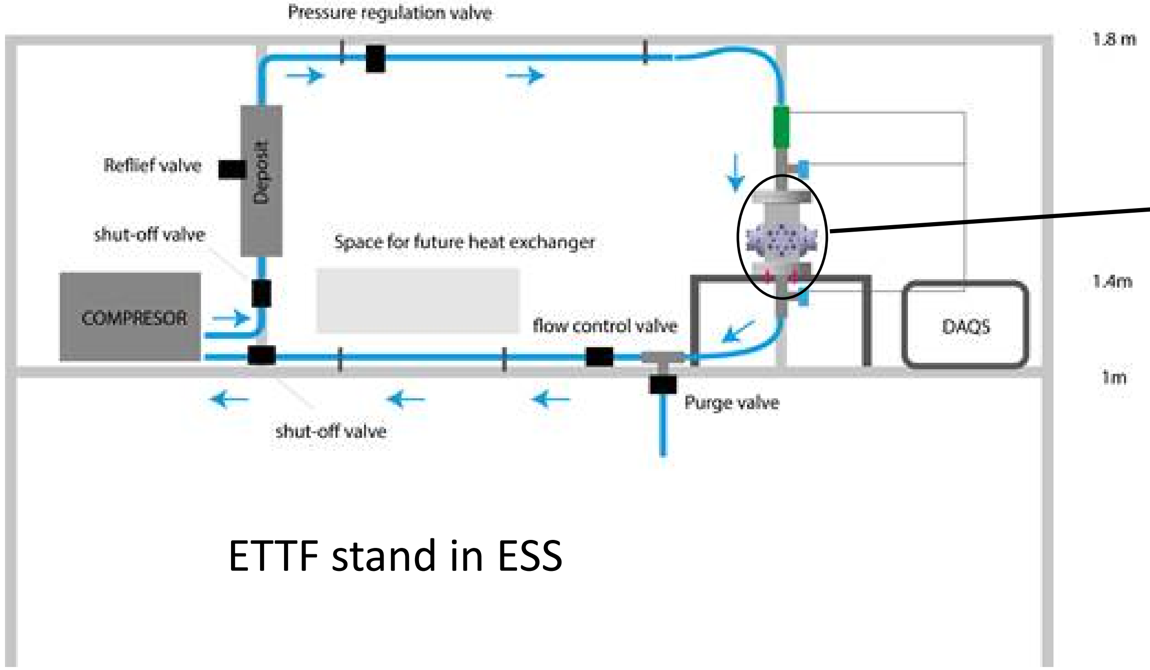
Ti pellets (4000 pellets D_{pellet} = 3 mm)



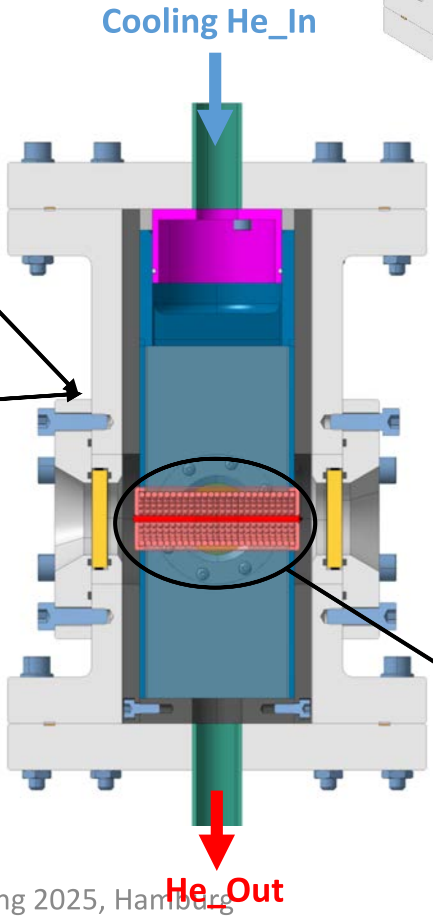
ESSnuSB Target R&D Test Facility (ETTF)

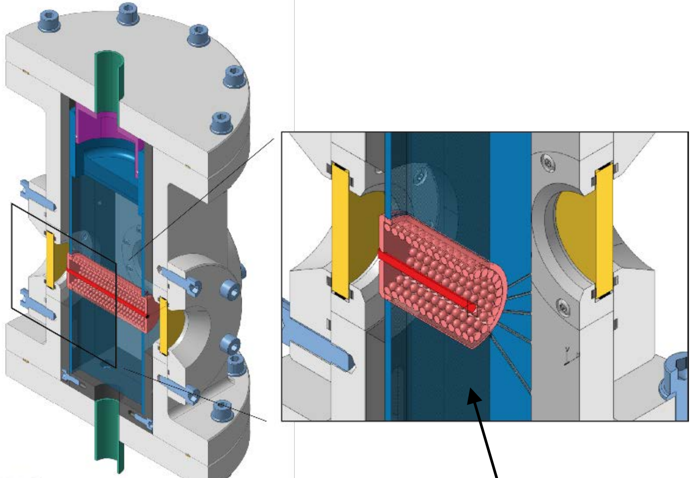
Parameter	Value
Target type	Packed-bed
Target material	Titanium (spheres)
Single sphere	3 mm
Canister radius	12 mm
Canister length	780 mm
Cooling medium	Helium

ETTF test chamber in ESS

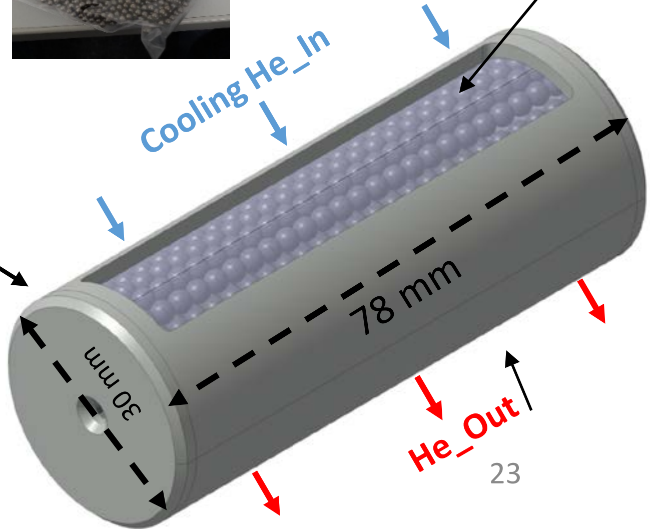


ETTF stand in ESS

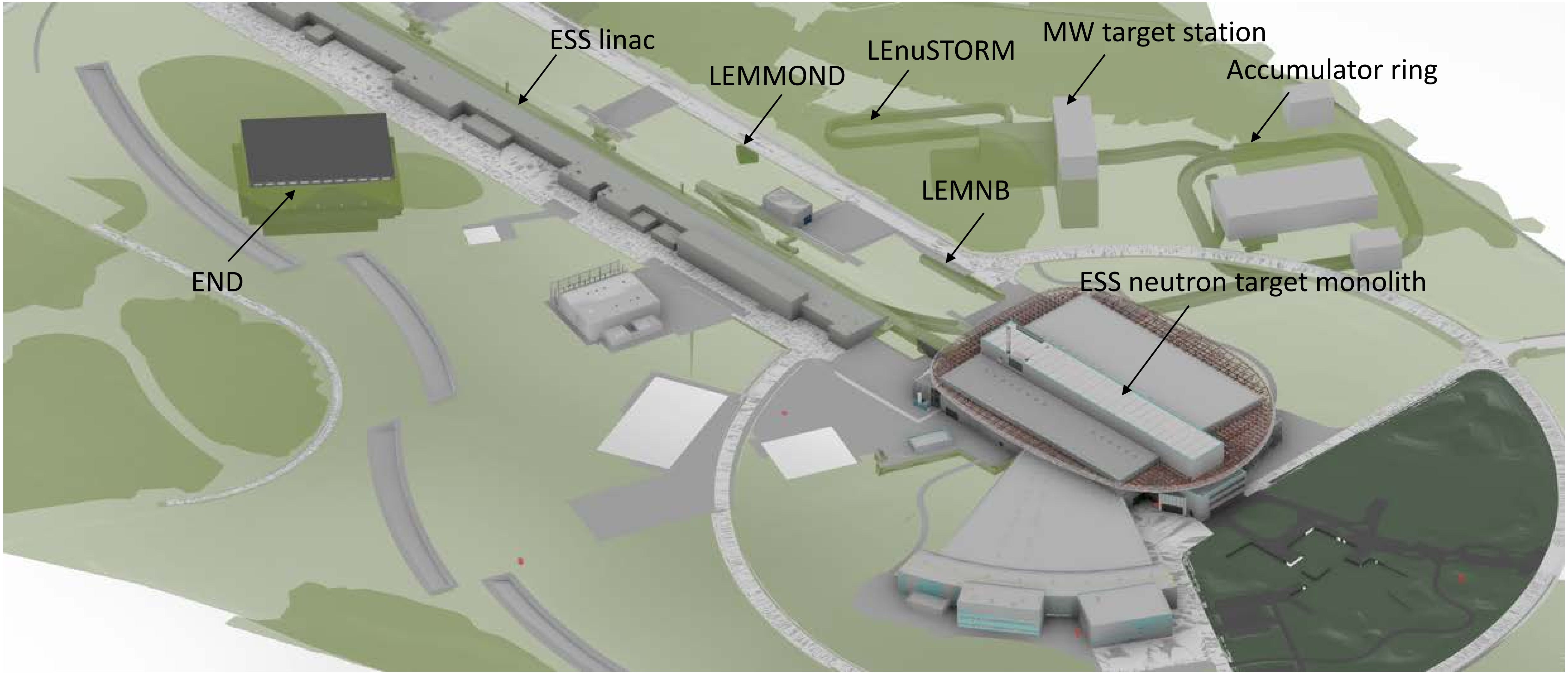




Ti pellets
(4000 pellets
D_{pellet} = 3 mm)



ESS Upgrades to Host the **ESSnuSB+**



Staged Implementation

Stage 1
LEMNB

- Proton beam from ESS linac, up to 2.86 ms pulses, long-pulses up to 10^{14} protons/pulse,
- ~300kW target station, pion capture using conventional magnets, instrumented decay tunnel
- Beam to near detector LEMMOND at ~40-50 m from the target

Stage 2
LENUSTORM

- H^- source, and transfer line to accumulator
- Accumulator ring, 1.25 MW target station, horn for pion capture, transfer line and injection to LEnuSTORM ring
- LENUSTORM ring, beam to near detector LEMMOND at ~10-15 m from ring, and to END at 290 m from target

Stage 3
ESSnuSB CPV LBL

- H^- source, and transfer line to accumulator
- Accumulator ring, 5MW target station, horn for pion capture
- Decay tunnel, beam to END at 290 m from target and FD

ESSnuSB project time evolution

ϑ_{13} measurement

Nobel prize:
T. Kajita &
A. McDonald

2015

2008-2012
EUROν Design Study (FP7)

2012
inception of the ESSnuSB project

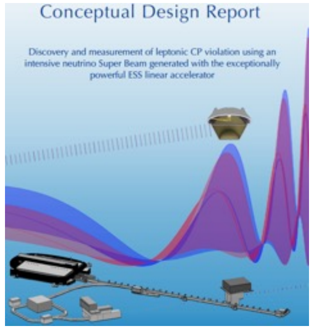
Nucl. Phys. B 885 (2014) 127

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

2016-2020
COST Action EuroNuNet

ESS NEUTRINO SUPER BEAM

2018-2022
ESSνSB Design Study, CDR (EU-H2020)



ESSνSB CDR

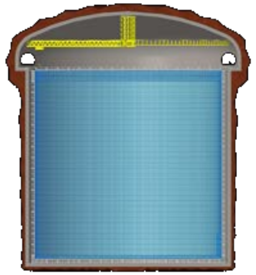
ESFRI

ESS neutrino Super Beam plus

2023-2026
ESSνSB+ Design Study, CDR (EU-HE) and preparatory phase

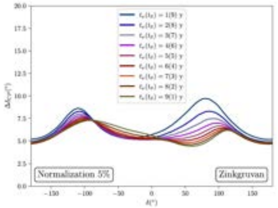
EUROPEAN SPALLATION SOURCE

2027-2030
TDR Phase, International Agreement

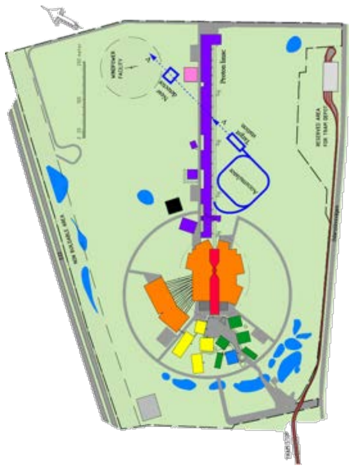


2030-2040
Construction in stages, including commissioning

physics

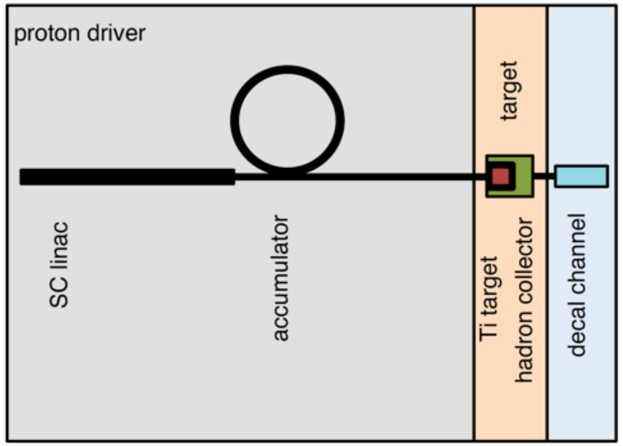


Data Taking (stages)



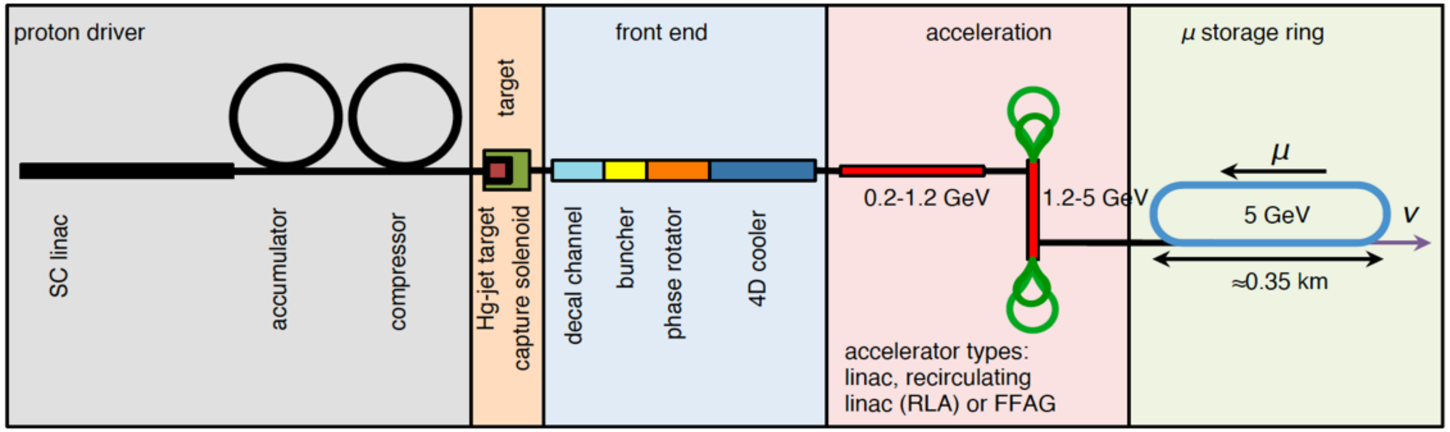
ESSnuSB synergies with other (muon) projects

Super Beam

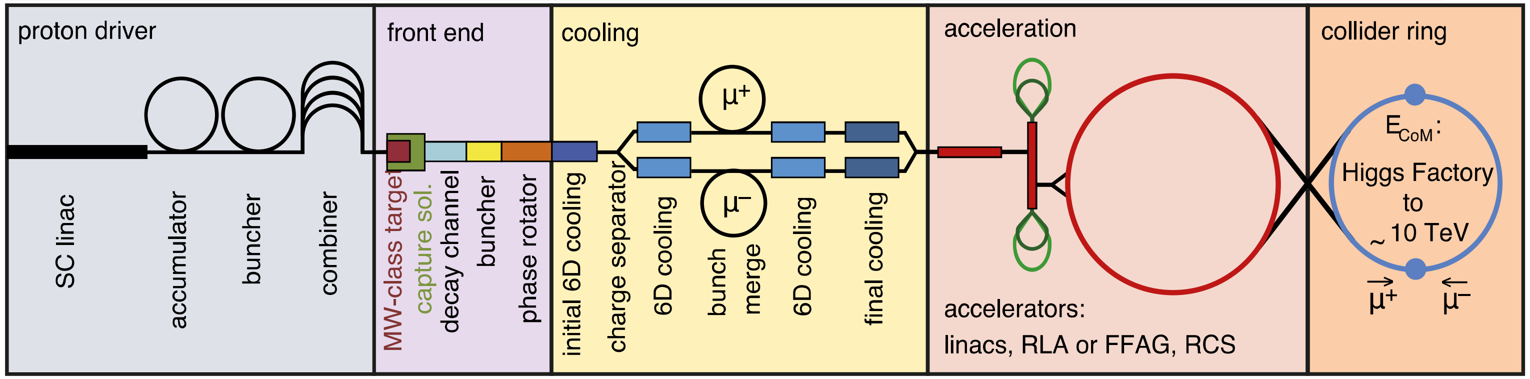


+Decay At Rest and Coherent scat.
(with short pulses)

Neutrino Factory



Muon Collider



Conclusion and Outlook

- Neutrino physics is the only field so far that showed results for physics beyond the standard model (BSM).
- CP violation in the lepton sector is the next major possible discovery in physics BSM.
- Neutrino long-baseline (LBL) facilities are the only way to discover CPV in lepton sector.
- Two LBL projects are under construction in USA and Japan aiming to become the first neutrino Super Beams, provided they will exceed 1 MW proton power.
- A major goal of ESSnuSB is to measure the lepton CP violation with the **highest possible precision** and thereby to identify a theory explaining the presence of matter in the Universe.
- The first phase of European Design Study, the ESSnuSB, has shown that

➔ *ESS can be used to produce an intense neutrino beam for CPV discovery in the lepton sector and*

➔ *measure the CPV phase-angle with an unprecedented precision better than 8 degrees, as required for the effective selection of a Leptogenesis theory that could explain the presence of matter in the Universe.*

- A second EU feasibility study, ESSnuSB+, started in 2023 aims at precisely measuring the neutrino cross–sections below 600 MeV in order to further decrease the systematic uncertainty.

Conclusion and Outlook

- ESSnuSB+ proposing to stage the operations towards the final neutrino facility.

  ➔ *The low energy Monitored Neutrino Beam to measure* ν_μ *cross–sections*

  ➔ *The low energy nuSTORM to measure* ν_μ *and* ν_e *cross-sections* (possibility to perform sterile neutrino searches)

- ESSnuSB has in addition a wide range of non-beam physics program: studying interactions of atmospheric neutrinos, solar neutrinos, supernova neutrinos, Geo-neutrinos and proton decay.

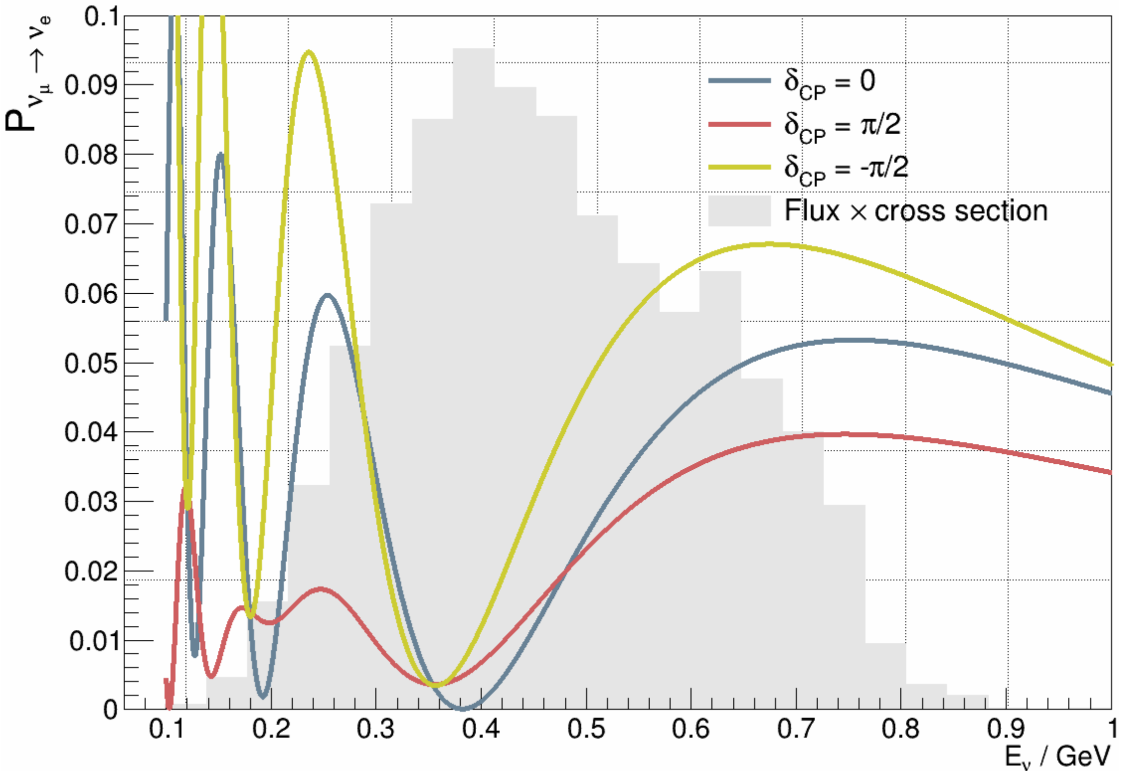
- ESSnuSB has been included in the German particle and astroparticle physics communities input to the European Strategy for Particle Physics 2026

Backup

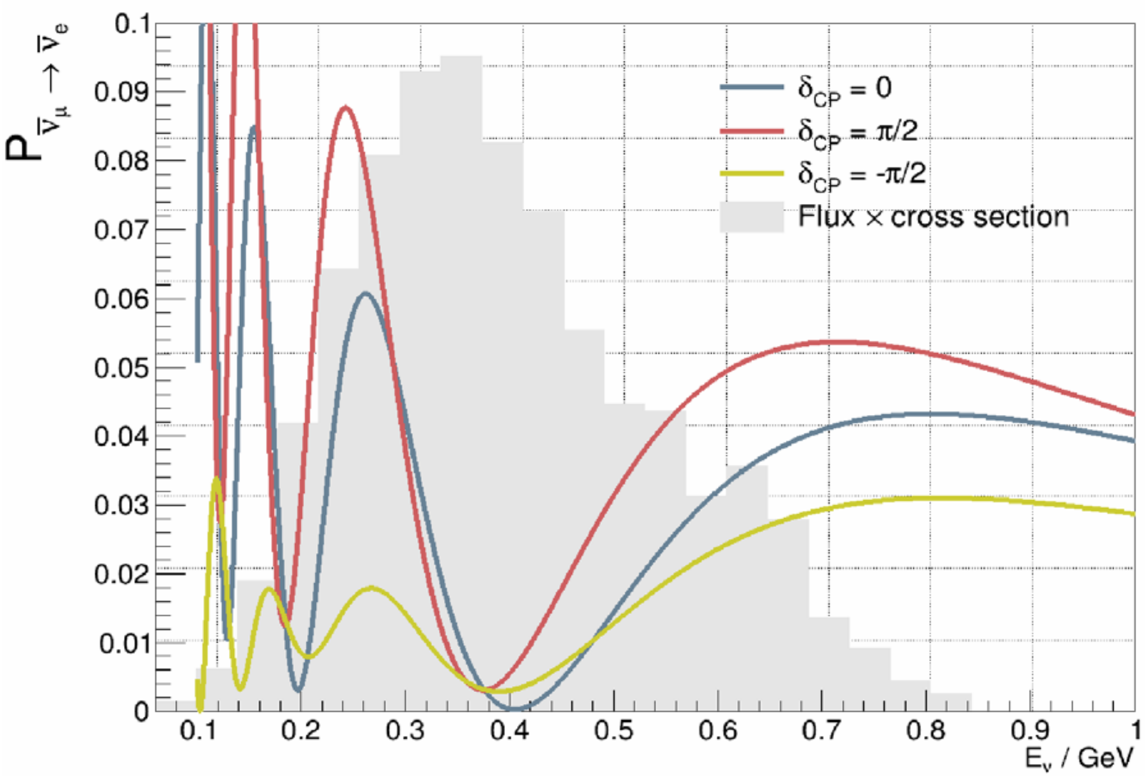
ESSnuSB energy coverage

Baseline = 360 km

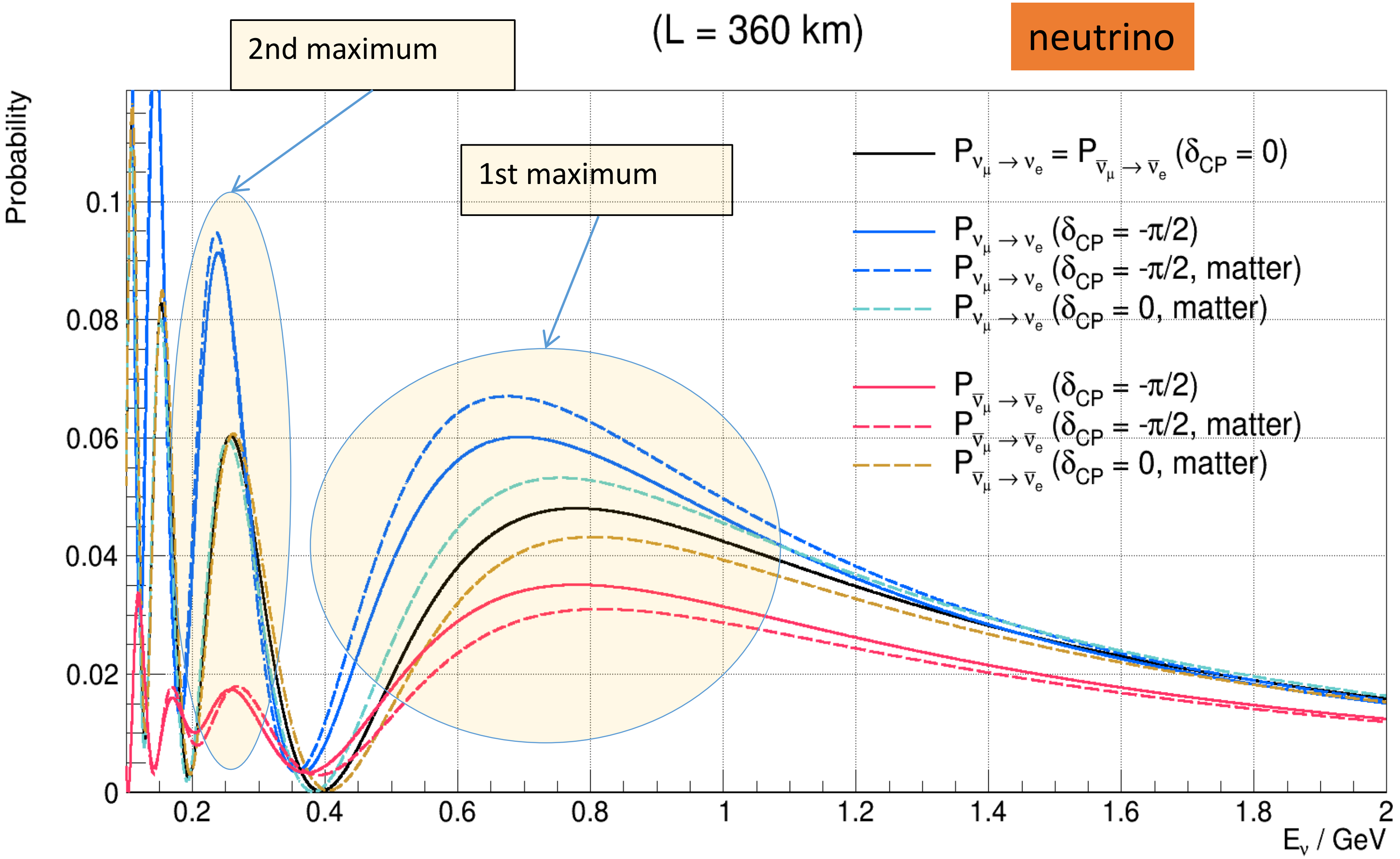
neutrinos



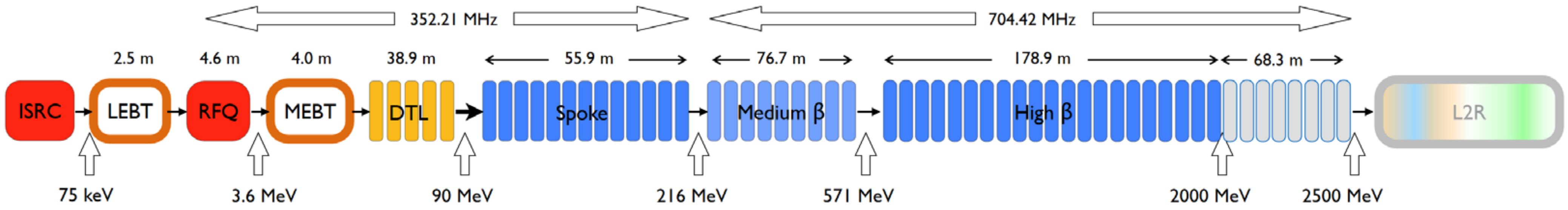
antineutrinos



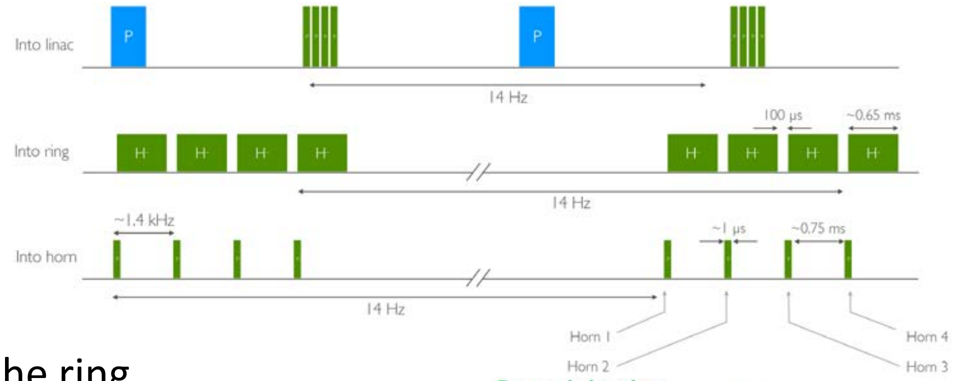
ESSnuSB energy coverage



ESS Proton Linac Upgrade and the Accumulator Ring

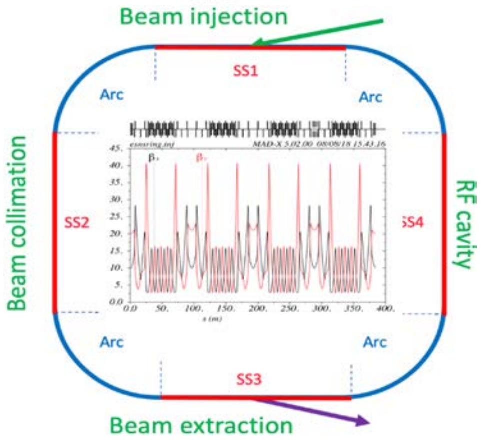


Pulsing scheme



- ESS*ν*SB proposes to increase the ESS LINAC power from 5 MW to 10 MW.
- The dedicated proton beam will be shortened to 1.3 µs:
  - ➢ With the help of the accumulator ring.
  - ➢ Will be split in four (batches) already in the LINAC.
  - ➢ Each batch is accumulated and then extracted before the next batch enters the ring.
  - ➢ Each batch hits a different target thanks to the switching in the switchyard.
- To avoid excessive injection losses, H^- ions are injected into the LINAC and stripped by a foil before entering the accumulator.
- Ring-to-switchyard, L2R, transfer-line extract the proton pulses from the ring to the beam switchyard and distribute the resulting four beam batches over four targets.

Accumulator Ring

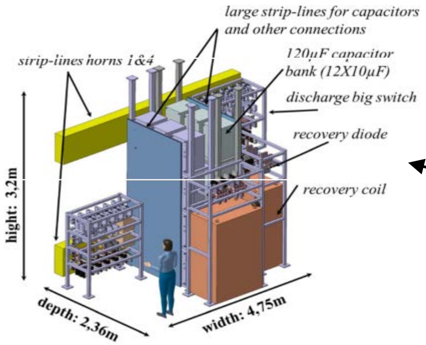


- Accumulation and storage, no acceleration.
- 384 m circumference, 1.33 µs revolution period

ESSνSB Target Station Facility

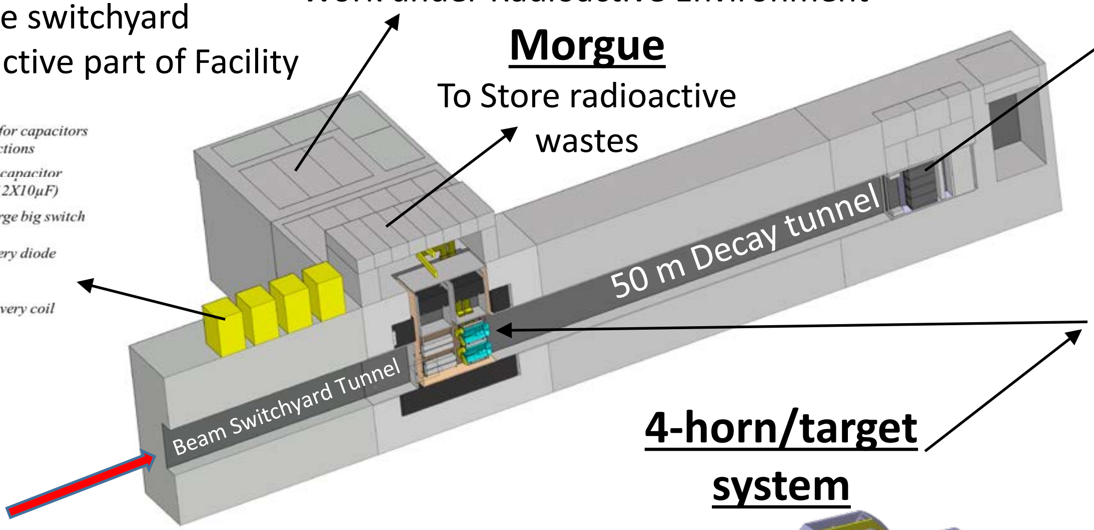
To produce $\nu_\mu(\bar{\nu}_\mu)$ beam and to withstand the energy deposition from the 5 MW proton beam on the 4-horn/target system

Power Supply Unit
- 16 modules (350 kA, 1.3 μs)
- Located above the switchyard
- Outside of radioactive part of Facility

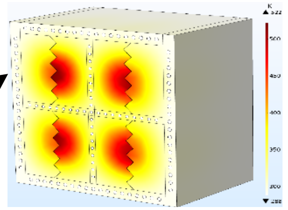


Hot Cell
- Able to manipulate/repair hadronic collector
- Work under Radioactive Environment

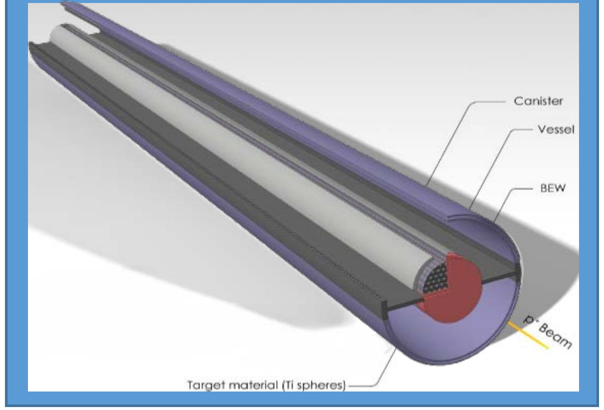
Morgue
To Store radioactive wastes



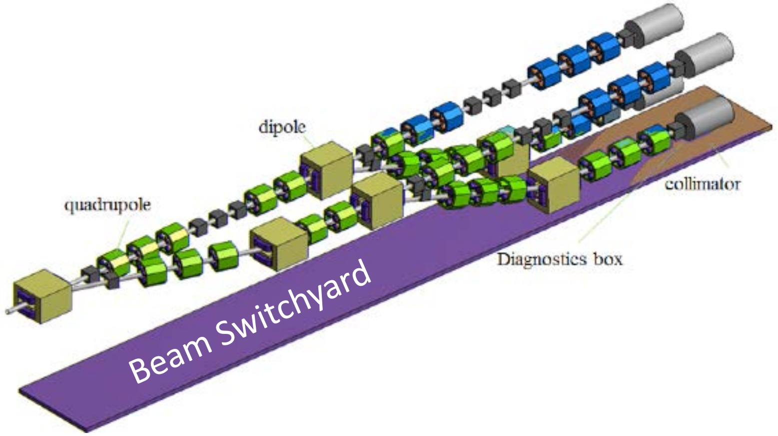
Beam dump



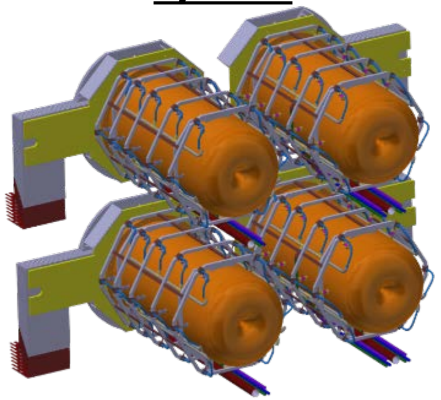
Granular Target Concept
- Target made of 3 mm titanium spheres cooled by transverse helium gas cooling



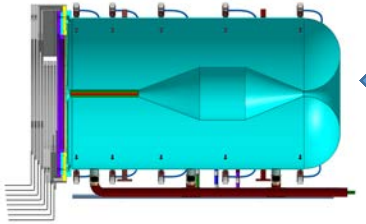
Proton Beam



4-horn/target system

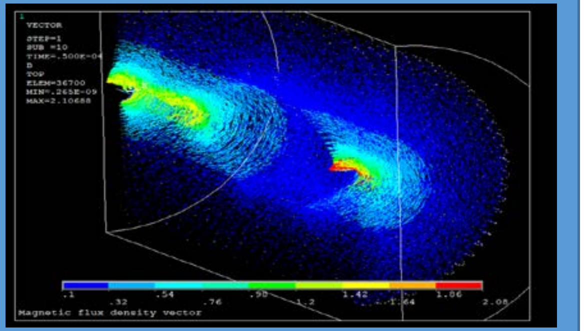


Hadronic Collector



Horn
Shape optimized with genetic algorithm

Magnetic field (350 kA; 1.3 μs pulse)

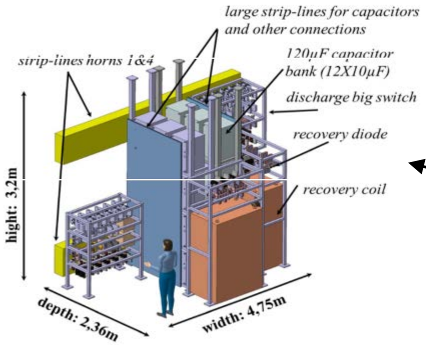


ESSνSB+ Target Station Facility

To produce $\pi^{\pm}$ **beam** and to withstand the energy deposition from the **1.25 MW** proton beam on the **1-horn/target** system

Power Supply Unit

- 8 modules (350 kA, 1.3 μs)
- Located above the switchyard
- Outside of radioactive part of Facility

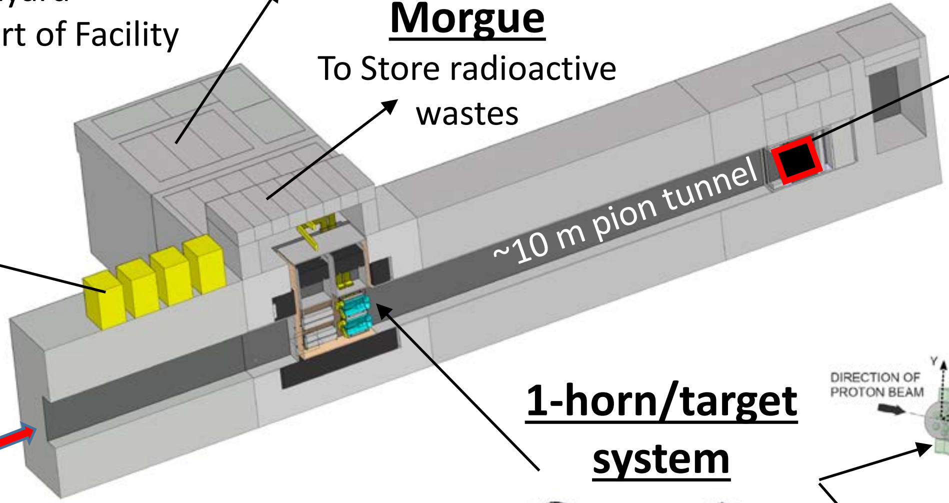


Hot Cell

- Able to manipulate/repair hadronic collector
- Work under Radioactive Environment

Morgue

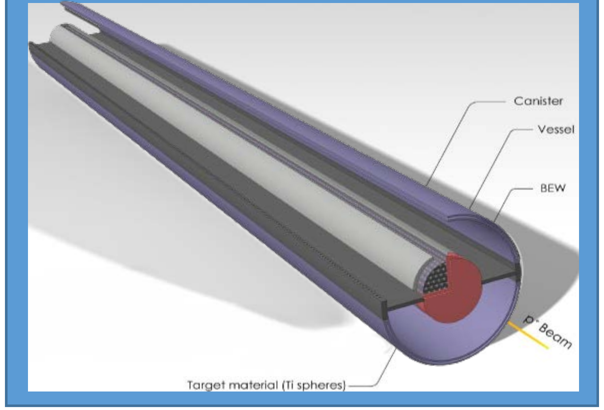
To Store radioactive wastes



Dipole Magnet

Granular Target Concept

- Target made of 3 mm titanium spheres cooled by transverse helium gas cooling

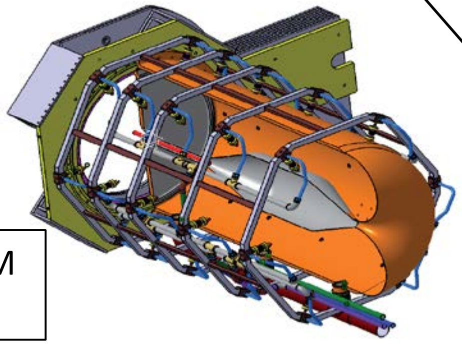


Proton Beam

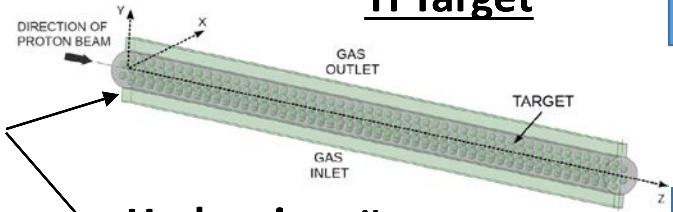
(Ep=2.5 GeV, 14 Hz)

1 x 1.25 MW

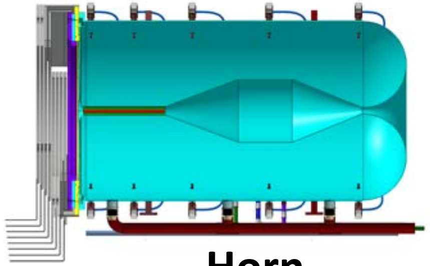
1-horn/target system



Ti Target



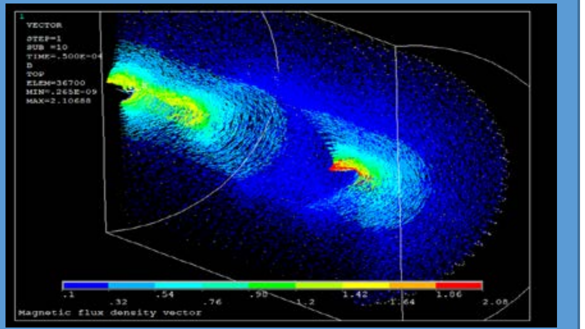
Hadronic Collector

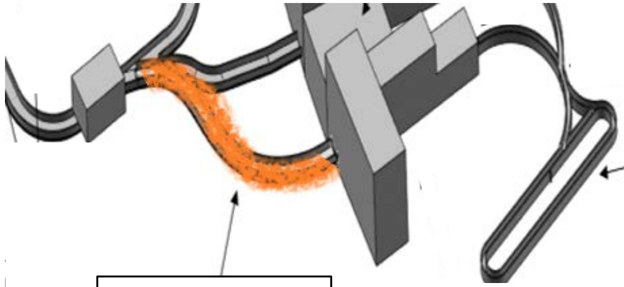


Horn

Shape optimized with genetic algorithm

Magnetic field (350 kA; 1.3 μs pulse)



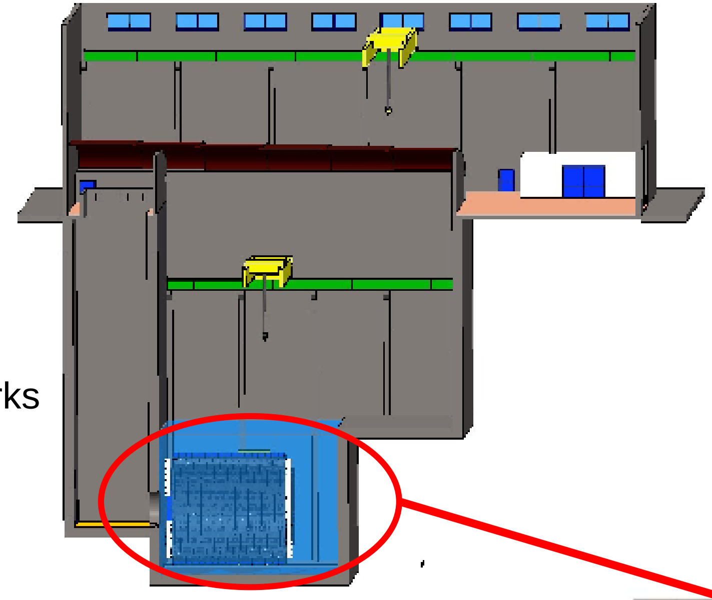


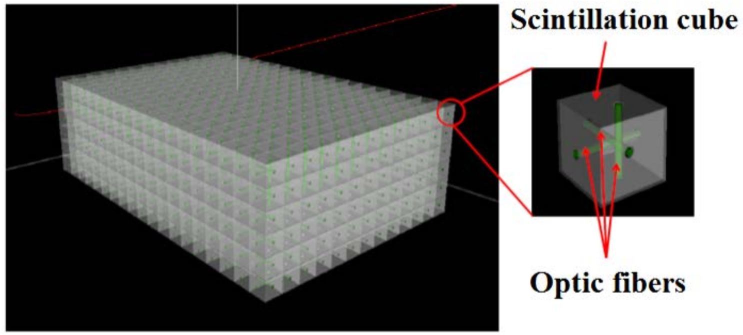
LEnuSTORM racetrack

Transfer Line

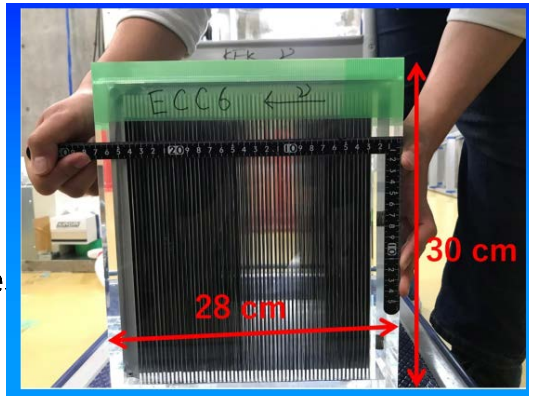
ESSnuSB Near Detector

- END hall distance from source is ~250 m
- **Near Water Cherenkov detector (NearWatCh)**
  - Event rate measurement and flux normalization
  - Neutrino – water cross section measurement
  - Cylindrical tank (9.4 m x 10.8 m)
  - Fiducial mass 0.42 kt
  - Event reconstruction optimization using neural networks
- **Super Fine–Grained Detector (SFGD)**
  - Neutrino energy estimation and flavour identification
  - Neutrino interaction cross section measurement
  - Rectangular cuboid (1.4 m × 1.4 m × 0.5 m)
  - Plastic scintillator (10^6 (1 x 1 x 1) cm^3 cubes)
  - Fiducial mass 1 t
- **NINJA-like water-emulsion detector (viking)**
  - Neutrino - water cross section measurements
  - Precise discrimination between neutrino interaction mode
  - Cube (2 m x 2 m x 2 m) with 140 NINJA type ECCs
  - Fiducial mass 1 t
  - Nuclear emulsion with water target

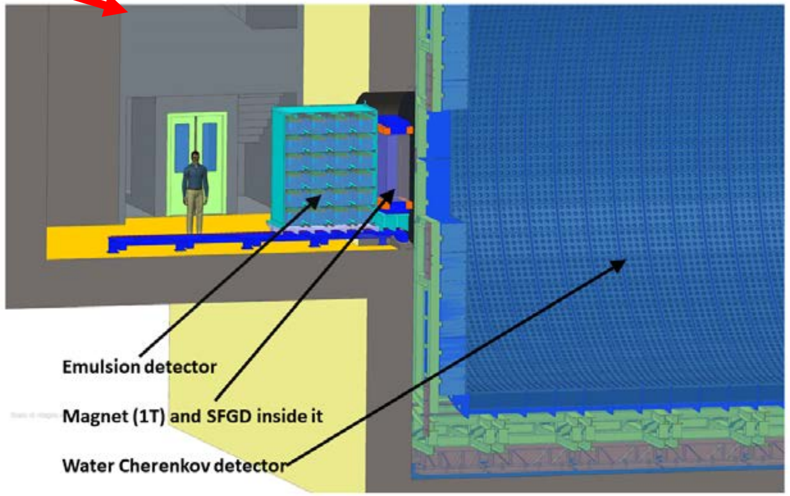

END hall



SFGD



NINJA type ECC



Near detector site

Expected Number of Events in ESSnuSB

Table 40 Expected number of neutrino interactions in the 538 kt FD fiducial volume at a distance of 360 km (Zinkgruvan mine) in 200 days (one effective year). Shown for positive (negative) horn polarity

	Channel	Non oscillated		Oscillated					
				$\delta_{CP} = 0$		$\delta_{CP} = \pi/2$		$\delta_{CP} = -\pi/2$	
CC	$\nu_\mu \to \nu_\mu$	22,630.4	(231.0)	10,508.7	(101.6)	10,430.6	(5.8)	10,430.6	(100.9)
	$\nu_\mu \to \nu_e$	0	(0)	768.3	(8.6)	543.8	(5.8)	1 159.9	(12.8)
	$\nu_e \to \nu_e$	190.2	(1.2)	177.9	(1.1)	177.9	(1.1)	177.9	(1.1)
	$\nu_e \to \nu_\mu$	0	(0)	5.3	(3.3×10^{-2})	7.3	(4.5×10^{-2})	3.9	(2.4×10^{-2})
	$\overline{\nu}_\mu \to \overline{\nu}_\mu$	62.4	(3640.3)	26.0	(1896.8)	26.0	(1898.9)	26.0	(1898.9)
	$\overline{\nu}_\mu \to \overline{\nu}_e$	0	(0)	2.6	(116.1)	3.5	(164.0)	1.4	(56.8)
	$\overline{\nu}_e \to \overline{\nu}_e$	1.3×10^{-1}	(18.5)	1.3×10^{-1}	(17.5)	1.3×10^{-1}	(17.5)	1.2×10^{-1}	(17.5)
	$\overline{\nu}_e \to \overline{\nu}_\mu$	0	(0)	3.0×10^{-3}	(4.0×10^{-1})	1.5×10^{-3}	(2.1×10^{-1})	4.1×10^{-3}	(5.6×10^{-1})
NC	ν_μ				16,015.1 (179.3)				
	ν_e				103.7 (0.7)				
	$\overline{\nu}_\mu$				55.2 (3265.5)				
	$\overline{\nu}_e$				1×10^{-1} (13.6)				

Table 45 Signal and major background events for the appearance channel corresponding to positive (negative) polarity per year for $\delta = 0°$

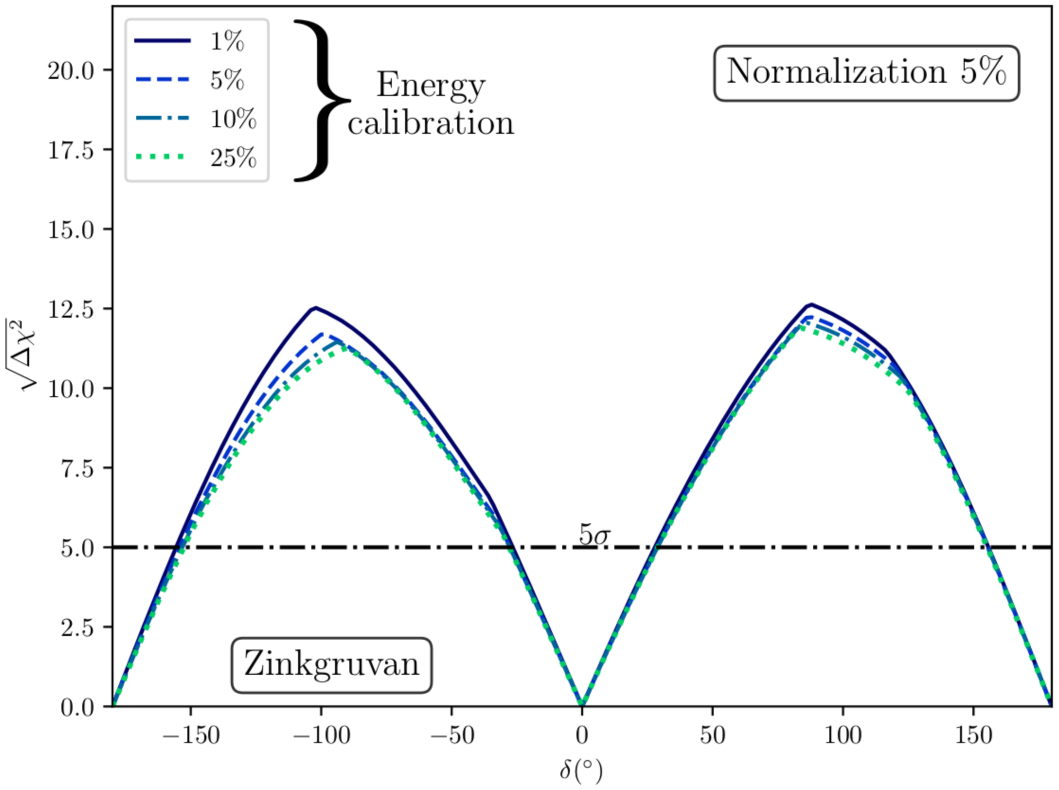
	Channel	$L = 540$ km	$L = 360$ km
Signal	$\nu_\mu \to \nu_e$ $(\bar{\nu}_\mu \to \bar{\nu}_e)$	272.22 (63.75)	578.62 (101.18)
Background	$\nu_\mu \to \nu_\mu$ $(\bar{\nu}_\mu \to \bar{\nu}_\mu)$	31.01 (3.73)	67.23 (11.51)
	$\nu_e \to \nu_e$ $(\bar{\nu}_e \to \bar{\nu}_e)$	67.49 (7.31)	151.12 (16.66)
	ν_μ NC $(\bar{\nu}_\mu$ NC)	18.57 (2.10)	41.78 (4.73)
	$\bar{\nu}_\mu \to \bar{\nu}_e$ $(\nu_\mu \to \nu_e)$	1.08 (3.08)	1.94 (6.47)

Effect of Energy Calibration Uncertainty

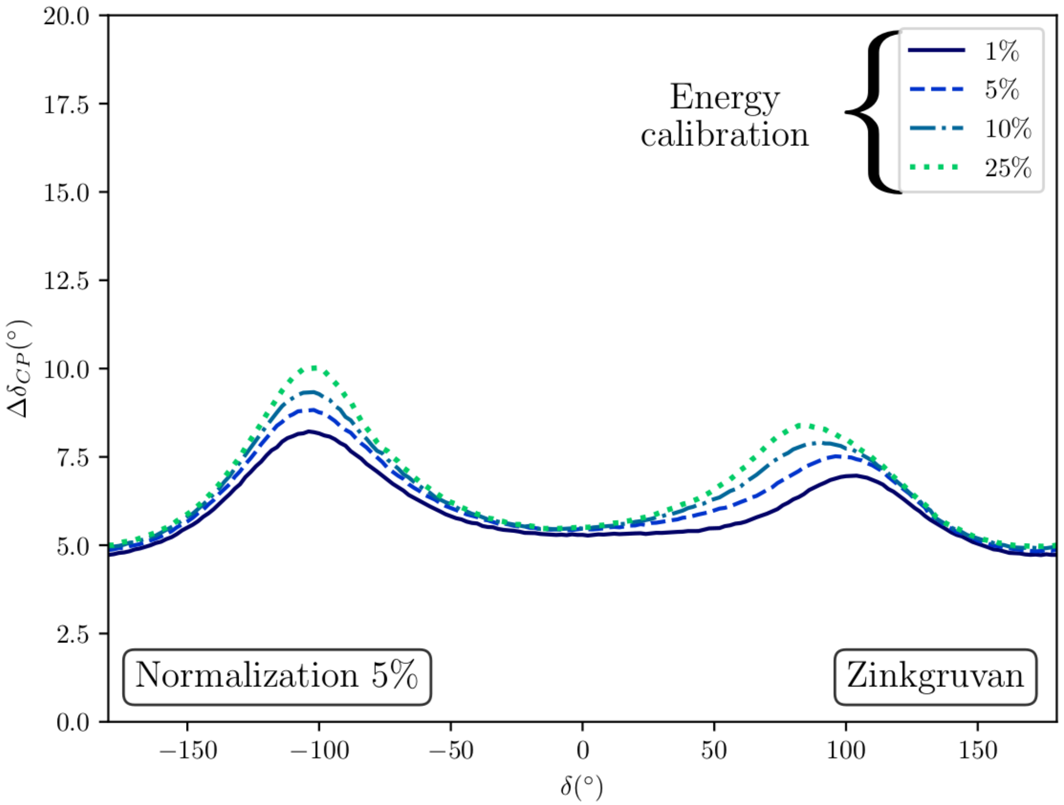
ESSnuSB
- θ_{12} = 33.44°
- θ_{13} = 8.57°
- θ_{23} = 49.2°
- Δm^2_{21} = 7.42e-5
- Δm^2_{31} = +2.52e-3
- 2nd osc. max.
- 507 ktons far detector

Baseline = 360 km

Sensitivity



Precision

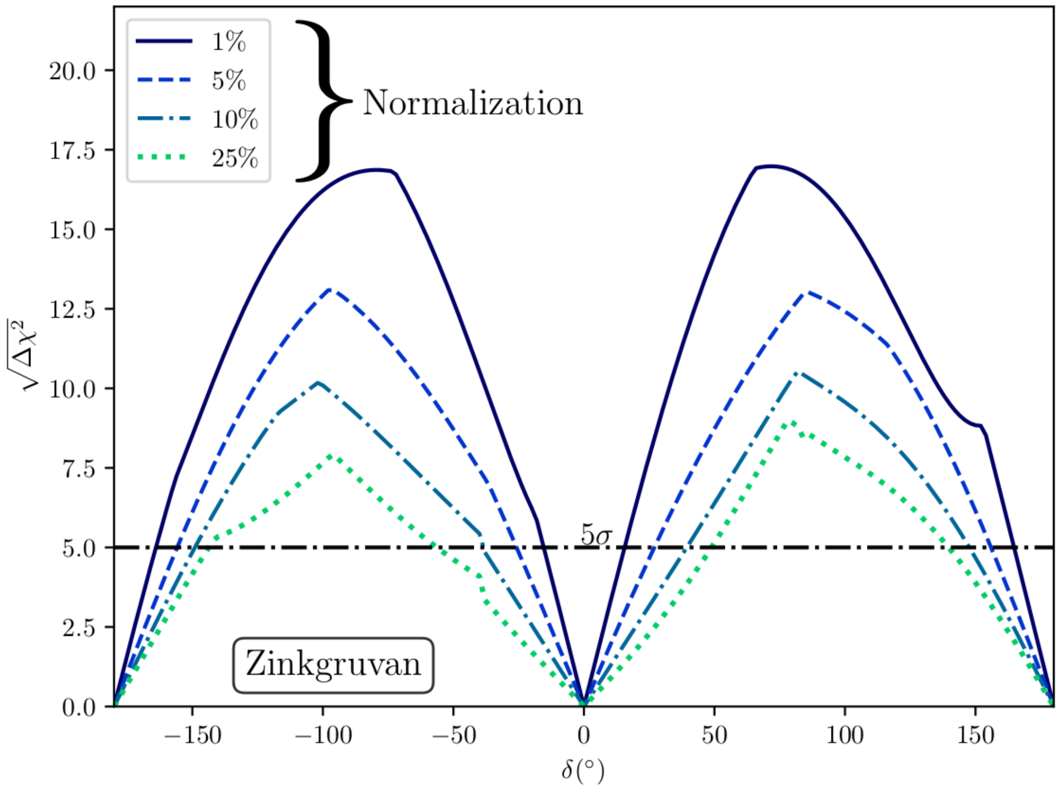


Effect of Normalization Uncertainty
Future Opportunities

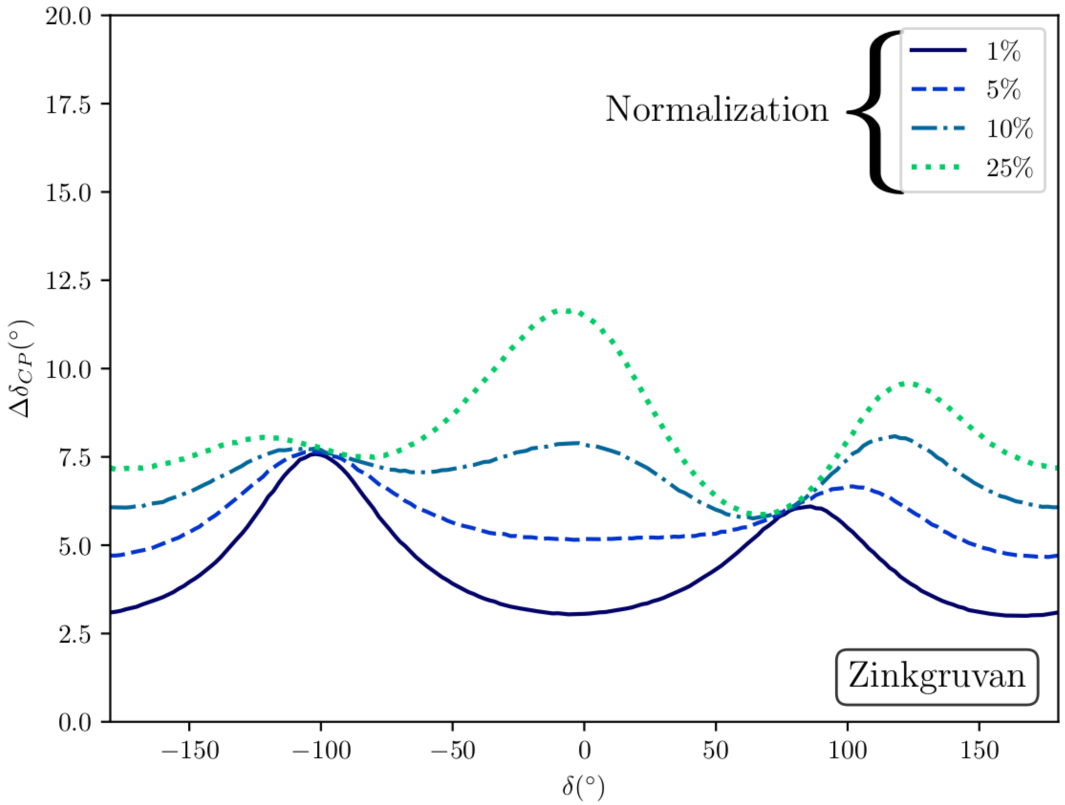
ESSnuSB
- θ_{12} = 33.44°
- θ_{13} = 8.57°
- θ_{23} = 49.2°
- Δm^2_{21} = 7.42e-5
- Δm^2_{31} = +2.52e-3
- 2nd osc. max.
- 507 ktons far detector

Baseline = 360 km

Sensitivity



Precision

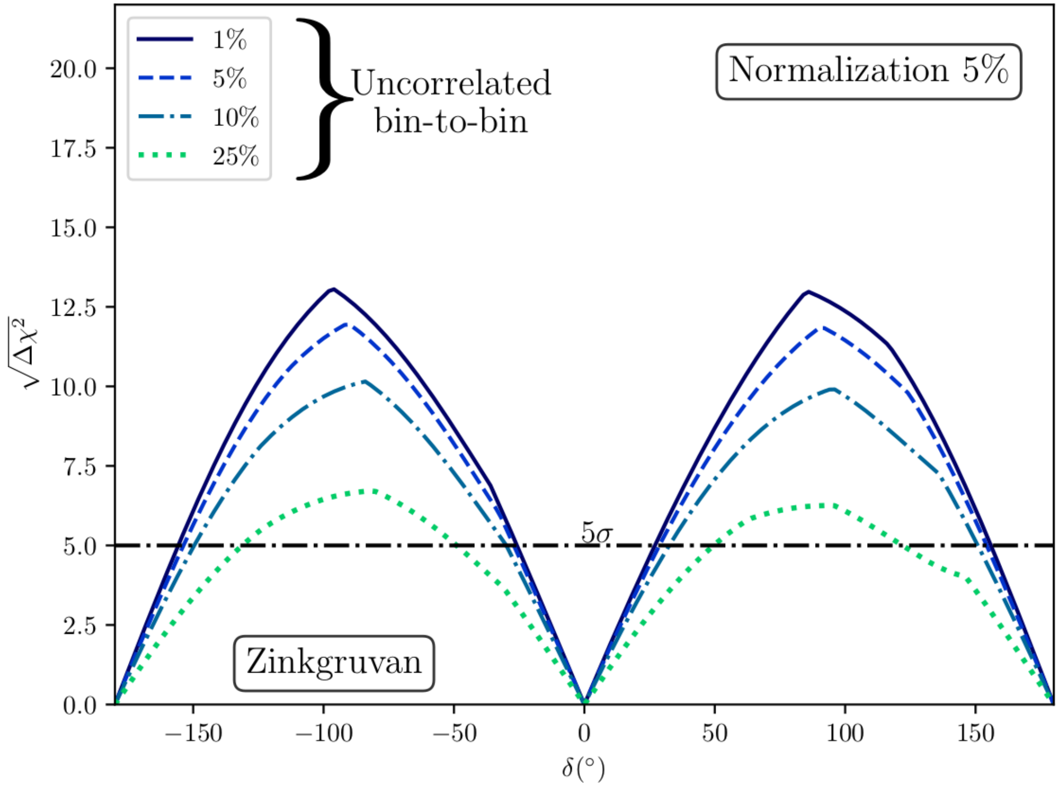


Effect of bin-to-bin Uncorrelated Uncertainty

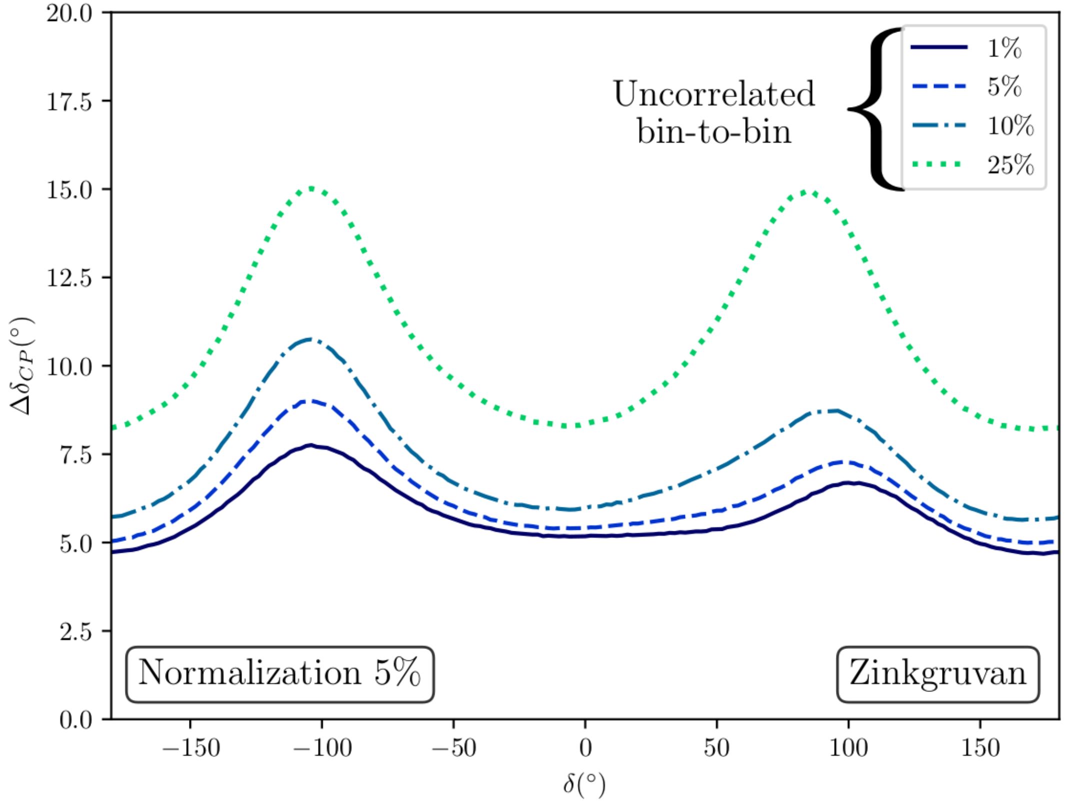
ESSnuSB
- θ_{12} = 33.44°
- θ_{13} = 8.57°
- θ_{23} = 49.2°
- Δm^2_{21} = 7.42e-5
- Δm^2_{31} = +2.52e-3
- 2nd osc. max.
- 507 ktons far detector

Baseline = 360 km

Sensitivity



Precision



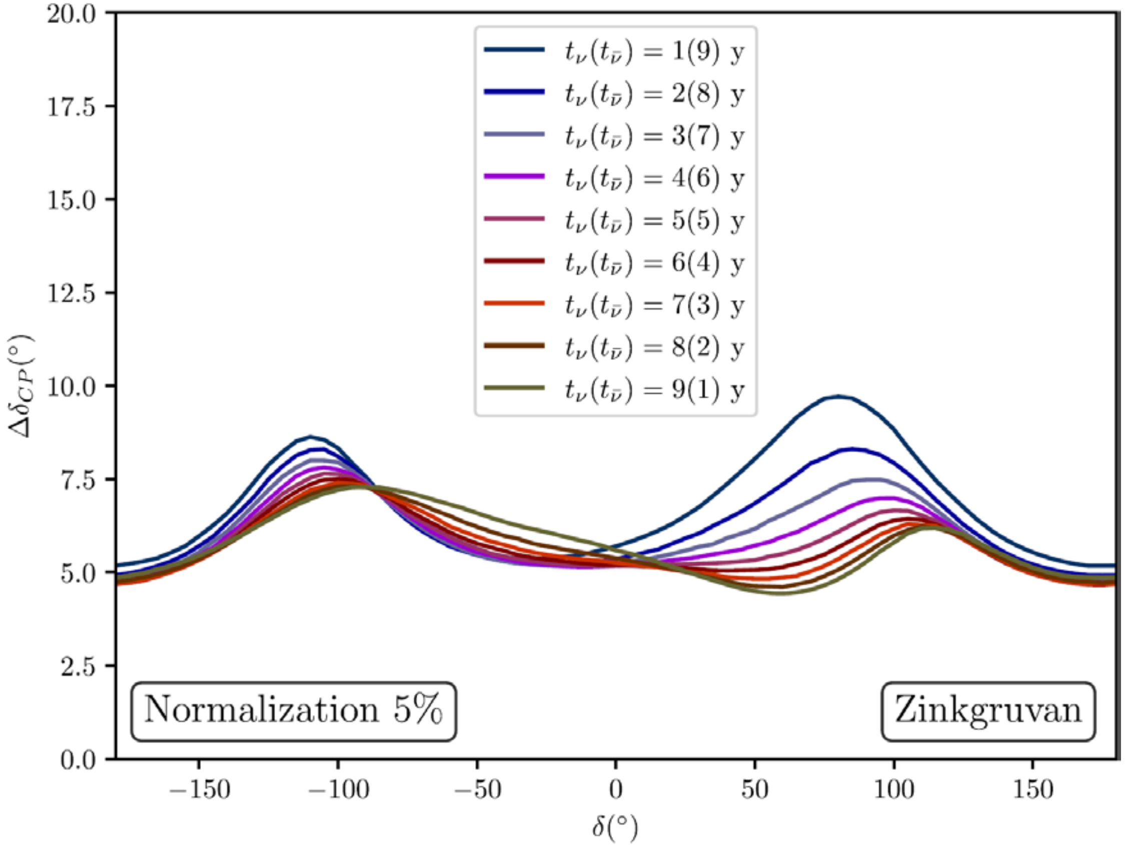
ESSnuSB Physics Reach

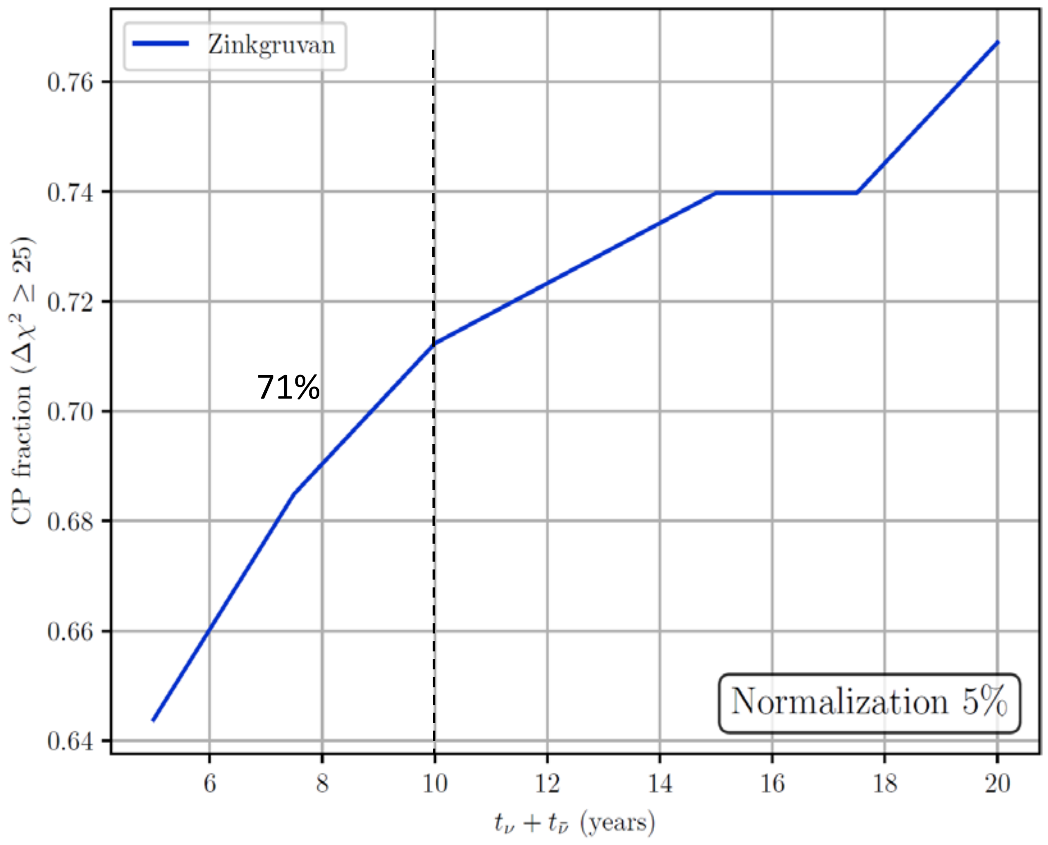
Baseline = 360 km

$\Delta\delta_{CP}$ for different running time splittings

Eur. Phys. J. ST. 231 (21), (2022) 3779

δ_{CP} coverage vs running time (@ 5 σ C.L.)





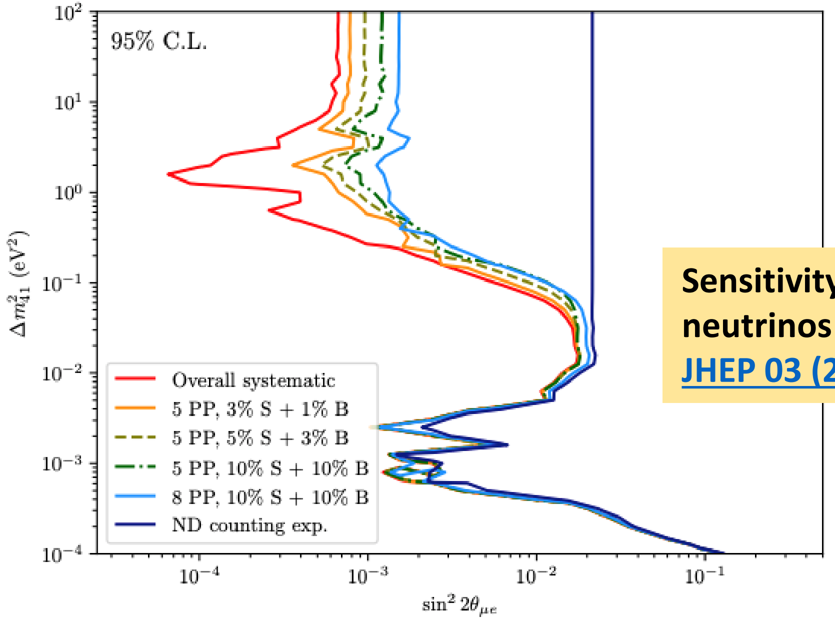
Systematic errors

Baseline = 360 km

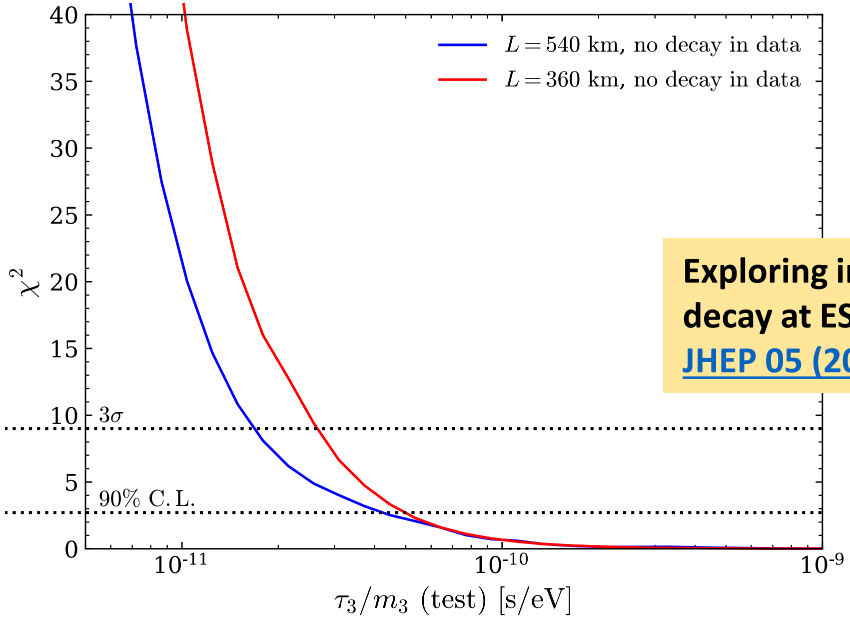
	SB			BB			NF		
Systematics	Opt.	Def.	Cons.	Opt.	Def.	Cons.	Opt.	Def.	Cons.
Fiducial volume ND	0.2%	0.5%	1%	0.2%	0.5%	1%	0.2%	0.5%	1%
Fiducial volume FD (incl. near-far extrap.)	1%	2.5%	5%	1%	2.5%	5%	1%	2.5%	5%
Flux error signal ν	5%	7.5%	10%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background ν	10%	15%	20%	correlated			correlated		
Flux error signal $\bar{\nu}$	10%	15%	20%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background $\bar{\nu}$	20%	30%	40%	correlated			correlated		
Background uncertainty	5%	7.5%	10%	5%	7.5%	10%	10%	15%	20%
Cross secs × eff. QE†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs × eff. RES†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs × eff. DIS†	5%	7.5%	10%	5%	7.5%	10%	5%	7.5%	10%
Effec. ratio ν_e/ν_μ QE*	3.5%	11%	–	3.5%	11%	–	–	–	–
Effec. ratio ν_e/ν_μ RES*	2.7%	5.4%	–	2.7%	5.4%	–	–	–	–
Effec. ratio ν_e/ν_μ DIS*	2.5%	5.1%	–	2.5%	5.1%	–	–	–	–
Matter density	1%	2%	5%	1%	2%	5%	1%	2%	5%

Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]]

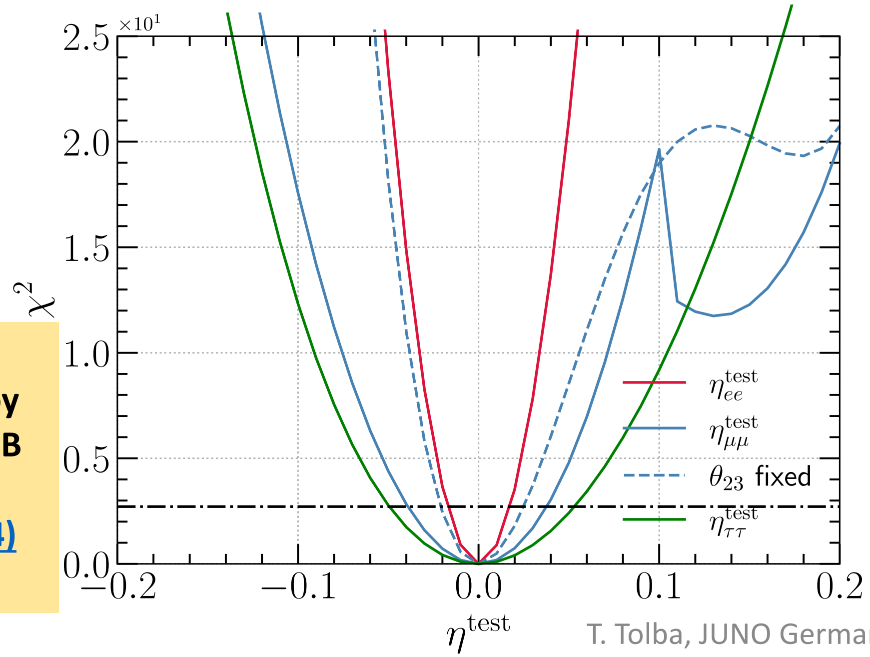
ESSnuSB Sensitivity to Constrain New Physics



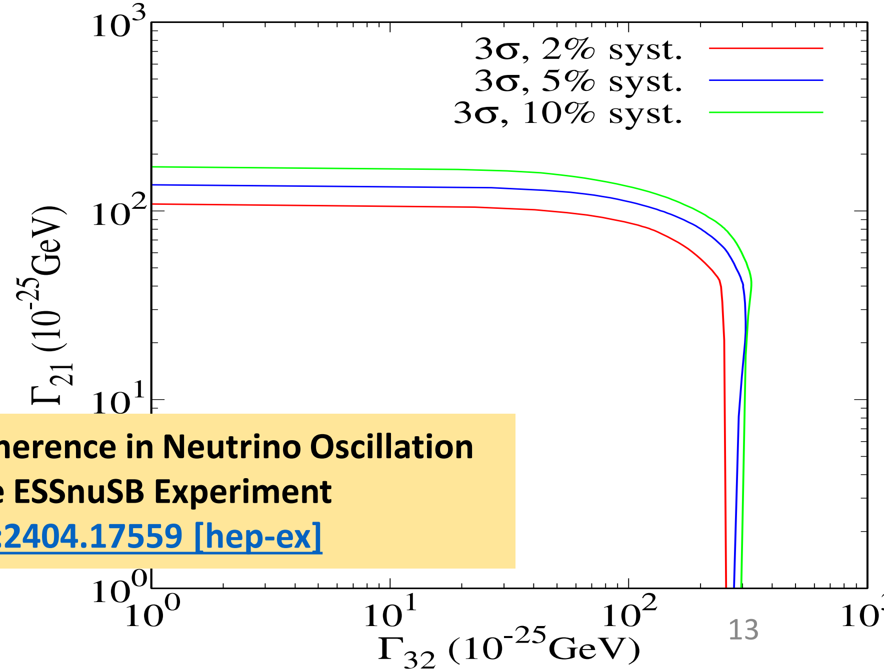
Sensitivity to light sterile neutrinos at ESSnuSB
JHEP 03 (2020), 026



Exploring invisible neutrino decay at ESSnuSB
JHEP 05 (2021), 133



Study of non-standard interaction mediated by a scalar field at ESSnuSB experiment
Phys. Rev. D 109, (2024) 115010

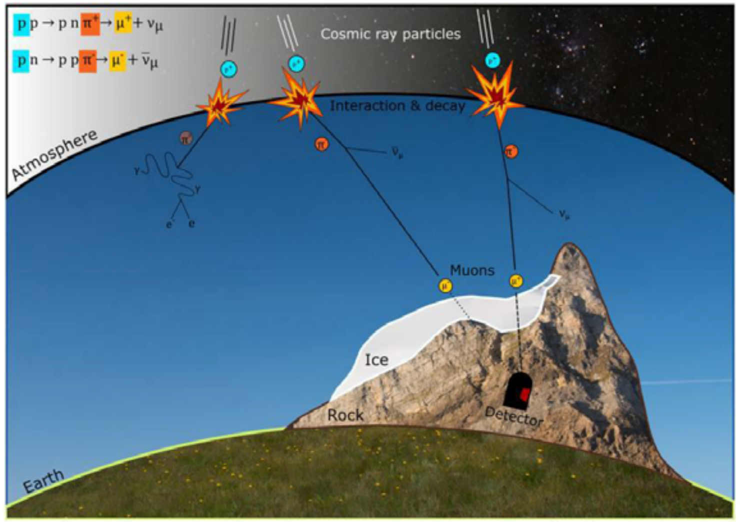


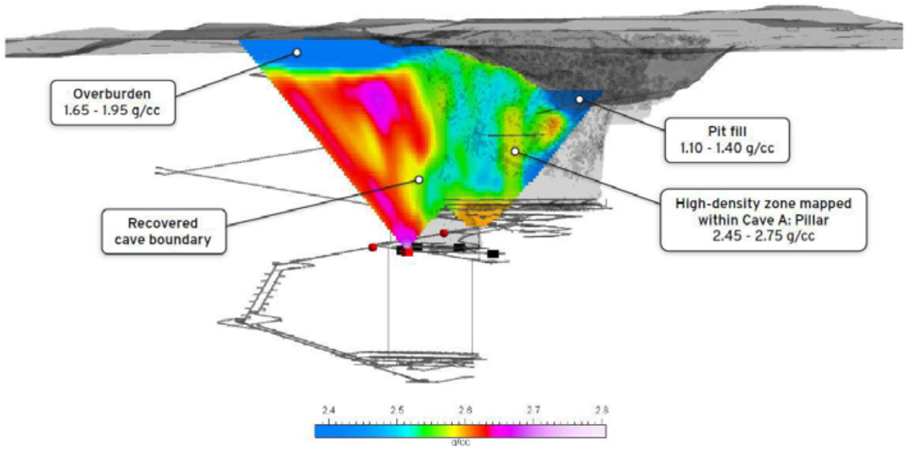
Decoherence in Neutrino Oscillation at the ESSnuSB Experiment
arXiv:2404.17559 [hep-ex]

Muon Tomography with ESSnuSB FD

Concurrent use of the Cherenkov detector for muon tomography 0.5 M€

Thessaloniki, Strasbourg and Oulo Technical University





Using muon tomography, the Ideon Technologies company remotely mapped the full cave back at the New Afton Mine in Canada to 25 m or less spatial resolution at a depth of approximately 800 m, using no additional drilling to image 830 million m3 of earth. Presented at International Mass Mining Conference and Exhibition **(MassMin) in Kiruna, Sweden September 18 2024**.

Muon Tomography with ESSnuSB FD

JUNO Top Muon Tracker Prototype at Strasbourg

The Muon Telescope (JUNO Top Tracker Prototype) consists of 4 XY planes and each XY plane has two crossed modules.

Each modules is made of 64 plastic scintillators strip equipped each with one Wave Length Shifting fibers.

The size of a plastic scintillator bar has a cross section of 10mmx25,6mm and about 1.68m long.

All the 64 fibers are read by a 64 channels multianodes photomultipliers from Hamamatsu.

Coverage 1.68m x 1.68m
Muon track angular resolution 0.85°

ESSνSB+ (Work-Packages)

Engineering and Infrastructures

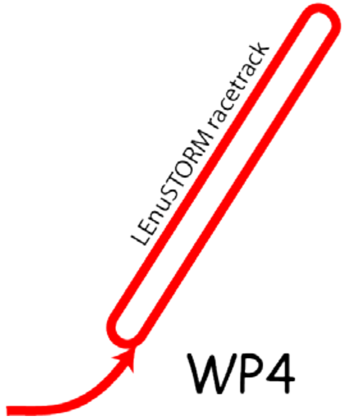
- Civil engineering studies will be performed of the already proposed installations of ESSνSB.
- During the same period, analogue studies will be performed at the Zinkgruvan mine at the place where the ESSνSB far detector will be installed.
- The analysis of the already existing data will be completed and described in a comprehensive report.

Target Station

- An optimised design of the hadron collector for neutrino production has been produced during the ESSνSB studies. A first evaluation of whether this design is well suited also for pion collection for LEnuSTORM and LEMNB usage will be done.
- A pion beam simulation will be performed. The resulting characteristics will be provided to WP4, WP5 and WP6 to define the initial design of the other ESSνSB+ parts.

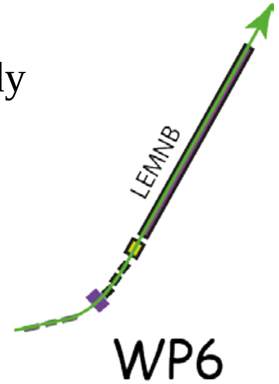
ESSνSB+ WP

LEnuSTORM



- Lattice and beam optics design will be elaborated from the existing higher energy proposals.
- Shape and dimensions of the racetrack ring will be established.
- The study will include the transfer lines from the ESSνSB complex to the target and from the initial capture an extraction up to the injection point in the ring.

LEMNB

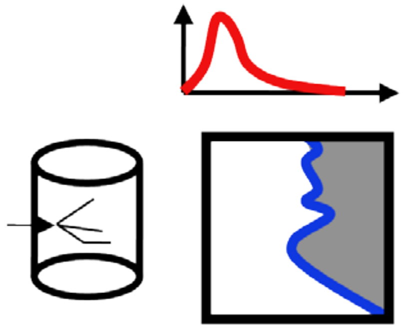


- A preliminary design of the ca 30 m long EMNB decay tunnel will be made on the basis of the H2020 ESSνSB Design Study and ERC ENUBET project.
- Muons from pion decays, which are produced with an average emission angle of order 50 mrad at 1 GeV, are monitored at the single-particle level using sampling calorimeters for muon/pion separation.
- Thanks to the additional sample of electron neutrinos originating from the decay in flight, the ESS monitored neutrino beam will be able to assess also the electron neutrino versus muon neutrino difference of cross-sections below 1 GeV.

ESSνSB+ (Work-Packages)

Detector and physics performance:

- Design of an additional detector which will be used by LEnuSTORM and LEMNB for cross-section measurements;
  - it will also be used as LEnuSTORM near detector for sterile neutrino searches.
- The near detector of ESSνSB will be used as a far detector of LEnuSTORM.
- The WP will also use the information provided by all the other WPs to determine and maximise the physics reach of LEnuSTORM and LEMNB, taking into account the additional information coming from concurrently running experiments that may become available.
- It will also compare the performance of ESSνSB+ with that of other planned or proposed facilities.
- The potential of the ESSνSB far detector **doped with Gadolinium** for non-beam related physics (natural neutrino sources, proton decay) will be studied.



The ENUBET (Enhanced NeUtrino BEams from kaon Tagging)

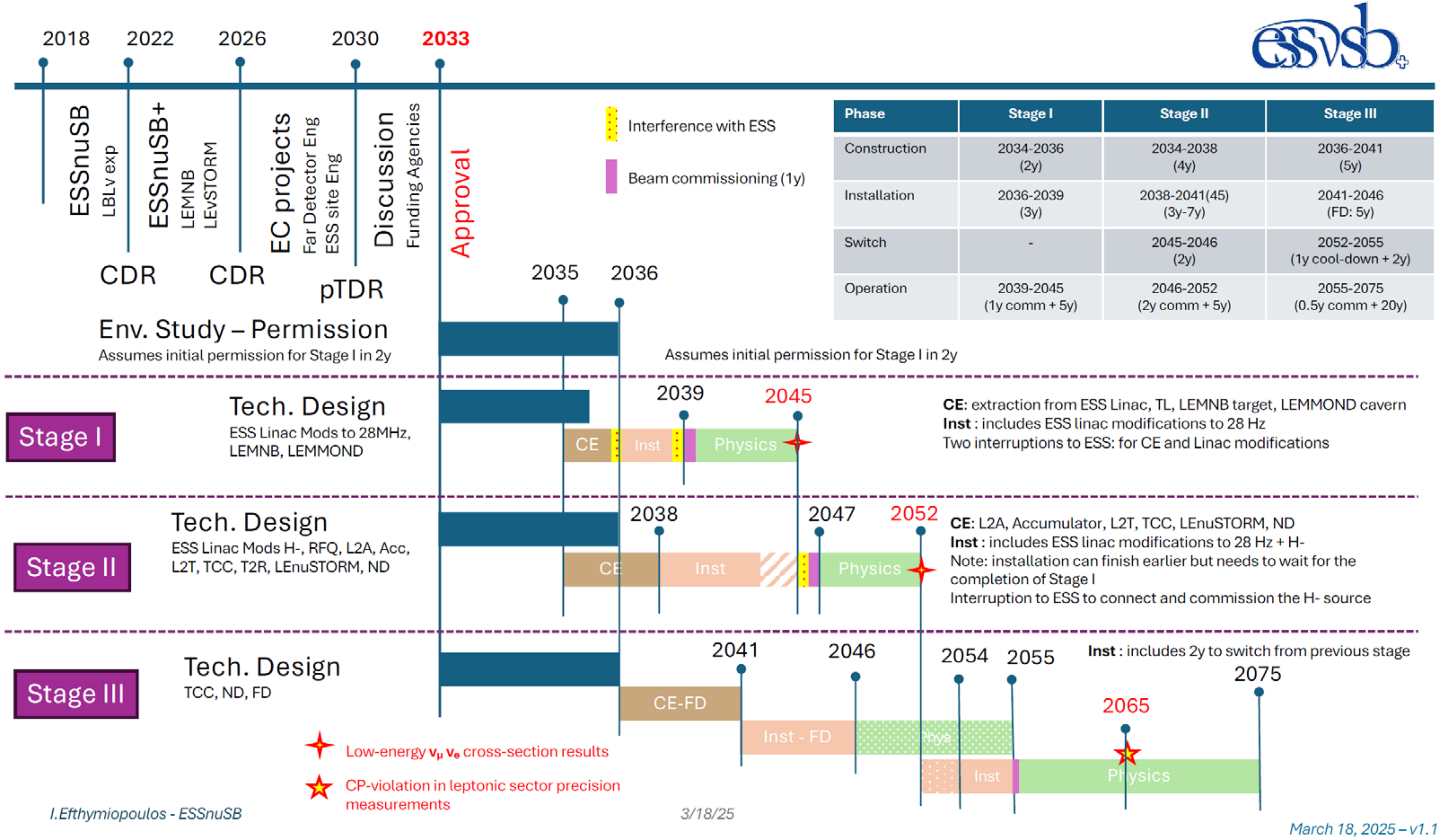
- Proposes a dedicated facility to measure ν_μ and ν_e cross-sections precisely using a combination of monitored, narrow-band neutrino beams at the GeV energy scale and by instrumenting the meson-decay tunnel with a segmented calorimeter.

- The ENUBET approach is based on monitoring the production of large-angle positrons from $K^+ \rightarrow \pi^0 e^+ \nu_e$ (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 ν_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 ν_e flux directly. Consequently, the monitored ν_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 ν_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 ν_μ interaction vertex.

nuSTORM (Neutrinos from Stored Muons)

- It has been designed to deliver a definitive neutrino nucleus scattering programme using beams of (anti)ν_e and (anti)ν_μ from the decay of muons confined within a storage ring.
- 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.

ESSνSB timeplan



Phase	Stage I	Stage II	Stage III
Construction	2034-2036 (2y)	2034-2038 (4y)	2036-2041 (5y)
Installation	2036-2039 (3y)	2038-2041(45) (3y-7y)	2041-2046 (FD: 5y)
Switch	-	2045-2046 (2y)	2052-2055 (1y cool-down + 2y)
Operation	2039-2045 (1y comm + 5y)	2046-2052 (2y comm + 5y)	2055-2075 (0.5y comm + 20y)