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Measuring leptonic CP violation at the second neutrino oscillation maximum with ESSnuSB

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On behalf of the ESSnuSB project

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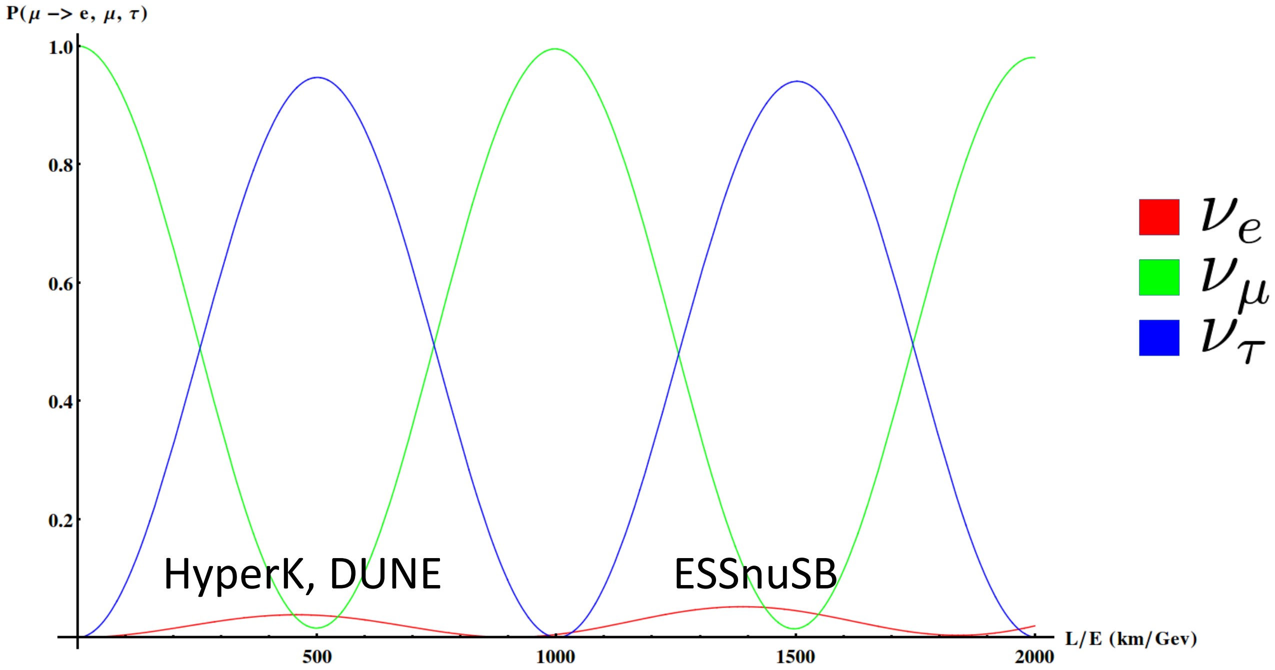
ESSnuSB

A design study for an experiment to measure CP violation at 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

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

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

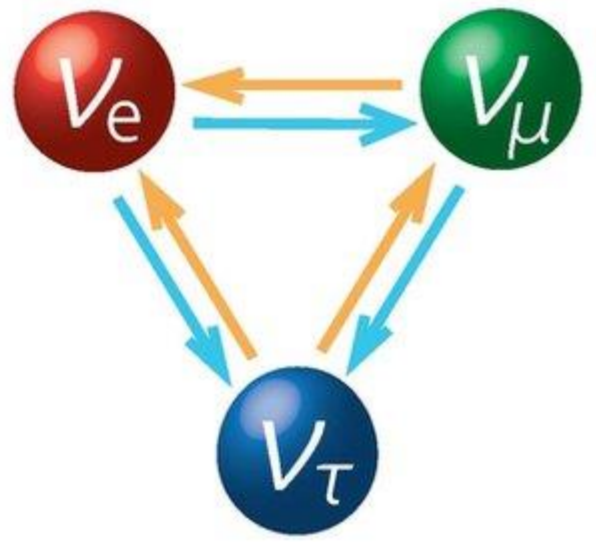
The plan:
1. Run with ν_μ and look at ν_e appearance, then
2. Run with $\overline{\nu}_\mu$ and look at $\overline{\nu}_e$ appearance

Why 2^{nd} maximum?

Large signal and small matter effects

Neutrino oscillations

Neutrino flavour can effectively change between its creation and interaction.



Neutrino oscillations

Neutrino flavor eigenstate is not a mass eigenstate

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

$$|\nu_\alpha\rangle = \sum_{i=1}^{n} U^*_{\alpha i} \, |\nu_i\rangle$$

flavour eigenstate   mixing matrix   mass eigenstates

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

- $U_{\alpha i}$ 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

Neutrino oscillations (3 generations)

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

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

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

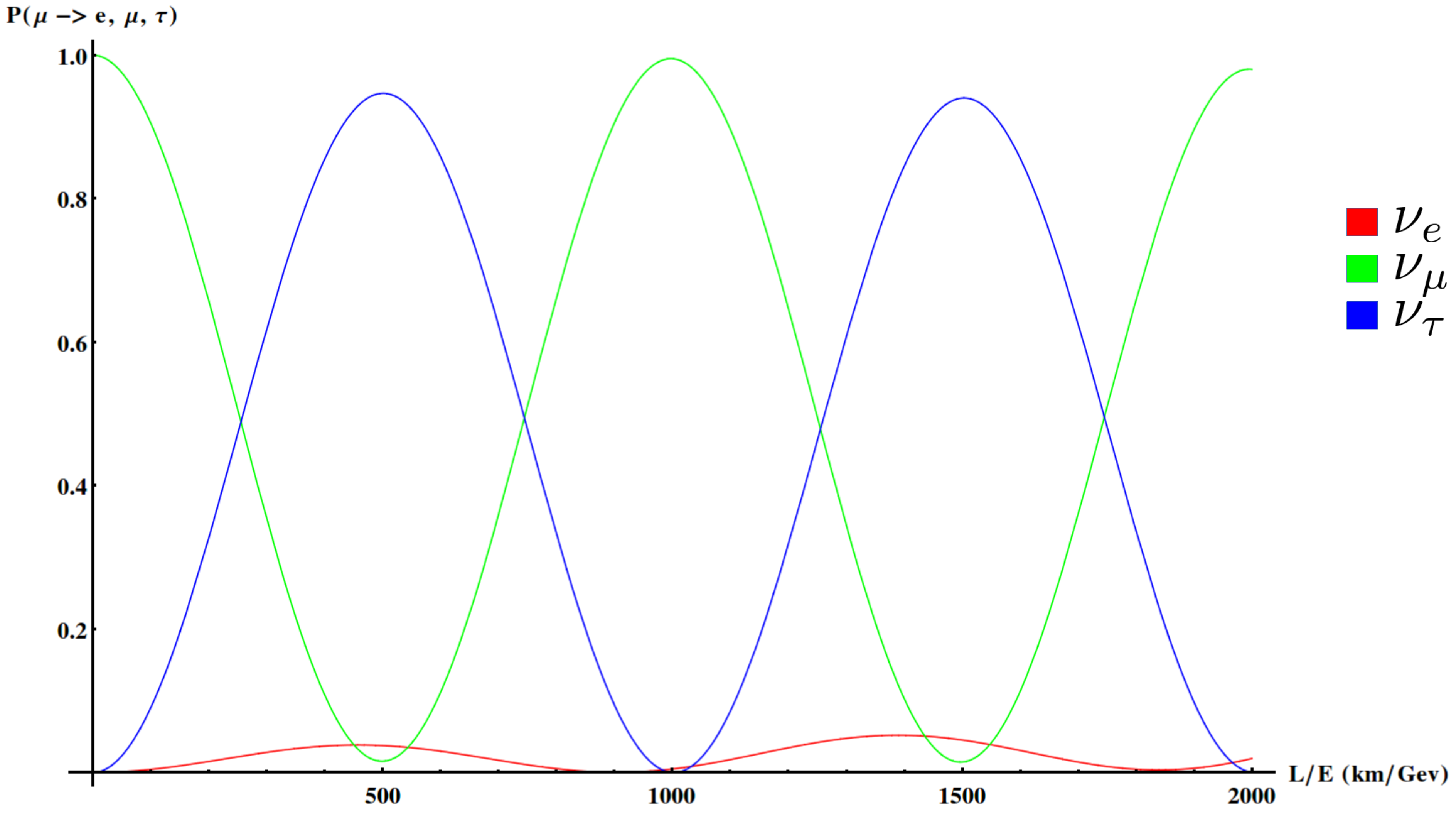
$$c_{ij} \equiv \cos\theta_{ij}$$

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

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

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

Neutrino oscillations



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

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

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

← 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”:

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

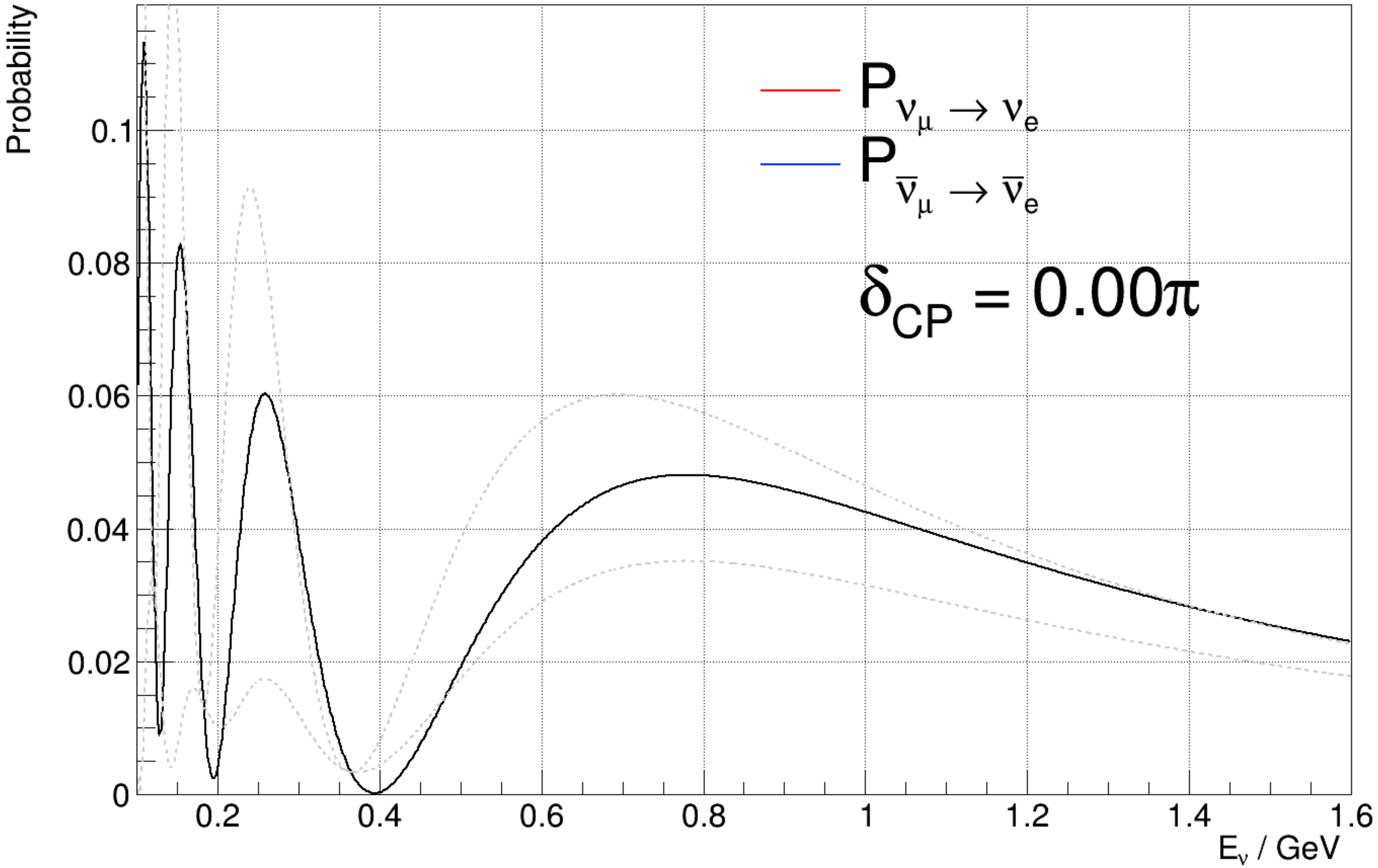
ESSnuSB CP violation

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

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

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

Effect of δ_{CP} on oscillations in vacuum

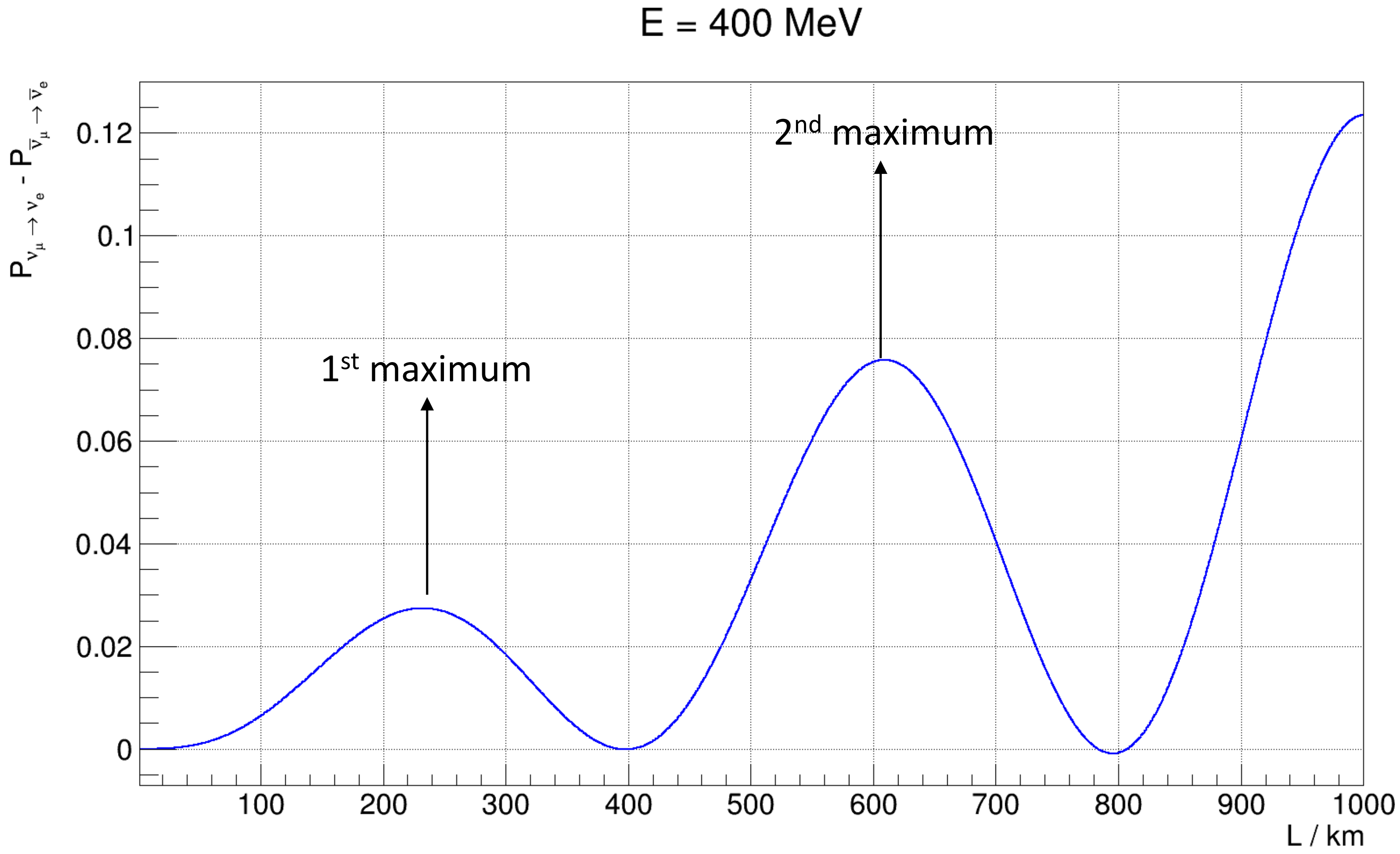


Thanks to my student L. Halić for patiently making plots specifically for this talk!

CP violation in ESSnuSB

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

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

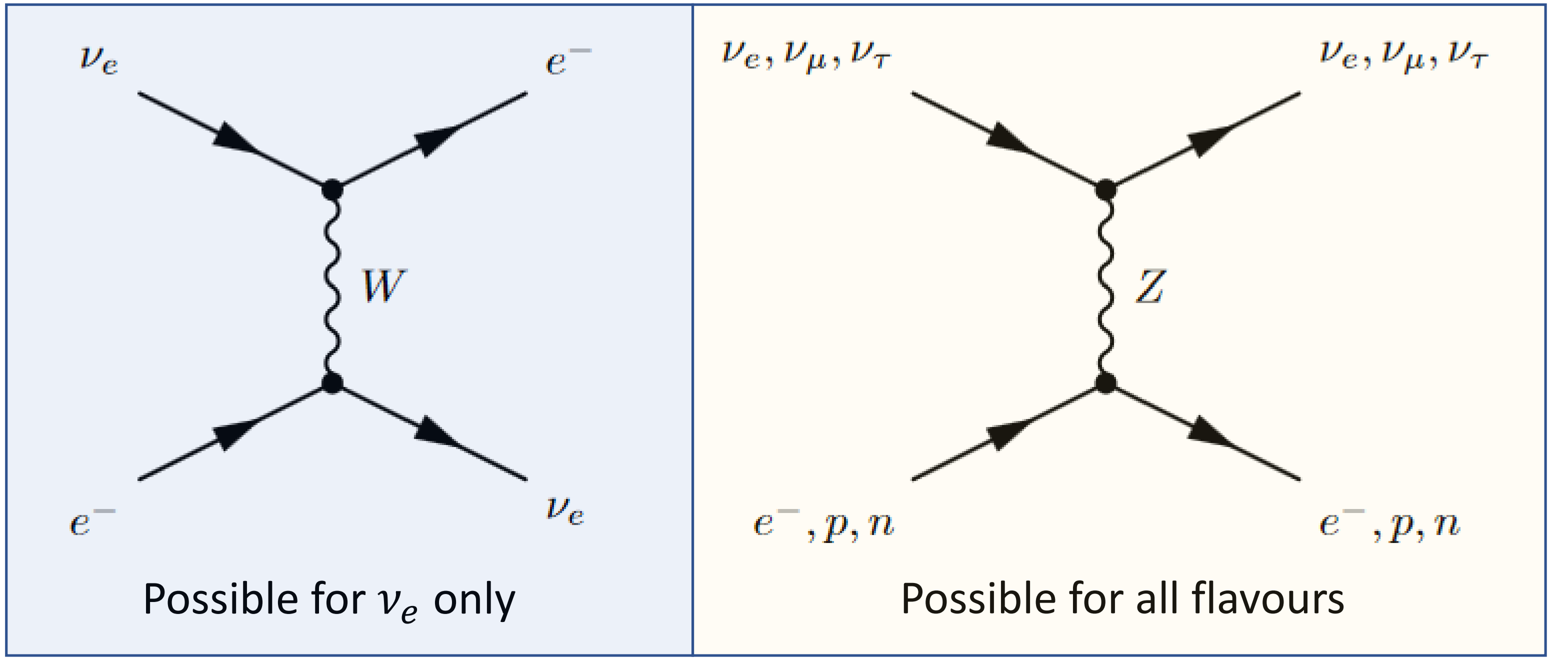


$$\frac{A_{CP} \text{ @ 2nd max}}{A_{CP} \text{ @ 1st max}} \sim 2.7$$

- 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



Possible for ν_e only

Possible for all flavours

- Elastic neutrino scattering can proceed through:
  - NC interactions for all flavour/mass eigenstates
  - CC interactions with electrons for electron neutrinos
- Therefore electron neutrinos see a slightly different effective potential than muon and tau neutrinos
  - This modifies the evolution of flavour states in matter

Matter effects

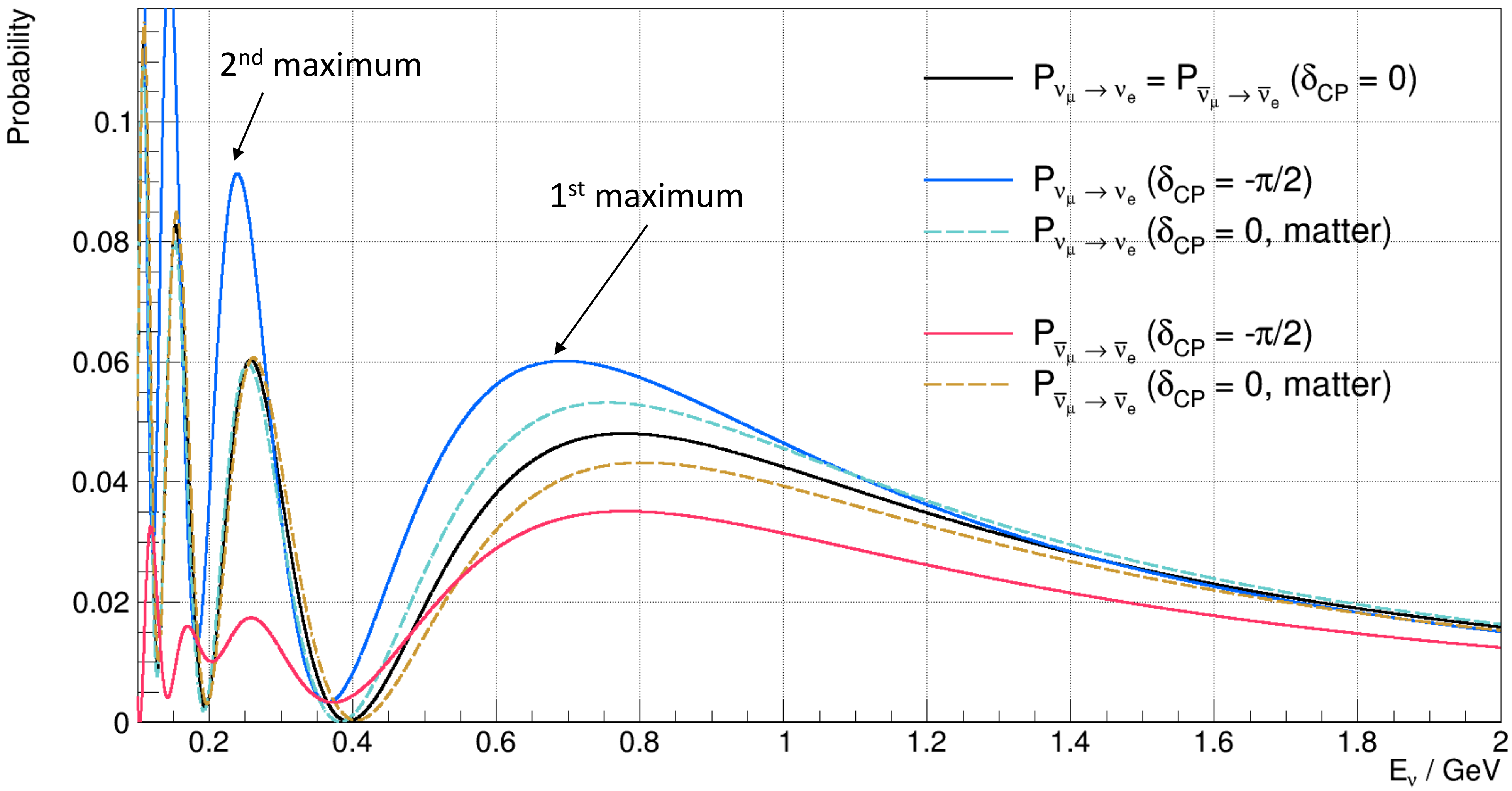
- For uniform matter density, these effects can be included by replacing vacuum oscillation parameters with effective “matter parameters”
  - $\theta_{ij} \to \theta_{ij}^{(m)}(E)$, $\delta_{CP} \to \delta_{CP}^{(m)}(E)$ and $\Delta m_{ij}^2 \to \Delta M_{ij}^2(E)$
  - the effective parameters now depend on energy

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

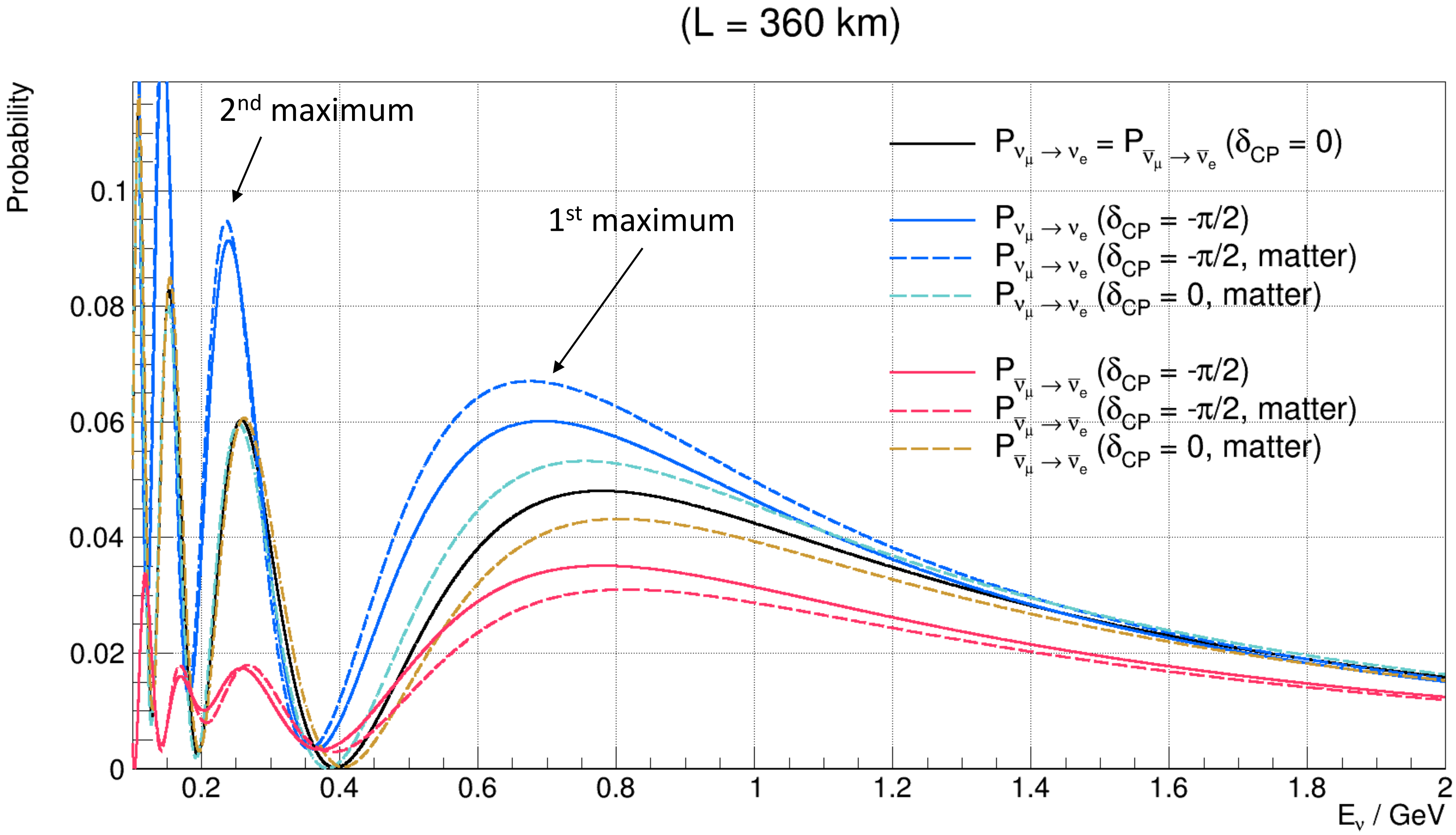
- For non-uniform densities it requires numerical calculation of probabilities

Matter effects

(L = 360 km)



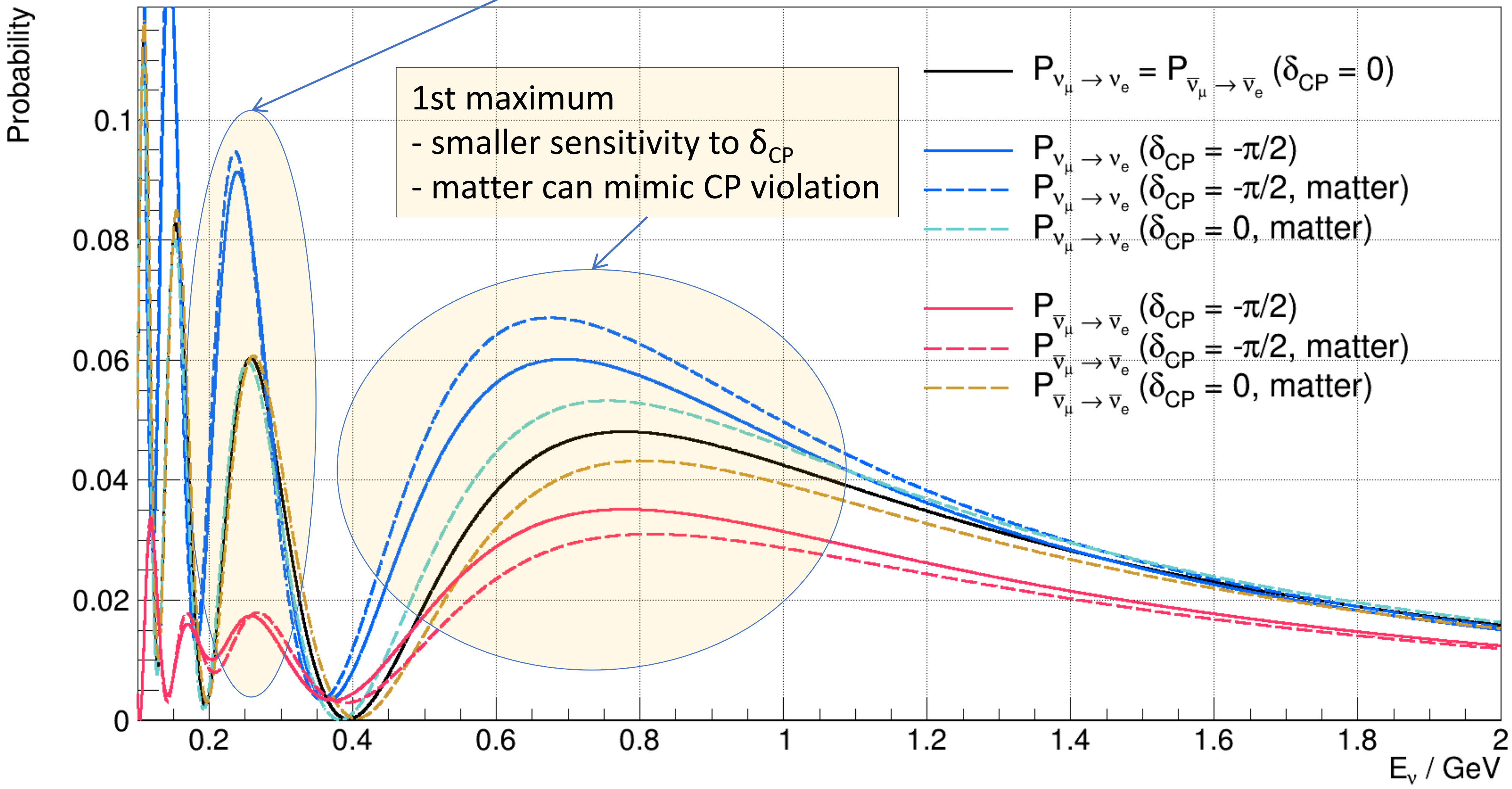
Matter effects



Matter effects

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

(L = 360 km)

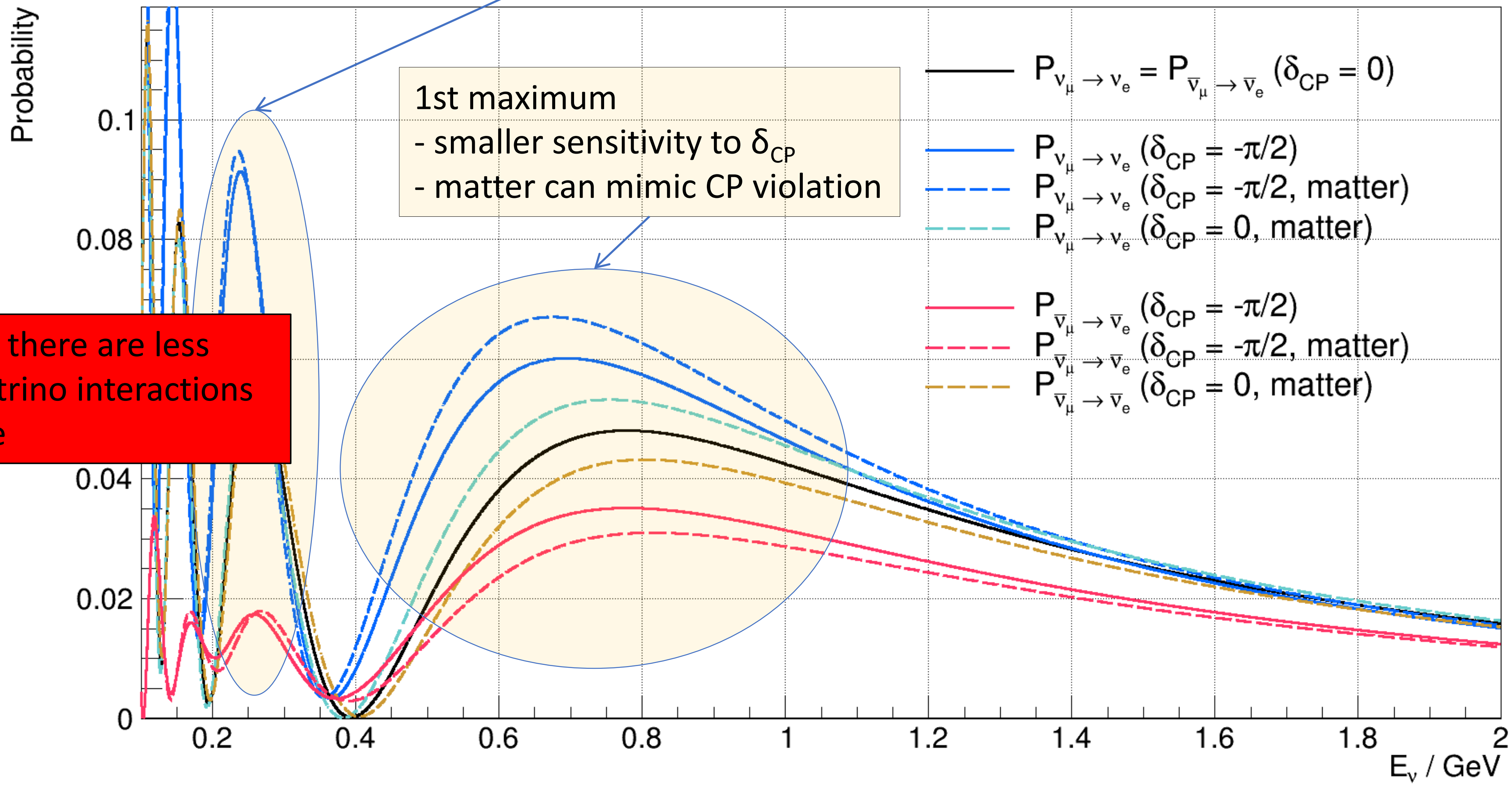


1st maximum
- smaller sensitivity to δ_{CP}
- matter can mimic CP violation

Matter effects

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

(L = 360 km)



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

But, there are less neutrino interactions here

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 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 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 better
  - more statistics, even though the effect is smaller.

ESSnuSB project

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

Neutrino beam production

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

Hot Cell

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

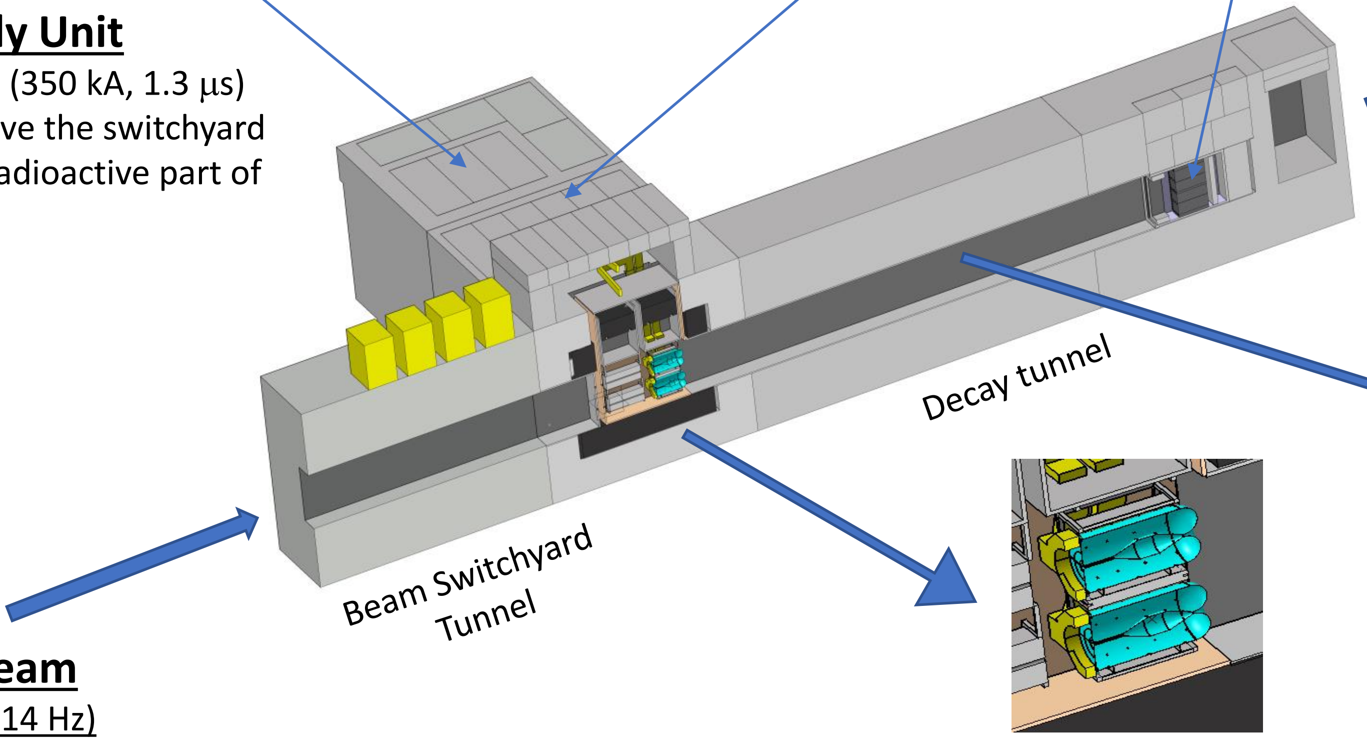
Morgue

To Store radioactive wastes

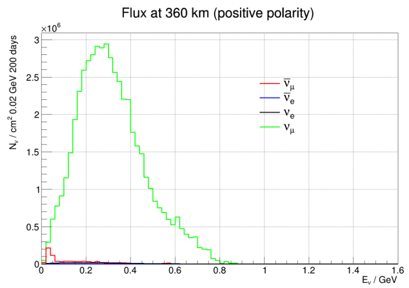
Beam dump

Power Supply Unit

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



Neutrino Beam



Pions decay in-flight here

Hadronic Collector

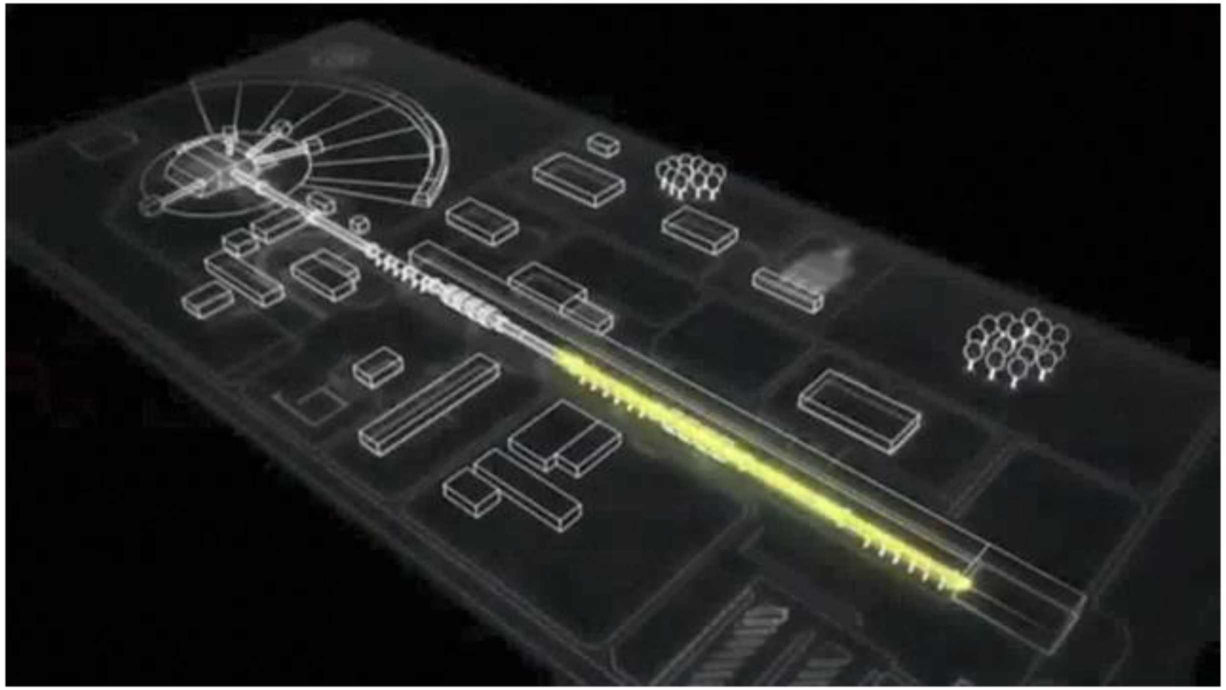
Proton Beam

(Ep=2.5 GeV, 14 Hz)

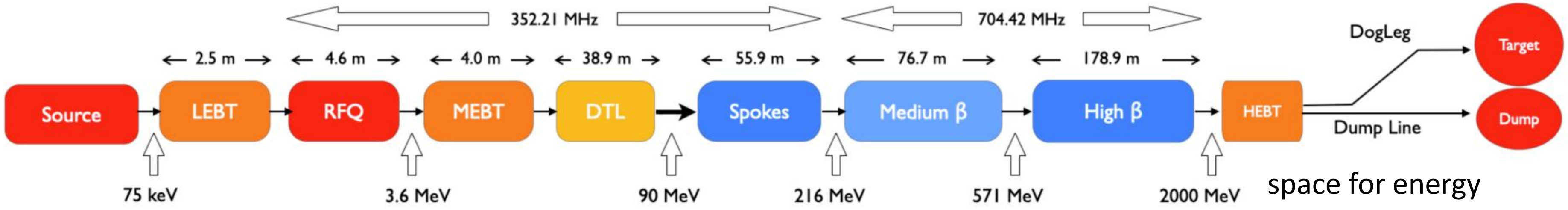
4 x 1.25 MW

Can we go to 2nd maximum?

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



ESS proton linac



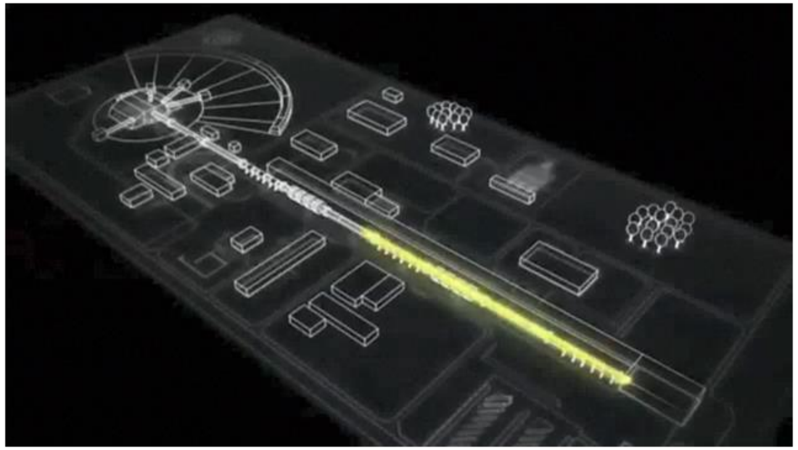
352.21 MHz
704.42 MHz
← 2.5 m →
← 4.6 m →
← 4.0 m →
← 38.9 m →
← 55.9 m →
← 76.7 m →
← 178.9 m →
Source
LEBT
RFQ
MEBT
DTL
Spokes
Medium β
High β
HEBT
DogLeg
Dump Line
Target
Dump
75 keV
3.6 MeV
90 MeV
216 MeV
571 MeV
2000 MeV

space for energy upgrades

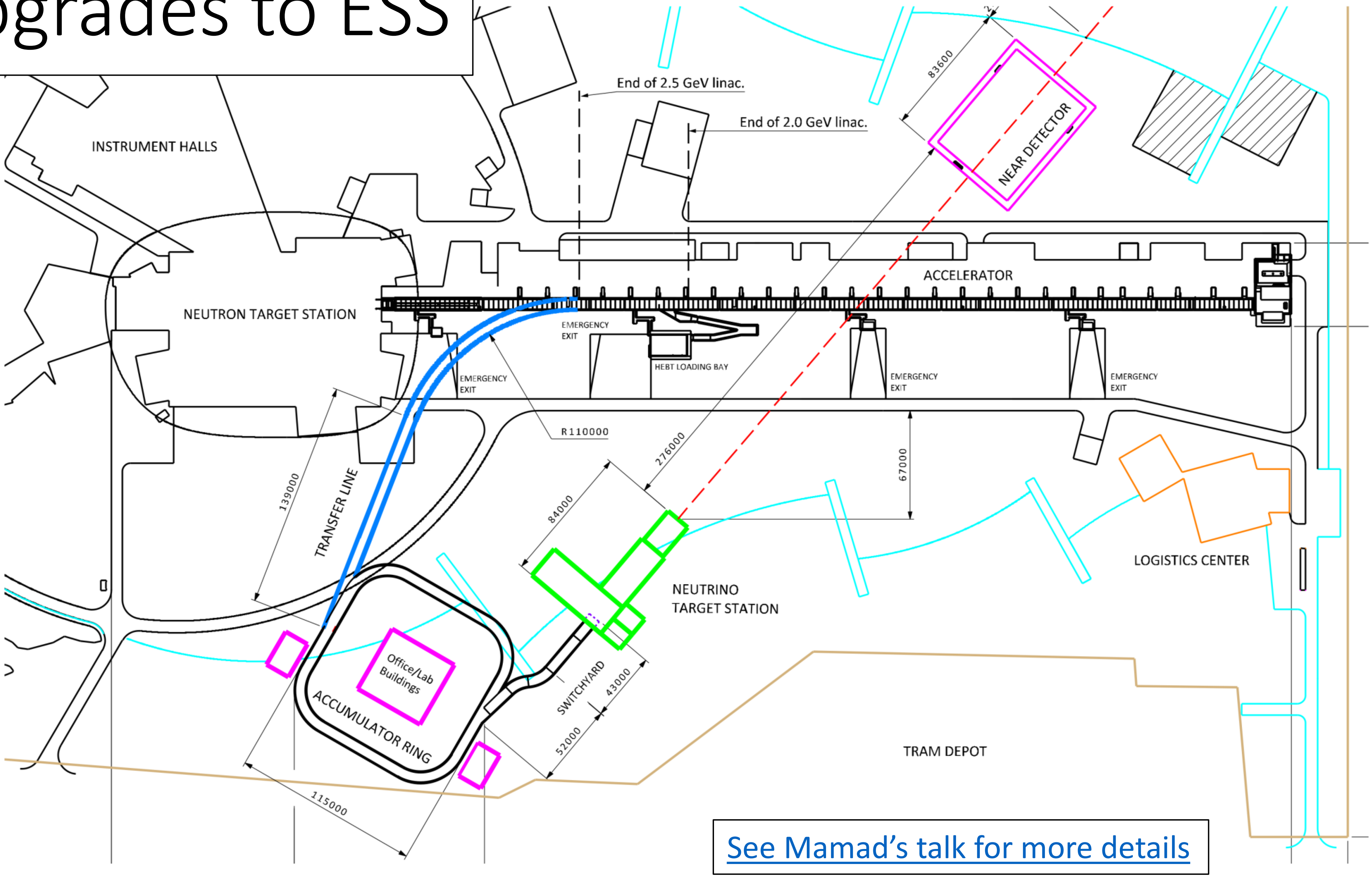
- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power.
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV kinetic energy protons
    - up to 3.5 GeV with linac upgrades
- **>2.7x10^{23} p.o.t/year.**

First beam on target expected in 2024.

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



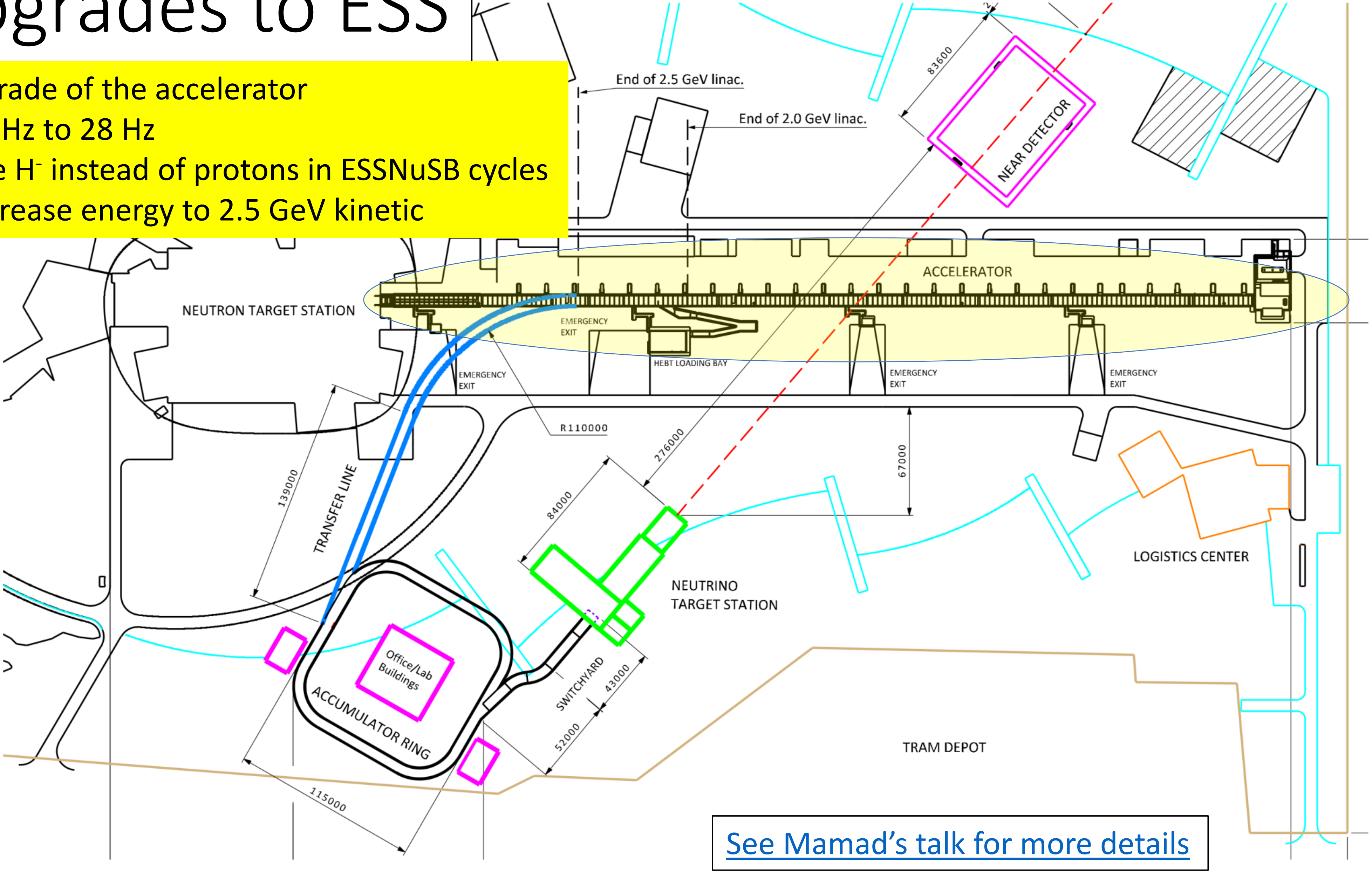
Upgrades to ESS



See Mamad’s talk for more details

Upgrades to ESS

Upgrade of the accelerator
- 14 Hz to 28 Hz
- use H^- instead of protons in ESSNuSB cycles
- increase energy to 2.5 GeV kinetic



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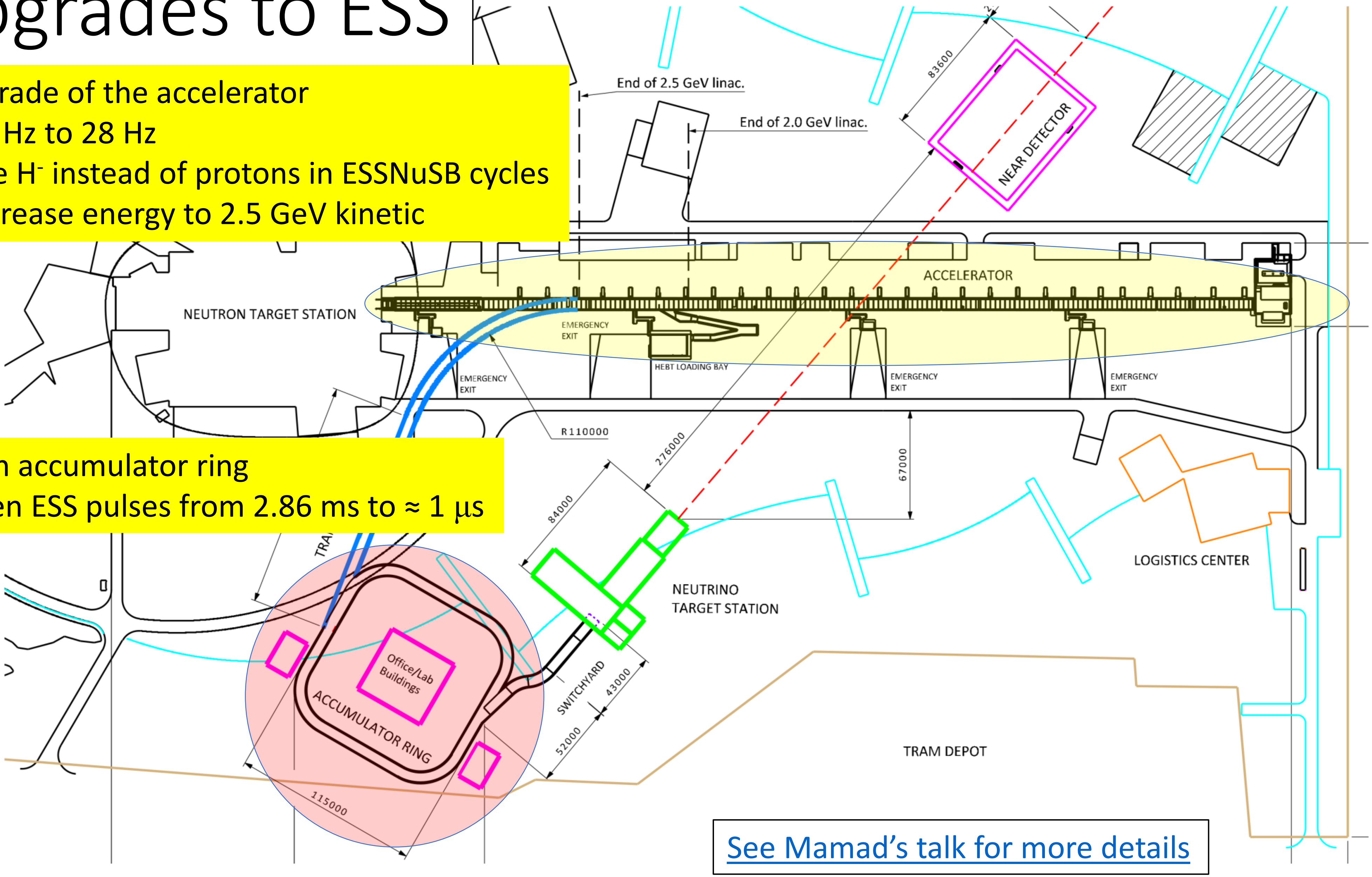

Build an accumulator ring
- shorten ESS pulses from 2.86 ms to ≈ 1 µs

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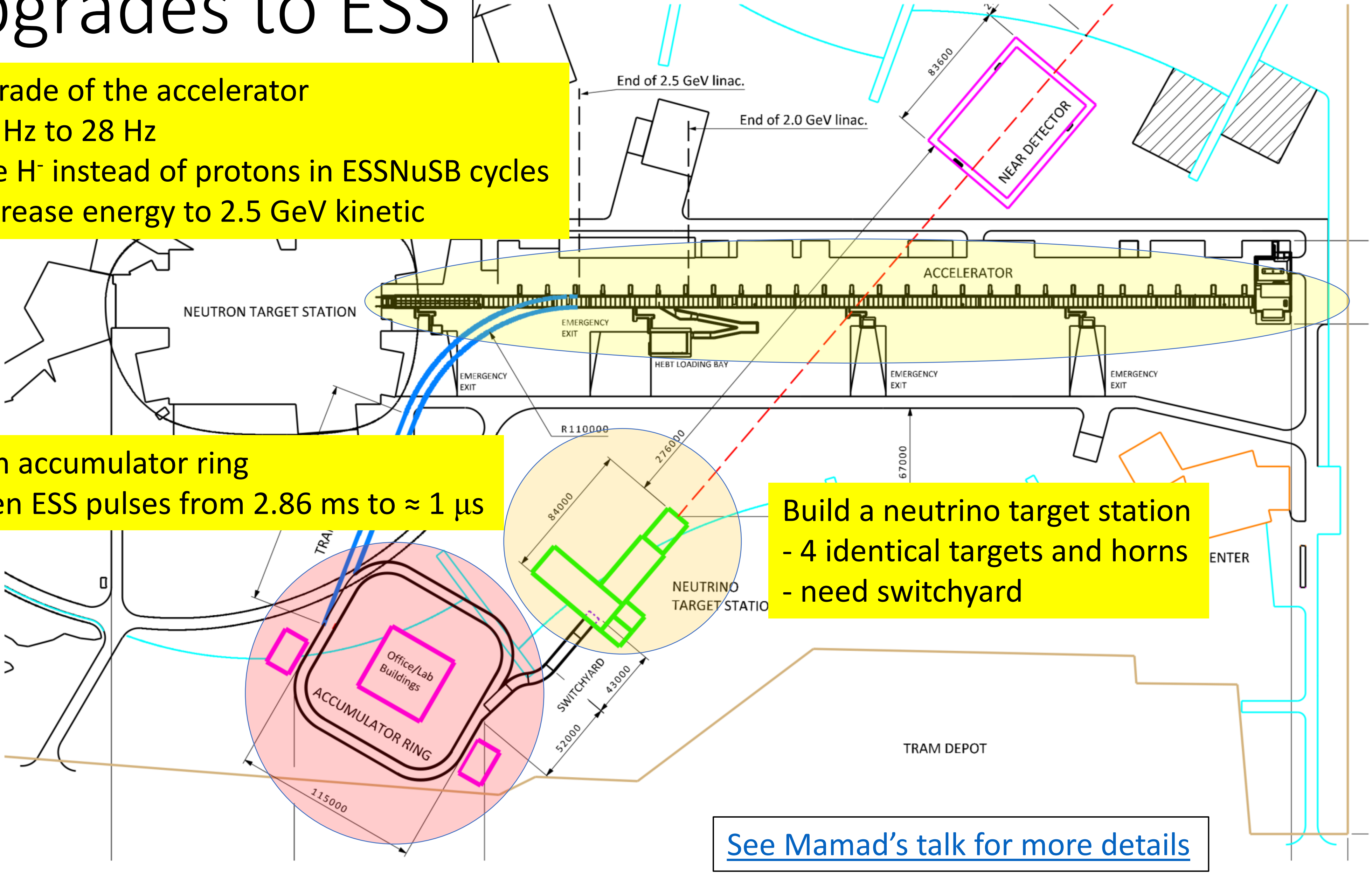

Build an accumulator ring
- shorten ESS pulses from 2.86 ms to ≈ 1 μs

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

See Mamad's talk for more details

Upgrades to ESS

Upgrade of the accelerator
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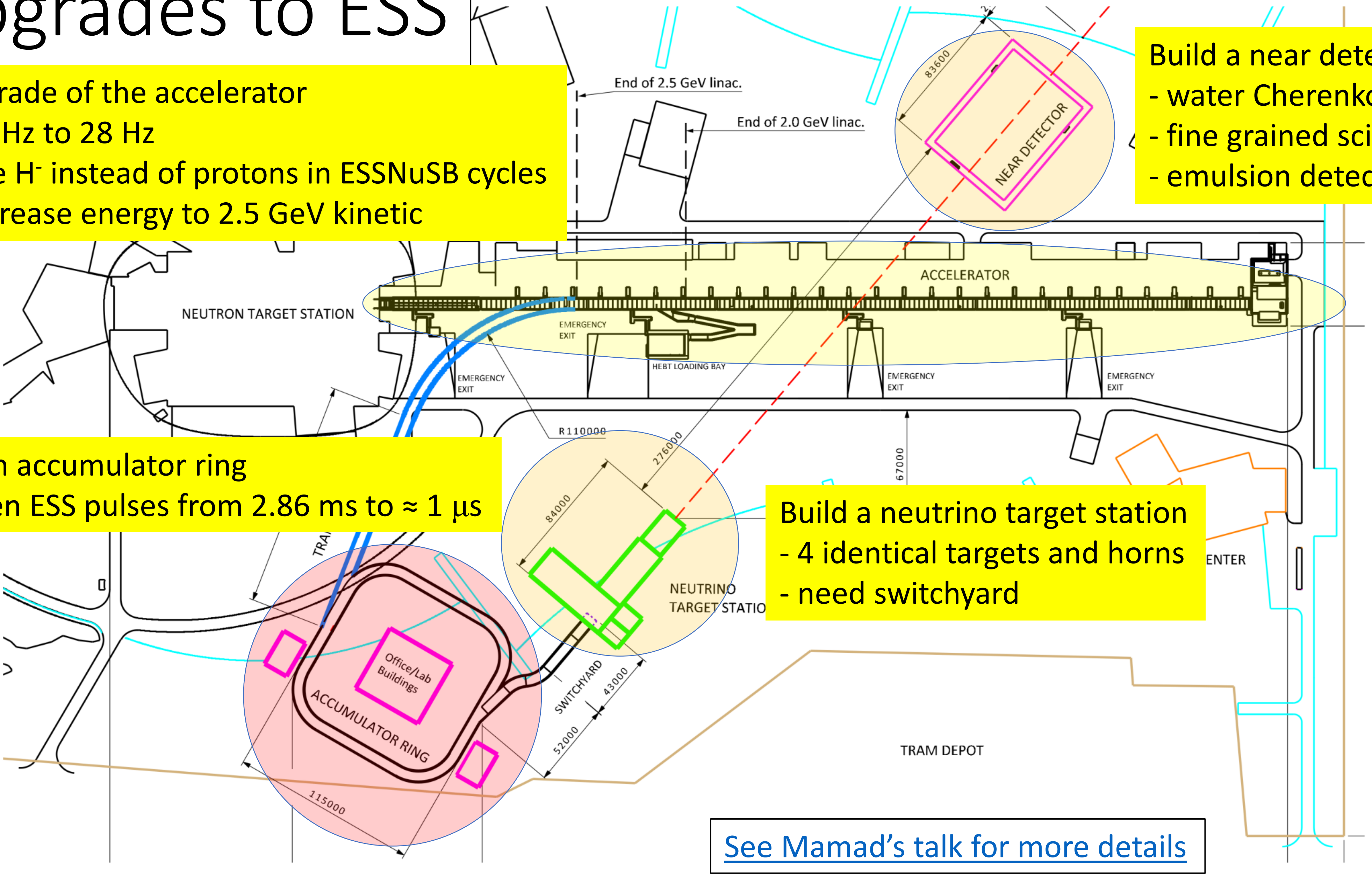
Build a near detector site
- water Cherenkov detector
- fine grained scintillator
- emulsion detector



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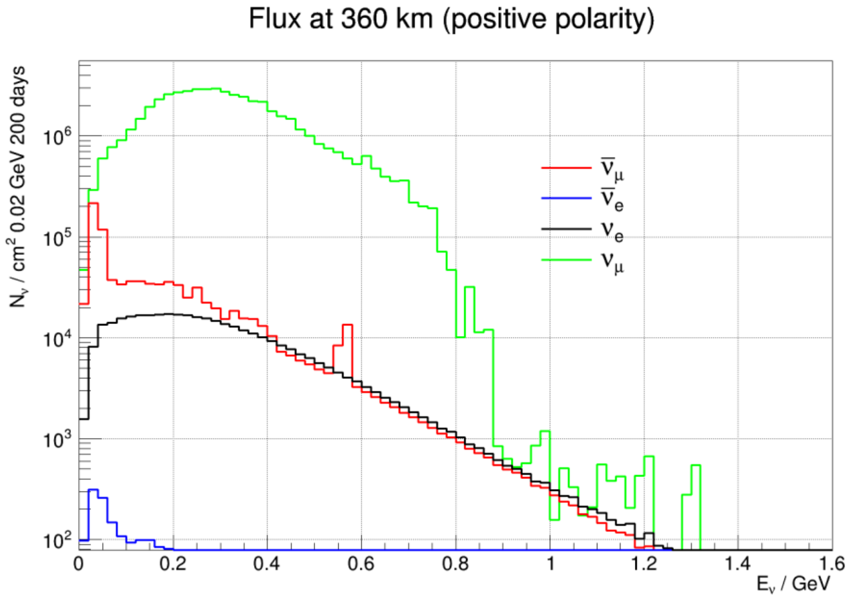
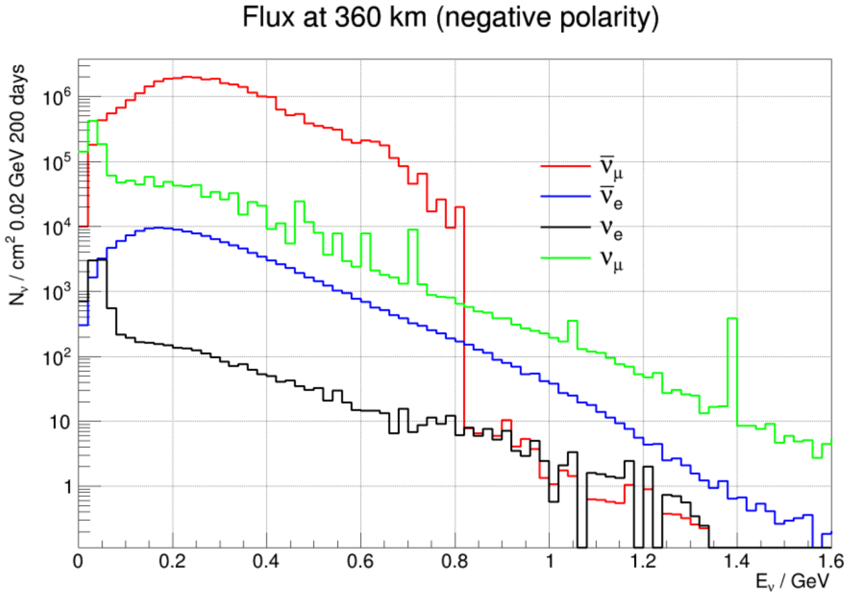
ESSνSB ν energy distribution
(after optimisation)


Flux at 360 km (positive polarity)


Flux at 360 km (negative polarity)

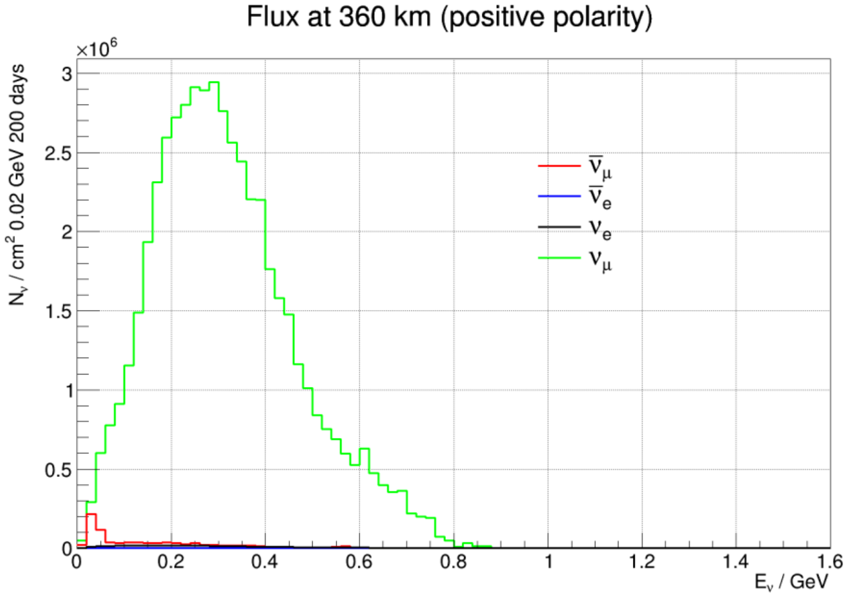
- almost pure ν_μ beam
- small ν_e contamination which will be used to measure ν_e cross-sections in a near detector

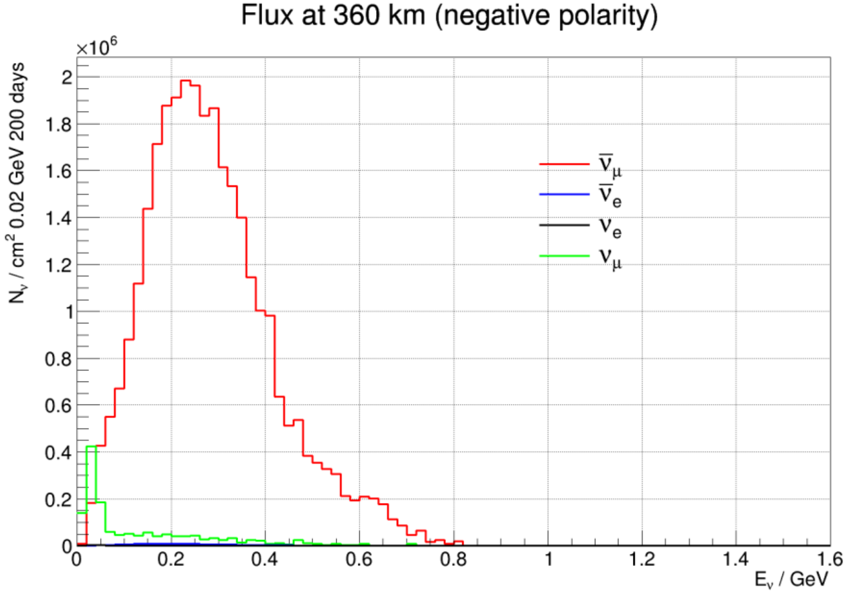
Flavour	ν Mode		$\bar{\nu}$ Mode	
	N_ν (10^5/ cm^2)	%	N_ν (10^5/ cm^2)	%
ν_μ	**520.06**	**97.6**	15.43	4.7
ν_e	**3.67**	**0.67**	0.10	0.03
$\bar{\nu}_\mu$	9.10	1.7	**305.55**	**94.8**
$\bar{\nu}_e$	0.023	0.03	**1.43**	**0.43**

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

ESSνSB ν energy distribution

(after optimisation)





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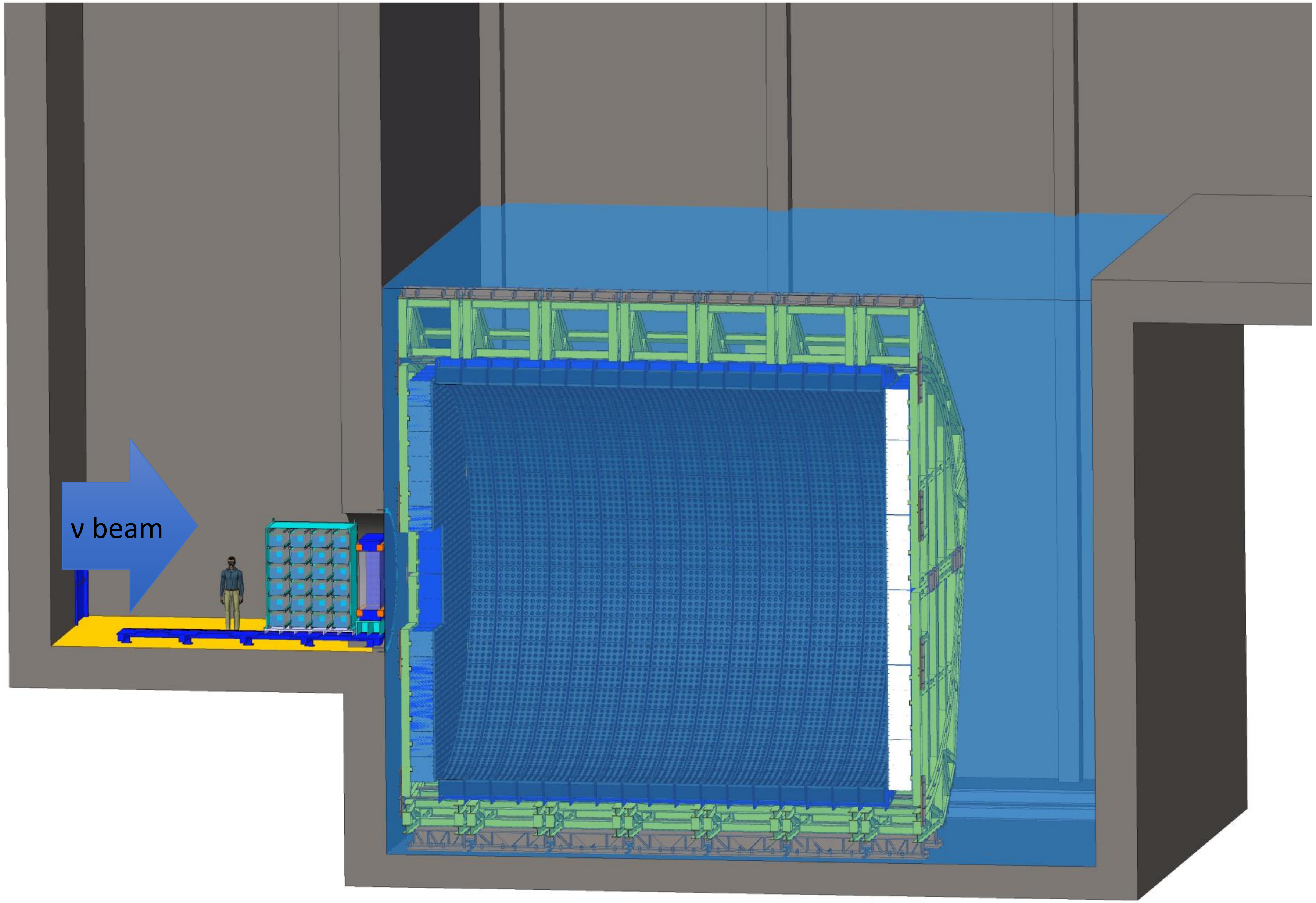
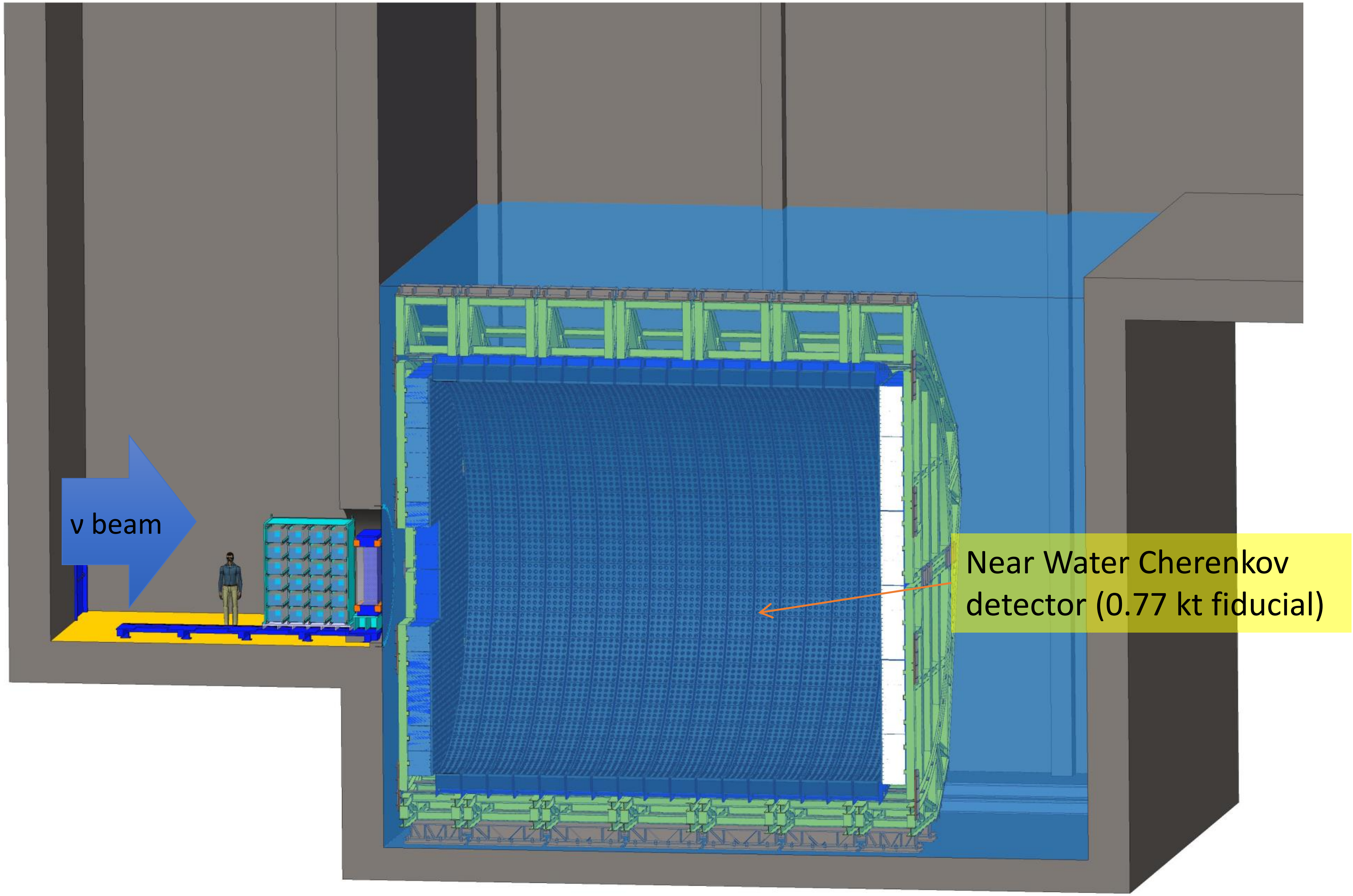
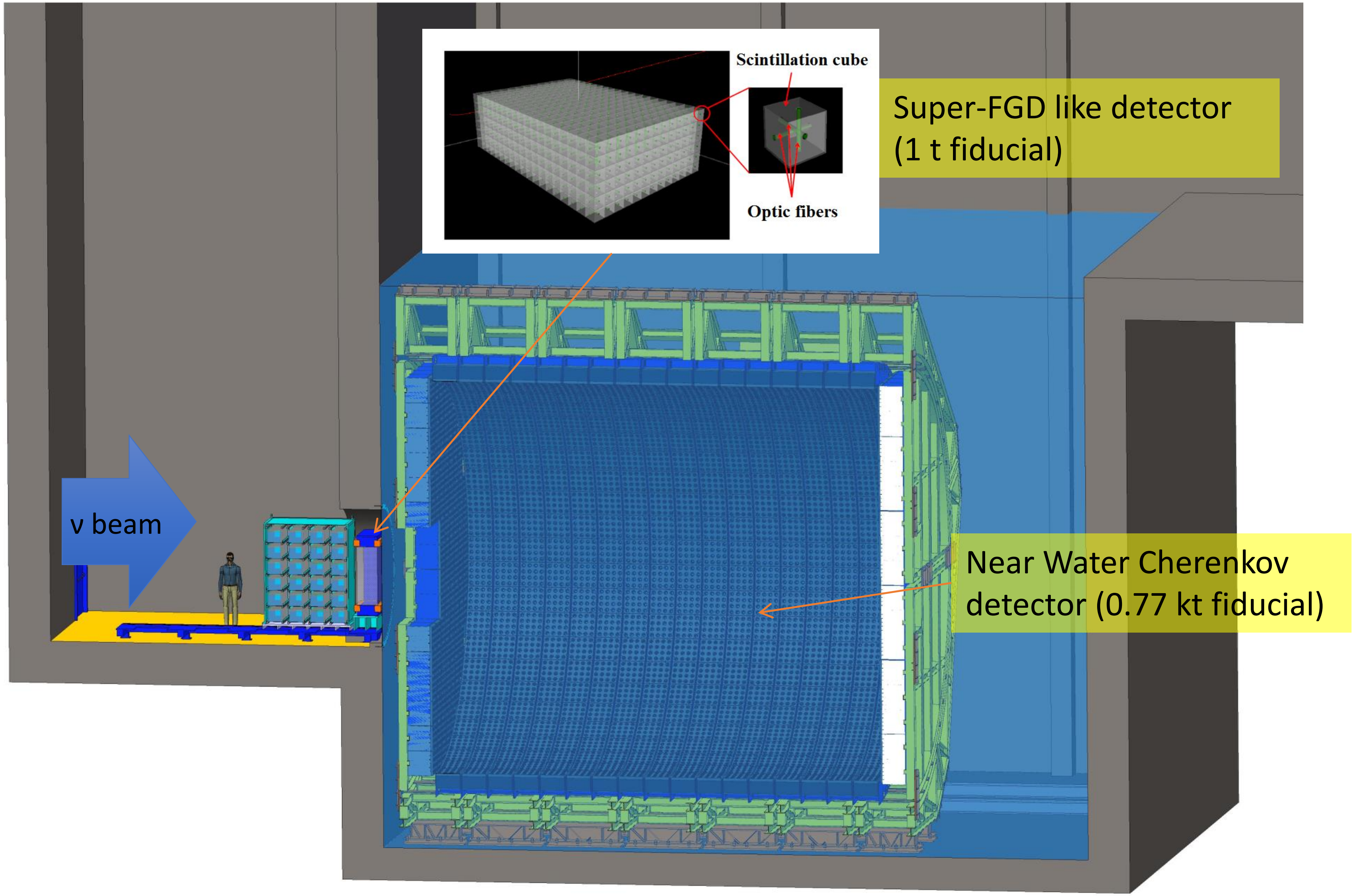
Near detectors



Near detectors



Near detectors

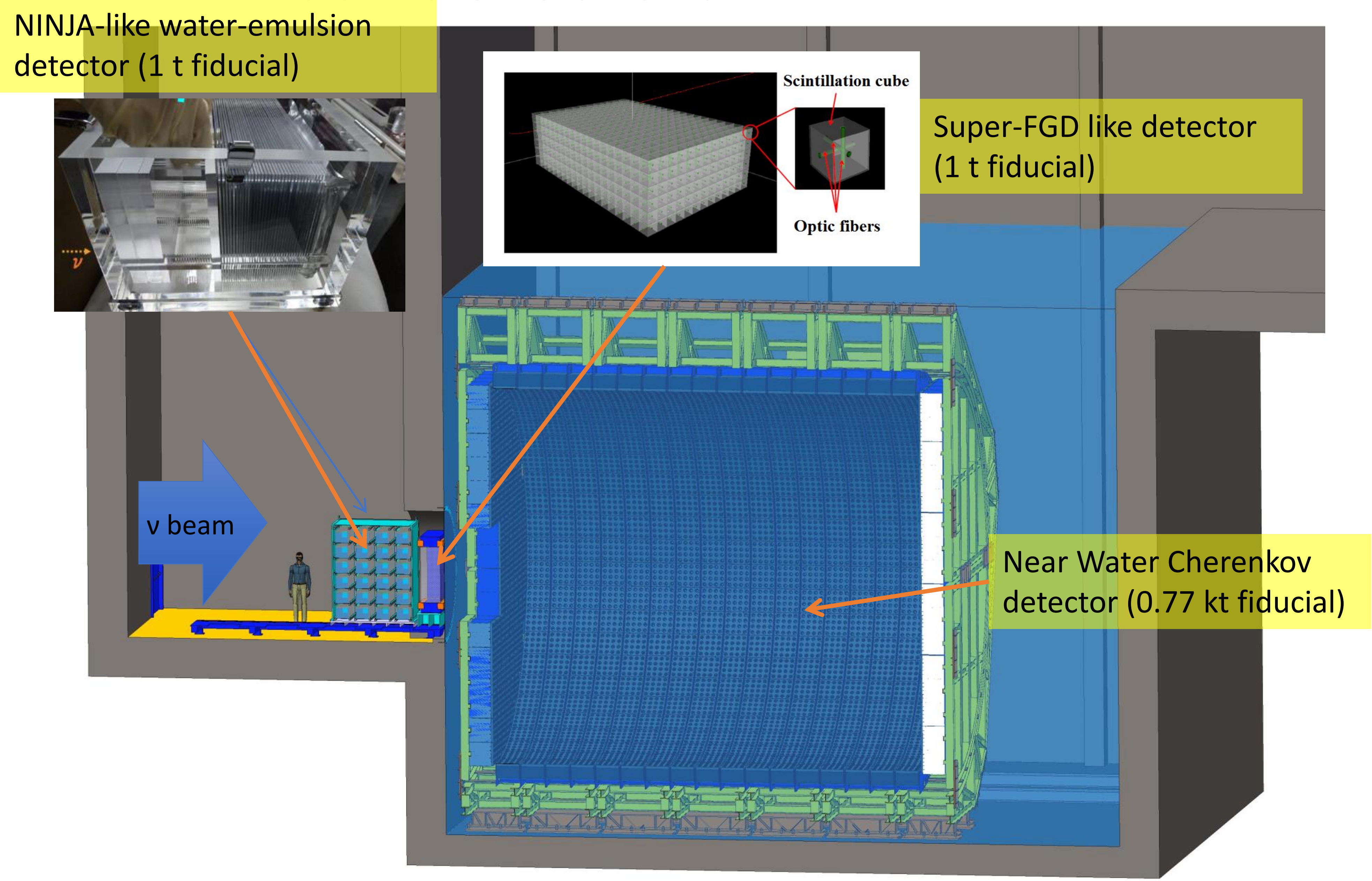


Super-FGD like detector (1 t fiducial)

ν beam

Near Water Cherenkov detector (0.77 kt fiducial)

Near detectors

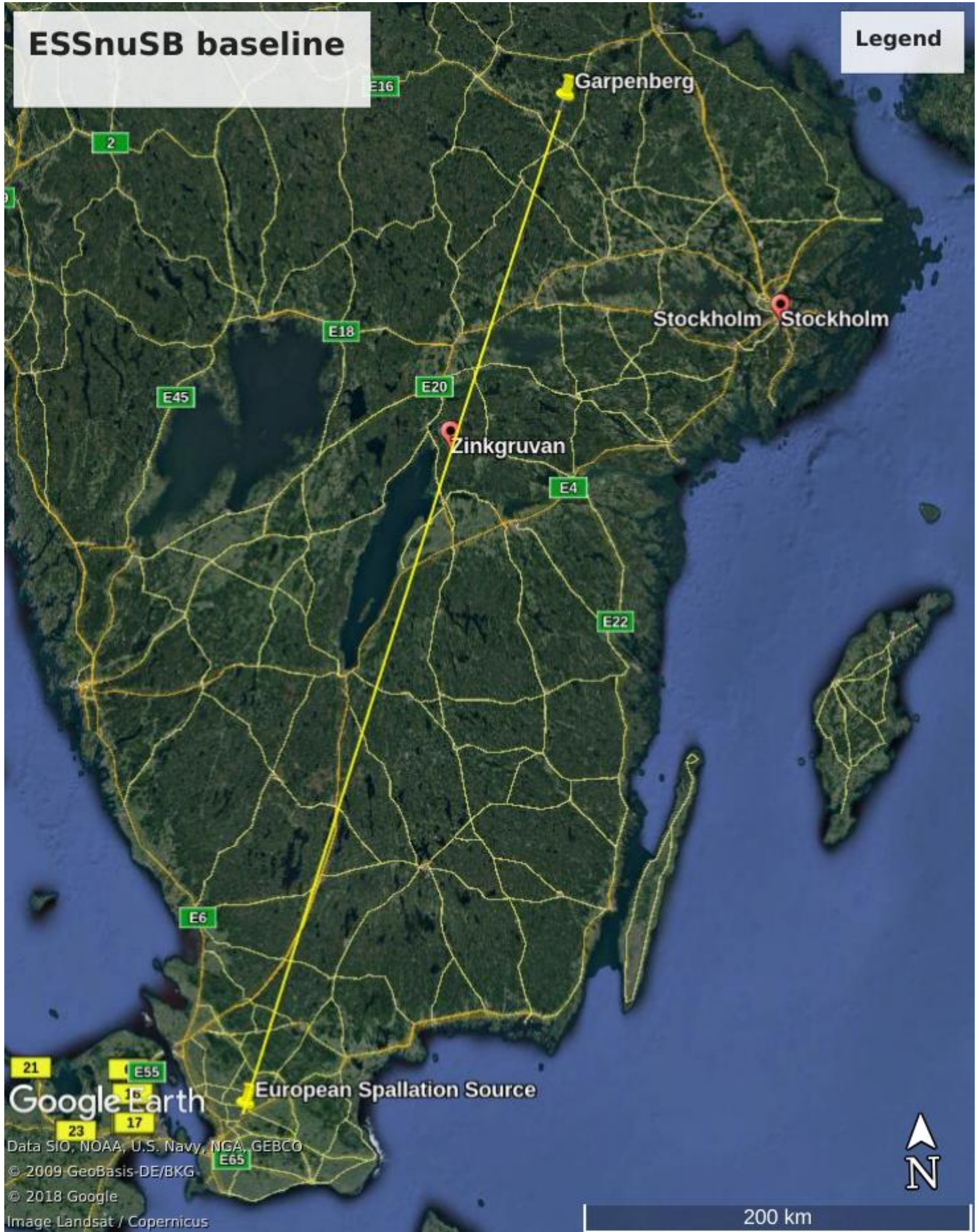


NINJA-like water-emulsion detector (1 t fiducial)

Super-FGD like detector (1 t fiducial)

ν beam

Near Water Cherenkov detector (0.77 kt fiducial)



Far detector position

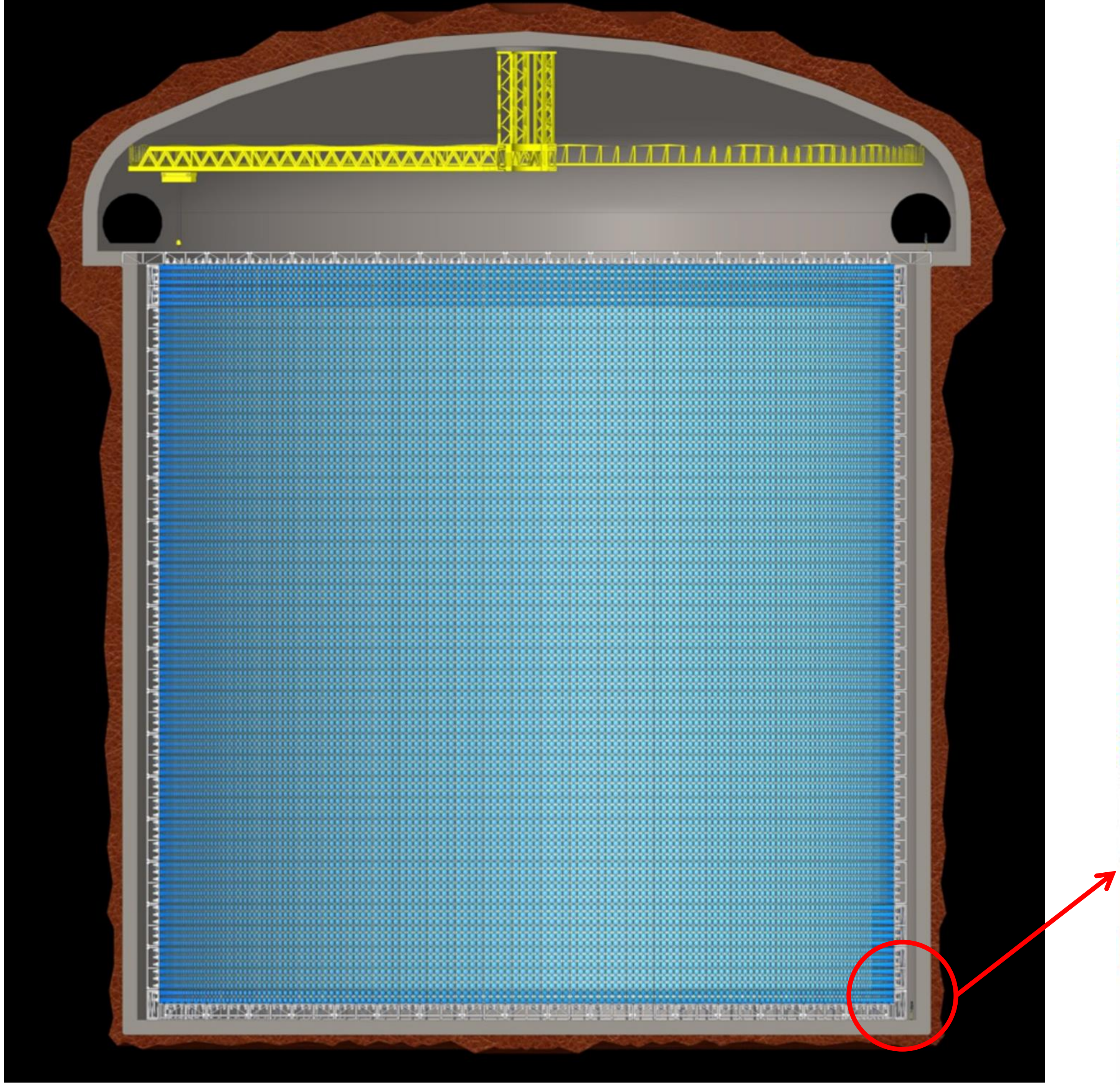
Selected baseline:

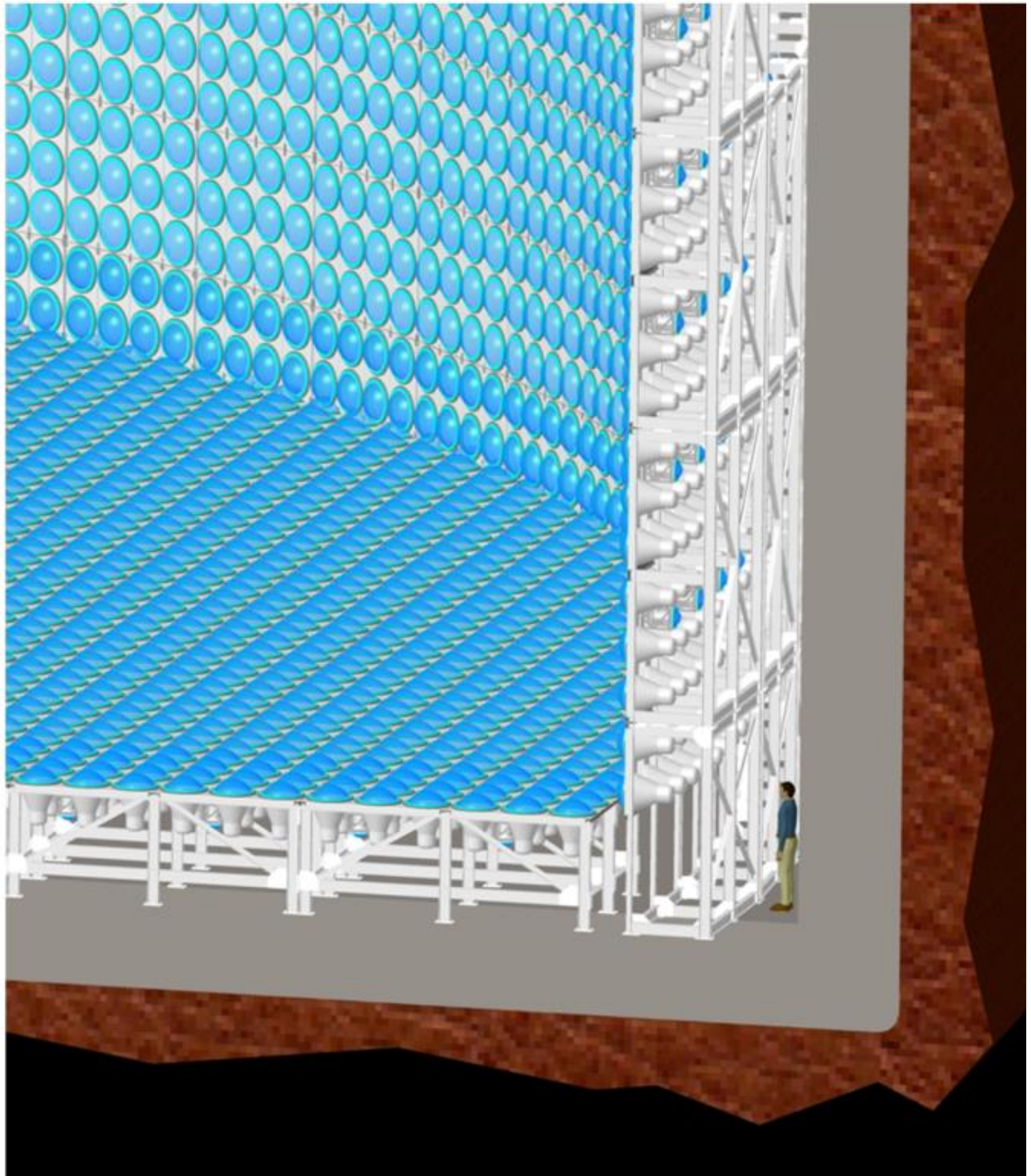
- Zinkgruvan mine, 360 km from the source, partly covernig 1st and 2nd maximum
    - Number of interactions at 2nd maximum similar to Garpenberg

Alternative (not selected)

- Garpenberg mine, 540 km from the neutrino source, corresponding to 2nd oscillation maximum.

Far detector





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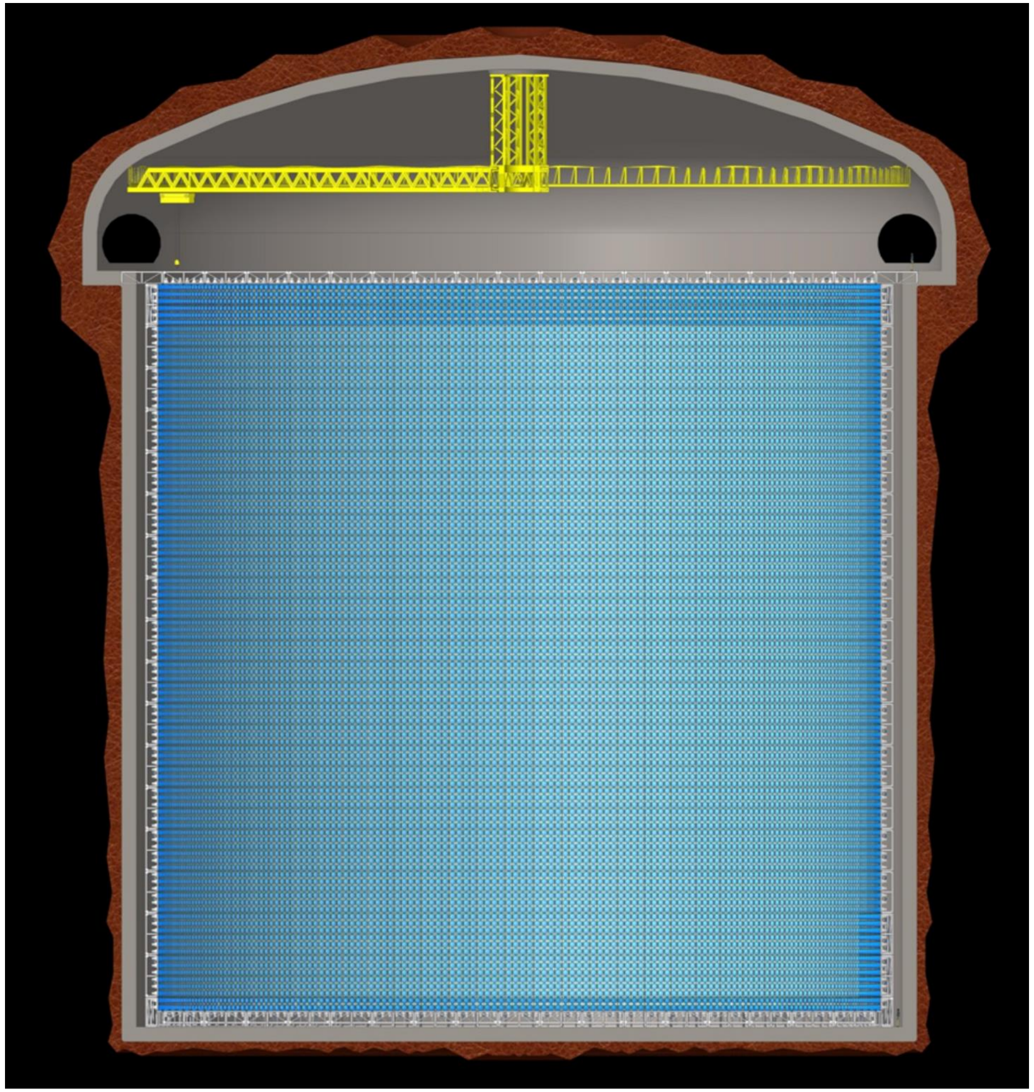


Design

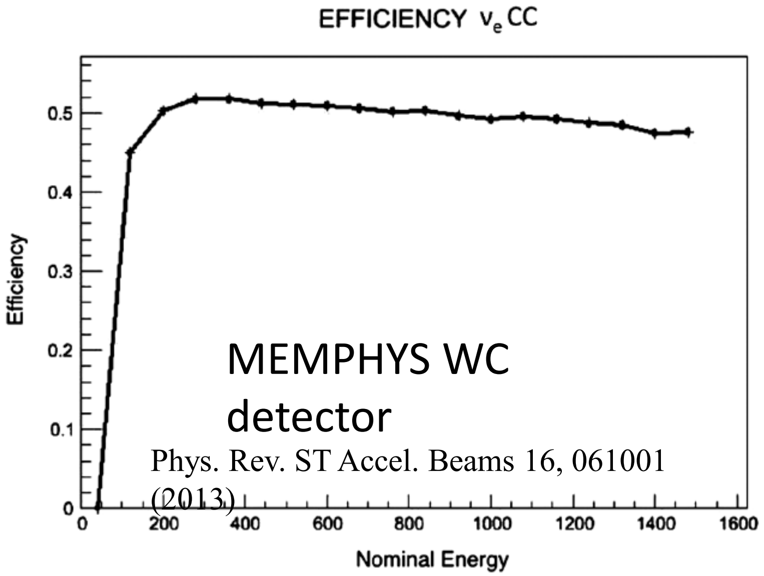
- 2 x 270 kt fiducial volume (~20xSuperK)
- Readout: 2 x 38k 20” PMTs
- 30% optical coverage
  - design here for 40% with an option that ¼ PMTs will not be installed

Can also be used for other purposes:

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

Improvements on sensitivity

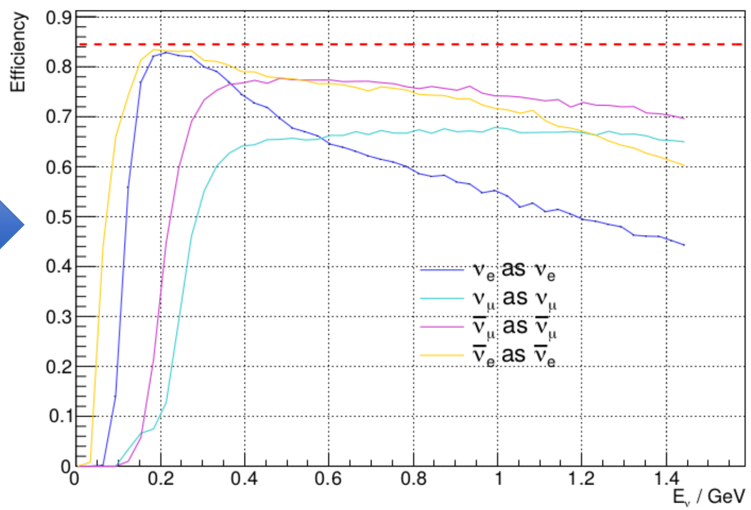
- Near detectors optimized for flux and cross-section measurement - 5% systematics within easy reach
- Far detectors’ response optimized for ESSnuSB flux – very high efficiency and purity at ESSnuSB energies
- Genetic Algorithm for Target Station optimization – more neutrinos



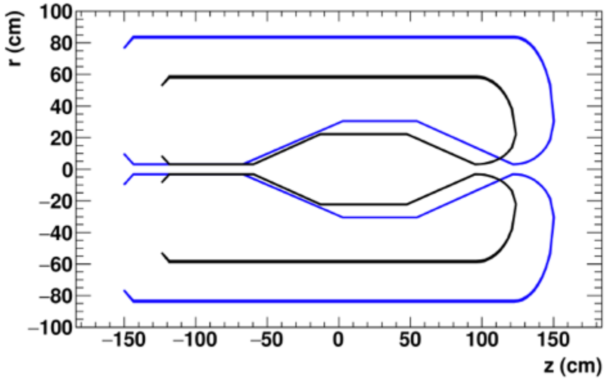
MEMPHYS WC detector

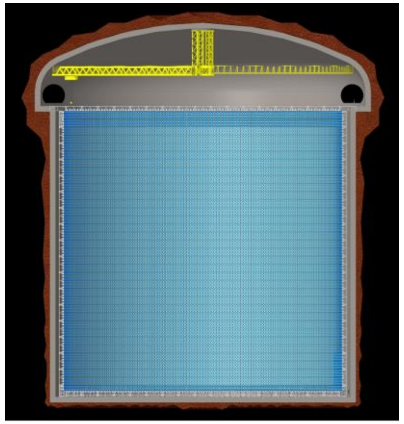
Phys. Rev. ST Accel. Beams 16, 061001 (2013)

Efficiency ESSnuSB FD

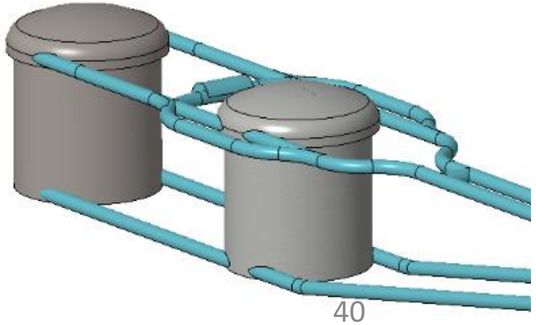


horn optimisation





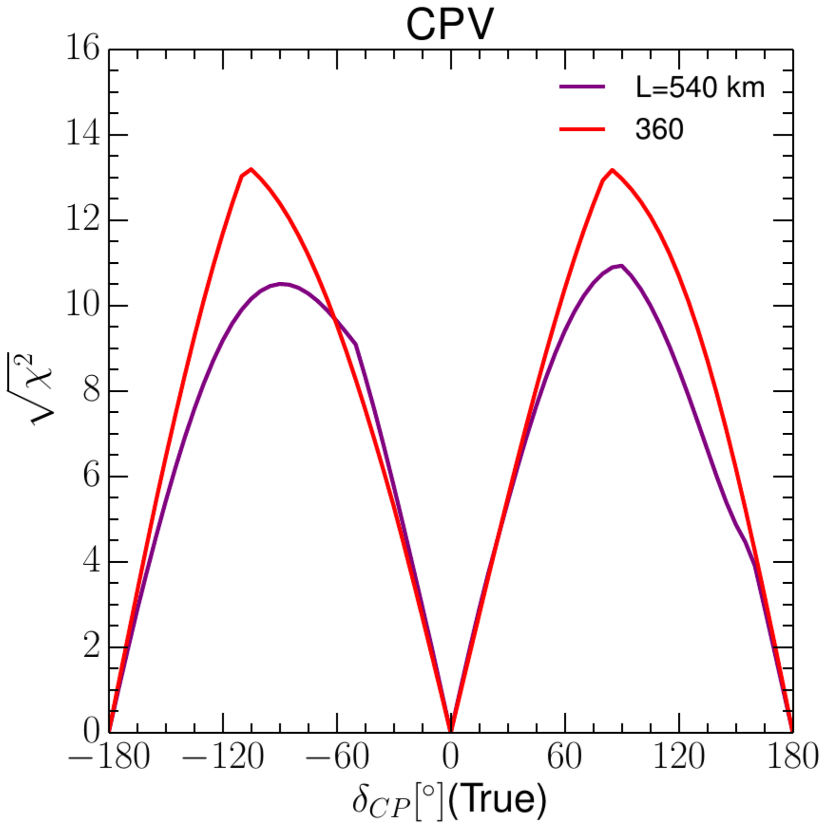
538 kt
total fiducial



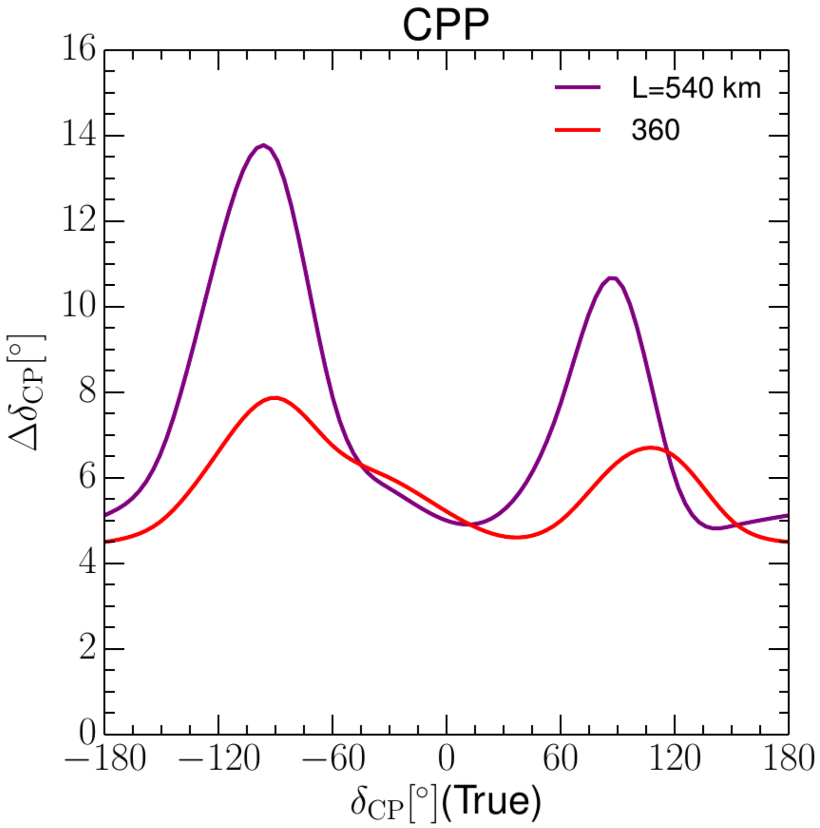
Updated physics performance of the ESSnuSB experiment,

Eur.Phys.J.C 81 (2021) 12, 1130
DOI:10.1140/epjc/s10052-021-09845-8, arXiv:2107.07585

State of analysis
June 2021



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

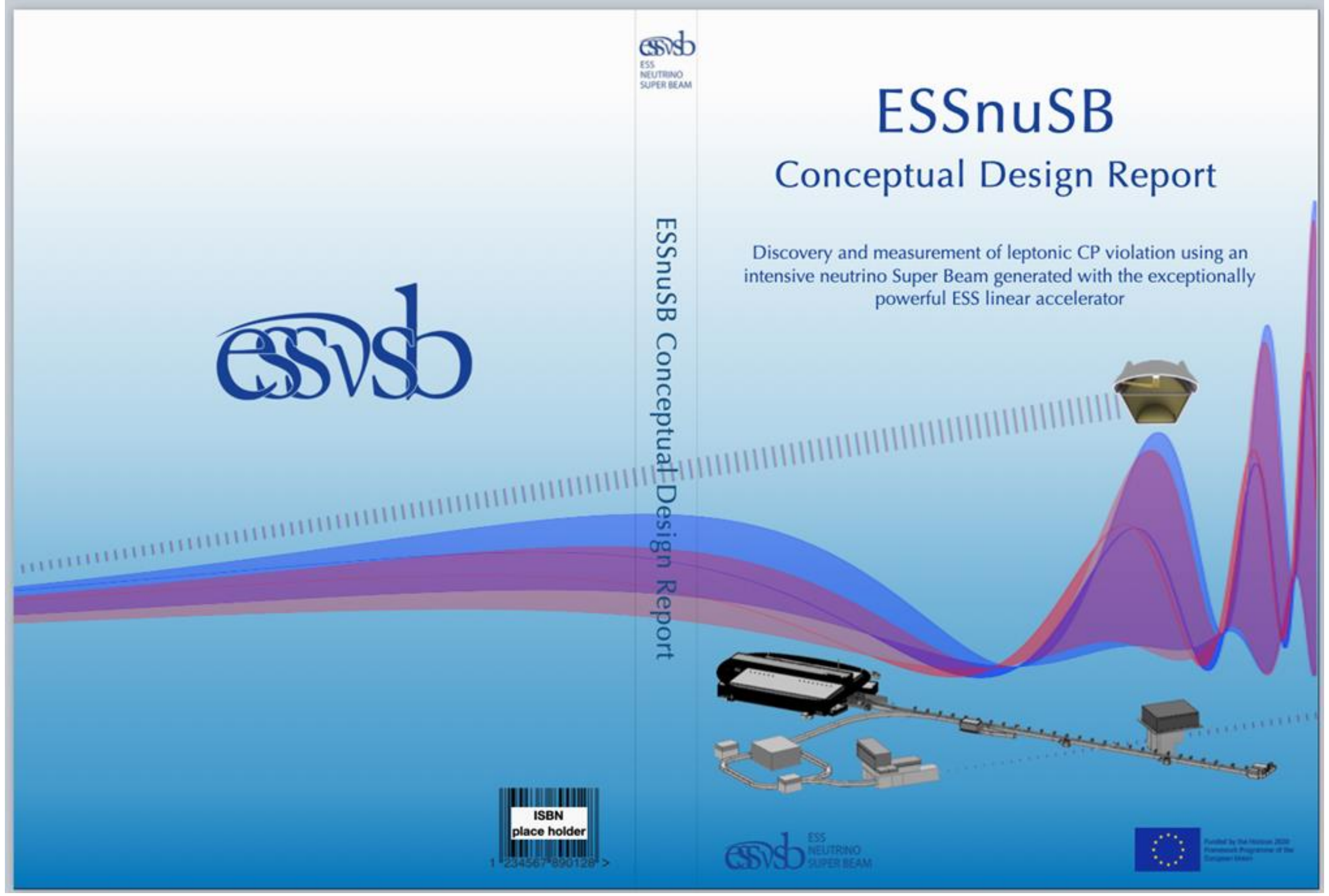


High precision of δ_{CP} measurement

Latest physics reach

- Since our previous publication:
  - Improved flux simulation
  - Improved detector geometry simulation
  - Improved handling of systematic errors

- Will be published within the CDR soon



ESSnuSB

Conceptual Design Report

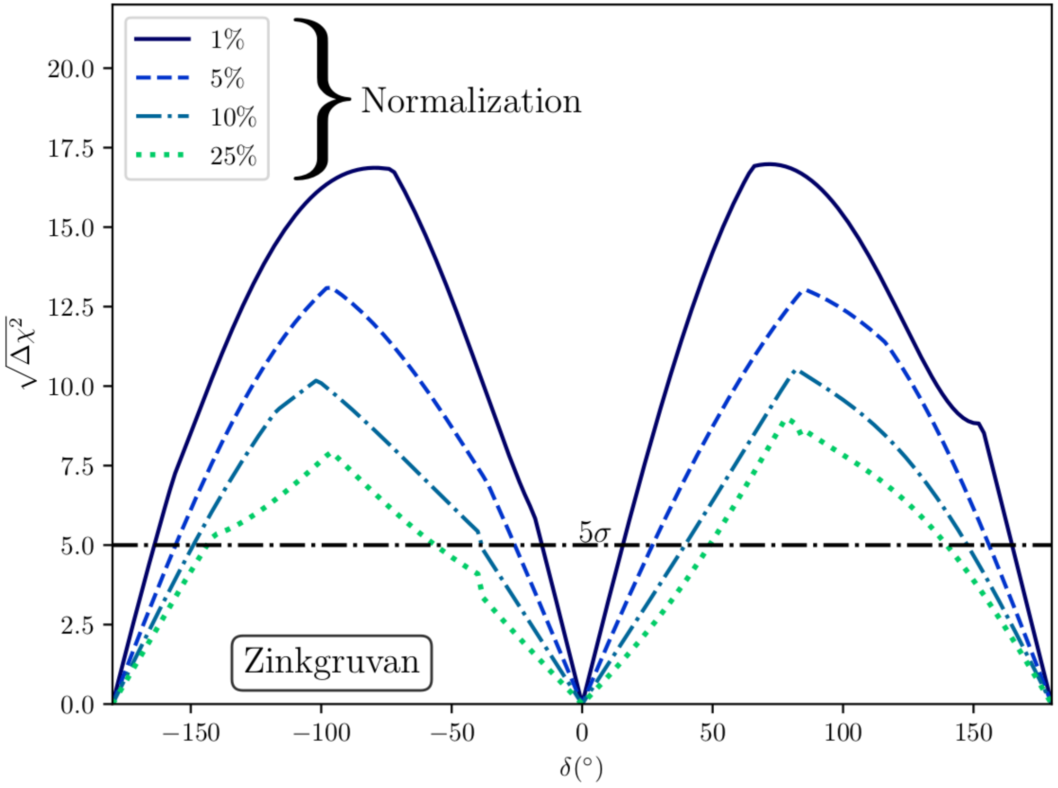
Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator

ESSnuSB Conceptual Design Report

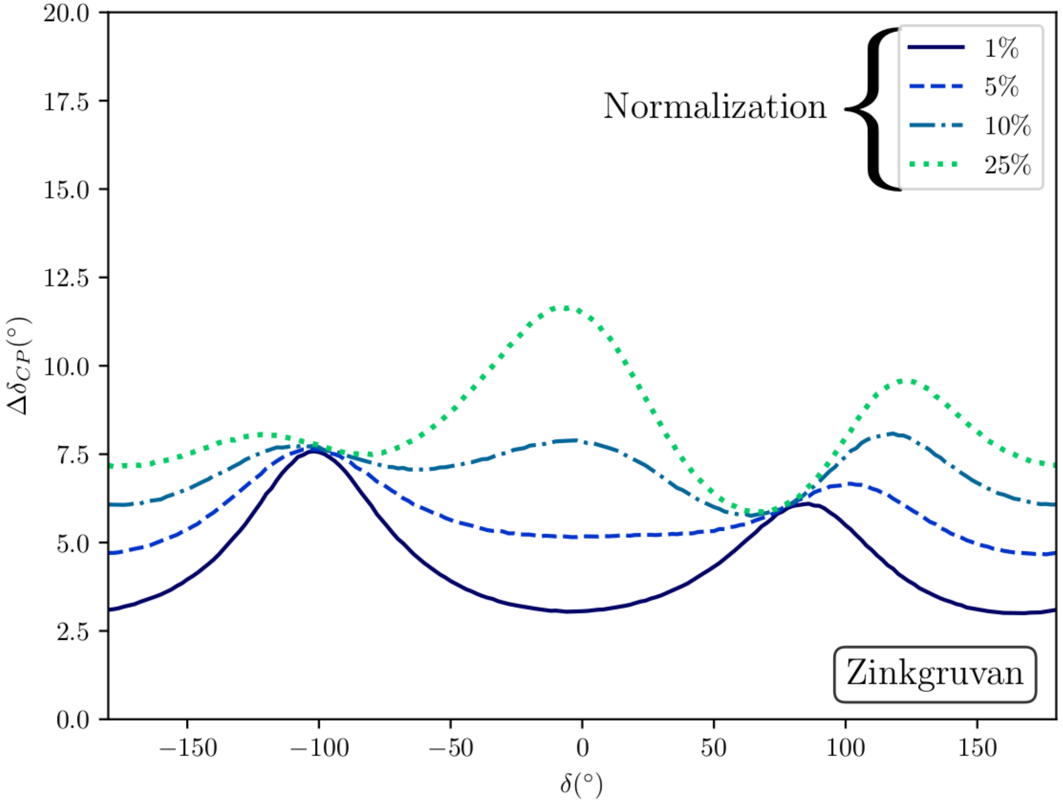
ISBN
place holder

Effect of normalization uncertainty

Sensitivity

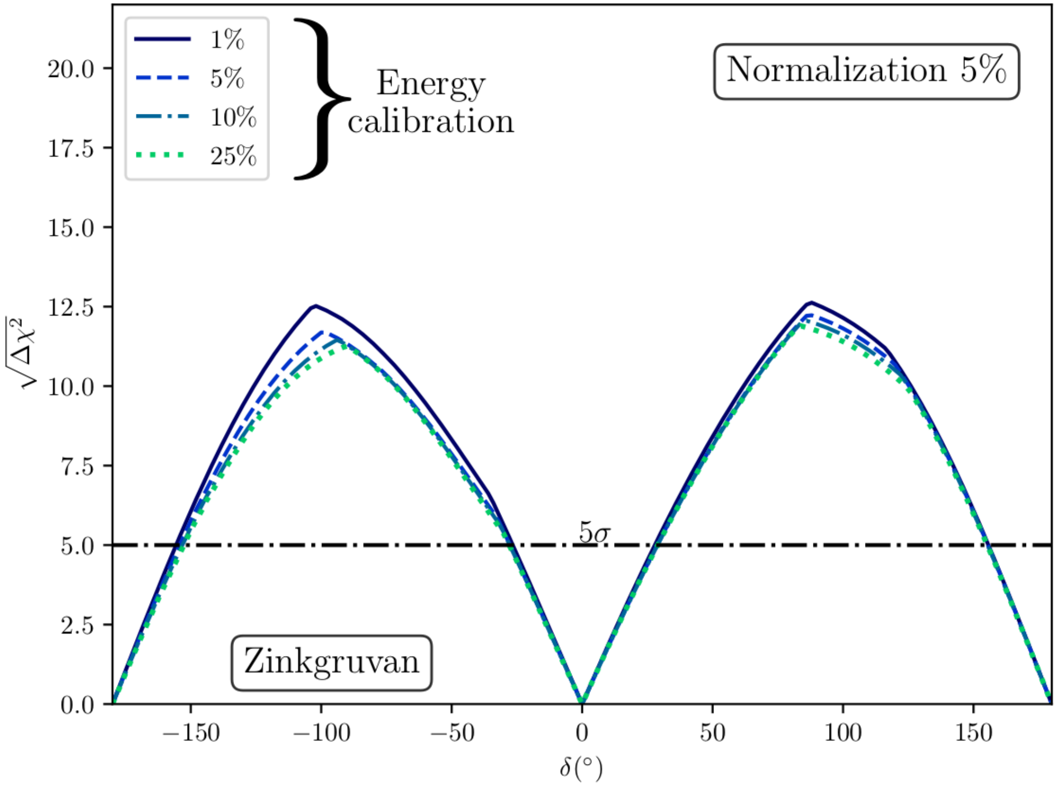


Precision

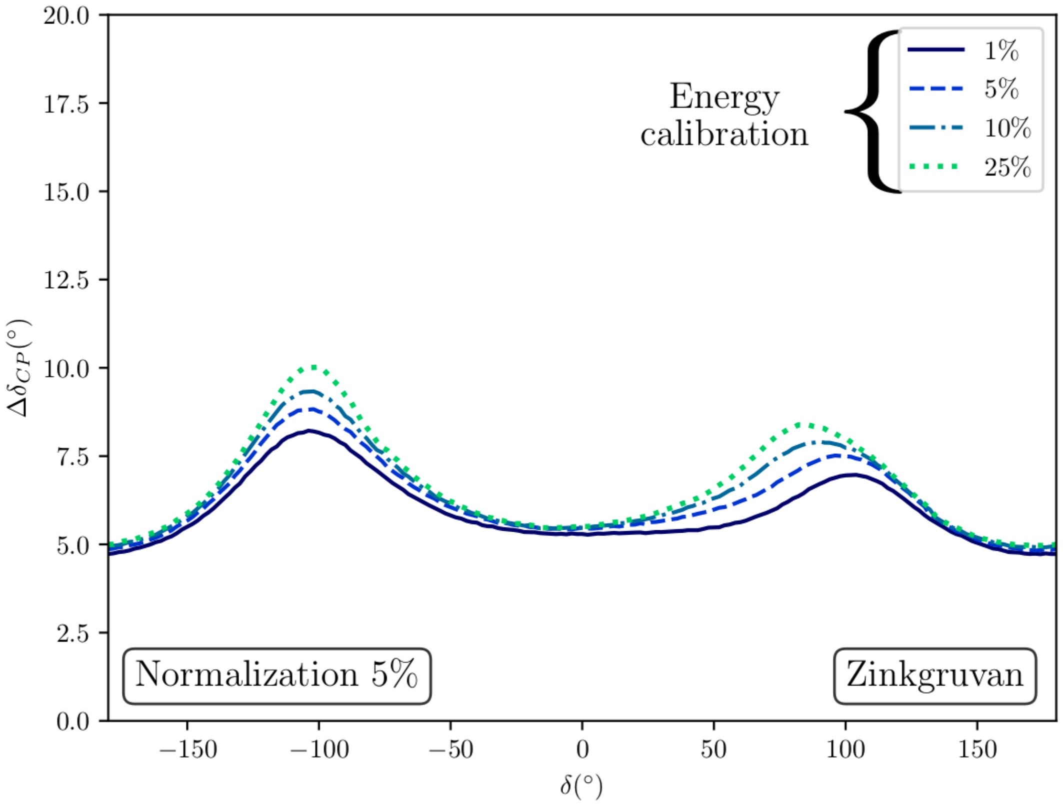


Effect of energy calibration uncertainty

Sensitivity

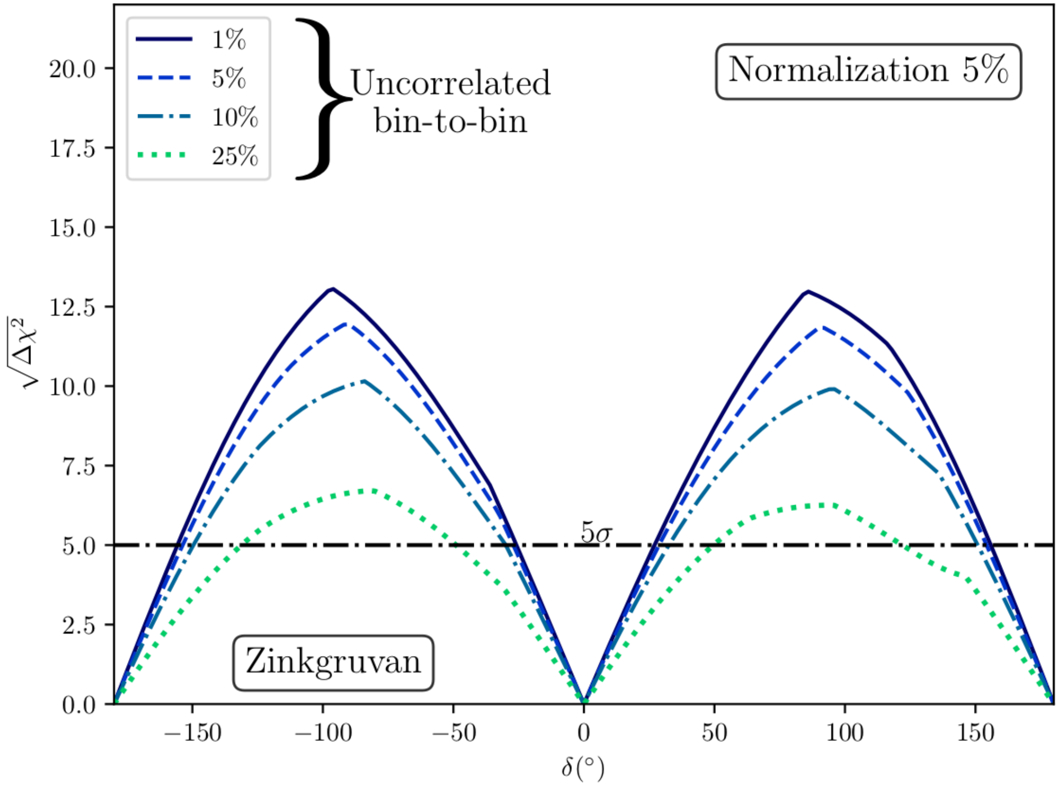


Precision

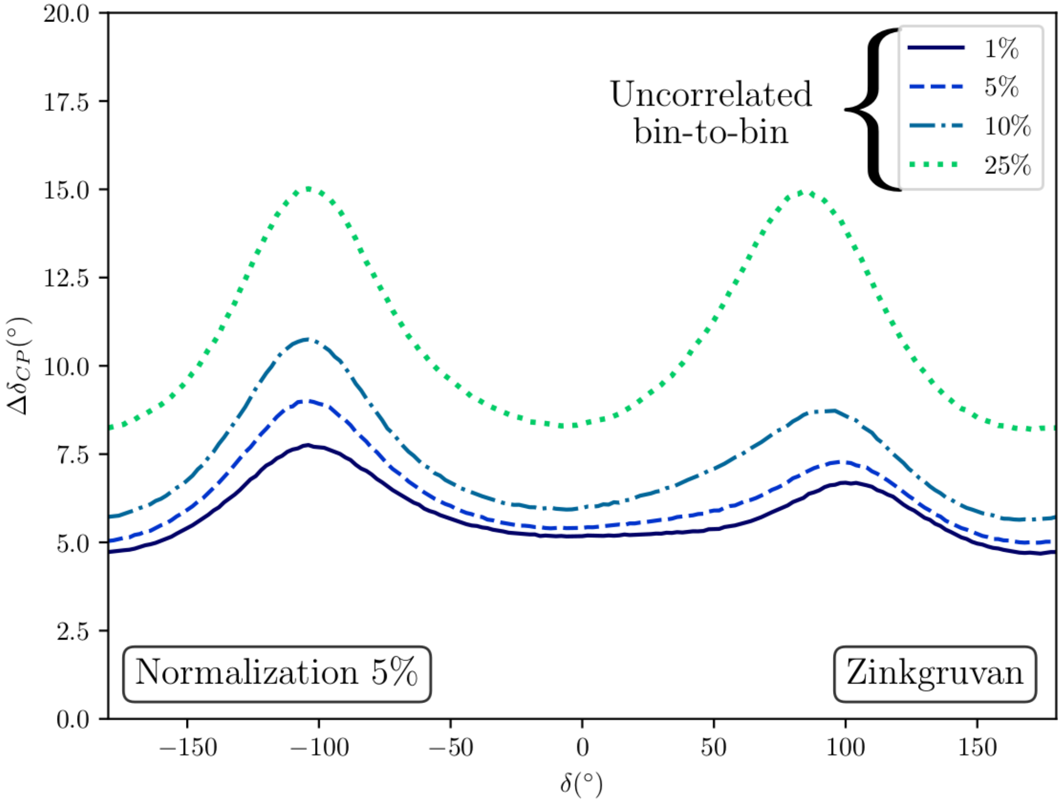


Effect of bin-to-bin uncorrelated uncertainty

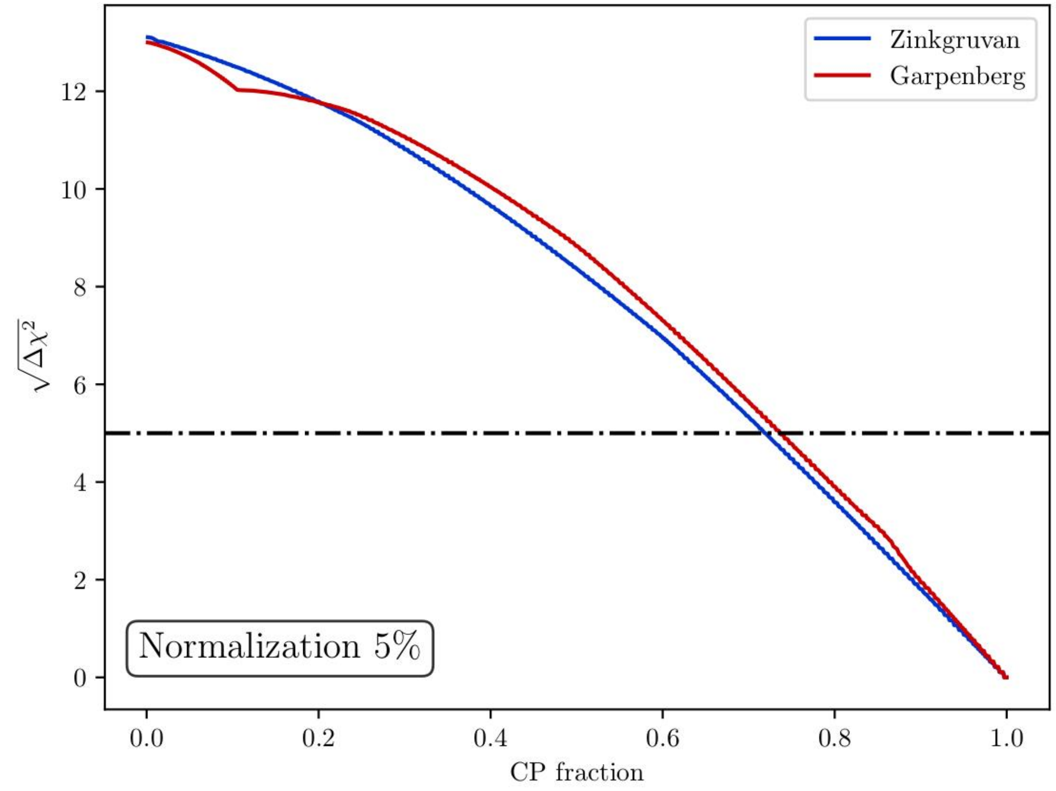
Sensitivity



Precision



CP coverage

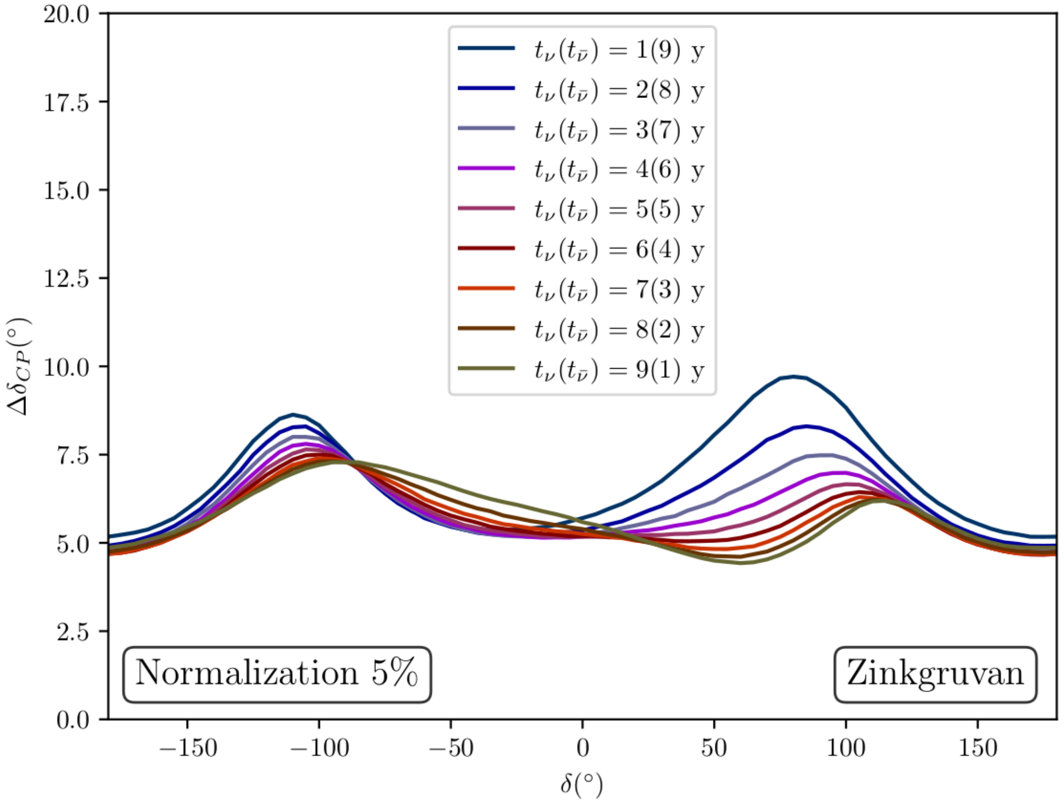


71% coverage of δ_{CP} range with more than 5 σ

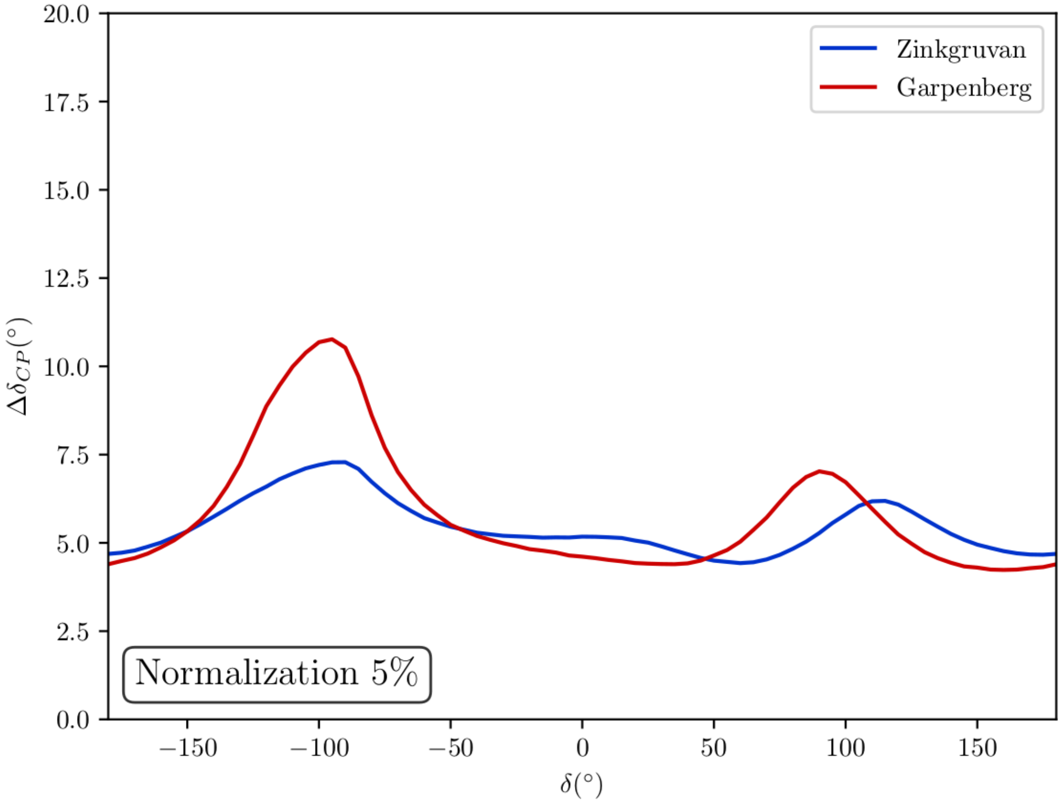
Optimization for precision

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

Precision for different neutrino (antineutrino) run times

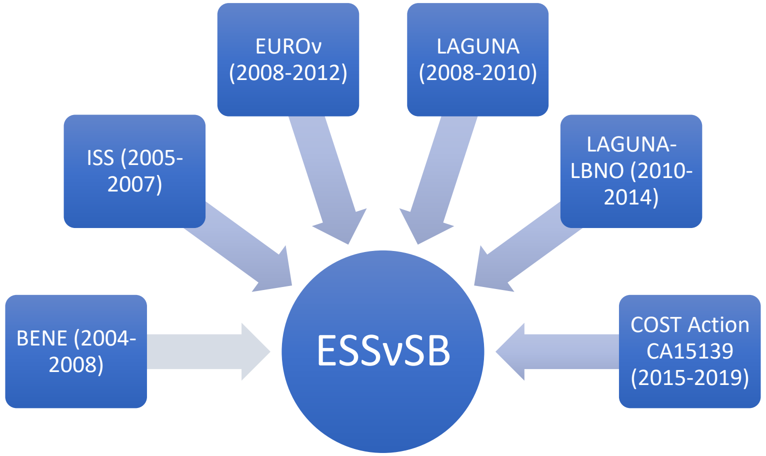


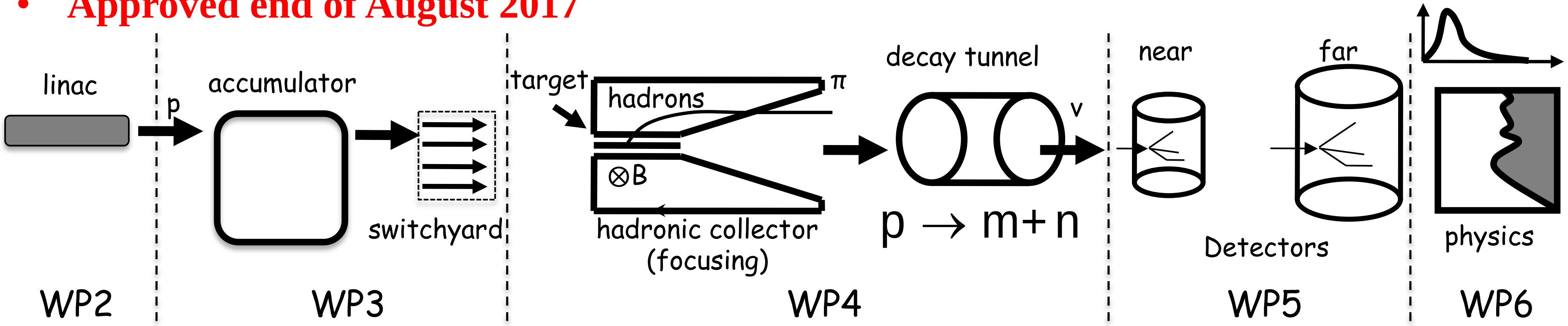
Optimal precision for known δ_{CP}



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**





Schedule for a 2nd generation ESS-based neutrino Super Beam ESSnuSB

2012:
Inception of the project

Nucl. Phys. B 885 (2014) 127

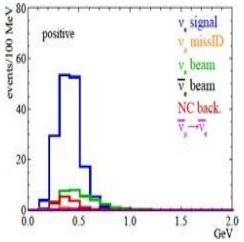
2016-2019:
Beginning of COST Action EuroNuNet

2018:
Beginning of ESSνSB Design Study (EU-H2020)

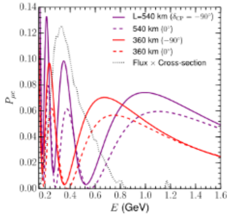
2022: End of ESSνSB Design Study, preliminary costing and CDR

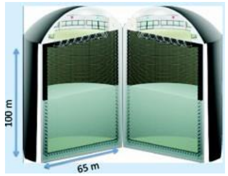
2023-2026:
Continuation of Design Study, final costing and an TDR to ESFRI

2027-2028:
Preconstruction Phase, International Agreements



2029-2035:
Construction o
the facility an
detectors,
including
commissionin



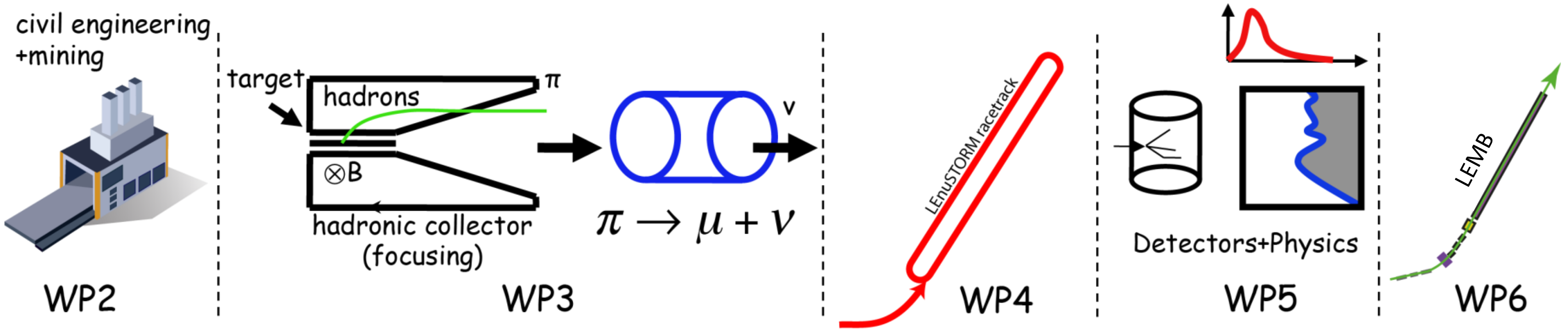


2036-:
Start of data taking

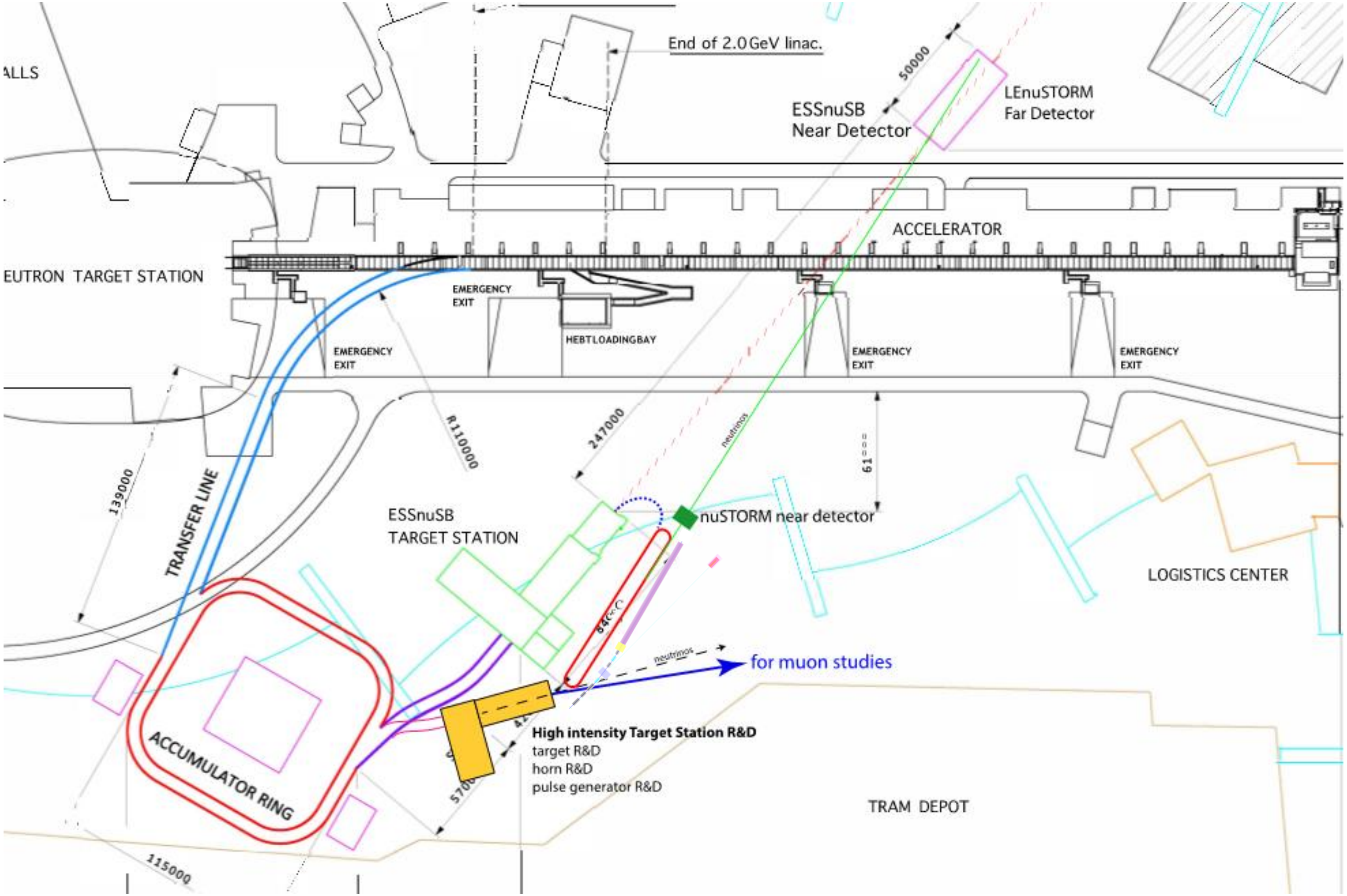
The ESSnuSB+ project proposal

- 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 very 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

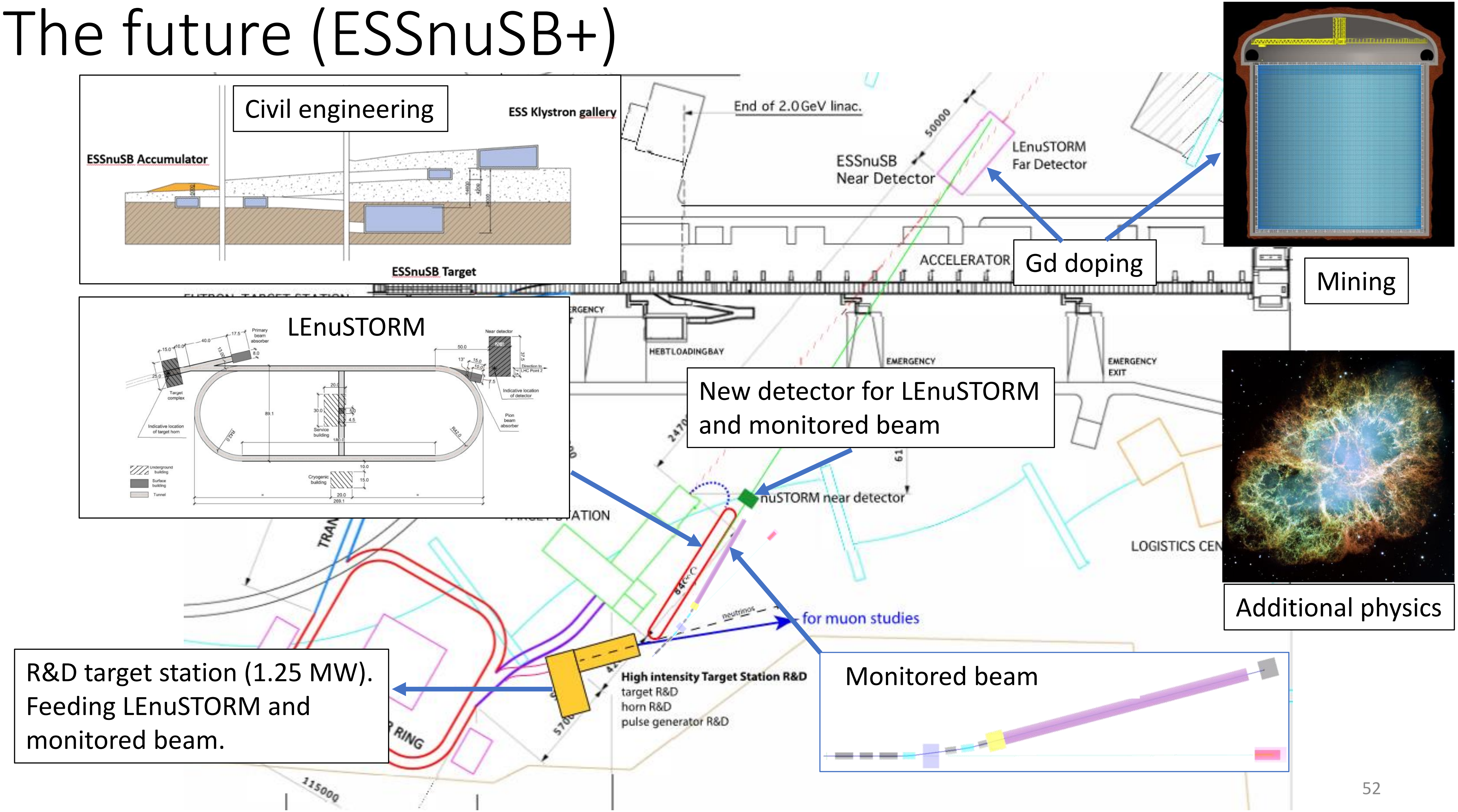
- We have received strong support from the ESS management



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

ESSnuSB movies

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

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

Special thanks to my ESSnuSB colleagues!

The content presented here is a result of 4 years of collaborative effort of many people involved in ESSnuSB project.

Thank you all for making this possible!

Funded by the Horizon 2020 Framework Programme of the European Union

Conclusions

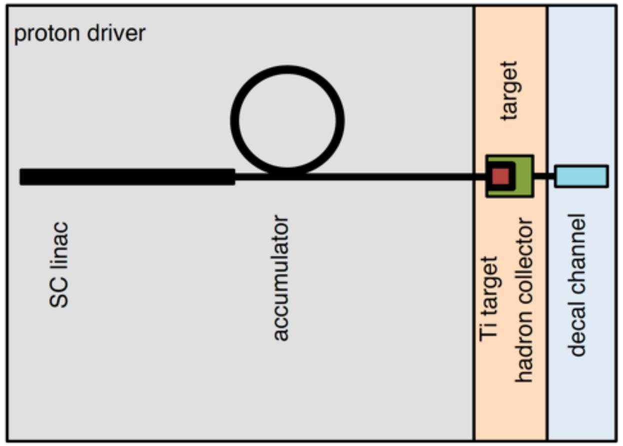
- **ESSnuSB** aims to observe CP violation in neutrino oscillations at the 2nd oscillation maximum using 538 kt WC detector
  - **2nd maximum** makes the measurement resilient to systematic errors and matter effects
  - **Recent optimizations** predict that in 10 years of data taking ESSnuSB will be able to
    - reach 5 σ over 71% of δ_{CP} range
    - reach δ_{CP} resolution of less than 8°
    - determine neutrino mass hierarchy
- **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 2025, decision on neutrino programme pending
  - proposed modifications would allow a **rich additional physics** programme at ESS
    - muon physics, DAR experiments, short neutron pulses, ...
- **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 are about to seek **renewed support from EU-Horizon Europe** for the period 2023-2026
  - ESSnuSB+ received in March 2022 a letter of strong support from the ESS Director General Helmut Schober

Thank you for your attention

ESSνSB and (R&D) synergies

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

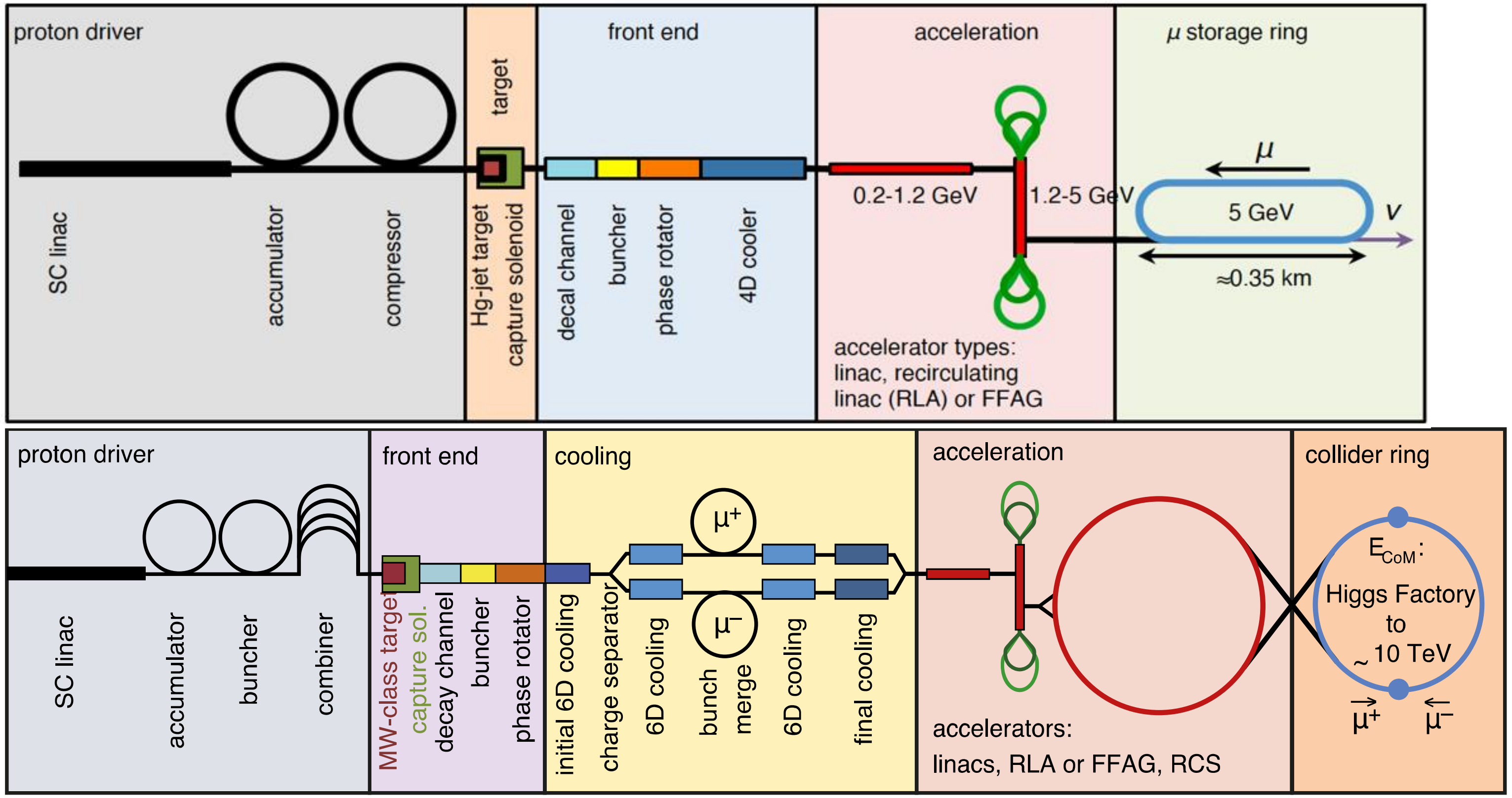
Super Beam



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

Neutrino Factory

Muon Collider



Neutrino oscillations

Flavour state evolution

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

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:

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

Assuming:

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

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

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

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

One gets the final relation:

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

PMNS matrix parametrization (Dirac neutrino)

Standard parametrization used in modern literature:

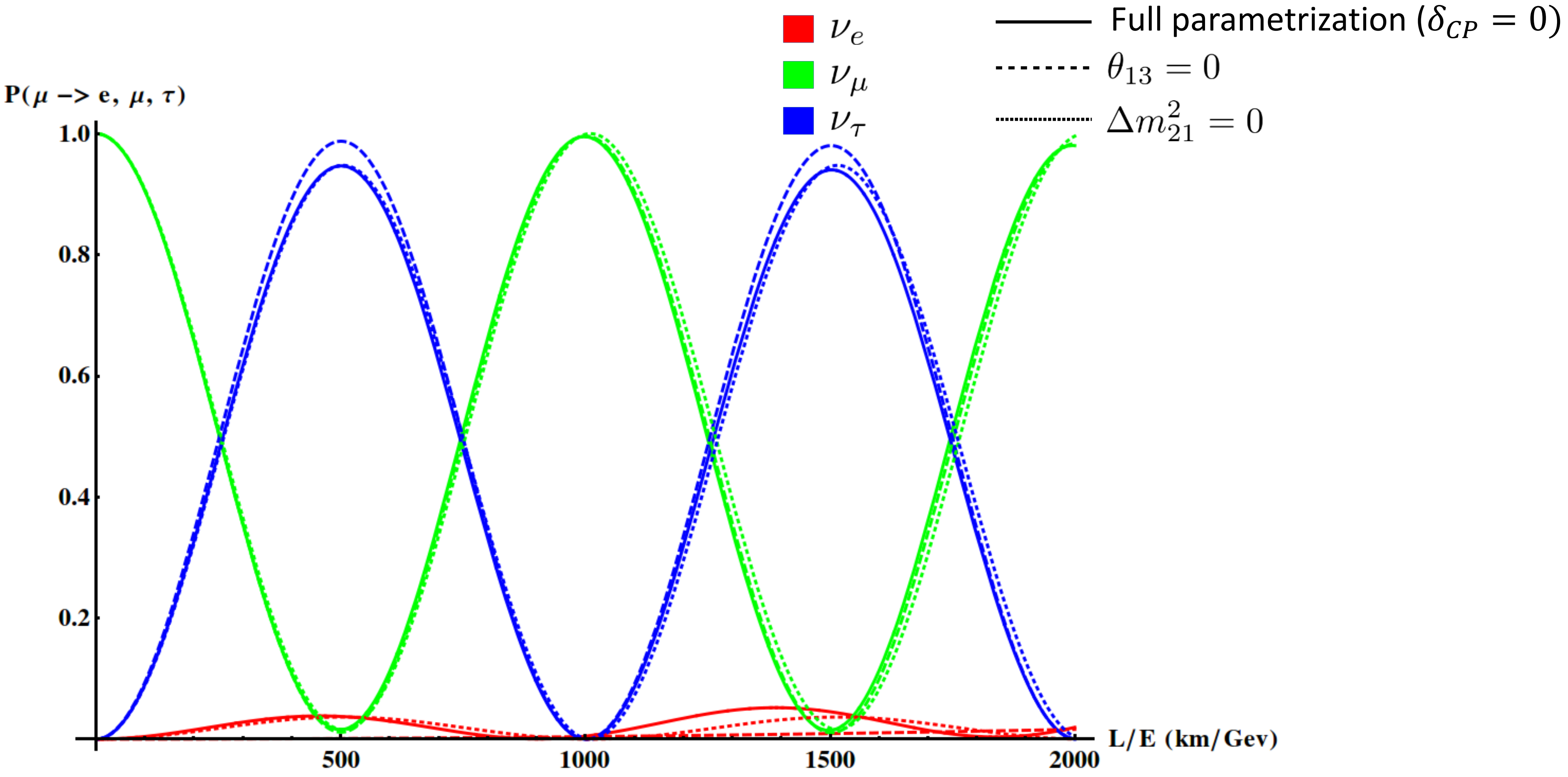
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

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

- 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

Muon neutrino oscillations



Hot Cell

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

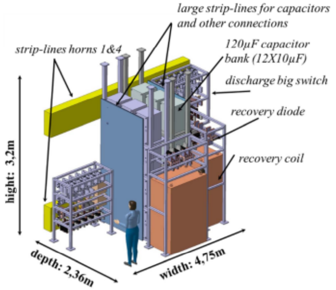
Morgue

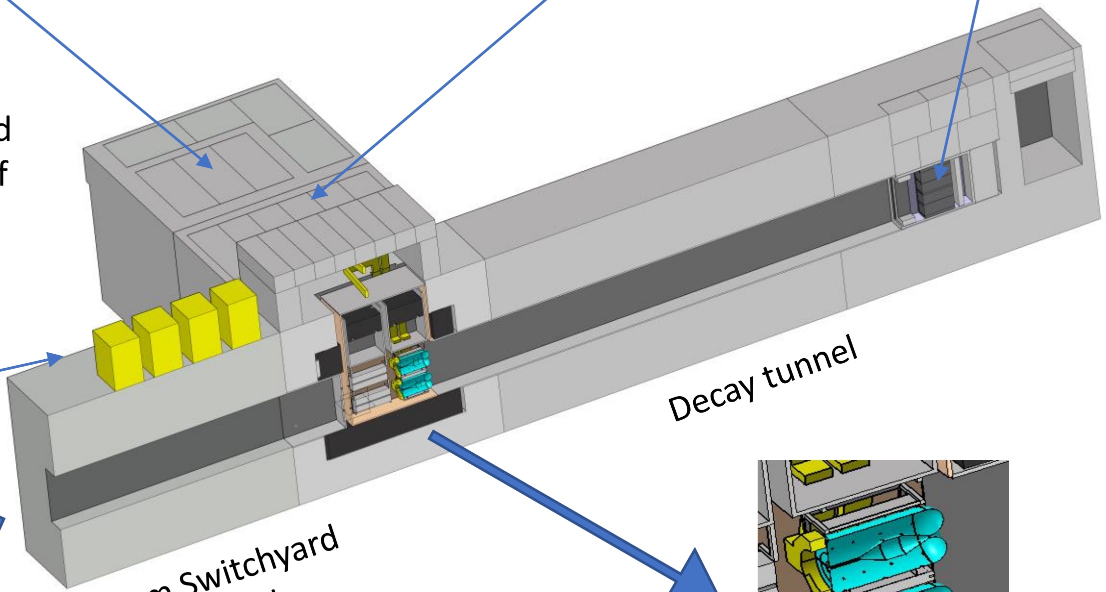
To Store radioactive wastes

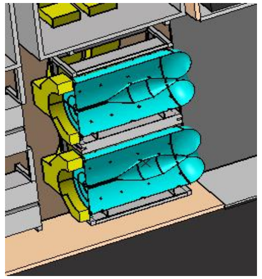
Beam dump

Power Supply Unit

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



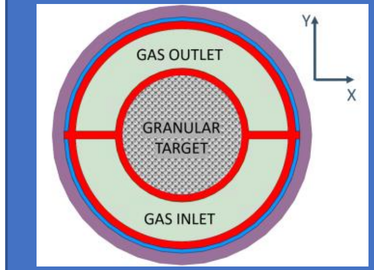


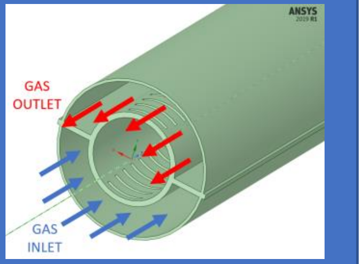


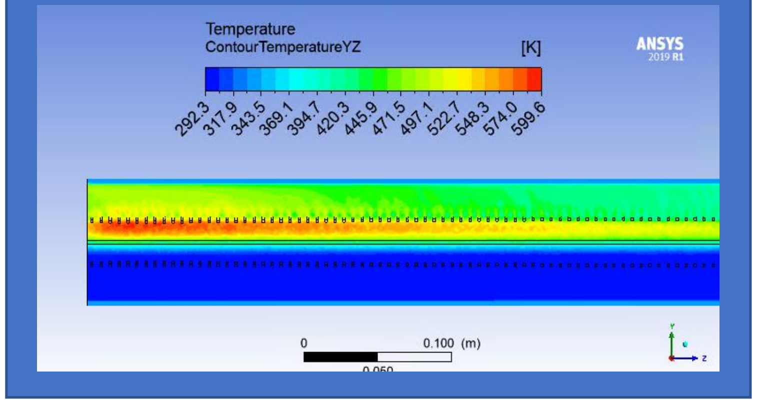
Hadronic Collector

Granular Target Concept

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



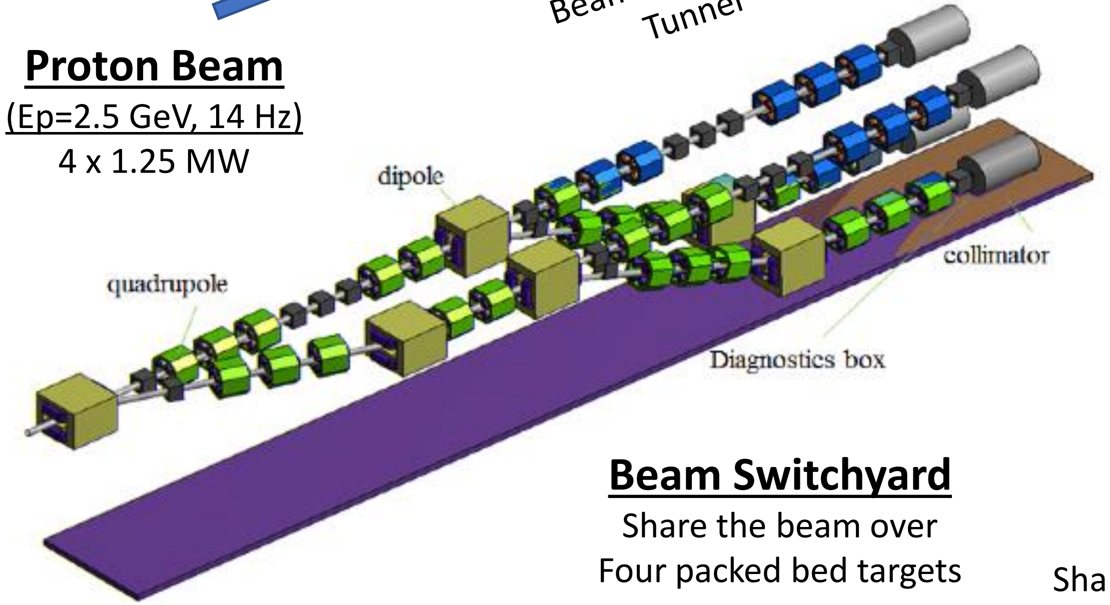




Proton Beam

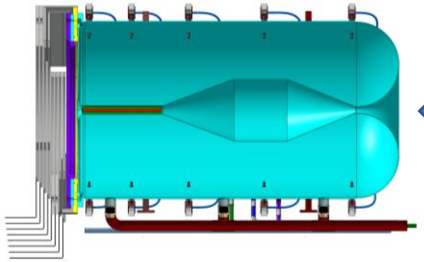
(Ep=2.5 GeV, 14 Hz)

4 x 1.25 MW



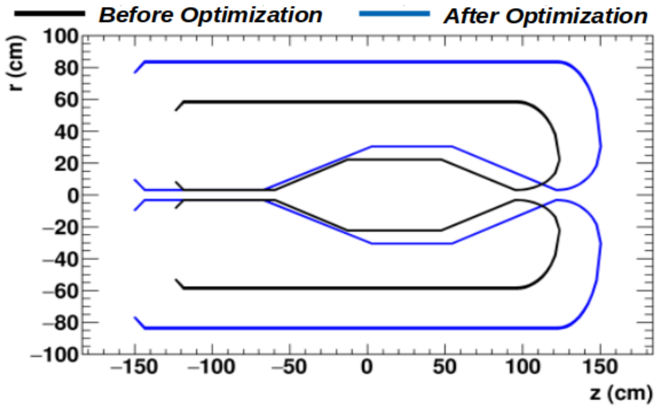
Beam Switchyard

Share the beam over Four packed bed targets



MiniBoone Like Horn

Shape optimized with genetic algorithm

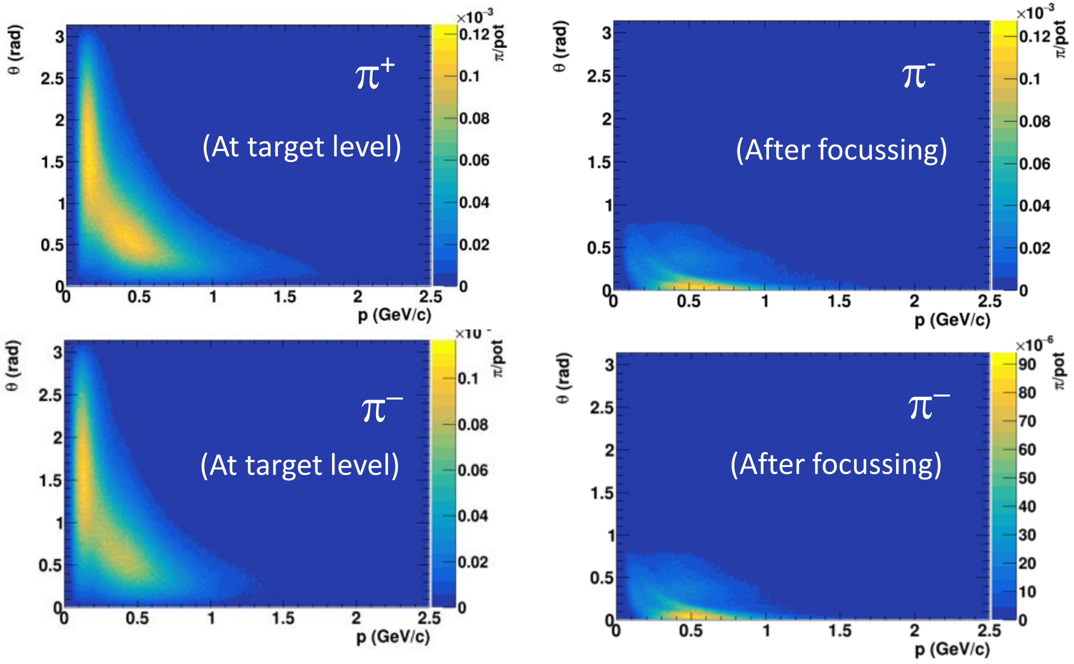


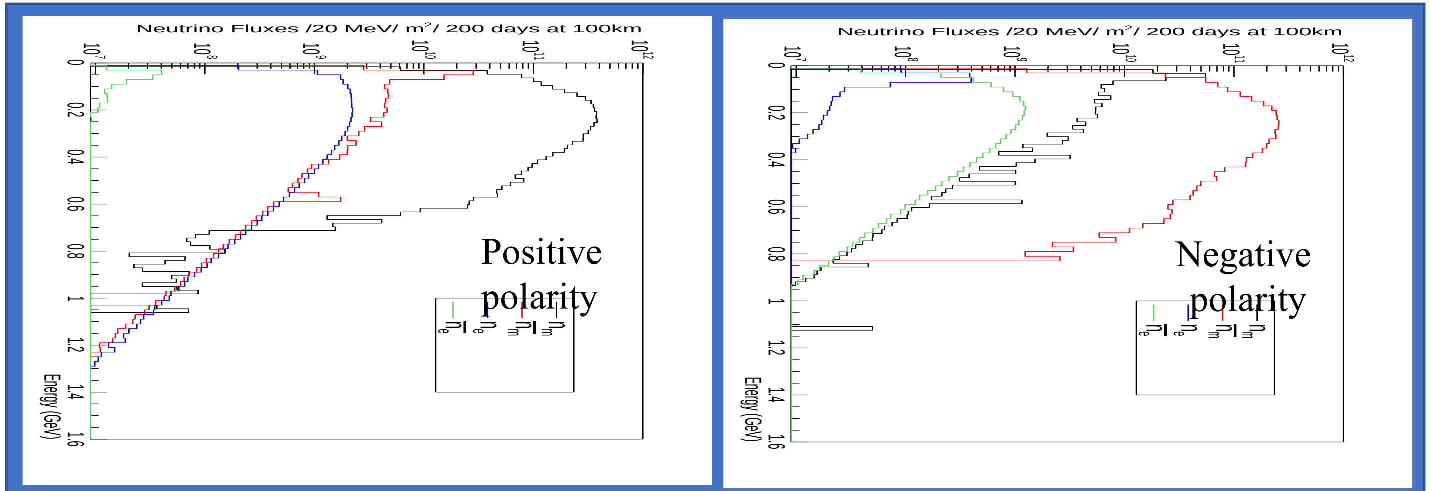
Neutrino beam production

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

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

Horn focussing

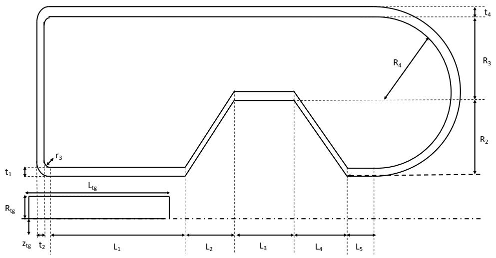




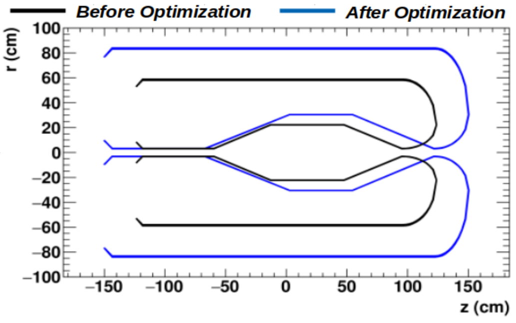
Neutrino flux composition.

	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

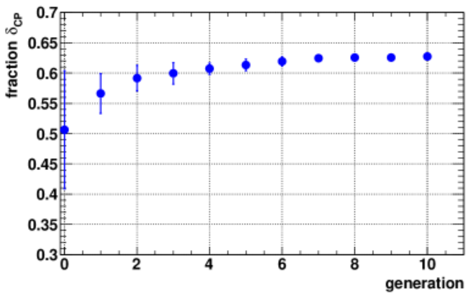
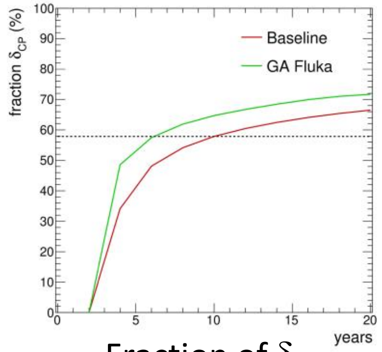
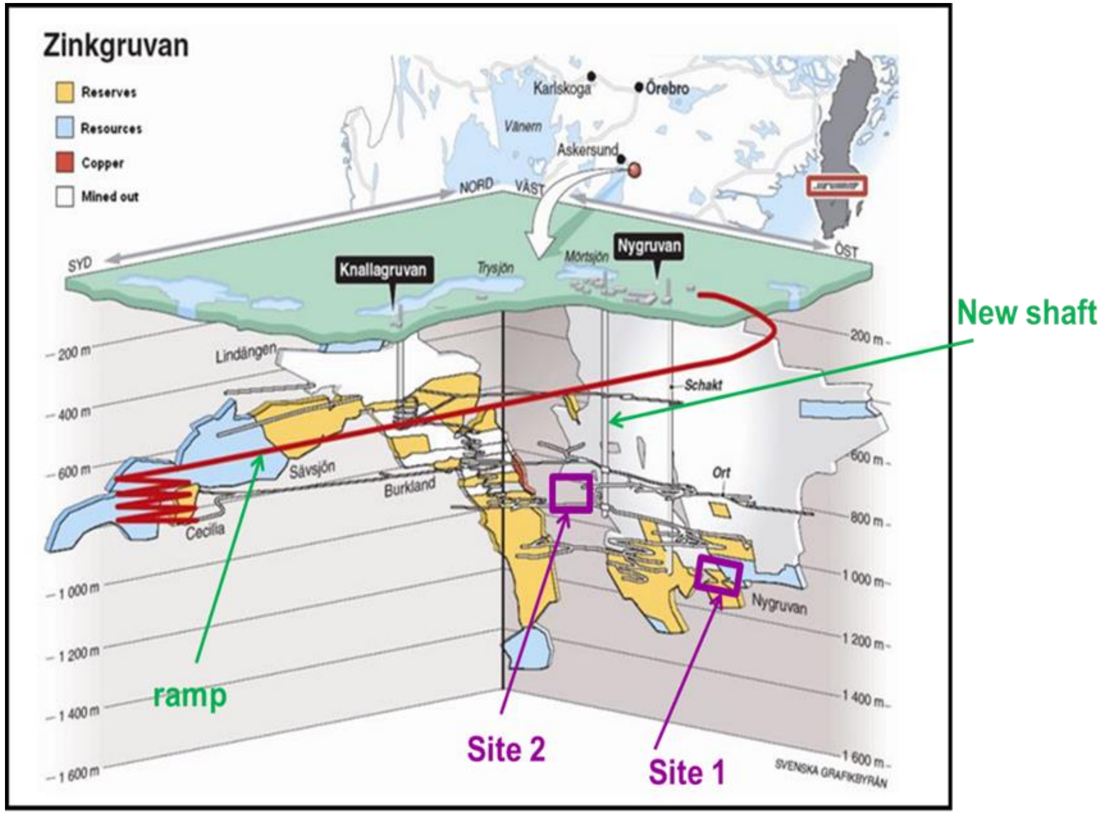


Figure of Merit based on δ_{cp}

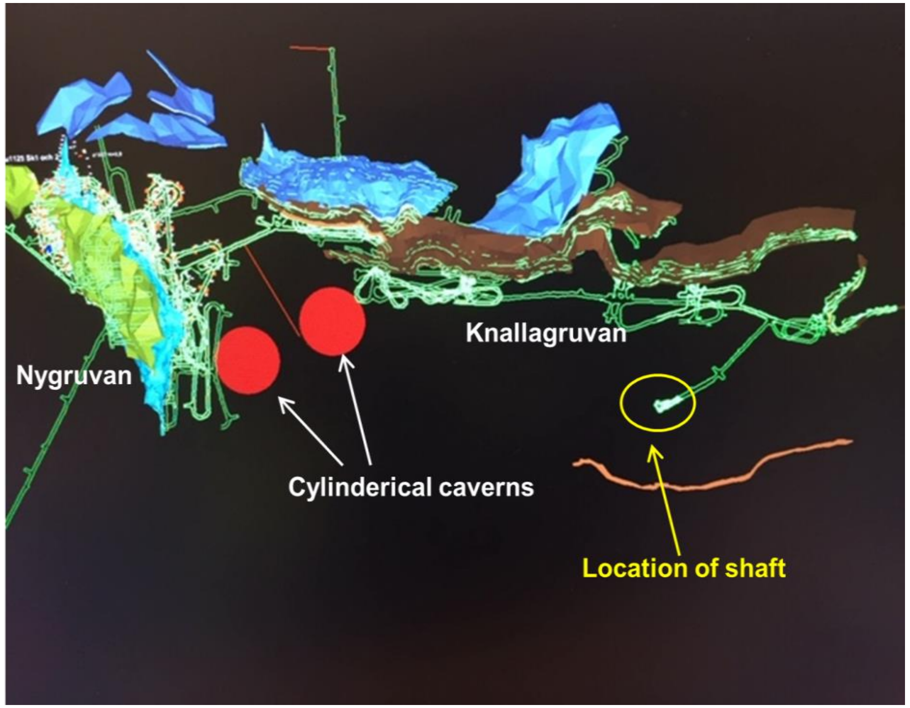


Fraction of δ_{cp}

Zinkgruvan mine

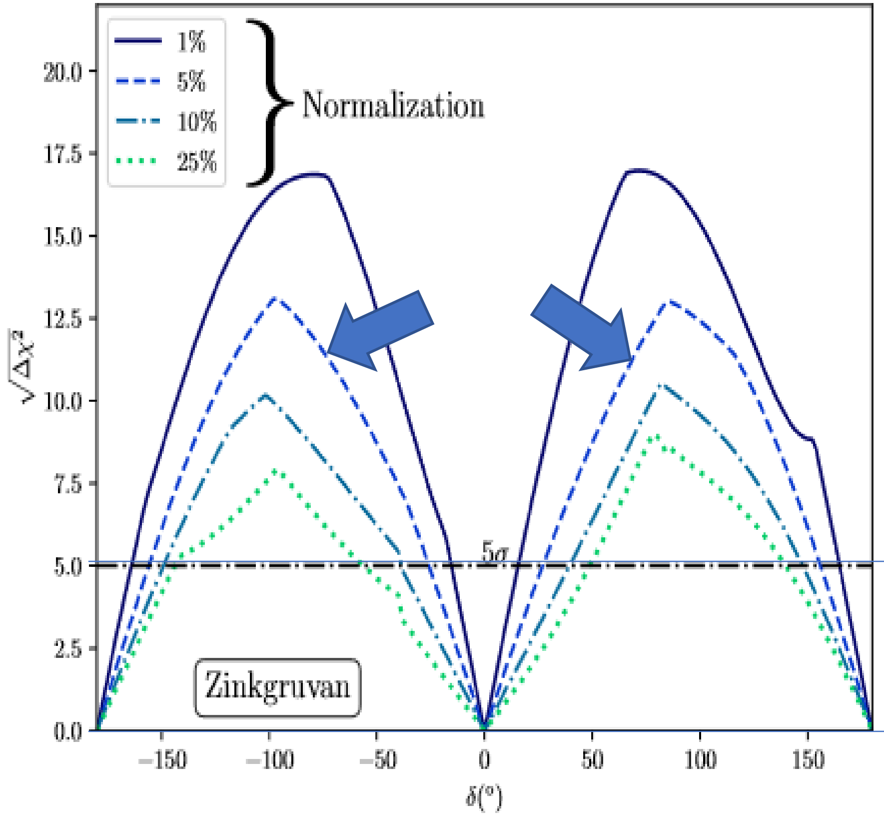


Potential location in Site 2

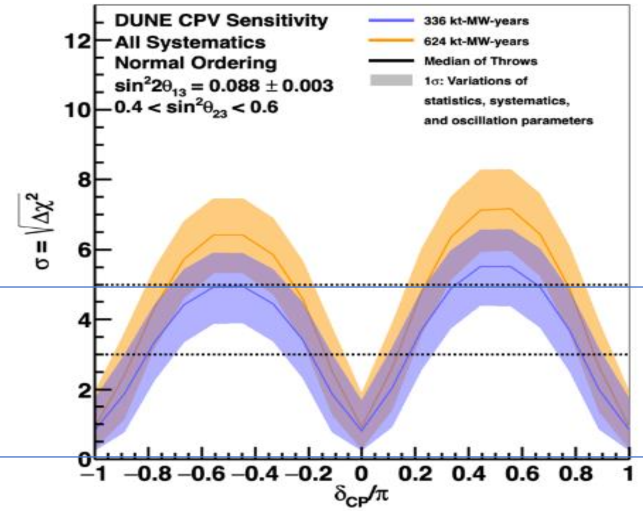


Site 2 is considered as best considering access to main transport infrastructure and located in an area less disturbed by mining activities

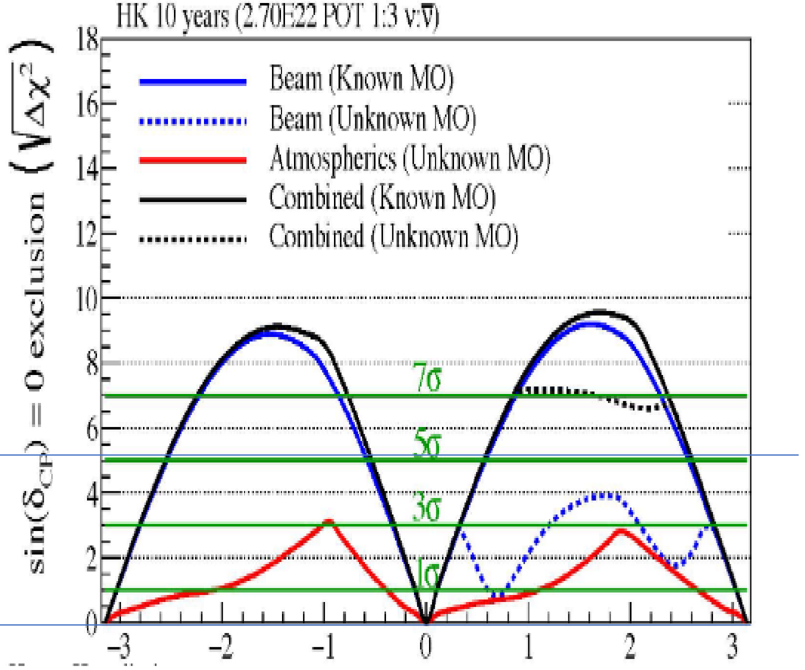
ESSnuSB in the international context – CPV discovery



ESSnuSB March 2022 with 5% normalization error

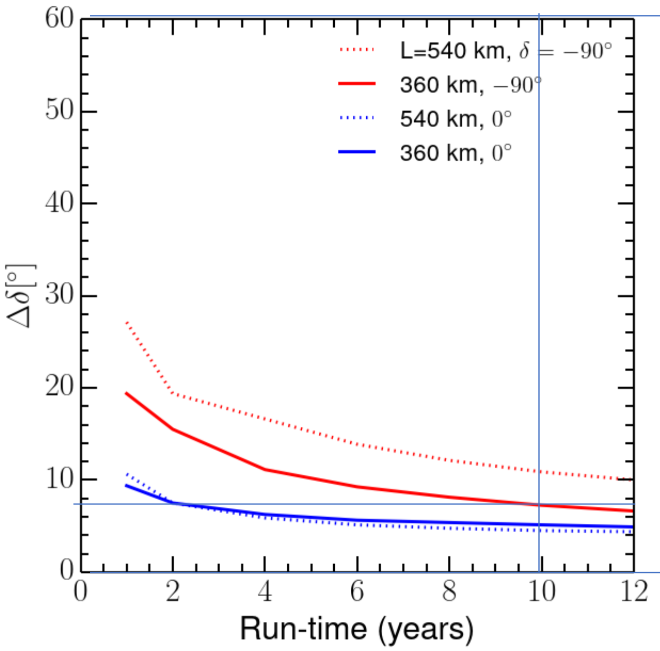


DUNE Snowmass March 2022

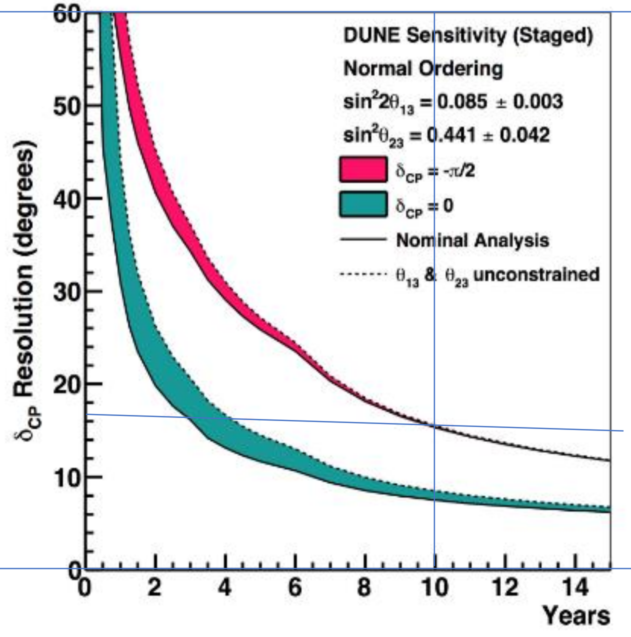


Hyper-Kamiokande Snowmass March 2022

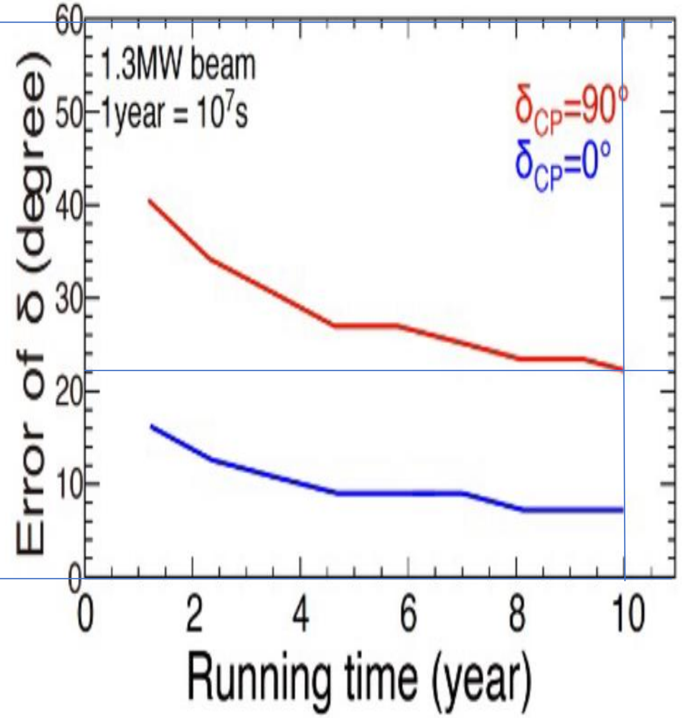
ESSnuSB in the international context – CPV resolution



ESSnuSB March 2022 with 5% normalization error

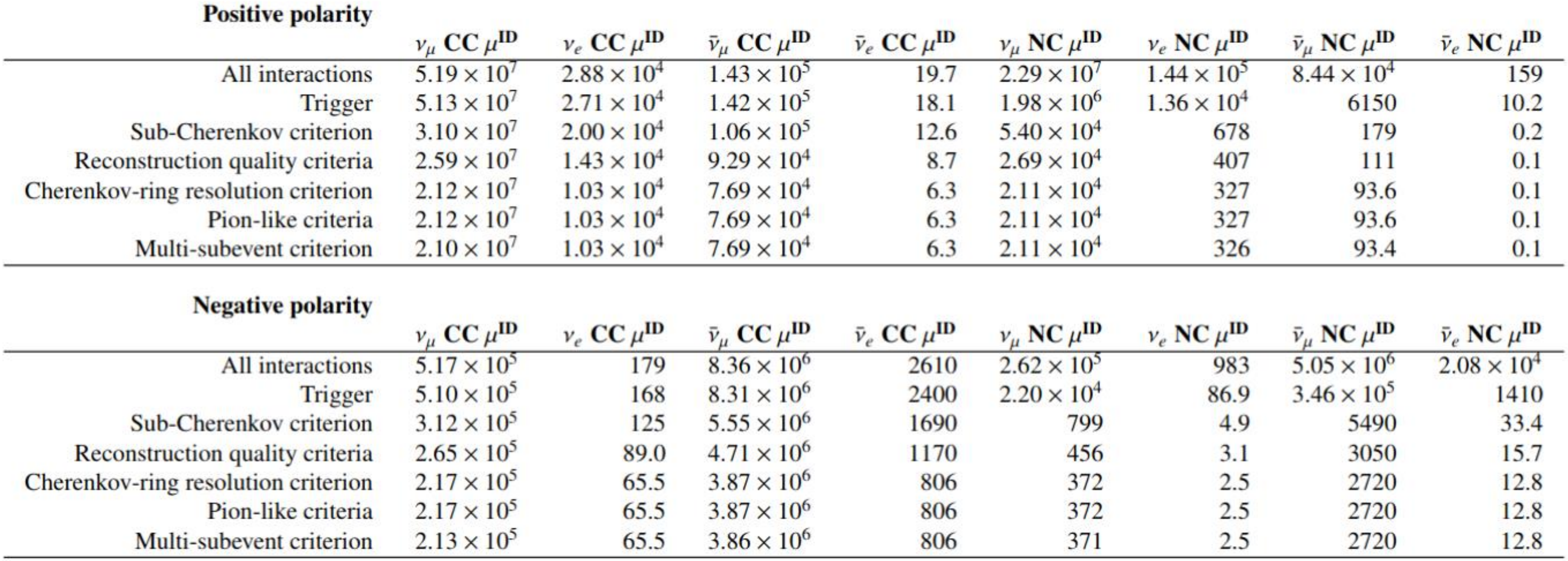


DUNE Snowmass March 2022



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

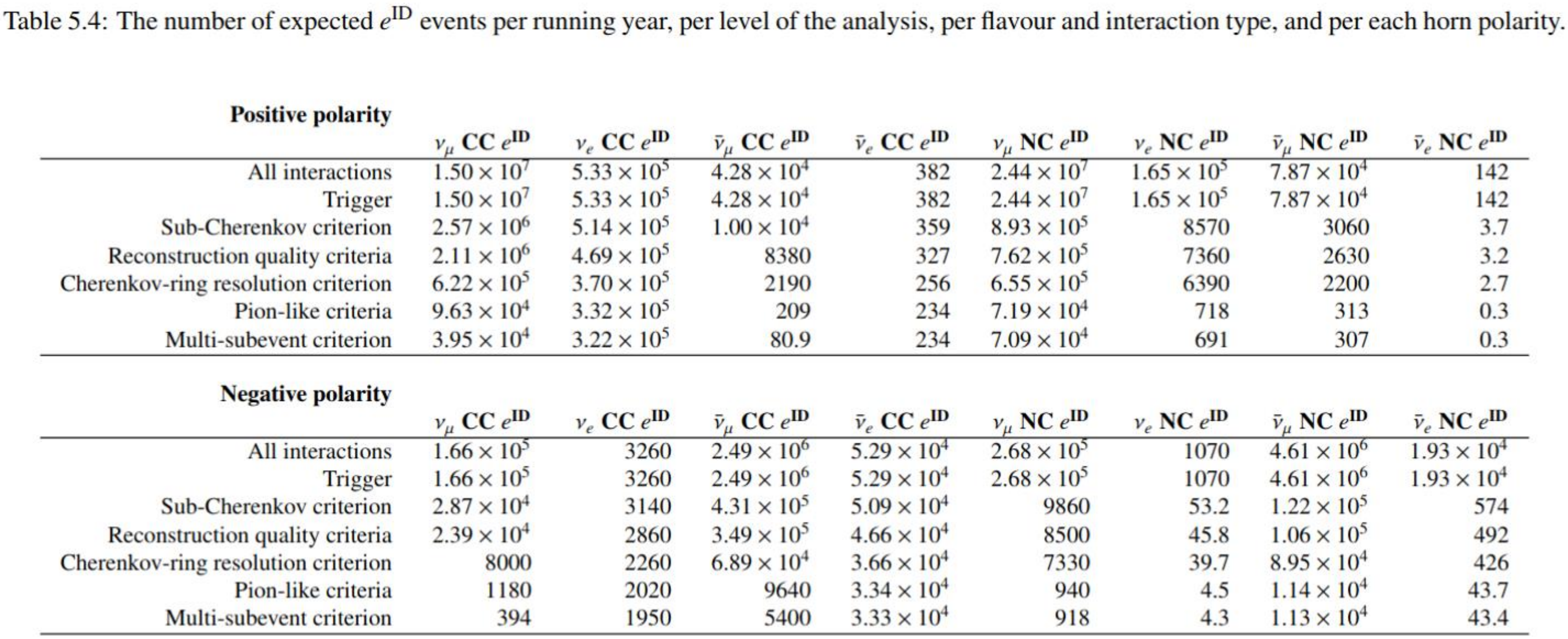


Table 5.4: The number of expected e^{ID} events per running year, per level of the analysis, per flavour and interaction type, and per each horn polarity.

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

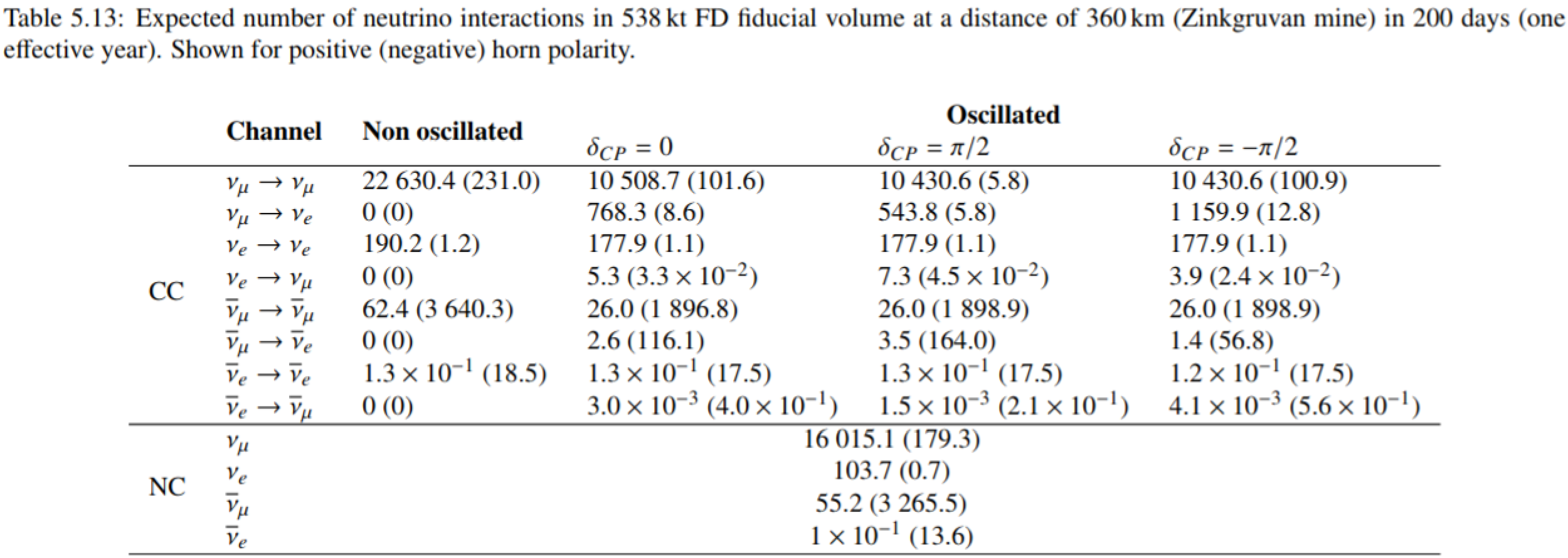
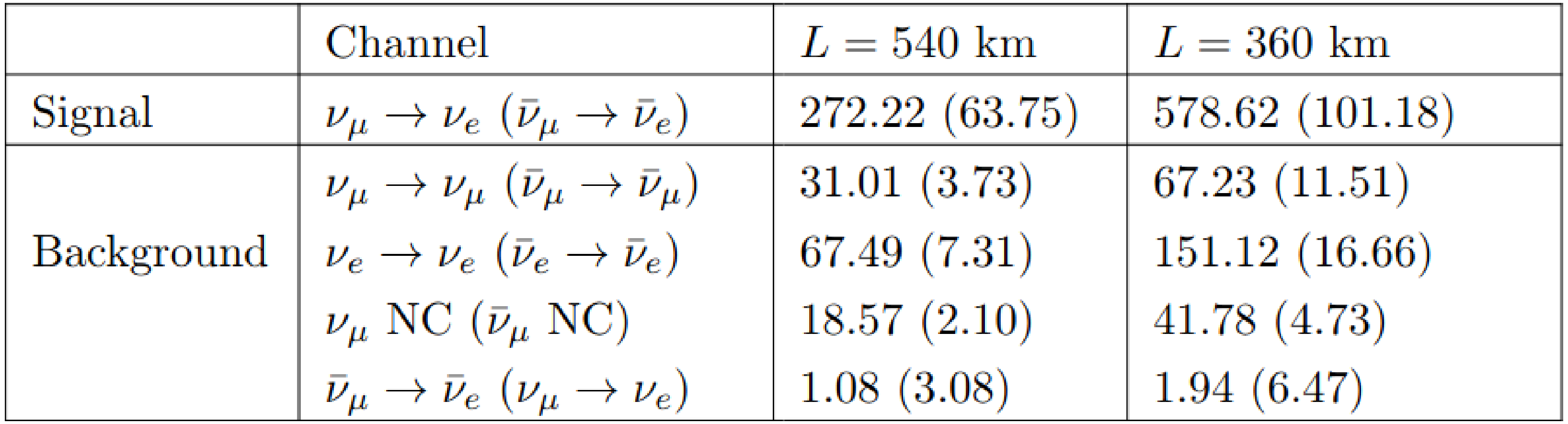


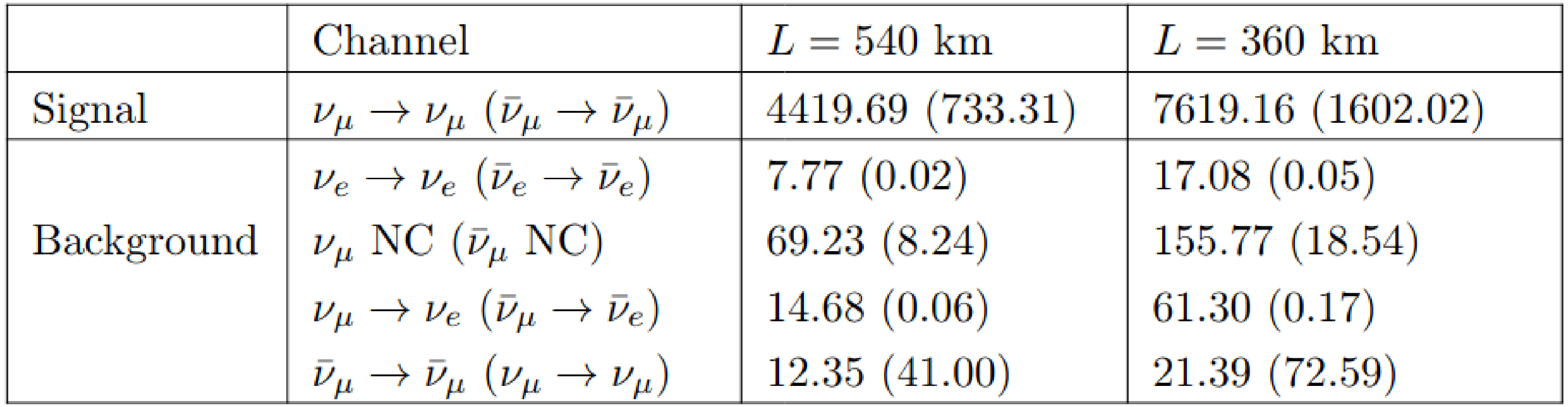
Table 5.13: Expected number of neutrino interactions in 538 kt FD fiducial volume at a distance of 360 km (Zinkgruvan mine) in 200 days (one effective year). Shown for positive (negative) horn polarity.

	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 $\delta_{\mathrm{CP}} = 0°$.