Co-funded by
the European Union

ESS neutrino Super Beam plus

Neutrino oscillation prospects with ESSnuSB

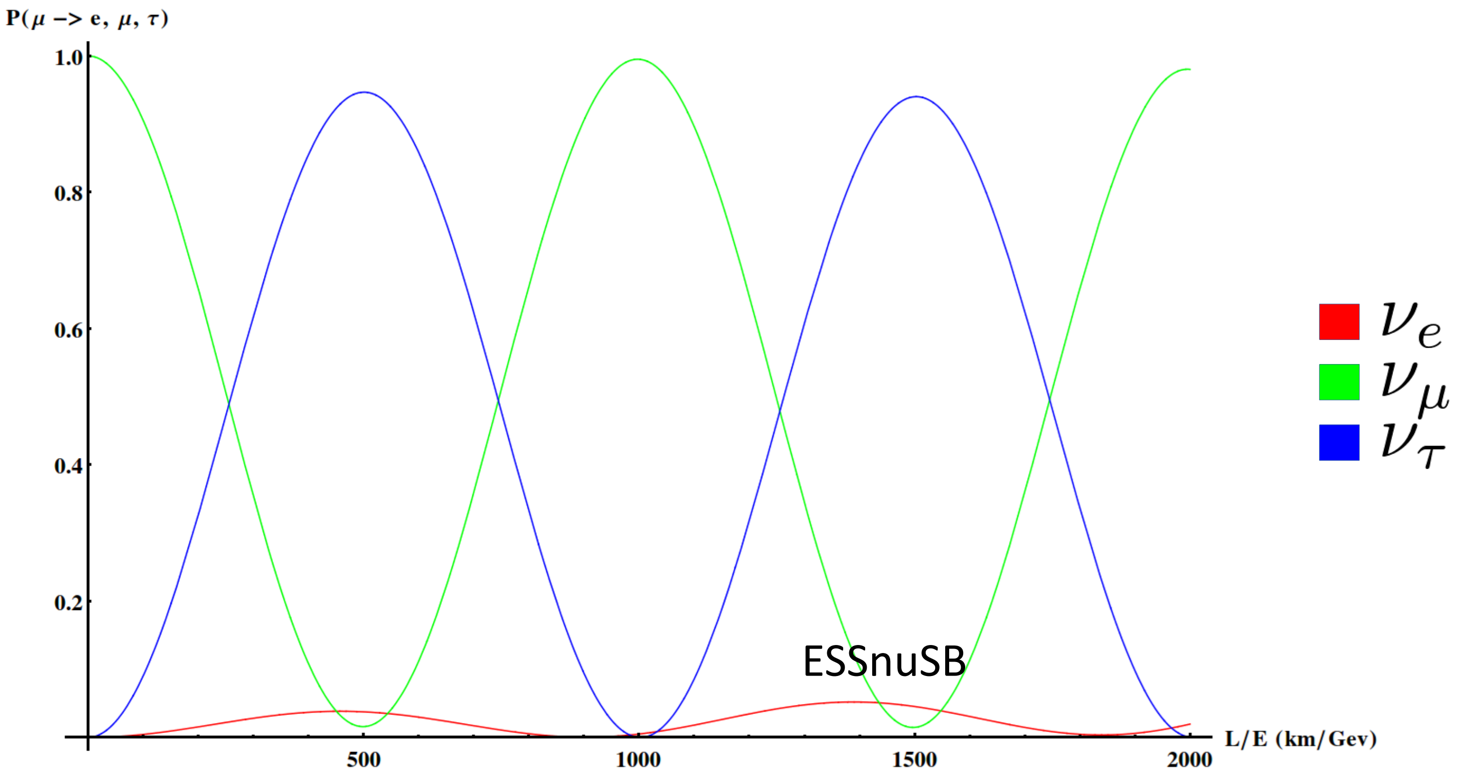
Budimir Kliček
On behalf of the ESSnuSB+ project

Ruđer Bošković Institute, Zagreb, Croatia

Neutrino Workshop at IFIRSE
19 July 2023

ESSnuSB / ESSnuSB+

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



CP violation in neutrino oscillations

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

probability of oscillation

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

neutrino flavour at production

neutrino flavour at detection

CP violation in ESSnuSB

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

We will study ν_e and $\overline{\nu}_e$ appearance in ν_μ and $\overline{\nu}_\mu$ beam, respectively

The plan:
1. Run with ν_μ and look at ν_e appearance, then
2. Run with $\overline{\nu}_\mu$ and look at $\overline{\nu}_e$ appearance

Why 2nd maximum?

Large signal and small matter effects

Neutrino oscillations (3 generations)

$$U = \begin{array}{cc} \left(\begin{array}{ccc} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{cp}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{cp}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{cp}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{cp}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{cp}} & c_{23}c_{13} \end{array}\right) & \begin{array}{c} e \\ \mu \\ \tau \end{array} \\ \begin{array}{ccc} 1 & 2 & 3 \end{array} & \end{array}$$

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

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

$$\Delta m^2_{ij} \equiv m_i^2 - m_j^2 \Rightarrow \Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$

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

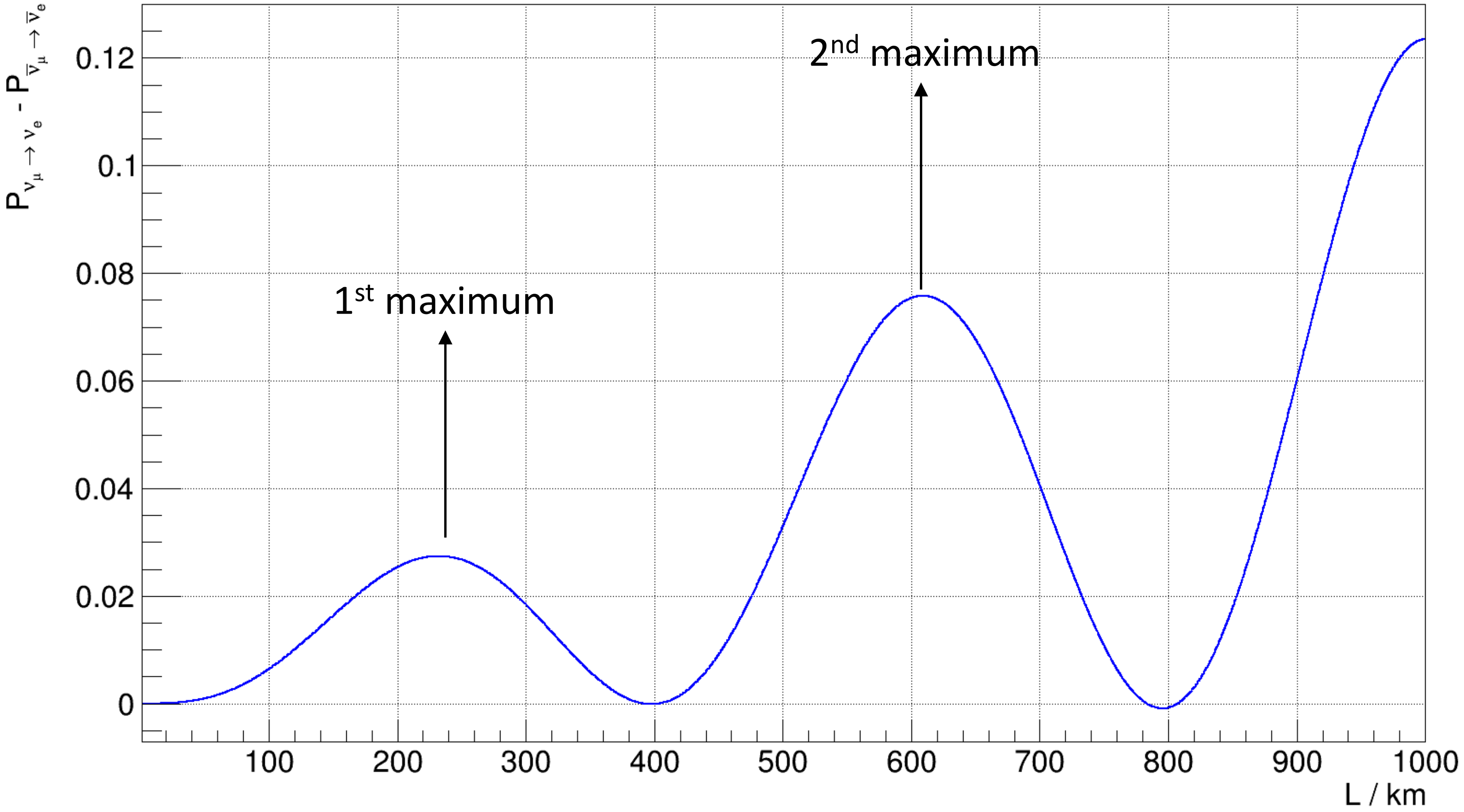
Six parameters in total: $\Delta m^2_{21}, \Delta m^2_{32}, \theta_{12}, \theta_{13}, \theta_{23}, \delta_{cp}$

CP violation in ESSnuSB

$$s_{ij} \equiv \sin\theta_{ij}$$
$$c_{ij} \equiv \cos\theta_{ij}$$
$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$
$$A_{ij}^{\alpha\beta} \equiv U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*$$
$$J = s_{12}c_{12}s_{13}c_{13}s_{23}c_{23}c_{13}\sin\delta_{\mathrm{CP}}$$

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

E = 400 MeV

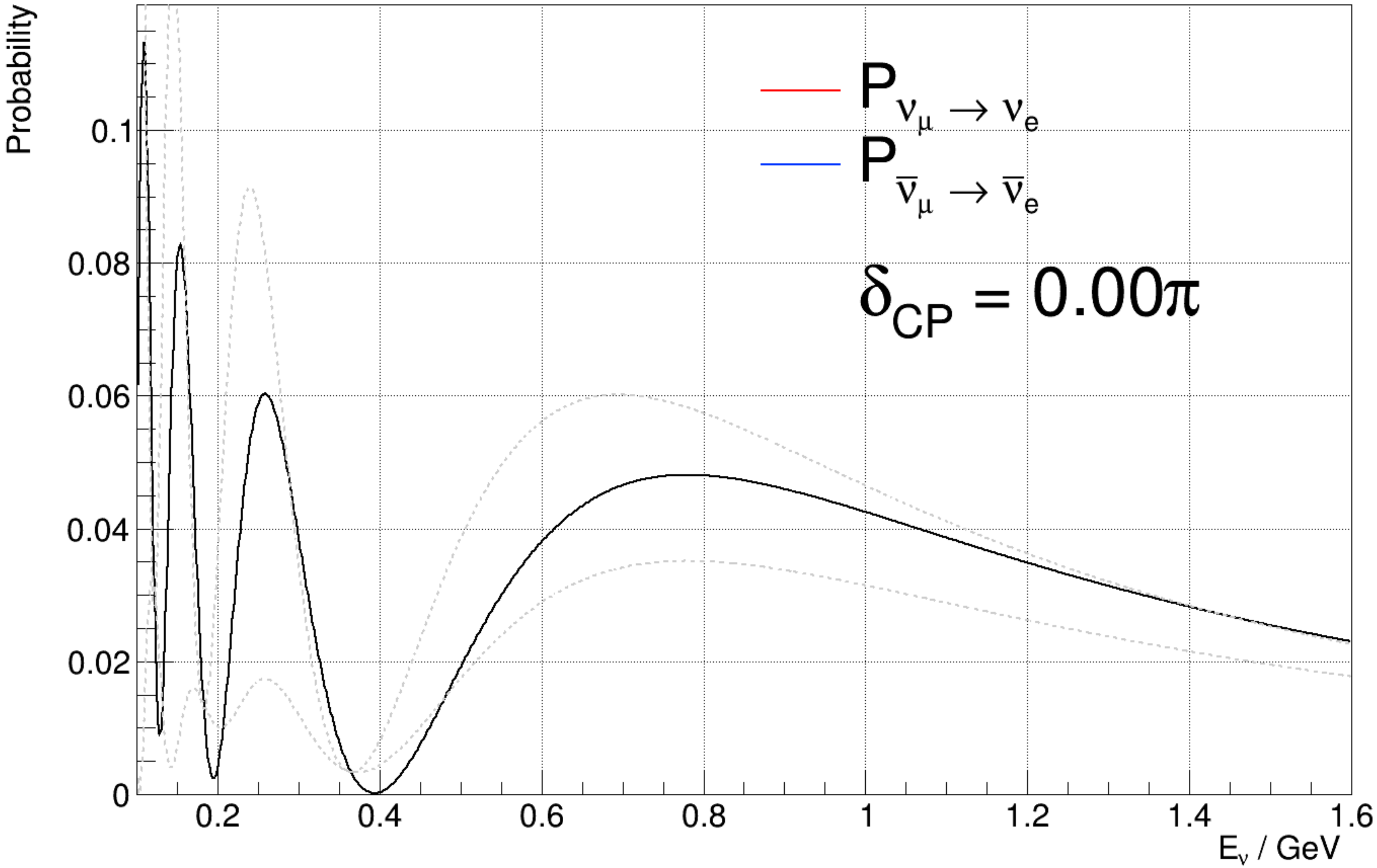


$$\frac{A_{CP}\ @\ \text{2nd max}}{A_{CP}\ @\ \text{1st max}} \sim 2.7$$

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

Vacuum

Effect of δ_{CP} on oscillations in vacuum

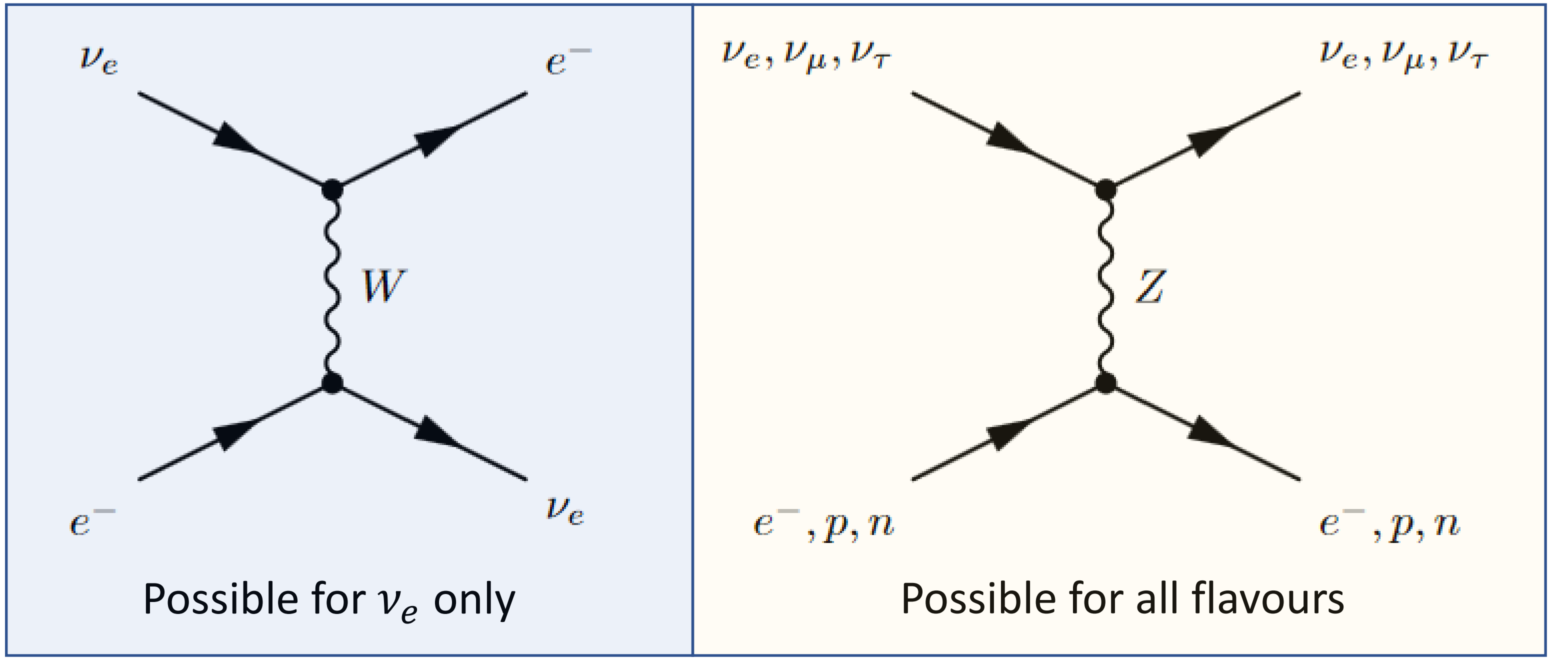


L = 360 km

Thanks to my student L. Halić for patiently making plots specifically for this talk!

Matter effects

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



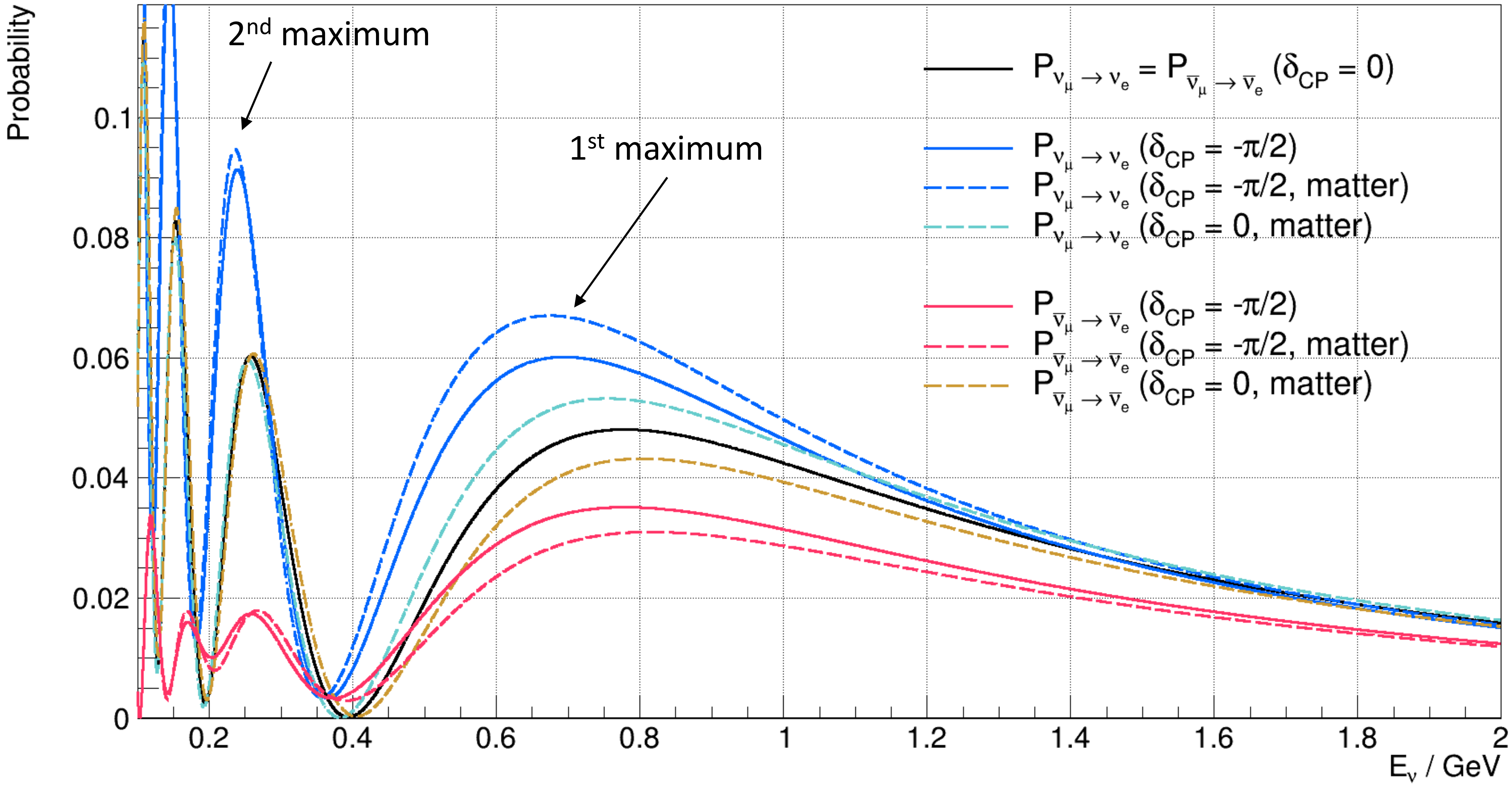
Possible for ν_e only

Possible for all flavours

- 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)

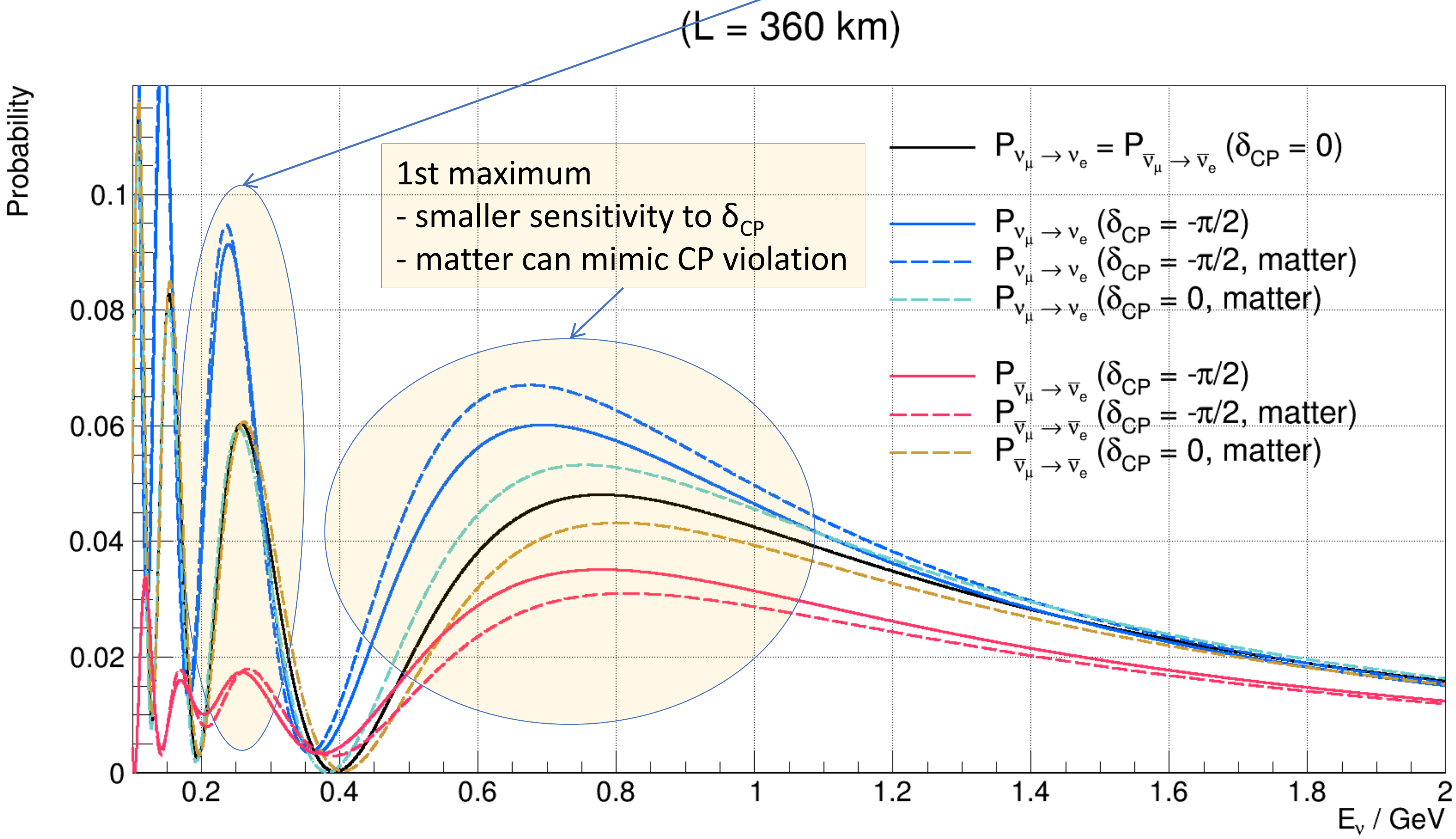


2nd maximum

1st maximum

Oscillation pattern

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



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

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.

ESSnuSB project

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

Neutrino beam production

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

Hot Cell

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

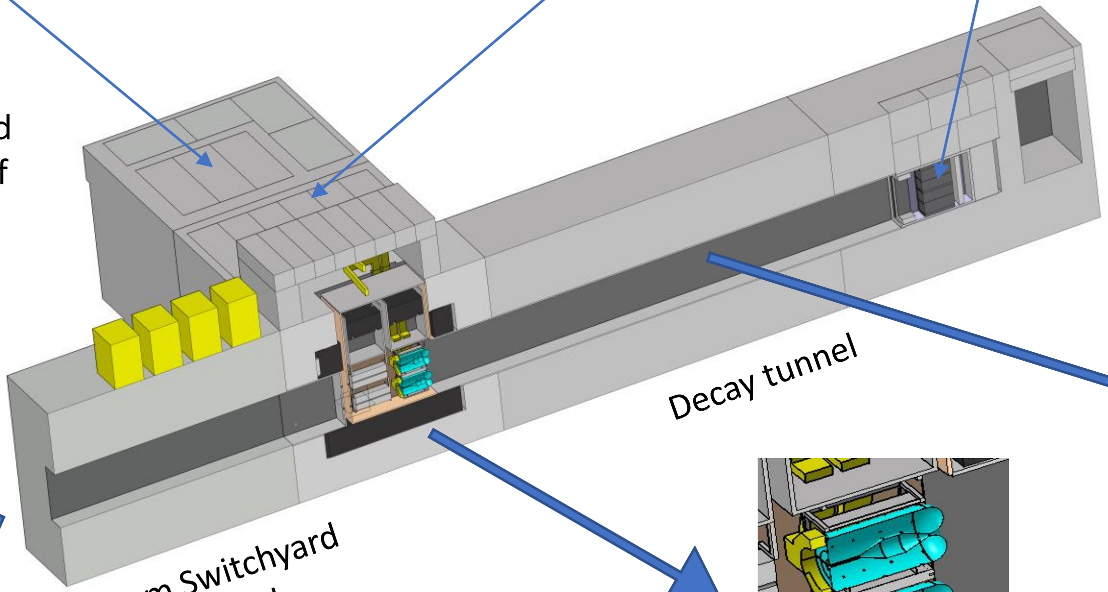
Power Supply Unit

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

Morgue

To Store radioactive wastes

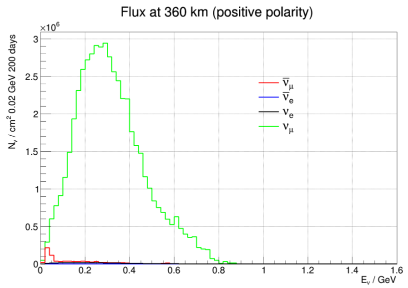
Beam dump



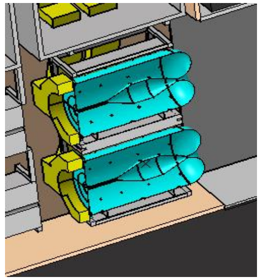
Decay tunnel

Beam Switchyard Tunnel

Neutrino Beam



Pions decay in-flight here



Hadronic Collector

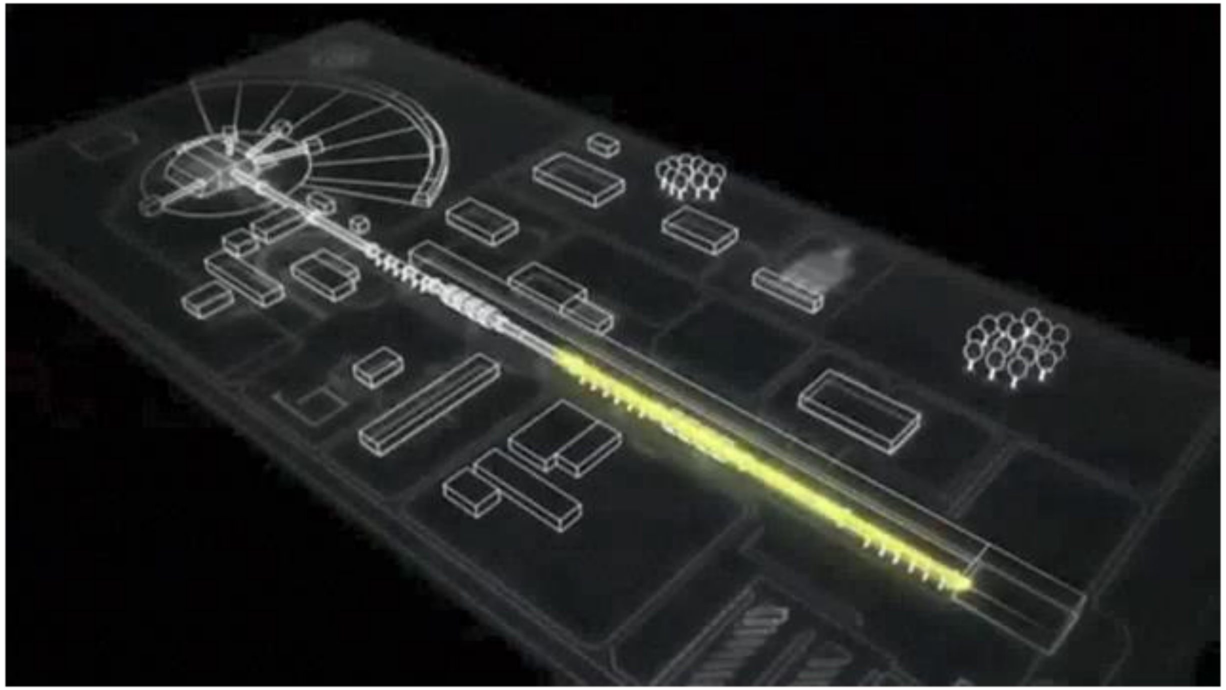
Proton Beam

(Ep=2.5 GeV, 14 Hz)

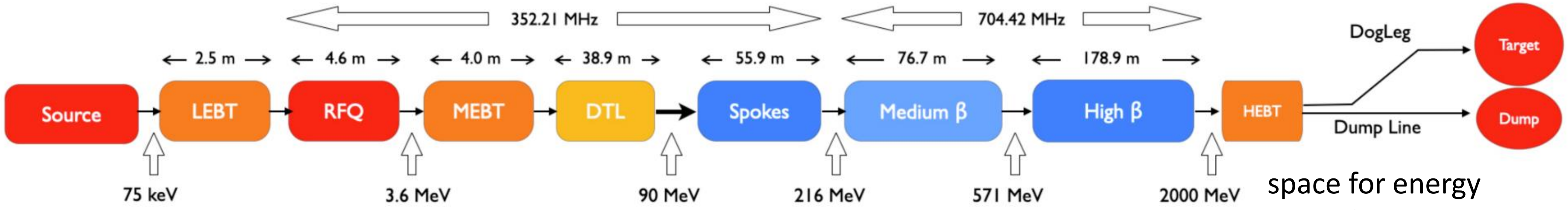
4 x 1.25 MW

Can we go to 2nd maximum?

A very intense proton linac is in construction near Lund, Sweden.



ESS proton linac

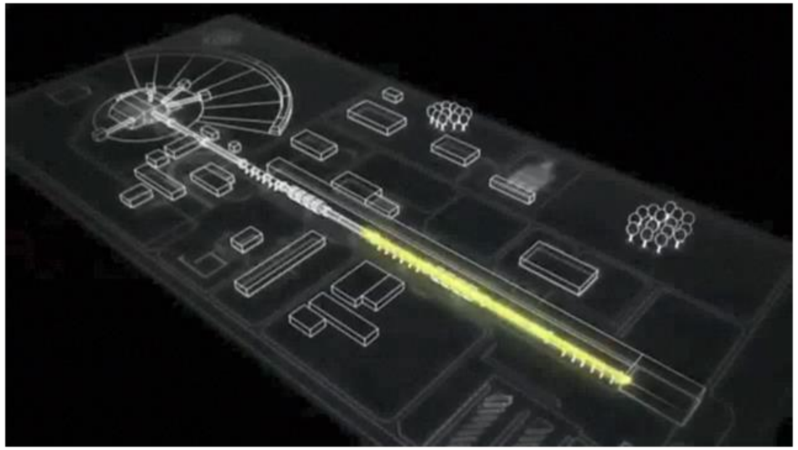


space for energy upgrades

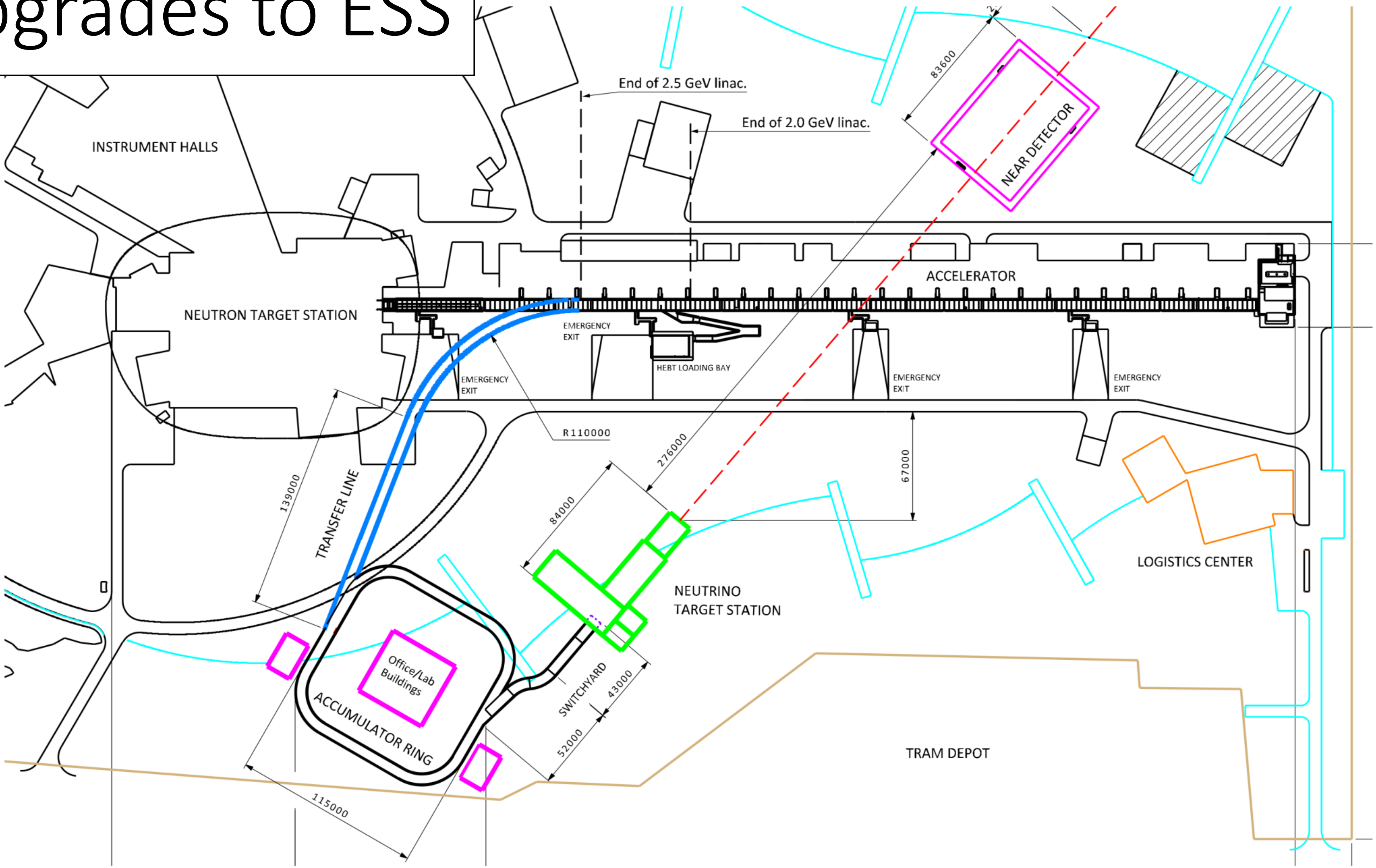
- The ESS will be a copious source of spallation neutrons.
- **5 MW average beam power.**
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV kinetic energy protons
  - up to 3.5 GeV with linac upgrades
- **>2.7x10^{23} p.o.t/year.**

First beam on target expected in 2026.

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

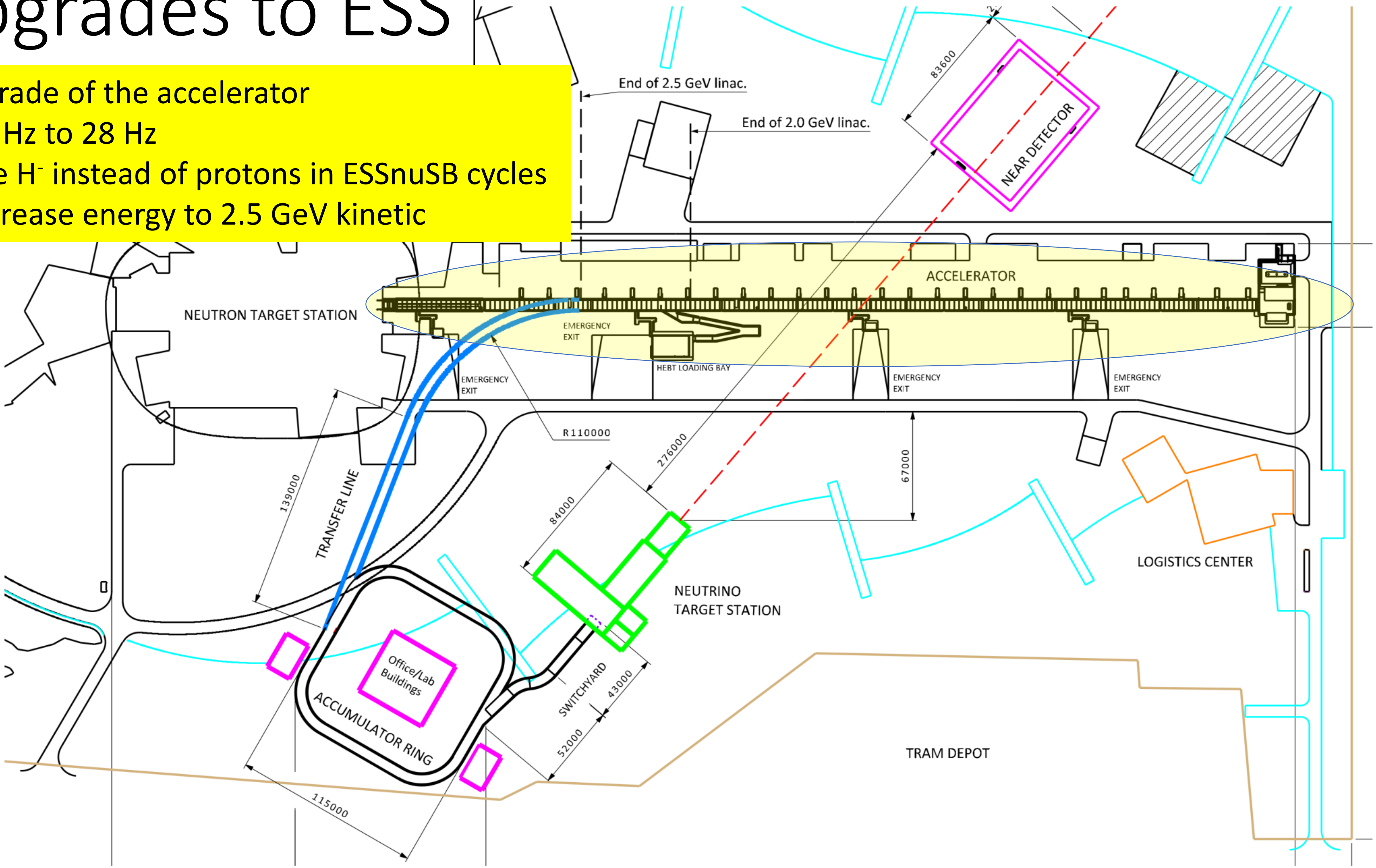


Upgrades to ESS



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

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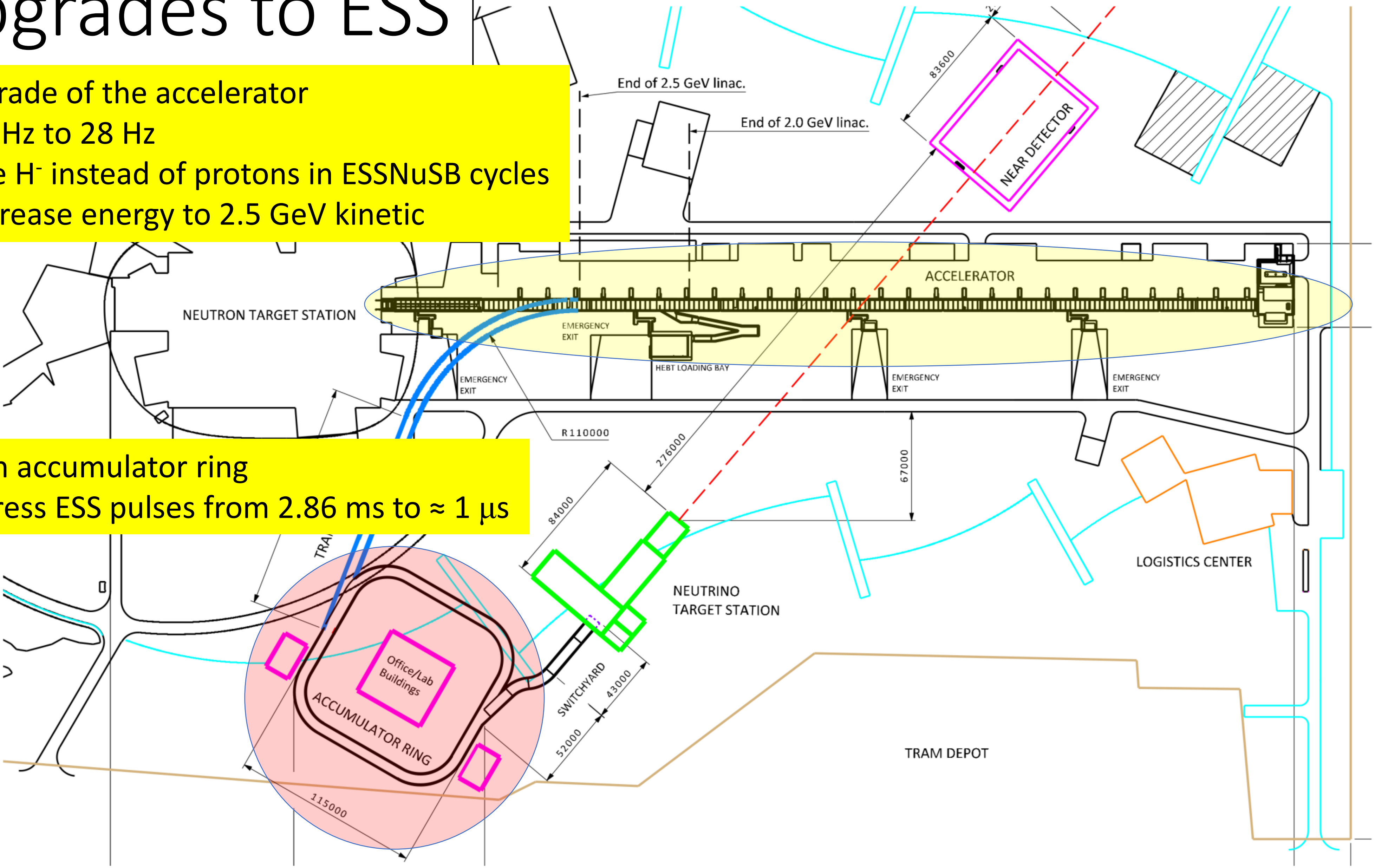
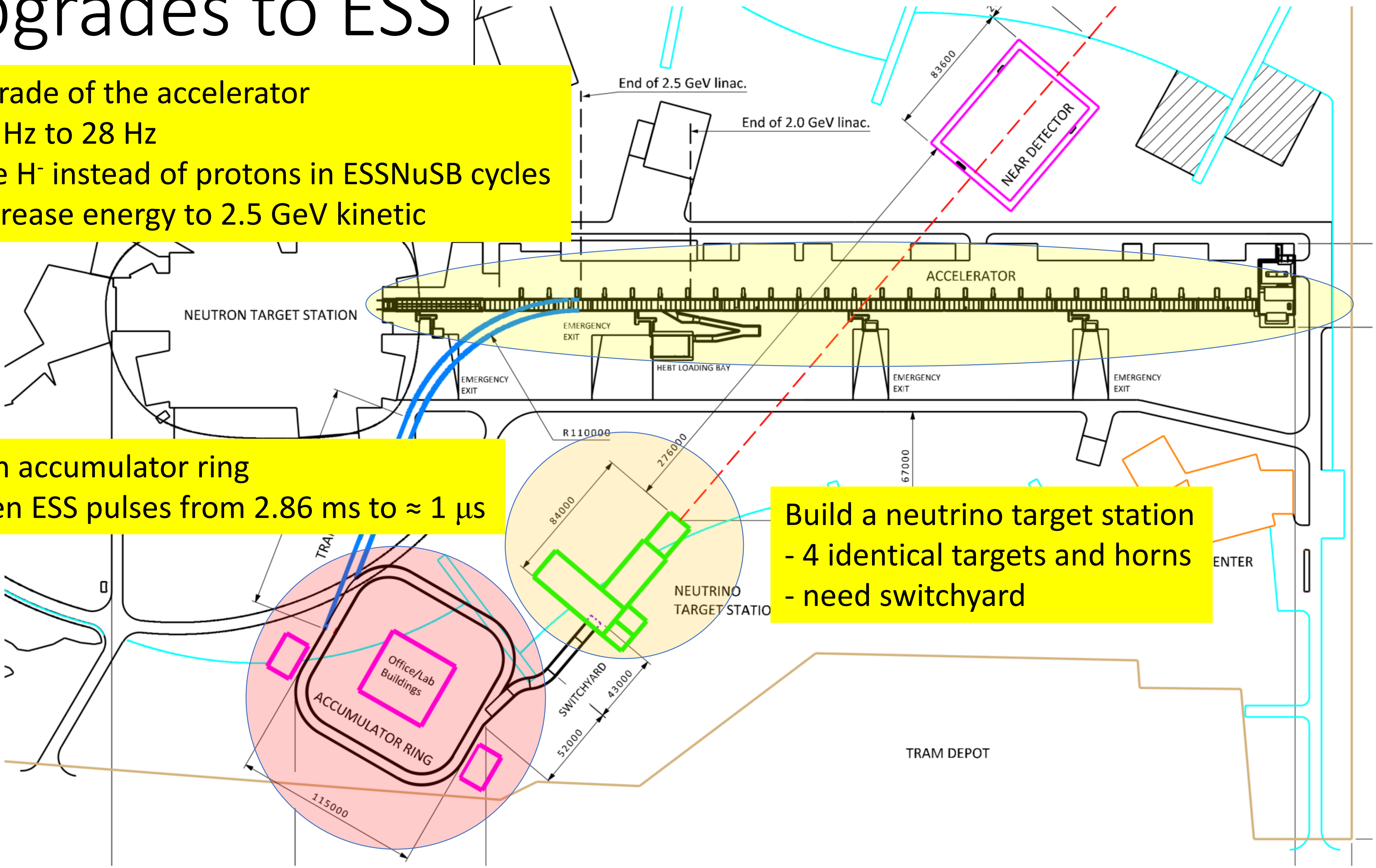
Build an accumulator ring
- compress ESS pulses from 2.86 ms to ≈ 1 µs



Upgrades to ESS



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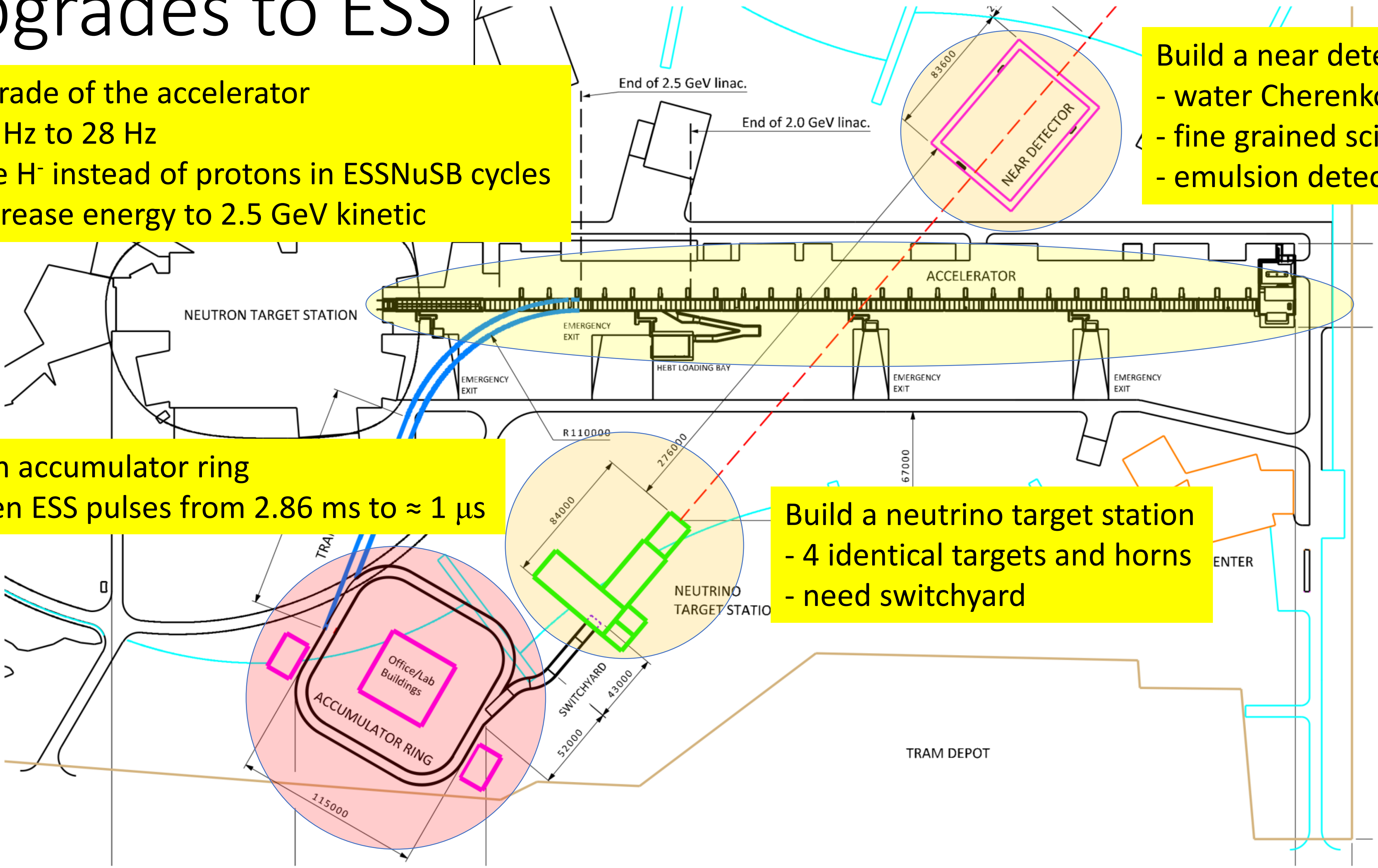
Build a neutrino target station
- 4 identical targets and horns
- need switchyard

Upgrades to ESS



Upgrade of the accelerator
- 14 Hz to 28 Hz
- use H^- instead of protons in ESSNuSB cycles
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Build a near detector site
- water Cherenkov detector
- fine grained scintillator
- emulsion detector

Build an accumulator ring
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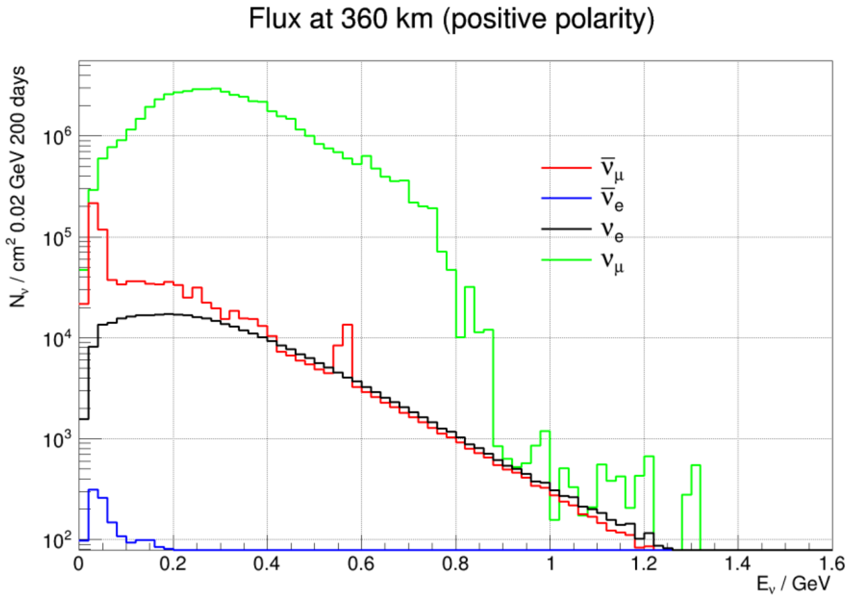
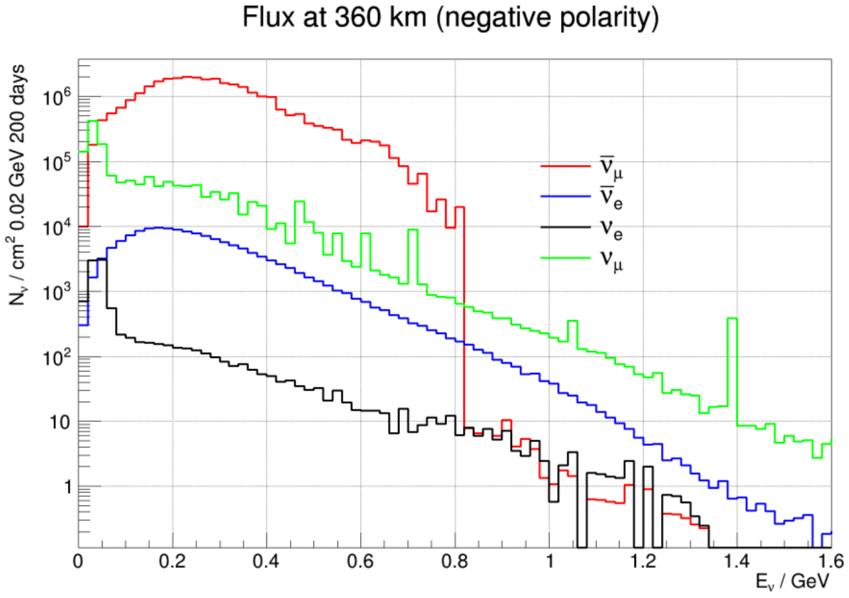
ESSνSB ν energy distribution
(after optimisation)


Flux at 360 km (positive polarity)

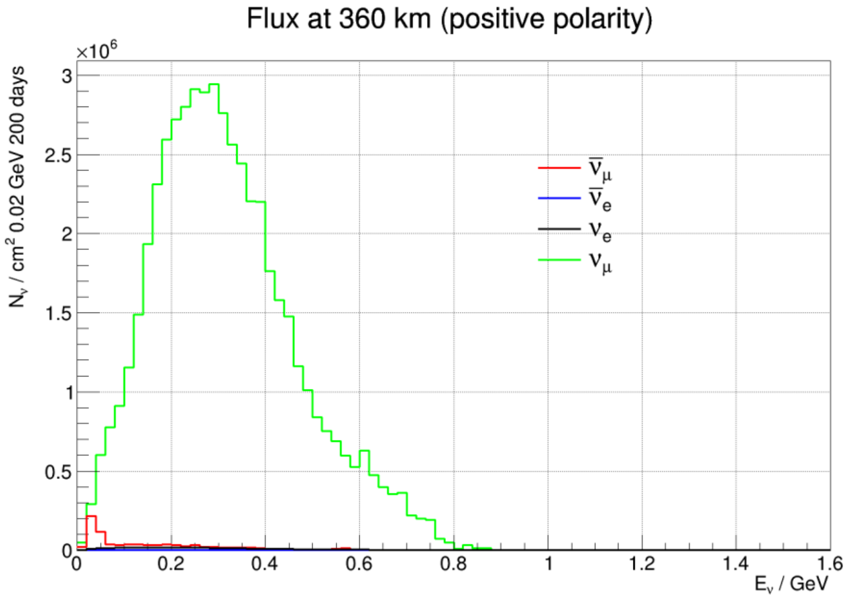

Flux at 360 km (negative polarity)

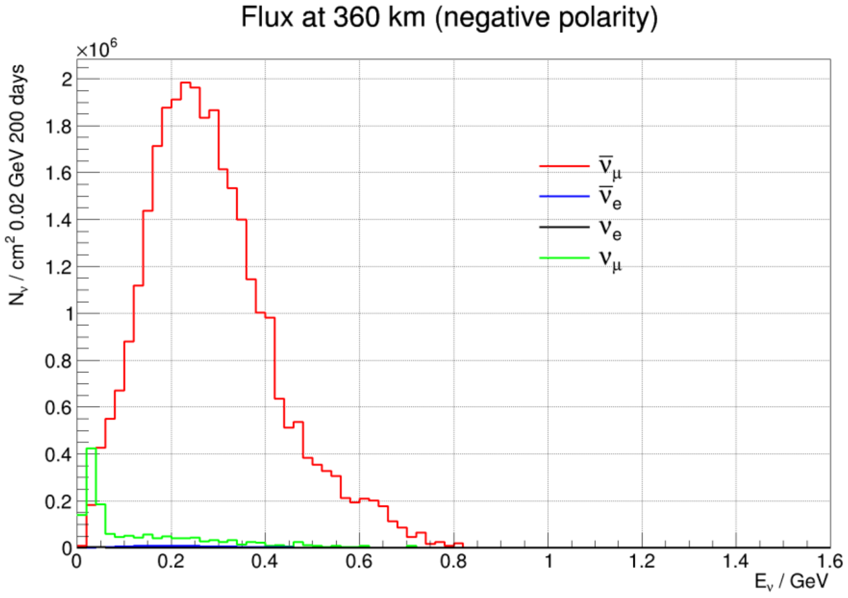
- almost pure ν_μ beam
- small ν_e contamination which will be used to measure ν_e cross-sections in a near detector

Flavour	ν Mode		$\bar{\nu}$ Mode	
	N_ν (10^5/ 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**

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

ESSνSB ν energy distribution
(after optimisation)





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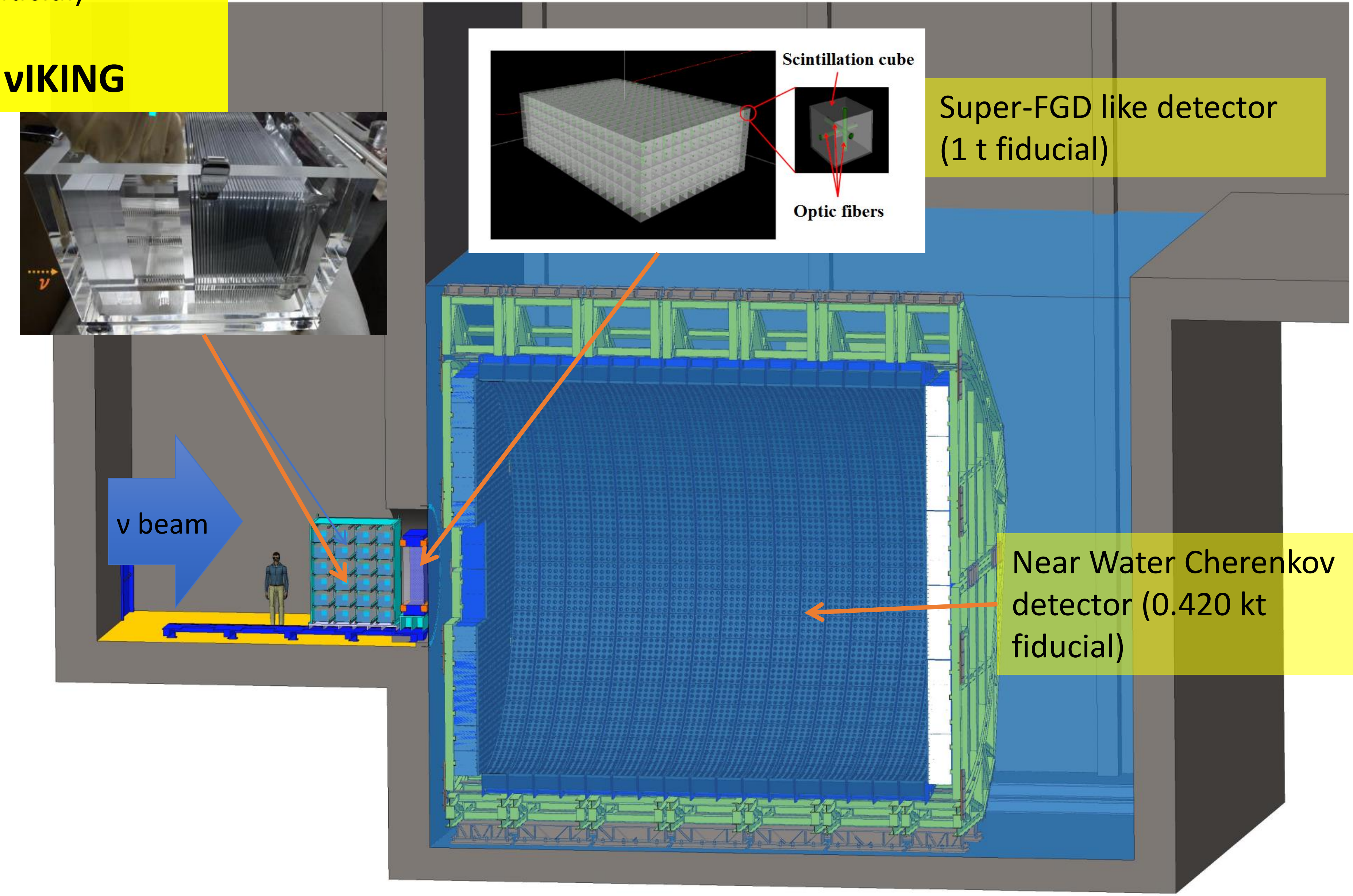
at 360 km from the target and per year (in absence of oscillations)

Near detectors

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

Code name: **νIKING**

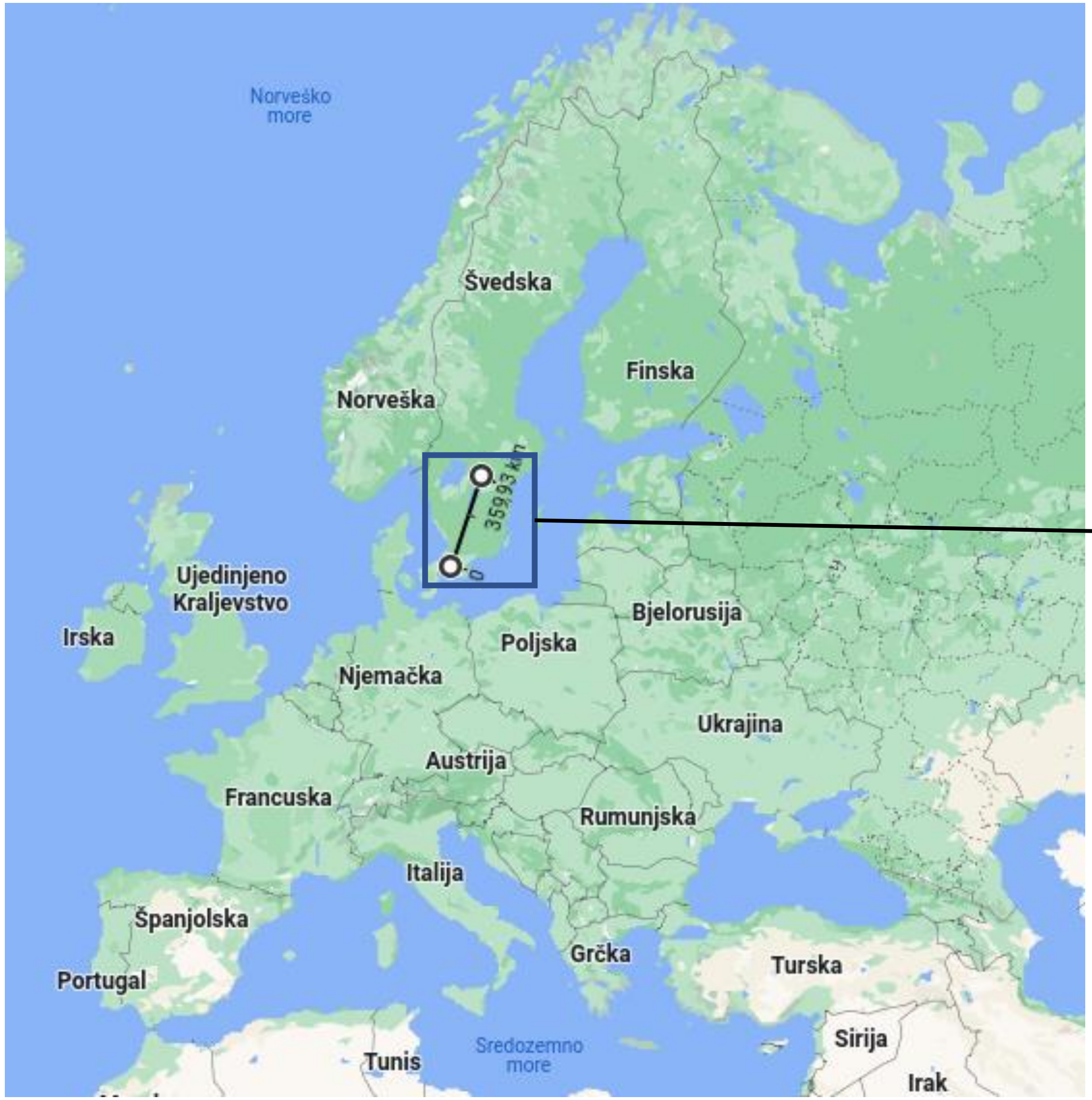


Super-FGD like detector (1 t fiducial)

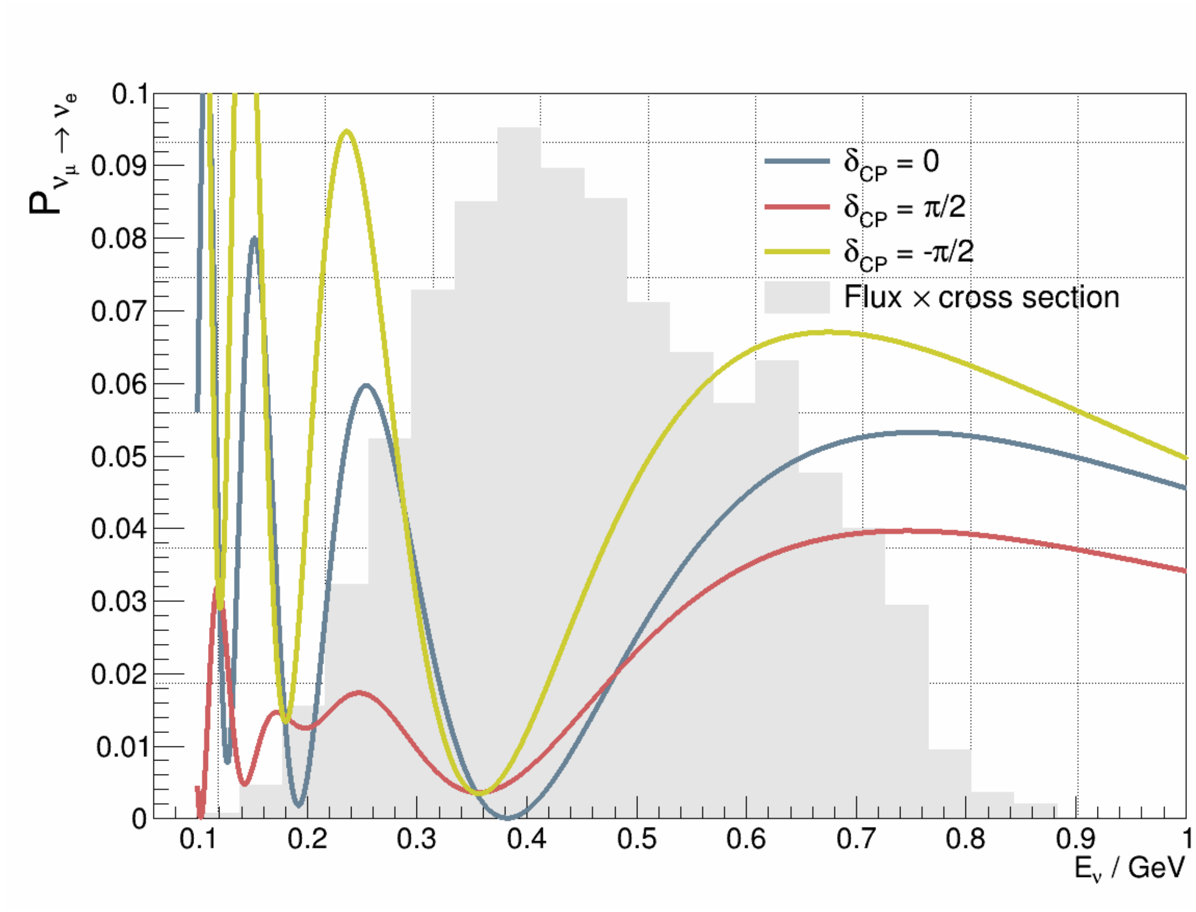
Near Water Cherenkov detector (0.420 kt fiducial)

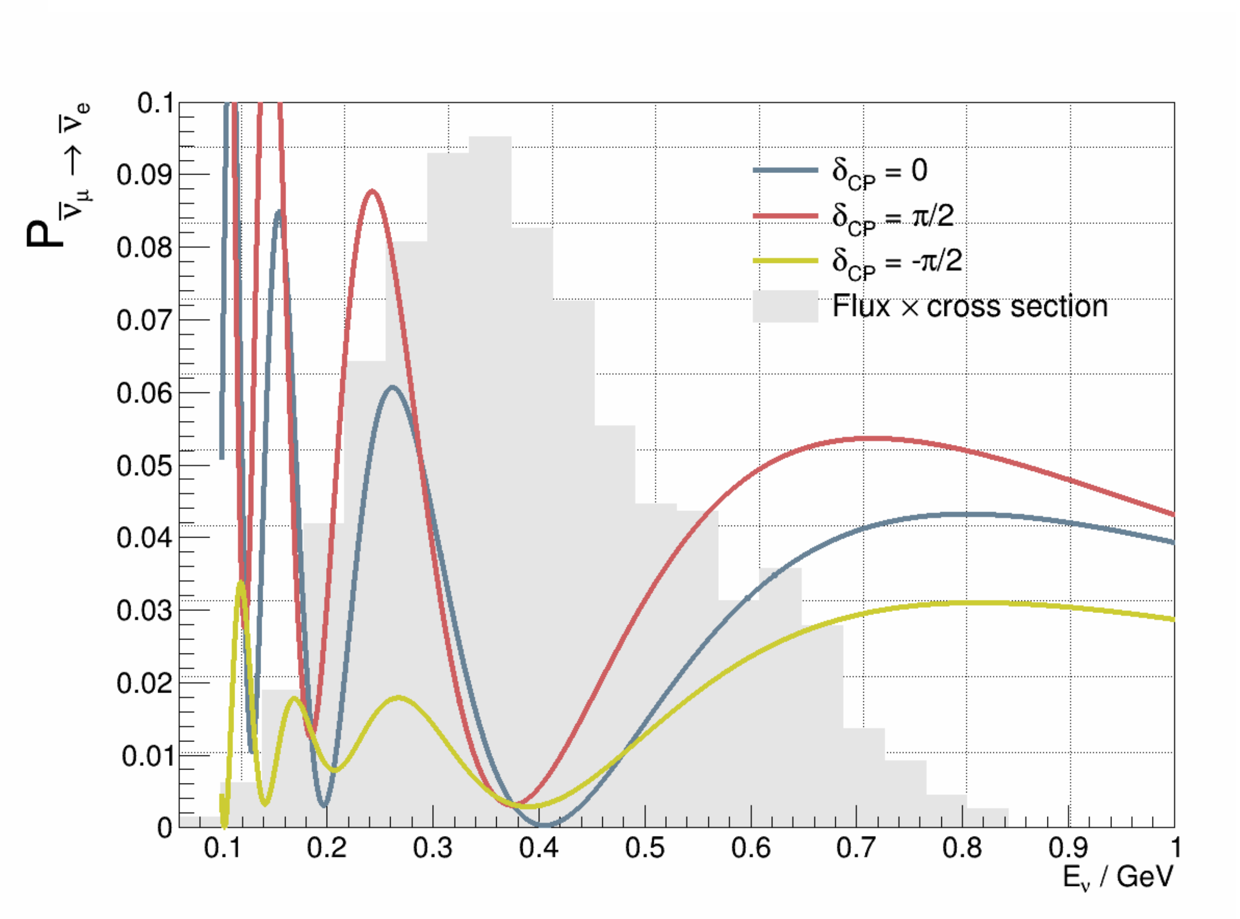
ESSnuSB neutrino baseline

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

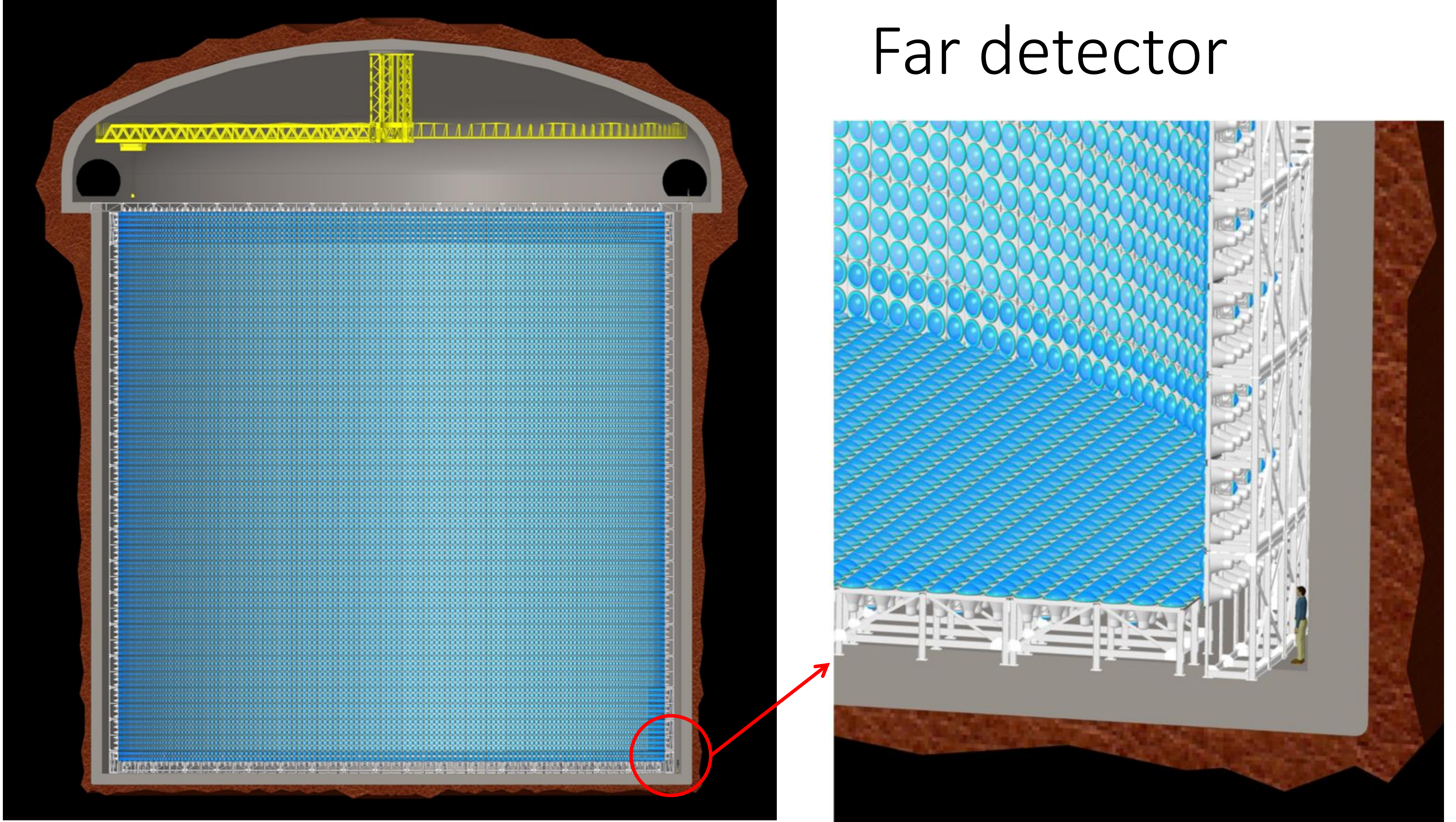


Oscillation coverage

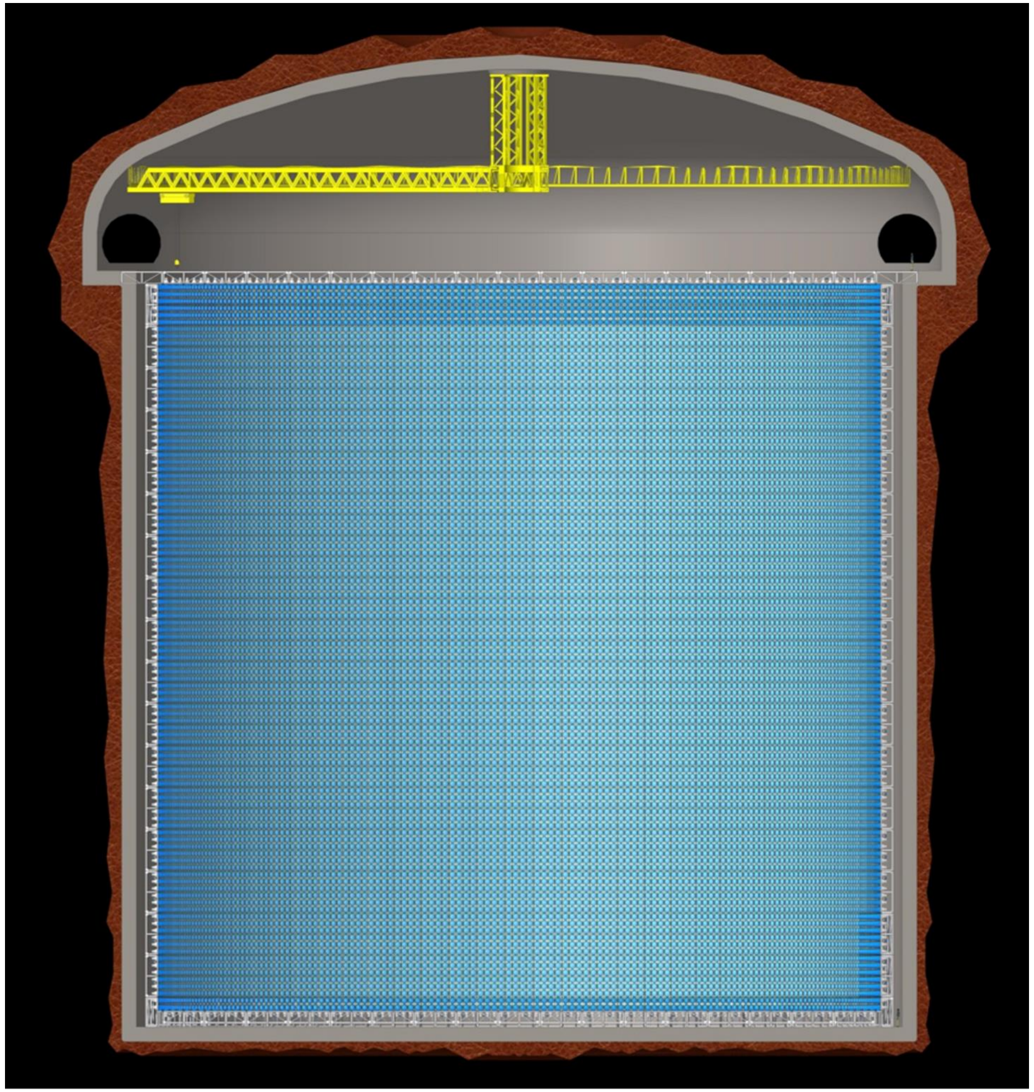




Far detector



Far detectors



Design

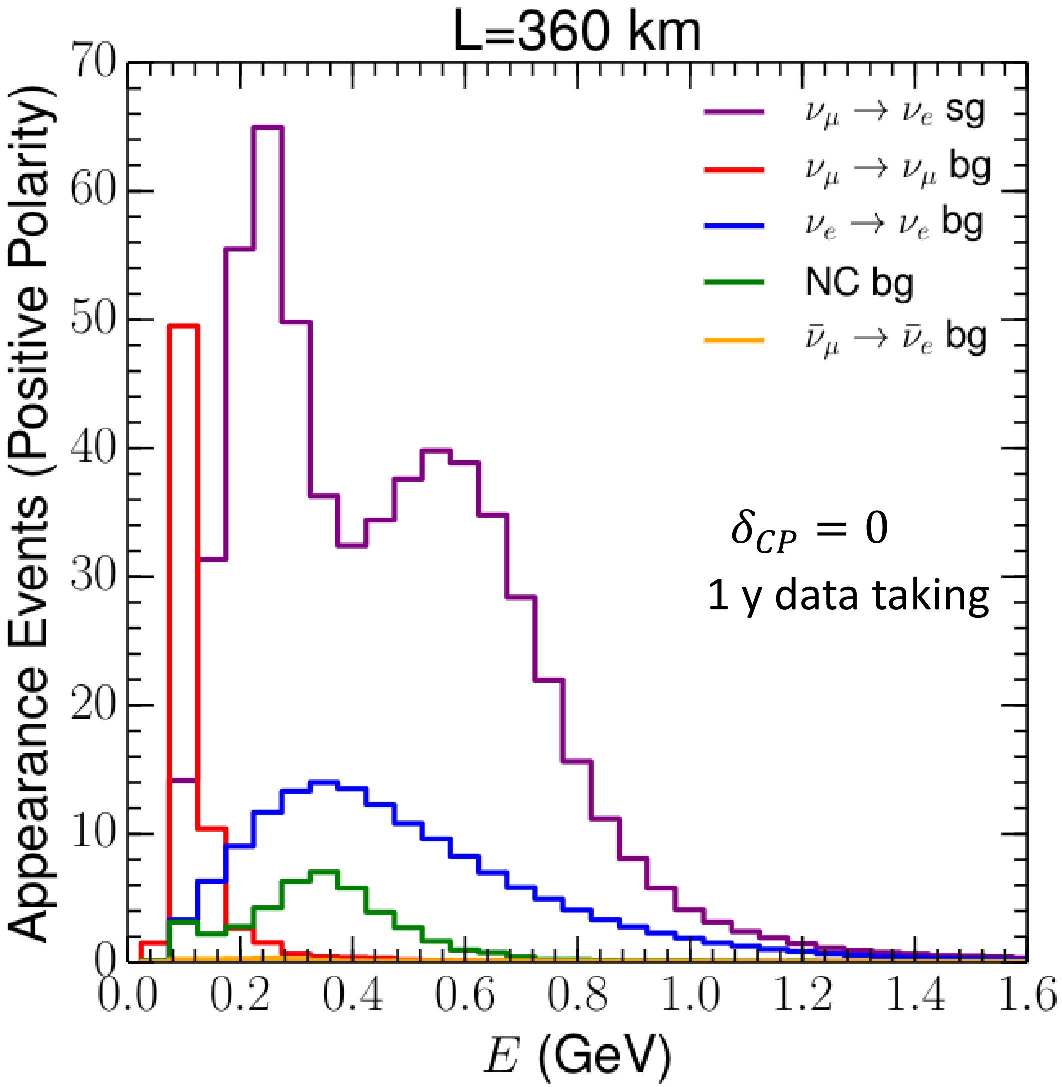
- 2 x 270 kt fiducial volume (~2x HyperK)
- Readout: 2 x 38k 20” PMTs
- 30% optical coverage
  - design here for 40% with an option that ¼ PMTs will not be installed

Can also be used for other purposes:

- Proton decay
- Astroparticles
- Galactic SN ν
- Diffuse supernova neutrino background
- Solar Neutrinos
- Atmospheric Neutrinos

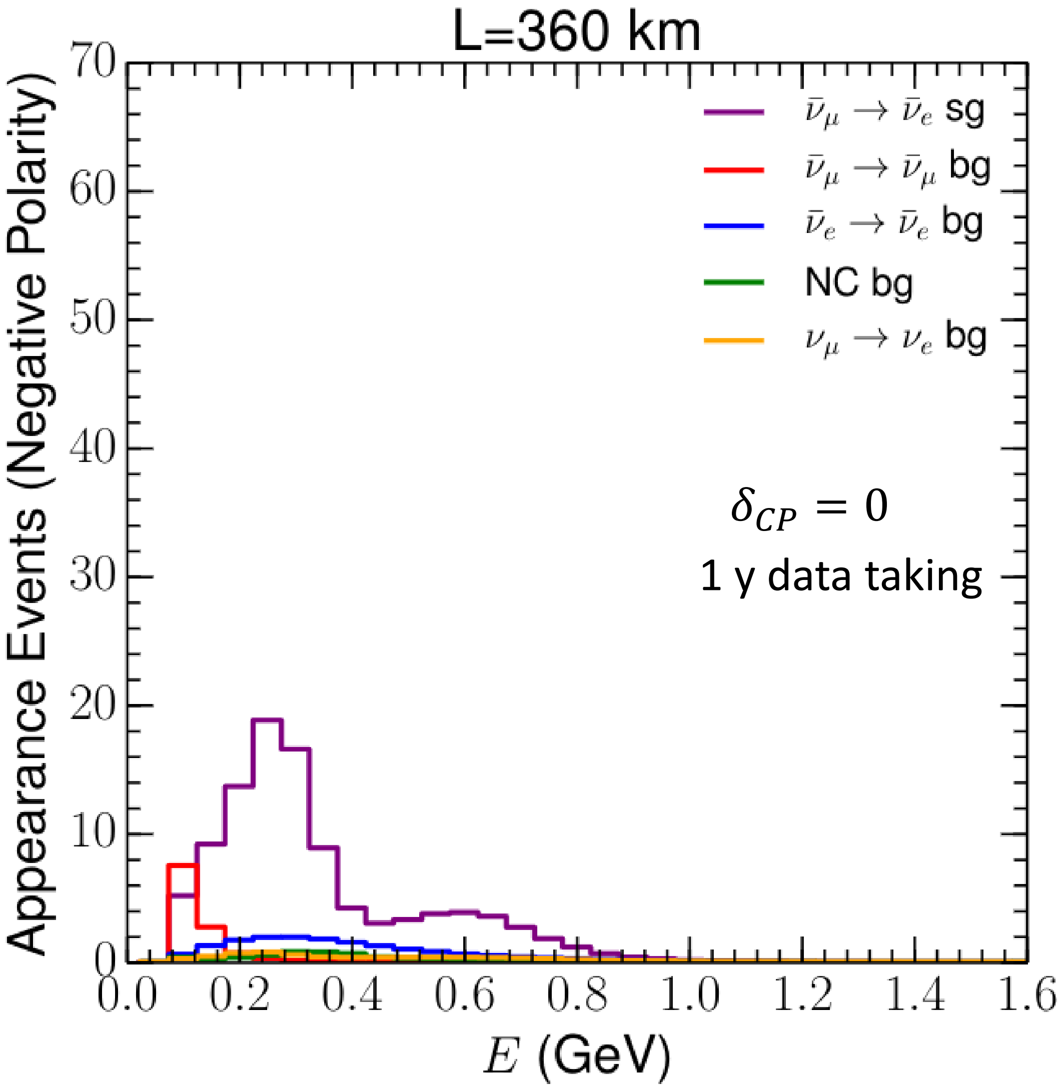
Expected event spectra

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



$\delta_{CP} = 0$

1 y data taking



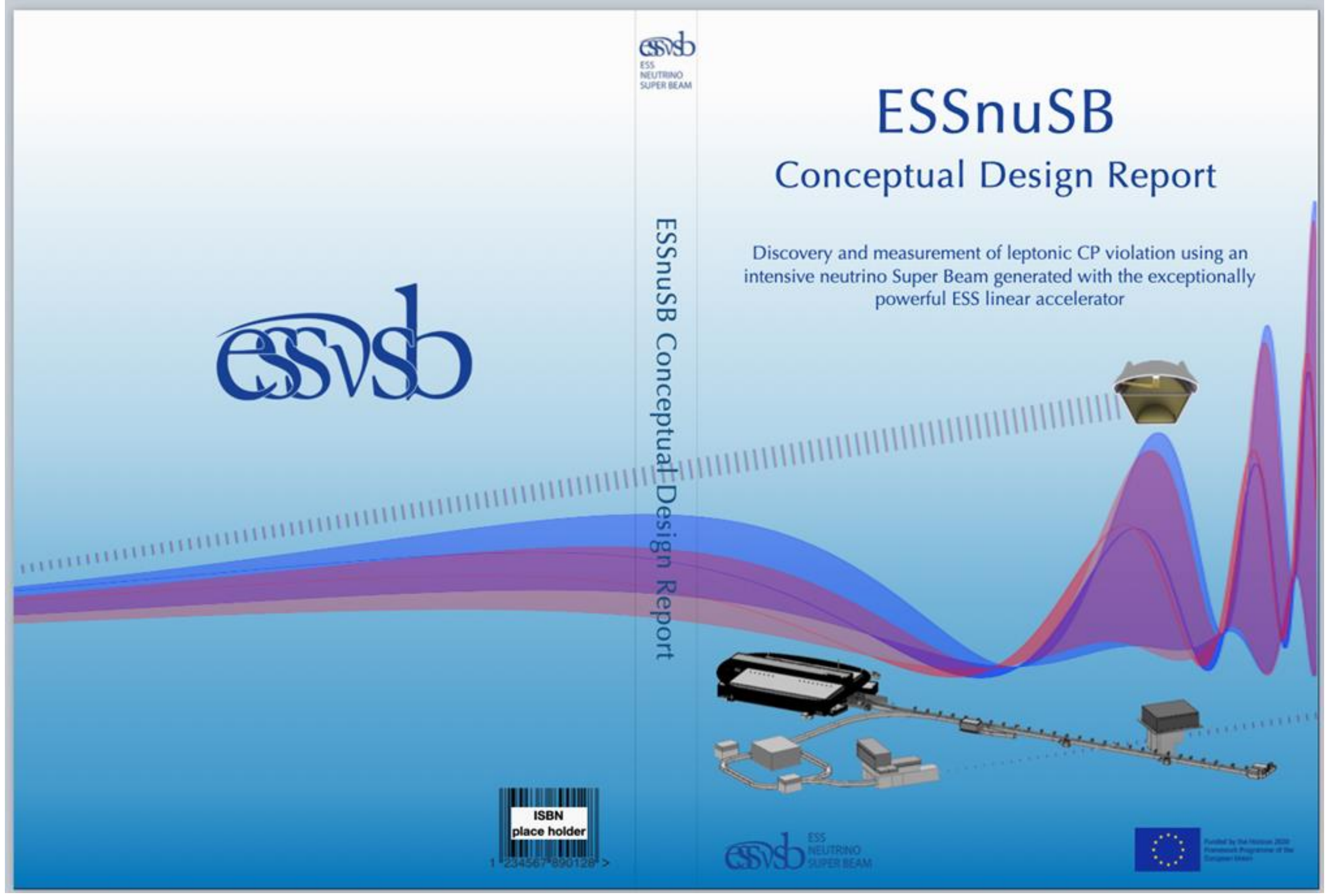
$\delta_{CP} = 0$

1 y data taking

Oscillation physics

ESSnuSB conceptual design report

- Most up to date evaluation of the CPV discovery potential



ESSnuSB

Conceptual Design Report

Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator

ESSnuSB Conceptual Design Report

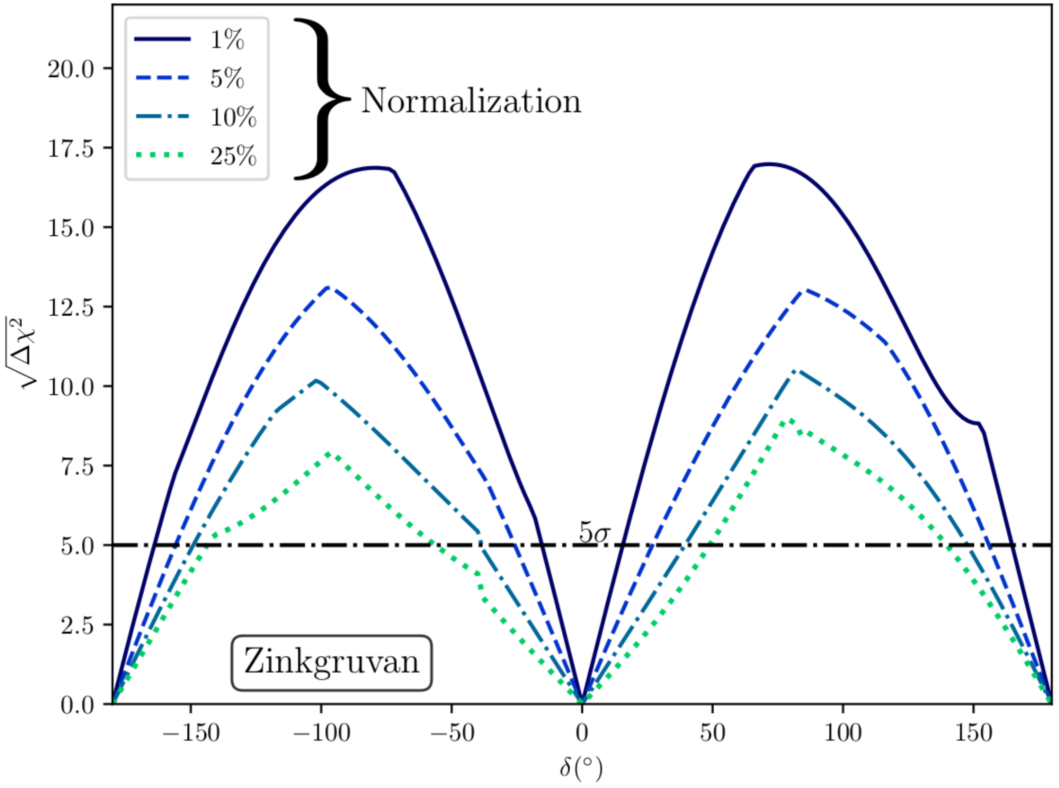
ESS NEUTRINO SUPER BEAM

ISBN place holder

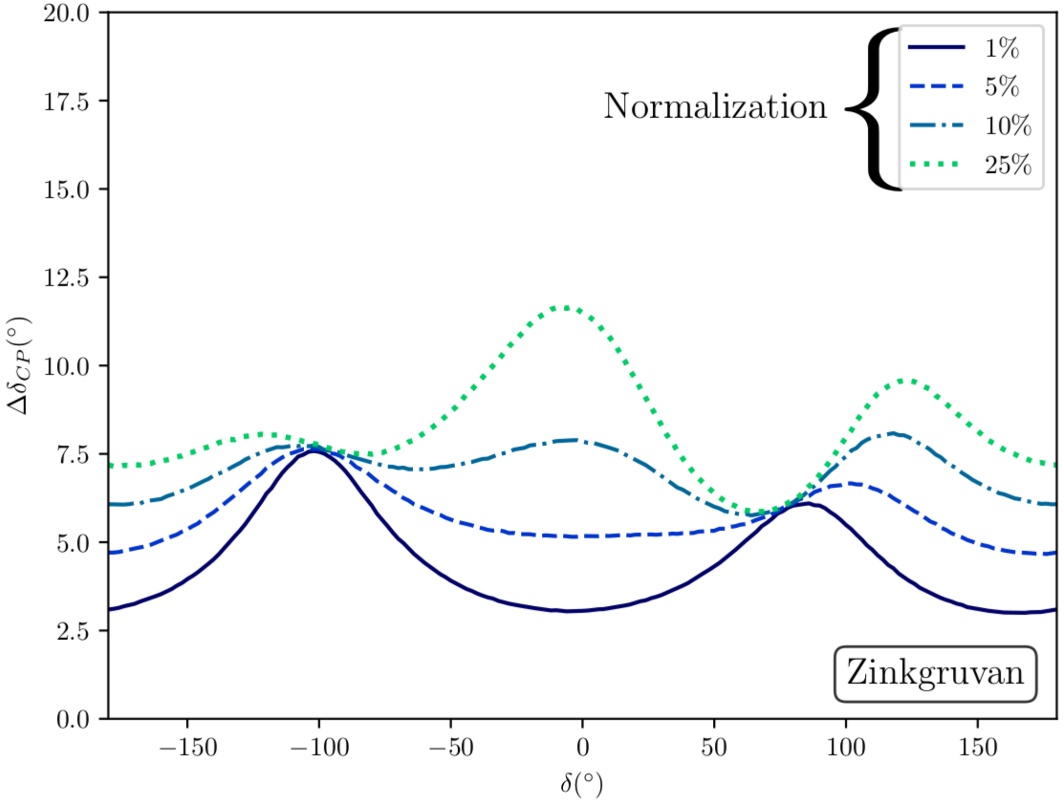
Alekou, A., Baussan, E., Bhattacharyya, A.K. et al. “The European Spallation Source neutrino super-beam conceptual design report”. Eur. Phys. J. Spec. Top. (2022). https://doi.org/10.1140/epjs/s11734-022-00664-w
arXiv: https://arxiv.org/abs/2203.08803 (includes costing)

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

Sensitivity



Precision



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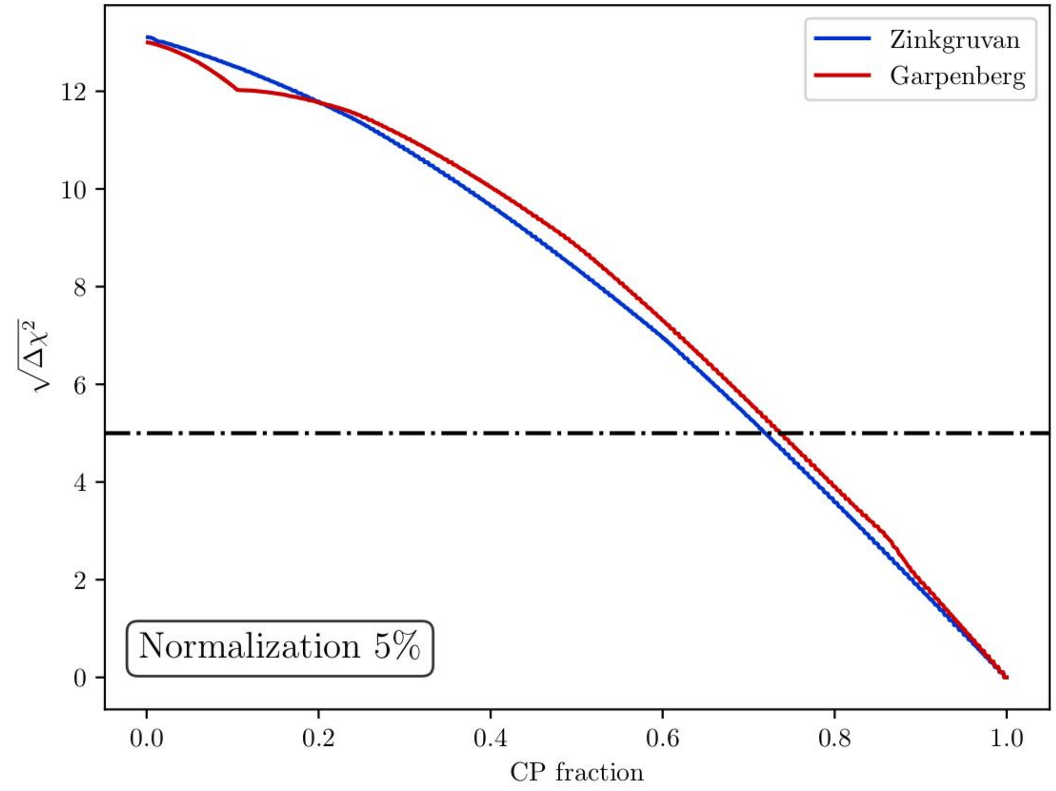
CP coverage



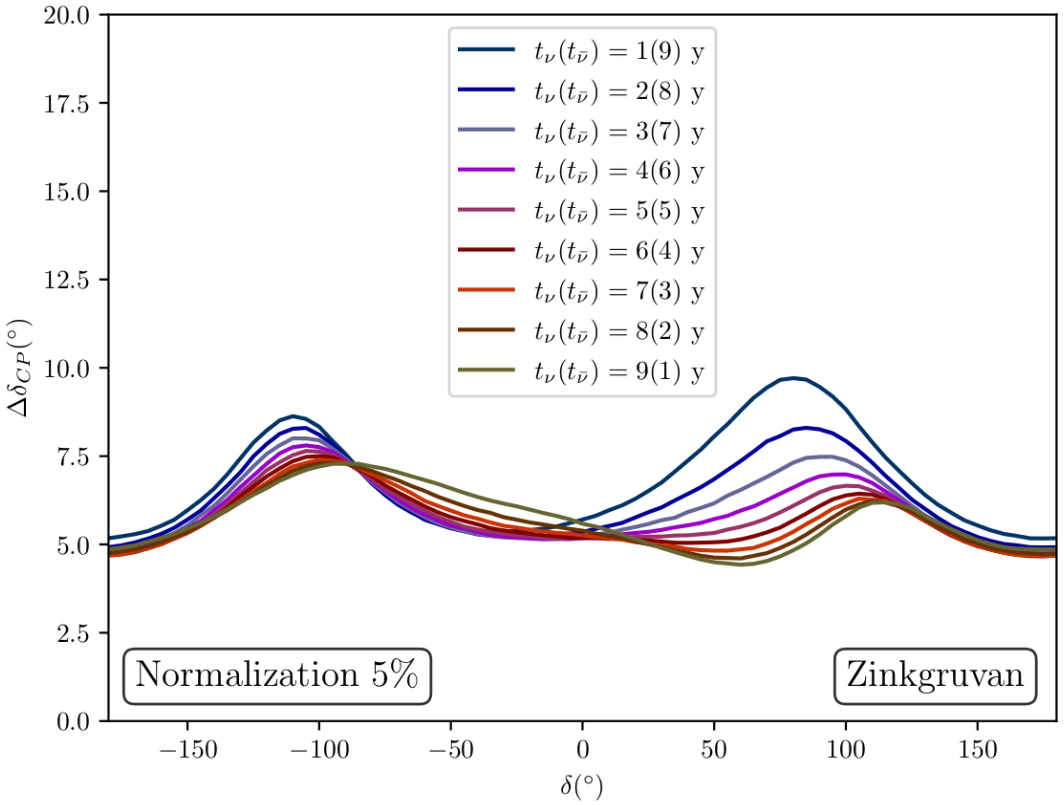
71% coverage of δ_{CP} range with more than 5 σ in 10 y of data taking

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

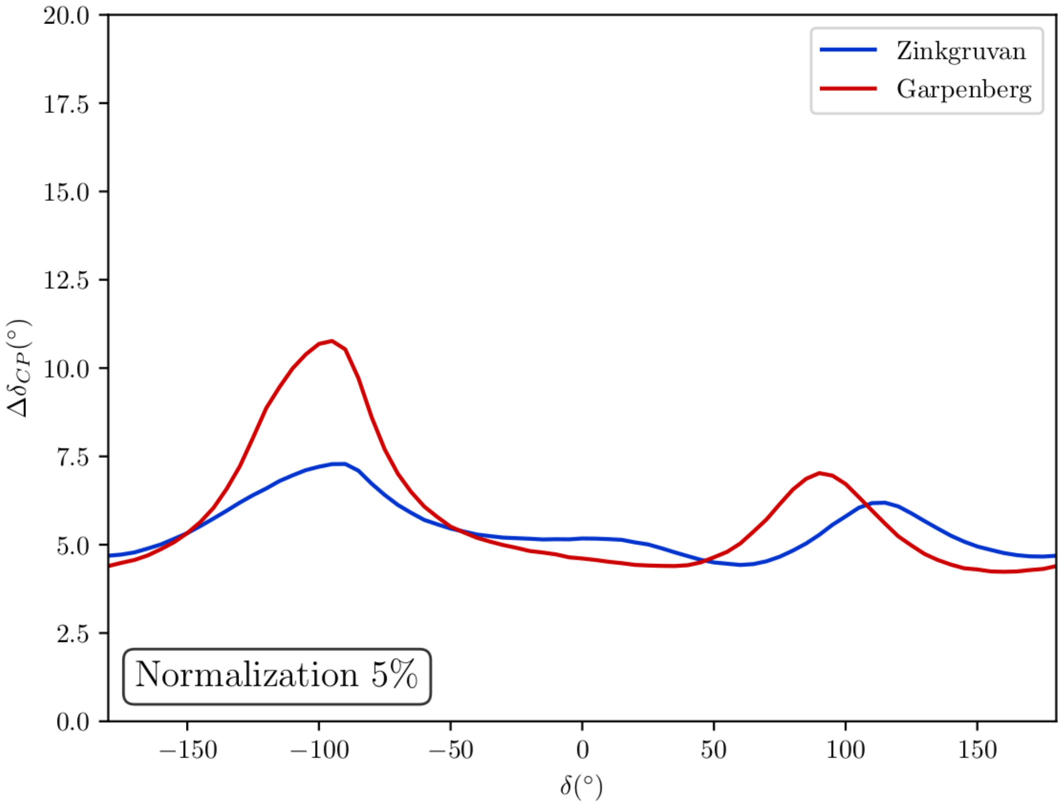
Optimization for precision

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}



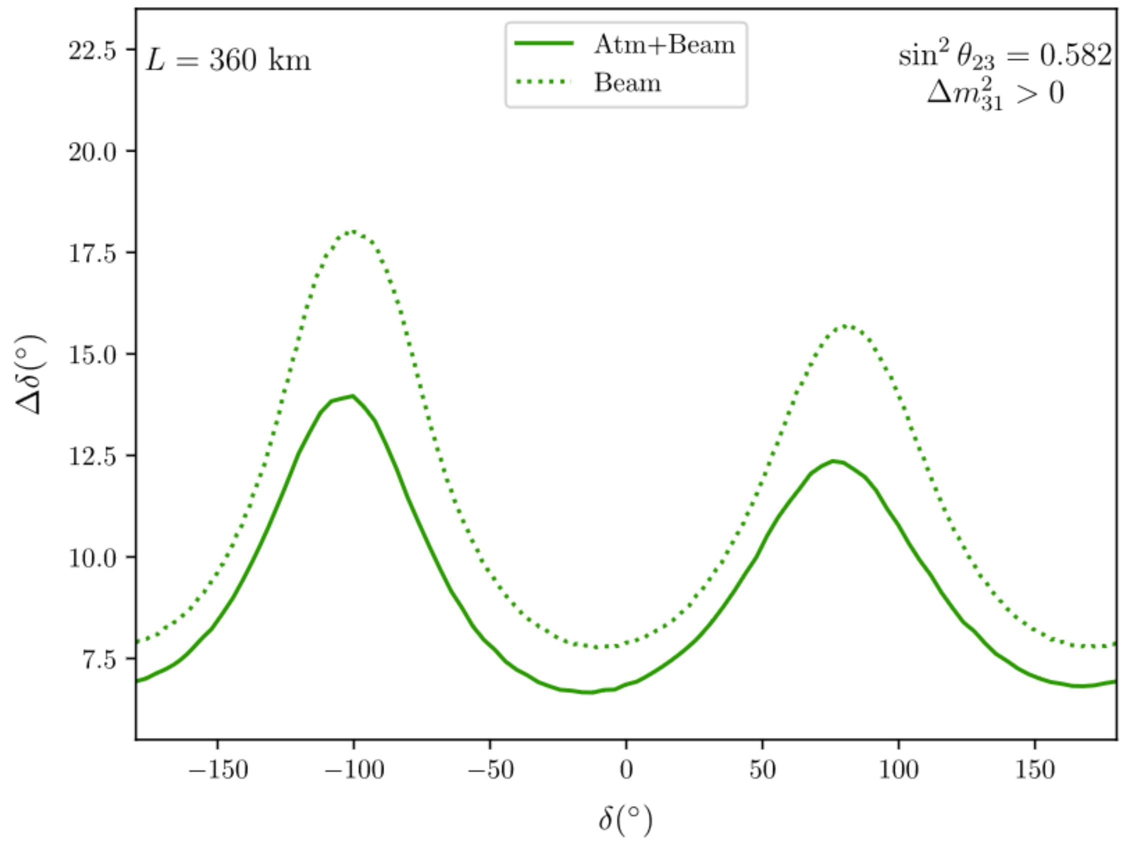
From the ESSnuSB CDR: https://doi.org/10.1140/epjs/s11734-022-00664-w & https://arxiv.org/abs/2203.08803

Non-CPV oscillation physics

- Published as intermediate result, state of analysis in June 2021
  - A. Alekou et al. (ESSnuSB Collaboration). "**Updated physics performance of the ESSnuSB experiment**", Eur.Phys.J.C 81 (2021) 12, 1130, DOI:10.1140/epjc/s10052-021-09845-8, arXiv:2107.07585
- Includes:
  - neutrino mass hierarchy sensitivity
  - θ_{23} octant sensitivity
  - Δm_{31} precision
  - … and more
- See backup slides ☺

- A new analysis using the latest models of flux/cross-section/detector response and state-of-the art statistics will be published in the future

Adding the atmospheric neutrino signal (analysis before experiment optimization)



- Early result before experimental setup optimization
- Including atmospheric neutrinos at far detector further improves the δ_{CP} precision
- New analysis is currently underway to update this result

Blennow, M., Fernandez-Martinez, E., Ota, T. et al. “Physics potential of the ESSνSB”. Eur. Phys. J. C 80, 190 (2020). https://doi.org/10.1140/epjc/s10052-020-7761-9 & https://arxiv.org/abs/1912.04309

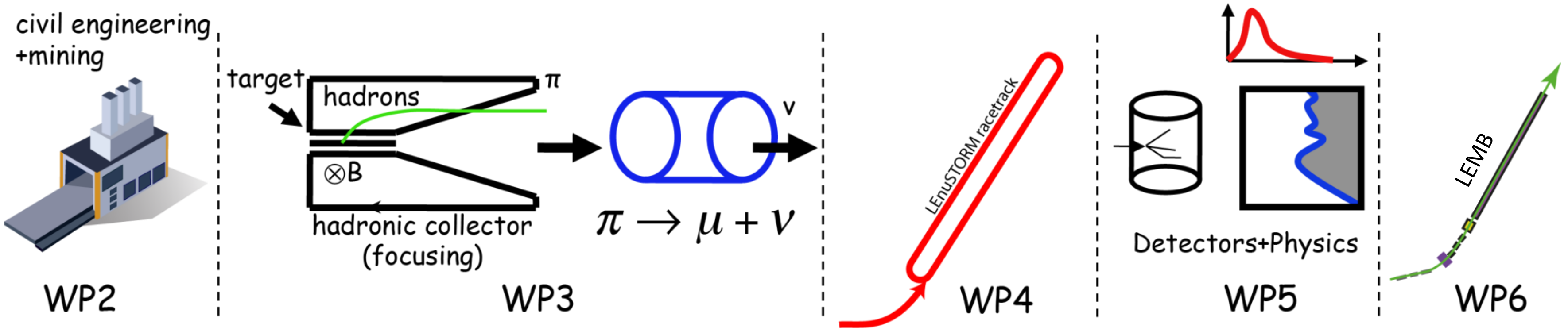
Beyond 3-flavour PMNS model

- **Sterile neutrinos**
  - Ghosh, M., Ohlsson, T. & Rosauro-Alcaraz, S. “Sensitivity to light sterile neutrinos at ESSnuSB”. *J. High Energ. Phys.* **2020**, 26 (2020). https://doi.org/10.1007/JHEP03(2020)026
- **Invisible neutrino decay**
  - Choubey, S., Ghosh, M., Kempe, D. *et al.* “Exploring invisible neutrino decay at ESSnuSB”. *J. High Energ. Phys.* **2021**, 133 (2021). https://doi.org/10.1007/JHEP05(2021)133
- **Large extra dimension**
  - Roy S. “Capability of the proposed long-baseline experiments to probe large extra dimension”, **2023,** https://doi.org/10.48550/arXiv.2305.16234
- **Non-Unitarity of the PMNS matrix**
  - Sabya Sachi Chatterjee, O. G. Miranda, M. Tórtola, and J. W. F. Valle “Nonunitarity of the lepton mixing matrix at the European Spallation Source”, Phys. Rev. D 106, 075016. **2022,** https://doi.org/10.1103/PhysRevD.106.075016
- **NSI mediated by a vector field**
  - Blennow, M., Choubey, S., Ohlsson, T. *et al.* “Exploring source and detector non-standard neutrino interactions at ESS*ν*SB”. *J. High Energ. Phys.* **2015**, 96 (2015). https://doi.org/10.1007/JHEP09(2015)096
- **NSI mediated by a scalar field**
  - Rubén Cordero, Luis A. Delgadillo, and O. G. Miranda “European Spallation Source as a searching tool for an ultralight scalar field”, Phys. Rev. D 107, 075023. **2023** https://doi.org/10.1103/PhysRevD.107.075023
- **NSI (vector field), non-unitarity and sterile neutrinos**
  - Capozzi, F., Giunti, C. & Ternes, C.A. “Improved sensitivities of ESS*ν*SB from a two-detector fit”. *J. High Energ. Phys.* **2023**, 130 (2023). https://doi.org/10.1007/JHEP04(2023)130

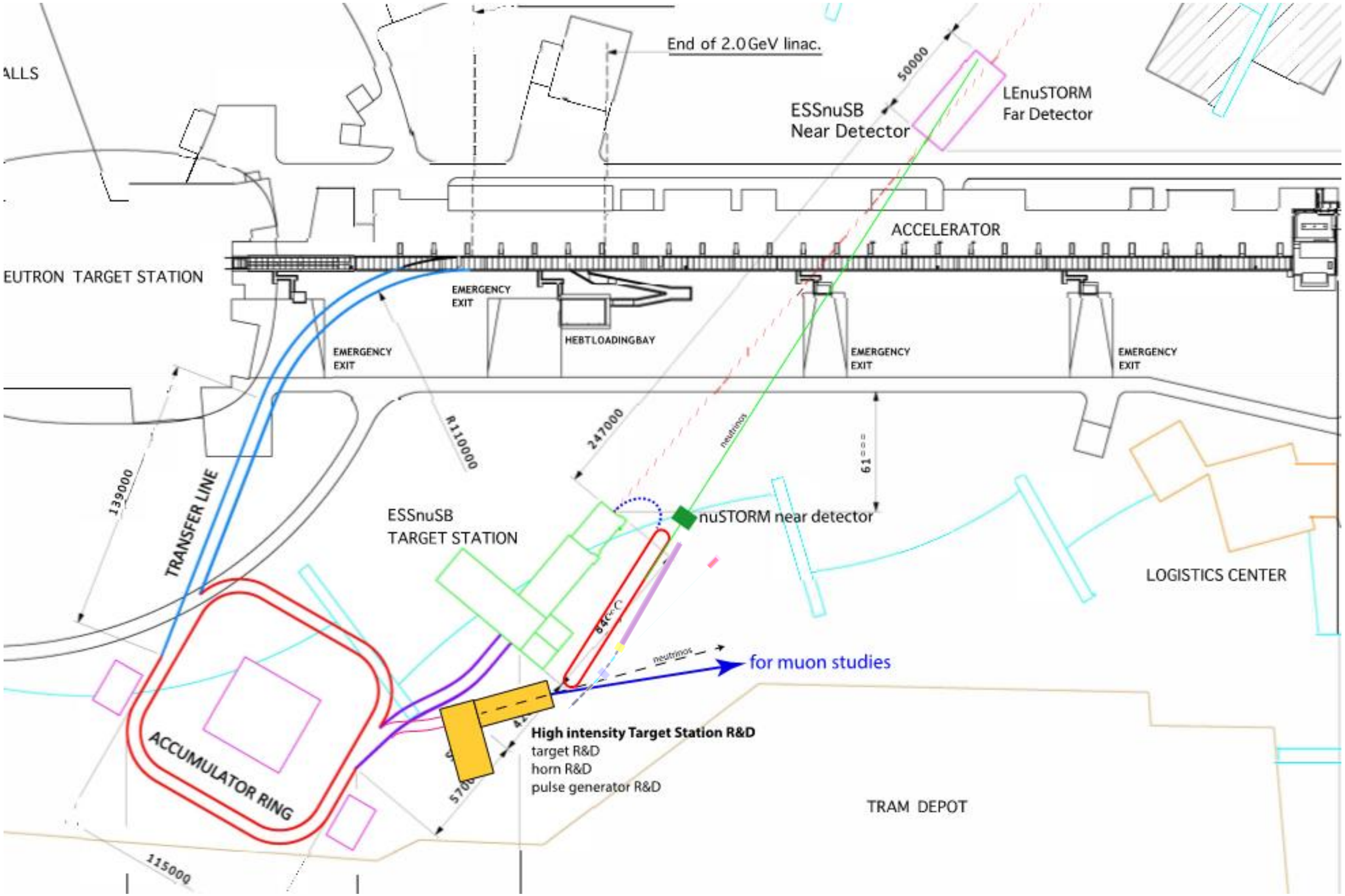
The ESSnuSB+ project

- Having finished the conceptual design of the facility for CP violation 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

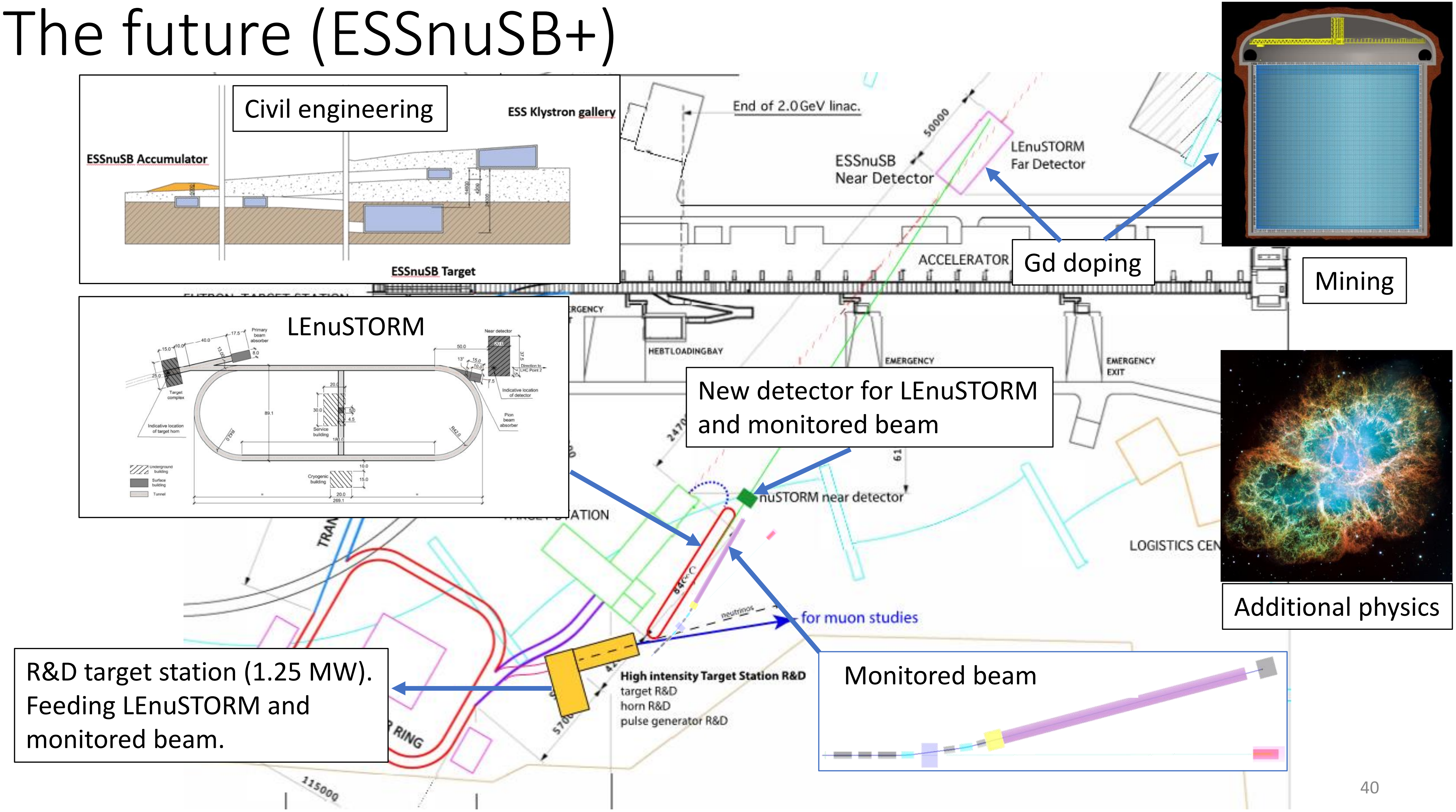
- Secured funding by EU



The future (ESSnuSB+)



The future (ESSnuSB+)



Civil engineering

LEnuSTORM

Gd doping

Mining

New detector for LEnuSTORM and monitored beam

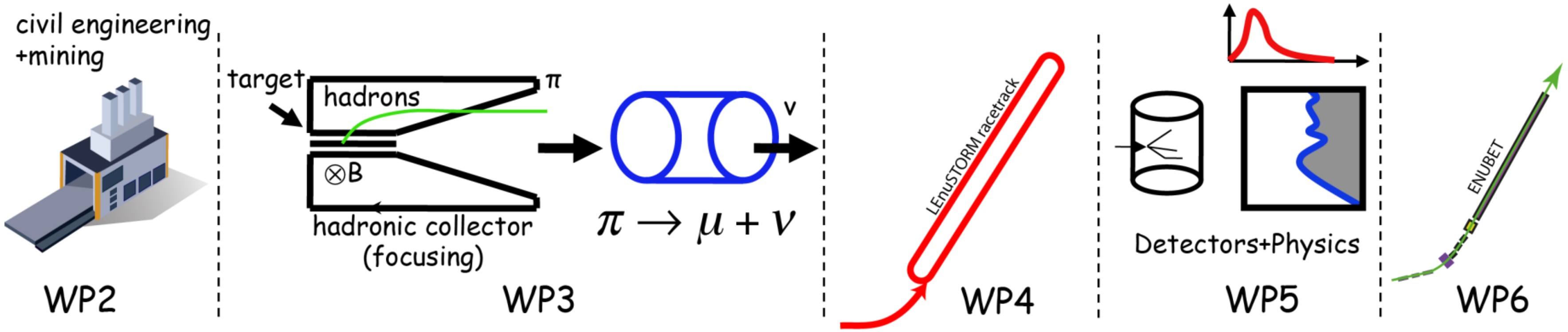
Additional physics

R&D target station (1.25 MW). Feeding LEnuSTORM and monitored beam.

Monitored 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**



ESSnuSB movies

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

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

Timeline

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

ESSνSB
ESS NEUTRINO
SUPER BEAM

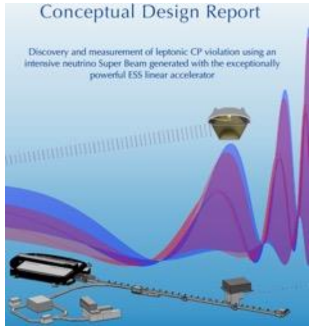
2018-2022: ESSνSB
Design Study, CDR
(EU-H2020)

ESSνSB+
ESS neutrino Super Beam plus

ESFRI

ESS
EUROPEAN
SPALLATION
SOURCE

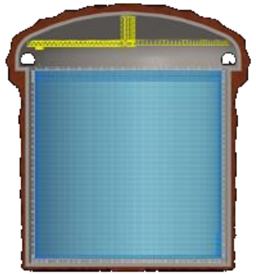
2023-2026: ESSνSB+
Design Study, CDR (EU-HE) and preparatory
phase



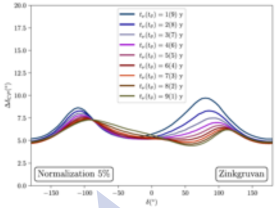
Conceptual Design Report

Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator

[ESSνSB CDR]

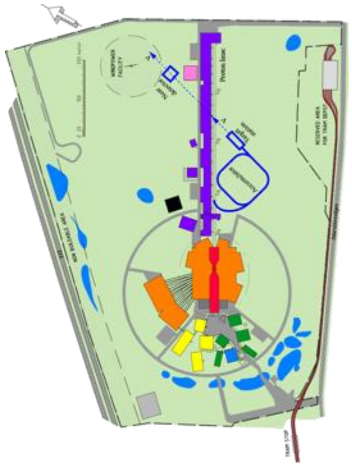


2026-2028: TDR
Phase, International
Agreement



Data taking

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



Co-funded by
the European Union

Conclusions

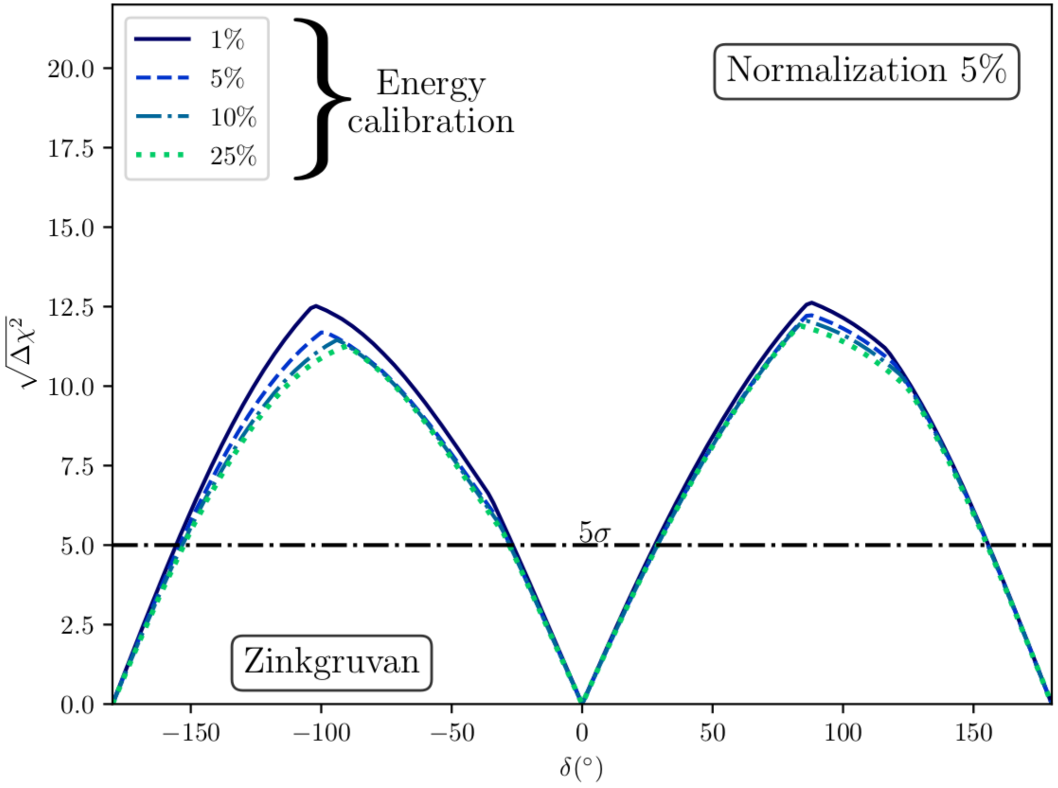
- **ESSnuSB** aims to precisely measure CP amplitude by observing neutrino oscillations at the 2nd oscillation maximum
  - **2nd maximum** makes the measurement resilient to systematic errors and matter effects
  - We predict that in 10 years of data taking ESSnuSB will be able to
    - reach 5 σ over 71% of δ_{CP} range
    - reach δ_{CP} resolution of less than 8°
    - determine neutrino mass hierarchy
  - Data taking could commence in the late 2030's (next-to-next generation experiment)
- **ESS linac** will be most powerful proton accelerator in the world
  - can be used to generate intense neutrino beam 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.
- We have been awarded **renewed support from EU-Horizon Europe** for the period 2023-2026 as the **ESSnuSB+ project**

Co-funded by
the European Union

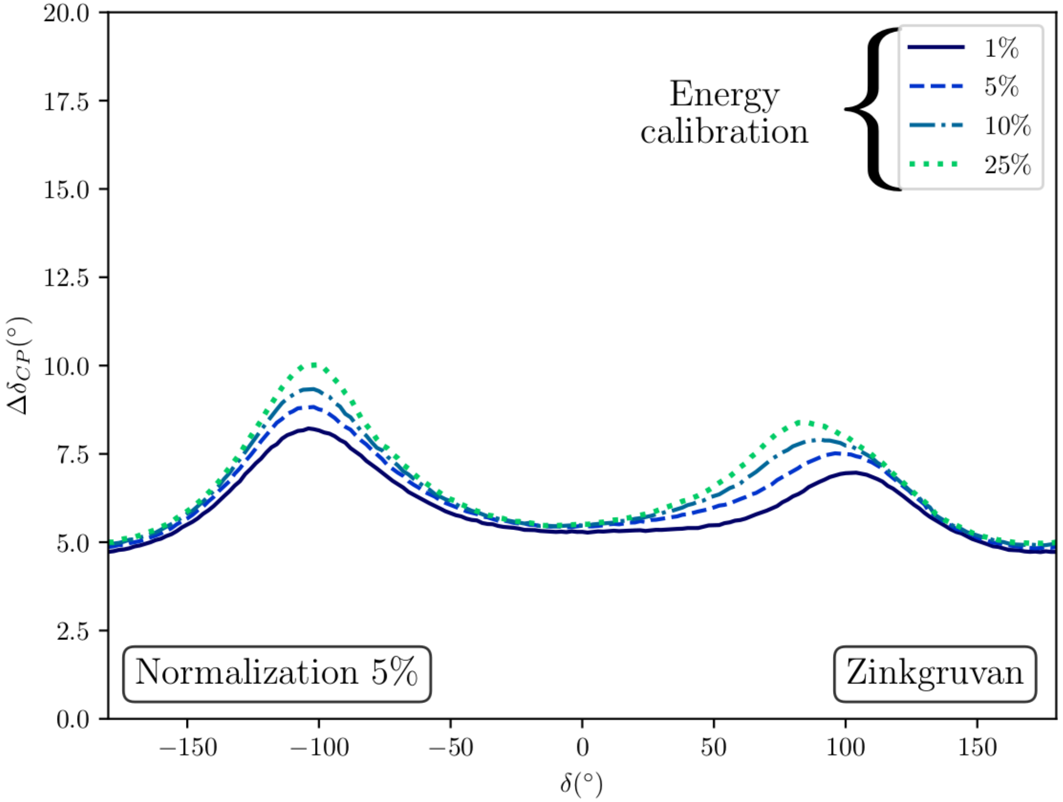
Thank you for your attention

Effect of energy calibration uncertainty on CPV measurements

Sensitivity



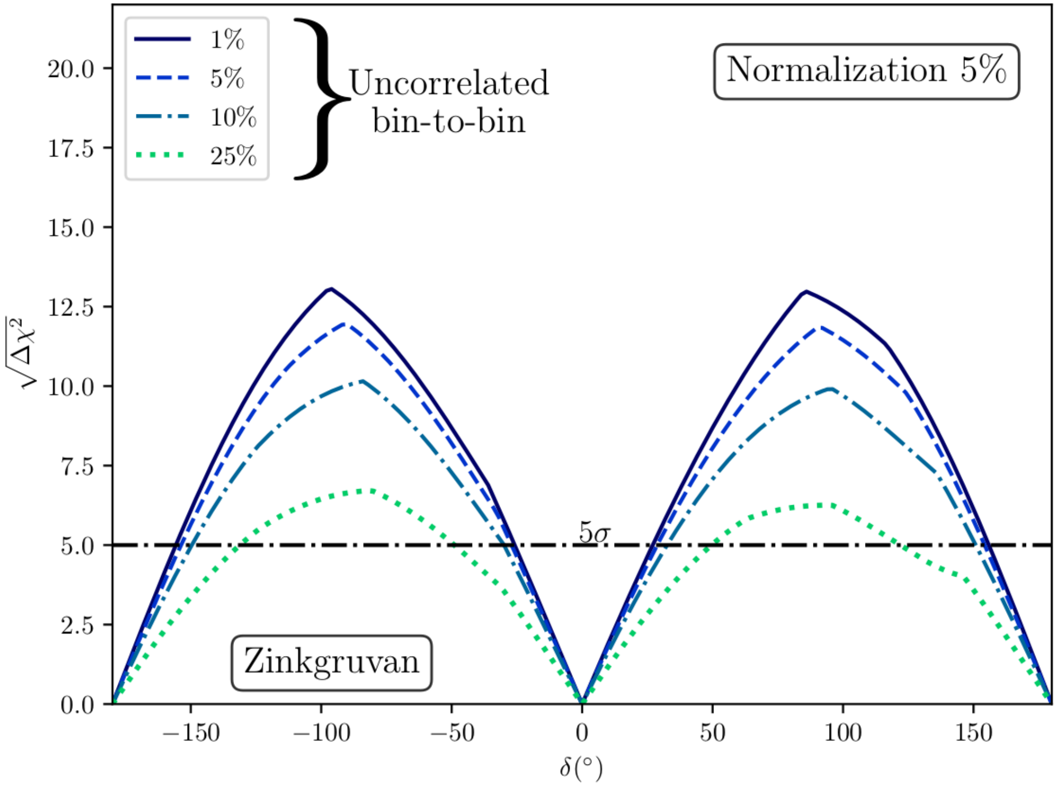
Precision



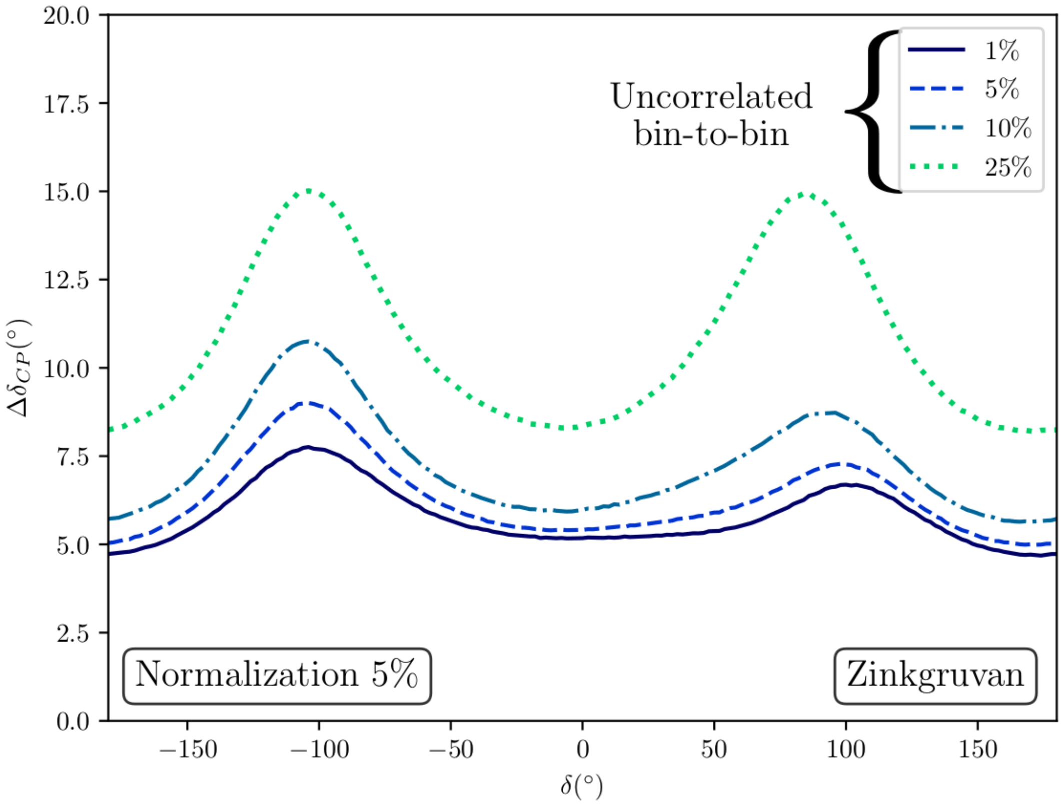
From the ESSnuSB CDR: https://doi.org/10.1140/epjs/s11734-022-00664-w & https://arxiv.org/abs/2203.08803

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

Sensitivity



Precision

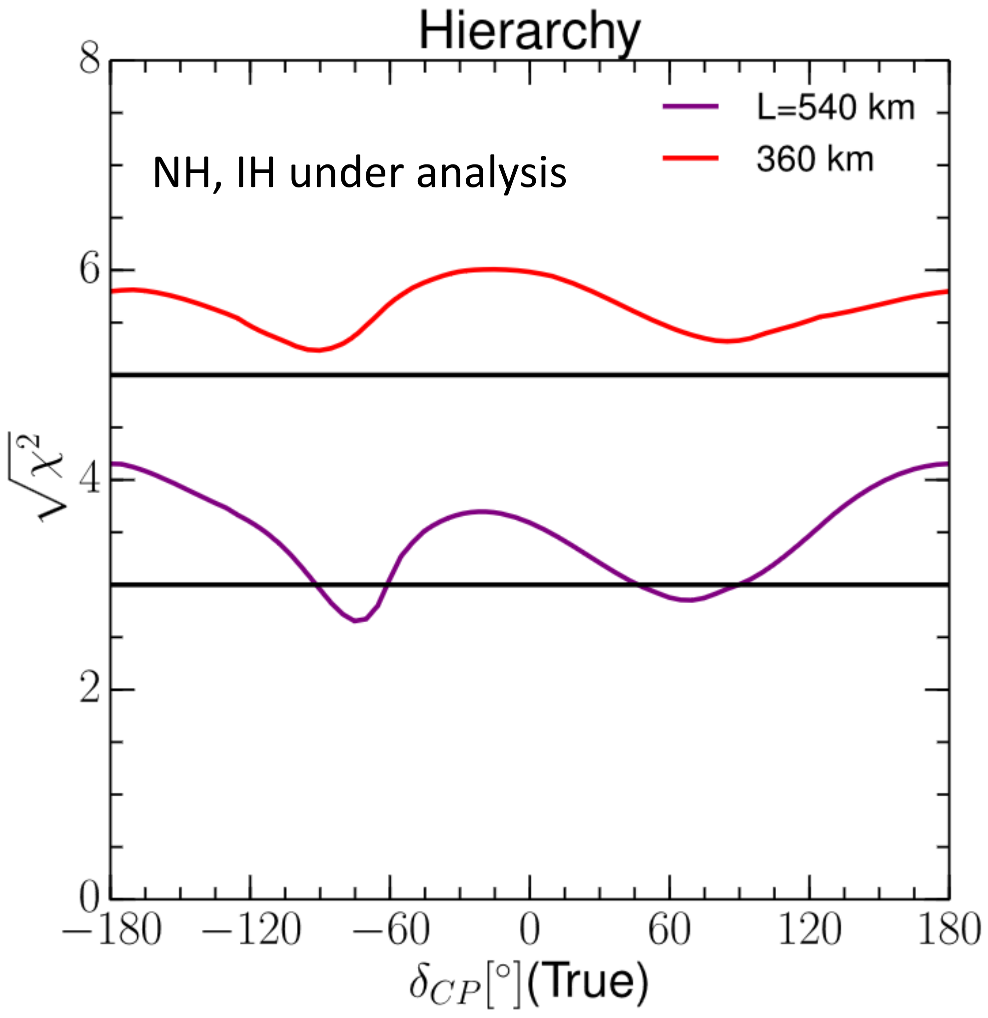


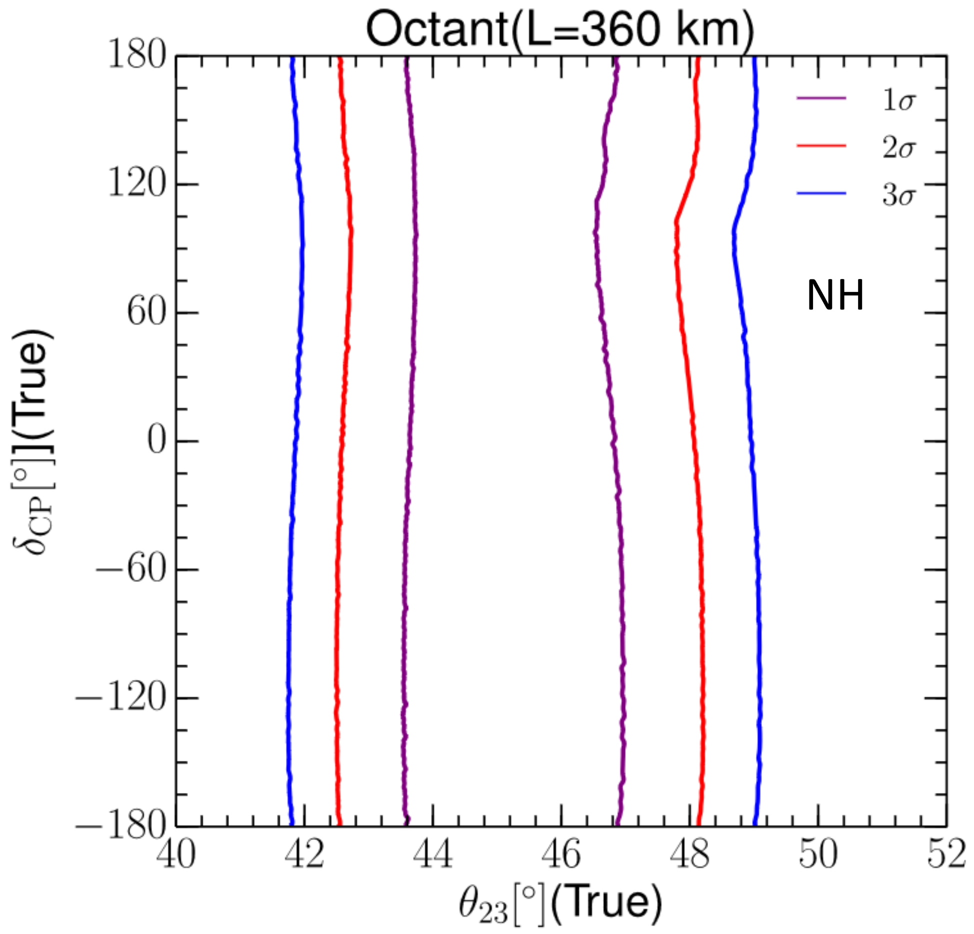
From the ESSnuSB CDR: https://doi.org/10.1140/epjs/s11734-022-00664-w & https://arxiv.org/abs/2203.08803

Hierarchy and octant determination

From: DOI:10.1140/epjc/s10052-021-09845-8, arXiv:2107.07585

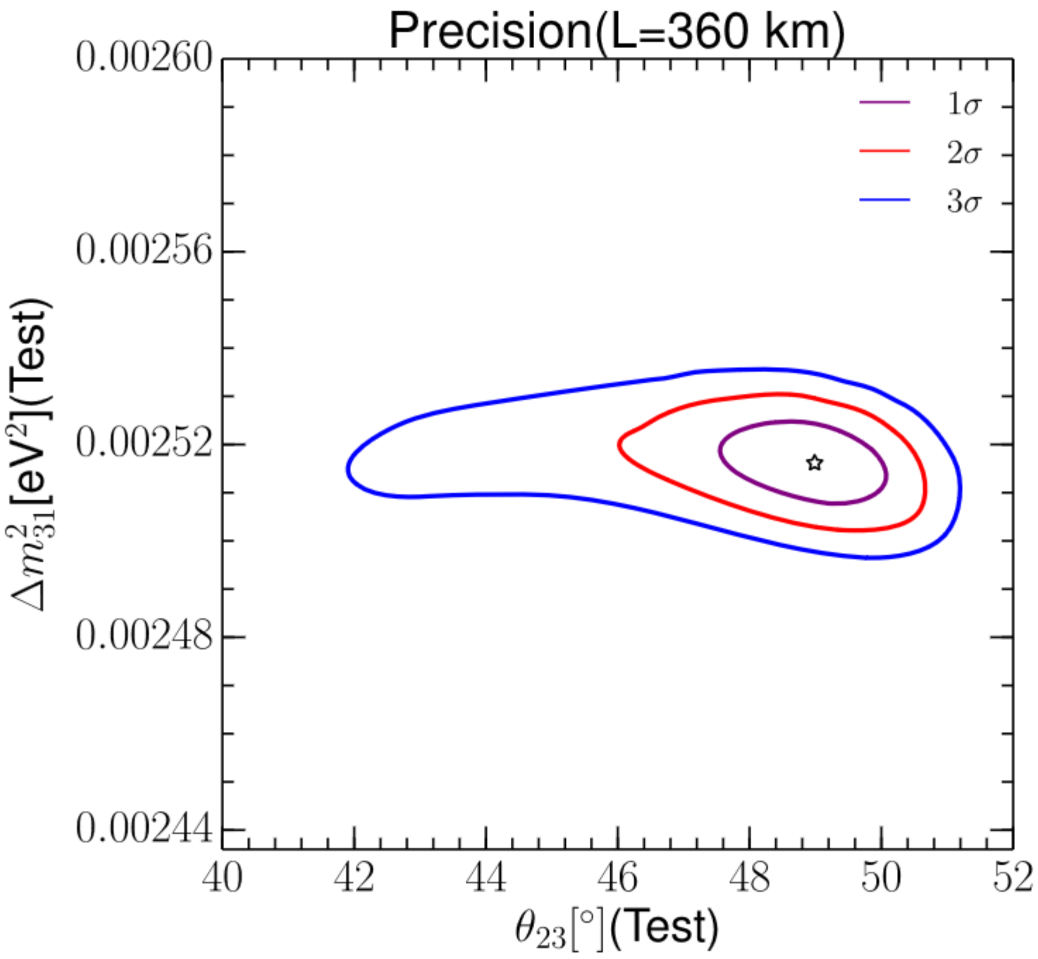
10 y of data taking


NH, IH under analysis


NH

Precision for Δm_{31} vs θ_{23}

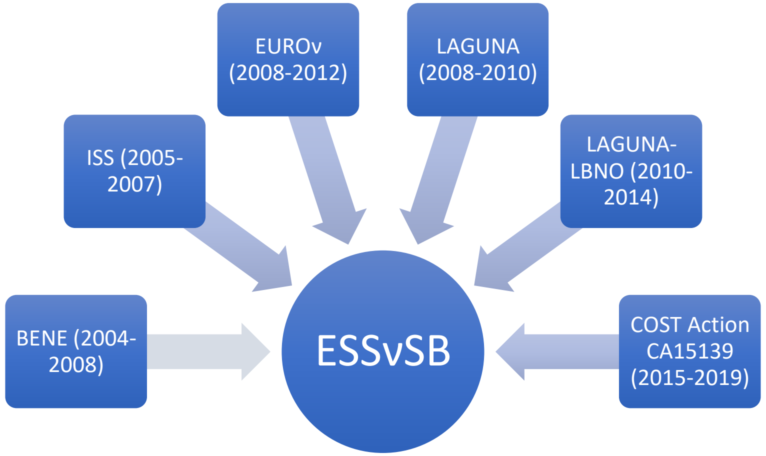
From: DOI:10.1140/epjc/s10052-021-09845-8, arXiv:2107.07585

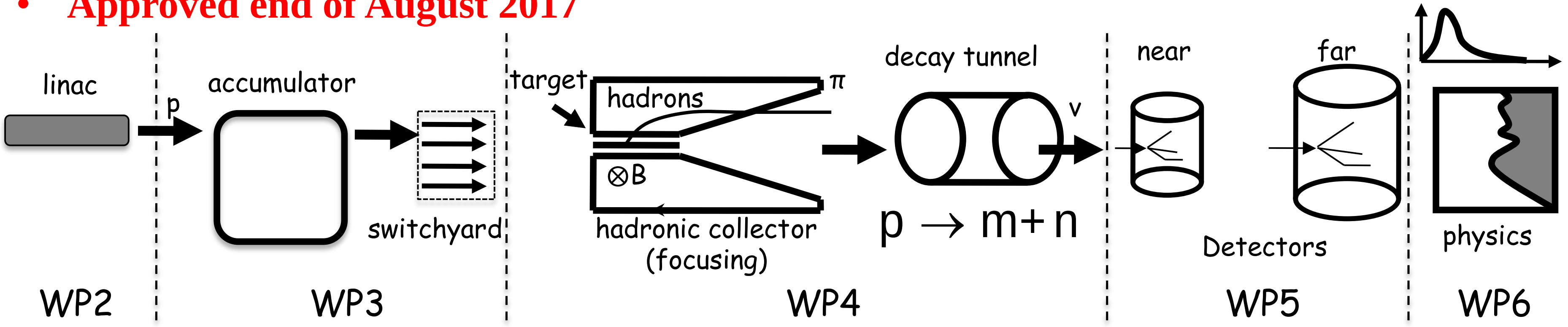


- Plot ranges are approximately current limit on parameters

ESSνSB at the European level

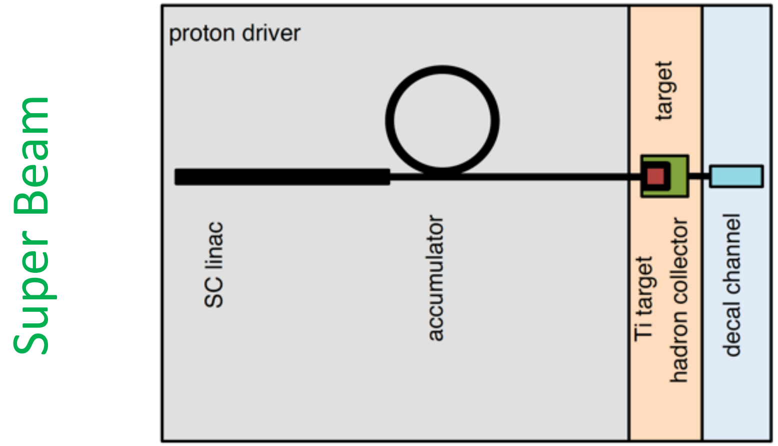
- A **H2020** EU **Design Study** (Call INFRADEV-01-2017)
  - **Title of Proposal**: Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator
  - **Duration: 4 years**
  - **Total cost: 4.7 M€**
  - **Requested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


EUROν (2008-2012)
LAGUNA (2008-2010)
ISS (2005-2007)
LAGUNA-LBNO (2010-2014)
BENE (2004-2008)
ESSνSB
COST Action CA15139 (2015-2019)

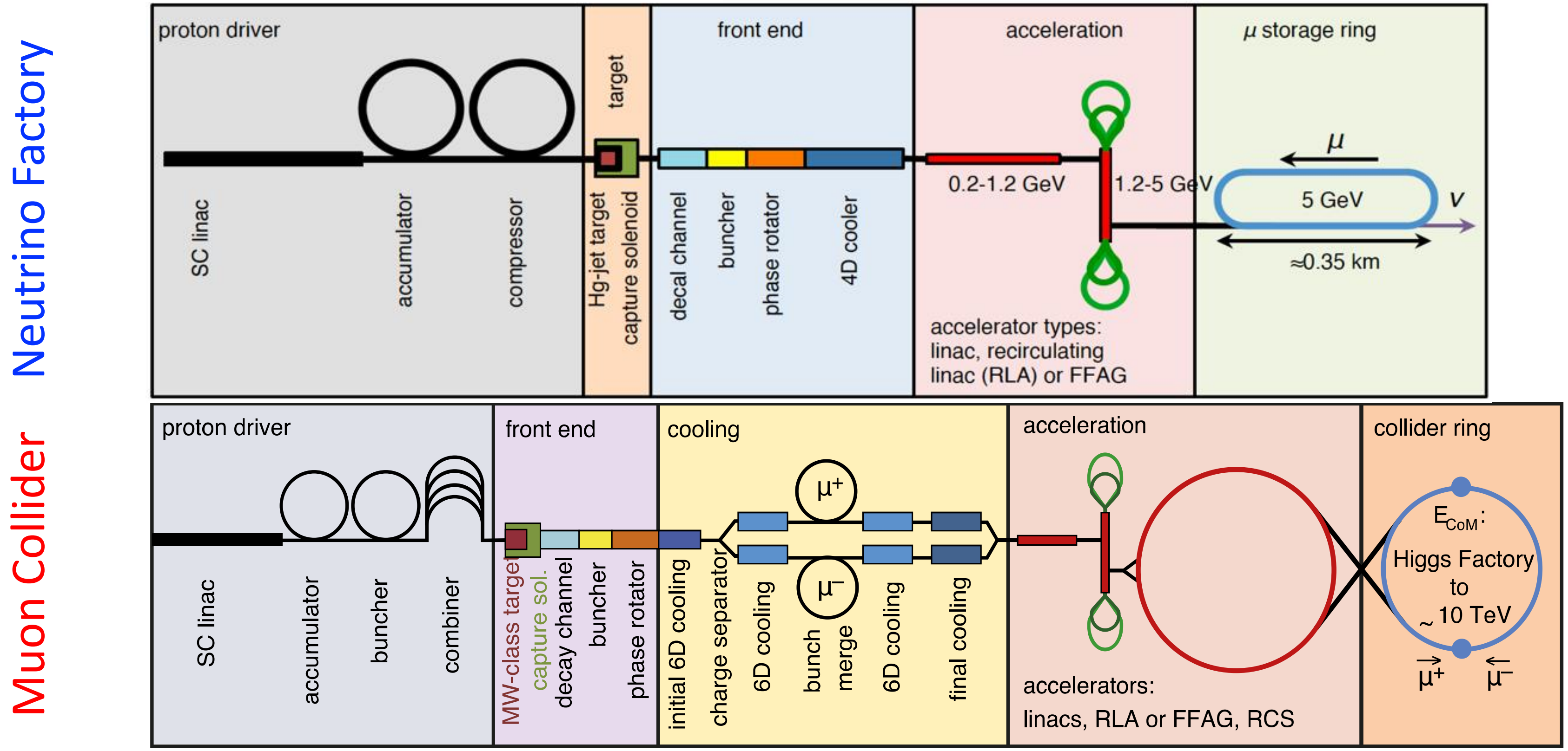


ESSνSB and (R&D) synergies

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



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



Neutrino oscillations

Flavour state evolution

Relativistic space-time translation operator

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

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:

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

And finally:

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

Neutrino oscillations

Oscillation probability in vacuum

Oscillation probability:

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

Assuming:

$\vec{L}$ parallel to $\vec{p_i}$ - neutrino travels in the direction of its momentum

$$\left.\begin{aligned} T &= L/\beta \approx L \\ E_i + p_i &\approx 2E \end{aligned}\right\} E \gg m_i$$

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

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

One gets the final relation:

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

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

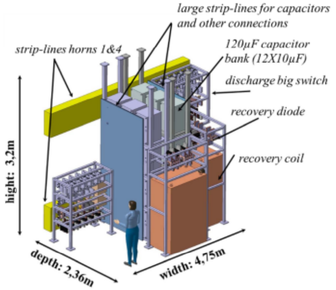
Morgue

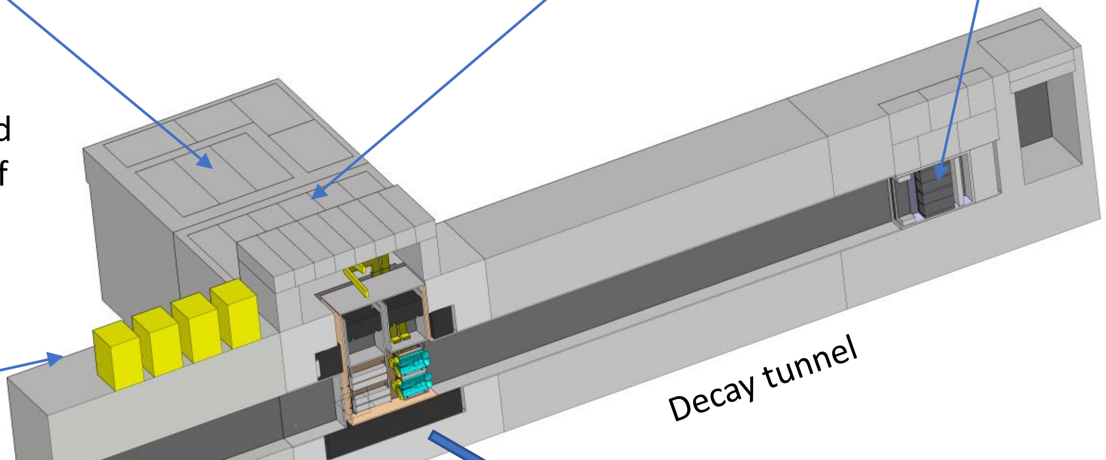
To Store radioactive wastes

Beam dump

Power Supply Unit

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

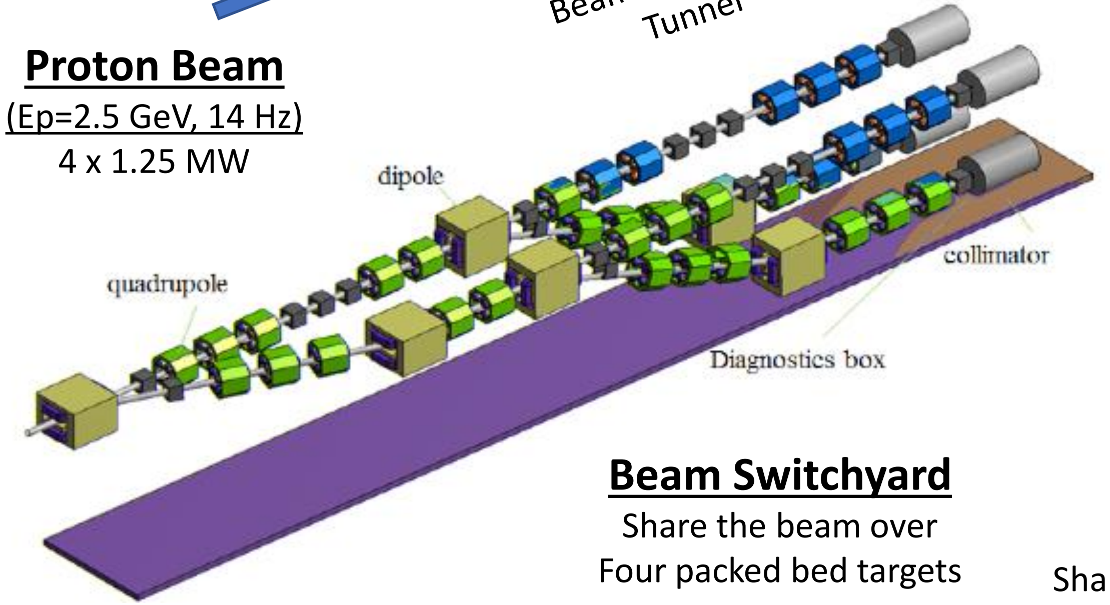




Proton Beam

(Ep=2.5 GeV, 14 Hz)

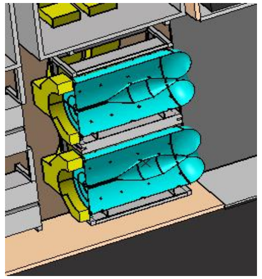
4 x 1.25 MW



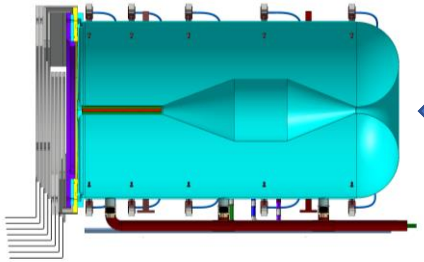
Beam Switchyard

Share the beam over

Four packed bed targets

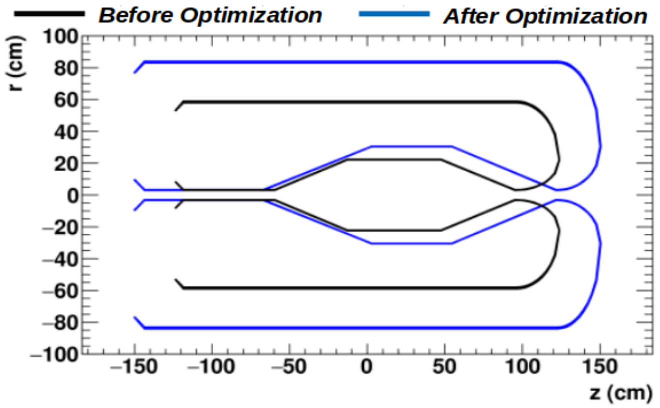


Hadronic Collector



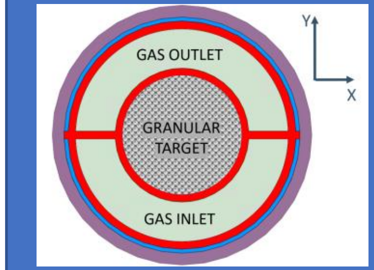
MiniBoone Like Horn

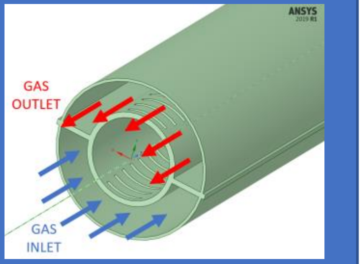
Shape optimized with genetic algorithm

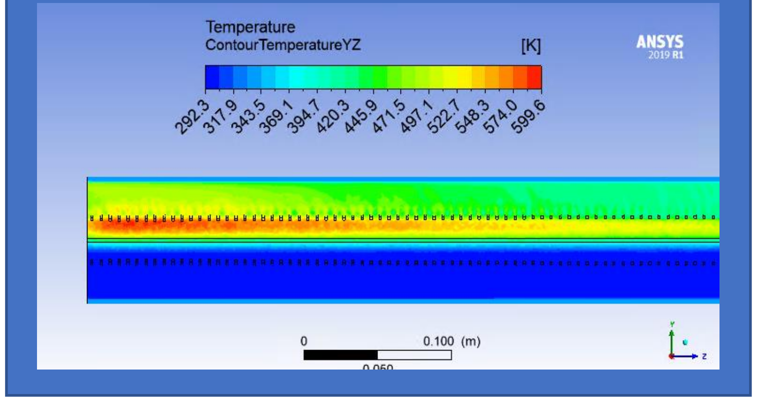


Granular Target Concept

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





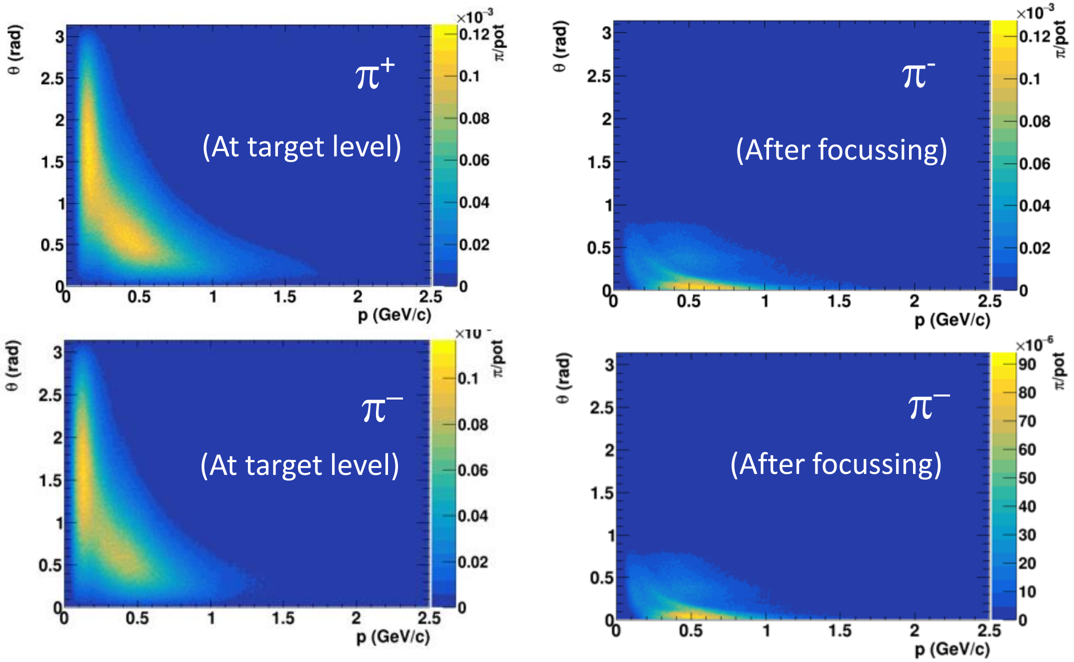


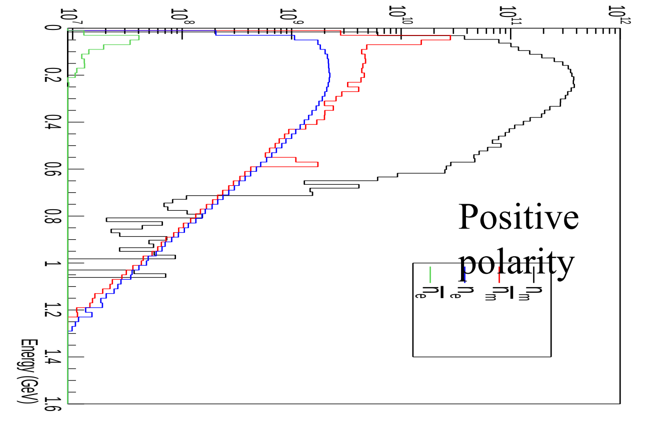
Neutrino beam production

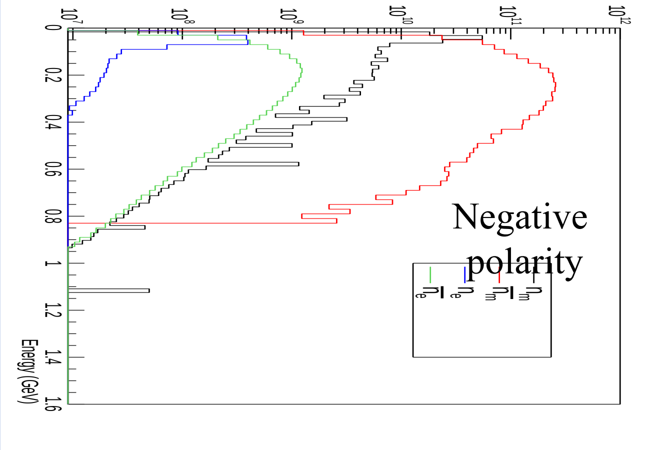
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \text{(Positive polarity)}$$

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

Horn focussing



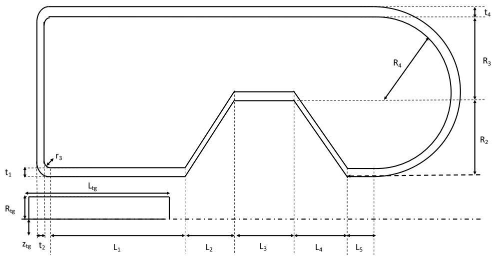




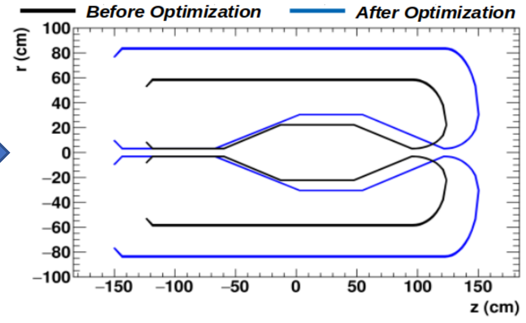
Neutrino flux composition.

	ϕ_ν 10^{10}.m^{-2}	%	ϕ_ν 10^{10}.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



Horn parametrisation



Optimisation based on Genetic Algorithm

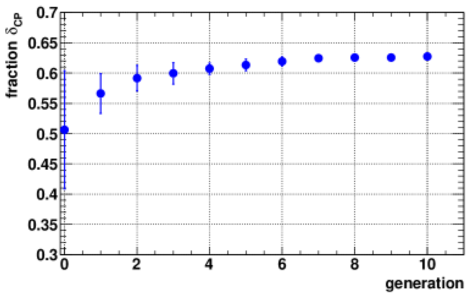
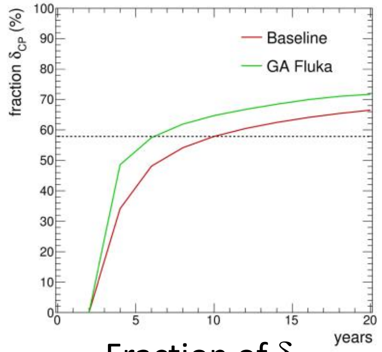
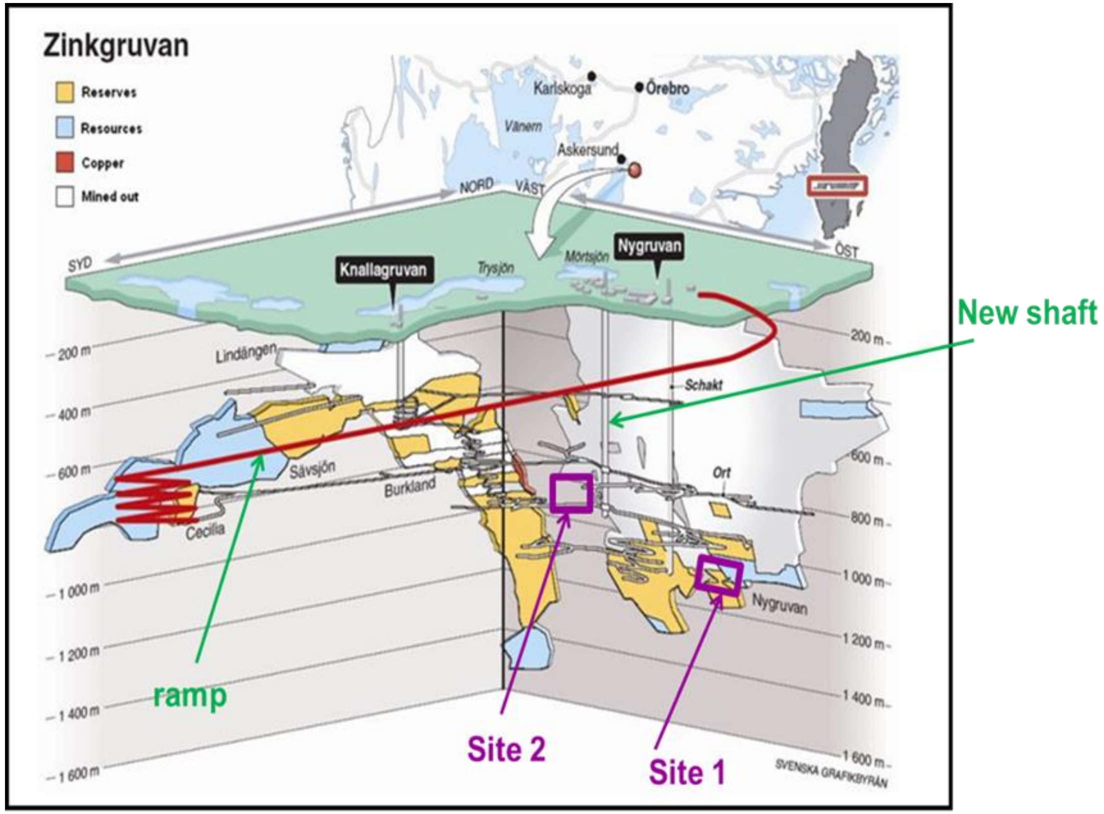


Figure of Merit based on δ_{cp}

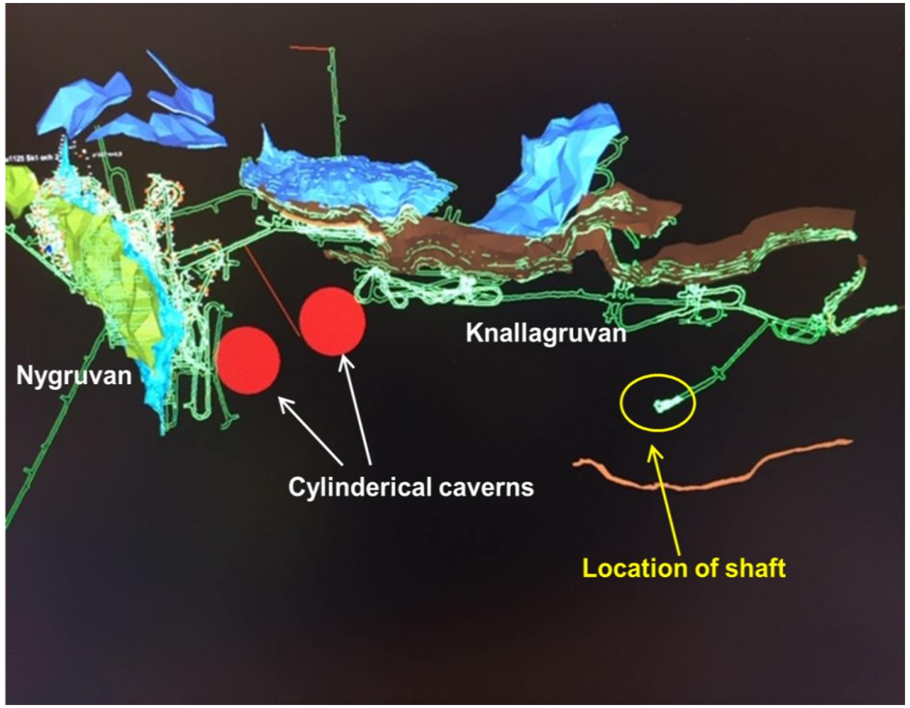


Fraction of δ_{cp}

Zinkgruvan mine

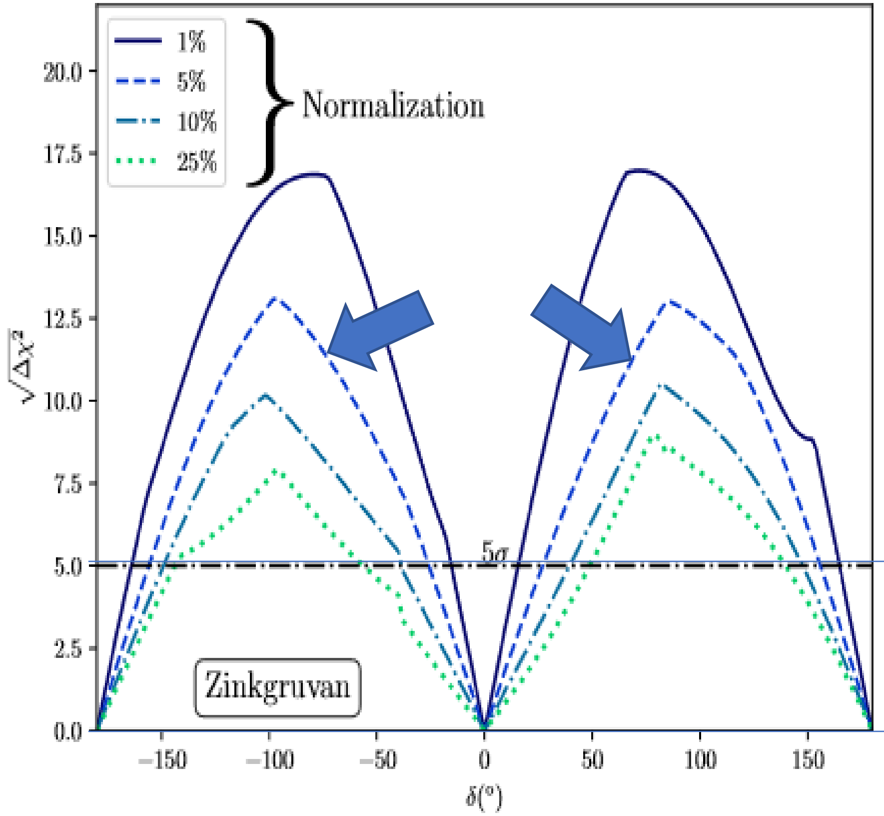


Potential location in Site 2

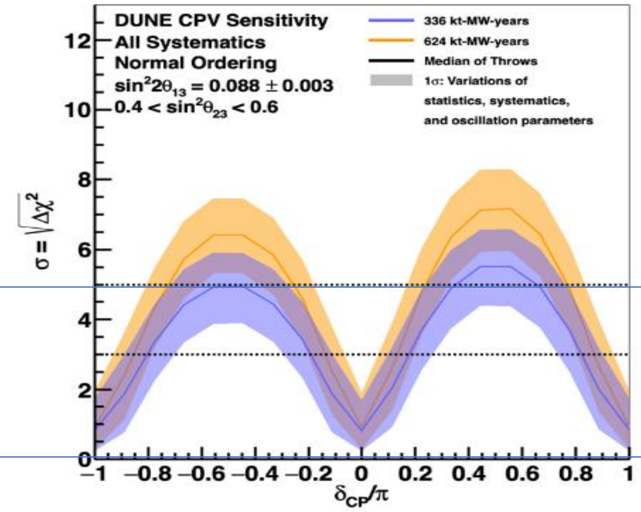


Site 2 is considered as best considering access to main transport infrastructure and located in an area less disturbed by mining activities

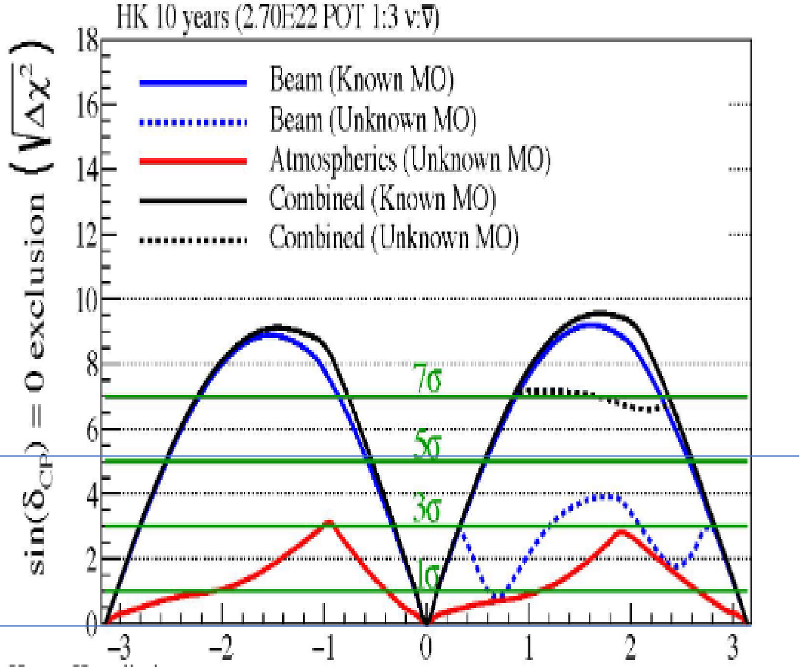
ESSnuSB in the international context – CPV discovery



ESSnuSB March 2022 with 5% normalization error

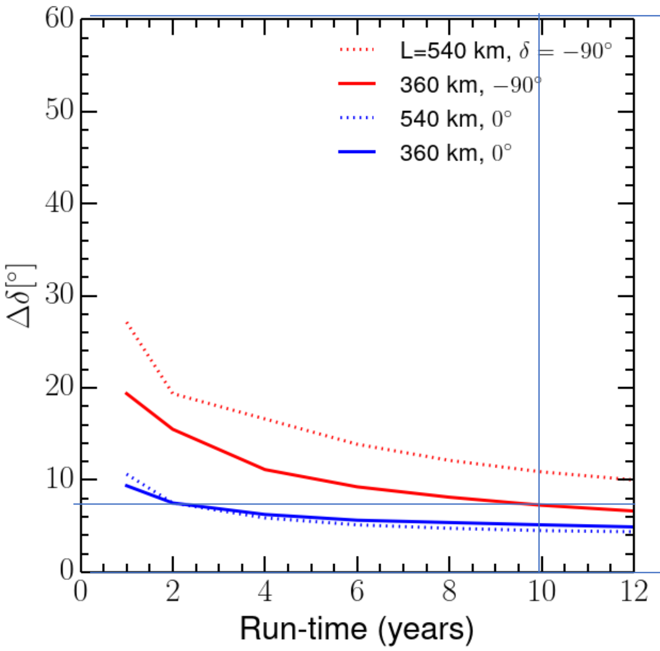


DUNE Snowmass March 2022

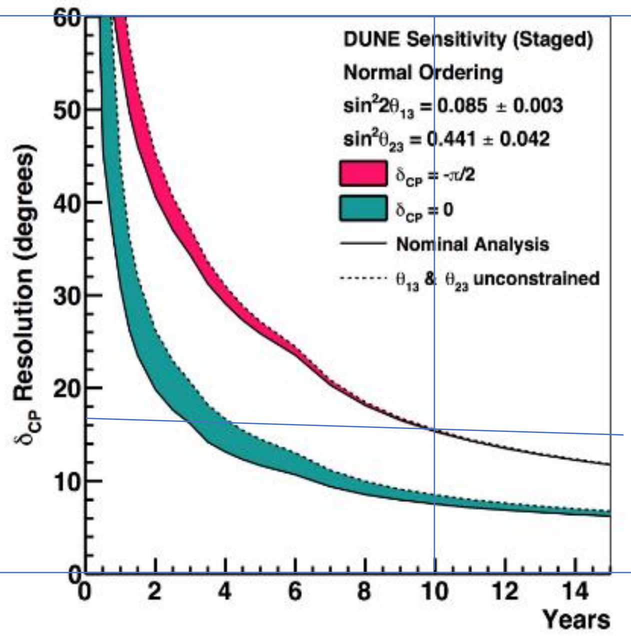


Hyper-Kamiokande Snowmass March 2022

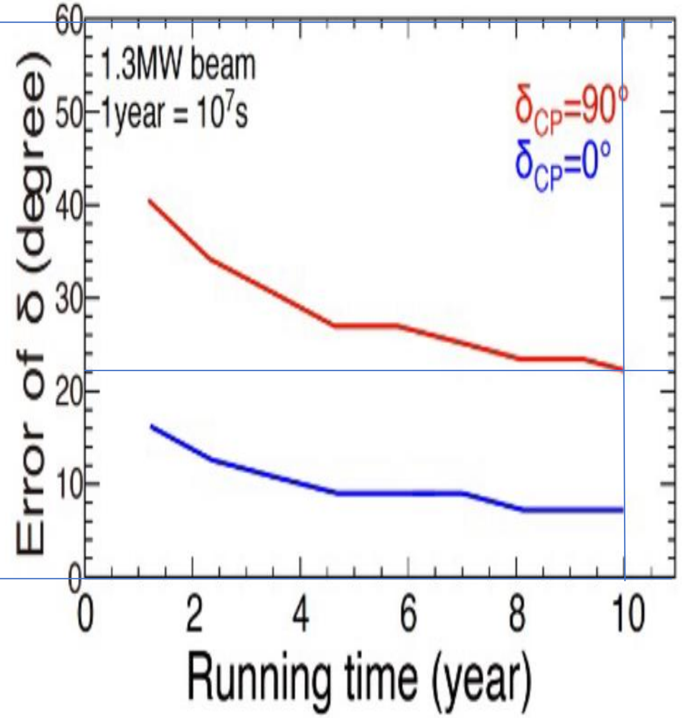
ESSnuSB in the international context – CPV resolution



ESSnuSB March 2022 with 5% normalization error



DUNE Snowmass March 2022



Hyper-Kamiokande Snowmass March 2022

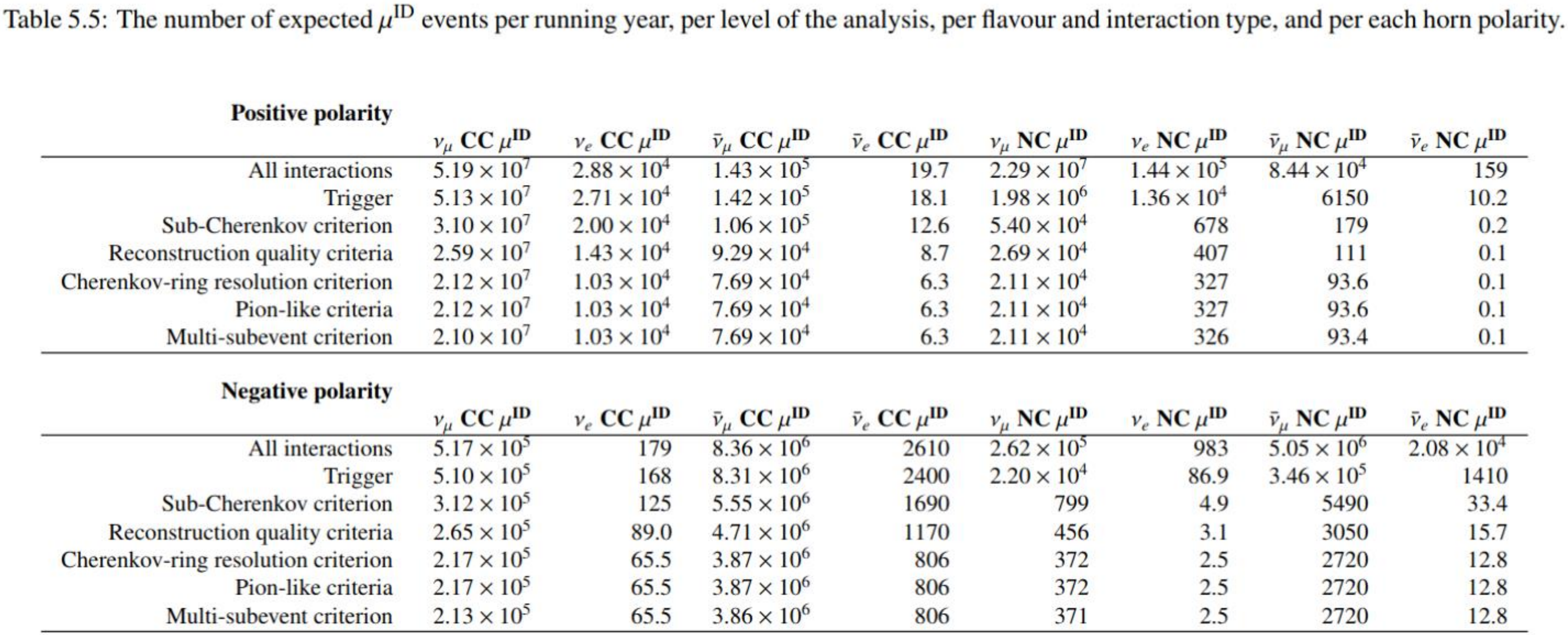


Table 5.5: The number of expected μ^{ID} events per running year, per level of the analysis, per flavour and interaction type, and per each horn polarity.

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

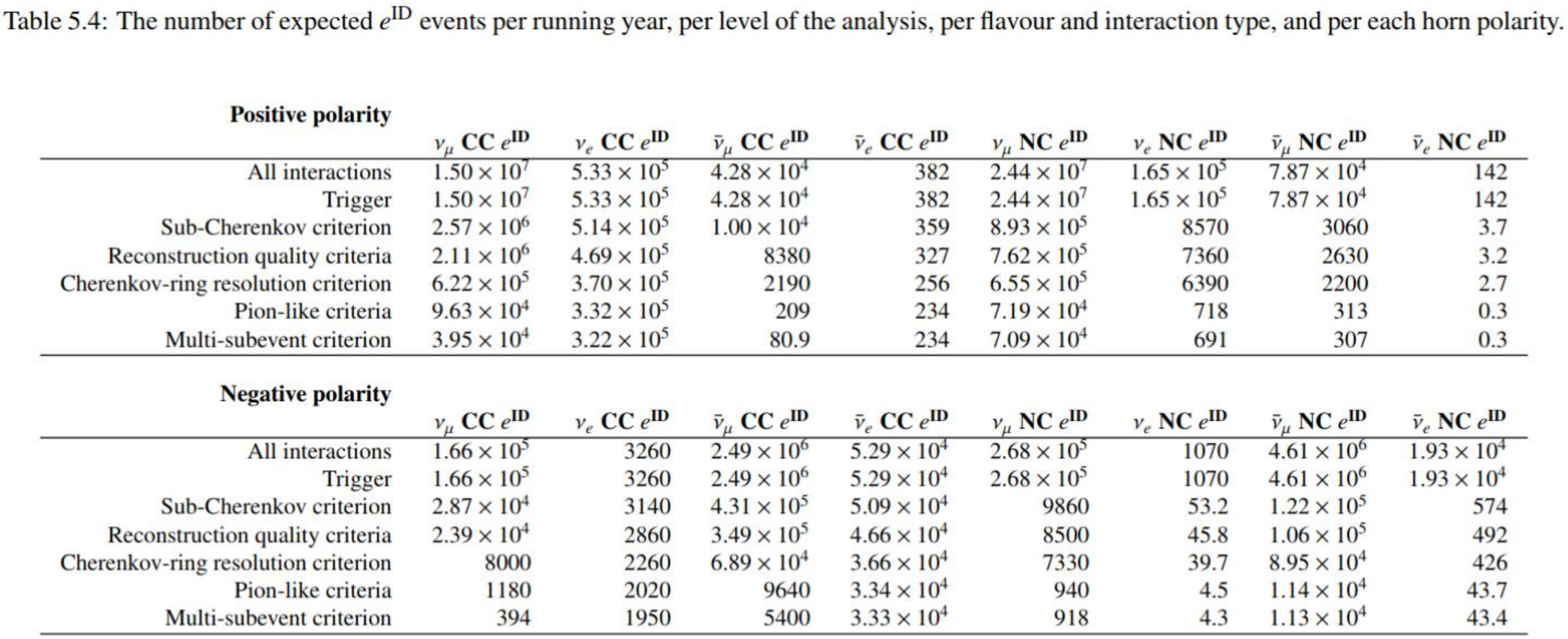


Table 5.4: The number of expected e^{ID} events per running year, per level of the analysis, per flavour and interaction type, and per each horn polarity.

Positive polarity	**ν_μ CC e^{ID}**	**ν_e CC e^{ID}**	**$\bar{\nu}_\mu$ CC e^{ID}**	**$\bar{\nu}_e$ CC e^{ID}**	**ν_μ NC e^{ID}**	**ν_e NC e^{ID}**	**$\bar{\nu}_\mu$ NC e^{ID}**	**$\bar{\nu}_e$ NC e^{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	**ν_μ CC e^{ID}**	**ν_e CC e^{ID}**	**$\bar{\nu}_\mu$ CC e^{ID}**	**$\bar{\nu}_e$ CC e^{ID}**	**ν_μ NC e^{ID}**	**ν_e NC e^{ID}**	**$\bar{\nu}_\mu$ NC e^{ID}**	**$\bar{\nu}_e$ NC e^{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

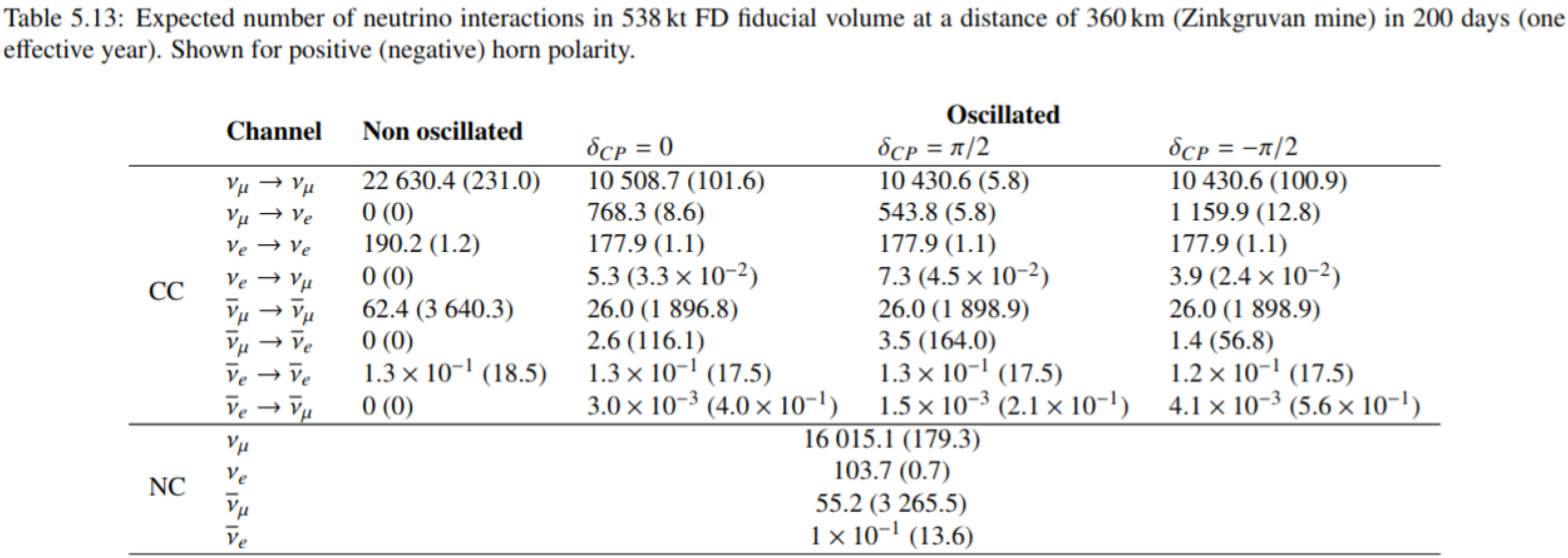
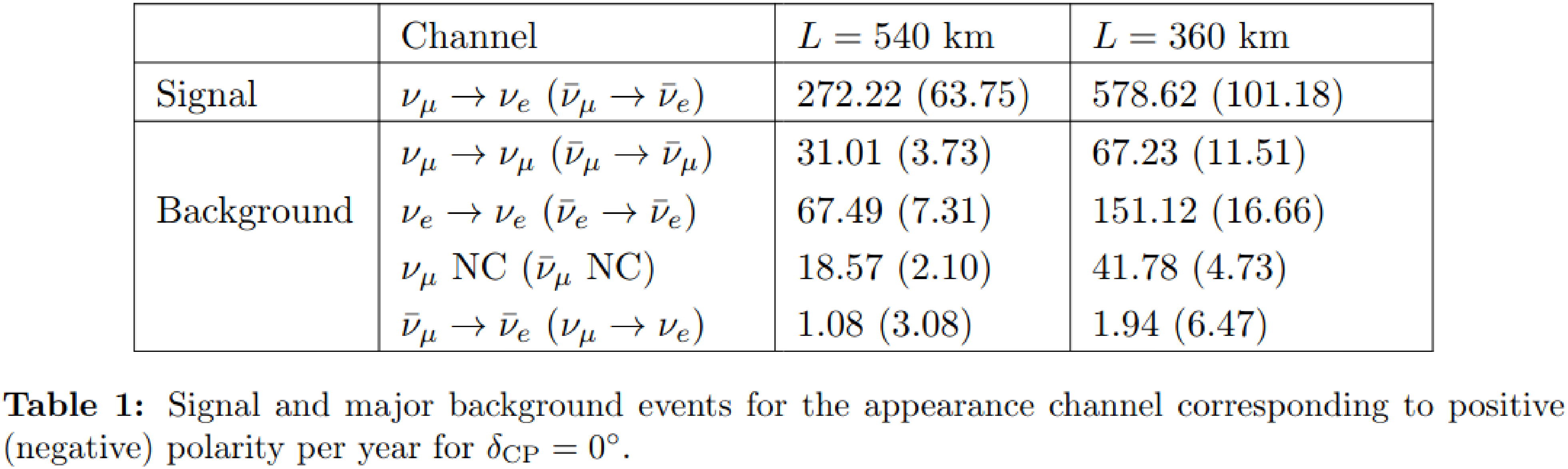


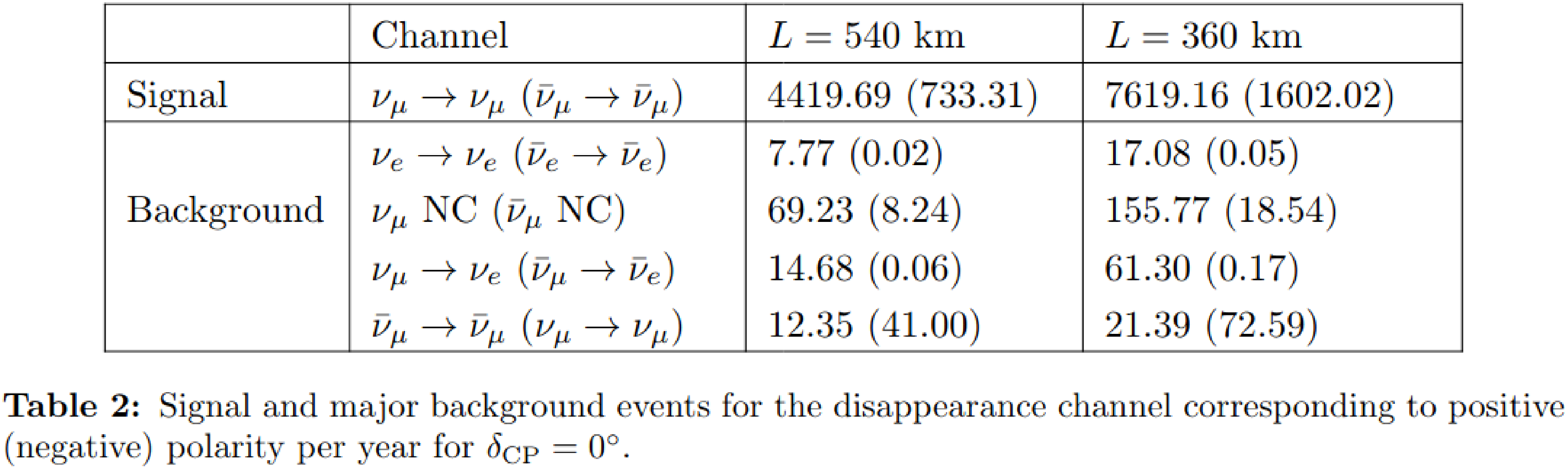
Table 5.13: Expected number of neutrino interactions in 538 kt FD fiducial volume at a distance of 360 km (Zinkgruvan mine) in 200 days (one effective year). Shown for positive (negative) horn polarity.

	Channel	**Non oscillated**	**Oscillated**		
			$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = -\pi/2$
CC	$\nu_\mu \to \nu_\mu$	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 (3 640.3)	26.0 (1 896.8)	26.0 (1 898.9)	26.0 (1 898.9)
	$\overline{\nu}_\mu \to \overline{\nu}_e$	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 (3 265.5)			
	$\overline{\nu}_e$	1×10^{-1} (13.6)			



	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)

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



	Channel	$L = 540$ km	$L = 360$ km
Signal	$\nu_\mu \to \nu_\mu$ $(\bar{\nu}_\mu \to \bar{\nu}_\mu)$	4419.69 (733.31)	7619.16 (1602.02)
Background	$\nu_e \to \nu_e$ $(\bar{\nu}_e \to \bar{\nu}_e)$	7.77 (0.02)	17.08 (0.05)
	ν_μ NC ($\bar{\nu}_\mu$ NC)	69.23 (8.24)	155.77 (18.54)
	$\nu_\mu \to \nu_e$ $(\bar{\nu}_\mu \to \bar{\nu}_e)$	14.68 (0.06)	61.30 (0.17)
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$ $(\nu_\mu \to \nu_\mu)$	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 $\delta_{\mathrm{CP}} = 0°$.

Neutrino oscillations

Neutrino flavor eigenstate is not a mass eigenstate

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U^* \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$$\underset{\text{flavour eigenstate}}{|\nu_\alpha\rangle} = \sum_{i=1}^{n} \underset{\text{mixing matrix}}{U^*_{\alpha i}} \, \underset{\text{mass eigenstates}}{|\nu_i\rangle}$$

$$|\nu_i\rangle \ \text{ has a mass } m_i$$

- $U_{\alpha i}$ is called the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix
- $U_{\alpha i}$ must be unitary for probability conservation
  - for *n* generations of neutrinos it is a *n* x *n* complex matrix
  - here we focus on standard 3 neutrino generations

CP violation in vacuum

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

CP violation

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

T violation

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

CPT symmetry

$$P_{\nu_\alpha\to\nu_\beta} = P_{\overline{\nu}_\beta\to\overline{\nu}_\alpha}$$

All three equations can be proven using the formula above.

CP violation “amplitude”:

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

Jarlskog invariant

$$s_{ij} \equiv \sin\theta_{ij}$$
$$c_{ij} \equiv \cos\theta_{ij}$$
$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$
$$A^{\alpha\beta}_{ij} \equiv U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}$$

$$\mathrm{Im}\left(A^{\alpha\beta}_{ij}\right) \equiv \pm J$$

← Definition of Jarlskog invariant

Imaginary part of $A^{\alpha\beta}_{ij}$ is constant up to a sign for all $\alpha \neq \beta$ and $i \neq j$, else it is zero

- this is a “measure” of CP violation in 3-generation neutrino model

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

← Jarlskog invariant in standard 3-gen PMNS parametrization

- J = 0 if any of the mixing angles θ_{ij} is 0 or $\pi/2$, or δ_{CP} is 0 or π
  - in that case there is no CP violation
- $J \sim -0.03$ assuming current PDG central values

CP violation “amplitude”:

$$P_{\alpha\to\beta} - P_{\overline{\alpha}\to\overline{\beta}} = 4\sum_{i>j}\mathrm{Im}\left(A^{\alpha\beta}_{ij}\right)\sin\frac{\Delta m^2_{ij}L}{2E}$$

$$s_{ij} \equiv \sin\theta_{ij}$$
$$c_{ij} \equiv \cos\theta_{ij}$$
$$\Delta m^2_{ij} \equiv m_i^2 - m_j^2$$
$$A^{\alpha\beta}_{ij} \equiv U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}$$

CP violation in ESSnuSB

General CP violation “amplitude”:

$$P_{\nu_\alpha \to \nu_\beta} - P_{\overline{\nu}_\alpha \to \overline{\nu}_\beta} = 4 \sum_{i>j} \mathrm{Im}\left(A^{\alpha\beta}_{ij}\right) \sin\frac{\Delta m^2_{ij} L}{2E}$$

ESSnuSB CP violation

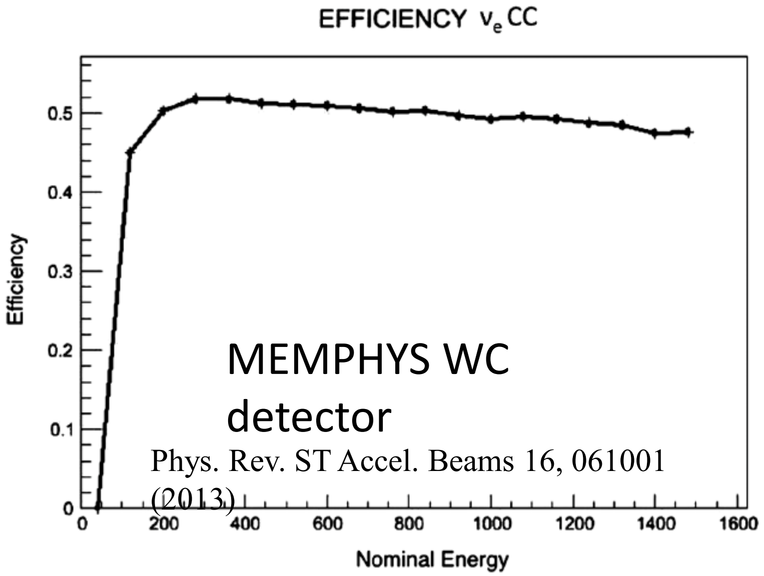
$$P_{\nu_\mu \to \nu_e} - P_{\overline{\nu}_\mu \to \overline{\nu}_e} = 4J\left(\sin\frac{\Delta m^2_{31} L}{2E} - \sin\frac{\Delta m^2_{32} L}{2E} - \sin\frac{\Delta m^2_{21} L}{2E}\right)$$
$$= -16J \sin\frac{\Delta m^2_{31} L}{4E} \sin\frac{\Delta m^2_{32} L}{4E} \sin\frac{\Delta m^2_{21} L}{4E}$$

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

To have CP violation we must have $J \neq 0$,
but also $\Delta m^2_{ij} \neq 0$ --> all three masses must be different

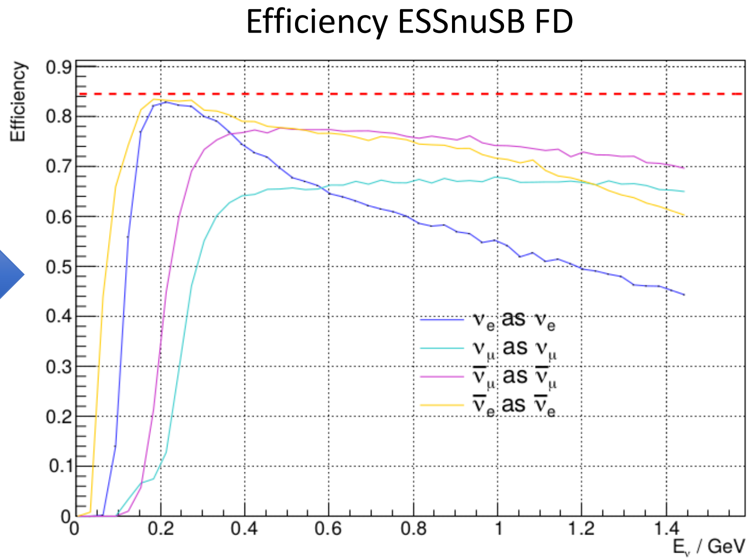
Sensitivity improvements since project start

- Near detectors optimized for flux and cross-section measurement - 5% systematics within easy reach
- Far detectors’ response optimized for ESSnuSB flux – very high efficiency and purity at ESSnuSB energies
- Genetic Algorithm for Target Station optimization – more neutrinos

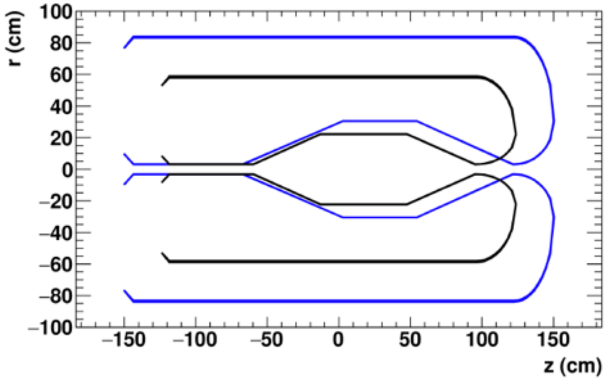


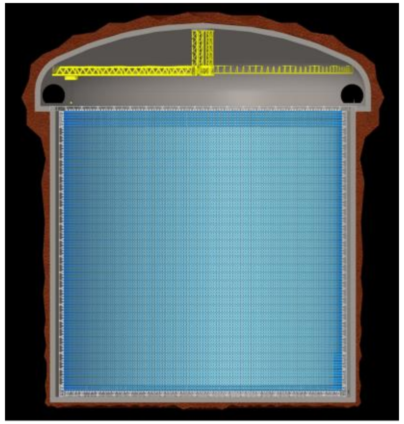
MEMPHYS WC detector

Phys. Rev. ST Accel. Beams 16, 061001 (2013)

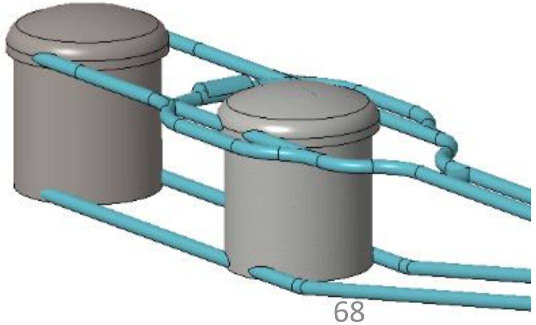

Efficiency ESSnuSB FD

horn optimisation





538 kt
total fiducial

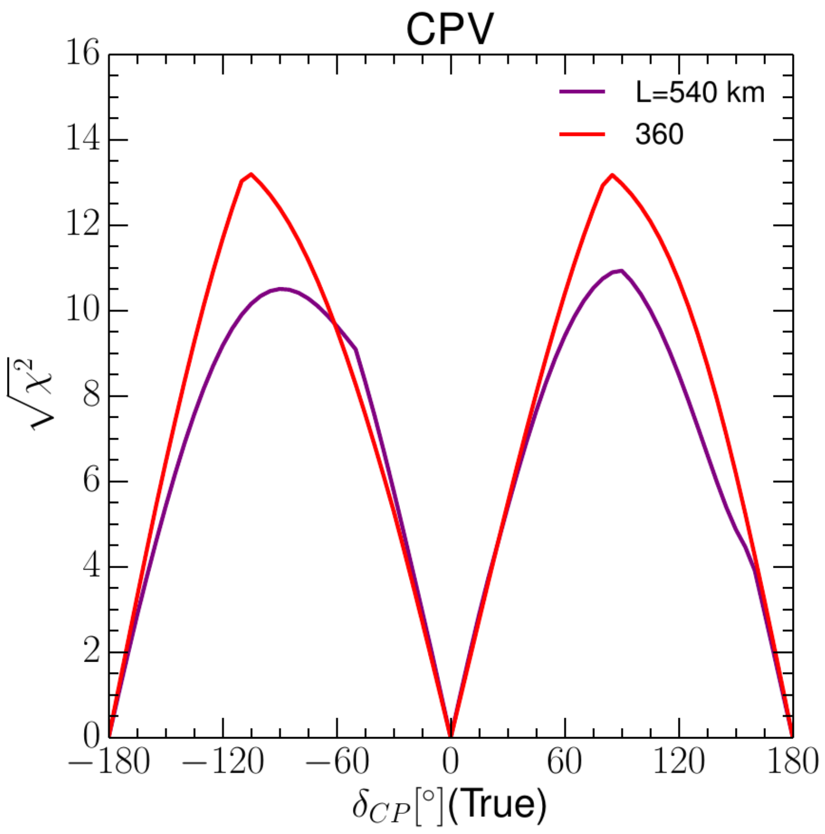


Updated physics performance of the ESSnuSB experiment,

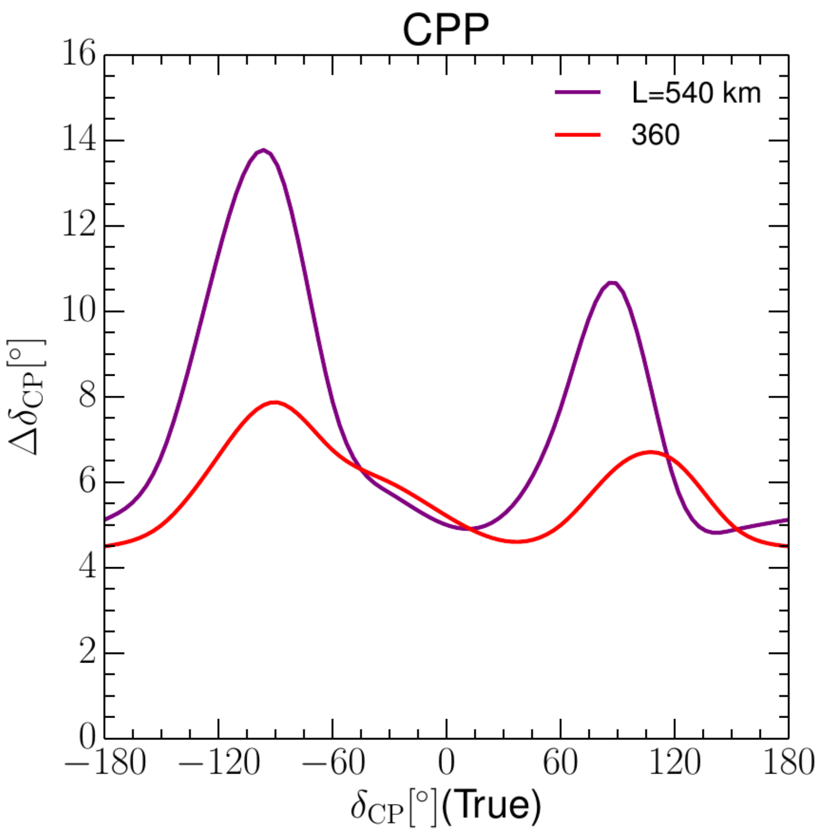
Eur.Phys.J.C 81 (2021) 12, 1130

[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)

Intermediate result, state of analysis in June 2021

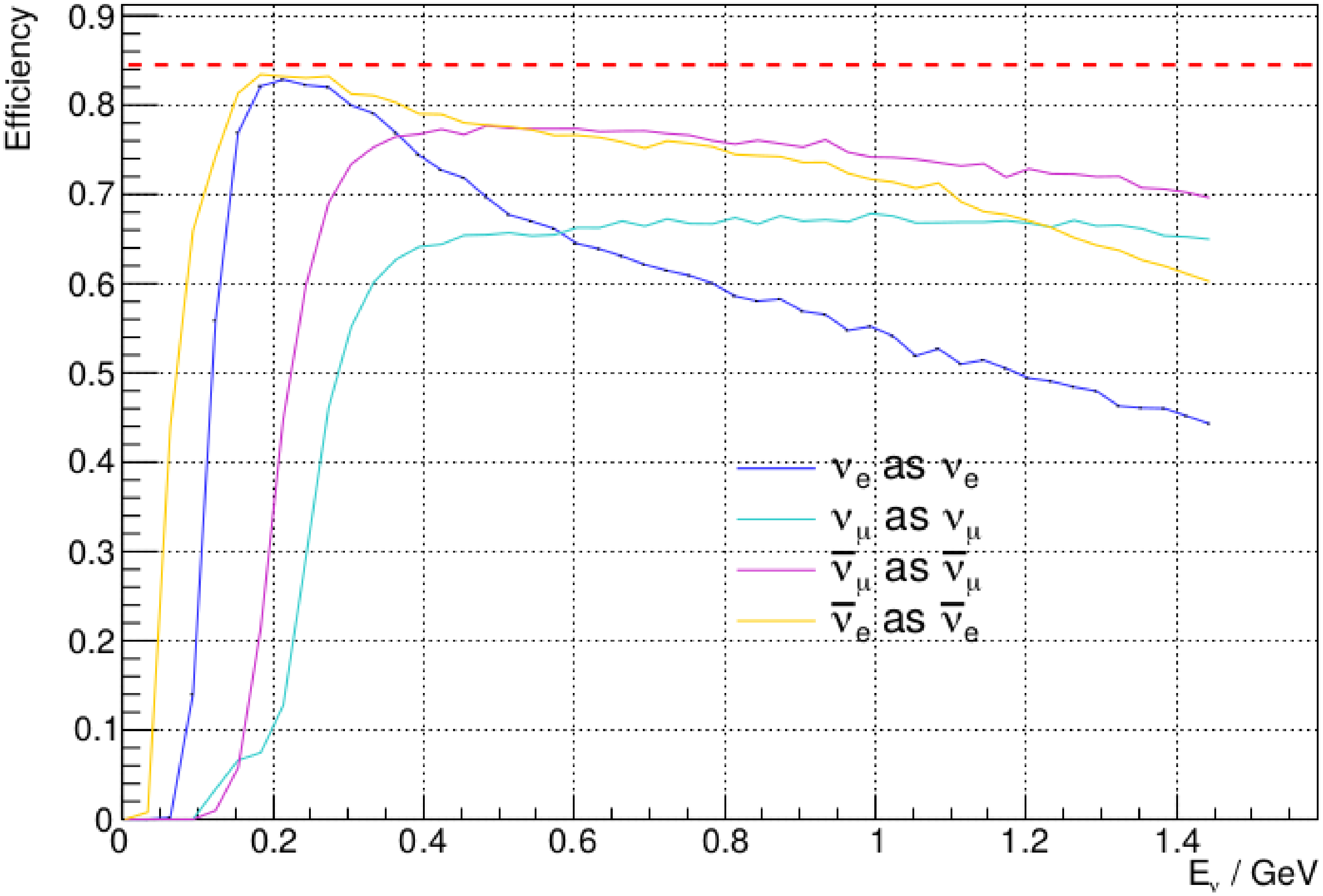


Sensitivity for $\delta_{CP} = \pm \pi/2$:
11 σ (540 km)
13 σ (360 km)

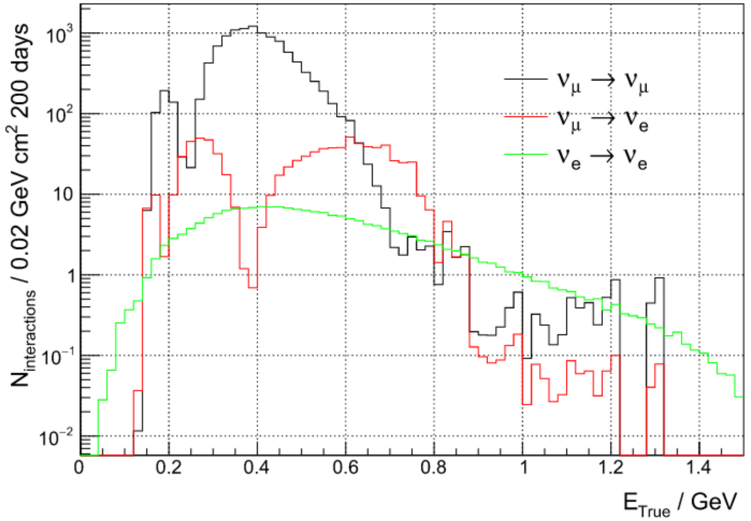


High precision of δ_{CP} measurement

Neutrino detection efficiency at FD



Expected spectrum positive polarity



(a) Positive polarity

Very high efficiency at 2nd maximum