ESS NEUTRINO SUPER BEAM

ESS neutrino Super Beam plus

Co-funded by the European Union

The European Spallation Source neutrino Super Beam (ESSνSB)project:

Status and Prospects

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On behalf of the ESSnuSB collaboration

ESS neutrino Super Beam plus

Co-funded by the European Union

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

13 countries
23 Institutes

AGH
UNIVERSITEIT GENT
ESS bilbao
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Luleå University of Technology
ess
Université de Strasbourg
CERN
Università degli Studi di Milano Bicocca
Roma Tre Università degli Studi
Aristotle University of Thessaloniki
Università degli Studi di Padova
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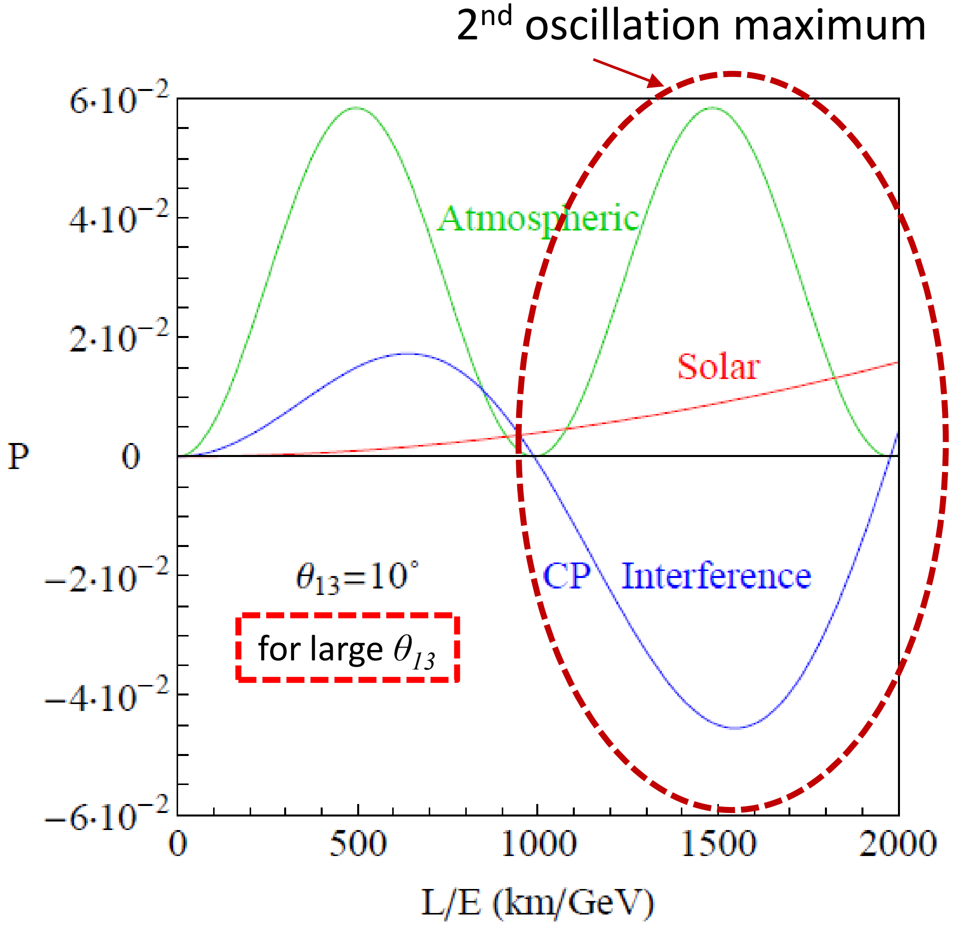
Lunds Universitet
KTH Vetenskap och Konst
Hellenic Open University
名古屋大学 Nagoya University
INFN Istituto Nazionale di Fisica Nucleare
cnrs
IPHC Institut Pluridisciplinaire Hubert Curien Strasbourg

ESSnuSB (2018-2022) / ESSnuSB+ (2023-2026)

(European Spallation Source neutrino Super Beam)

A proposed next generation long-baseline experiment, based on the powerful ESS proton beam, **to measure the CP violation in the leptonic sector with *precision*,** taking advantage of the measurement at the ***second neutrino oscillation maximum.***



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

$$s_{ij} \equiv \sin\theta_{ij} \qquad \Delta m^2_{ij} \equiv m^2_{\nu_i} - m^2_{\nu_j} \qquad J = s_{12}c_{12}s_{13}c_{13}s_{23}c_{23}c_{13}\sin\delta_{\rm CP}$$

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

Matter-antimatter Asymmetry:

$$A \equiv \frac{|P(\nu_\mu \to \nu_e) - \bar{P}(\bar{\nu}_\mu \to \bar{\nu}_e)|}{[P(\nu_\mu \to \nu_e) + \bar{P}(\bar{\nu}_\mu \to \bar{\nu}_e)]}$$

$$A_{CP}(1st\ Osci.max) = \mathbf{0.3} \cdot sin\delta_{CP}$$

$$A_{CP}(2nd\ Osci.max) = \mathbf{0.75} \cdot sin\delta_{CP}$$

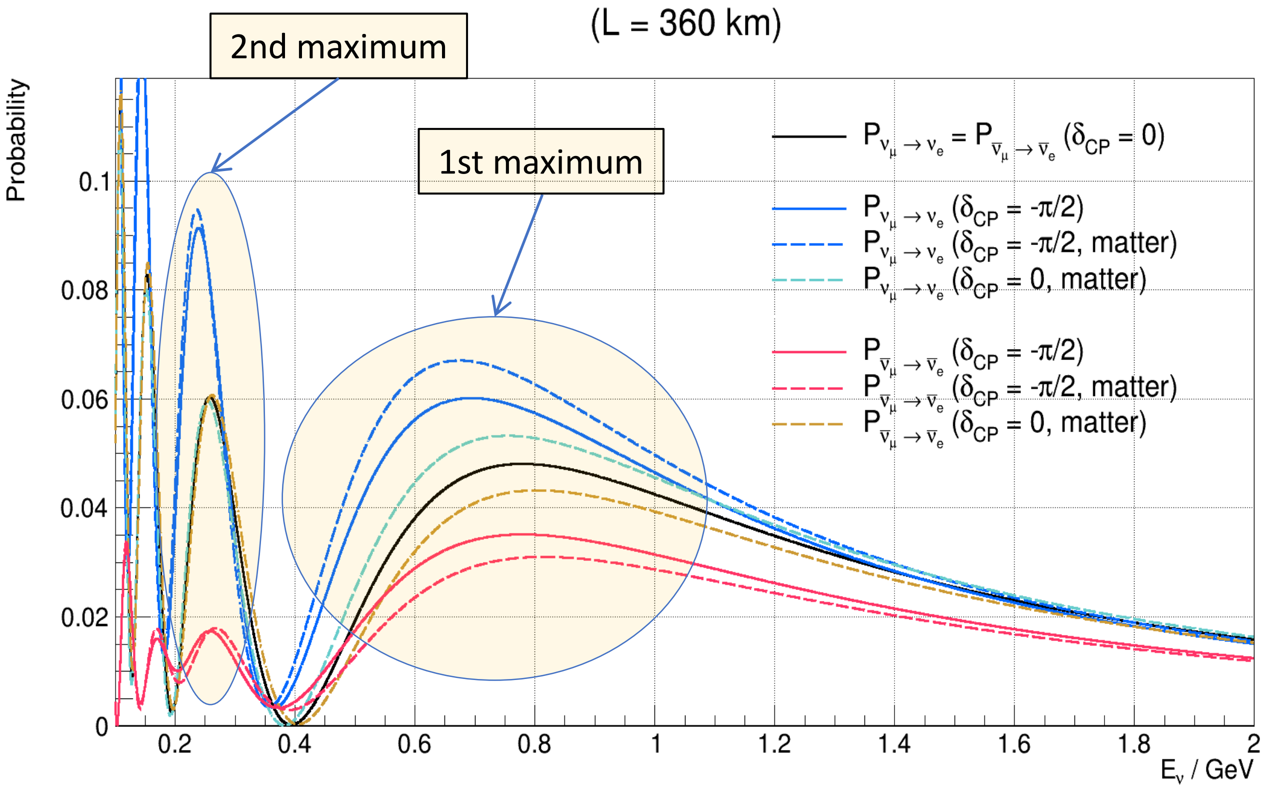
$$\frac{A_{CP}@\ 2nd\ max.}{A_{CP}@\ 1nd\ max.} \sim 2.5$$

S. Parke, https://arxiv.org/pdf/1310.5992

The larger L/E (second Oscillation Maximum) also makes the CP discovery potential more stable against systematic uncertainties for large θ_{13}, since the CP interference term will become a leading part of the oscillation probability and hence harder to hide behind systematic errors.

What about matter effects?

- The elastic interactions of neutrinos with matter modify the oscillation probabilities (only the electron neutrinos have CC elastic scattering with electrons).
- For uniform matter density, these effects can be included by replacing vacuum oscillation parameters with effective "matter parameters"
  - $\theta_{ij} \rightarrow \theta_{ij}^{(m)}(E),\ \delta_{CP} \rightarrow \delta_{CP}^{(m)}(E)$ and $\Delta m_{ij}^2 \rightarrow \Delta M_{ij}^2(E)$
  - the effective parameters now depend on energy
- For non-uniform densities numerical calculation of probabilities is required



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

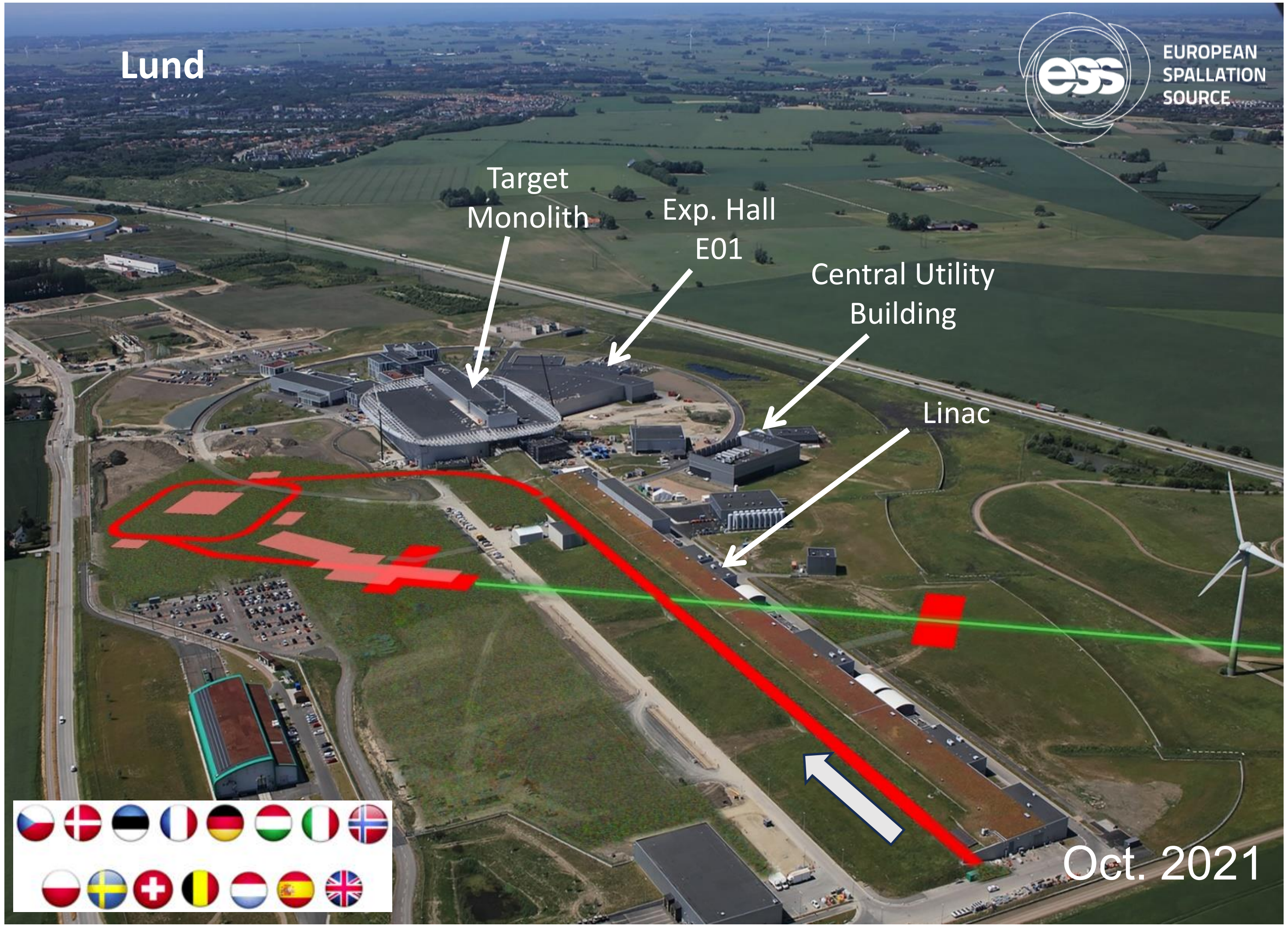
At 2nd maximum:
- larger sensitivity to δ_{CP}
- matter doesn't matter

The European Spallation Source (ESS)

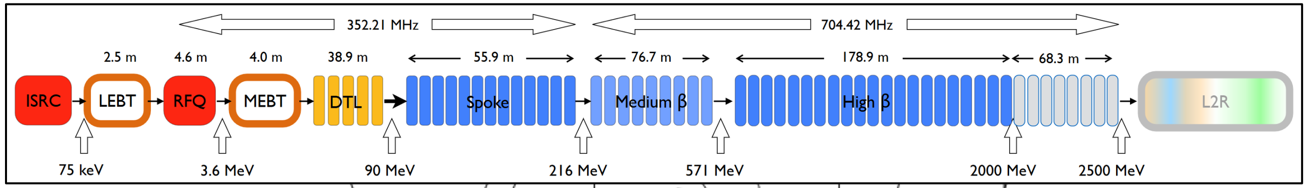
- ➢ The ESS facility is under construction in Lund, Sweden. First beam expected in 2026.
- ➢ Using a powerful proton linear accelerator, designed for $E_{kinetic}$ = 2 GeV and 5 MW power.
- ➢ to produce the world's most powerful neutron source.
- ➢ 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- ➢ up to 3.5 GeV with linac upgrades, **> 2.7x10^{23} p.o.t/year.**

Using this powerful accelerator, we can produce a high intensity neutrino super beam!

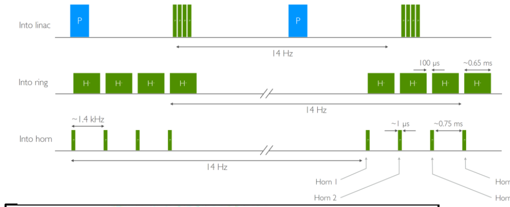
The European Spallation Source Neutrino Super Beam (ESSνSB)

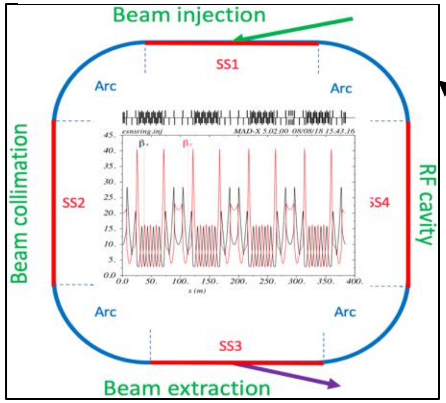


ESS upgrades to host ESSnuSB

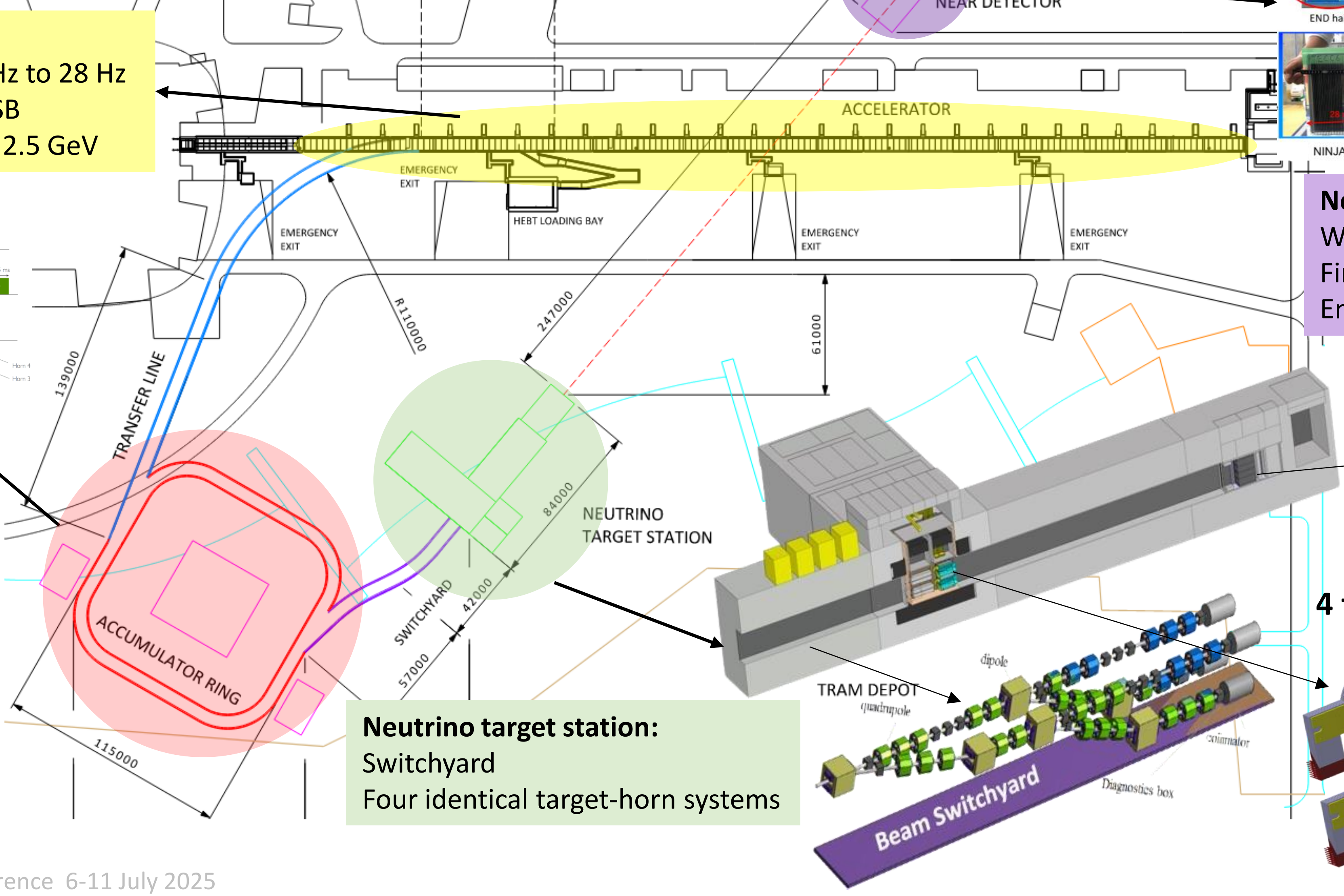


Upgrade of the accelerator
Increase pulse frequency 14 Hz to 28 Hz
Use H^- instead of p for ESSnuSB
Increase $E_{kinetic}$ from 2 GeV to 2.5 GeV

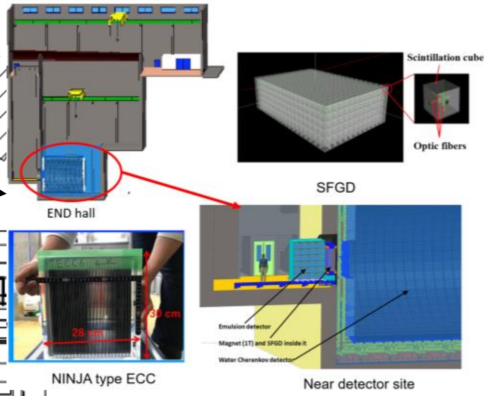




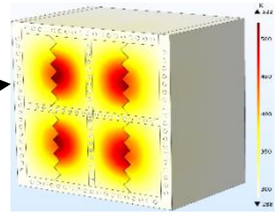
Build an accumulator ring
Compress ESS pulse length from 2.86 ms to 4x 1.2 μs



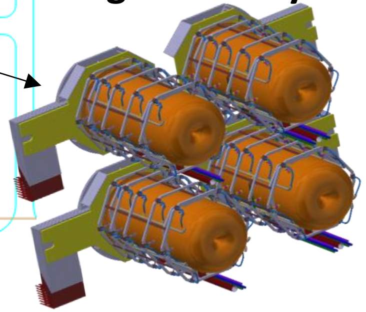
Neutrino target station:
Switchyard
Four identical target-horn systems



Near detector:
Water Cherenkov detector
Fine grained scintillator
Emulsion detector

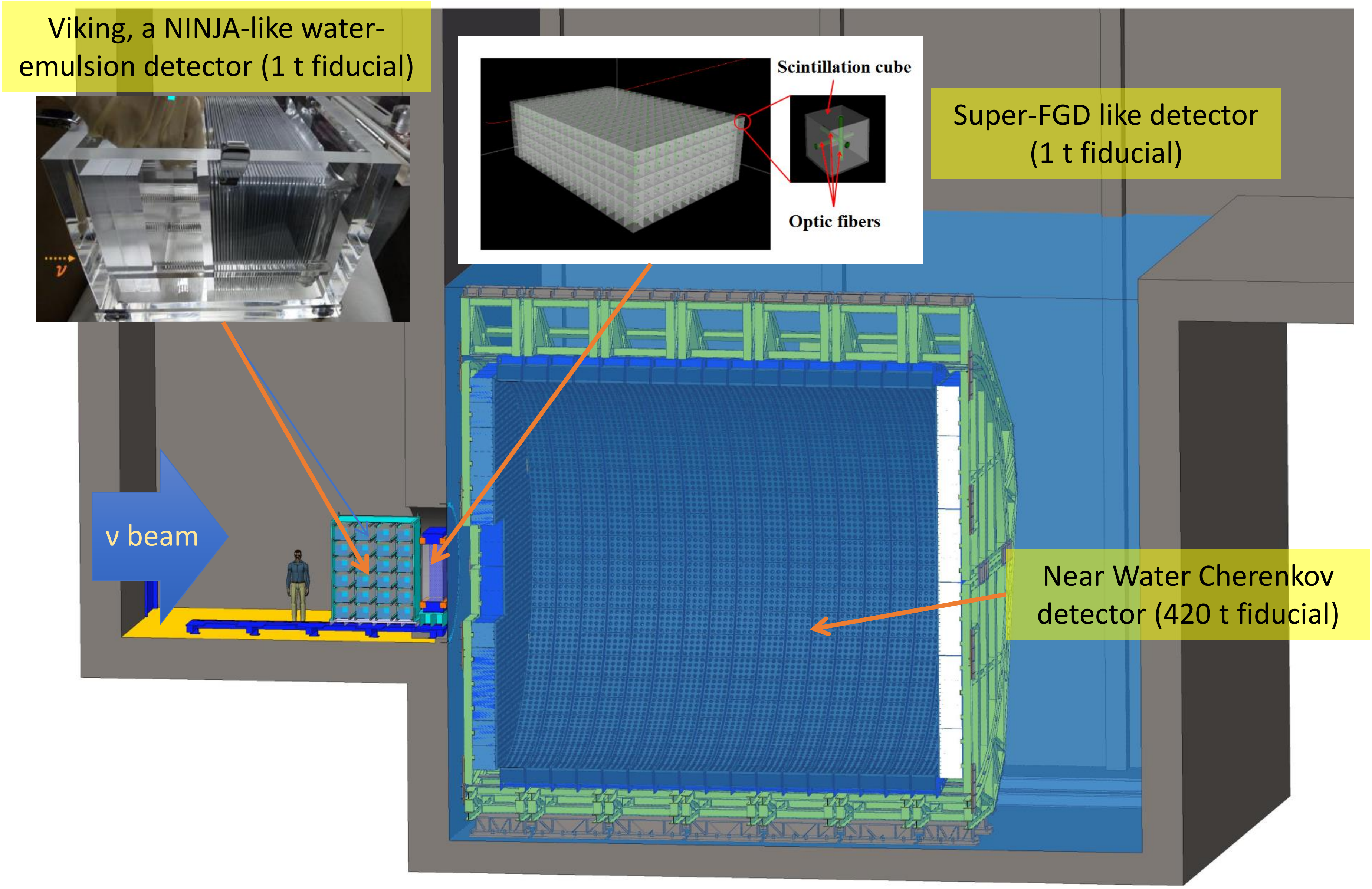


4 target-horn systems

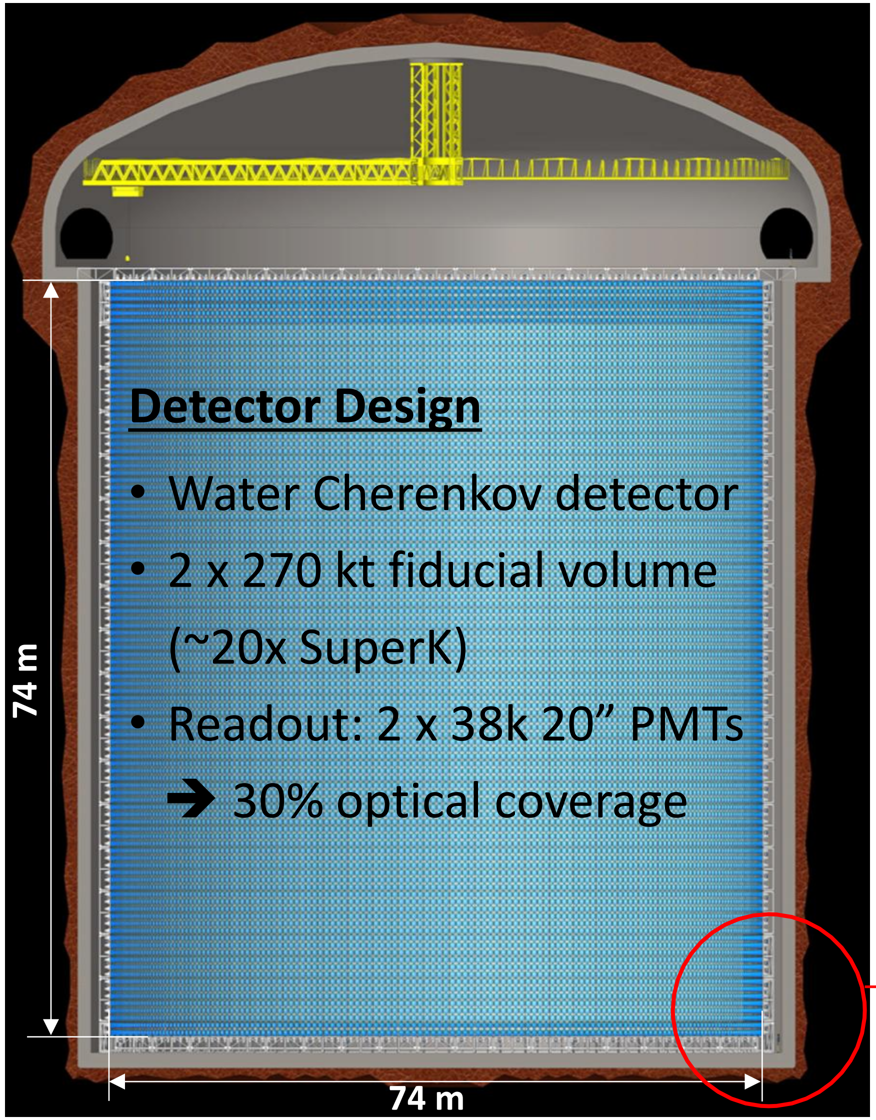


ESSnuSB Near Detectors (END)

At 0.25 Km, to monitor neutrino beam intensity and measure muon and electron neutrino and antineutrino cross sections



ESSnuSB far Detector



Detector Design

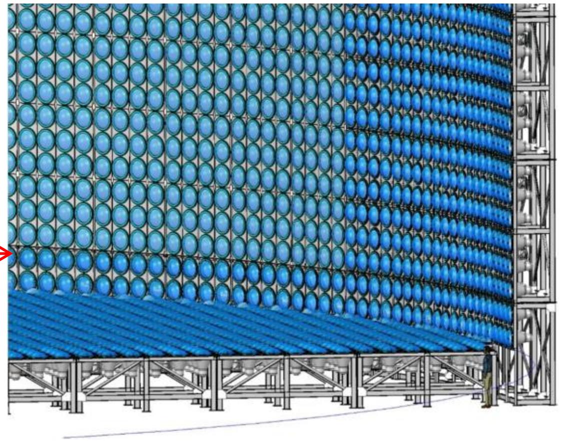
- Water Cherenkov detector
- 2 x 270 kt fiducial volume (~20x SuperK)
- Readout: 2 x 38k 20" PMTs
  ➔ 30% optical coverage

Detector Specifications

- Baseline 360 km
- Detector diameter 74.0 m (Internal)
- Detector height 74.0 m (Internal)
- Depth (w.r.t. ground level): 1000 m

Detector Performance

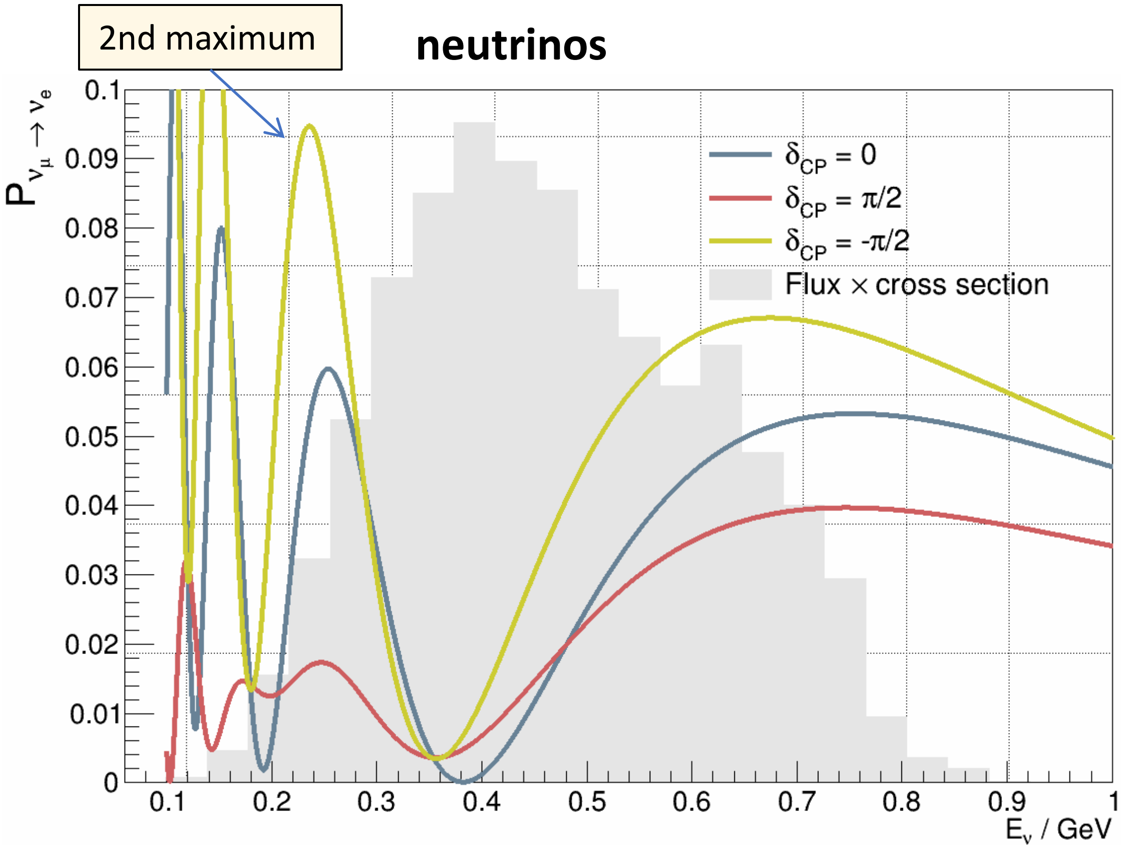
- Detector efficiency for correctly identifying neutrinos > 85%.
- Flavour misidentification probability < 1%.



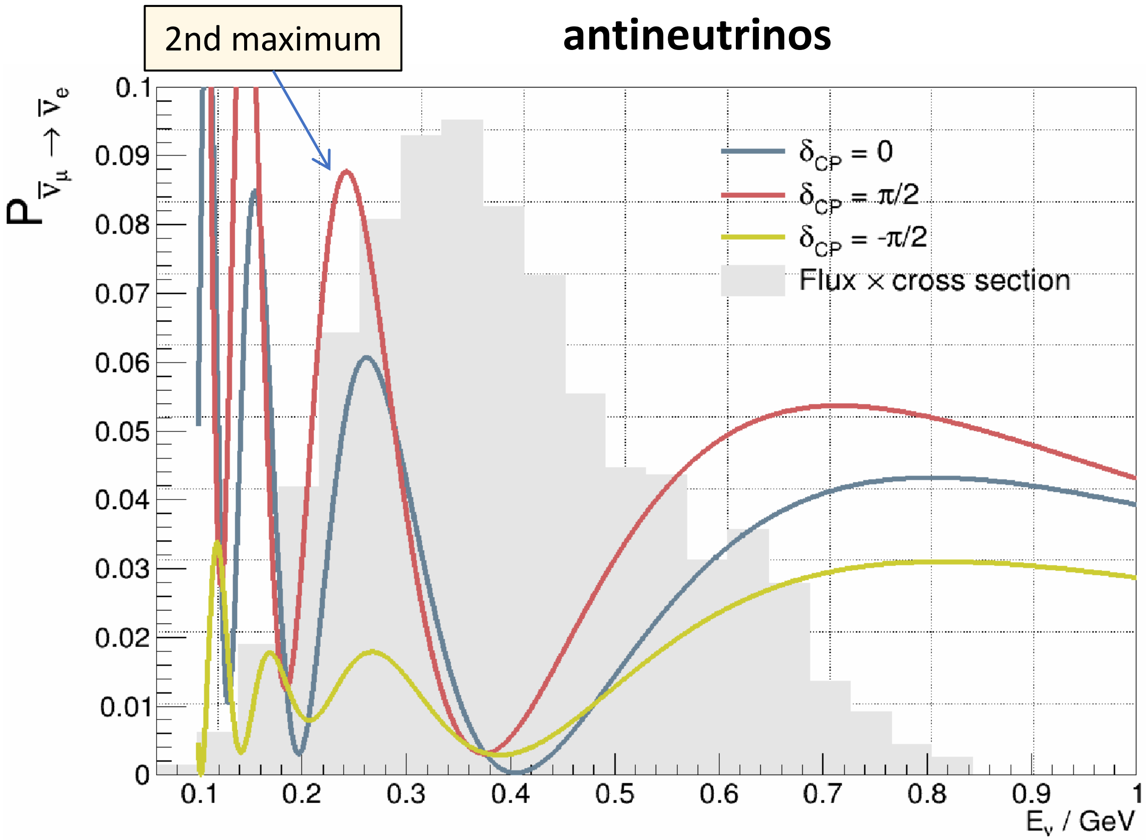
ESSνSB Energy coverage

Baseline = 360 km (Zinkgruvan mine)

neutrinos



antineutrinos

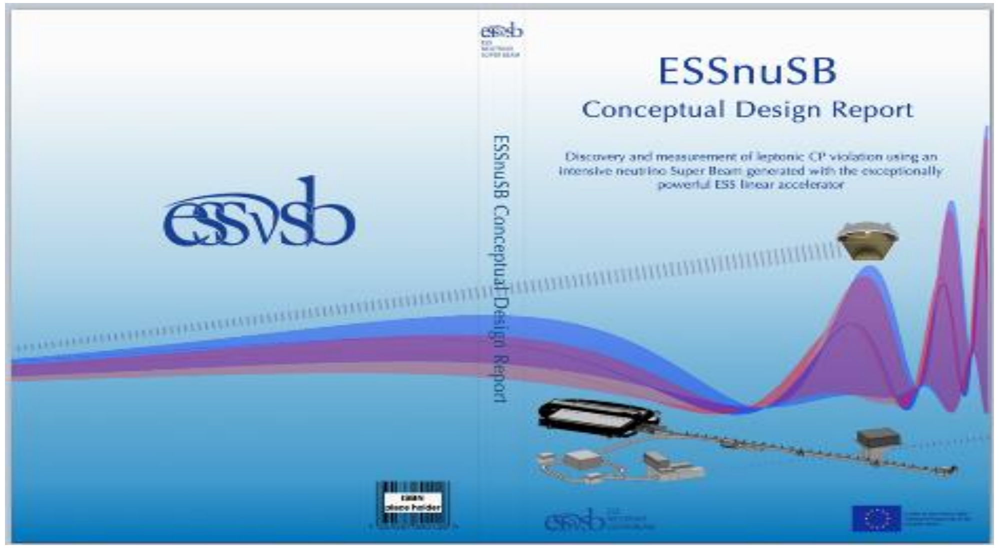


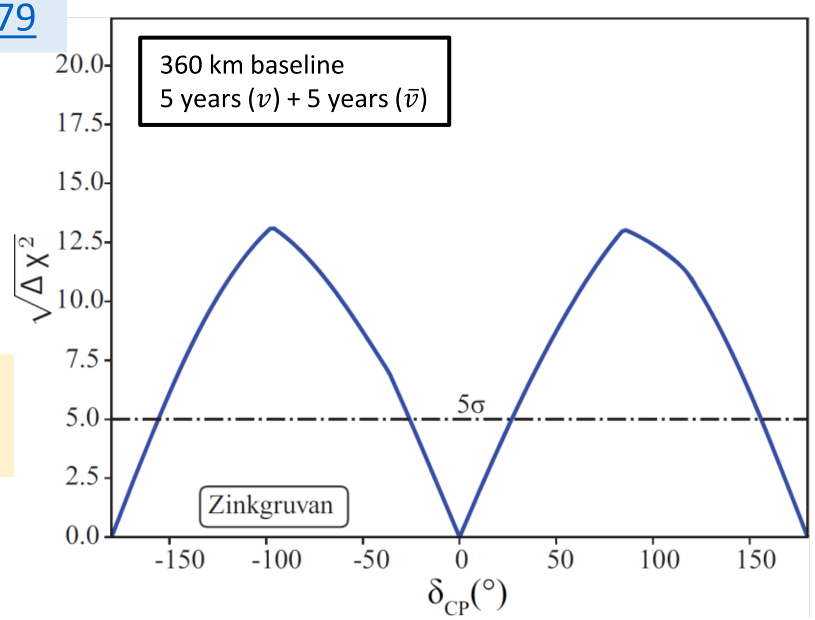
First and Second Oscillation maxima covered at 360 km baseline!

ESSνSB main Physics reach

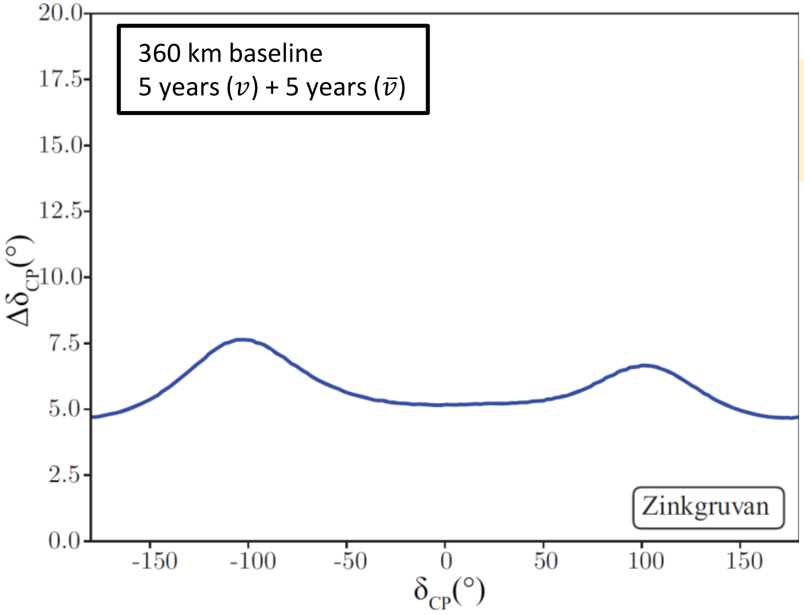
Eur. Phys. J. ST. 231 (21), (2022) 3779

Conceptual design report

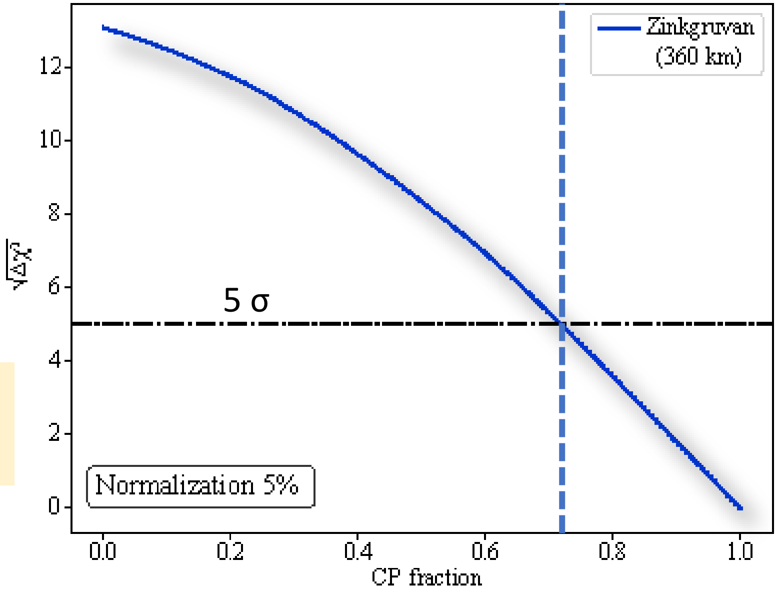




Sensitivity for $\delta_{CP} = \pm \pi/2$ ~ 12 σ



$\Delta\delta_{CP} < 8°$ for all δ_{CP} values



Covers 72% of δ_{CP} values in ~ 10 years (@ 5 σ C.L.)

The EU-Horizon ESSnuSB+ project (2023-2026)

Having finished the conceptual design of the facility for CP violation measurement,

we needed to take further steps and expand our Physics potential:

- Study the civil engineering needed for the facility implementation at the ESS site as well as those needed for the ESSνSB far detector site.
- Study the feasibility and implementation of a special target station for pion production and extraction for injection to a low energy nuSTORM decay ring and to a low energy Monitored Neutrino Beam decay tunnel, for precision neutrino cross-section measurements.
- Design facilities for very precise neutrino cross-section measurements: Low Energy nuSTORM (LEnuSTORM), Low Energy Monitored neutrino Beam (LEMNB) and a near-near Detector (LEMMOND).
- Explore the additional physics capabilities of the Far Detector complex including the benefits of adding Gadolinium.
- Study the capabilities of the proposed setup for Sterile Neutrino searches and Astroparticle physics.

- Promote the ESSνSB project proposal to its stakeholders, including scientists, politicians, funders, industrialists and the general public, in order to pave the way to include this facility in the ESFRI (European Strategy Forum for Research Infrastructures) list.

The new project (ESSnuSB+) is funded by EU-Horizon for the period 2023-2026.

ESSnuSB+

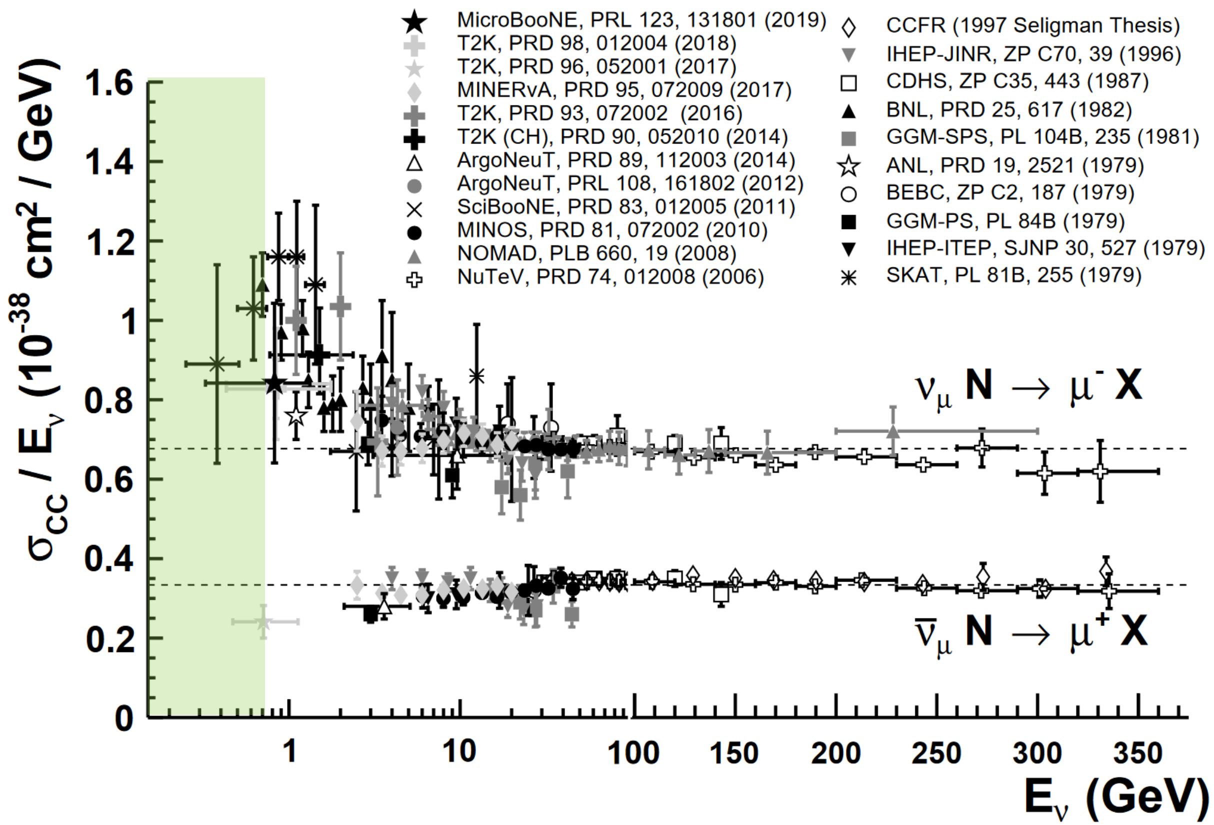
(European Spallation Source neutrino Super Beam plus)

The uncertainty in the neutrino-nucleus cross section below 600 MeV is the dominant term of the systematic uncertainty in ESSnuSB.

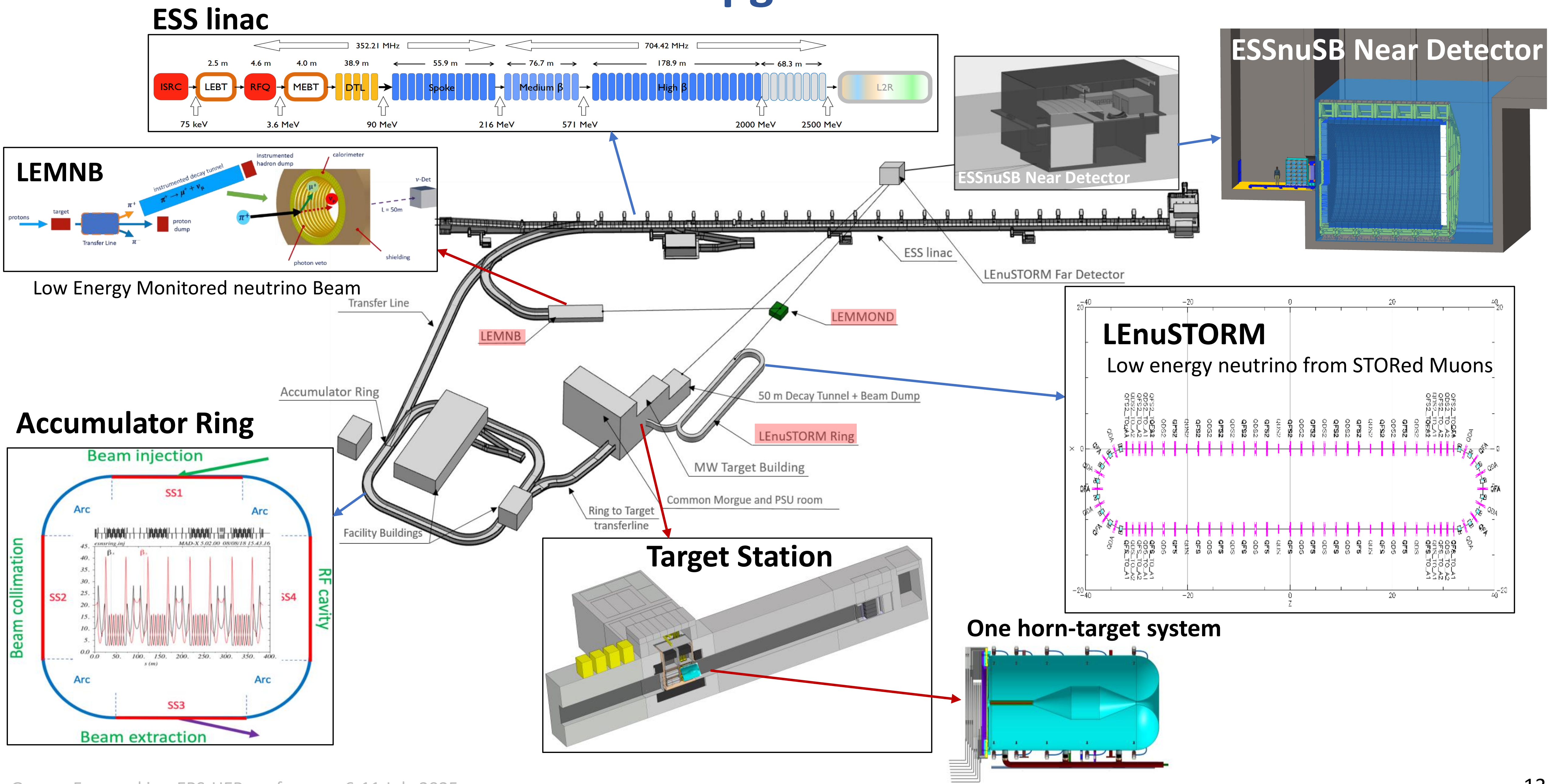
Even though the effect of systematics for the CP violation measurement is much less in ESSnuSB it is crucial to obtain new precise results in this direction

https://pdg.lbl.gov/2022/reviews/rpp2022-rev-nu-cross-sections.pdf

missing measurements at the ESSnuSB region: below 600 MeV



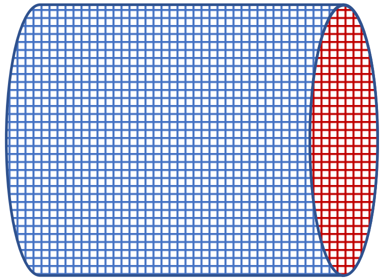
Additional ESS upgrades for ESSnuSB+



LEMMOND: the near-near detector of ESSnuSB+

Low Energy Neutrino Stored Muons and Monitored Beam Near Detector

Design work in progress



A cylindrical detector with about 2.5m radius and 10 m length and a water volume ~200 tons, located 50 m downstream of LEnuSTORM or LEMNB facilities. It will serve to precisely measure neutrino cross sections at the ESSnuSB energy range but also as a near detector for a Short Base Line setup.

Initially, before developing a full simulation of the detector, **we used a "toy" model with a flat detector to**:

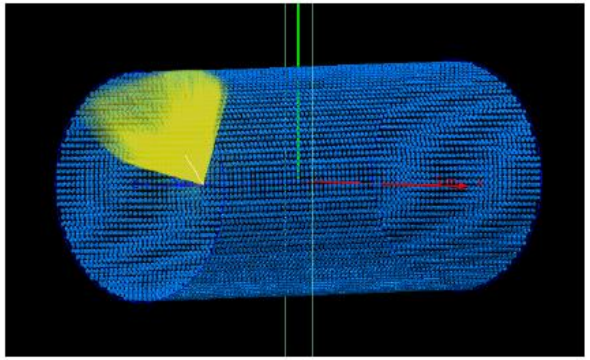
- Establish the track simulation techniques, photoelectron collection and muons/electrons track reconstruction.
- Distinguish muons from electrons

Used GEANT4 simulated tracks:

- Tracks produced with [$\theta=0^o$ or $\theta=30^o$ and $\phi=0^o$] initial direction, wrt to the detector, starting ~200cm away from the Detector
- The detector is a 400 x 400 cm^2 plane (6400 5x5 cm^2 pads) with time resolution 1.5 ns or 120 ps.
- Employing the log likelihood methodology, the angle resolution (θ or ϕ) was about 1^o and the vertex resolution 2.9 cm for the 1.5 ns and 0.6 m for the 120 ps detectors.

Established a realistic cylindrical detector with varying detector coverage. Based on total photoelectrons detected the following momentum resolutions were obtained:

- Muon Momentum resolution 1.5% (300 MeV)
- Electron Momentum resolution 5% (100 MeV)



To reduce time processing and take into account the correlations due to multiple scattering we are employing GNN methodology.

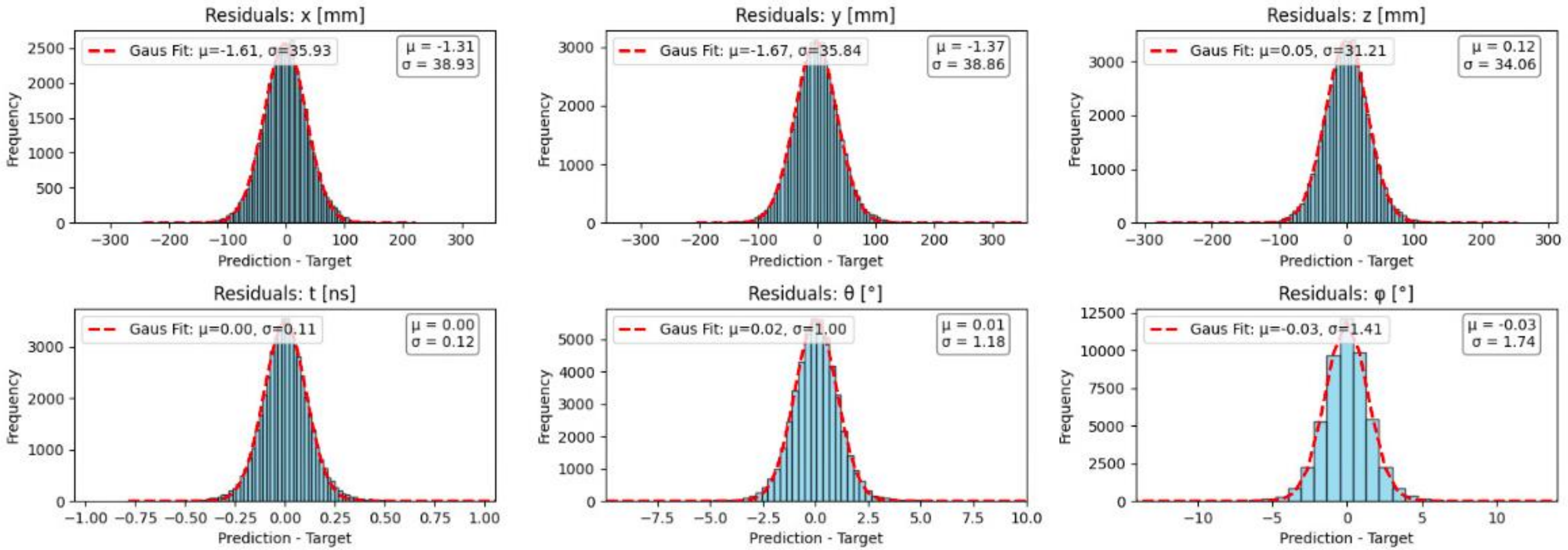
Runs with muon tracks illuminating a corner of the detector (flat plus cylindrical sections) show promising angle, vertex and time-zero resolutions: $\Delta\theta=1^o$, $\Delta\phi=1.5^o$, Δx, Δy, Δz =~4 cm, $\Delta\tau$=0.1ns. Electrons in progress…

Work is in progress to determine the efficiency of the detector for identifying neutrino interactions.

LEMMOND: the near-near detector of ESSnuSB+

Parameter prediction errors with muon tracks (200-600MeV) using GNN - Preliminary

GNN trained with 500,000 muon tracks..

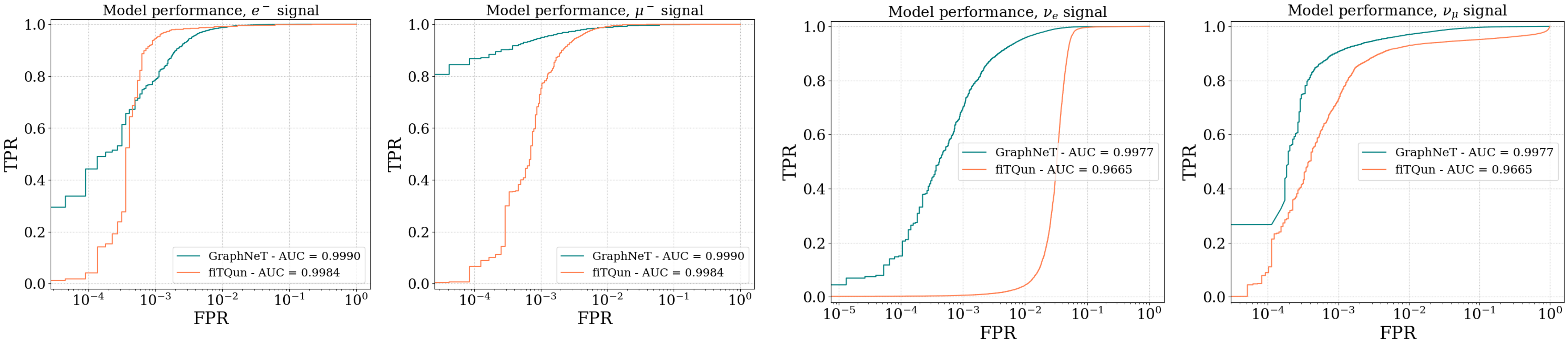


Improving event selection via Graph Neural Networks (GNN)

arXiv:2503.15247, prepared for submission to JINST

Why the need to use GNN?

- **Fast and reliable** event reconstruction enables testing of different detector layouts
- Log Likelihood (LLH)-based methods are accurate, but reconstruction is **slow (1 min/event)**
- ML methods are **fast once trained**, GNNs are well suited for sparse events with irregular geometry
- Multiple reconstruction methods provides a way to **cross check and find systematic errors**



TPR (True Positive Rate ≡ efficiency), FPR (False Positive Rate ≡ the probability of labeling a background event as signal).

For pure charged lepton simulations with filtering of difficult events, the GNN is on par with the fiTQun LLH method (SK). However:

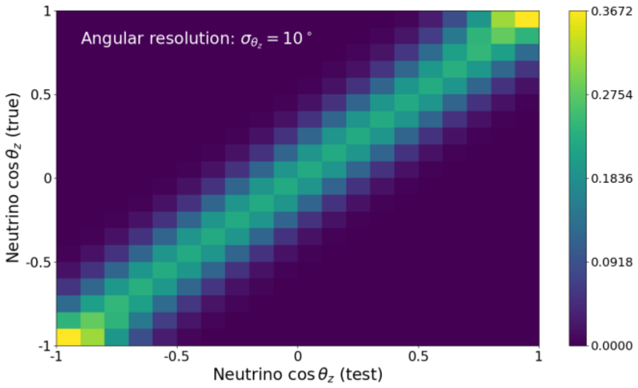
- Event filter relies on fiTQun reconstructed variables
- Full neutrino events can contain more than single charged leptons (pions, double-decays etc.)

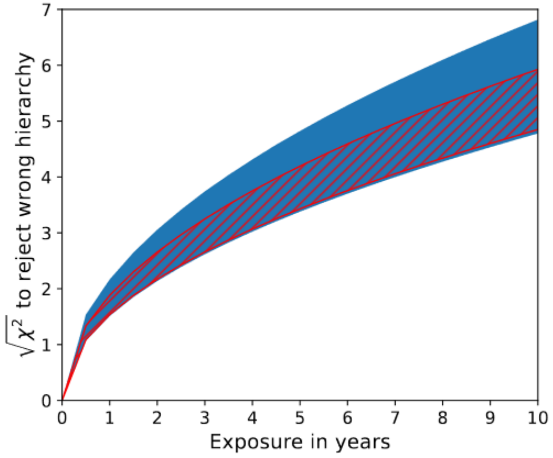
- The GNN (based on GraphNet (initially developed by IceCube) has a better performance even on the full neutrino events
- Using the GNN, the data cuts can be made obsolete

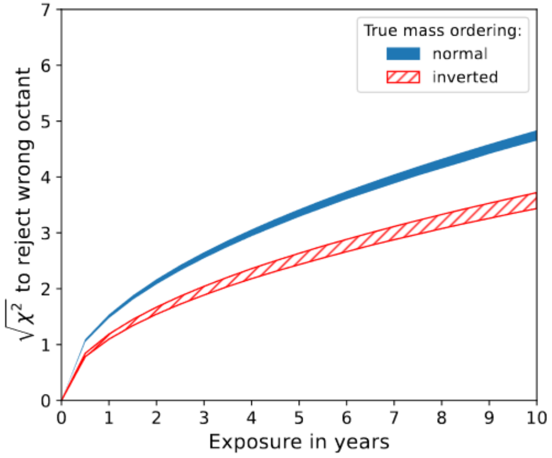
Exploring atmospheric neutrino oscillations at ESSnuSB

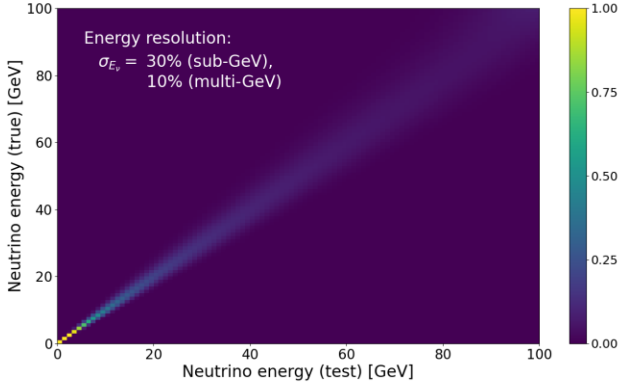
http://arxiv.org/abs/2407.21663 , https://doi.org/10.1007/JHEP10(2024)187

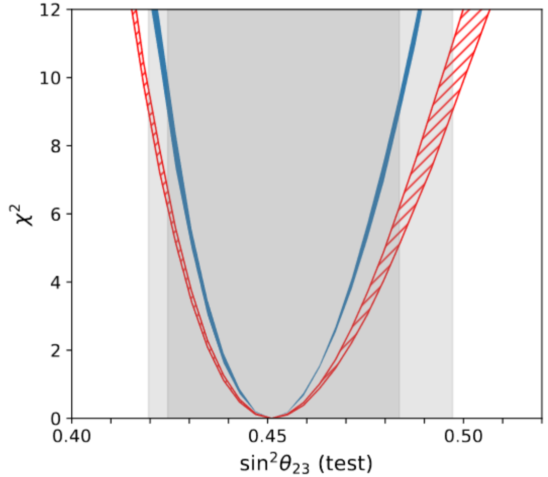
A Monte Carlo study has been conducted assuming two 70mX70m cylindrical vessels and 10 years exposure.

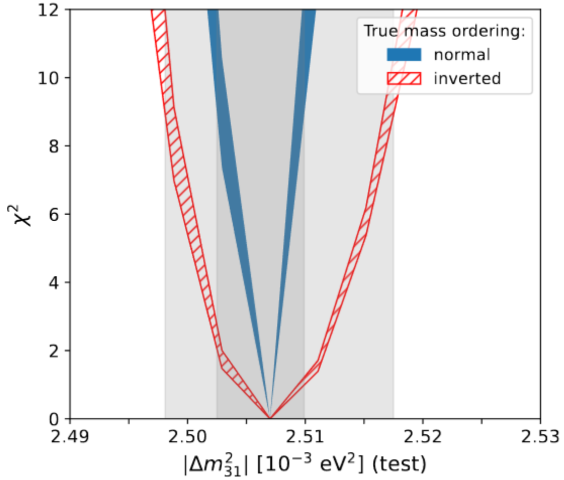








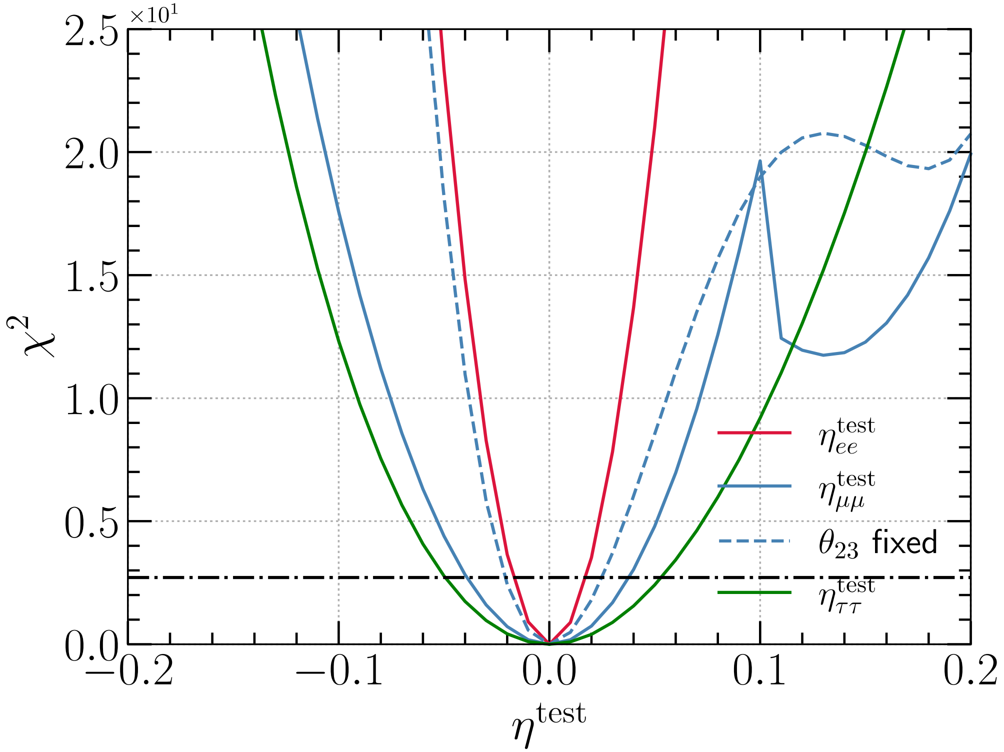




ESSnuSB could determine the correct neutrino mass ordering at 3σ CL after 4 years, regardless of the mass ordering. It could determine the θ_{23} octant at 3σ in 4 (7) years for normal (inverted) ordering and provide constraints on θ_{23} and Δm^2_{31} (shaded areas indicate the allowed values for normal-dark and inverted-light ordering).

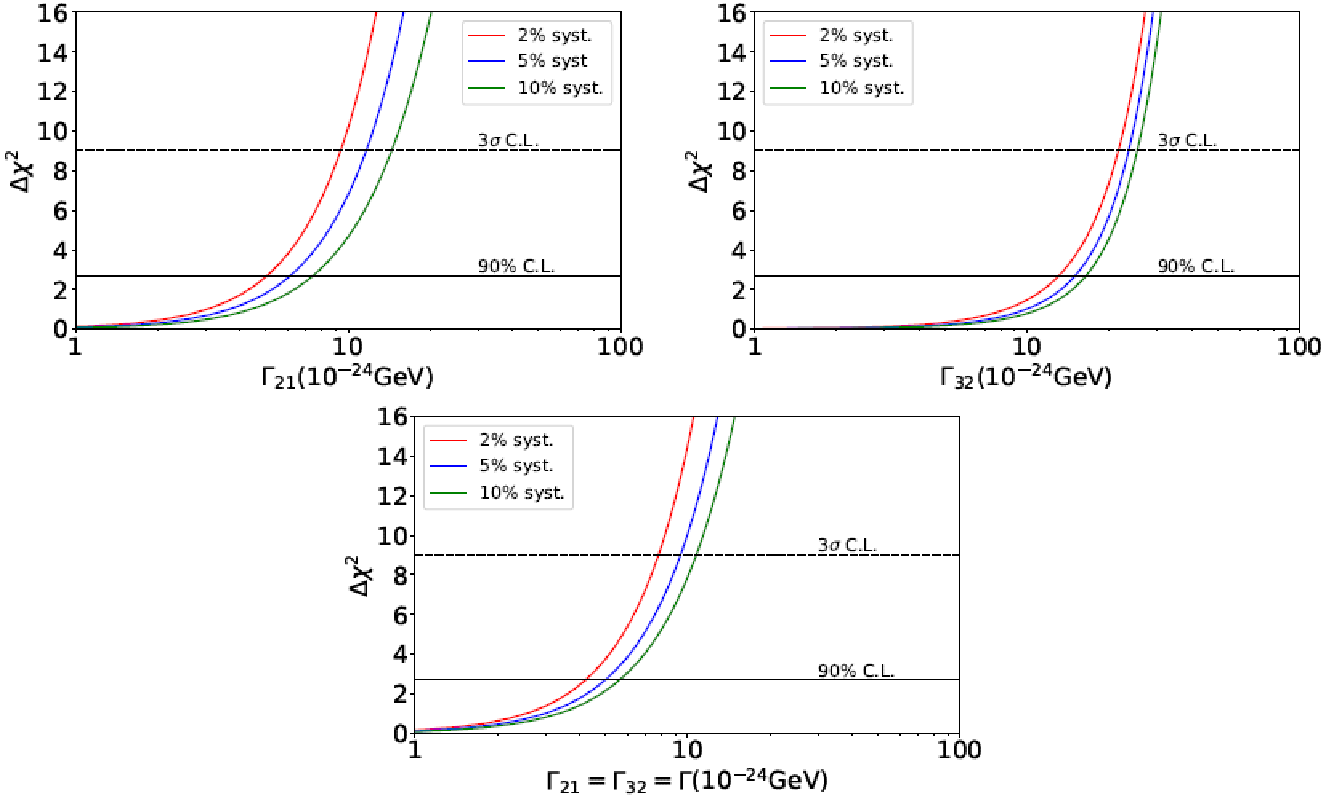
ESSνSB sensitivity to BSM physics - I

Constraints on scalar NSI parameters



Study of non-standard interaction mediated by a scalar field at the ESSnuSB experiment
Phys. Rev. D 109, (2024) 115010

Constraints on Decoherence dissipative parameters



Decoherence in Neutrino Oscillation at the ESSnuSB Experiment
arXiv:2404.17559 [hep-ex], https://doi.org/10.1007/JHEP08(2024)063

Summary

The Conceptual Designs ESSnuSB (2018-2022) and ESSnuSB-Plus (ESSnuSB+, 2023-2026) - WHY?

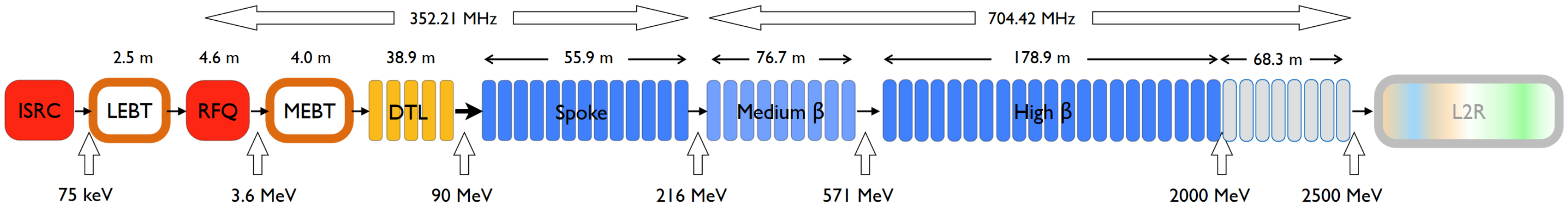
- **ESSnuSB** aims to observe CP violation in neutrino oscillations at the 2nd oscillation maximum using a 538 kt WC Far detector complex and a suite of Near detectors to form a Long baseline (LBL) neutrino oscillation experiment.
  - **2nd maximum** makes the measurement resilient to systematic errors and matter effects
  - **Recent optimizations** predict that in 10 years of data taking ESSnuSB will be able to:
    - reach 5 σ over 72% of δ_{CP} range
    - reach δ_{CP} resolution of less than 8°
- **ESSnuSB+** proposes additions which will allow for additional physics opportunities.
  - A Low Energy nuSTORM (LEnuSTORM)
  - A Low Energy Monitored Neutrino Beam (LEMNB-an Instrumented beam line a la ENUBET)
  - A near-near WC Detector (LEMMOND) will form a Short Base Line (SBL) experiment
  - **The proposed modifications would allow for**:

    precise neutrino flux, neutrino cross sections, muon physics, SBL for sterile neutrinos search, etc…
  - **GNN analysis implemented and more Physics cases being investigated (BSM…).**
  - **The Large far detectors** enriched with Gadolinium will allow for an even richer physics program:
    - Astroparticle physics
    - Atmospheric neutrinos
    - Solar neutrinos
    - Proton decay

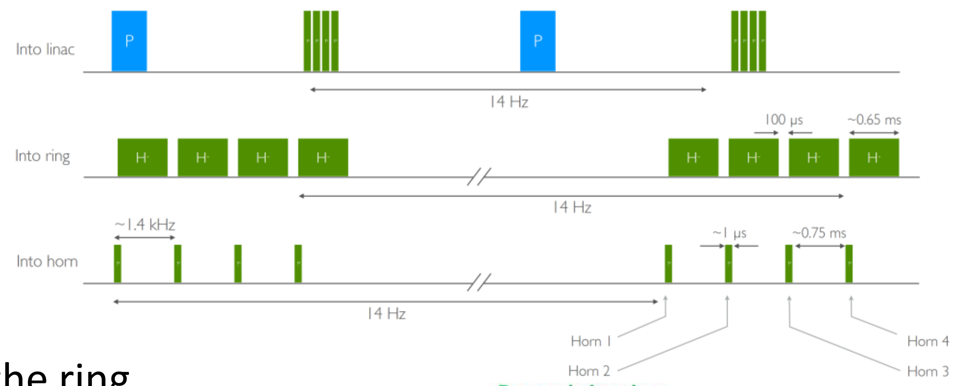
Thanks for your attention !

Backup slides

ESS Proton Linac Upgrade and the Accumulator Ring

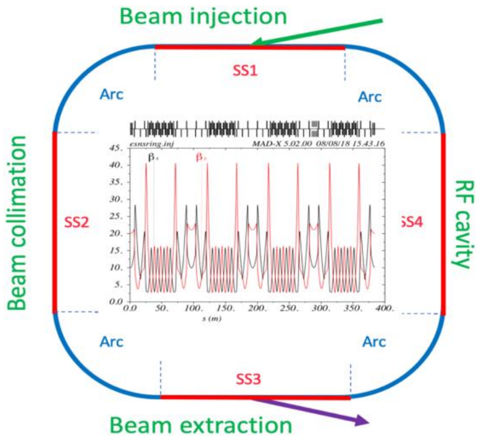


Pulsing scheme



- ESS*ν*SB proposes to increase the ESS LINAC power from 5 MW to 10 MW.
- The dedicated proton beam will be shortened to 1.3 μs:
  - ➢ With the help of the accumulator ring.
  - ➢ Will be split in four (batches) already in the LINAC.
  - ➢ Each batch is accumulated and then extracted before the next batch enters the ring.
  - ➢ Each batch hits a different target thanks to the switching in the switchyard.
- To avoid excessive injection losses, H^- ions are injected into the LINAC and stripped by a foil before entering the accumulator.
- Ring-to-switchyard, L2R, transfer-line extract the proton pulses from the ring to the beam switchyard and distribute the resulting four beam batches over four targets.

Accumulator Ring

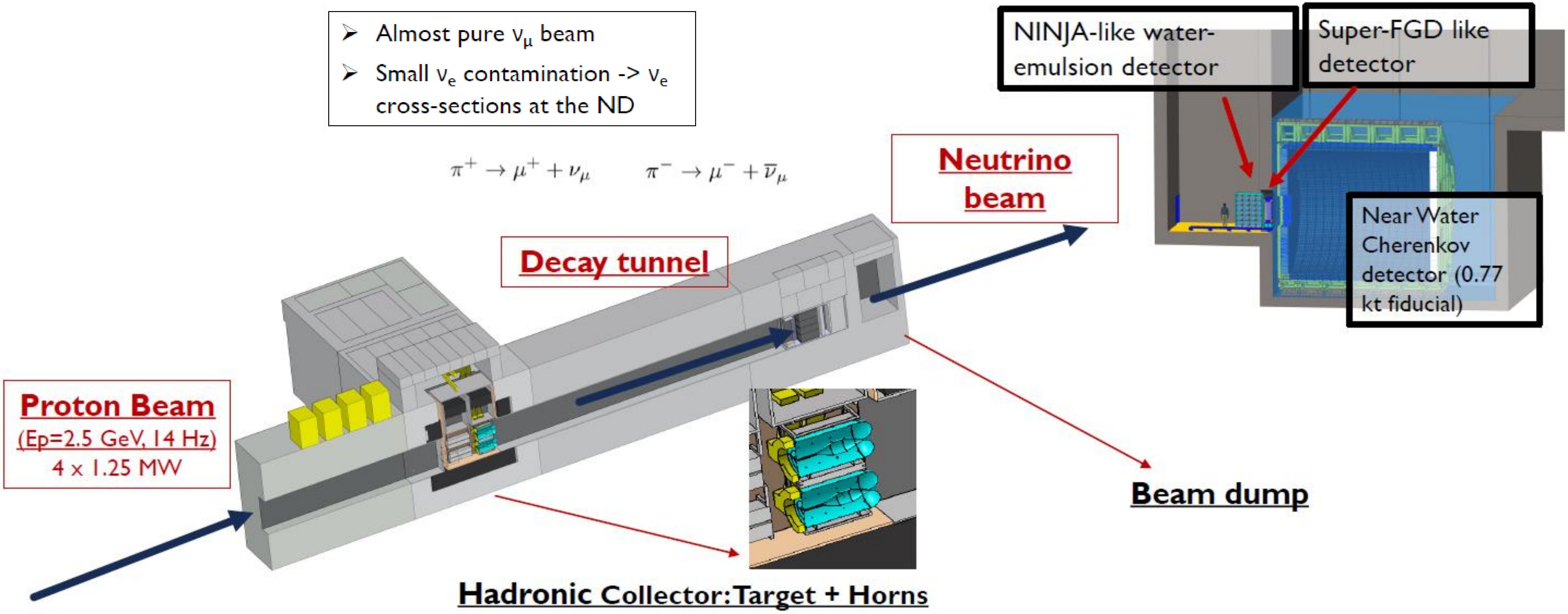


- Accumulation and storage, no acceleration.
- 384 m circumference, 1.33 μs revolution period

ESSnuSB neutrino beam and near Detector

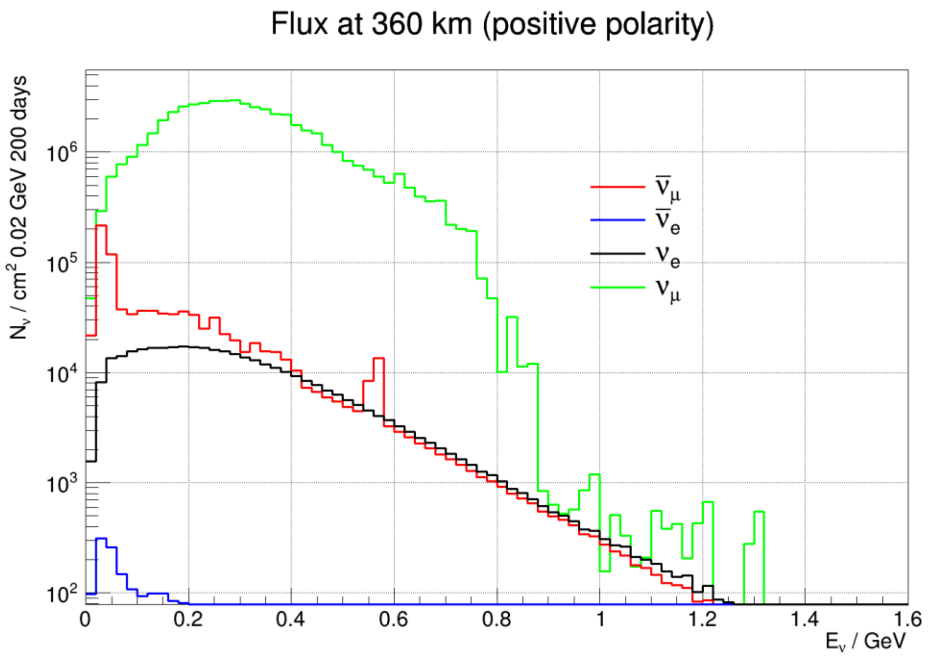
- Almost pure ν_μ beam
- Small ν_e contamination -> ν_e cross-sections at the ND

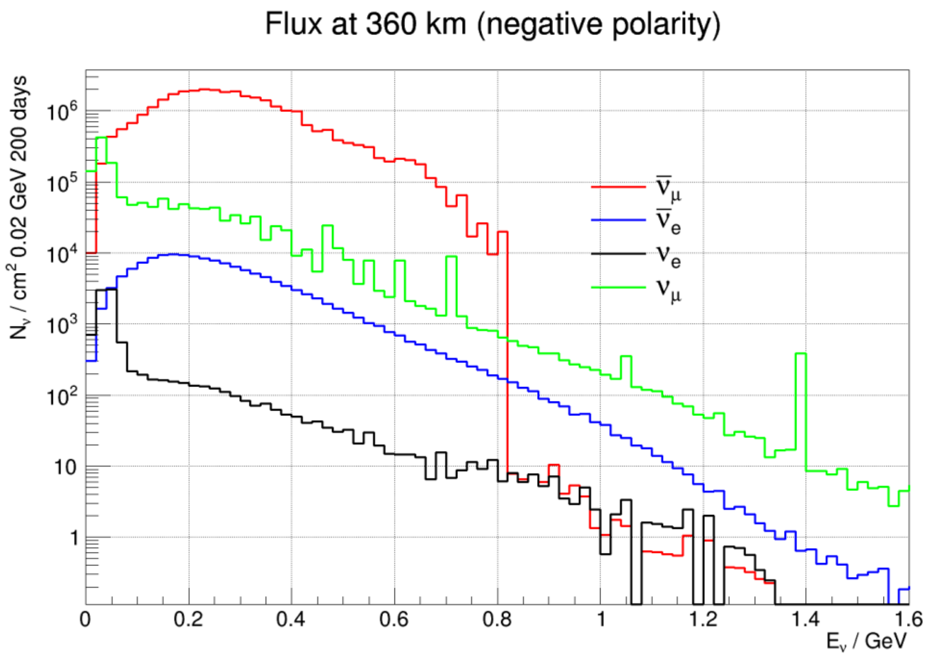
$$\pi^+ \to \mu^+ + \nu_\mu \qquad \pi^- \to \mu^- + \overline{\nu}_\mu$$



The expected neutrino and antineutrino flux for ESSnuSB

At 360 Km from the target, for 200 days, in absence of neutrino oscillations





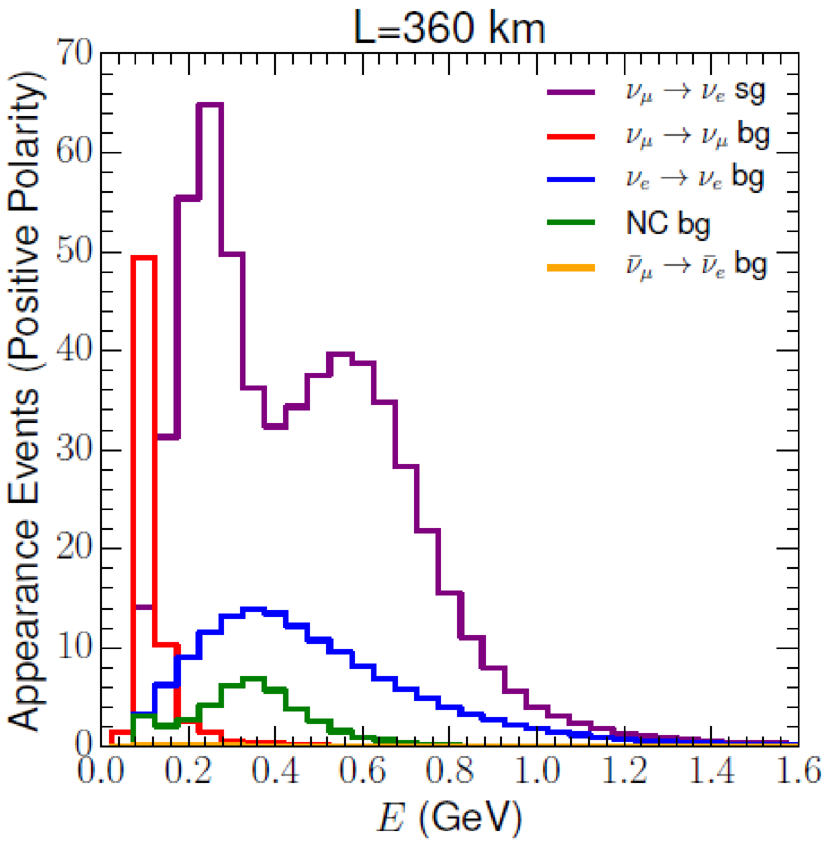
- almost pure ν_μ beam
- small ν_e contamination which will be used to measure ν_e cross-sections in a near detector

Neutrino flux at 360 km from the target per year (in absence of ν oscillations)

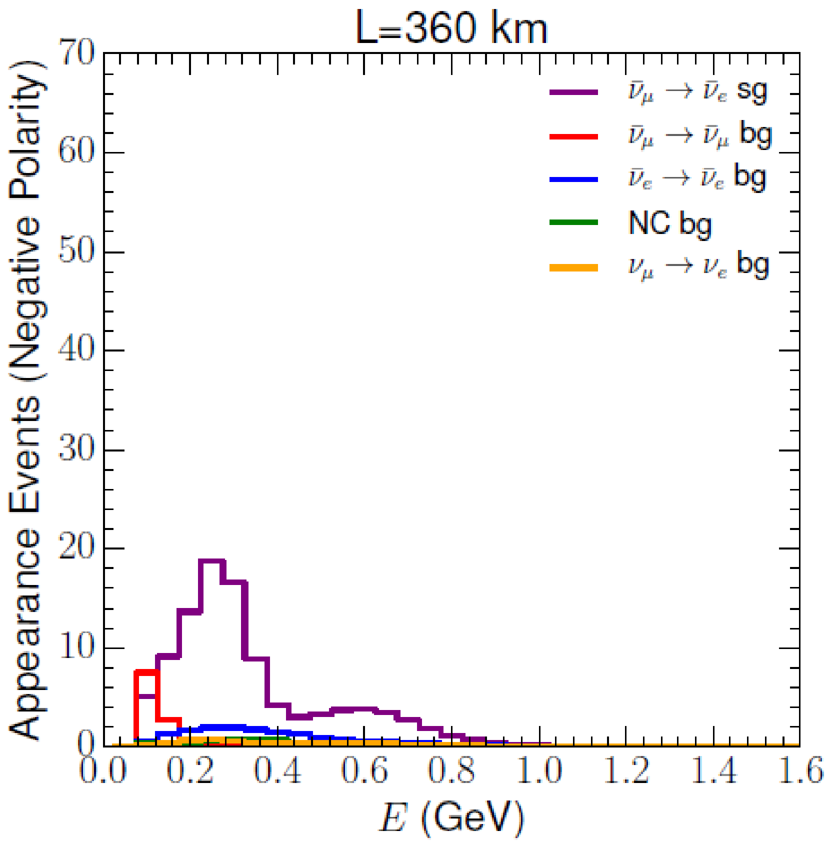
Flavour	ν Mode		$\bar{\nu}$ Mode	
	N_ν (10^5/ cm^2)	%	N_ν (10^5/ cm^2)	%
ν_μ	**520.06**	**97.6**	15.43	4.7
ν_e	**3.67**	**0.67**	0.10	0.03
$\bar{\nu}_\mu$	9.10	1.7	**305.55**	**94.8**
$\bar{\nu}_e$	0.023	0.03	**1.43**	**0.43**

The expected number of observed events in FD

in a running year (200 days)



(a) Neutrino mode



(b) Antineutrino mode

The expected number of observed neutrino events as a function of reconstructed neutrino energy in the far detectors, shown for the signal channel and the most significant background channels. Each plot corresponds to 200 days (effective year) of data taking.

Expected Number of Events in ESSnuSB

Table 40 Expected number of neutrino interactions in the 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	(3640.3)	26.0	(1896.8)	26.0	(1898.9)	26.0	(1898.9)
	$\overline{\nu}_\mu \to \overline{\nu}_e$	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 (3265.5)				
	$\overline{\nu}_e$				1×10^{-1} (13.6)				

Table 45 Signal and major background events for the appearance channel corresponding to positive (negative) polarity per year for $\delta = 0°$

	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)

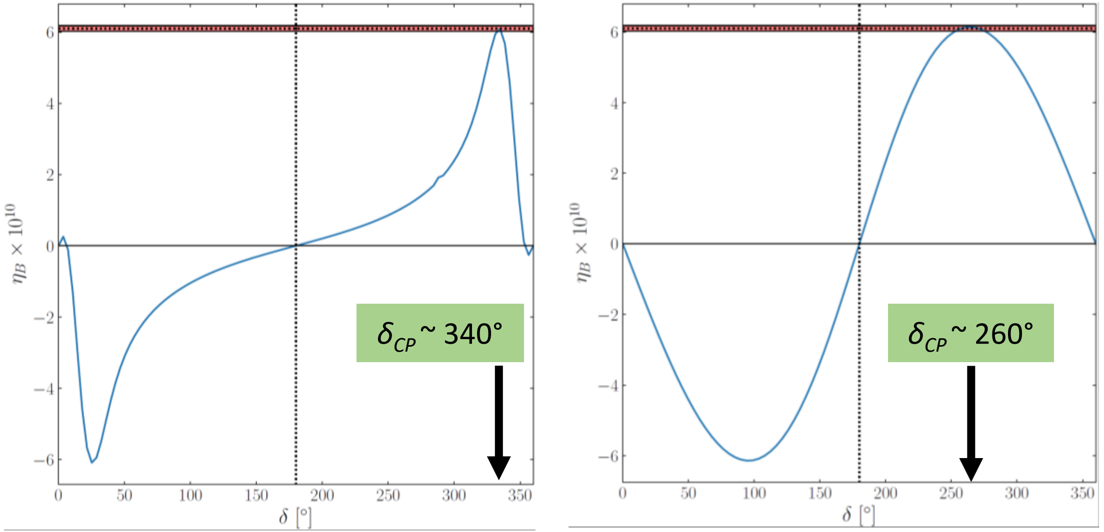
Why the need to measure the CP violating phase so precisely?

In the precision era for the neutrino oscillation measurements, **precision is mandatory to probe theories which might explain the matter-antimatter asymmetry in the Universe (leptogenesis) and the flavor structure of the SM.**

Leptogenesis Theories [K. Moffat et al., arXiv:1809.08251 (2019)]

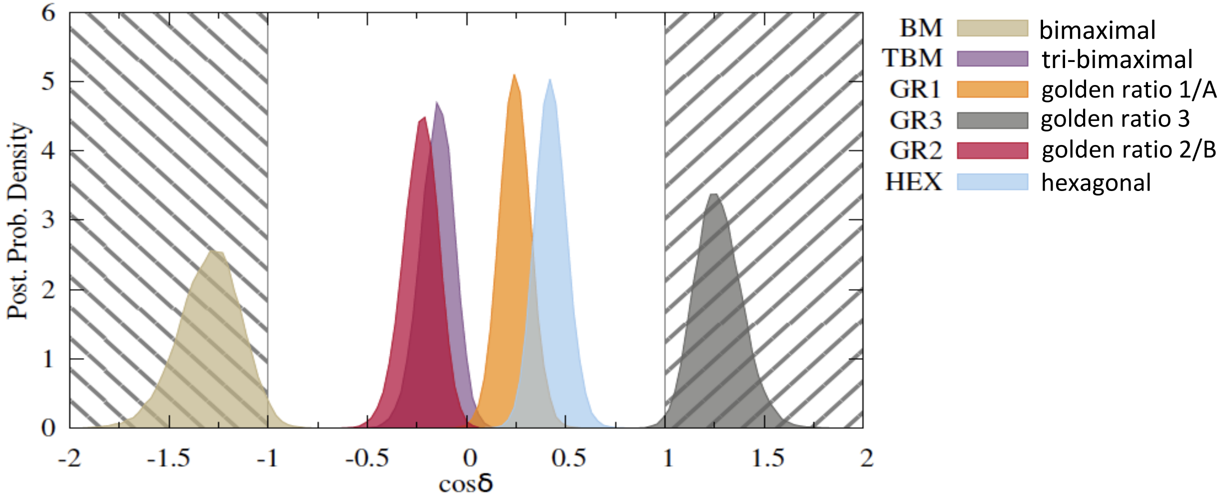
Low mass flavor regime M_1 (GeV) < 10^9

Intermediate mass flavor regime $10^9 < M_1$ (GeV) < 10^{12}



Flavour Theories [P. Ballett *et al.*, JHEP12 (2014) 122]

four different symmetry forms of the neutrino mixing matrix



❖ Prospective (useful / requested) precision for δ_{CP}: $\delta(\delta) \leq 12^\circ$ **at** $\delta = 3\pi/2$

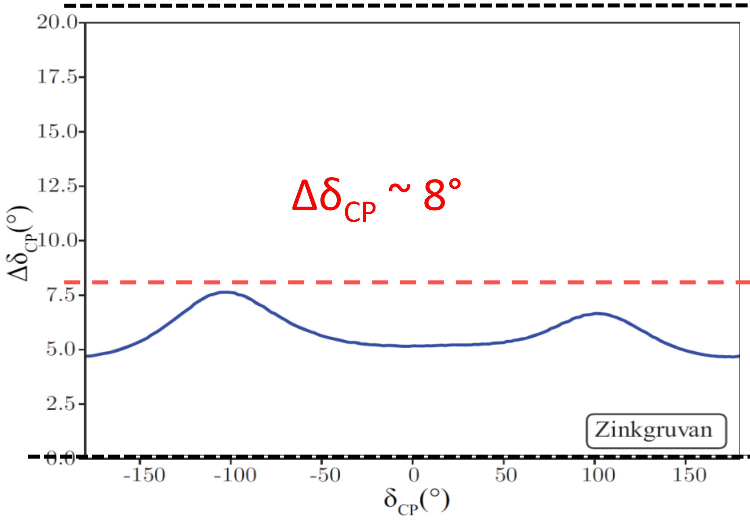
(S.T. Petcov, NPB 2024, IAS, HKUST, Hong Kong 20/02/2024)

Only ESSnuSB can reach such precision!

ESSnuSB in the international context – CPV resolution

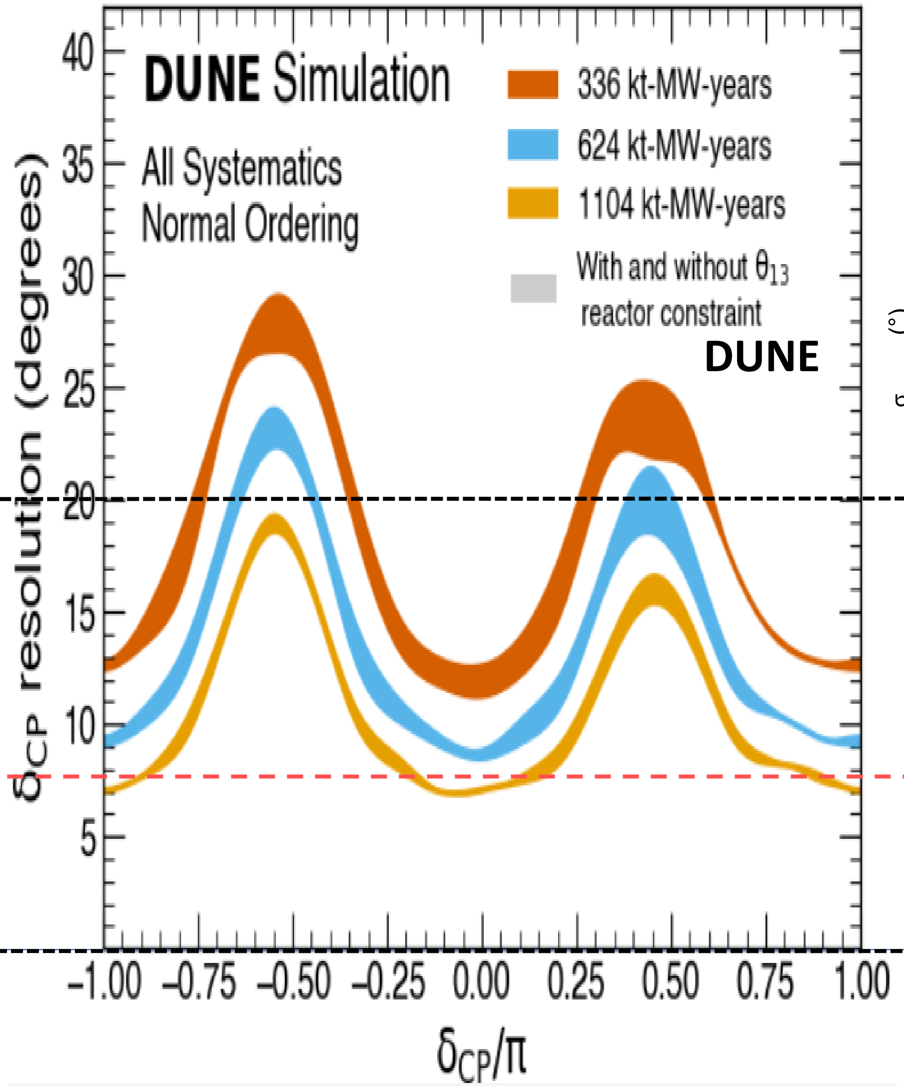
precision of the δ_{CP} measurement

ESSnuSB



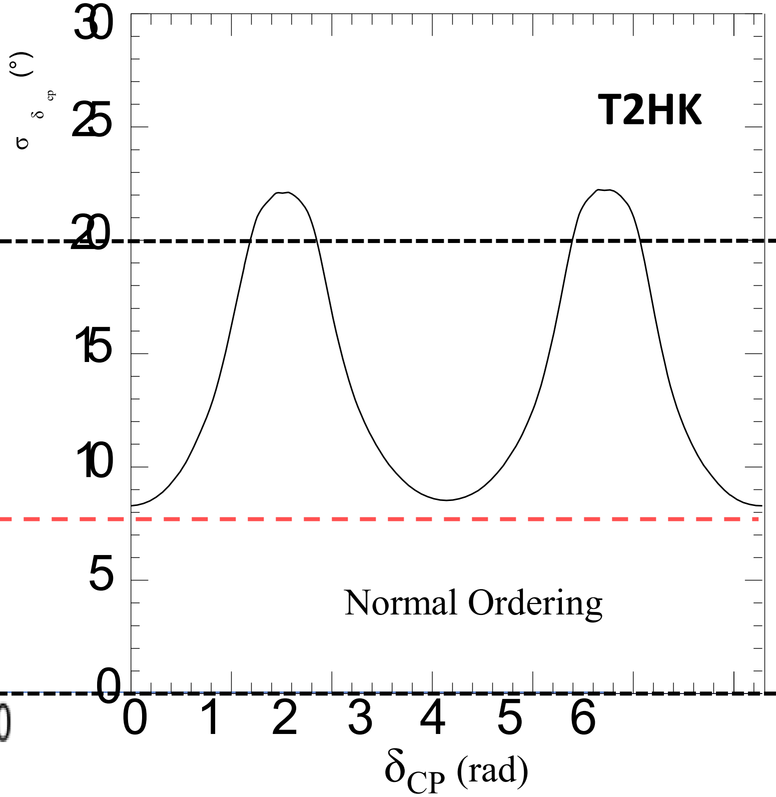
ESSnuSB 10 years

https://arxiv.org/abs/2206.01208 p. 205



DUNE 10 years, yellow curve

https://arxiv.org/abs/2002.03005 p. 174



HyperKamiokande 10 years

https://arxiv.org/abs/1611.06118 p. 60

ESSnuSB+ (2023-2026)

Research and Innovation actions

Innovation actions

Design Study

HORIZON-INFRA-2022-DEV-01

Title of Proposal: Study of the use of the ESS facility to accurately measure the neutrino cross-sections for ESSνSB leptonic CP violation measurements and to perform sterile neutrino searches and astroparticle physics.

Acronym of Proposal: ESSνSB+

Participant no.	Participant organisation name	Part. short name	Country
1 (Coordinator)	Centre National de la Recherche Scientifique	CNRS	France
2	Université de Strasbourg	UNISTRA[1]	France
3	Rudjer Boskovic Institute	RBI	Croatia
4	Tokai National Higher Education and Research System, National University Corporation	NU[2]	Japan
5	Uppsala Universitet	UU	Sweden
6	Lunds Universitet	ULUND	Sweden
7	**European Spallation Source ERIC**	ESS	Sweden
8	Kungliga Tekniska Hoegskolan	KTH	Sweden
9	Universitaet Hamburg	UHH	Germany
10	University of Cukurova	CU	Turkey
11	National Center for Scientific Research "Demokritos"	NCSRD	Greece
12	Aristotelio Panepistimio Thessalonikis	AUTH[1]	Greece
13	Sofia University St. Kliment Ohridski	UniSofia	Bulgaria
14	Lulea Tekniska Universitet	LTU	Sweden
15	**European Organisation for Nuclear Research**	CERN	IEIO[3]
16	Universita degli Studi Roma Tre	UNIROMA3	Italy
17	Universita degli Istudi di Milano-Bicocca	UNIMIB	Italy
18	Istituto Nazionale di Fisica Nucleare	INFN	Italy
19	Universita degli Istudi di Padova	UNIPD[1]	Italy
20	Consorcio para la construccion, equipamiento y explotacion de la sede espanola de la fuente Europea de neutrones por espalacion	ESSB	Spain

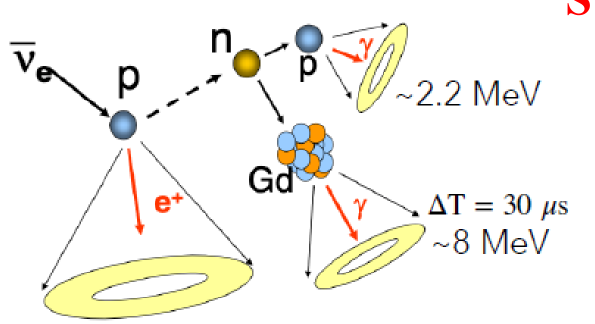
20 Institutions
11 countries
(in the proposal)

Neutron tagging by Gadolinium

The charge identification issue can be addressed, in the simple **quasi-elastic scattering** process where no additional particles are produced, by identifying the final-state nucleon as either a proton (implying the reaction $\nu_\mu + n \rightarrow \mu^- + p$, or the equivalent for other flavors) or a neutron (implying $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$).

Proton momentum is below Cherenkov threshold but doping the water with 0.2% gadolinium (by dissolving $Gd_2(SO_4)_3$) could provide a way to distinguish neutrino from antineutrino interactions. Neutrons are captured by Gd with a 90% efficiency emitting a cascade of ~8 MeV gammas whose Cherenkov light is detected ~30 μs later. Since in T2K (similarly in ESSnuSB) the detection of such photons is 90% efficient, it is estimated that the expected overall tagging neutron efficiency is 80%.

Neutron tagging by Gd



$\bar{\nu}_e$ can be identified by delayed coincidence

A promising plan to detect Supernova Neutrinos and Diffuse Supernova Neutrino Background (or Supernova Relic Neutrinos) !

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

From:

J.F. Beamon, M.R. Vagins, Phys. Rev. Lett. 93 (2004) 171101

The energy spectra expected in Super-K for the main reactions producing a positron and a neutron in coincidence.

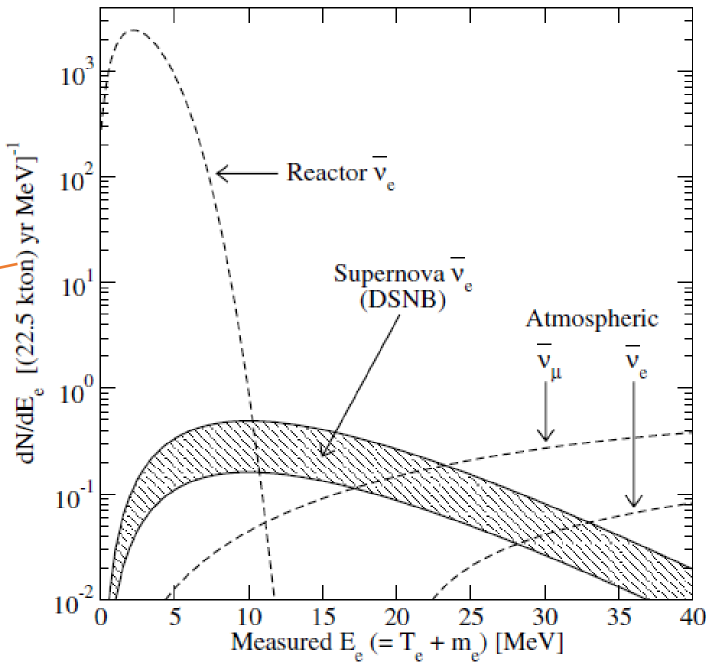
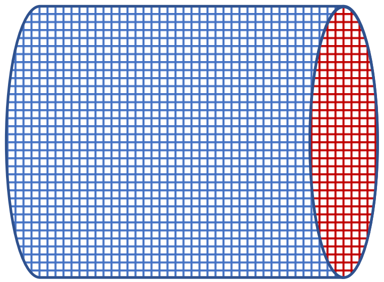


Figure 2: Spectra of low energy $\bar{\nu}_e + p \rightarrow e^+ + n$ coincident signals in Super-K. From [12].

LEMMOND: the near-near detector of ESSnuSB+

Low Energy Neutrino Stored Muons and Monitored Beam Near Detector

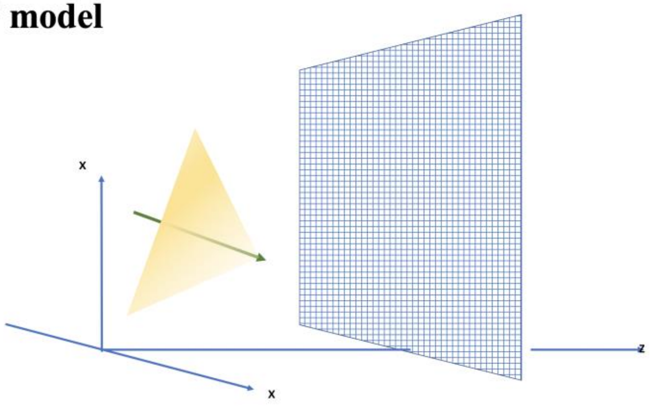


A cylindrical detector with about 2.5m radius and 10 m length and a water volume ~200 tons, located 50 m downstream of LEnuSTORM or LEMNB facilities. It will serve to precisely measure neutrino cross sections at the ESSnuSB energy range but also as a near detector for a Short Base Line setup.

Before developing a full simulation of the detector, we used a “toy” model for:

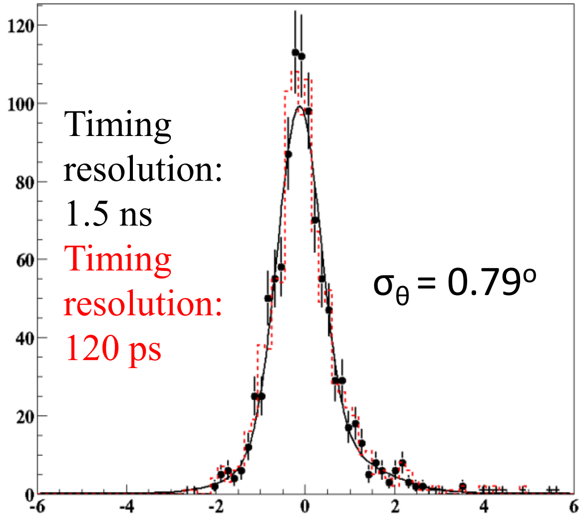
- Establishing the techniques for track simulation, photoelectron collection, track reconstruction for muons and electrons.
- Distinguishing muons from electrons

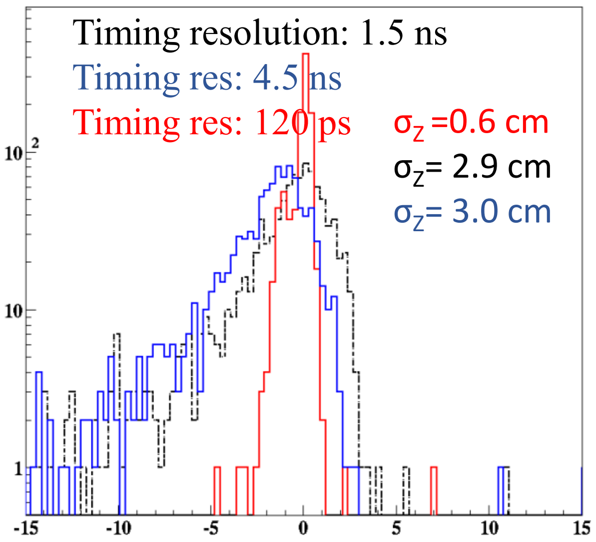
the “toy” model



GEANT4 simulated tracks:

- Tracks produced with [$\theta=0^o$ or $\theta=30^o$ and $\phi=0^o$] initial direction, wrt to the detector, starting ~200cm away from the Detector
- The detector is a 400 x 400 cm^2 plane (6400 5x5 cm^2 pads)





Likelihood

$$\mathcal{L} = \prod_{j}^{\text{unhit}} P_j(\text{unhit}|\mu_j) \cdot \prod_{i}^{\text{hit}} ([1 - P_i(\text{unhit}|\mu_i)] \cdot f_q(q_i|\mu_i) \cdot f_t(t_i|\vec{x})) \qquad (4)$$

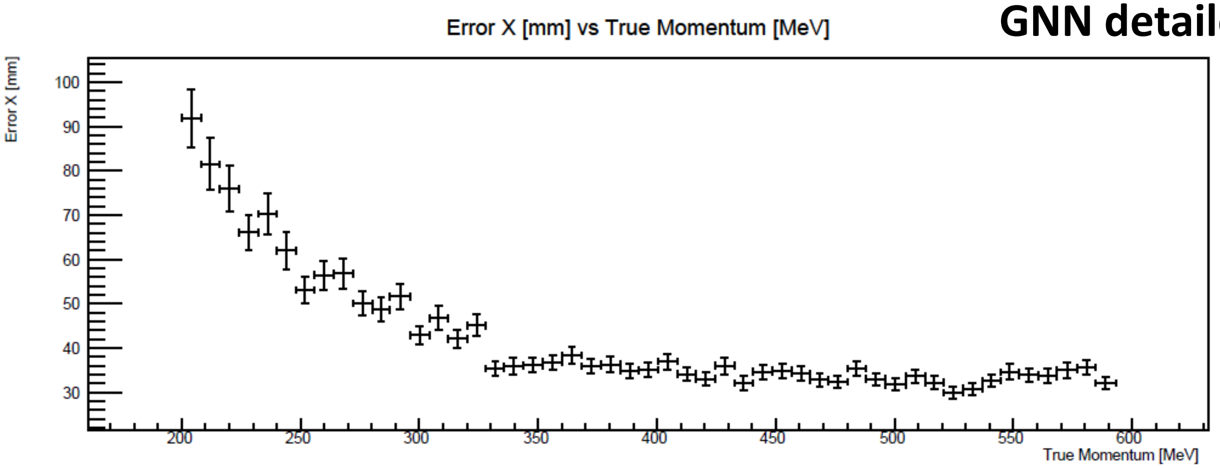
- $\vec{x}$: vector all vertex parameters $(x_{vertex}, y_{vertex}, z_{vertex}, t_{vertex}, \theta_{vertex}, \phi_{vertex}, ParticleID)$
- q_i is the charge of the i^{th} photodetector's signal
- t_i is the arrival time of the i^{th} photodetector's signal
- $P_j(\text{unhit}|\mu_j)$ is the probability that the j_{th} photodetector does not have any signal in the case μ_j photons are expected.
- $f_q(q_i|\mu_i)$ the P.D.F of observing a signal with charge q_i in the i^{th} photodetector when μ_i photons are expected.
- $f_t(t_i|\vec{x})$ is the P.D.F.that the signal of the i_{th} detector arrives at time t_i given $\vec{x}$.

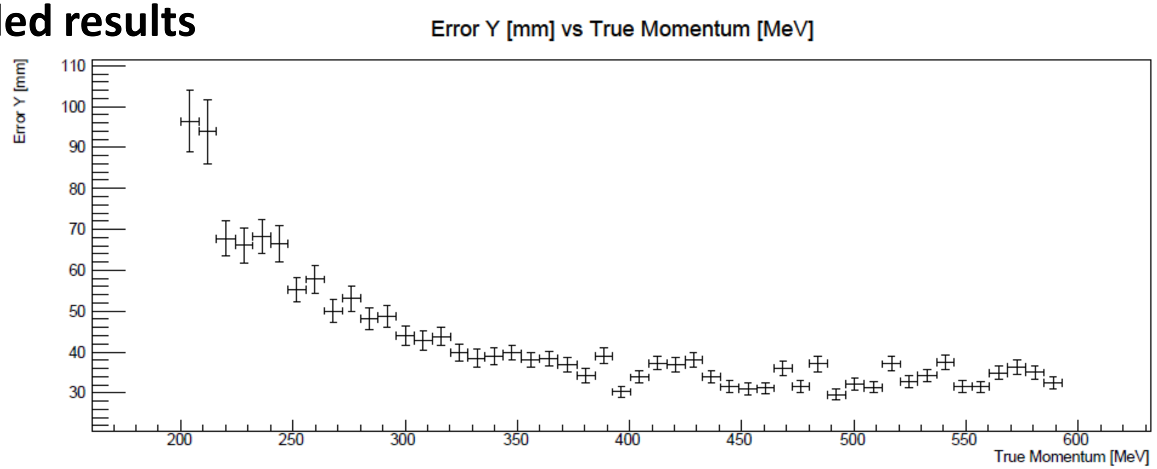
Assuming that if we expect μ photoelectrons then the detected will follow Poisson distribution and thus:

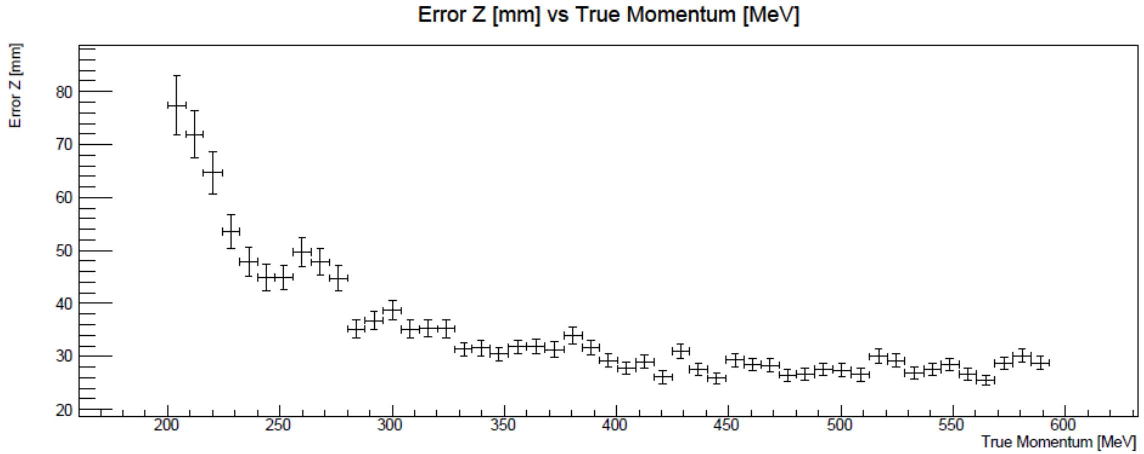
P_N is an N-Polya distribution

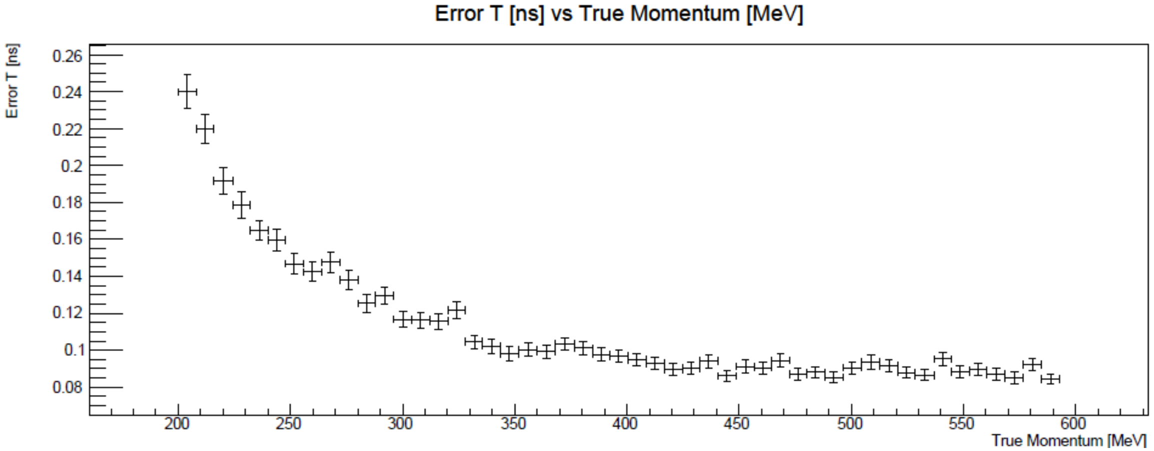
$$f_q(q_i|\mu_i) = \sum_{i=1}^{\infty} \frac{\mu^N e^{-\mu}}{N} \cdot P_N(Q; \theta, \overline{Q}, N) \qquad (5)$$

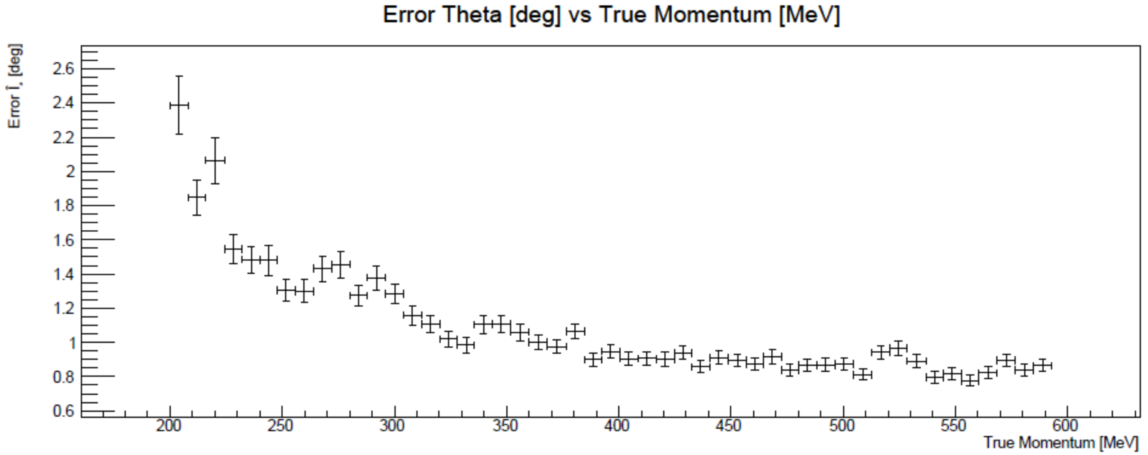
GNN detailed results

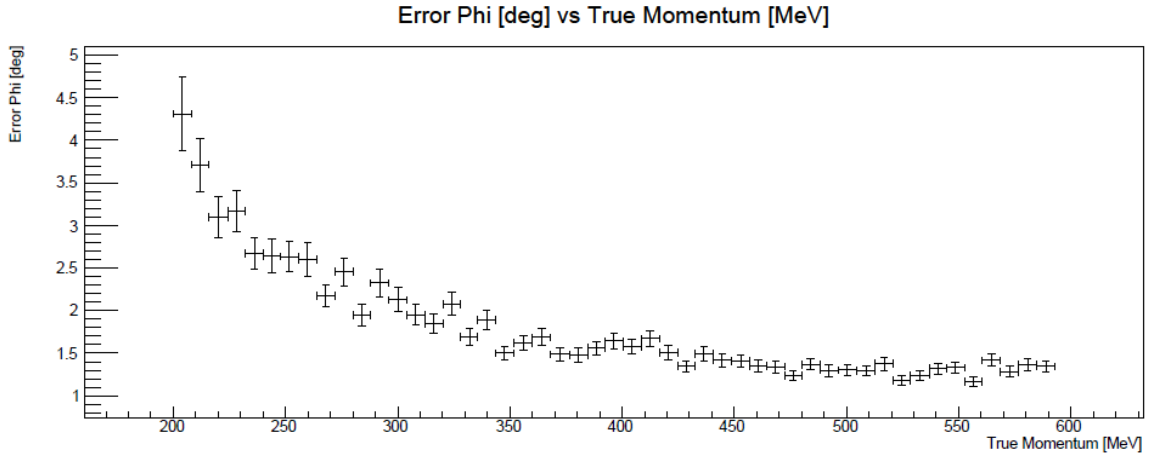






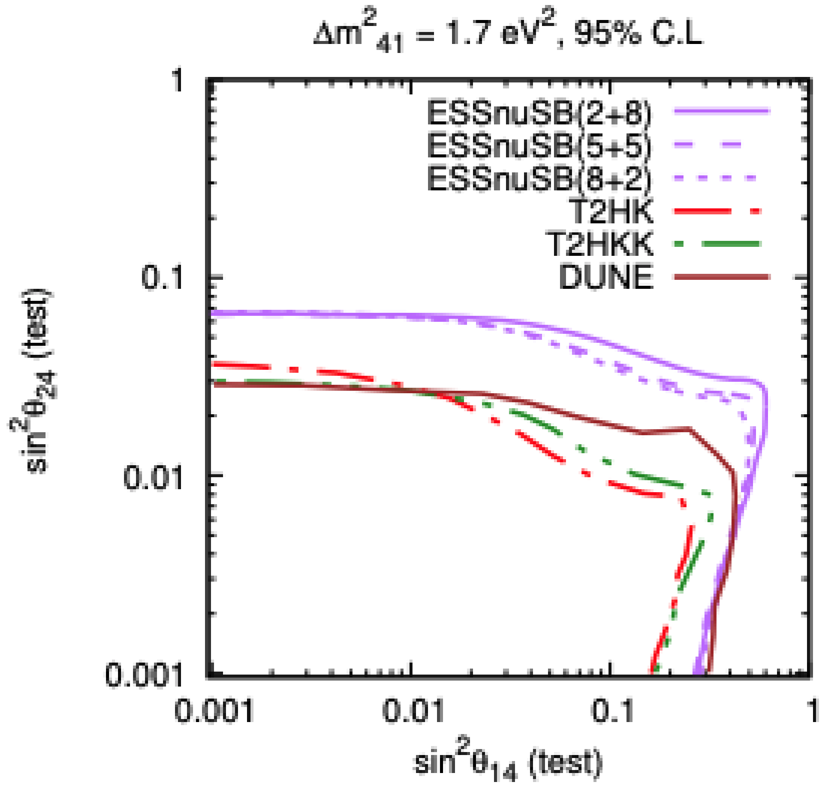






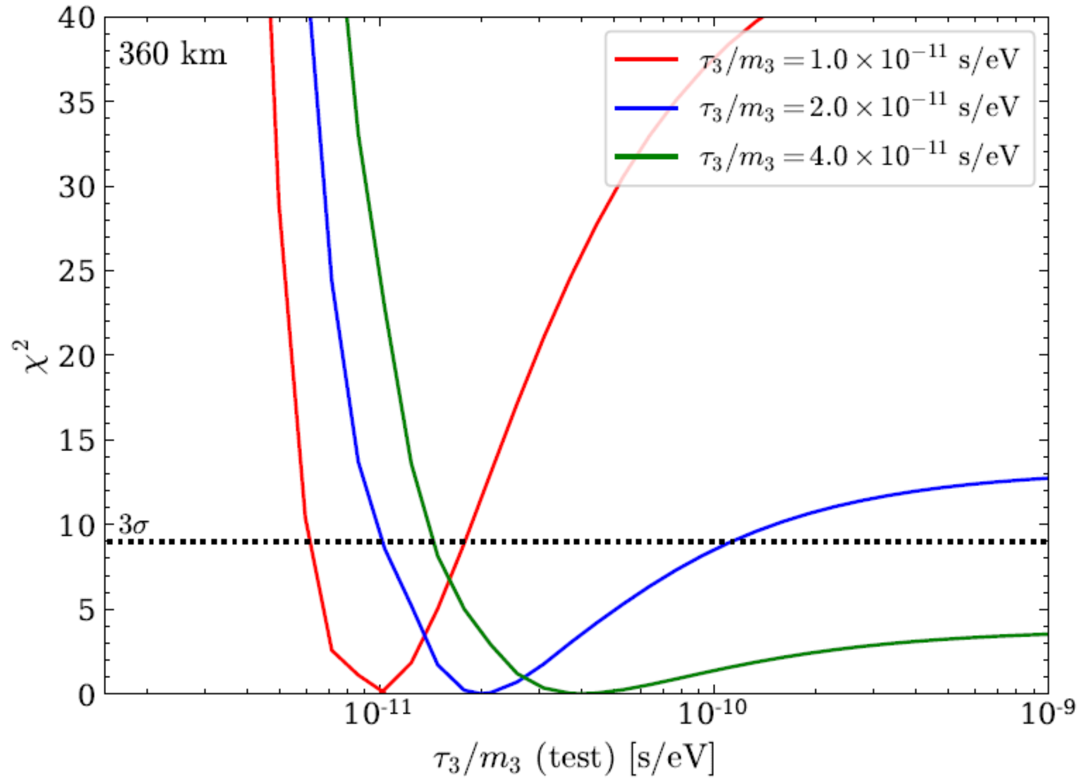
ESSνSB sensitivity to BSM physics - II

Light sterile neutrinos (3+1)



Comparison of bounds on sterile neutrinos mixing angles
JHEP 03 (2020), 026

Invisible neutrino decays



Precision χ^2 as a function of τ_3/m_3(test) for three different values of the decay parameter τ_3/m_3(true).

Exploring invisible neutrino decay at ESSnuSB
JHEP 05 (2021), 133

ESSnuSB Implementation Approach

Staged Implementation

Stage 1
LEMNB

- Proton beam from ESS linac, up to 2.86 ms pulses, long-pulses up to 10^{14} protons/pulse,
- ~300kW target station, pion capture using conventional magnets, instrumented decay tunnel
- Beam to near detector LEMMOND at ~40-50 m from the target

Stage 2
LENUSTORM

- H^- source, and transfer line to accumulator
- Accumulator ring, 1.25 MW target station, horn for pion capture, transfer line and injection to LEnuSTORM ring
- LENUSTORM ring, beam to near detector LEMMOND at ~10-15 m from ring, and to END at 290 m from target

Stage 3
ESSnuSB CPV LBL

- H^- source, and transfer line to accumulator
- Accumulator ring, 5MW target station, horn for pion capture
- Decay tunnel, beam to END at 290 m from target and to FD