Co-funded by
the European Union

ESS neutrino Super Beam plus

Status and perspective of ESSnuSB+

Budimir Kliček

On behalf of the ESSnuSB+ project

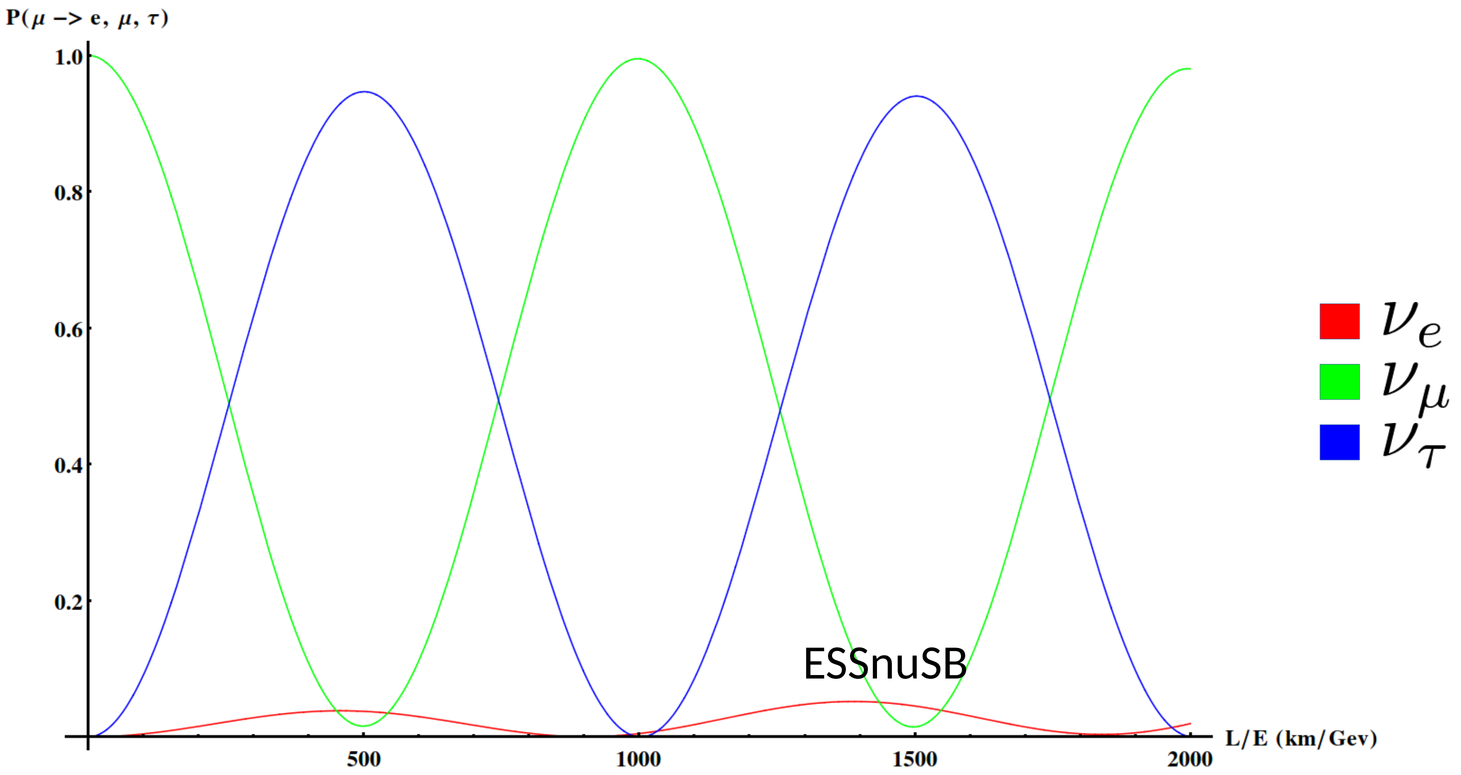
budimir.klicek@irb.hr

Ruđer Bošković Institute, Zagreb, Croatia

1 October 2024

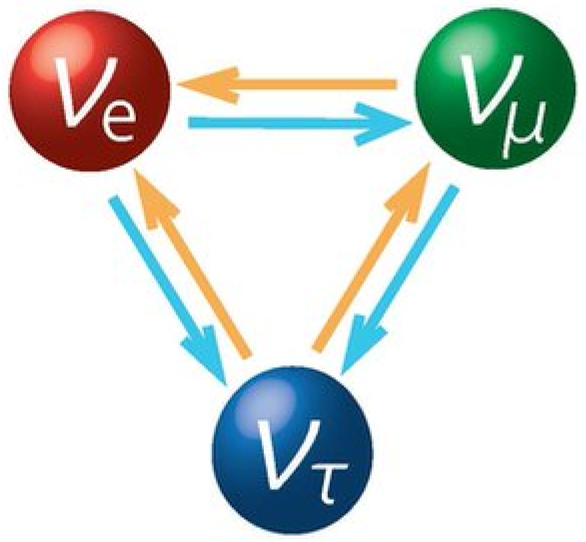
ESSnuSB / ESSnuSB+

A design study for a **long baseline accelerator neutrino oscillation experiment** to precisely measure leptonic CP violation amplitude at the 2nd neutrino oscillation maximum.

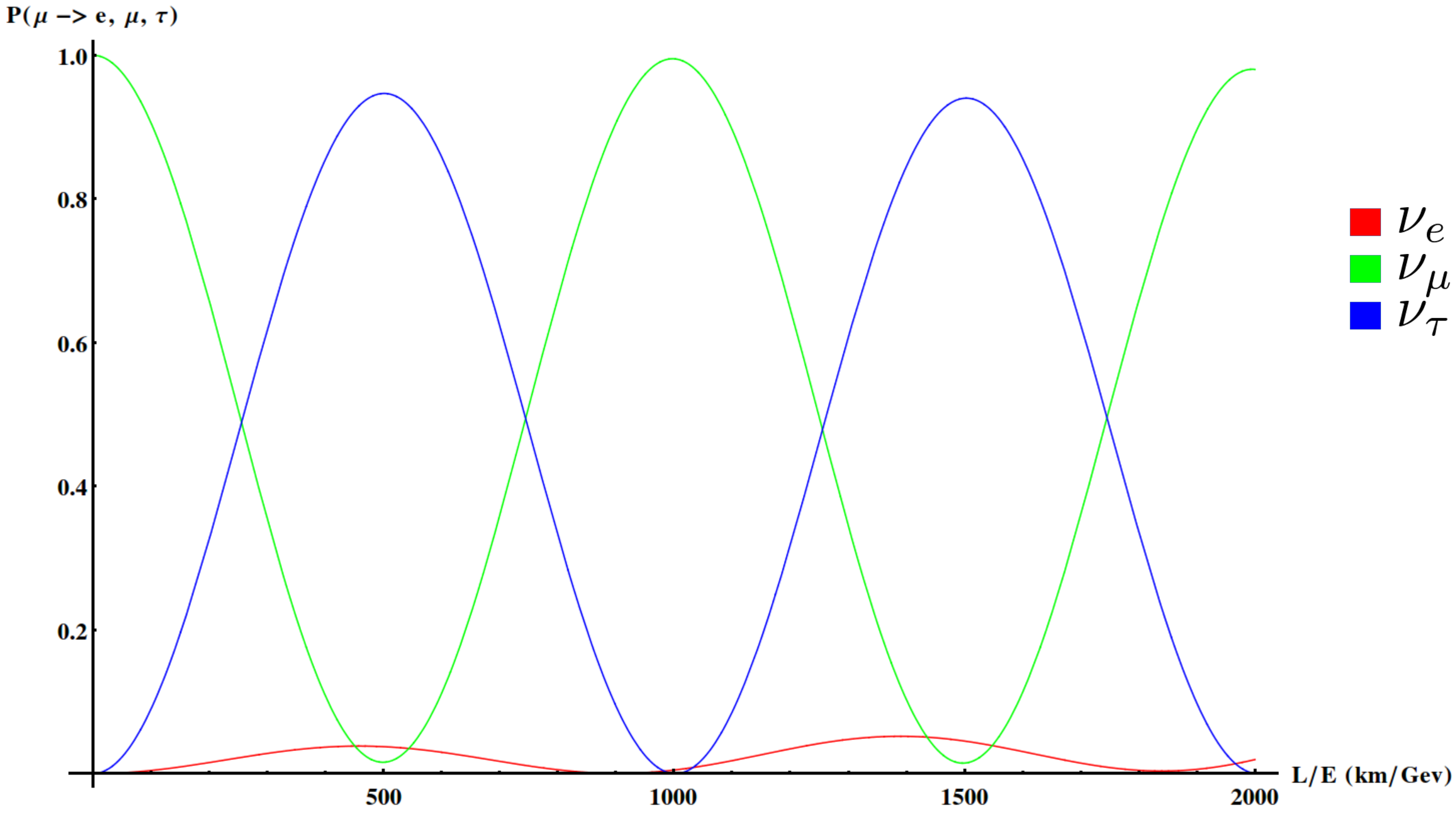


Neutrino oscillations

Neutrino flavour can effectively change between its creation and interaction.



Neutrino oscillations



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 2nd maximum?

Large signal and small matter effects

Neutrino oscillations (3 generations)

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

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

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

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

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

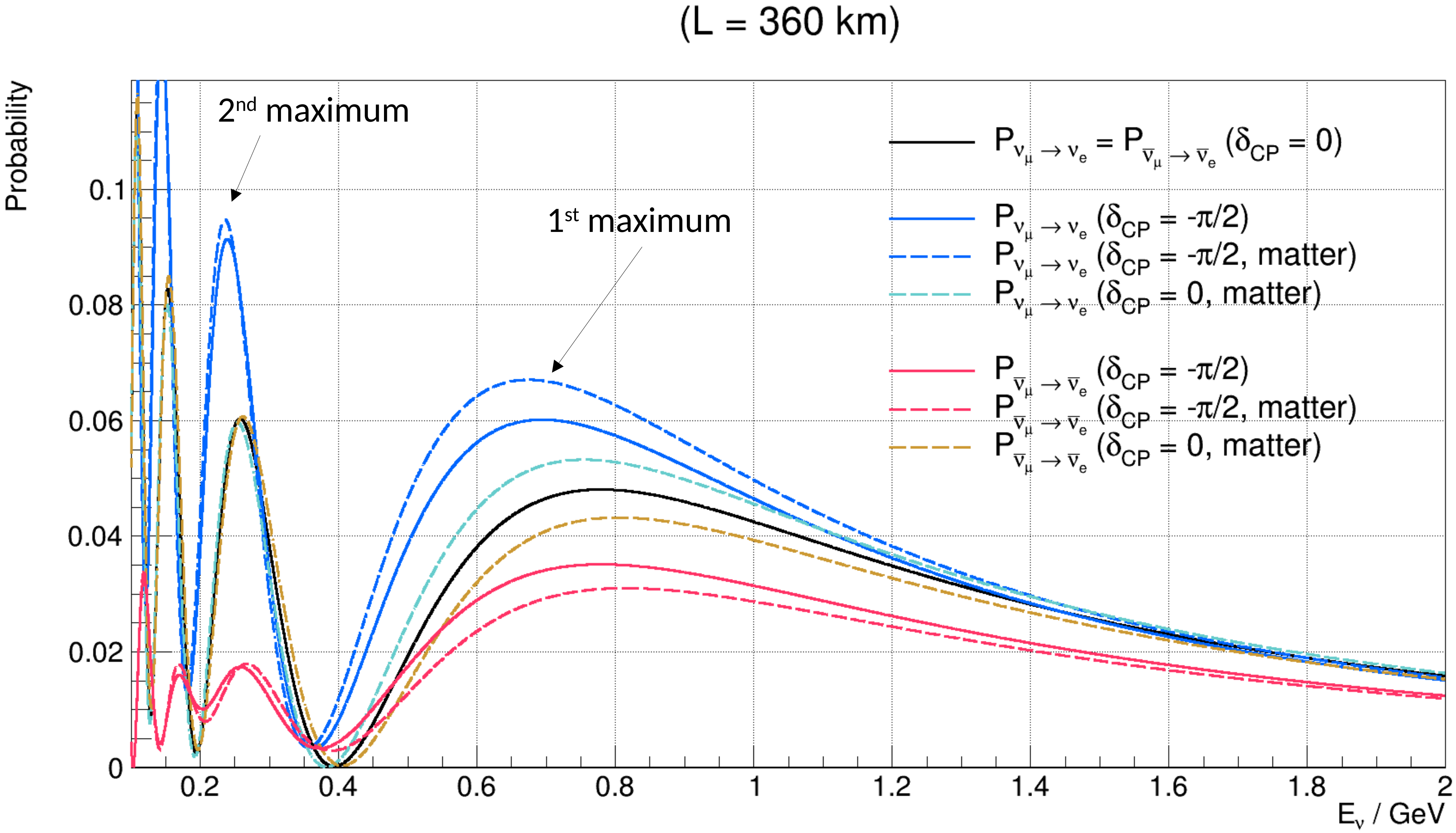
$$A_{ij}^{\alpha\beta} \equiv U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*$$

Six parameters in total: $\underbrace{\Delta m_{21}^2, \Delta m_{32}^2, \theta_{12}, \theta_{13}, \theta_{23},}_{\text{Known reasonably well}} \delta_{cp}$

CPV hint
@ 3 sigma

Sign unknown

Oscillation pattern



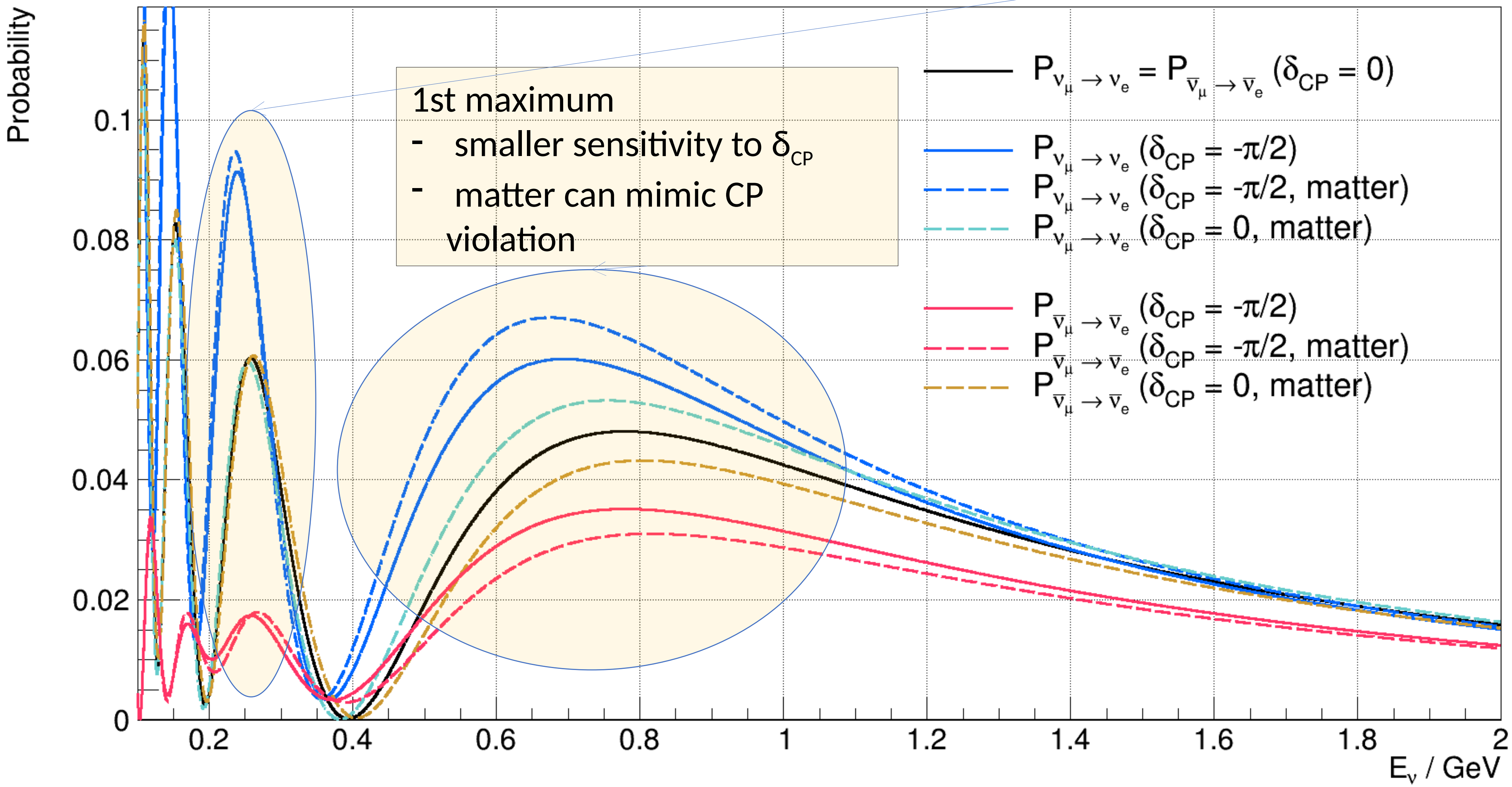
2nd maximum

1st maximum

Oscillation pattern

2nd maximum
- larger sensitivity to δ_{CP}
- matter doesn’t matter
- **but less statistics!**

(L = 360 km)



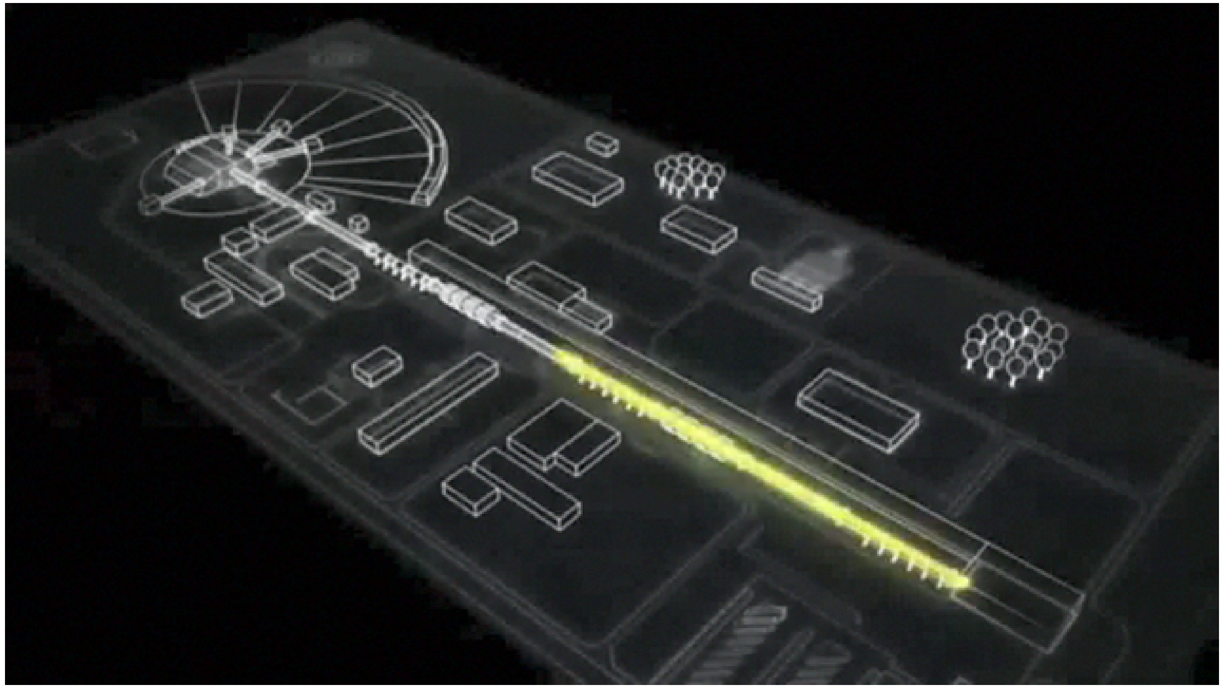
1st maximum
- smaller sensitivity to δ_{CP}
- matter can mimic CP violation

ESSnuSB project

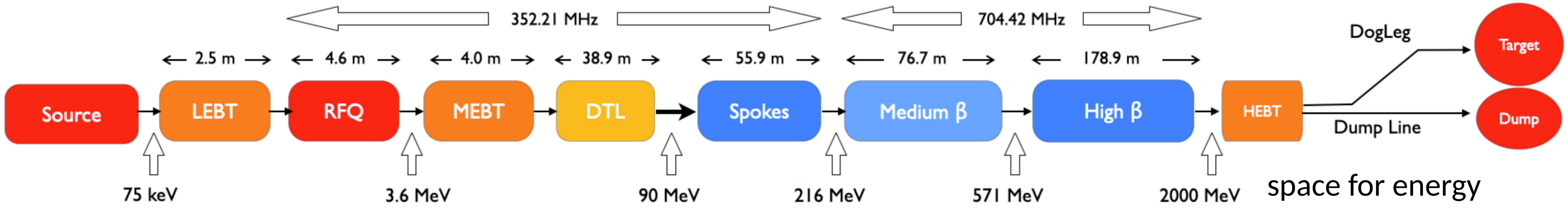
How to observe the CP violation in the 2nd oscillation maximum

Can we go to 2nd maximum?

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



ESS proton linac

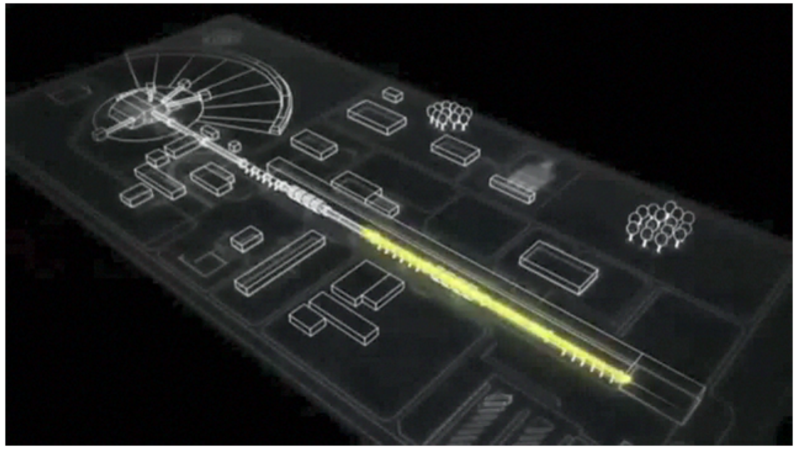


space for energy upgrades

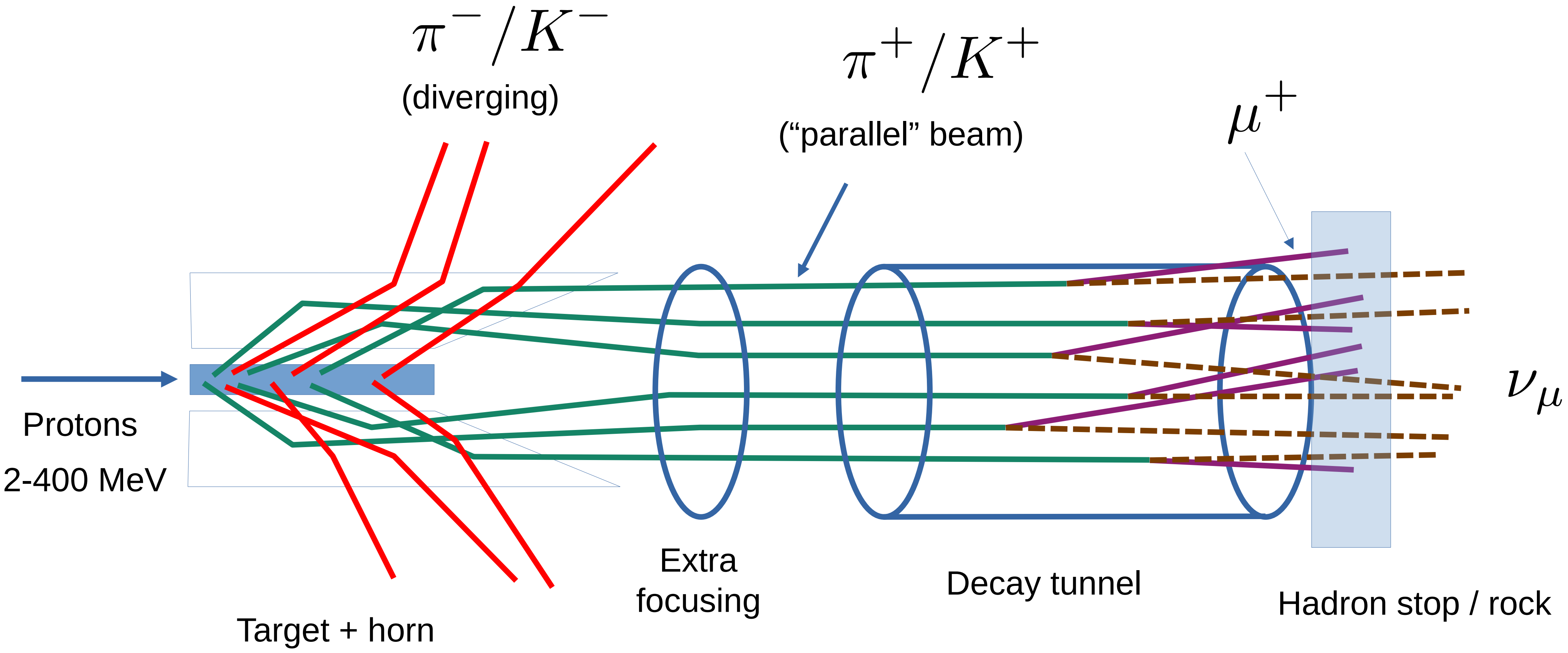
- The ESS will be a copious source of spallation neutrons.
- **5 MW average beam power.**
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV kinetic energy protons
  - up to 3.5 GeV with linac upgrades
- **>2.7x10^{23} p.o.t/year.**

First beam on target expected in 2026.

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



Neutrino beam production



π^- / K^-

(diverging)

π^+ / K^+

("parallel" beam)

μ^+

ν_μ

Protons

2-400 MeV

Target + horn

Extra focusing

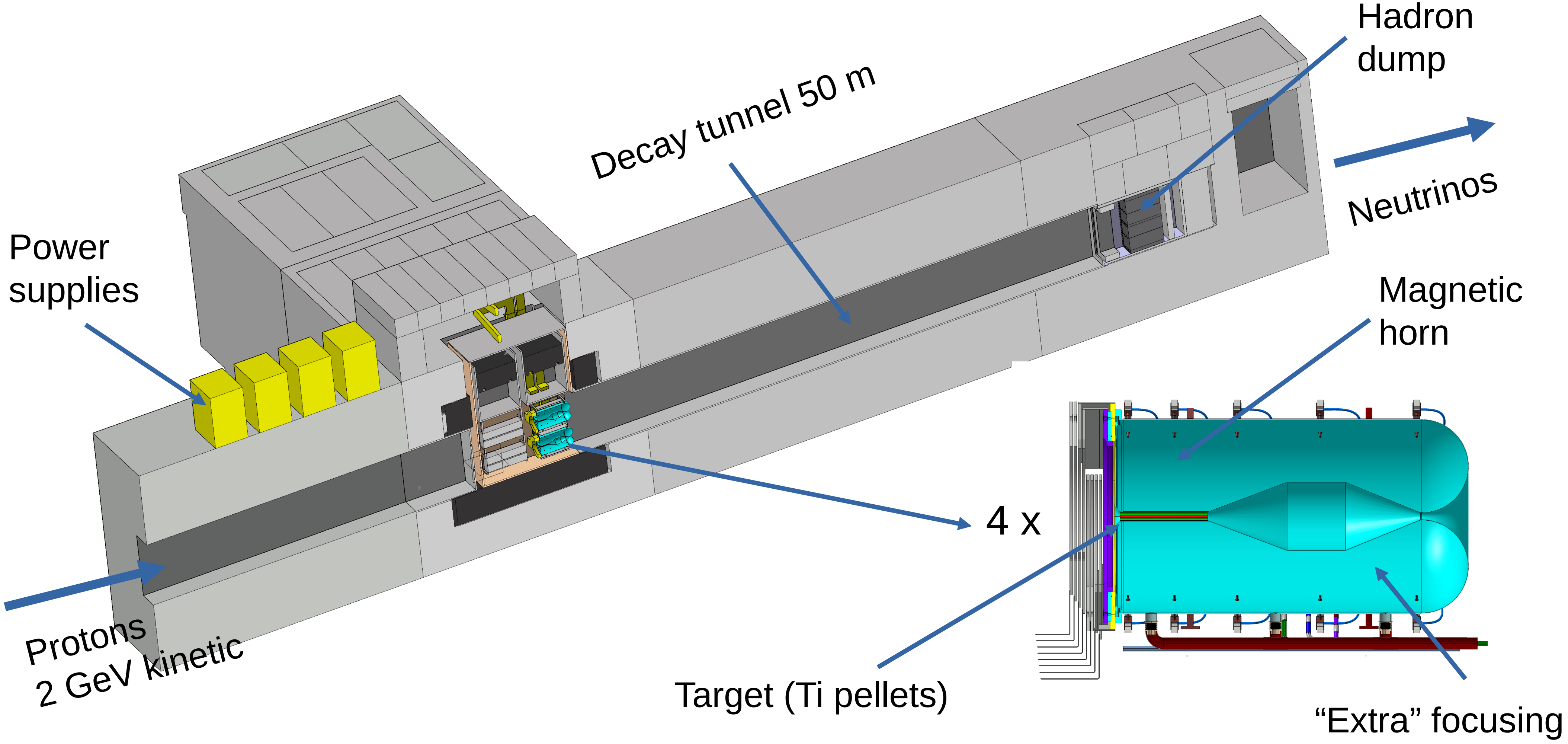
Decay tunnel

Hadron stop / rock

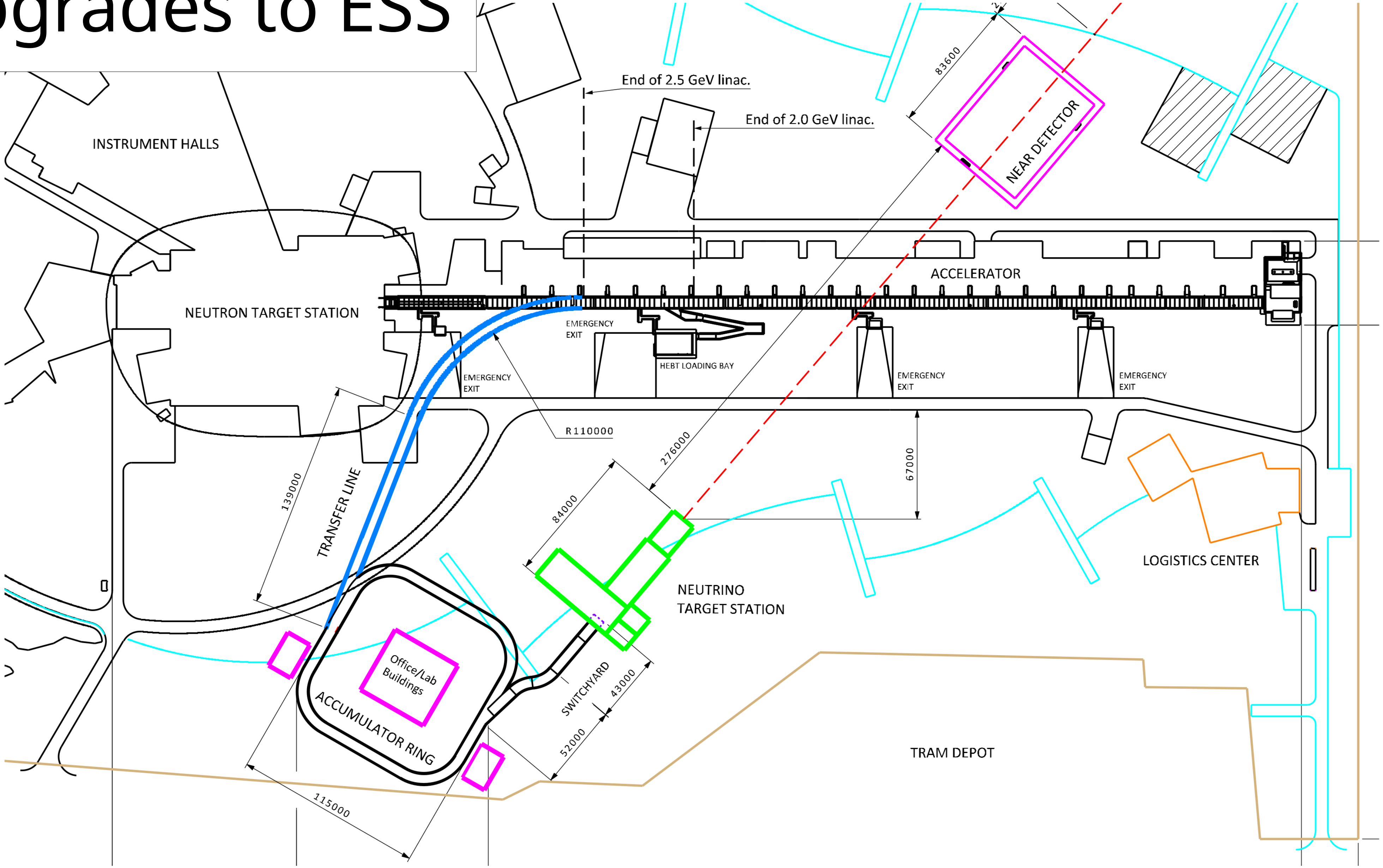
ESSnuSB – 2.5 GeV kinetic (ESS)
T2K – 30 GeV (J-Parc)
NUMI – 120 GeV (Fermilab)
CNGS – 400 GeV (SPS)

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

ESSnuSB target station design



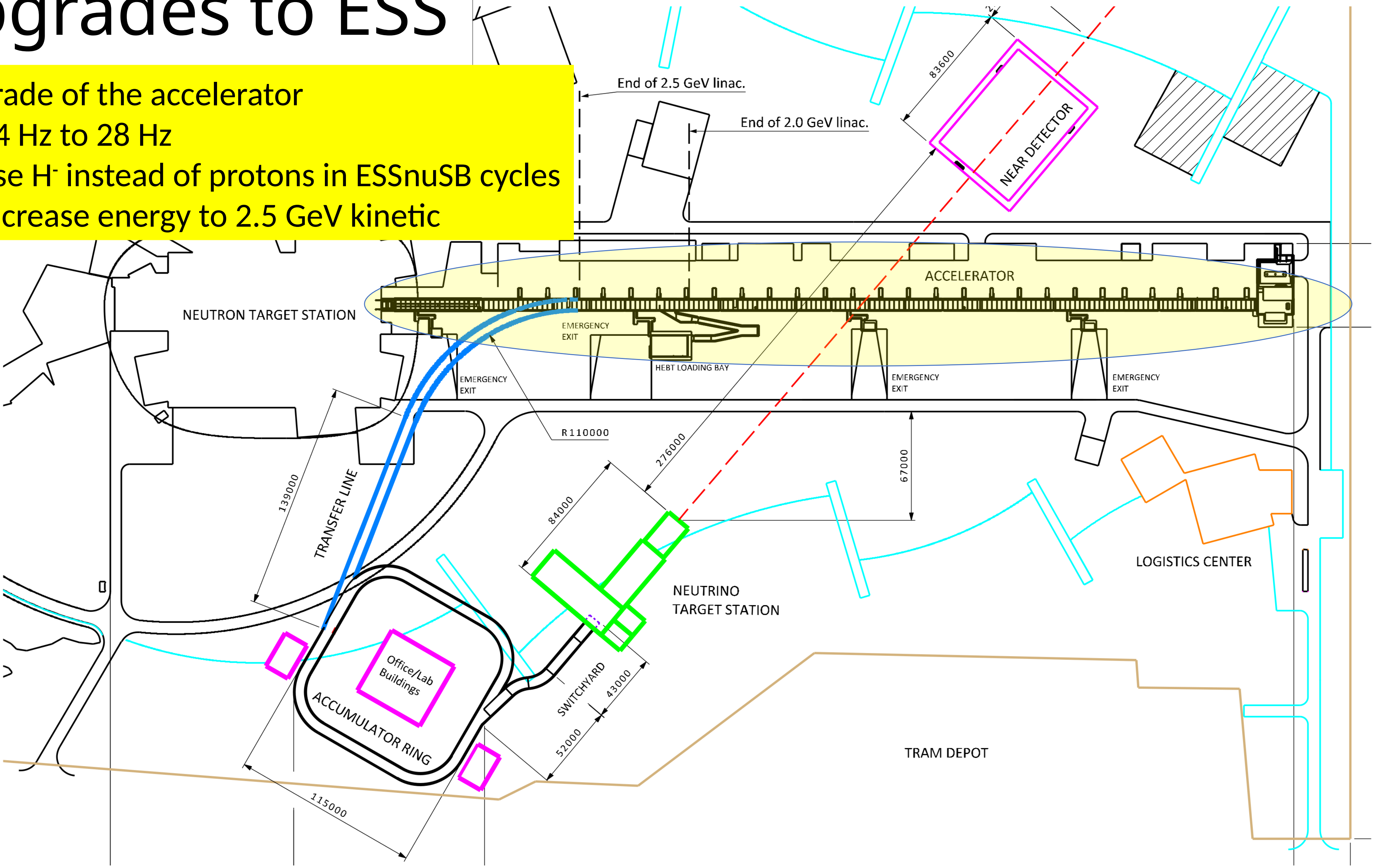
Upgrades to ESS



Upgrades to ESS

Upgrade of the accelerator

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



Upgrades to ESS

Upgrade of the accelerator

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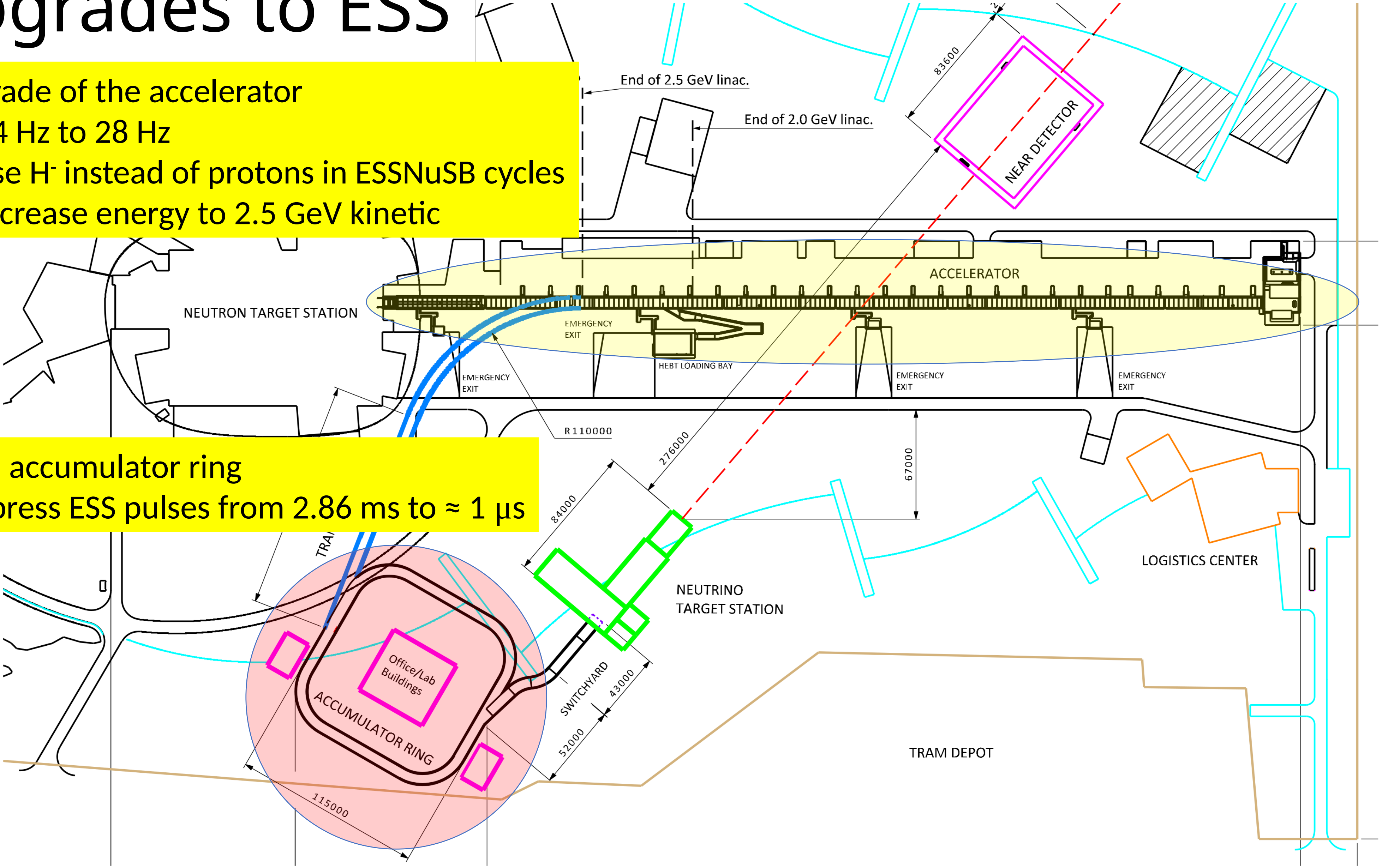
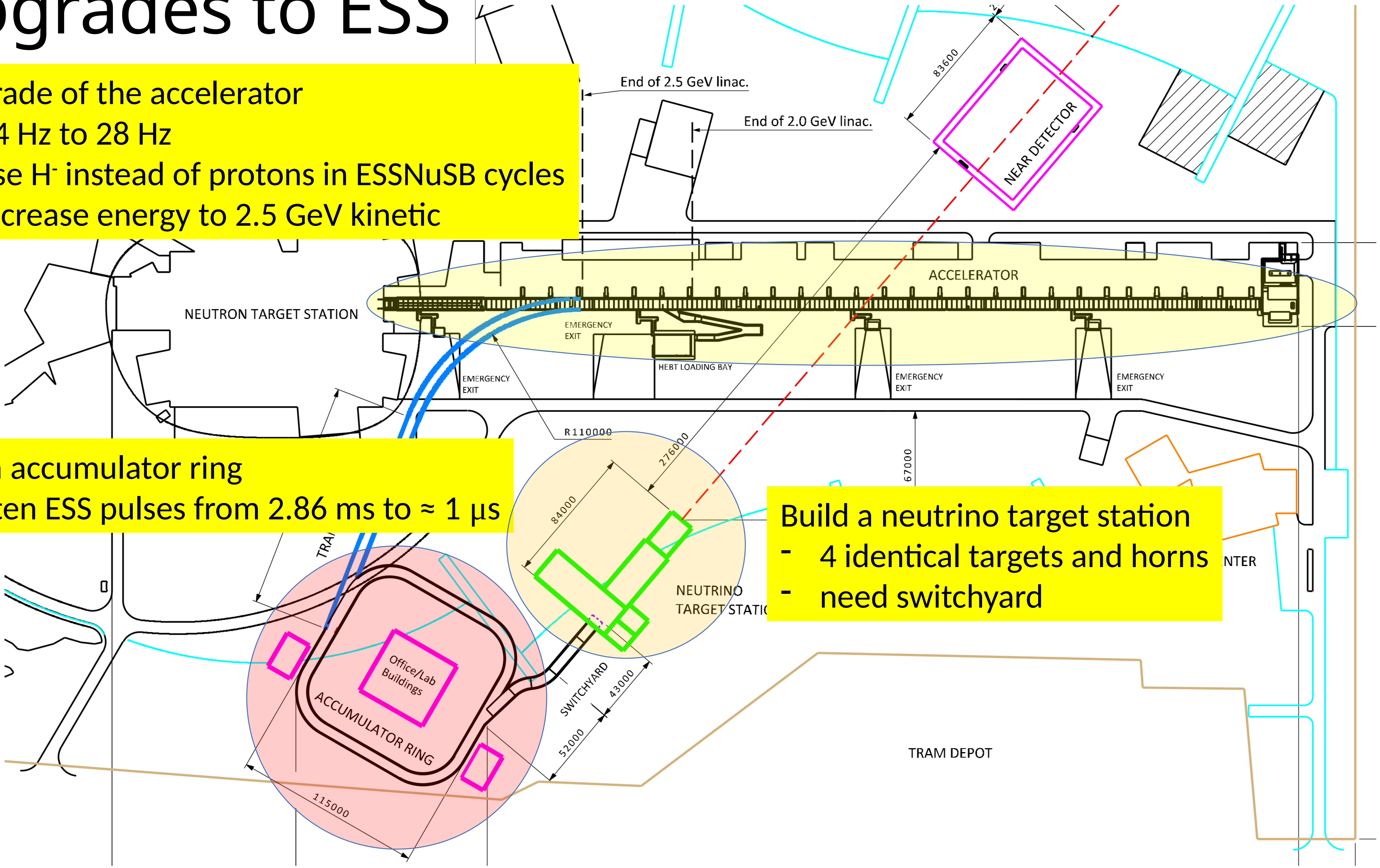
Build an accumulator ring

- compress ESS pulses from 2.86 ms to ≈ 1 µs



Upgrades to ESS



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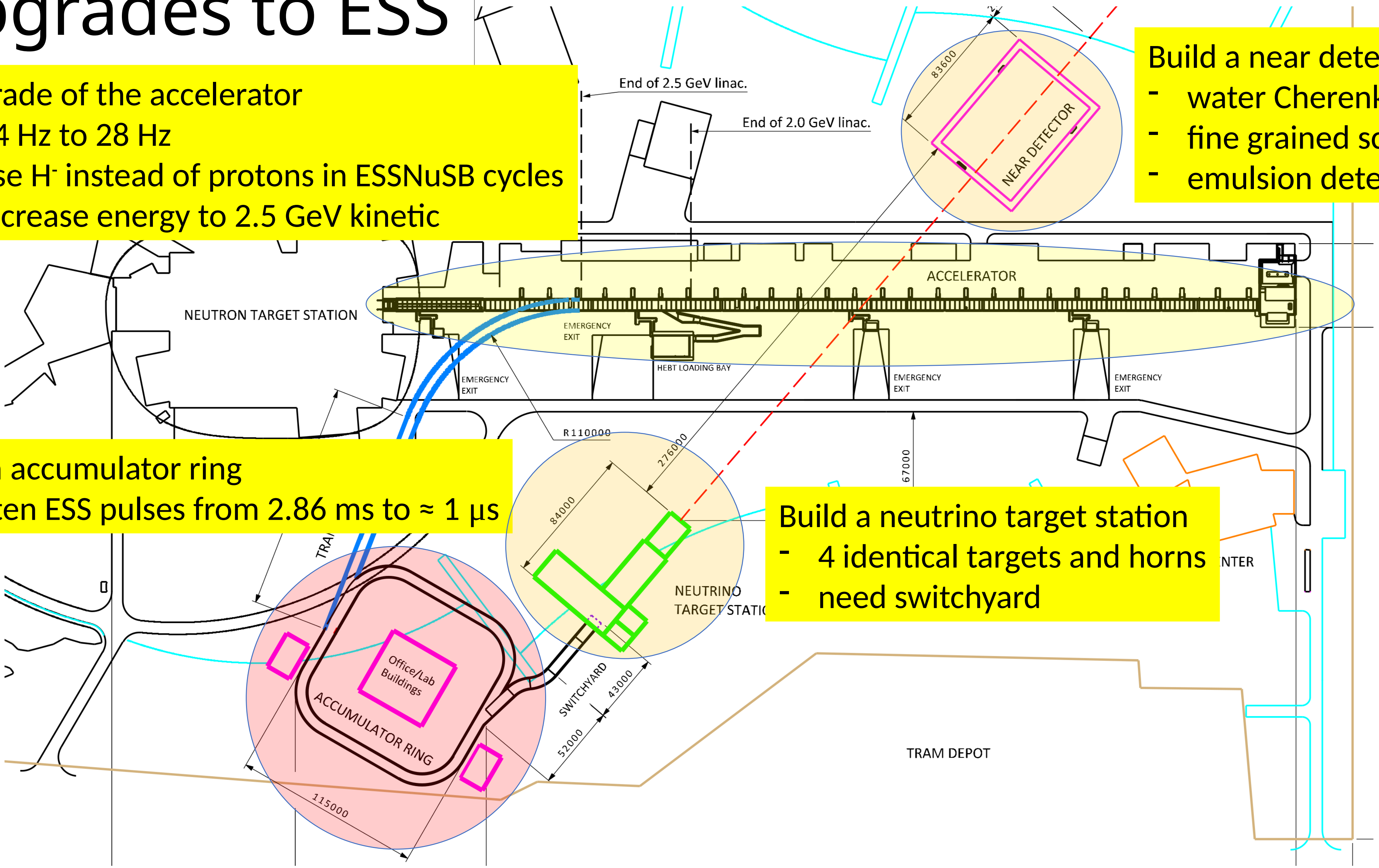
Build an accumulator ring

- shorten ESS pulses from 2.86 ms to ≈ 1 µs

Build a neutrino target station

- 4 identical targets and horns
- need switchyard

Upgrades to ESS



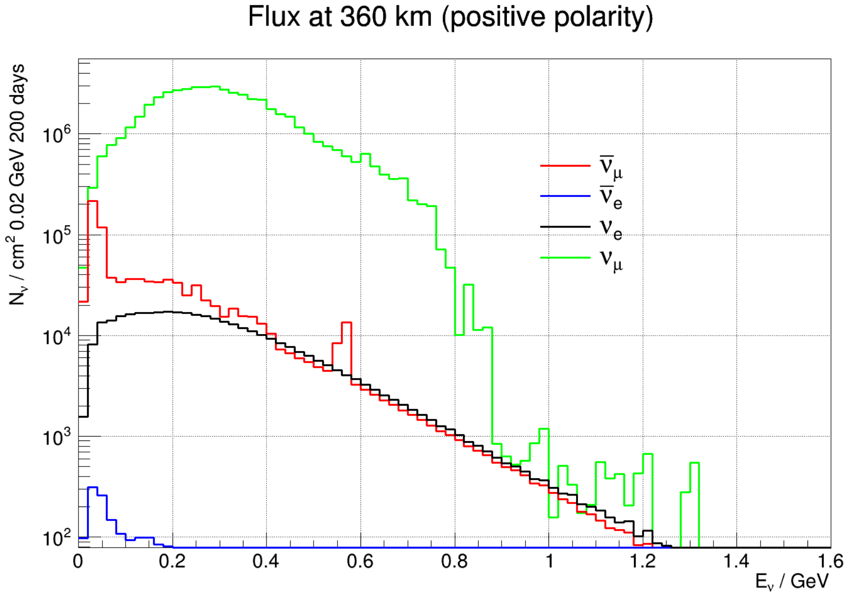
Upgrade of the accelerator
- 14 Hz to 28 Hz
- use H^- instead of protons in ESSNuSB cycles
- increase energy to 2.5 GeV kinetic

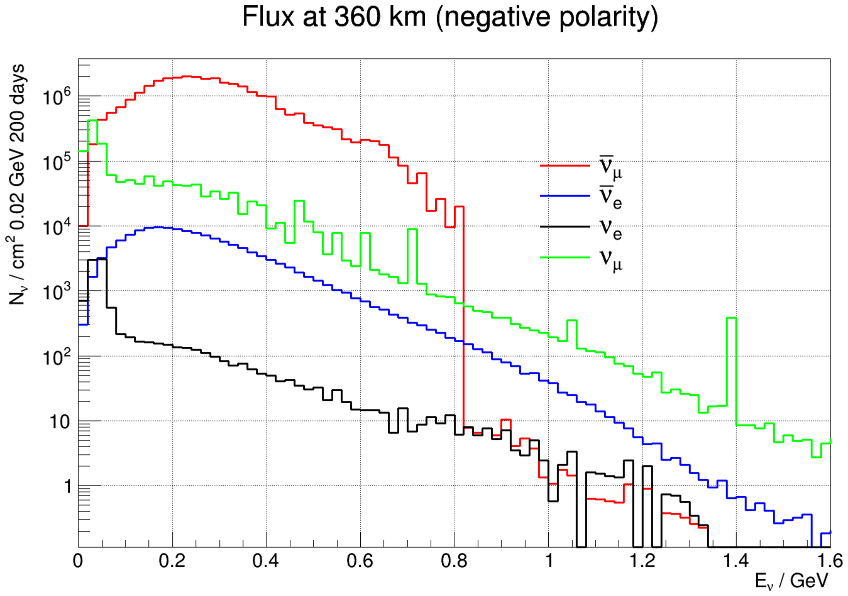
Build a near detector site
- water Cherenkov detector
- fine grained scintillator
- emulsion detector

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

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

ESSνSB ν energy distribution
(after optimisation)


Flux at 360 km (positive polarity)

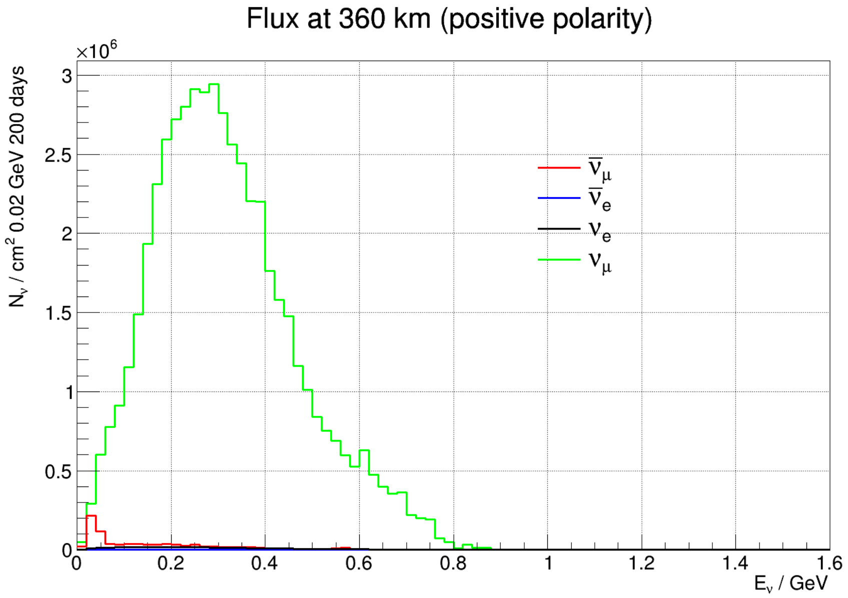

Flux at 360 km (negative polarity)

- 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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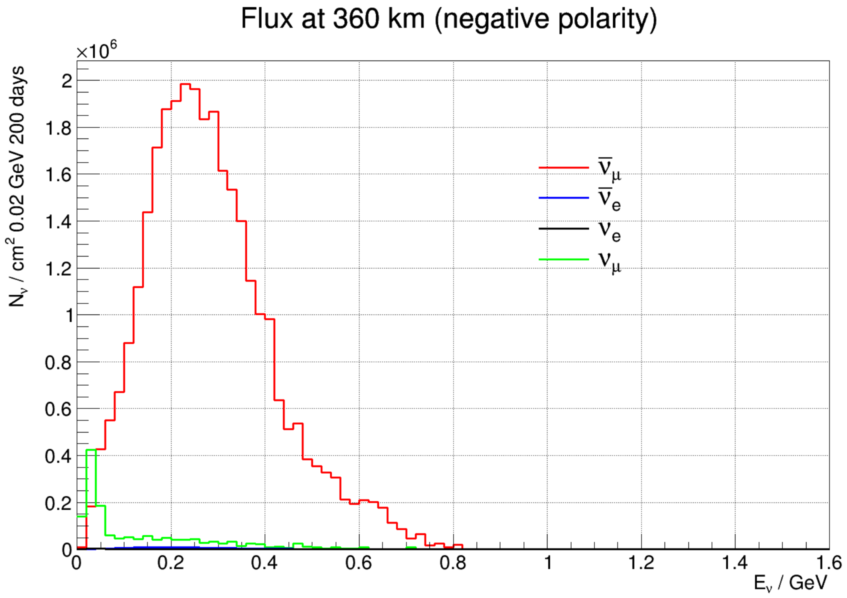
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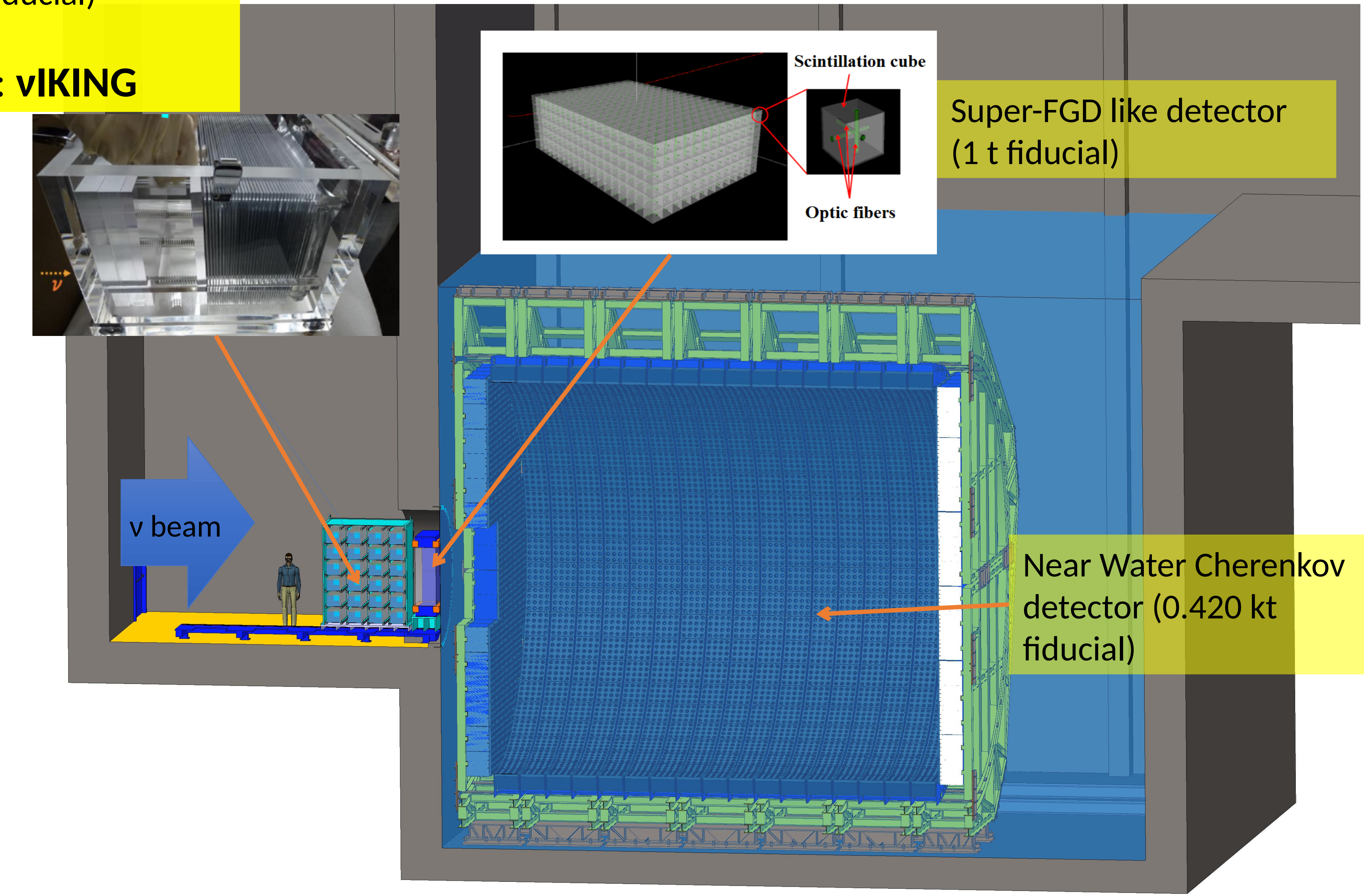
Near detectors



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

Code name: **νIKING**

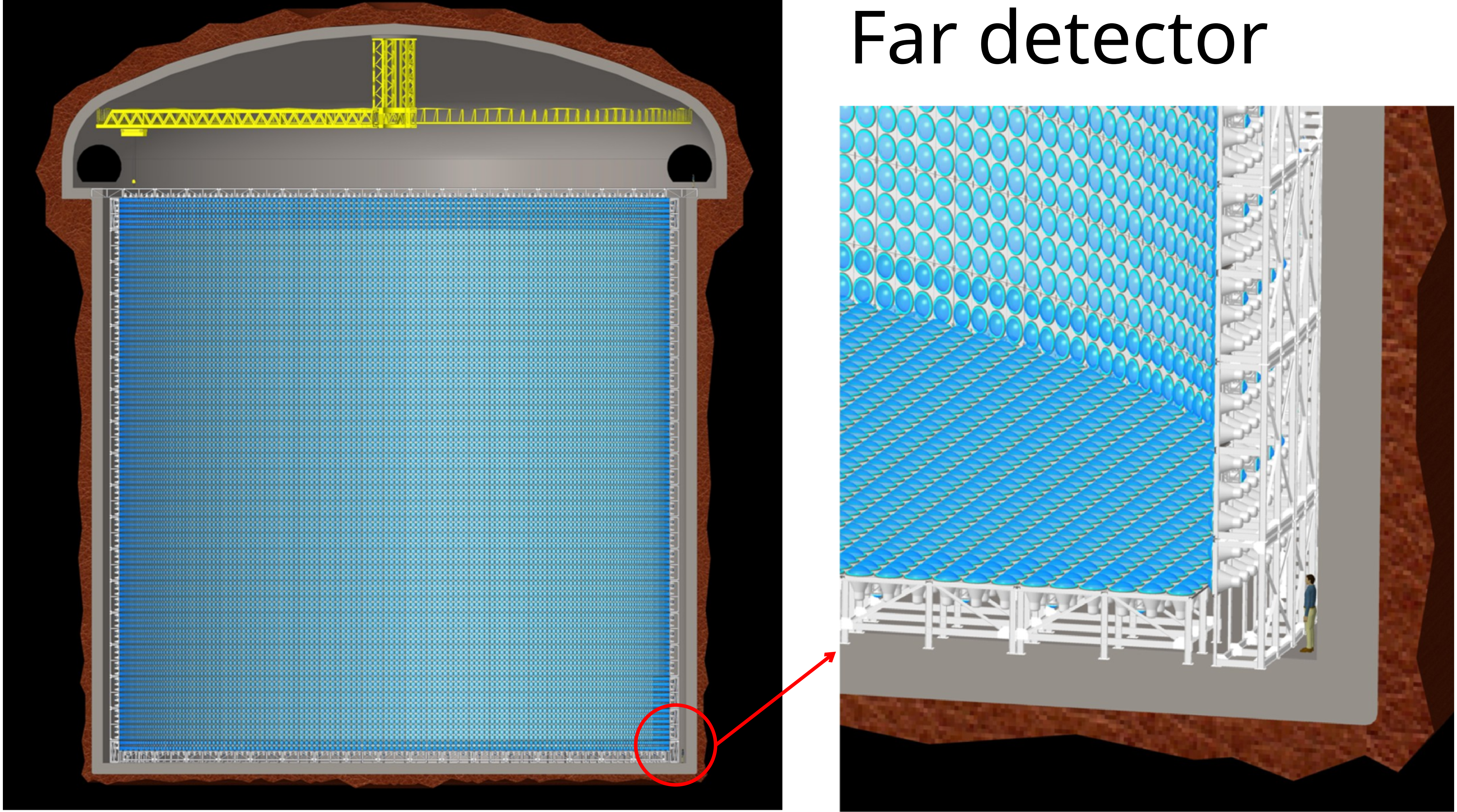
Super-FGD like detector (1 t fiducial)

Near Water Cherenkov detector (0.420 kt fiducial)

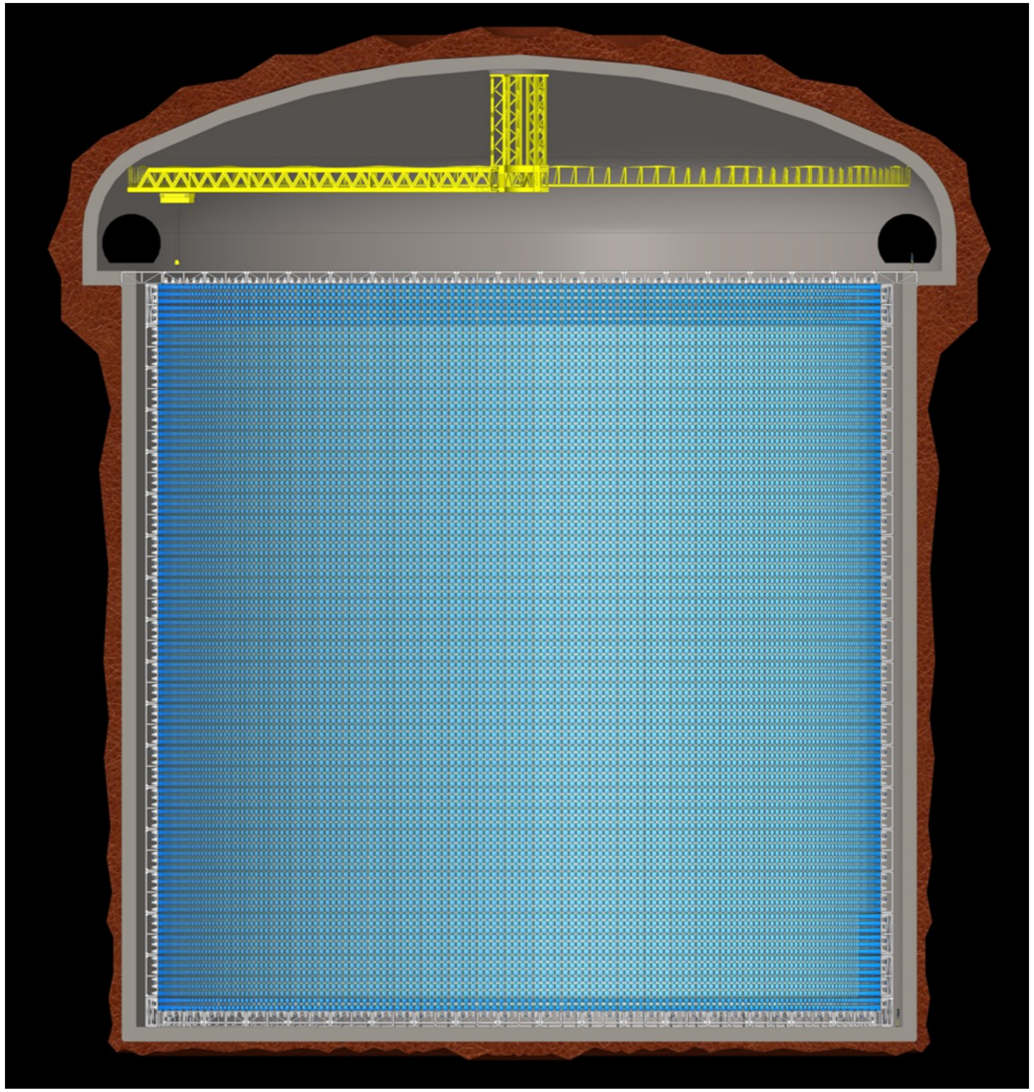
ESSnuSB neutrino baseline

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

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 number of events at FD

Events per 1 y of operation (200 days)

Neutrino mode

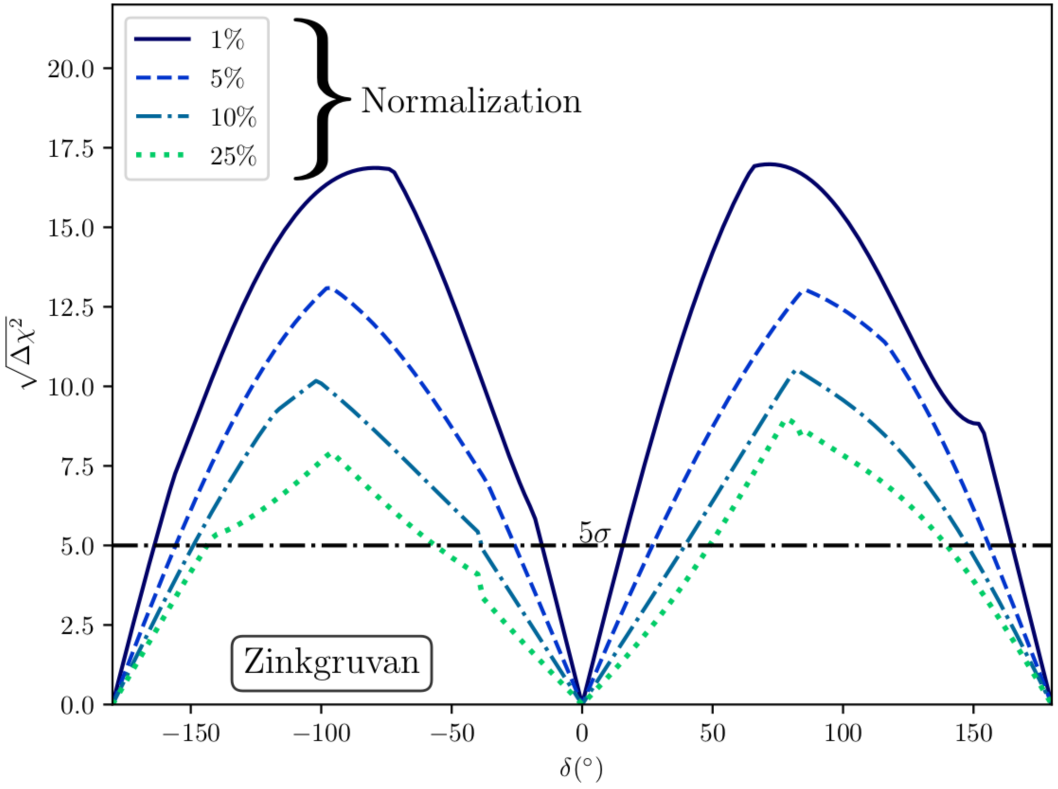
Channel	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = -\pi/2$
$\nu_\mu \rightarrow \nu_\mu$	10 509	10 431	10 430
$\nu_\mu \rightarrow \nu_e$	768	543	1 159
$\nu_e \rightarrow \nu_e$	178	178	178

Antineutrino mode

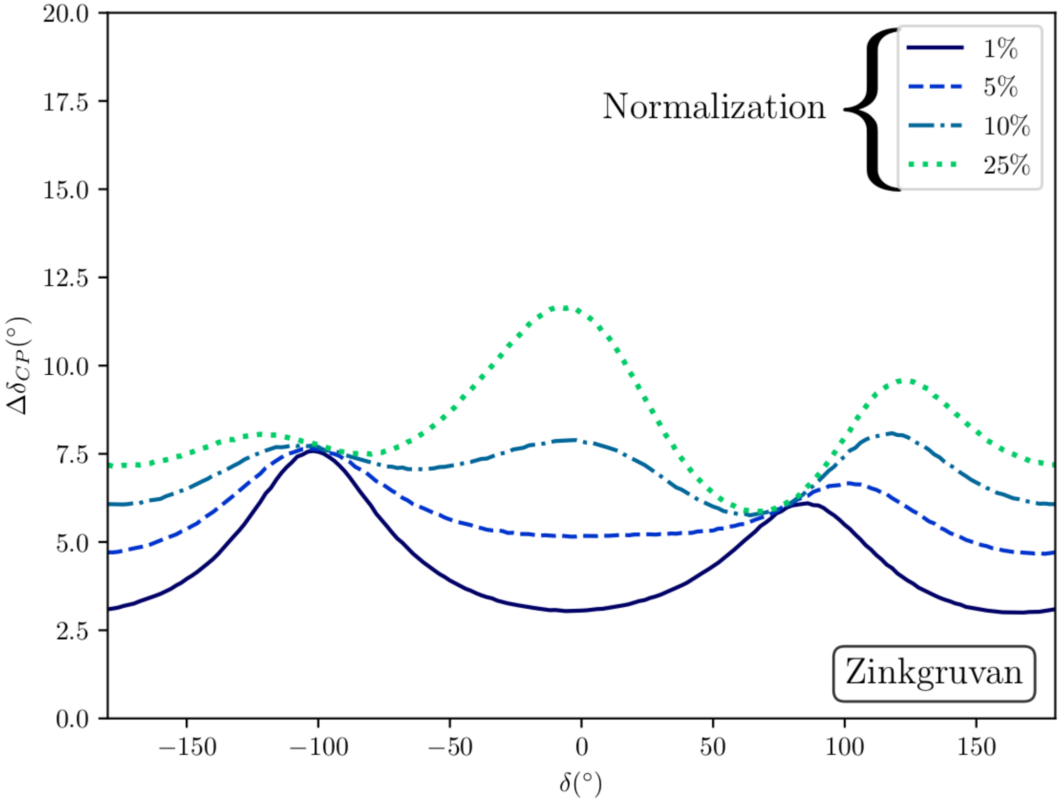
Channel	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = -\pi/2$
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	1 898	1 899	1 899
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	116	164	57
$\bar{\nu}_e \rightarrow \bar{\nu}_e$	18	18	18

Discovery potential and precision

Sensitivity



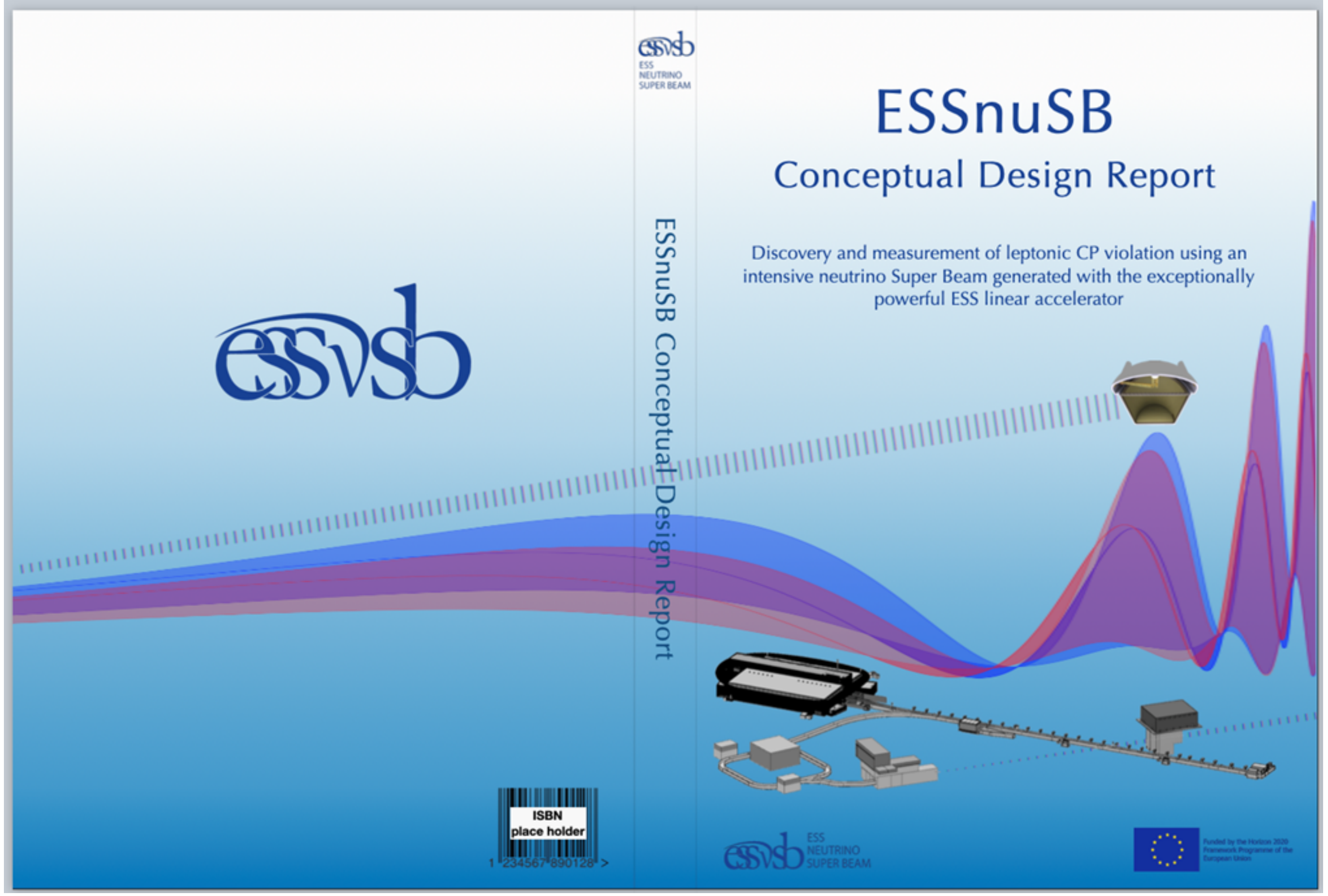
Precision



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

ESSnuSB conceptual design report

- Most up to date evaluation of the CPV discovery potential



ESS NEUTRINO SUPER BEAM

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
1 234567 890128 >

ESS NEUTRINO SUPER BEAM

Funded by the Horizon 2020 Framework Programme of the European Union

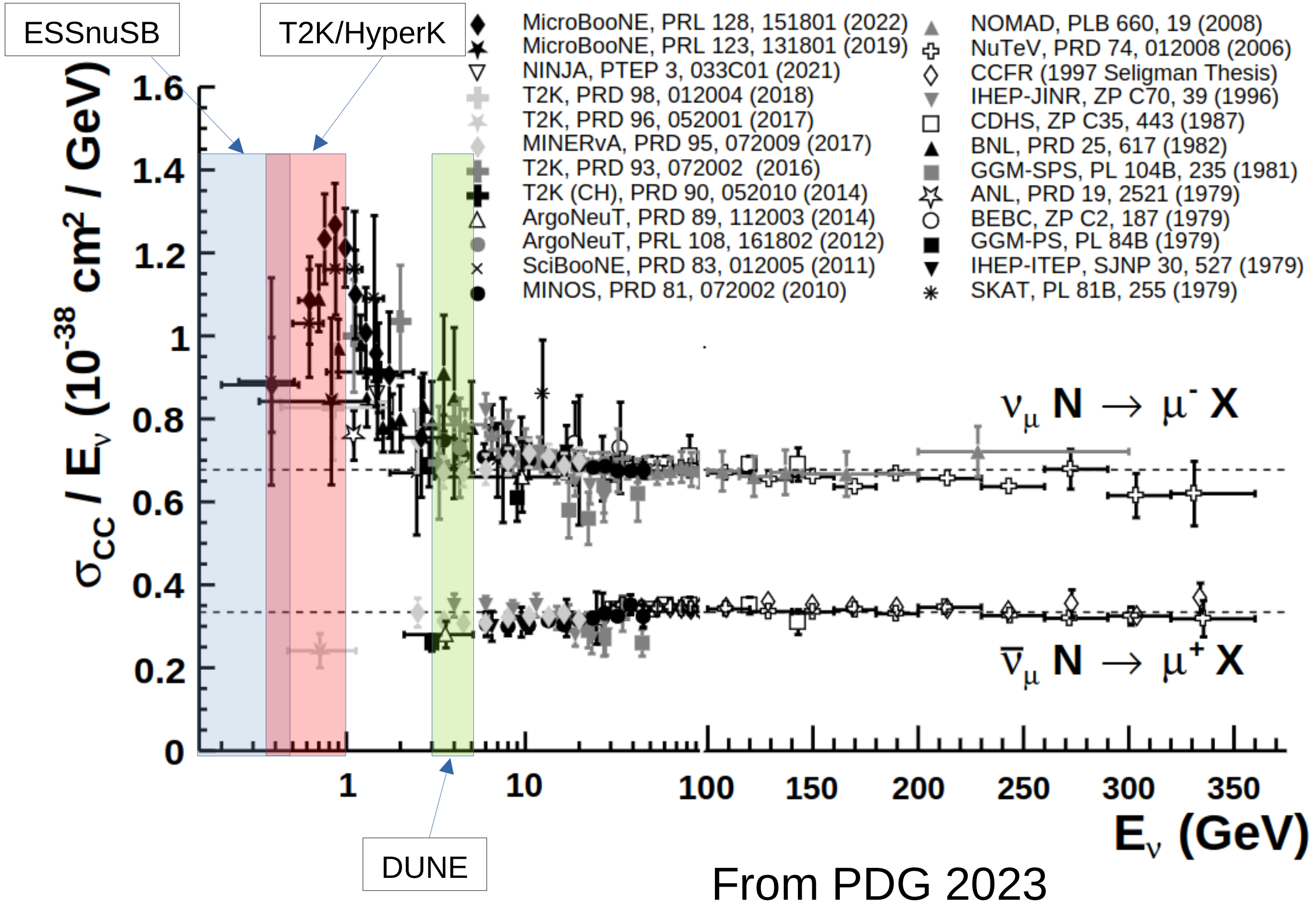
Alekou, A., Baussan, E., Bhattacharyya, A.K. et al. “The European Spallation Source neutrino super-beam conceptual design report”. Eur. Phys. J. Spec. Top. (2022). https://doi.org/10.1140/epjs/s11734-022-00664-w
arXiv: https://arxiv.org/abs/2203.08803 (includes costing)

The ESSnuSB+ project

- Continuation of the ESSnuSB
- Goals:
    - **Neutrino interaction cross-section measurement**
    - Extra physics
    - Civil engineering

Neutrino interaction cross-sections

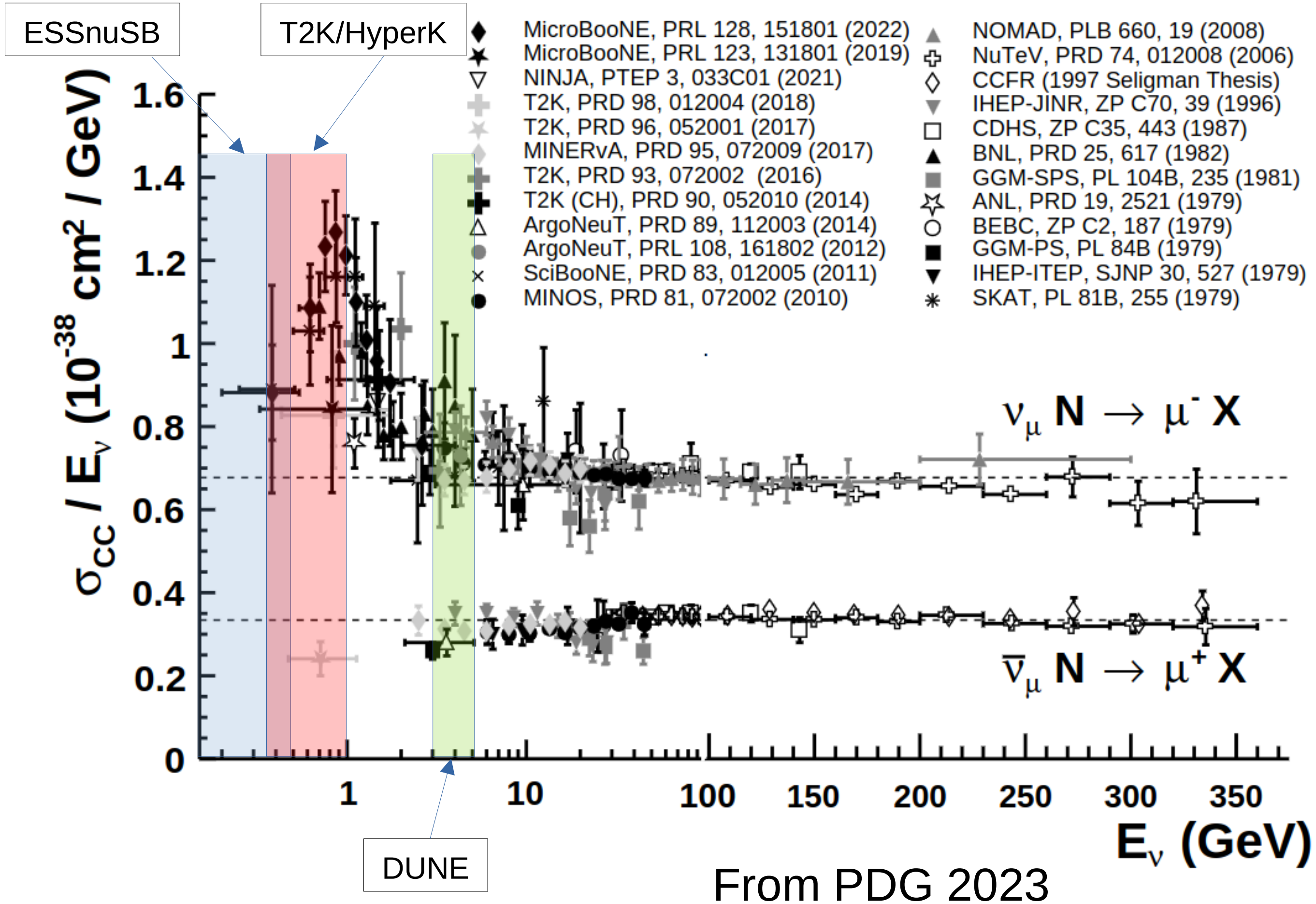
- Inclusive CC xsec for ν_μ per nucleon



From PDG 2023

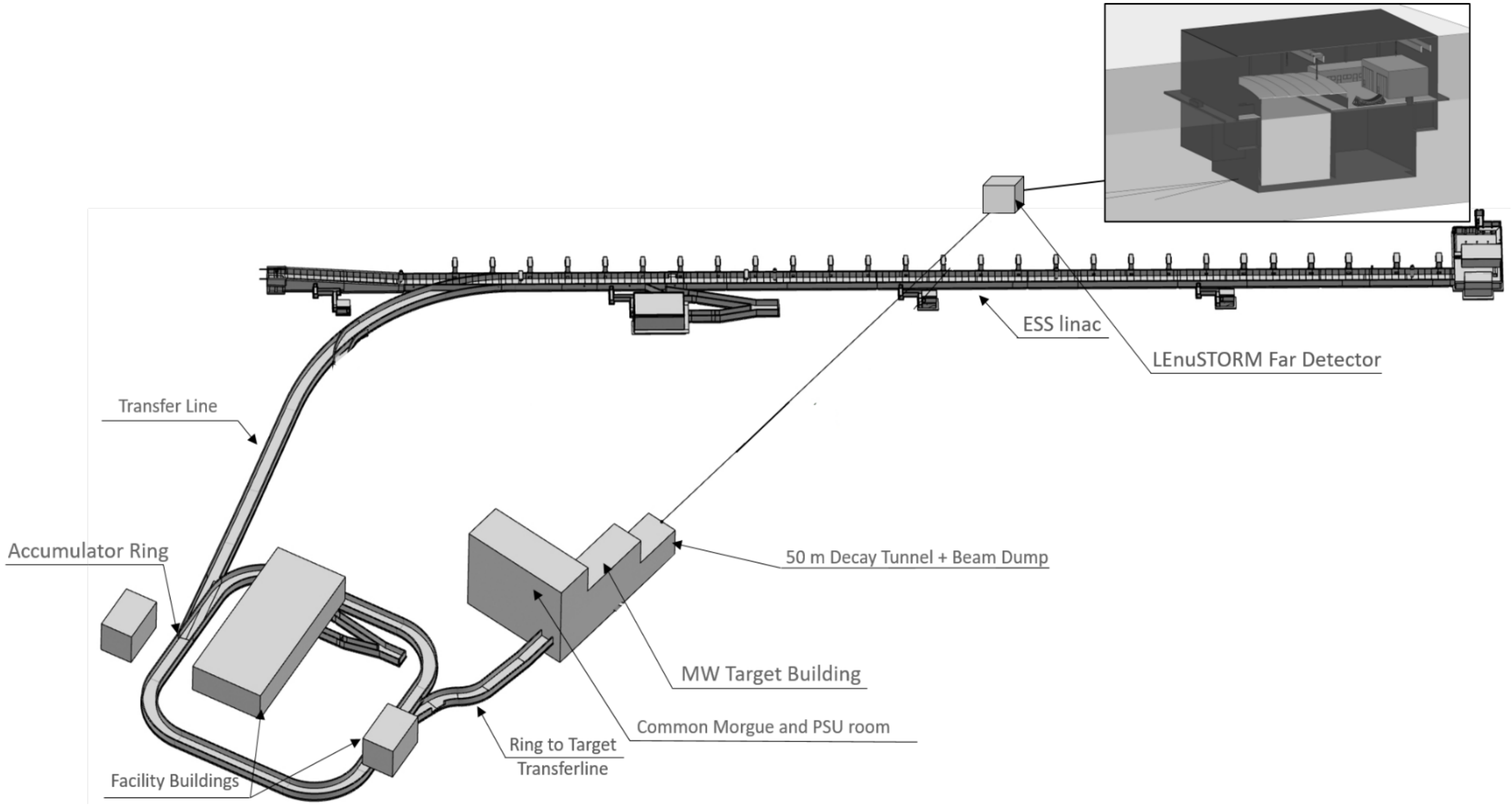
Neutrino interaction cross-sections

- Inclusive CC xsec for ν_μ per nucleon
    - don't you need ν_e?
    - proton or neutron?
    - nuclear effects, final state interactions, …?
- We need to measure ν xsec for each nucleus (target) separately



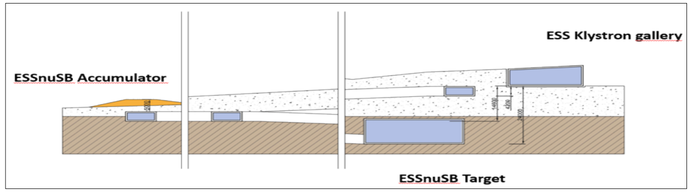
From PDG 2023

ESS Upgrades to Host the ESSnuSB+

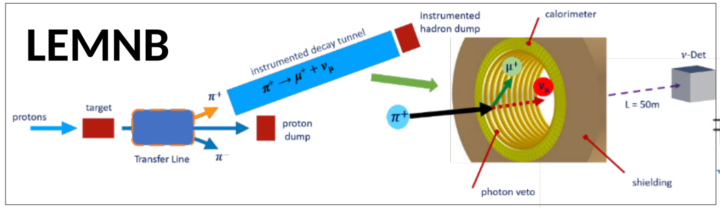


ESS Upgrades to Host the ESSnuSB+

Civil engineering

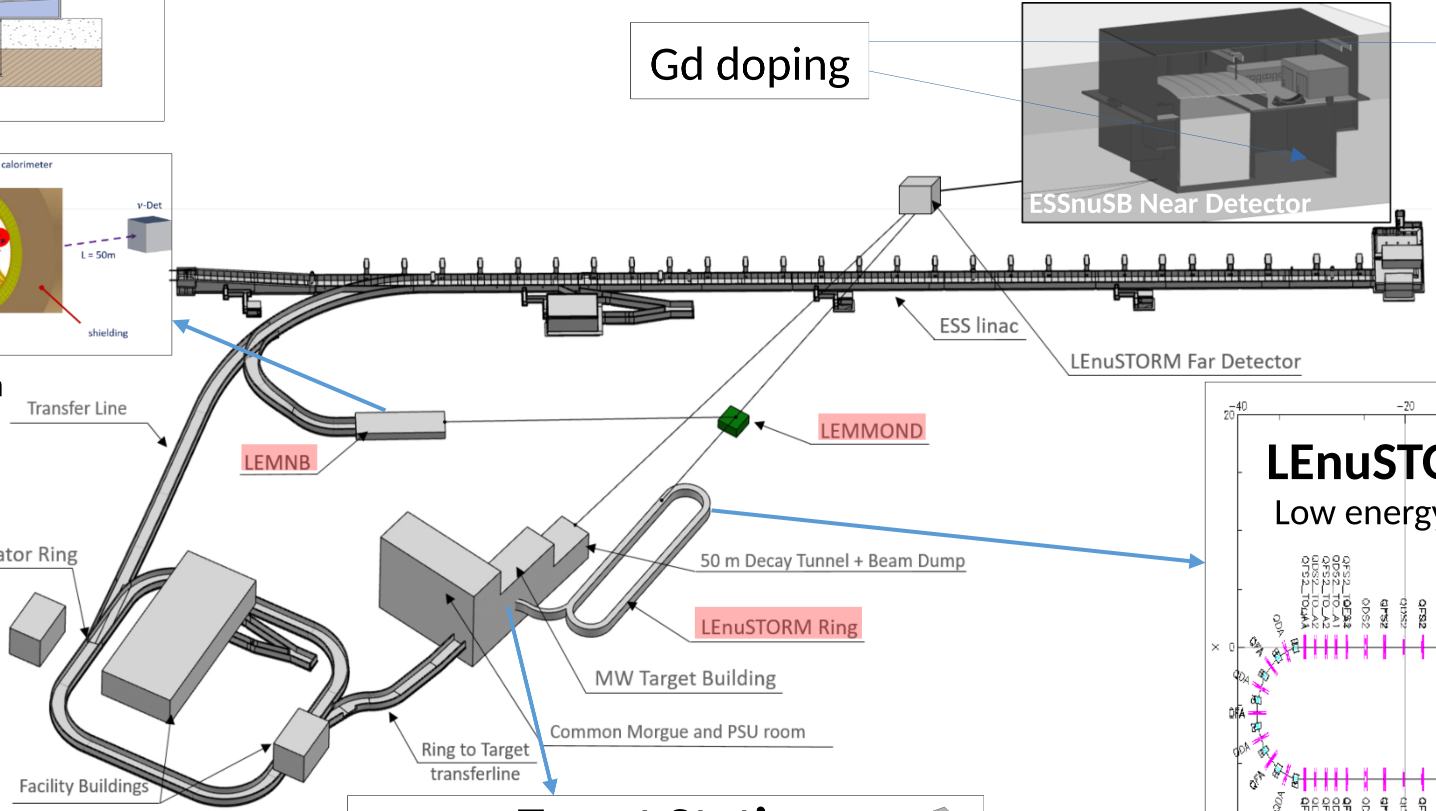


LEMNB

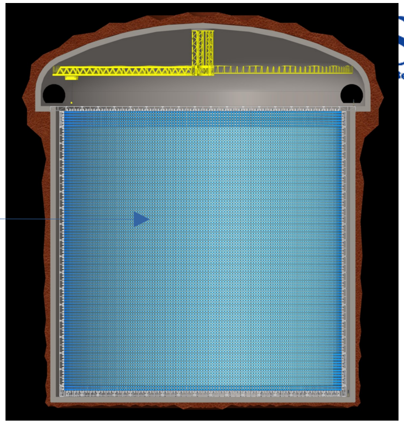


Low Energy Monitored neutrino Beam

ENUBET



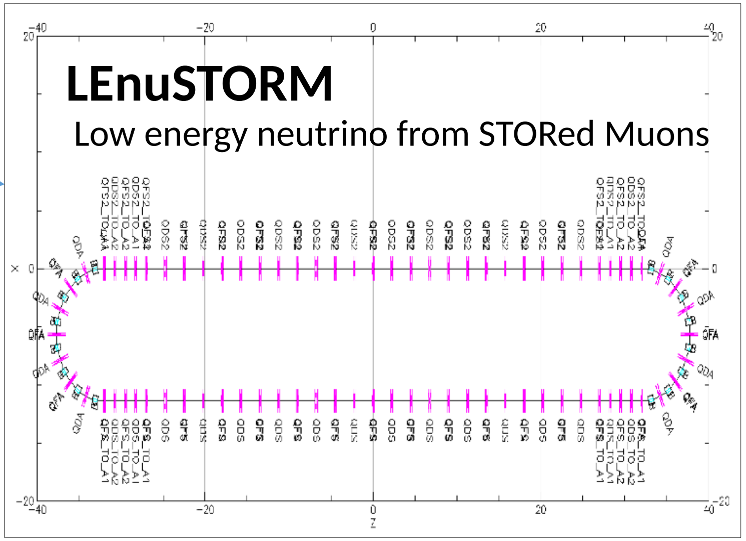
Gd doping

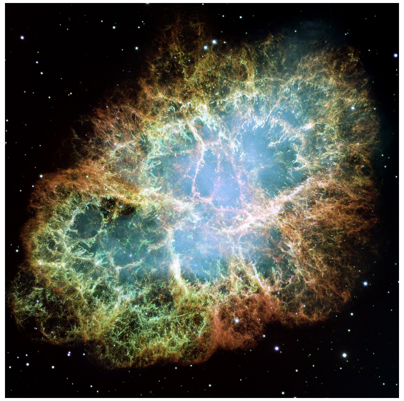


Mining

LEnuSTORM

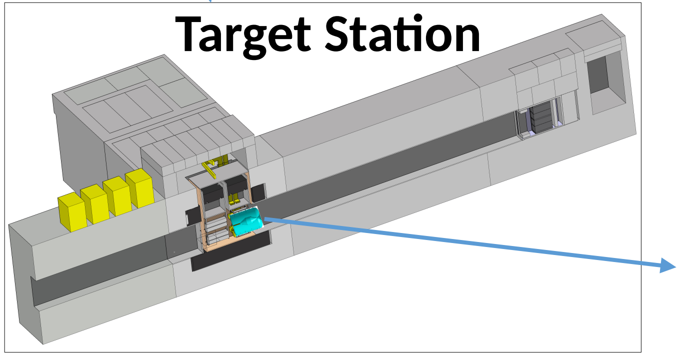
Low energy neutrino from STORed Muons



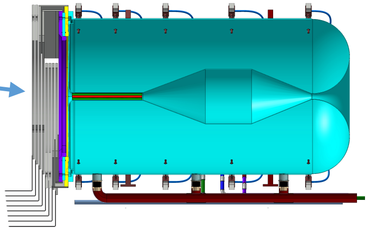


Additional physics

Target Station



One horn-target system



Timeline

θ_{13} measurement

Nobel prize: T. Kajita & A. McDonald

2015

2008-2012: EUROνDesign Study (FP7)

2012: inception of the ESSnuSB project

Nucl. Phys. B 885 (2014) 127

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

ESS NEUTRINO SUPER BEAM

2016-2020: COST Action EuroNuNet

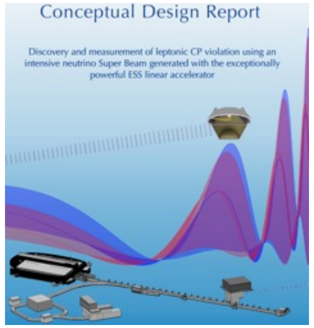
2018-2022: ESSνSB Design Study, CDR (EU-H2020)

ESS neutrino Super Beam plus

ESFRI

EUROPEAN SPALLATION SOURCE

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

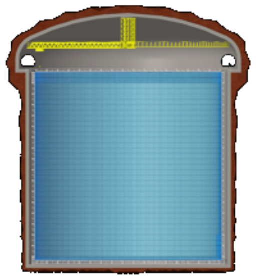


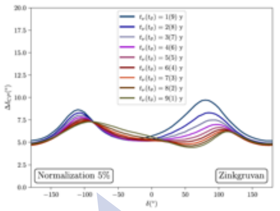
Conceptual Design Report

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

ESSνSB CDR

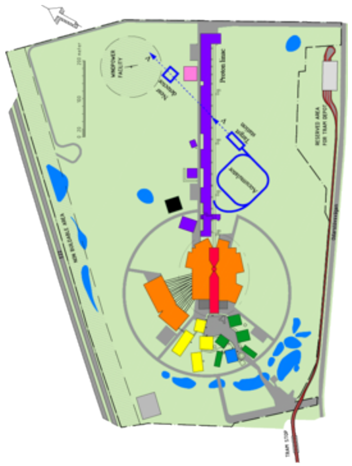
2026-2028: TDR Phase, International Agreement





Data taking

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



ESS neutrino Super Beam plus

13 countries
23 Institutes

Co-funded by the European Union

Horizon-2020 (2018 - 2022), 3 M€
Horizon-Europe (2023 - 2026), 3 M€

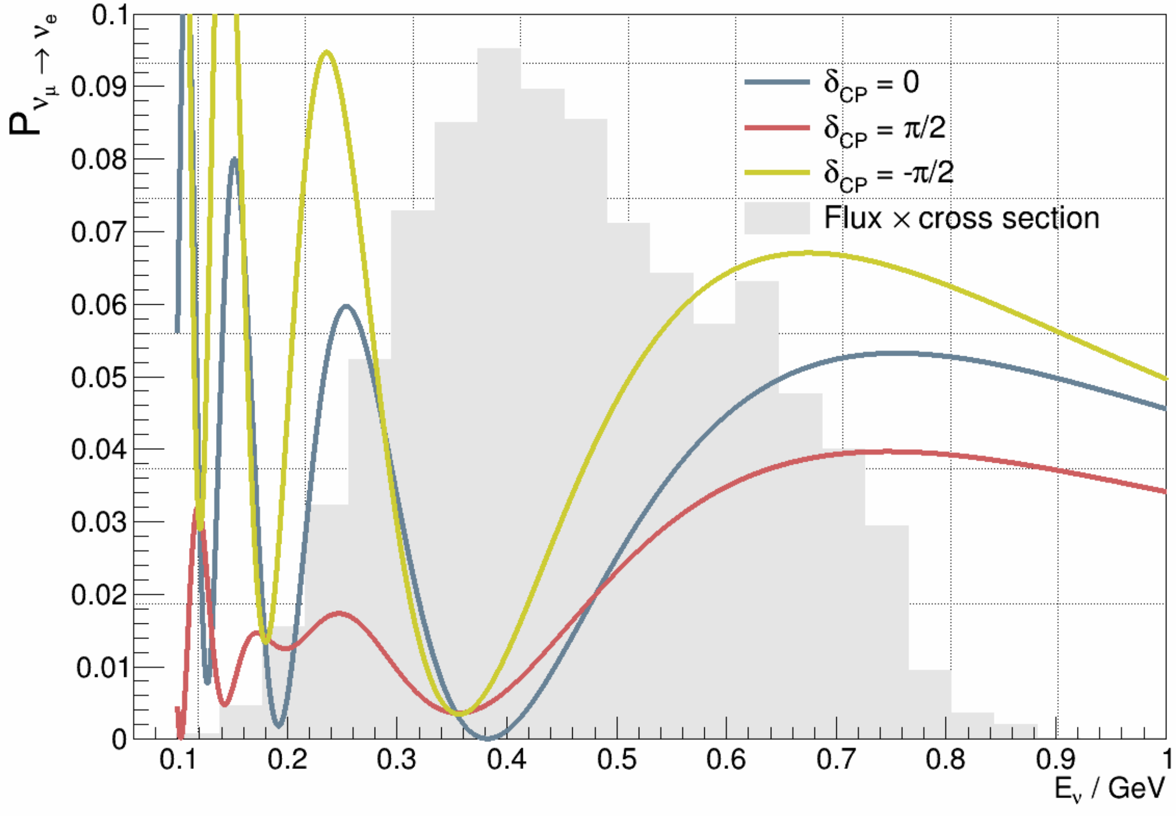
Universiteit Gent
Università degli Studi di Milano Bicocca
CERN
Luleå University of Technology
ESS
Université de Strasbourg
ESS Bilbao
Universität Hamburg
Roma Tre Università degli Studi
Università degli Studi di Padova
Aristotle University of Thessaloniki
Uppsala Universitet
Lunds Universitet
KTH Vetenskap och Konst
Nagoya University
Hellenic Open University
INFN Istituto Nazionale di Fisica Nucleare
CNRS
IPHC Institut Pluridisciplinaire Hubert Curien Strasbourg
AGH
RB

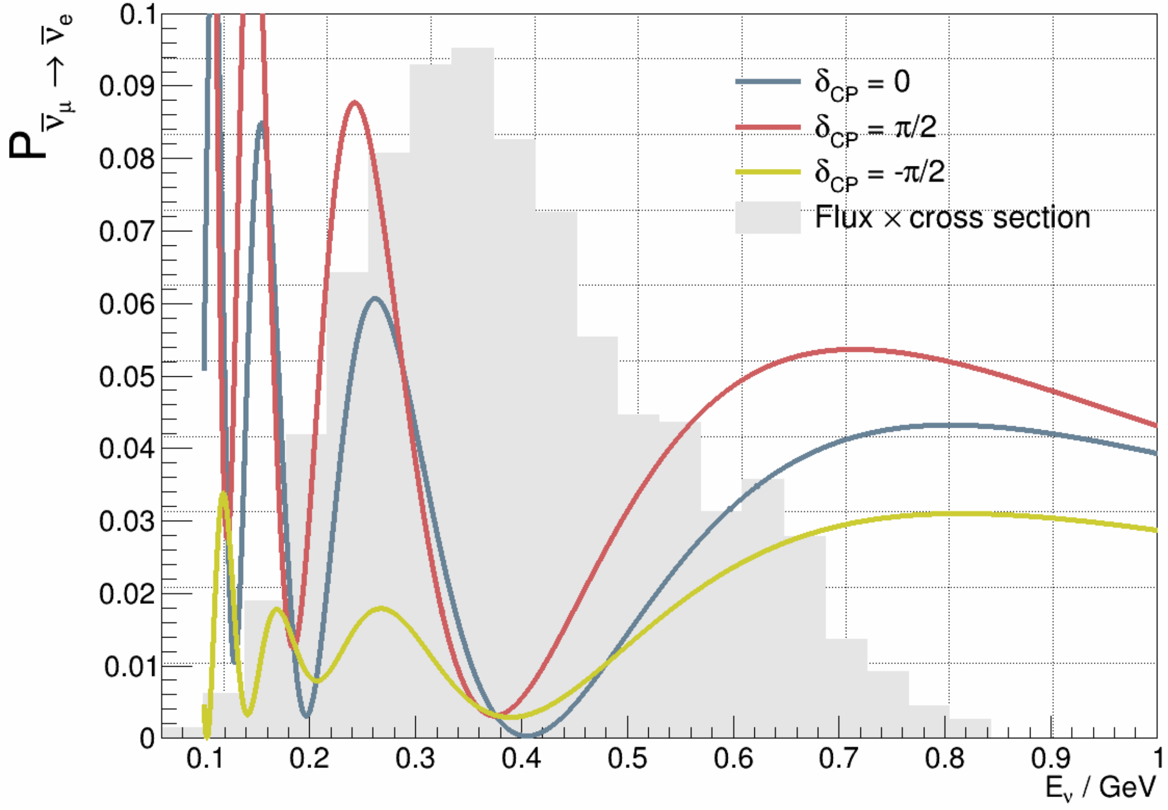
Conclusions

- ESSnuSB/ESSnuSB+ are design studies for a neutrino project in Europe
- Aim is to precisely measure the CP violation in the leptonic sector
- Uses the 5 MW ESS linear accelerator
- Estimated start of data taking around 2040

Thank you for your attention

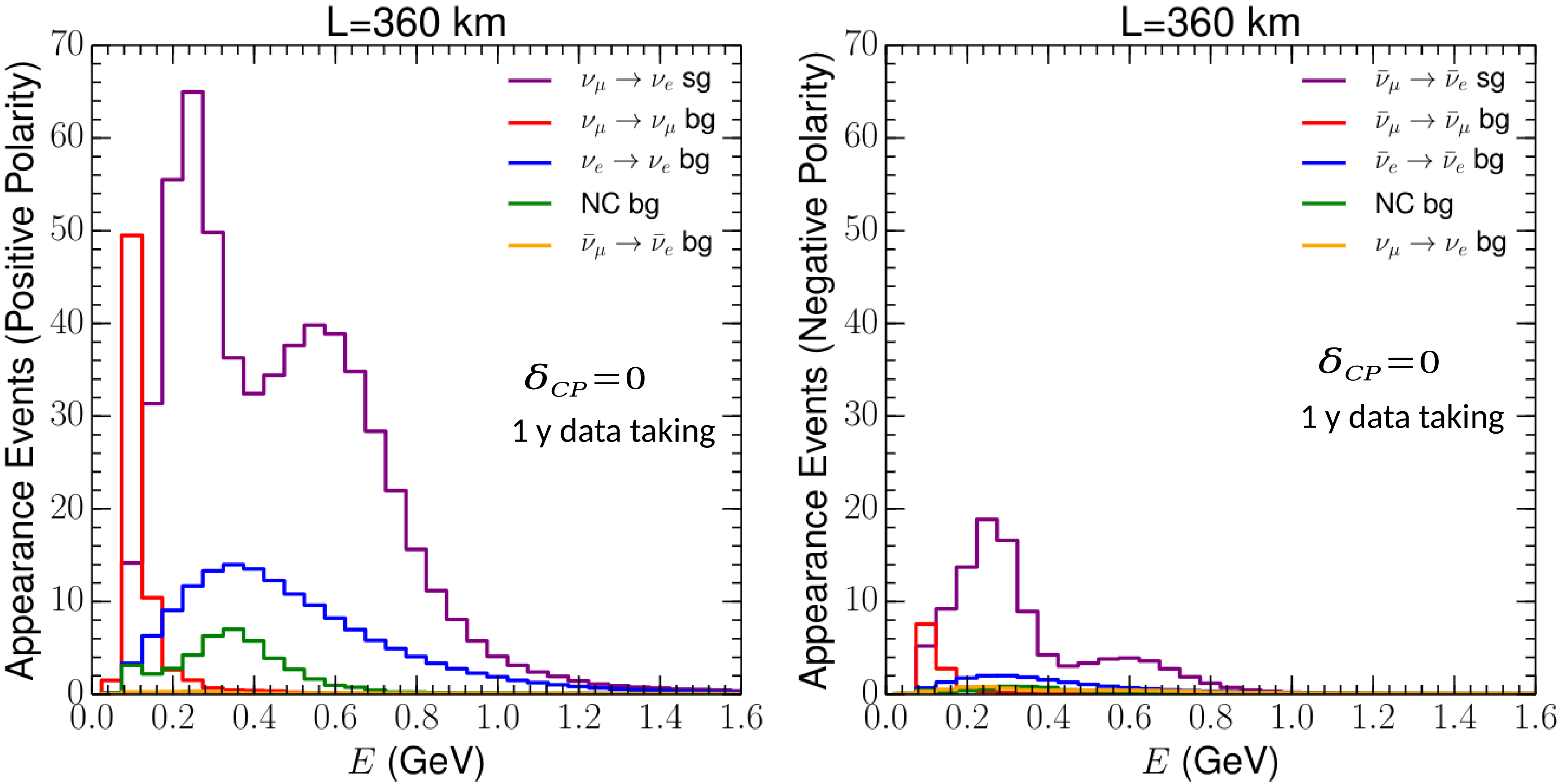
Oscillation coverage





Expected event spectra

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



$\delta_{CP} = 0$

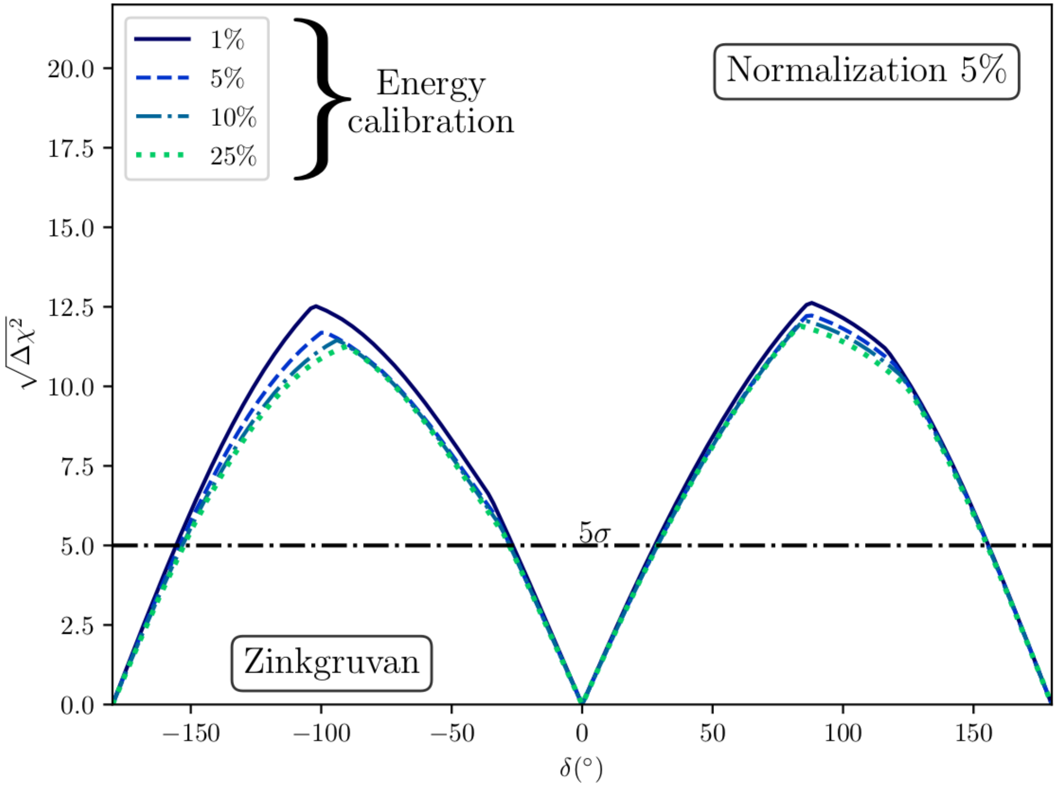
1 y data taking

$\delta_{CP} = 0$

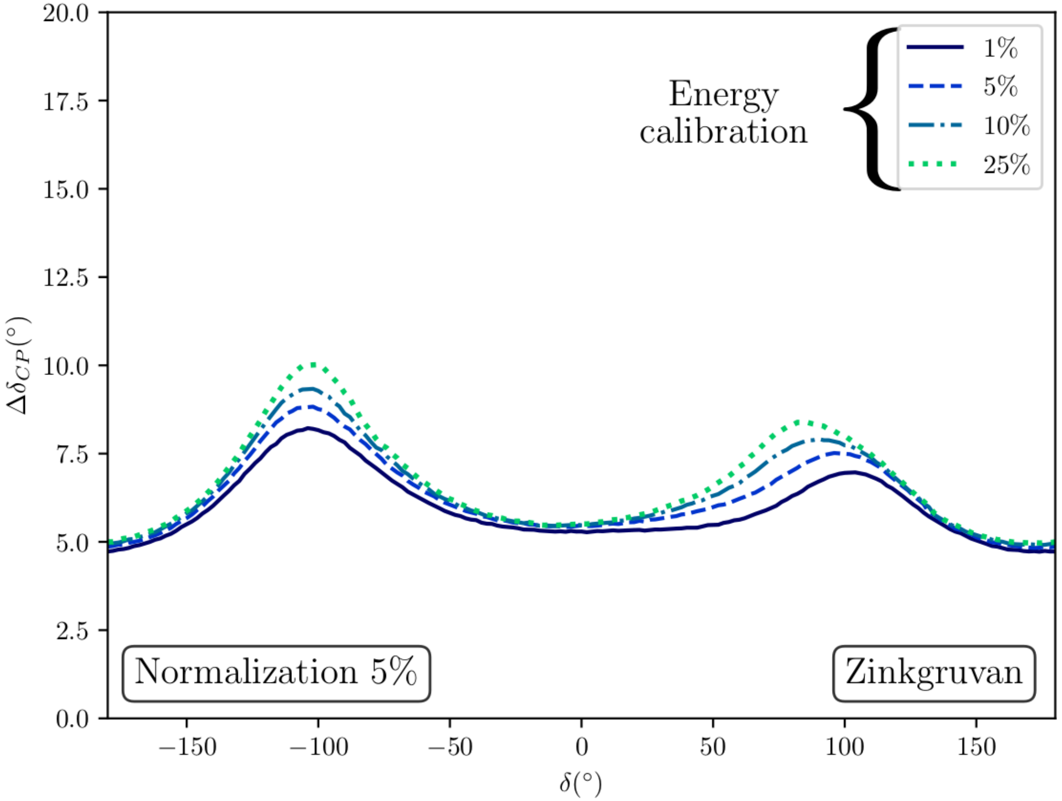
1 y data taking

Effect of energy calibration uncertainty on CPV measurements

Sensitivity



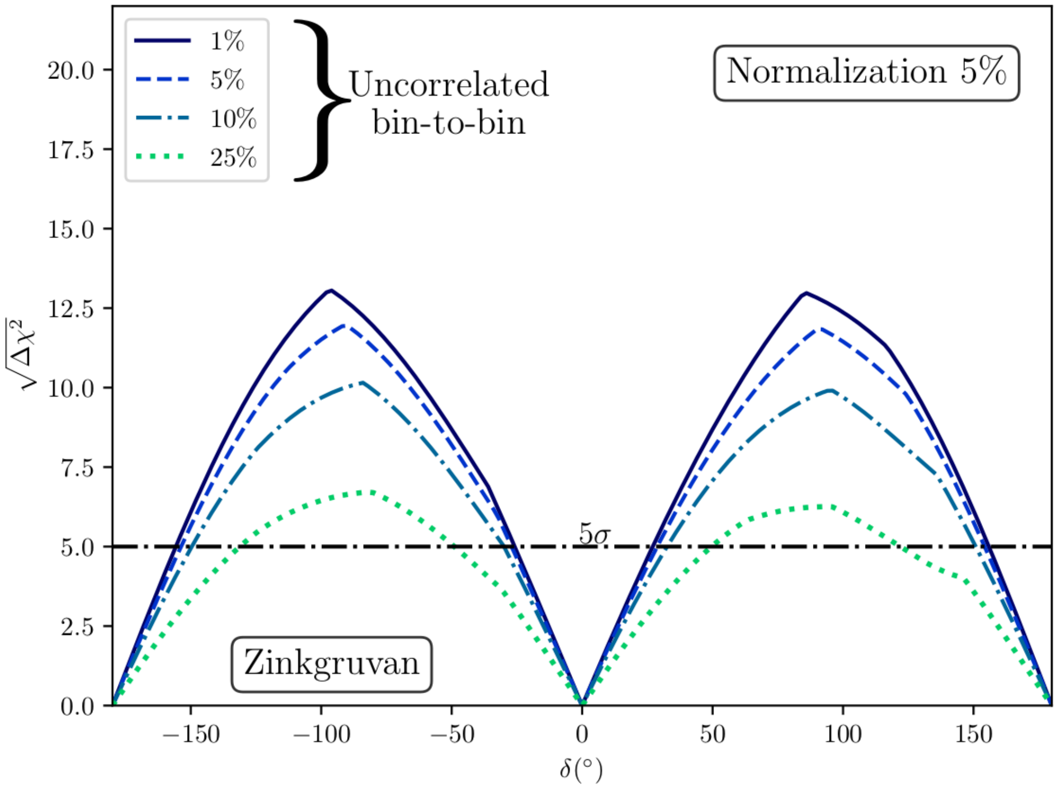
Precision



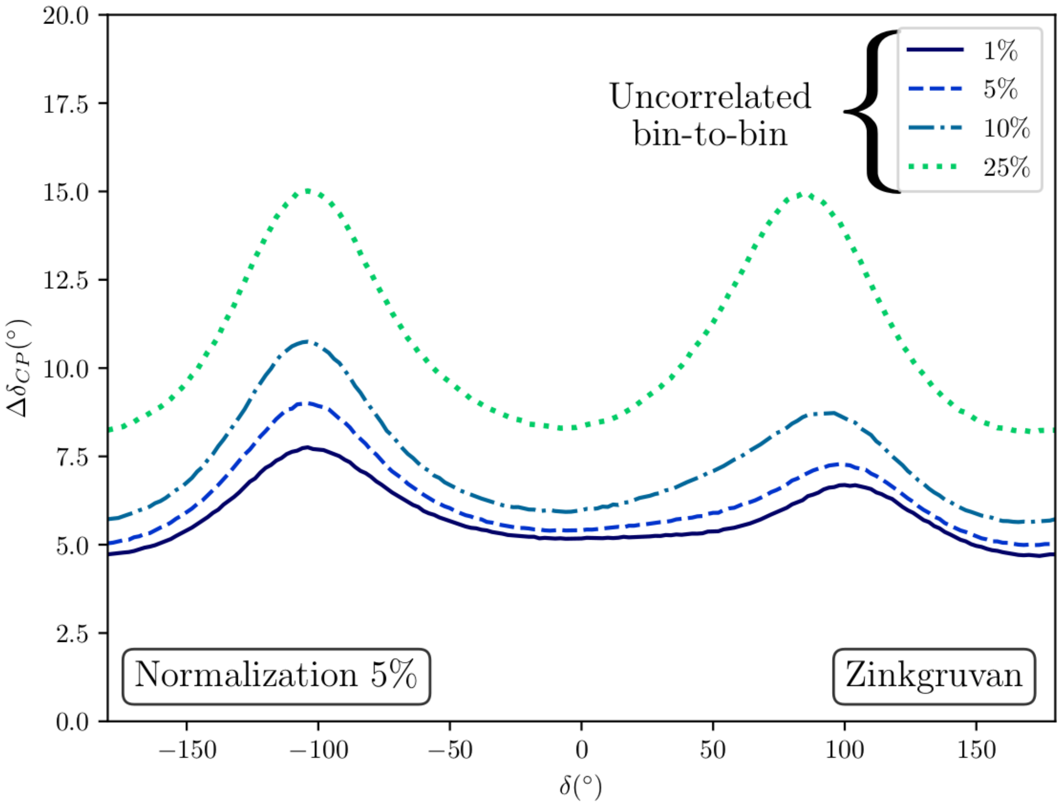
From the ESSnuSB CDR: https://doi.org/10.1140/epjs/s11734-022-00664-w & https://arxiv.org/abs/2203.08803

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

Sensitivity



Precision

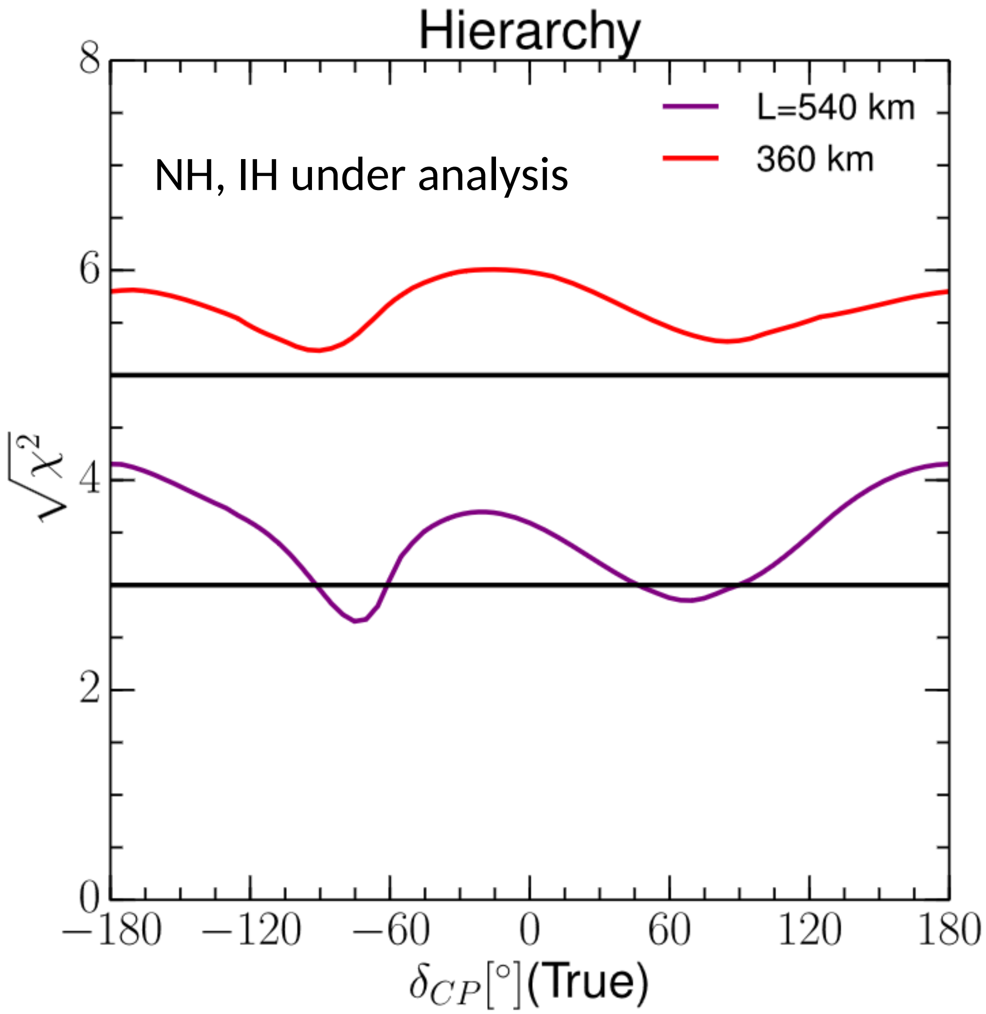


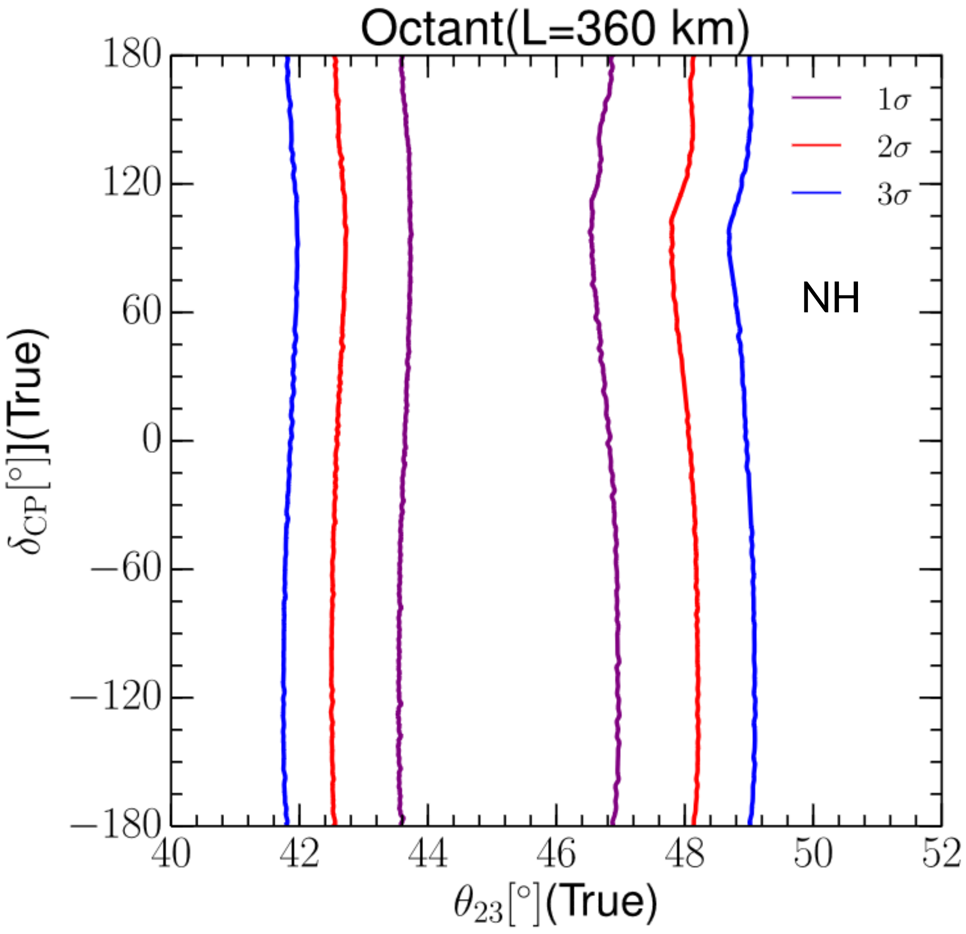
From the ESSnuSB CDR: https://doi.org/10.1140/epjs/s11734-022-00664-w & https://arxiv.org/abs/2203.08803

Hierarchy and octant determination

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

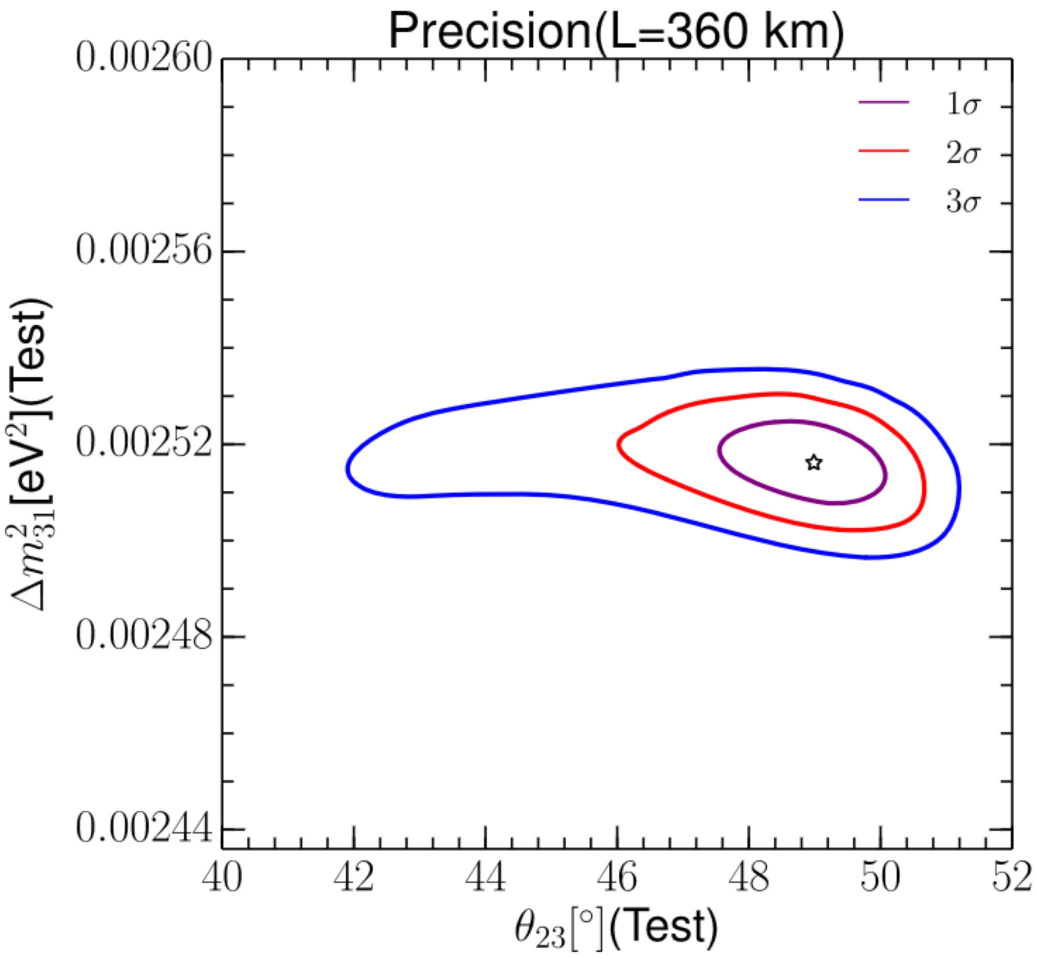
10 y of data taking





Precision for Δm_{31} vs θ_{23}

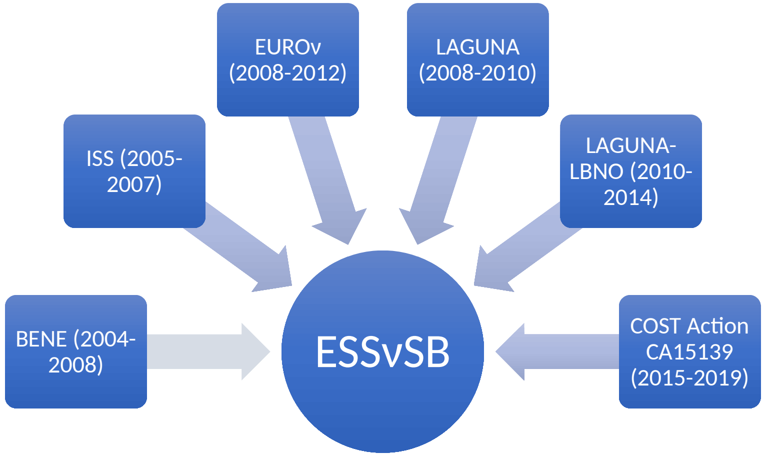
From: DOI:10.1140/epjc/s10052-021-09845-8, arXiv:2107.07585



- 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)

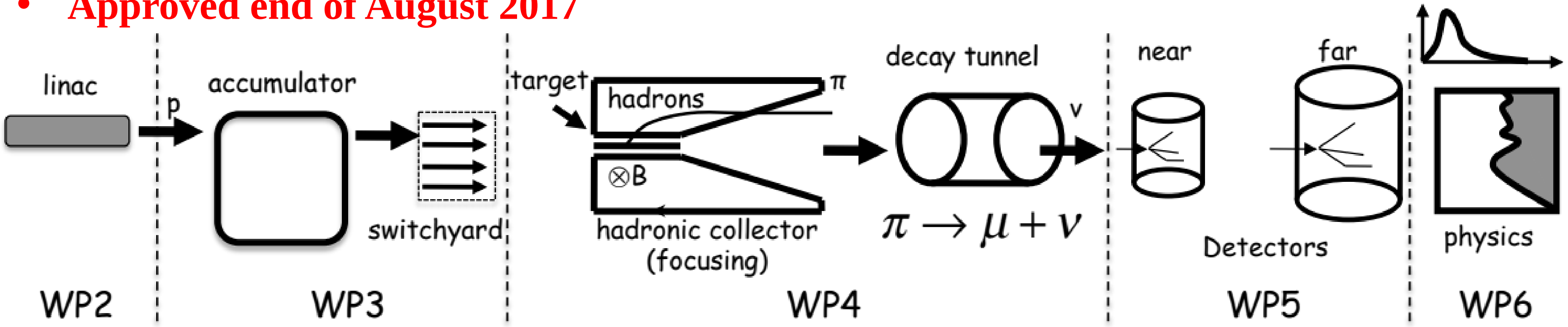
ISS (2005-2007)

LAGUNA-LBNO (2010-2014)

BENE (2004-2008)

ESSνSB

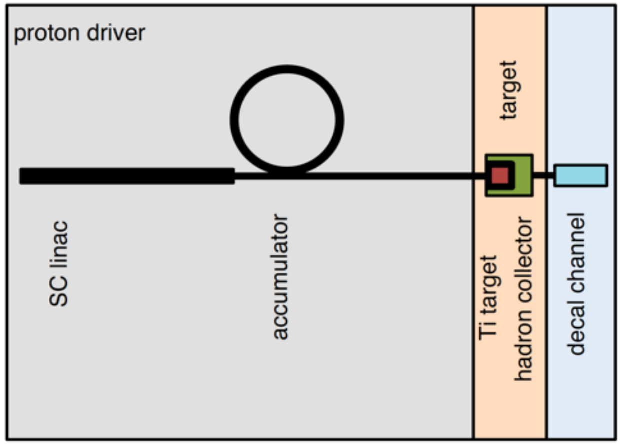
COST Action CA15139 (2015-2019)



ESSvSB and (R&D) synergies

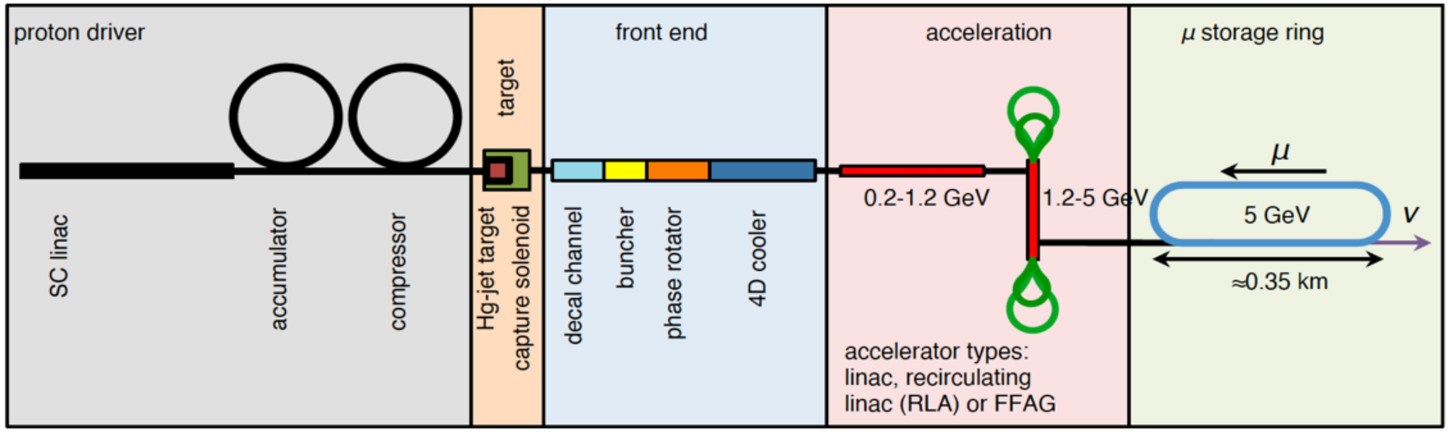
Dedicated series of workshops is organized
https://indico.cern.ch/event/849674/

Super Beam

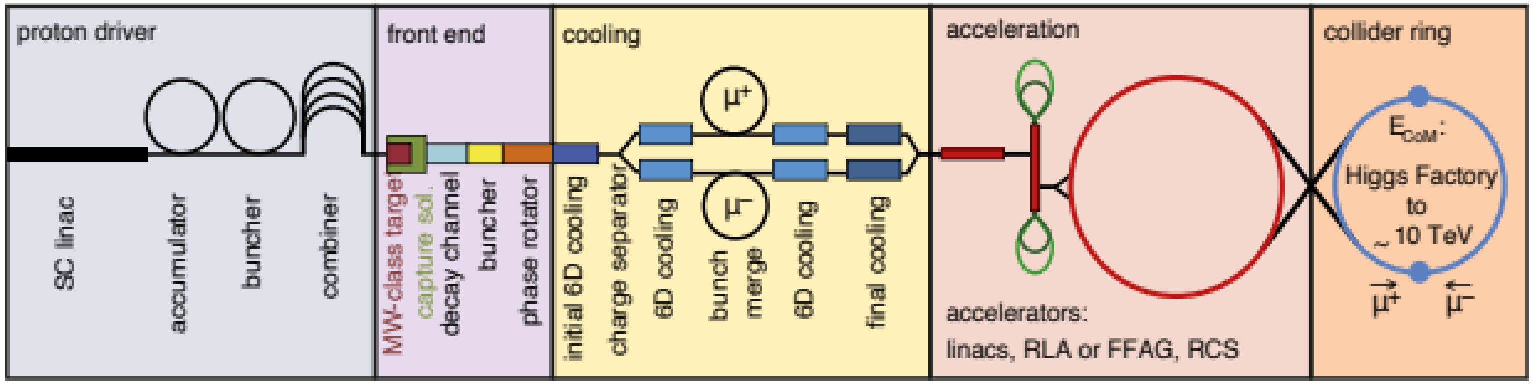


+Decay At Rest and Coherent scat.
(with short pulses)

Neutrino Factory



Muon Collider



Neutrino oscillations

Flavour state evolution

Relativistic space-time translation operator

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

Neutrino quantum state at distance *L* and after time *T*

Neutrino quantum state at creation

Free particle energy operator

Free particle momentum operator

For mass eigenstates:

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

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

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

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$

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

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

Hot Cell

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

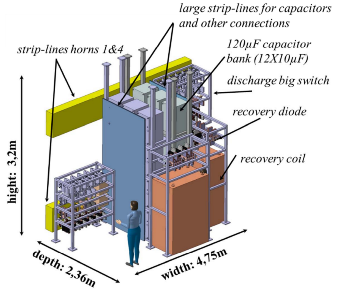
Morgue

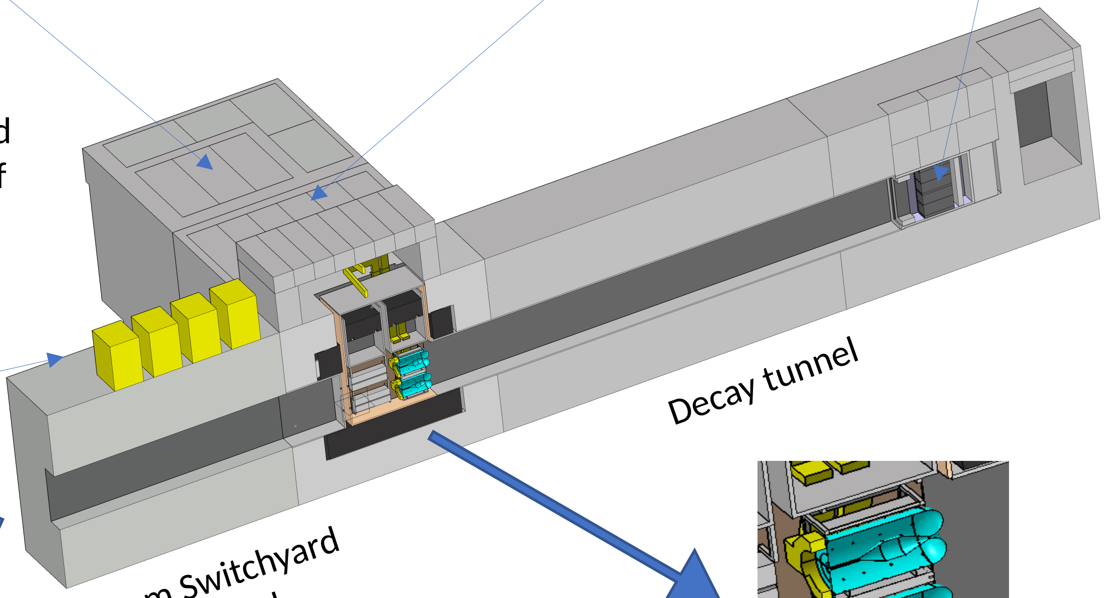
To Store radioactive wastes

Beam dump

Power Supply Unit

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

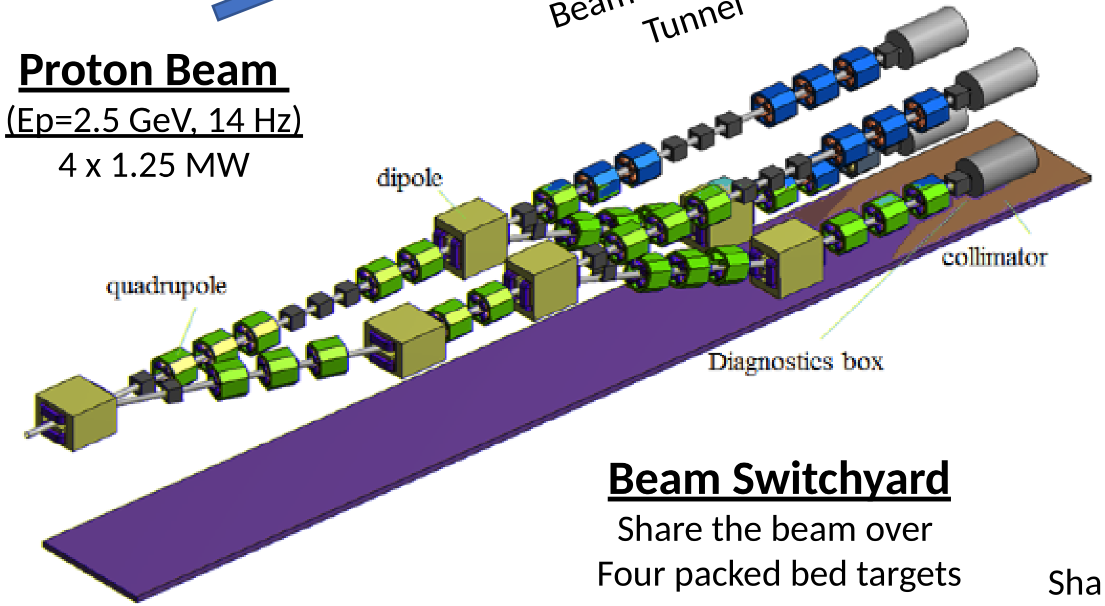




Proton Beam

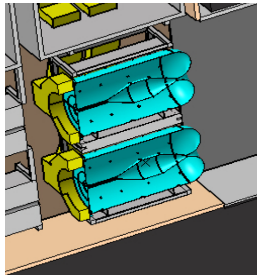
(Ep=2.5 GeV, 14 Hz)

4 x 1.25 MW

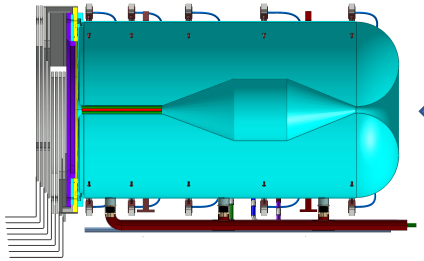


Beam Switchyard

Share the beam over
Four packed bed targets



Hadronic Collector

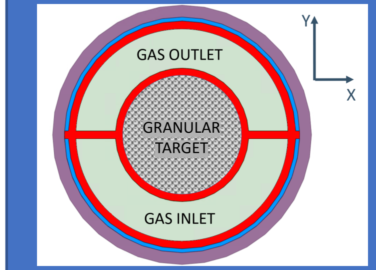


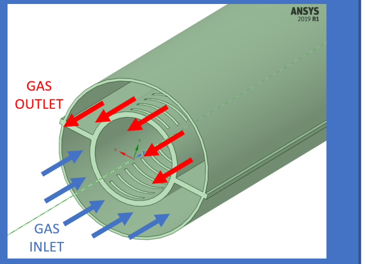
MiniBoone Like Horn

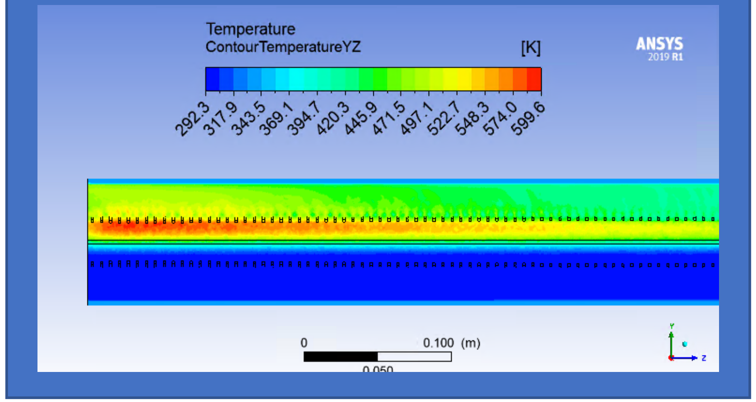
Shape optimized with genetic algorithm

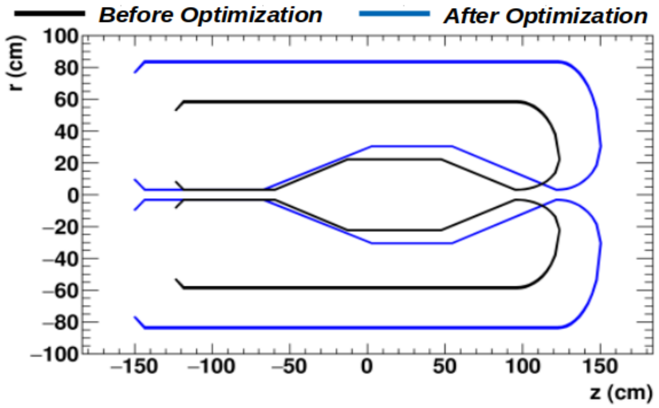
Granular Target Concept

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







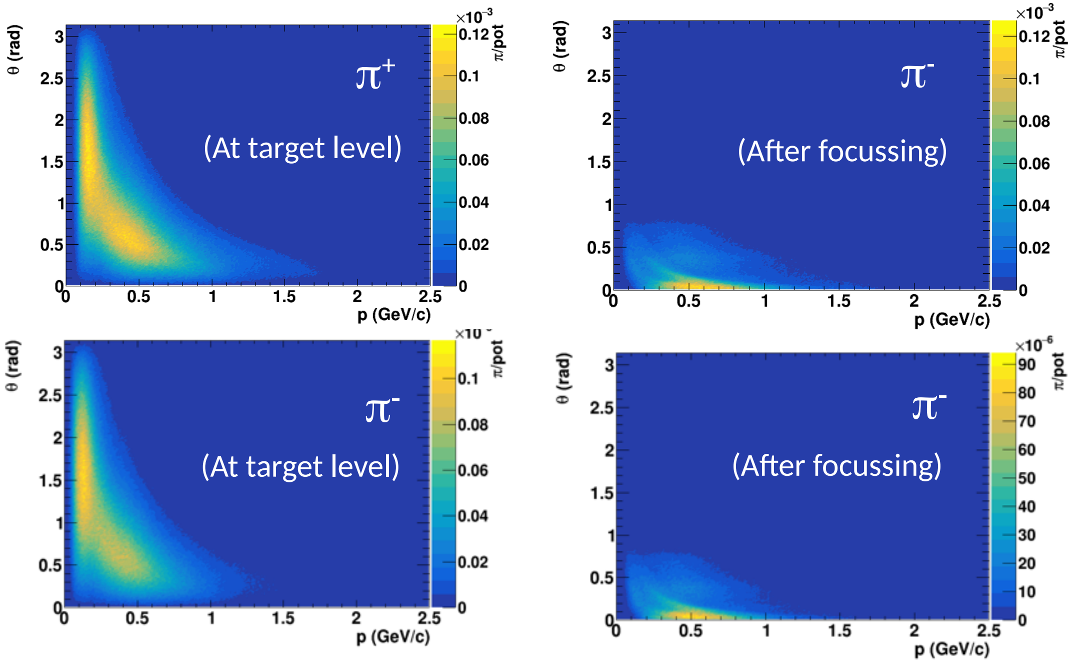


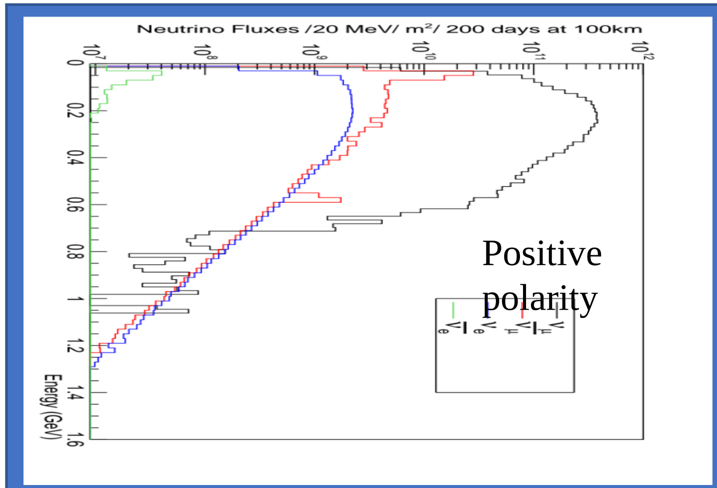
Neutrino beam production

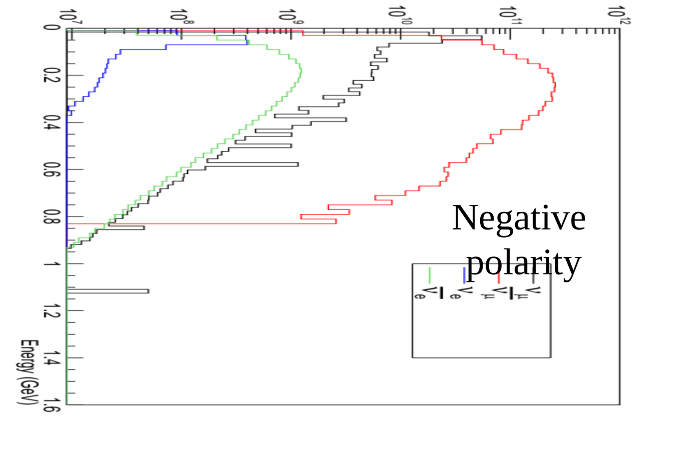
(Positive polarity)

(Negative polarity)

Horn focussing



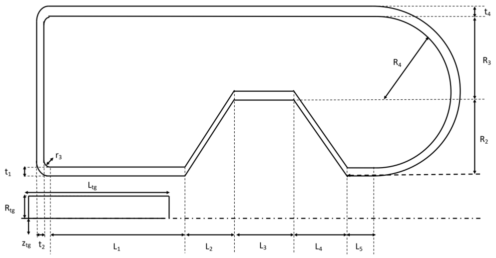




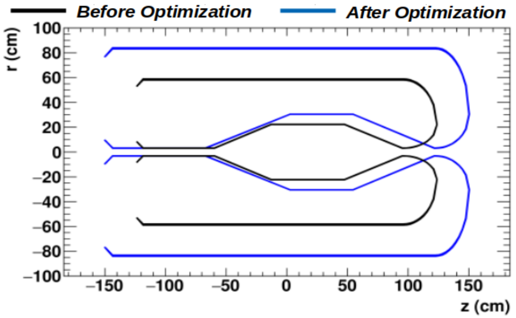
Neutrino flux composition.

	$10^{10}.m^{-2}$	%	$10^{10}.m^{-2}$	%
	674	97.6	20	4.7
	11.8	1.7	396	94.8
	4.76	0.67	0.13	0.03
	0.03	0.03	1.85	0.43

Horn optimisation procedure



Horn parametrisation



Optimisation based on Genetic Algorithm

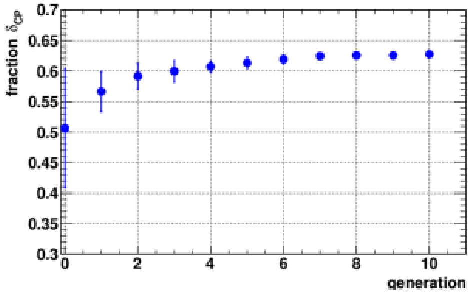
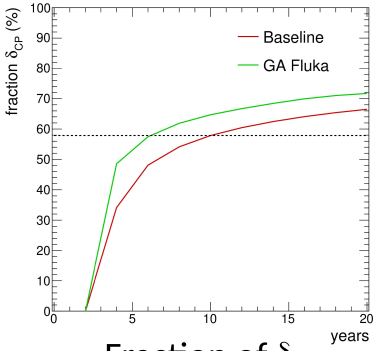
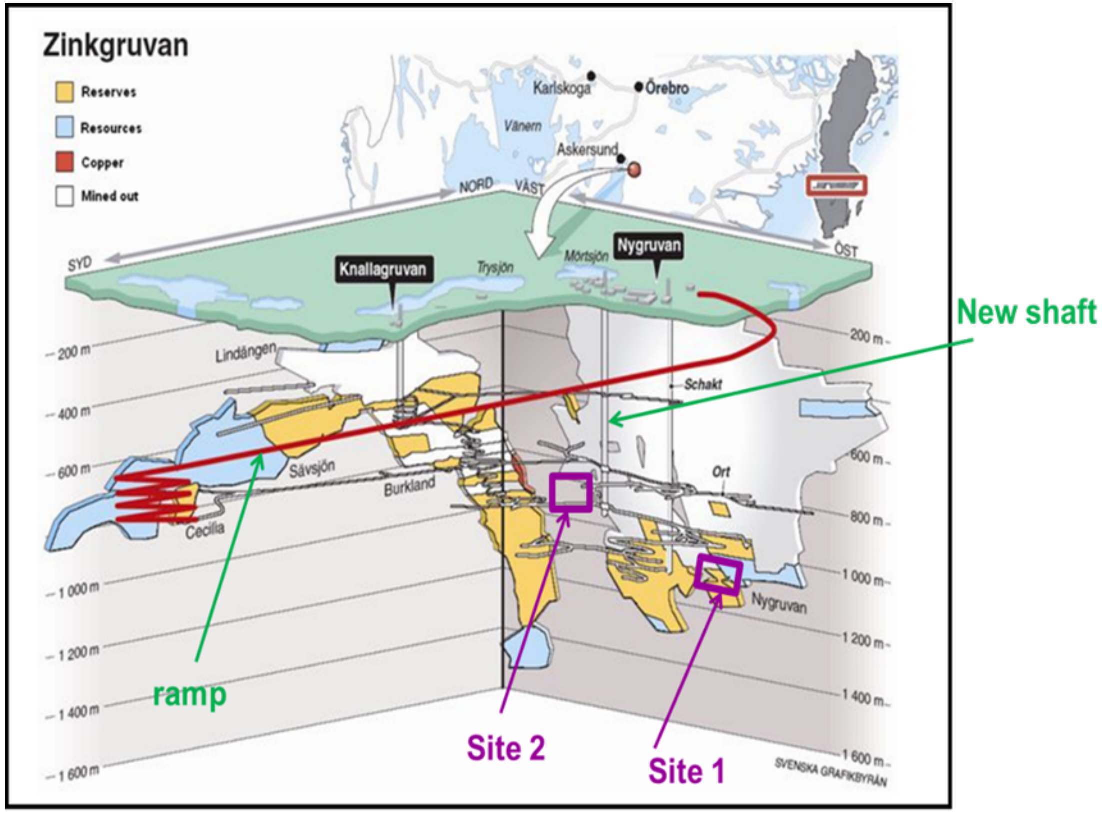


Figure of Merit based on δ_{cp}

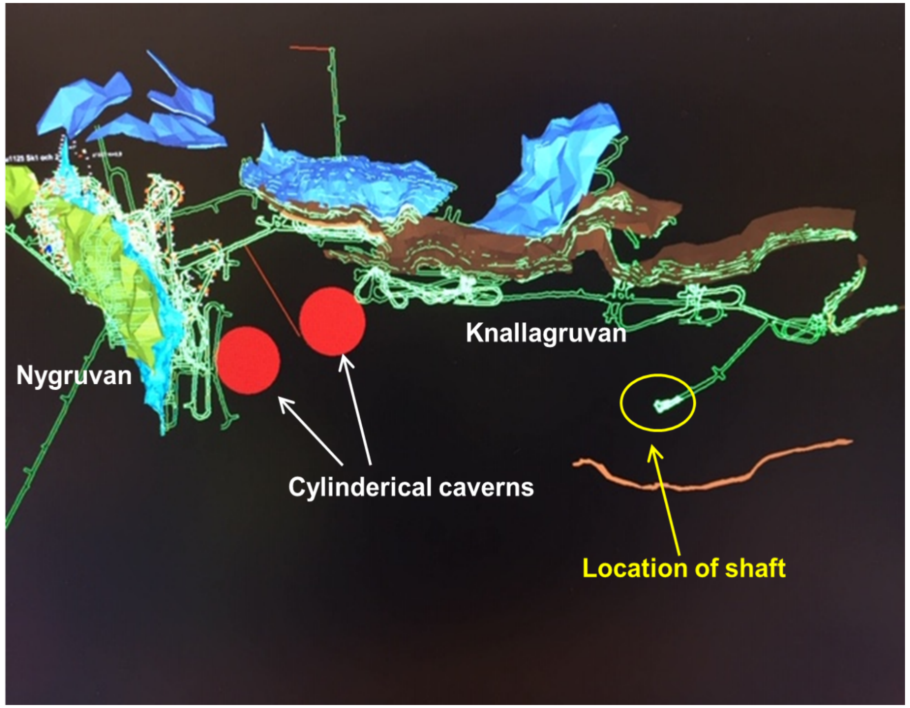


Fraction of δ_{cp}

Zinkgruvan mine

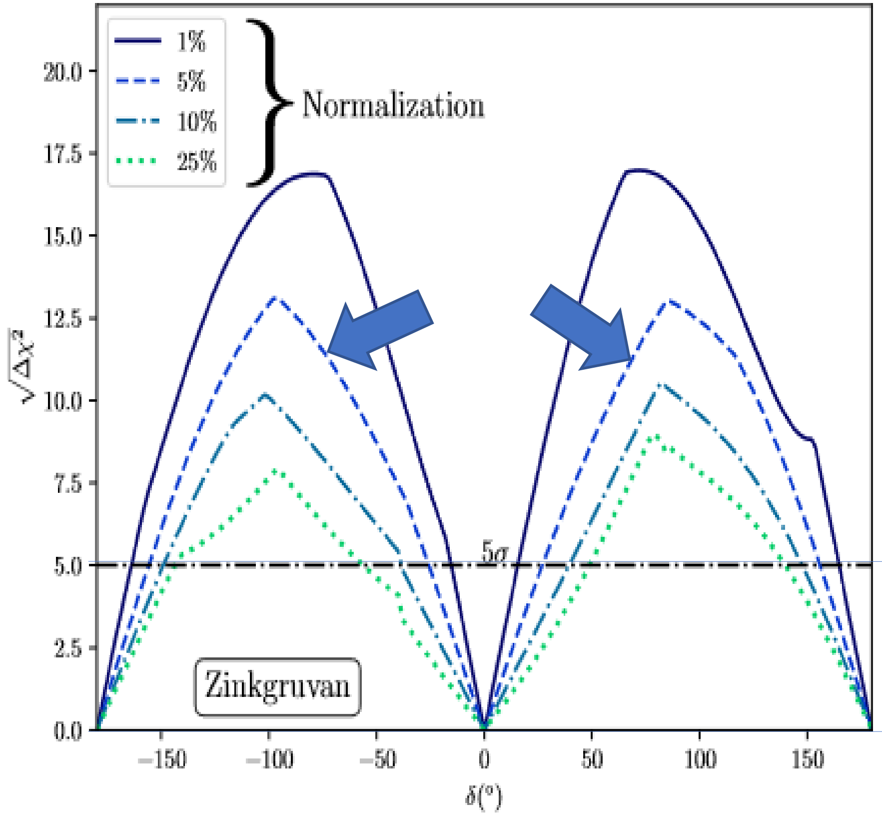


Potential location in Site 2

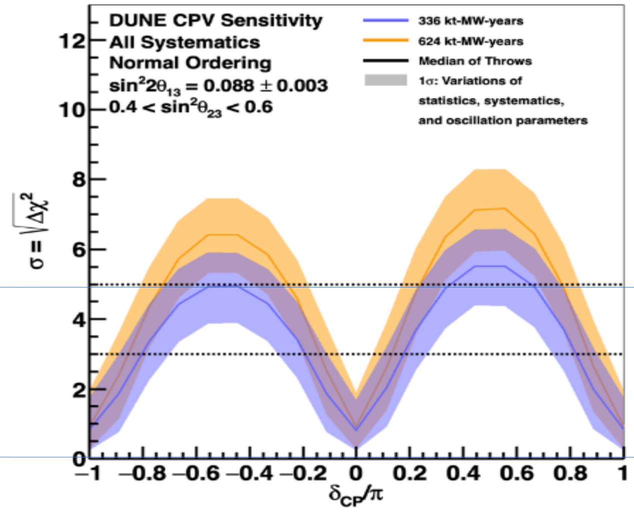


Site 2 is considered as best considering access to main transport infrastructure and located in an area less disturbed by mining activities

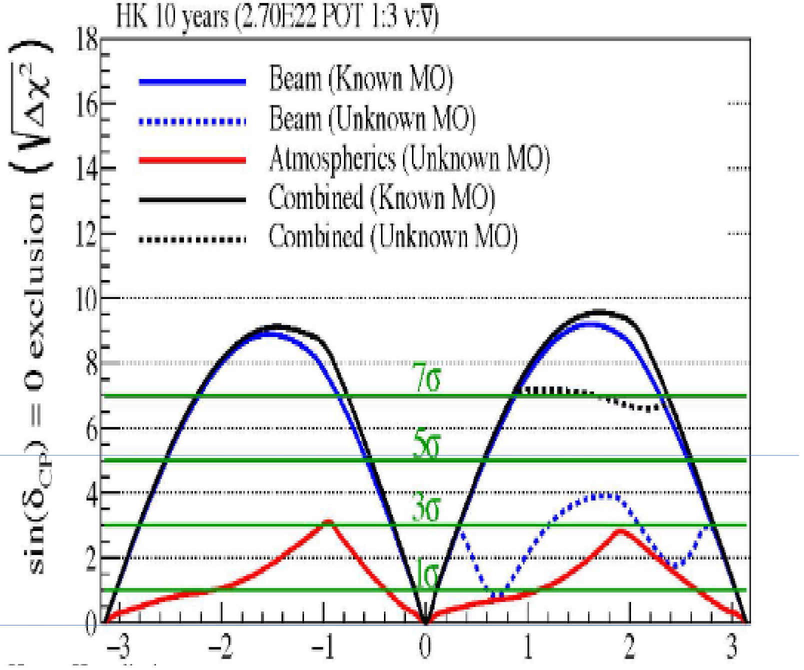
ESSnuSB in the international context – CPV discovery



ESSnuSB March 2022 with 5% normalization error

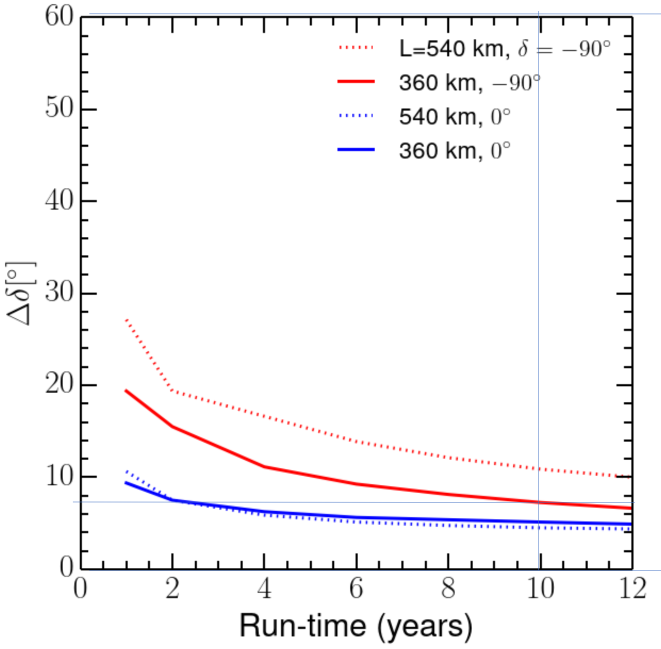


DUNE Snowmass March 2022

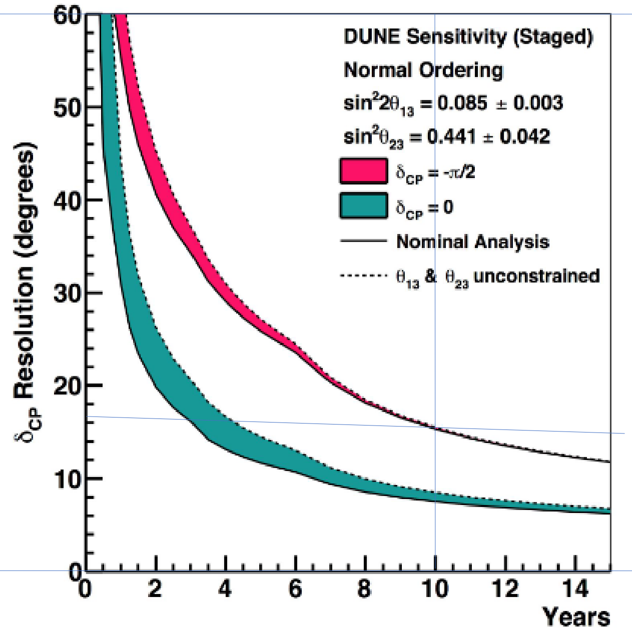


Hyper-Kamiokande Snowmass March 2022

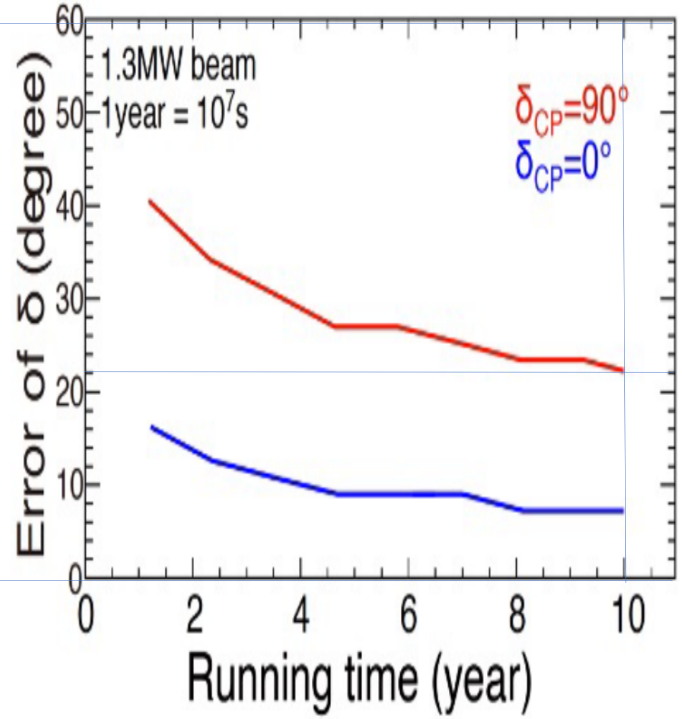
ESSnuSB in the international context – CPV resolution



ESSnuSB March 2022 with 5% normalization error



DUNE Snowmass March 2022



Hyper-Kamiokande Snowmass March 2022

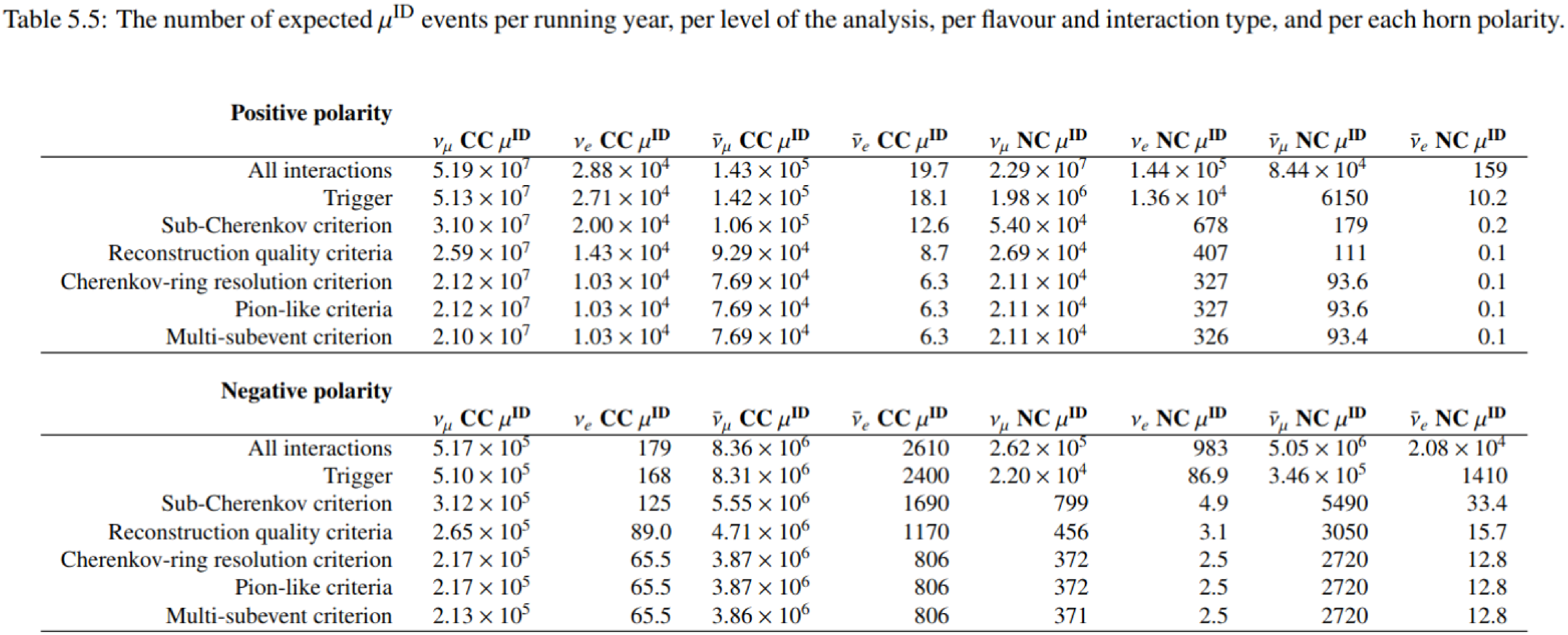


Table 5.5: The number of expected μ^{ID} events per running year, per level of the analysis, per flavour and interaction type, and per each horn polarity.

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

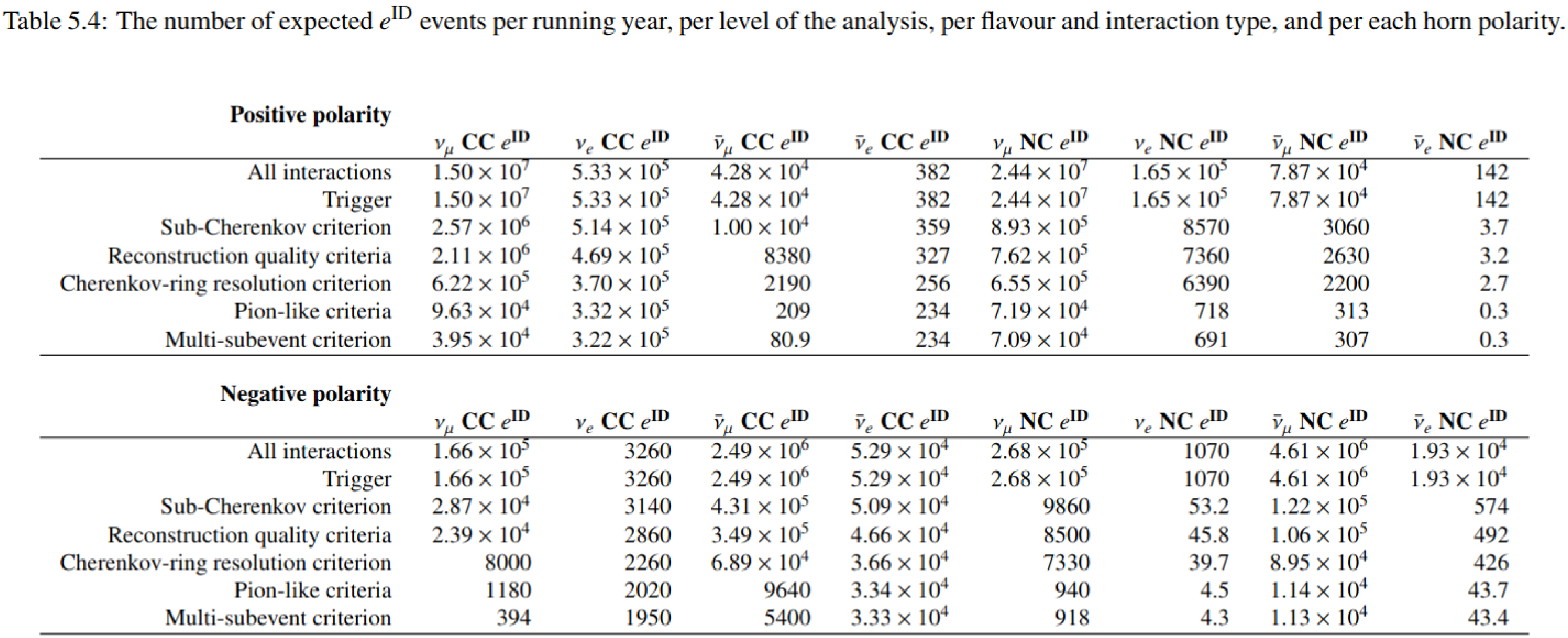


Table 5.4: The number of expected e^{ID} events per running year, per level of the analysis, per flavour and interaction type, and per each horn polarity.

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

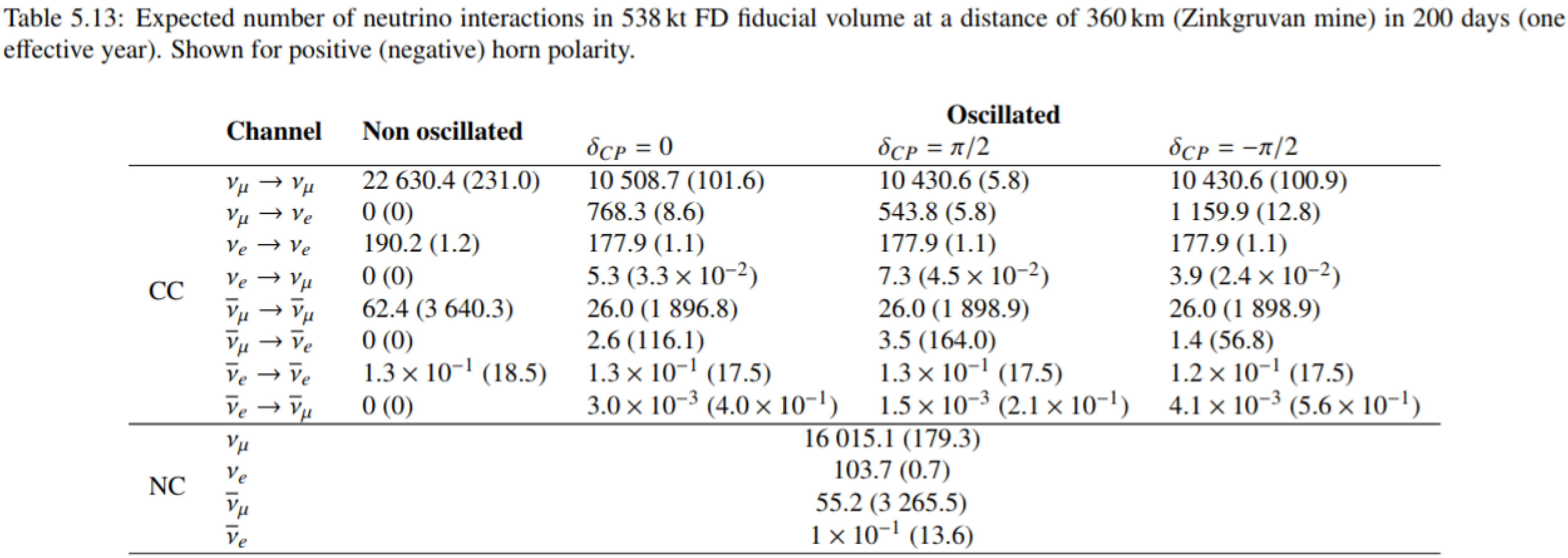
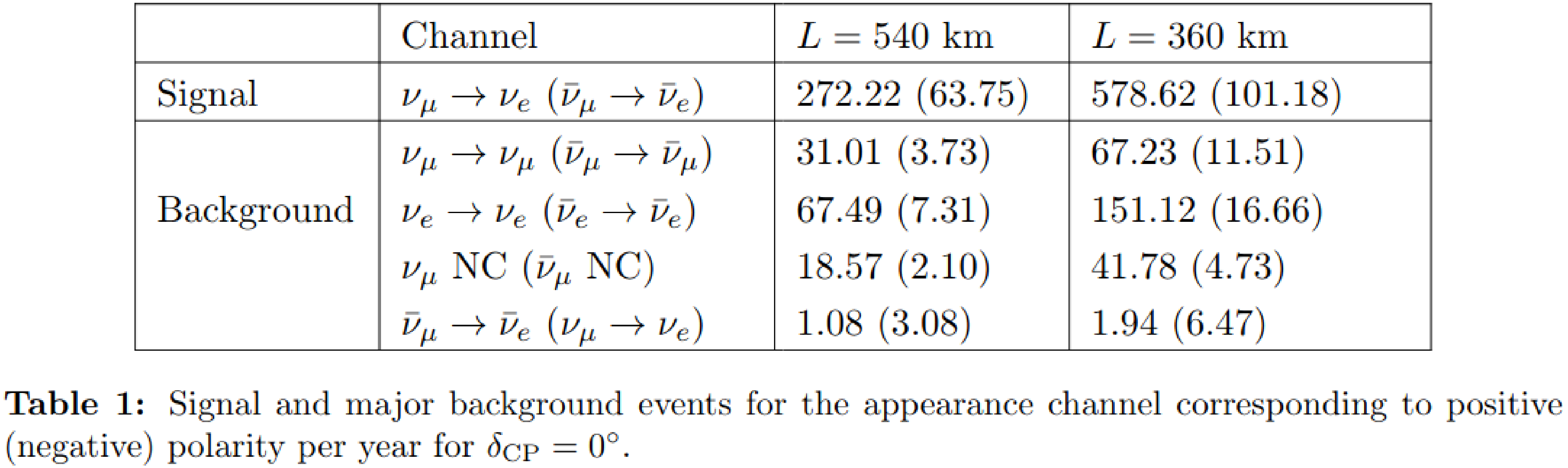


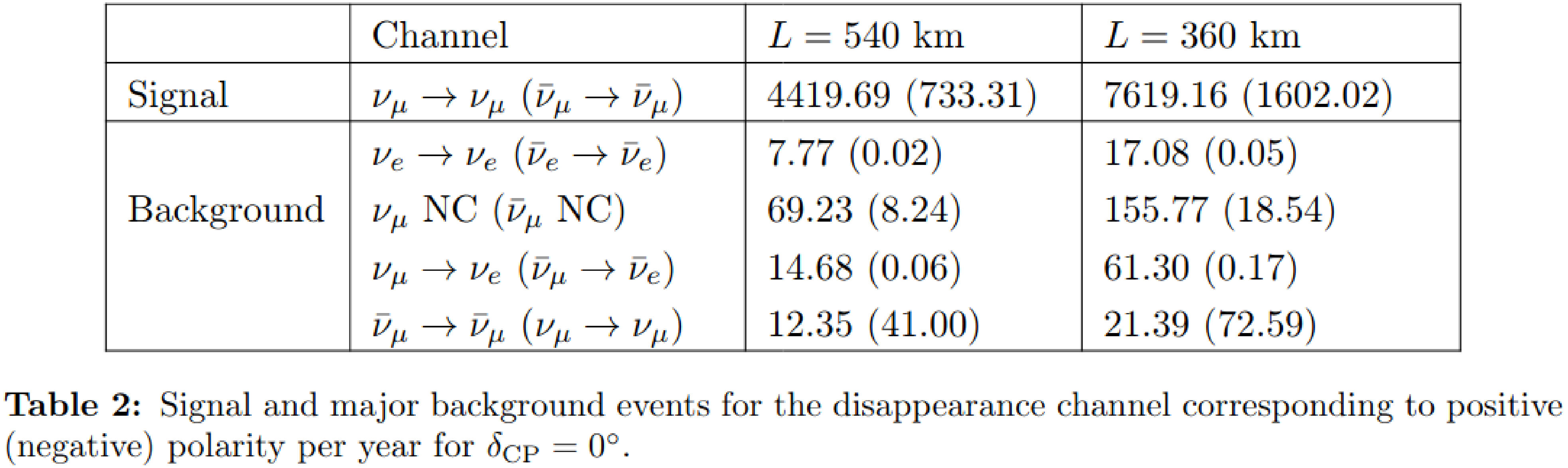
Table 5.13: Expected number of neutrino interactions in 538 kt FD fiducial volume at a distance of 360 km (Zinkgruvan mine) in 200 days (one effective year). Shown for positive (negative) horn polarity.

	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 $\delta_{\rm CP} = 0°$.



	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 $\delta_{\rm CP} = 0°$.

Neutrino oscillations

Neutrino flavor eigenstate is not a mass eigenstate

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

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

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

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 invarian

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

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

← Definition of Jarlskog invariant

Imaginary part of is constant up to a sign for all and , 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 is 0 or , or is 0 or
  - in that case there is no CP violation
- 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

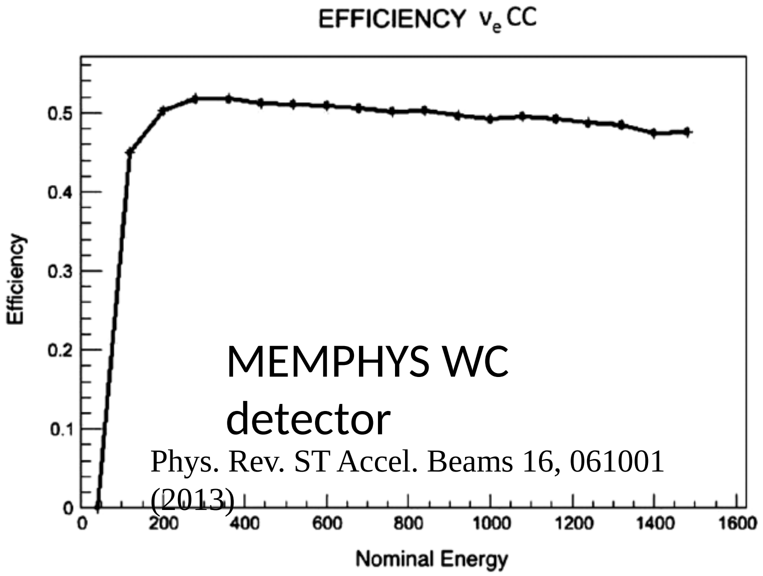
$$P_{\nu_\mu \to \nu_e} - P_{\overline{\nu}_\mu \to \overline{\nu}_e} = 4J\left(\sin\frac{\Delta m^2_{31} L}{2E} - \sin\frac{\Delta m^2_{32} L}{2E} - \sin\frac{\Delta m^2_{21} L}{2E}\right)$$
$$= -16J \sin\frac{\Delta m^2_{31} L}{4E} \sin\frac{\Delta m^2_{32} L}{4E} \sin\frac{\Delta m^2_{21} L}{4E}$$

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

To have CP violation we must have ,
but also --> all three masses must be different

Sensitivity improvements since project start

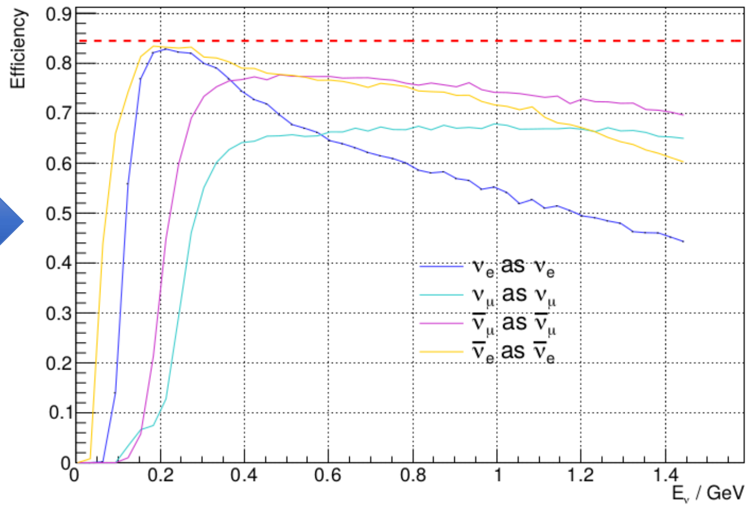
- Near detectors optimized for flux and cross-section measurement - 5% systematics within easy reach
- Far detectors’ response optimized for ESSnuSB flux – very high efficiency and purity at ESSnuSB energies
- Genetic Algorithm for Target Station optimization – more neutrinos



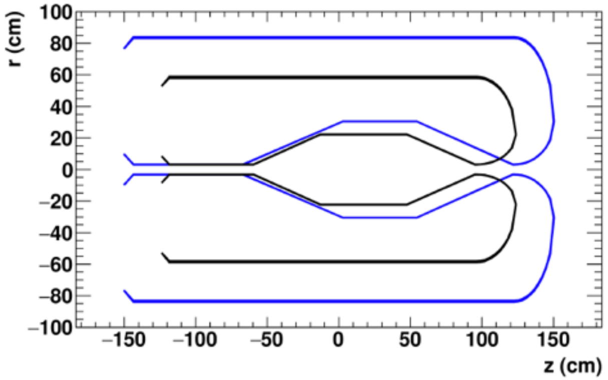
MEMPHYS WC detector

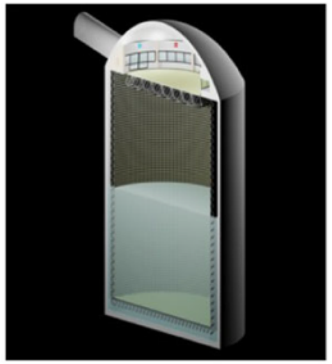
Phys. Rev. ST Accel. Beams 16, 061001 (2013)

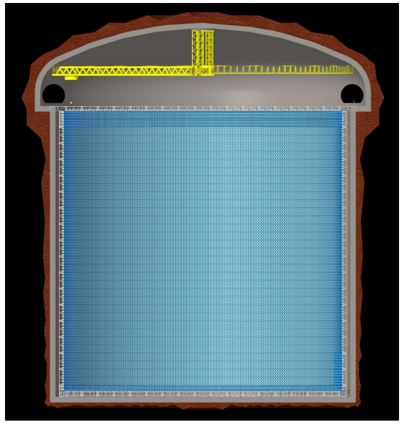
Efficiency ESSnuSB FD



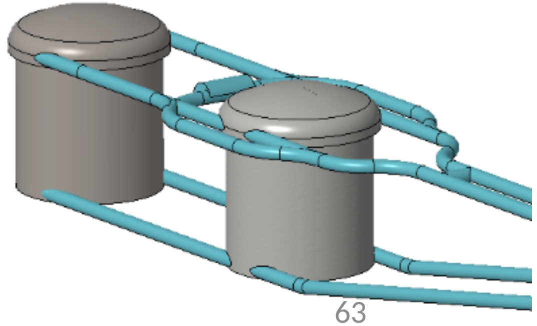
horn optimisation







538 kt
total fiducial

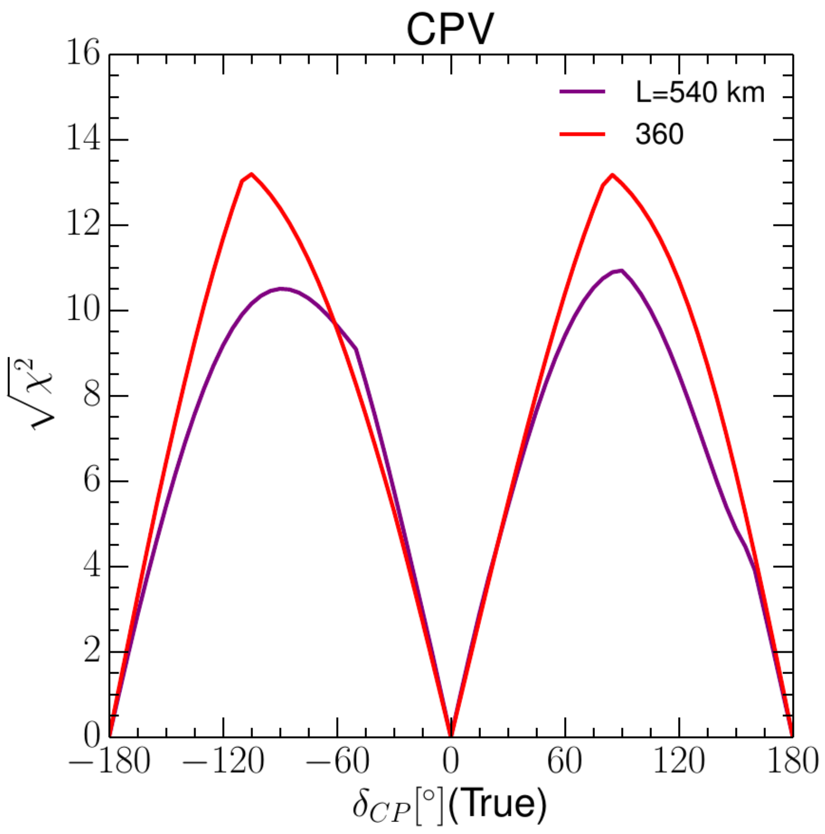


Updated physics performance of the ESSnuSB experiment,

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

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

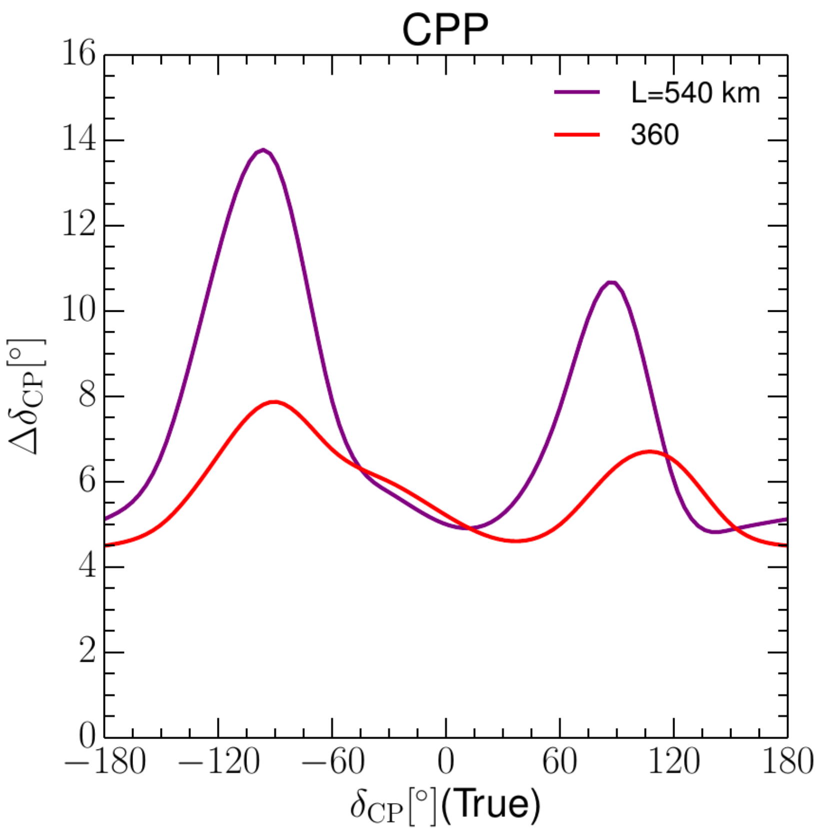
Intermediate result, state of analysis in June 2021



Sensitivity for $\delta_{CP} = \pm \pi/2$:

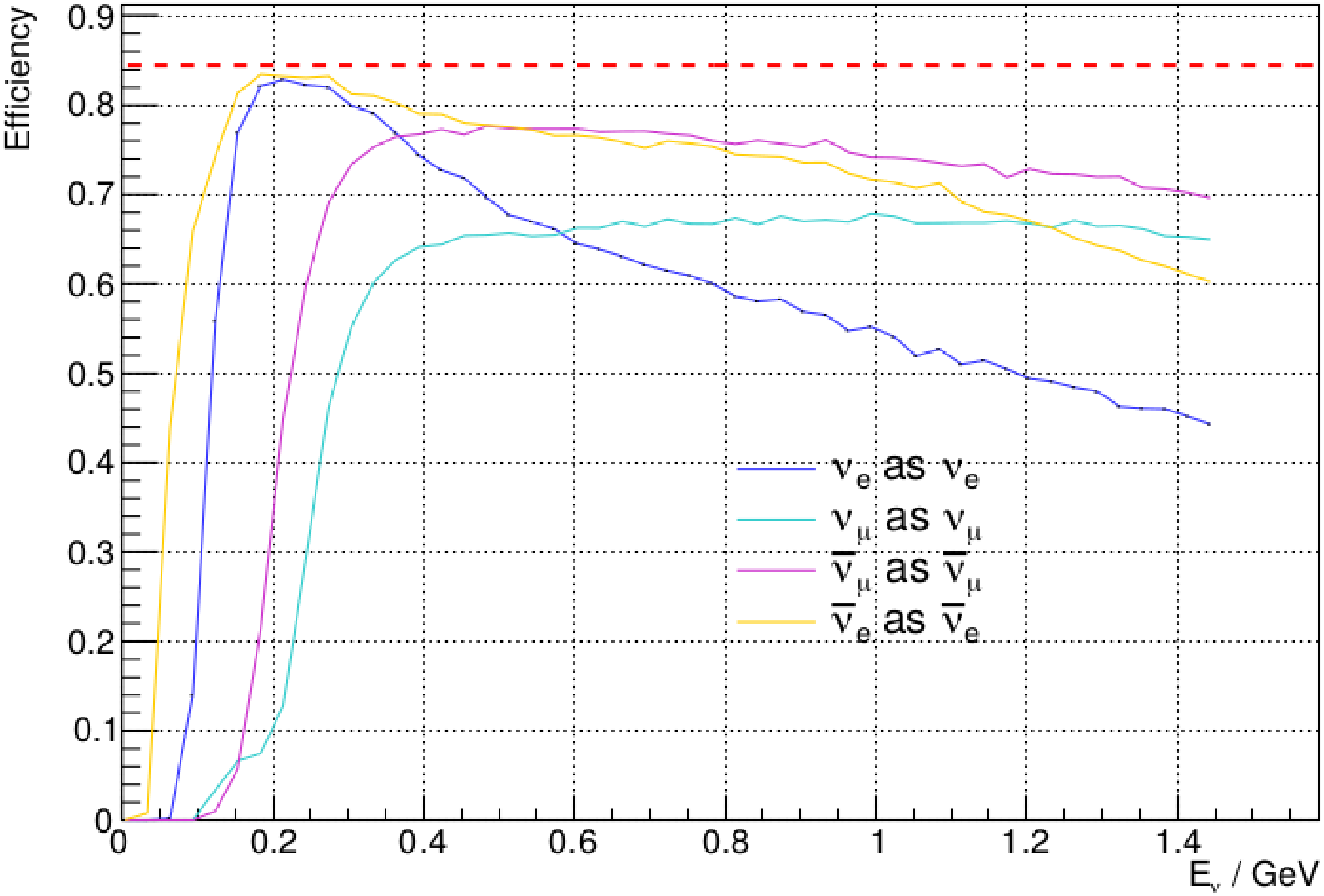
11 σ (540 km)

13 σ (360 km)

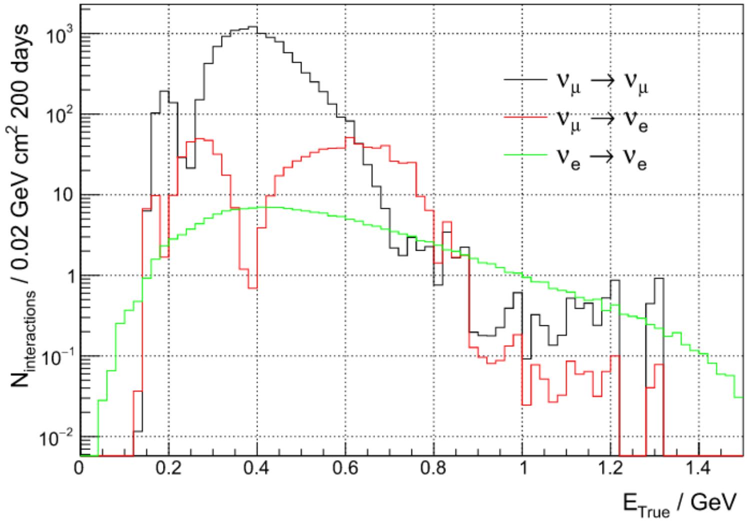


High precision of δ_{CP} measurement

Neutrino detection efficiency at FD



Expected spectrum positive polarity



(a) Positive polarity

Very high efficiency at 2nd maximum