Funded by the Horizon 2020
Framework Programme of the
European Union

The ESSnuSB project:

Measuring CP violation at the 2nd neutrino oscillation maximum

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Special thanks to my students: Martina Vujica, Leon Halić

High Energy Physics Seminar at the University of Warsaw

UNIVERSITY
OF WARSAW

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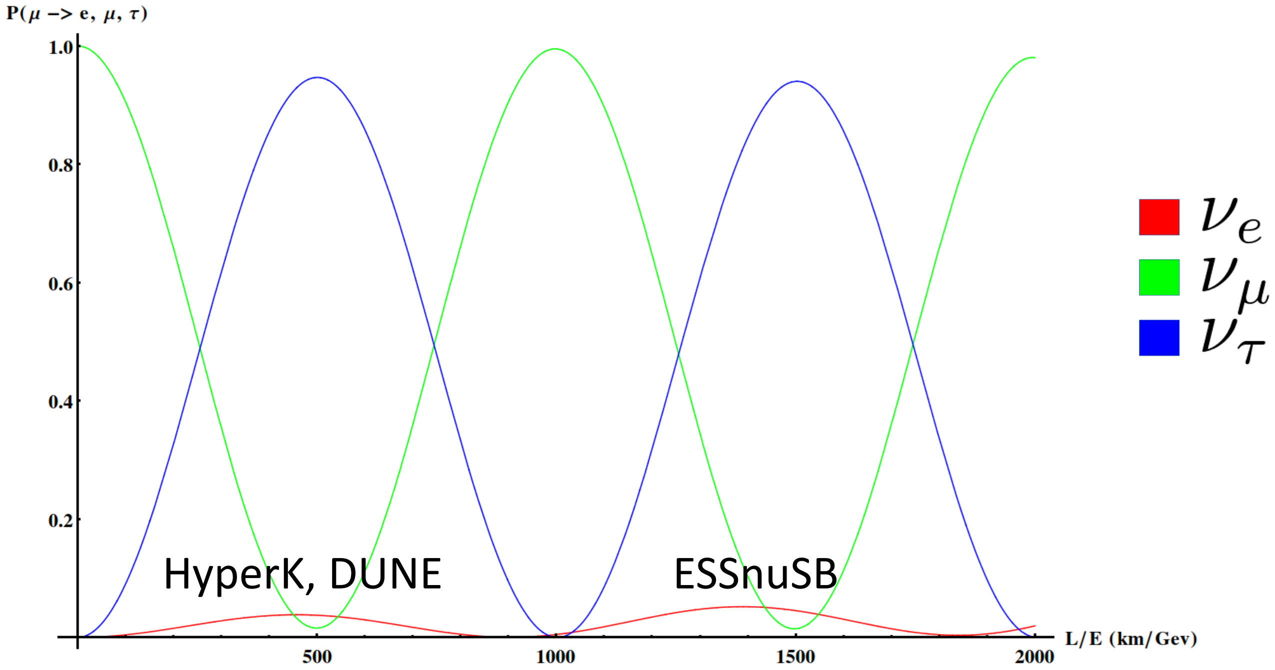
ESSnuSB

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

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

neutrino flavour at production

neutrino flavour at detection

CP violation in ESSnuSB

$$P_{\mu \to e} \neq P_{\overline{\mu} \to \overline{e}}$$

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

The plan:

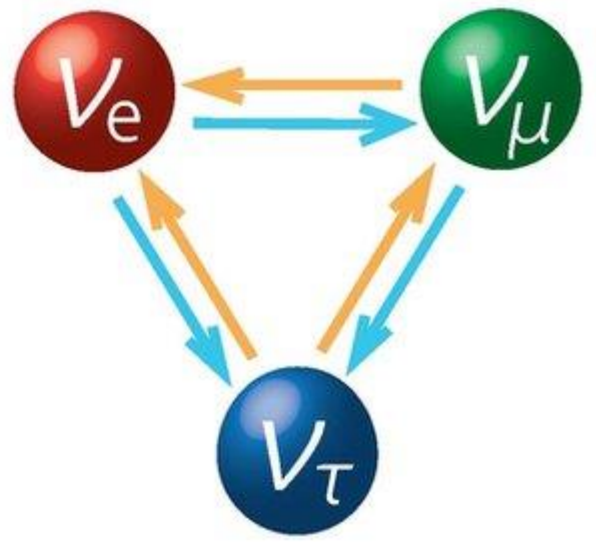
1. Run with ν_μ and look at ν_e appearance, then
2. Run with $\overline{\nu}_\mu$ and look at $\overline{\nu}_e$ appearance

CP violation in neutrino oscillations

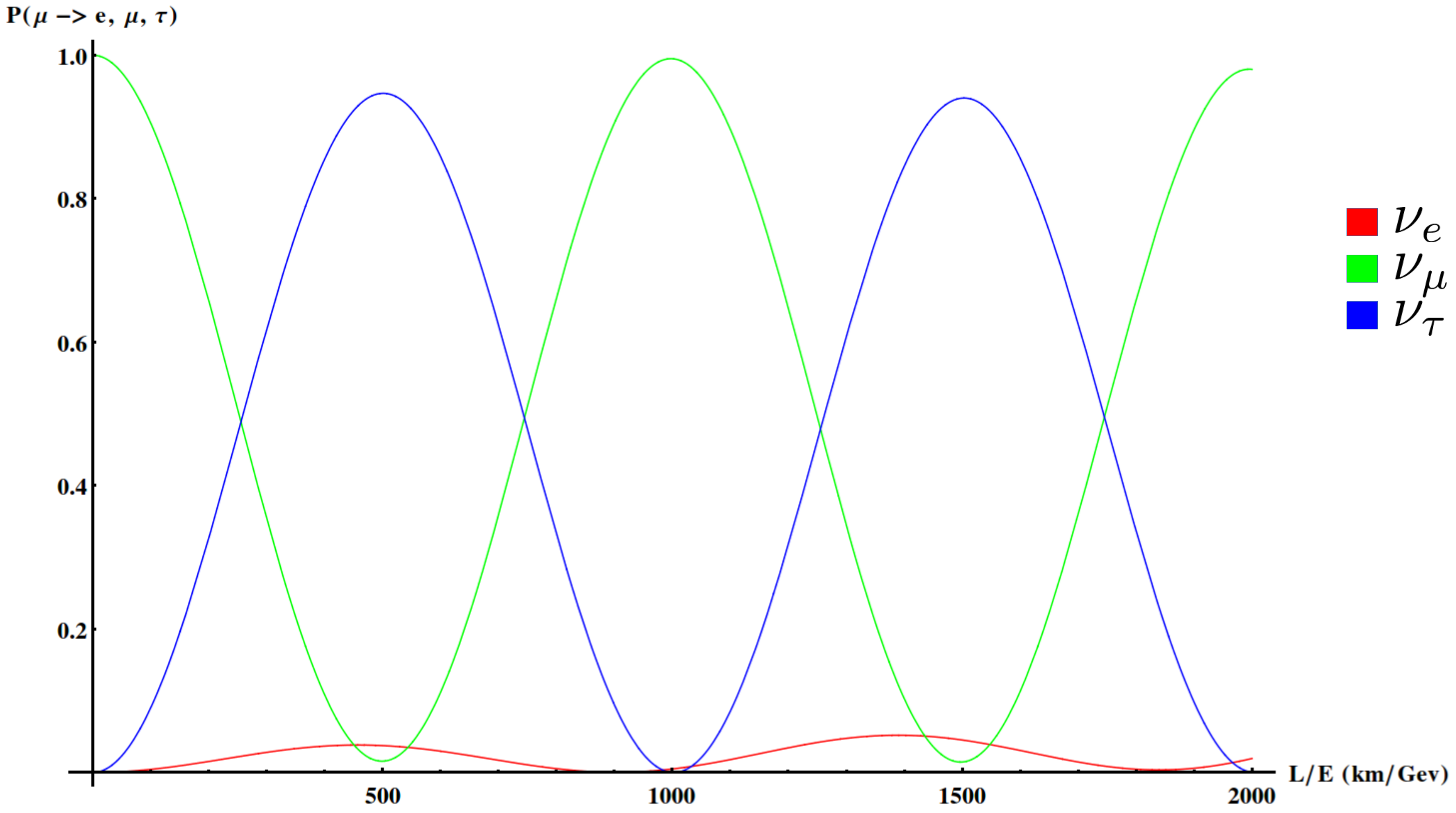
A crash course on why is 2nd oscillation maximum better

Neutrino oscillations

Neutrino flavour can effectively change between its creation and interaction.



Neutrino oscillations



Neutrino oscillations

Neutrino flavor eigenstate is not a mass eigenstate

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

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

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

- $U_{\alpha i}$ 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

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

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

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

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

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

Neutrino oscillations (3 generations)

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

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

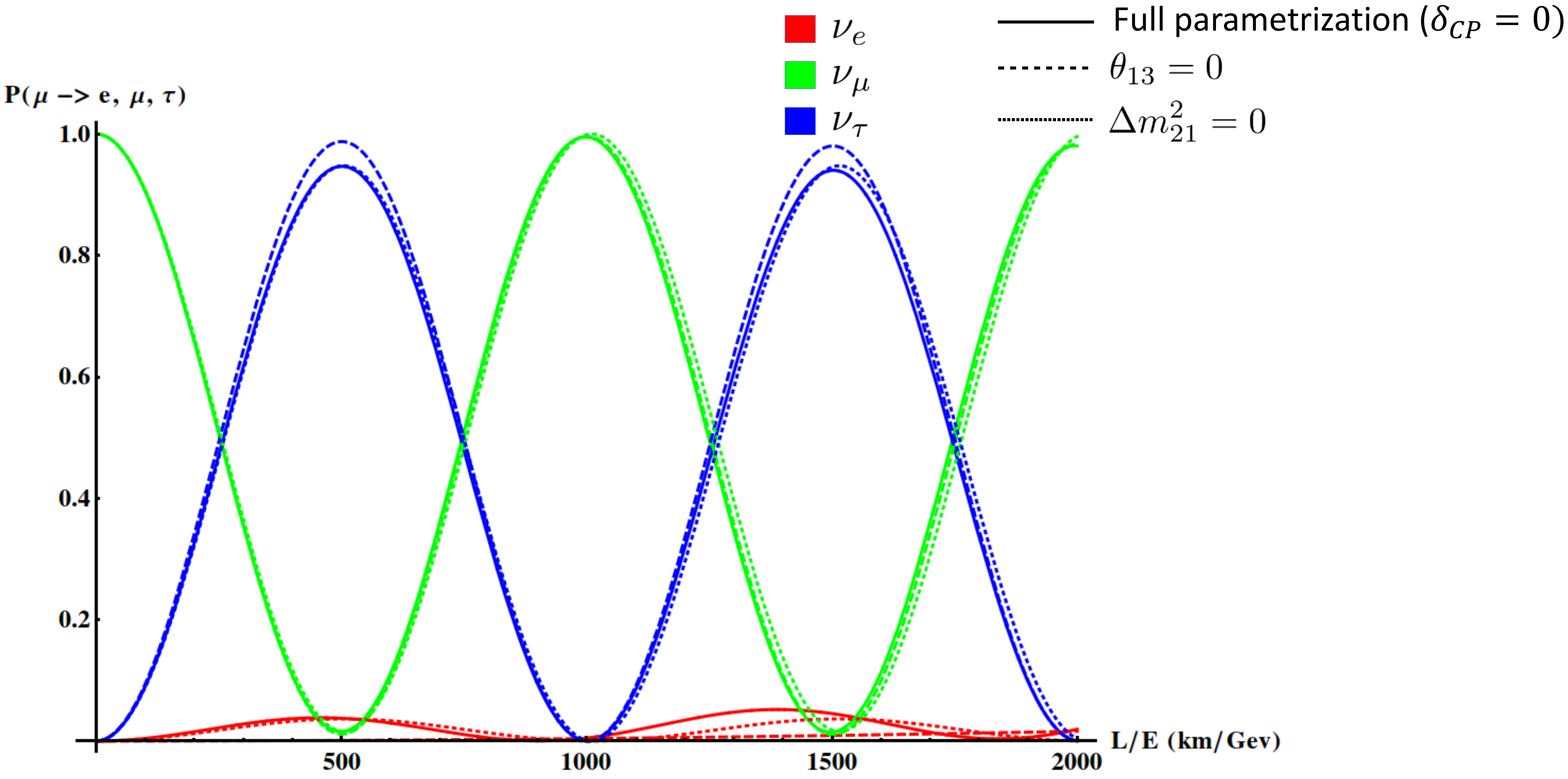
$$s_{ij} \equiv \sin\theta_{ij}$$
$$c_{ij} \equiv \cos\theta_{ij}$$

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

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

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

Muon neutrino oscillations



CP violation in vacuum

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

CP violation

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

T violation

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

CPT symmetry

$$P_{\alpha\to\beta} = P_{\overline{\beta}\to\overline{\alpha}}$$

All three equations can be proven using the formula above.

CP violation “amplitude”:

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

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”:

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

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

CP violation in ESSnuSB

General CP violation “amplitude”:

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

ESSnuSB CP violation

$$\begin{aligned} P_{\mu\to e} - P_{\overline{\mu}\to\overline{e}} &= 4J\left(\sin\frac{\Delta m^2_{31} L}{2E} - \sin\frac{\Delta m^2_{32} L}{2E} - \sin\frac{\Delta m^2_{21} L}{2E}\right) \\ &= -16J \sin\frac{\Delta m^2_{31} L}{4E} \sin\frac{\Delta m^2_{32} L}{4E} \sin\frac{\Delta m^2_{21} L}{4E} \end{aligned}$$

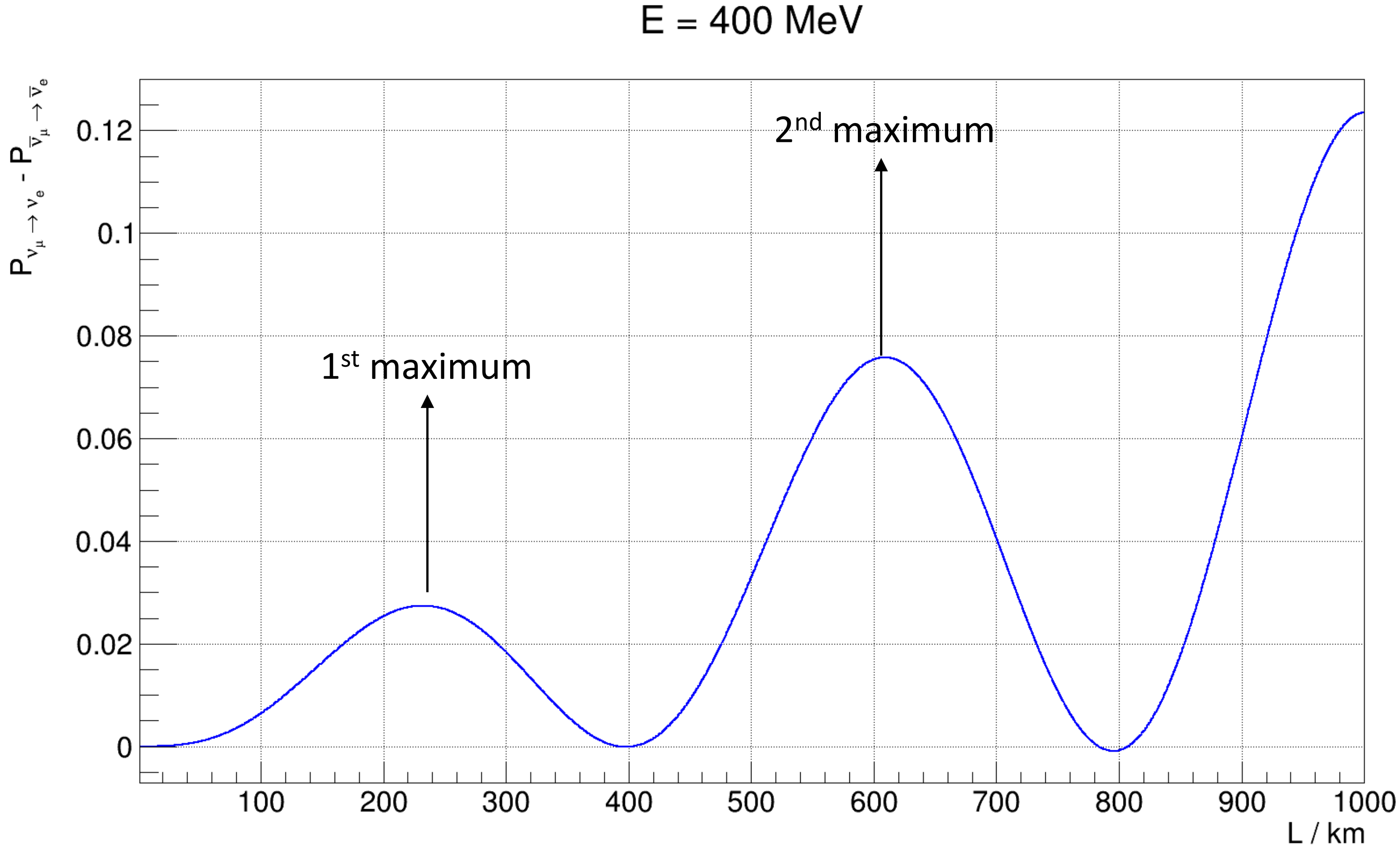
$$J = s_{12}c_{12}s_{13}c_{13}s_{23}c_{23}c_{13}\sin\delta_{\mathrm{CP}}$$

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

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

CP violation in ESSnuSB

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

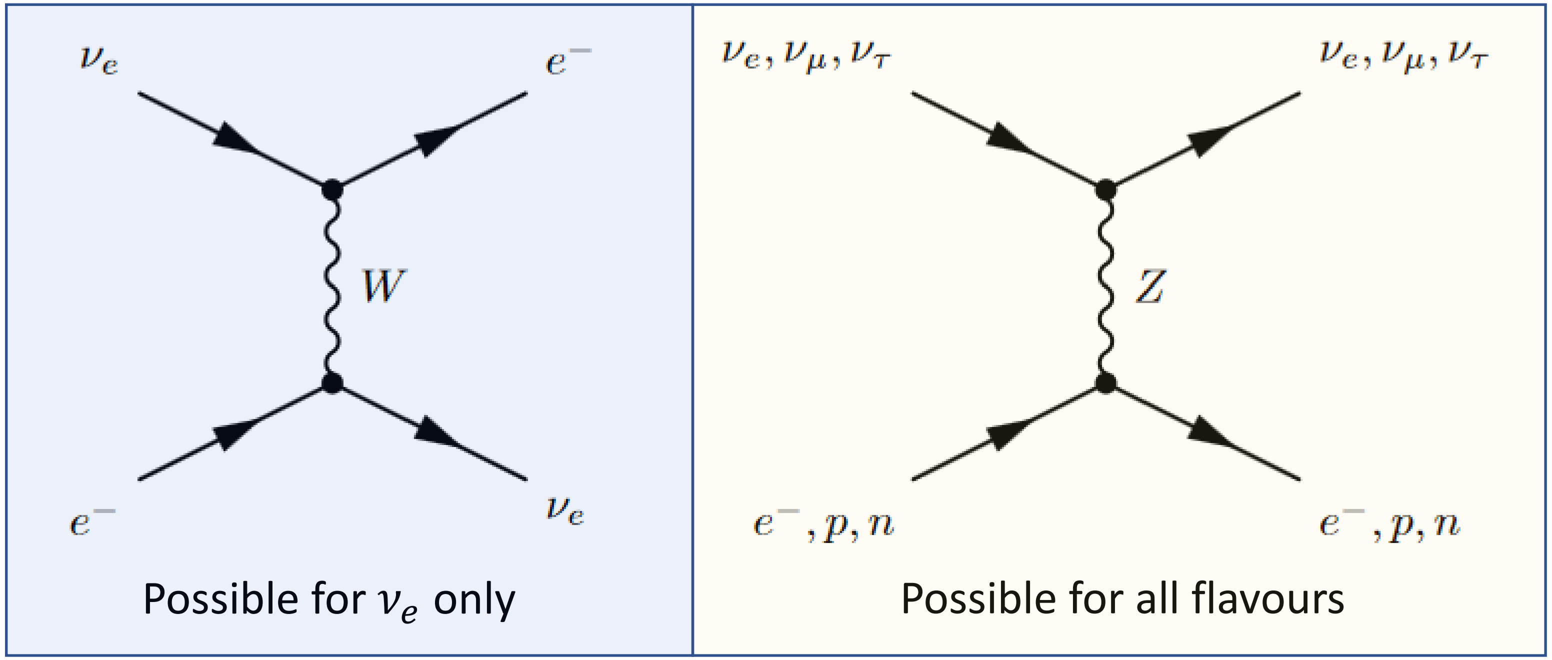


$$\frac{A_{CP} \text{ @ 2nd max}}{A_{CP} \text{ @ 1st max}} \sim 2.7$$

- 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

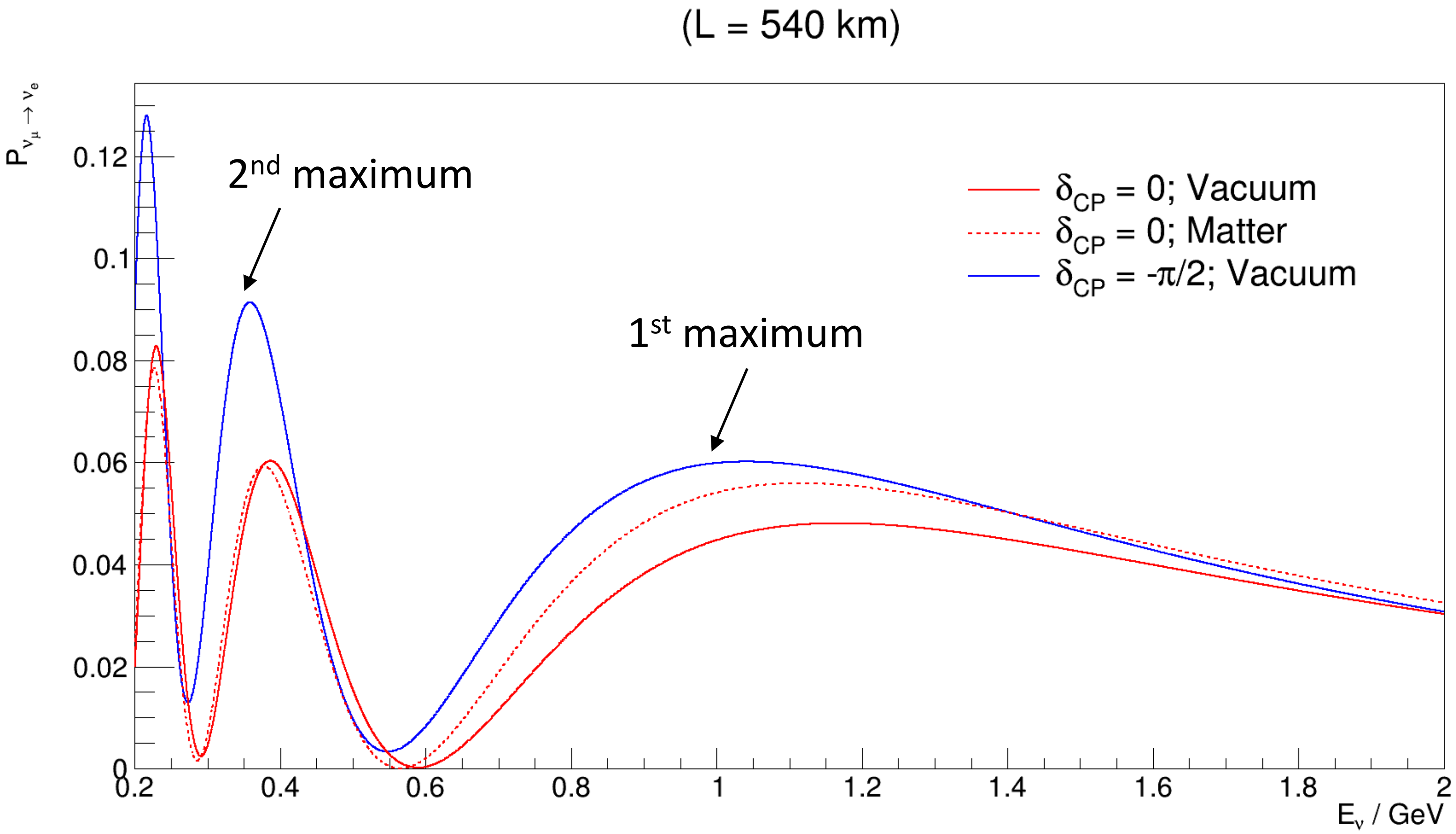
Matter effects

- For uniform matter density, these effects can be included by replacing vacuum oscillation parameters with effective “matter parameters”
  - $\theta_{ij} \rightarrow \theta_{ij}^{(m)}(E)$ and $\Delta m_{ij}^2 \rightarrow \Delta M_{ij}^2(E)$
  - however, the effective parameters depend on energy
    - and the function connecting them with vacuum values is quite cumbersome
    - see master thesis by Leon Halić: https://essnusb.eu/DocDB/public/ShowDocument?docid=1155

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

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

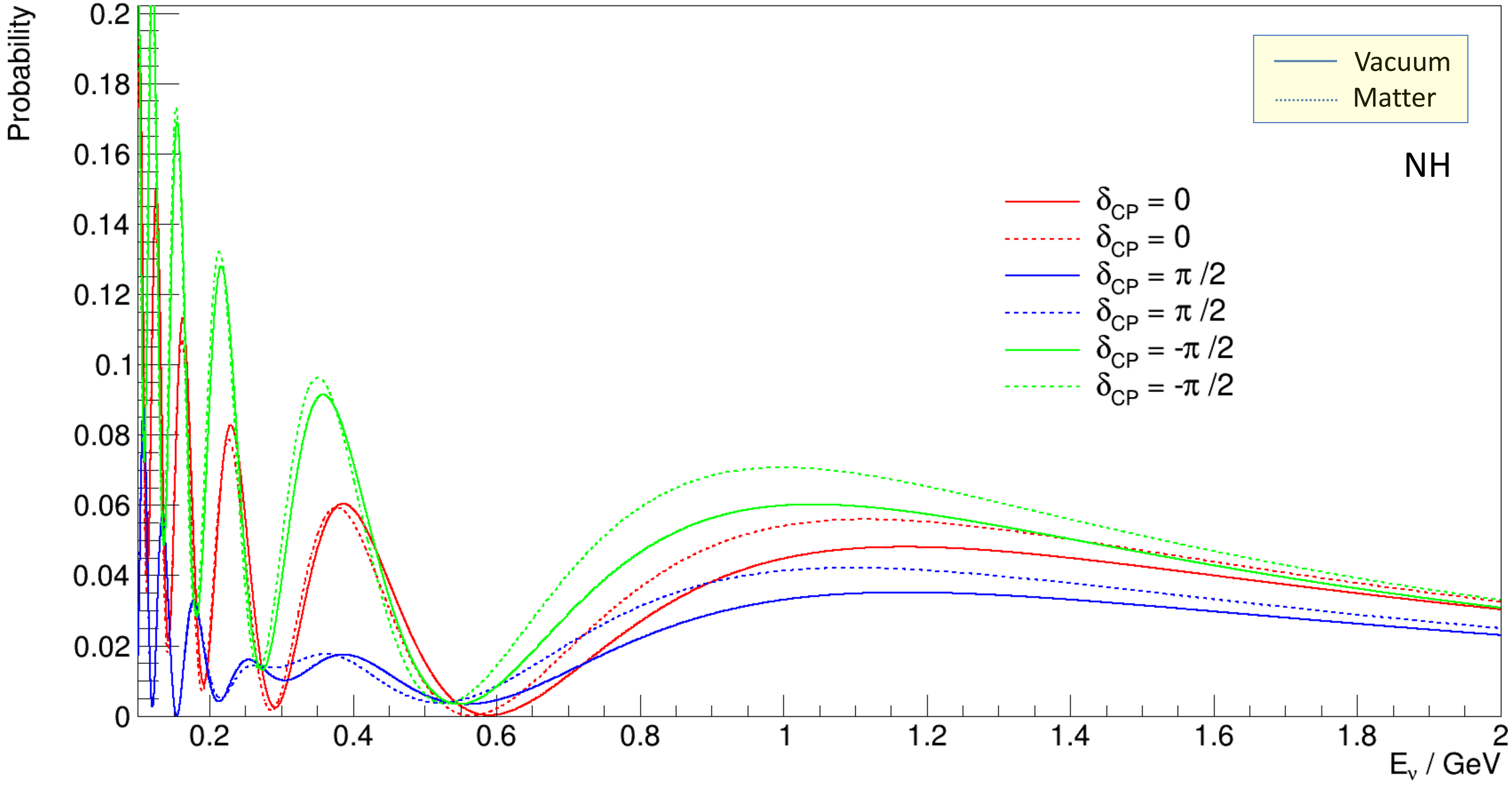
Matter effects



Matter effects can mimic CP violation!

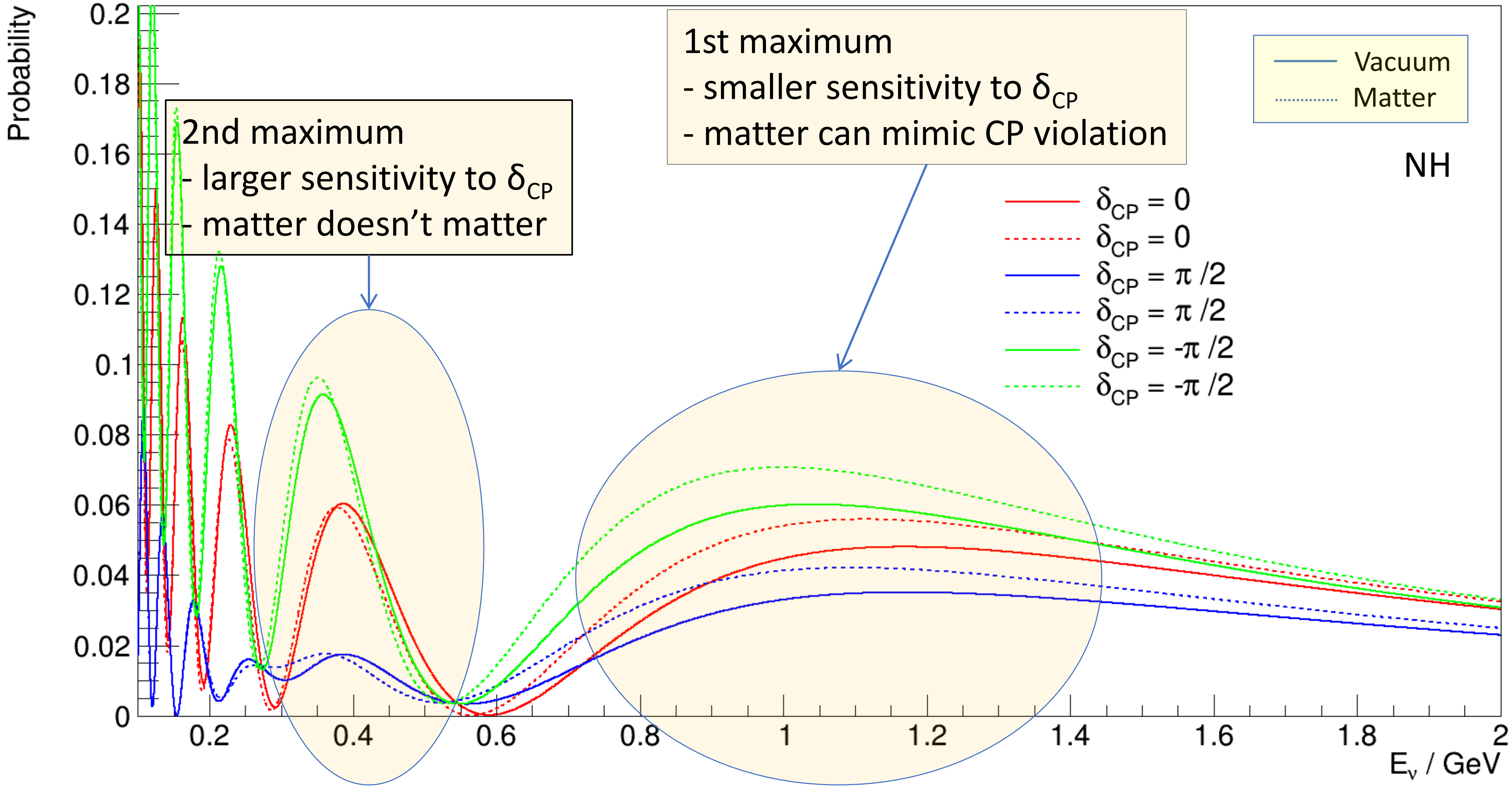
Why 2nd maximum?

$$P_{\nu_\mu \to \nu_e}\,(E_\nu; L = 540\ \mathrm{km})$$



Why 2nd maximum?

$$P_{\nu_\mu \to \nu_e}\left(E_\nu; L = 540\ \mathrm{km}\right)$$

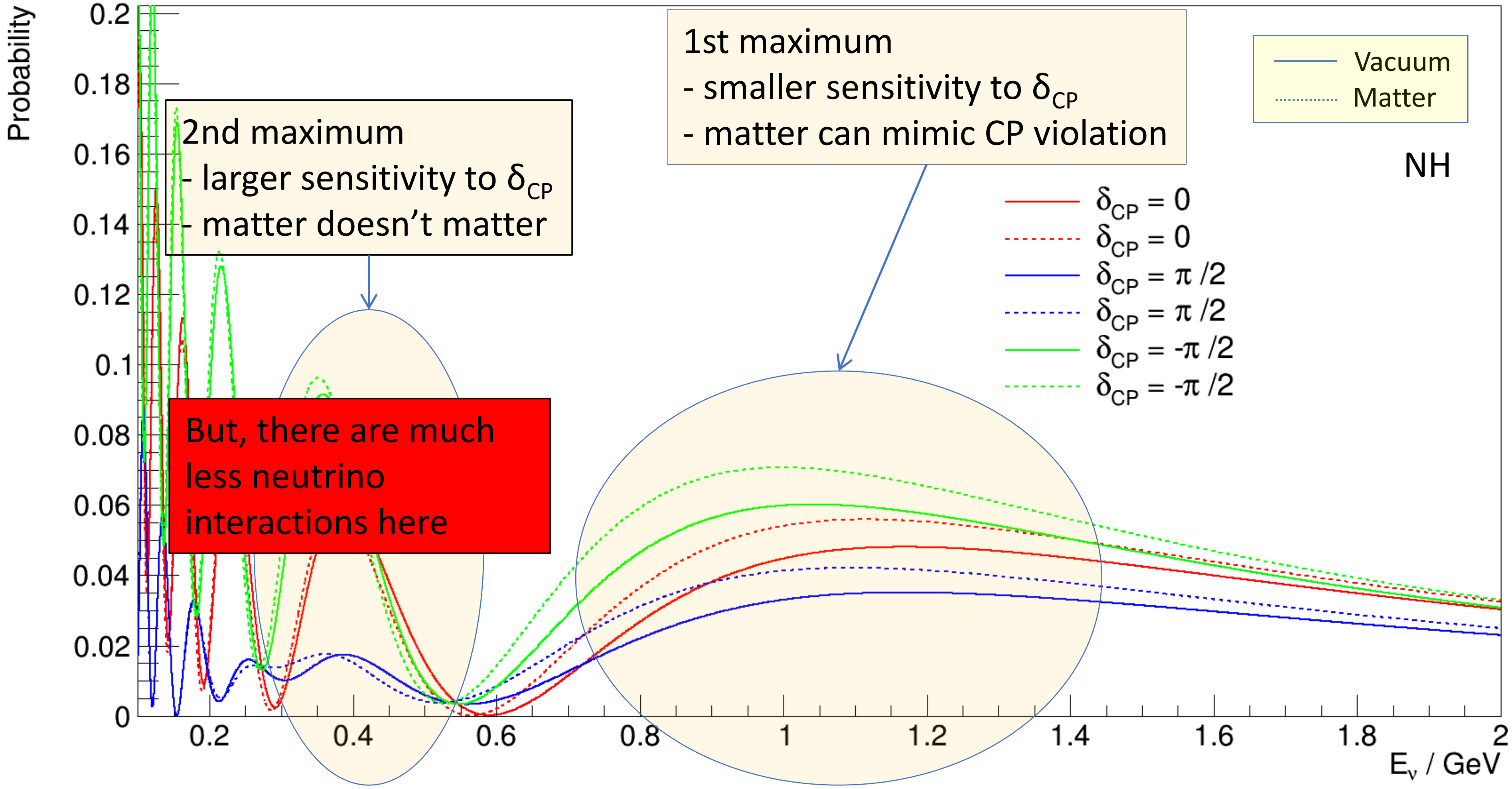


2nd maximum
- larger sensitivity to δ_{CP}
- matter doesn’t matter

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

Why 2nd maximum?

$$P_{\nu_\mu \to \nu_e}\left(E_\nu; L = 540\ \mathrm{km}\right)$$



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

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

But, there are much less neutrino interactions here

Why 2nd maximum?

(summary)

The good

$$\frac{\left(P_{\nu_\mu\to\nu_e} - P_{\overline{\nu}_\mu\to\overline{\nu}_e}\right) \text{@ 2 osc. max.}}{\left(P_{\nu_\mu\to\nu_e} - P_{\overline{\nu}_\mu\to\overline{\nu}_e}\right) \text{@ 1 osc. max.}} \sim 2.7$$

In vaccum, this ratio depends only on neutrino mass square differences

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 helps here, as does having larger θ_{13} because $P_{\mu\to e}$ and $P_{\overline{\mu}\to\overline{e}}$ are larger and we get more events.
- With no systematic error, first maximum is better
  - more statistics, even though the effect is smaller.

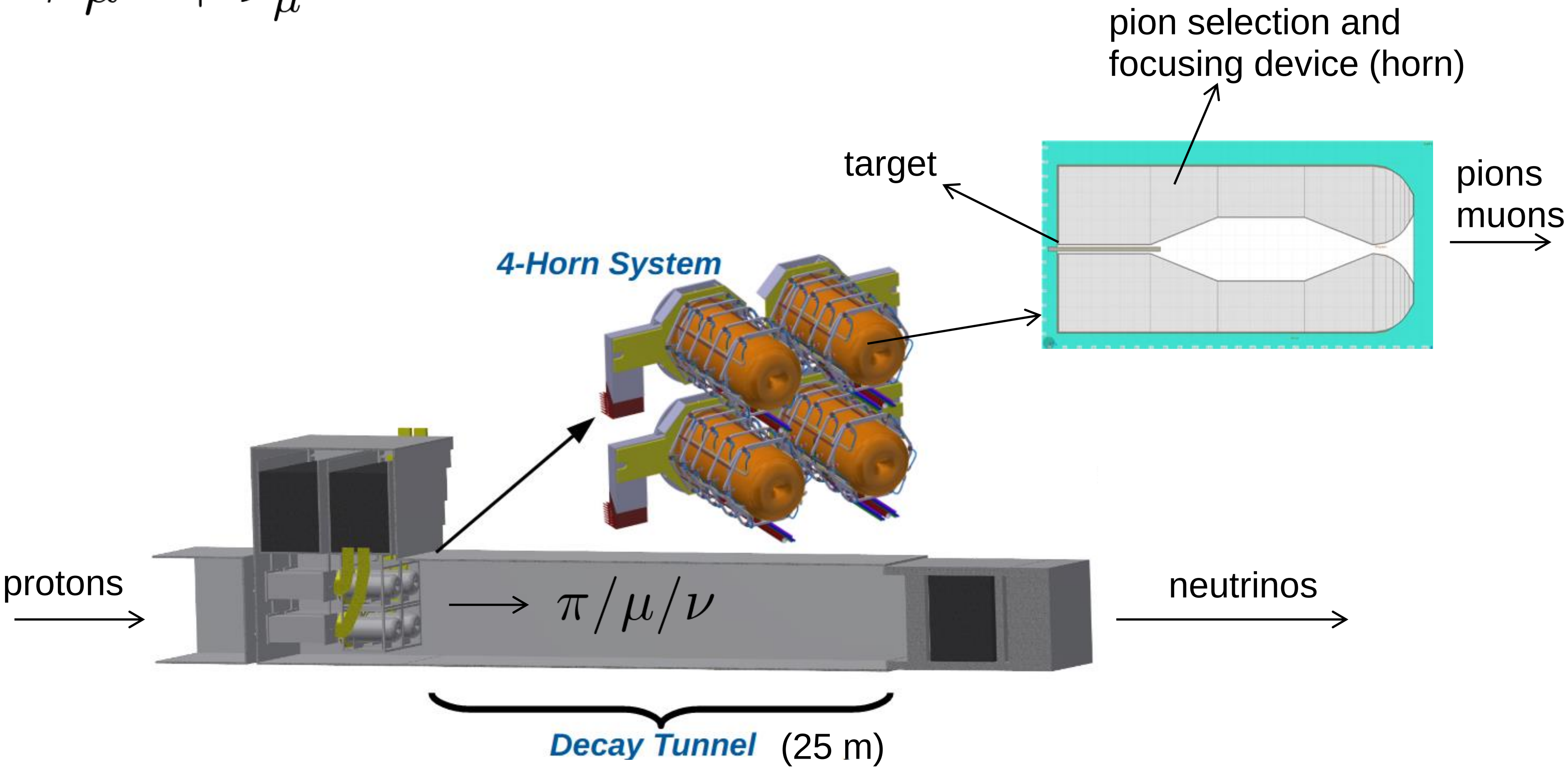
ESSnuSB project

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

Neutrino beam production

$$\pi^+ \to \mu^+ + \nu_\mu$$

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



pion selection and
focusing device (horn)

target

pions
muons

4-Horn System

protons

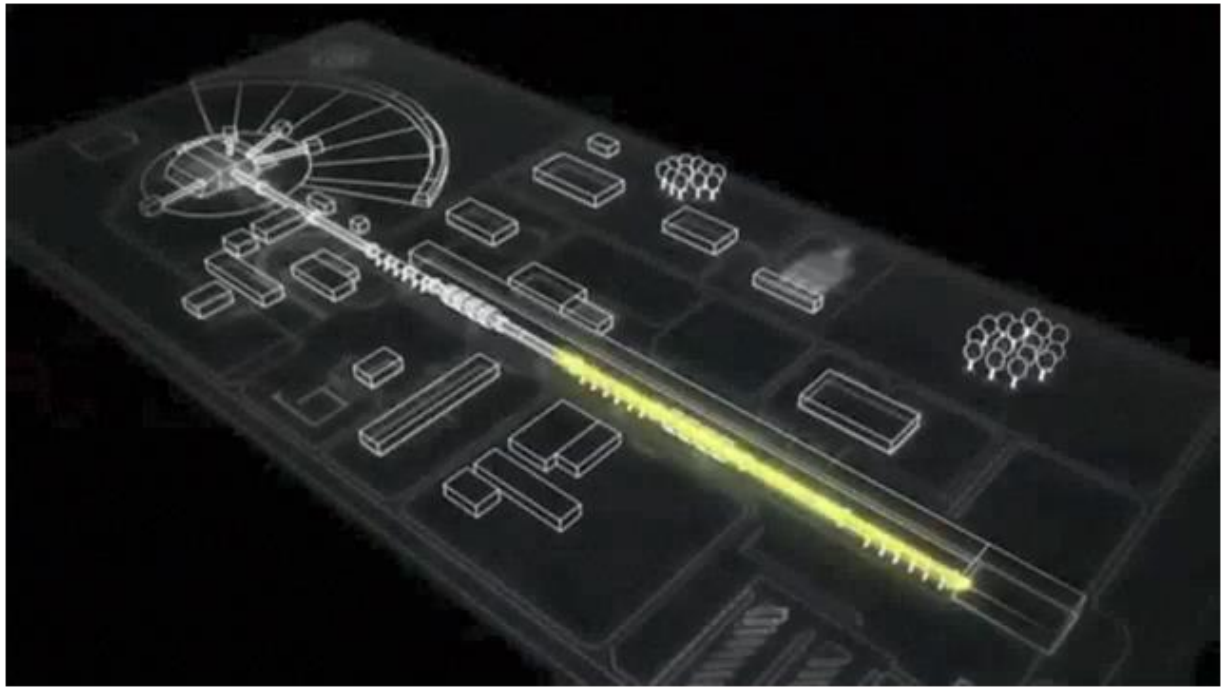
$\longrightarrow \pi/\mu/\nu$

neutrinos

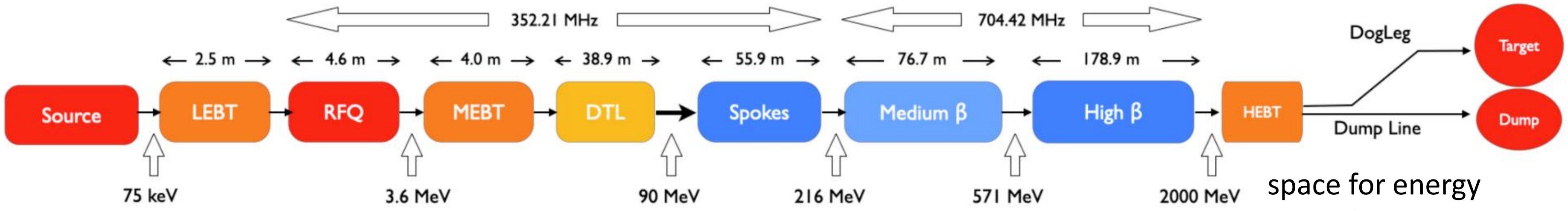
Decay Tunnel (25 m)

Can we afford 2nd maximum?

As it happens, a very intense proton linac is in construction near Lund, Sweden.



ESS proton linac

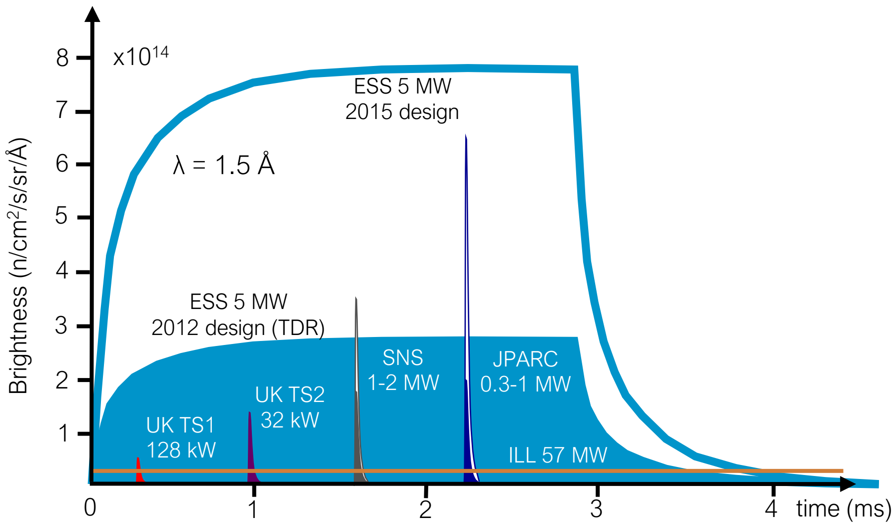


space for energy upgrades

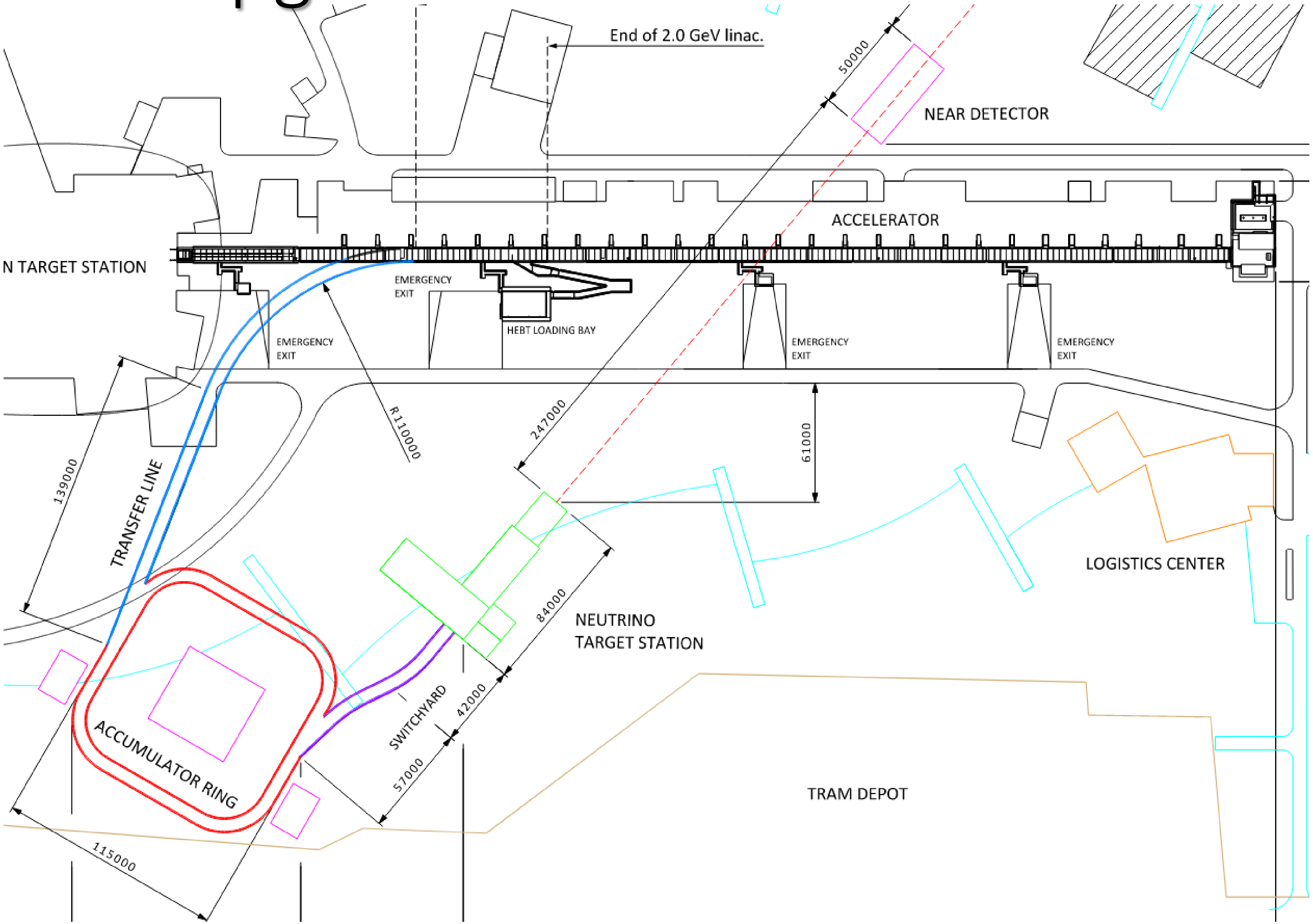
- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power.
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV kinetic energy protons
  - up to 3.5 GeV with linac upgrades
- **>2.7x10^{23} p.o.t/year.**

First operation of the linac in 2023.

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

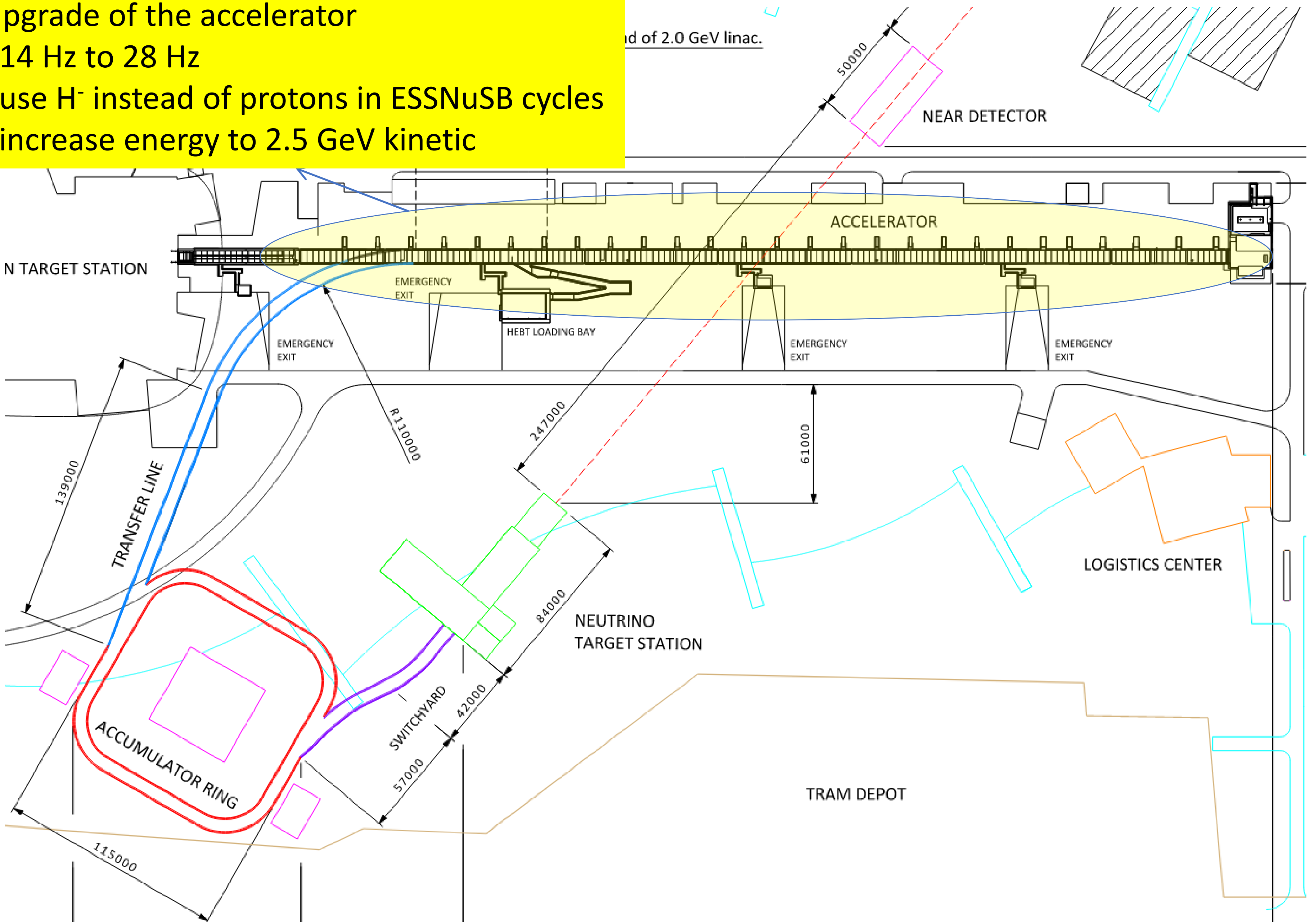


Upgrades to ESS



Upgrades to ESS

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



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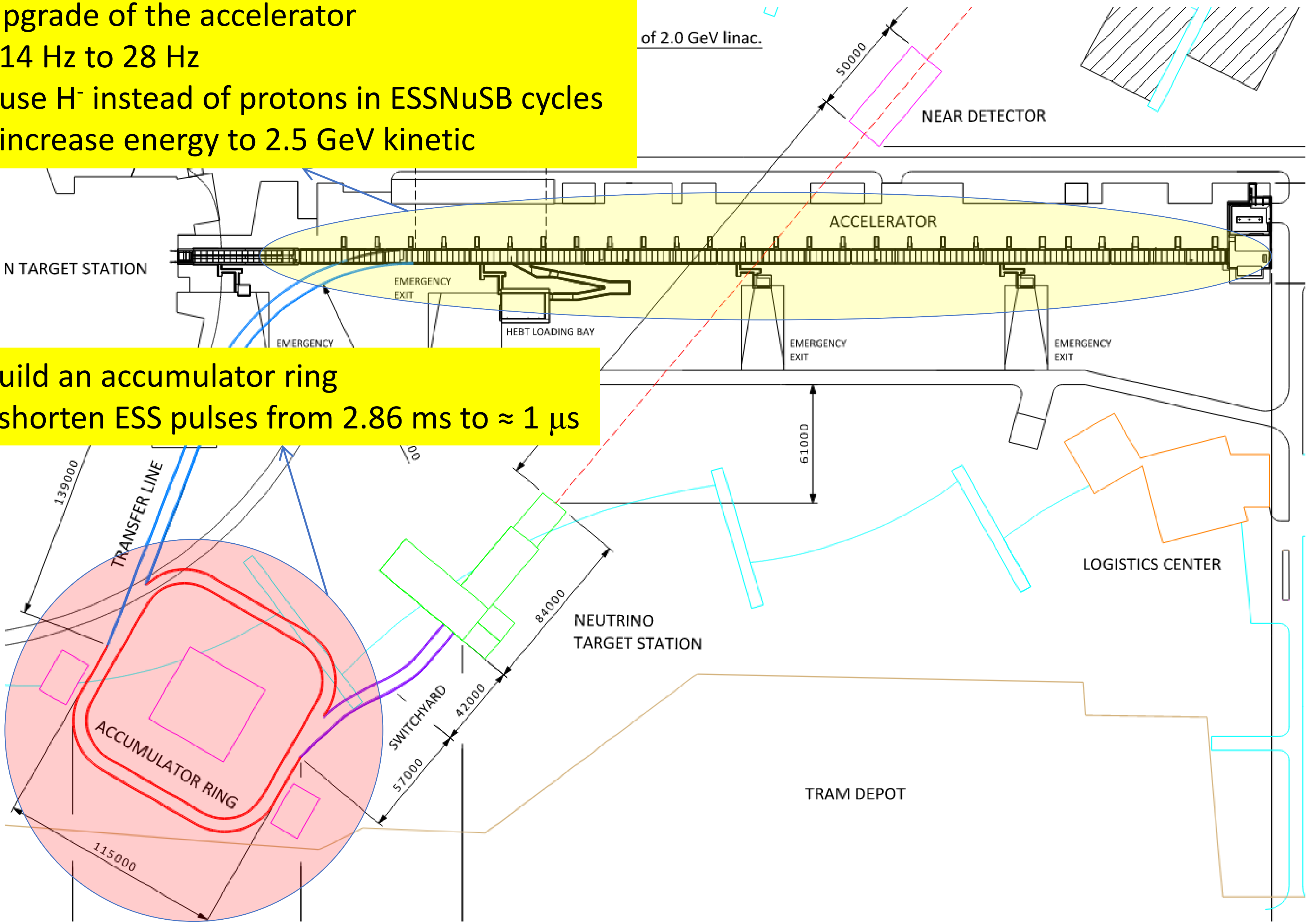
Build an accumulator ring
- shorten ESS pulses from 2.86 ms to ≈ 1 μs



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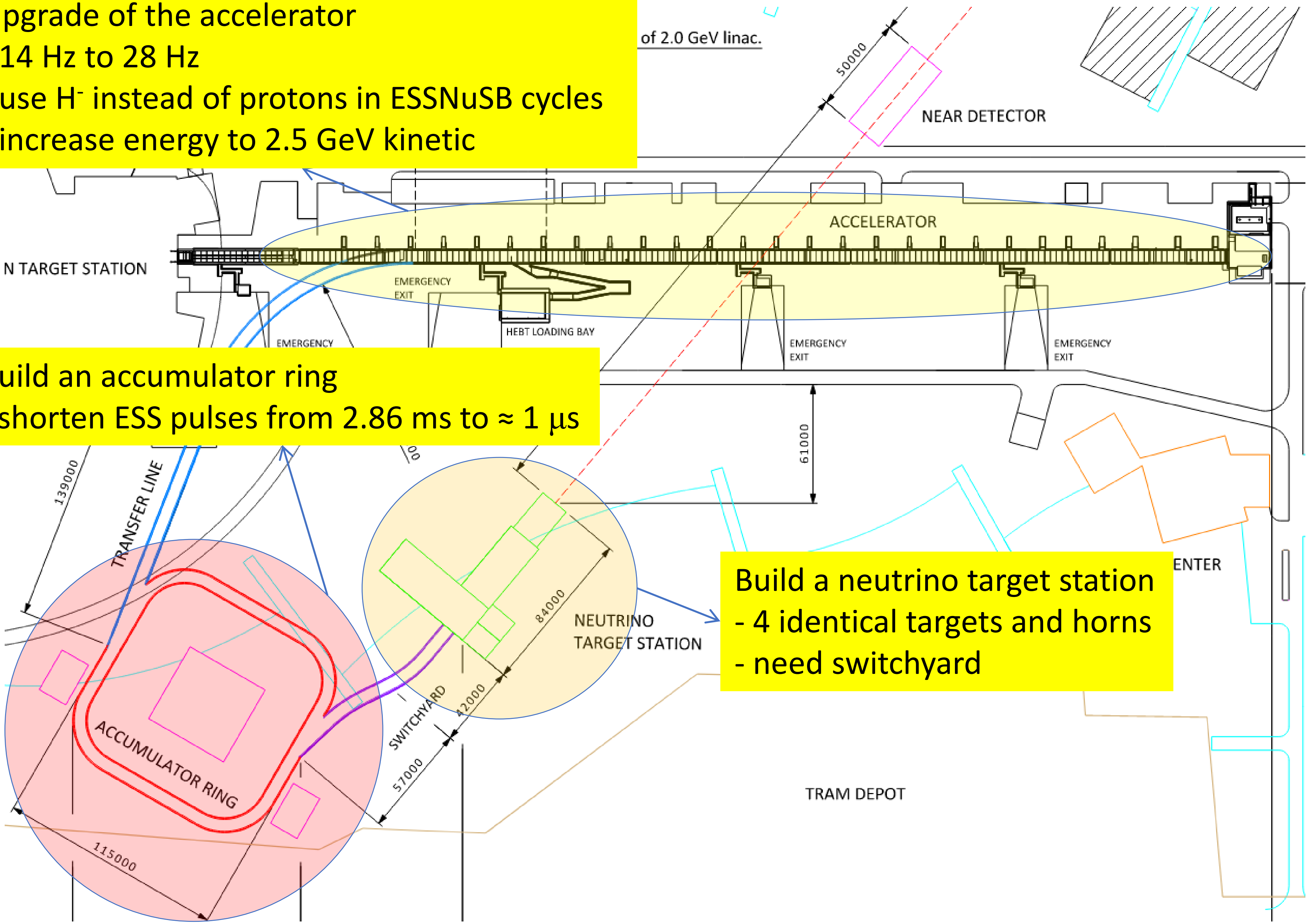

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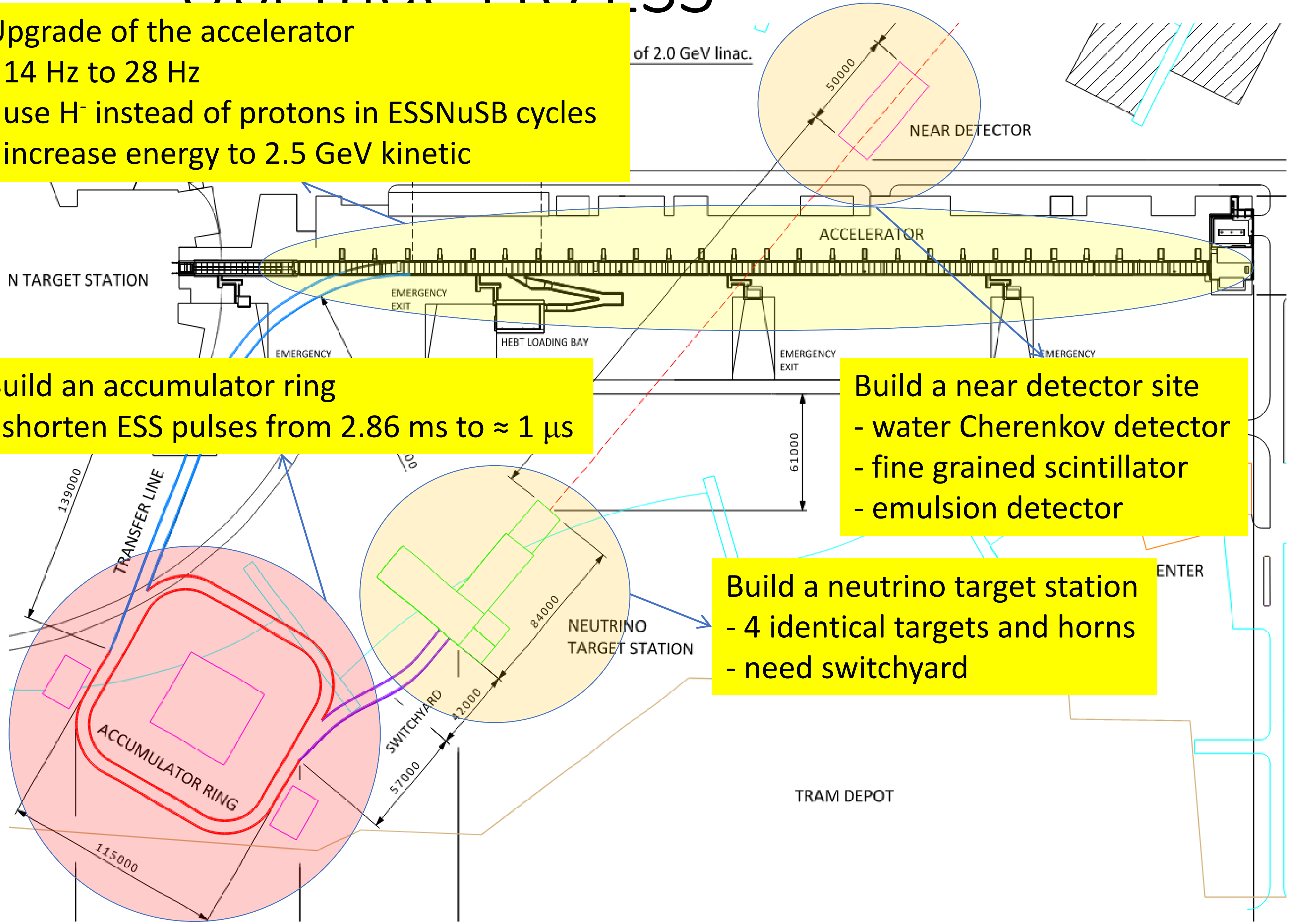
Build a neutrino target station
- 4 identical targets and horns
- need switchyard

Upgrades to ESS



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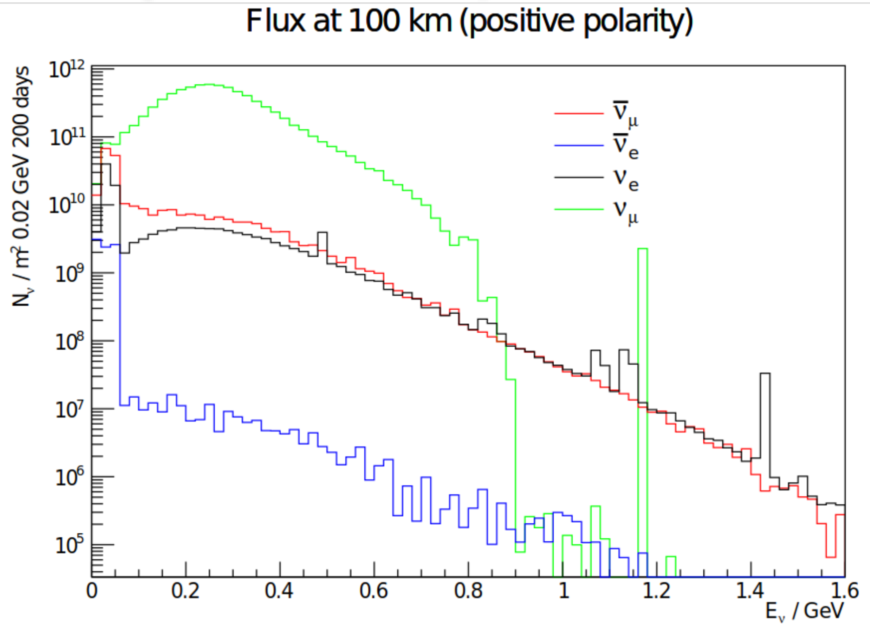
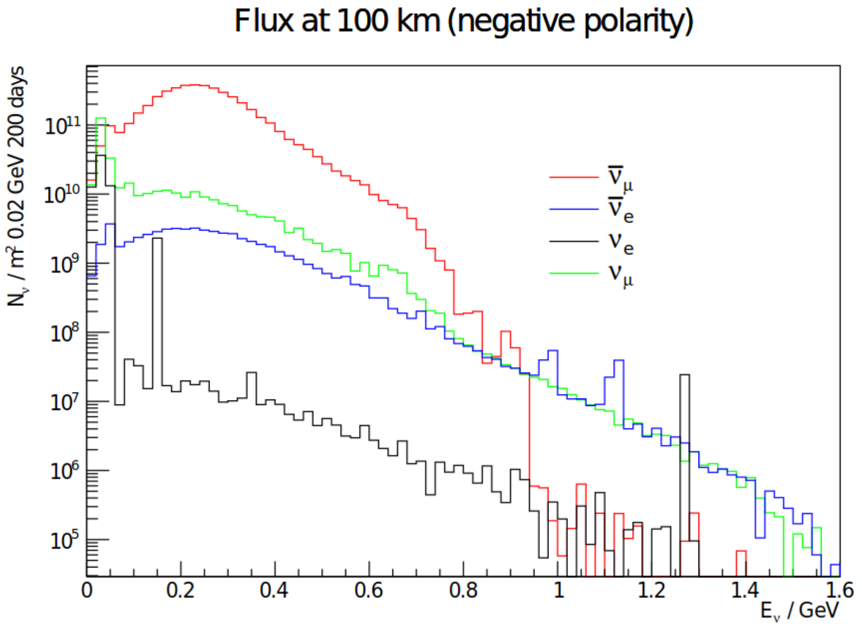
Build a near detector site
- water Cherenkov detector
- fine grained scintillator
- emulsion detector

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

ESSνSB ν energy distribution
(after optimisation)


Flux at 100 km (positive polarity)

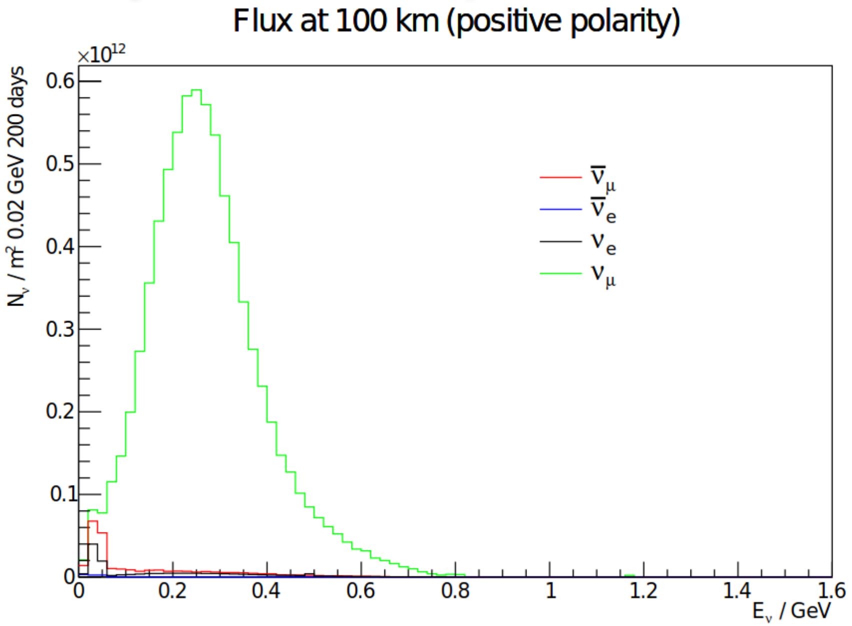

Flux at 100 km (negative polarity)

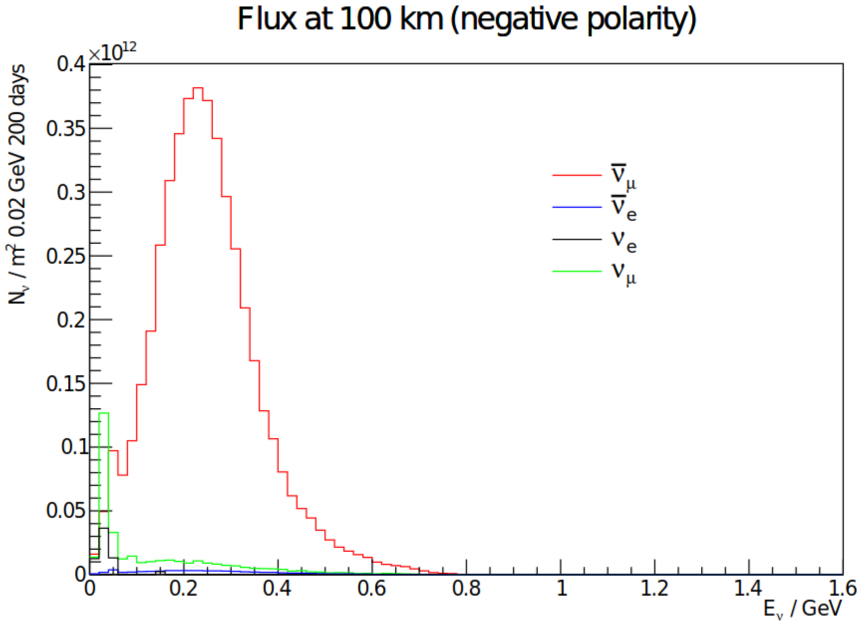
- almost pure ν_μ beam
- small ν_e contamination which could be used to measure ν_e cross-sections in a near detector

	Positive		**Negative**	
	$N_\nu\ (10^{10}/m^2)$	**%**	$N_\nu\ (10^{10}/m^2)$	**%**
ν_μ	**743**	**97.4**	**13.7**	**3.3**
$\bar{\nu}_\mu$	**14.5**	**1.9**	**397**	**95.9**
ν_e	**5.2**	**0.7**	**0.7**	**0.02**
$\bar{\nu}_e$	**0.01**	**0.002**	**2.7**	**0.7**

at 100 km from the target and per year (in absence of oscillations)

ESSνSB ν energy distribution
(after optimisation)





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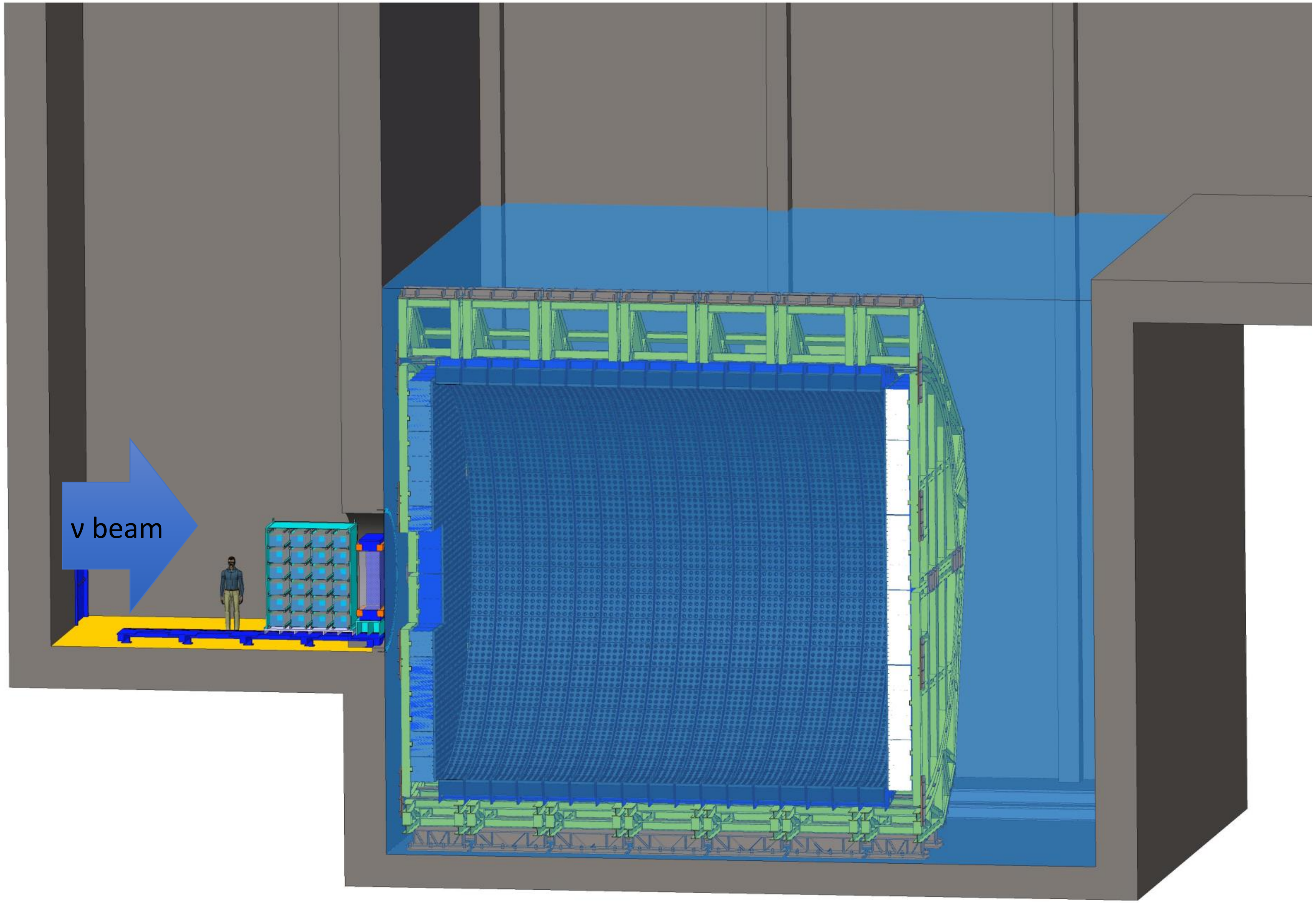
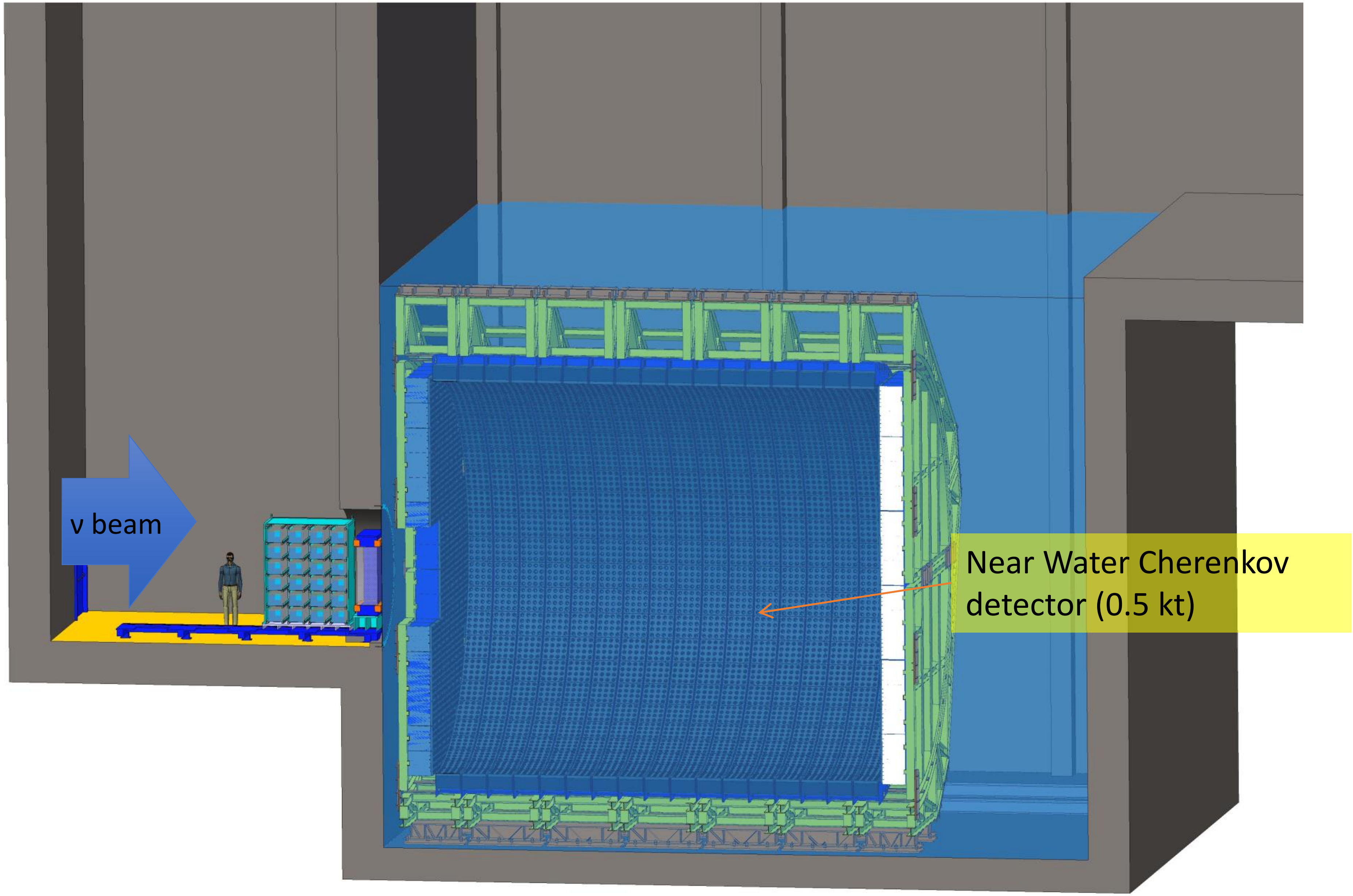
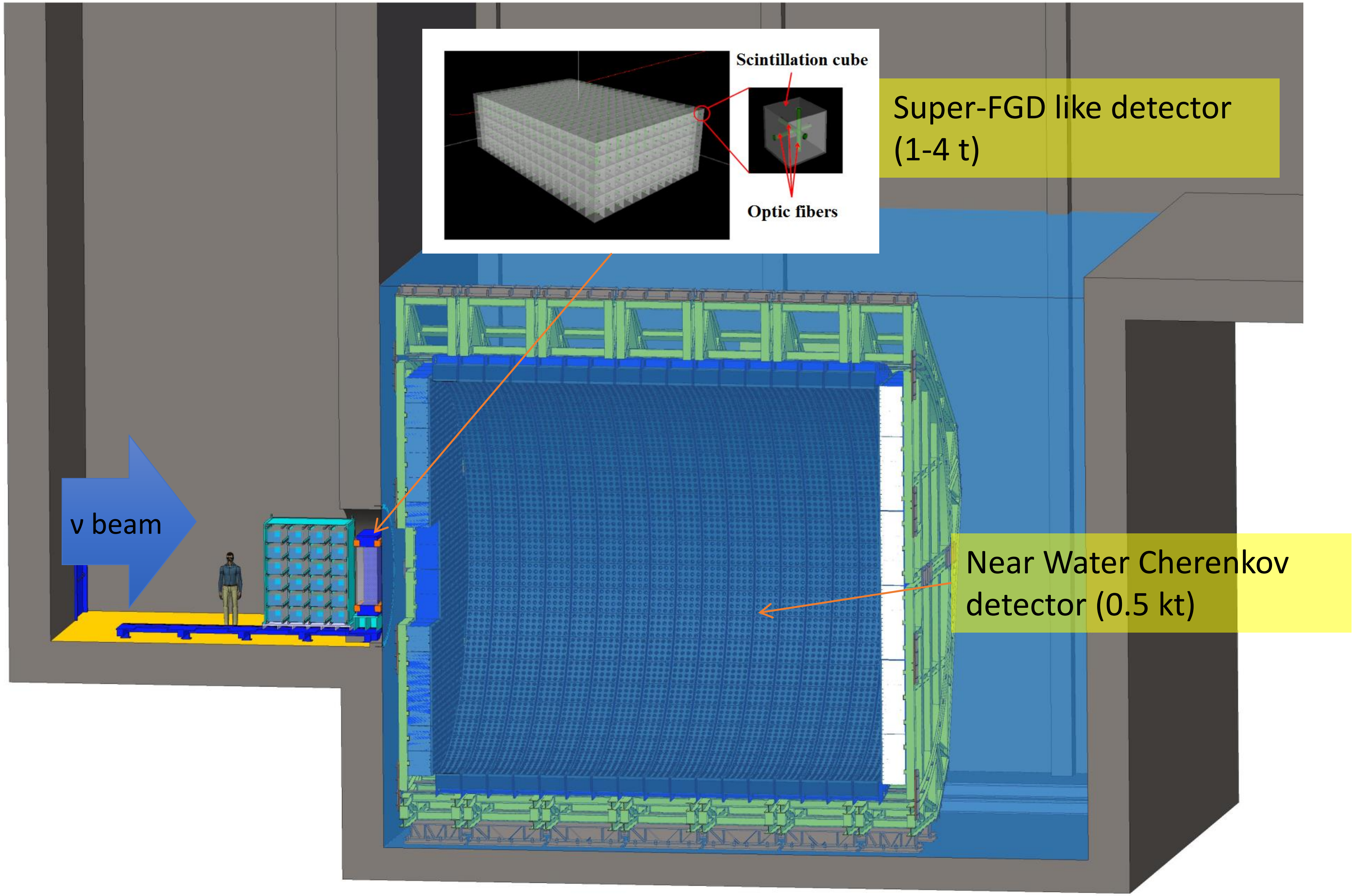
Near detectors



Near detectors



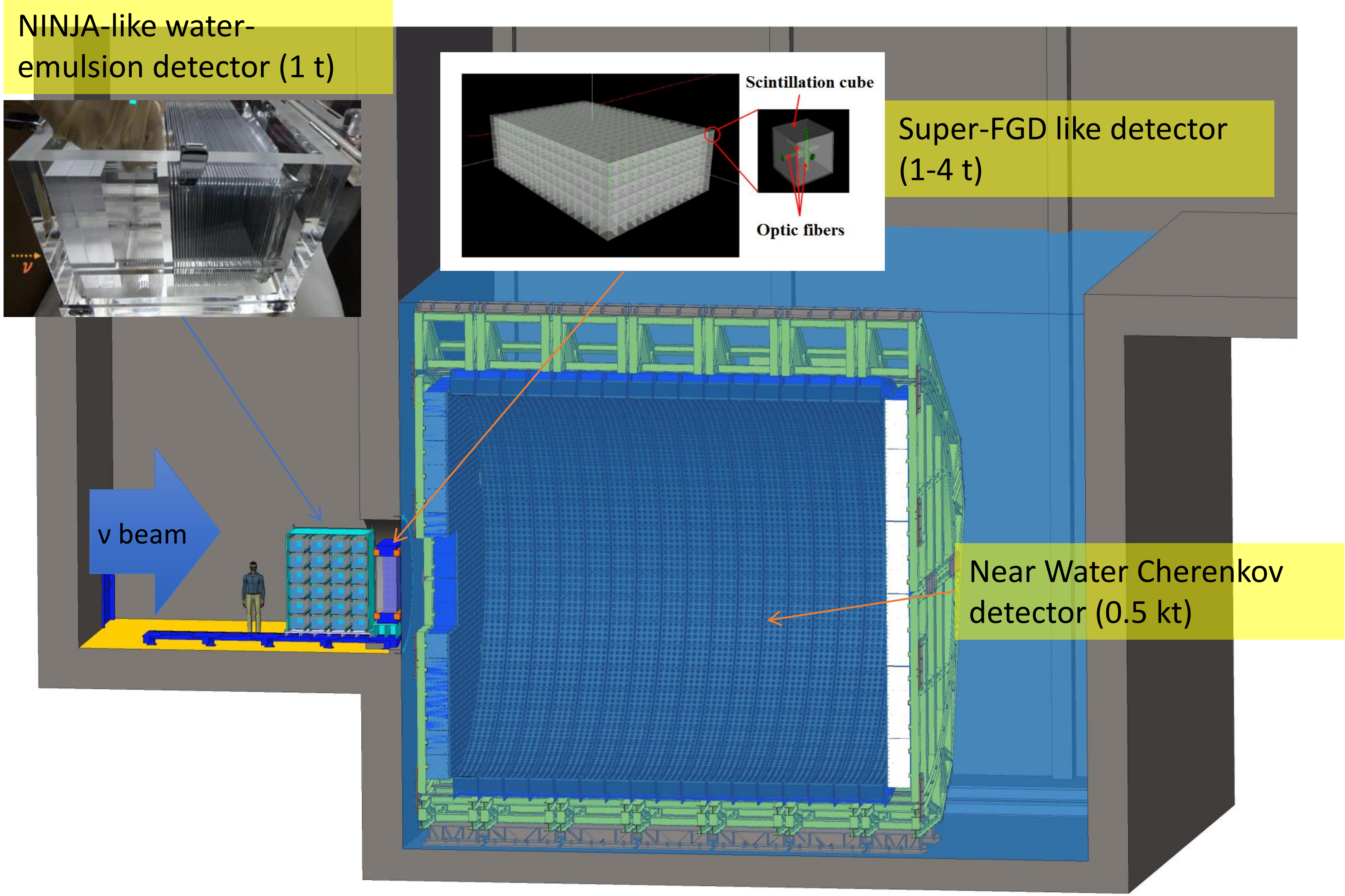
Near detectors



Super-FGD like detector (1-4 t)

Near Water Cherenkov detector (0.5 kt)

Near detectors

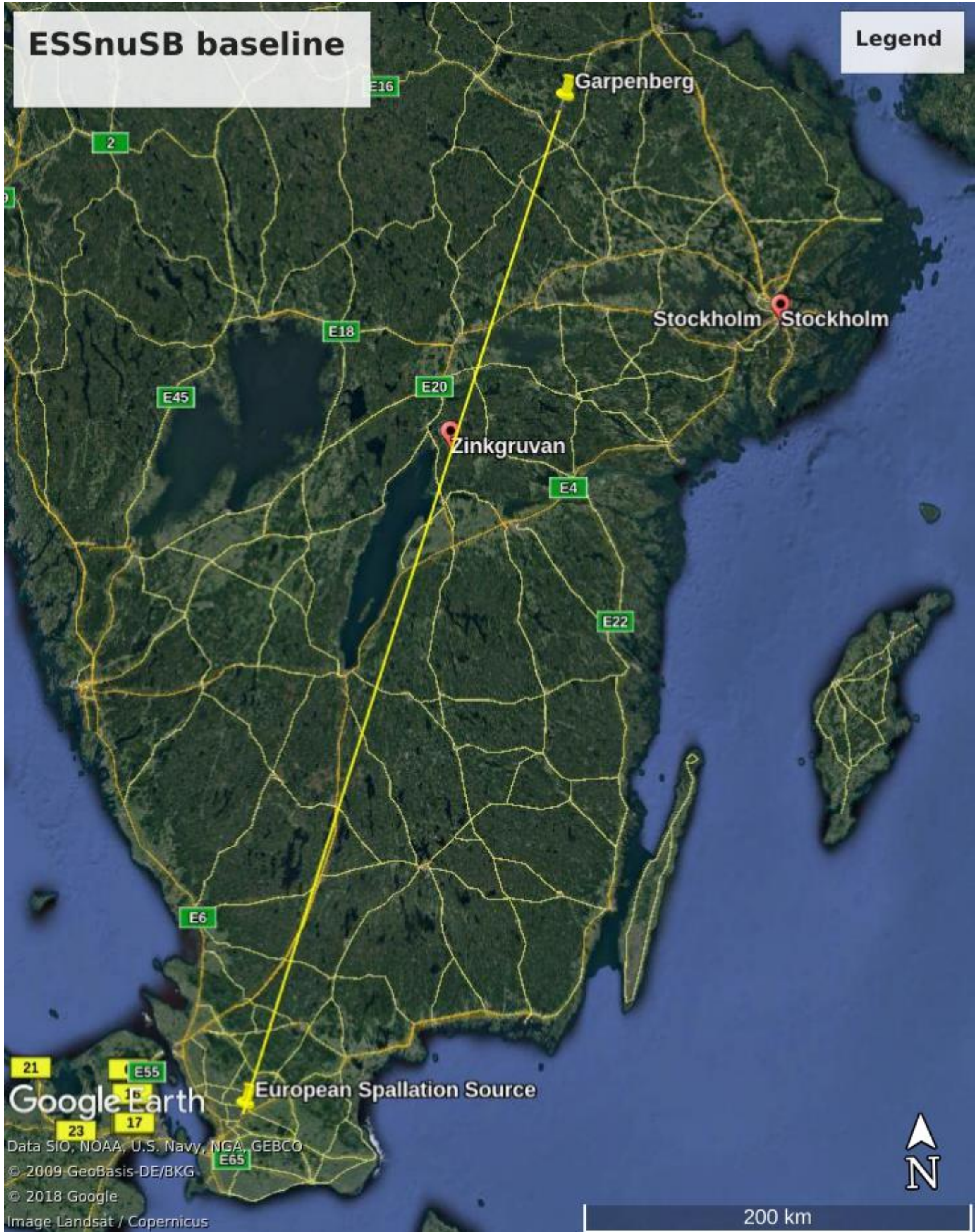


NINJA-like water-emulsion detector (1 t)

Super-FGD like detector (1-4 t)

ν beam

Near Water Cherenkov detector (0.5 kt)



Far detector position

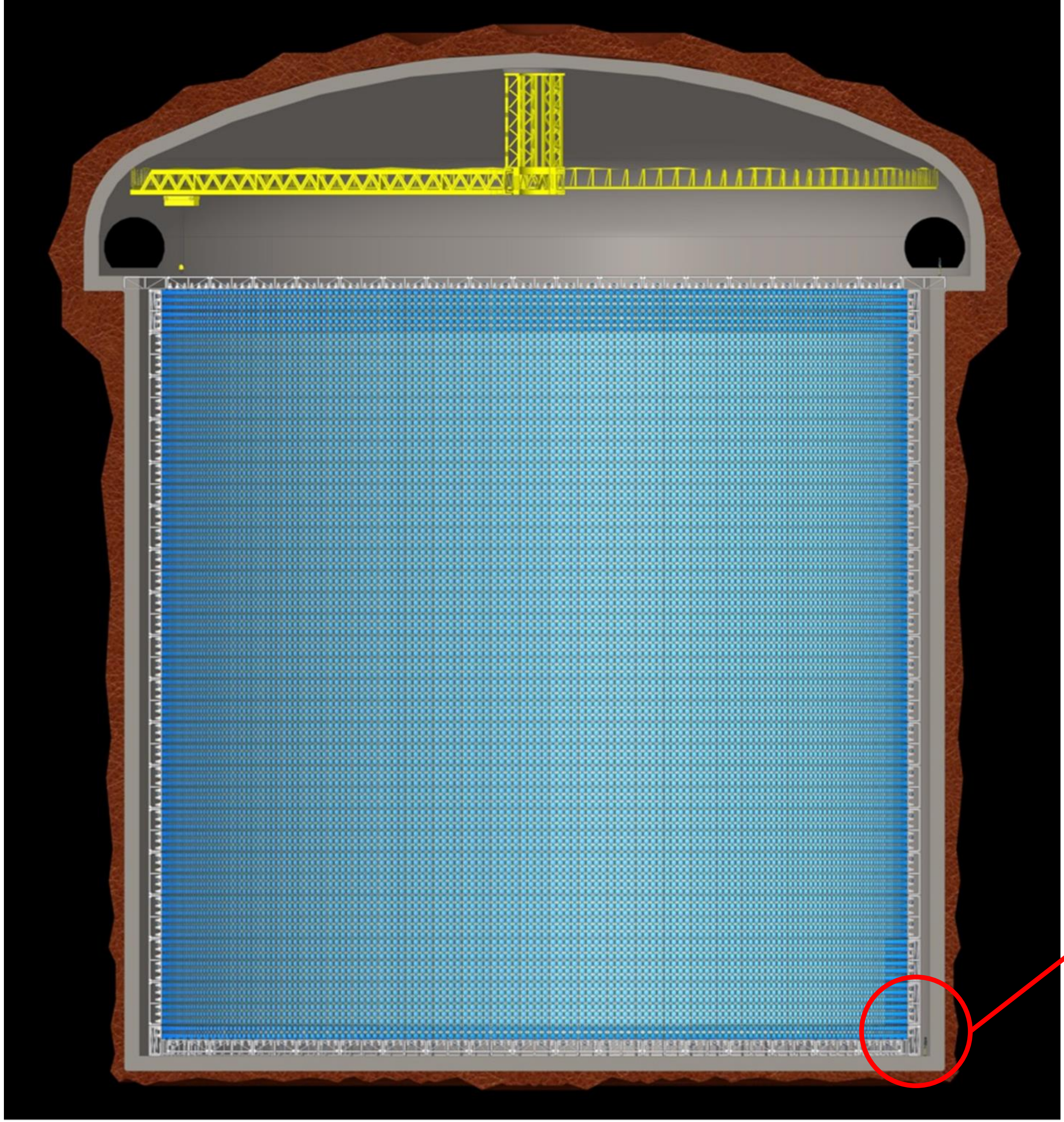
Selected baseline:

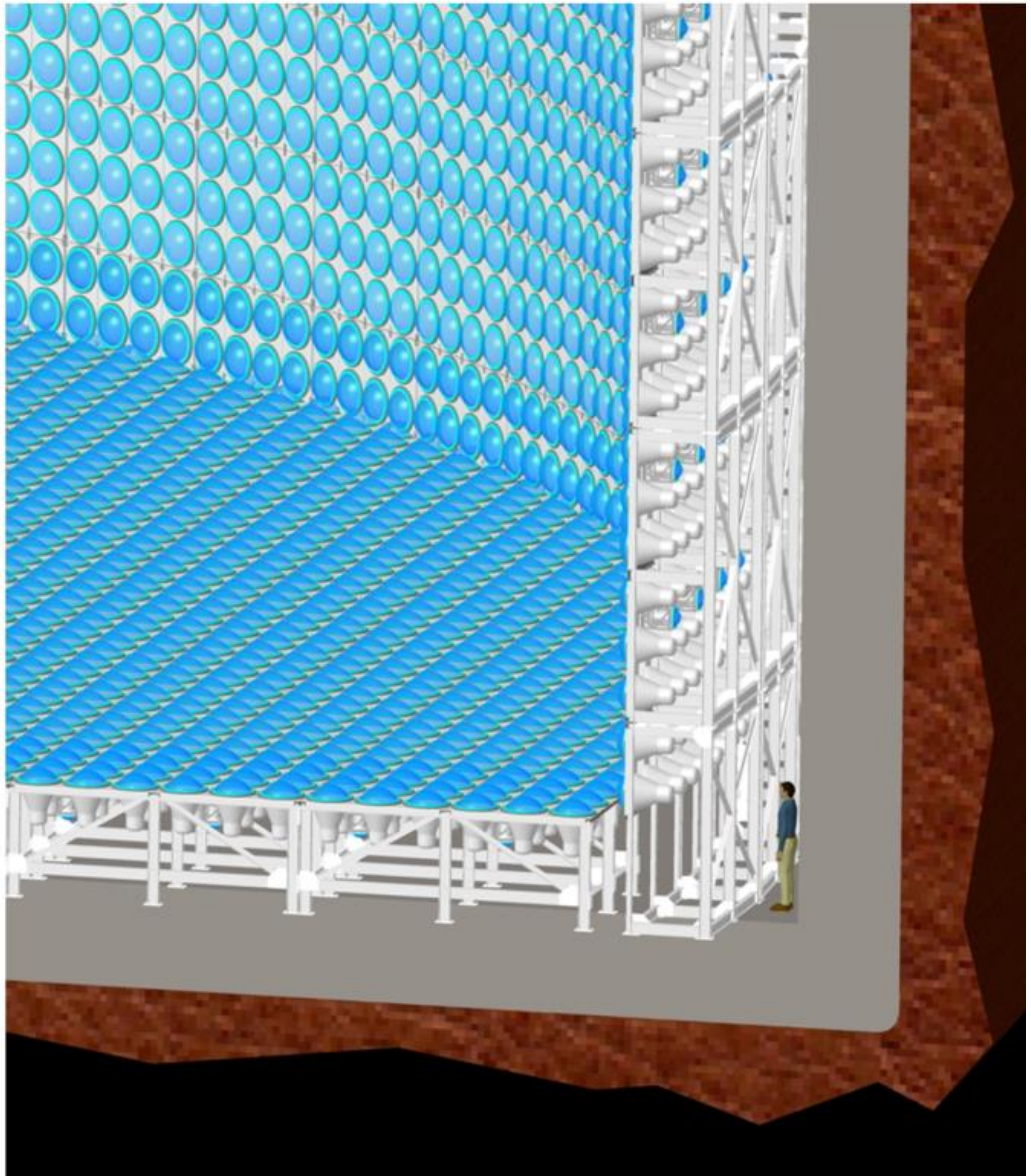
- Zinkgruvan mine, 340 km from the source, partly covernig 1st and 2nd maximum

Alternative (not selected)

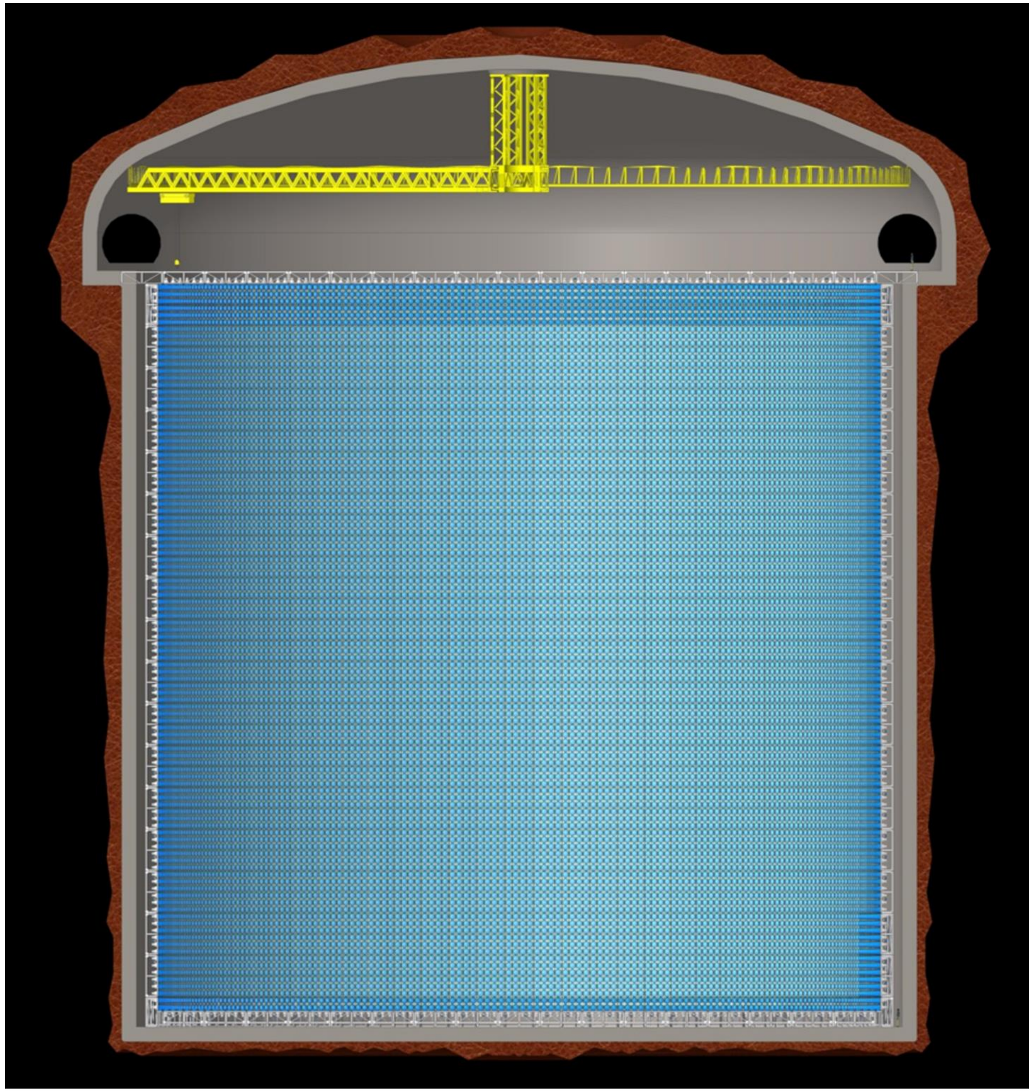
- Garpenberg mine, 540 km from the neutrino source, corresponding to 2nd oscillation maximum.

Far detector





Far detectors



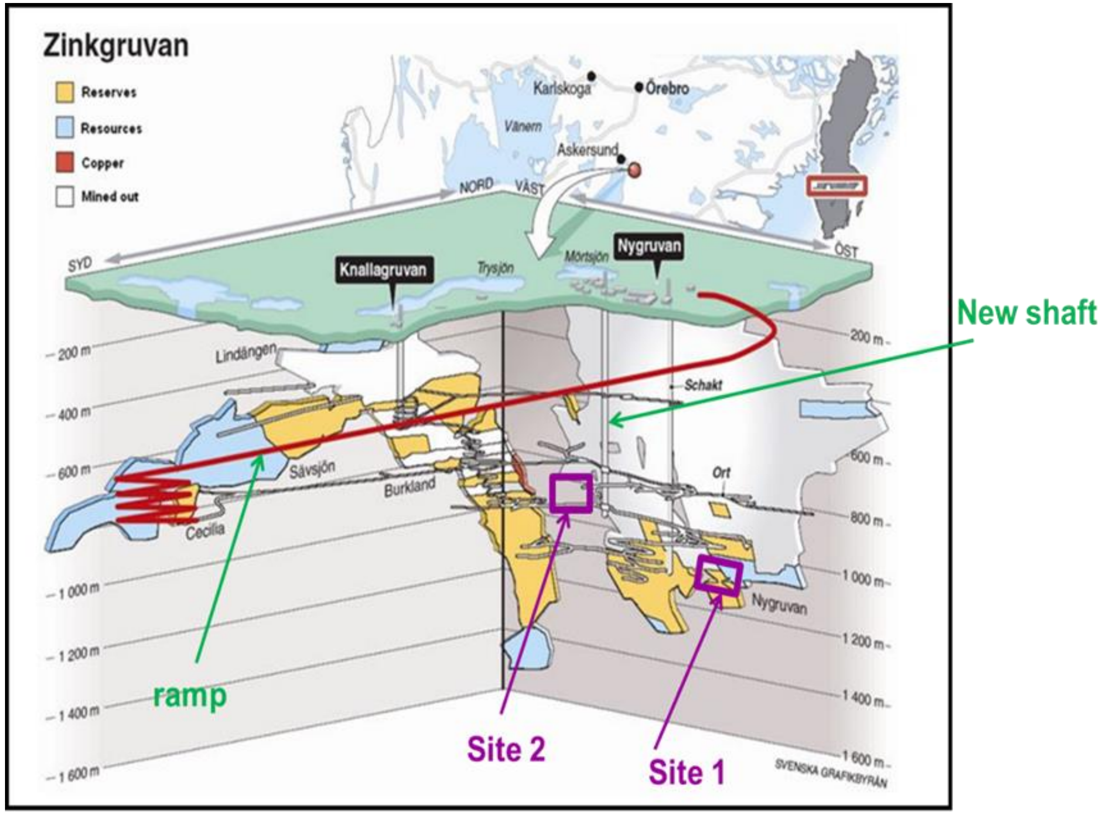
Design

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

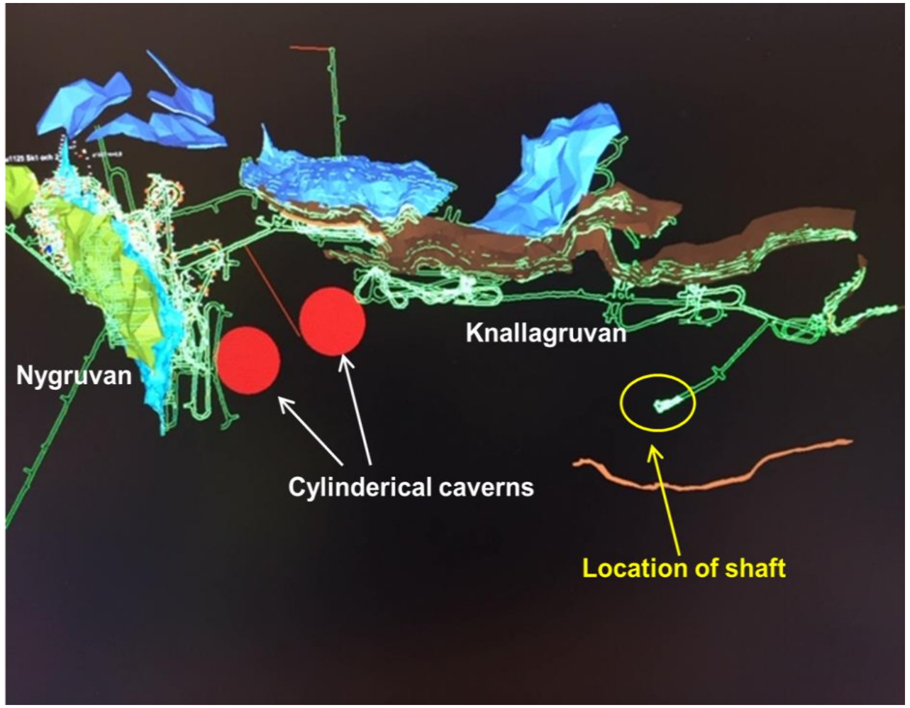
Can also be used for other purposes:

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

Zinkgruvan mine



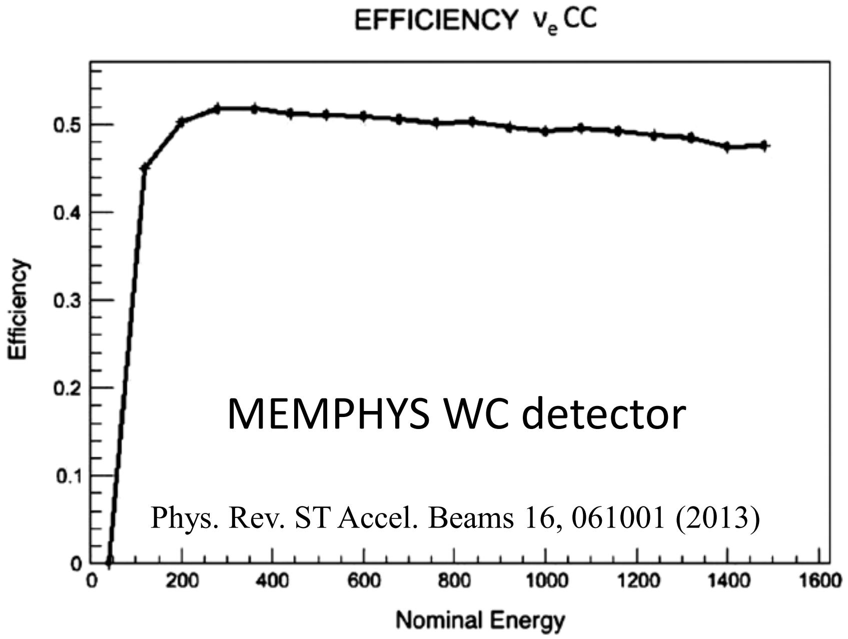
Potential location in Site 2



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

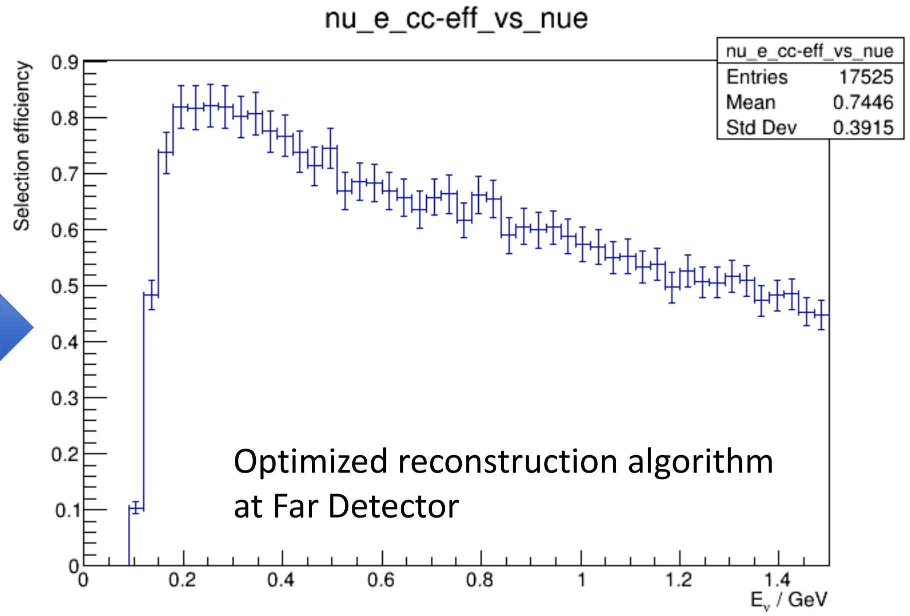
Improvements on sensitivity

- New detector response optimized for ESSnuSB flux
- Genetic Algorithm for Target Station optimisation



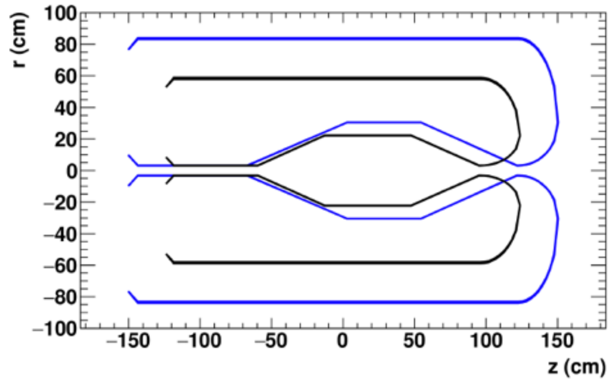
MEMPHYS WC detector

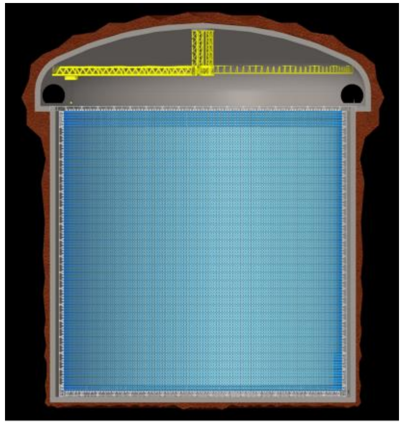
Phys. Rev. ST Accel. Beams 16, 061001 (2013)



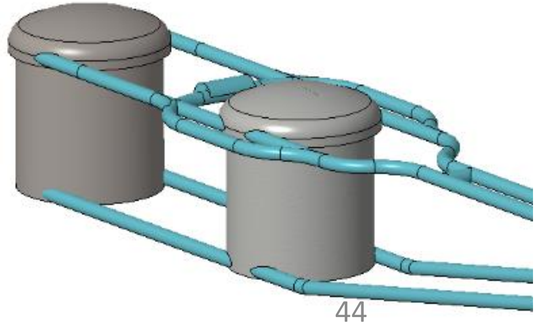
Optimized reconstruction algorithm
at Far Detector

horn optimisation





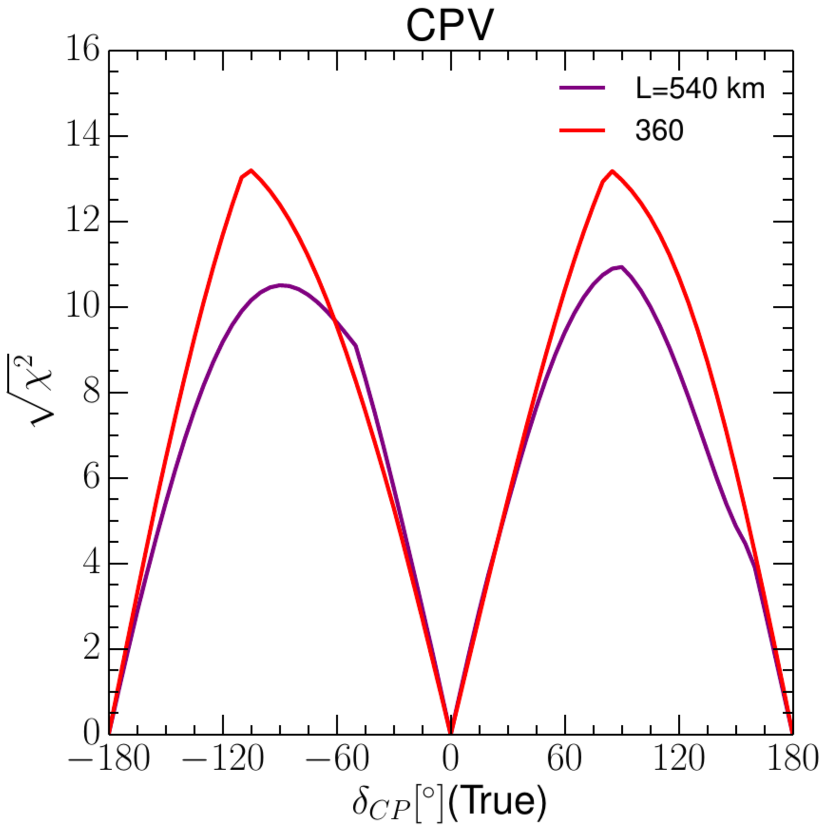
538 kt
total fiducial



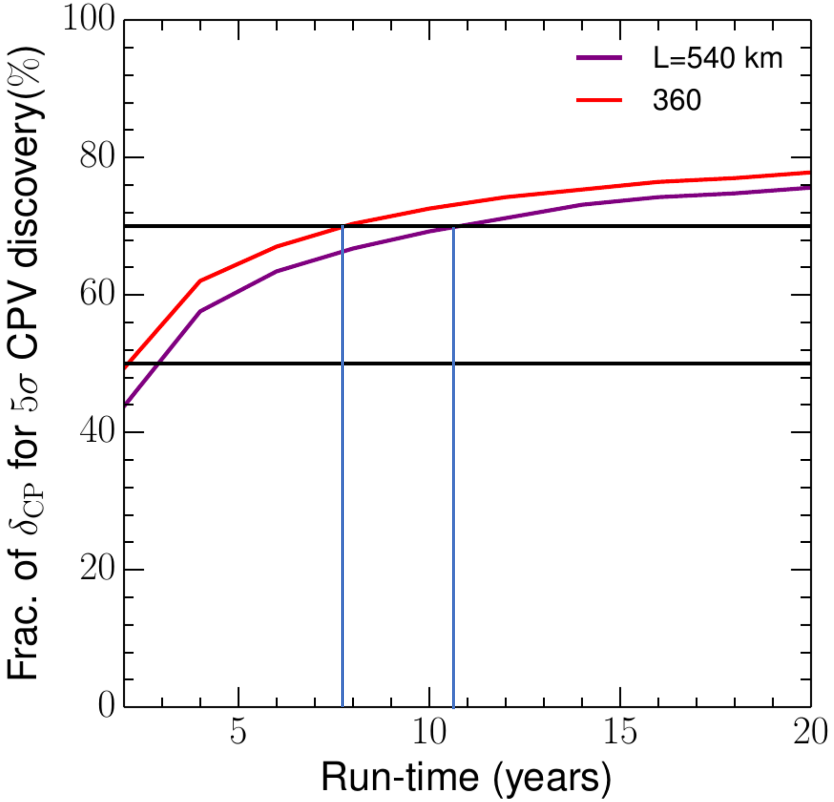
Updated physics performance (assumptions)

- **Distance from neutrino source (baseline)**
  - 540 km (Garpenberg)
  - 360 km (Zinkgruvan)
- **Experiment run time**
  - 5 years neutrino mode, 5 years anti-neutrino mode
- **Assumed systematic error**
  - 5 % on signal normalization
  - 10 % on background normalization
- **For more information see:** arXiv:2107.07585

Updated physics performance (sensitivity)



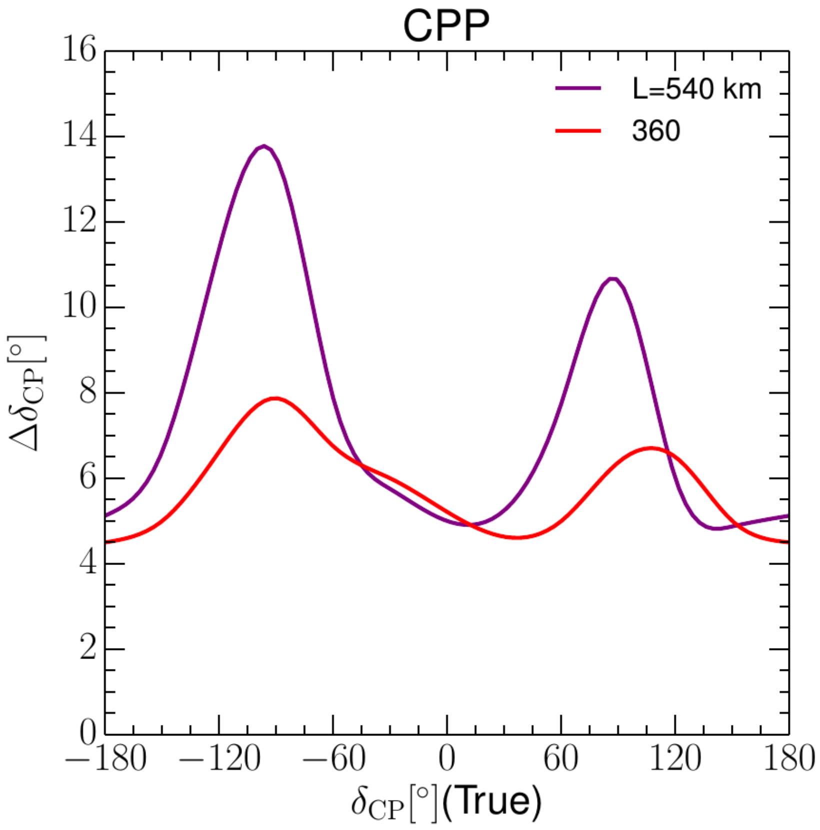
Sensitivity for $\delta_{CP} = \pm \pi/2$:
11 σ (540 km)
13 σ (360 km)



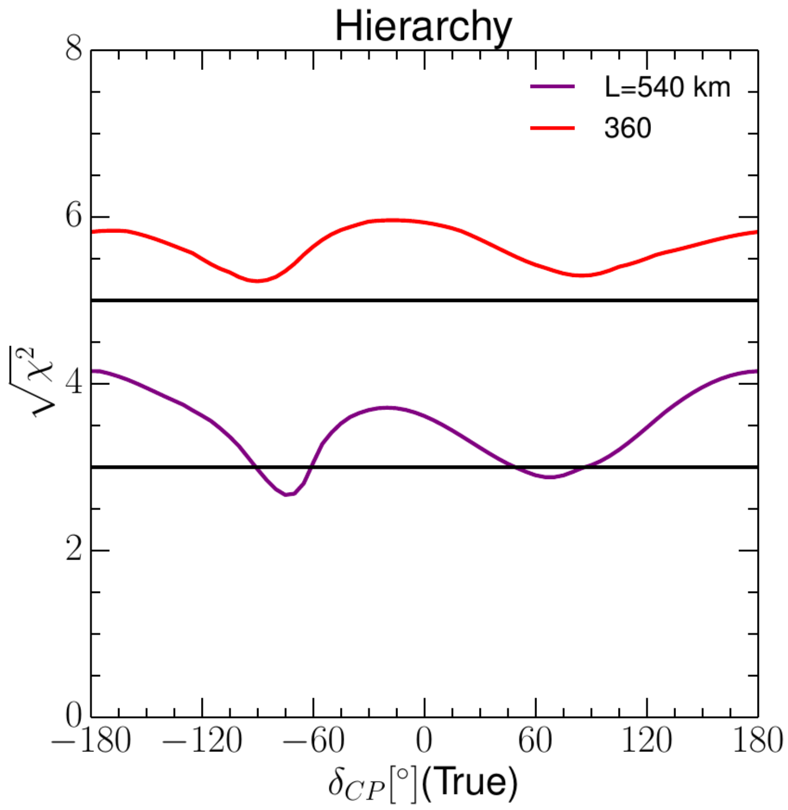
75% δ_{CP} coverage @ 5 σ:
11 years (540 km)
6 years (360 km)

From: arXiv:2107.07585

Updated physics performance (resolution and hierarchy)



High precision of δ_{CP} measurement

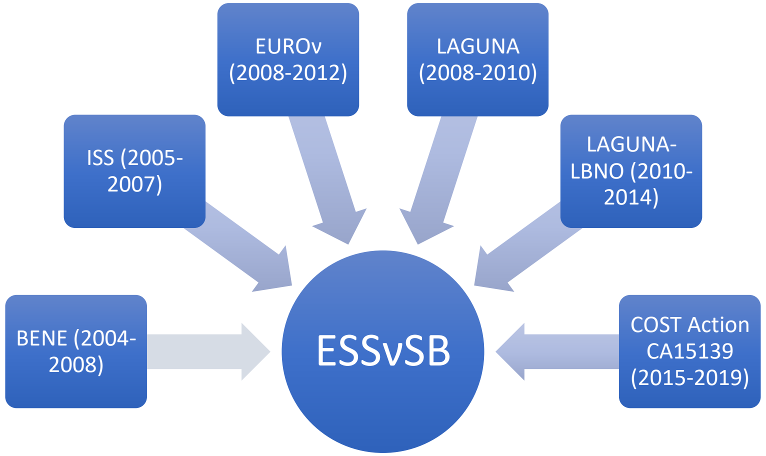


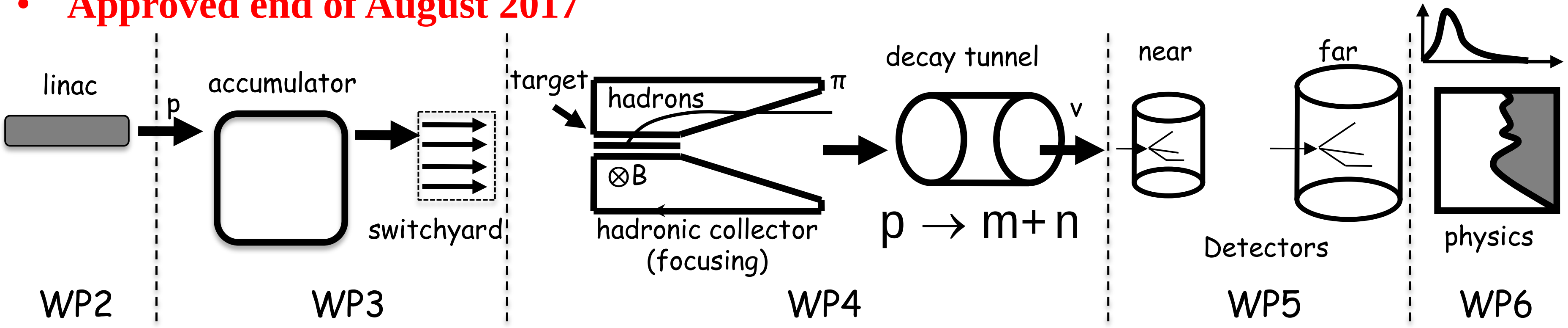
At 360 km mass hierarchy determined at 5 σ

From: arXiv:2107.07585

ESSvSB at the European level

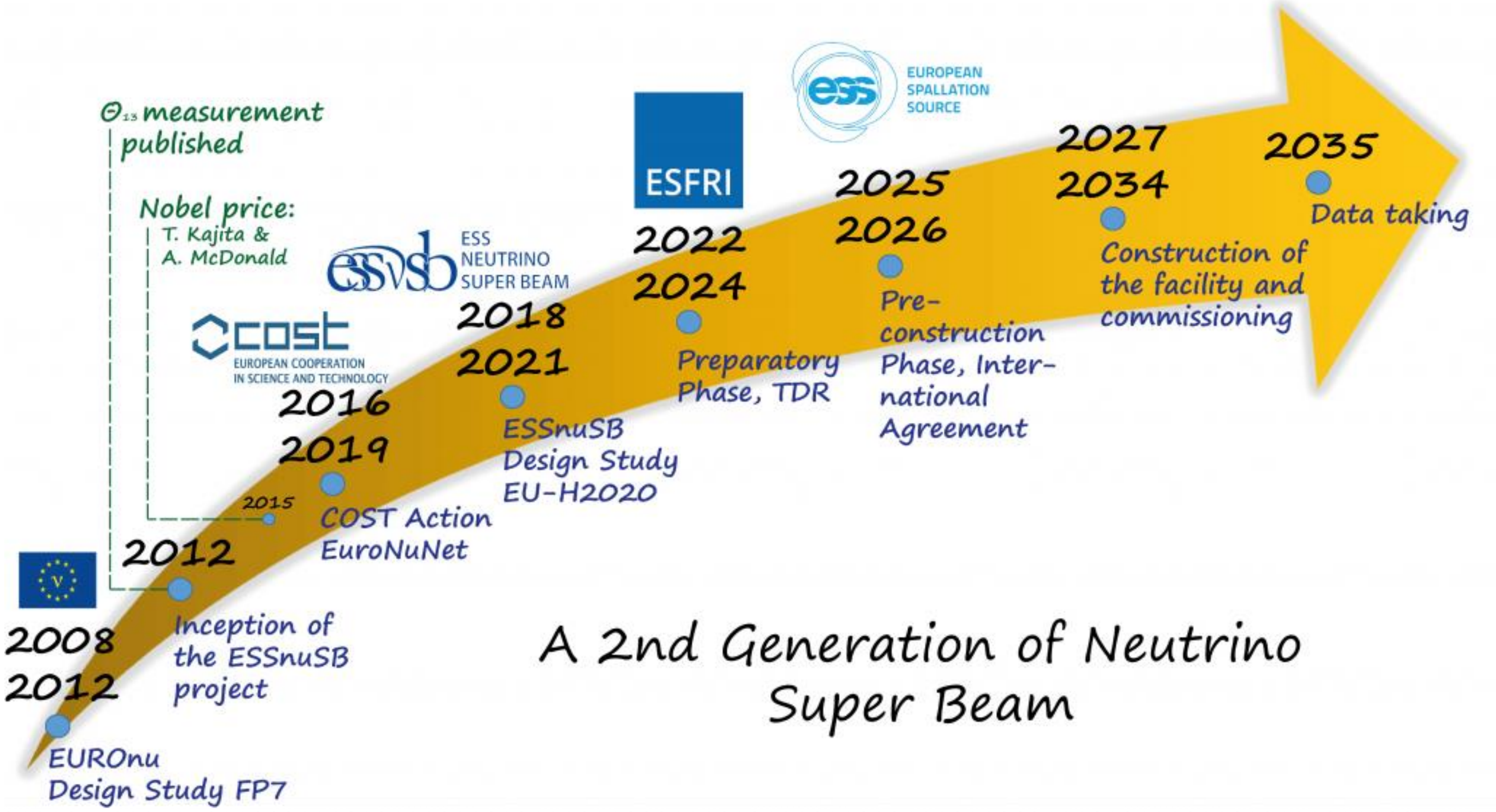
- A **H2020** EU **Design Study** (Call INFRADEV-01-2017)
  - **Title of Proposal**: Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator
  - **Duration: 4 years**
  - **Total cost: 4.7 M€**
  - **Requested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


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



Possible ESSνSB schedule

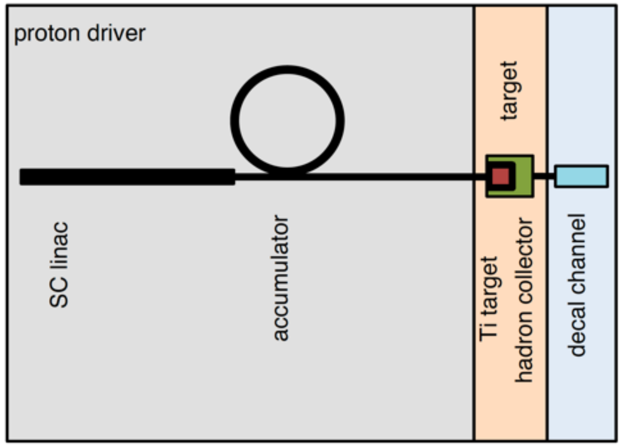
(2nd generation neutrino Super Beam)



ESSνSB and (R&D) synergies

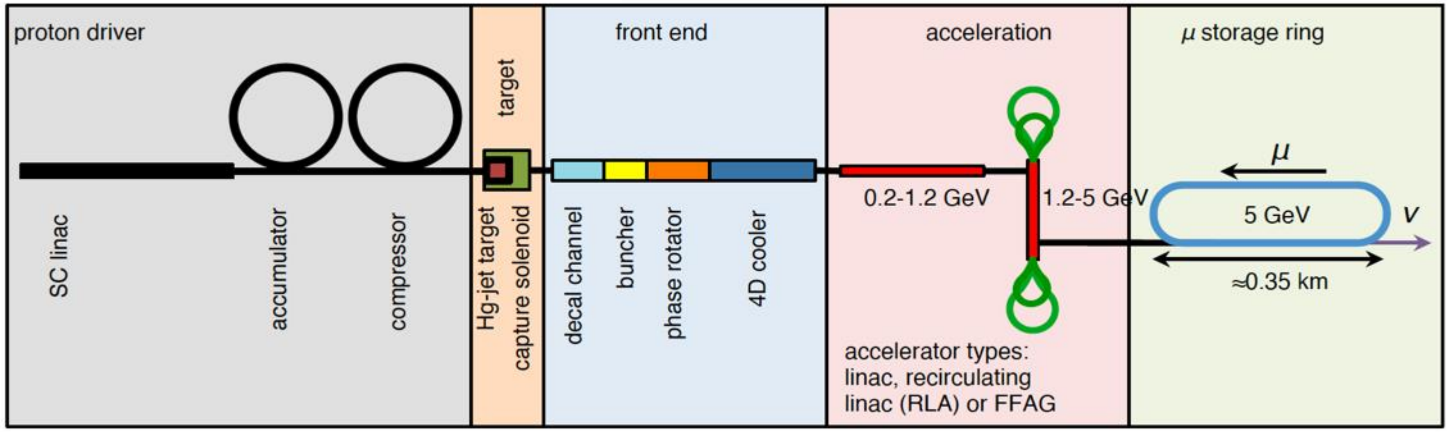
Dedicated series of workshops is organized
https://indico.cern.ch/event/849674/

Super Beam

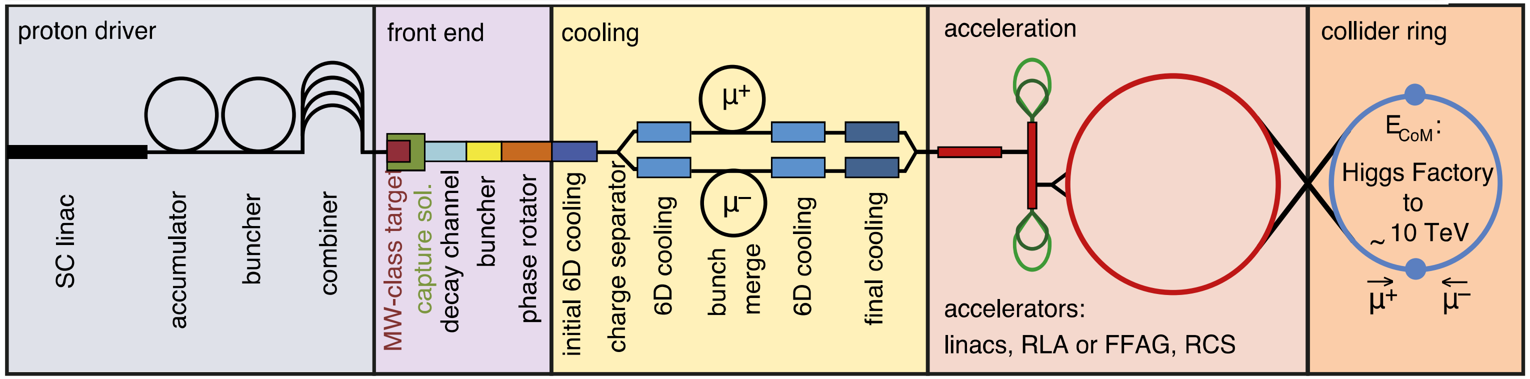


+Decay At Rest and Coherent scat.
(with short pulses)

Neutrino Factory



Muon Collider



ESSnuSB movies

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

- Not directly related, but interesting pitch for ESS from 10 years ago: https://www.youtube.com/watch?v=KG3Upzc3NGY

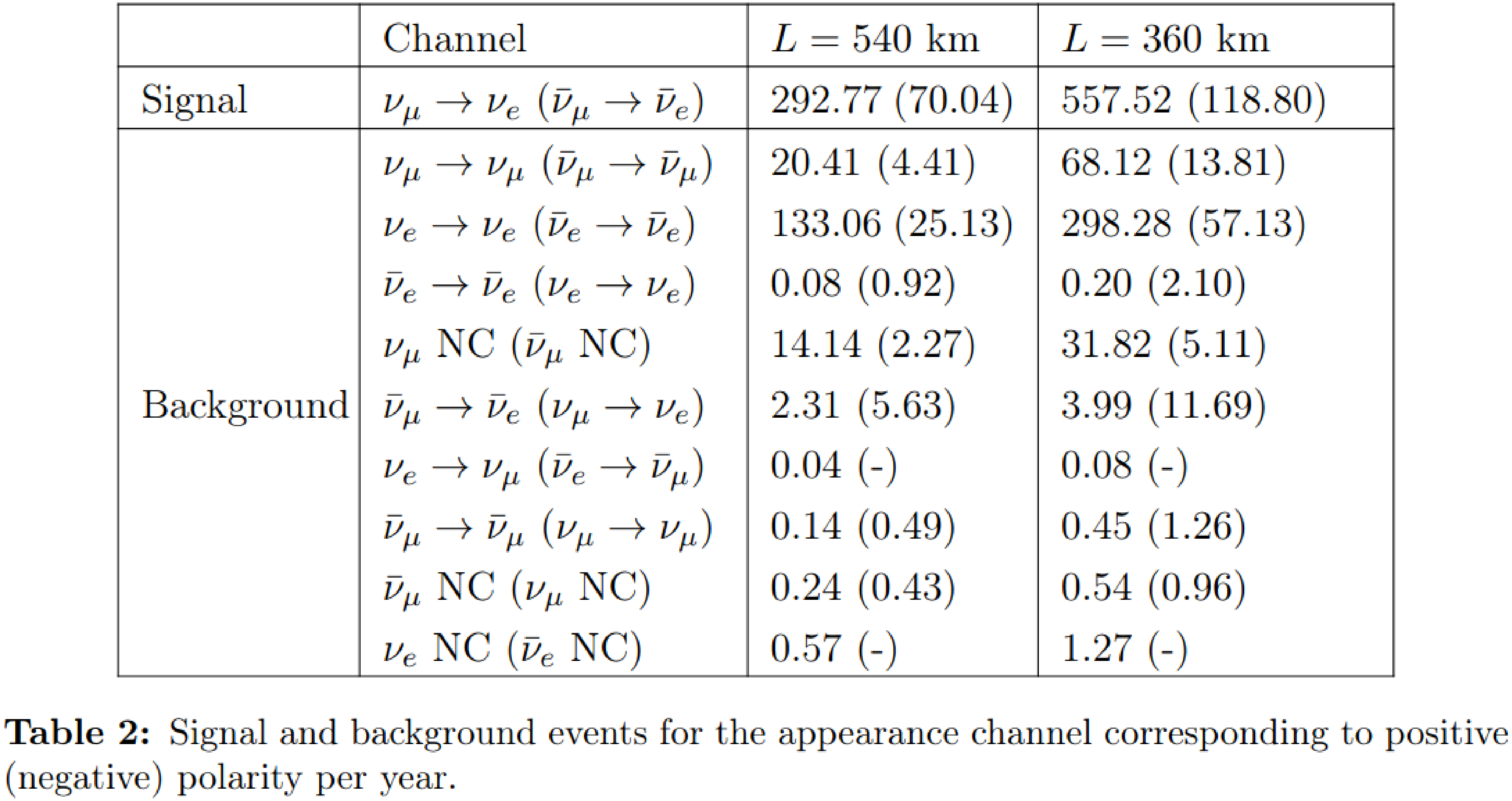
Funded by the Horizon 2020 Framework Programme of the European Union

Conclusions

- **ESSnuSB** aims to observe CP violation in neutrino oscillations at the 2nd oscillation maximum using 538 kt WC detector
    - **Recent optimizations** predict that in 10 years of data taking ESSnuSB will be able to
        - reach 5 σ over 75% 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
    - will start operation by 2023, 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
- **ESSnuSB EU-H2020** Design Study support this project

The end

Expected appearance events at FD

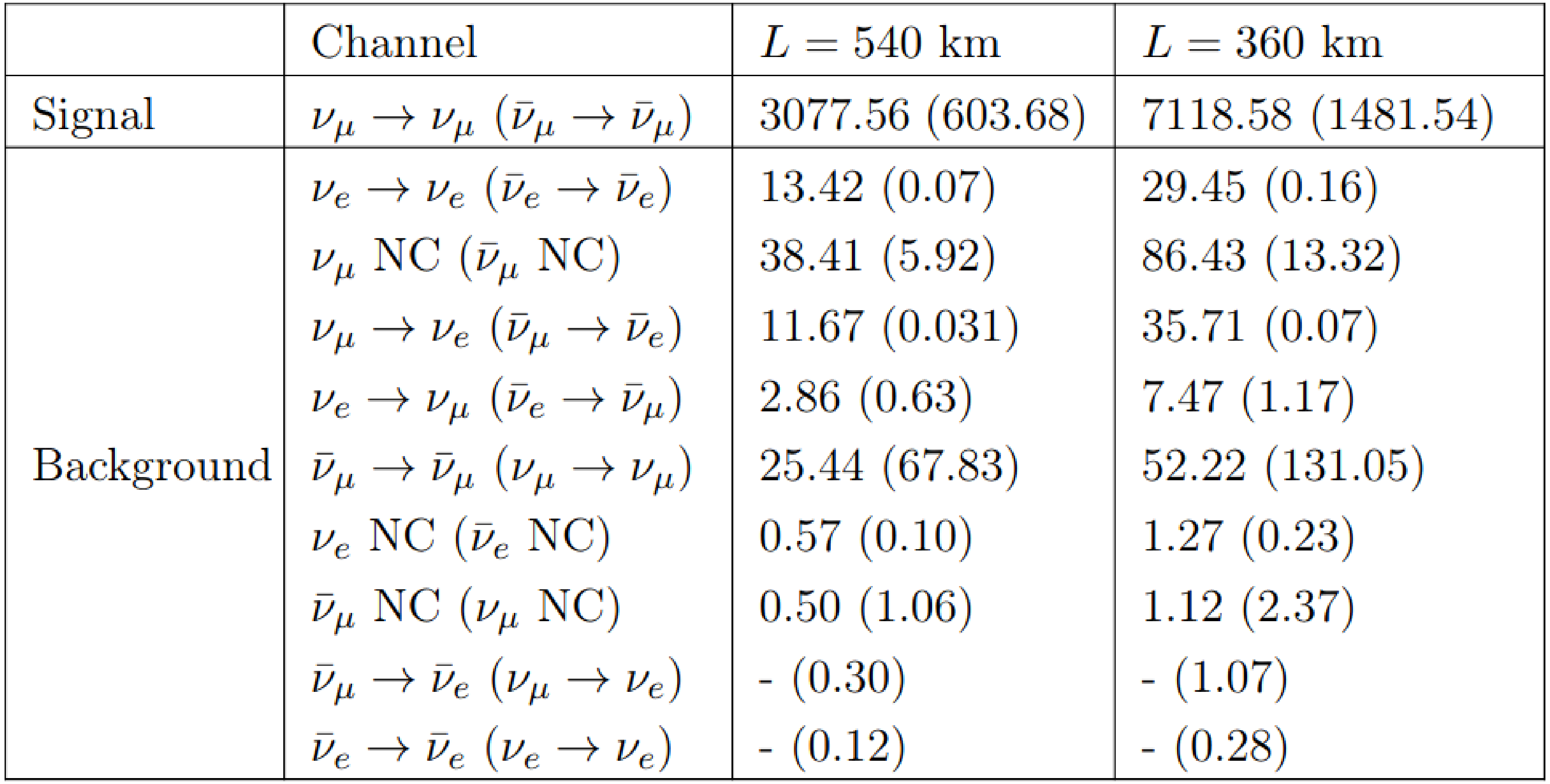


	Channel	$L = 540$ km	$L = 360$ km
Signal	$\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$)	292.77 (70.04)	557.52 (118.80)
Background	$\nu_\mu \to \nu_\mu$ ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)	20.41 (4.41)	68.12 (13.81)
	$\nu_e \to \nu_e$ ($\bar{\nu}_e \to \bar{\nu}_e$)	133.06 (25.13)	298.28 (57.13)
	$\bar{\nu}_e \to \bar{\nu}_e$ ($\nu_e \to \nu_e$)	0.08 (0.92)	0.20 (2.10)
	ν_μ NC ($\bar{\nu}_\mu$ NC)	14.14 (2.27)	31.82 (5.11)
	$\bar{\nu}_\mu \to \bar{\nu}_e$ ($\nu_\mu \to \nu_e$)	2.31 (5.63)	3.99 (11.69)
	$\nu_e \to \nu_\mu$ ($\bar{\nu}_e \to \bar{\nu}_\mu$)	0.04 (-)	0.08 (-)
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$ ($\nu_\mu \to \nu_\mu$)	0.14 (0.49)	0.45 (1.26)
	$\bar{\nu}_\mu$ NC (ν_μ NC)	0.24 (0.43)	0.54 (0.96)
	ν_e NC ($\bar{\nu}_e$ NC)	0.57 (-)	1.27 (-)

Table 2: Signal and background events for the appearance channel corresponding to positive (negative) polarity per year.

From: arXiv:2107.07585

Expected disappearance events at FD



	Channel	$L = 540$ km	$L = 360$ km
Signal	$\nu_\mu \to \nu_\mu$ ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)	3077.56 (603.68)	7118.58 (1481.54)
Background	$\nu_e \to \nu_e$ ($\bar{\nu}_e \to \bar{\nu}_e$)	13.42 (0.07)	29.45 (0.16)
	ν_μ NC ($\bar{\nu}_\mu$ NC)	38.41 (5.92)	86.43 (13.32)
	$\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$)	11.67 (0.031)	35.71 (0.07)
	$\nu_e \to \nu_\mu$ ($\bar{\nu}_e \to \bar{\nu}_\mu$)	2.86 (0.63)	7.47 (1.17)
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$ ($\nu_\mu \to \nu_\mu$)	25.44 (67.83)	52.22 (131.05)
	ν_e NC ($\bar{\nu}_e$ NC)	0.57 (0.10)	1.27 (0.23)
	$\bar{\nu}_\mu$ NC (ν_μ NC)	0.50 (1.06)	1.12 (2.37)
	$\bar{\nu}_\mu \to \bar{\nu}_e$ ($\nu_\mu \to \nu_e$)	- (0.30)	- (1.07)
	$\bar{\nu}_e \to \bar{\nu}_e$ ($\nu_e \to \nu_e$)	- (0.12)	- (0.28)

From: arXiv:2107.07585

Appearance event spectra at FD

From: [arXiv:2107.07585](https://arxiv.org/abs/2107.07585)

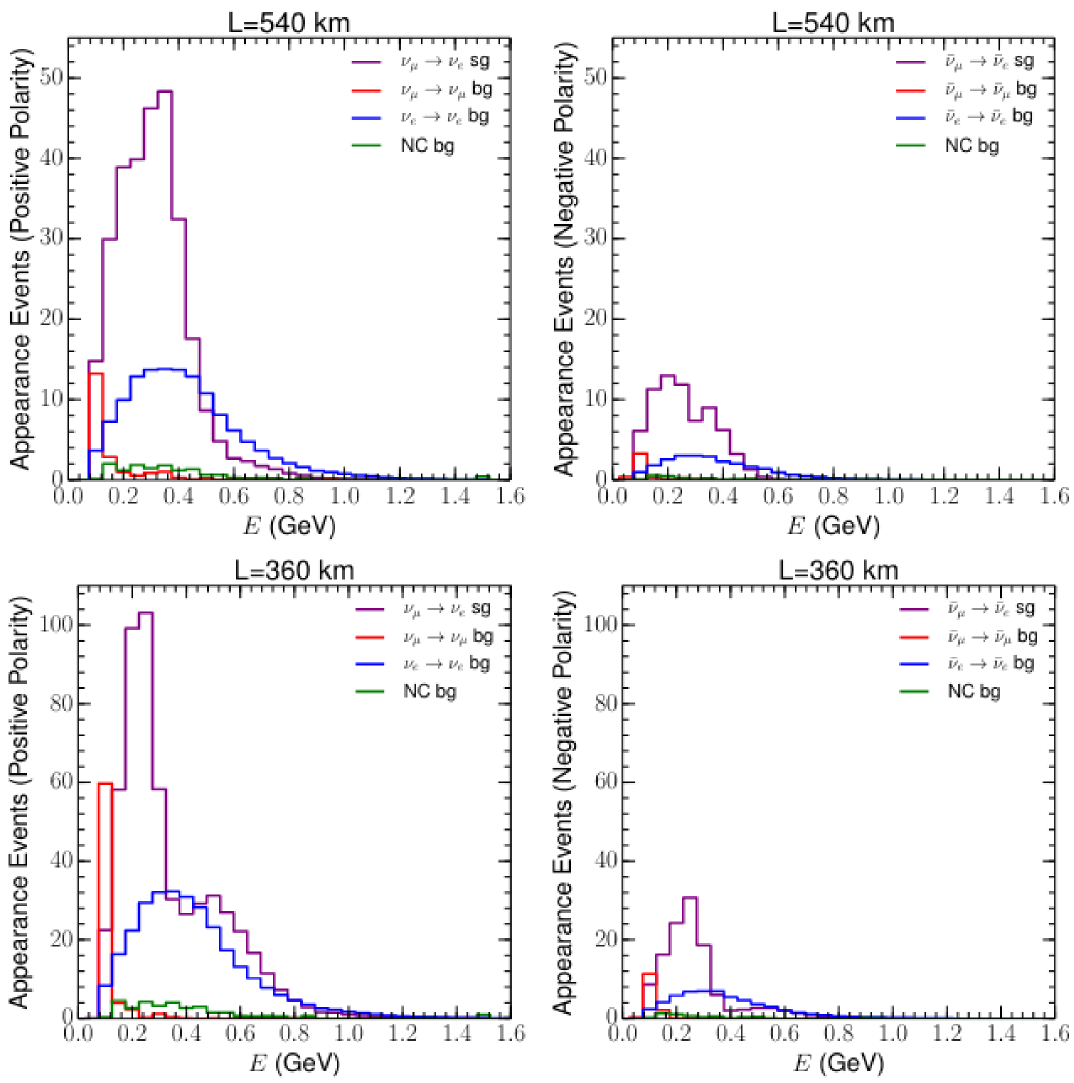


Figure 3: Appearance channel event spectrum vs reconstructed energy. The upper panels are for the baseline option of 540 km and the lower panels are for the baseline option of 360 km. Note the difference in scales between upper and lower panels.

Disappearance event spectra at FD

From: arXiv:2107.07585

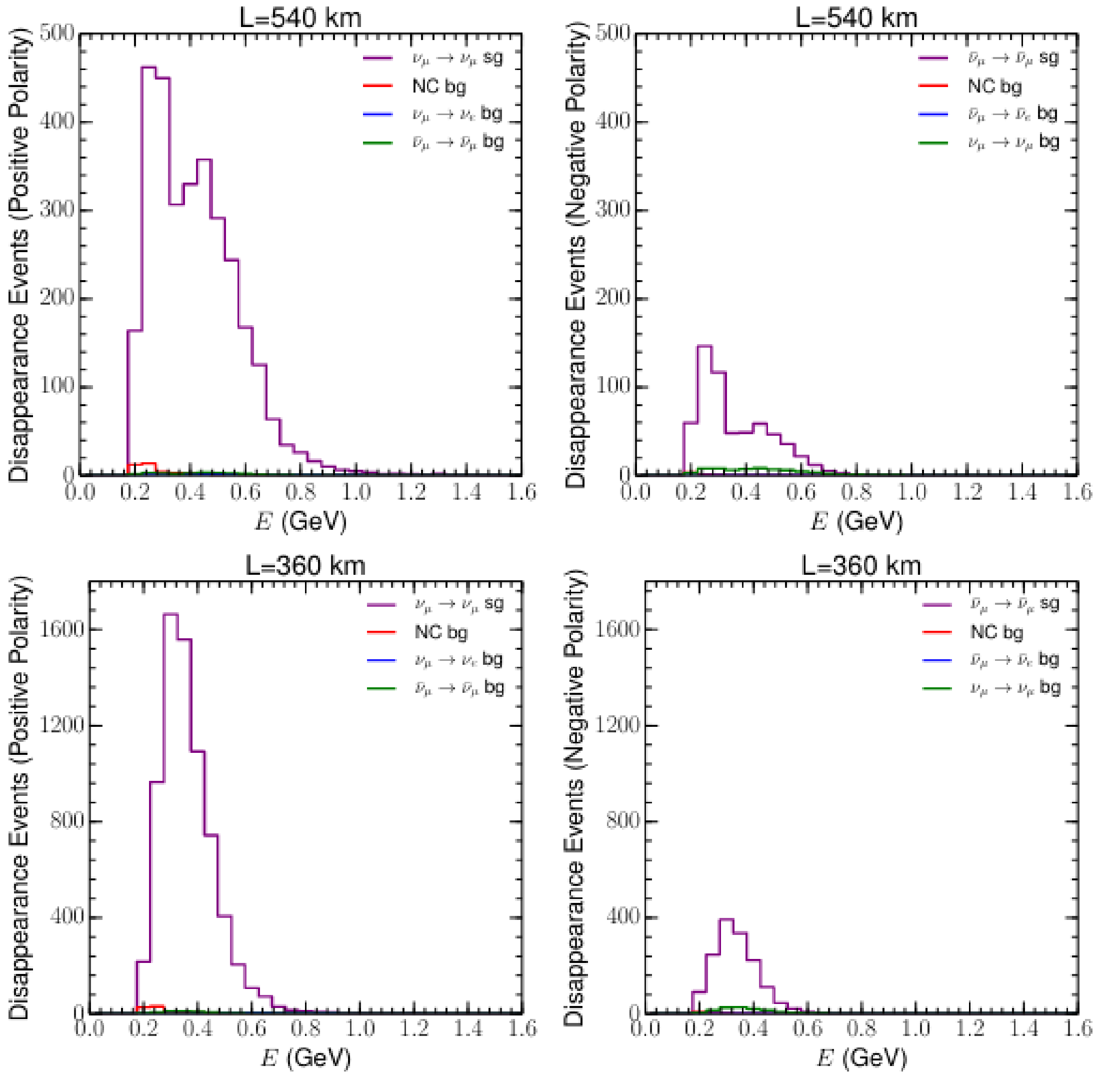
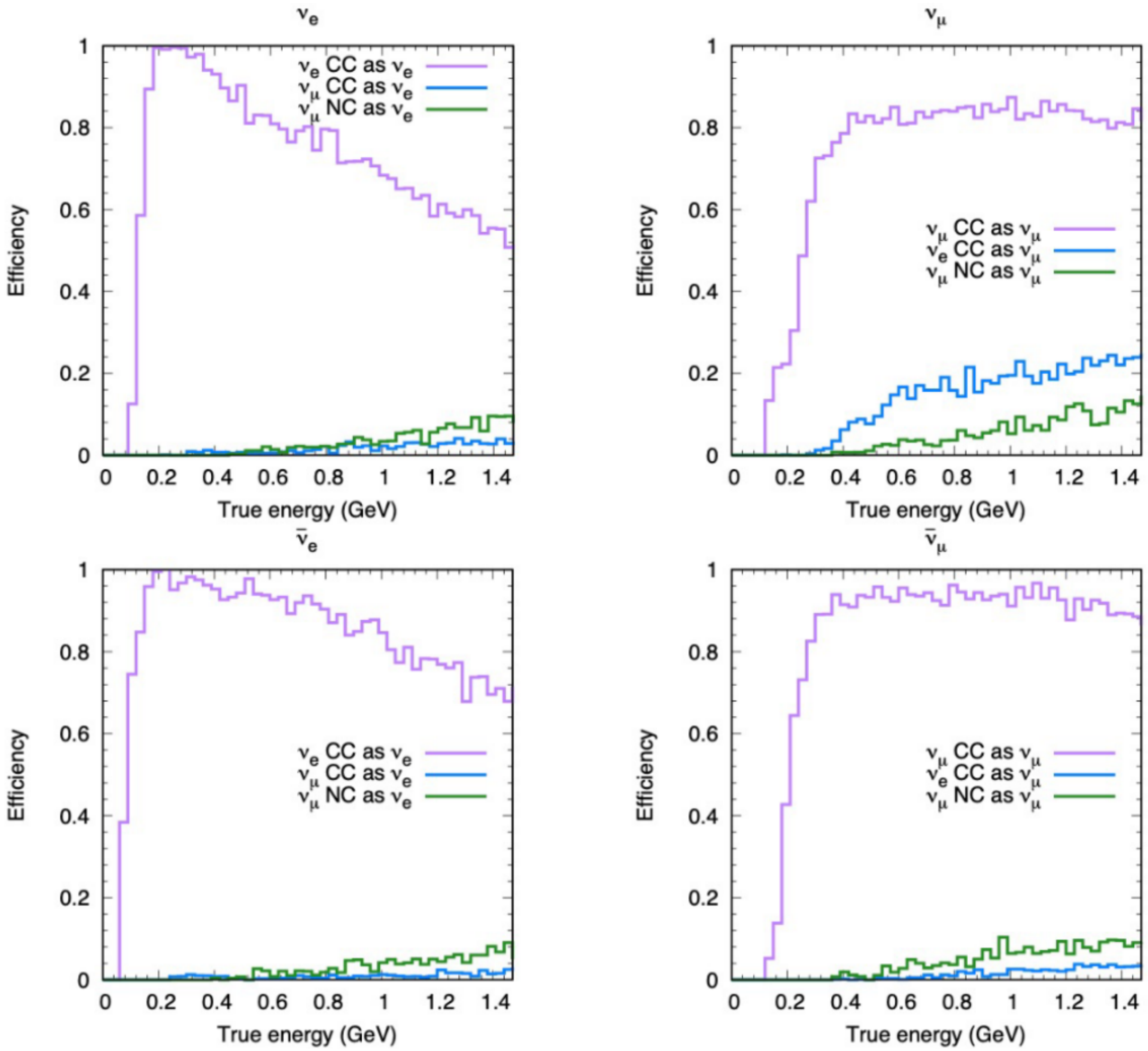


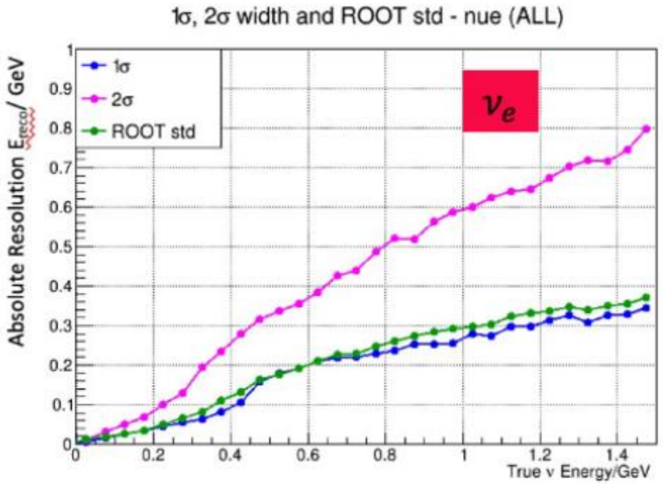
Figure 4: Disappearance channel event spectrum vs reconstructed energy. The upper panels are for the baseline option of 540 km and the lower panels are for the baseline option of 360 km. Note the difference in scales between upper and lower panels.

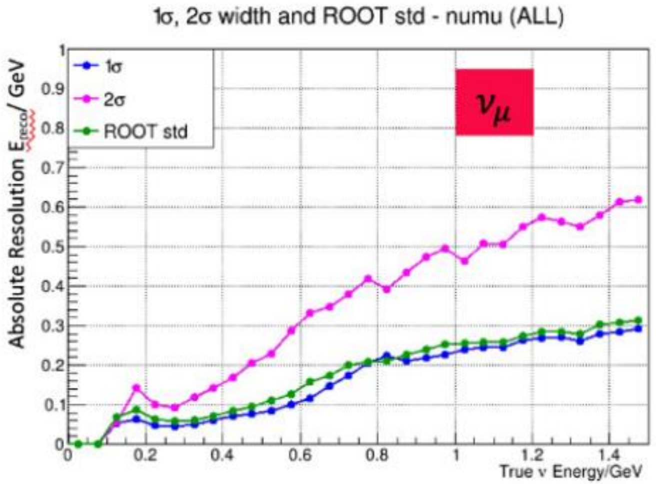
Efficiencies at FD



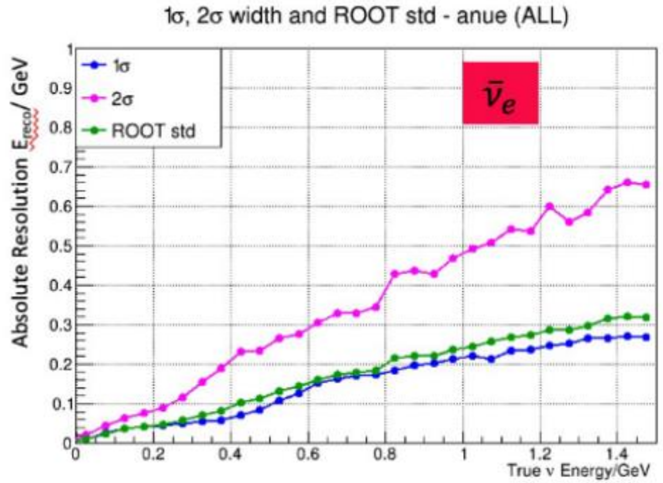
From the poster
by Olga Zormpa

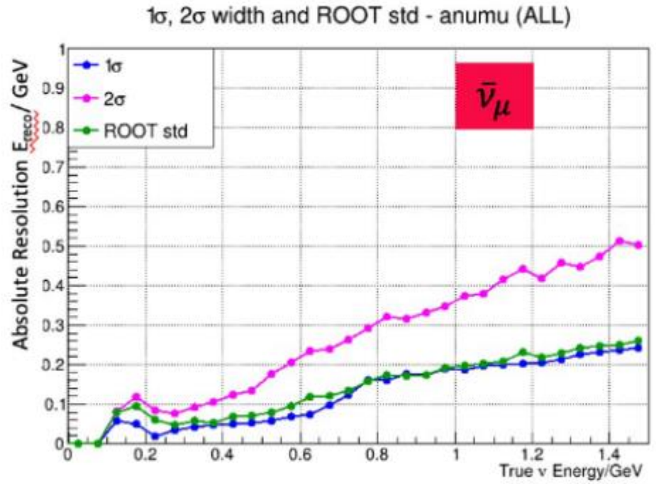
Absolute FD resolutions





From the poster
by Olga Zormpa





Migration matrices at FD

From the poster by Olga Zormpa