



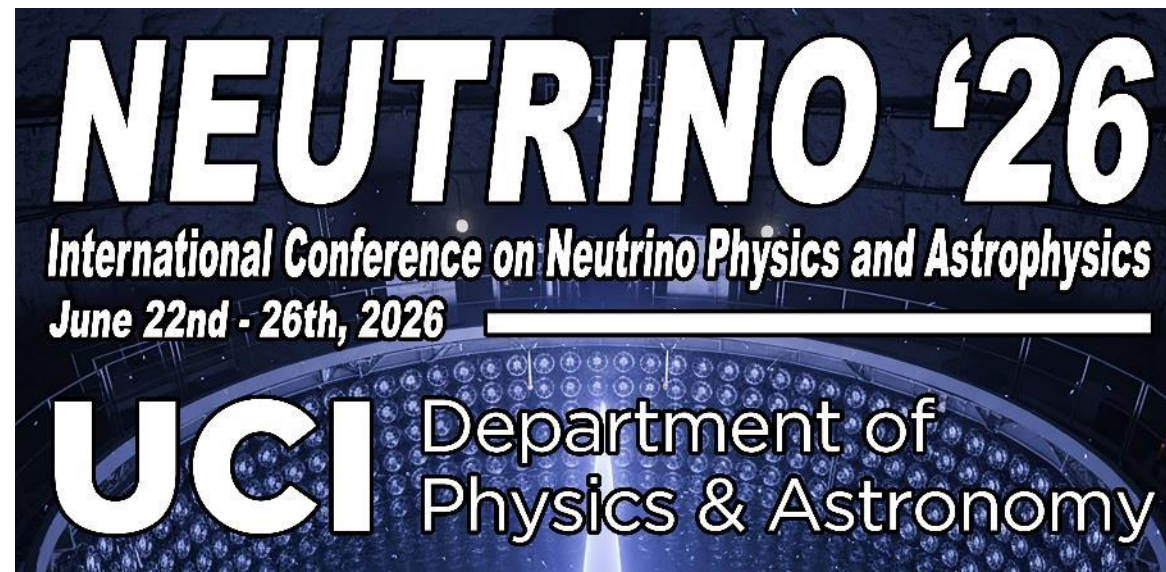
Co-funded by
the European Union



Future Long-baseline accelerator neutrino experiments (including ESSnuSB) - Beyond DUNE, HK

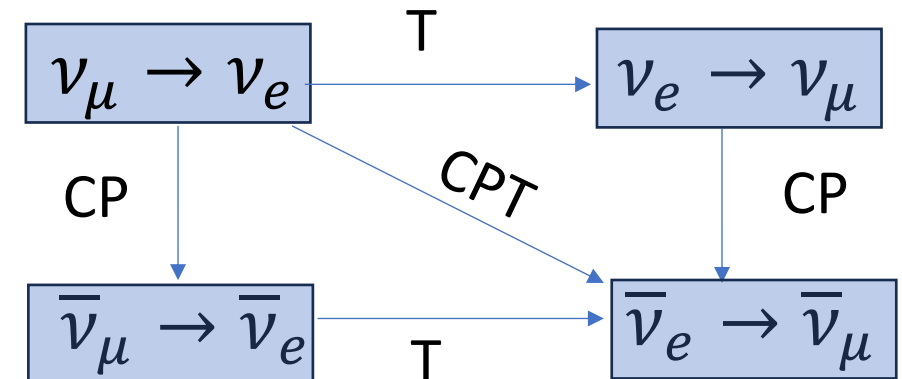
Budimir Kliček

On behalf of the ESSnuSB+ project
Ruđer Bošković Institute, Zagreb, Croatia



Why need for future LBL experiments?

- Precise measurement of neutrino osc. parameters in laboratory conditions (PMNS matrix, delta-m-squares) in all osc. channels
 - strive towards the precision of the CKM matrix
- Some of the things we can check:
 - Unitarity of PMNS
 - Mass ordering (recheck)
 - Consistency of oscillation channels
- These could have far-reaching consequences
 - Leptogenesis in the early Universe
 - Check CP, T, and CPT consistency
 - Extra neutrino flavours
 - Unexpected new physics



CKM vs. PMNS measured values

← Quarks | Neutrinos →

$$|V_{\text{CKM}}| = \begin{pmatrix} 0.97431 \pm 0.00016 & 0.22517 \pm 0.00068 & 0.003763^{+0.000088}_{-0.000083} \\ 0.22503 \pm 0.00068 & 0.97345 \pm 0.00016 & 0.04189^{+0.00081}_{-0.00069} \\ 0.00863^{+0.00019}_{-0.00017} & 0.04117^{+0.00079}_{-0.00068} & 0.999115^{+0.000029}_{-0.000034} \end{pmatrix}$$

$$\sin \theta_{12} = 0.22517 \pm 0.00068,$$

$$\sin \theta_{23} = 0.04189^{+0.00081}_{-0.00069},$$

$$\sin \theta_{13} = 0.003763^{+0.000088}_{-0.000083},$$

$$\delta = 1.154 \pm 0.025.$$

CKM parameters

[F. Takahashi et al. \(Particle Data Group\)](#), to be published in Int. J. Mod. Phys. A **41**, 2630011 (2026)

$$|U|_{3\sigma}^{\text{IC23 w/o SK-atm}} = \begin{pmatrix} 0.810 \rightarrow 0.834 & 0.532 \rightarrow 0.568 & 0.144 \rightarrow 0.156 \\ 0.258 \rightarrow 0.502 & 0.479 \rightarrow 0.680 & 0.650 \rightarrow 0.758 \\ 0.274 \rightarrow 0.512 & 0.486 \rightarrow 0.684 & 0.635 \rightarrow 0.745 \end{pmatrix}$$

$$|U|_{3\sigma}^{\text{IC24 with SK-atm}} = \begin{pmatrix} 0.810 \rightarrow 0.834 & 0.532 \rightarrow 0.568 & 0.144 \rightarrow 0.156 \\ 0.259 \rightarrow 0.498 & 0.514 \rightarrow 0.678 & 0.652 \rightarrow 0.756 \\ 0.280 \rightarrow 0.512 & 0.488 \rightarrow 0.659 & 0.637 \rightarrow 0.743 \end{pmatrix}$$

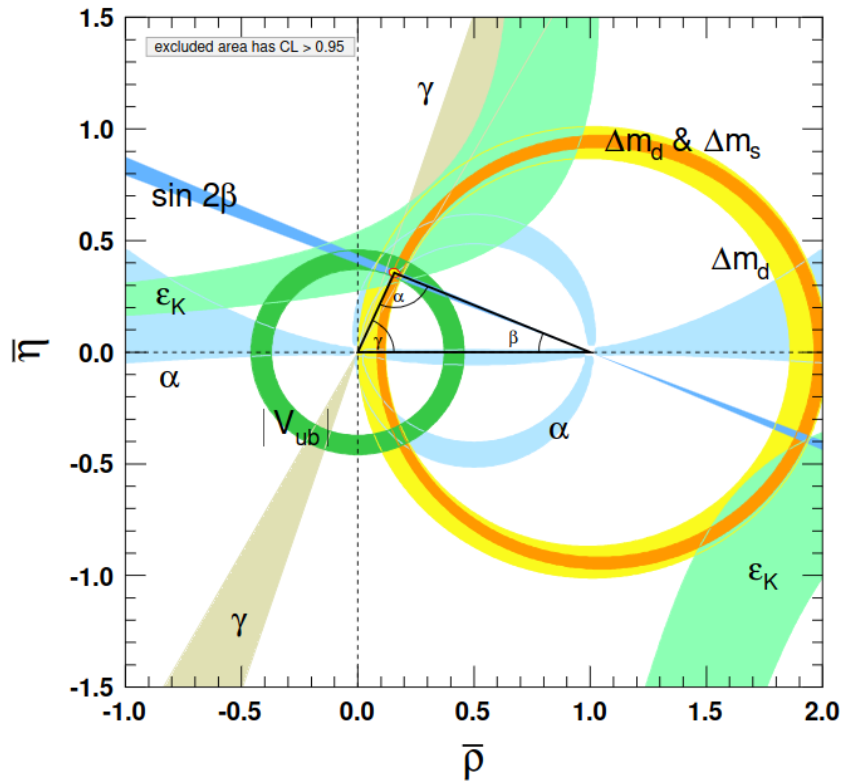
NuFIT 6.1 (2025)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 5.9$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
IC24 with SK atmospheric data	$\sin^2 \theta_{12}$	$0.3088^{+0.0067}_{-0.0066}$	0.2893 → 0.3295	$0.3088^{+0.0067}_{-0.0066}$	0.2893 → 0.3295
	$\theta_{12}/^\circ$	$33.76^{+0.42}_{-0.41}$	32.54 → 35.03	$33.76^{+0.42}_{-0.41}$	32.54 → 35.03
	$\sin^2 \theta_{23}$	$0.470^{+0.017}_{-0.014}$	0.435 → 0.584	$0.550^{+0.013}_{-0.016}$	0.439 → 0.584
	$\theta_{23}/^\circ$	$43.29^{+0.96}_{-0.79}$	41.27 → 49.86	$47.90^{+0.73}_{-0.92}$	41.51 → 49.83
	$\sin^2 \theta_{13}$	$0.02248^{+0.00055}_{-0.00059}$	0.02064 → 0.02418	$0.02262^{+0.00057}_{-0.00056}$	0.02093 → 0.02441
	$\theta_{13}/^\circ$	$8.62^{+0.11}_{-0.11}$	8.26 → 8.95	$8.65^{+0.11}_{-0.11}$	8.32 → 8.99
	$\delta_{\text{CP}}/^\circ$	212^{+26}_{-36}	125 → 365	274^{+22}_{-25}	203 → 335
	$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.537^{+0.094}_{-0.10}$	7.236 → 7.823	$7.537^{+0.094}_{-0.10}$	7.236 → 7.822
	$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.511^{+0.021}_{-0.020}$	+2.450 → +2.576	$-2.483^{+0.020}_{-0.020}$	-2.547 → -2.421

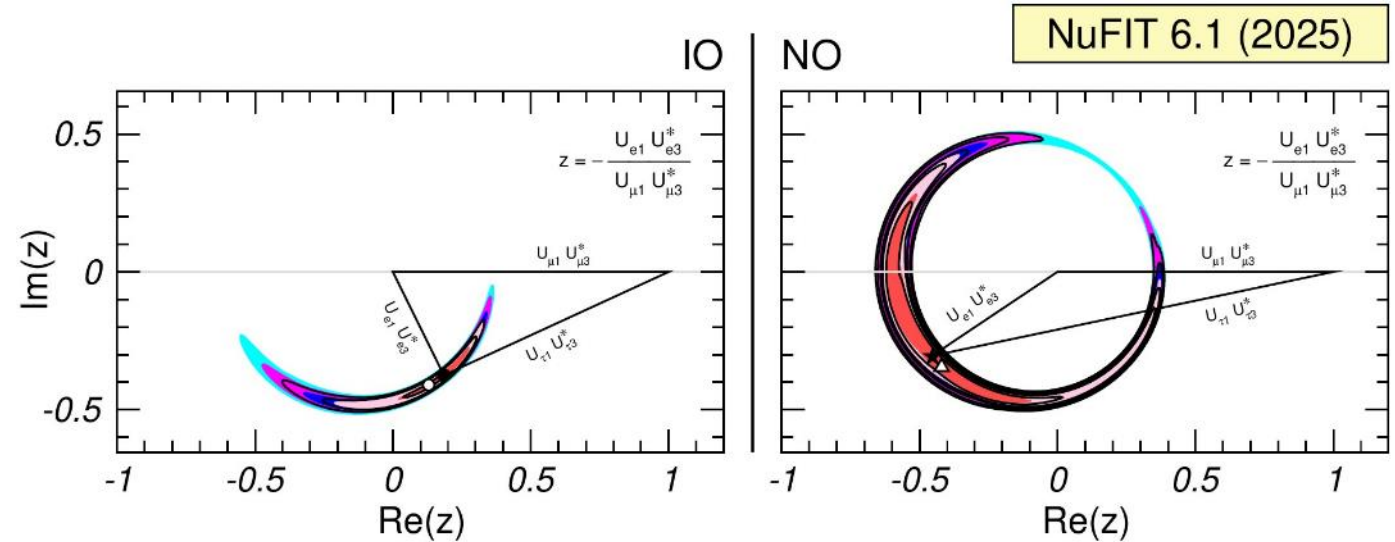
[JHEP 12 \(2024\) 216 \[arXiv:2410.05380\]](#)
and [NuFIT 6.1 \(2025\), www.nu-fit.org](#).

Unitarity triangle CKM vs. PMNS

← Quarks | Neutrinos →



CKM



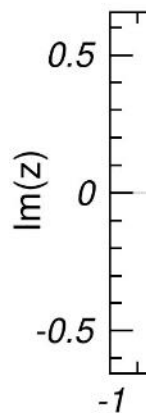
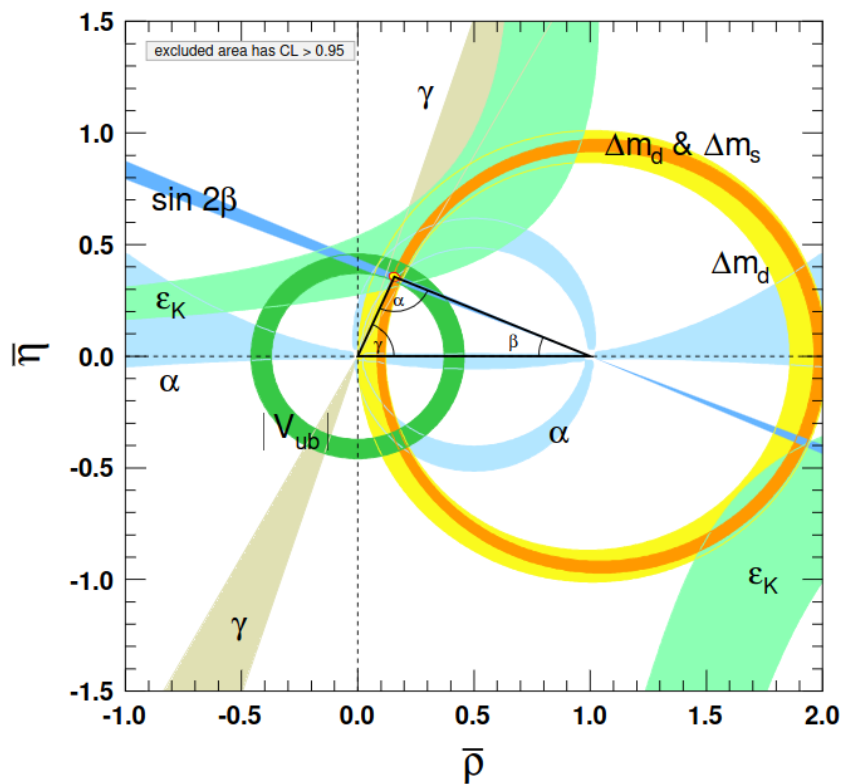
NuFIT 6.1 (2025)

[JHEP 12 \(2024\) 216 \[arXiv:2410.05380\]](#) and [NuFIT 6.1 \(2025\), www.nu-fit.org](#).

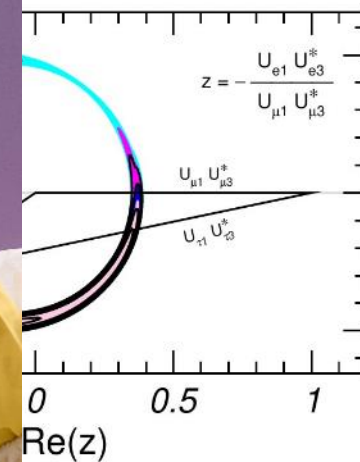
[F. Takahashi et al. \(Particle Data Group\)](#), to be published in Int. J. Mod. Phys. A **41**, 2630011 (2026)

Unitarity triangle CKM

← Quarks Neutrinos



NuFIT 6.1 (2025)



5), www.nu-fit.org.



We've got some measuring to do.

F. Takahashi et al. (Particle Data Group), to be published in Int. J. Mod. Phys. A 41, 2630011 (2026)

CKM

Future Long-baseline accelerator neutrino experiments (including ESSnuSB) - Beyond DUNE, HK

- What fits this description?
 - ESSnuSB
 - P2O
 - Beta beams
 - Neutrino factory
 - Tau beams
 - Other ideas?
- HyperKK (proposed parallel with HK)

ESSnuSB

A design study for a next-to-next generation experiment to precisely measure CP violation amplitude using the 2nd neutrino oscillation maximum.

CP violation in ESSnuSB (and HyperK and DUNE)

$$P_{\nu_{\mu} \rightarrow \nu_e} \neq P_{\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e}$$

We will study ν_e and $\bar{\nu}_e$ appearance in ν_{μ} and $\bar{\nu}_{\mu}$ beam, respectively

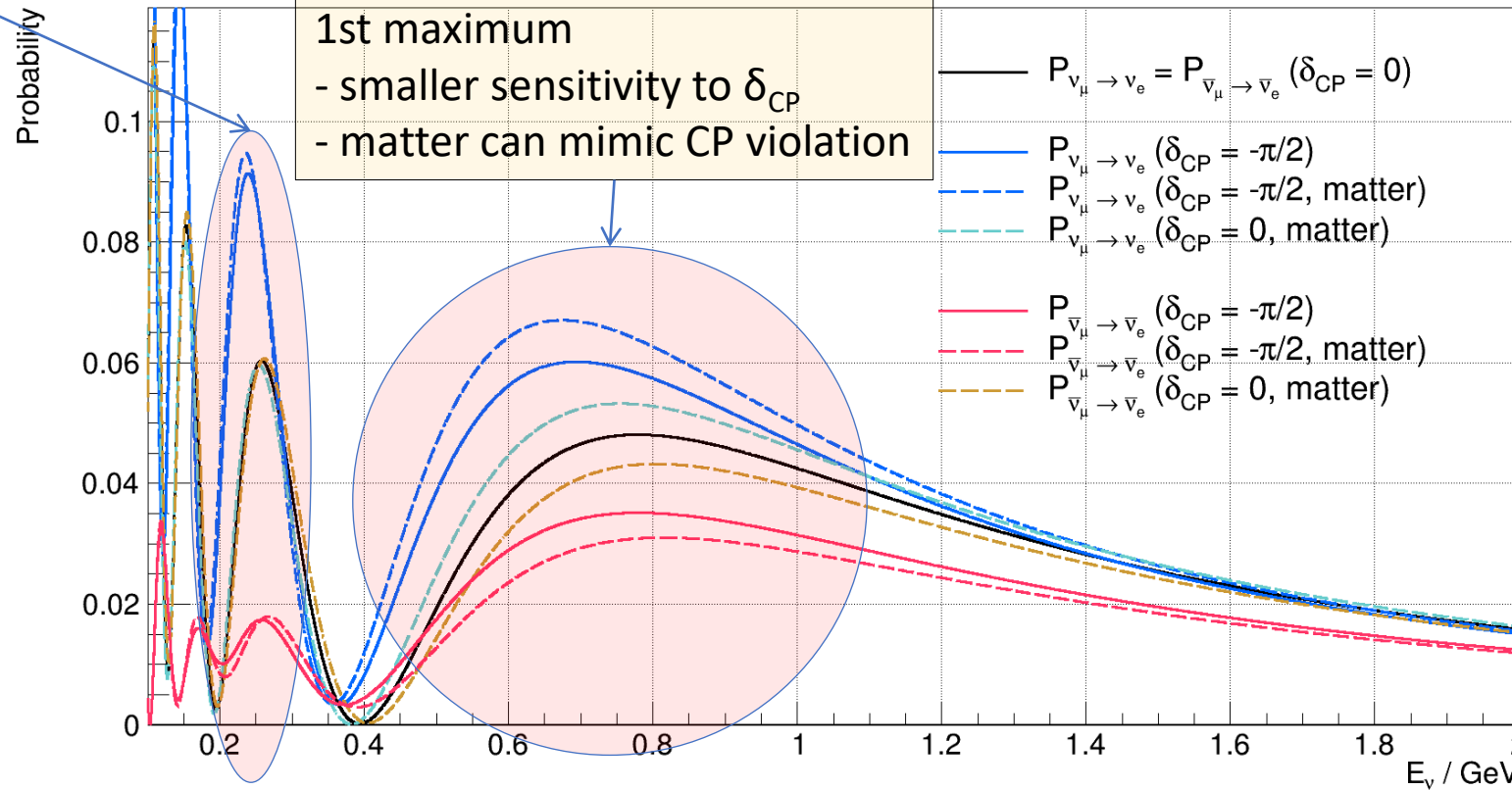
The plan:

1. Run with ν_{μ} and look at ν_e appearance, then
2. Run with $\bar{\nu}_{\mu}$ and look at $\bar{\nu}_e$ appearance

Oscillation pattern at 1st and 2nd maximum

2nd maximum
 - larger sensitivity to δ_{CP}
 - matter doesn't matter

(L = 360 km)



1st maximum
 - smaller sensitivity to δ_{CP}
 - matter can mimic CP violation

$$A_{CP} = P_{\nu_{\mu} \rightarrow \nu_e} - P_{\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e}$$

$$\frac{A_{CP} @ 2nd \text{ max}}{A_{CP} @ 1st \text{ max}} \sim 2.7$$

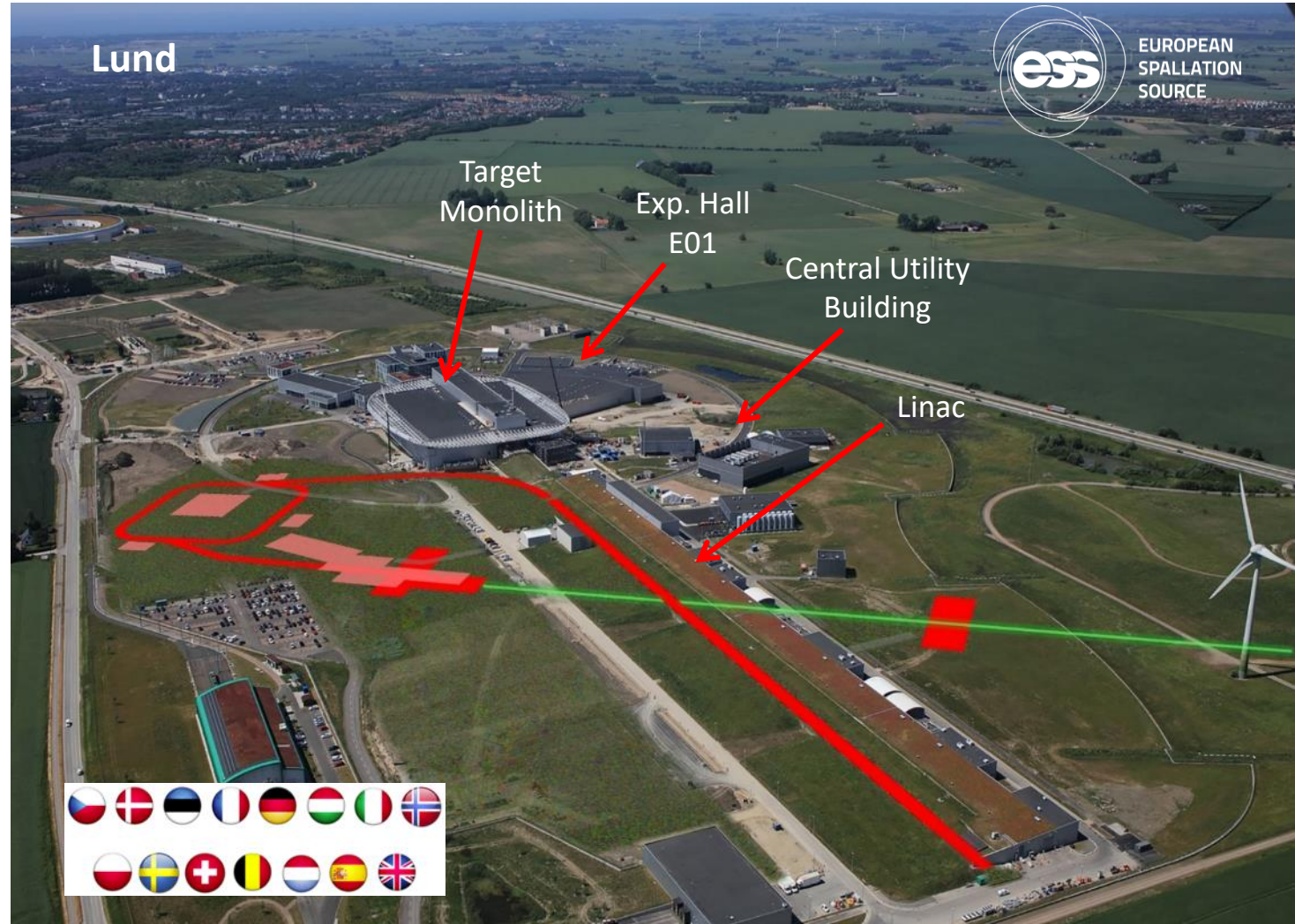
- Does not depend on PMNS matrix elements
- Depends only on mass splittings

The European Spallation Source (ESS)

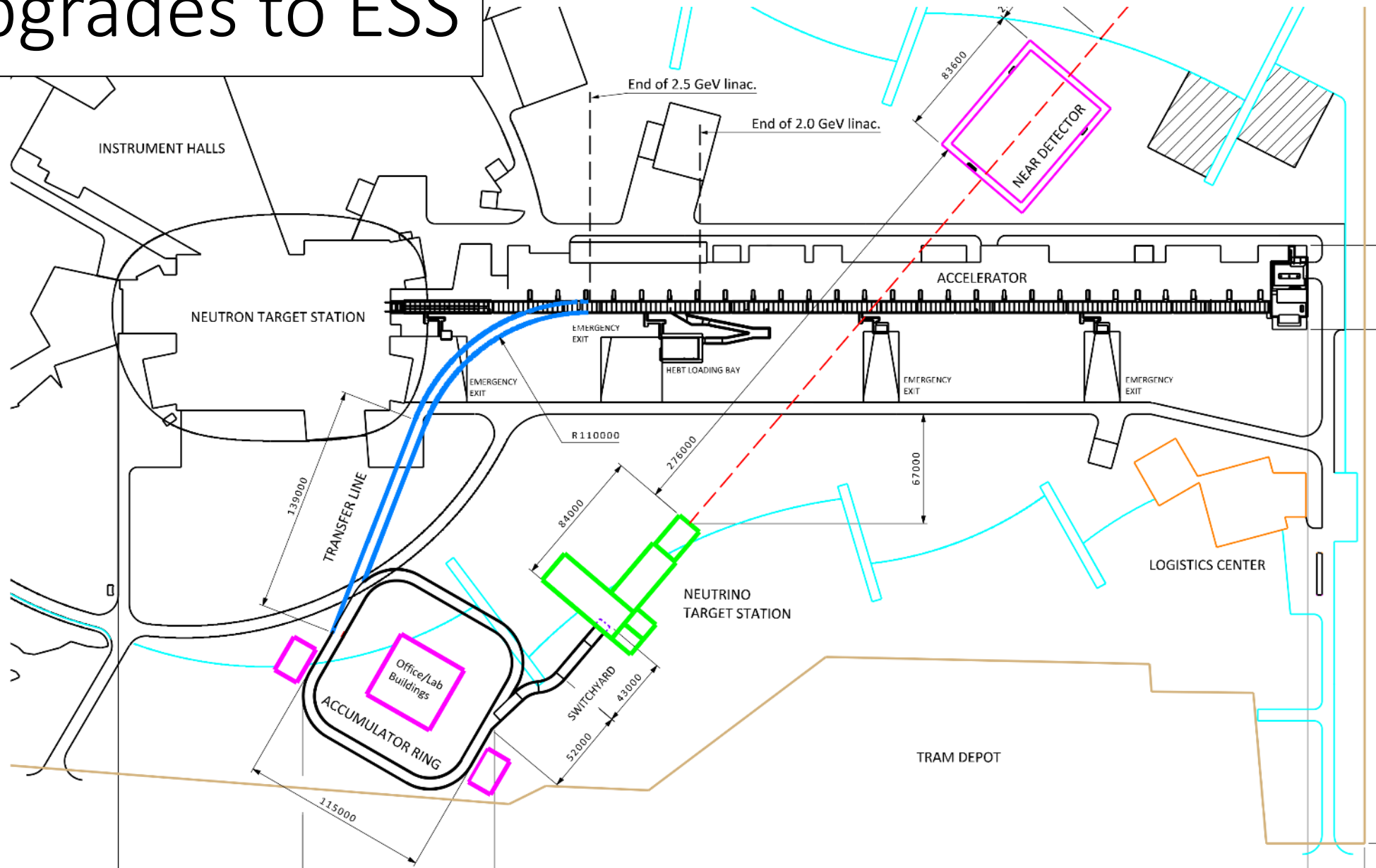
- The ESS will be a copious source of spallation neutrons.
- **5 MW average beam power.**
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV kinetic energy protons
 - up to 3.5 GeV with linac upgrades
- **$>2.7 \times 10^{23}$ p.o.t./year.**

First beam on dump in 2025.

**450 mg of protons/year
at 95% speed of light!**



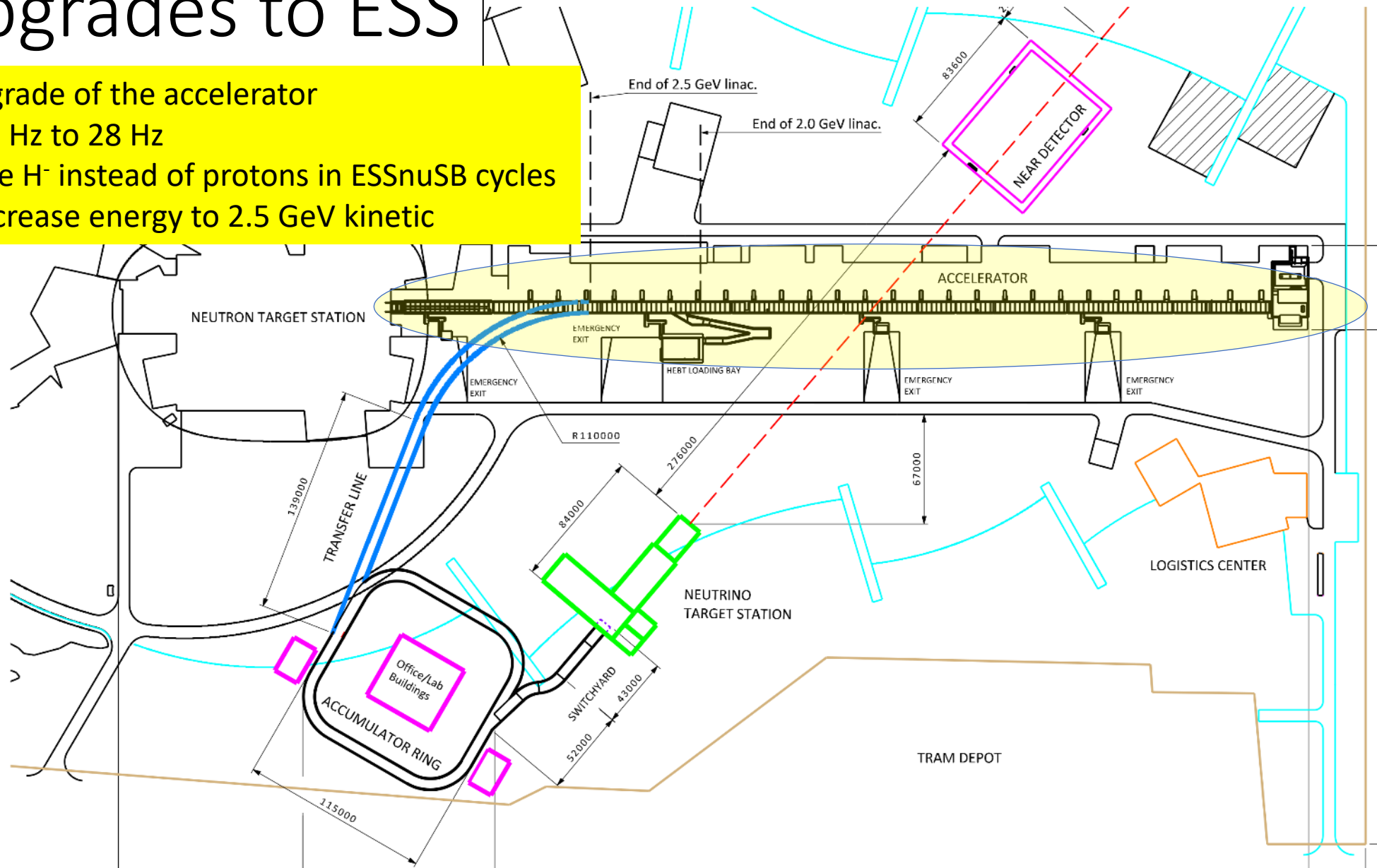
Upgrades to ESS



Upgrades to ESS

Upgrade of the accelerator

- 14 Hz to 28 Hz
- use H^- instead of protons in ESSnuSB cycles
- increase energy to 2.5 GeV kinetic



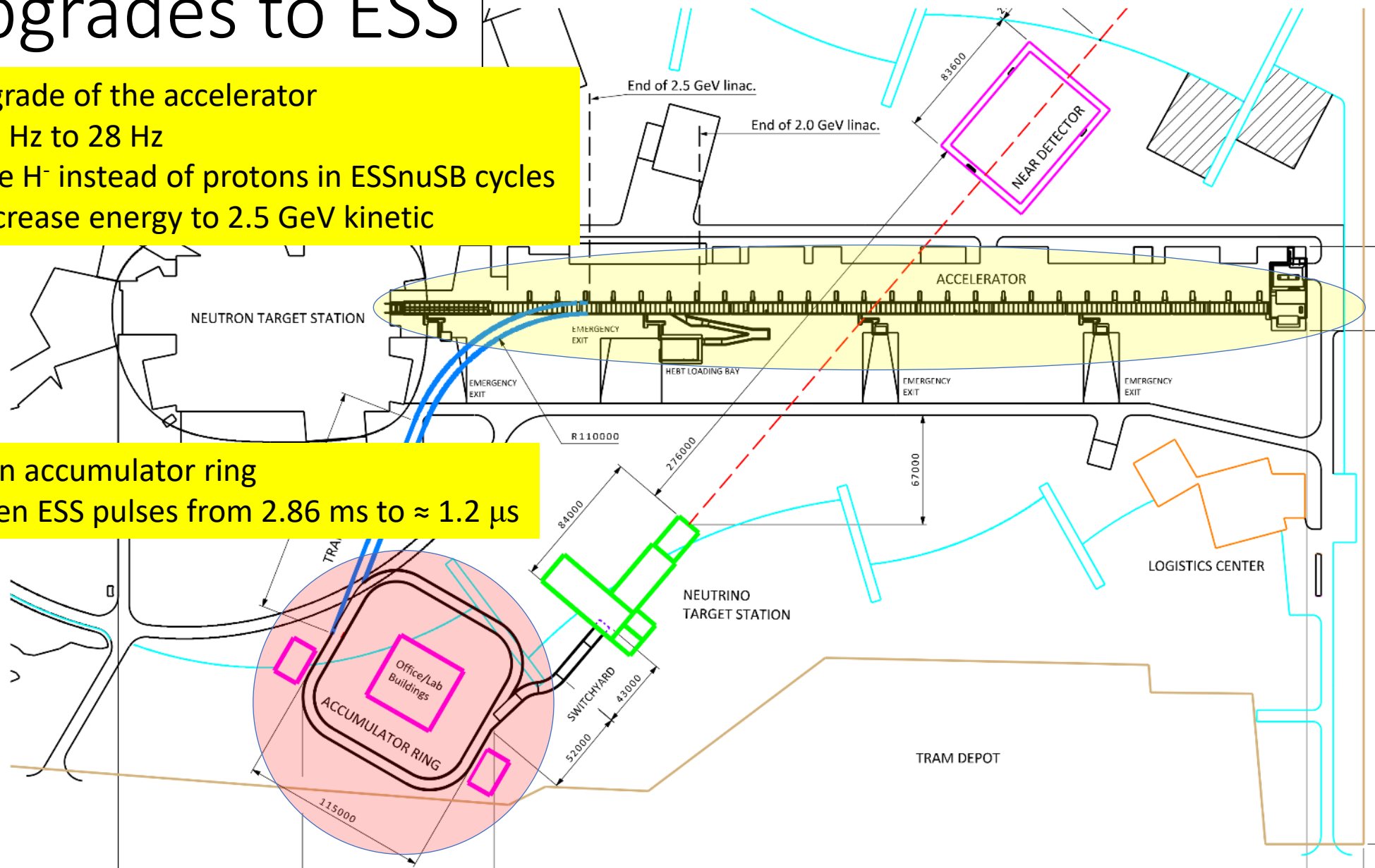
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Build an accumulator ring

- shorten ESS pulses from 2.86 ms to $\approx 1.2 \mu s$



Upgrades to ESS

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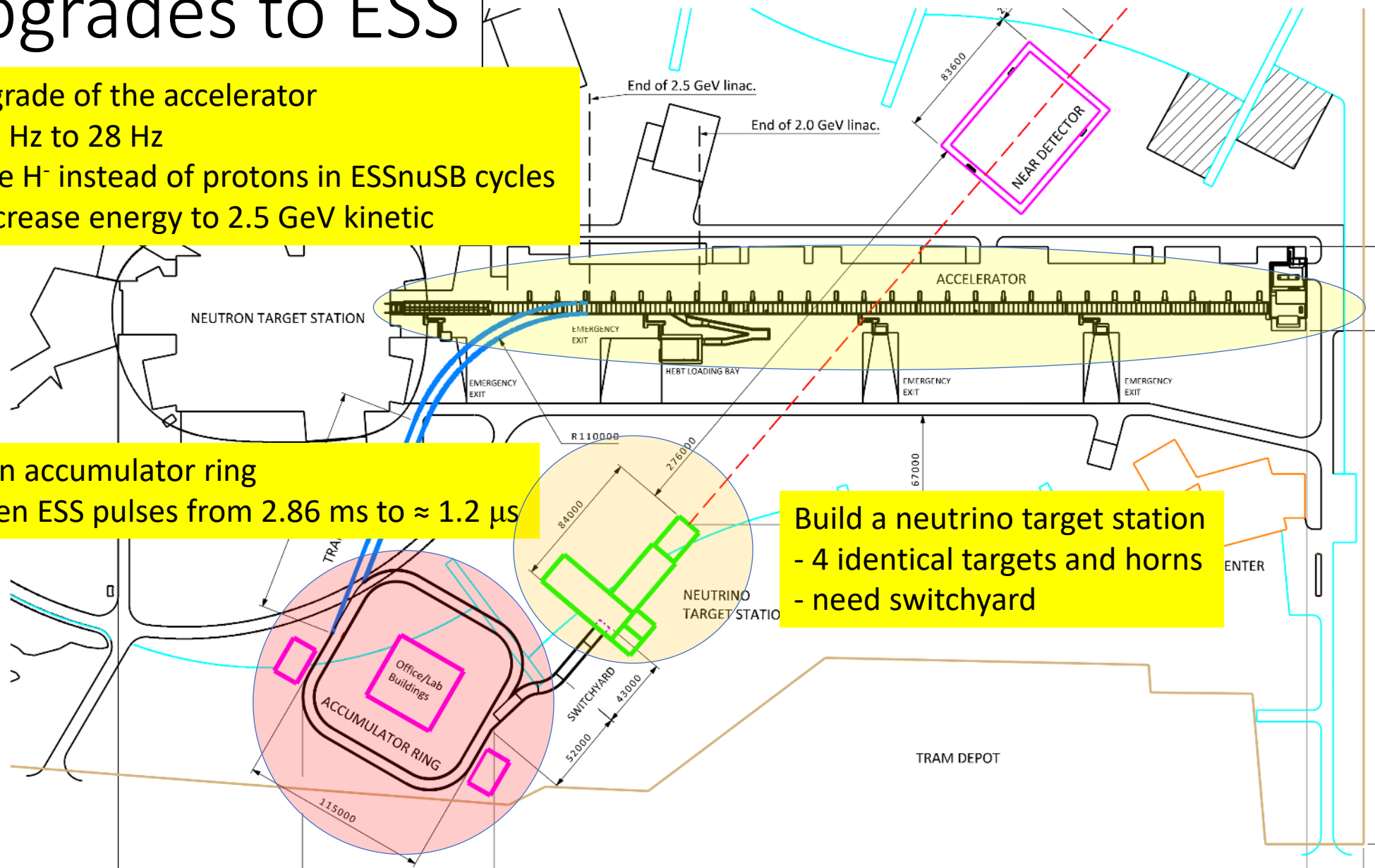
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Build a neutrino target station

- 4 identical targets and horns
- need switchyard



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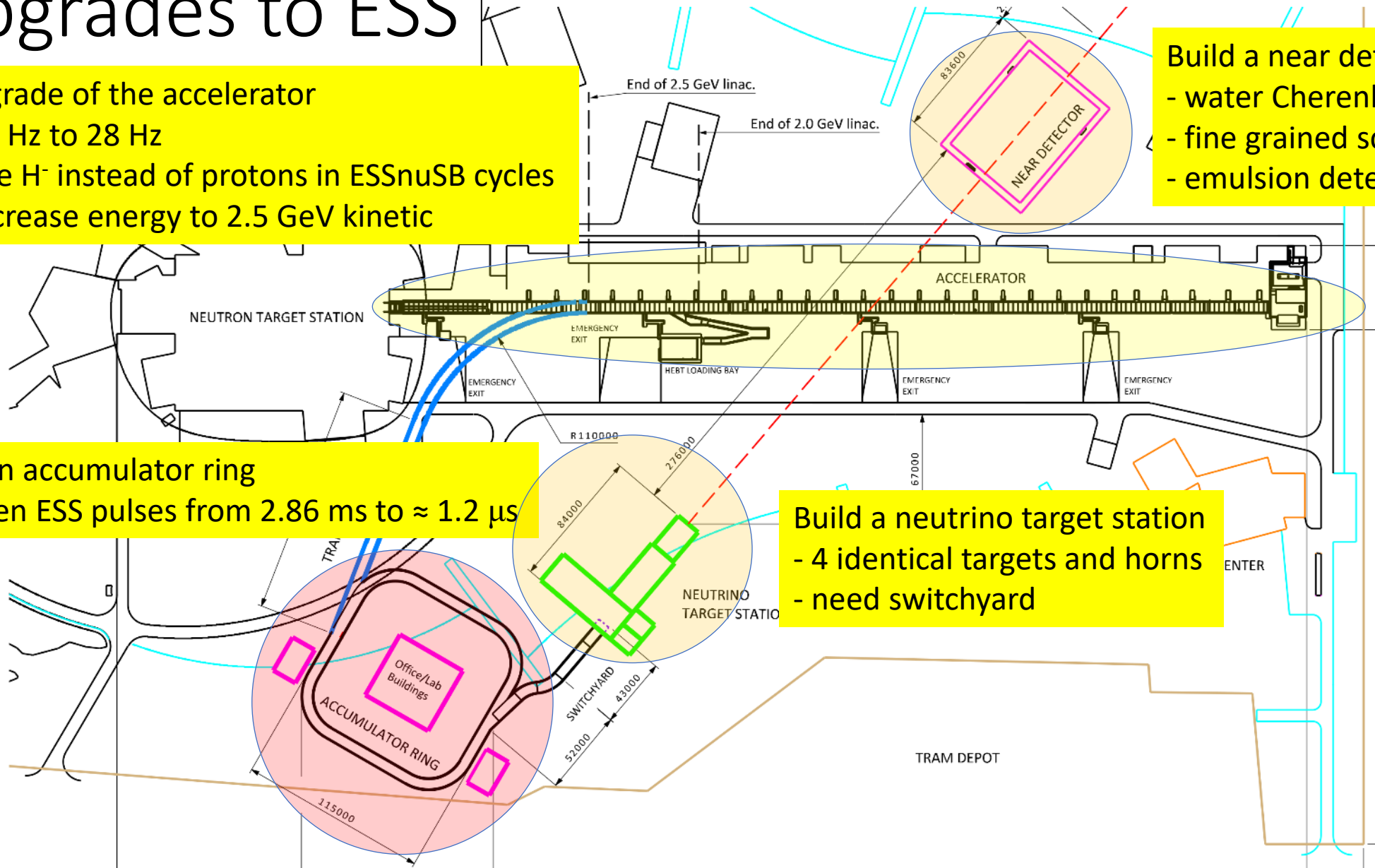
- ## Build a near detector site
- water Cherenkov detector
 - fine grained scintillator
 - emulsion detector

Build an accumulator ring

- shorten ESS pulses from 2.86 ms to $\approx 1.2 \mu s$

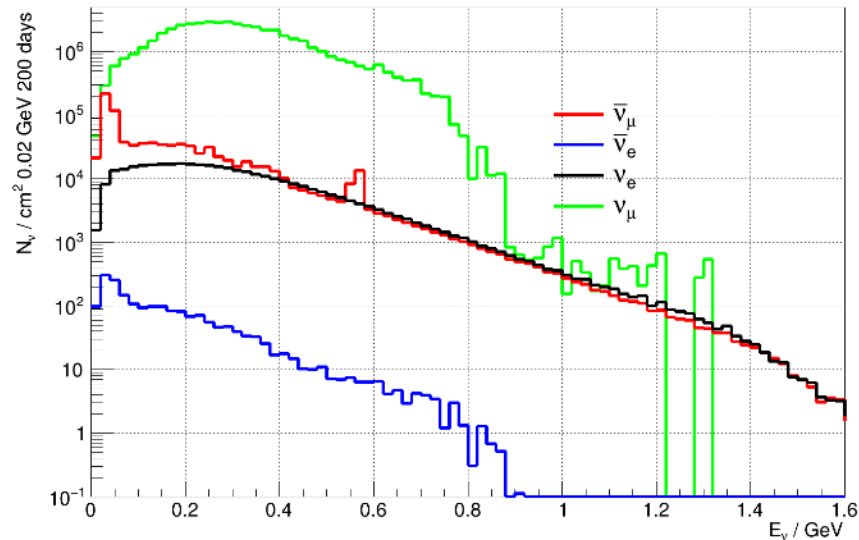
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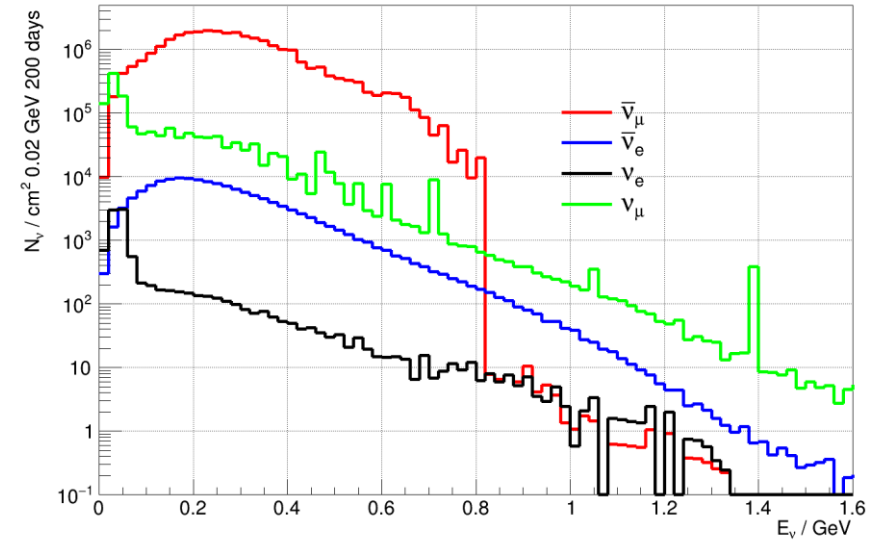


ESSvSB ν energy distribution (after optimisation)

Flux at 360 km (positive polarity)



Flux at 360 km (negative polarity)

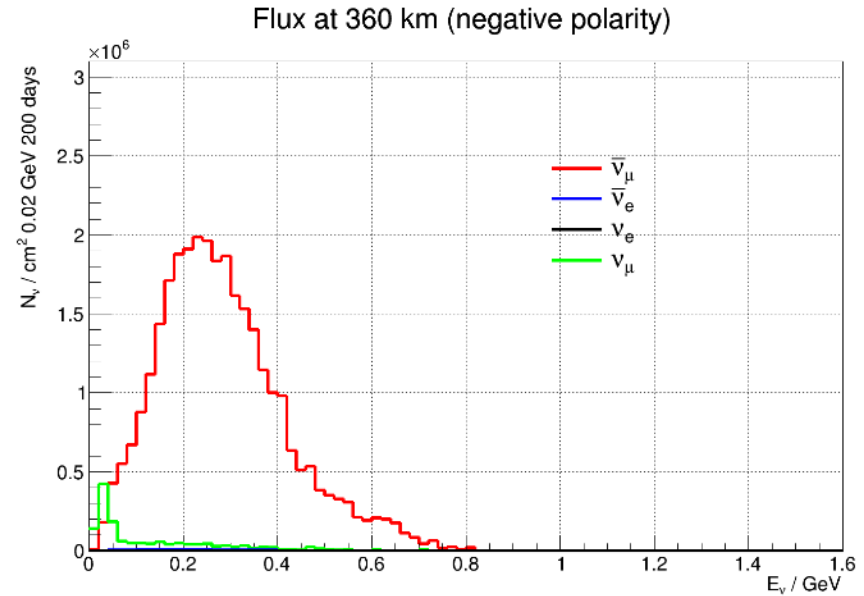
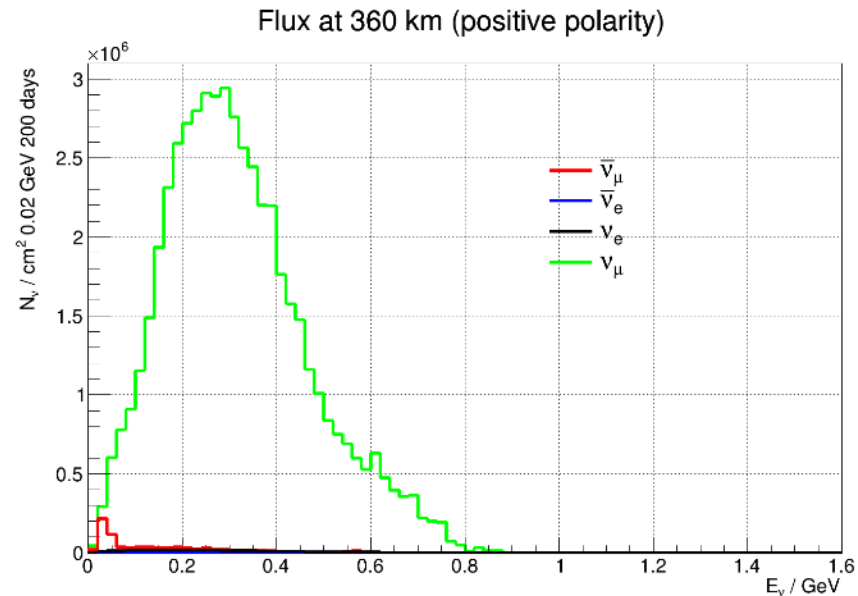


- almost pure ν_μ beam
- small ν_e contamination which will be used to measure ν_e cross-sections in a near detector

Flavour	ν Mode		$\bar{\nu}$ Mode	
	N_ν ($10^5 / \text{cm}^2$)	%	N_ν ($10^5 / \text{cm}^2$)	%
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

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

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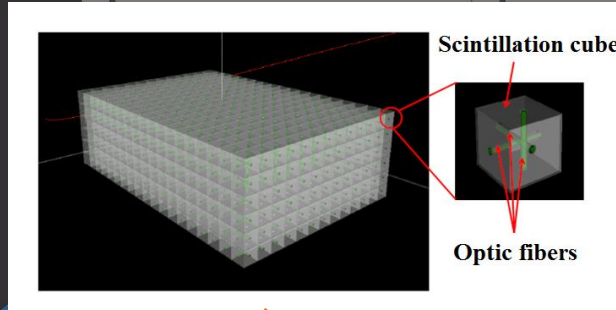
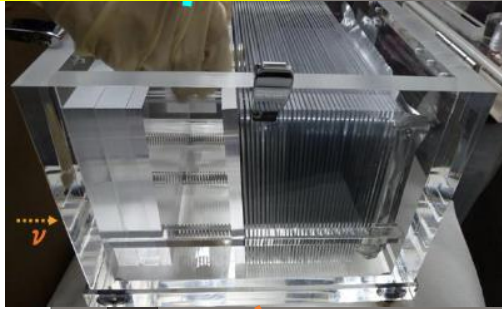
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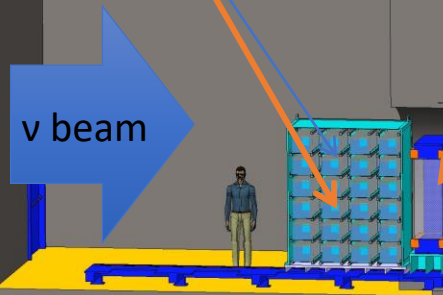
Near detectors

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

Code name: **VIKING**



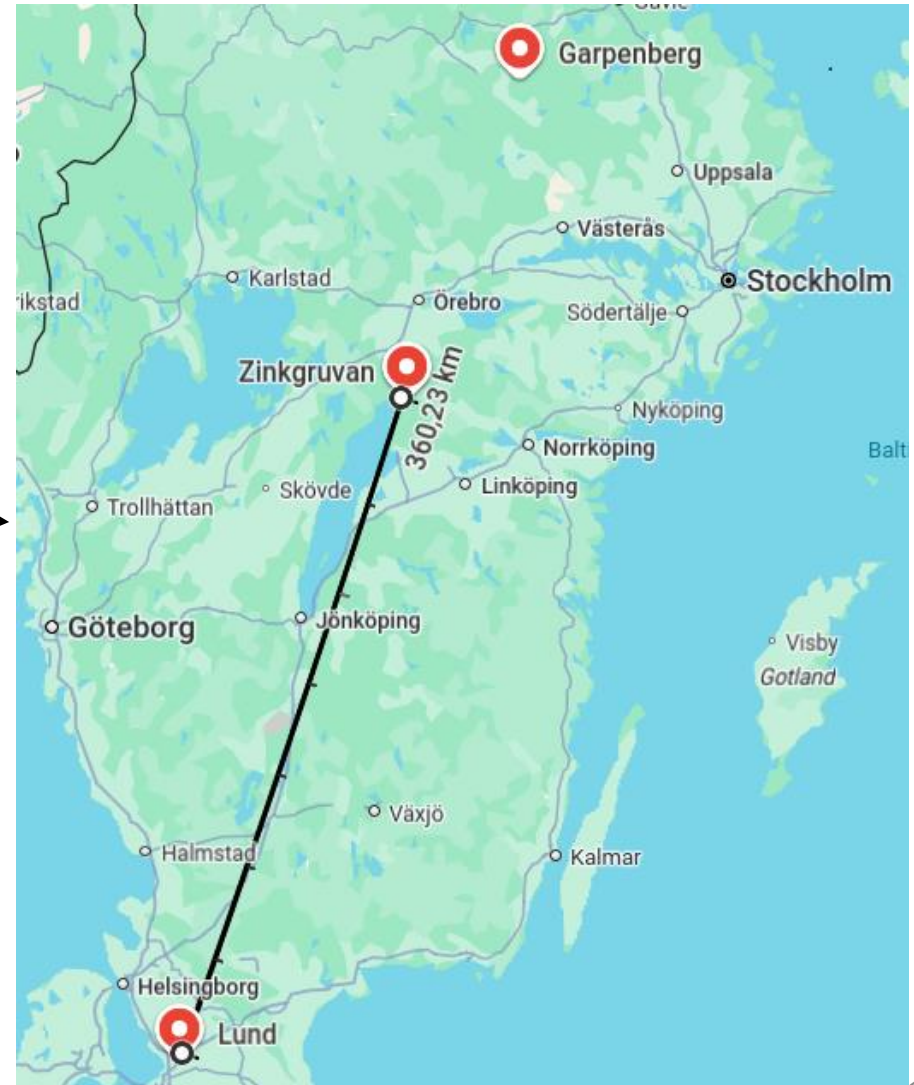
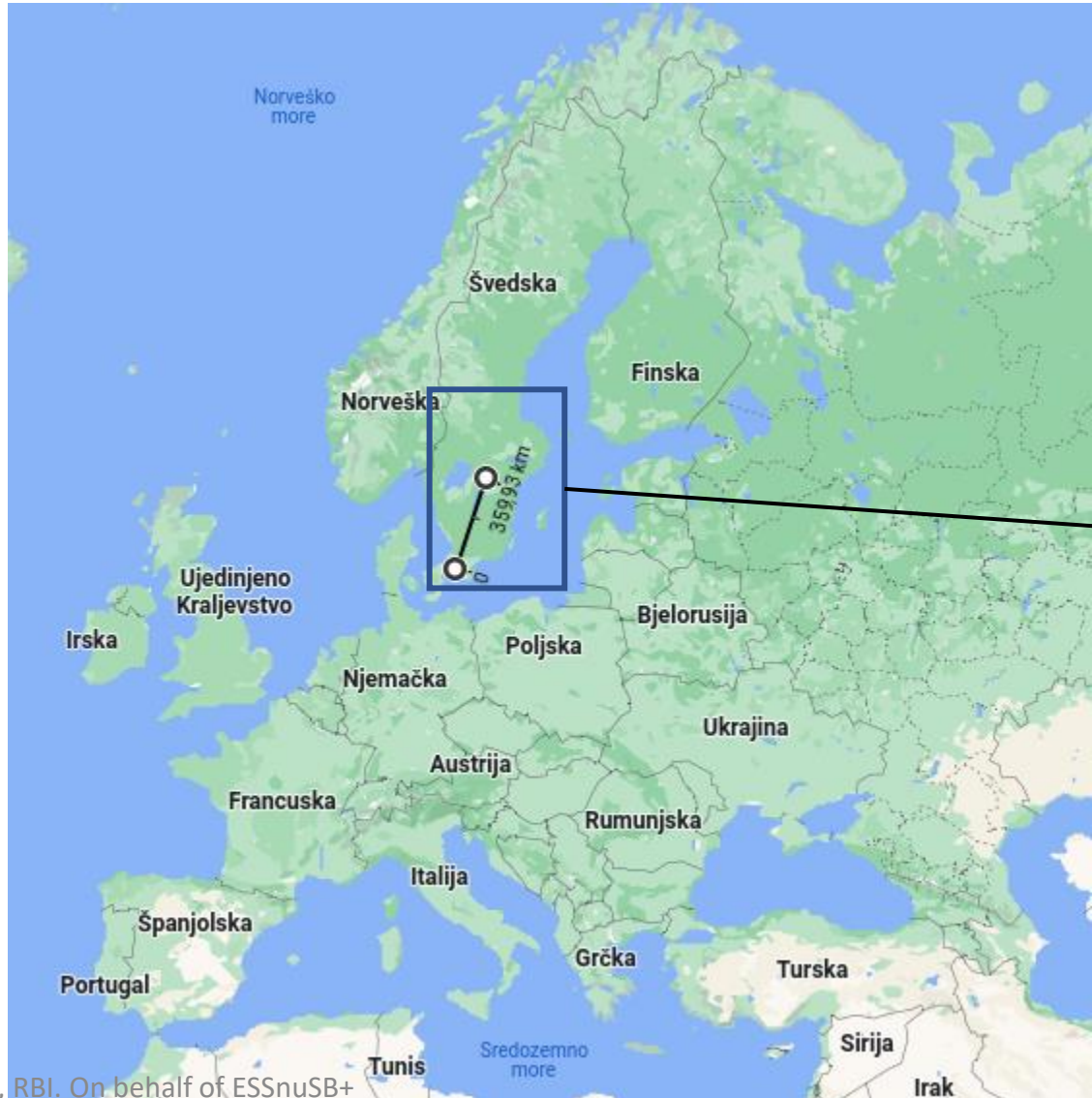
Super-FGD like detector (1 t fiducial)



Near Water Cherenkov detector (0.420 kt fiducial)

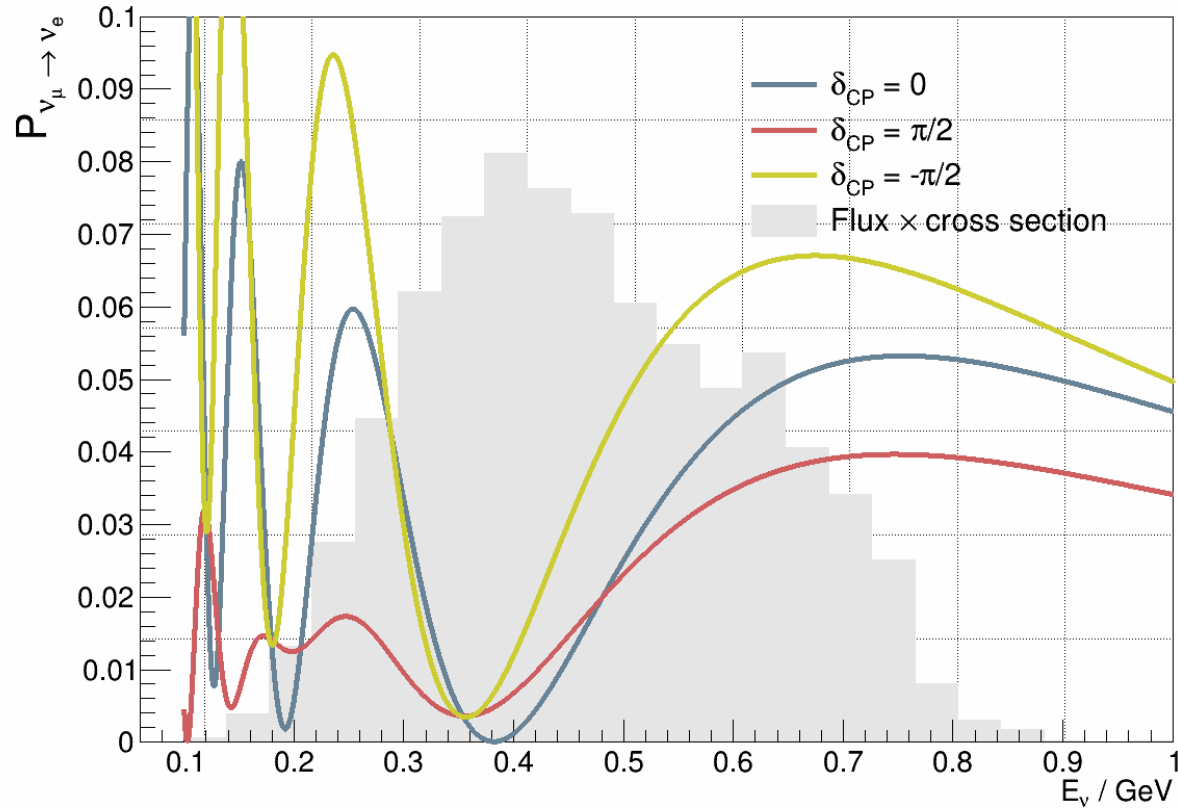
ESSnuSB neutrino baseline

Zinkgruvan mine, 360 km from the source, partly covering 1st and 2nd maximum



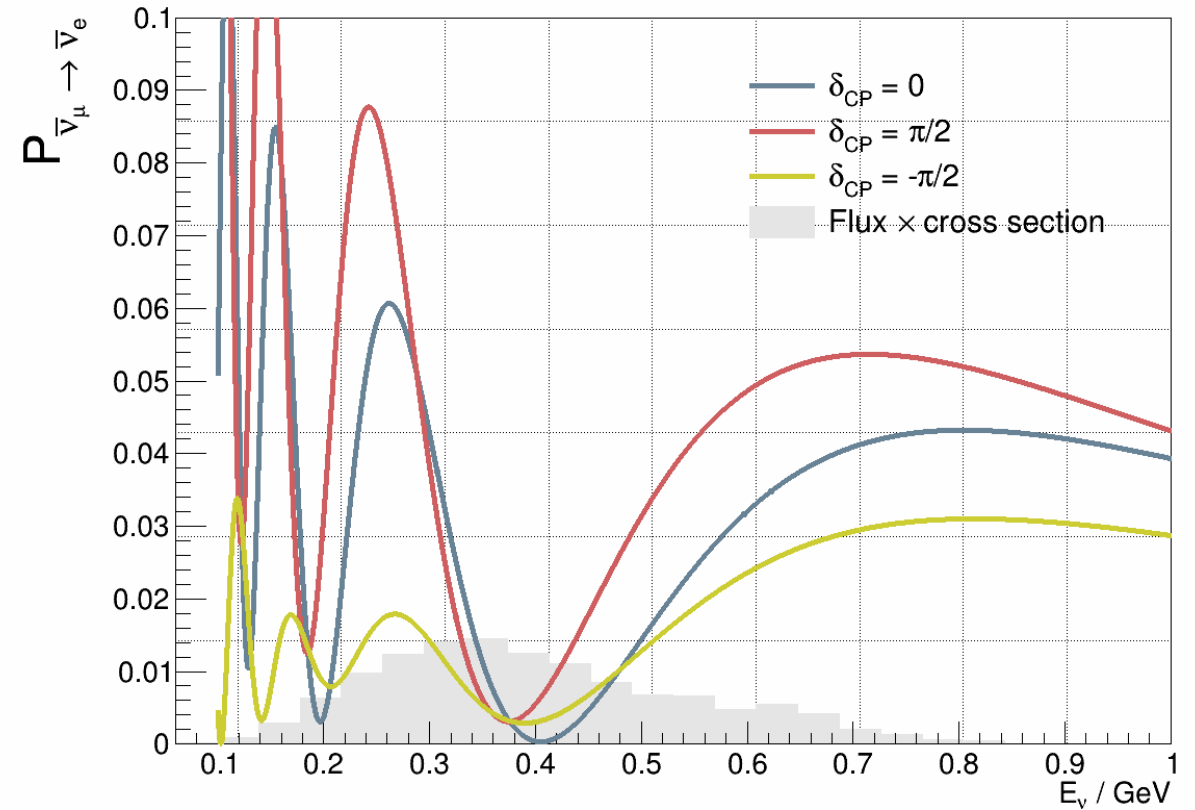
Oscillation coverage

L = 360 km



Neutrino

L = 360 km

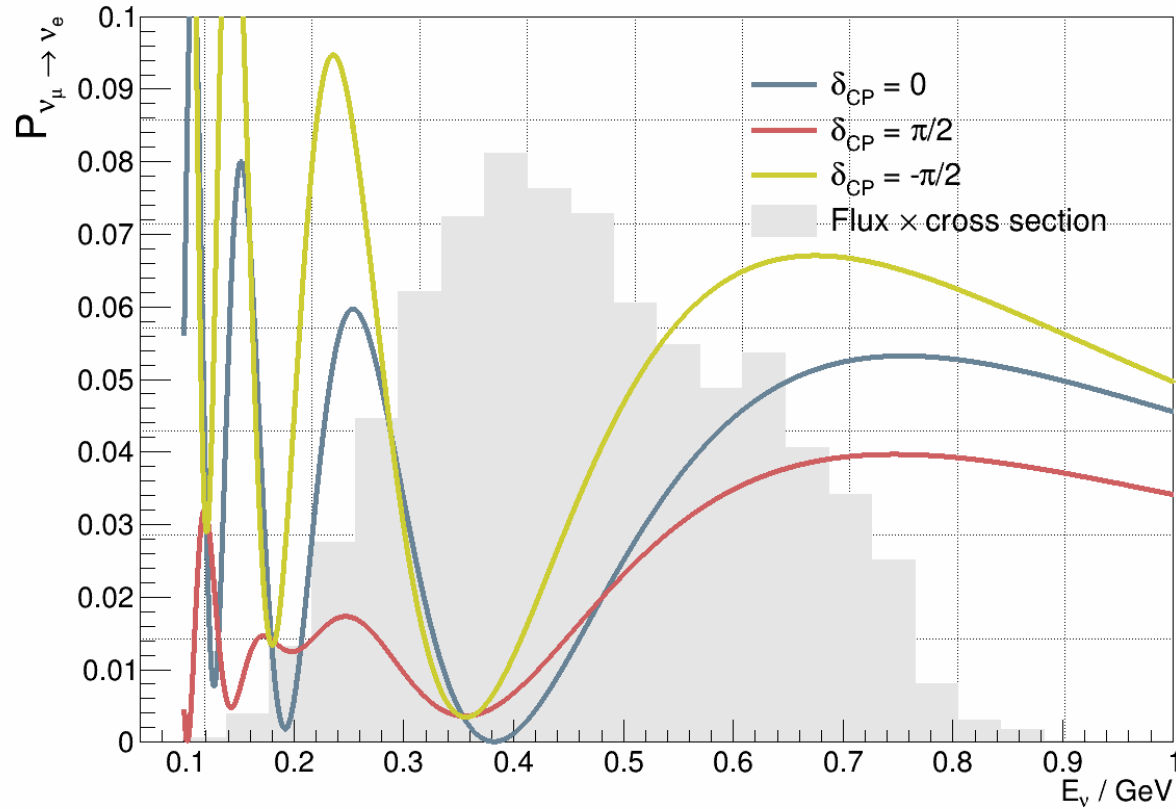


Antineutrino

Oscillation coverage

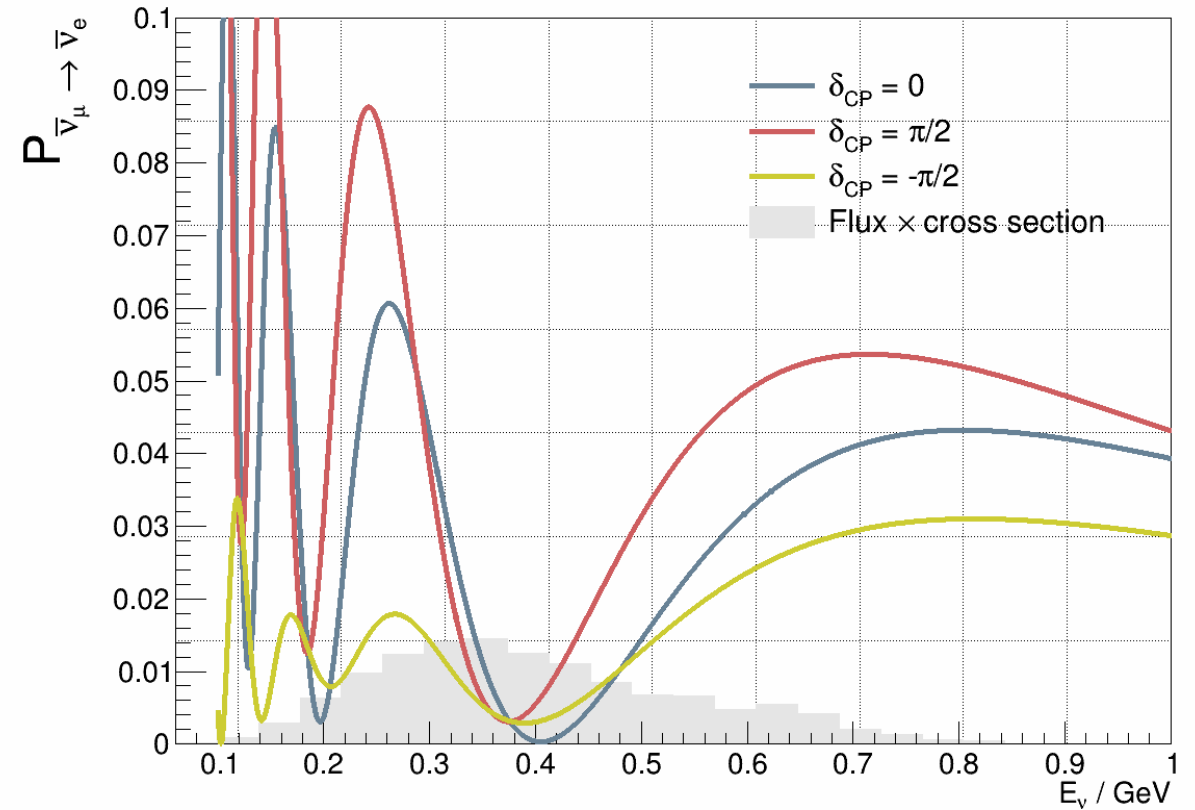
Going from Zinkgruvan to Garpenberg

L = 360 km



Neutrino

L = 360 km



Antineutrino

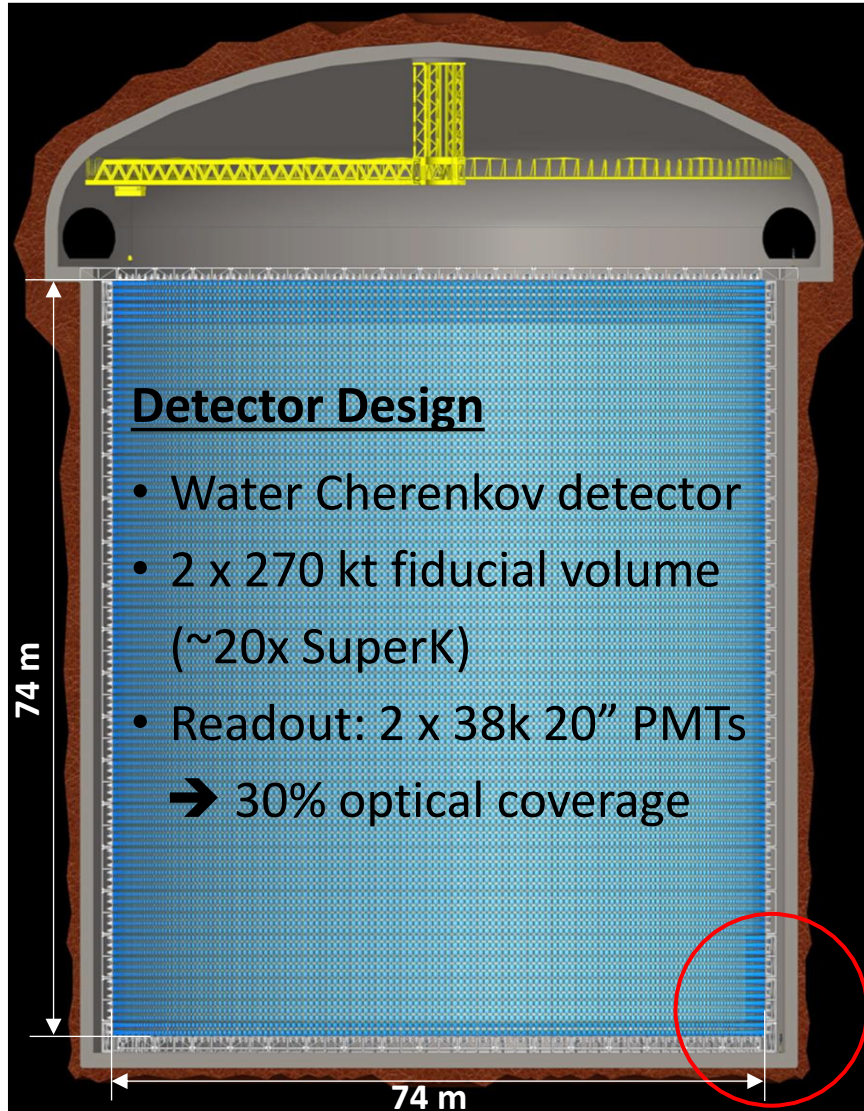
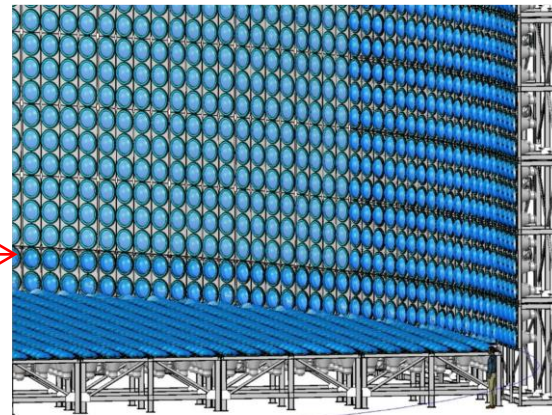
ESSnuSB Far Detector

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

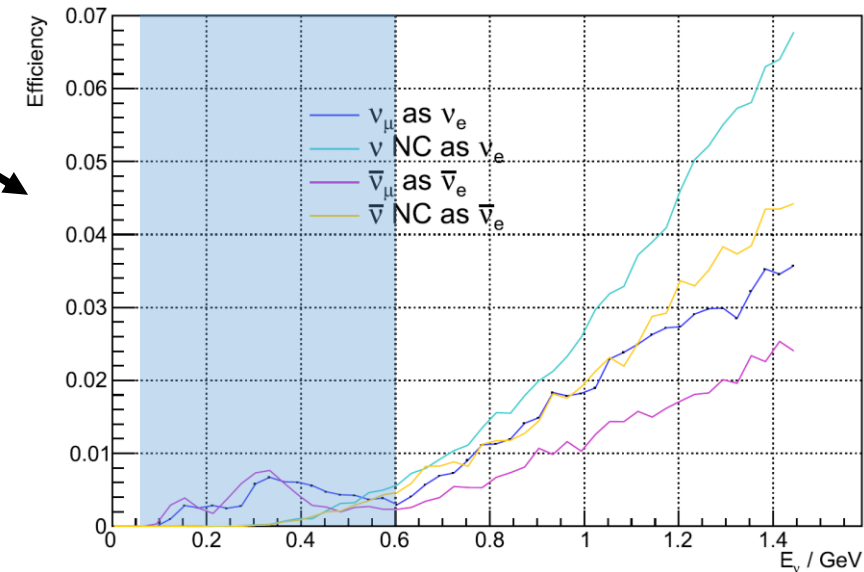
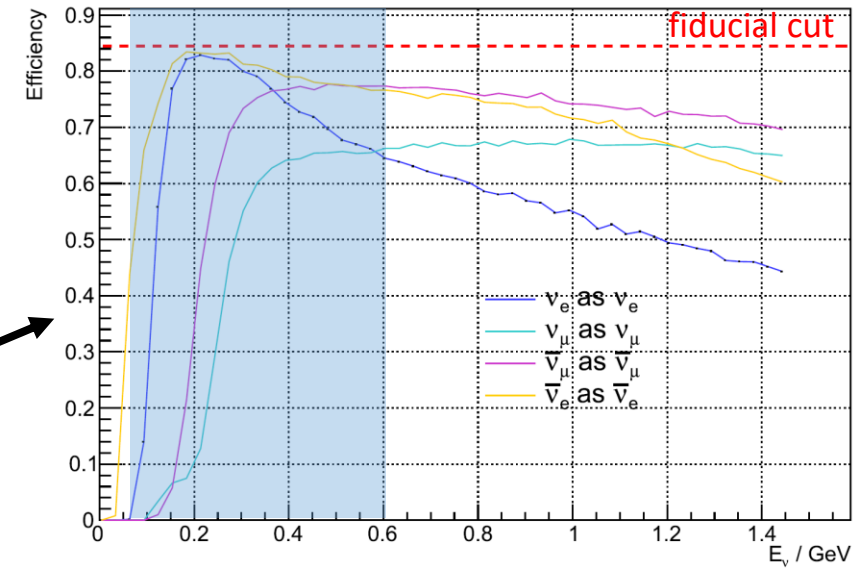
- Detector efficiency for correctly identifying neutrinos > 85%.
- Flavour misidentification probability < 1%.



Detector Design

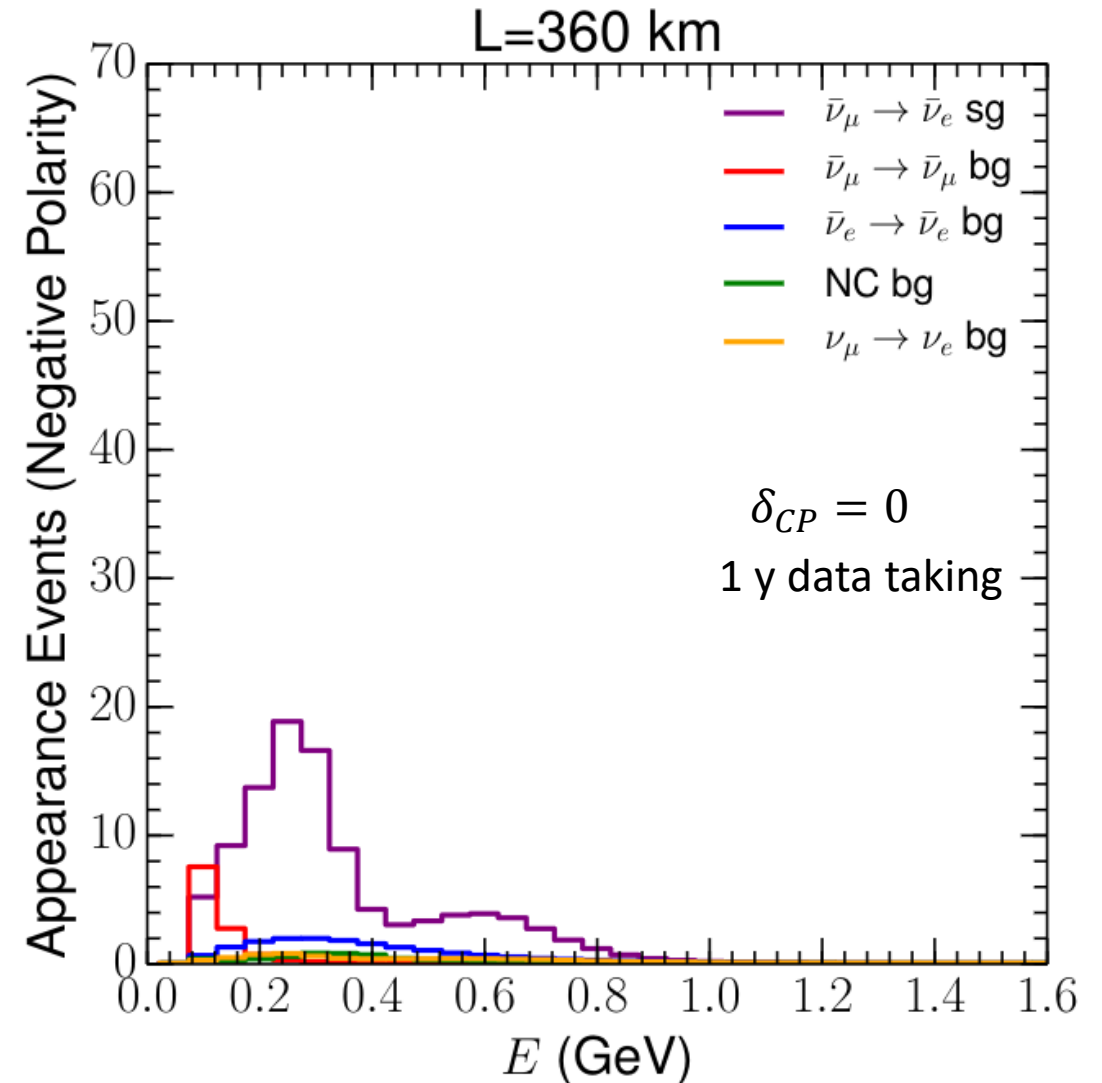
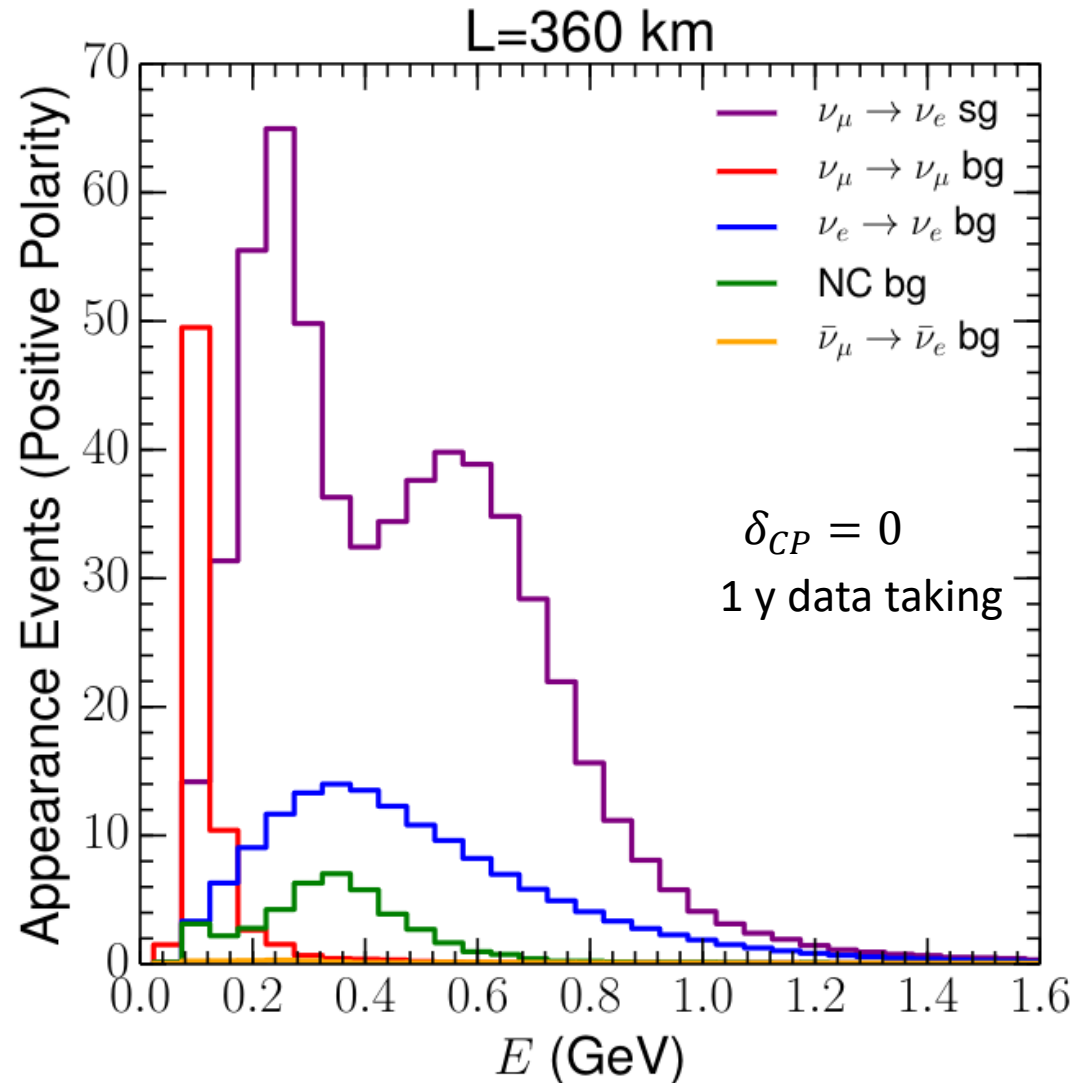
- Water Cherenkov detector
- 2 x 270 kt fiducial volume (~20x SuperK)
- Readout: 2 x 38k 20" PMTs
→ 30% optical coverage

ESSnuSB Particle selection efficiency



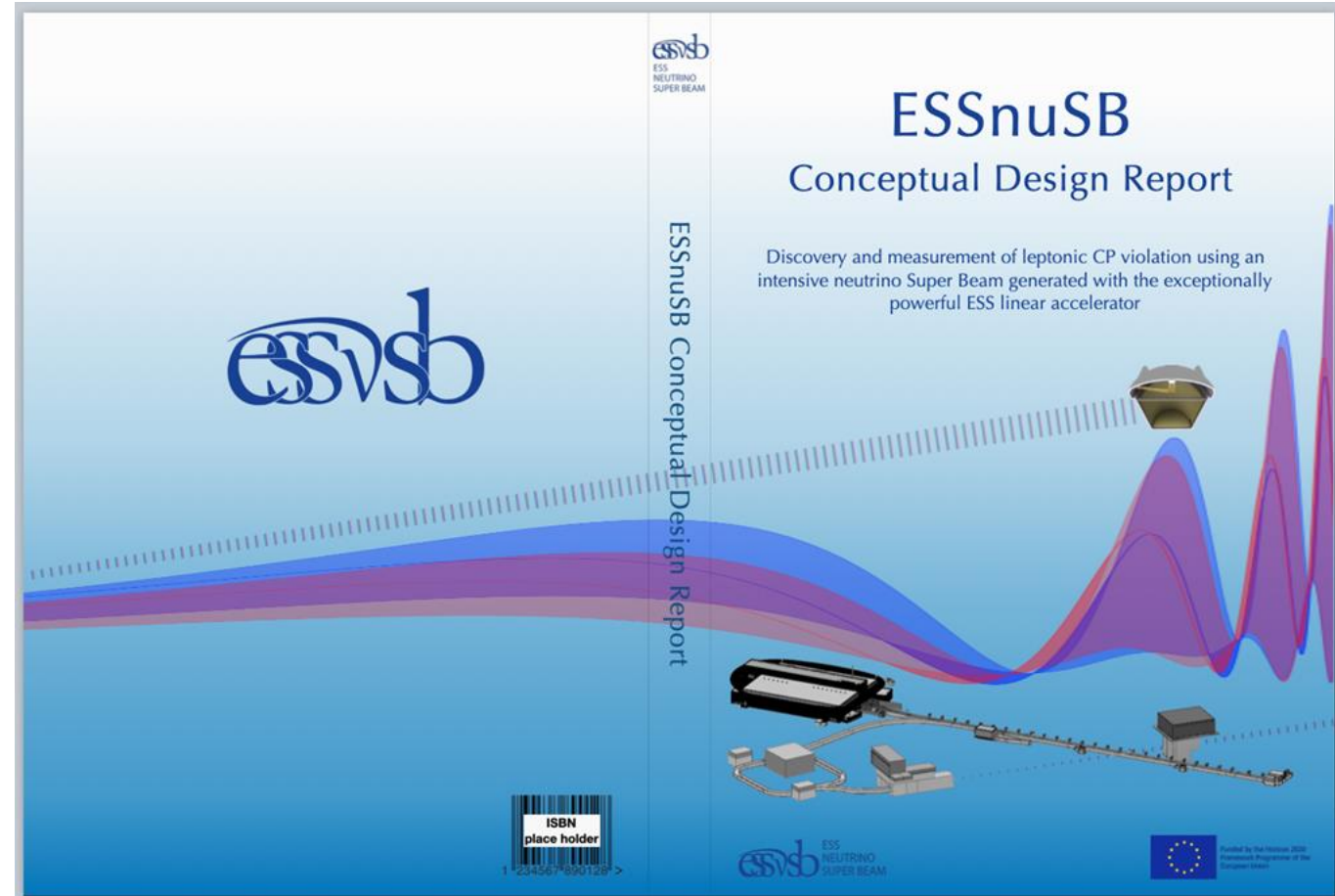
Expected event spectra

From the ESSnuSB CDR: <https://doi.org/10.1140/epjs/s11734-022-00664-w> & <https://arxiv.org/abs/2203.08803>



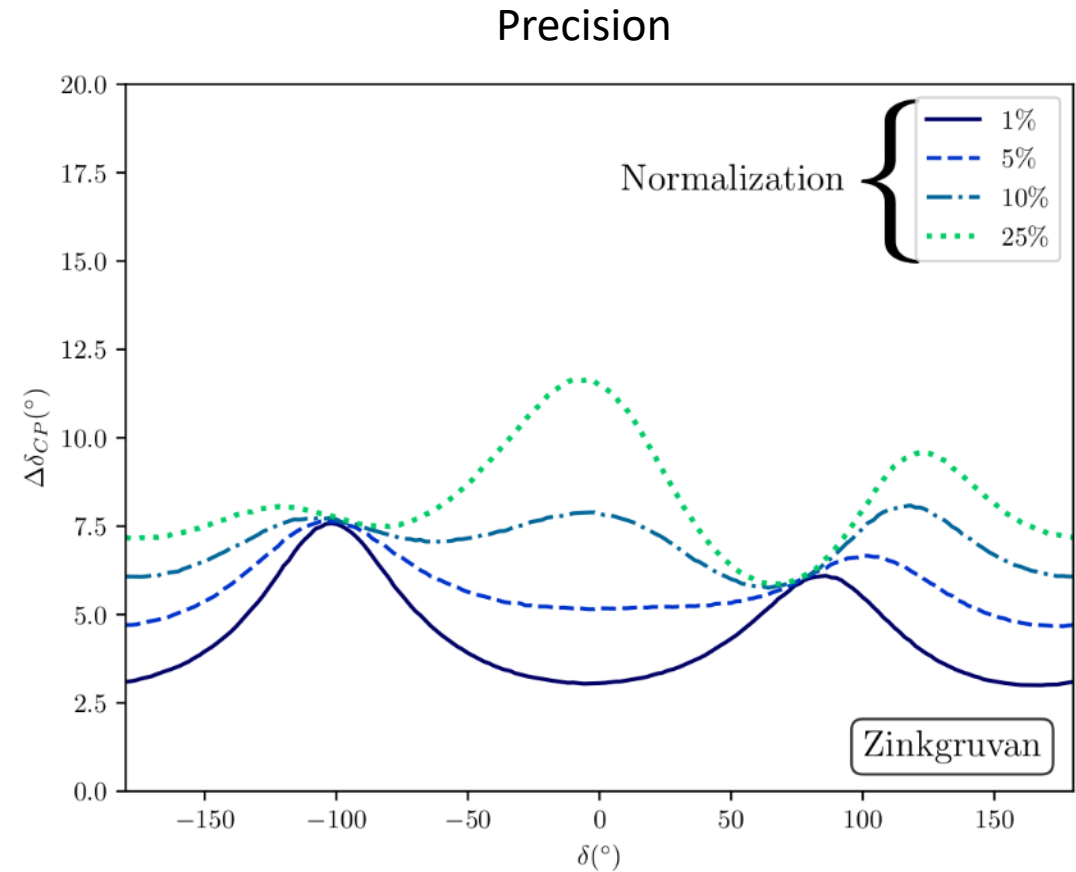
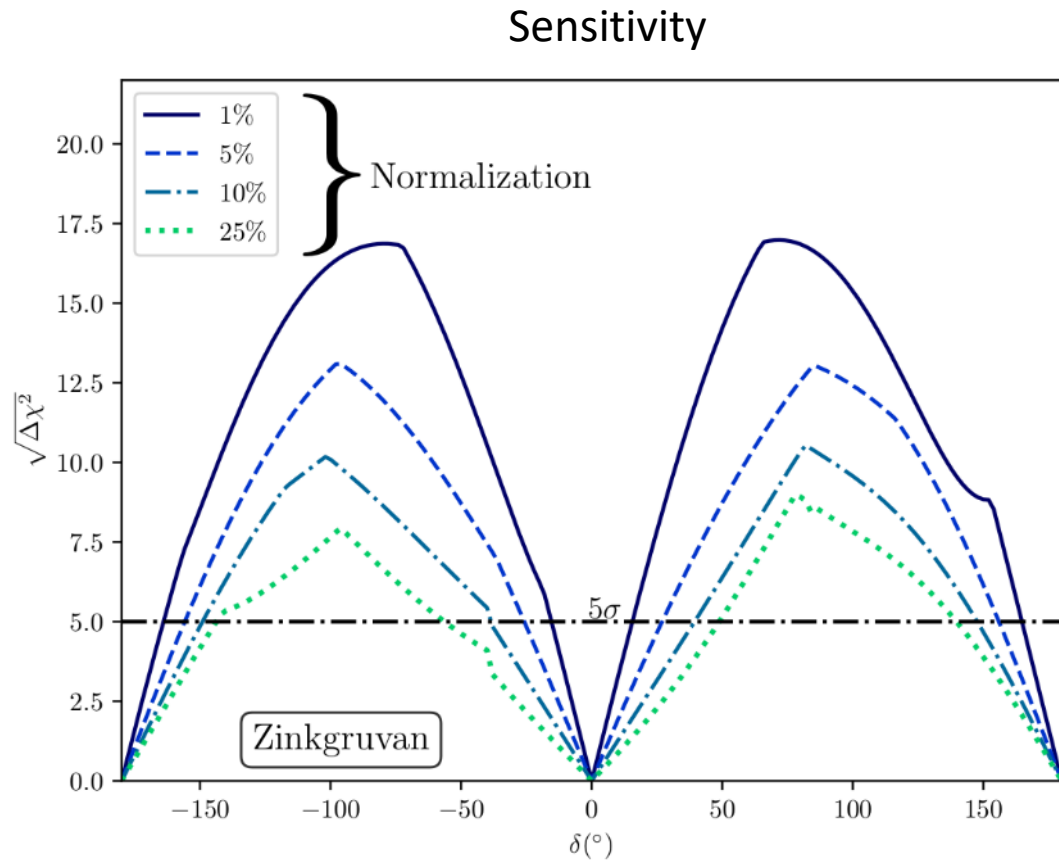
ESSnuSB conceptual design report

- Most up to date evaluation of the CPV discovery potential
 - arXiv version includes costing



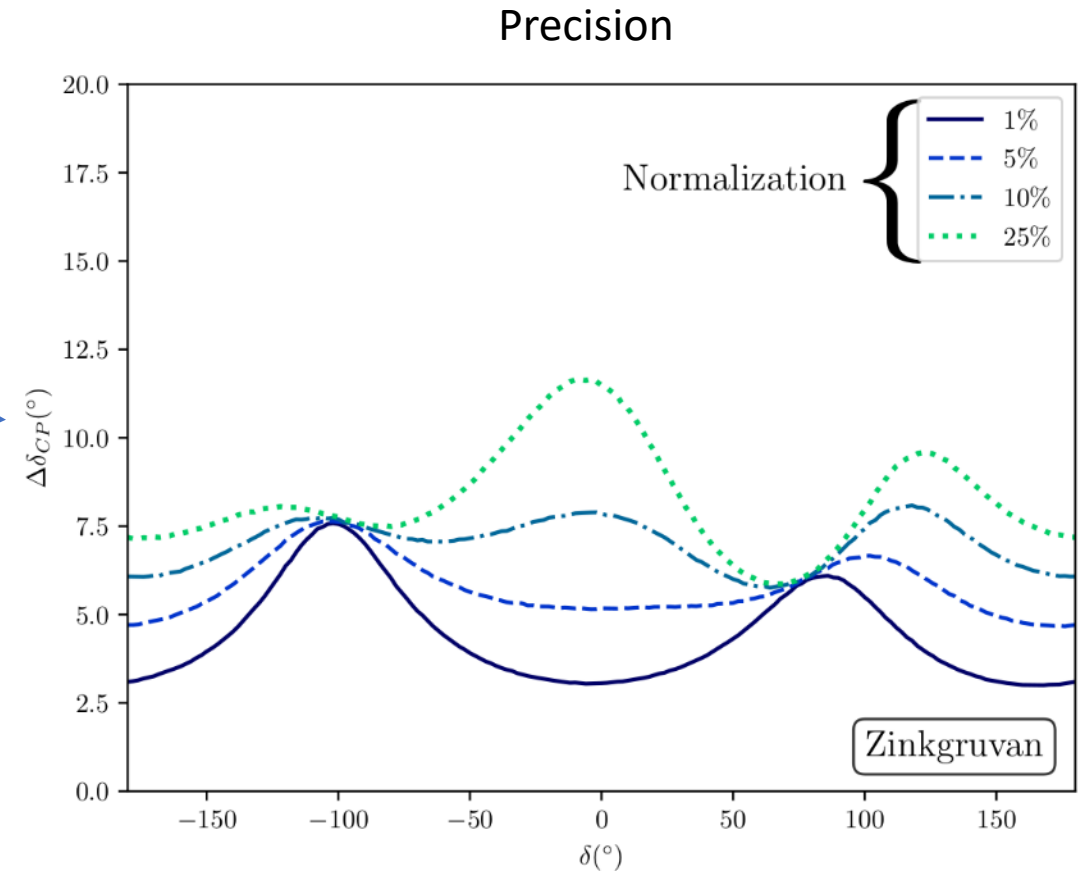
Ale kou, A., Baussan, E., Bhattacharyya, A.K. et al. “The European Spallation Source neutrino super-beam conceptual design report”. Eur. Phys. J. Spec. Top. (2022). <https://doi.org/10.1140/epjs/s11734-022-00664-w>
arXiv: <https://arxiv.org/abs/2203.08803> (includes costing)

CPV sensitivity and precision



From the ESSnuSB CDR: <https://doi.org/10.1140/epjs/s11734-022-00664-w> & <https://arxiv.org/abs/2203.08803>

CPV sensitivity and precision



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Why precision on CPV?

- Why not?
- Discriminate between different leptogenesis and different flavour models

Desired precision

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

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

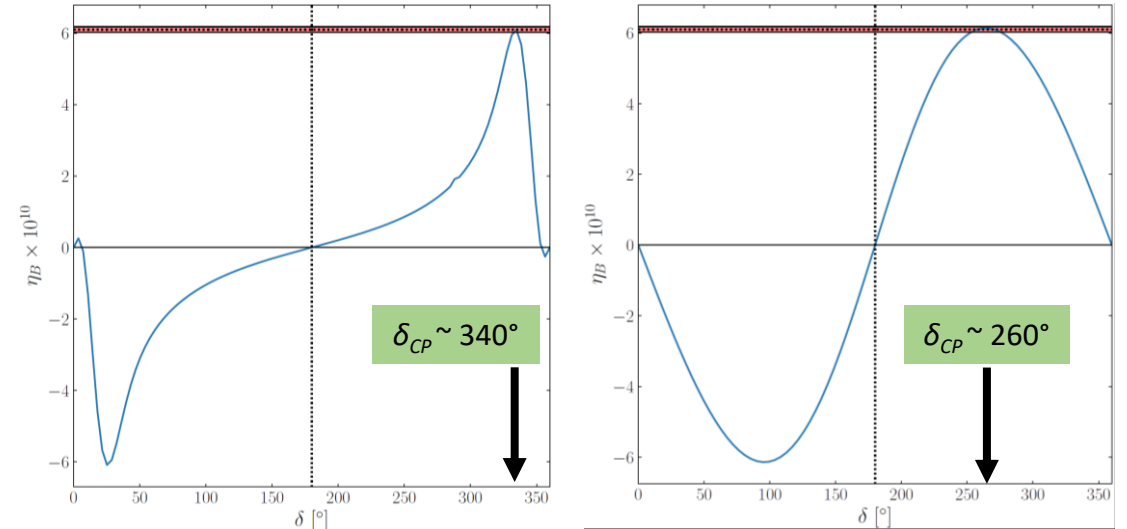
Leptogenesis Theories [K. Moffat et al., arXiv:1809.08251 \(2019\)](#)

Low mass flavor regime

$$M_1 \text{ (GeV)} < 10^9$$

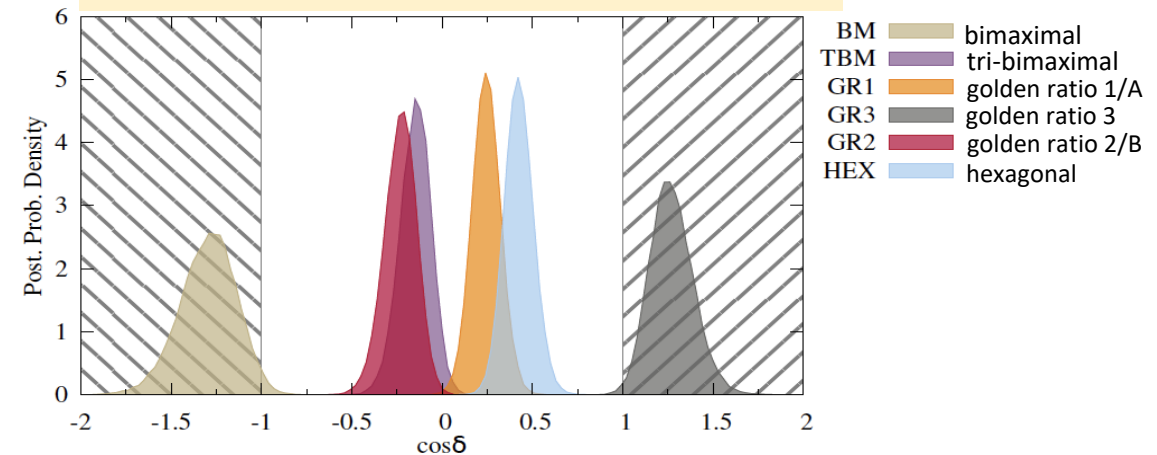
Intermediate mass flavor regime

$$10^9 < M_1 \text{ (GeV)} < 10^{12}$$



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

four different symmetry forms of the neutrino mixing matrix



So, we're all good?

So, we're all good?

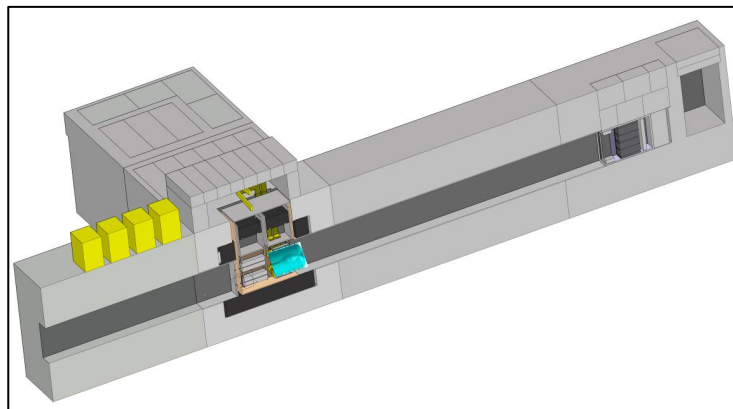


Powerful proton gun

So, we're all good?



Powerful proton gun



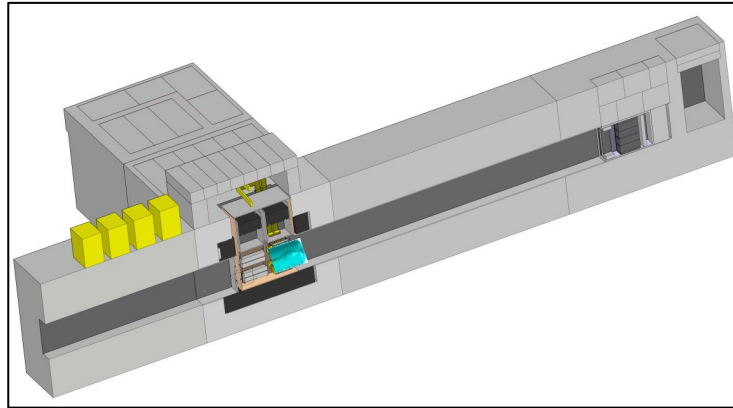
Cool target station

+

So, we're all good?



Powerful proton gun



Cool target station

+

=

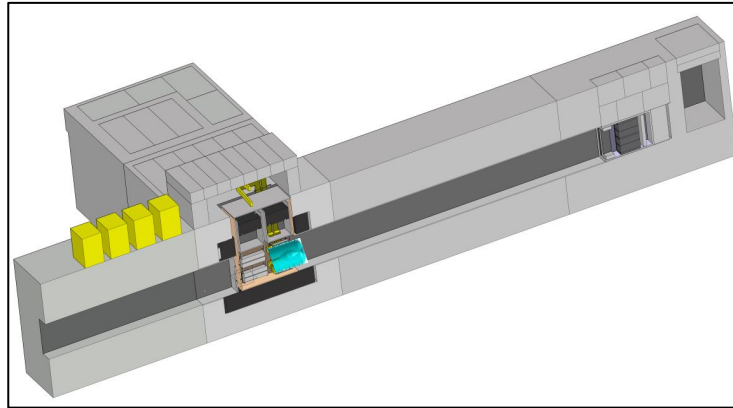


Lots of neutrinos, good physics

So, we're all good?



Powerful proton gun



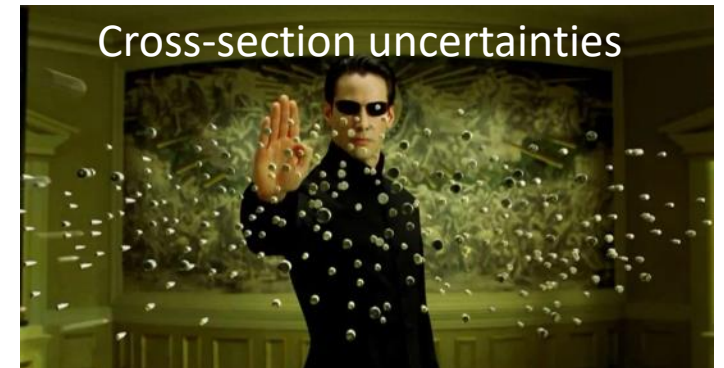
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Lots of neutrinos, good physics

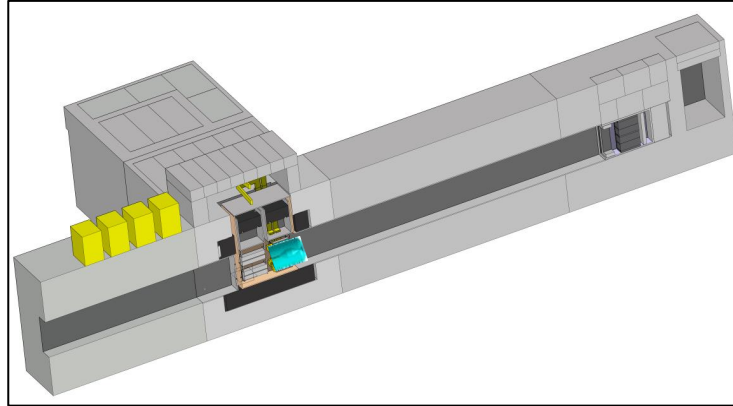


Not so fast

So, we're all good?



Powerful proton gun



Cool target station

+

=



Lots of neutrinos, good physics



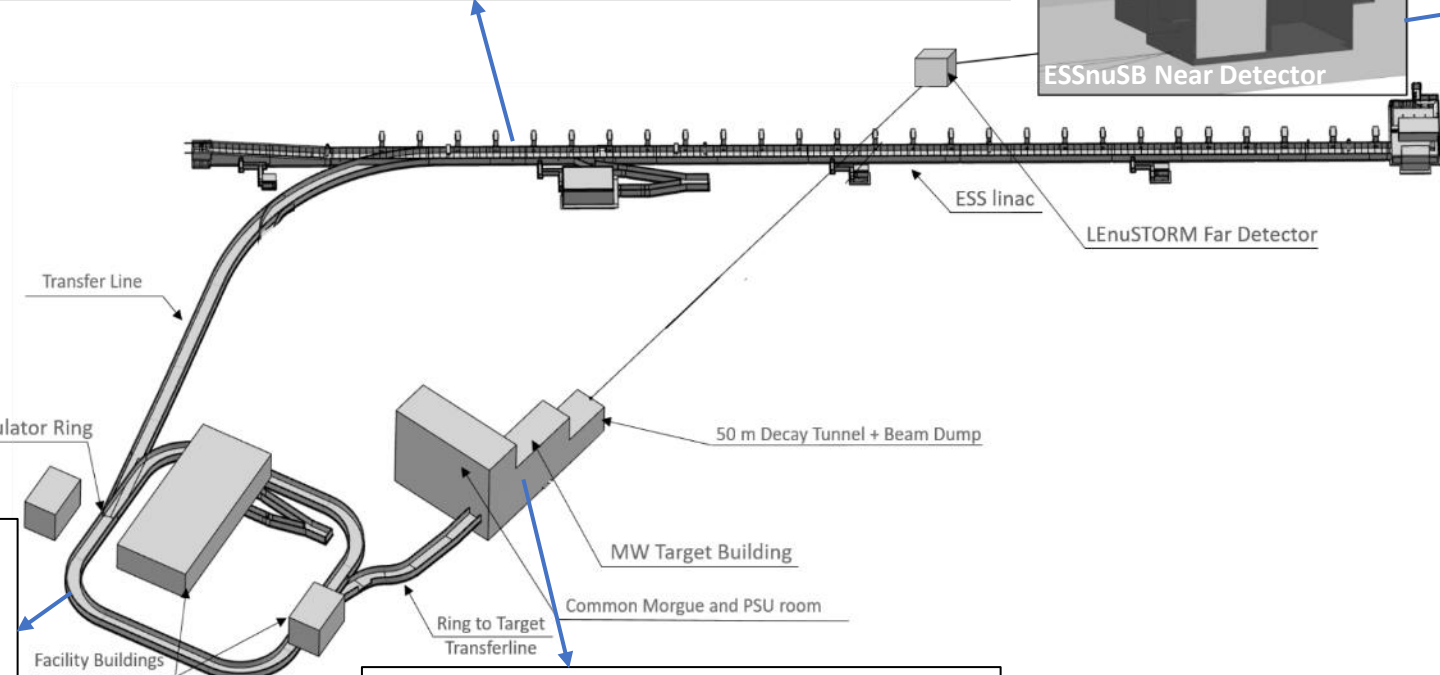
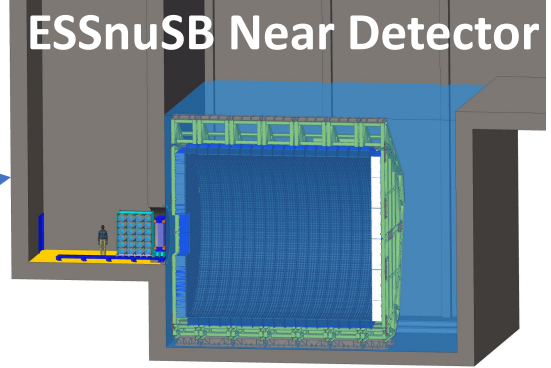
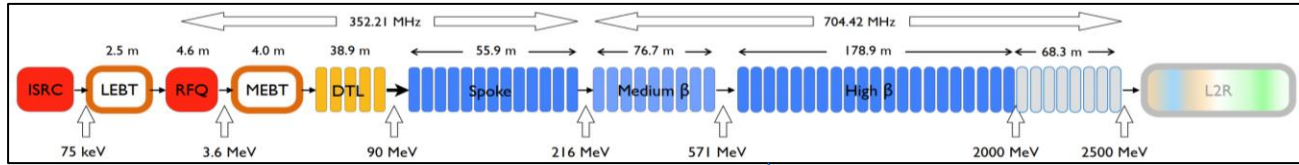
Not so fast

The ESSnuSB+ project

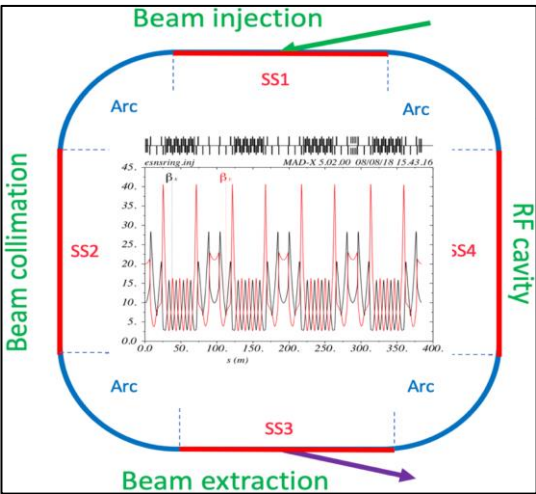
- Start with the civil engineering and infrastructure development
- Design prototyping facilities at ESS
- Explore additional physics opportunities offered by ESSnuSB with addition of LEnuSTORM and LEMNB
- **Design facilities for precise neutrino cross-section measurement:**
 - low energy nuSTORM (LEnuSTORM) and monitored beam (LEMNB)
- **Study non-beam physics with far detectors**
 - Atmospheric neutrinos, supernova neutrinos, solar neutrinos, galactic neutrinos, geoneutrinos, proton decay ...

ESS upgrades to host the ESSnuSB+

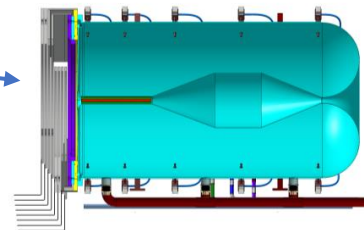
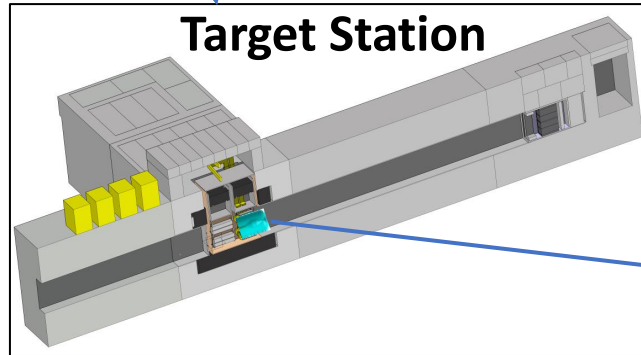
ESS linac



Accumulator Ring



Target Station

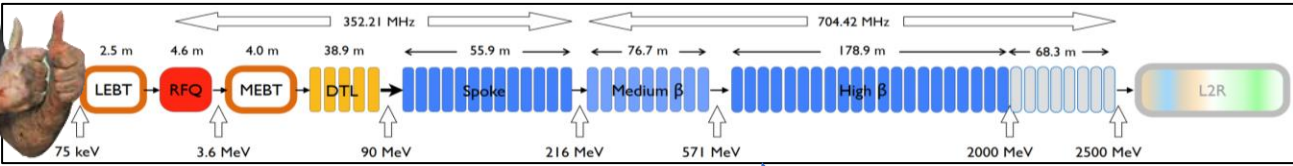


One horn-target system

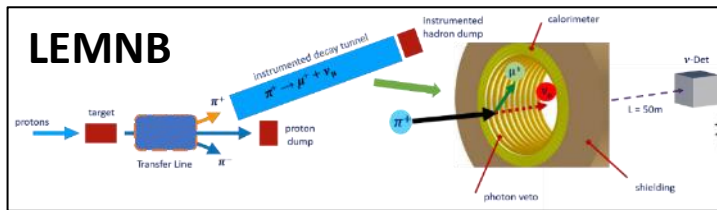
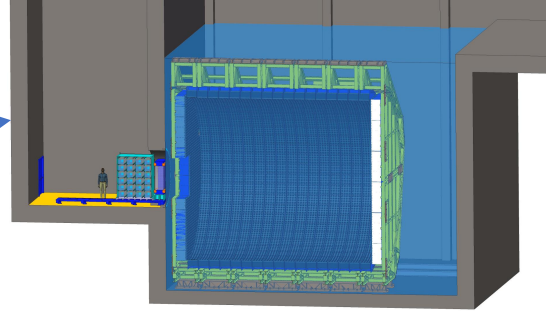
ESS upgrades to host the ESSnuSB+



ESS linac

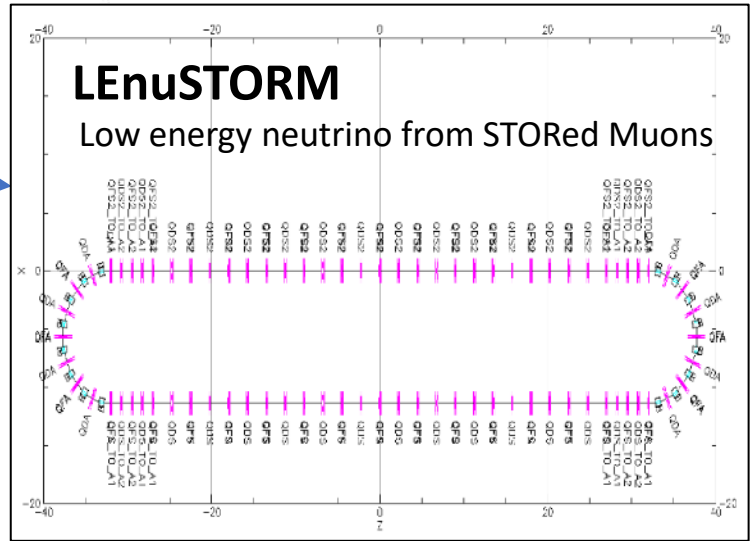
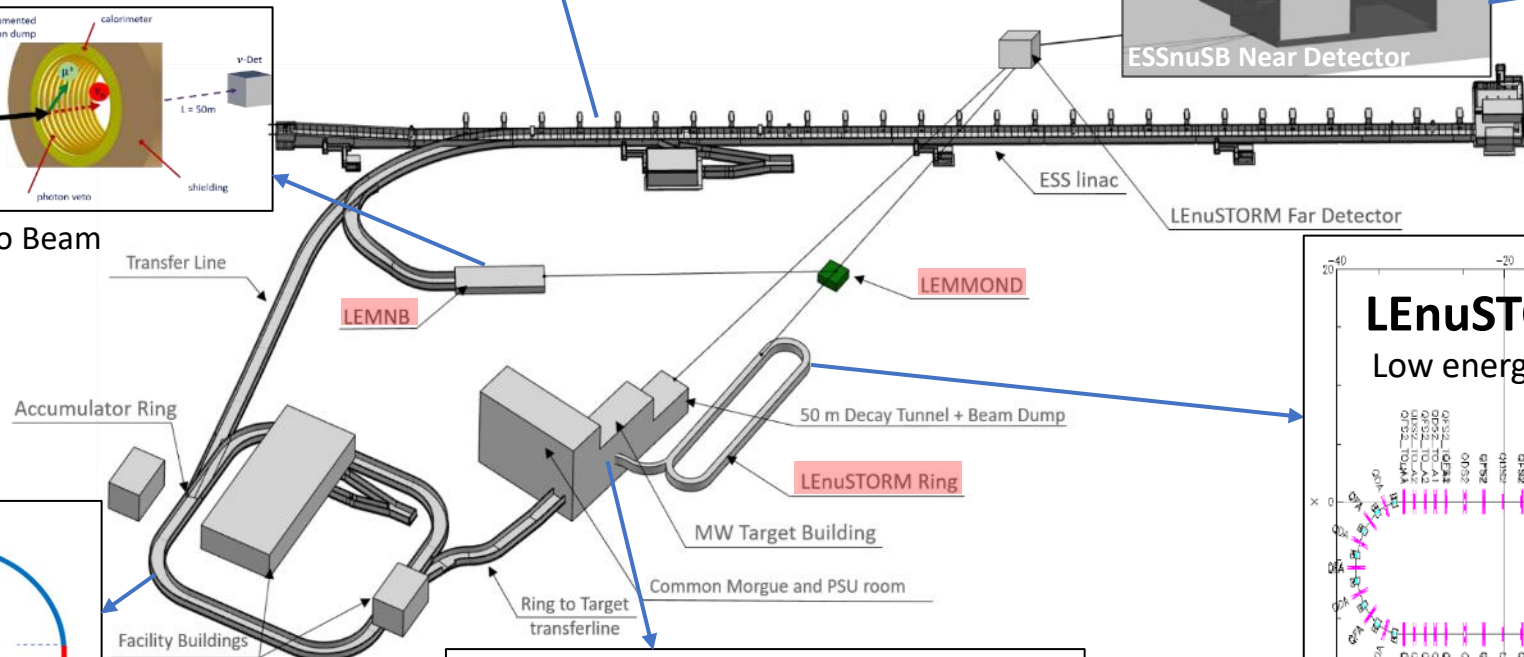


ESSnuSB Near Detector

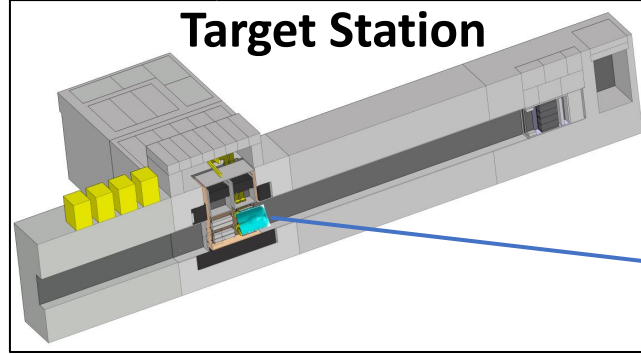
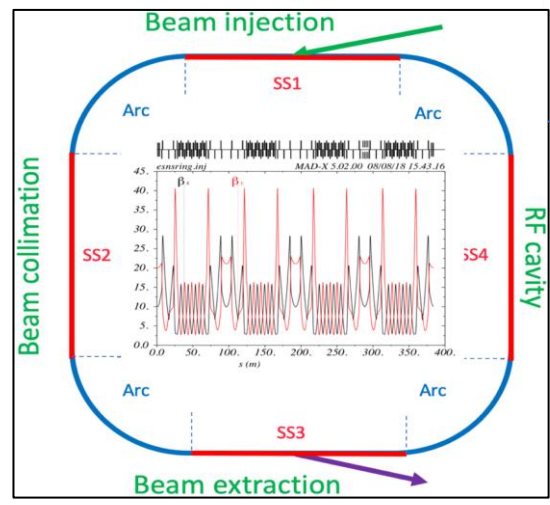


Low Energy Monitored neutrino Beam

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

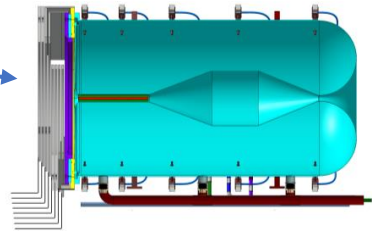


Accumulator Ring

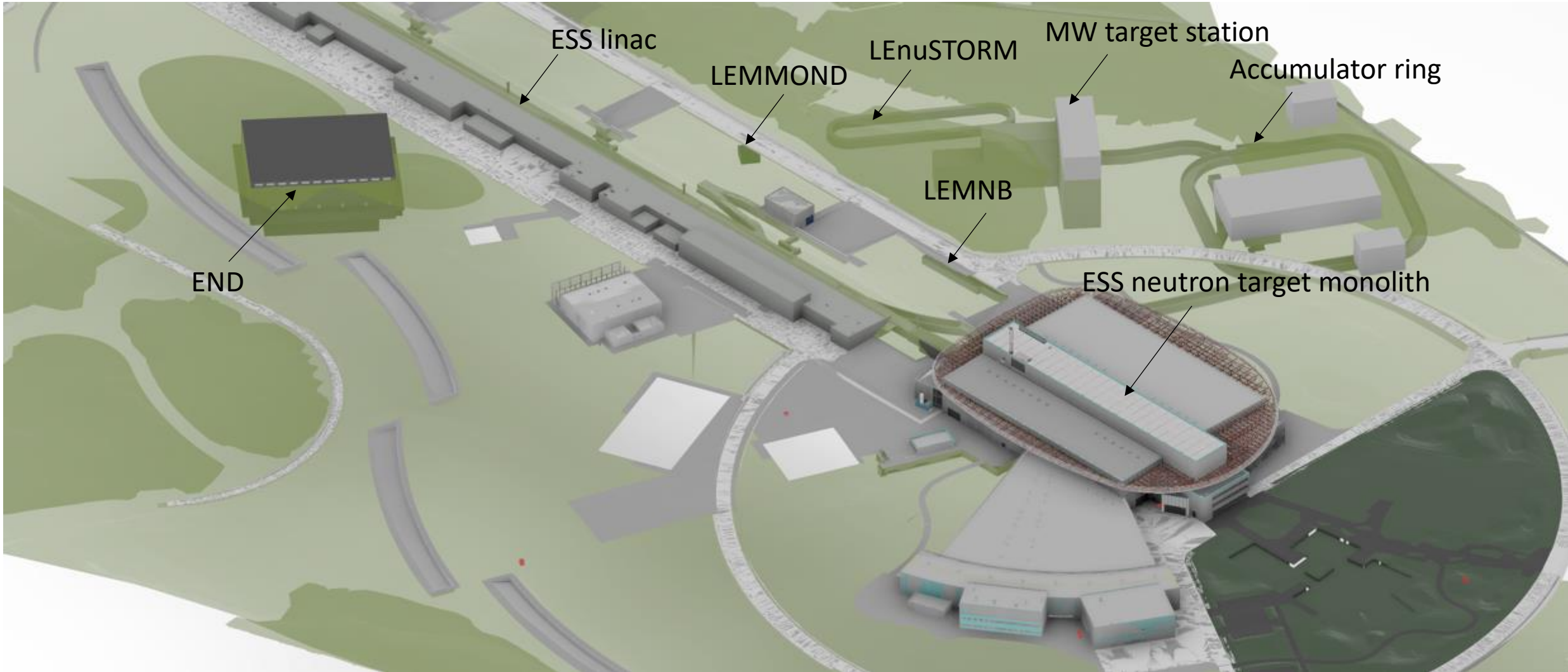


$$\mu^{+(-)} \rightarrow e^{+(-)} + \nu_{\mu}^{(-)} + \bar{\nu}_e^{(-)}$$

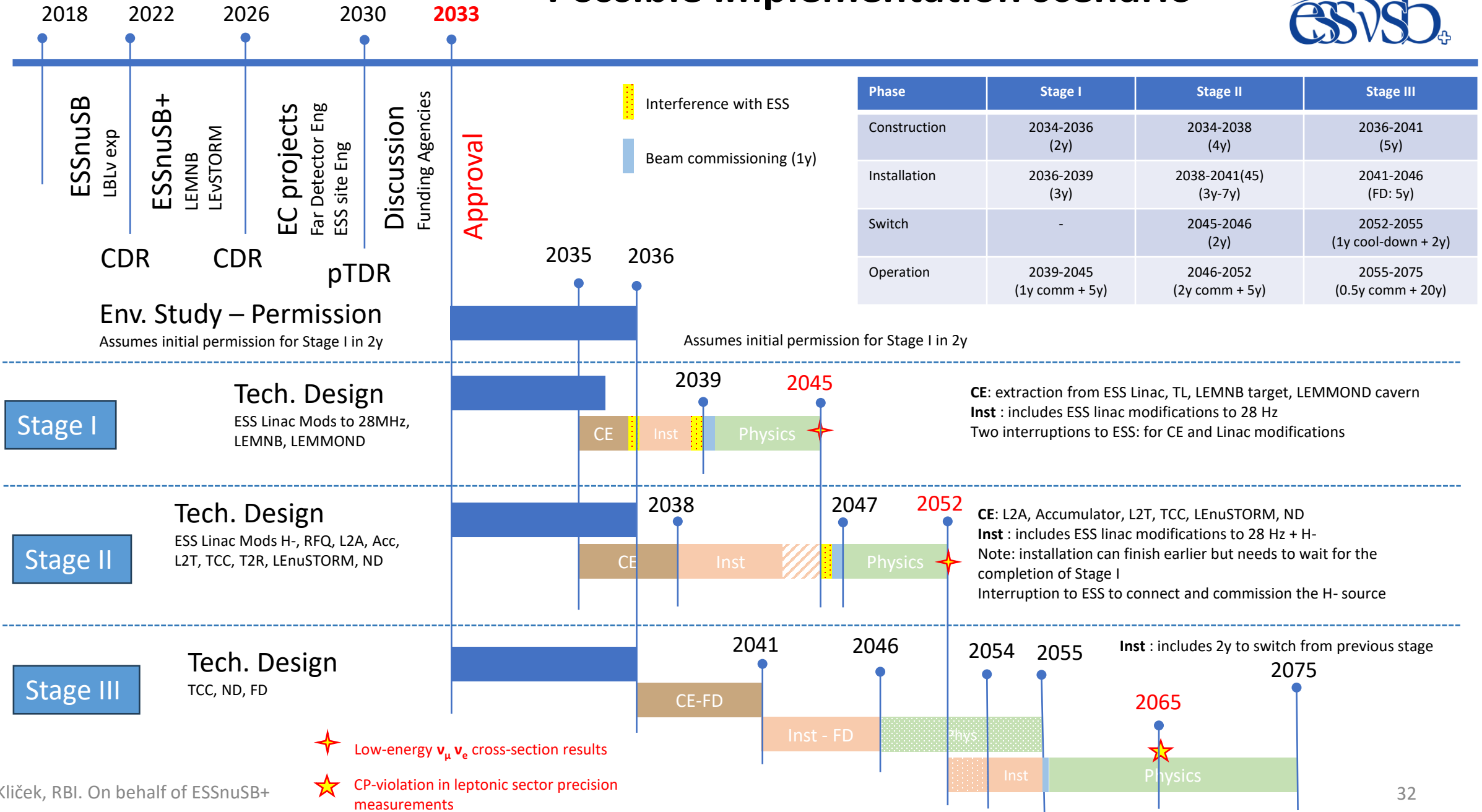
One horn-target system



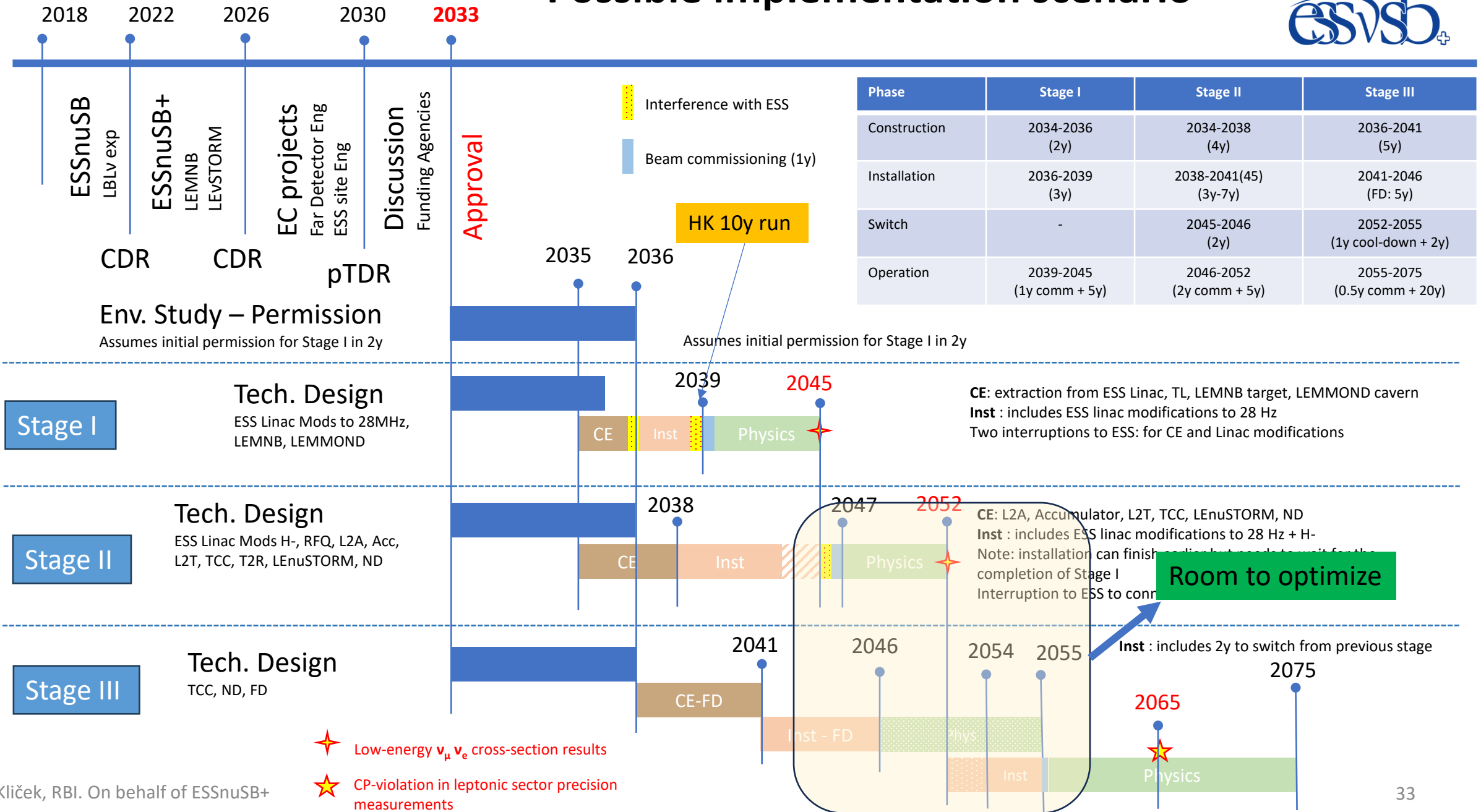
ESS Upgrades to Host the **ESSnuSB+**



Possible implementation scenario



Possible implementation scenario



ESSnuSB EU support programmes

- **COST Action EuroNuNet (CA15139): 2016 - 2020**

0.3 M€ from COST

➤ <https://euronunet.in2p3.fr>

➤ video for scientists:

<https://www.youtube.com/watch?v=PwzNzLQh-Dw>

ESSnuSB Design Study Project



- **EU-H2020 Design Study ESSvSB: 2018 - 2023**

Total 4.7 MEUR
(3 M€ from EU)

➤ <https://essnusb.eu>

➤ video for general public:

<https://www.youtube.com/watch?v=qAnvft0nAlg>

ESSnuSB looking for the answer.



- **EU-Horizon Europe Design Study ESSvSB+: 2023-2026**

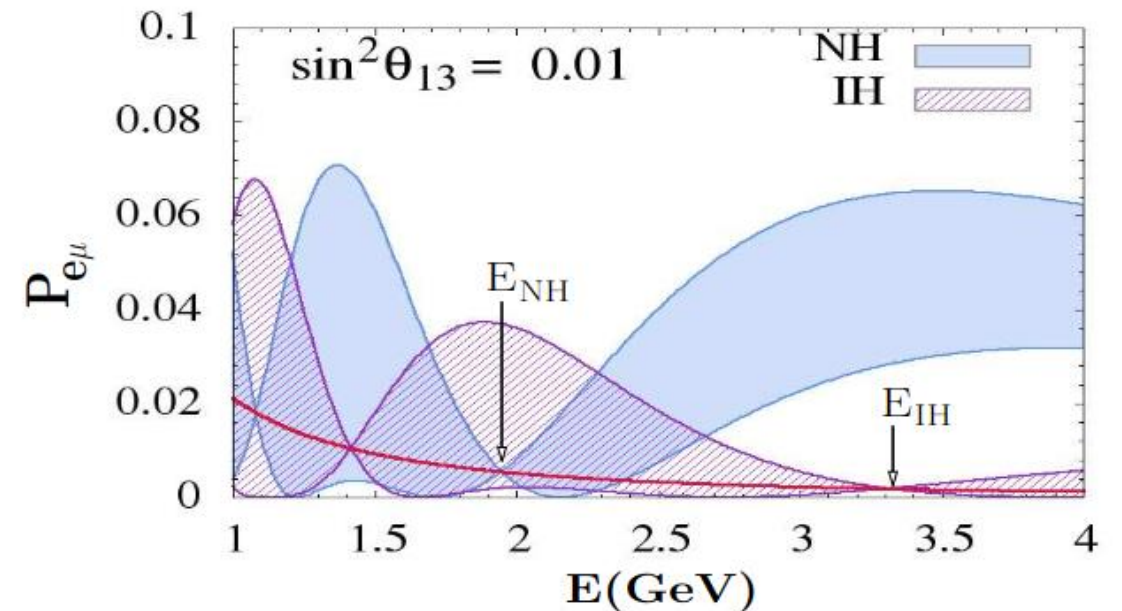
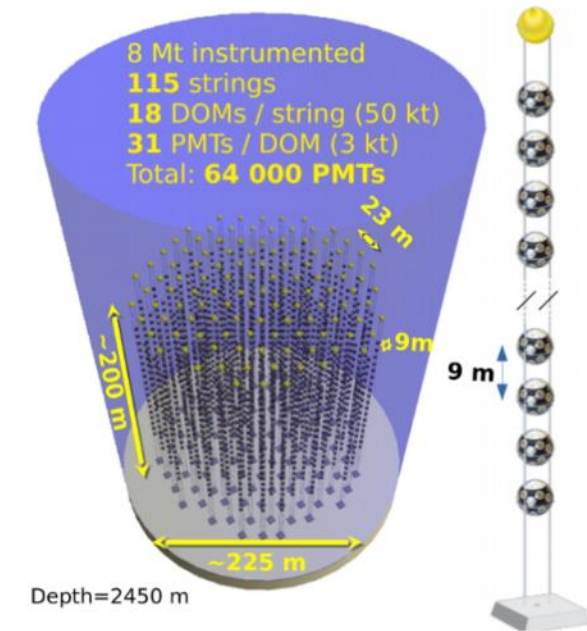
Total 5 MEUR
(3 M€ from EU)

➤ ongoing



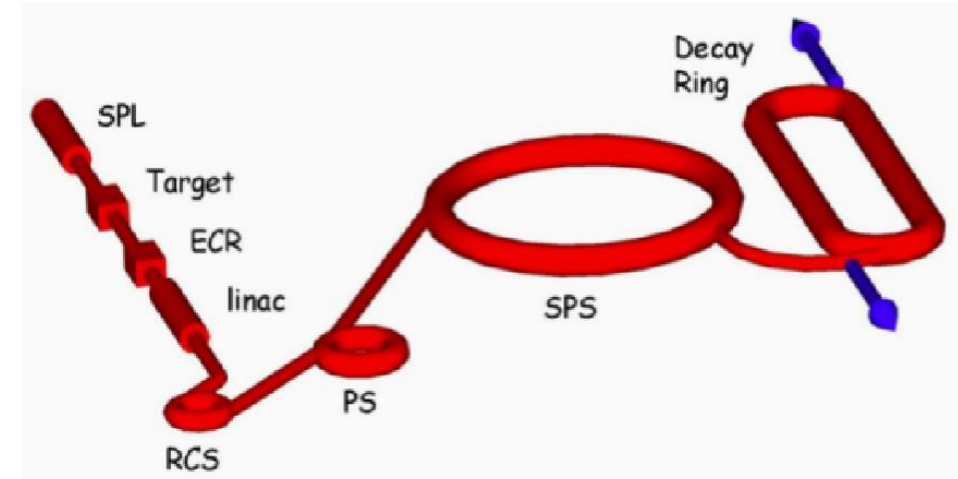
P2O (Protvino to Orca)

- Main purpose: mass hierarchy measurement
- Parameters
 - Long baseline: 2695 km
 - about 8 Mt water Cherenkov detector
 - 450 kW beam
- Bi-magic baseline
 - hierarchy measurement independent of δ_{CP}
- Lol from 2019
<https://arxiv.org/abs/1902.06083>
 - now on indefinite hold



Beta beams

- Accelerate beta emitting nuclei
- Pure and narrow spectrum on ν_e or $\bar{\nu}_e$
 - Possible to observe $\nu_e \rightarrow \nu_\mu$ and maybe $\nu_e \rightarrow \nu_\tau$ appearance
- Main technical difficulty is intensity
 - Difficult to produce isotopes at a sufficient rate
 - On hold since early 2010's

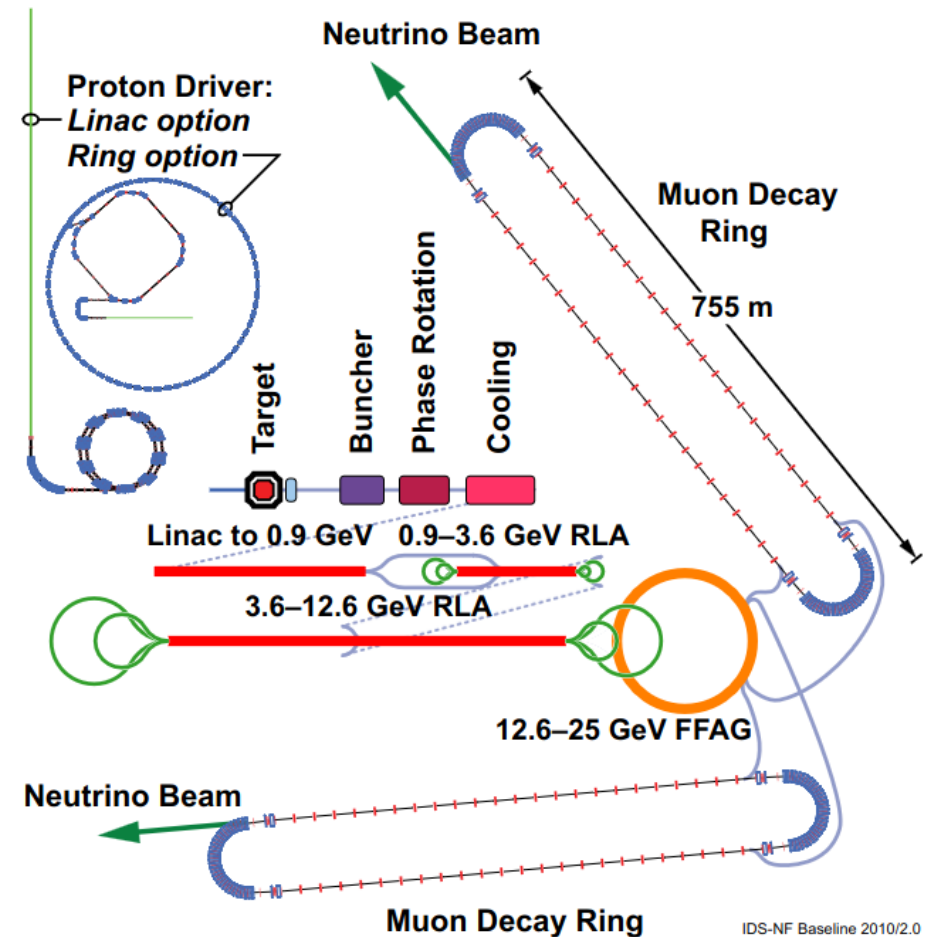


EURISOL scenario at CERN

<https://doi.org/10.1016/j.nuclphysbps.2012.09.037>

Neutrino factory

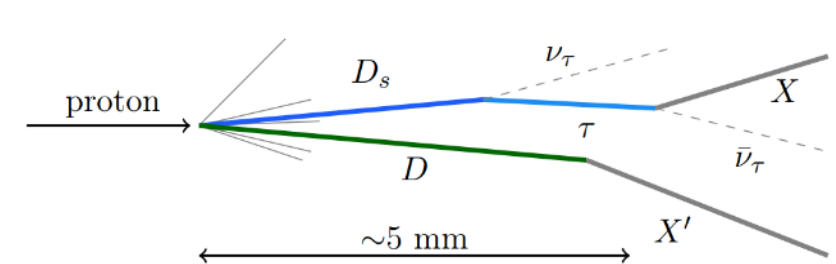
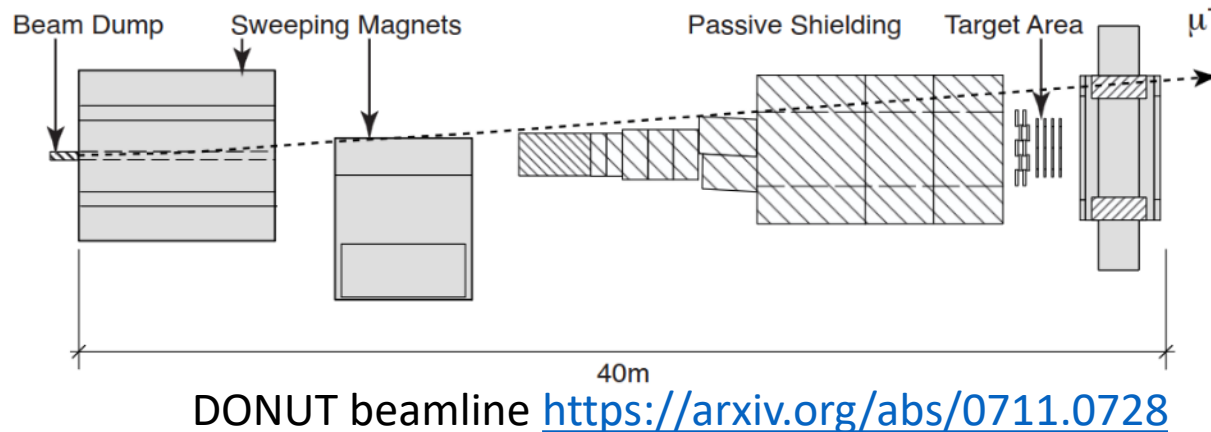
- Accelerate muons and put them in a storage ring
 - nuSTORM just stores the muons, SBL only
- Controlled and intense source of ν_e and $\bar{\nu}_\mu$ (or $\bar{\nu}_e$ and ν_μ)
- Main technical difficulties
 - accelerating muons
 - magnetized far detector
- Proposed sites: CERN, RAL, Fermilab, ..
- Progress slowed down at the beginning of 2010s
 - Large θ_{13} made CPV (and other) measurements accessible to conventional beams
- Interesting new possibilities:
 - nu factory at ESS (backup slide)
 - Low energy nuSTORM could be a step forward
 - nu factory at Fermilab with DUNE as far detectors
 - <https://arxiv.org/abs/2407.02572>



Generic nu fact design from 2011
<https://arxiv.org/abs/1112.2853>

Tau neutrino beams?

- Produced by shooting protons on thick target and sweep/stop anything other than D_s
 - about 3% neutrinos are ν_τ



- currently only SBL (DONUT, SHiP)
- DsTau (NA65): a running experiment at CERN to measure ν_τ production
 - To reduce systematics for past and future ν_τ experiments
- Maybe LBL in future?
 - Perhaps via oscillations?

Conclusions

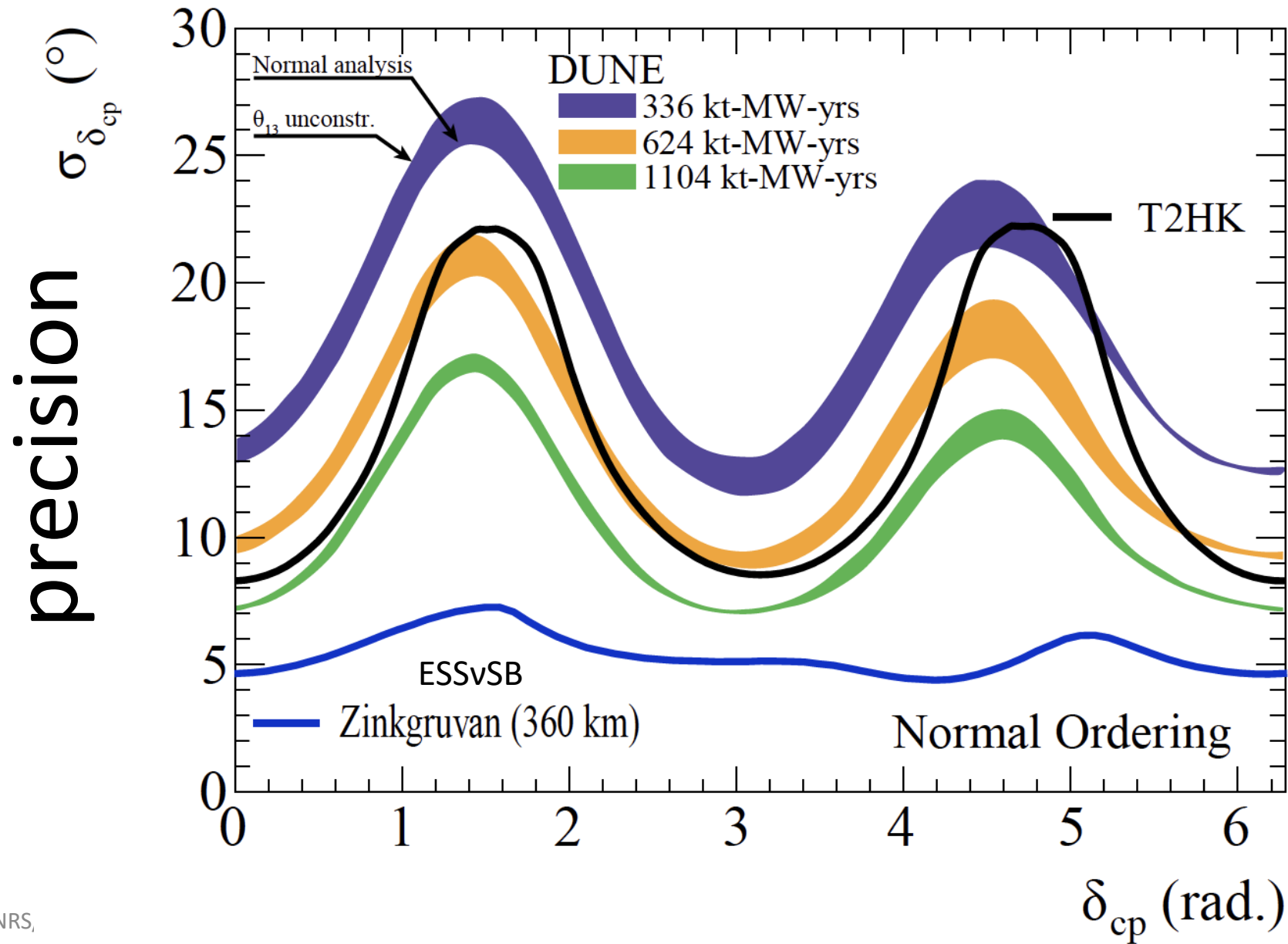
- Long baseline neutrino experiments let us study neutrino oscillations in detail in laboratory conditions (we control both source and detector)
 - After next generation of neutrino experiments we expect to have a good estimation of all oscillation parameters
 - However, we need precise measurements and cross-checks using different osc. channels: **new physics can hide in the details!**
- Several proposed ideas for LBL experiments after HyperK and DUNE
 - ESSnuSB, P2O, Beta beams, Neutrino factory
- ESSnuSB is currently the most active, practical and feasible
 - Allows very precise leptonic CP violation measurement at the second oscillation maximum

Thank you for your attention



Possible scenario of new physics hiding in the details.

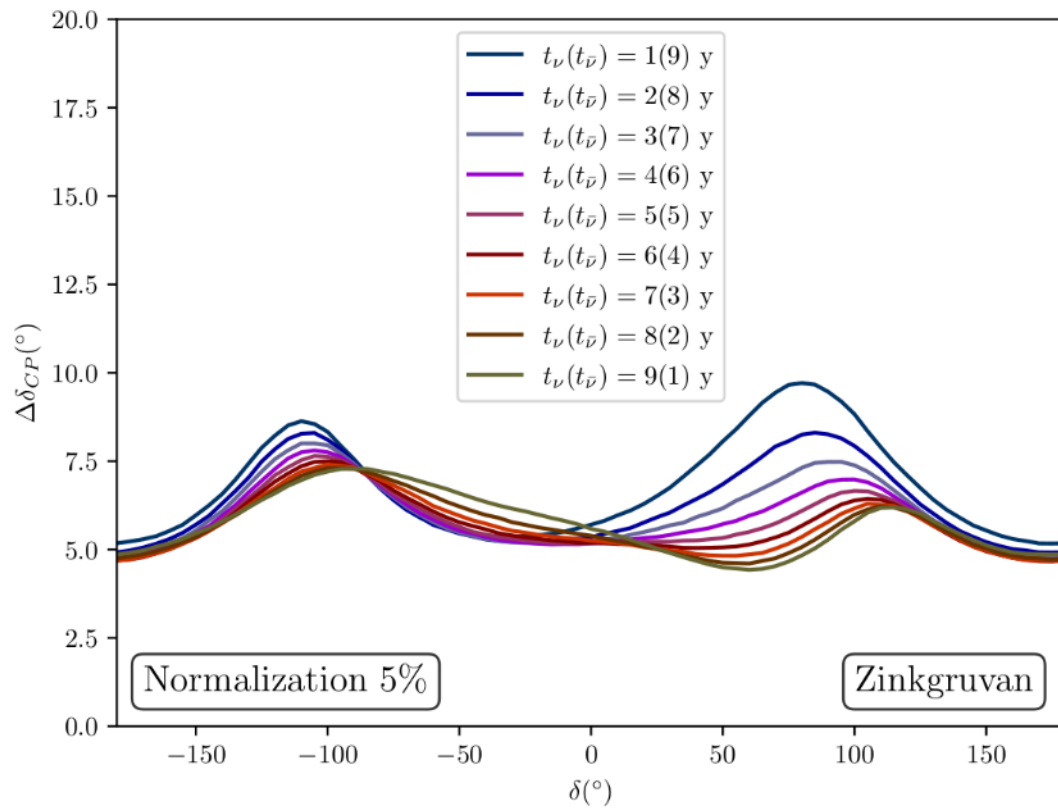
Precision comparison with current projects



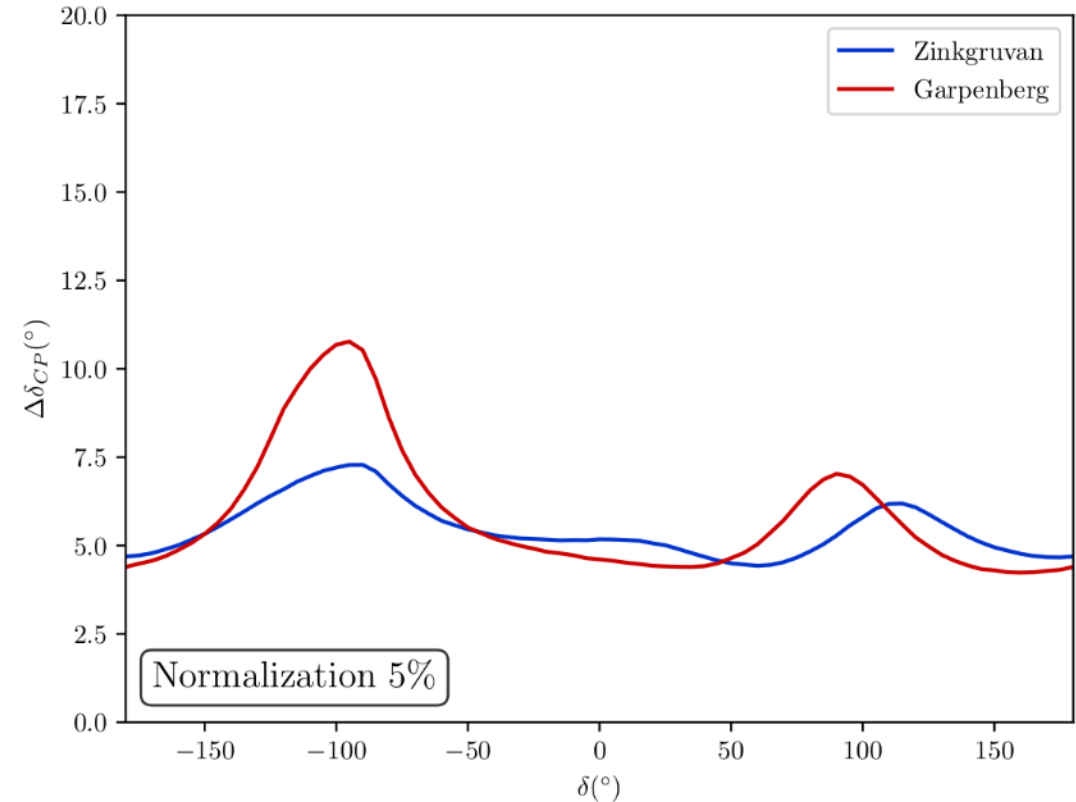
Optimization for precision

Supposing that value of δ_{CP} is roughly known at ESSnuSB time

Precision for different neutrino (antineutrino) run times

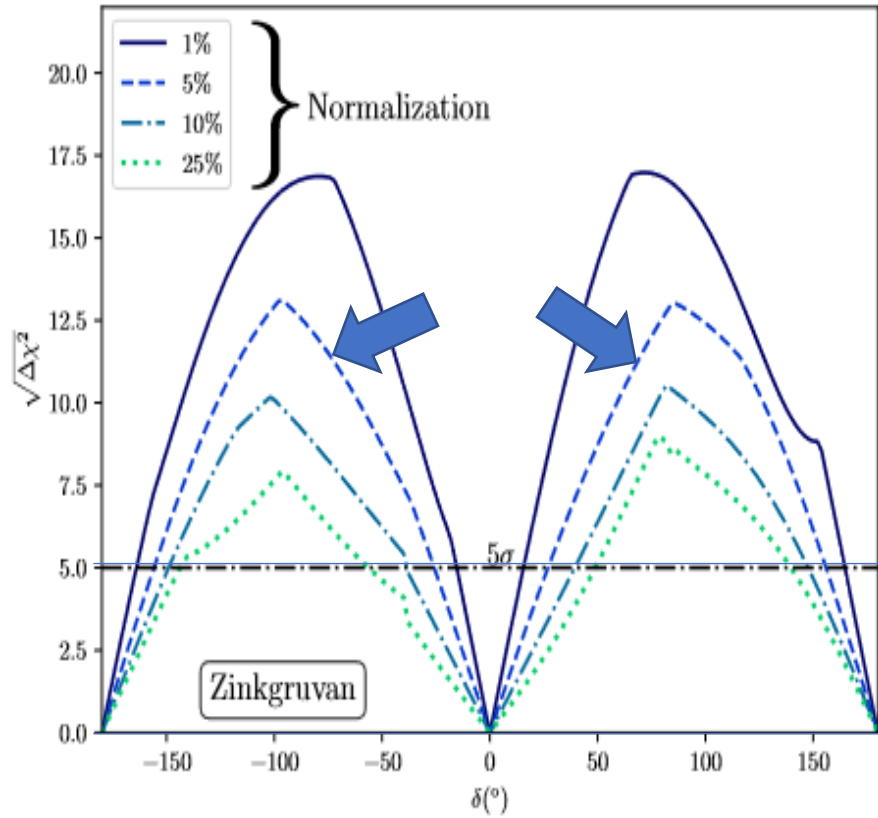


Optimal precision for known δ_{CP}

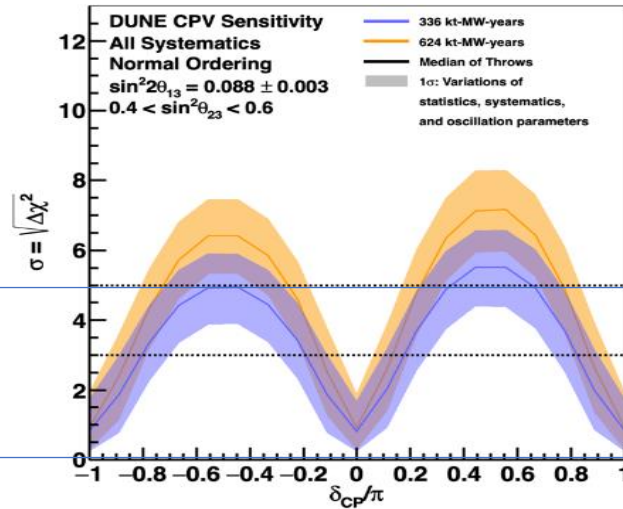


From the ESSnuSB CDR: <https://doi.org/10.1140/epjs/s11734-022-00664-w> & <https://arxiv.org/abs/2203.08803>

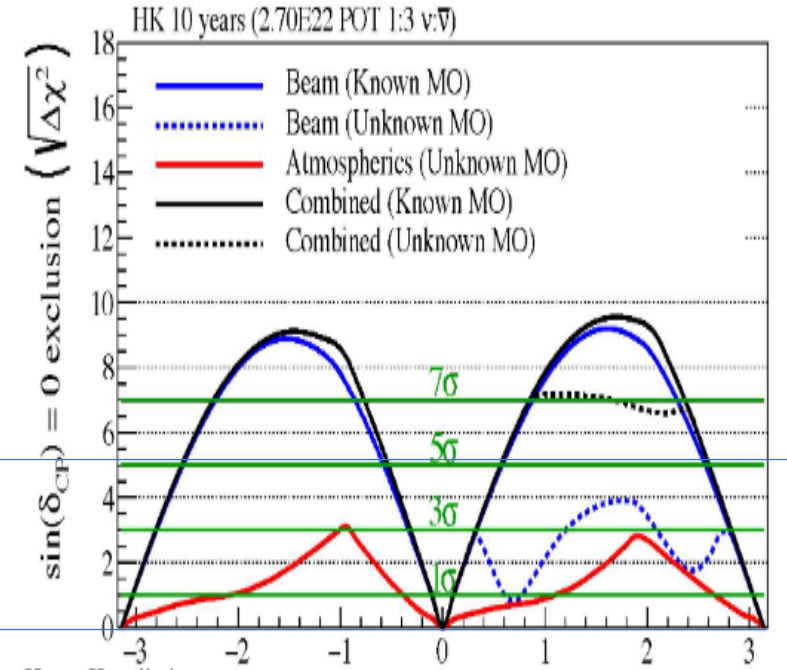
ESSnuSB in the international context – CPV discovery



ESSnuSB March 2022 with 5% normalization error



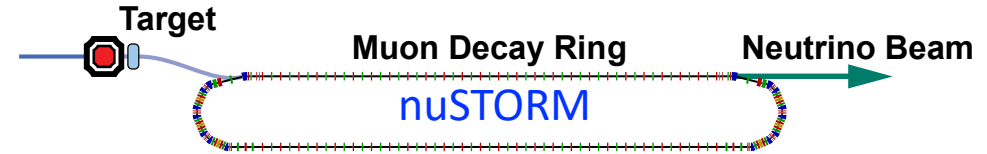
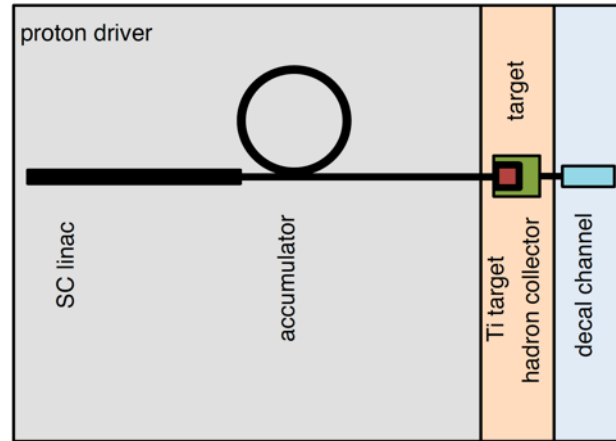
DUNE Snowmass March 2022



Hyper-Kamiokande Snowmass March 2022

ESSvSB and (R&D) synergies

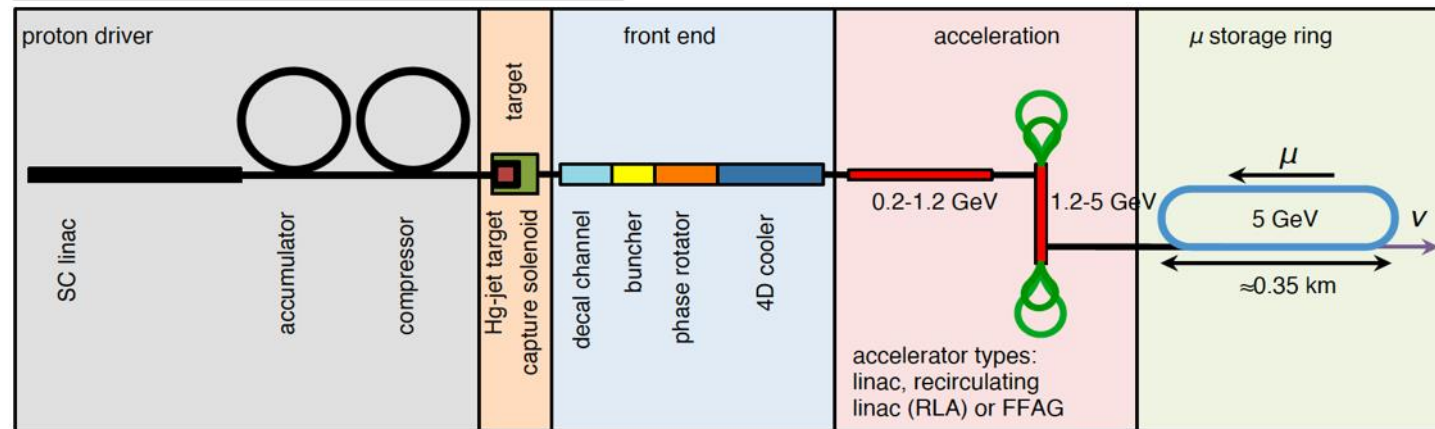
Super Beam



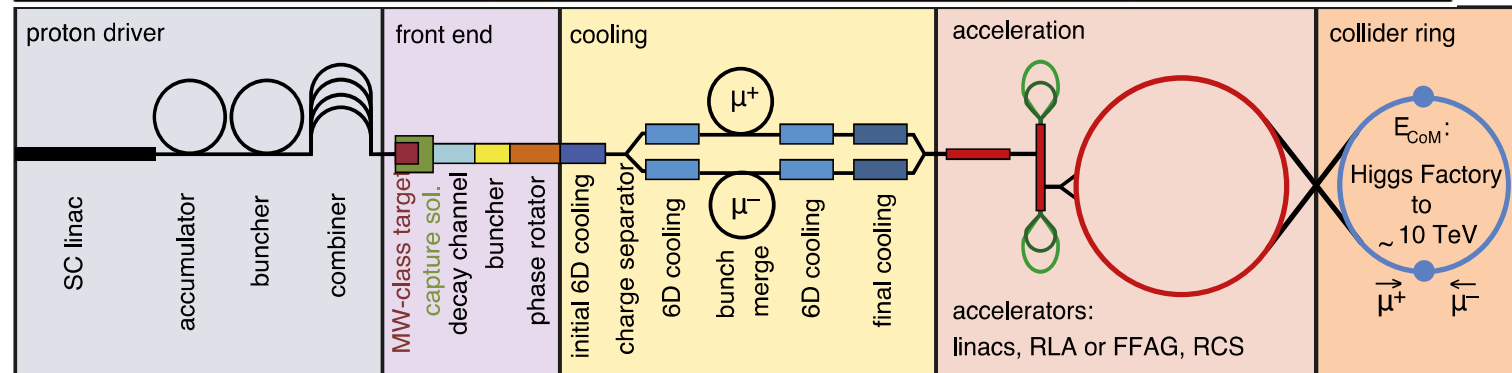
Dedicated series of workshops is organized
<https://indico.cern.ch/event/849674/>

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

Neutrino Factory



Muon Collider

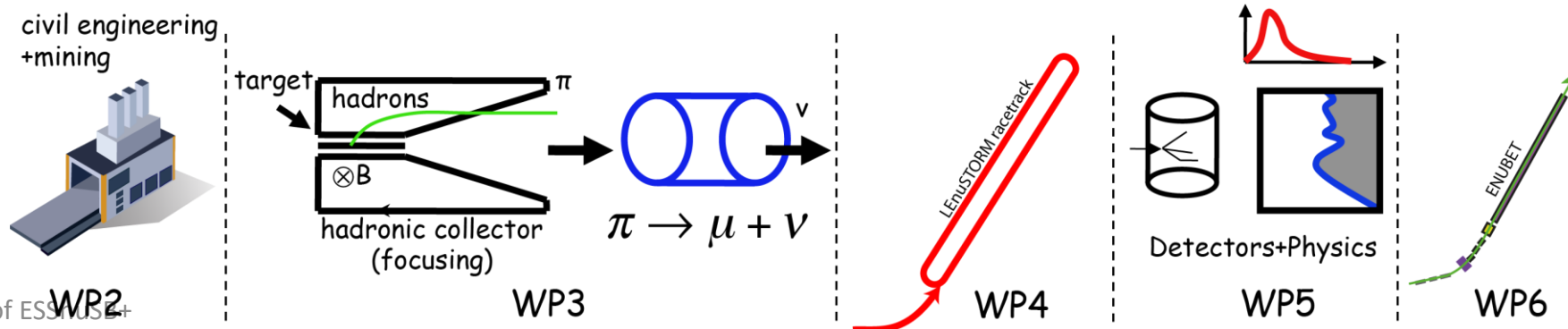


Crazy ideas

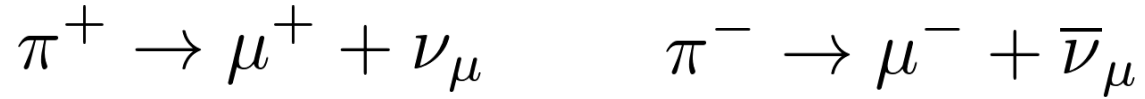
- Put a neutrino detector in a geostationary orbit (A.L.)
- Long baseline tagged beam (L.M.)
- Use LHC in FCC era to produce high-energy neutrino beam
- Make a tau neutrino beam

ESSνSB+ at the European level

- A **Horizon Europe Design Study** (Call HORIZON-INFRA-2022-DEV-01)
- **Title of Proposal:** Study of the use of the ESS facility to accurately measure the neutrino cross-sections for ESSnuSB leptonic CP violation measurements and to perform sterile neutrino searches and astroparticle physics
- **Duration: 4 years**
- **Total cost: 5 M€**
- **Requested budget: 3 M€**
- **20 participating institutes**, including CERN and ESS
- 6 Work Packages
- **Approved August 2022**



Neutrino beam production

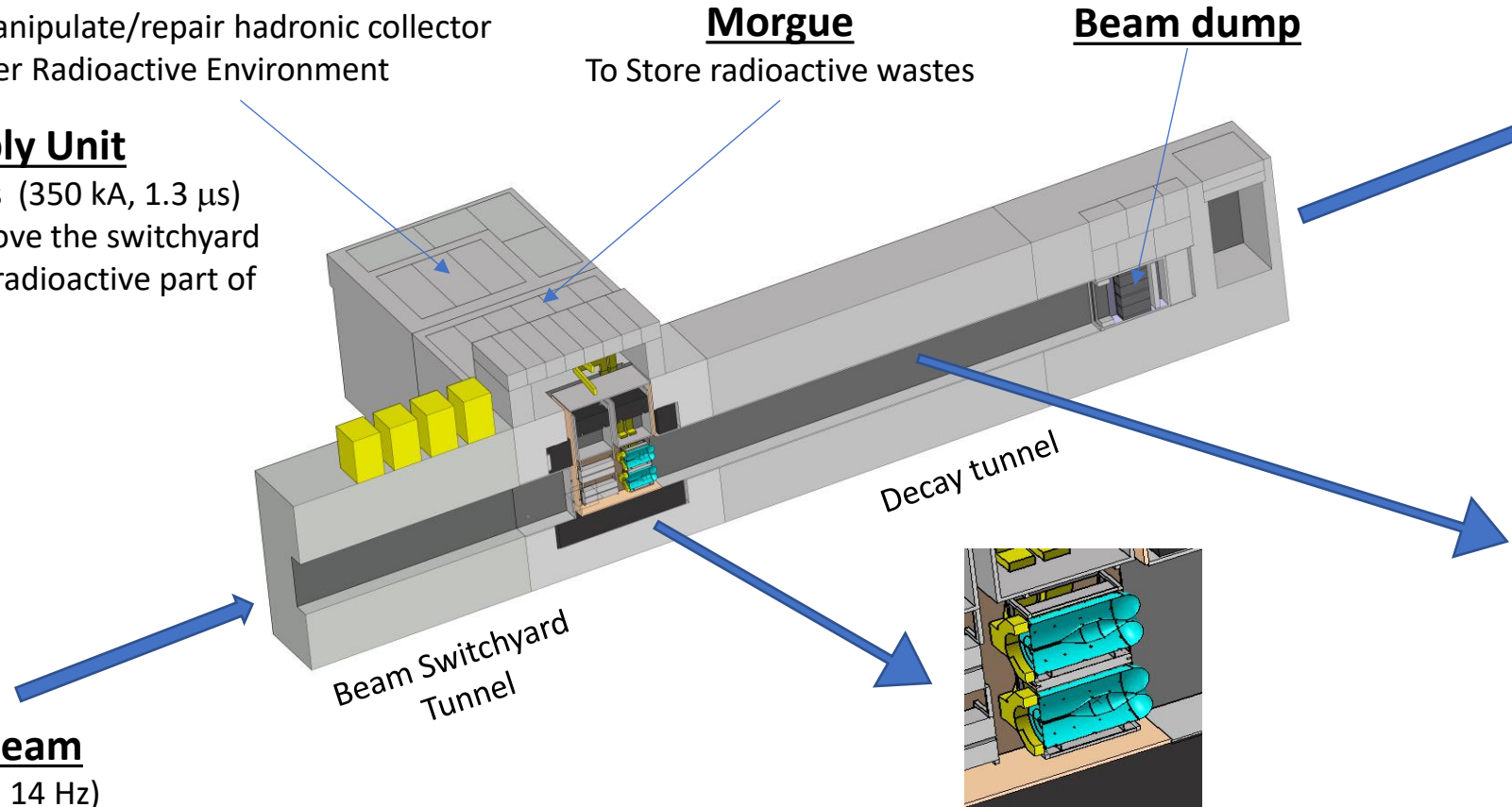


Hot Cell

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

Power Supply Unit

- 16 modules (350 kA, 1.3 μ s)
- Located above the switchyard
- Outside of radioactive part of Facility



Proton Beam

($E_p=2.5$ GeV, 14 Hz)

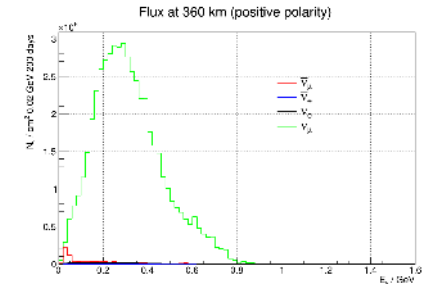
4 x 1.25 MW

Morgue

To Store radioactive wastes

Beam dump

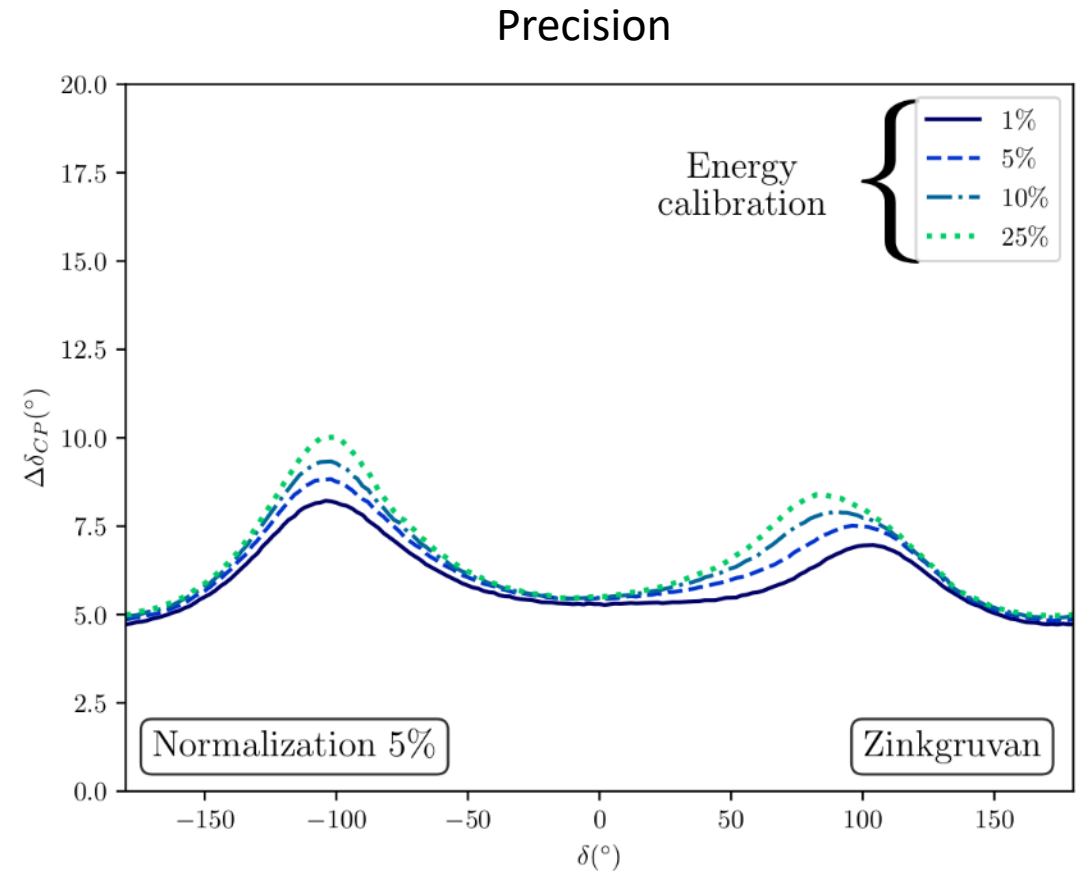
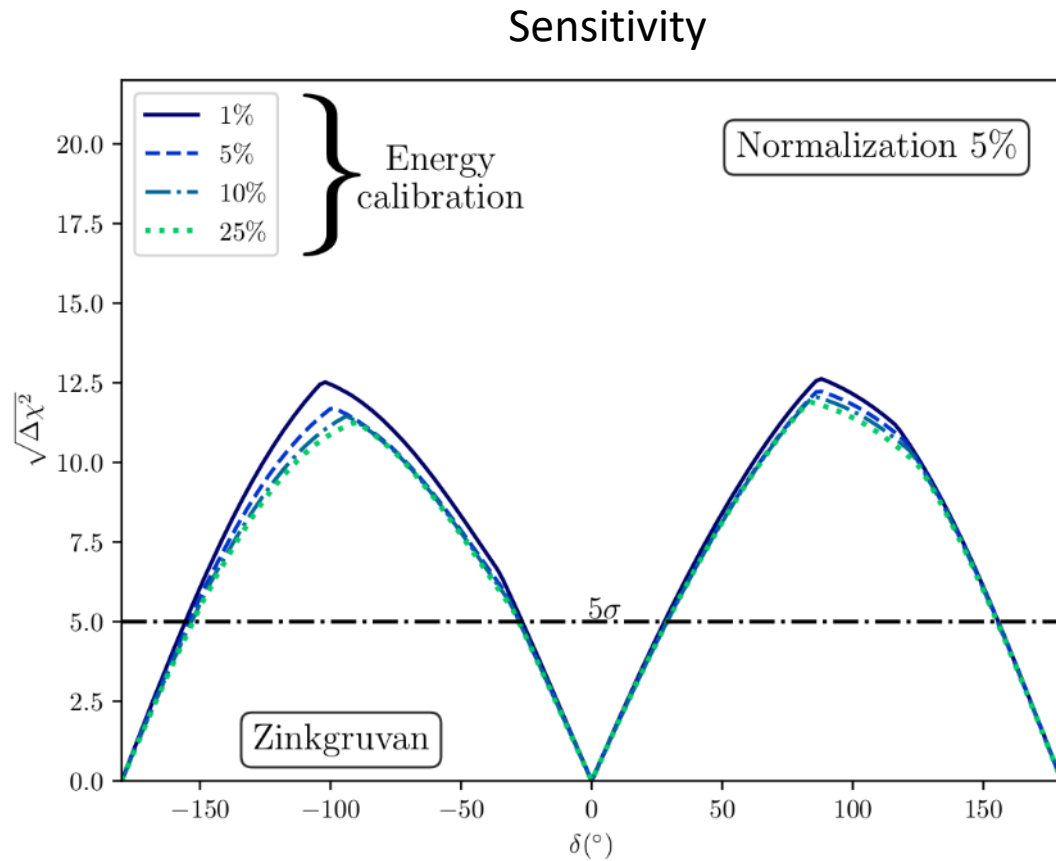
Neutrino Beam



Pions decay in-flight here

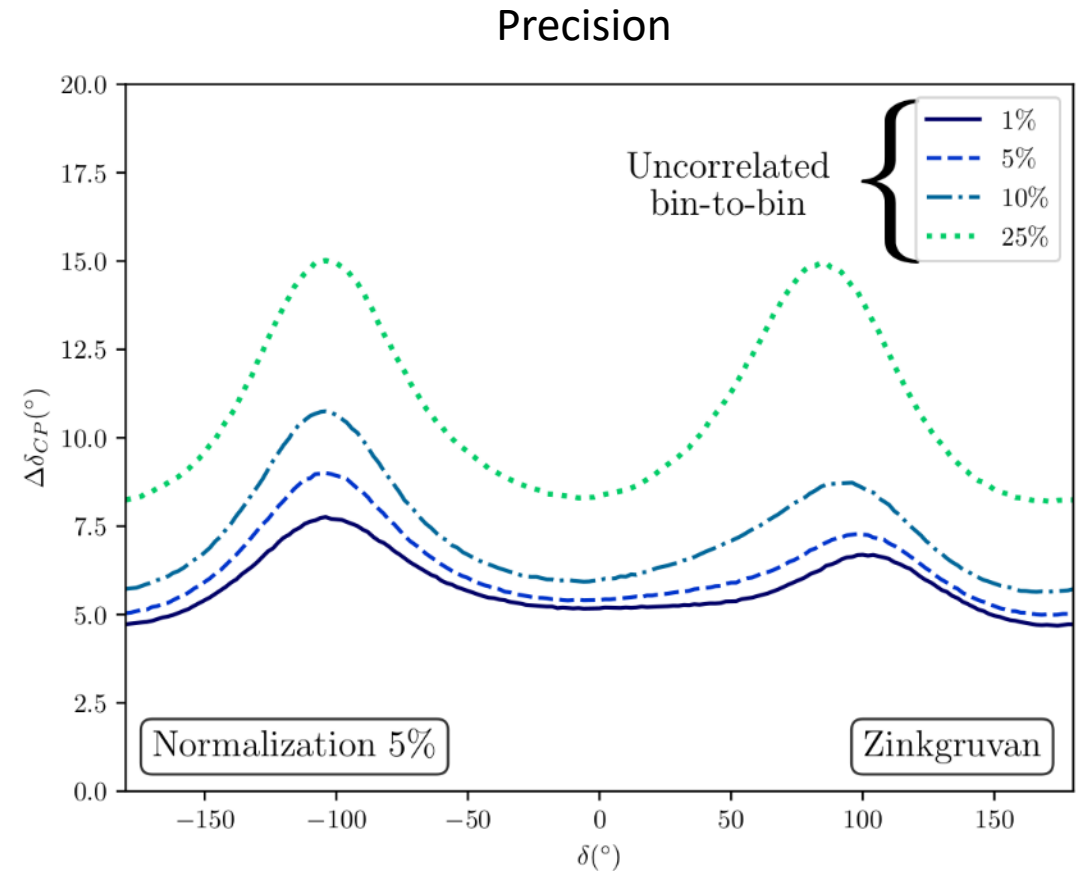
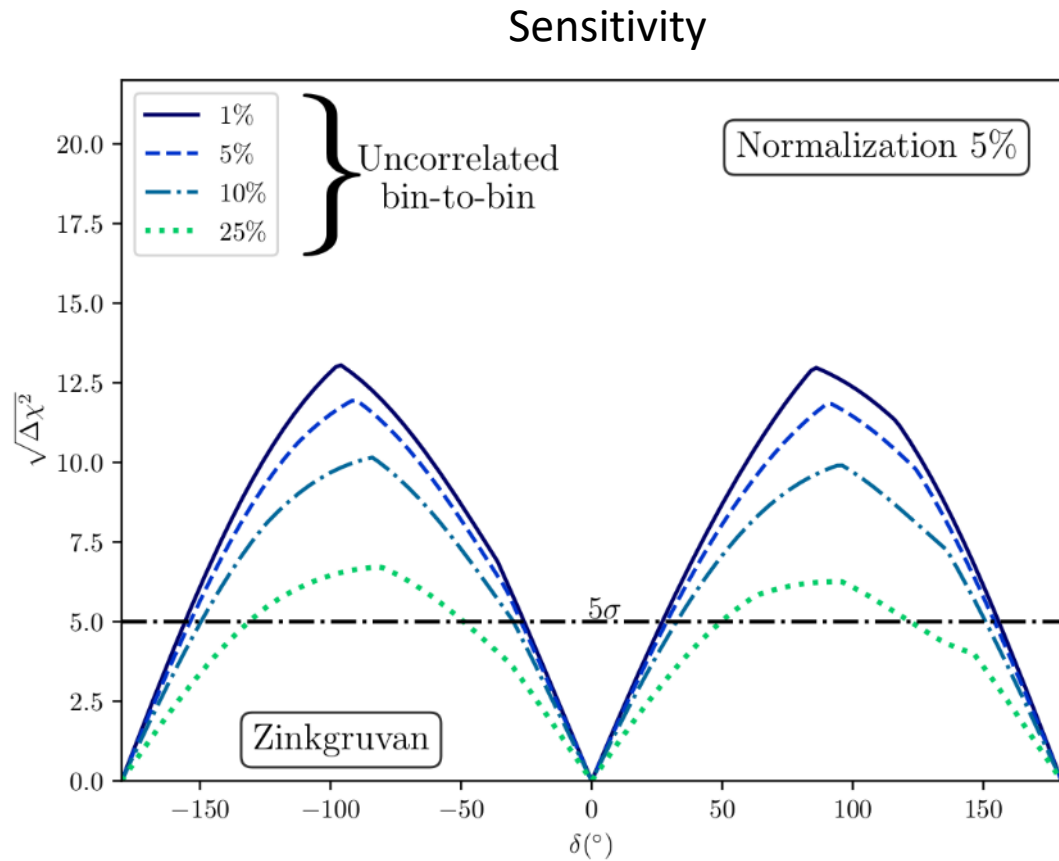
Hadronic Collector

Effect of energy calibration uncertainty on CPV measurements



From the ESSnuSB CDR: <https://doi.org/10.1140/epjs/s11734-022-00664-w> & <https://arxiv.org/abs/2203.08803>

Effect of bin-to-bin uncorrelated uncertainty on CPV measurements

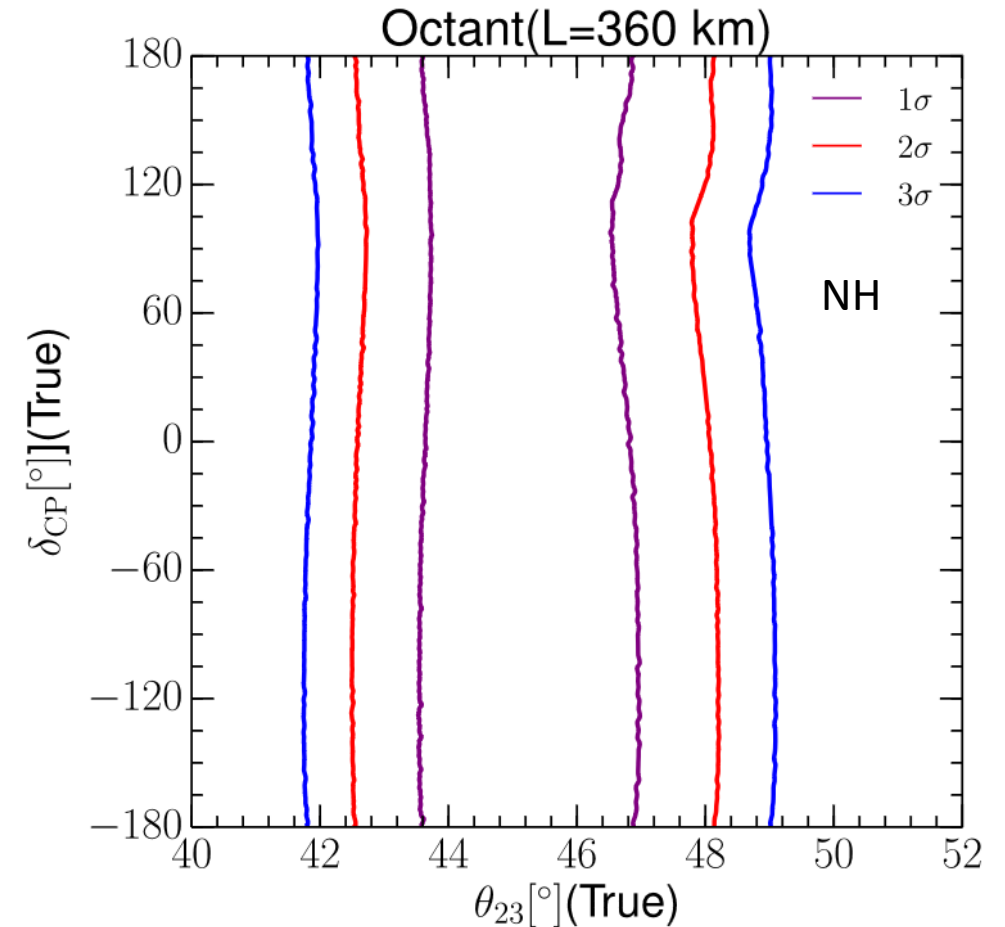
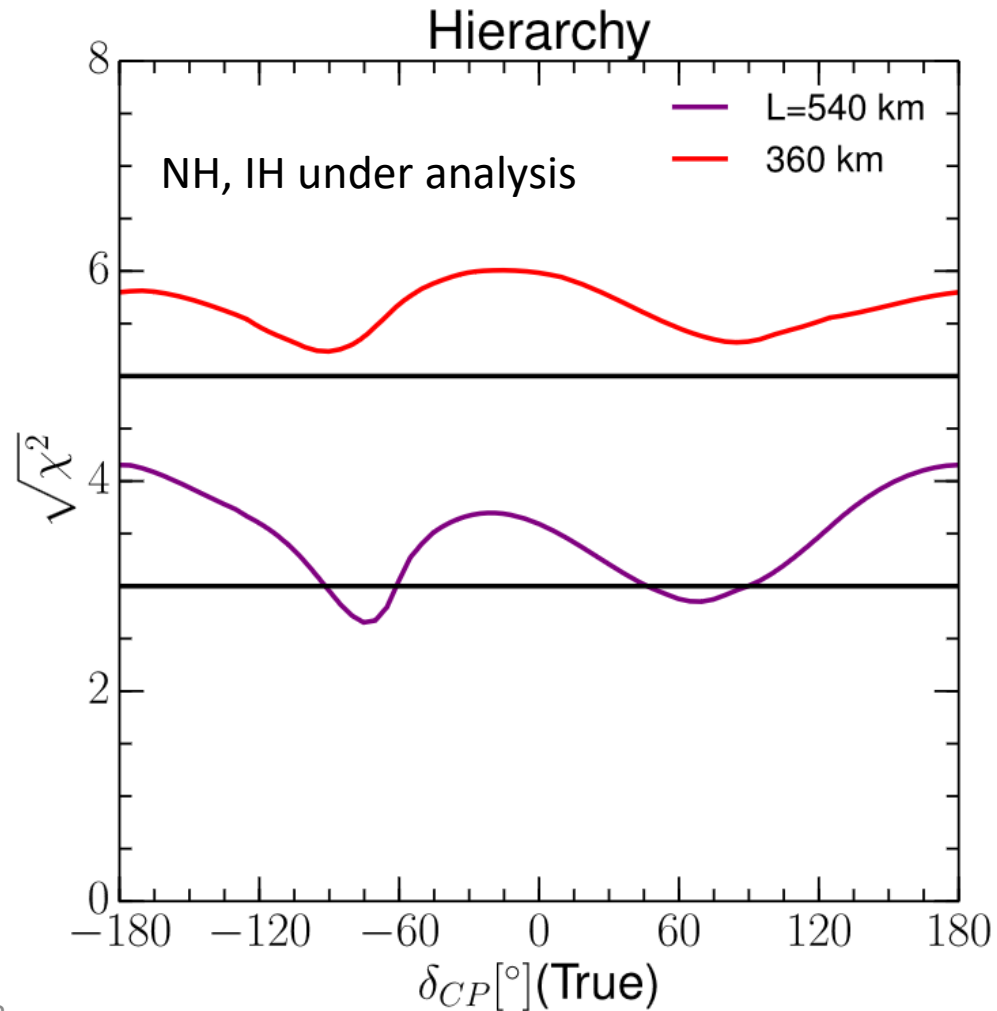


From the ESSnuSB CDR: <https://doi.org/10.1140/epjs/s11734-022-00664-w> & <https://arxiv.org/abs/2203.08803>

Hierarchy and octant determination

From: [DOI:10.1140/epjc/s10052-021-09845-8](https://doi.org/10.1140/epjc/s10052-021-09845-8), [arXiv:2107.07585](https://arxiv.org/abs/2107.07585)

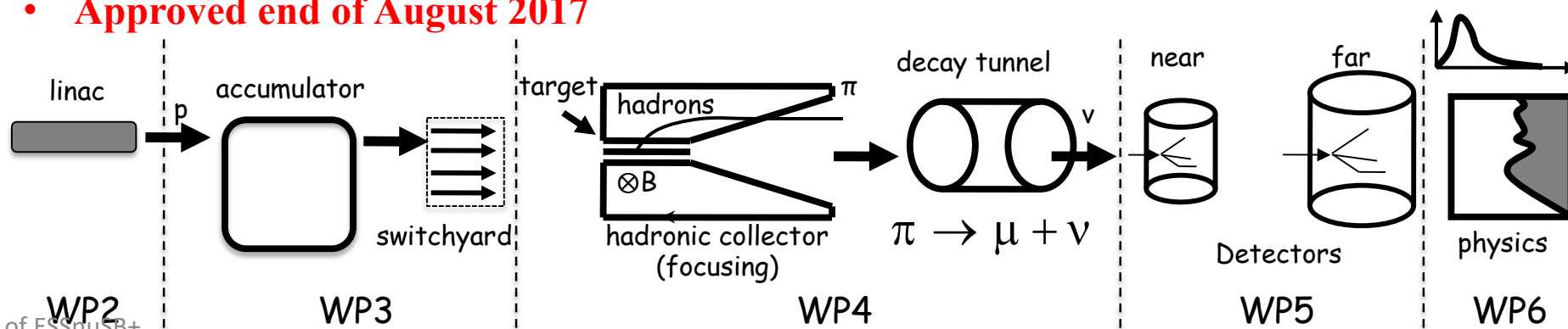
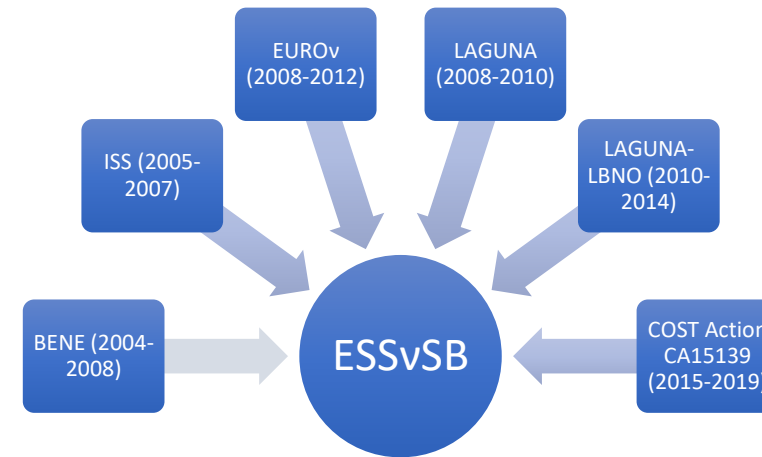
10 y of data taking



ESSvSB at the European level



- 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**

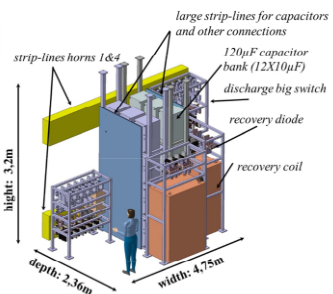


Hot Cell

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Power Supply Unit

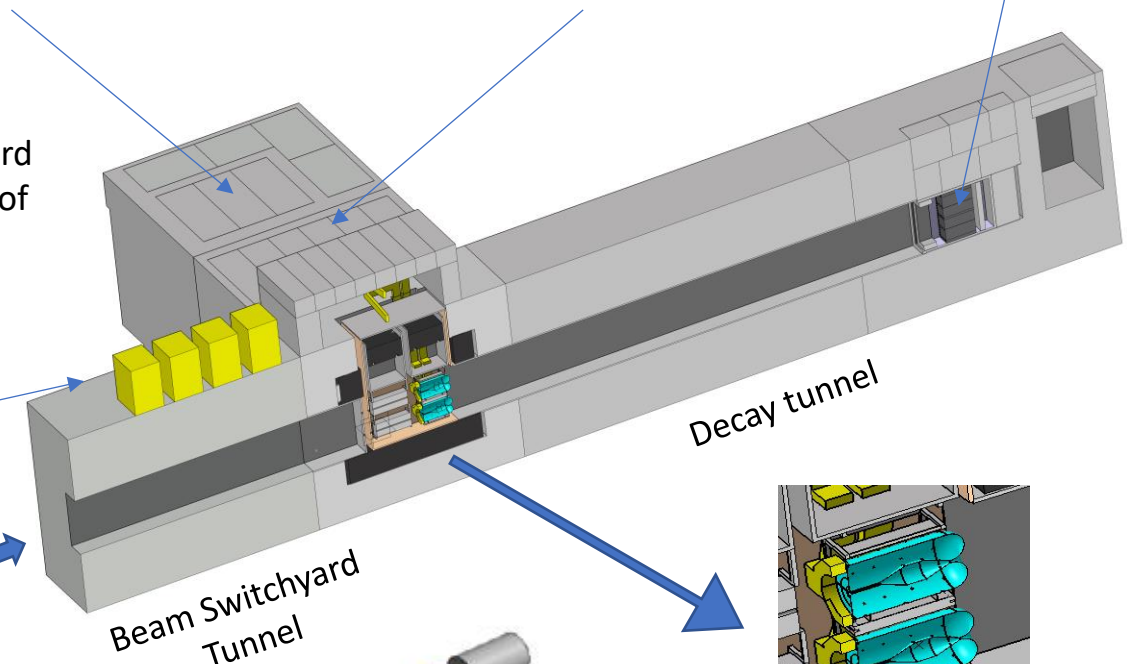
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Morgue

To Store radioactive wastes

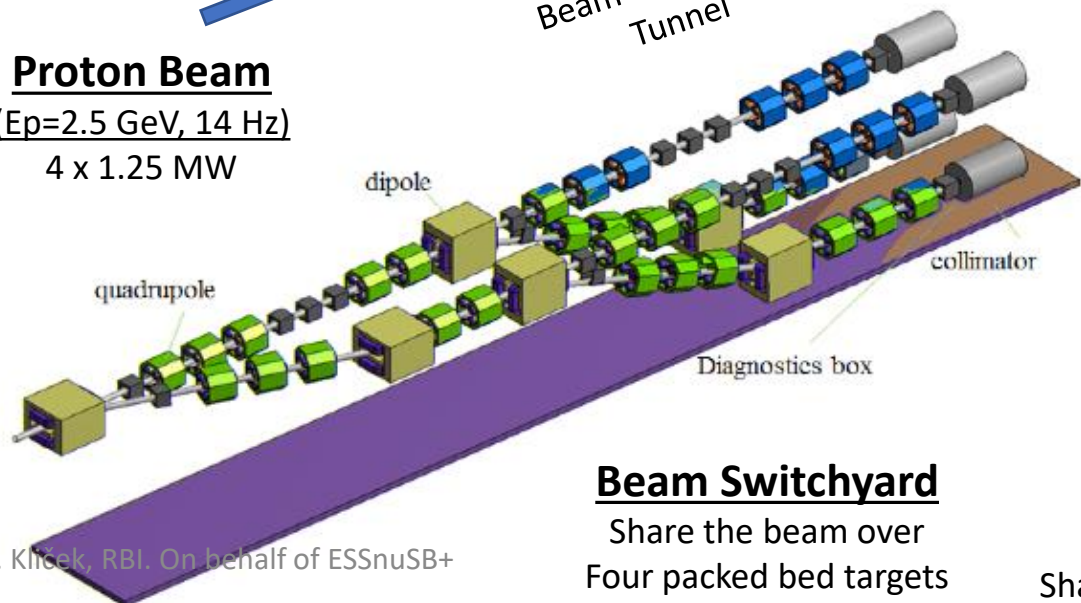
Beam dump



Proton Beam

($E_p=2.5$ GeV, 14 Hz)

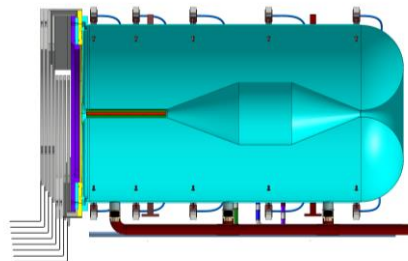
4 x 1.25 MW



Beam Switchyard

Share the beam over Four packed bed targets

Hadronic Collector

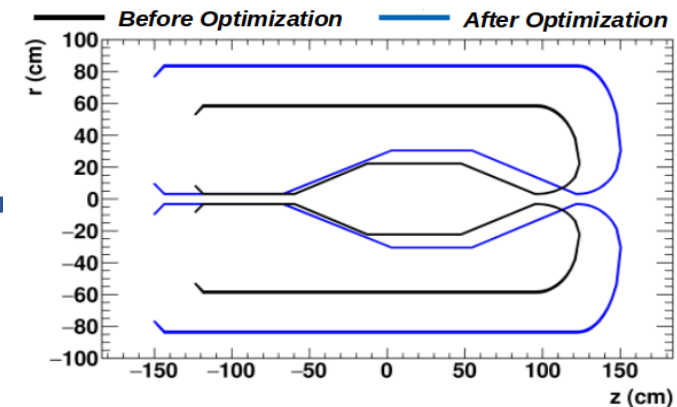
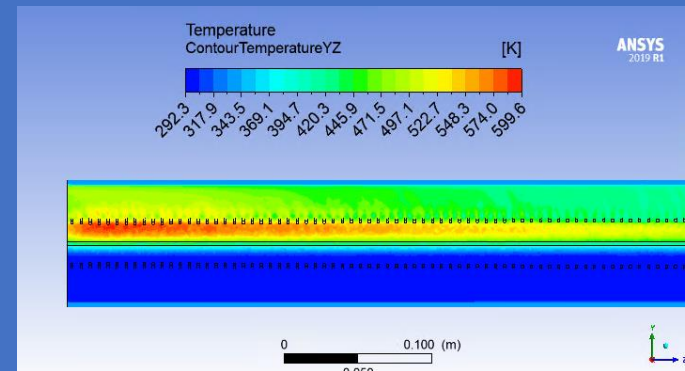
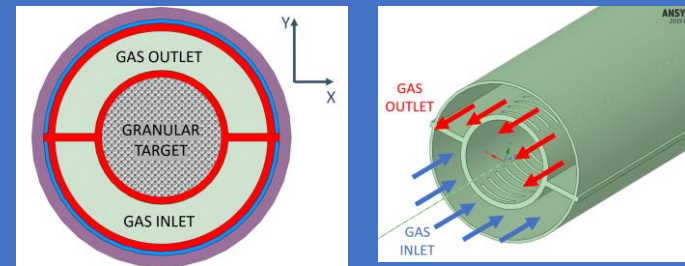


MiniBoone Like Horn

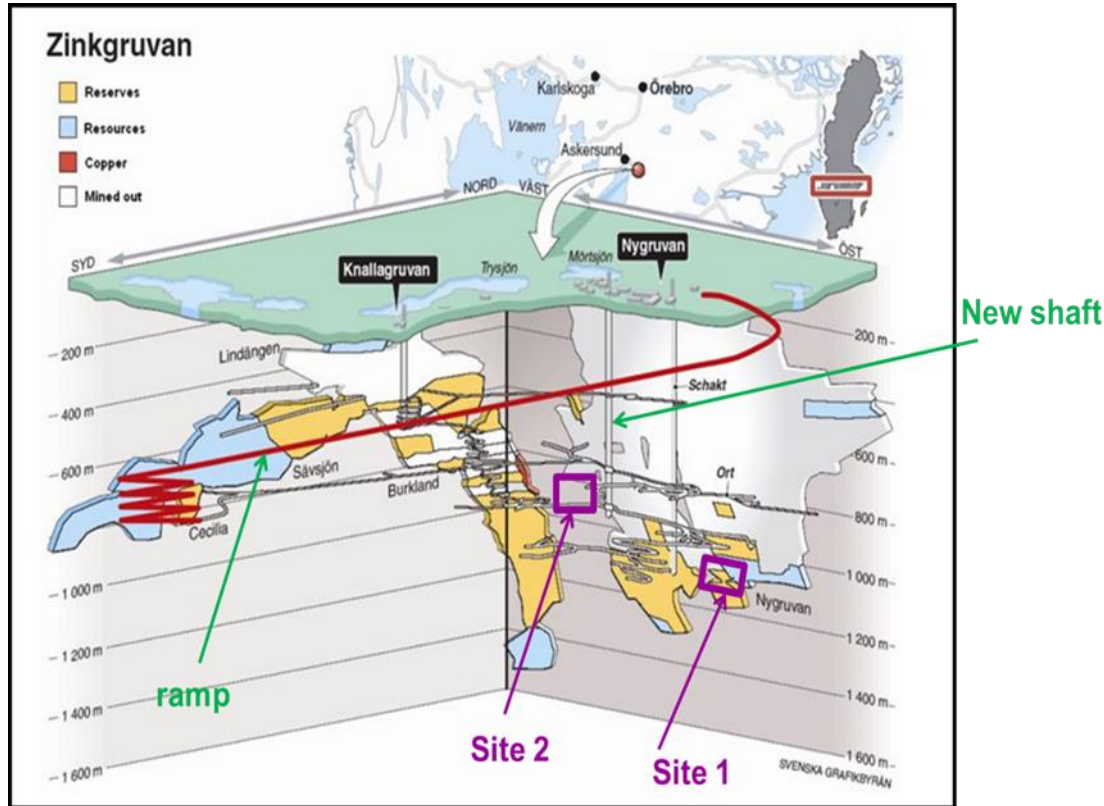
Shape optimized with genetic algorithm

Granular Target Concept

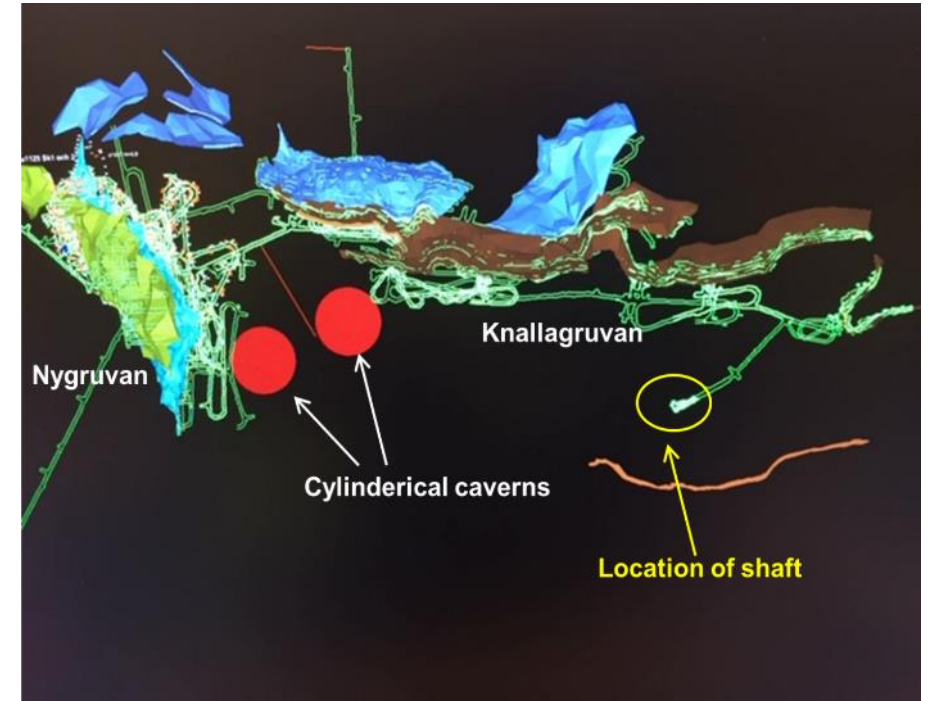
- Target made of 3 mm titanium spheres cooled by transverse helium gas cooling



Zinkgruvan mine



Potential location in Site 2



Site 2 is considered as best considering access to main transport infrastructure and located in an area less disturbed by mining activities

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

Table 1: Signal and major background events for the appearance channel corresponding to positive (negative) polarity per year for $\delta_{\text{CP}} = 0^\circ$.

	Channel	$L = 540$ km	$L = 360$ km
Signal	$\nu_\mu \rightarrow \nu_\mu$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)	4419.69 (733.31)	7619.16 (1602.02)
Background	$\nu_e \rightarrow \nu_e$ ($\bar{\nu}_e \rightarrow \bar{\nu}_e$)	7.77 (0.02)	17.08 (0.05)
	ν_μ NC ($\bar{\nu}_\mu$ NC)	69.23 (8.24)	155.77 (18.54)
	$\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)	14.68 (0.06)	61.30 (0.17)
	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ ($\nu_\mu \rightarrow \nu_\mu$)	12.35 (41.00)	21.39 (72.59)

Table 2: Signal and major background events for the disappearance channel corresponding to positive (negative) polarity per year for $\delta_{\text{CP}} = 0^\circ$.

CP violation in ESSnuSB

$$A_{CP} \equiv P_{\nu_\mu \rightarrow \nu_e} - P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e} = -16J \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$

$$E = 400 \text{ MeV}$$

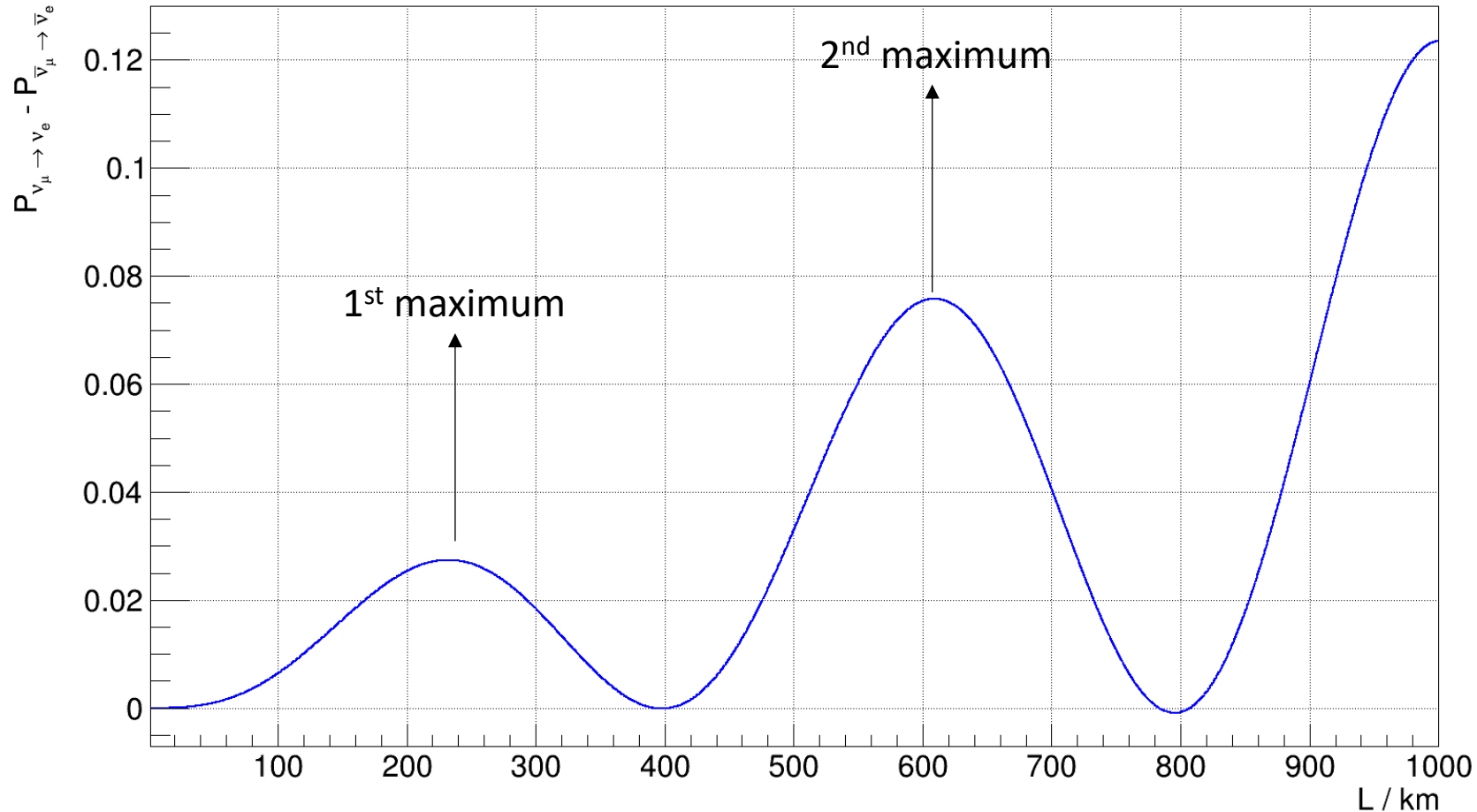
$$s_{ij} \equiv \sin \theta_{ij}$$

$$c_{ij} \equiv \cos \theta_{ij}$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

$$A_{ij}^{\alpha\beta} \equiv U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*$$

$$J = s_{12} c_{12} s_{13} c_{13} s_{23} c_{23} c_{13} \sin \delta_{CP}$$



$$\frac{A_{CP} \text{ @ 2nd max}}{A_{CP} \text{ @ 1st max}} \sim 2.7$$

- Does not depend on J , i.e. PMNS matrix elements
- Depends only on mass splittings

Vacuum

ESSnuSB Implementation Approach

Staged Implementation

