Co-funded by the European Union

Physics with next generation neutrino experiments: ESSnuSB

Monojit Ghosh

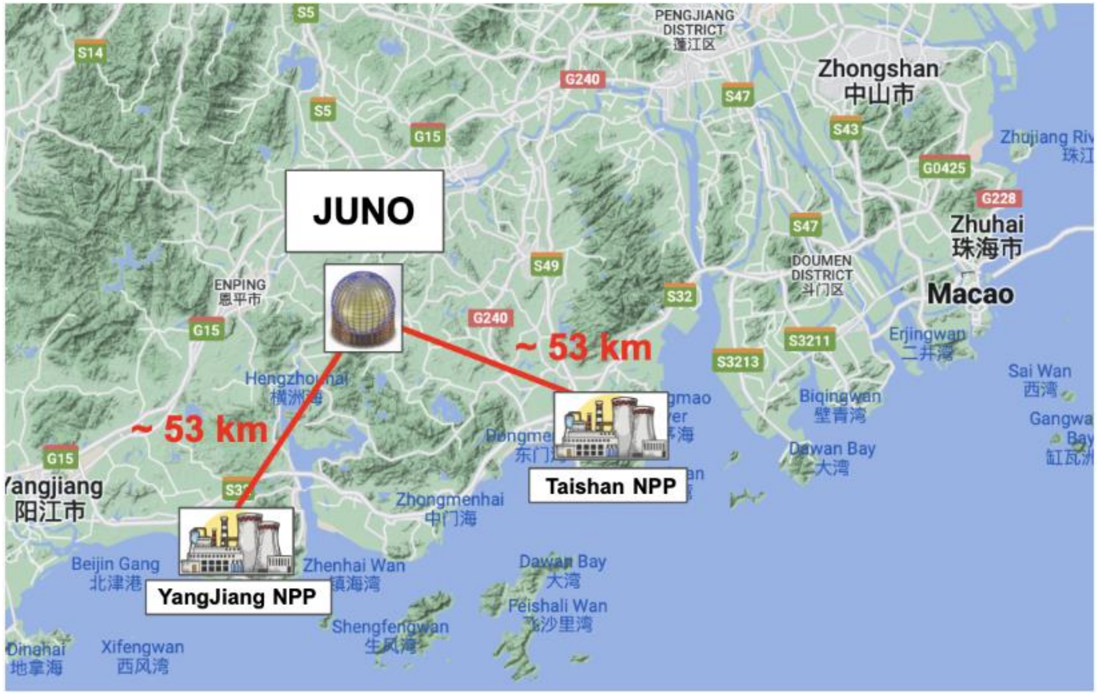
Ruđer Bosković Institute, Zagreb, Croatia

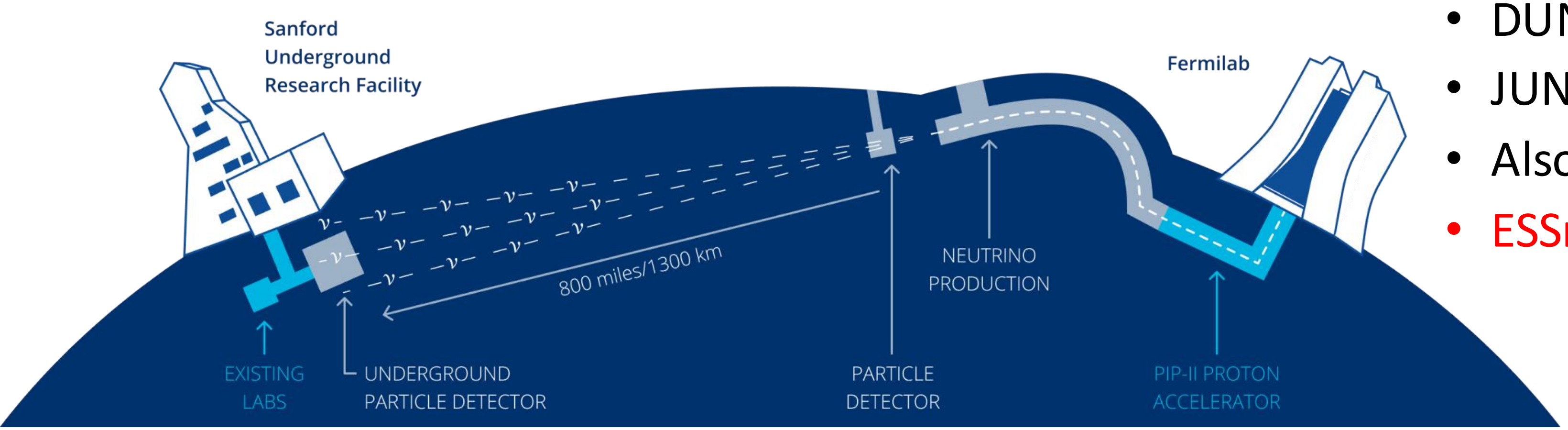
ESS neutrino Super Beam plus

MTTD 2025

Katowice, Poland 15 - 19 September 2025

Next Generation Experiments

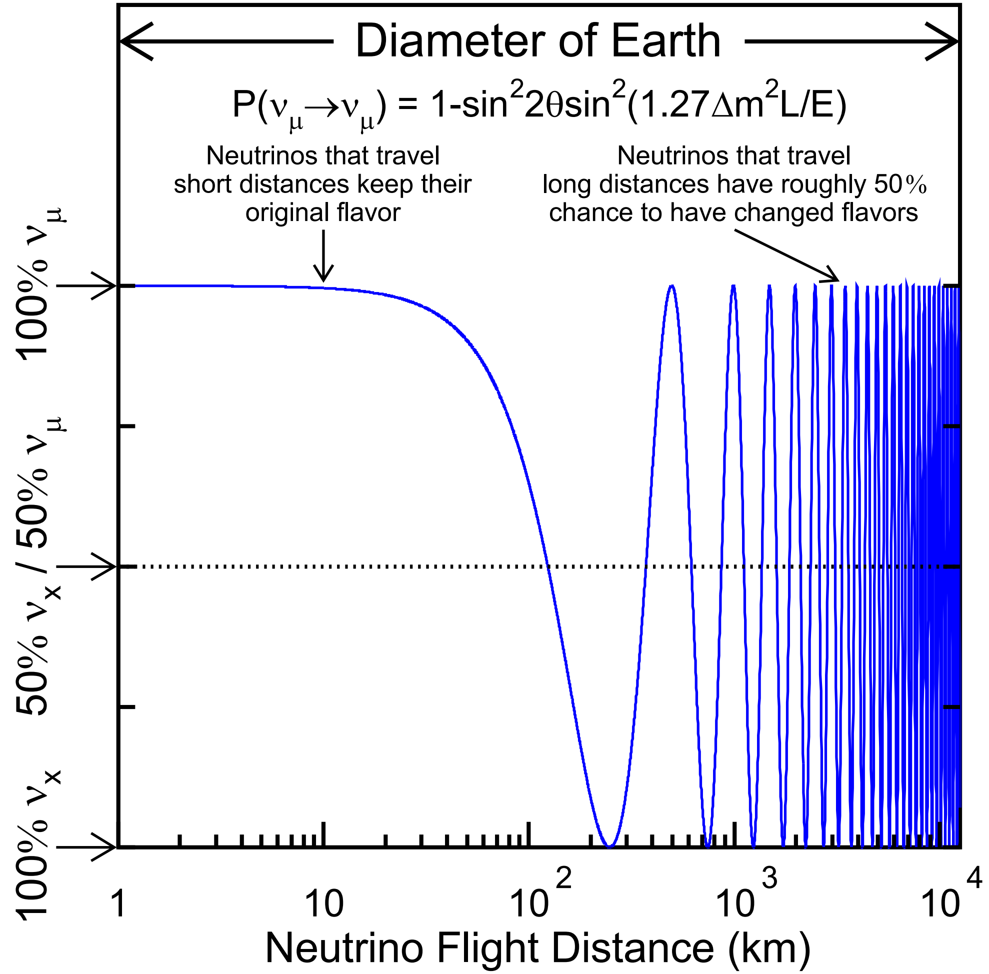




- Hyper-K in Japan – Talk by Lakshmi
- DUNE in USA
- JUNO in China – Recently started taking data
- Also KM3NET, ICeCube
- ESSnuSB in Sweden

This talk

Neutrino Oscillation



- Oscillation from one flavour to another

- Because flavour states and mass states are not the same

$$|\nu_\alpha\rangle = U_{\alpha i}\ |\nu_i\rangle$$

U is the PMNS matrix

- The transition probability is given by

$$P_{\alpha\beta} = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2$$

3 mixing angles and 1 phase: $U^{3\nu}$ = $R_{23}(\theta_{23})\ R_{13}(\theta_{13}, \delta_{CP})\ R_{12}(\theta_{12})$

2 mass squared difference: $\Delta m^2_{21} = m^2_2 - m^2_1$, $\Delta m^2_{31} = m^2_3 - m^2_1$

Two instrinsic parameters: baseline L and energy E

Global fit status

... while fractional accuracy of **known** parameters improved.

In particular, Δm^2 formally determined at the subpercent level, $1\sigma = 0.8\%$

Large uncertainty – δ_{CP}: 18%

- The main goal of ESSnuSB
(i) Measurement of δ_{CP}

- Additiona goals
(i) new physics
(ii) non-beam physics
(i) cross-section measurement

TABLE I: Global 3ν oscillation analysis: best-fit values and allowed ranges at $N_\sigma = 1, 2, 3$, for either NO or IO. The last column shows the formal "1σ parameter accuracy," defined as 1/6 of the 3σ range, divided by the best-fit value (in percent). We recall that $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$ and that δ/π is cyclic (mod 2). Last row: $\Delta\chi^2$ offset between IO and NO.

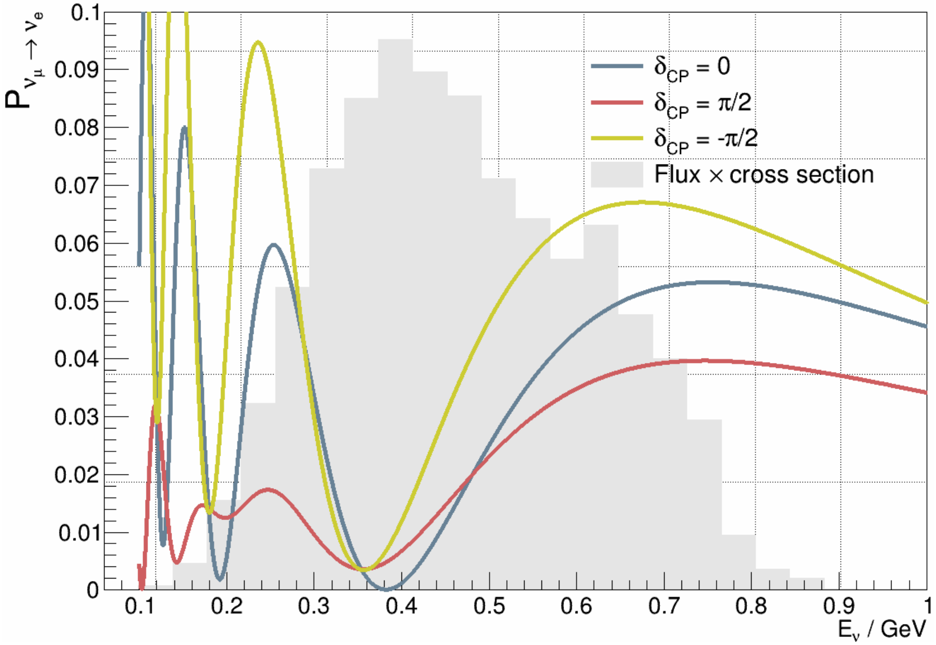
Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.37	7.21 – 7.52	7.06 – 7.71	6.93 – 7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.91 – 3.17	2.77 – 3.31	2.64 – 3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.495	2.475 – 2.515	2.454 – 2.536	2.433 – 2.558	0.8
	IO	2.465	2.444 – 2.485	2.423 – 2.506	2.403 – 2.527	0.8
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.17 – 2.27	2.11 – 2.33	2.06 – 2.38	2.4
	IO	2.23	2.19 – 2.30	2.14 – 2.35	2.08 – 2.41	2.4
$\sin^2\theta_{23}/10^{-1}$	NO	4.73	4.60 – 4.96	4.47 – 5.68	4.37 – 5.81	5.1
	IO	5.45	5.28 – 5.60	4.58 – 5.73	4.43 – 5.83	4.3
δ/π	NO	1.20	1.07 – 1.37	0.88 – 1.81	0.73 – 2.03	18
	IO	1.48	1.36 – 1.61	1.24 – 1.72	1.12 – 1.83	8
$\Delta\chi^2_{\text{IO-NO}}$	IO–NO	+5.0				

But there are reasons to be cautious about subpercent accuracy levels...

E.g., correlated effects of ν interaction uncertainties in different expts need improvement

Talk by Eligio at FLASY 2025

The ESSnuSB Experiment



Source at Lund, Far detector at Zinkgruvan: 360 km

Designed to probe second oscillation maximum

CP sensitivity is higher at 2nd maximum

ESS neutrino Super Beam plus

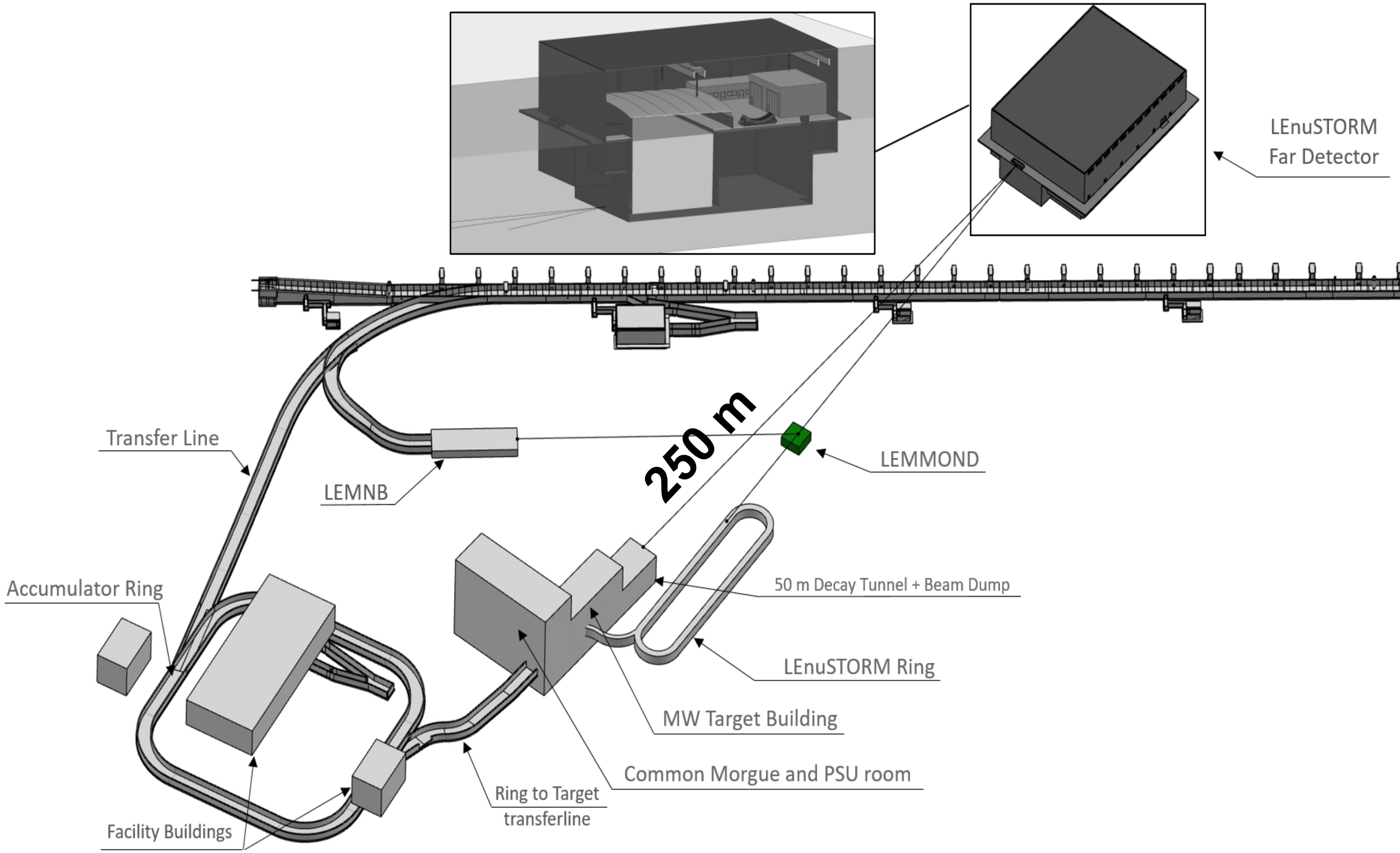
Co-funded by the European Union

Collaboration annual meeting – Hamburg 2024

13 countries
23 Institutes

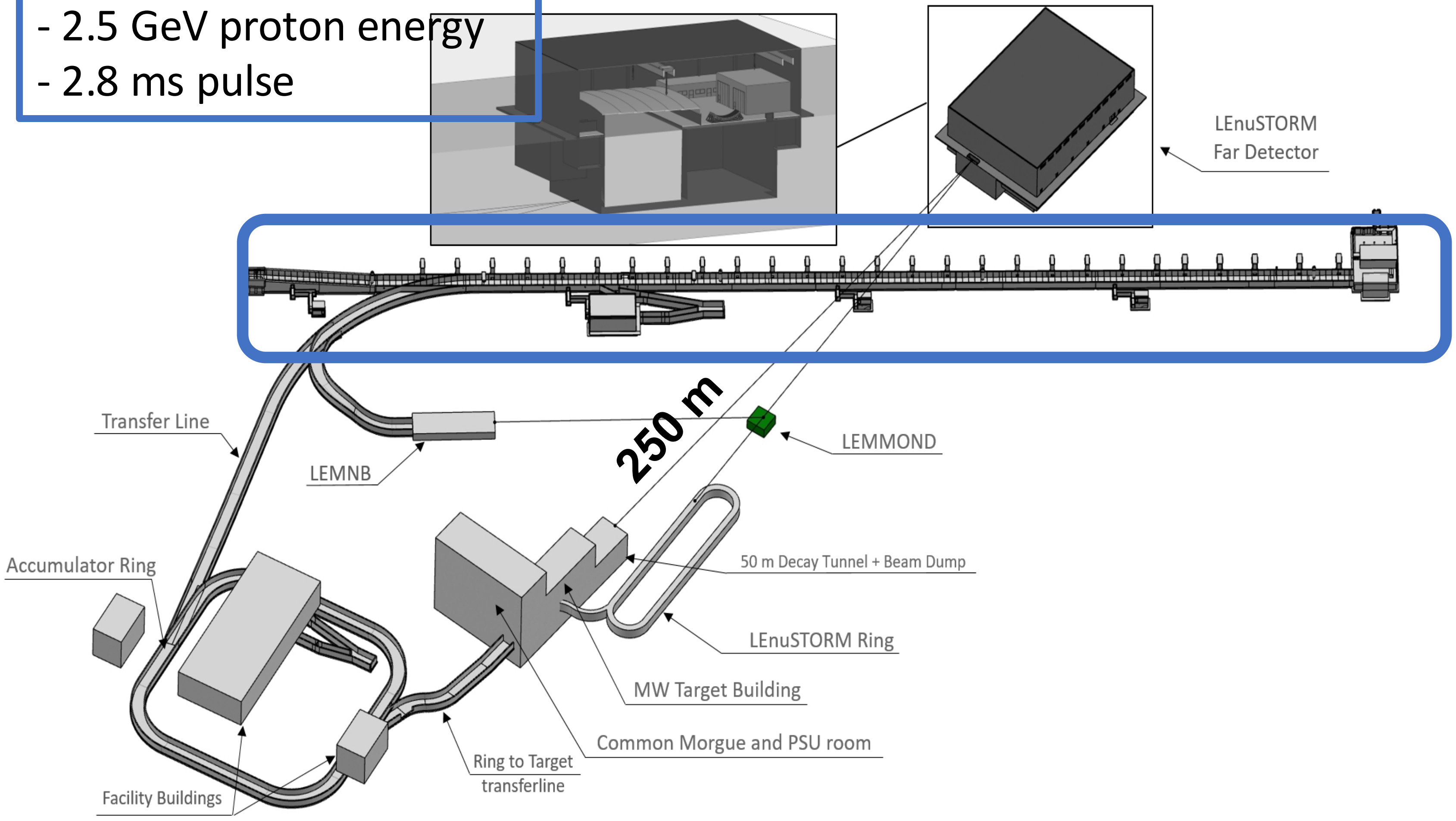
Horizon-2020 (2018 - 2022), 3 M€
Horizon-Europe (2023 - 2026), 3 M€

ESSnuSB+ setup



ESSnuSB+ setup

1. Main accelarator (ESS)
- 5 MW proton beam
- 2.5 GeV proton energy
- 2.8 ms pulse



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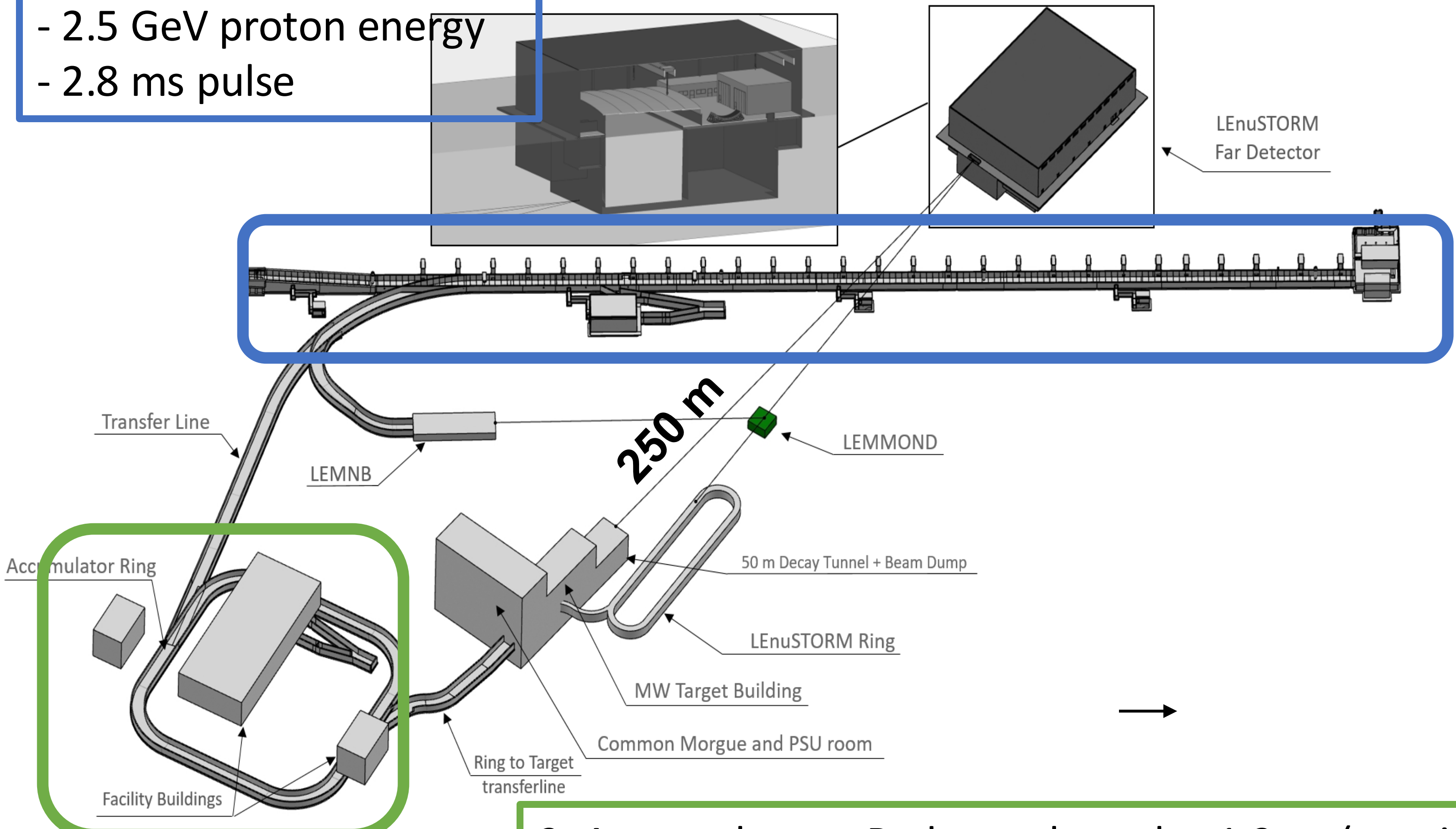

2. Accumulator – Reduces the pulse 1.2 μs (to minimize atmospheric background)

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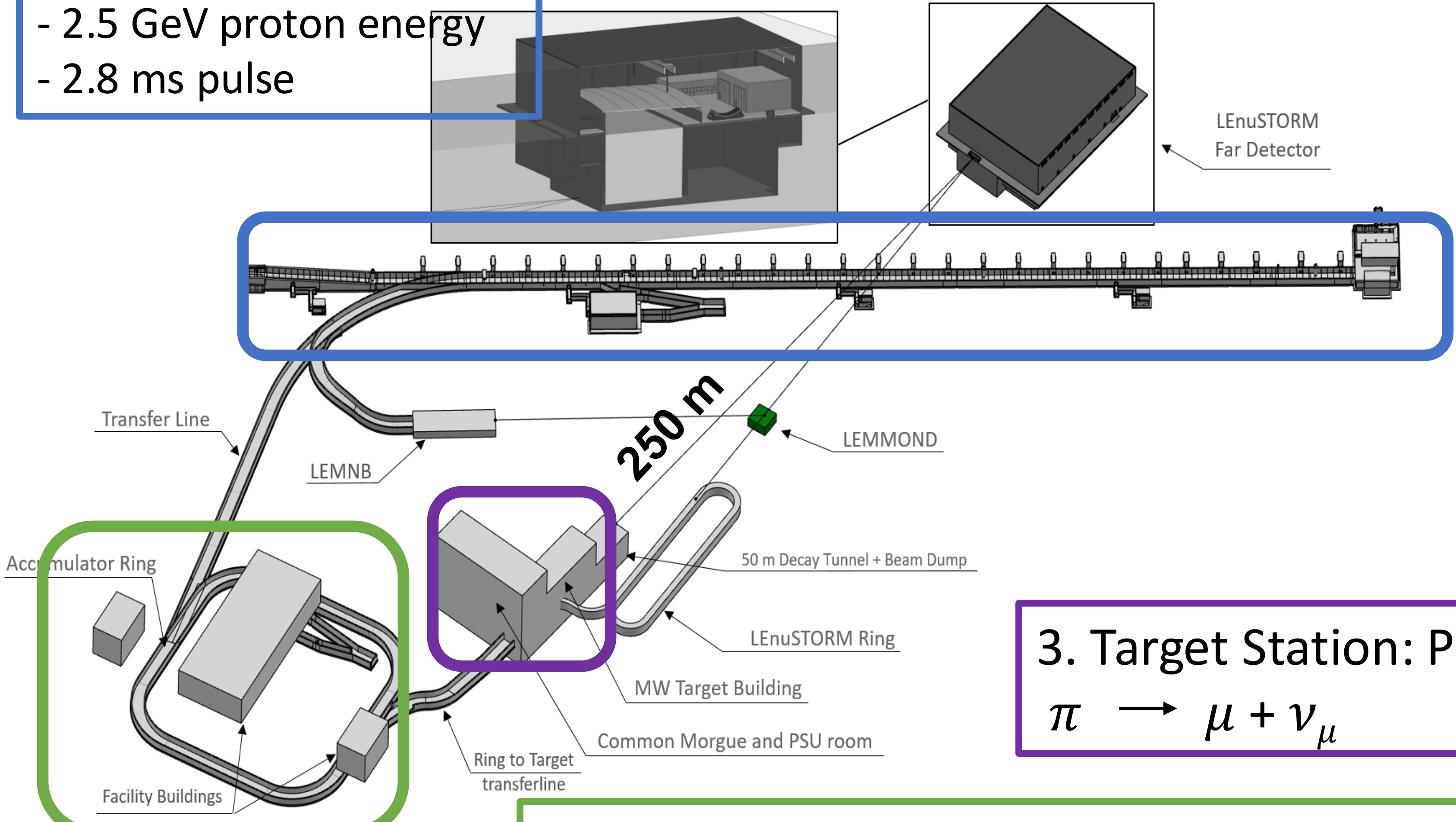

3. Target Station: Protons collide to produce π

$$\pi \longrightarrow \mu + \nu_\mu$$

2. Accumulator – Reduces the pulse 1.2 µs (to minimize atmospheric background)

ESSnuSB+ setup

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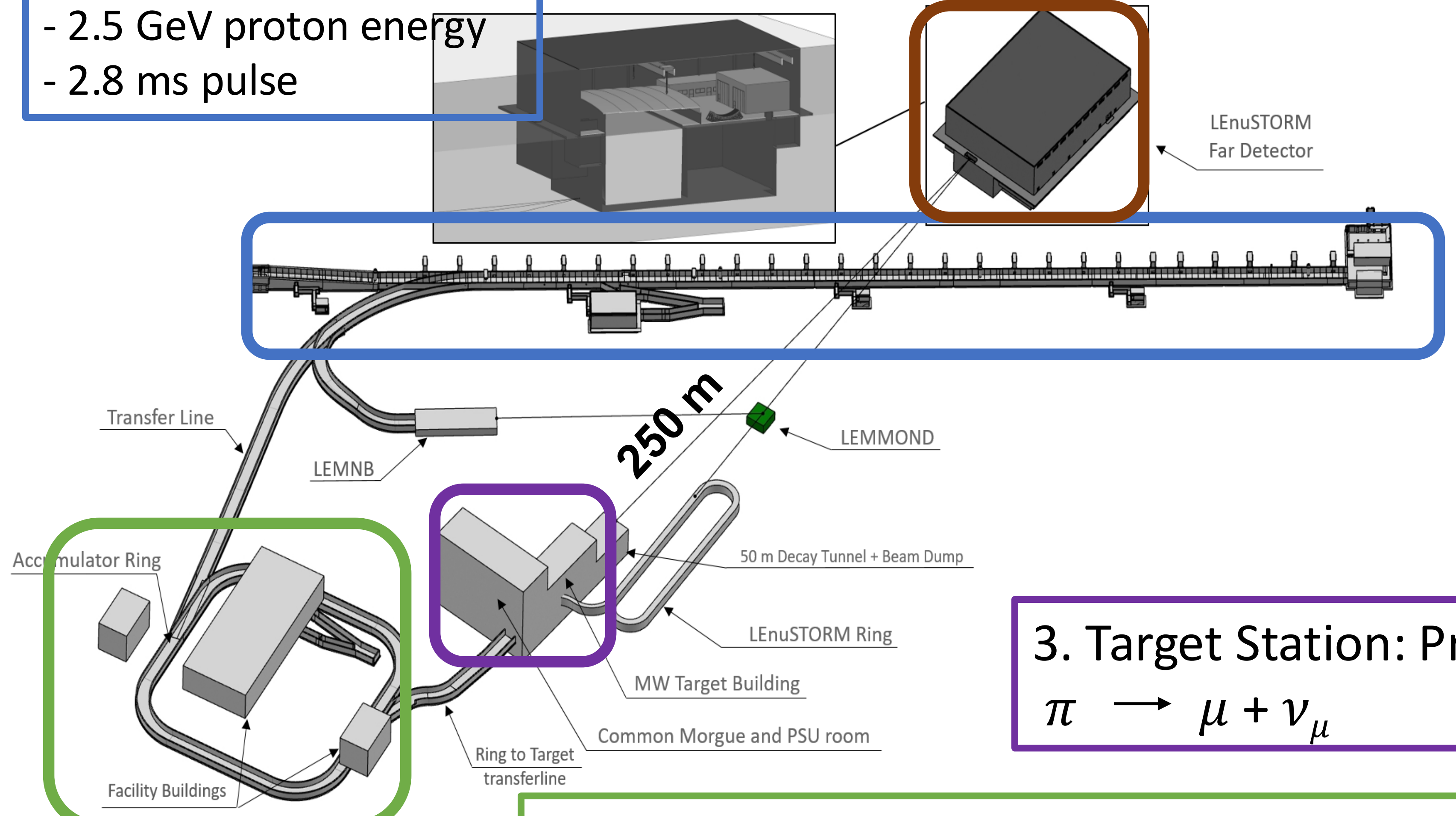
4. Near Detector (END)



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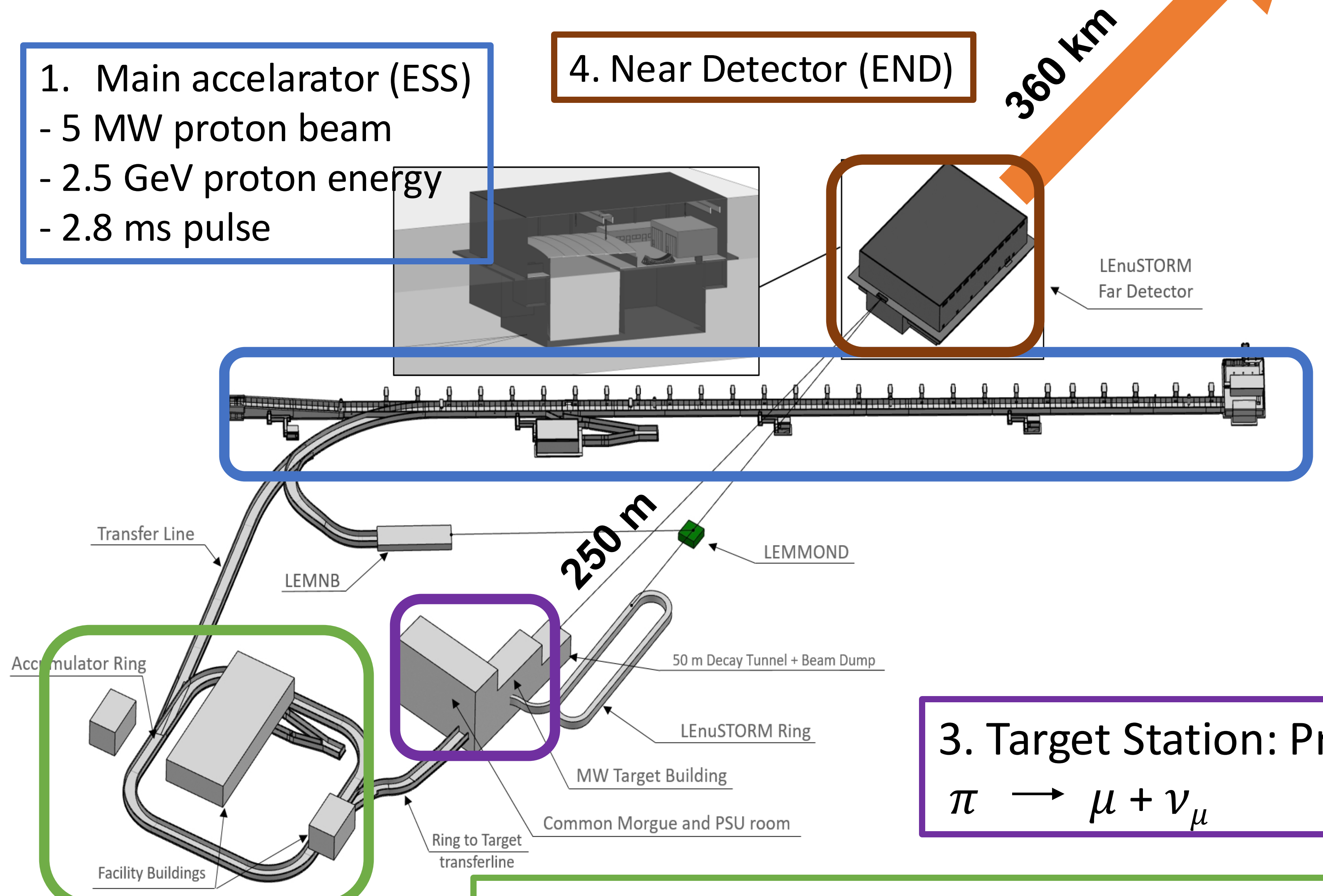
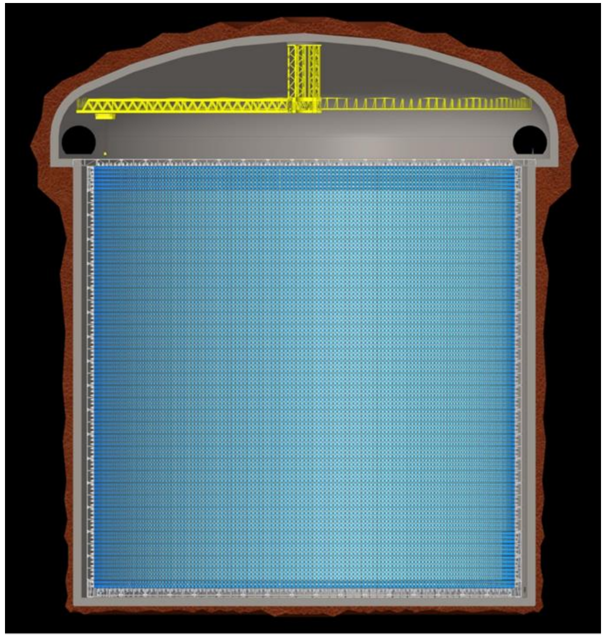


5. Far Detector (FD)
- 540 kt water cerenkov



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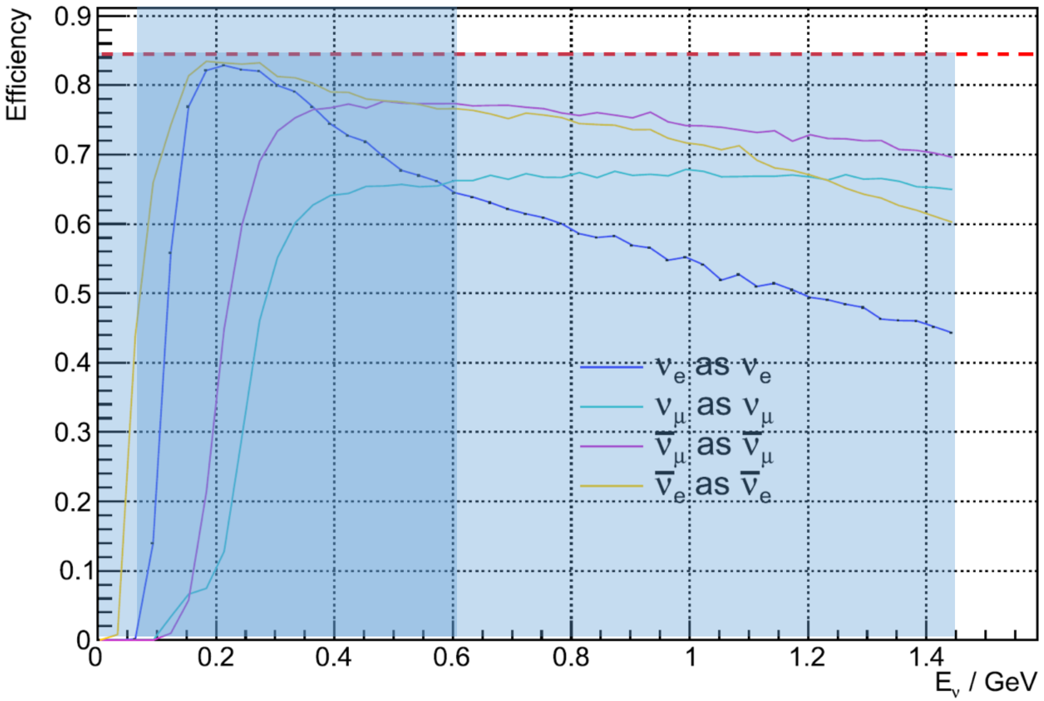
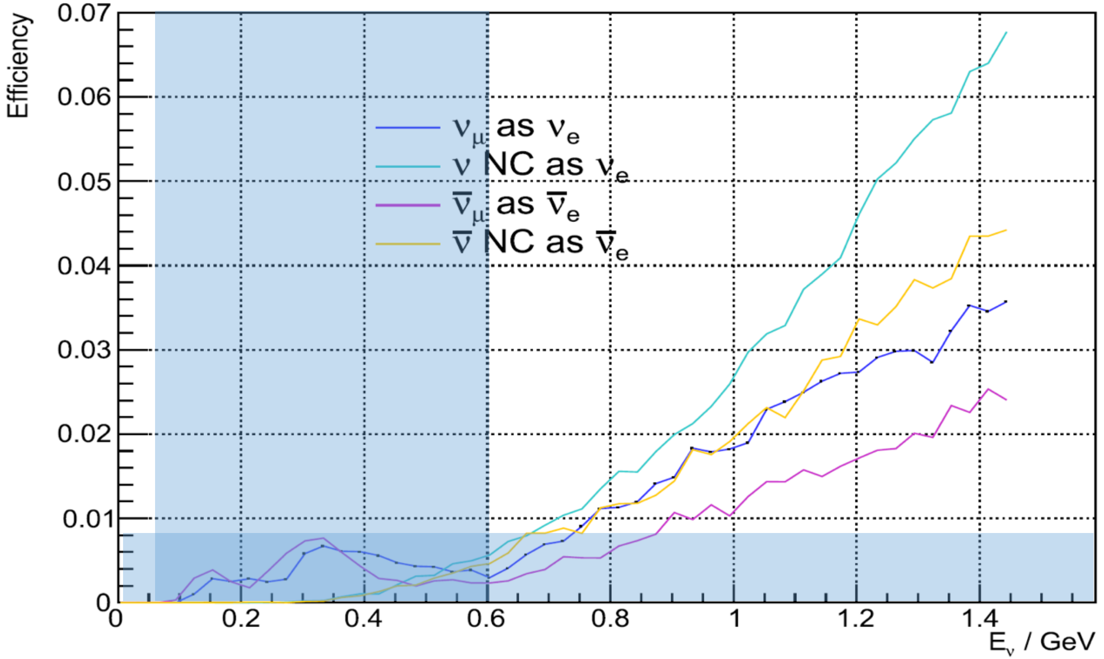
2. Accumulator – Reduces the pulse 1.2 µs (to minimize atmospheric background)

Detector

<u>**Detector Performance**</u>

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





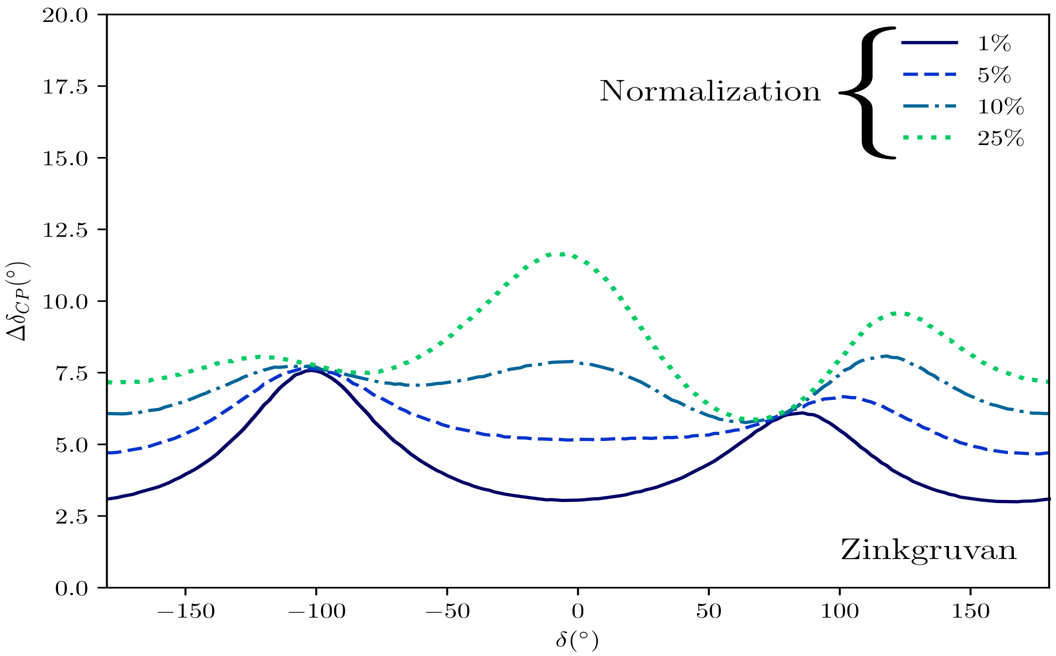
Alekou, *et al.* [ESSnuSB] Eur. Phys. J. ST **231** (2022), 3779-3955

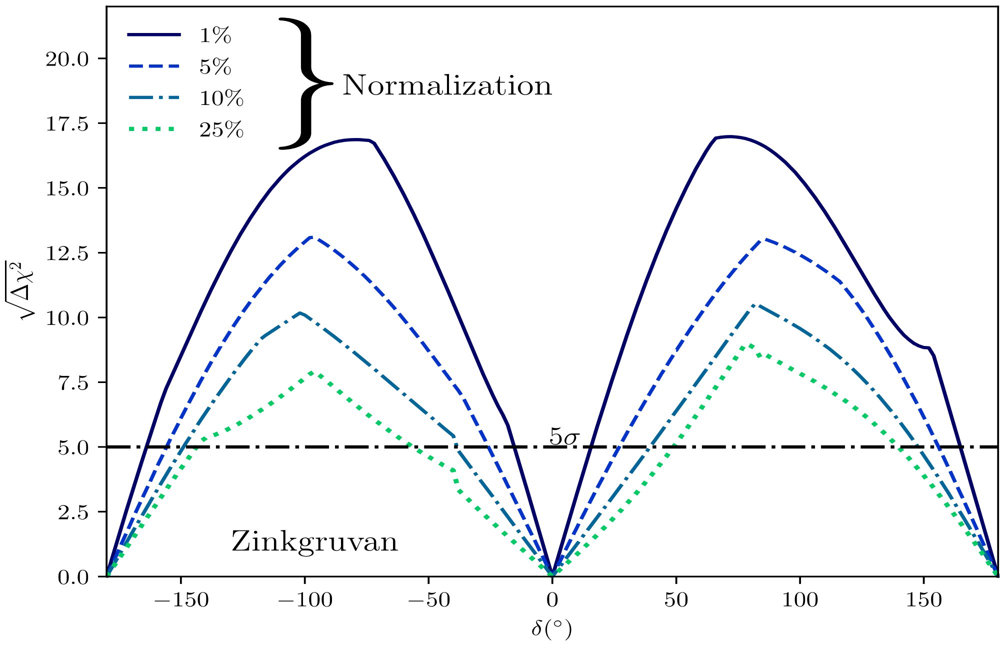
Sensitivity to δ_{CP}

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right) + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{21}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$
$$+ \tilde{J}\frac{\Delta_{21}}{A}\frac{\Delta_{31}}{\tilde{B}_\mp} \sin\left(\frac{AL}{2}\right)\sin\left(\frac{\tilde{B}_\mp L}{2}\right)\cos\left(\frac{\Delta_{31} L}{2} \pm \delta\right),$$

12 sigma sensitivity to discover CP violation for maximal values

Will measure δ_{CP} with less than 8° precision for all values

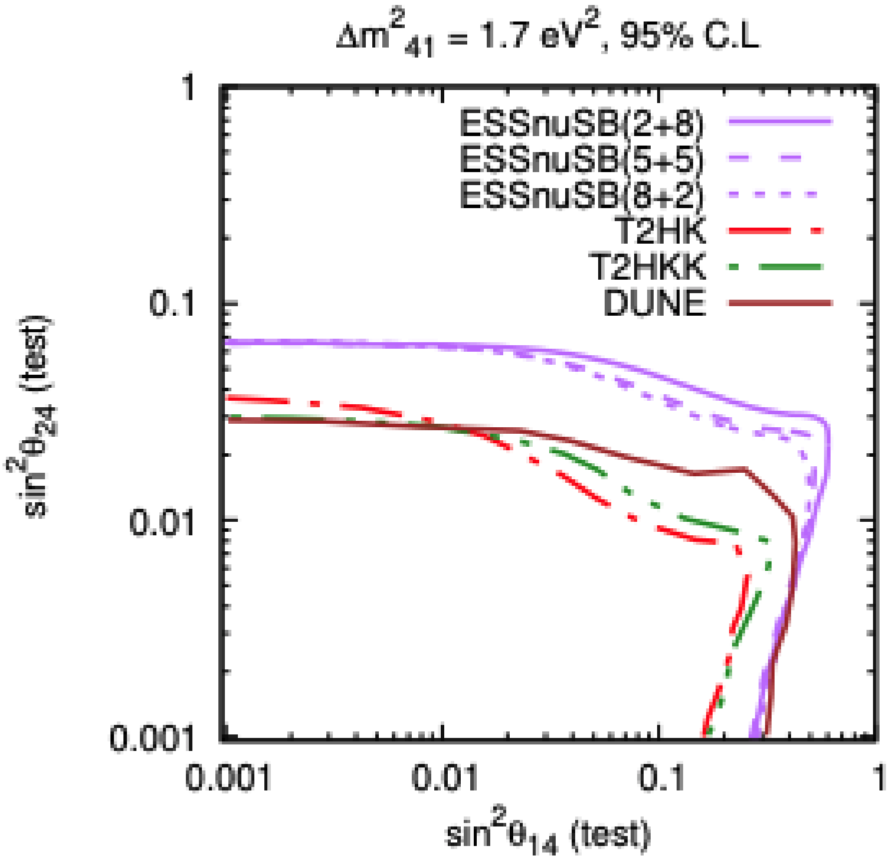




Alekou, *et al.* [ESSnuSB] Eur. Phys. J. ST **231** (2022), 3779-3955

Sterile neutrino

Experimental evidences suggest there might be a sterile neutrino at the eV scale



$$U = U_{34}(\theta_{34}, \delta_{34}) U_{24}(\theta_{24}, \delta_{24}) U_{14}(\theta_{14}, 0) U^{3\nu},$$
$$U^{3\nu} = U_{23}(\theta_{23}, 0) U_{13}(\theta_{13}, \delta_{13}) U_{12}(\theta_{12}, 0),$$

$$P_{\mu\mu}^{\mathrm{FD}} \simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{31} + 4 s_{13}^2 s_{23}^2 \cos 2\theta_{23} \sin^2 \Delta_{31} - \frac{1}{2} s_{24}^2 \left(3 + 2\cos 4\theta_{23} \sin^2 \Delta_{31} + \cos 2\Delta_{31}\right) + 4 s_{13} s_{14} s_{24} \left(\sin 3\theta_{23} - s_{23}\right) \cos(\delta_{13} + \delta_{24}) \sin^2 \Delta_{31}.$$

At the far detector:

$\Delta m^2{}_{41}$ cannot be studied
θ_{14} and θ_{24} can be probed

This study is with the old flux
Need to redo with updated flux

MG, Ohlsson and Rosauro-Alcaraz, JHEP 03 (2020), 026

Neutrino decay

Invisible neutrino decay: heavy neutrino state decays to a light sterile neutrino

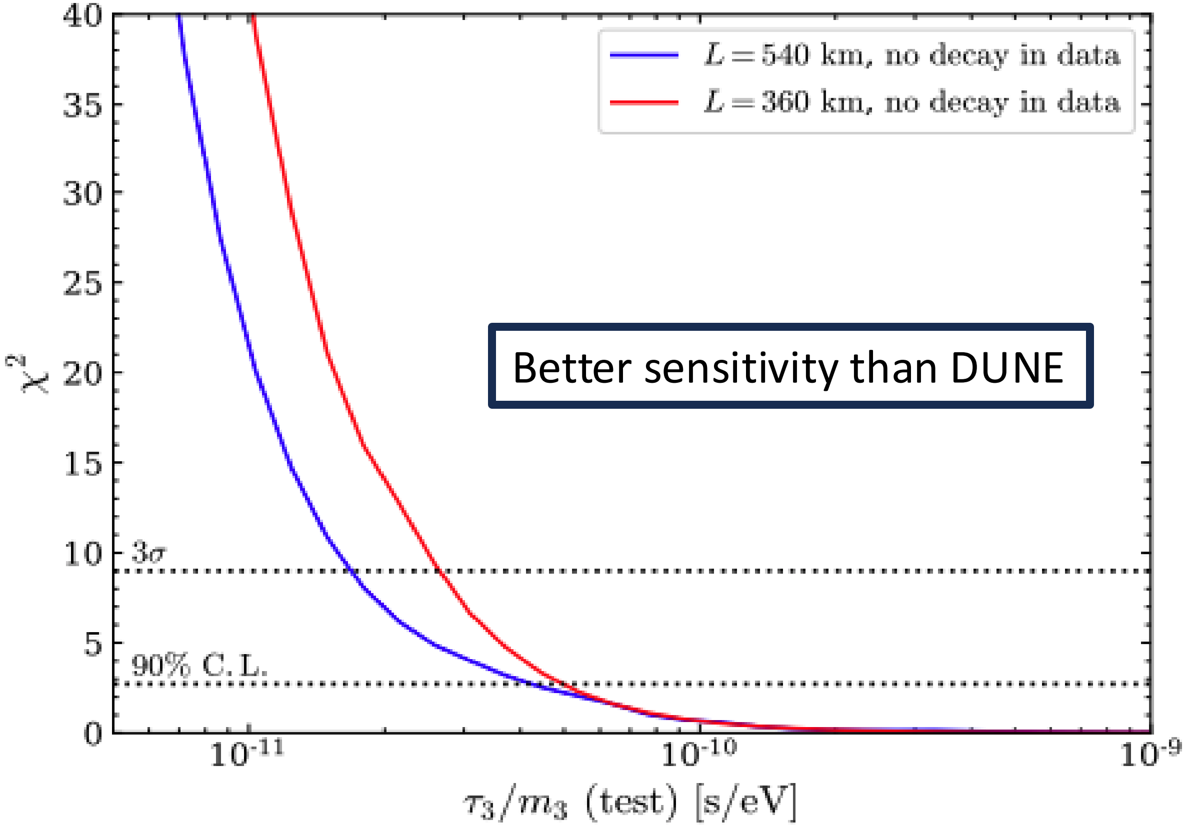
$$P_{\mu e} \simeq s_{13}^2 c_{13}^2 s_{23}^2 \left[4 \sin^2 \frac{\Delta_{\rm atm}}{2} - (1 - e^{-\Gamma_3}) + 2 \cos \Delta_{\rm atm} \left(1 - e^{-\frac{\Gamma_3}{2}}\right)\right],$$

$$\nu_j \to \nu_s + J$$

$$P_{\mu\mu} \simeq 1 - c_{13}^2 s_{23}^2 \left[4(1 - c_{13}^2 s_{23}^2) \sin^2 \frac{\Delta_{\rm atm}}{2} + c_{13}^2 s_{23}^2 (1 - e^{-\Gamma_3}) + 2(1 - c_{13}^2 s_{23}^2) \cos \Delta_{\rm atm} \left(1 - e^{-\frac{\Gamma_3}{2}}\right)\right],$$

ν_3 decays: $\Delta m_{31}^2 \to \Delta m_{31}^2 - i\alpha_3$

$$\Gamma_3 \equiv \alpha_3 L/E = m_3 L/(\tau_3 E).$$

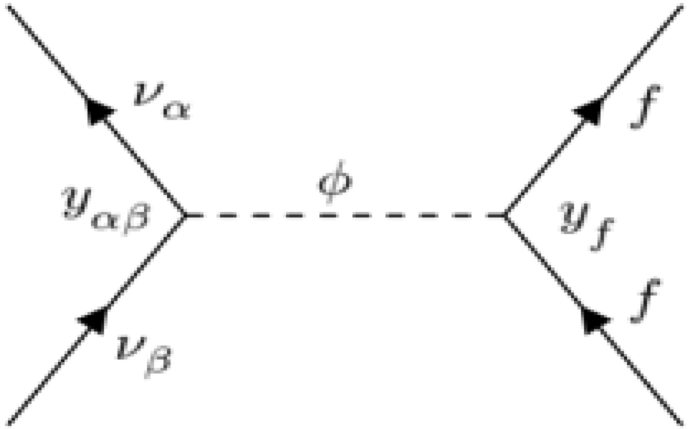


Experiment	90 % C.L. (3σ) bound on τ_3/m_3 [s/eV]
T2K + NOνA	$2.3\ (1.5) \times 10^{-12}$
T2K + MINOS	$2.8\ (1.8) \times 10^{-12}$
SK + MINOS	$2.9\ (0.54) \times 10^{-10}$
MOMENT	$2.8\ (1.6) \times 10^{-11}$
ESSnuSB (540 km)	$4.22\ (1.68) \times 10^{-11}$
DUNE (CC)	$4.50\ (2.38) \times 10^{-11}$
ESSnuSB (360 km)	$4.95\ (2.64) \times 10^{-11}$
DUNE (CC + NC)	$5.1\ (2.7) \times 10^{-11}$
JUNO	$9.3\ (4.7) \times 10^{-11}$
INO	$1.51\ (0.566) \times 10^{-10}$
KM3NeT-ORCA	$2.5\ (1.4) \times 10^{-10}$

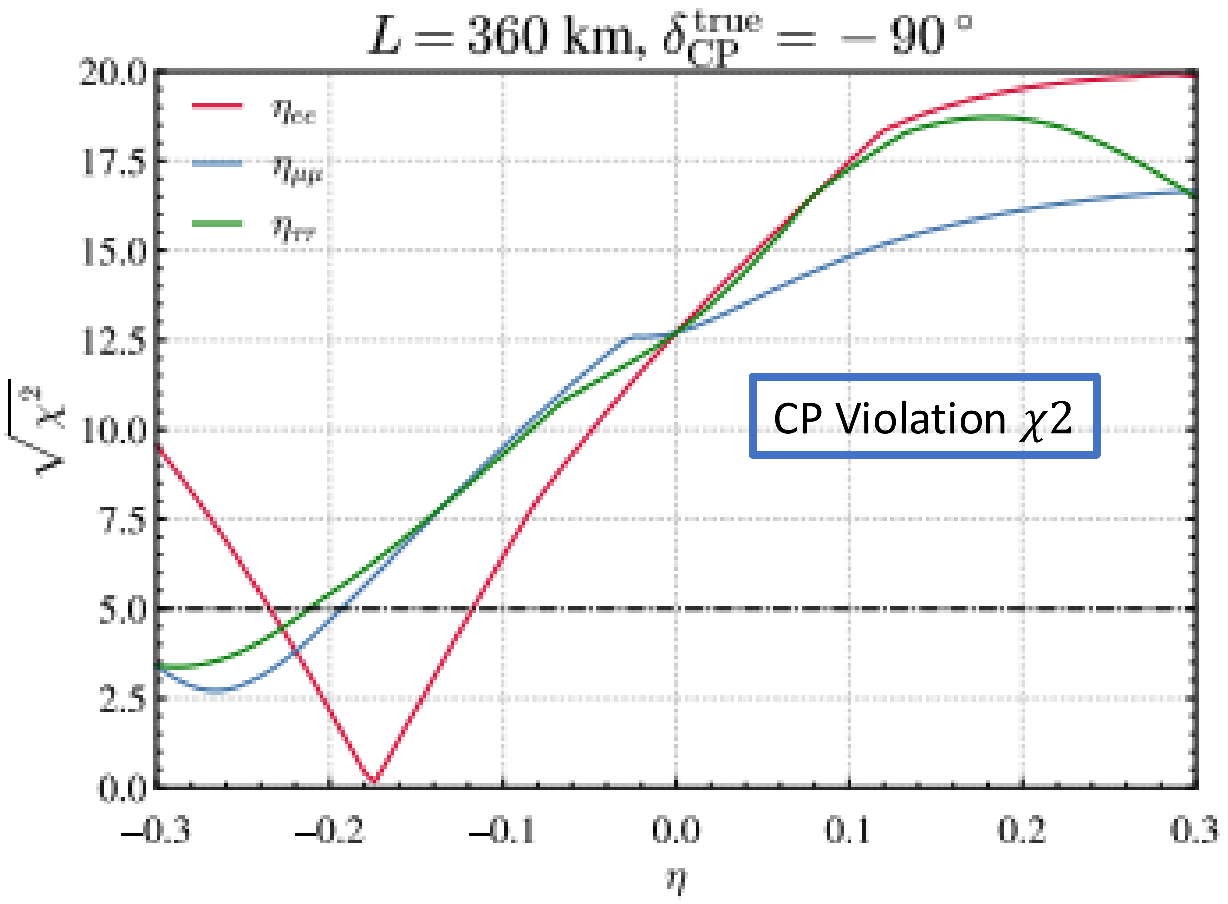
Choubey, MG, Kempe and Ohlsson, JHEP 05 (2021), 133

Scalar NSI

Non-standard interaqctions mediated by a scalar field



$$\mathcal{L} = \bar{\nu}(i\gamma^\mu\partial_\mu - m_\nu)\nu - (y_\nu)_{\alpha\beta}\bar{\nu}_\alpha\nu_\beta\phi - (y_f)_{\alpha\beta}\bar{f}_\alpha f_\beta\phi - \frac{1}{2}(\partial_\mu\phi)^2 - \frac{m_\phi^2}{2}\phi^2$$



$$\mathcal{L}_{\mathrm{eff}} = \sum_{f,\alpha,\beta} \frac{y_f y_\nu}{m_\phi^2}(\bar{\nu}_\alpha\nu_\beta)(f\bar{f}),$$

$$\delta M = \sqrt{|\Delta m_{31}^2|}\begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{\mu e} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta_{\tau e} & \eta_{\tau\mu} & \eta_{\tau\tau}, \end{pmatrix}$$

$$H = E_\nu + \frac{MM^\dagger}{2E_\nu} + V,$$

For η_{ee} = -0.18, CP sensitivity vanishes

Aguilar et al. [ESSnuSB], Phys. Rev. D 109 (2024), 115010

Quantum Decoherence

Open quantum system: Neutrino as a subsystem interacting with the environment giving rise to decoherence

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 2\sum_{i>j} \mathrm{Re}\left[\tilde{U}^*_{\alpha i}\tilde{U}_{\beta i}\tilde{U}_{\beta j}\tilde{U}^*_{\beta j}\right] \left[1 - \cos\left(2\tilde{\Delta}_{ij}\right)\, e^{-\Gamma_{ij}L}\right]$$
$$+ 2\sum_{i>j} \mathrm{Im}\left[\tilde{U}^*_{\alpha k}\tilde{U}_{\beta k}\tilde{U}_{\beta j}\tilde{U}^*_{\beta j}\right] \sin\left(2\tilde{\Delta}_{ij}\right)\, e^{-\Gamma_{ij}L},$$

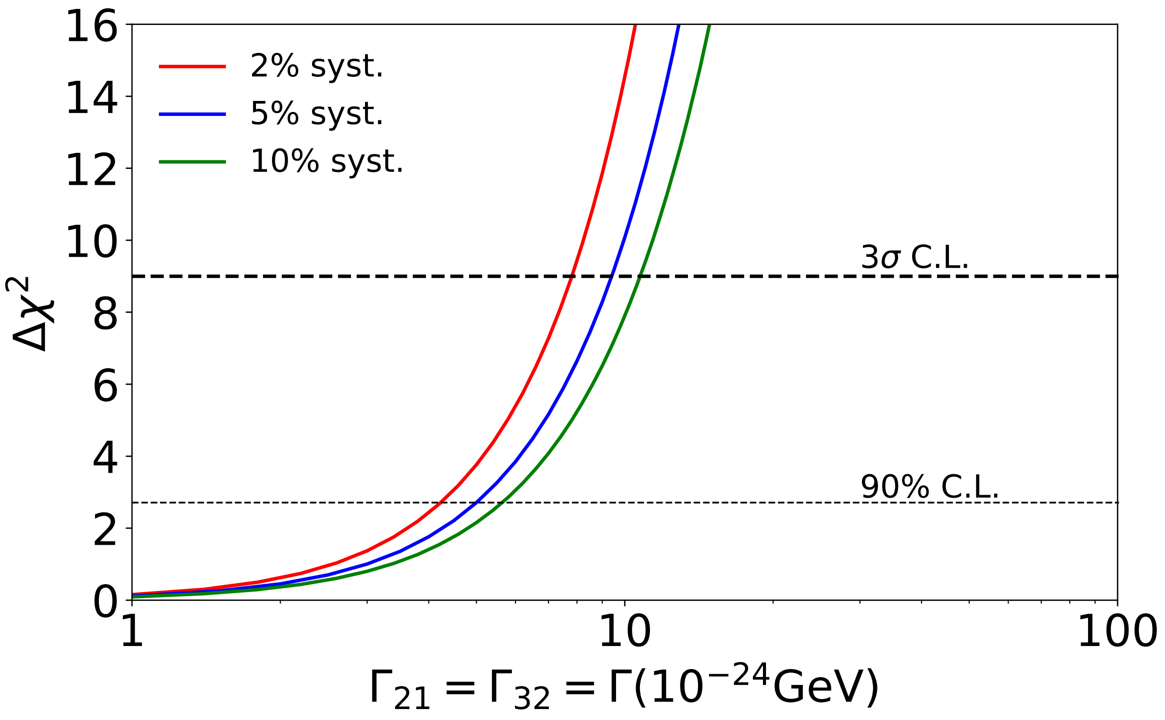
$$\frac{\partial \rho(t)}{\partial t} = -i[H, \rho(t)] + \mathcal{D}[\rho(t)]$$

H: Neutrino Oscillation Hamiltonian in matter
ρ = Density Matrix, $\mathcal{D}$ = Dissipator
λ = Gell-Mann Matrices

$$P_{\alpha\beta} = \mathrm{Tr}\left[\rho_\alpha(0)\rho_\beta(x)\right]$$

$$D_{jk} = -\mathrm{diag}(\Gamma_{21}, \Gamma_{21}, 0, \Gamma_{31}, \Gamma_{31}, \Gamma_{32}, \Gamma_{32}, 0)$$

$$\Gamma_{21} < 1.2 \times 10^{-23}\ \mathrm{GeV}\ \ [\mathrm{DUNE}, (90\%\ \mathrm{C.L.})]$$
$$\Gamma_{32} < 4.7 \times 10^{-24}\ \mathrm{GeV}\ \ [\mathrm{DUNE}, (90\%\ \mathrm{C.L.})]\,.$$

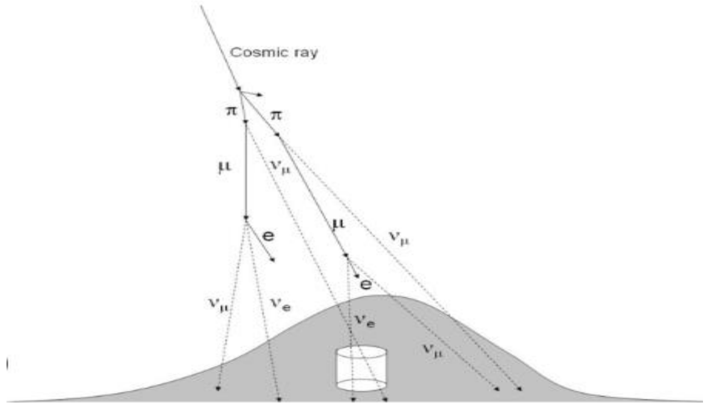


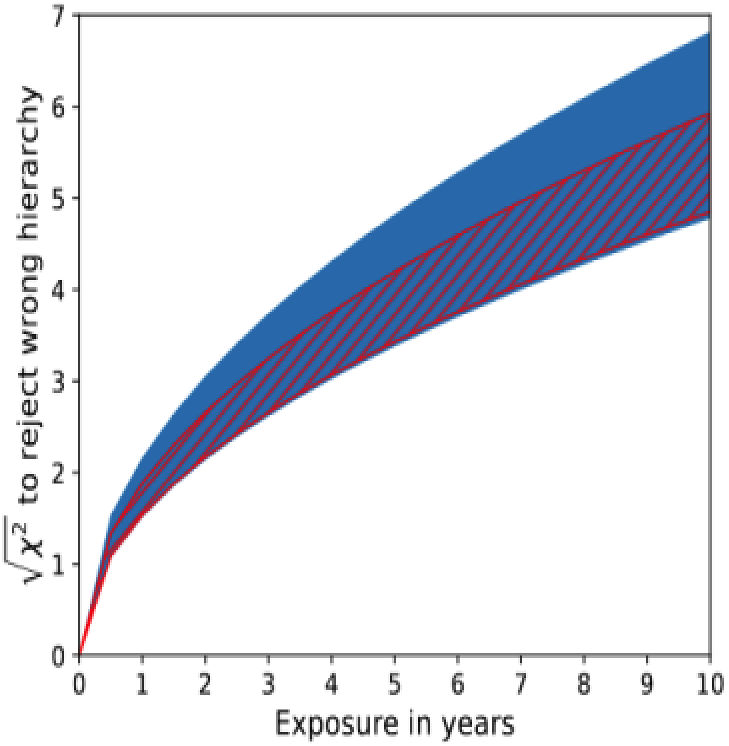
Bound comparable to DUNE

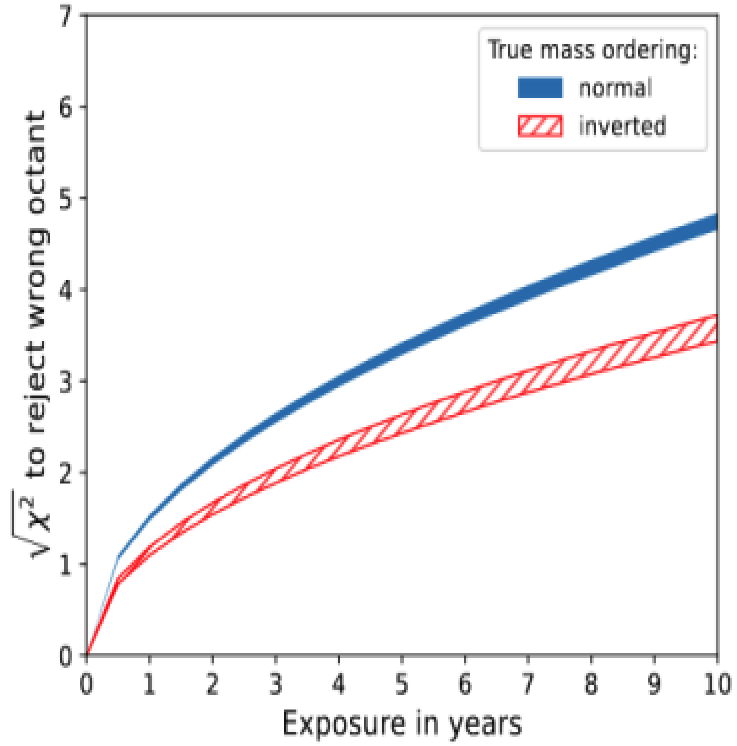
J. Aguilar et al. [ESSnuSB], JHEP 08 (2024), 063

Atmopsheric neutrino

Atmopsheric neutrinos are produced in Earth's atmosphere via interaction with the cosmic rays

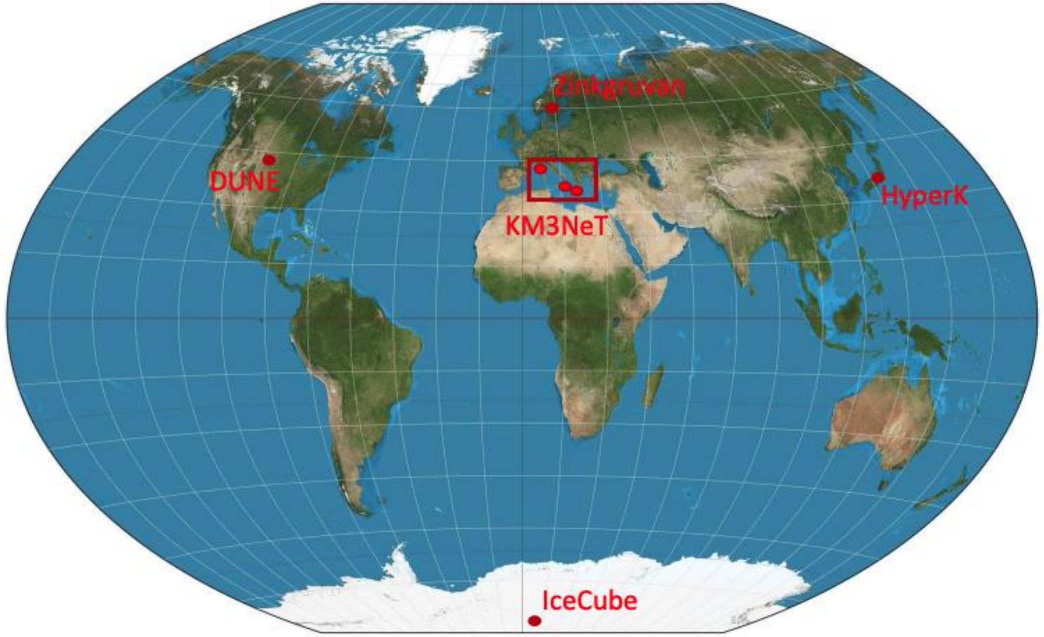






Excellent sensitivity due to

- Strong flux near the pole
- Larger detector volume



J. Aguilar et al. [ESSnuSB], JHEP 10 (2024), 187

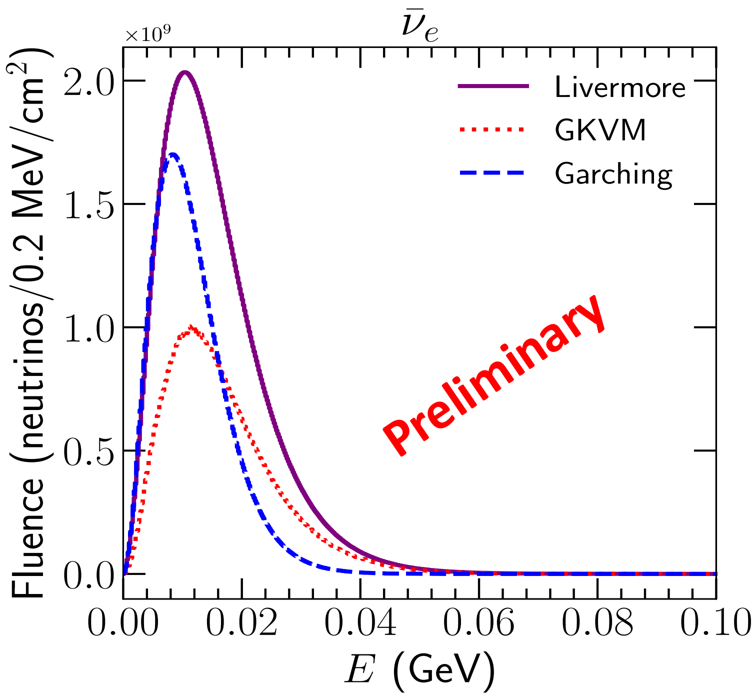
Supernova neutrinos

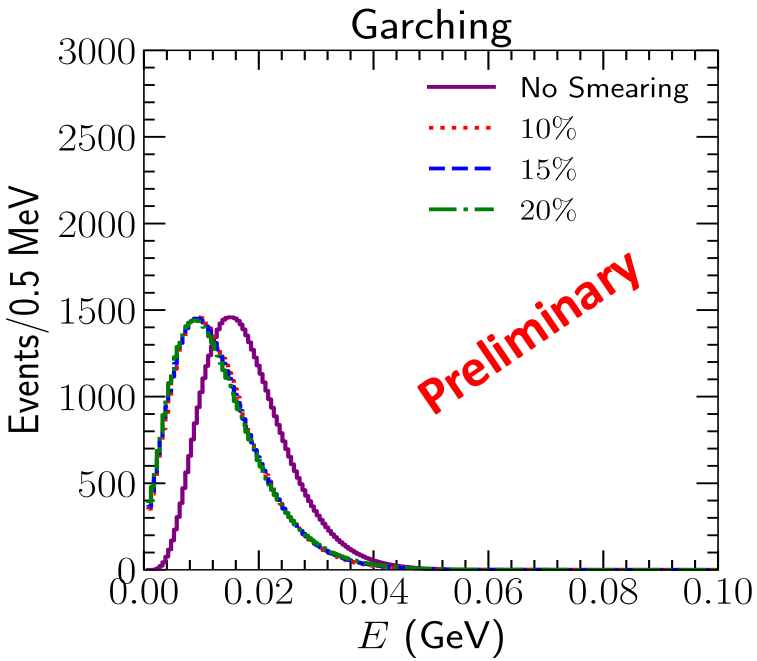
The huge FD can detect a future supernova explotion in our galaxy

Dominant detection channel: $\bar{\nu}_e + p \rightarrow n + e^+$

Livermore	GKVM	Garching
148,686	88,528	51,068

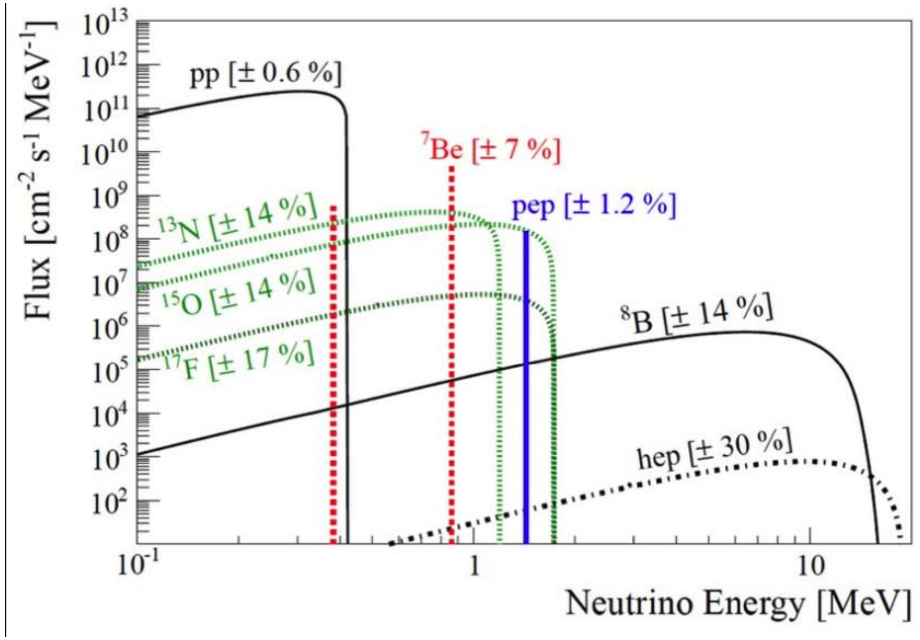
- Large uncertainty on supernova flux - Depends on the model
- Different model predicts different event rates
- Study on capability of ESSnuSB in disntiguishing diiferent models is ongoing



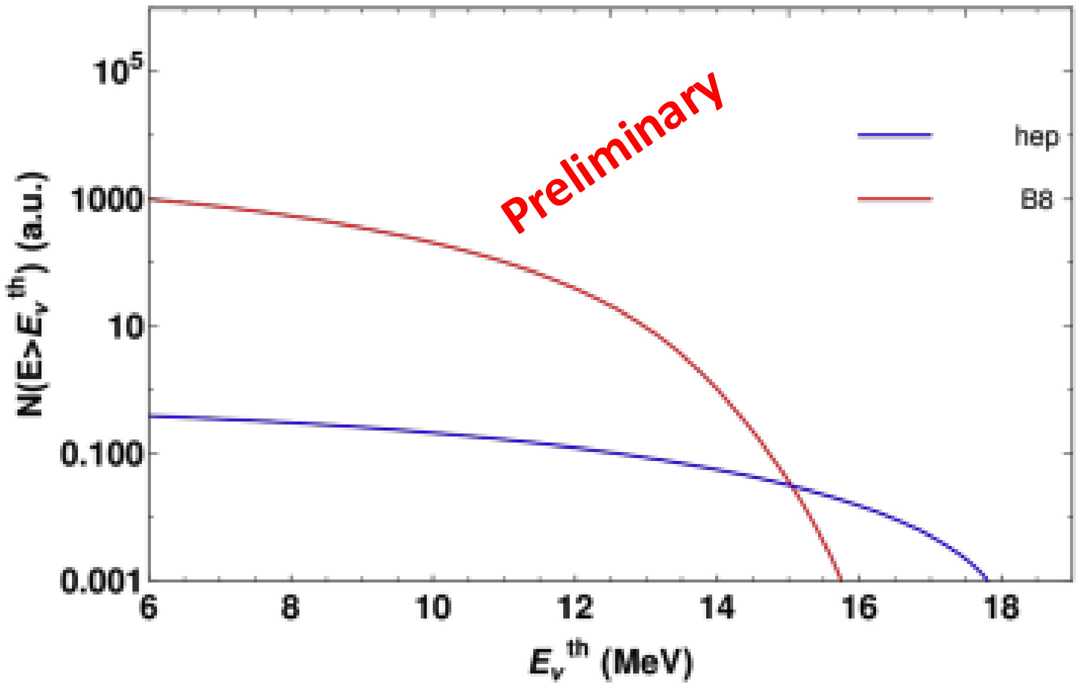


Solar neutrinos

Some of the remaining challenges in solar neutrinos can be solved with ESSnuSB



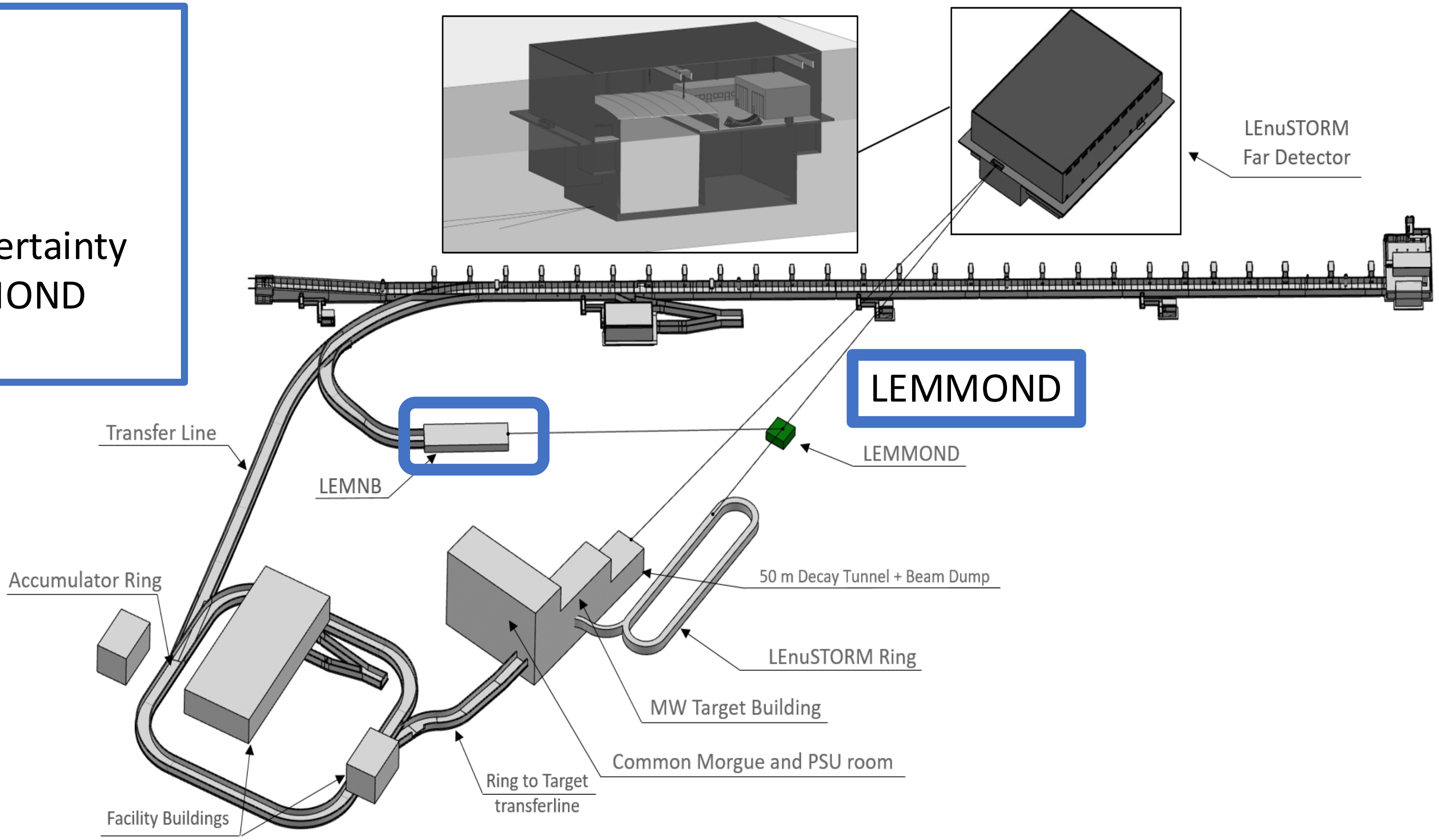
- hep neutrinos have not been observed so far
- The large ESSnuSB far detector can distinguish between 8B and hep neutrinos
- ESSnuSB FD expects to see around 370 events/day



Low Energy Monitered Beam (LEMNB)

Low energy monitored beam (WP6)

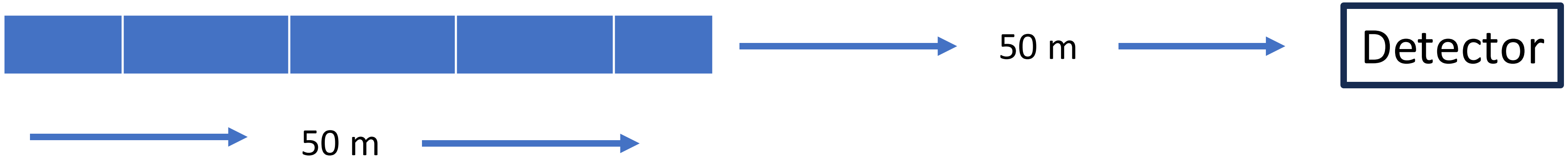
- Inspired by original ENUBET idea
- Instrumented decay pipe
- To measure neutrino flux to 1% uncertainty
- Neutrinos will be detected at LEMMOND
- Also suitable for sterile neutrinos



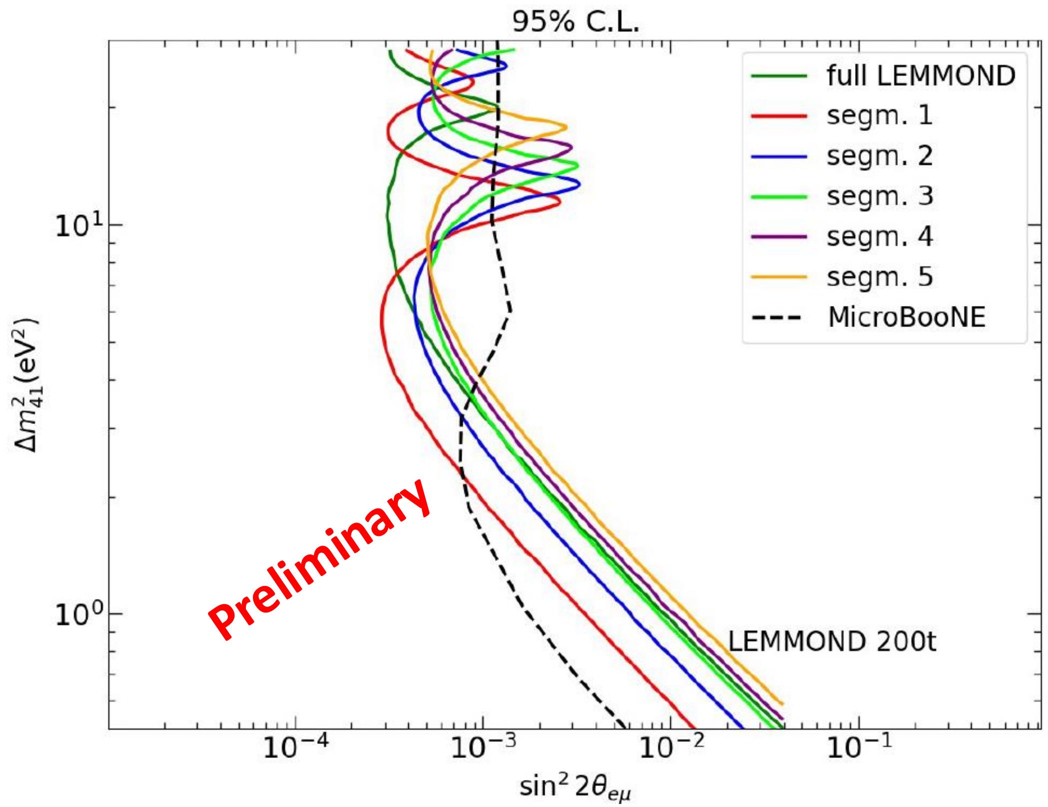
Sterile neutrinos at LEMNB

Effective baseline can change depenidng on the Production point of the neutrinos in the decay pipe

Decay pipe ($\pi \longrightarrow \mu + \nu_\mu$)



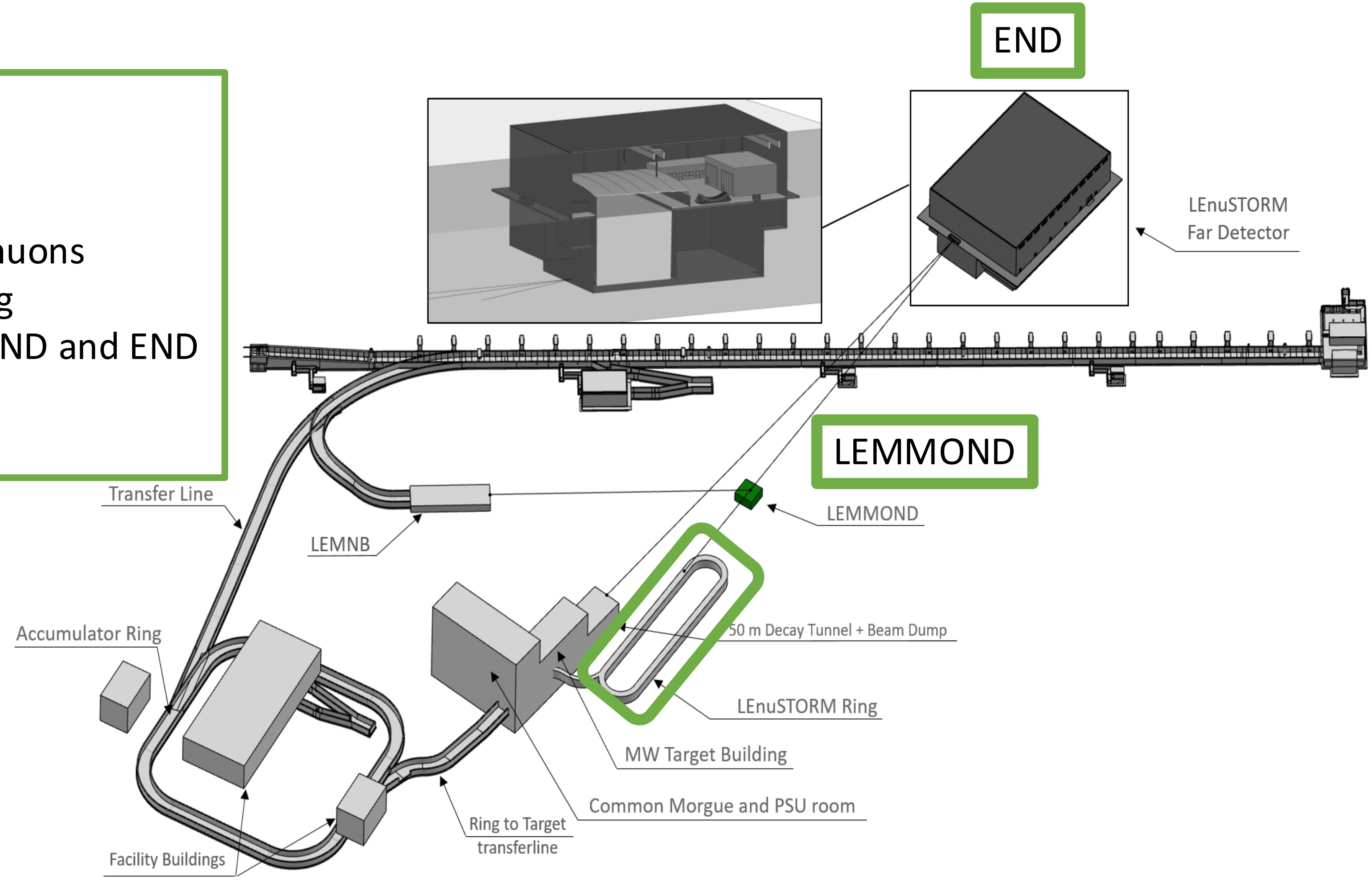
Baselines:
- Segm.1 = 90m
- Segm.2 = 82 m
- Segm.3 = 74 m
- Segm.4 = 66 m
- Segm.5 = 58 m
- Full = 50 m



Low Energy nuSTORM (LEnuSTORM)

LEnuSTORM (WP4)

- Inspired by original nuSTORM idea
- Neutrinos produced from decay of muons
- Muons will be stored in a storage ring
- Neutrino will be detected in LEMMOND and END
- Mainly for cross-section studies
- Also suitable for sterile neutrinos



Summary

ESSnuSB+ setup is consists of 3 neutrio sources and 3 detectors:

Neutrino sources: main ESS beam, LEMNB and LEnuSTORM

Detectors: FD, END and LEMMOND

Very strong sensitivities for both beam and non beam based physics including flux and cross-section measurement

One advertisement in next slide

Advertisement for IRB

- Recently a multilateral project (MAPS) got funded by SNSF (85%) and HRZZ (15%)
- Three Institutes: IRB (PI: Me), University of Silesila in Katowice (PI: Janusz) and University of Geneva (PI: Federico Sanchez)
- Started on July 2025, duration: 4 year
- To work on neutrino phenomenology and experiment (oscillation, flavour models, interaction, cross-section, T2K, NINJA etc)
- Post-doc positions will open soon

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Thank You