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ESS neutrino Super Beam plus

Co-funded by the European Union

The ESSnuSB Project:

Search for and Precision Measurement of Leptonic CP Violation

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

Institut für Experimentalphysik, Universität Hamburg, Germany

NEUTRINO 2024

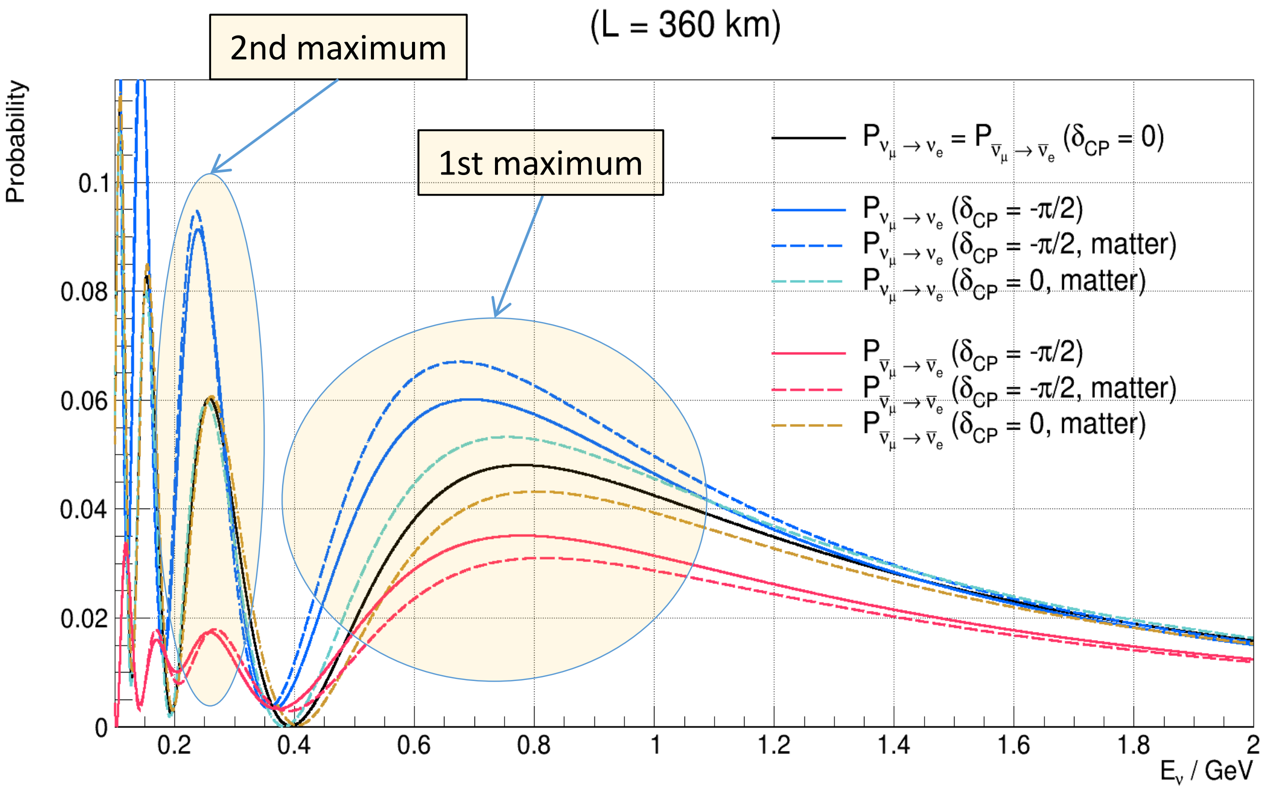
XXXI International Conference on Neutrino Physics and Astrophysics

Milano (Italy) - June 16-22, 2024

ESSnuSB

(European Spallation Source neutrino Super Beam)

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



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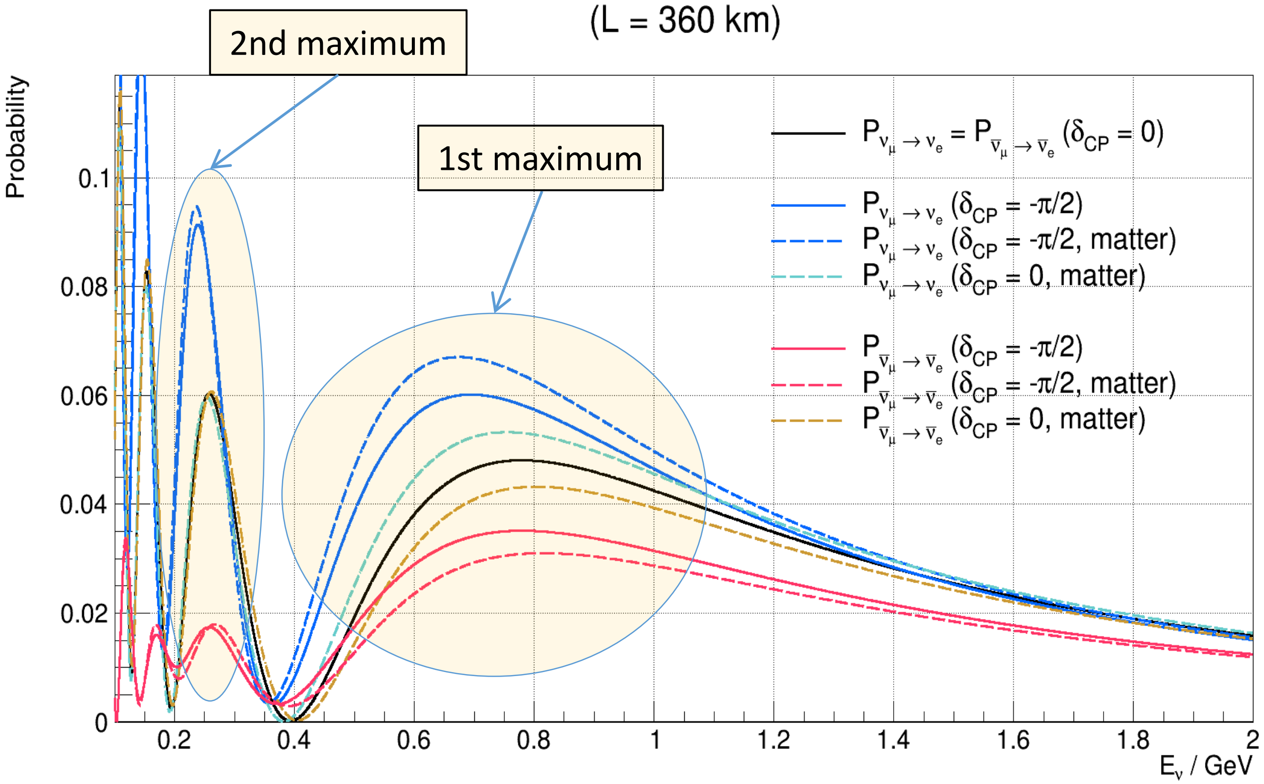


Matter-antimatter Asymmetry

$$A \equiv \frac{|P(\nu_\mu \to \nu_e) - \bar{P}(\bar\nu_\mu \to \bar\nu_e)|}{[P(\nu_\mu \to \nu_e) + \bar{P}(\bar\nu_\mu \to \bar\nu_e)]}$$

$$A_{CP}(1st\ Osci.max) = \mathbf{0.3} \cdot sin\delta_{CP}$$

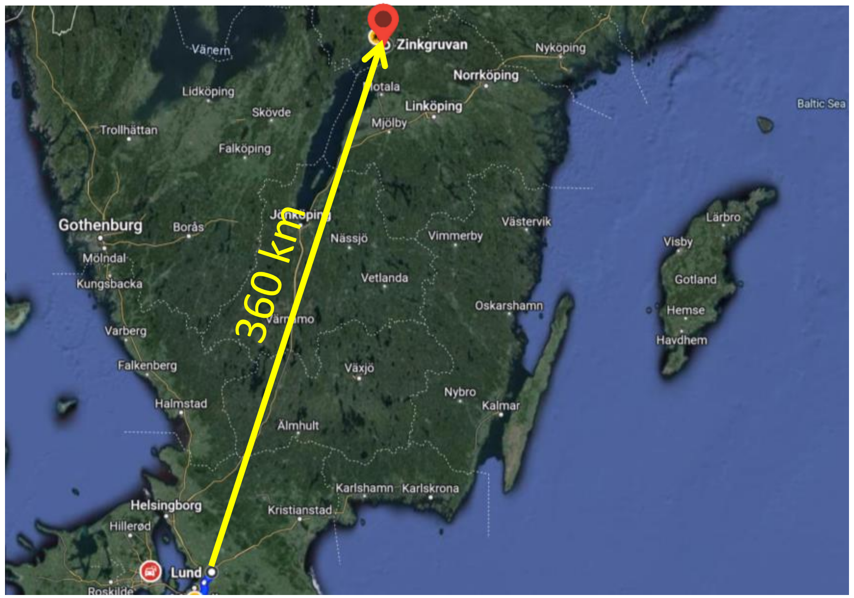
$$A_{CP}(2nd\ Osci.max) = \mathbf{0.75} \cdot sin\delta_{CP}$$

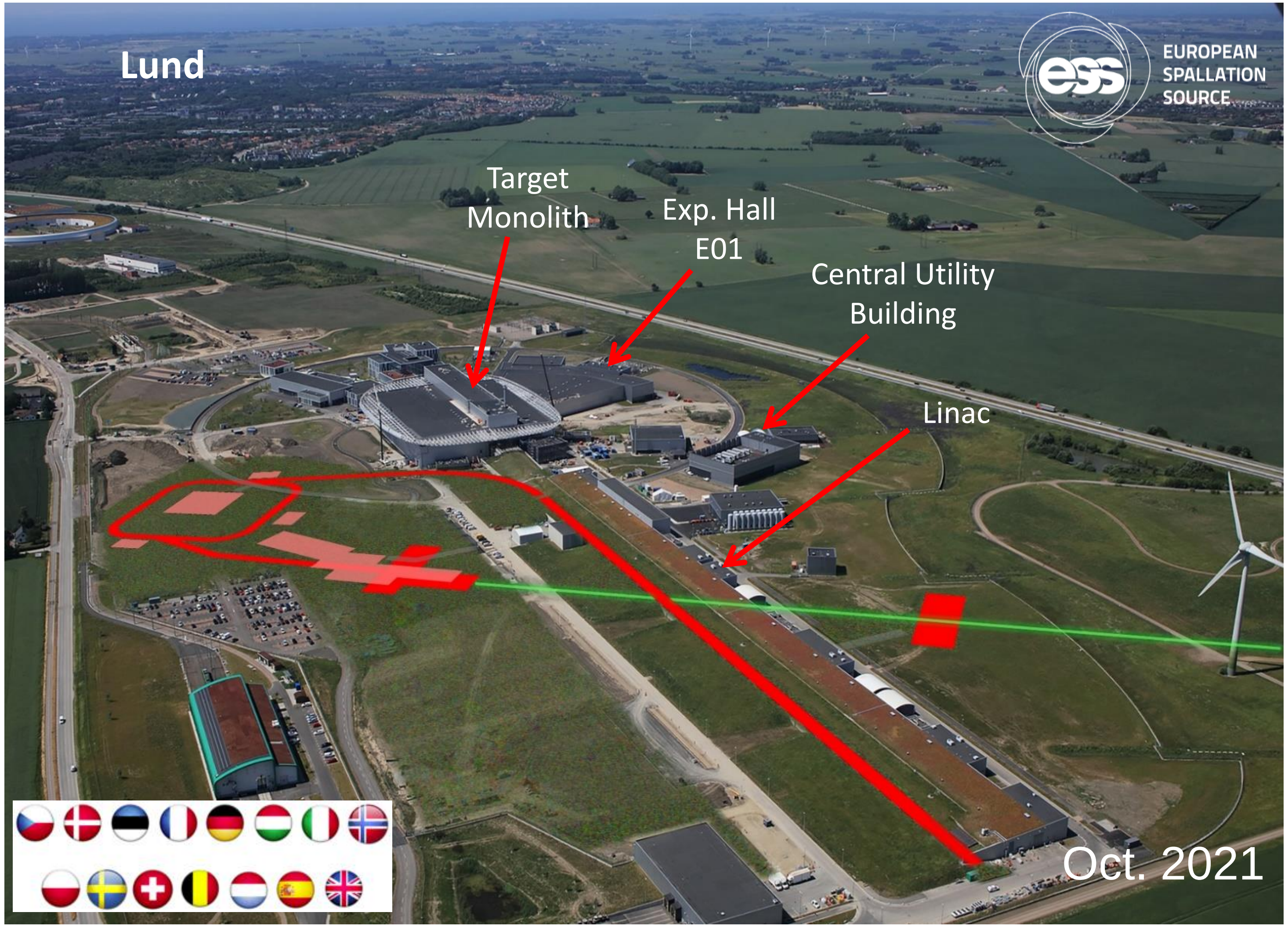
$$\frac{A_{CP}@\ 2nd\ max.}{A_{CP}@\ 1nd\ max.} \sim 2.5$$

S. Parke, https://arxiv.org/pdf/1310.5992

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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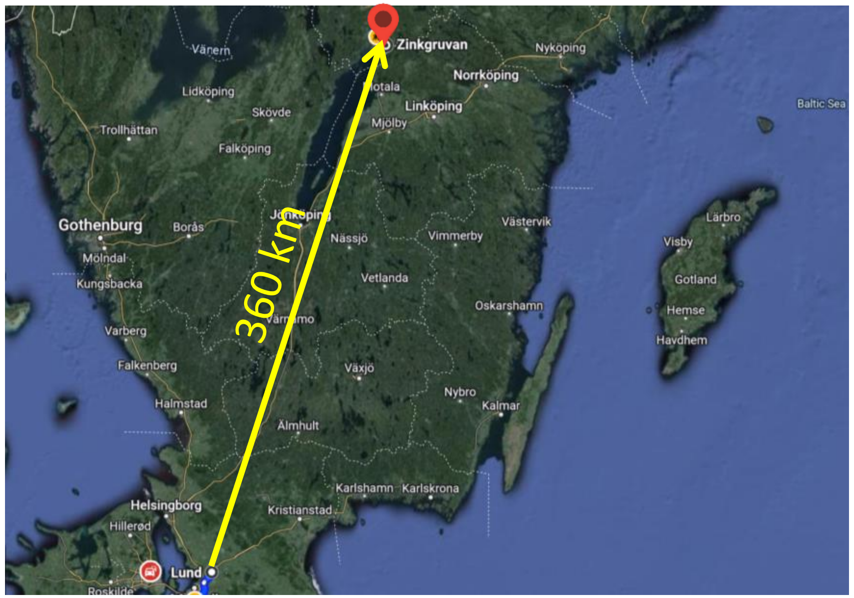

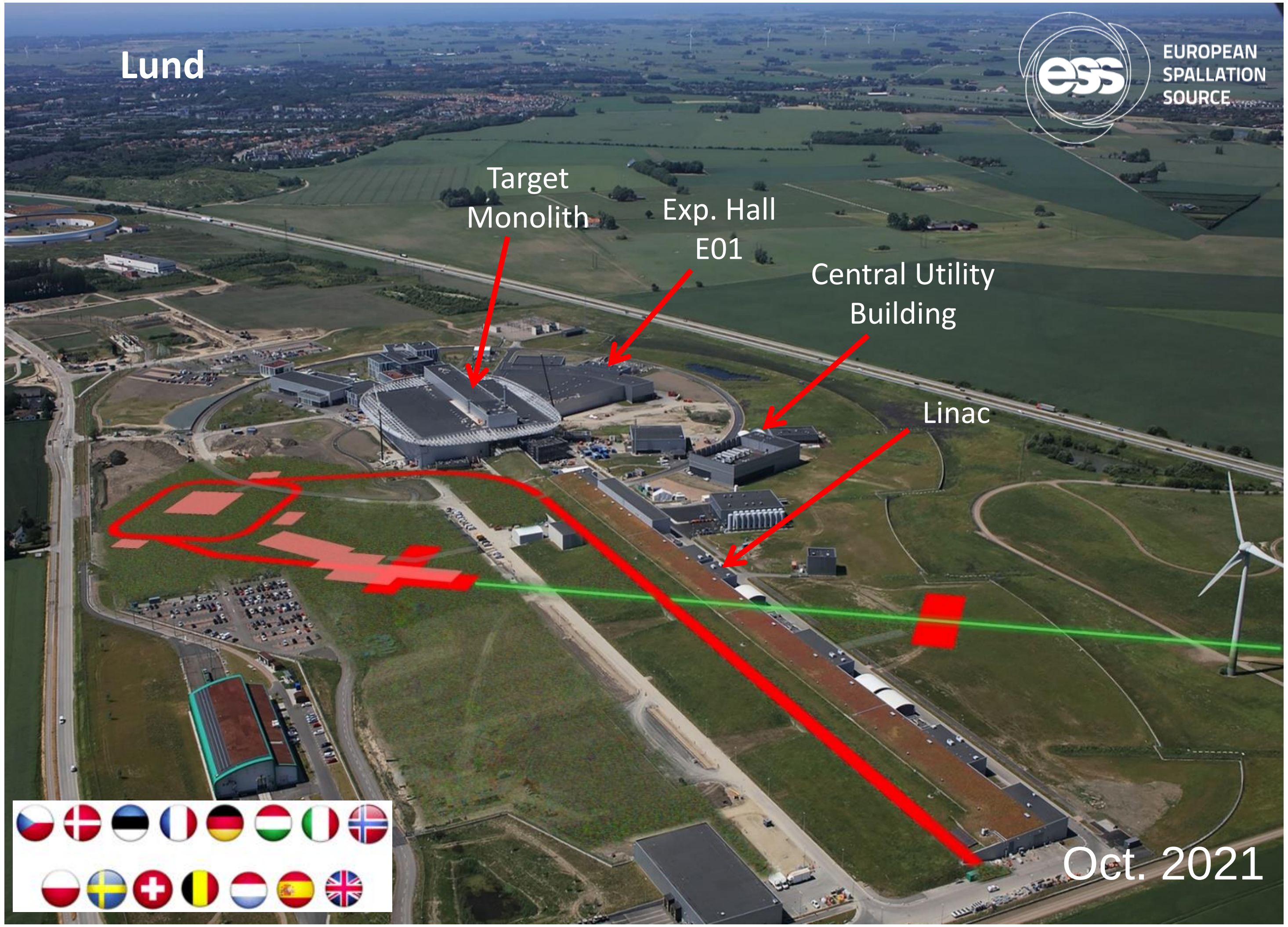

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- The most powerful proton linear accelerator
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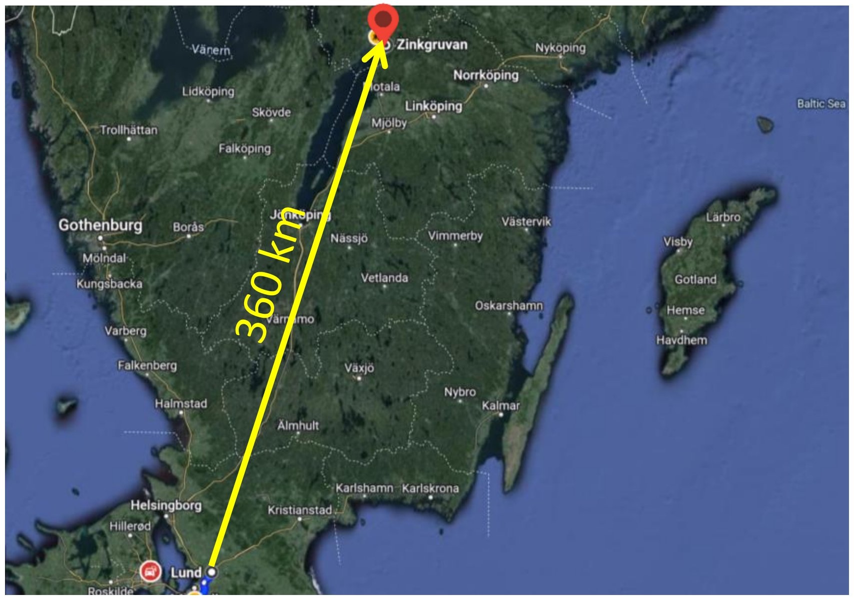
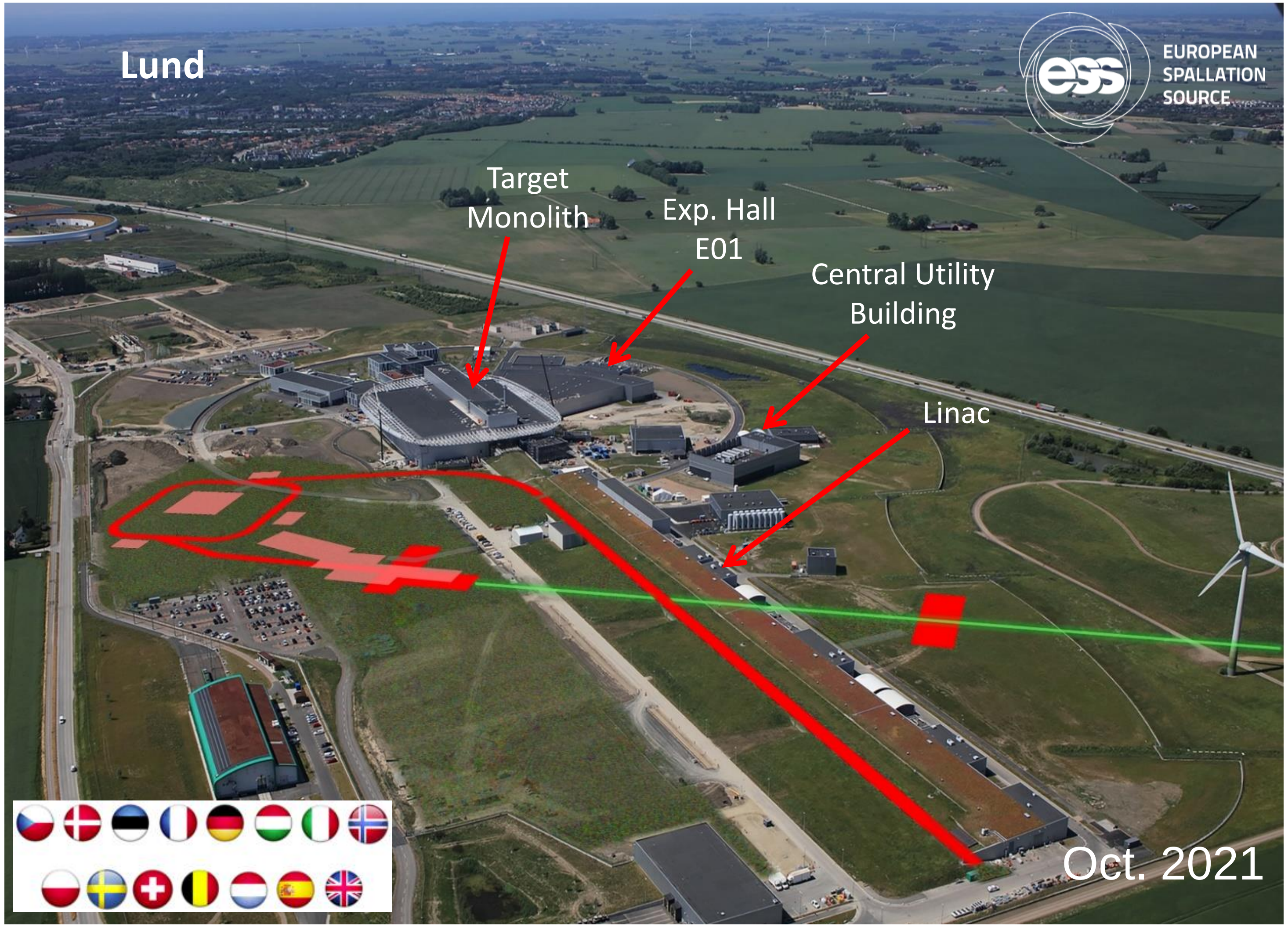
- Designed for $E_{kinetic}$ = 2 GeV and power of 5 MW ➔ **Makes longer baseline possible**





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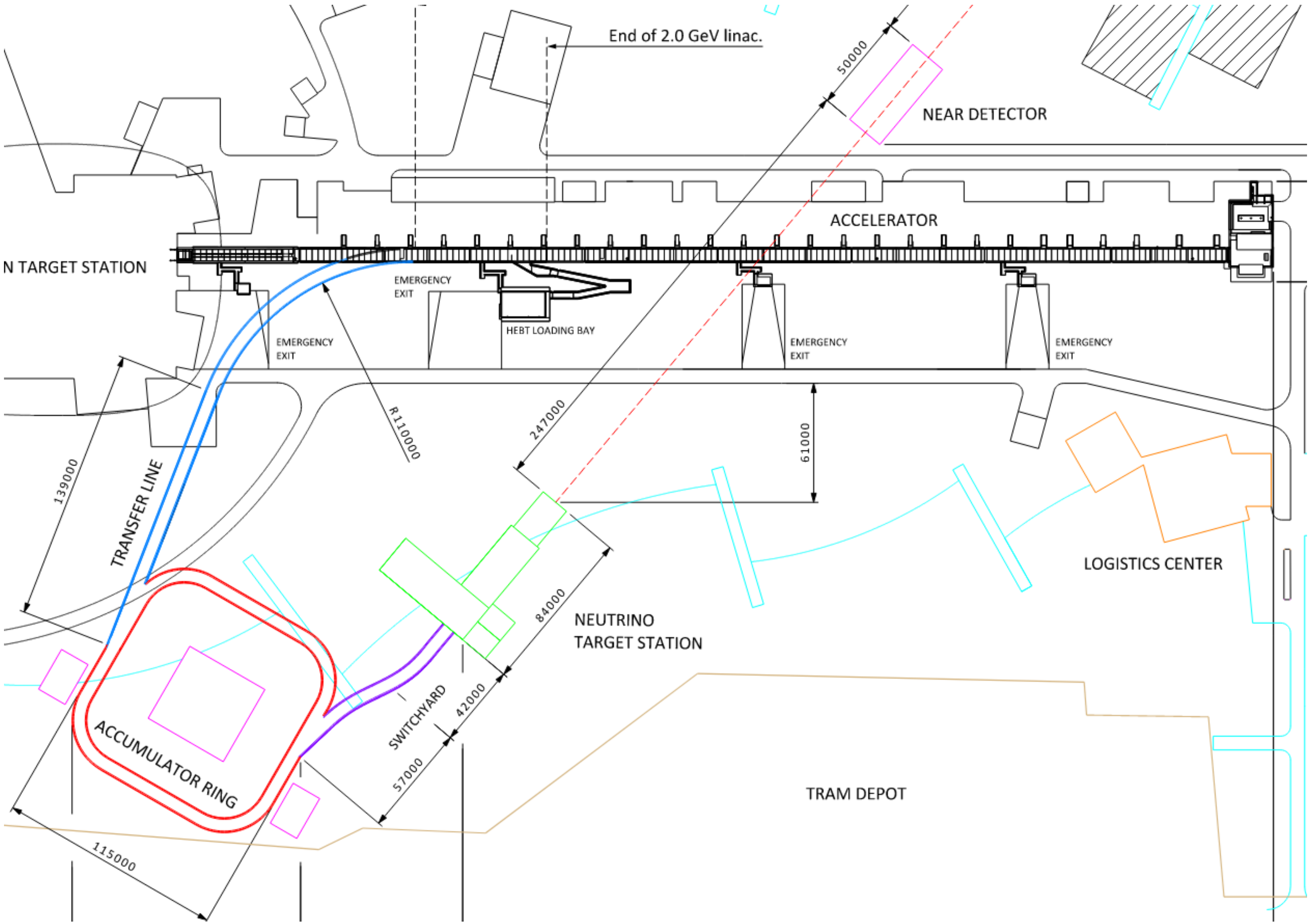
ESS Upgrades to Host the Neutrino Experiment



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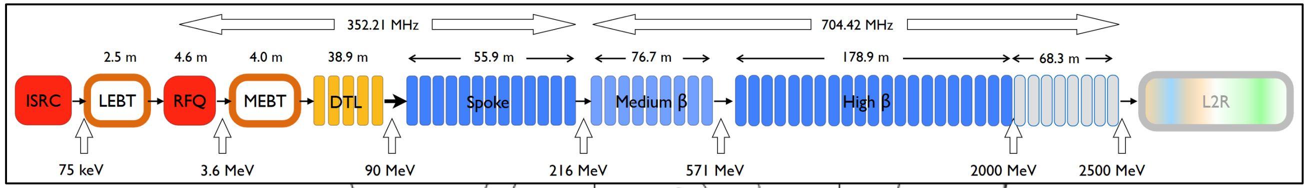
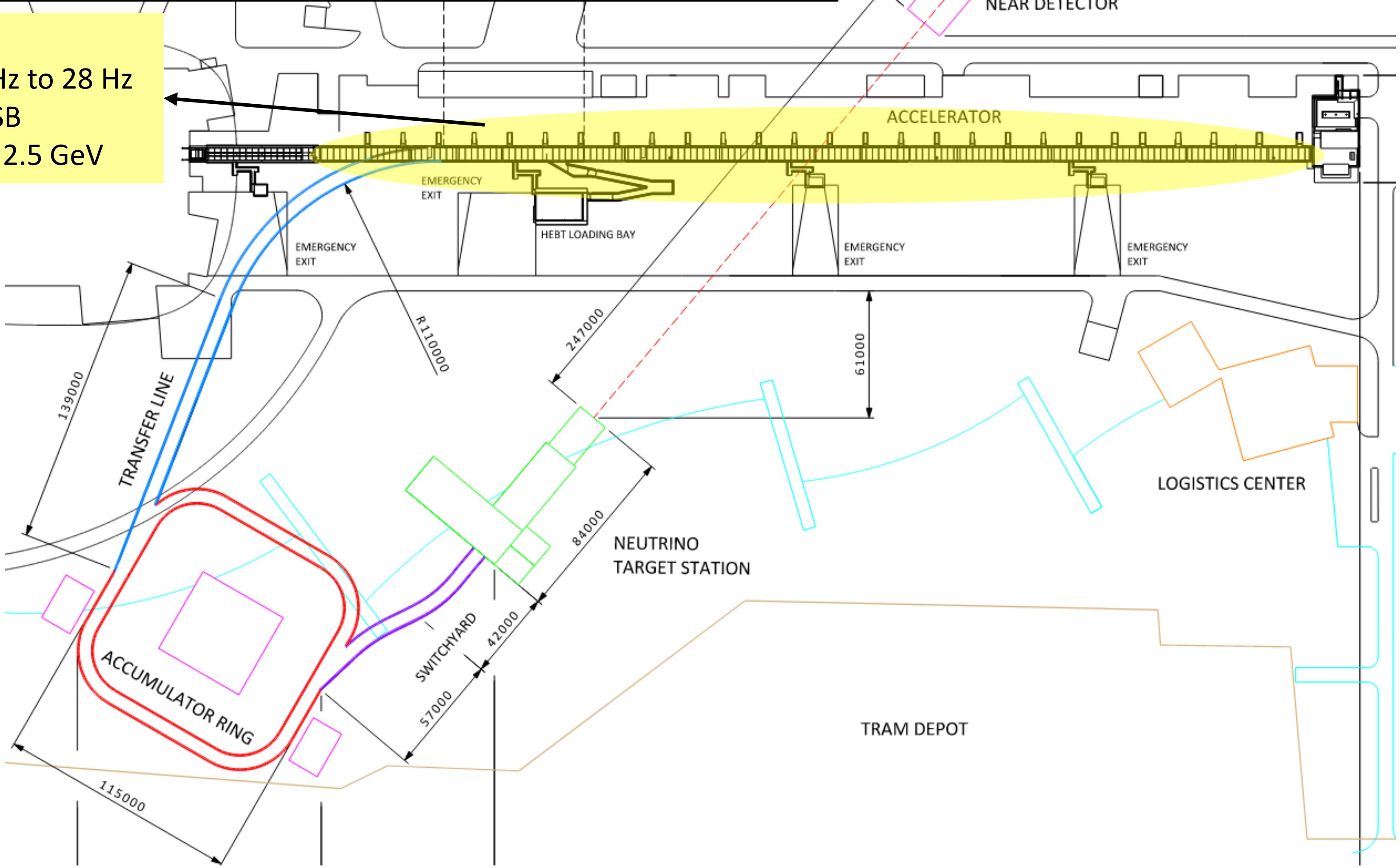


Upgrade of the accelerator

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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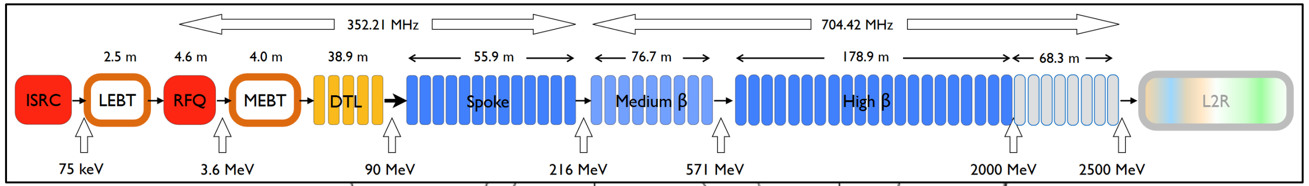

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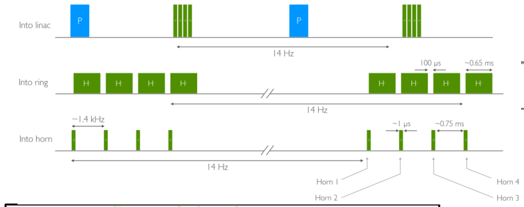
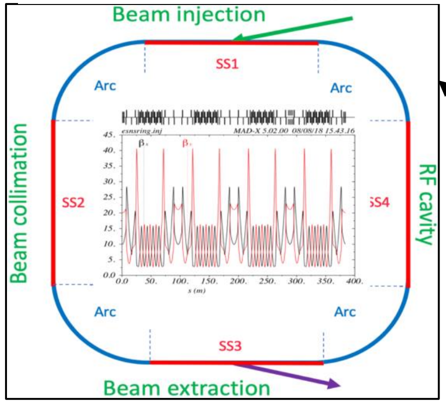
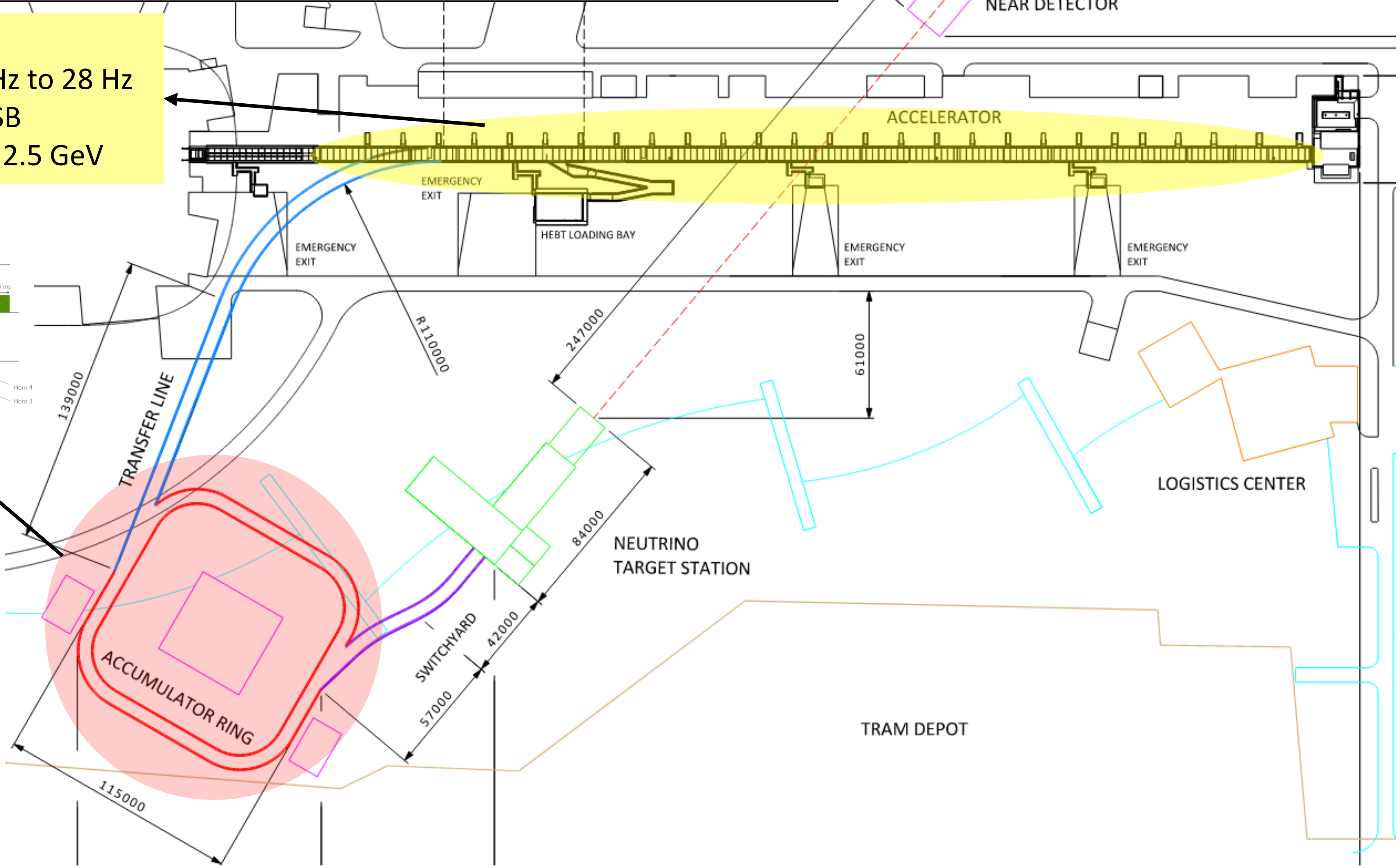
Pulsing scheme



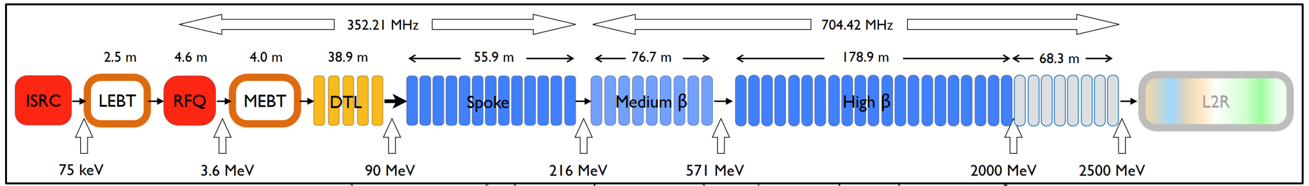


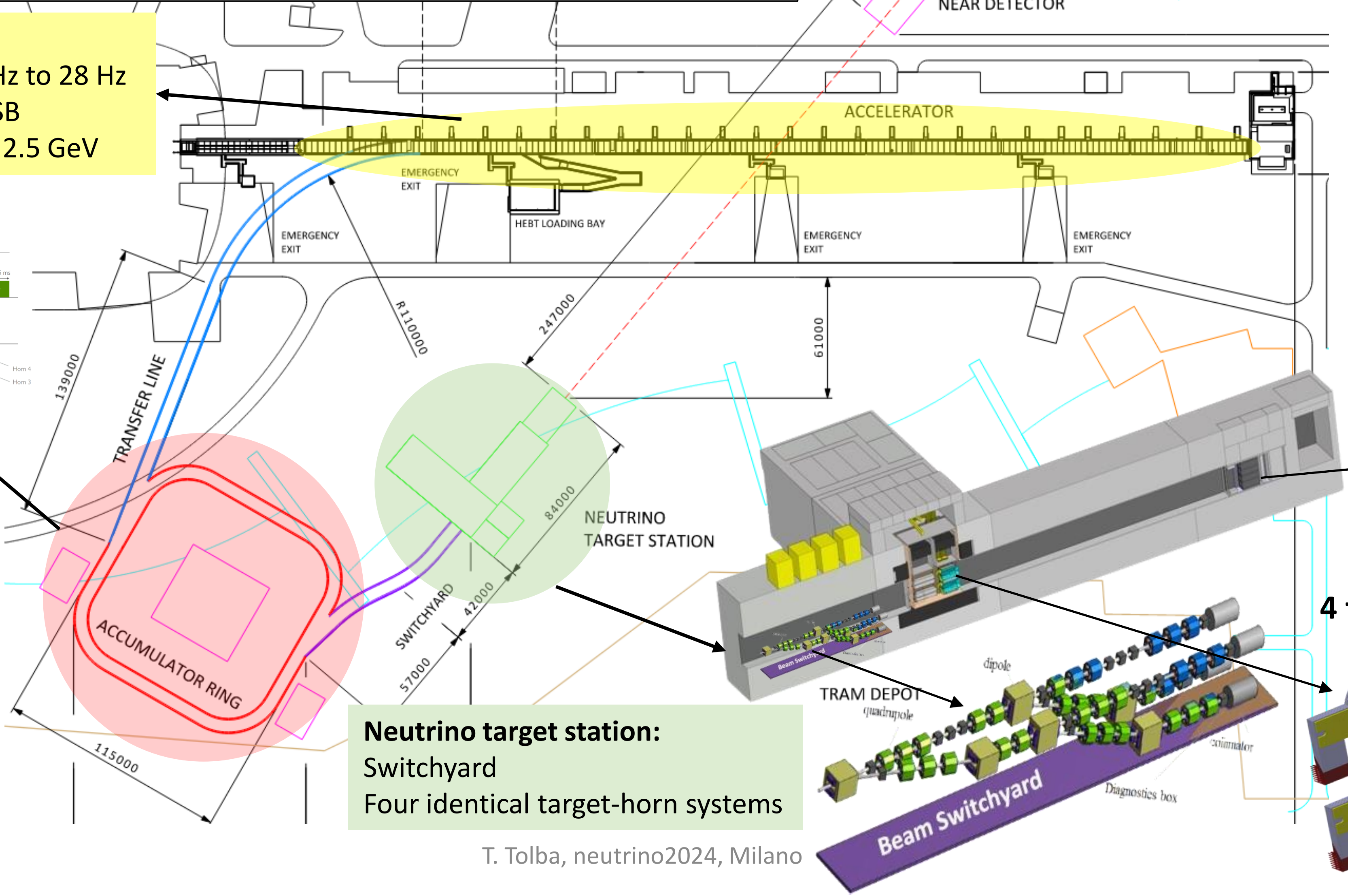


Build an accumulator ring

Compress ESS pulse length from 2.86 ms to 4x 1.2 µs

ESS Upgrades to Host the Neutrino Experiment





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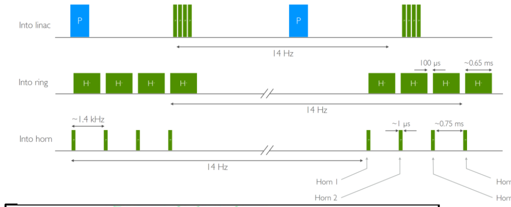

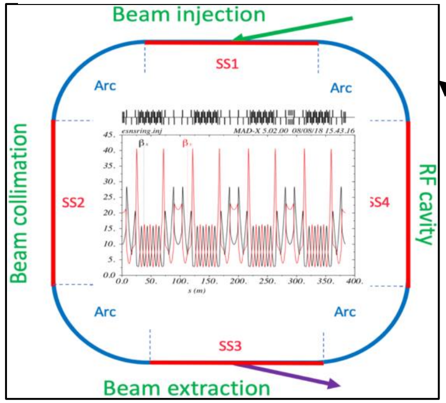

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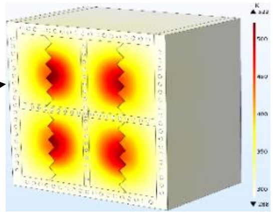
Neutrino target station:

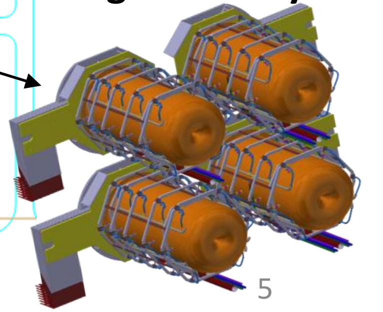
Switchyard

Four identical target-horn systems

Beam dump



4 target-horn systems



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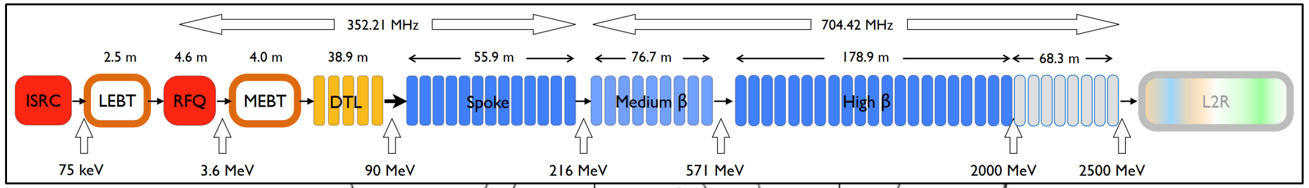

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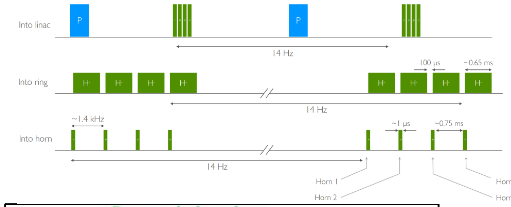

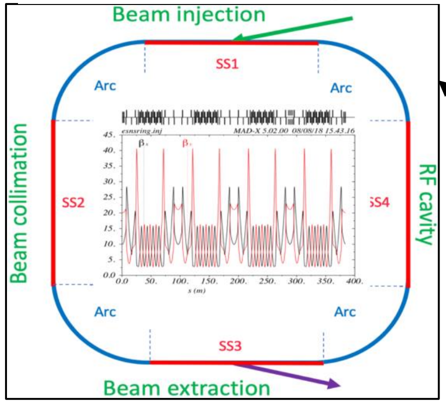

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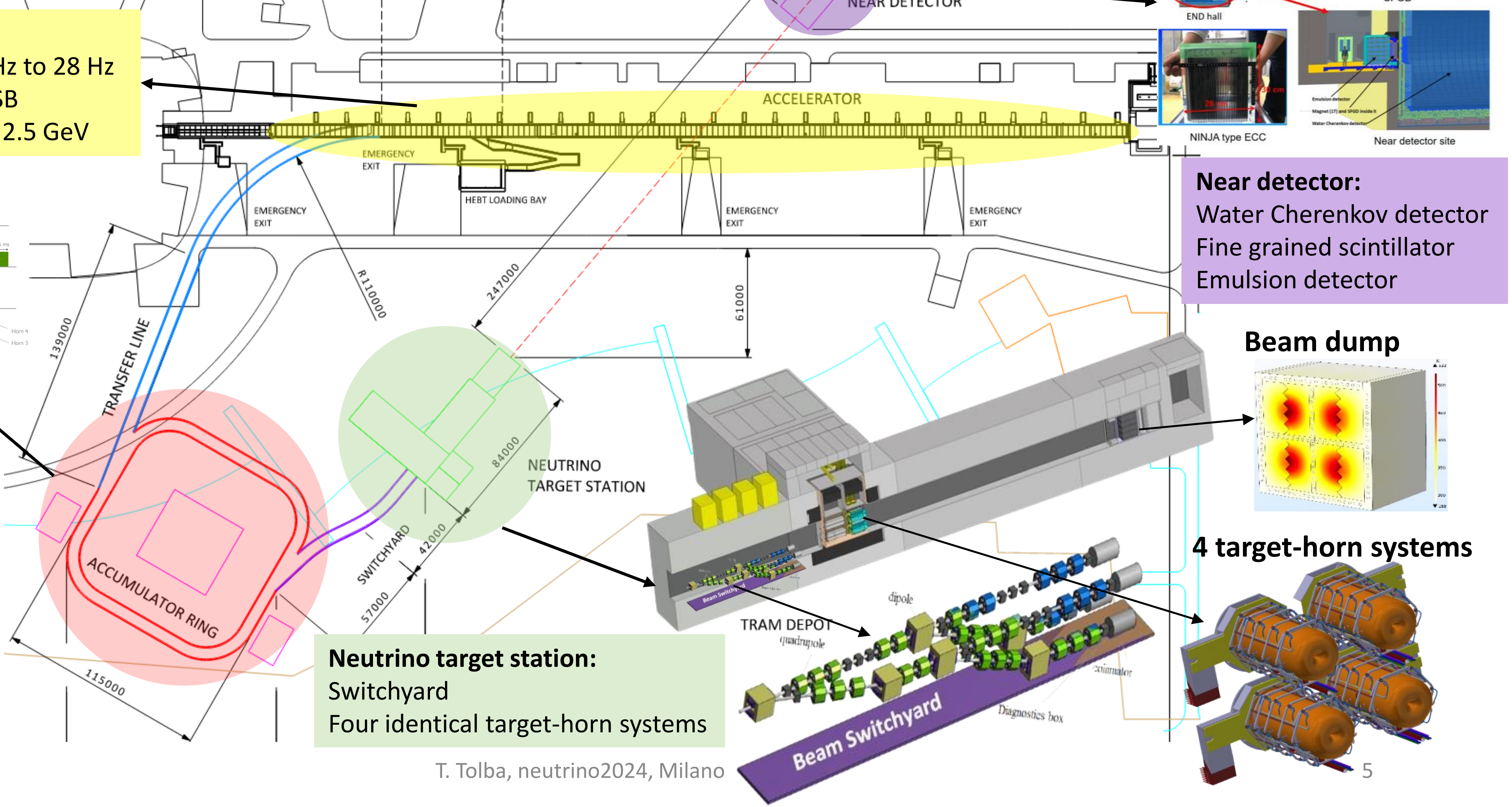


Near detector:

Water Cherenkov detector

Fine grained scintillator

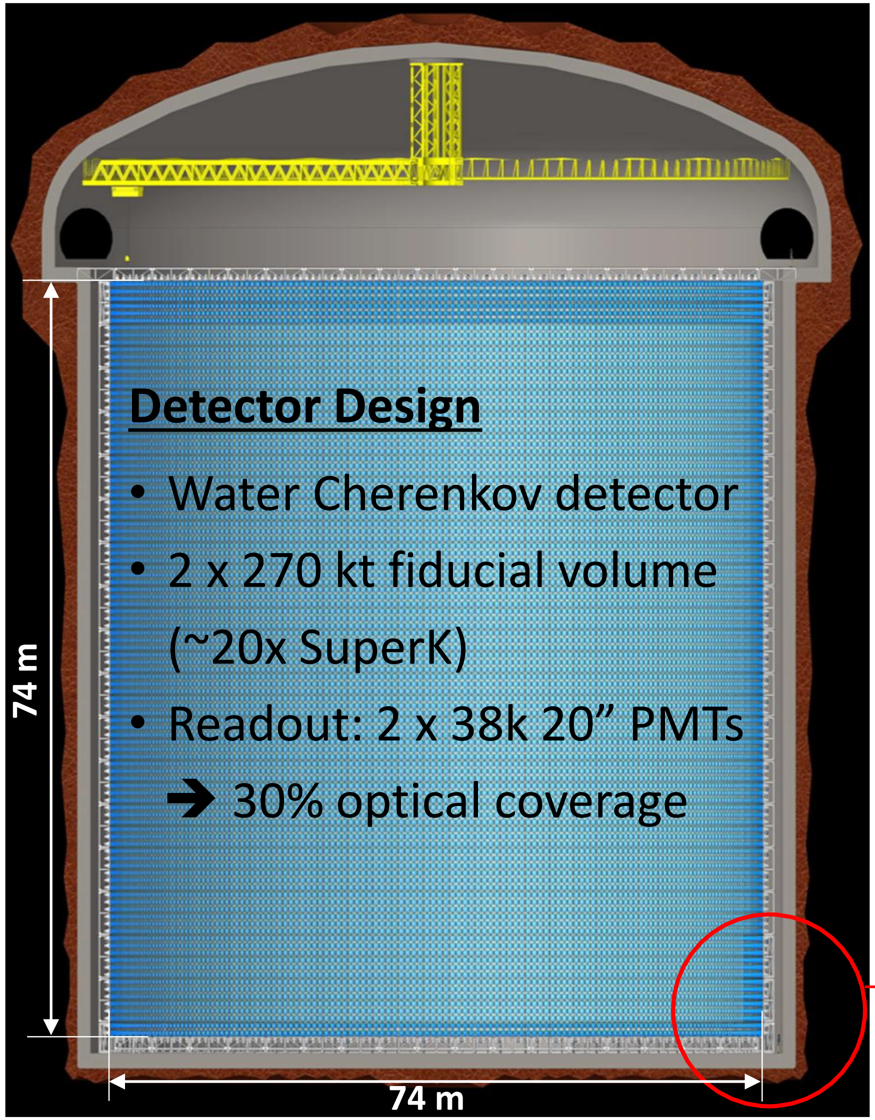
Emulsion detector

Neutrino target station:

Switchyard

Four identical target-horn systems

ESSnuSB Far Detector



Detector Design

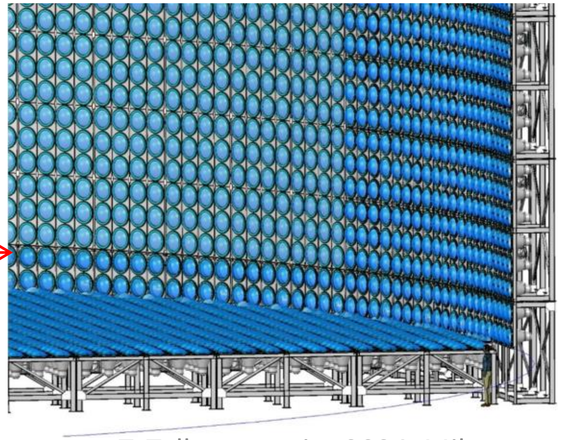
- Water Cherenkov detector
- 2 x 270 kt fiducial volume (~20x SuperK)
- Readout: 2 x 38k 20” PMTs
  ➔ 30% optical coverage

Detector Specifications

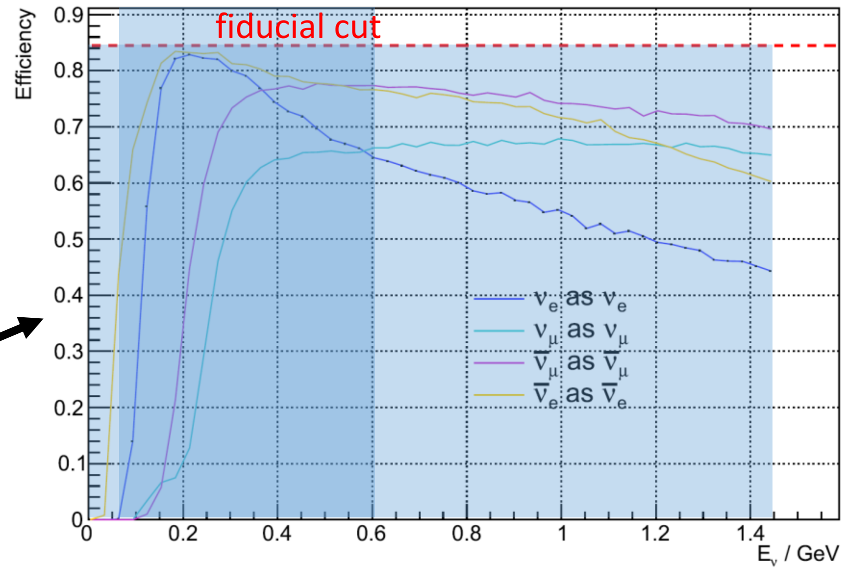
- Baseline 360 km
- Detector diameter 74.0 m (Internal)
- Detector height 74.0 m (Internal)
- Depth (w.r.t.) ground level : 1000 m

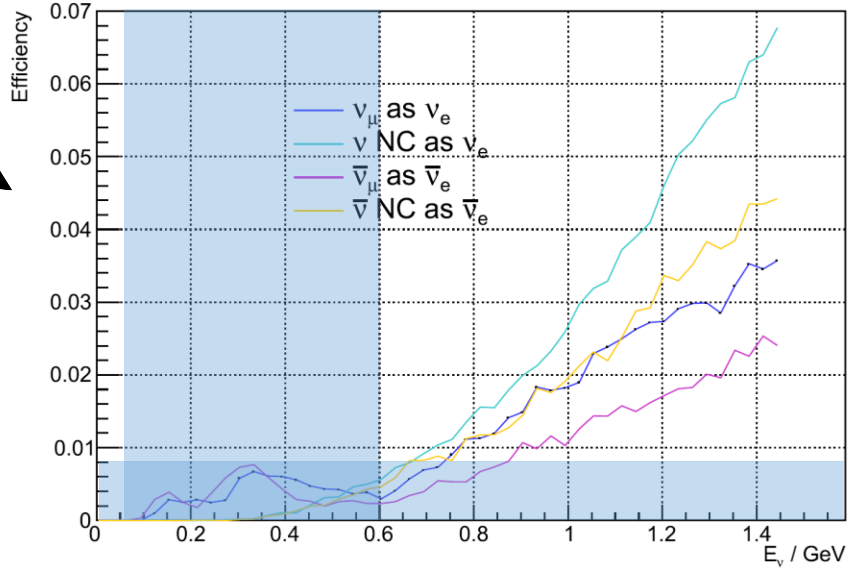
Detector Performance

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



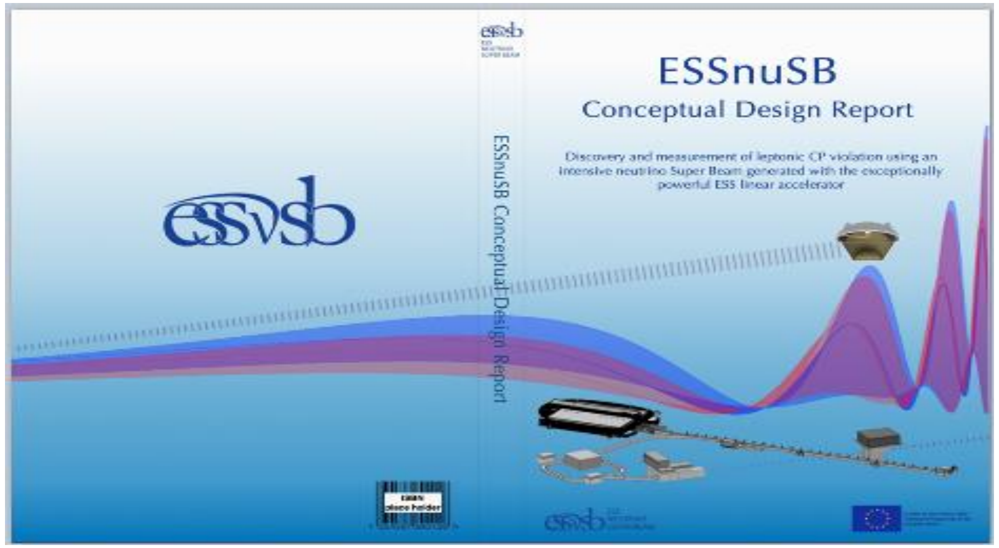
ESSnuSB Particle selection efficiency



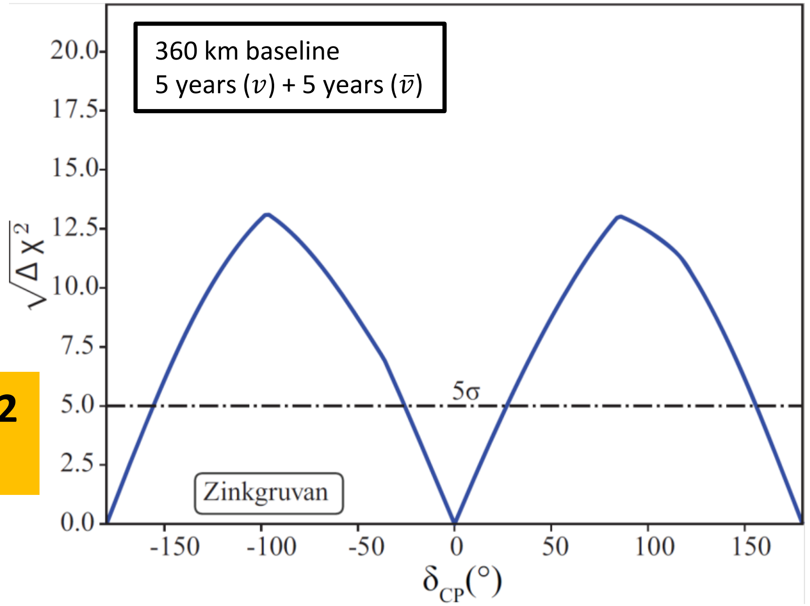


Eur. Phys. J. Spec. Top. 231, (2022) 3779–3955

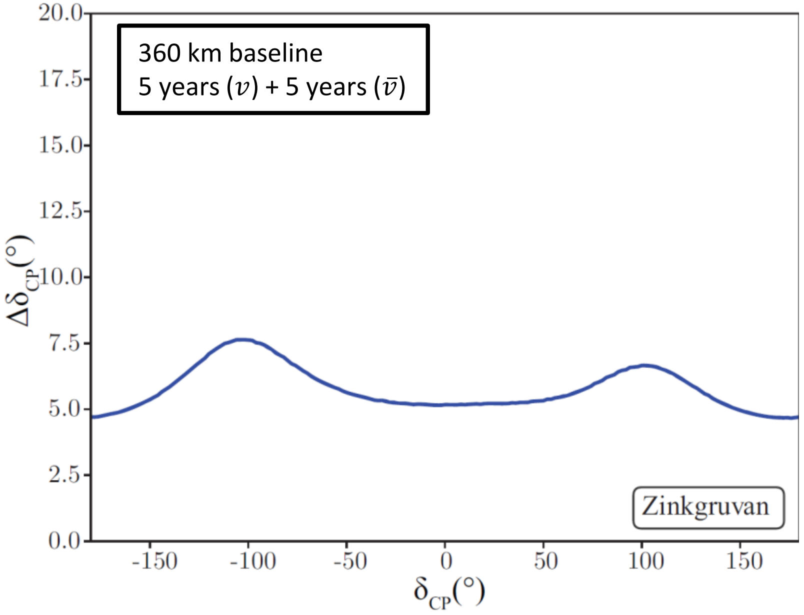
ESSnuSB Physics Reach



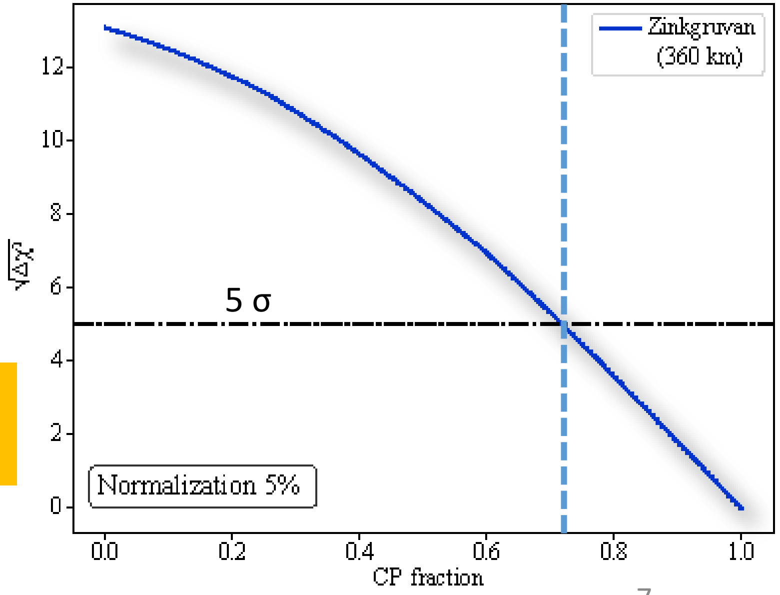
[Eur. Phys. J. ST. 231 (21), (2022) 3779]



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.)

Why Measure Leptonic CPV Precisely?

- The observed matter in the universe >> observed amount of CP violation in the quark sector of the SM
- 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:

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

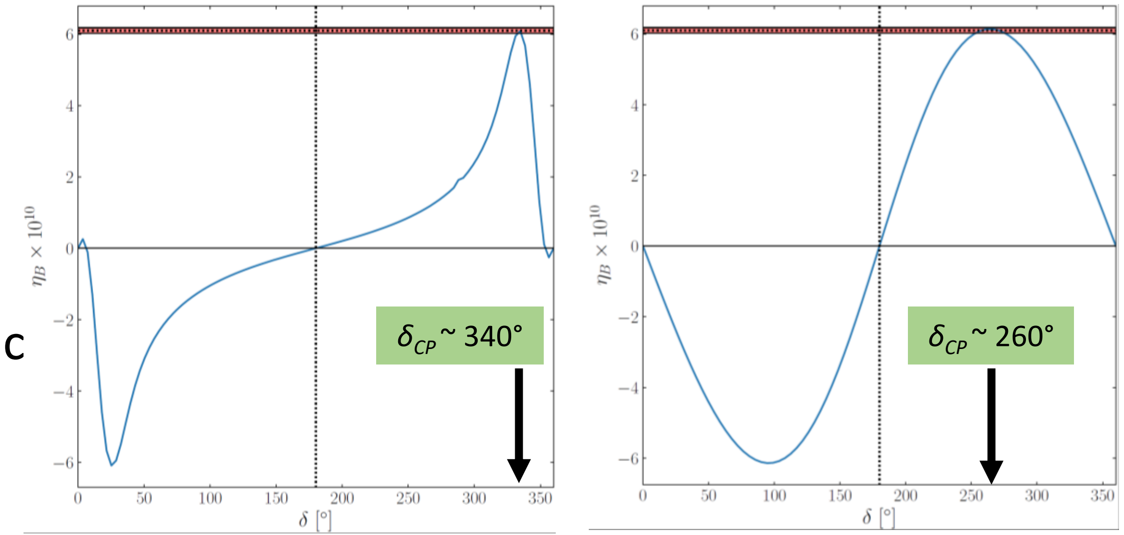
(S.T. Petcov, NPB 2024, IAS, HKUST, Hong Kong 20/02/2024)

➔**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)]

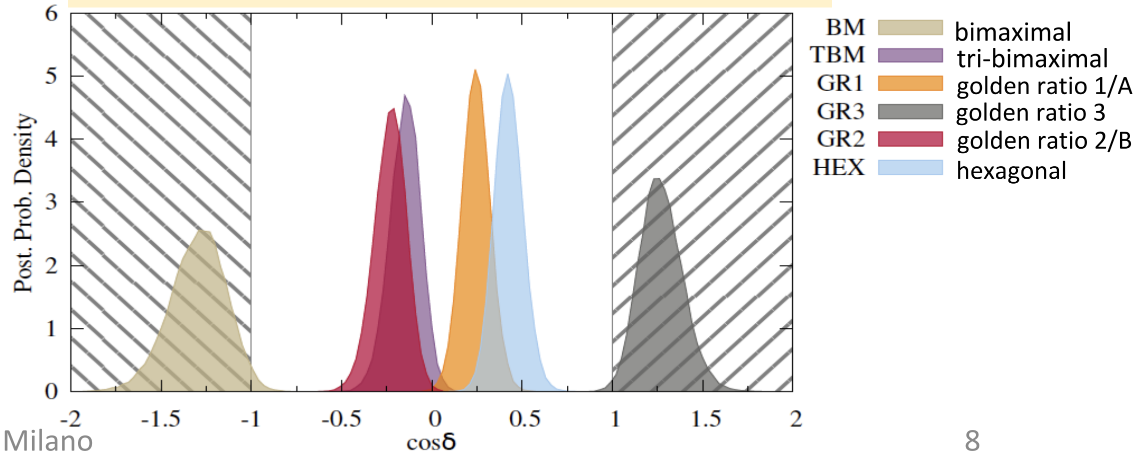
Low mass flavor regime M_1 (GeV) < 10^9

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+

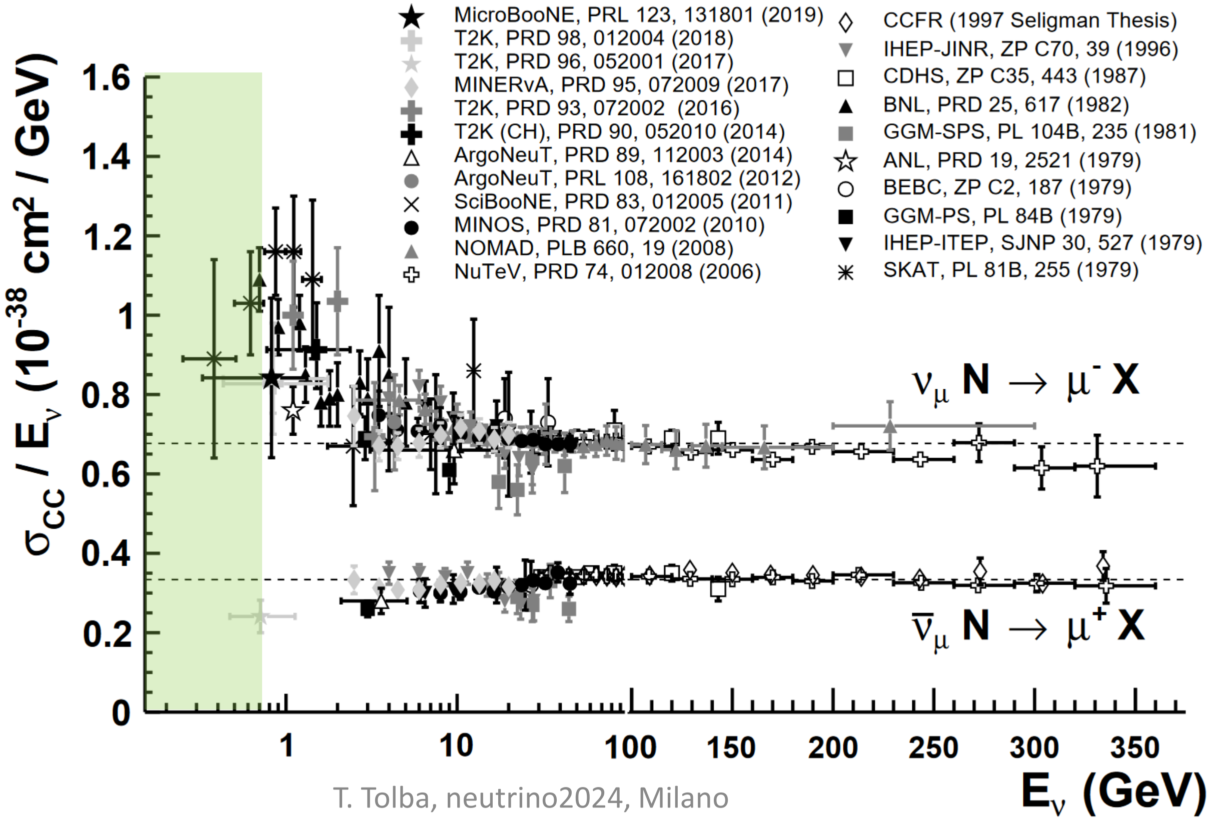
(European Spallation Source neutrino Super Beam plus)

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

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

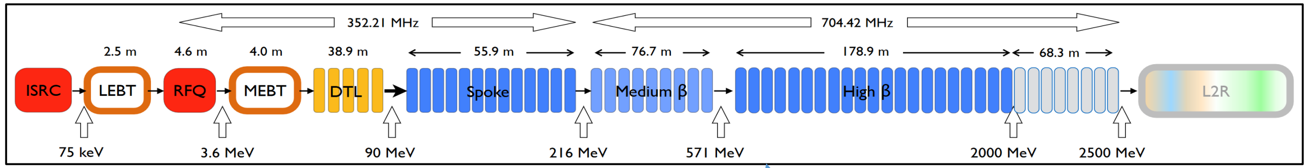
missing measurements at the ESSnuSB region: below 600 MeV

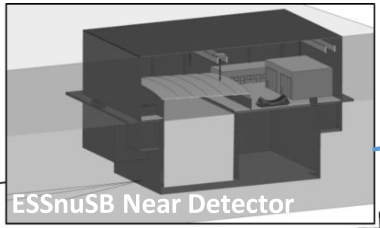
https://pdg.lbl.gov/2022/reviews/rpp2022-rev-nu-cross-sections.pdf

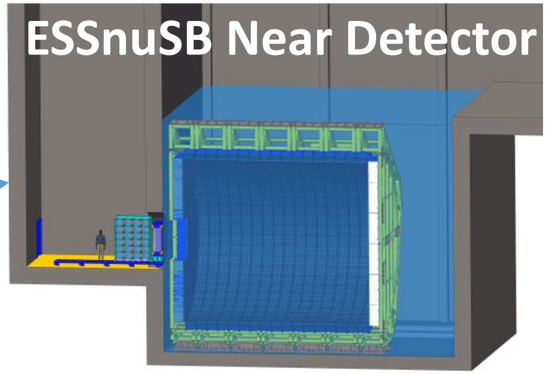


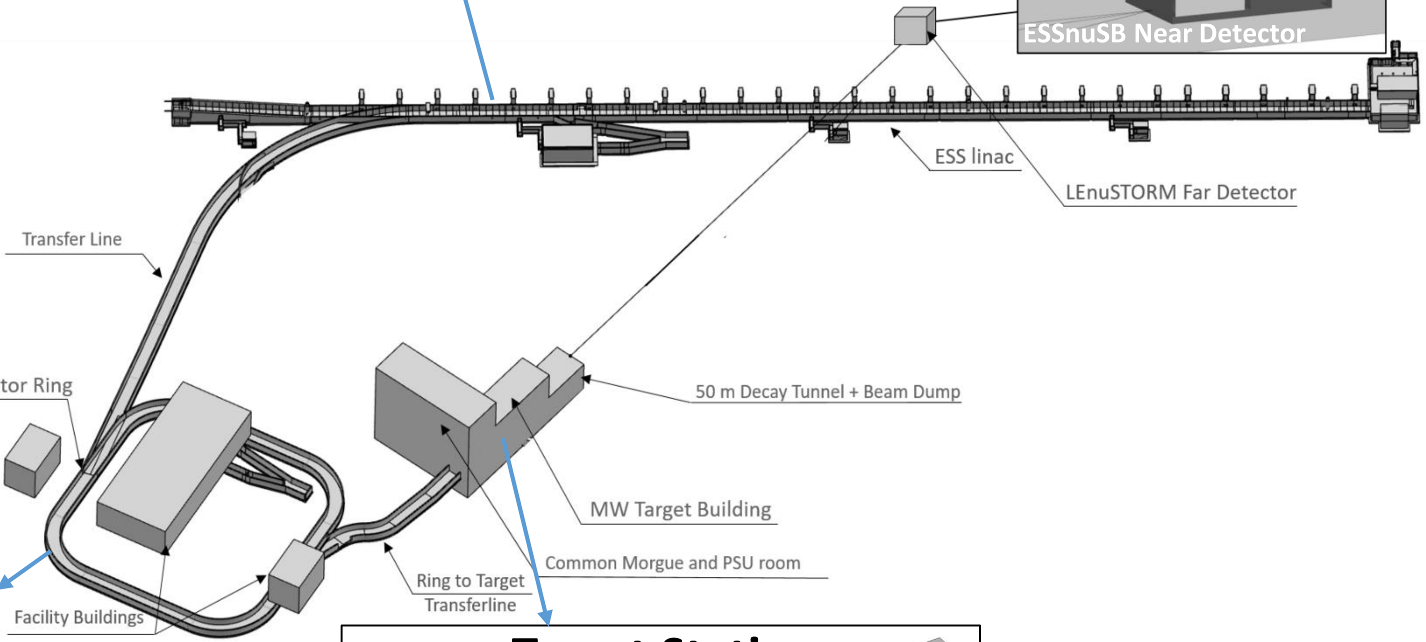
ESS Upgrades to Host the ESSnuSB+

ESS linac

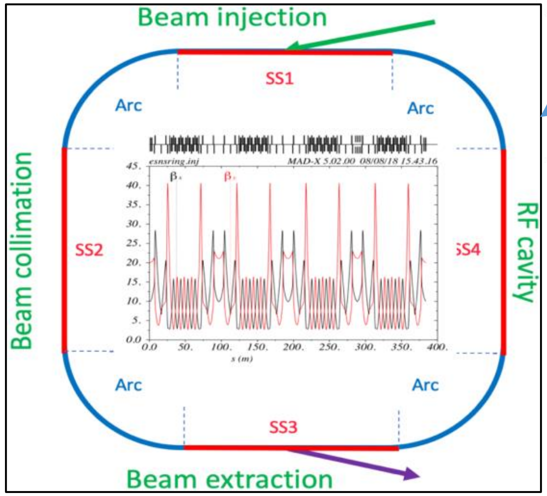




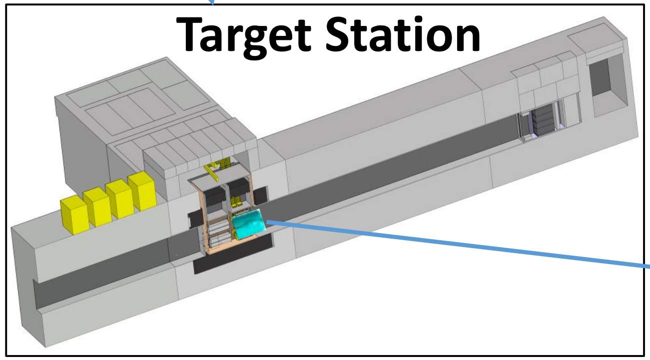




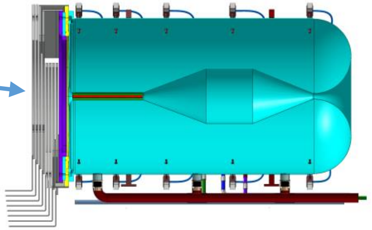
Accumulator Ring



Target Station



One horn-target system



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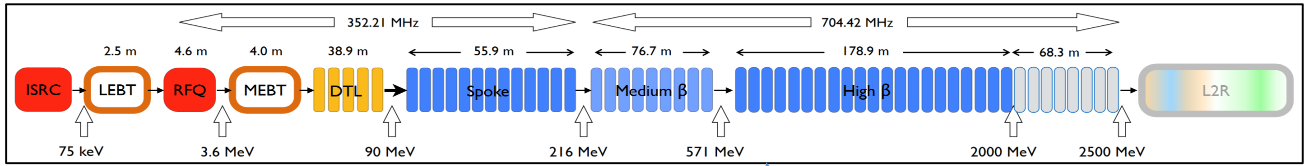
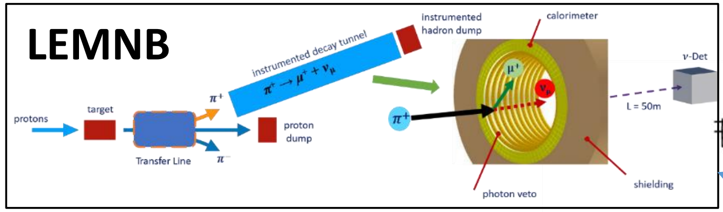
ESS Upgrades to Host the ESSnuSB+

ESS linac

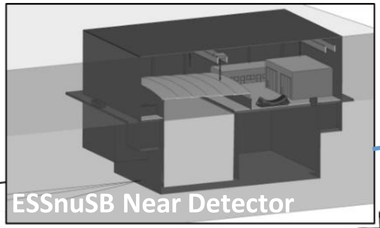


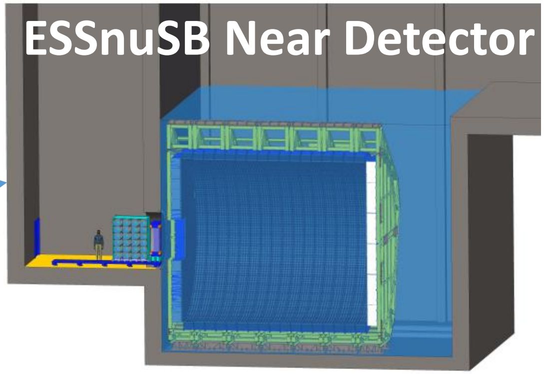
LEMNB

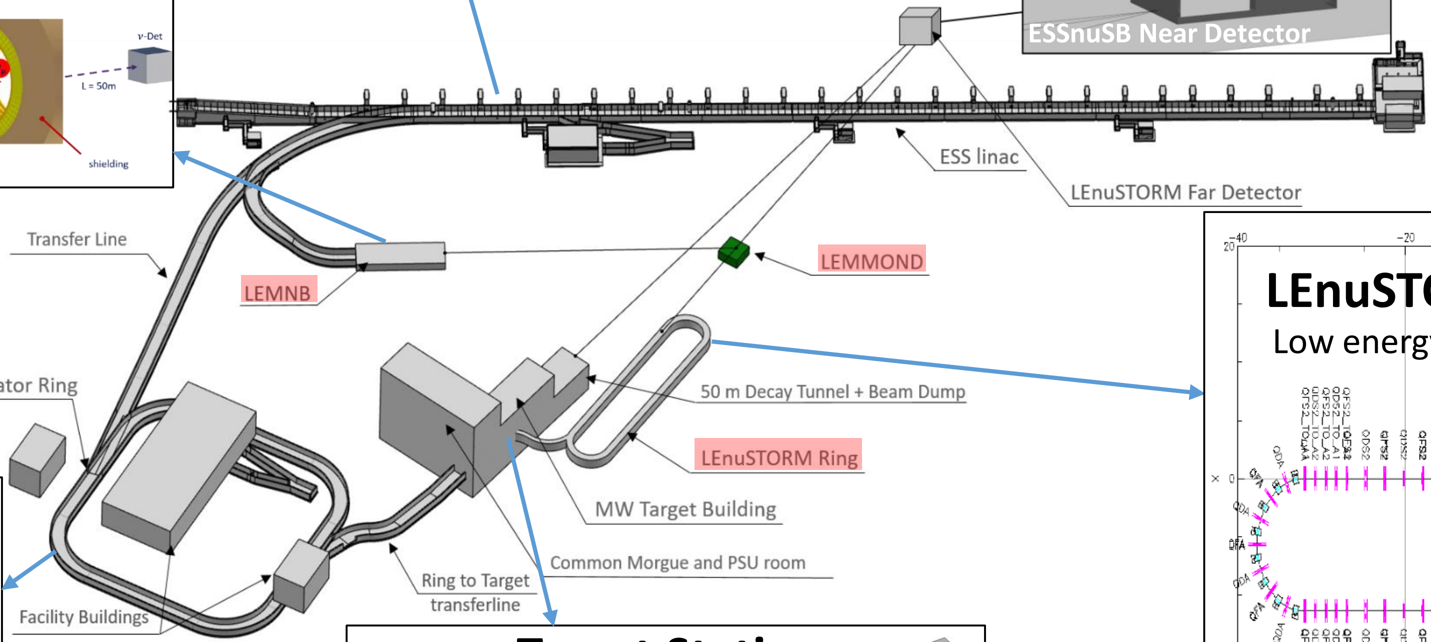


Low Energy Monitored neutrino Beam

ENUBET	Giulia Brunetti
Friday	11:20 - 11:40

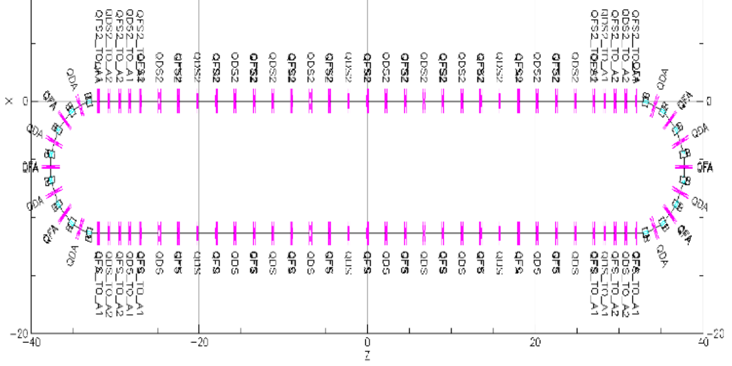




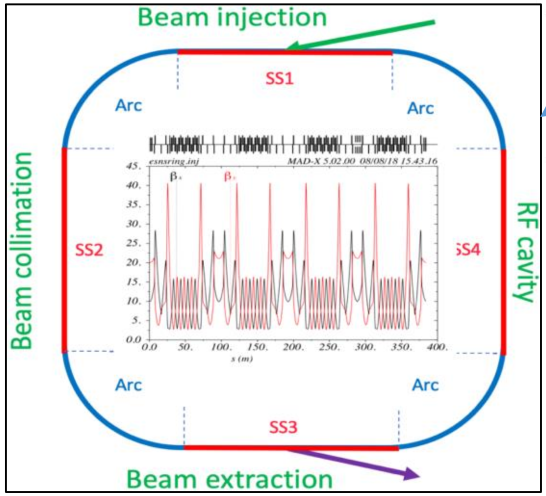


LEnuSTORM

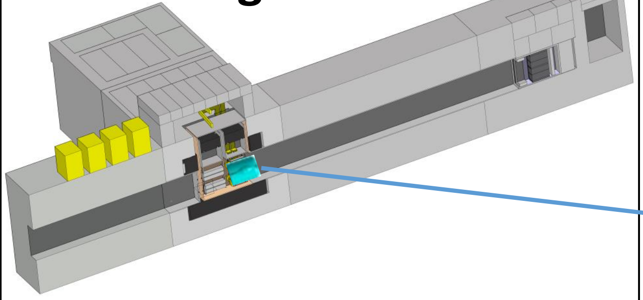
Low energy neutrino from STORed Muons



Accumulator Ring



Target Station



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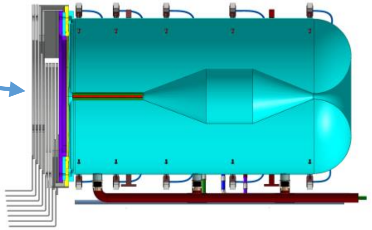
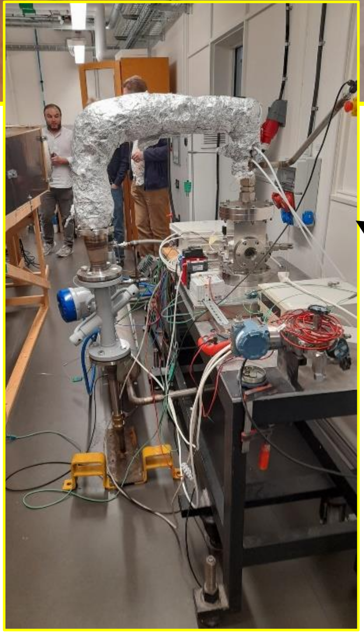


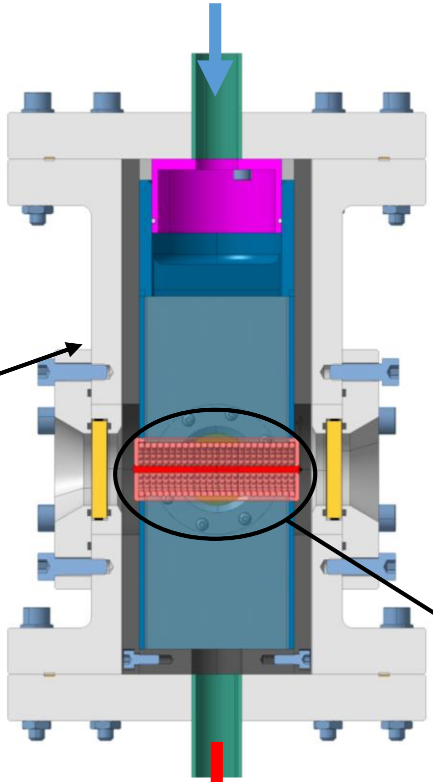
ESSnuSB R&D Program (Target Prototyping)

- 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.

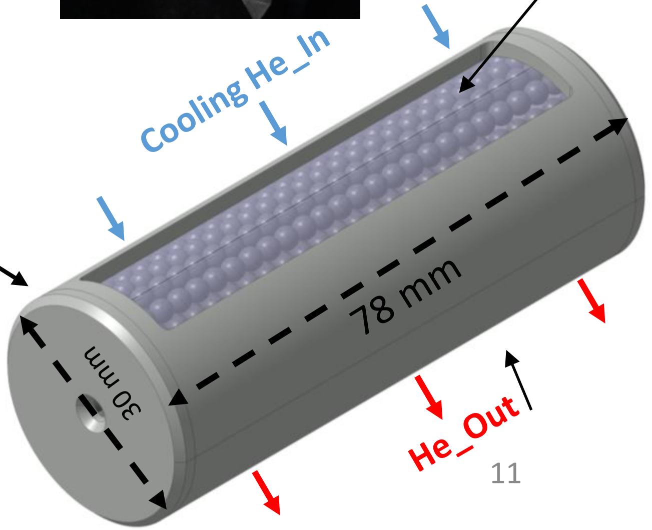
Mechanical Measurements Lab (MML) @ESS



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 Implementation Approach

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

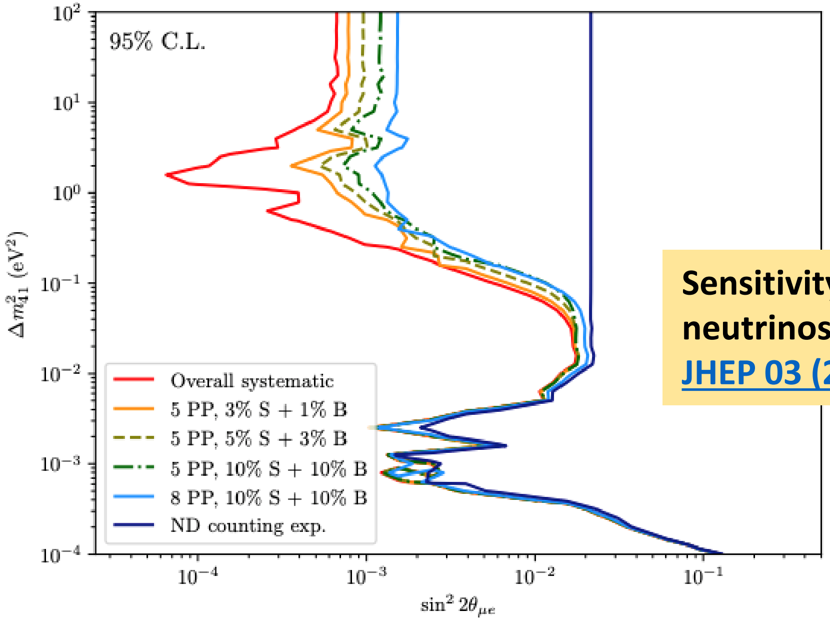
Stage 2
LENUSTORM

- 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

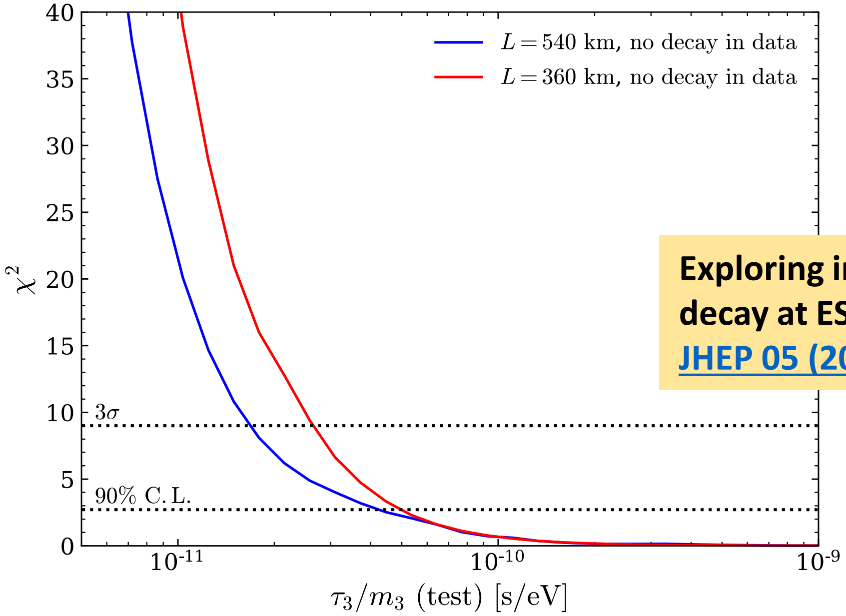
Stage 3
ESSnuSB CPV LBL

- 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

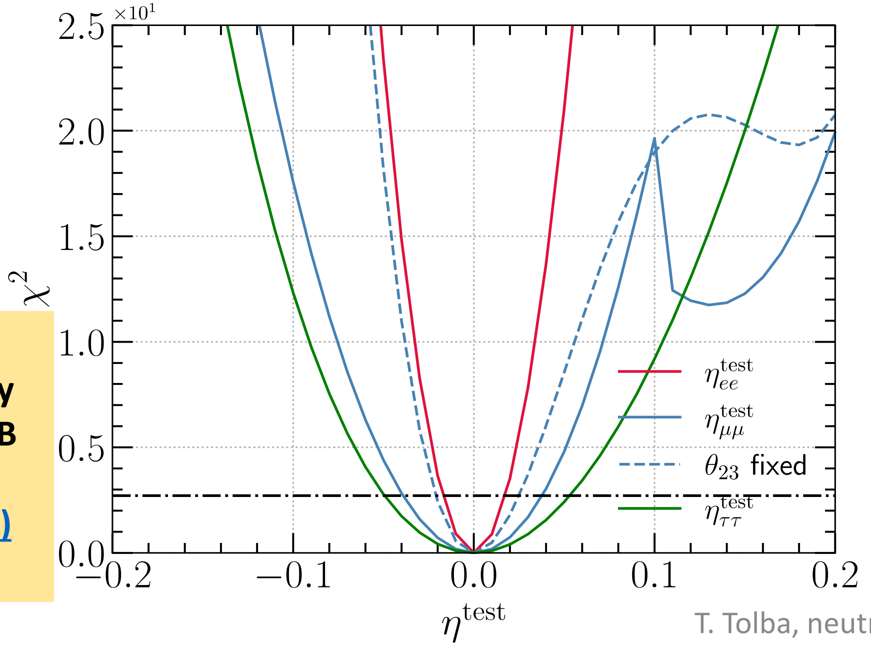
ESSnuSB Sensitivity to Constrain New Physics



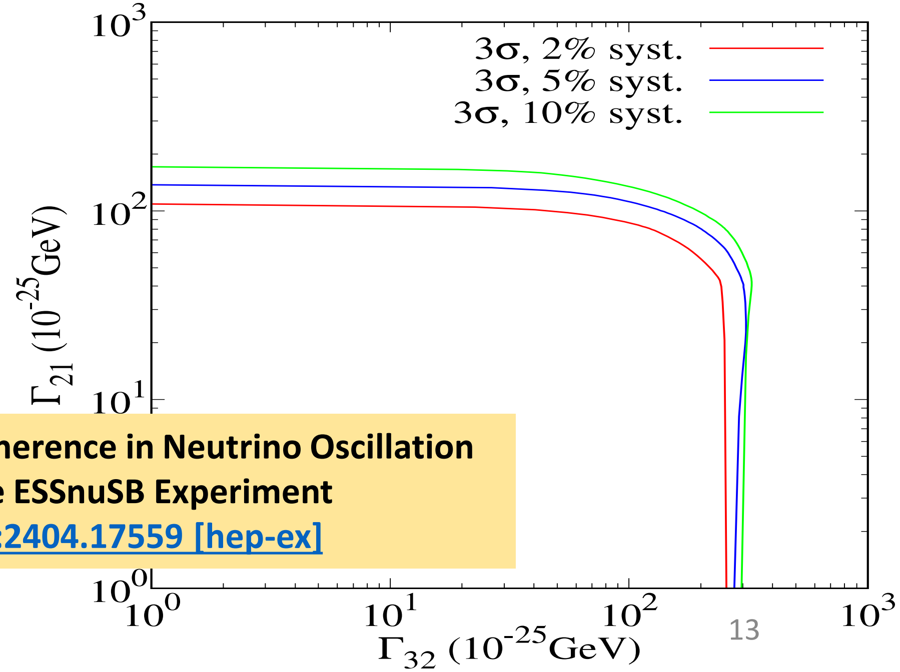
Sensitivity to light sterile neutrinos at ESSnuSB
[JHEP 03 (2020), 026]



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]]

Conclusion and Outlook

- The first phase of European Design Study of the ESSnuSB program has shown that the ESS can be used to produce an intense neutrino beam for CP violation discovery in the leptonic sector and measure the leptonic CP violating phase-angle with an error equal to or smaller than 8 degrees as required for the effective selection of a Letogenesis theory that is able to explain the presence of matter in 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.
- ESSnuSB+ proposing to stage the operations towards the final neutrino facility.
  - ➔ *The low energy ENUBET 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 [ESFRI landscape analysis 2024] in the Gaps and Needs in the Domain “Physical Sciences and Engineering ” section

ESSnuSB @ neutrino 2024

Tuesday, Jun. 18, 2024, 5:30 PM

- *Physics opportunities at the ESSnuSB/ESSnuSB+ setup* (**poster #18**). Monojit Ghosh
- *The ESSnuSB/ESSnuSB+ detector design* (**poster #28**). Budimir Kliček
- *The ESSnuSB+ Target Station* (**poster #29**). Eric Baussan / Tamer Tolba
- *Exploring new physics at ESSnuSB+* (**poster #82**). Alessio Giarnetti
- *Search for the leptonic CP violation with the ESSnuSBplus project* (**poster #370**). Marcos Dracos / Tamer Tolba

Friday, Jun. 21, 2024, 5:30 PM

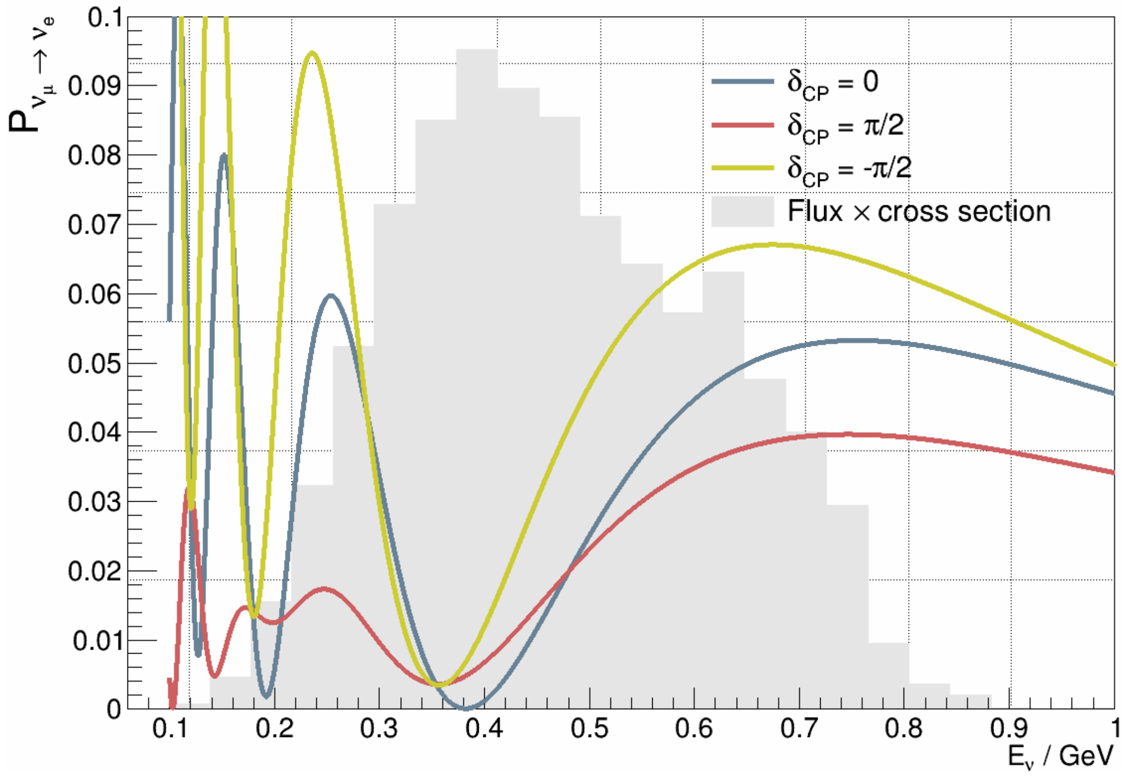
- *Investigating Quantum Decoherence in Neutrino Oscillation at ESSnuSB Experiment* (**poster #40**). Monojit Ghosh

Spare slides

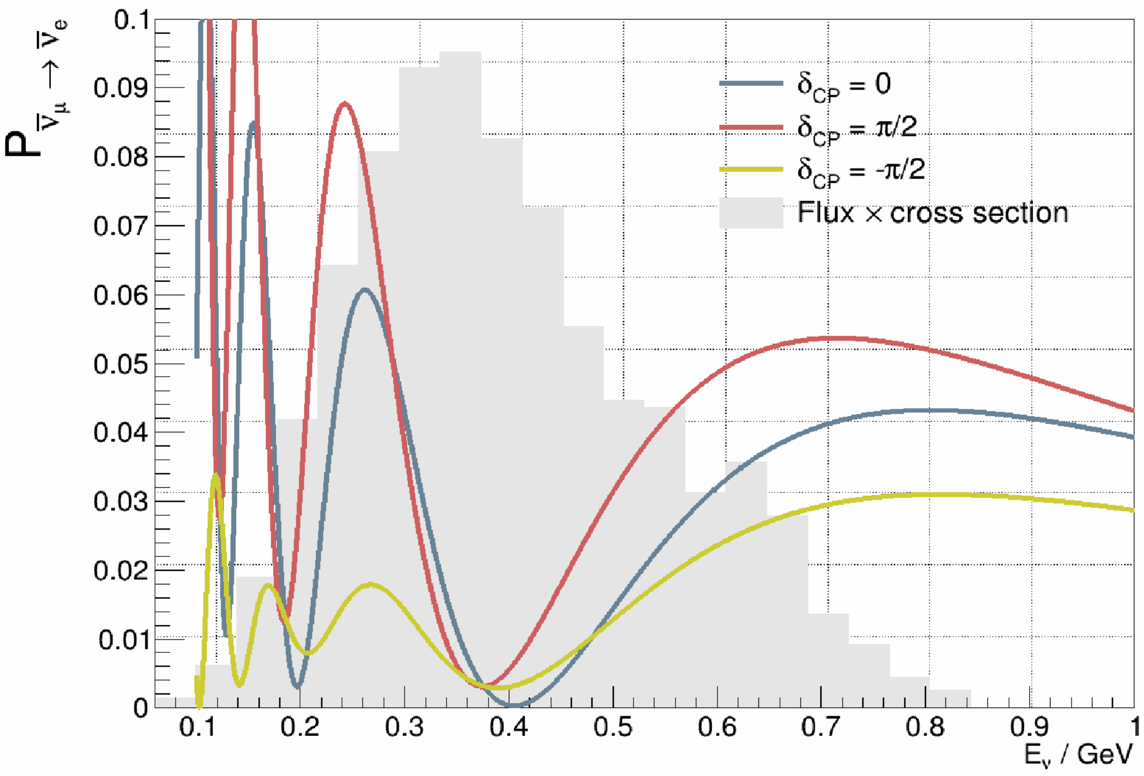
ESSnuSB energy coverage

Baseline = 360 km

neutrinos



antineutrinos



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

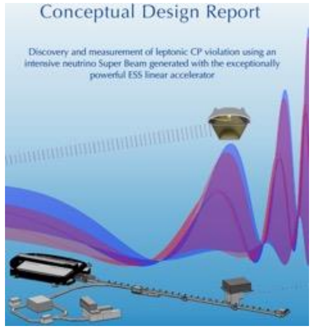
Nucl. Phys. B 885 (2014) 127

COST
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

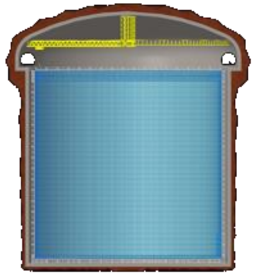
ESFRI

EUROPEAN SPALLATION SOURCE

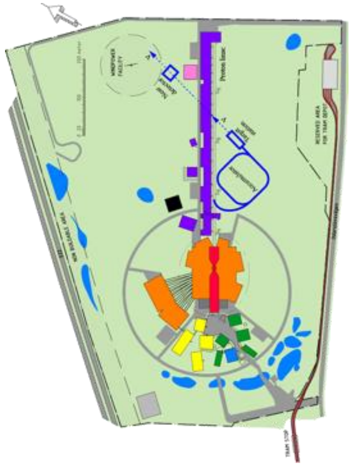
ESS neutrino Super Beam plus

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

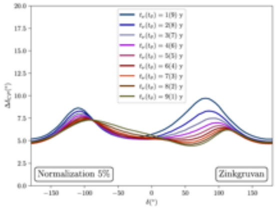
2026-2028: TDR Phase, International Agreement



2028-2037: Construction of the facility and detectors, including commissioning



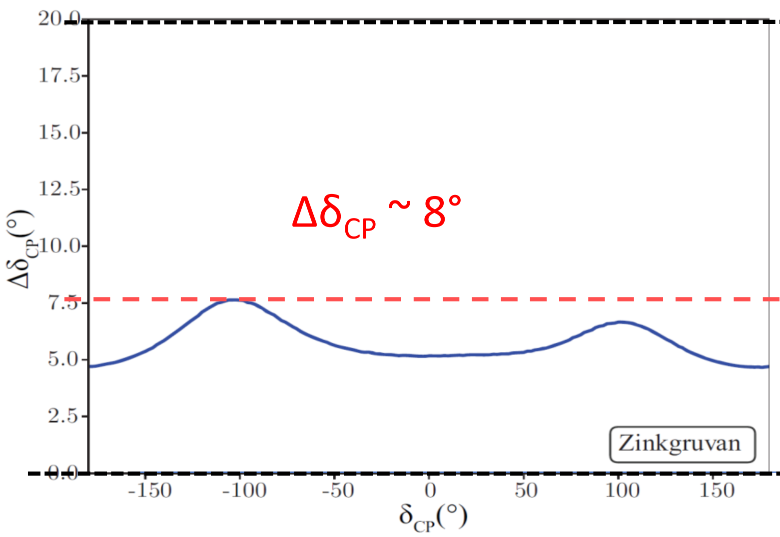
physics



Data Taking

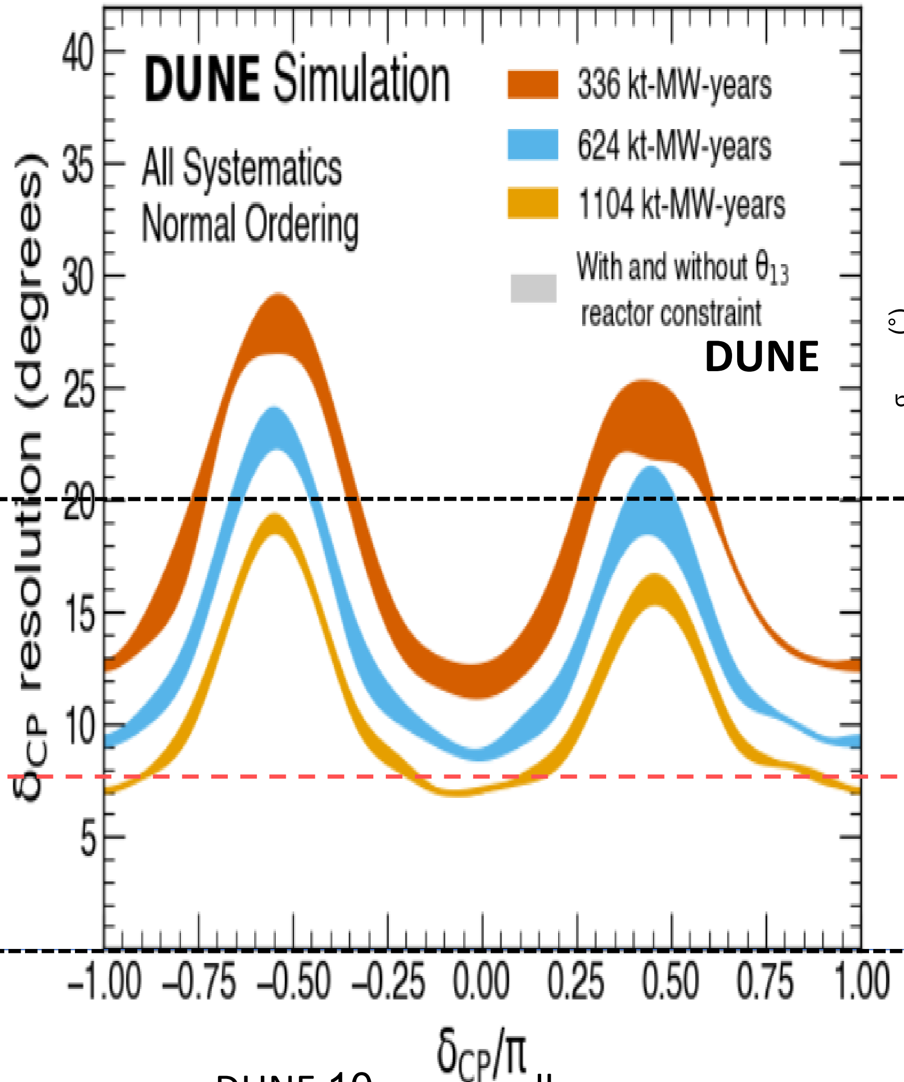
ESSnuSB Performance Comparison with Other Experiments

ESSnuSB in the international context – precision in δ_{CP}



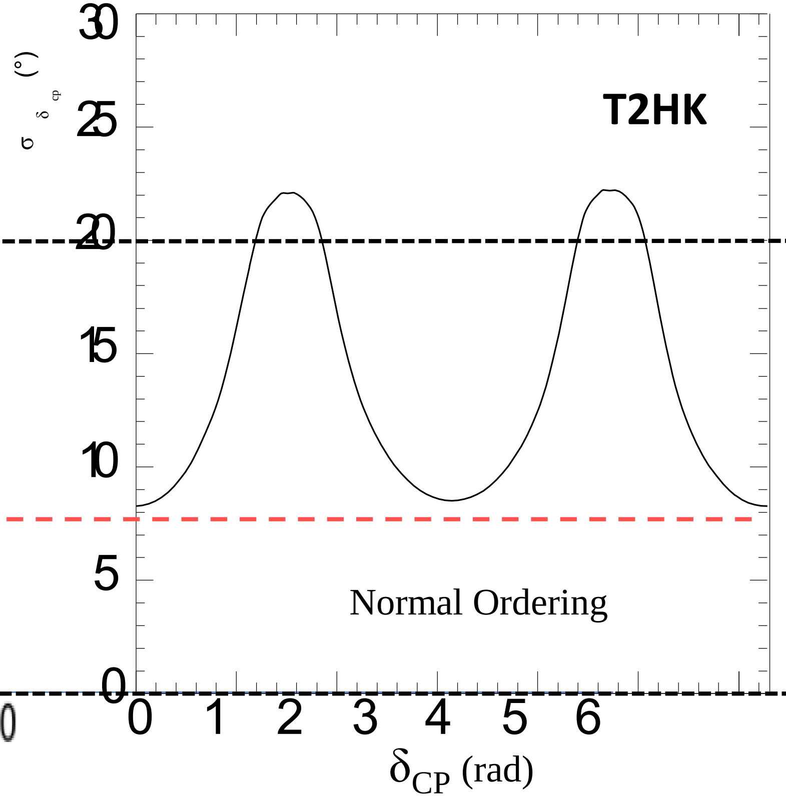
ESSnuSB 10 years

https://arxiv.org/abs/2206.01208 p. 205



DUNE 10 years, yellow curve

https://arxiv.org/abs/2002.03005 p. 174



HyperKamiokande 10 years

https://arxiv.org/abs/1611.06118 p. 60

Why 2nd Oscillation Maximum?

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

Picture before 2012

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

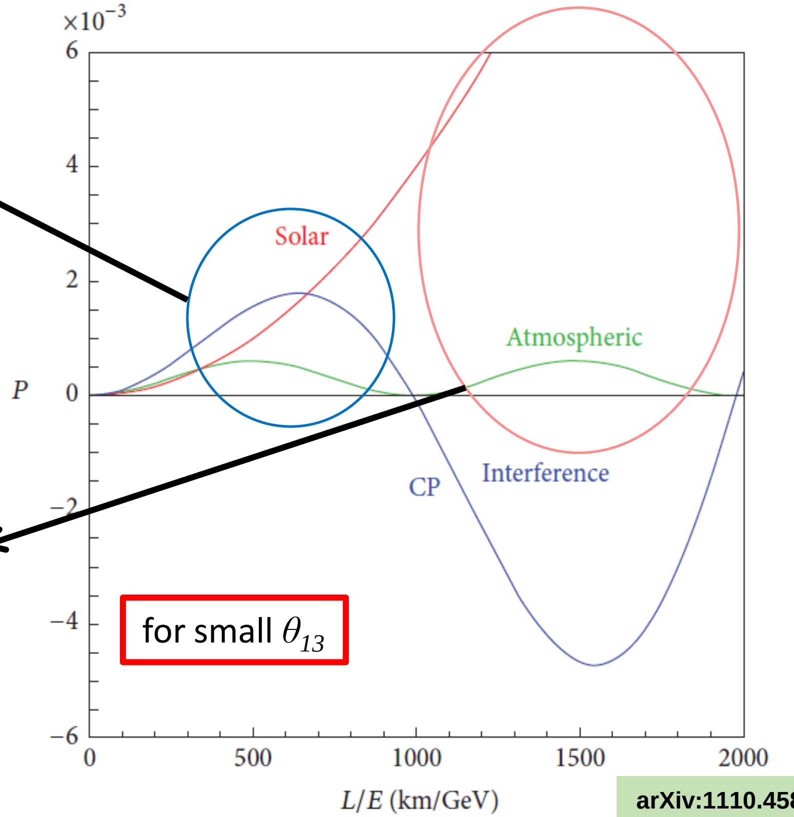
where $\bar{J} \equiv cos\theta_{13} sin2\theta_{12} sin2\theta_{23} sin2\theta_{13}$ and $\Delta_{ij} \equiv \Delta m^2_{ij}/2E_\nu$. E_ν is the neutrino energy, L is the source-to-detector distance, the *baseline, and* the sign of δ_{CP} is the opposite for antineutrinos.
In this plot $cos\left(\delta_{CP}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

Important for CPV in leptonic sector

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

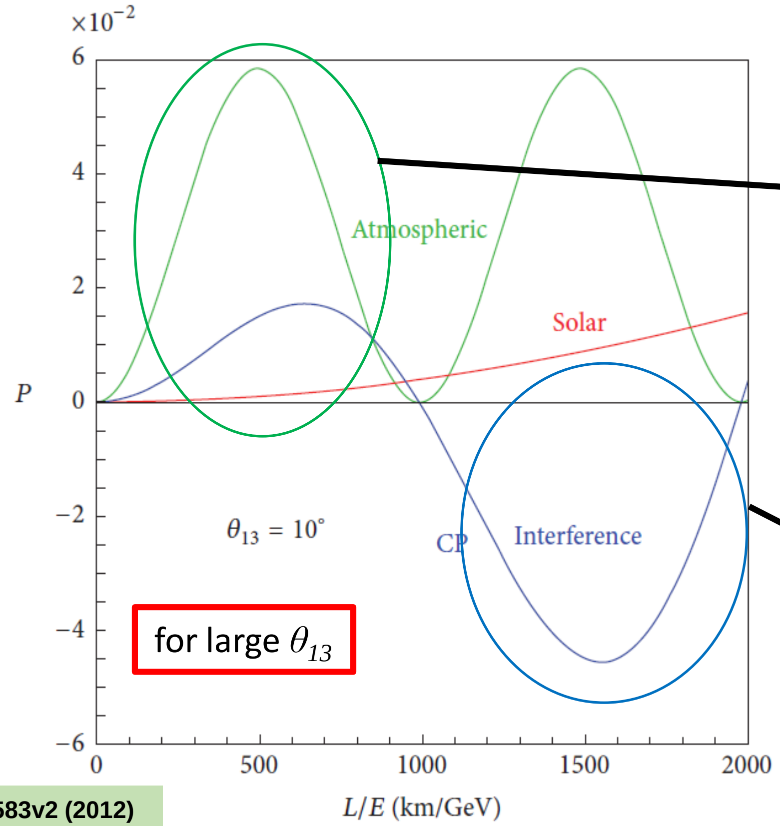
@ 1st oscillation max.
CP-interference dominates

@ 2nd oscillation max.
Solar term dominates



for small θ_{13}

arXiv:1110.4583v2 (2012)



for large θ_{13}

@ 1st oscillation max.
Atm. term dominates

@ 2nd oscillation max.
CP-interference dominates

Why 2nd Oscillation Maximum?

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

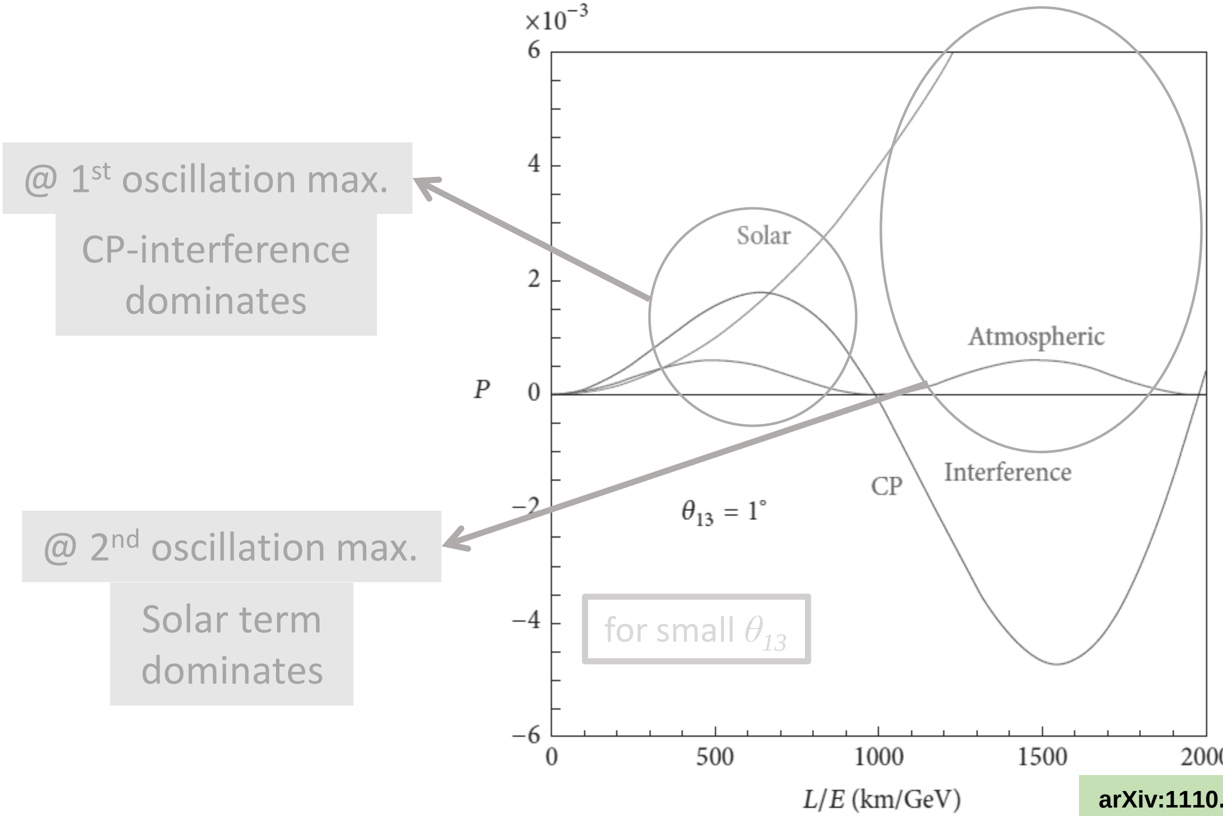
Picture after 2012

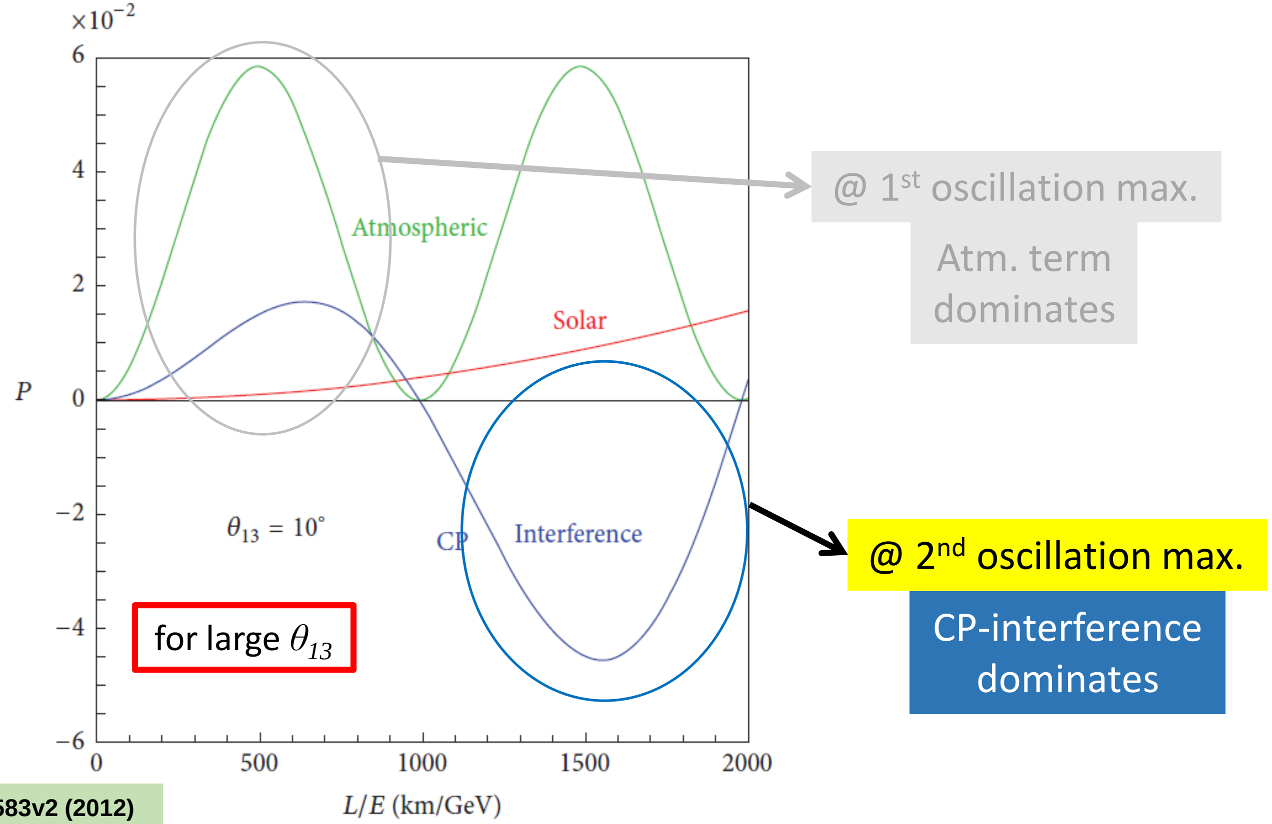
$$P(\nu_\mu \rightarrow \nu_e) = sin^2\theta_{23} sin^2 2\theta_{13} sin^2\left(\frac{\Delta m_{31} L}{2}\right) + cos^2\theta_{23} sin^2 2\theta_{12} sin^2\left(\frac{\Delta m_{21} L}{2}\right) + \bar{J} cos\left(\delta_{CP} - \frac{\Delta m_{31} L}{2}\right) sin\left(\frac{\Delta m_{21} L}{2}\right)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

where $\bar{J} \equiv cos\theta_{13} sin2\theta_{12} sin2\theta_{23} sin2\theta_{13}$ *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 $cos\left(\delta_{CP} - \frac{\Delta_{31} L}{2}\right) = 1$

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

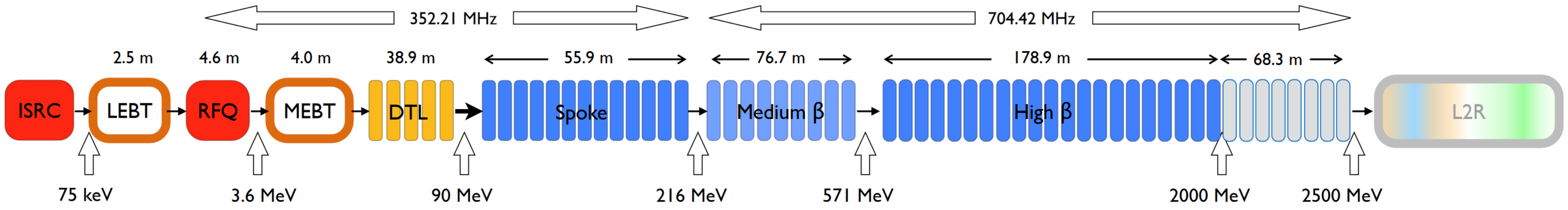
CPV is best studied at the 2nd oscillation maximum





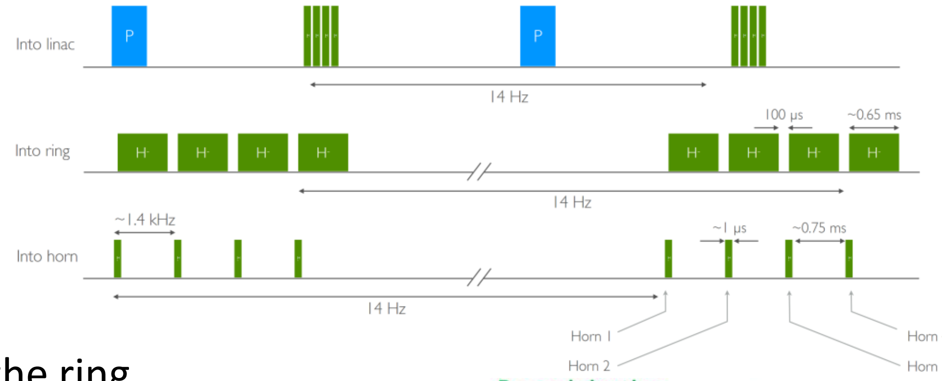
arXiv:1110.4583v2 (2012)

ESS Proton Linac Upgrade and the Accumulator Ring

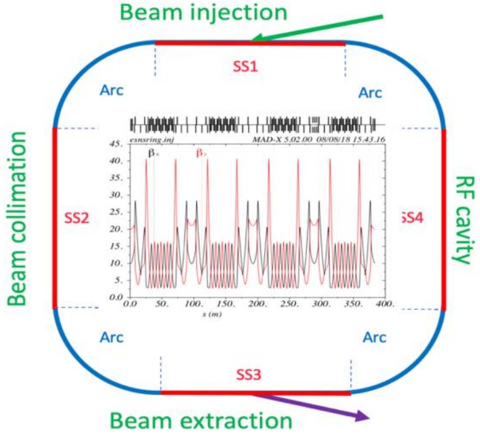


- ESS*v*SB proposes to increase the ESS LINAC power from 5 MW to 10 MW.
- The dedicated proton beam will be shortened to 1.3 μs:
  - ➢ With the help of the accumulator ring.
  - ➢ Will be split in four (batches) already in the LINAC.
  - ➢ Each batch is accumulated and then extracted before the next 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.

Pulsing scheme



Accumulator Ring



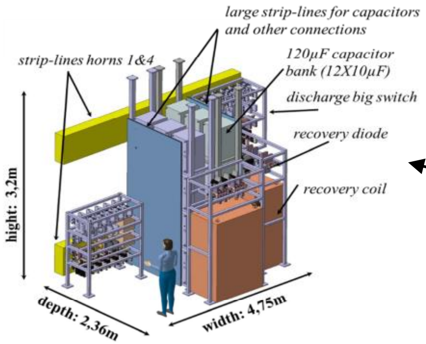
- Accumulation and storage, no acceleration.
- 384 m circumference, 1.33 μs revolution period

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

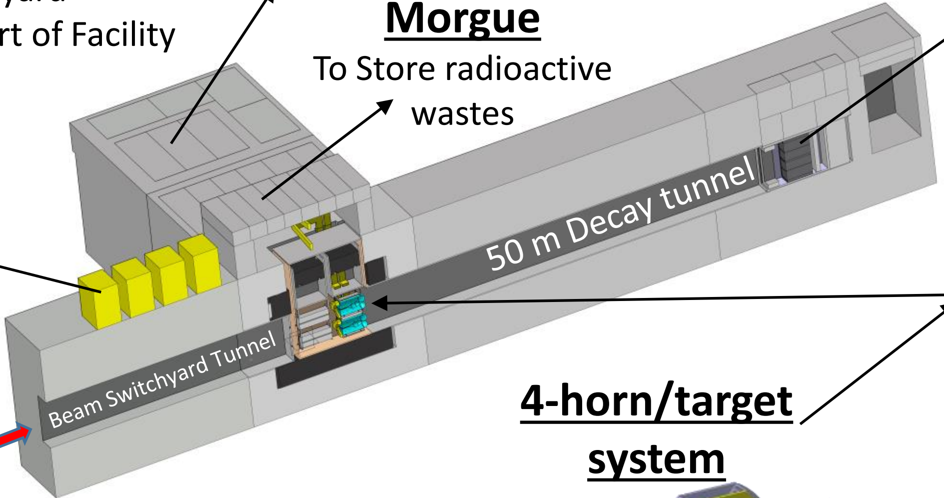


Hot Cell

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

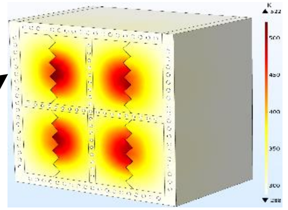
Morgue

To Store radioactive wastes

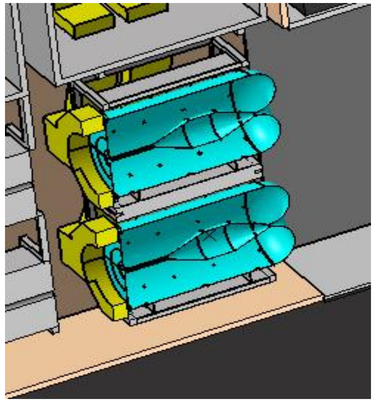


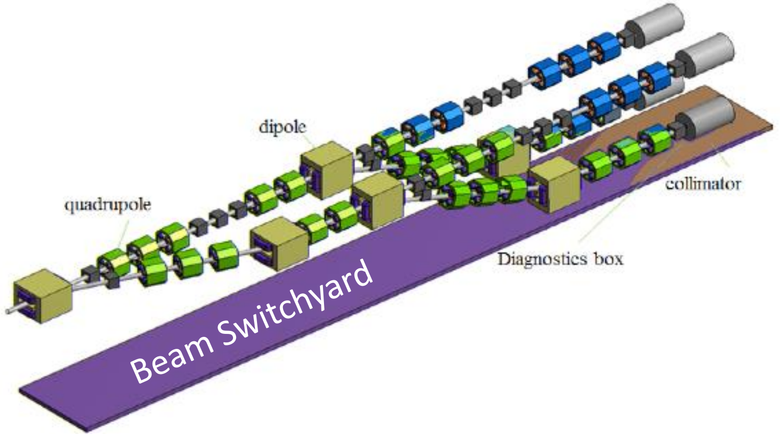
Proton Beam

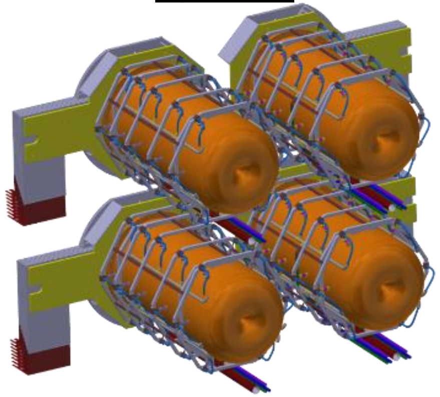
Beam dump



4-horn/target system

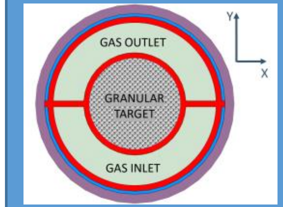


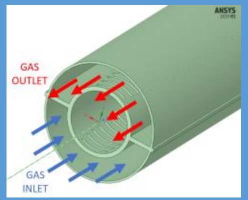


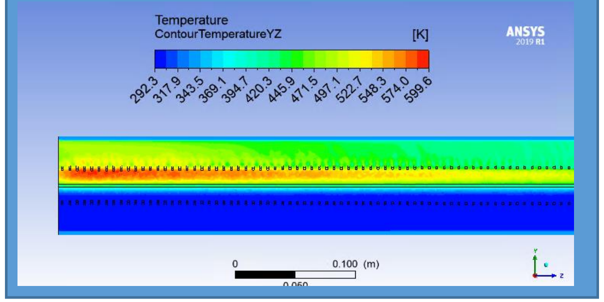


Granular Target Concept

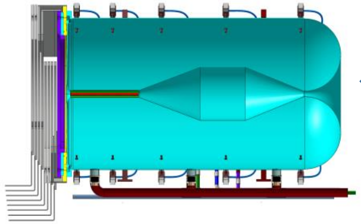
- Target made of 3 mm titanium spheres cooled by transverse helium gas cooling







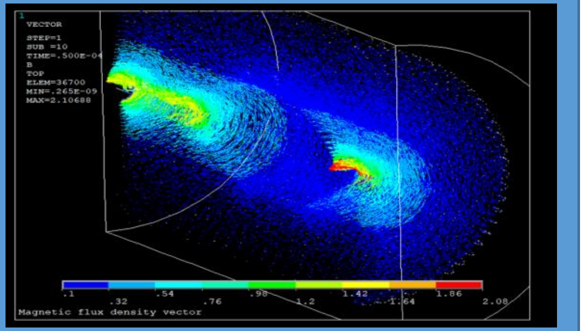
Hadronic Collector



Horn

Shape optimized with genetic algorithm

Magnetic field (350 kA; 1.3 μs pulse)



ESSνSB+ Target Station Facility

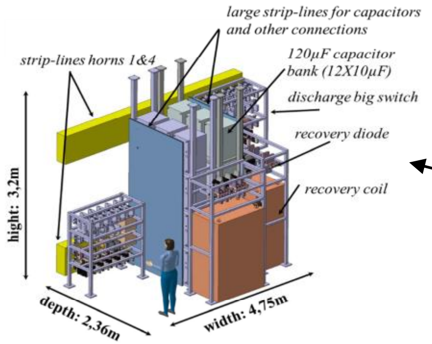
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

ESS neutrino Super Beam plus

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

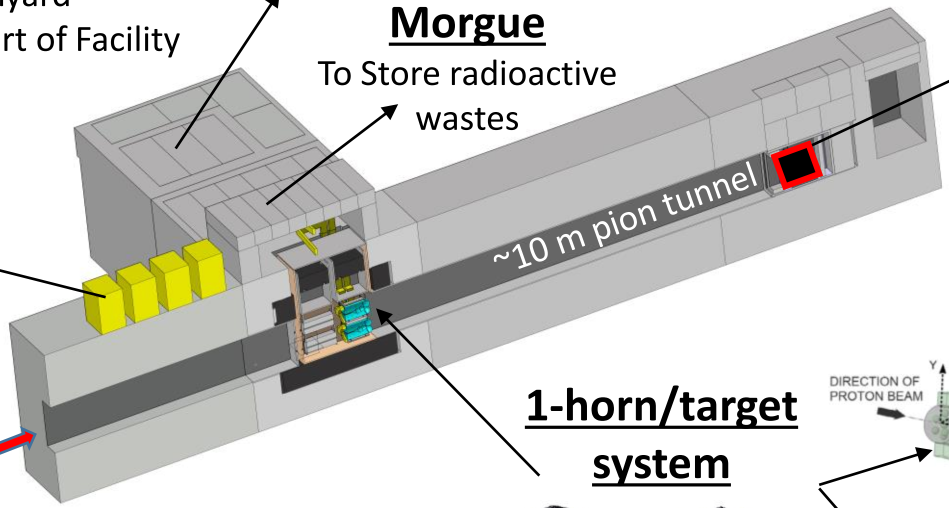


Hot Cell

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

Morgue

To Store radioactive wastes



Proton Beam

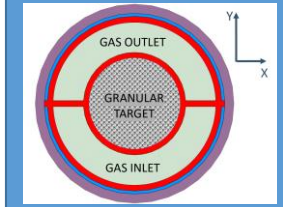
(Ep=2.5 GeV, 14 Hz)

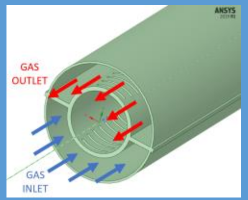
1 x 1.25 MW

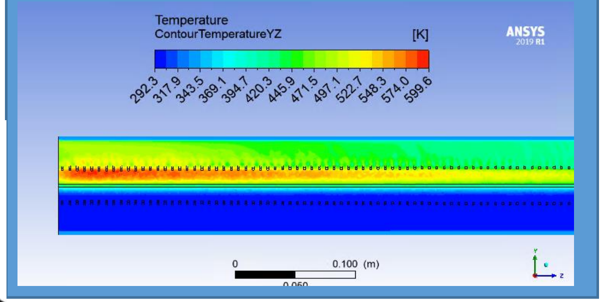
Dipole Magnet

Granular Target Concept

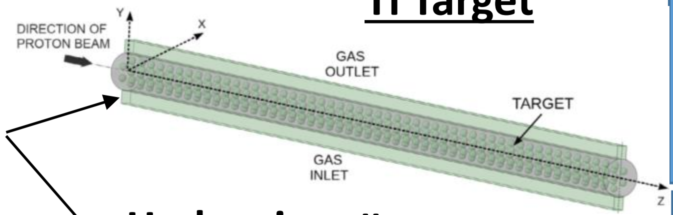
- Target made of 3 mm titanium spheres cooled by transverse helium gas cooling



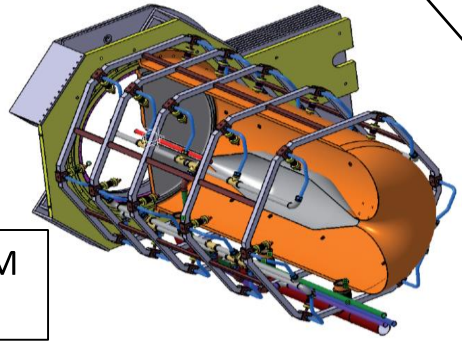




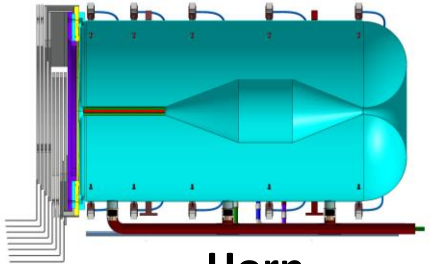
Ti Target



1-horn/target system



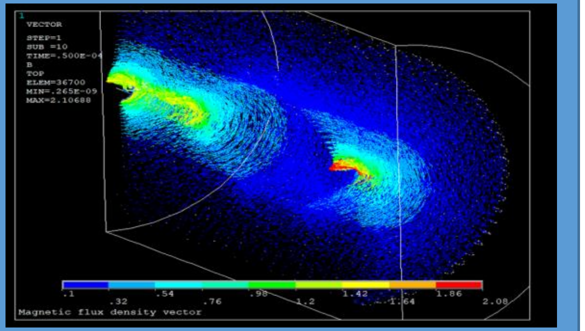
Hadronic Collector

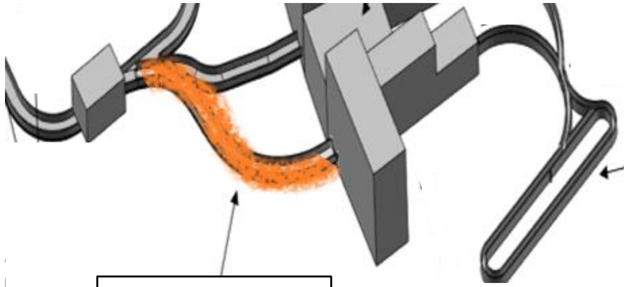


Horn

Shape optimized with genetic algorithm

Magnetic field (350 kA; 1.3 μs pulse)



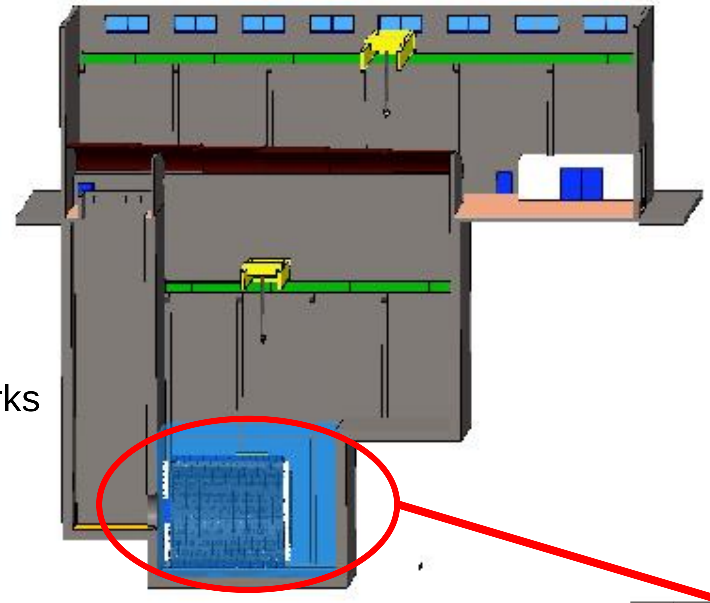


LEnuSTORM racetrack

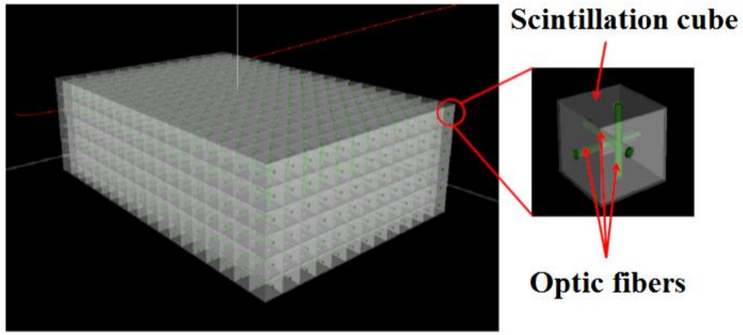
Transfer Line

ESSnuSB Near Detector

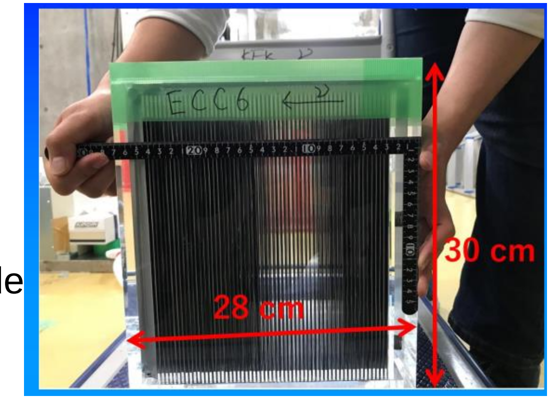
- END hall distance from source is ~250 m
- **Near Water Cherenkov detector (NearWatCh)**
  - Event rate measurement and flux normalization
  - Neutrino – water cross section measurement
  - Cylindrical tank (9.4 m x 10.8 m)
  - Fiducial mass 0.42 kt
  - Event reconstruction optimization using neural 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



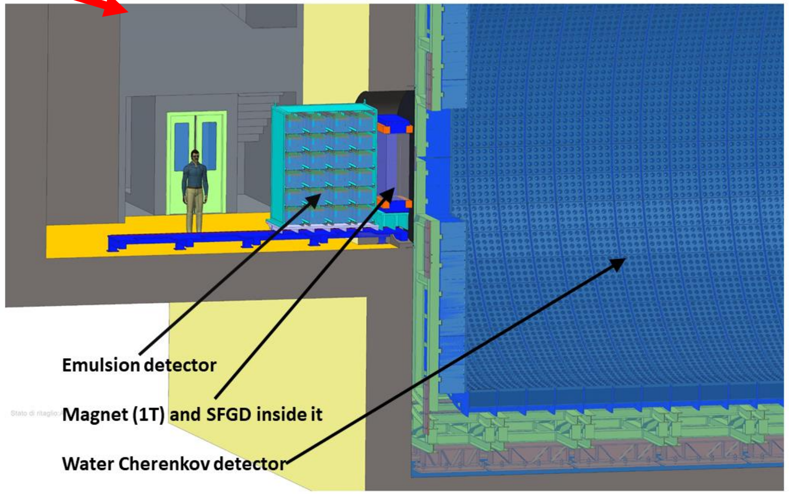
END hall



SFGD



NINJA type ECC



Near detector site

ESSnuSB Far Detector Performance

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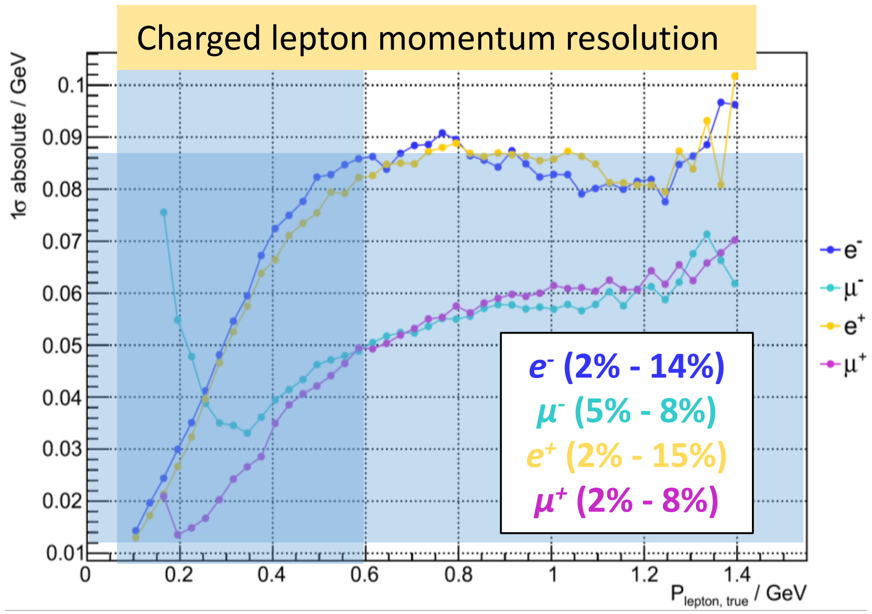
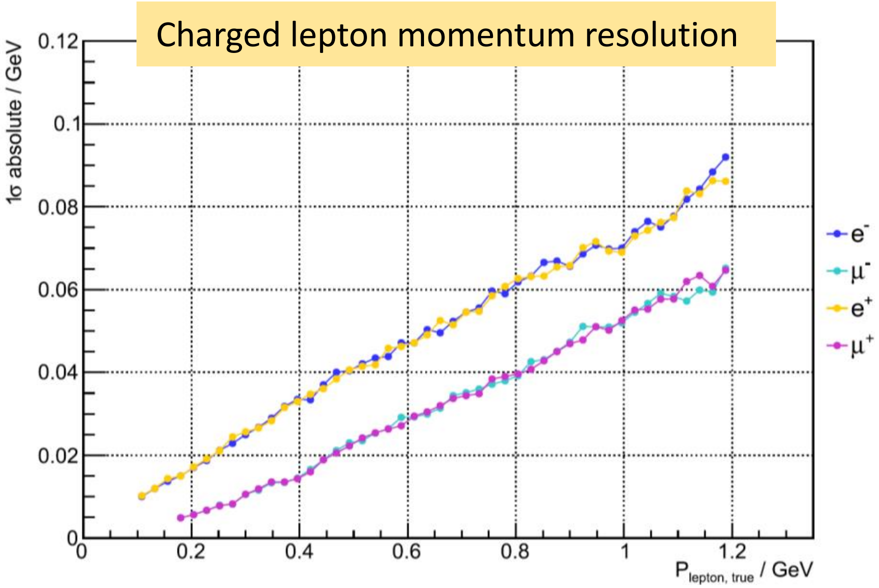
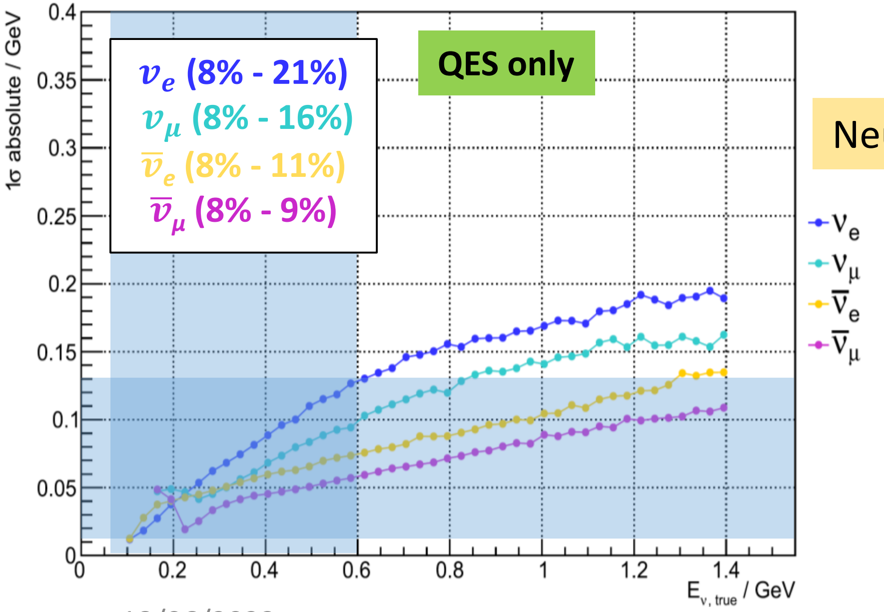
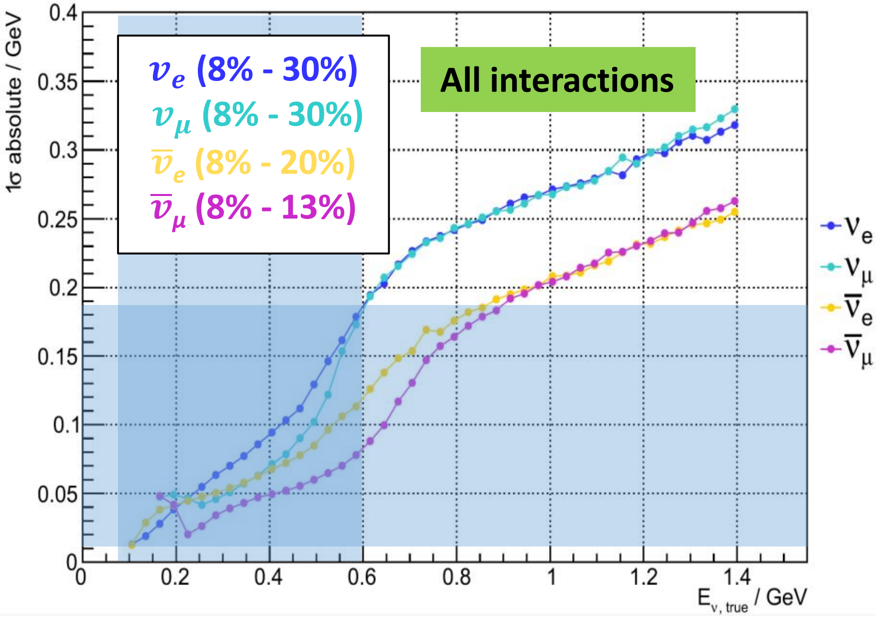


[Eur. Phys. J. Spec. Top. 231, (2022) 3779–3955]()





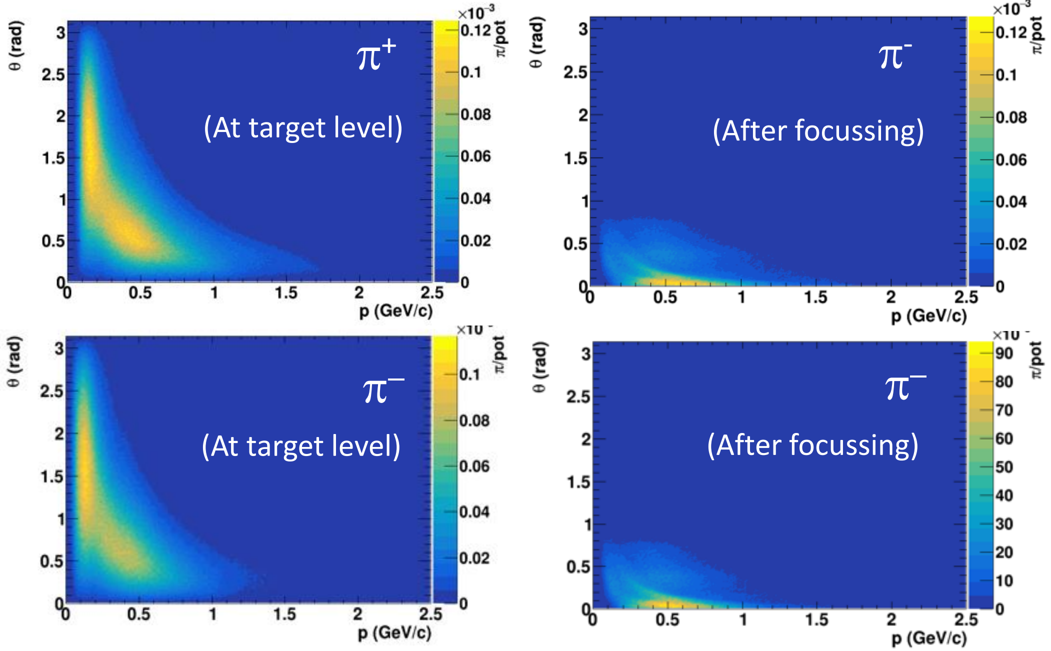
Neutirno energy resolution

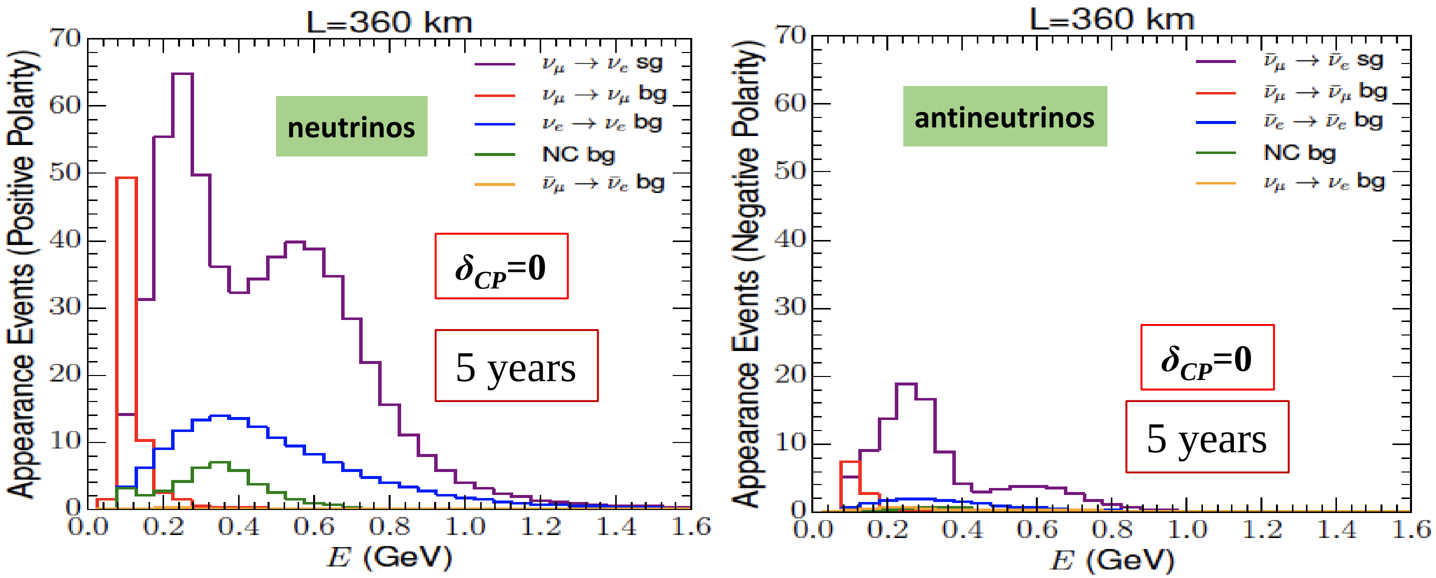


ESSnuSB Neutrino Beam

$\pi^+ \rightarrow \mu^+ + \nu_\mu$
(Positive polarity)

$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
(Negative polarity)





- Almost pure ν_μ beam
- Small ν_e contamination which could be used to measure ν_e cross-sections in the near detector

Neutrino flux at 360 km from the target per year (in absence of oscillations)

Flavour	ν Mode		$\bar{\nu}$ Mode	
	N_ν (10^5/ cm^2)	%	N_ν (10^5/ cm^2)	%
ν_μ	**520.06**	**97.6**	15.43	4.7
ν_e	**3.67**	**0.67**	0.10	0.03
$\bar{\nu}_\mu$	9.10	1.7	**305.55**	**94.8**
$\bar{\nu}_e$	0.023	0.03	**1.43**	**0.43**

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)

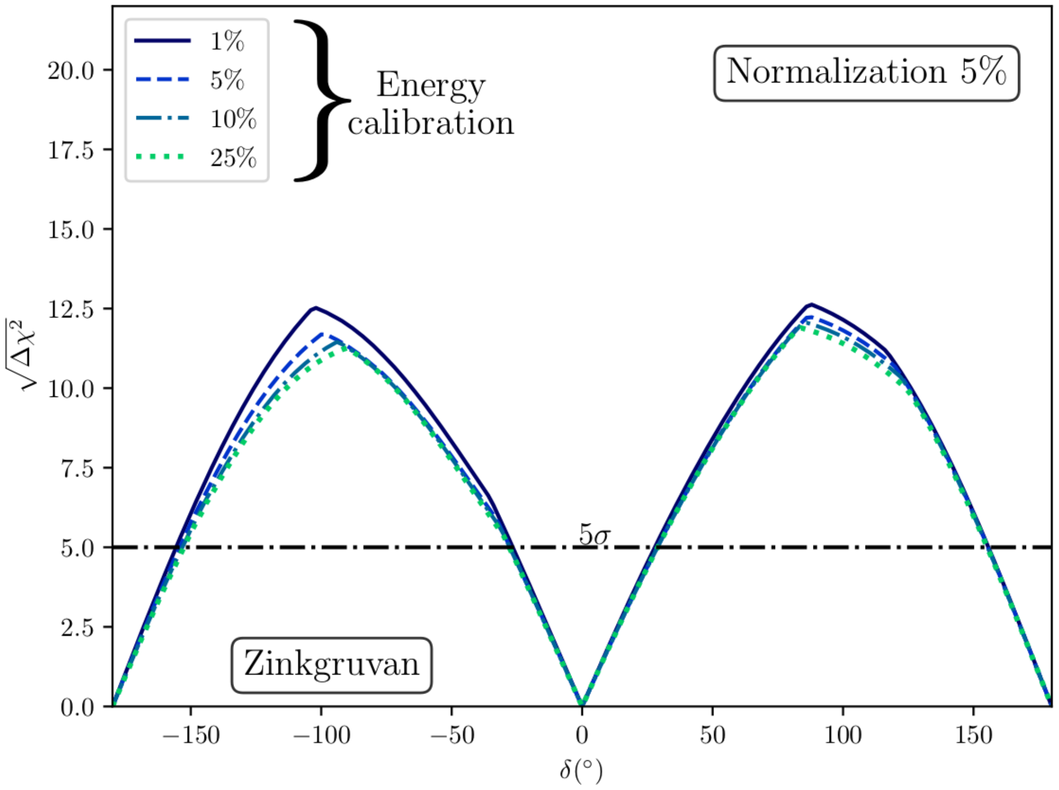
Effect of Energy Calibration Uncertainty

ESSnuSB

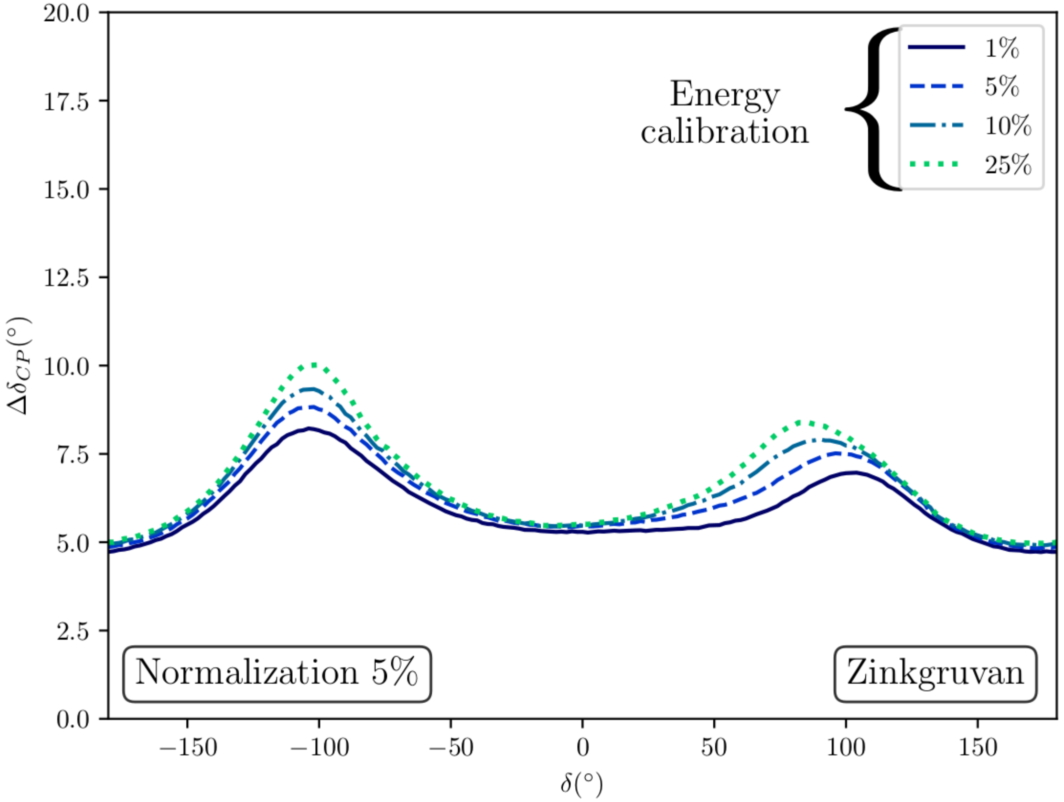
- θ_{12} = 33.44°
- θ_{13} = 8.57°
- θ_{23} = 49.2°
- Δm^2_{21} = 7.42e-5
- Δm^2_{31} = +2.52e-3
- 2^{nd} osc. max.
- 507 ktons far detector

Baseline = 360 km

Sensitivity



Precision

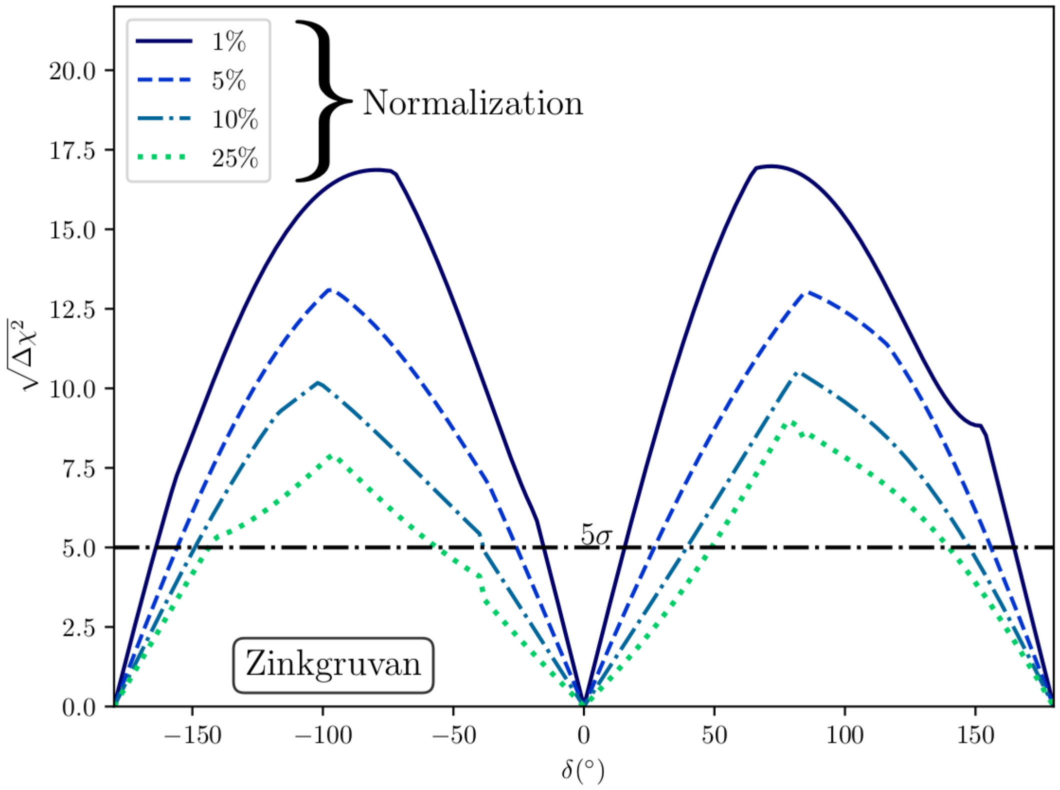


Effect of Normalization Uncertainty
Future Opportunities

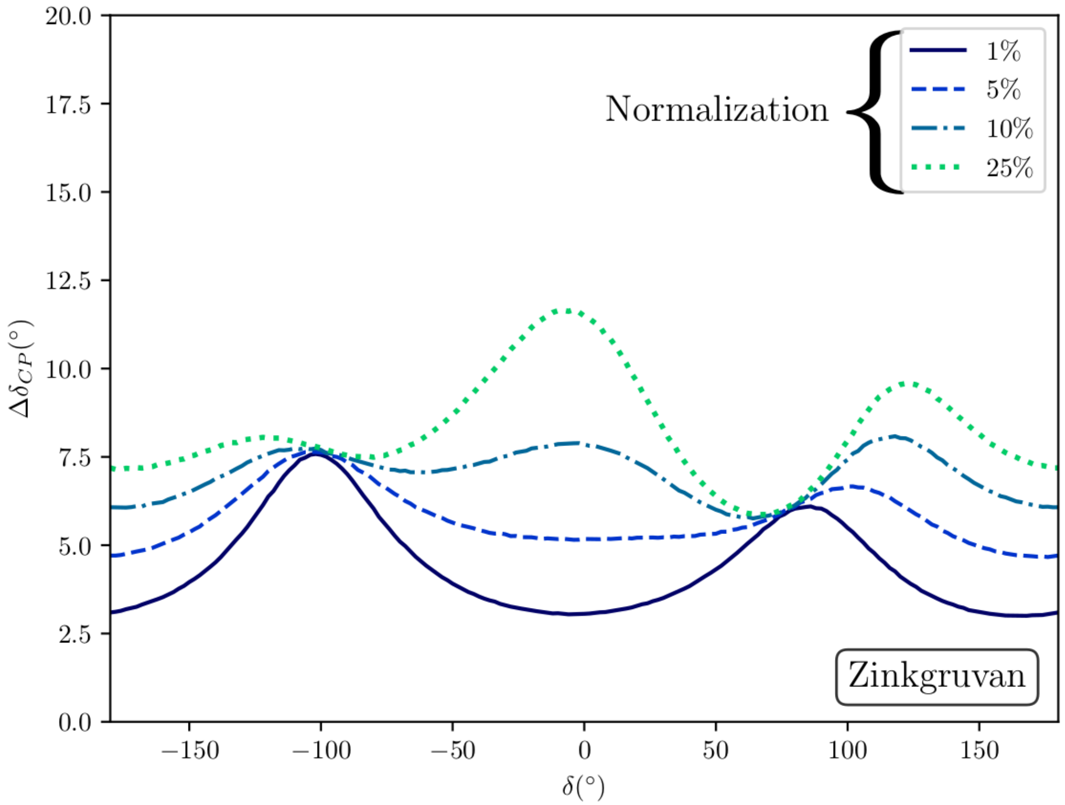
ESSnuSB
- θ_{12} = 33.44°
- θ_{13} = 8.57°
- θ_{23} = 49.2°
- Δm^2_{21} = 7.42e-5
- Δm^2_{31} = +2.52e-3
- 2nd osc. max.
- 507 ktons far detector

Baseline = 360 km

Sensitivity



Precision

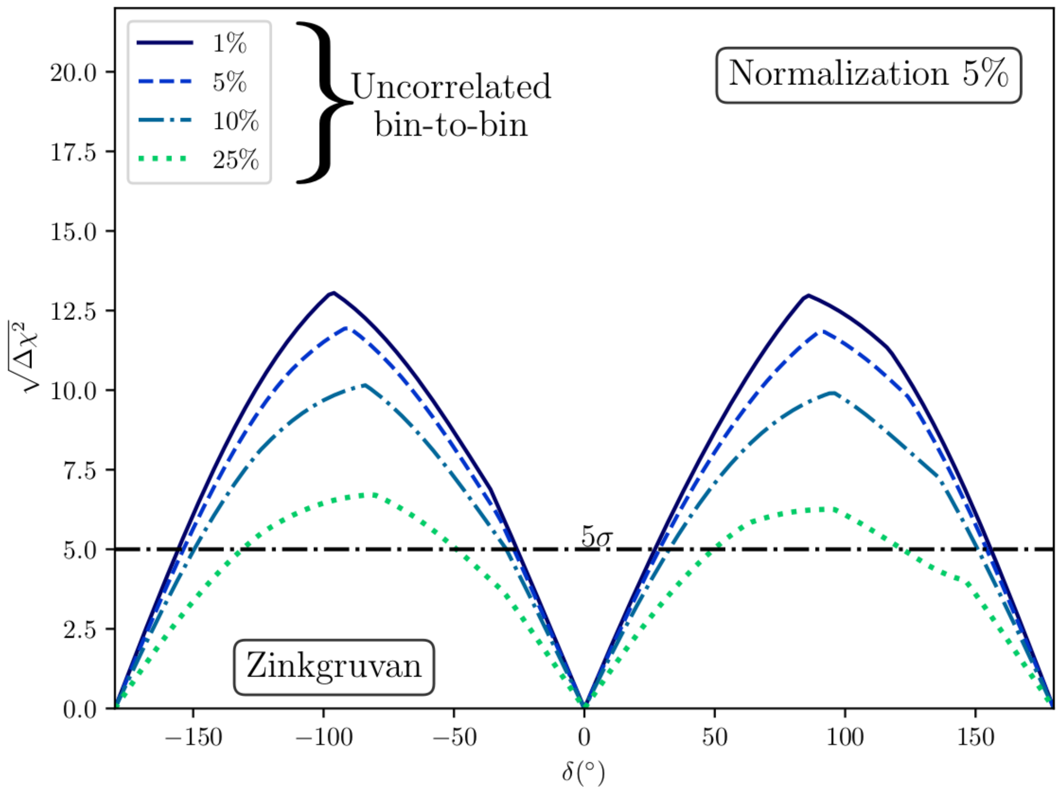


Effect of bin-to-bin Uncorrelated Uncertainty

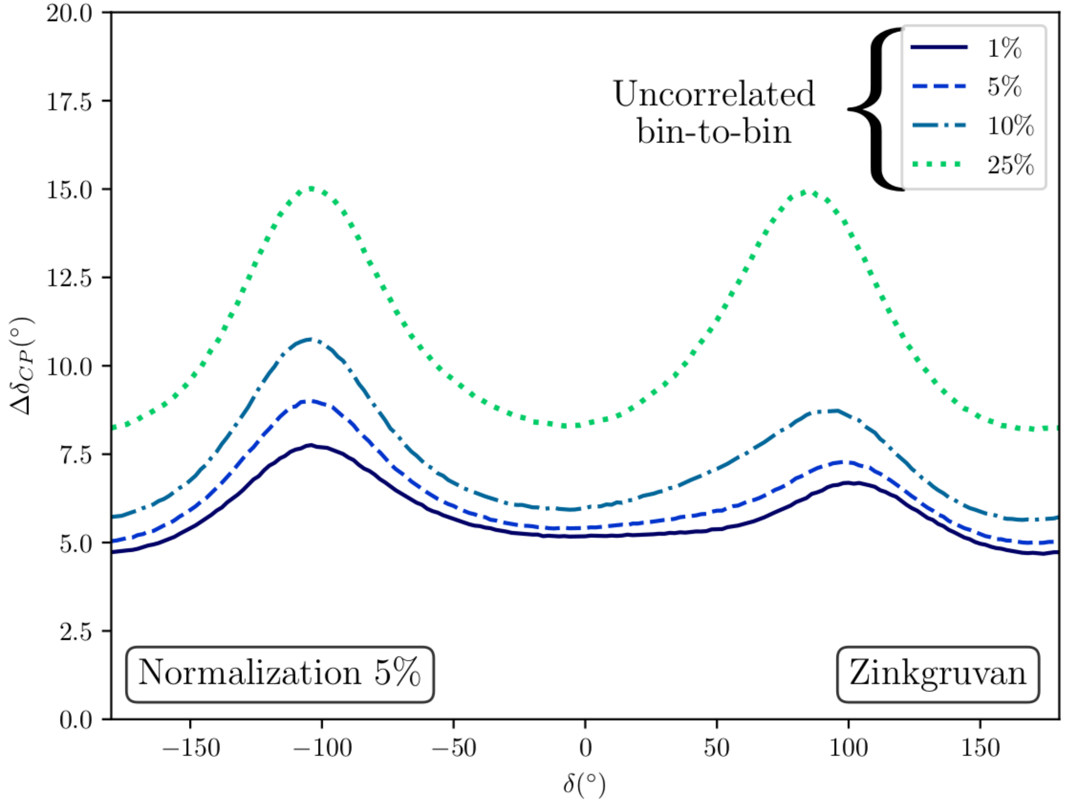
ESSnuSB
- θ_{12} = 33.44°
- θ_{13} = 8.57°
- θ_{23} = 49.2°
- Δm^2_{21} = 7.42e-5
- Δm^2_{31} = +2.52e-3
- 2^{nd} osc. max.
- 507 ktons far detector

Baseline = 360 km

Sensitivity



Precision



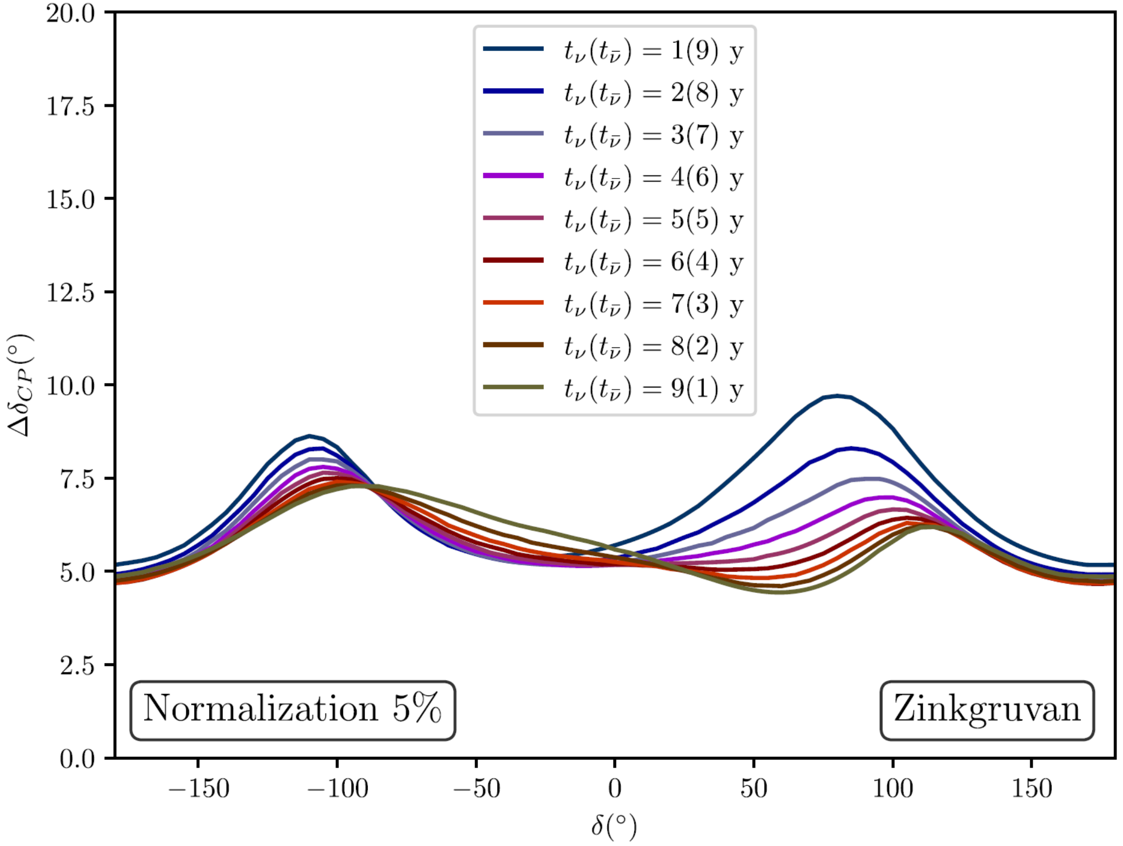
ESSnuSB Physics Reach

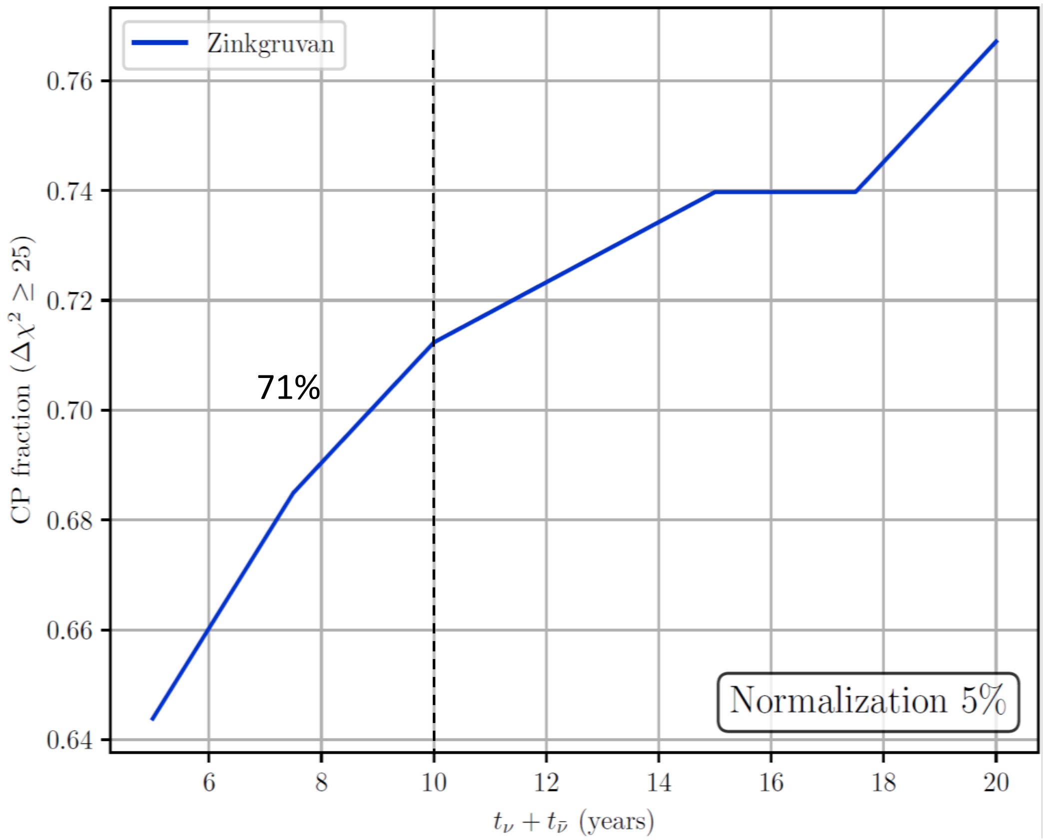
Baseline = 360 km

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

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

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





The European Spallation Source neutrino Super Beam plus (ESSnuSB+)

missing measurements at the ESSnuSB region: below 600 MeV

J. A. Formaggio and G. P. Zeller, Rev. Mod. Phys. 84 (2012), 1307