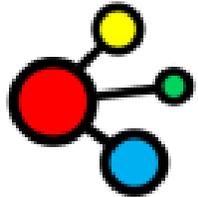




Co-funded by
the European Union



The latest progress and prospects of the ESSnuSB(+) project



Budimir Kliček

On behalf of the ESSnuSB+ project

Ruđer Bošković Institute, Zagreb, Croatia



Neutrino Conference
ICISE Quy Nhon, Vietnam
25 July 2025

ESSnuSB / 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 neutrino oscillations

Oscillation probability for neutrinos is different than oscillation probability for anti-neutrinos in vacuum.

probability of oscillation

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

neutrino flavour at production

neutrino flavour at detection

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

Why 2nd maximum?

Large signal and small matter effects

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 MeV

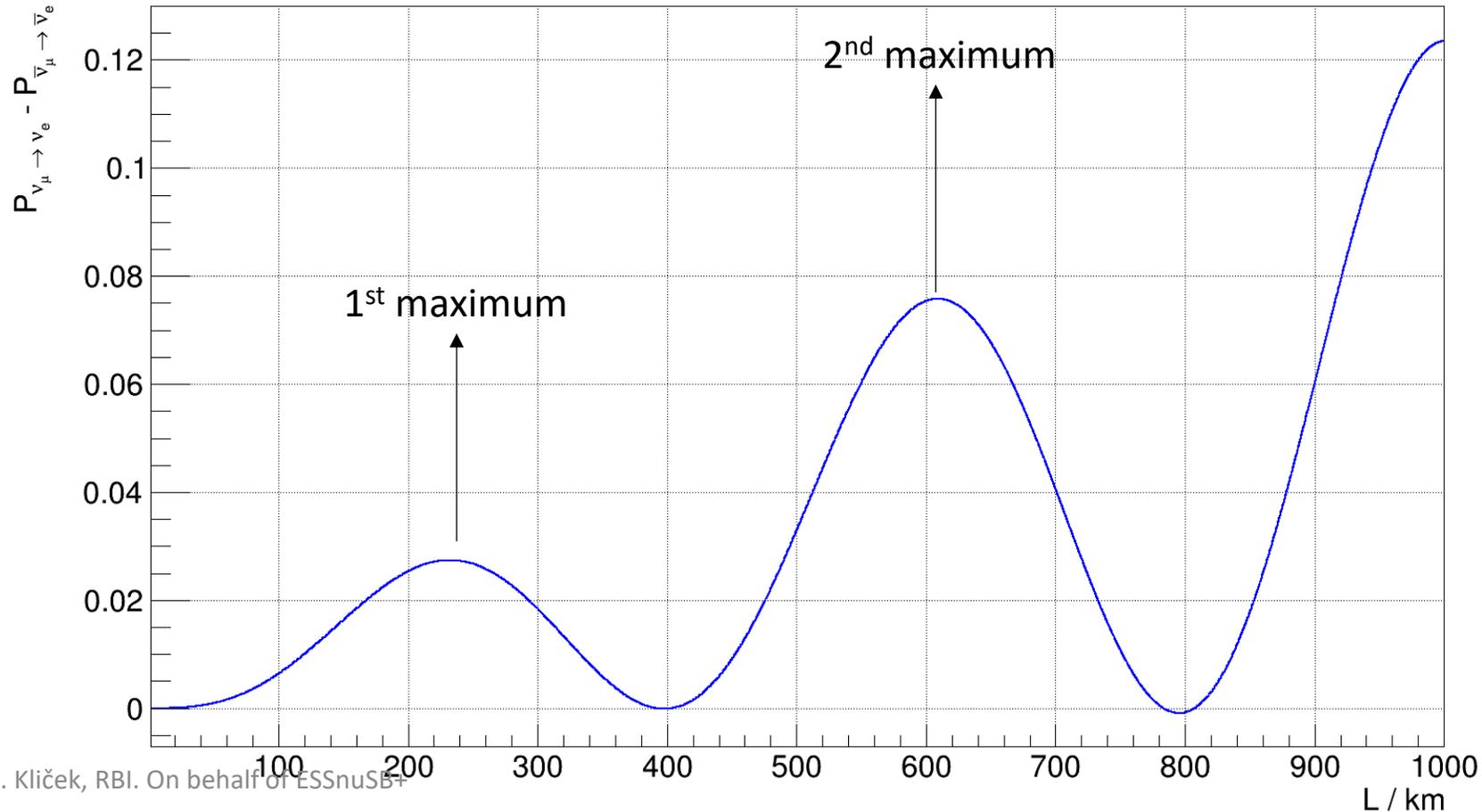
$$s_{ij} \equiv \sin \theta_{ij}$$

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

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

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

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

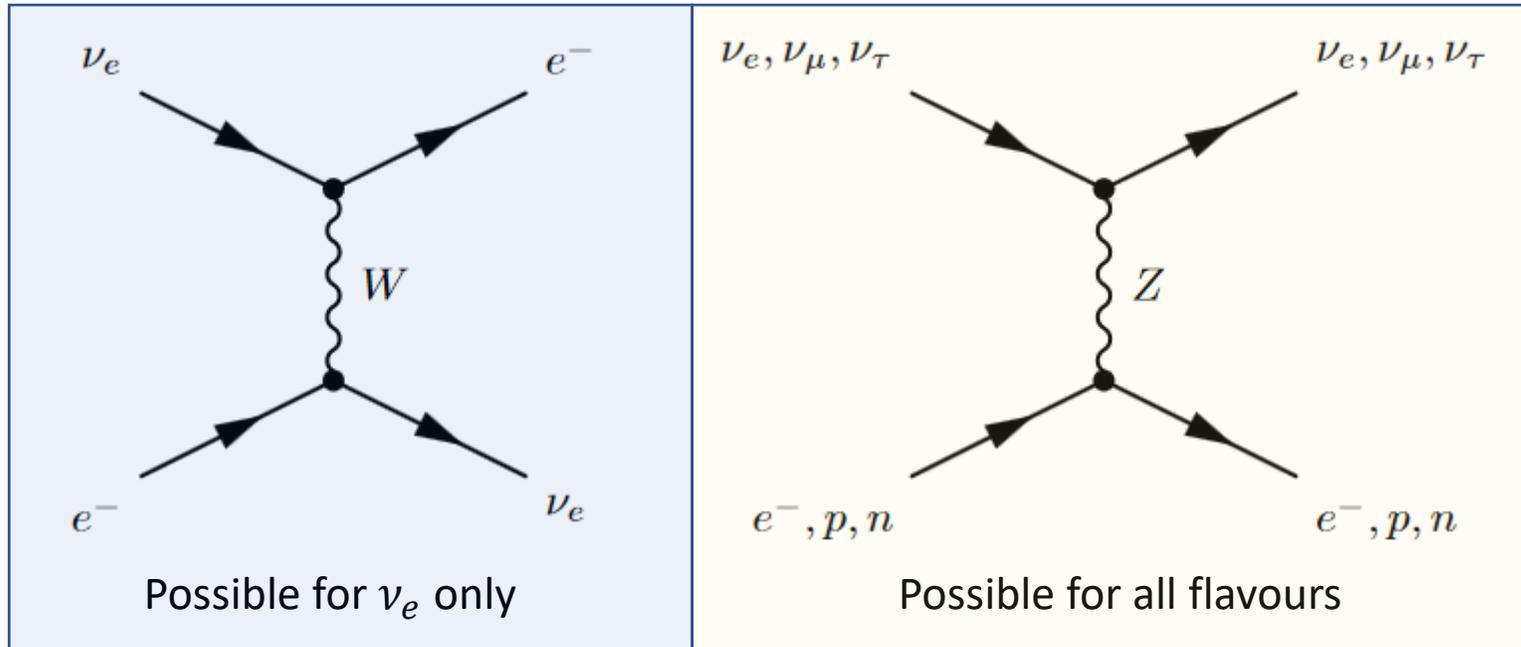


$$\frac{A_{CP} \text{ @ 2nd max}}{A_{CP} \text{ @ 1st max}} \sim 2.7$$

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

Matter effects

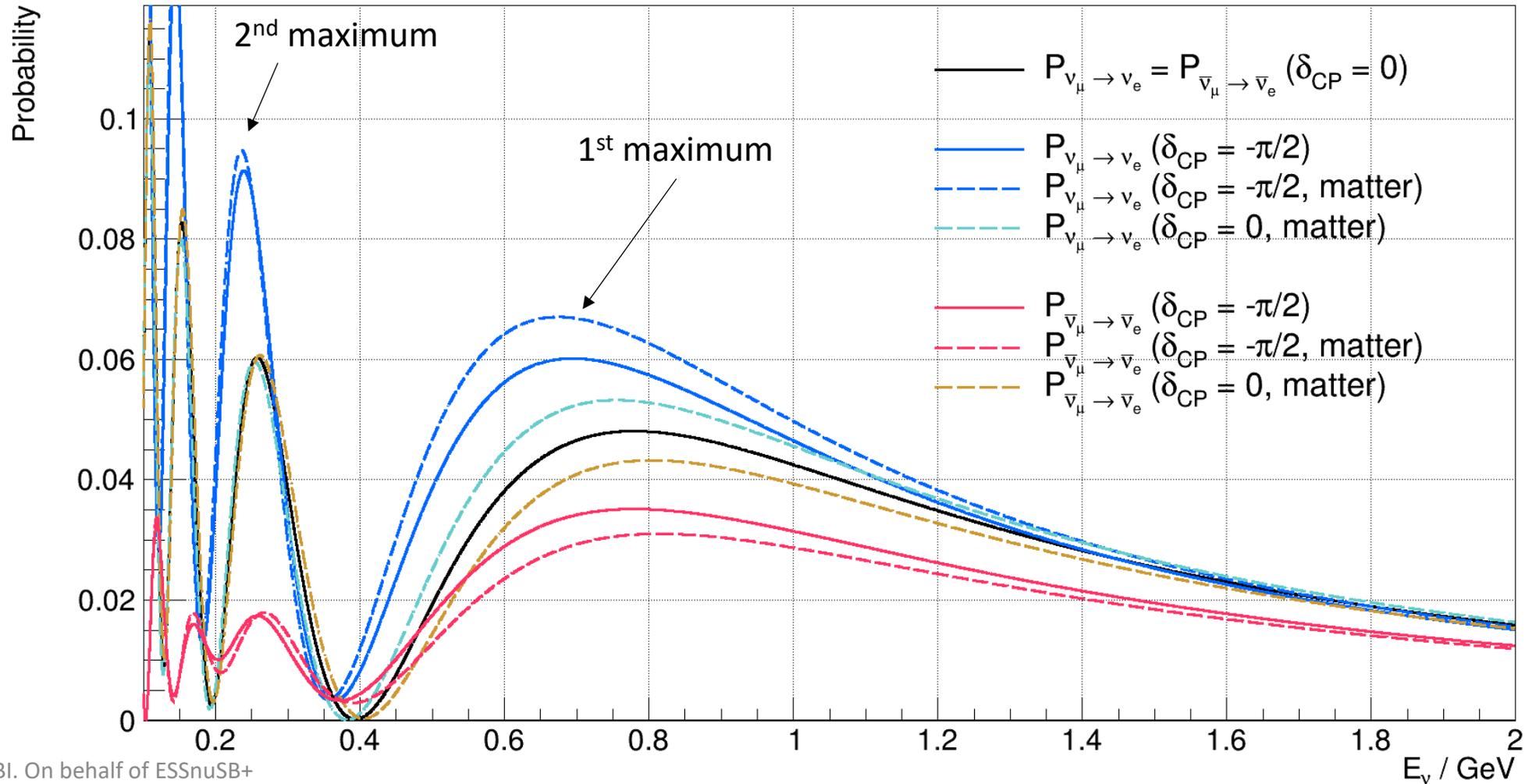
Distortion of oscillation probabilities due to elastic scattering of neutrinos with matter



- Electron neutrinos see a slightly different effective potential than muon and tau neutrinos
 - This modifies the evolution of flavour states in matter
- The effect of matter on neutrino oscillations rises with neutrino energy: it's larger at 1st max than in 2nd one

Oscillation pattern

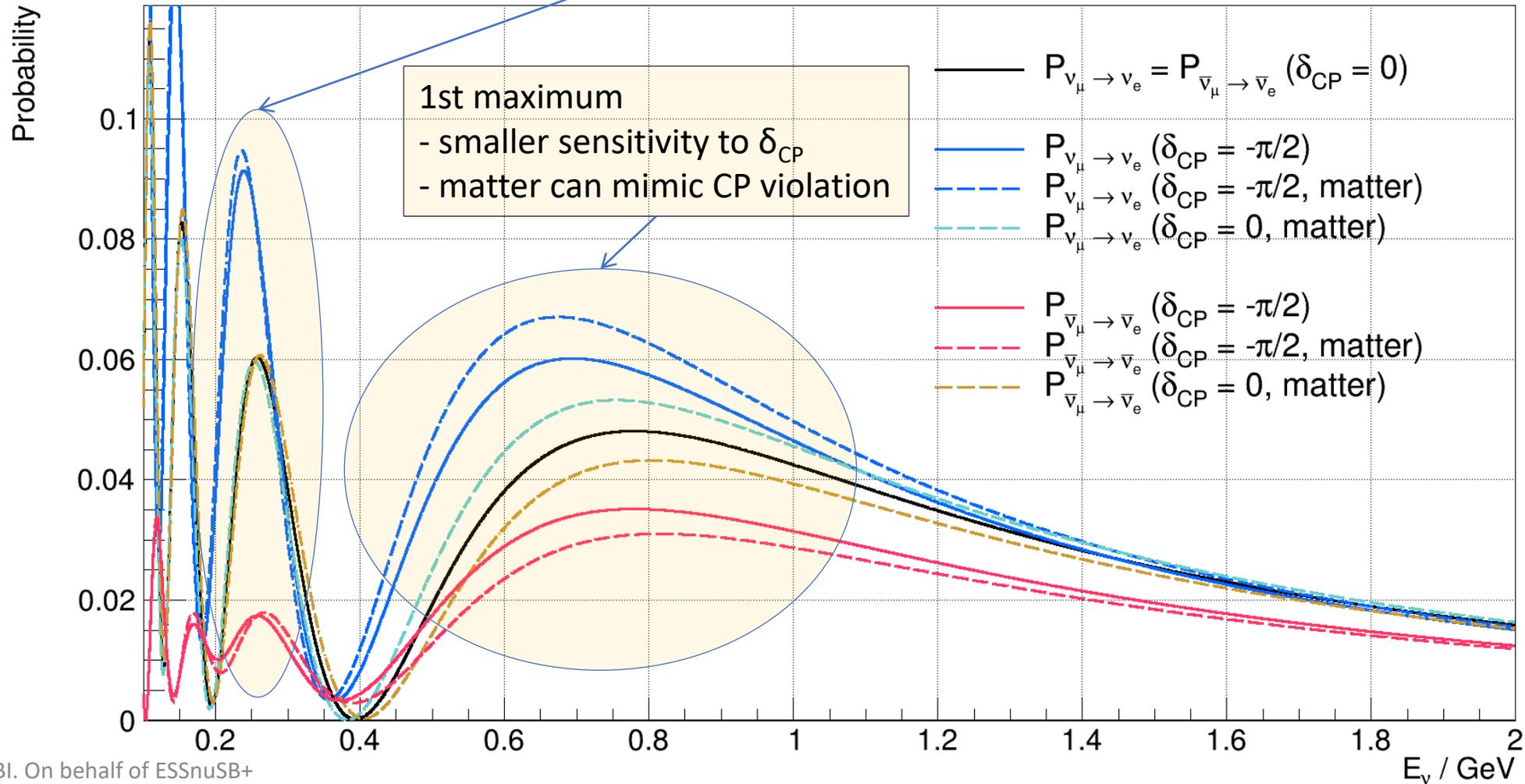
(L = 360 km)



Oscillation pattern

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

(L = 360 km)



ESSnuSB project

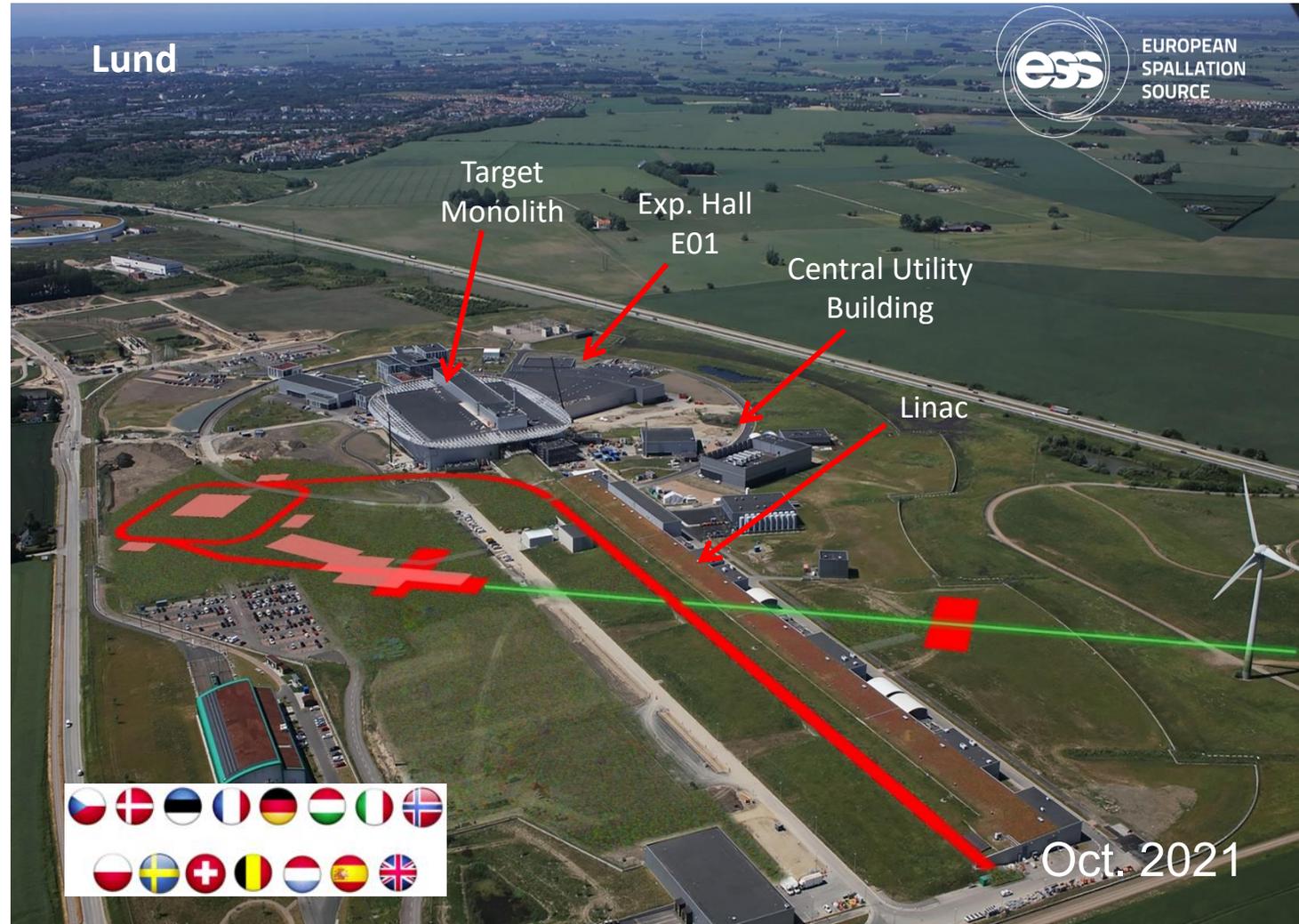
How to observe the CP violation in the 2nd oscillation maximum

The European Spallation Source (ESS)

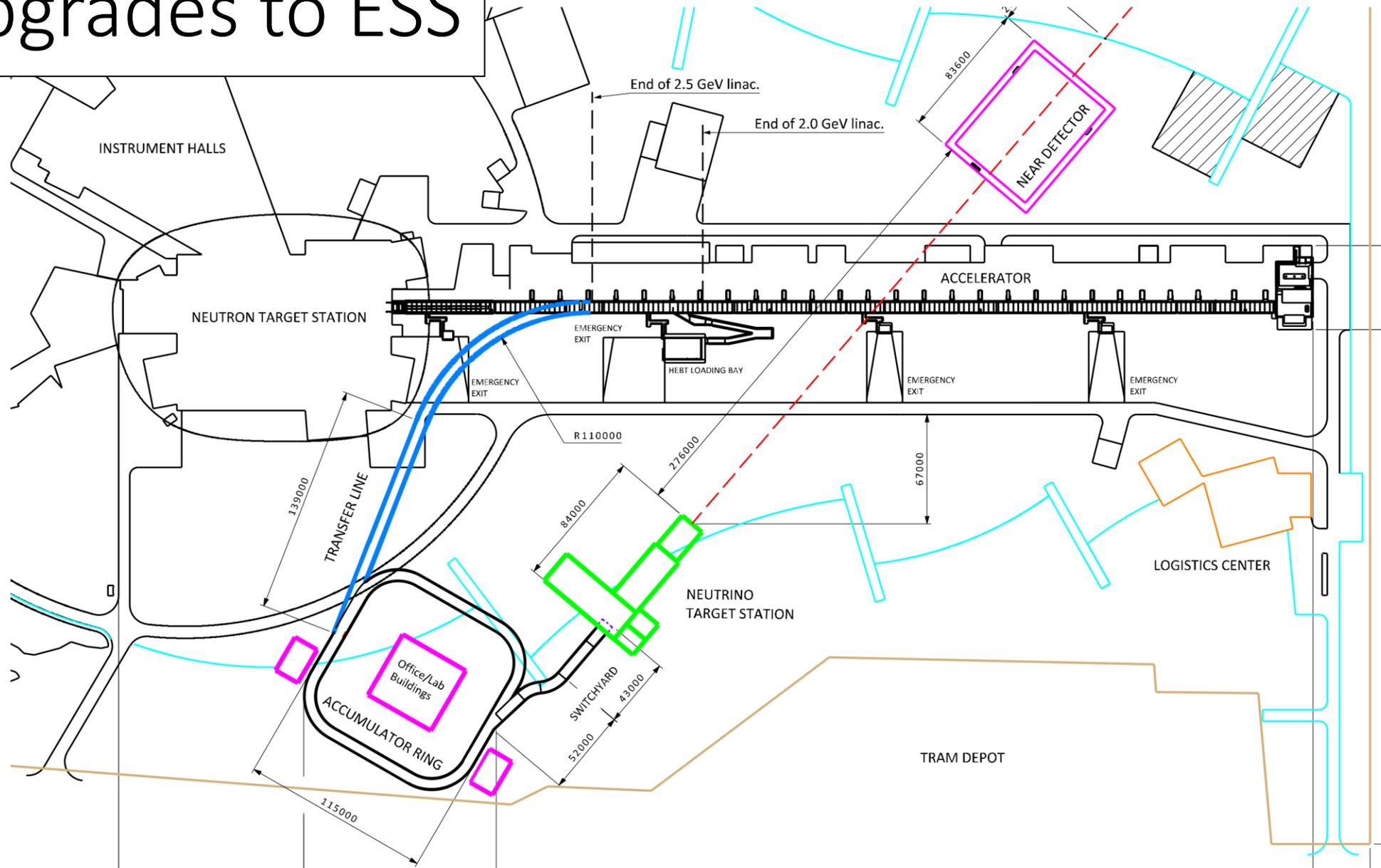
- The ESS will be a copious source of spallation neutrons.
- **5 MW average beam power.**
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV kinetic energy protons
 - up to 3.5 GeV with linac upgrades
- **$>2.7 \times 10^{23}$ p.o.t./year.**

First beam on target expected in 2026.

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



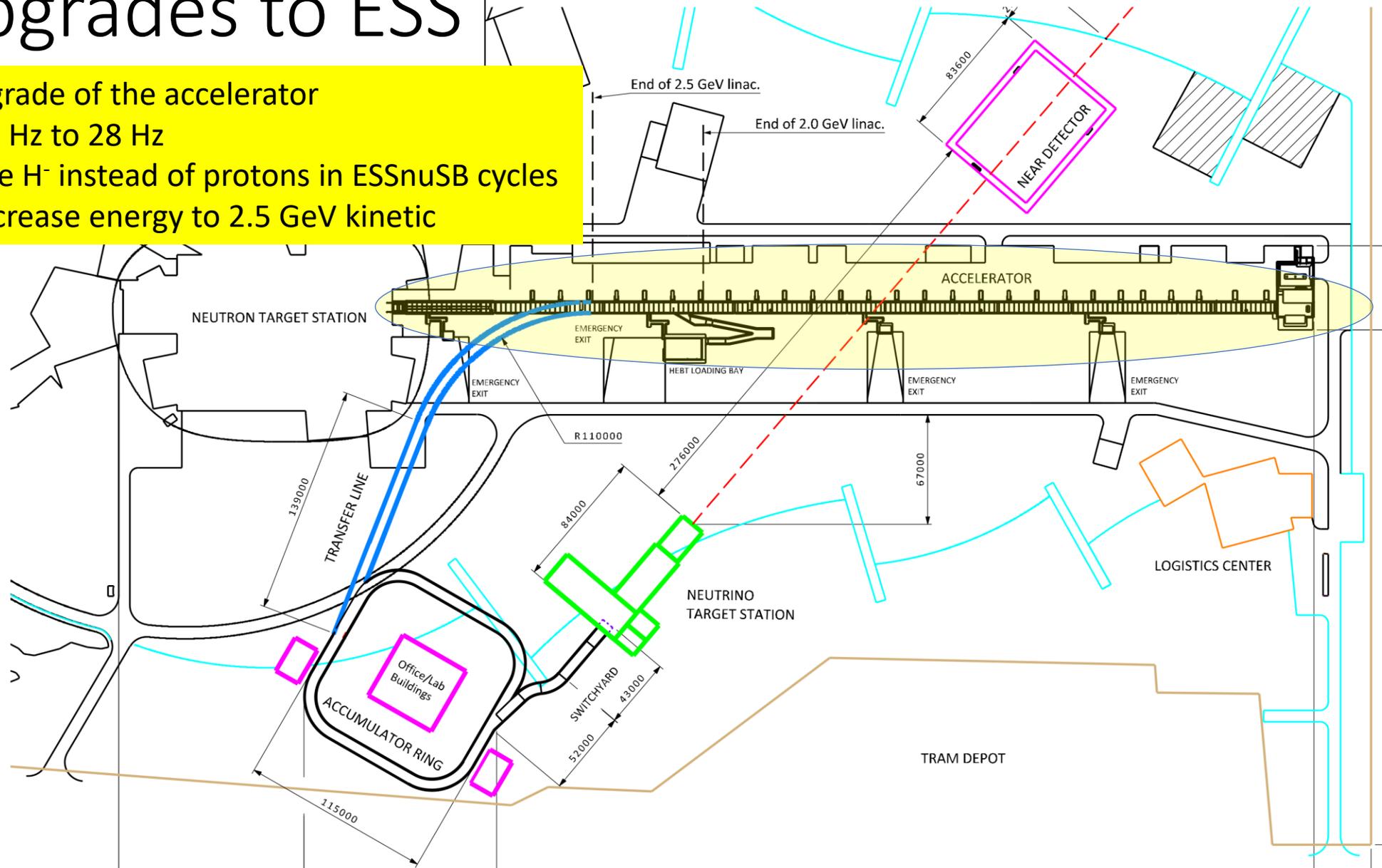
Upgrades to ESS



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



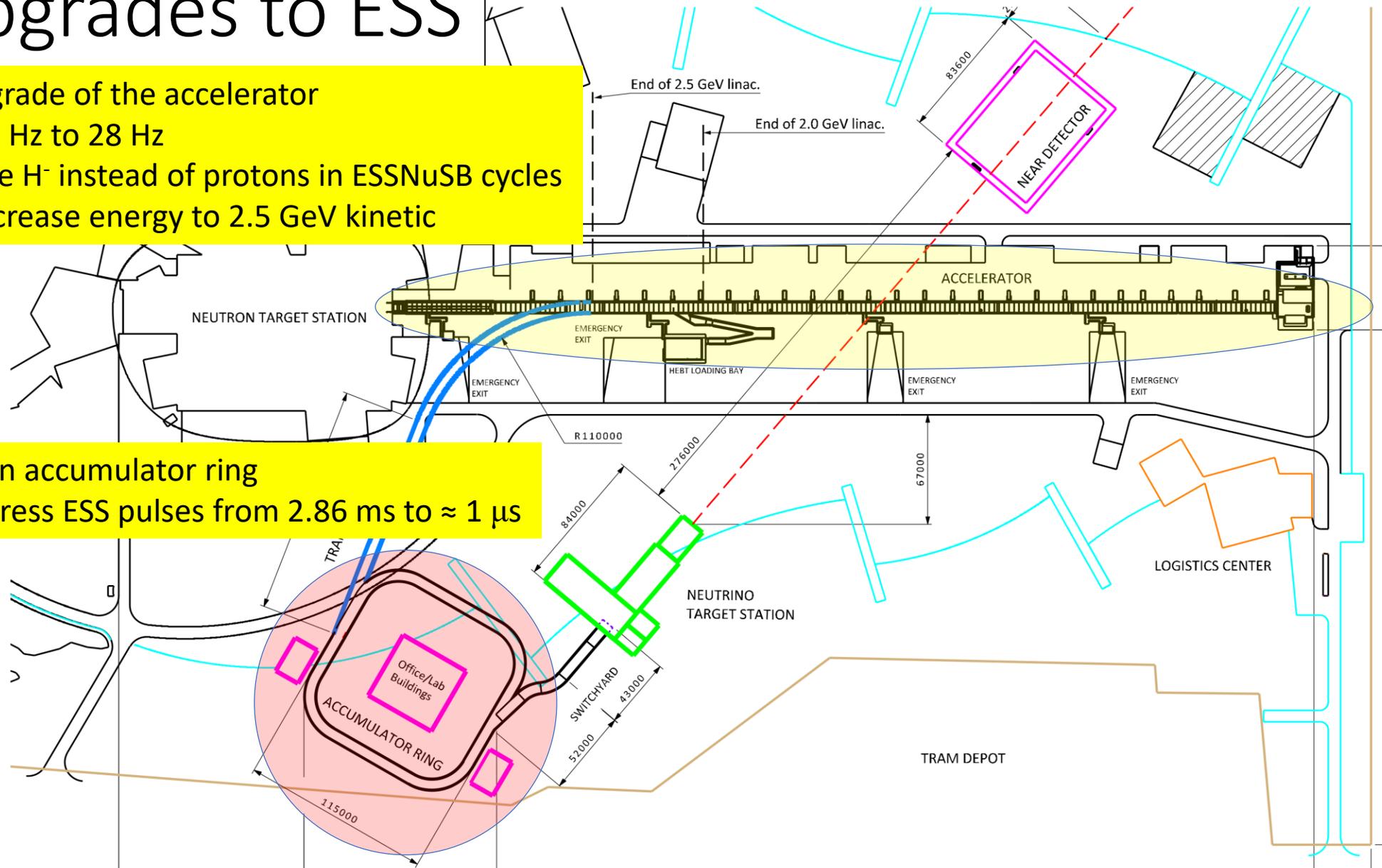
Upgrades to ESS

Upgrade of the accelerator

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Build an accumulator ring

- compress ESS pulses from 2.86 ms to $\approx 1 \mu s$



Upgrades to ESS

Upgrade of the accelerator

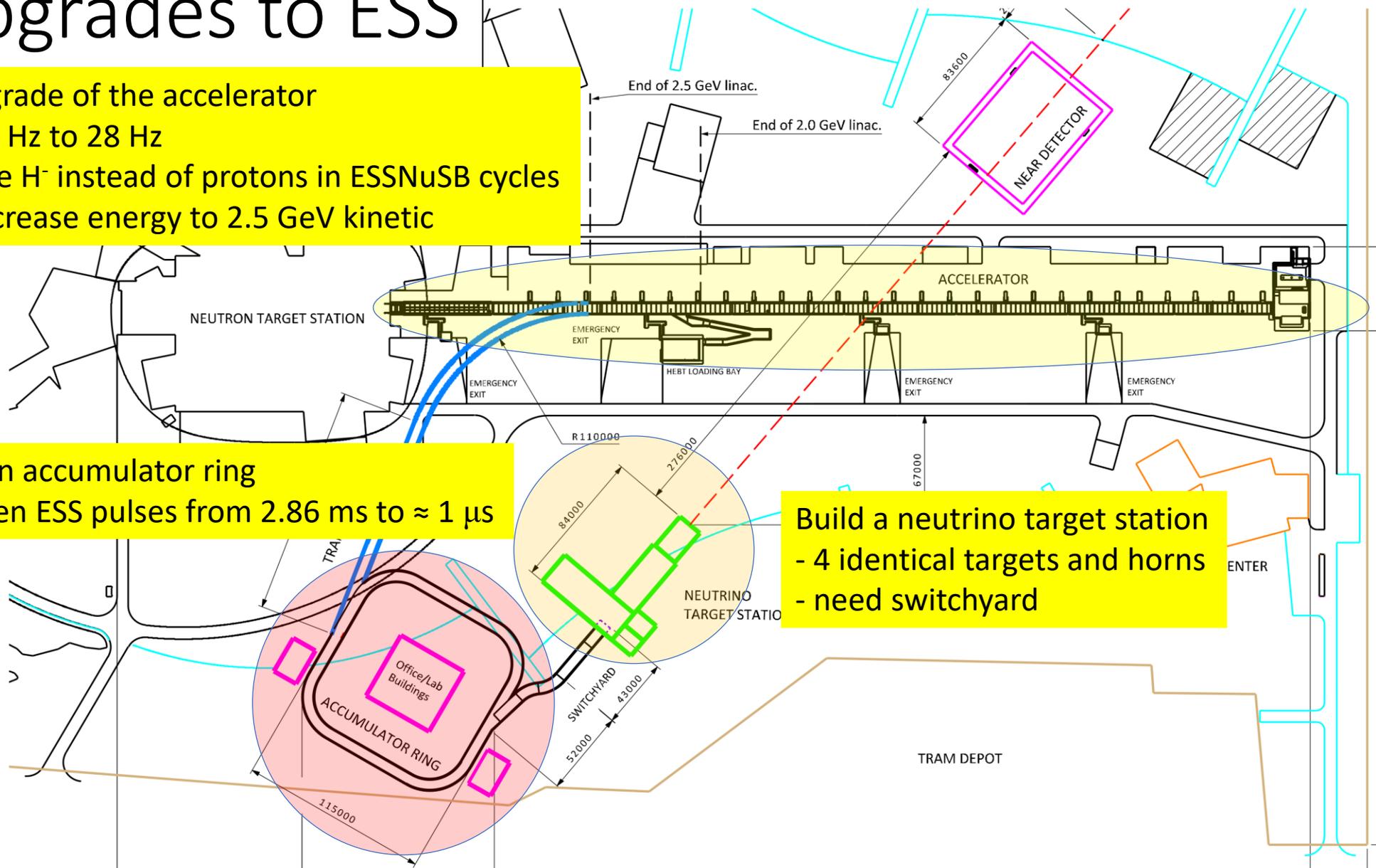
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Build a neutrino target station

- 4 identical targets and horns
- need switchyard



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

Build a near detector site

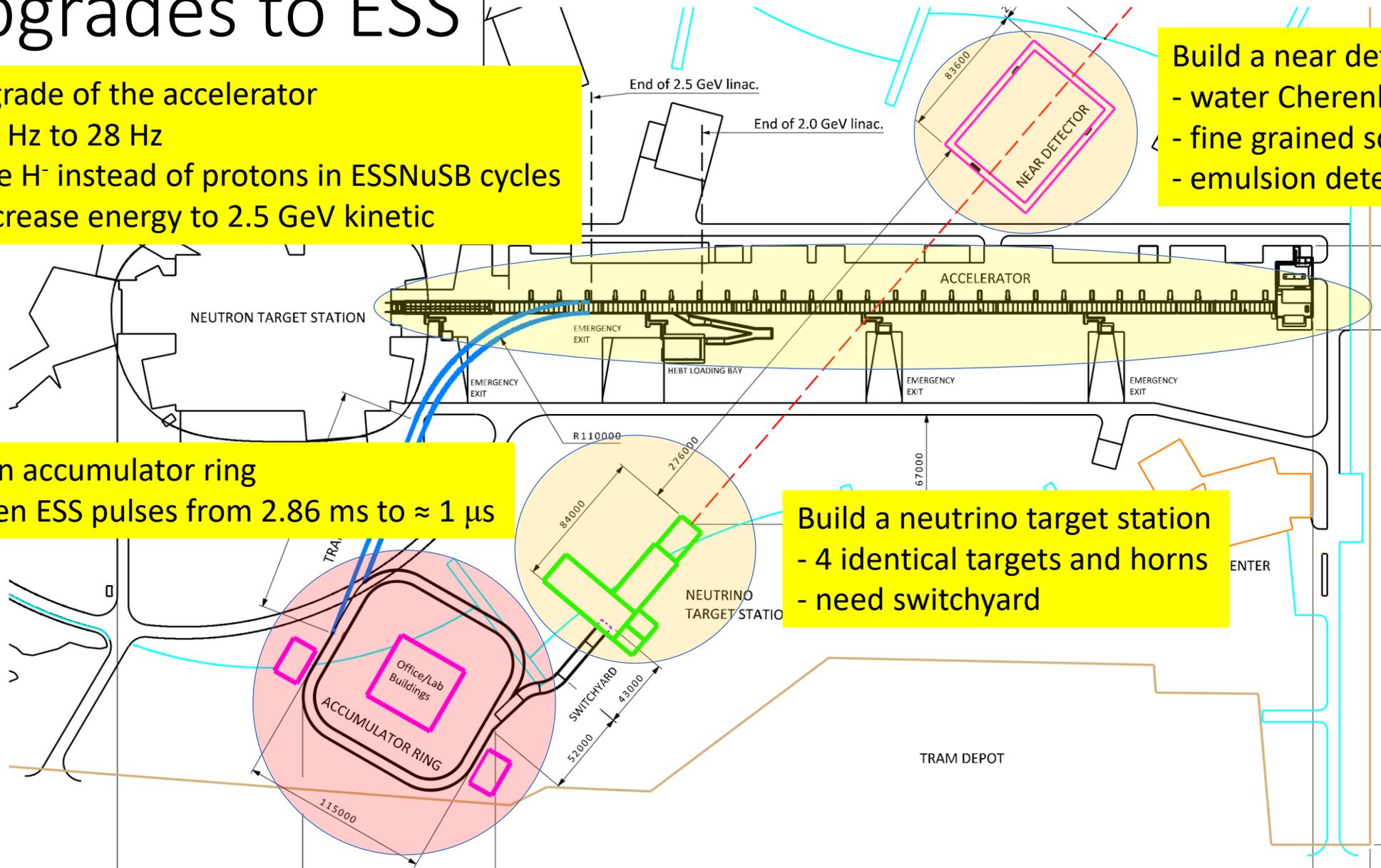
- water Cherenkov detector
- fine grained scintillator
- emulsion detector

Build an accumulator ring

- shorten ESS pulses from 2.86 ms to $\approx 1 \mu s$

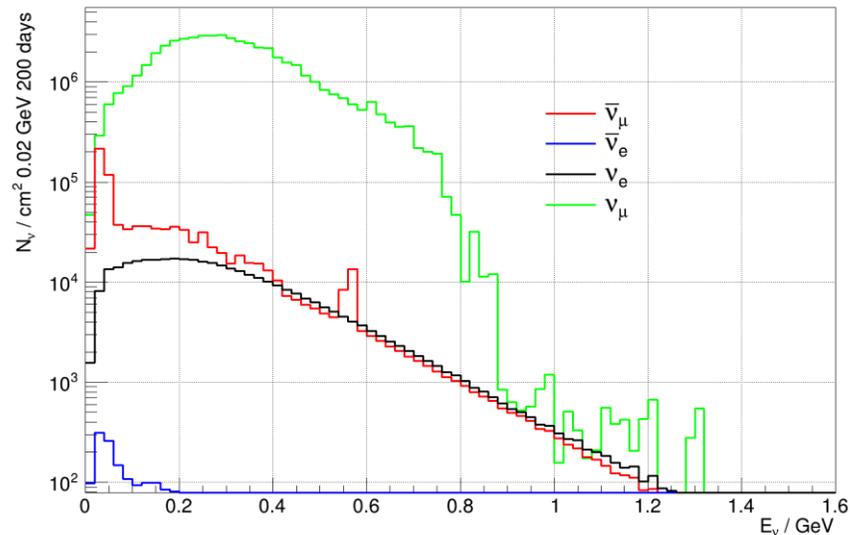
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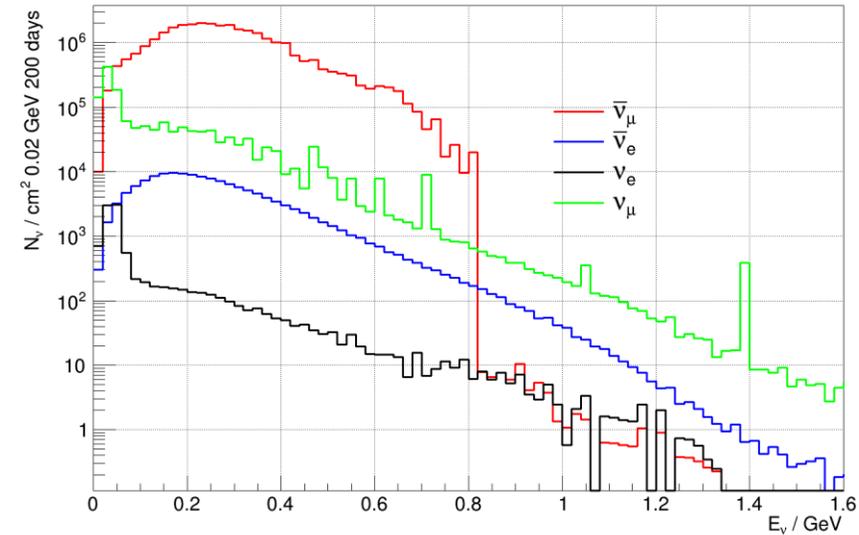


ESSvSB ν energy distribution (after optimisation)

Flux at 360 km (positive polarity)



Flux at 360 km (negative polarity)

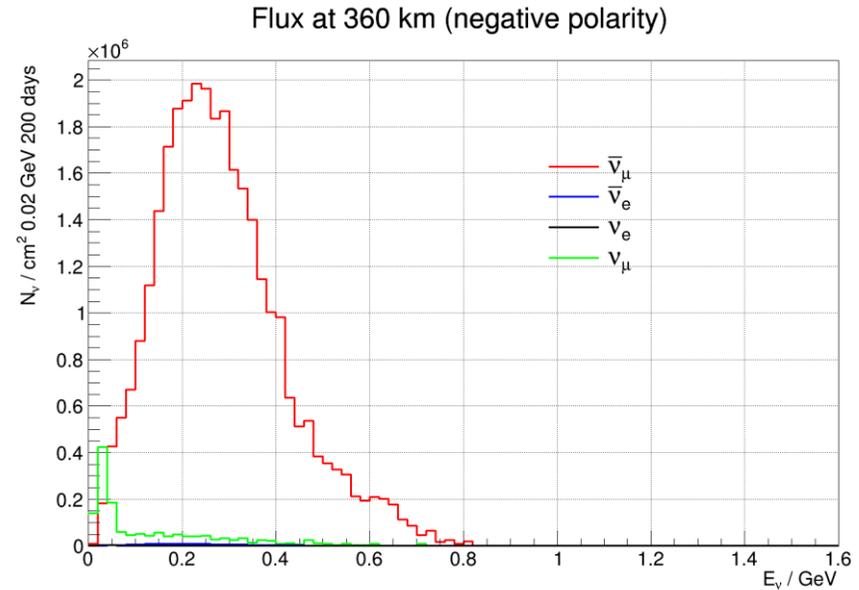
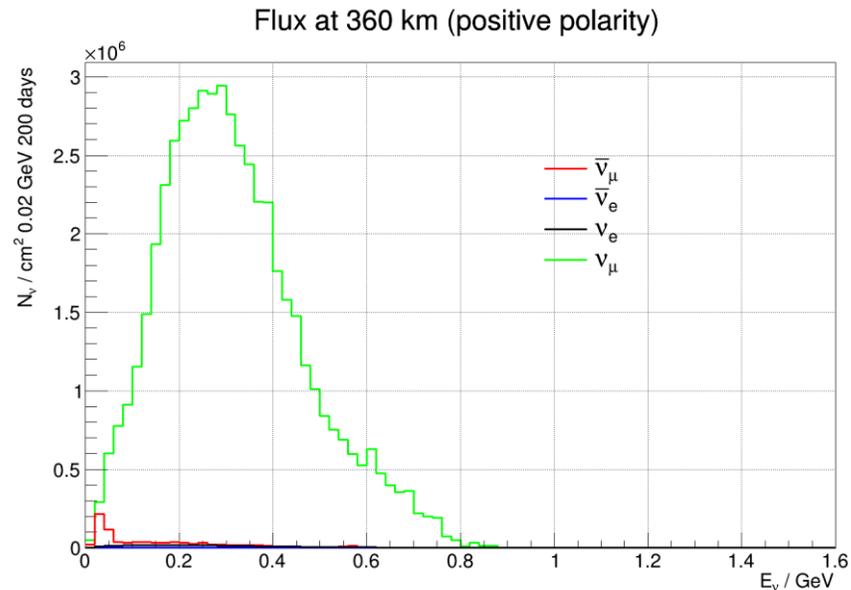


- almost pure ν_μ beam
- small ν_e contamination which will be used to measure ν_e cross-sections in a near detector

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)

ESSvSB ν energy distribution (after optimisation)



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

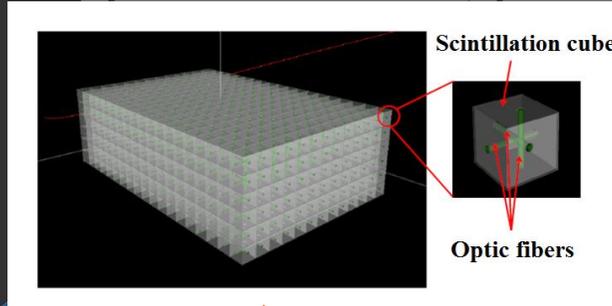
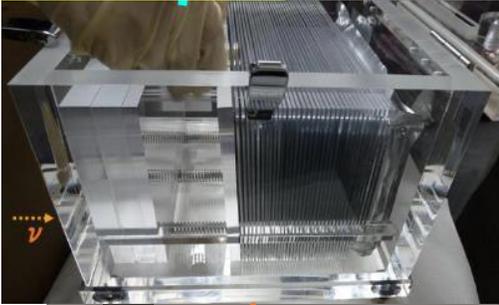
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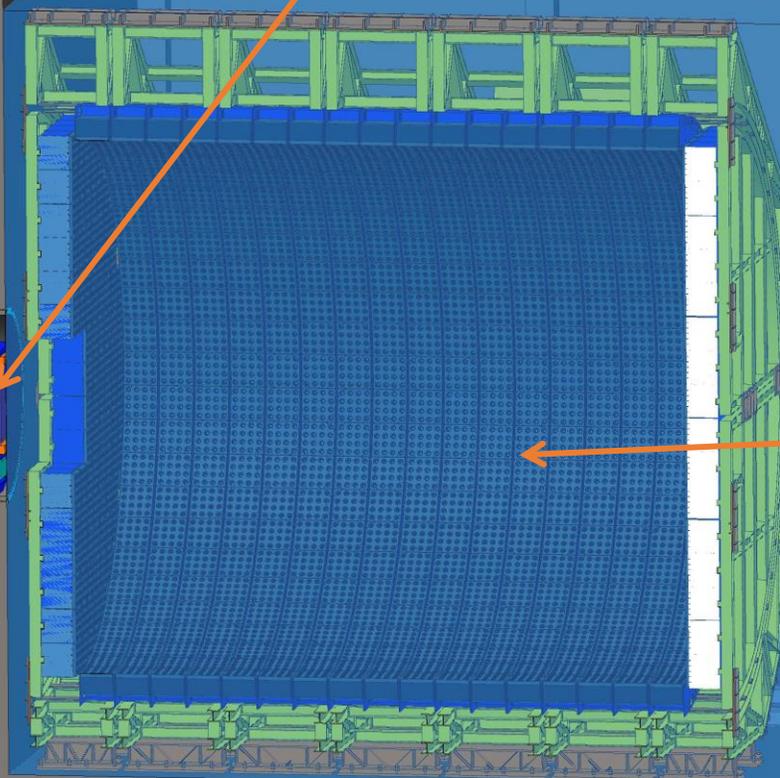
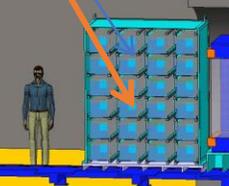
Near detectors

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

Code name: **VIKING**



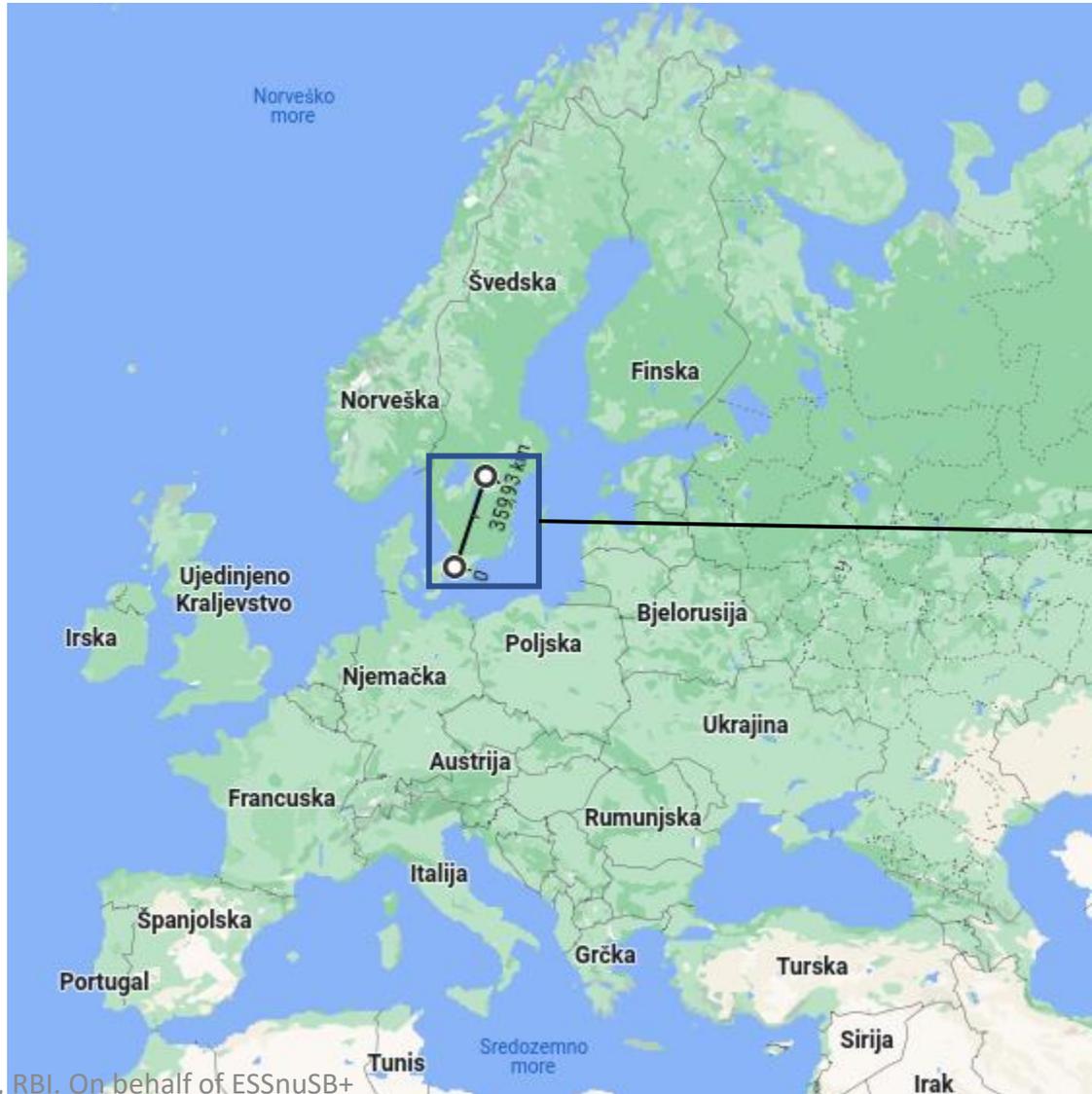
Super-FGD like detector (1 t fiducial)



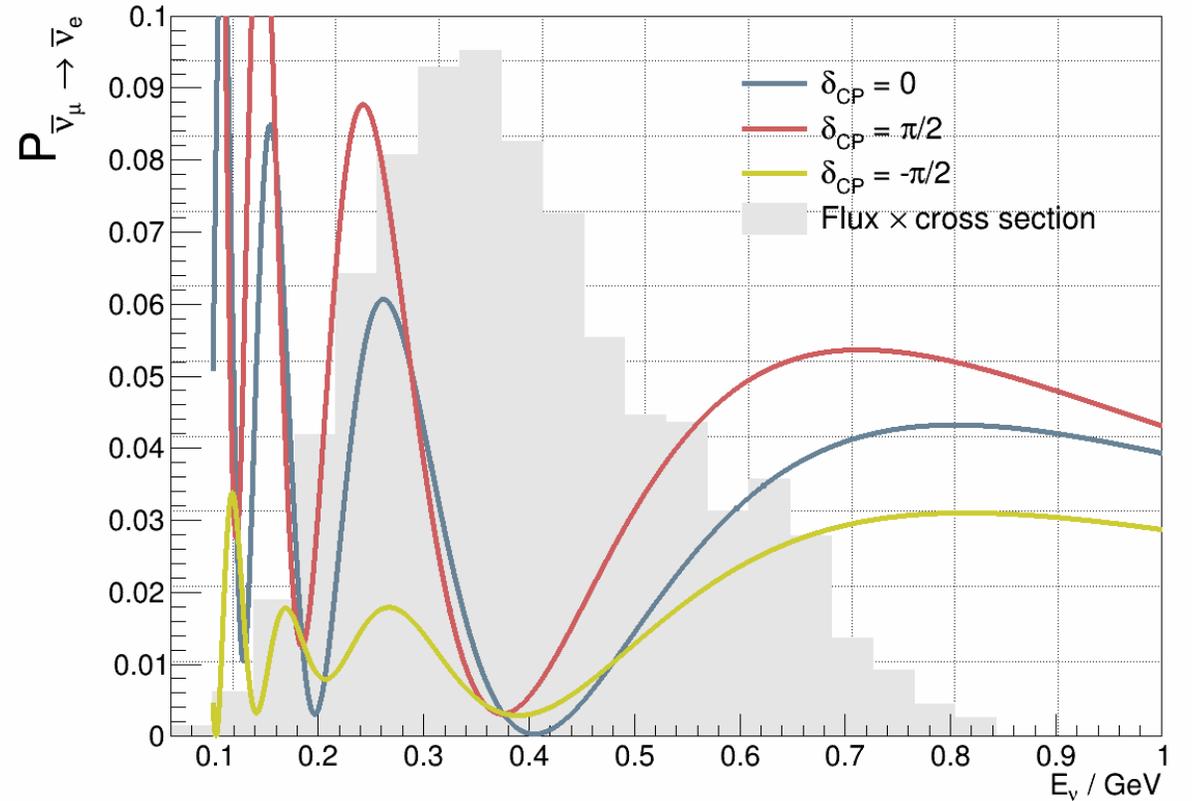
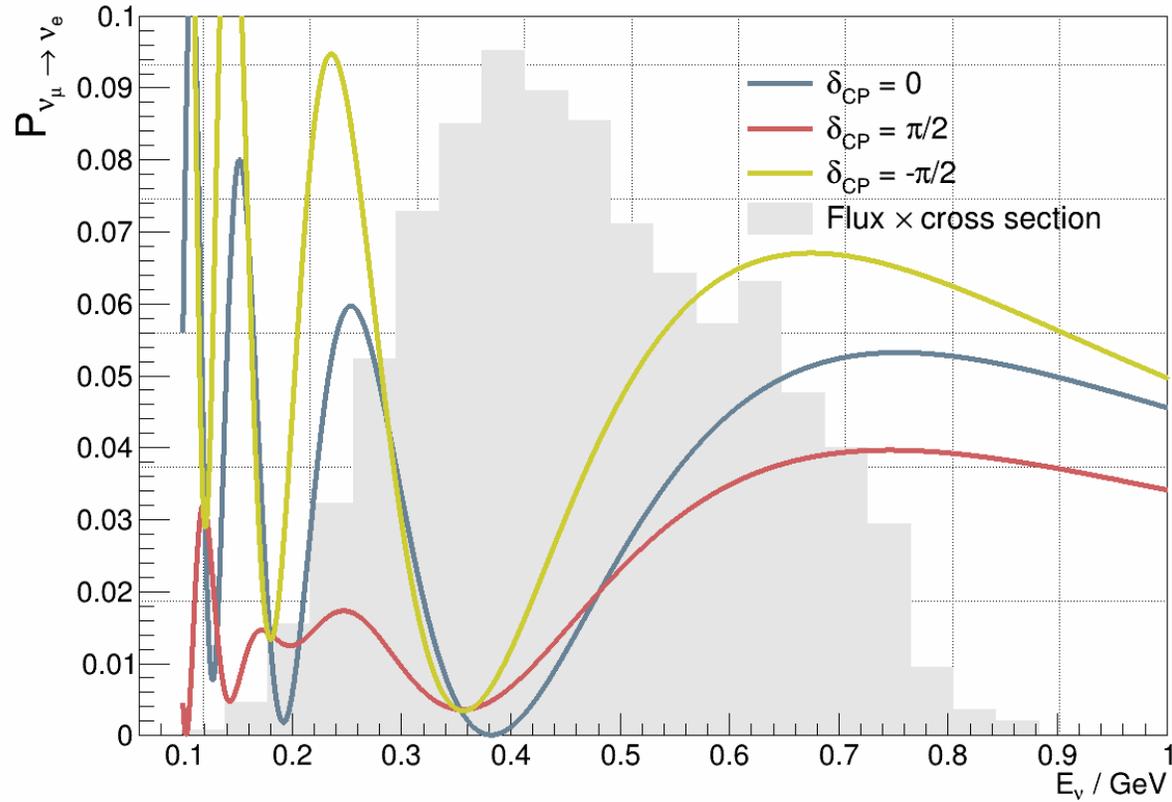
Near Water Cherenkov detector (0.420 kt fiducial)

ESSnuSB neutrino baseline

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



Oscillation coverage



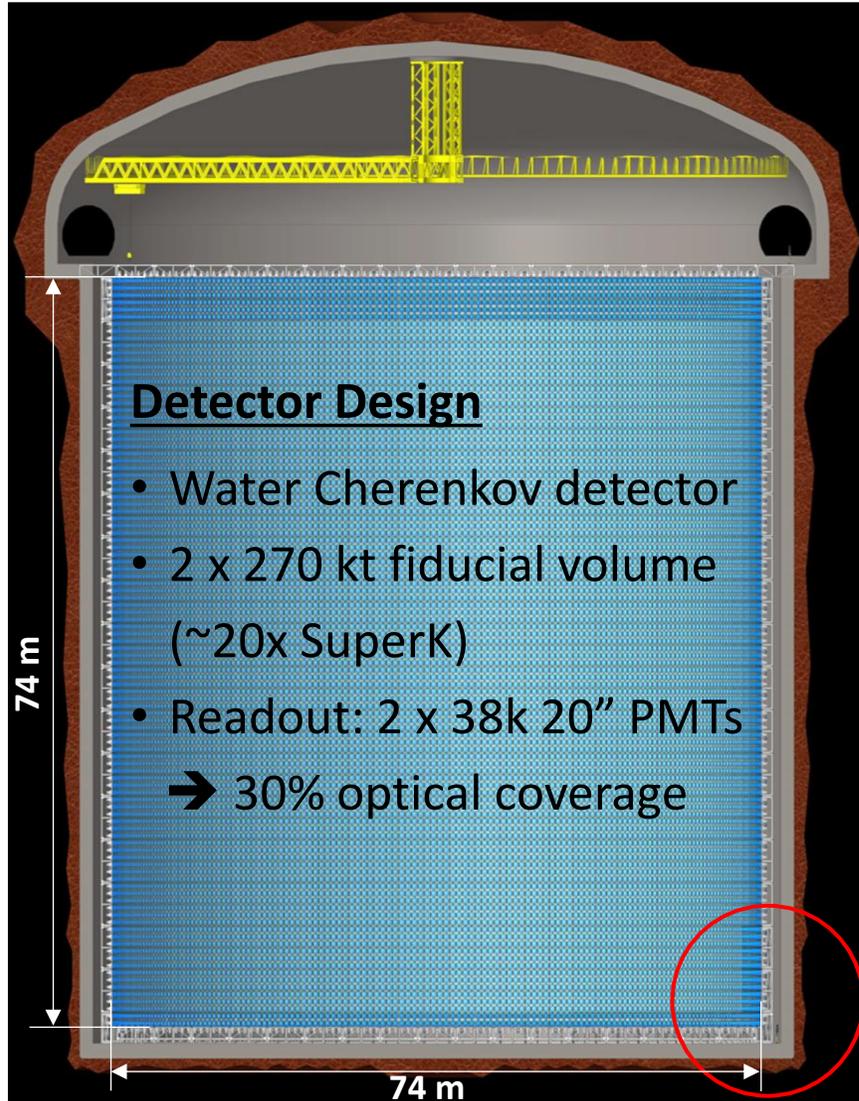
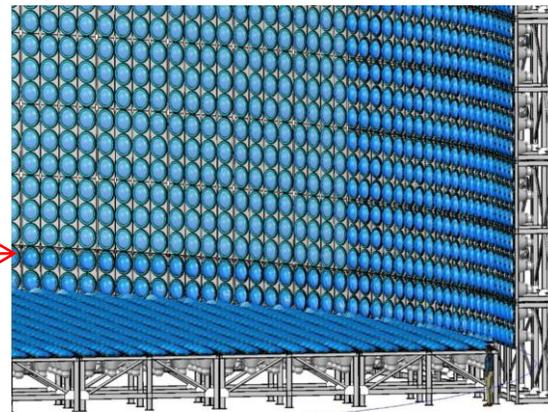
ESSnuSB Far Detector

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

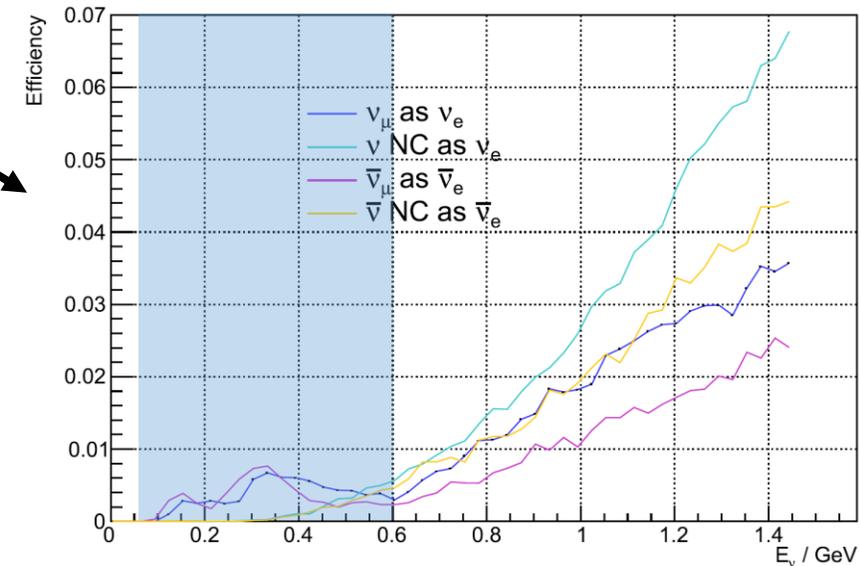
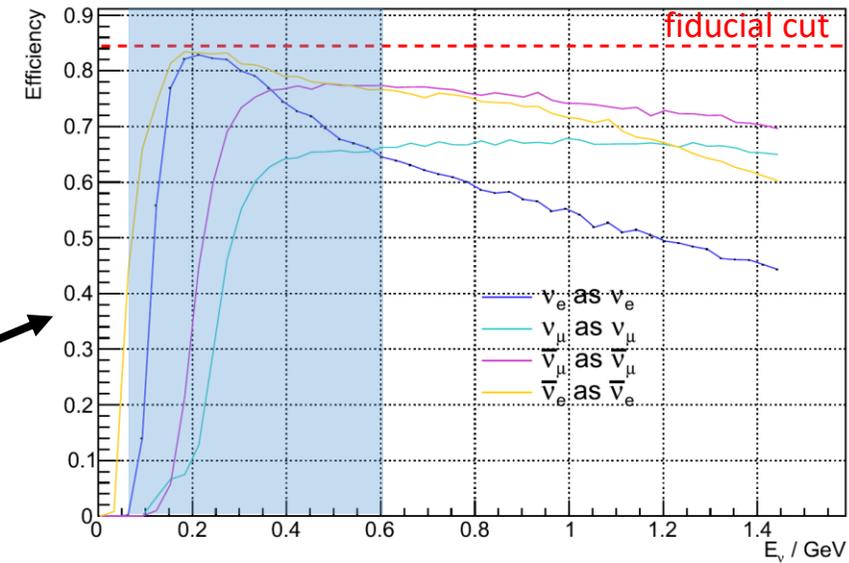
- Detector efficiency for correctly identifying neutrinos > 85%.
- Flavour misidentification probability < 1%.



Detector Design

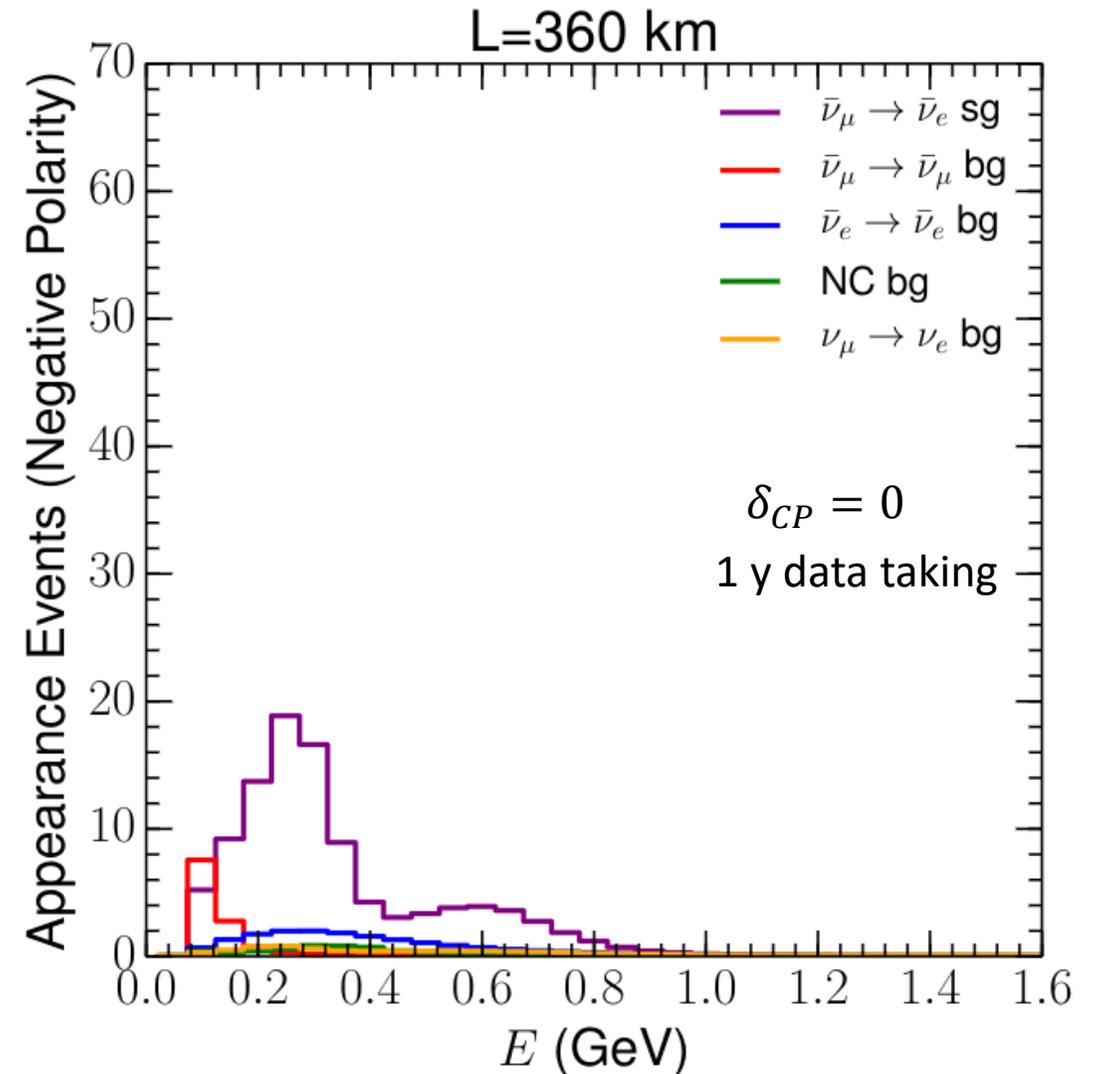
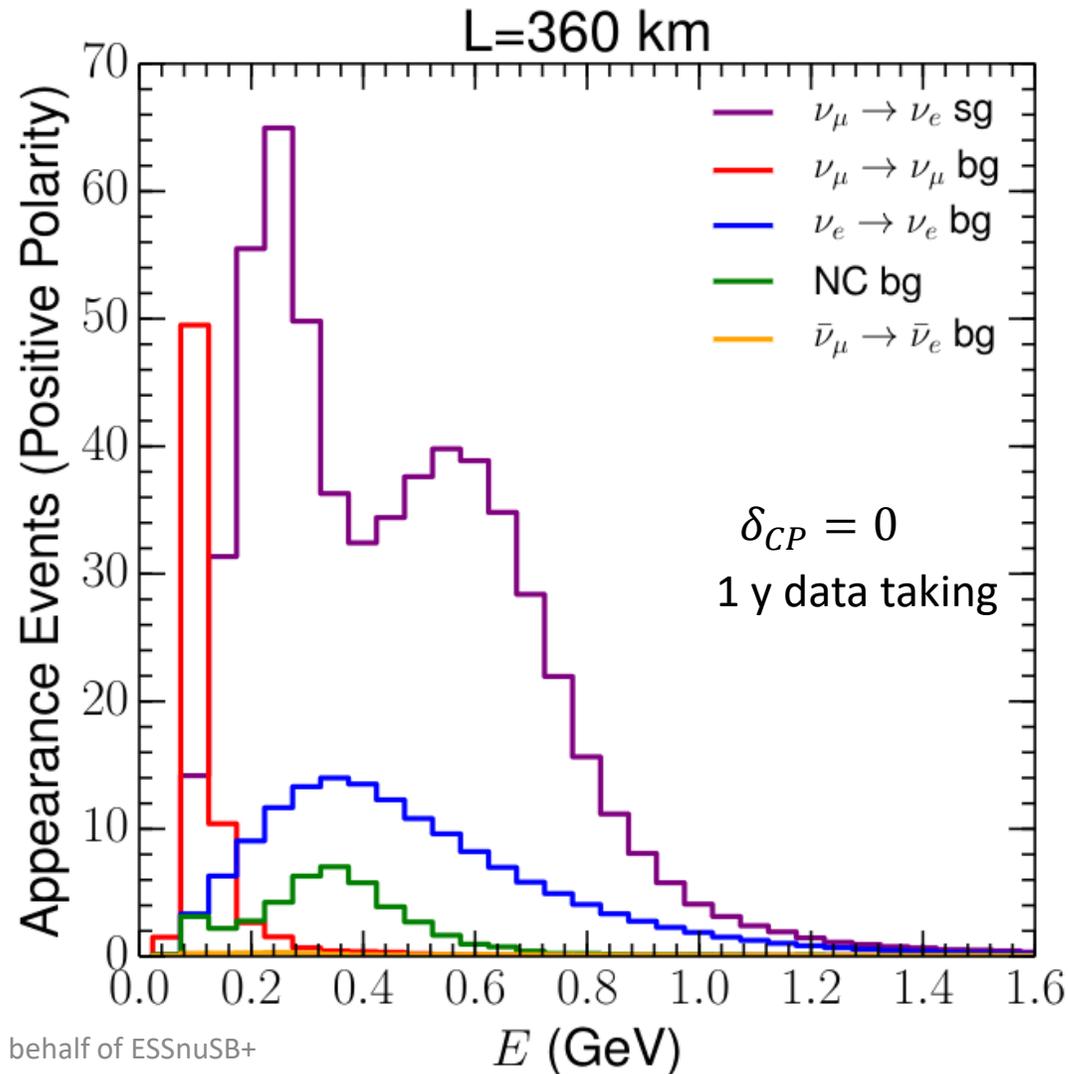
- Water Cherenkov detector
- 2 x 270 kt fiducial volume (~20x SuperK)
- Readout: 2 x 38k 20" PMTs
→ 30% optical coverage

ESSnuSB Particle selection efficiency



Expected event spectra

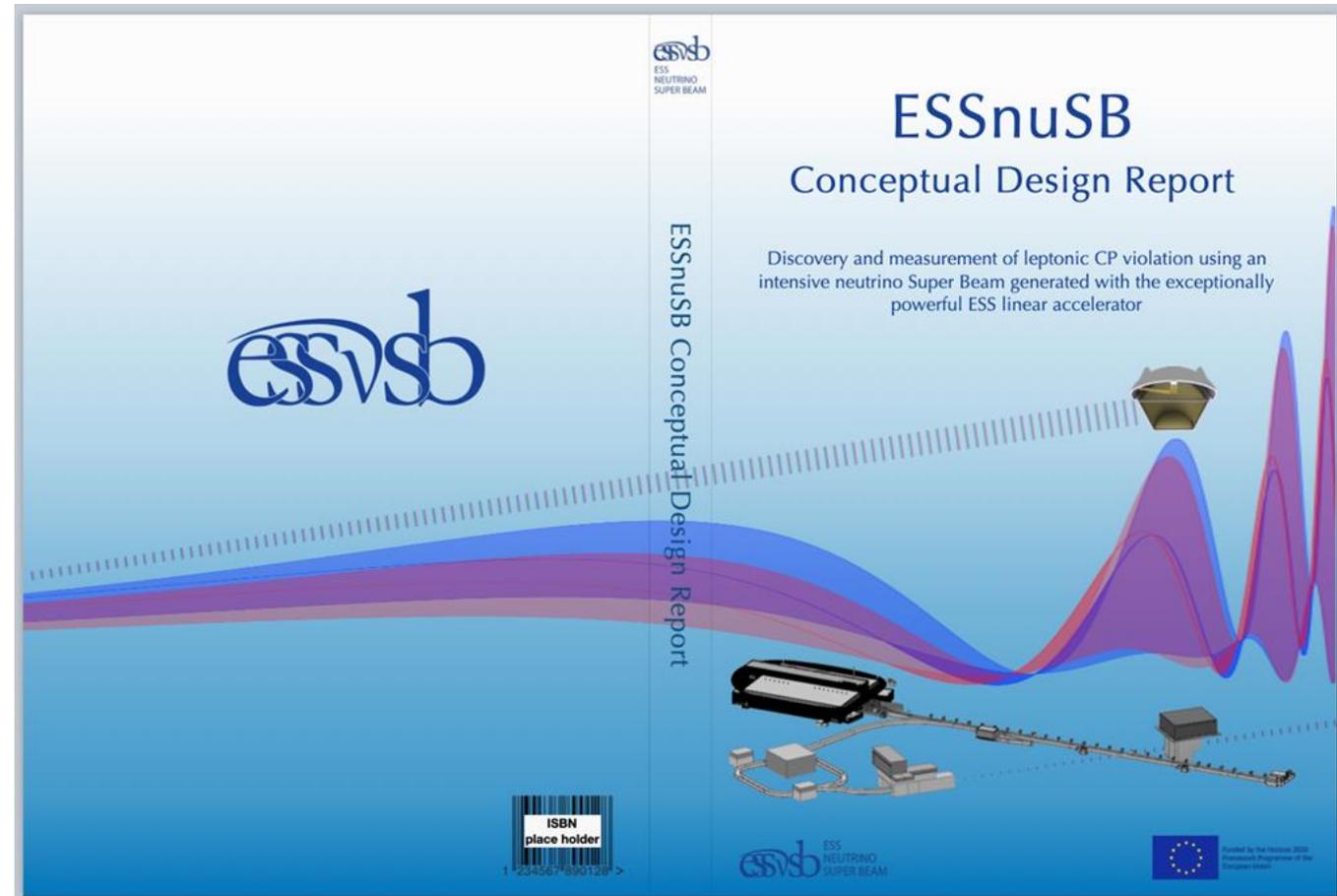
From the ESSnuSB CDR: <https://doi.org/10.1140/epjs/s11734-022-00664-w> & <https://arxiv.org/abs/2203.08803>



CPV sensitivity

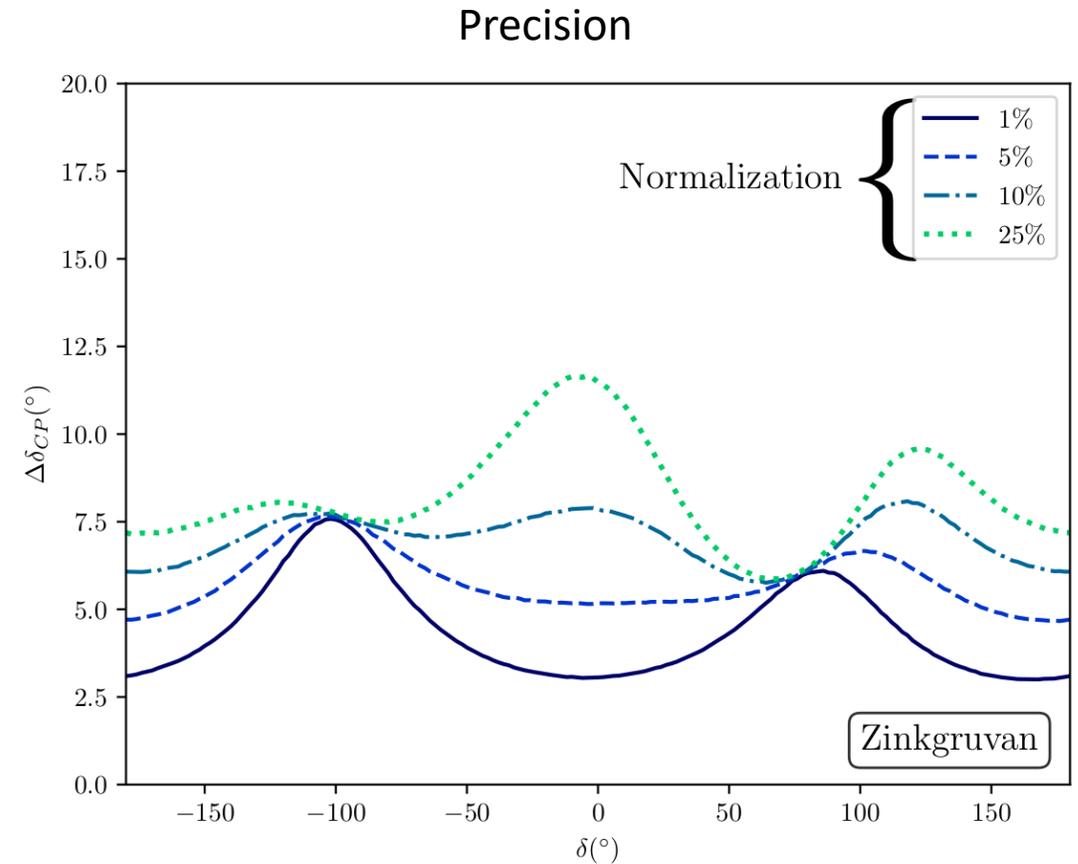
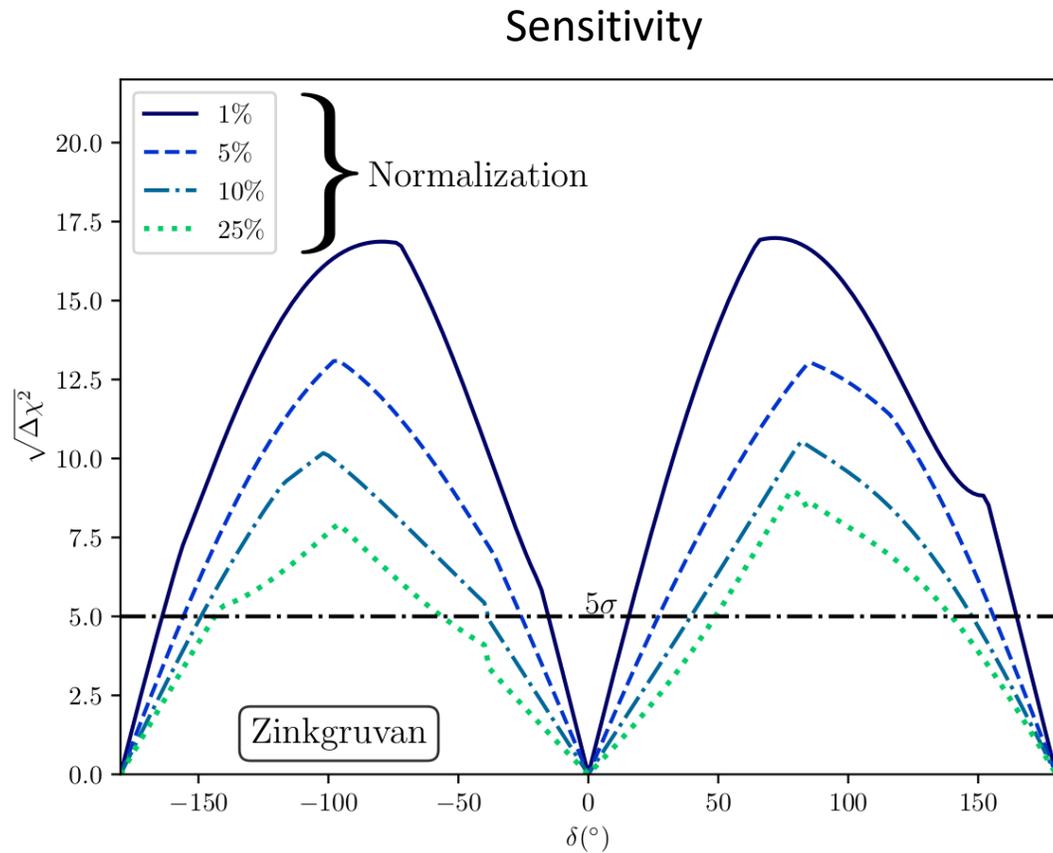
ESSnuSB conceptual design report

- Most up to date evaluation of the CPV discovery potential



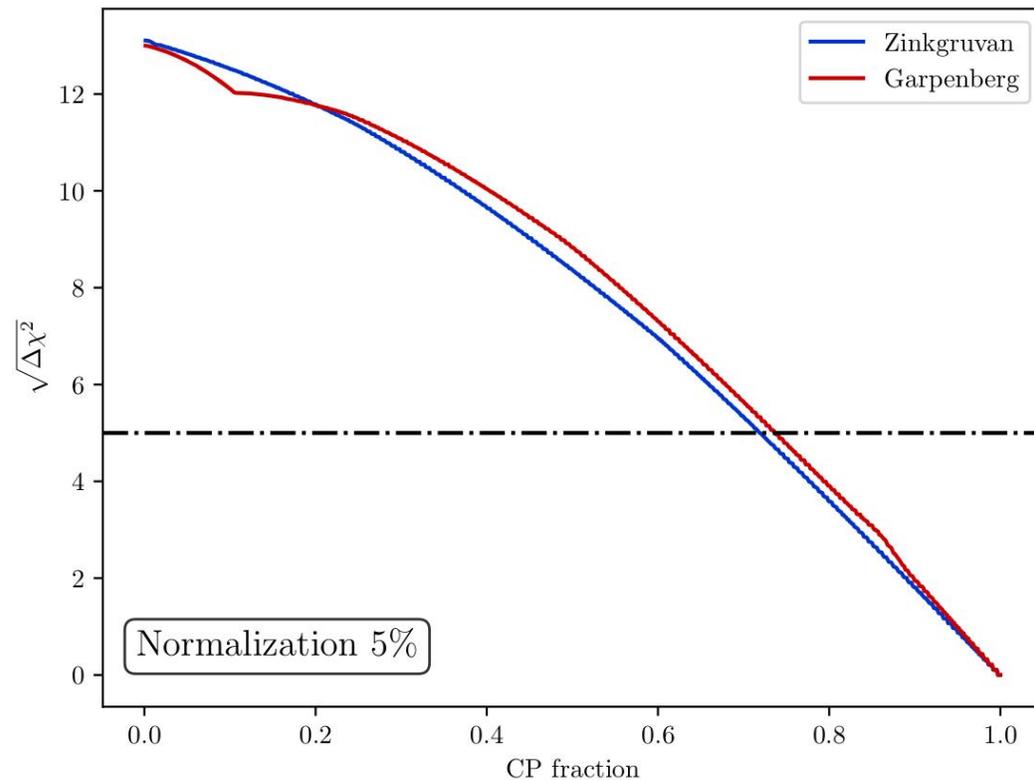
Aleku, A., Baussan, E., Bhattacharyya, A.K. et al. “The European Spallation Source neutrino super-beam conceptual design report”. Eur. Phys. J. Spec. Top. (2022). <https://doi.org/10.1140/epjs/s11734-022-00664-w>
arXiv: <https://arxiv.org/abs/2203.08803> (includes costing)

Effect of normalization uncertainty on CPV measurements (more in back-upslides)



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

CP coverage



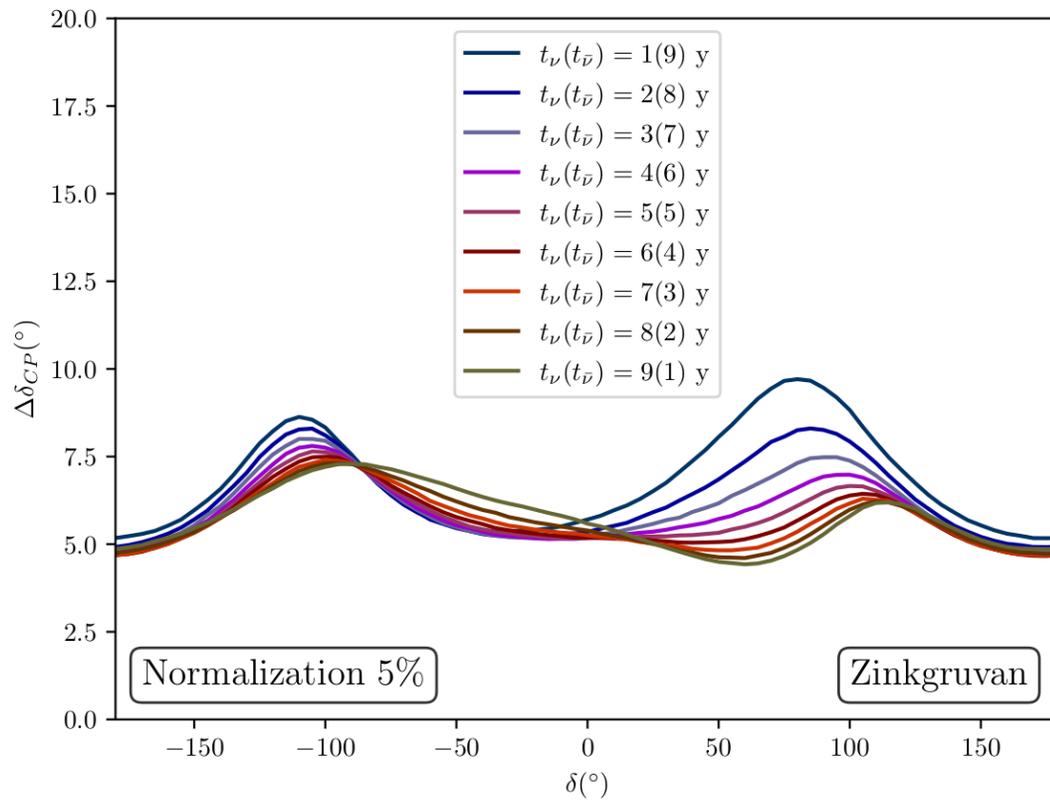
71% coverage of δ_{CP} range
with more than 5σ in 10 y
of data taking

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

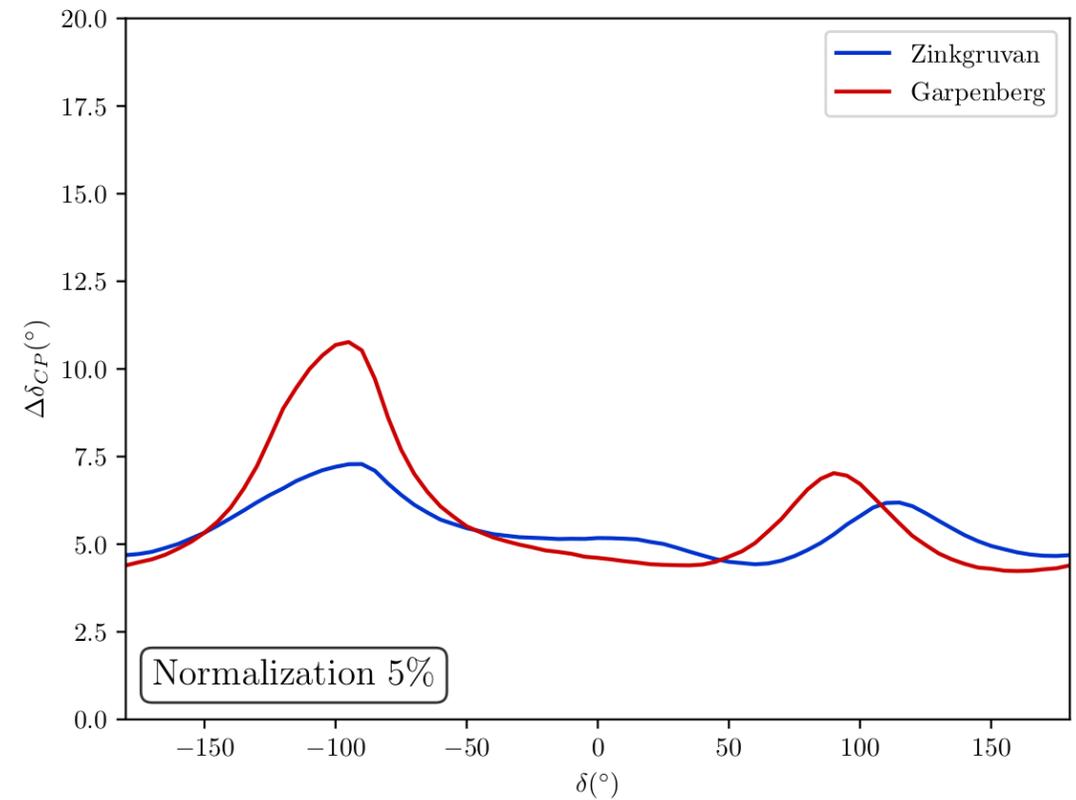
Optimization for precision

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

Precision for different neutrino (antineutrino) run times



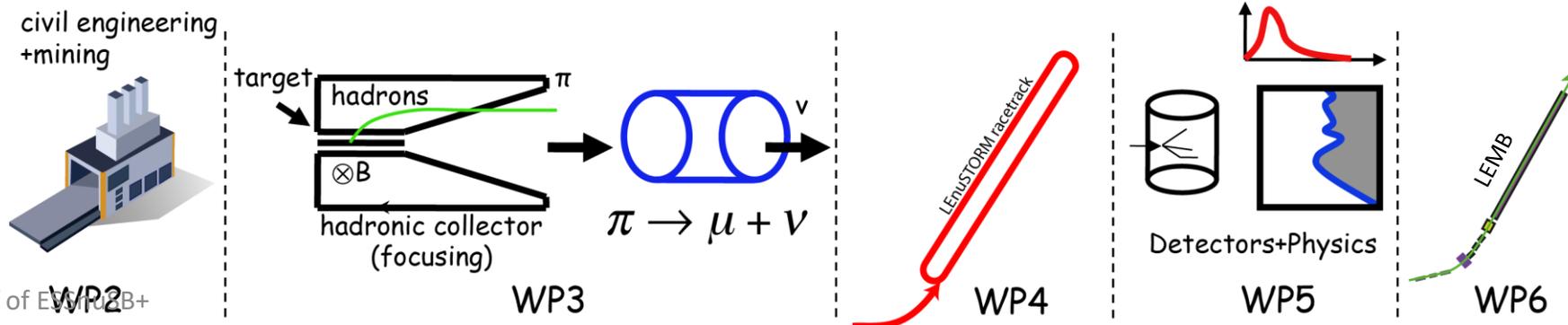
Optimal precision for known δ_{CP}



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

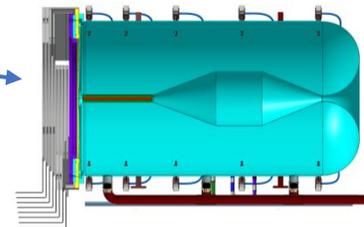
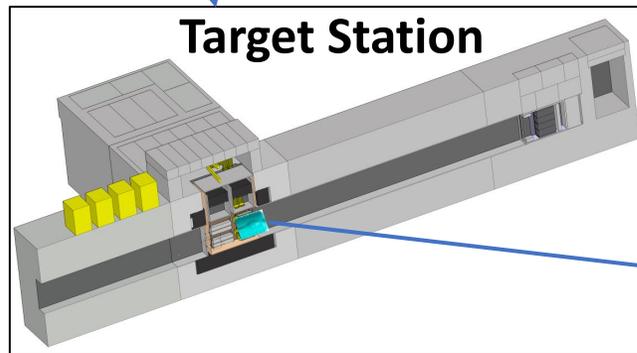
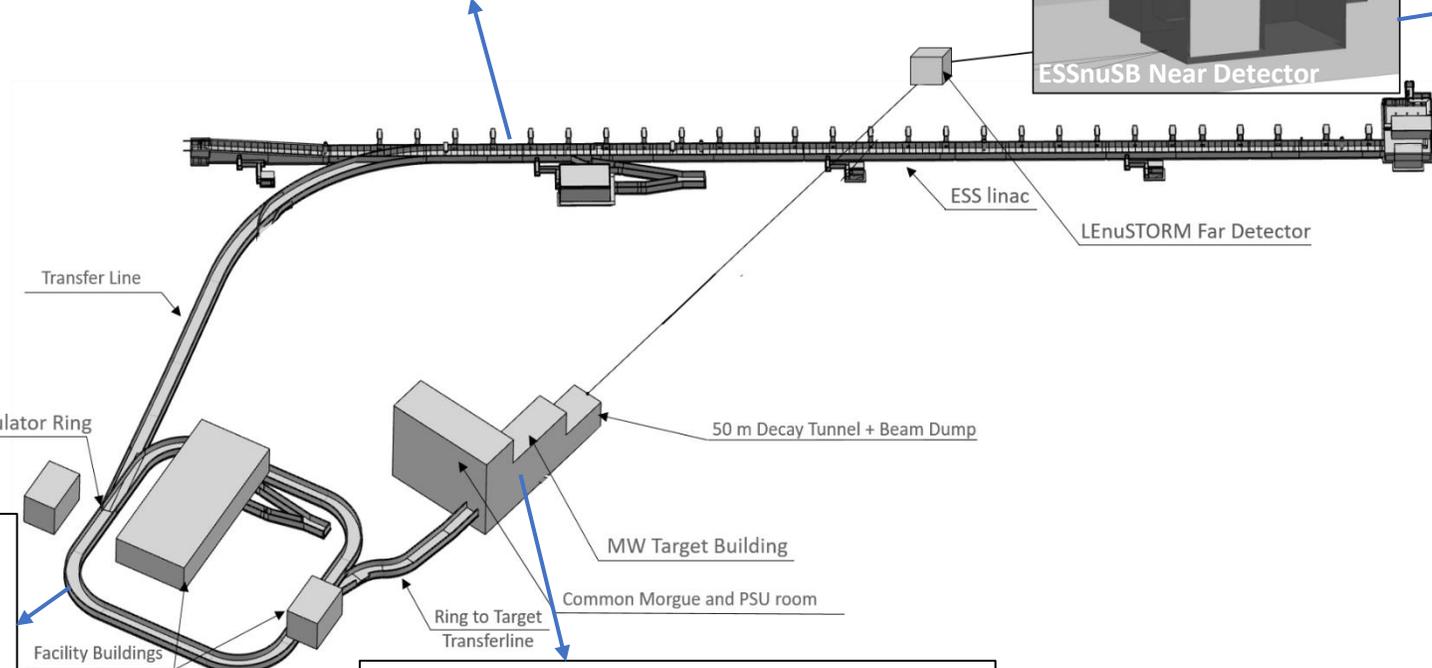
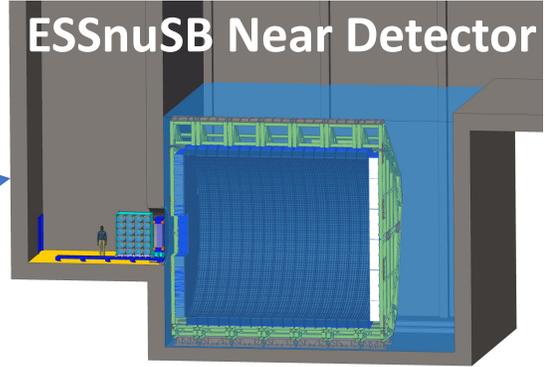
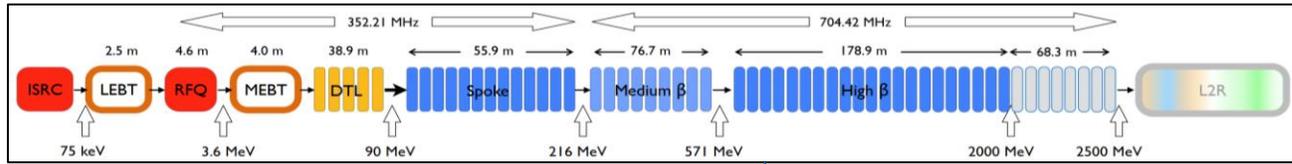
The ESSnuSB+ project

- Having finished the conceptual design of the facility for CPV measurement, we need to take further steps
- Start with the civil engineering and infrastructure development
- Design prototyping facilities at ESS
- **Design facilities for precise neutrino cross-section measurement: low energy nuSTORM (LEnuSTORM) and monitored beam (LEMB)**
- Explore additional physics opportunities offered by ESSnuSB with addition of LEnuSTORM and LEMB



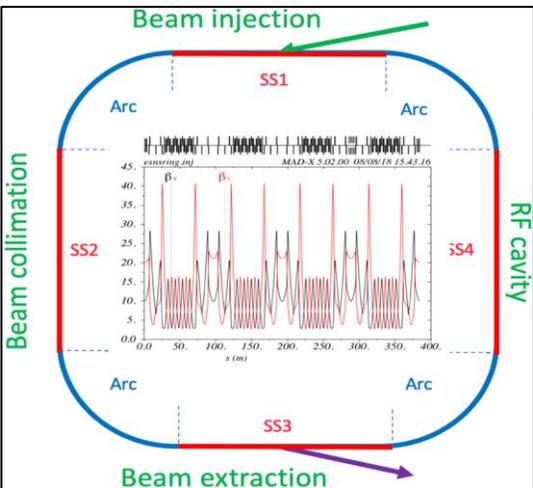
ESS upgrades to host the ESSnuSB+

ESS linac



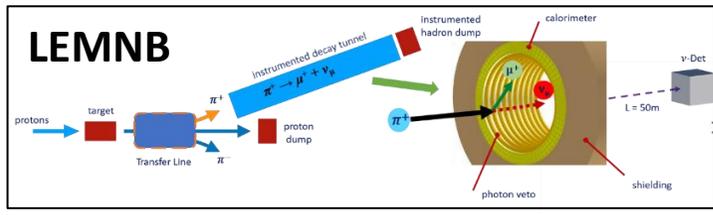
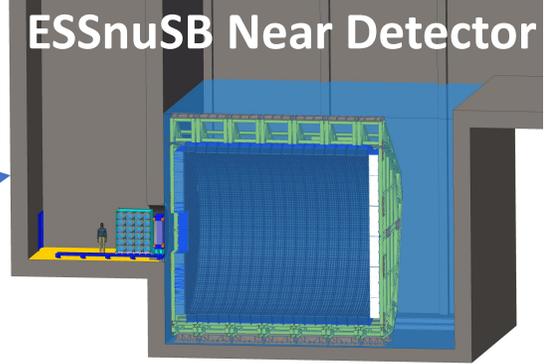
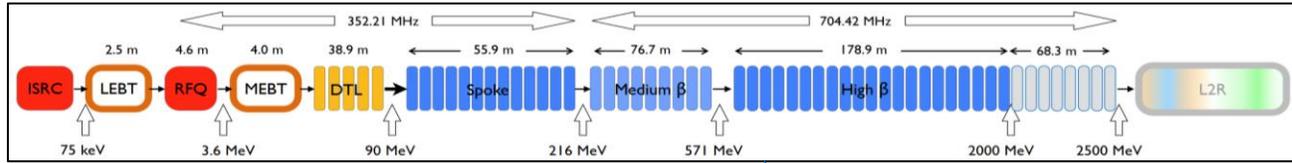
One horn-target system

Accumulator Ring



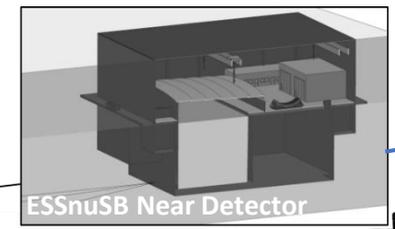
ESS upgrades to host the ESSnuSB+

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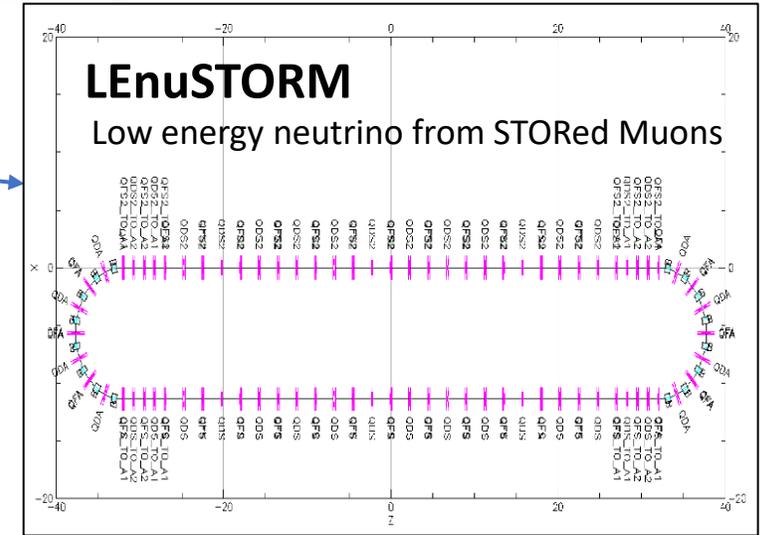
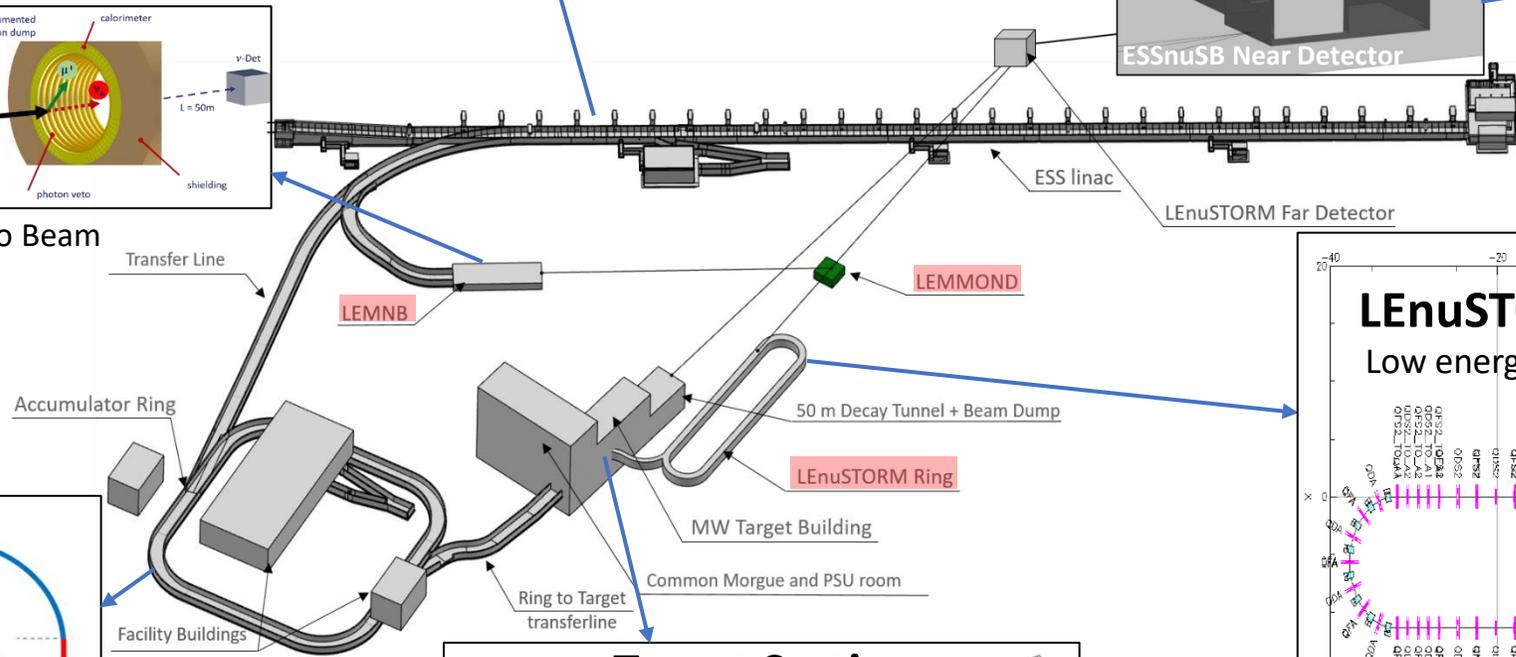


Low Energy Monitored neutrino Beam

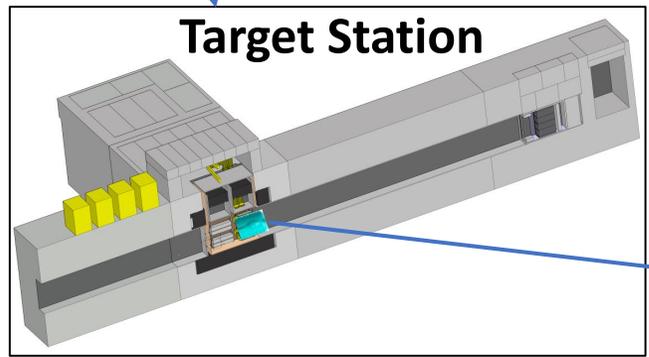
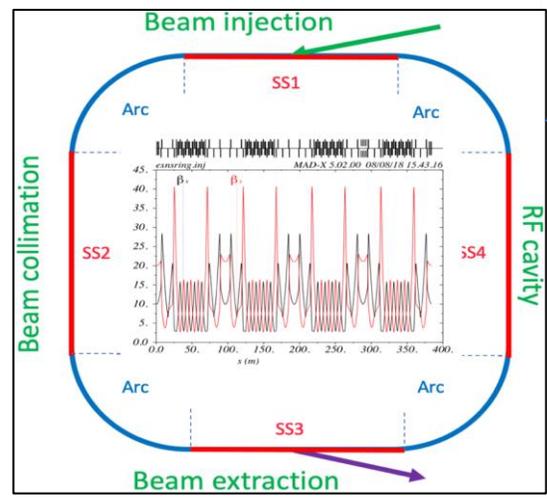
$$\pi^{+(-)} \rightarrow \mu^{+(-)} + \bar{\nu}_{\mu}(\nu_{\mu})$$



LEnuSTORM Far Detector

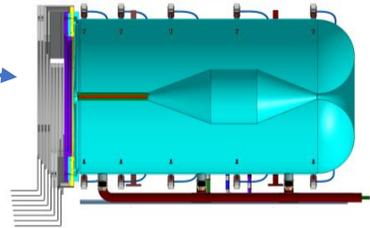


Accumulator Ring

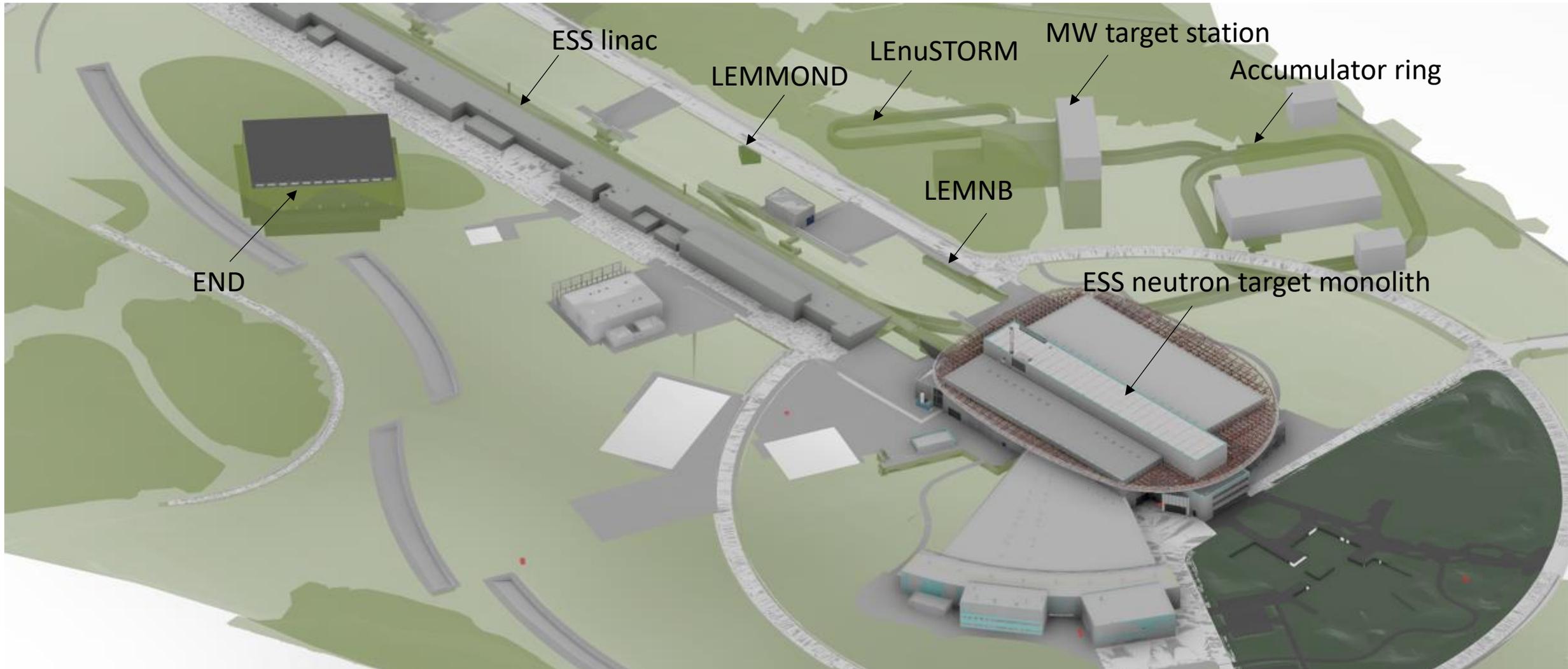


$$\mu^{+(-)} \rightarrow e^{+(-)} + \nu_{\mu}(\bar{\nu}_{\mu}) + \bar{\nu}_{e}(\nu_{e})$$

One horn-target system

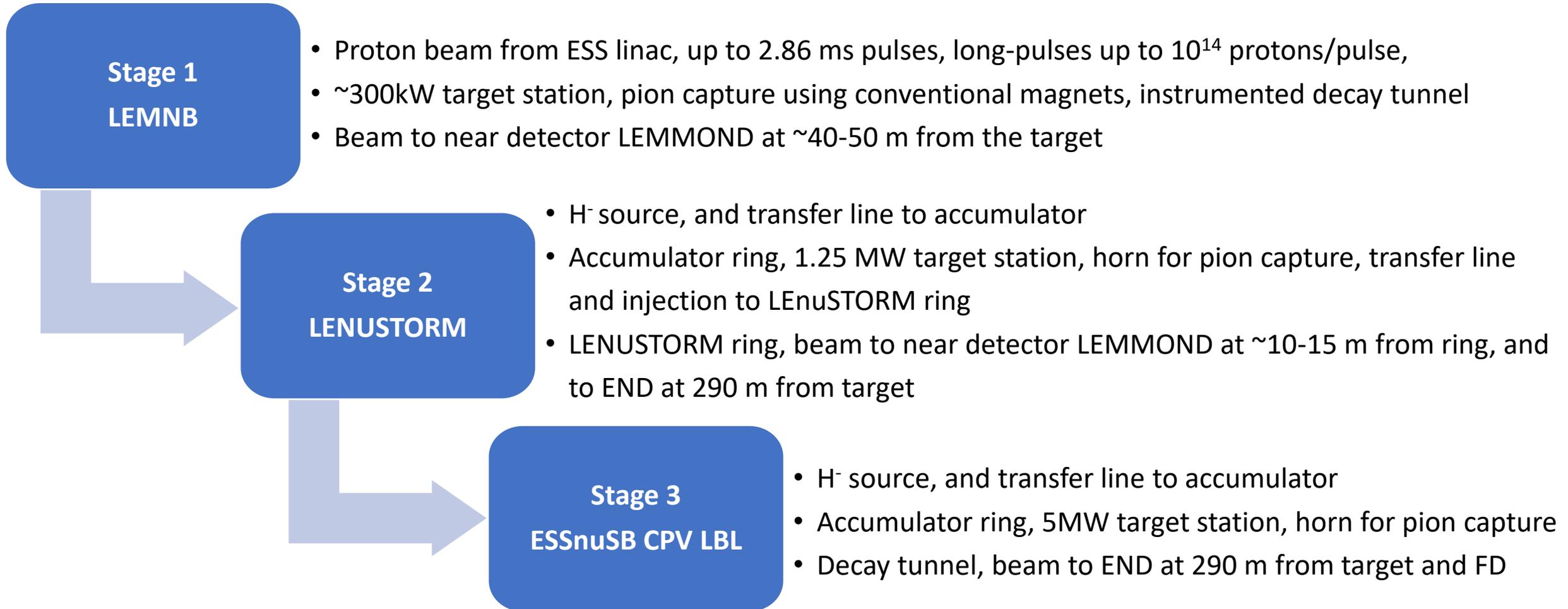


ESS Upgrades to Host the **ESSnuSB+**

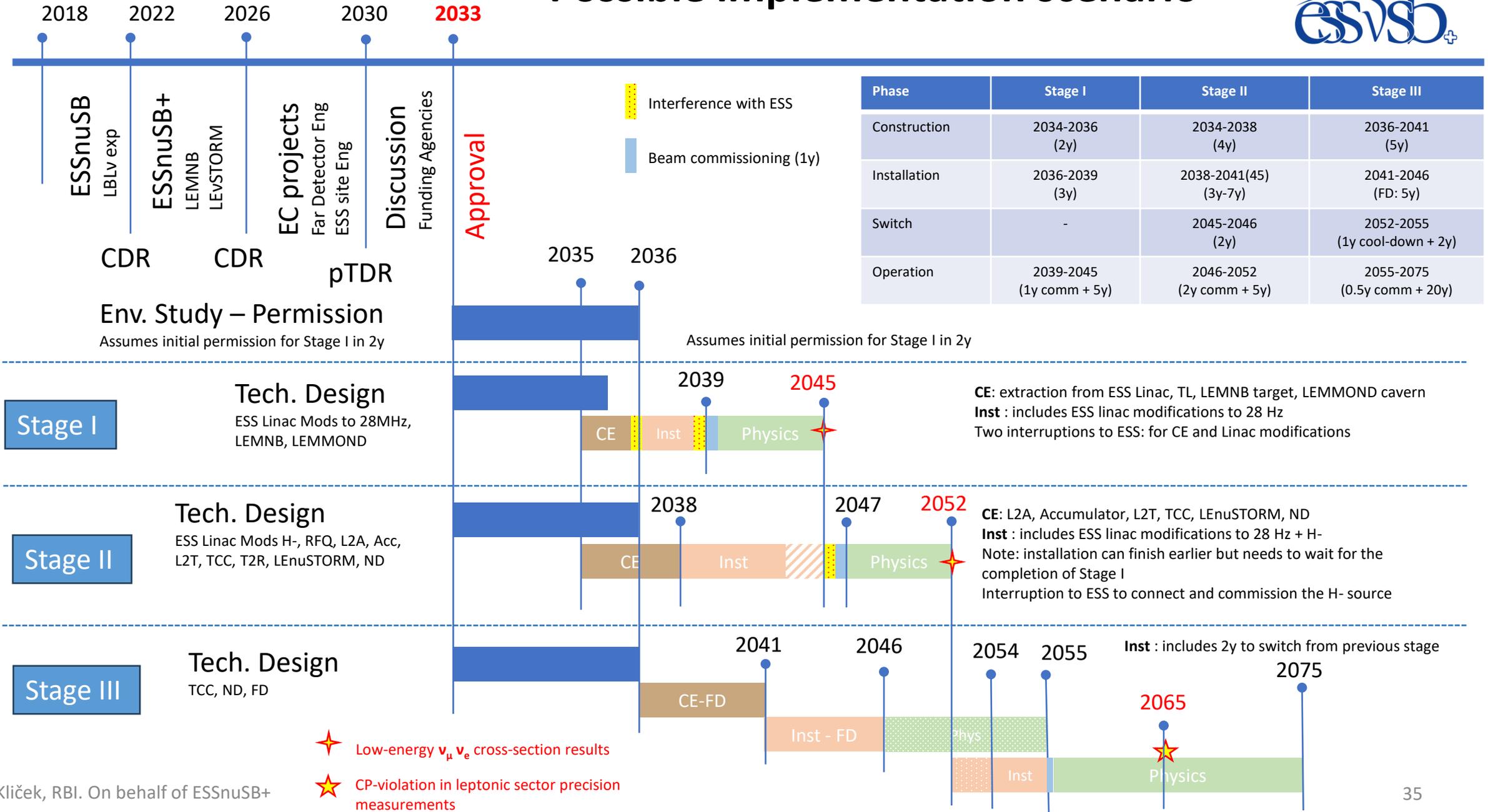


ESSnuSB Implementation Approach

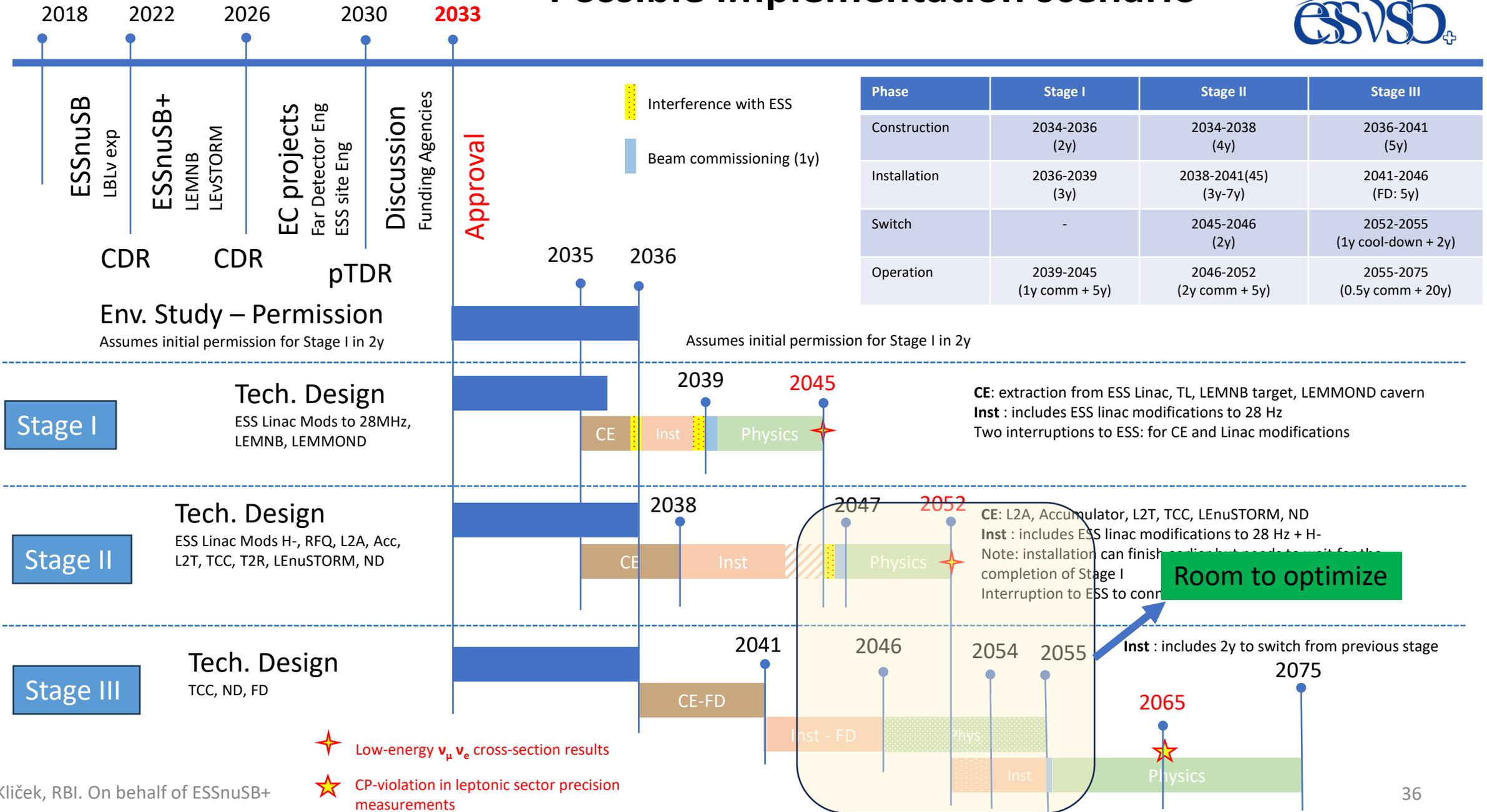
Staged Implementation



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





Conclusions

- **ESSnuSB** aims to precisely measure CP amplitude by observing neutrino oscillations at the 2nd oscillation maximum
 - **2nd maximum** makes the measurement resilient to systematic errors and matter effects
 - We predict that in 10 years of data taking ESSnuSB will be able to
 - reach 5 σ over 71% of δ_{CP} range
 - reach δ_{CP} resolution of less than 8°
 - determine neutrino mass hierarchy
 - Construction could commence in the 2030's (next-to-next generation experiment)
- **ESS linac** will be most powerful proton accelerator in the world
 - can be used to generate a neutrino beam intense enough to go to 2nd maximum
 - neutron user programme will start in 2026, decision on neutrino programme pending
- **Large far detectors** can also be used for rich astroparticle physics programme
- **The ESSnuSB Design Study** has been supported by EU-Horizon 2020 during the period 2018-2022.
- **The ESSnuSB+ project** is supported by EU-Horizon Europe for the period 2023-2026



Collaboration annual meeting – Hamburg 2024



Kliček, R. B. on behalf of ESSnuSB+

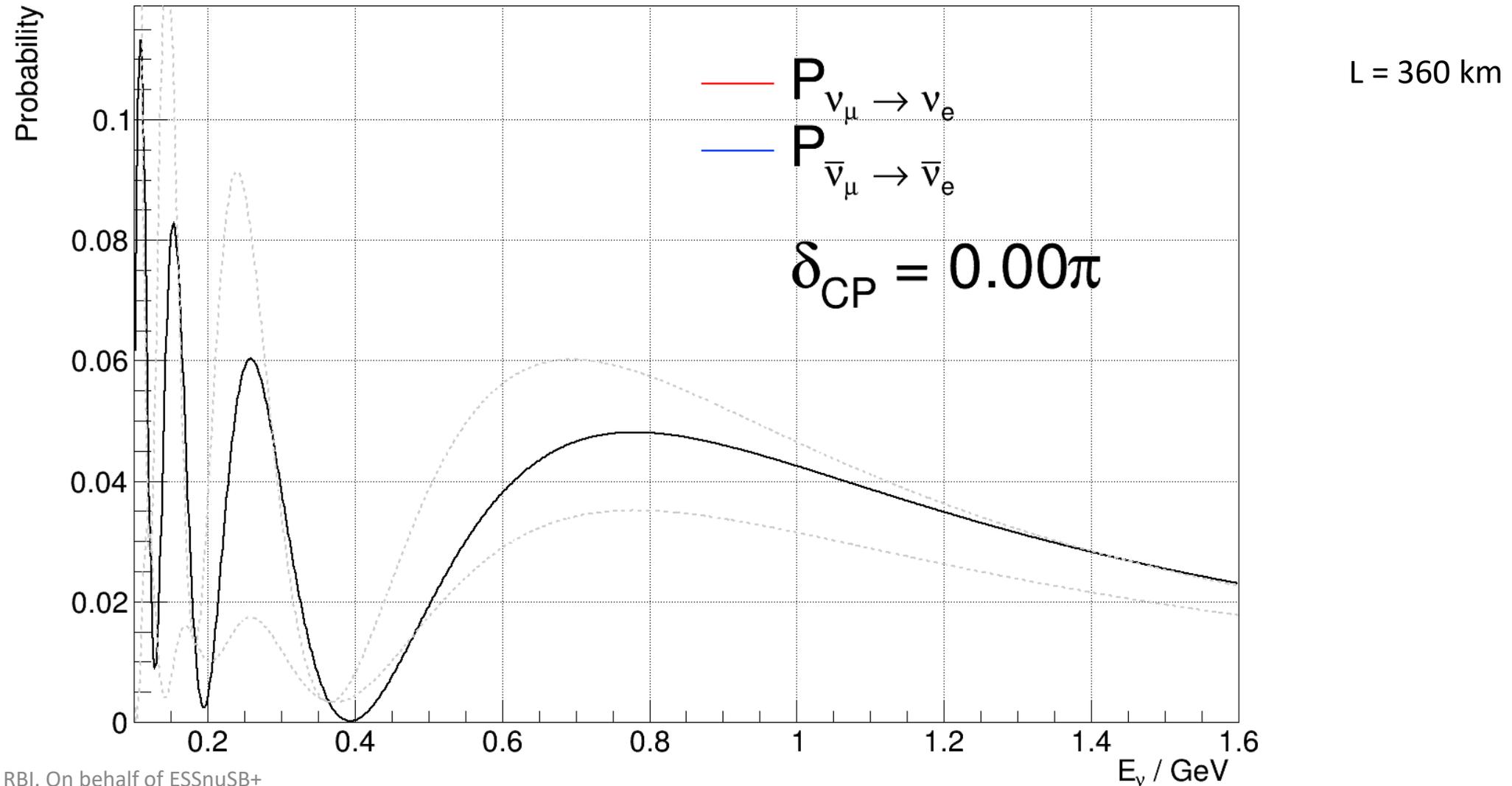


Co-funded by
the European Union



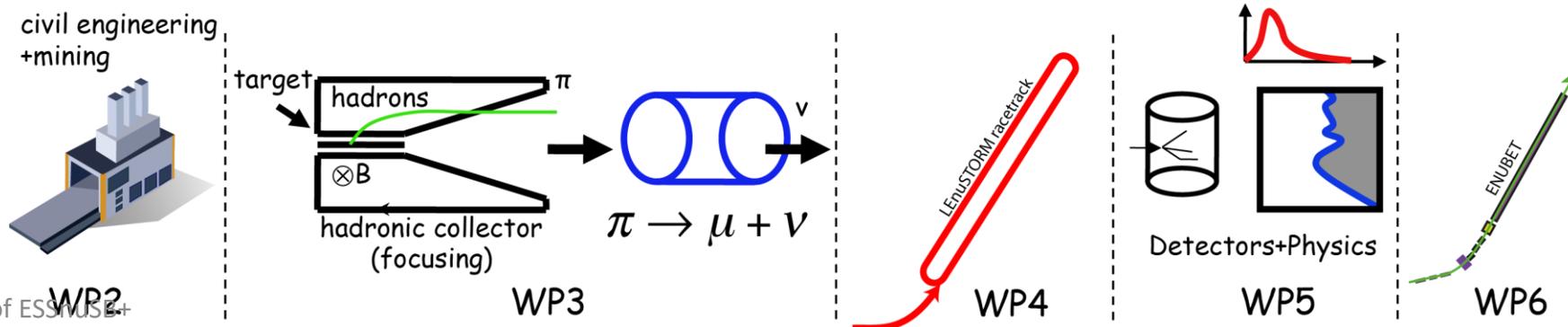
Thank you for your attention

Effect of δ_{CP} on oscillations in vacuum



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**



Why 2nd maximum?

(summary)

The good

Vacuum CPV signal 2.7 times larger than at 1st max.

Fake CPV signal from matter effects very small.

The bad

You **in principle** get less statistics because you have to either:

- Move 3x further than 1st maximum - flux 9x smaller
- Reduce energy 3x – cross-section at least 3x smaller

The optimal

- **Depends on the systematic error and beam intensity**

- 3x signal at 2nd osc. maximum is less obscured by systematics, but we **probably** have less statistics (measured appearance events).
 - If the signal at 2nd maximum is not obscured by larger statistical error, then 2nd maximum is better - **Intense beam is needed**
- With no systematic error, first maximum is at least slightly better
 - more statistics, even though the CPV effect is smaller.

Neutrino beam production

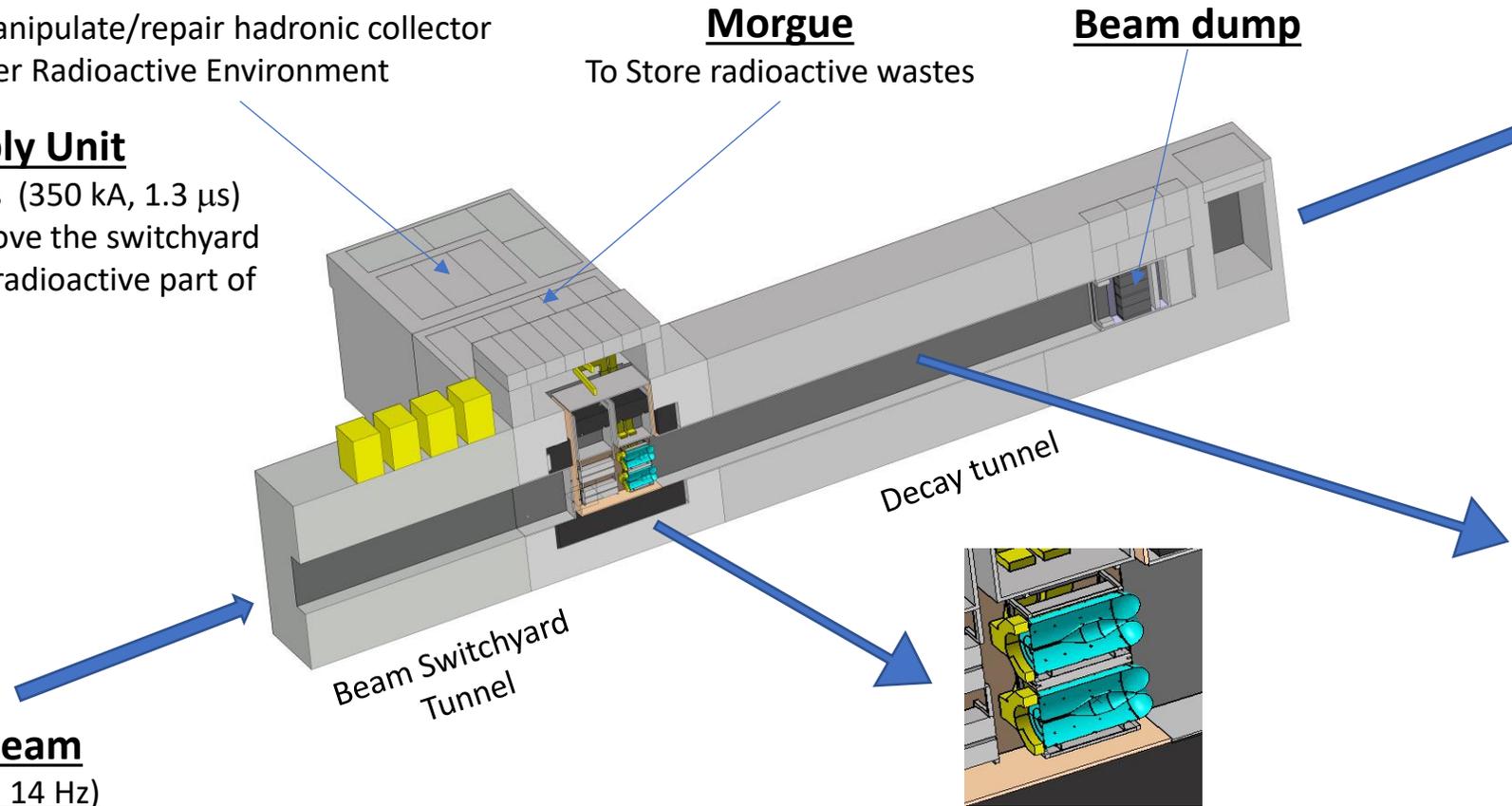


Hot Cell

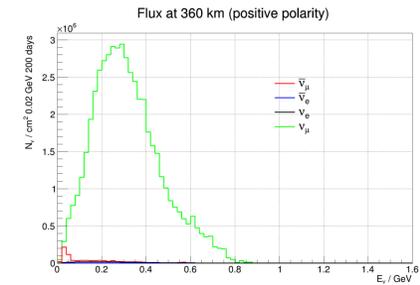
- Able to manipulate/repair hadronic collector
- Work under Radioactive Environment

Power Supply Unit

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



Neutrino Beam



Pions decay in-flight here

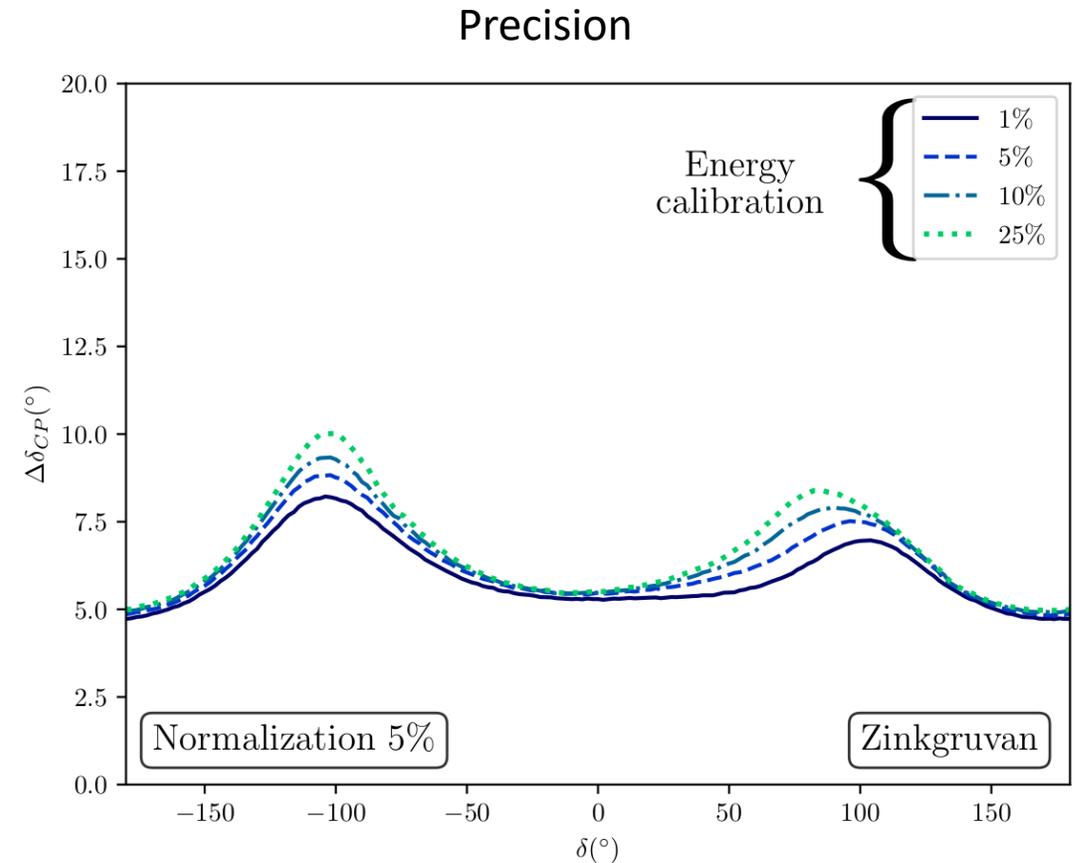
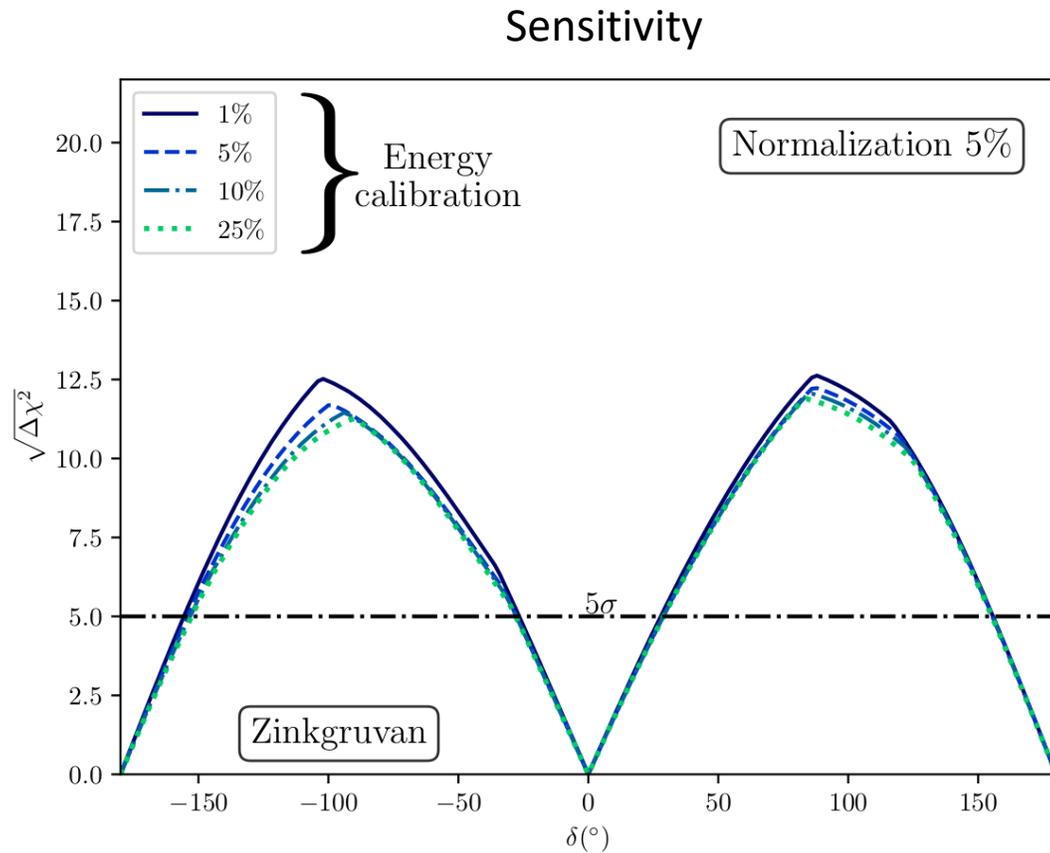
Proton Beam

($E_p=2.5$ GeV, 14 Hz)

4 x 1.25 MW

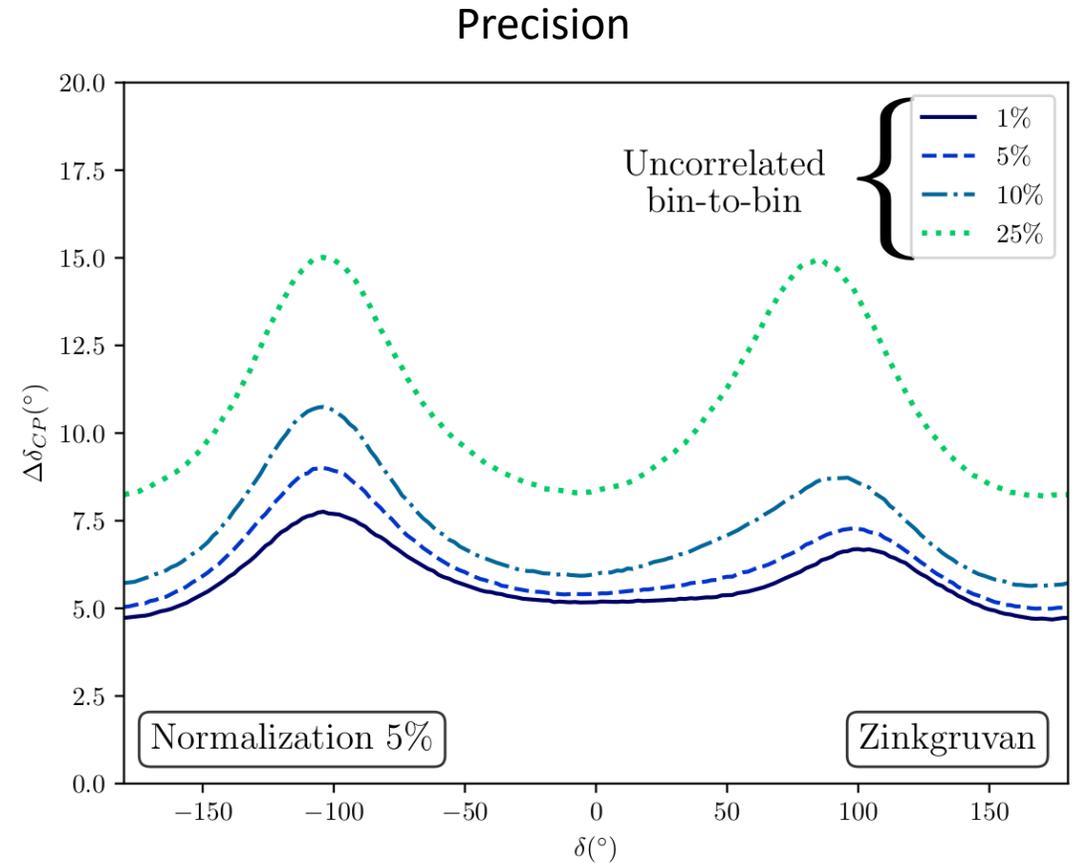
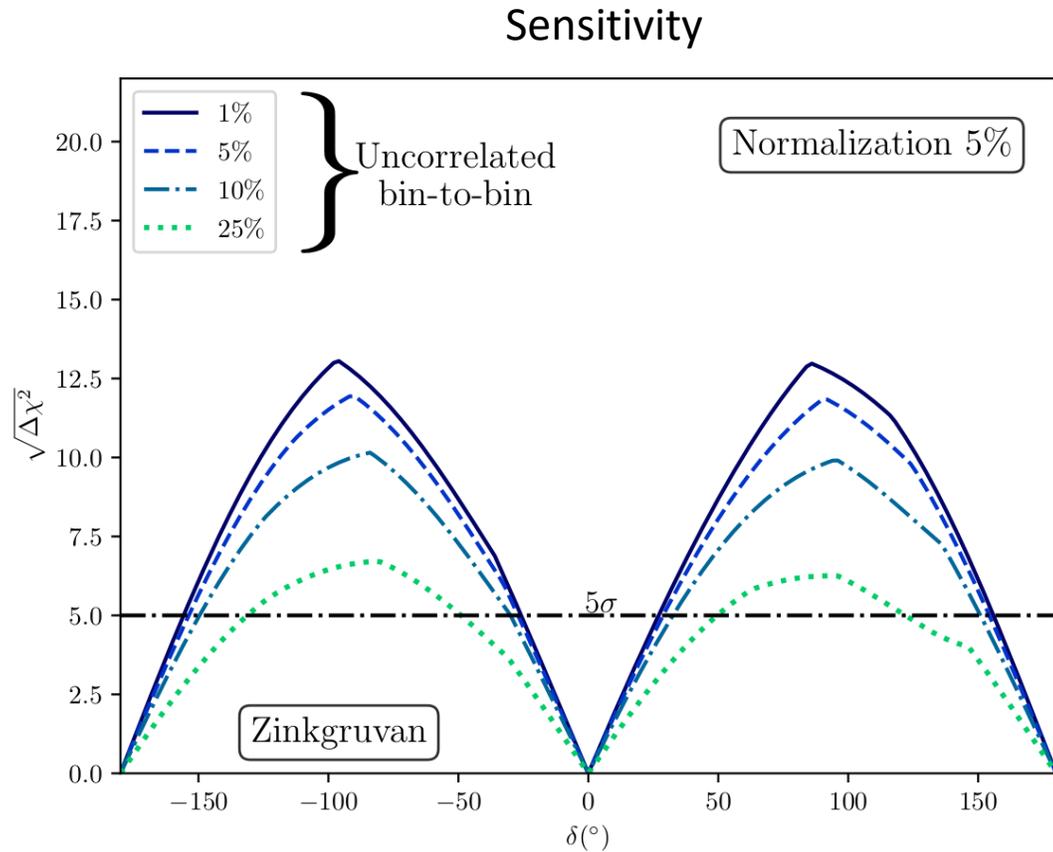
Hadronic Collector

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

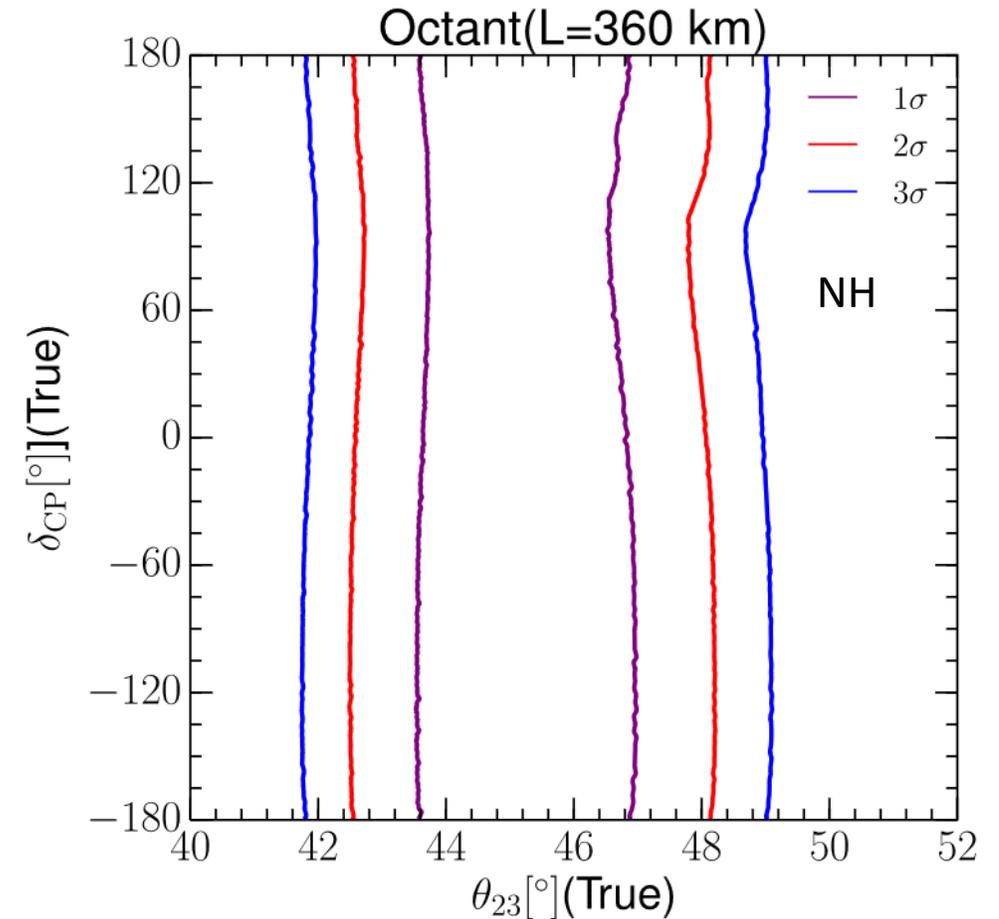
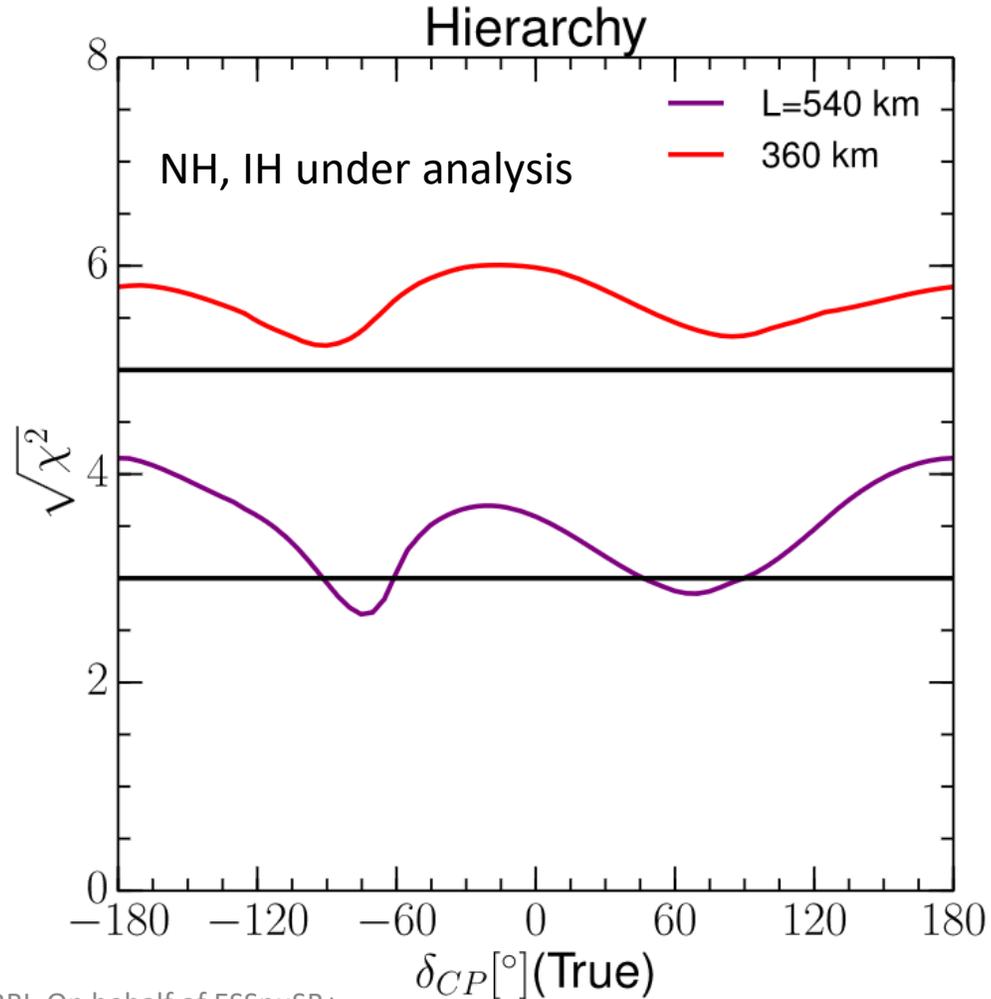


From the ESSnuSB CDR: <https://doi.org/10.1140/epjs/s11734-022-00664-w> & <https://arxiv.org/abs/2203.08803>

Hierarchy and octant determination

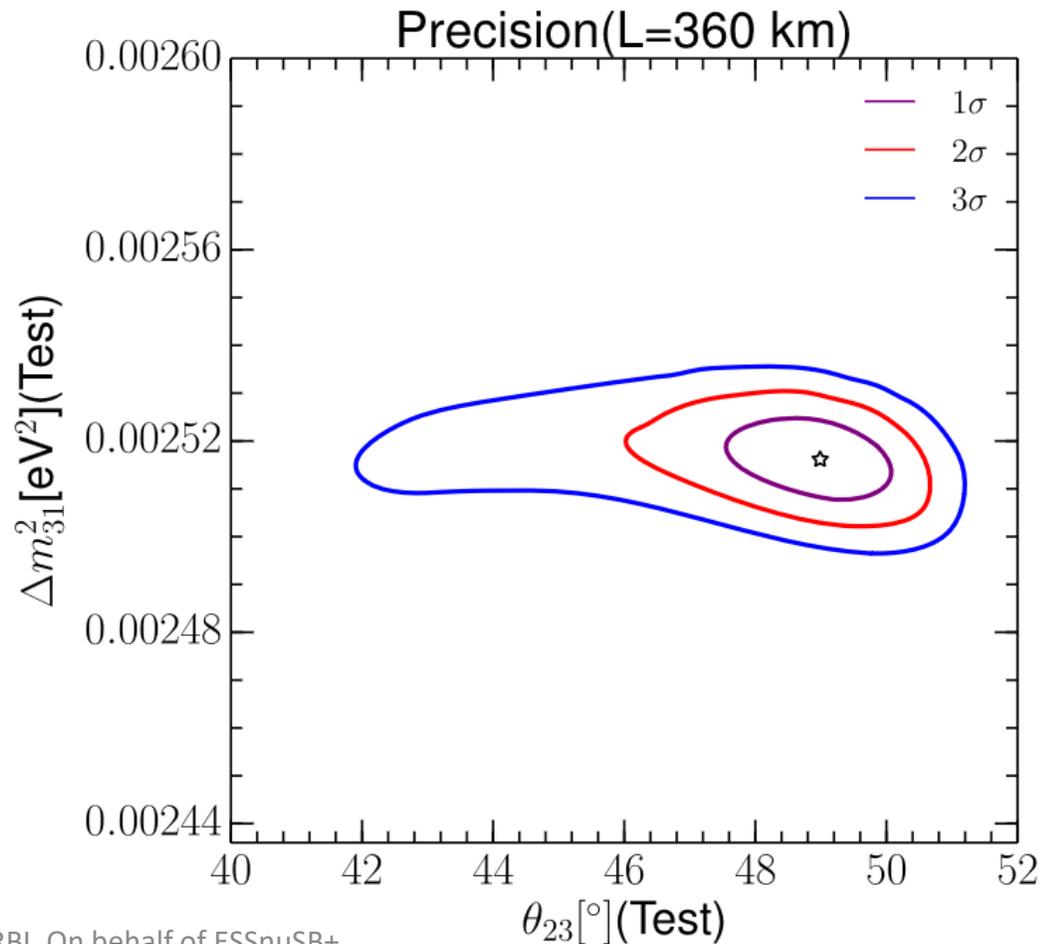
From: [DOI:10.1140/epjc/s10052-021-09845-8](https://doi.org/10.1140/epjc/s10052-021-09845-8), [arXiv:2107.07585](https://arxiv.org/abs/2107.07585)

10 y of data taking



Precision for Δm_{31} vs θ_{23}

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)

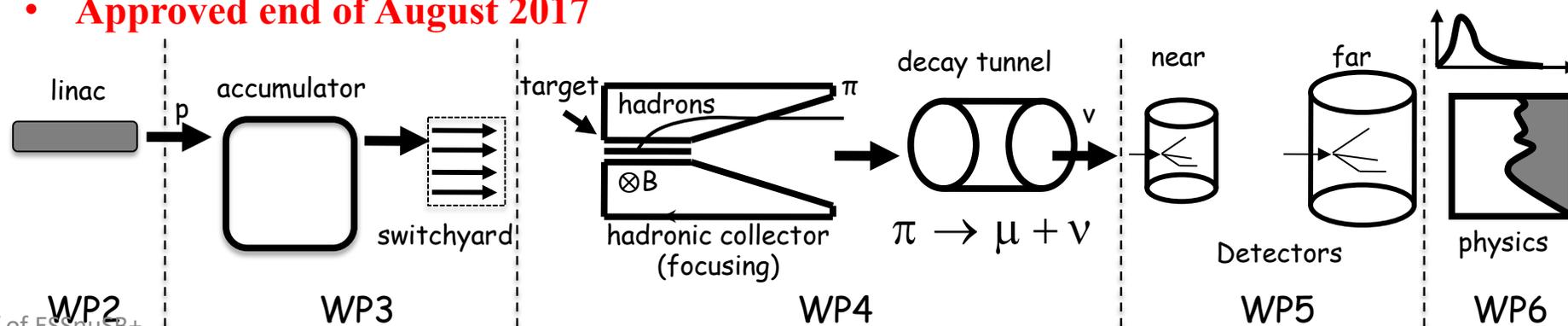
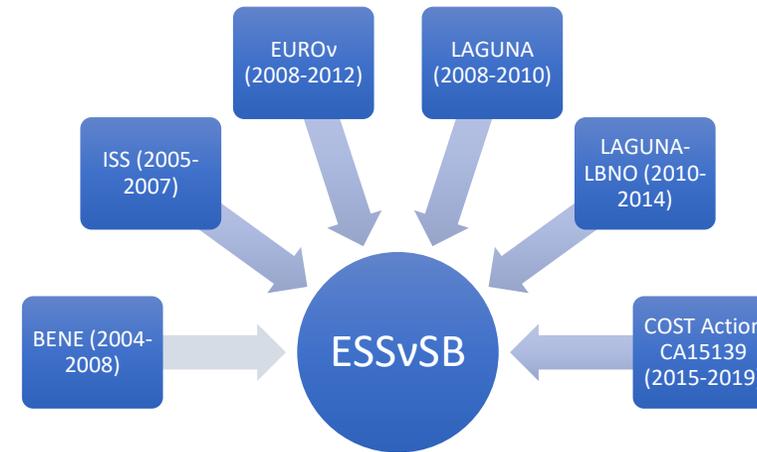


- Plot ranges are approximately current limit on parameters

ESSvSB at the European level

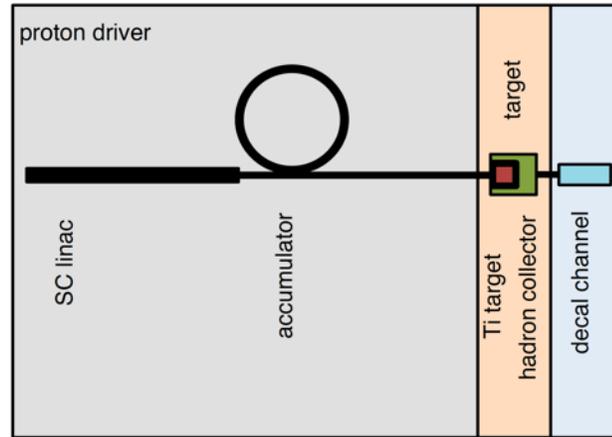


- A **H2020 EU Design Study** (Call INFRADEV-01-2017)
 - **Title of Proposal:** Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator
 - **Duration:** 4 years
 - **Total cost:** 4.7 M€
 - **Requested budget:** 3 M€
 - **15 participating institutes from 11 European countries including CERN and ESS**
 - 6 Work Packages
 - **Approved end of August 2017**



ESSvSB and (R&D) synergies

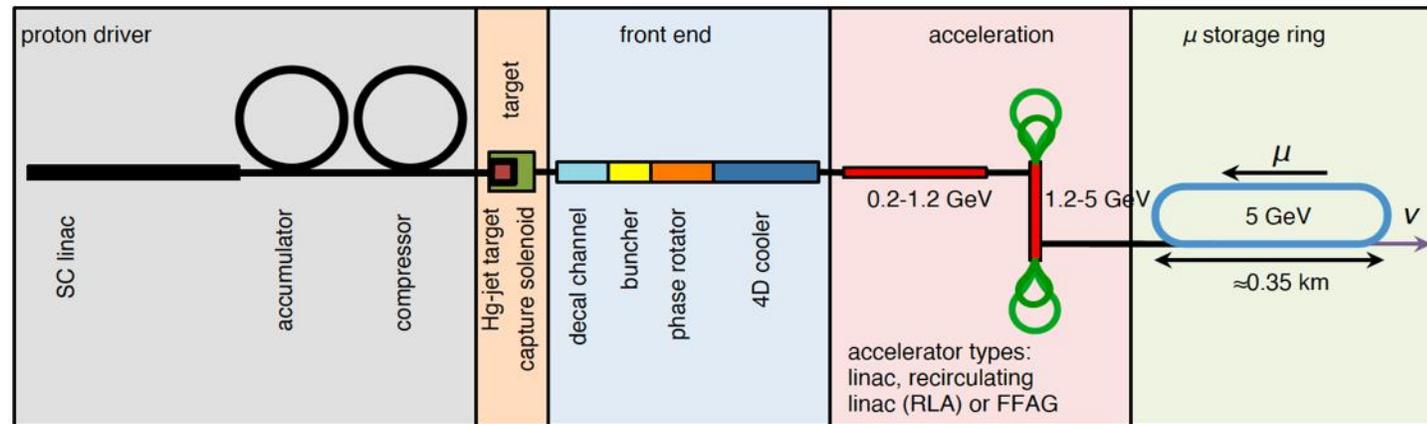
Super Beam



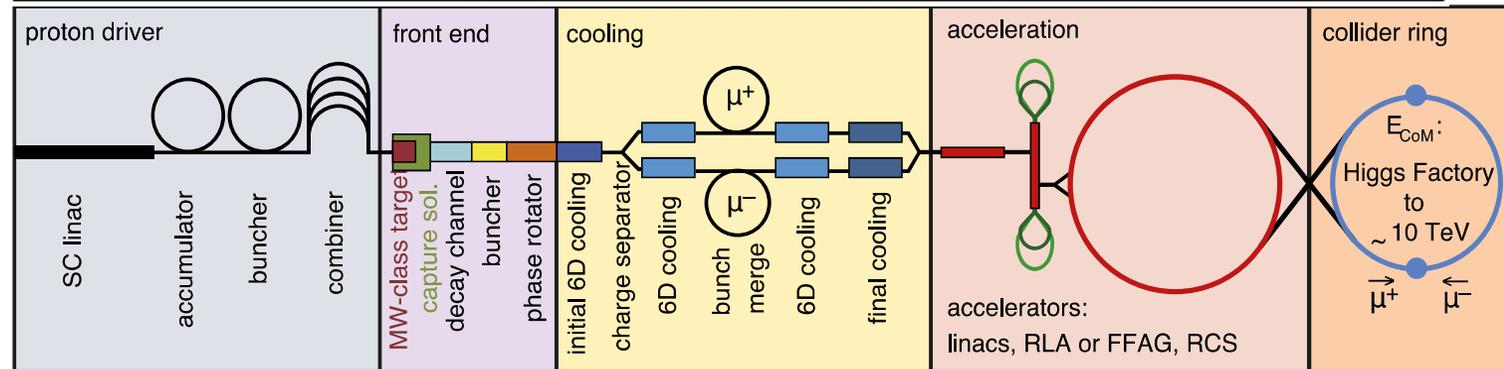
Dedicated series of workshops is organized
<https://indico.cern.ch/event/849674/>

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

Neutrino Factory



Muon Collider



Neutrino oscillations

Flavour state evolution

Relativistic space-time translation operator

$$\left| \nu_\alpha; t = T, \vec{x} = \vec{L} \right\rangle = e^{-i(\mathbf{E}T - \vec{\mathbf{p}}\vec{L})} \left| \nu_\alpha; t = 0, \vec{x} = \vec{0} \right\rangle$$

Neutrino quantum state at distance L and after time T

Neutrino quantum state at creation

Free particle energy operator

Free particle momentum operator

For mass eigenstates:

$$e^{-i(\mathbf{E}T - \vec{\mathbf{p}}\vec{L})} \left| \nu_i \right\rangle = e^{-i(E_i T - \vec{p}_i \vec{L})} \left| \nu_i \right\rangle$$

And finally:

$$\left| \nu_\alpha; t = T, \vec{x} = \vec{L} \right\rangle = e^{-i(E_i T - \vec{p}_i \vec{L})} U_{\alpha i}^* \left| \nu_i \right\rangle$$

Neutrino oscillations

Oscillation probability in vacuum

Oscillation probability:

$$P_{\alpha \rightarrow \beta} = \left| \left\langle \nu_{\beta} \left| \nu_{\alpha}; t = T, \vec{x} = \vec{L} \right. \right\rangle \right|^2$$

Assuming:

$$\left. \begin{array}{l} \vec{L} \text{ parallel to } \vec{p}_i \\ T = L/\beta \approx L \\ E_i + p_i \approx 2E \end{array} \right\} E \gg m_i \quad \text{- neutrino travels in the direction of its momentum}$$

One gets the final relation:

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

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

$$P_{\alpha \rightarrow \beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re} \left(A_{ij}^{\alpha\beta} \right) \sin^2 \frac{\Delta m_{ij}^2 L}{4E} \pm 2 \sum_{i>j} \text{Im} \left(A_{ij}^{\alpha\beta} \right) \sin \frac{\Delta m_{ij}^2 L}{2E}$$

PMNS matrix parametrization (Dirac neutrino)

Standard parametrization used in modern literature:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

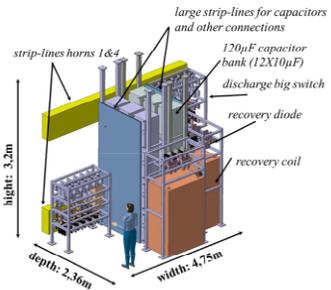
- Analogue to Euler matrices used for 3D rotations
- This is **not** the most general unitary matrix parametrization – a 3x3 unitary matrix has 6 phases
 - 5 phases can be canceled by rephasing charged lepton and neutrino fields
- A single leftover phase is always present in the middle factor

Hot Cell

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

Power Supply Unit

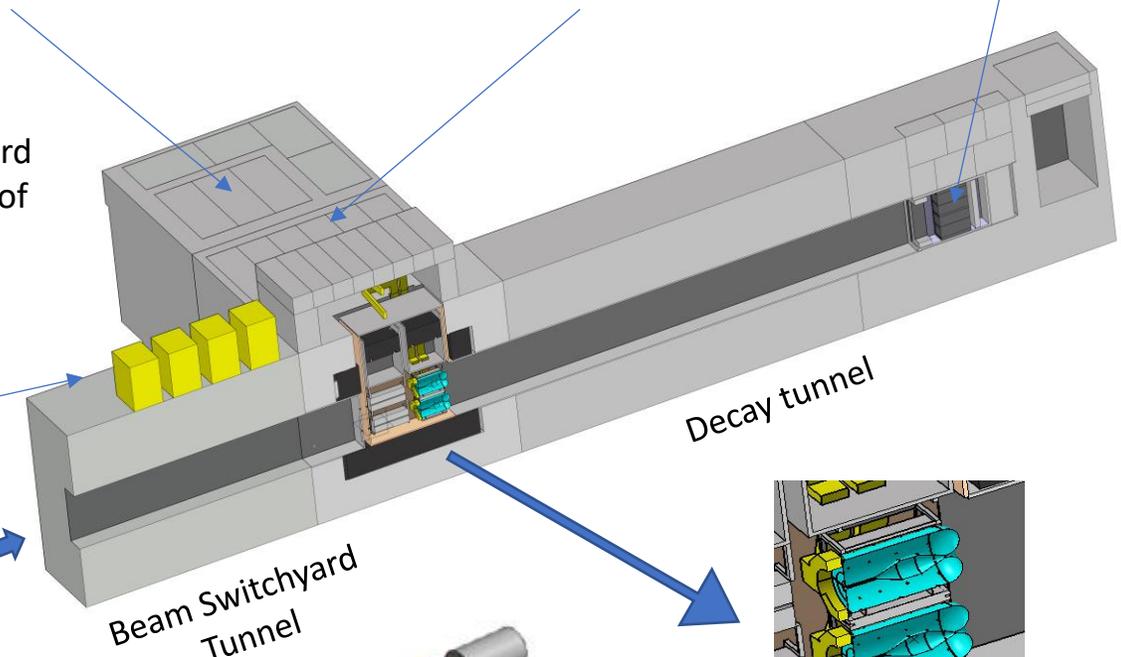
- 16 modules (350 kA)
- Located above the switchyard
- Outside of radioactive part of Facility



Morgue

To Store radioactive wastes

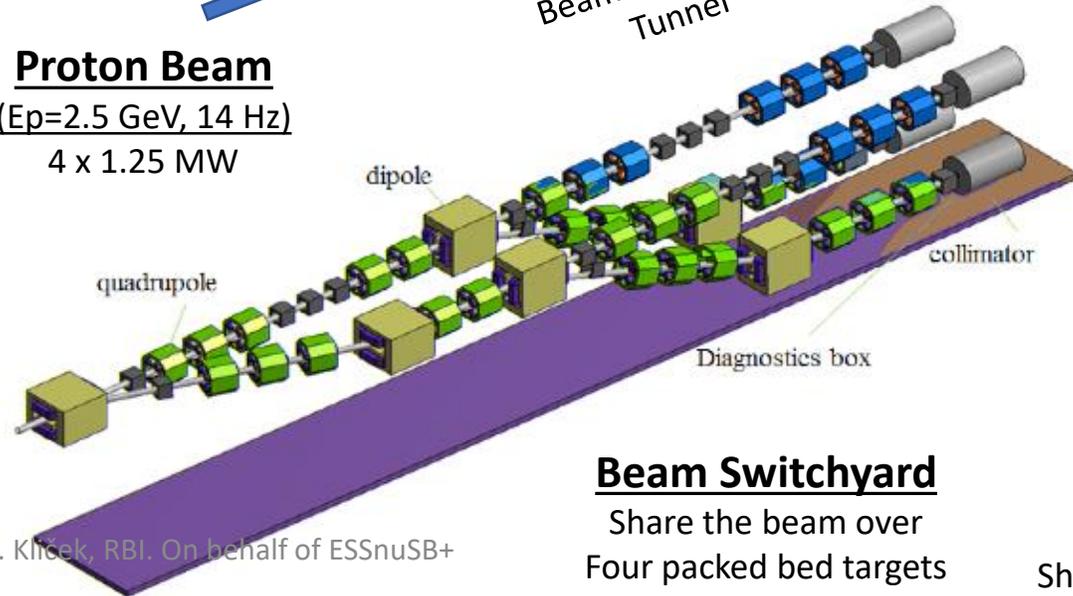
Beam dump



Proton Beam

($E_p=2.5$ GeV, 14 Hz)

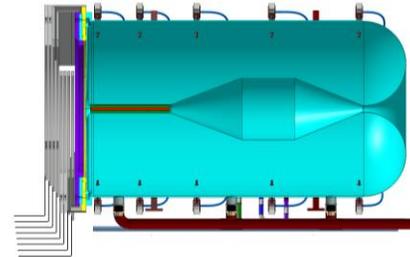
4 x 1.25 MW



Beam Switchyard

Share the beam over Four packed bed targets

Hadronic Collector

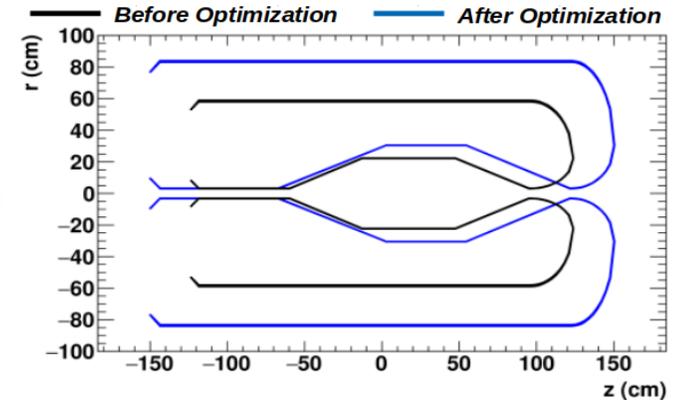
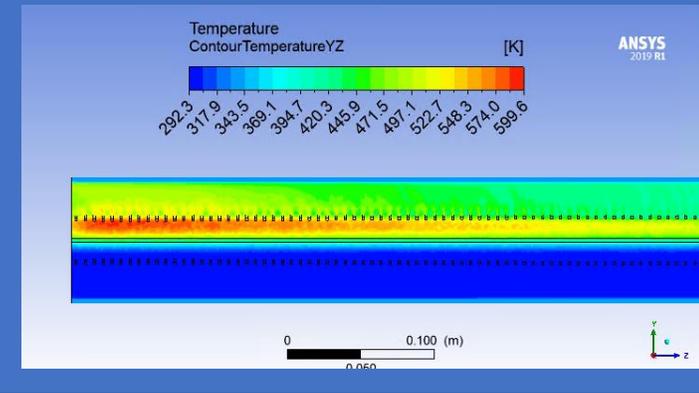
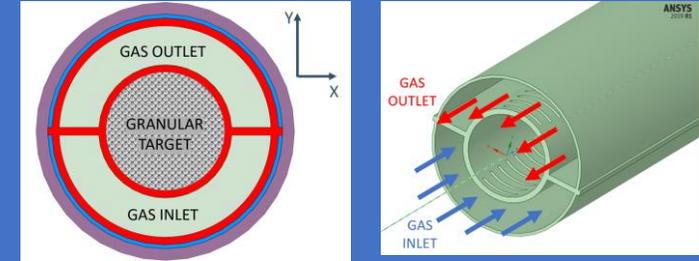


MiniBoone Like Horn

Shape optimized with genetic algorithm

Granular Target Concept

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

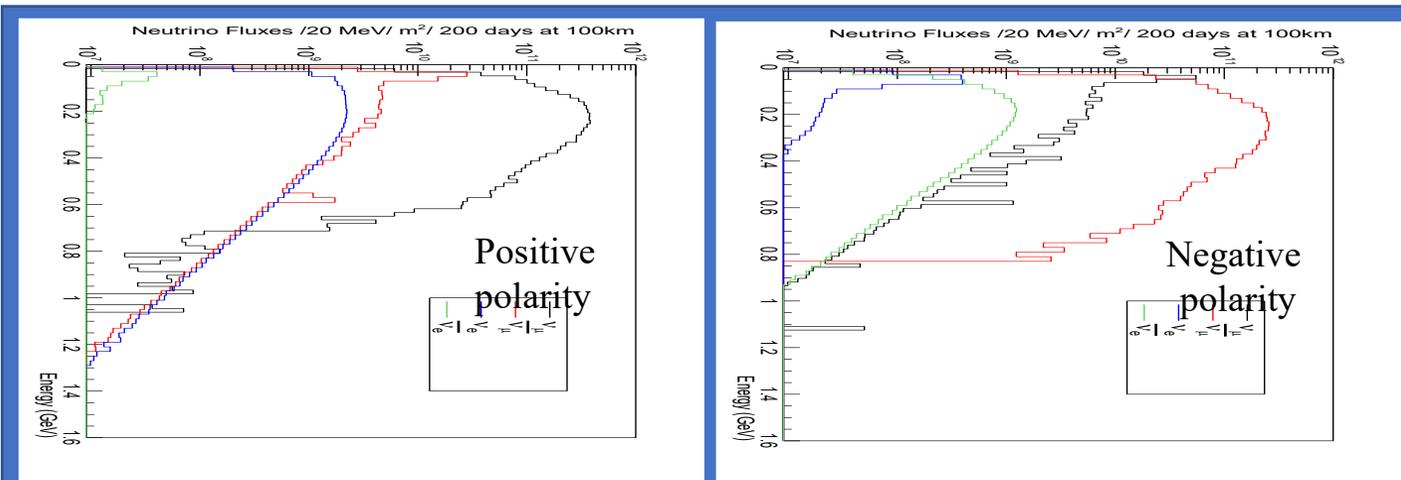
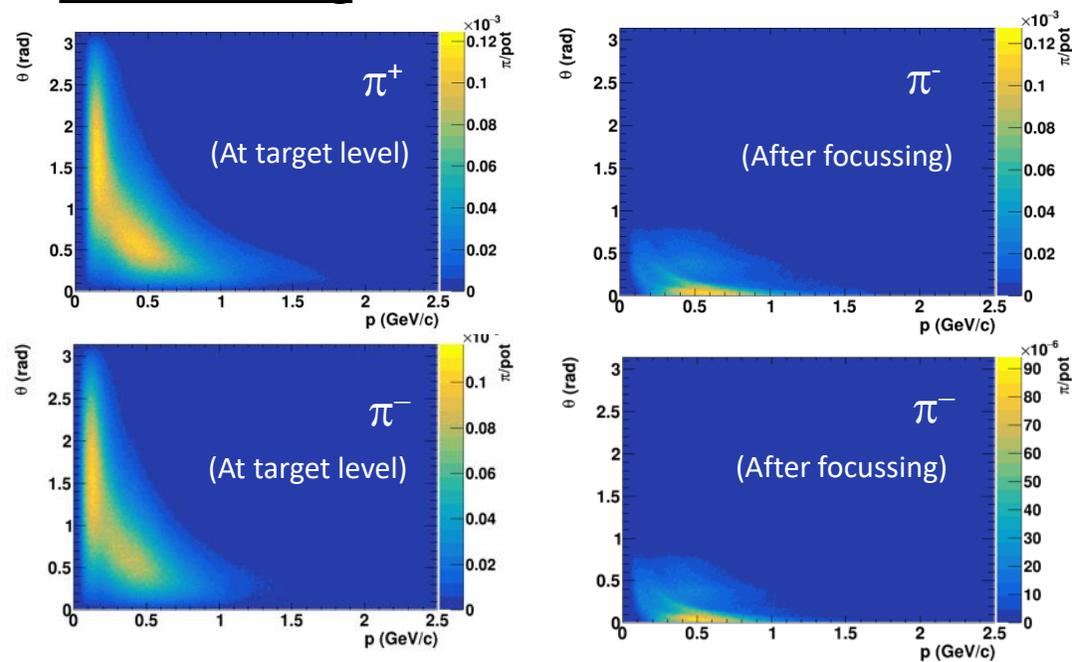


Neutrino beam production

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad (\text{Positive polarity})$$

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

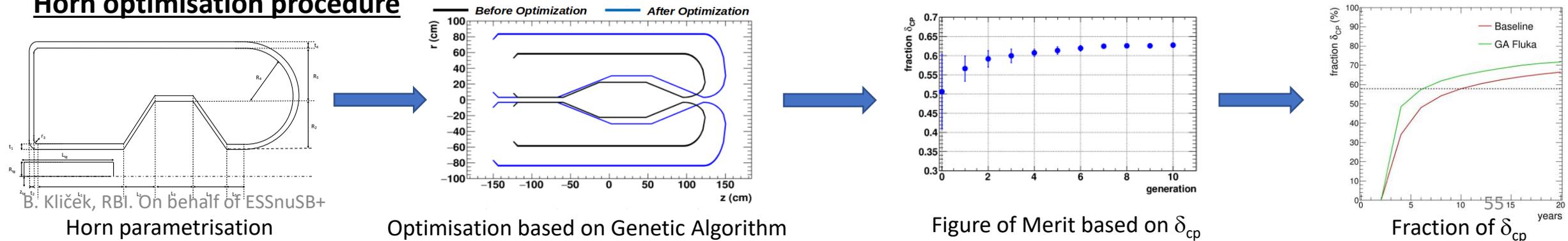
Horn focussing



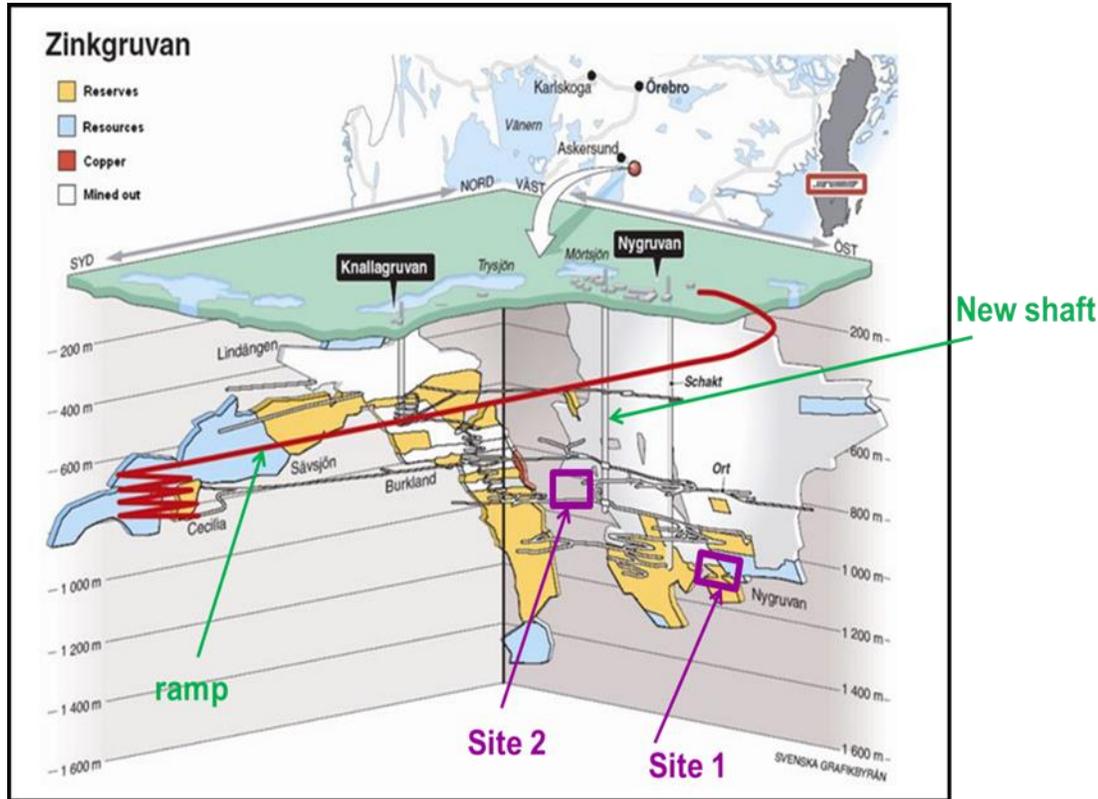
Neutrino flux composition.

	ϕ_ν $10^{10} \cdot \text{m}^{-2}$	%	ϕ_ν $10^{10} \cdot \text{m}^{-2}$	%
ν_μ	674	97.6	20	4.7
$\bar{\nu}_\mu$	11.8	1.7	396	94.8
ν_e	4.76	0.67	0.13	0.03
$\bar{\nu}_e$	0.03	0.03	1.85	0.43

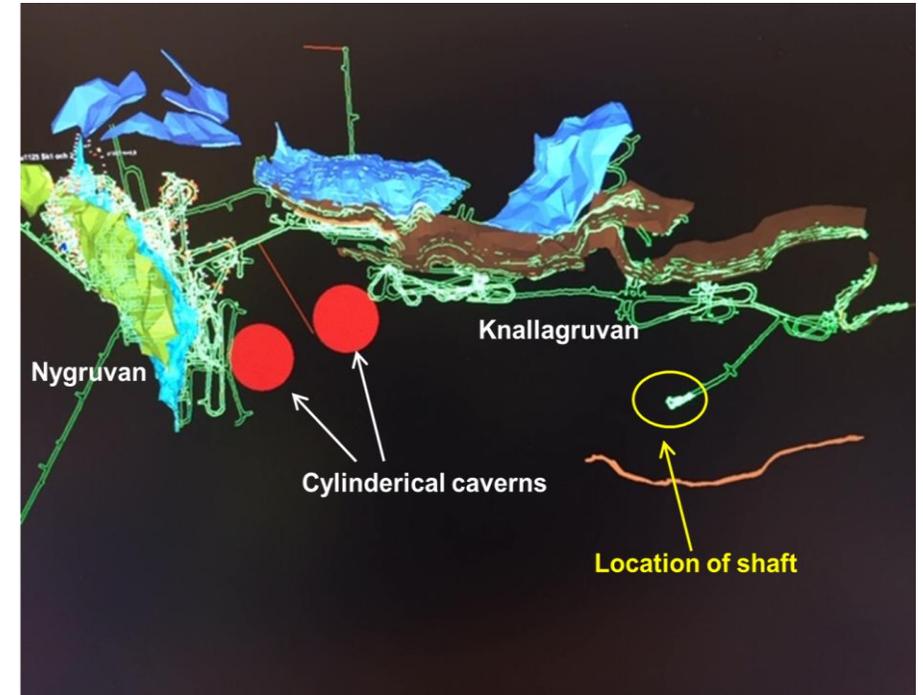
Horn optimisation procedure



Zinkgruvan mine

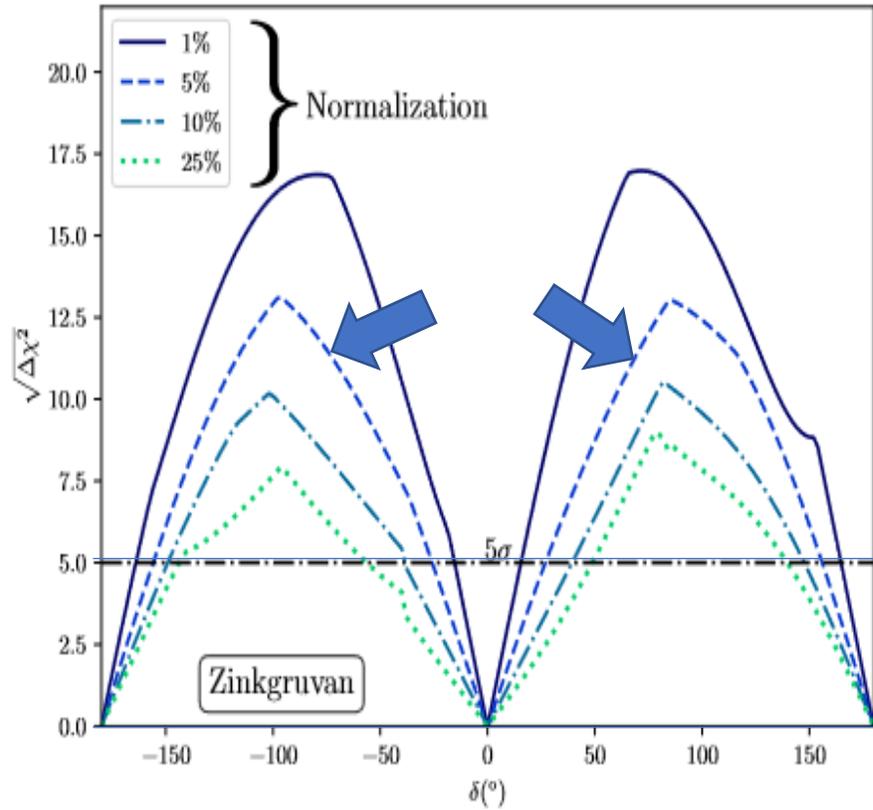


Potential location in Site 2

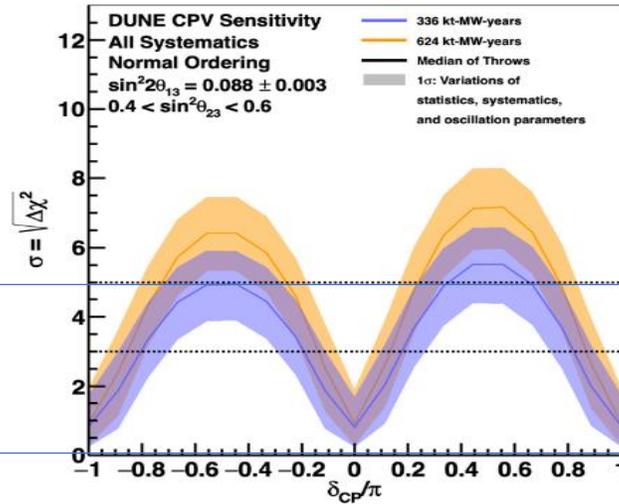


Site 2 is considered as best considering access to main transport infrastructure and located in an area less disturbed by mining activities

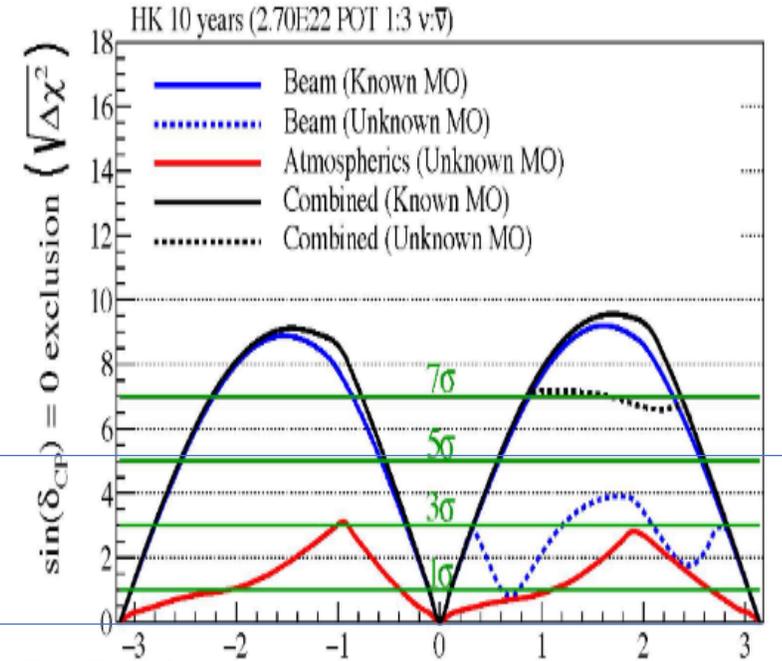
ESSnuSB in the international context – CPV discovery



ESSnuSB March 2022 with 5% normalization error

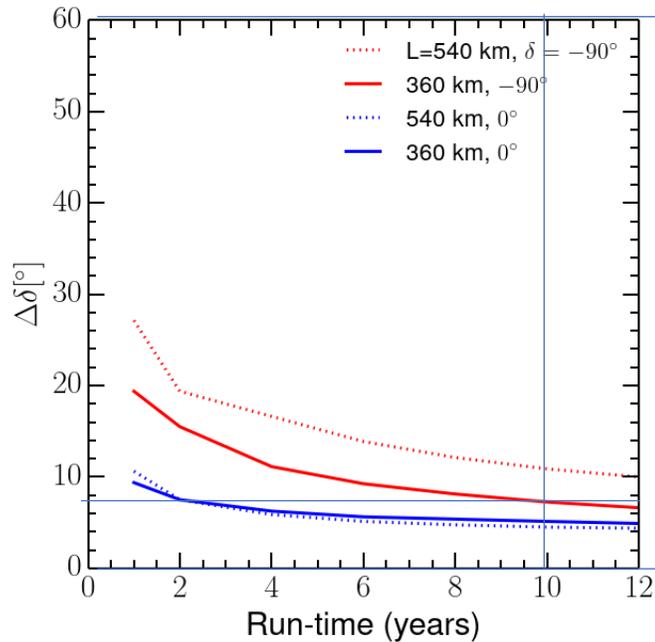


DUNE Snowmass March 2022



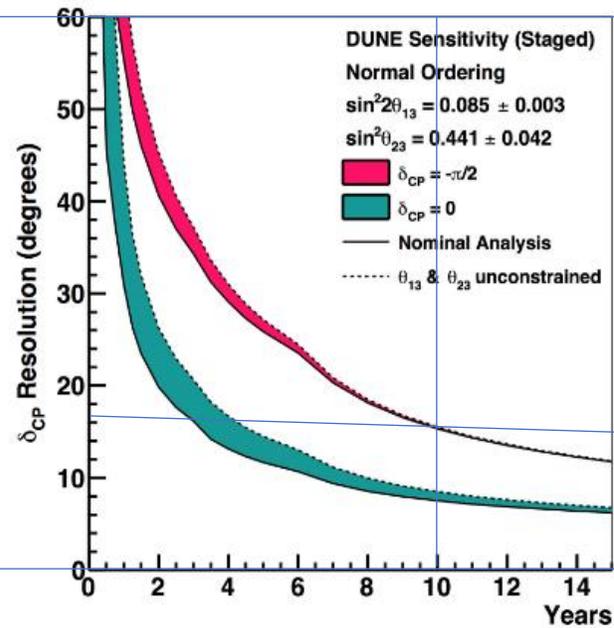
Hyper-Kamiokande Snowmass March 2022

ESSnuSB in the international context – CPV resolution

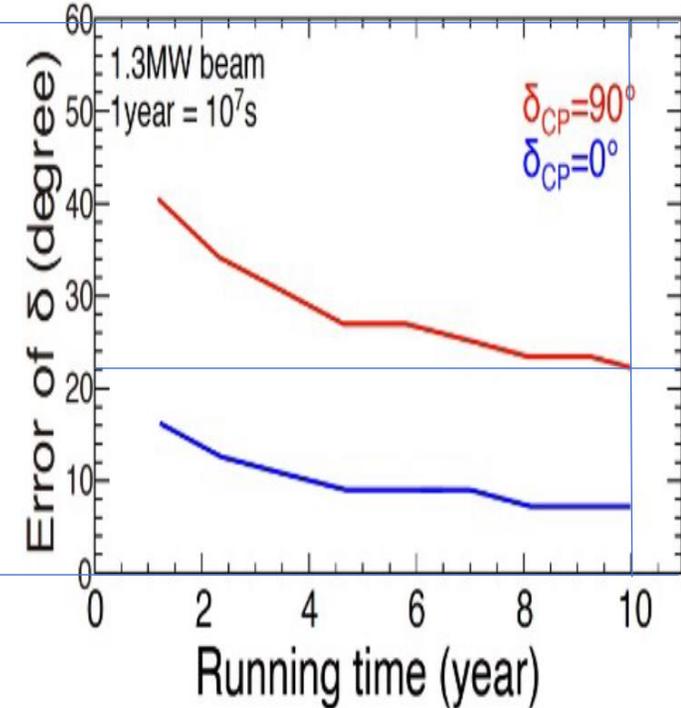


ESSnuSB March 2022 with 5%

normalization error



DUNE Snowmass March 2022



Hyper-Kamiokande Snowmass March 2022

Table 5.5: The number of expected μ^{ID} events per running year, per level of the analysis, per flavour and interaction type, and per each horn polarity.

Positive polarity								
	ν_{μ} CC μ^{ID}	ν_e CC μ^{ID}	$\bar{\nu}_{\mu}$ CC μ^{ID}	$\bar{\nu}_e$ CC μ^{ID}	ν_{μ} NC μ^{ID}	ν_e NC μ^{ID}	$\bar{\nu}_{\mu}$ NC μ^{ID}	$\bar{\nu}_e$ NC μ^{ID}
All interactions	5.19×10^7	2.88×10^4	1.43×10^5	19.7	2.29×10^7	1.44×10^5	8.44×10^4	159
Trigger	5.13×10^7	2.71×10^4	1.42×10^5	18.1	1.98×10^6	1.36×10^4	6150	10.2
Sub-Cherenkov criterion	3.10×10^7	2.00×10^4	1.06×10^5	12.6	5.40×10^4	678	179	0.2
Reconstruction quality criteria	2.59×10^7	1.43×10^4	9.29×10^4	8.7	2.69×10^4	407	111	0.1
Cherenkov-ring resolution criterion	2.12×10^7	1.03×10^4	7.69×10^4	6.3	2.11×10^4	327	93.6	0.1
Pion-like criteria	2.12×10^7	1.03×10^4	7.69×10^4	6.3	2.11×10^4	327	93.6	0.1
Multi-subevent criterion	2.10×10^7	1.03×10^4	7.69×10^4	6.3	2.11×10^4	326	93.4	0.1
Negative polarity								
	ν_{μ} CC μ^{ID}	ν_e CC μ^{ID}	$\bar{\nu}_{\mu}$ CC μ^{ID}	$\bar{\nu}_e$ CC μ^{ID}	ν_{μ} NC μ^{ID}	ν_e NC μ^{ID}	$\bar{\nu}_{\mu}$ NC μ^{ID}	$\bar{\nu}_e$ NC μ^{ID}
All interactions	5.17×10^5	179	8.36×10^6	2610	2.62×10^5	983	5.05×10^6	2.08×10^4
Trigger	5.10×10^5	168	8.31×10^6	2400	2.20×10^4	86.9	3.46×10^5	1410
Sub-Cherenkov criterion	3.12×10^5	125	5.55×10^6	1690	799	4.9	5490	33.4
Reconstruction quality criteria	2.65×10^5	89.0	4.71×10^6	1170	456	3.1	3050	15.7
Cherenkov-ring resolution criterion	2.17×10^5	65.5	3.87×10^6	806	372	2.5	2720	12.8
Pion-like criteria	2.17×10^5	65.5	3.87×10^6	806	372	2.5	2720	12.8
Multi-subevent criterion	2.13×10^5	65.5	3.86×10^6	806	371	2.5	2720	12.8

Table 5.4: The number of expected e^{ID} events per running year, per level of the analysis, per flavour and interaction type, and per each horn polarity.

Positive polarity								
	$\nu_\mu \text{ CC } e^{\text{ID}}$	$\nu_e \text{ CC } e^{\text{ID}}$	$\bar{\nu}_\mu \text{ CC } e^{\text{ID}}$	$\bar{\nu}_e \text{ CC } e^{\text{ID}}$	$\nu_\mu \text{ NC } e^{\text{ID}}$	$\nu_e \text{ NC } e^{\text{ID}}$	$\bar{\nu}_\mu \text{ NC } e^{\text{ID}}$	$\bar{\nu}_e \text{ NC } e^{\text{ID}}$
All interactions	1.50×10^7	5.33×10^5	4.28×10^4	382	2.44×10^7	1.65×10^5	7.87×10^4	142
Trigger	1.50×10^7	5.33×10^5	4.28×10^4	382	2.44×10^7	1.65×10^5	7.87×10^4	142
Sub-Cherenkov criterion	2.57×10^6	5.14×10^5	1.00×10^4	359	8.93×10^5	8570	3060	3.7
Reconstruction quality criteria	2.11×10^6	4.69×10^5	8380	327	7.62×10^5	7360	2630	3.2
Cherenkov-ring resolution criterion	6.22×10^5	3.70×10^5	2190	256	6.55×10^5	6390	2200	2.7
Pion-like criteria	9.63×10^4	3.32×10^5	209	234	7.19×10^4	718	313	0.3
Multi-subevent criterion	3.95×10^4	3.22×10^5	80.9	234	7.09×10^4	691	307	0.3
Negative polarity								
	$\nu_\mu \text{ CC } e^{\text{ID}}$	$\nu_e \text{ CC } e^{\text{ID}}$	$\bar{\nu}_\mu \text{ CC } e^{\text{ID}}$	$\bar{\nu}_e \text{ CC } e^{\text{ID}}$	$\nu_\mu \text{ NC } e^{\text{ID}}$	$\nu_e \text{ NC } e^{\text{ID}}$	$\bar{\nu}_\mu \text{ NC } e^{\text{ID}}$	$\bar{\nu}_e \text{ NC } e^{\text{ID}}$
All interactions	1.66×10^5	3260	2.49×10^6	5.29×10^4	2.68×10^5	1070	4.61×10^6	1.93×10^4
Trigger	1.66×10^5	3260	2.49×10^6	5.29×10^4	2.68×10^5	1070	4.61×10^6	1.93×10^4
Sub-Cherenkov criterion	2.87×10^4	3140	4.31×10^5	5.09×10^4	9860	53.2	1.22×10^5	574
Reconstruction quality criteria	2.39×10^4	2860	3.49×10^5	4.66×10^4	8500	45.8	1.06×10^5	492
Cherenkov-ring resolution criterion	8000	2260	6.89×10^4	3.66×10^4	7330	39.7	8.95×10^4	426
Pion-like criteria	1180	2020	9640	3.34×10^4	940	4.5	1.14×10^4	43.7
Multi-subevent criterion	394	1950	5400	3.33×10^4	918	4.3	1.13×10^4	43.4

Table 5.13: Expected number of neutrino interactions in 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	$\nu_\mu \rightarrow \nu_\mu$	22 630.4 (231.0)	10 508.7 (101.6)	10 430.6 (5.8)	10 430.6 (100.9)
	$\nu_\mu \rightarrow \nu_e$	0 (0)	768.3 (8.6)	543.8 (5.8)	1 159.9 (12.8)
	$\nu_e \rightarrow \nu_e$	190.2 (1.2)	177.9 (1.1)	177.9 (1.1)	177.9 (1.1)
	$\nu_e \rightarrow \nu_\mu$	0 (0)	5.3 (3.3×10^{-2})	7.3 (4.5×10^{-2})	3.9 (2.4×10^{-2})
	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	62.4 (3 640.3)	26.0 (1 896.8)	26.0 (1 898.9)	26.0 (1 898.9)
	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	0 (0)	2.6 (116.1)	3.5 (164.0)	1.4 (56.8)
	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	1.3×10^{-1} (18.5)	1.3×10^{-1} (17.5)	1.3×10^{-1} (17.5)	1.2×10^{-1} (17.5)
	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	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)	
	$\bar{\nu}_\mu$			55.2 (3 265.5)	
	$\bar{\nu}_e$			1×10^{-1} (13.6)	

	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 vacuum

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re} \left(A_{ij}^{\alpha\beta} \right) \sin^2 \frac{\Delta m_{ij}^2 L}{4E} \pm 2 \sum_{i>j} \text{Im} \left(A_{ij}^{\alpha\beta} \right) \sin \frac{\Delta m_{ij}^2 L}{4E}$$

CP violation

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

T violation

$$P_{\nu_\alpha \rightarrow \nu_\beta} \neq P_{\nu_\beta \rightarrow \nu_\alpha}$$

CPT symmetry

$$P_{\nu_\alpha \rightarrow \nu_\beta} = P_{\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha}$$

All three equations can be proven using the formula above.

CP violation “amplitude”:

$$P_{\nu_\alpha \rightarrow \nu_\beta} - P_{\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta} = 4 \sum_{i>j} \text{Im} \left(A_{ij}^{\alpha\beta} \right) \sin \frac{\Delta m_{ij}^2 L}{2E}$$