ESS
NEUTRINO
SUPER BEAM

Funded by the Horizon 2020 Framework Programme of the European Union

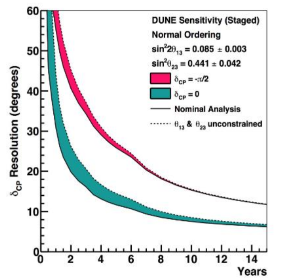
ESSnuSB – a second generation neutrino beam for high precision CPV measurements

NuPhys2023 19 Dec 2023 at Kings College, London

Tord Ekelöf, Uppsala University

On the benefit of having several neutrino long- baseline experiments, in particular one coming after the others

All largescale accelerator research infrastructures tend to saturate their statistics after the order of one to two decades of operation. As the preparation of these projects, from the inception up to the realisation, also takes of the order of one to two decades, the preparation of future more sensitive experiments must commence already at the start of operation of the current largescale accelerator infrastructures.



Science advances with time, in the case of neutrino super beams providing increased precision in the measurements of the PMNS matrix elements, in particular δ_{CP}, and other relevant parameters. This is made possible by technology advances like e.g. with the advent of more powerful accelerators and more sensitive detectors. Both these factors imply higher reach and higher precision of second-generation future experiments.

A special feature for this kind of particle physics, which operates at the intensity frontier and is based on the use of neutrinos, is the need for low energy proton beams of ever-increasing intensity. This provides synergy between fundamental particle-physics and the more applied material-science, the latter requiring an ever increasing flux of spallation neutrons. This cross-diciplinarity is of help when it comes to requesting public funding support to attain even higher intensities.

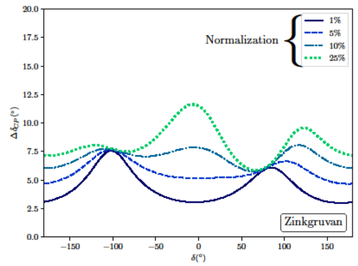
On the importance of a high δ_{CP} resolution

Violation of CP symmetry was discovered in neutral K-meson decay in 1964, demonstrating that CP symmetry is not, as earlier believed, an exact symmetry of Nature. This was at the time a fundamental discovery reworded with the Nobel prize in physics. The discovery was made in the quark sector. The measured matter-antimatter asymmetry is ca 9 orders of magnitudes larger than what can be explained by the quark CP violation in the Standard Model, whereas due to the high value of the leptonic Jarlskog parameter, a significant lepton CP violation could explain the presence of matter in Universe through leptogenesis.

In order to verify or falsify specific symmetry approaches to lepton flavours and the various leptpgenesis models with Dirac CP violation phase that describe the matter-antimatter asymmetry, each of which predicts a specific value of δ_{CP}, it will be very important to make a measurement of δ_{CP} with the highest possible precision. As CP symmetry has already been shown to be broken in Nature the decisive goal should thus, in our mind, not only be to discover leptonic CP violation but to measure it in terms of the CP phase-angle δ_{CP} with the highest precision possible.

$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

Owing to the use of the world-uniquely high power of the ESS linear accelerator the ESSnuSB project will enable a measurement of δ_{CP} with a standard error **below 8° for all values of δ_{CP}** to be compared with an error below 22° for all CP angles for DUNE and Hyper-K – ref. graphs here below. This higher precision of ESSnuSB will be decisive for the aim of confirming which of the various leptogenesis theories is valid and in which direction to go with these models.



Required leptonic CP phase angle resolution

Slide from Serguey Petcov's talk at NeuTel 2023

The measurement of the Dirac phase in the PMNS mixing matrix, together with an improvement of the precision on the mixing angles θ_{12}, θ_{13} and θ_{23}, can provide unique information about the possible existence of new fundamental symmetry in the lepton sector.

Prospective (useful/requested) precision:

Green percentages from Mariam Tórtola's talk this morning

Blue percentage from Cécile Jollet's talk this morning

$\delta(\sin^2\theta_{12}) = 0.7\%$ (JUNO), 5.2% 2.8%

$\delta(\sin^2\theta_{13}) = 3\%$ (Daya Bay), 3.0%

$\delta(\sin^2\theta_{23}) = 3\%$ (T2HK, DUNE; T2K+NOνA(?)). 5.1%

→ $\delta(\delta) = 10^\circ$ at $\delta = 3\pi/2$

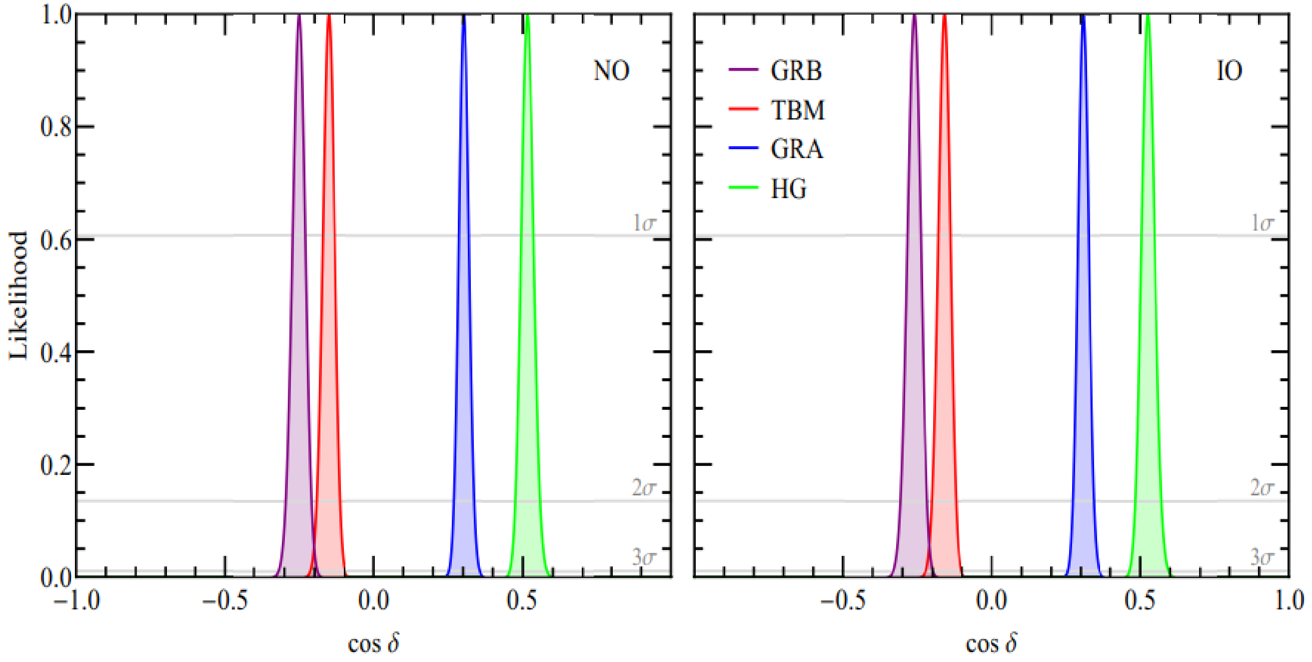
(THKK?; DUNE: accounting for both the 1st and 2nd probability maxima, Jogesh Rout, Poonam Mehta et al., PRD 2021, S. Goswami et al., 2012.04958; ESSnuSB)

S.T. Petcov, NuTel, Venice 23/10/2023

Test of flavour models

Slide from Serguey Petcov's talk at NeuTel2023

The 4 different colors and δ_{CP} values correspond to **different symmetry forms of the neutrino mixing matrix:**
tri-bimaximal (TBM),
golden ratio A (GRA) and B (GRB),
& hexagonal (HG)



I. Girardi, S.T.P., A. Titov

b.f.v. of $\sin^2\theta_{ij}$ (Esteban et al., Jan., 2018) + the prospective precision used.

$$\cos\delta = \frac{\tan\theta_{23}}{\sin 2\theta_{12}\sin\theta_{13}}\left[\cos 2\theta^{\nu}_{12} + \left(\sin^2\theta_{12} - \cos^2\theta^{\nu}_{12}\right)\left(1 - \cot^2\theta_{23}\sin^2\theta_{13}\right)\right].$$

$\delta(\sin^2\theta_{23}) = 3\%$ (T2HK, DUNE).

S.T. Petcov, NuTel, Venice 23/10/2023

Test of leptogensis models with Dirac CP violation phase

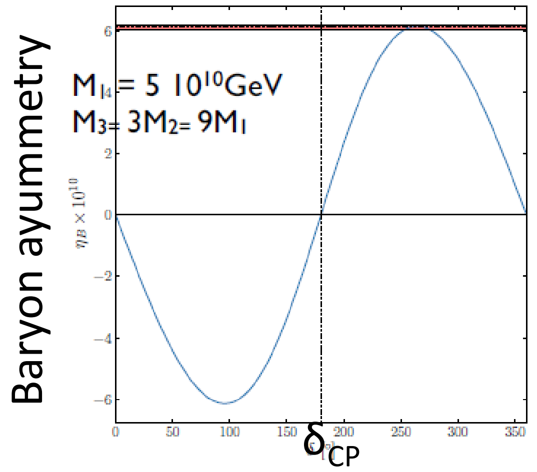
Slide from Silva Pascoli's talk at NeuTel2019

Does observing low energy CPV imply baryon asymmetry?

In see-saw type I, let's consider the case of low energy CPV, for instance delta (R real). An approximate formula:

$$|Y_B| \cong 2.4 \times 10^{-11} \, |\sin \delta| \left(\frac{s_{13}}{0.15} \right) \left(\frac{M_1}{10^{11}\text{ GeV}} \right)$$

SP, Petcov, Riotto, PRD and NPB 2007; SP 2014



Intermediate flavour regime:
$10^9\text{GeV} < M_1 < 10^{12}\text{GeV}$

$$\epsilon_{\tau\tau}^{(1)} = (0.515 - 3.94 c_{13})\, s_{13} \times 10^{-8} \sin \delta$$

$$\epsilon_{\tau\tau}^{(1)} = 3.14 \times 10^{-7} \cos \frac{\alpha_{21}}{2}$$

Moffat, SP, Petcov, Turner, 1804. 05066, 1809.08251

Prediction $\delta_{CP} = 260°$

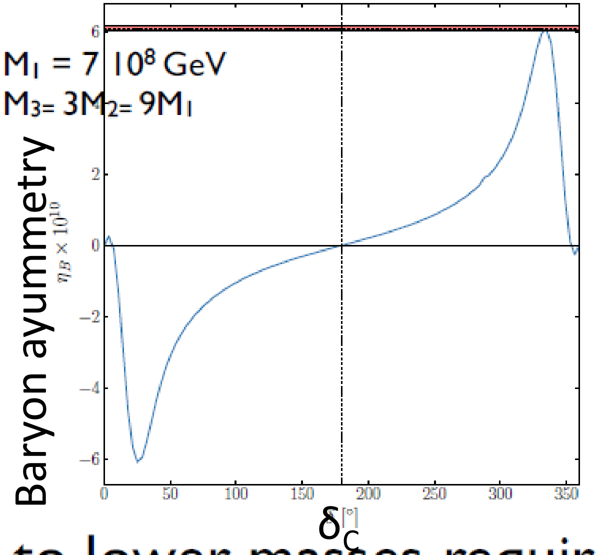
A full study shows that delta can give an important (even dominant) contribution to the baryon asymmetry. For Majorana CPV, effects enhanced by a factor of ~10.

Test of leptogensis models with Dirac CP violation phase

Slide from Silva Pascoli's talk at NeuTel2019

Low mass flavour regime: $M_1 < 10^9$GeV

$$R \approx \begin{pmatrix} R_{11} & R_{12} & R_{13} \\ \pm i R_{22} & R_{22} & R_{23} \\ -R_{22} & \pm i R_{22} & \pm i R_{23} \end{pmatrix}$$



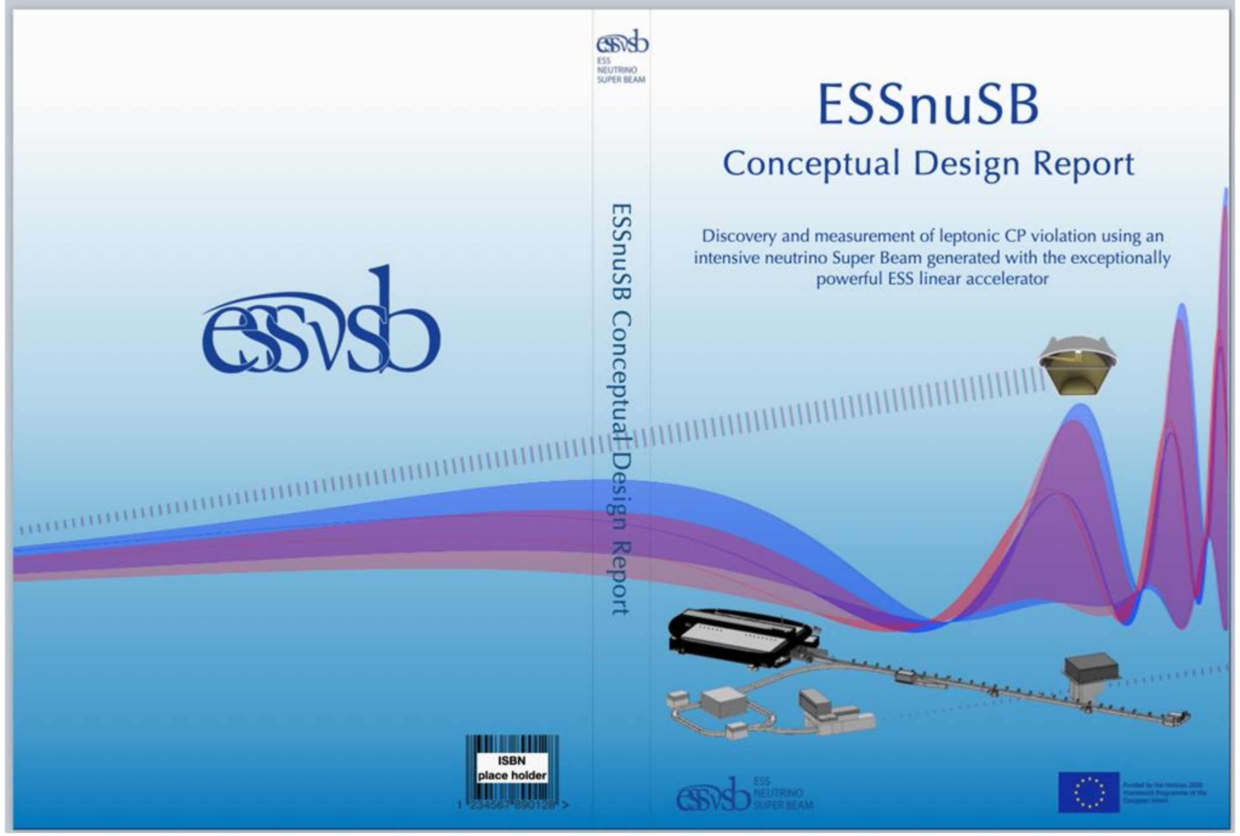
Prediction δ_{CP}= 330°

A special structure of the R matrix is required. R22>>1, enhancing the CP asymmetry without affecting neutrino masses (at three level). Going to lower masses requires finetuning as one-loop mass contributions are important.

High mass (unflavoured) regime: $M_1 > 10^{12}$GeV

Due to washout which is affected by flavour, even at high masses the low energy CPV phases play a role.

ESSnuSB Conceptual Design Report



Published on arXive 6 June 2022:
https://arxiv.org/abs/2206.01208
and in European Physical Journal 6 Nov 2022
Eur. Phys. J. Spec. Top. (2022) **231**: 3779-3955
https://link.springer.com/article/10.1140/epjs/s11734-022-00664-w

CDR outline:
1. Linac upgrade
2. An accumulator ring
3. A target station and 50 m decay tunnel
4. A near detector placed in the neutrino beam some 250 m downstream of the target statio
5. A far detector 360 km from the target station consisting of 2 large underground tanks filled each with 240’000 m^3 of water
6. Physics performance

https://arxiv.org/abs/2203.08803

Current view of ESS

The ESSnuSB+ Collaboration

1	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	FR
2	UNIVERSITE DE STRASBOURG	FR
3	RUDER BOSKOVIC INSTITUTE	HR
4	TOKAI NATIONAL HIGHER EDUCATION ANDRESEARCH SYSTEM, NATIONAL UNIVERSITY CORPORATION	JP
5	UPPSALA UNIVERSITET	SE
6	LUNDS UNIVERSITET	SE
7	EUROPEAN SPALLATION SOURCE ERIC	SE
8	KUNGLIGA TEKNISKA HOEGSKOLAN	SE
9	UNIVERSITAET HAMBURG	DE
10	UNIVERSITY OF CUKUROVA	TR
11	NATIONAL CENTER FOR SCIENTIFIC RESEARCH "DEMOKRITOS"	EL
12	ARISTOTELIO PANEPISTIMIO THESSALONIKIS	EL
13	SOFIA UNIVERSITY ST KLIMENT OHRIDSKI	BG
14	LULEA TEKNISKA UNIVERSITET	SE
15	ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE	CH
16	UNIVERSITA DEGLI STUDI ROMA TRE	IT
17	UNIVERSITA' DEGLI STUDI DI MILANO-BICOCCA	IT
18	ISTITUTO NAZIONALE DI FISICA NUCLEARE	IT
19	UNIVERSITA DEGLI STUDI DI PADOVA	IT
20	CONSORCIO PARA LA CONSTRUCCION, EQUIPAMIENTO Y EXPLOTACION DE LA SEDE ESPANOLA DE LA FUENTE EUROPEA DE NEUTRONES POR ESPALACION	ES

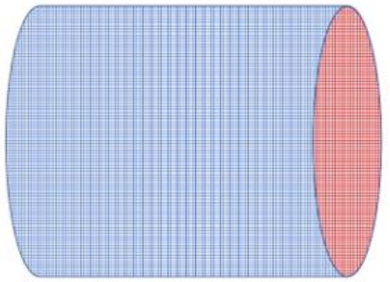
Partner Countries

Bulgaria, Croatia, France, Germany, Greece, Italy, Japan, Spain, Switzerland, Sweden, Turkey

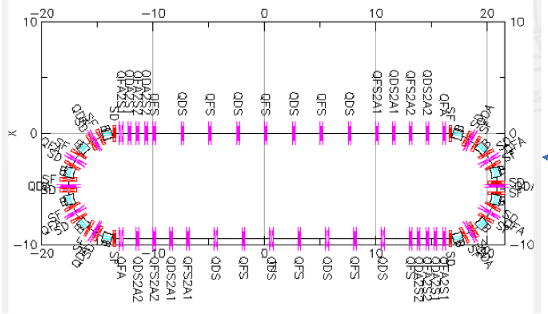
ESSnuSB+ additions for low energy cross-section measurements

that will be set up in a staged process starting with LEMNB, LEMMON and the Near Detector to be followed by LEnuSTORM and then the ESSnuSB programme

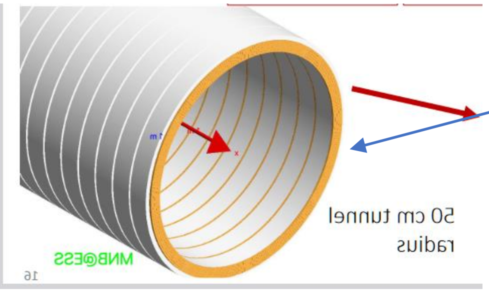
LEMMOND
near-near
Water Cherenkov
Detector with
fast readot

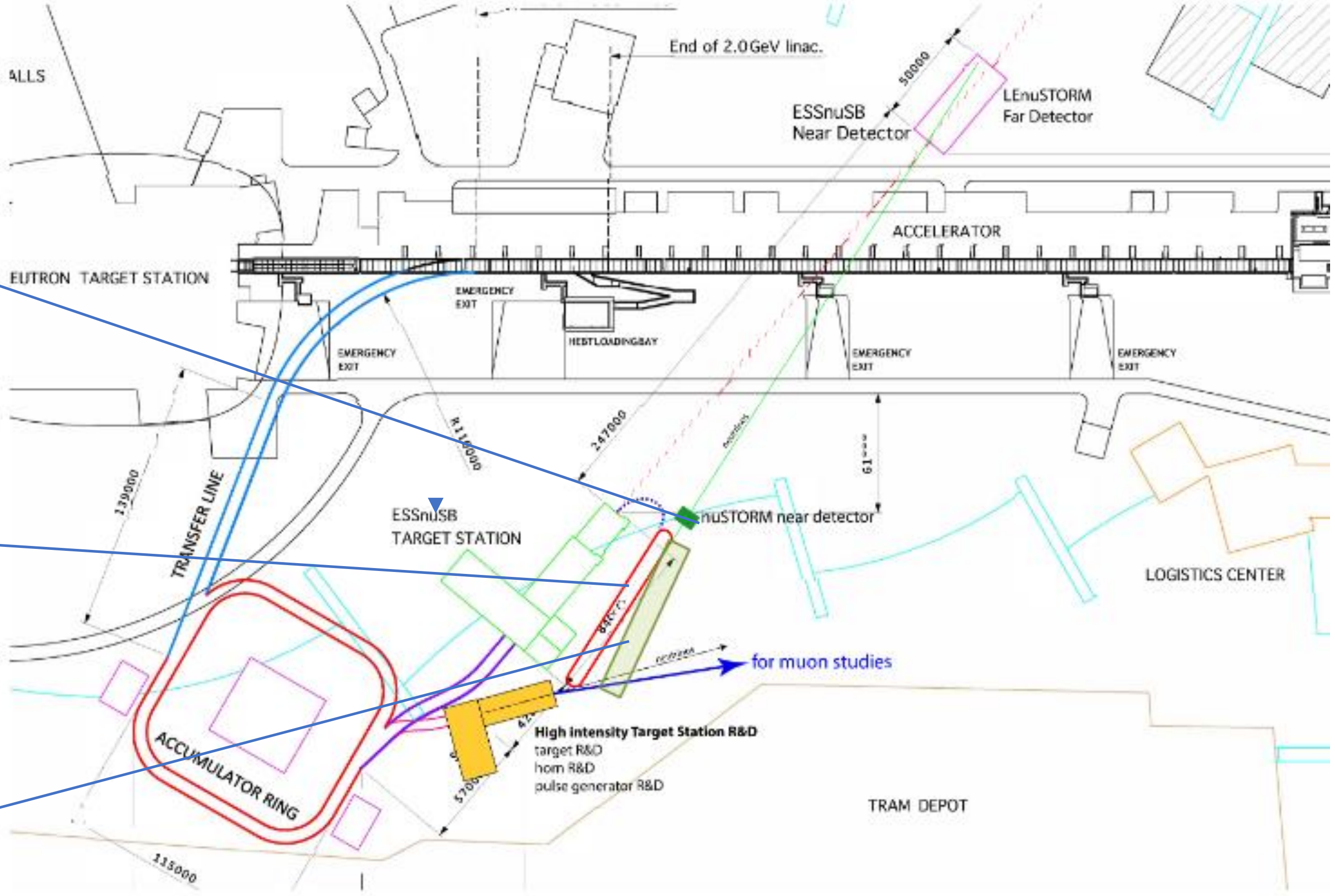


LEnuSTORM
a low energy
nuSTROM type
racetrack ring

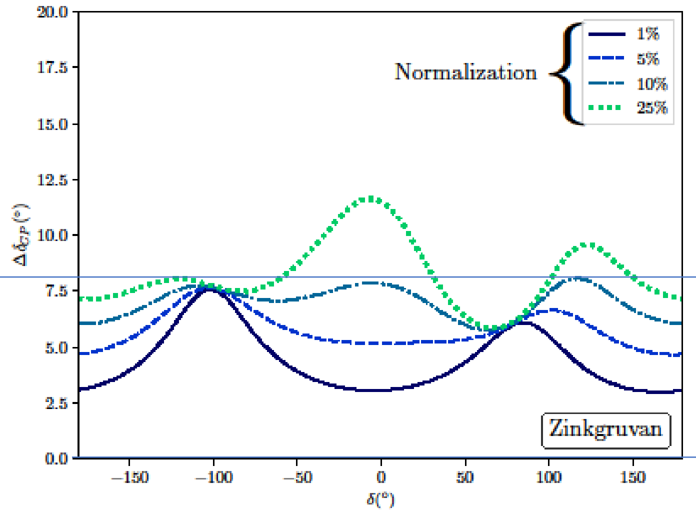


LEMNB, a low energy
ENUBET type
decay tunnel

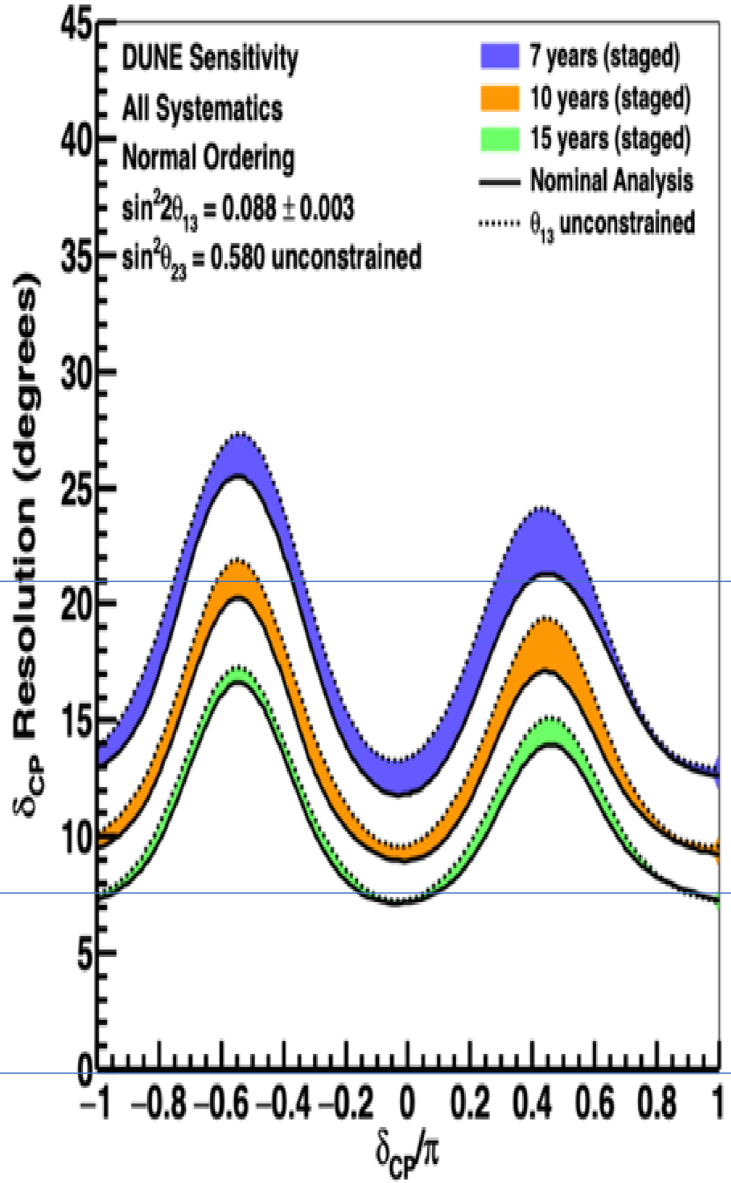




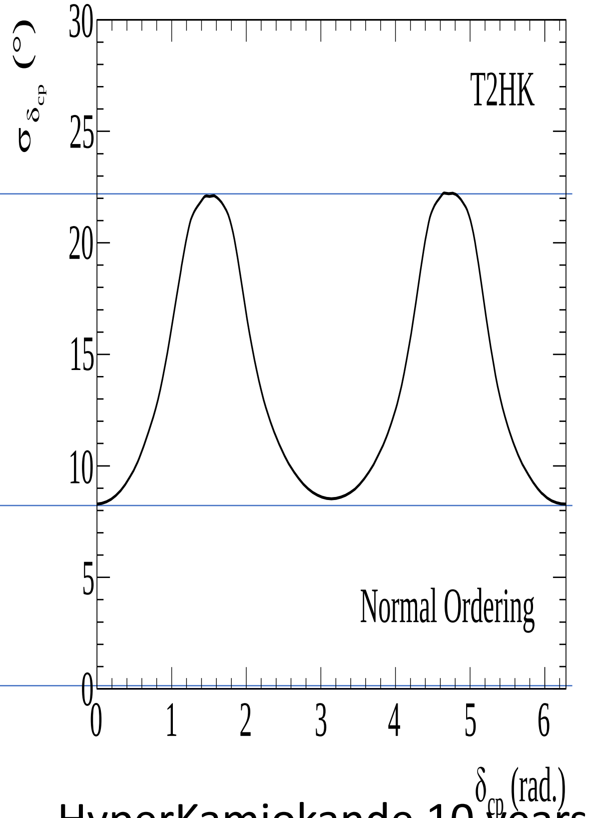
ESSnuSB in the international context – precision in δ_{CP}



ESSnuSB 10 years, light blue curves
https://arxiv.org/abs/2206.01208
p. 205

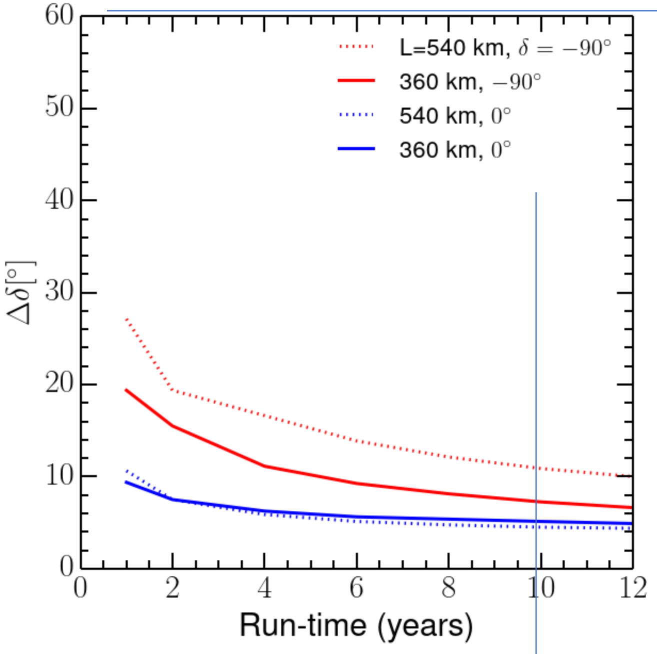


DUNE 10 years, yellow curve
https://arxiv.org/abs/2002.03005
p. 174

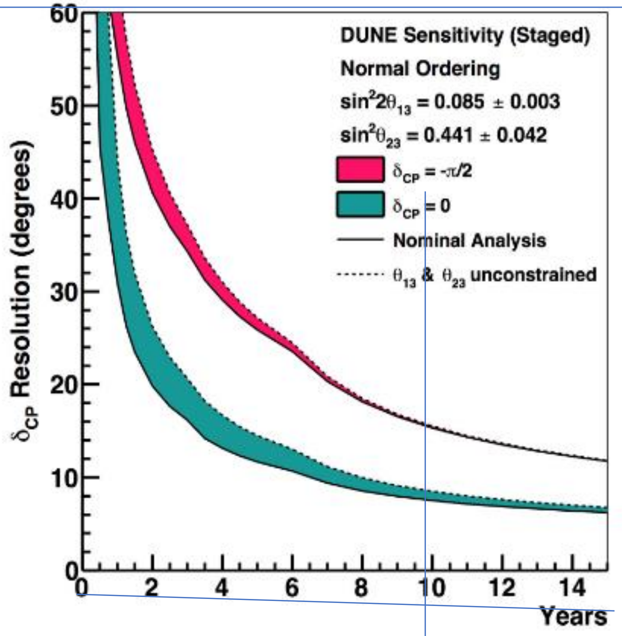


HyperKamiokande 10 years
https://arxiv.org/abs/1611.06118
p. 60, HKx1=one HK detector

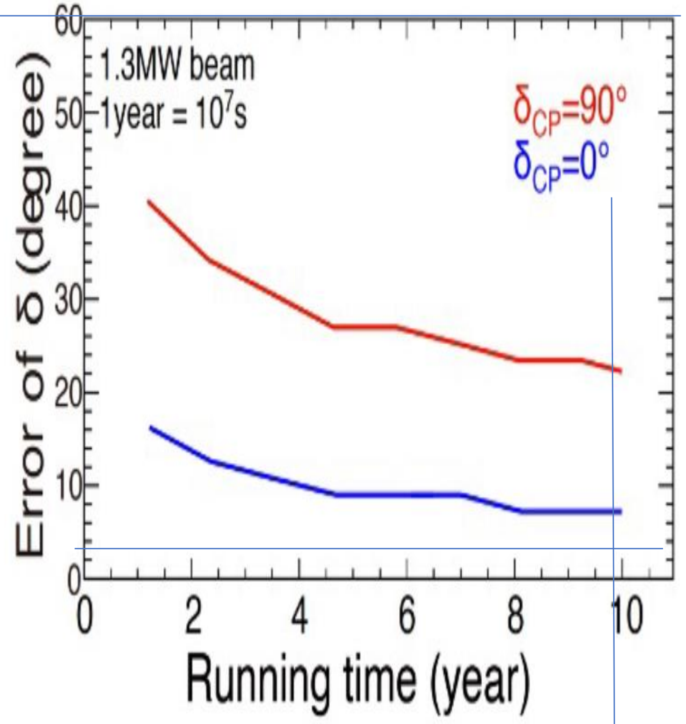
ESSnuSB in the international context – CPV resolution



ESSnuSB March 2022 with 5% normalization error

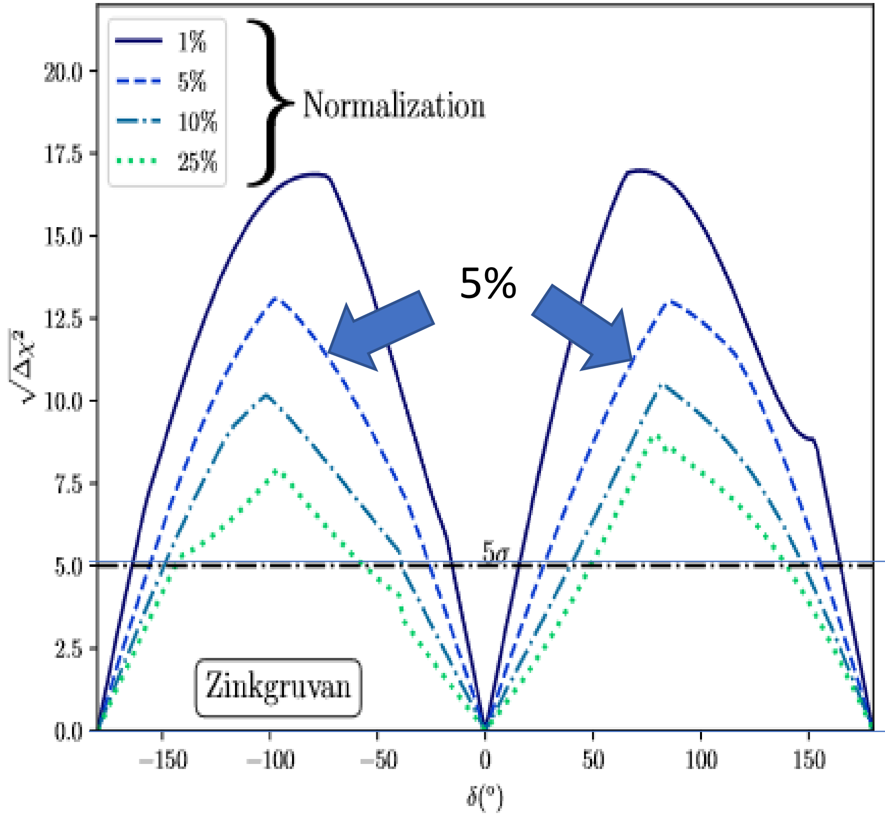


DUNE Snomass March 2022

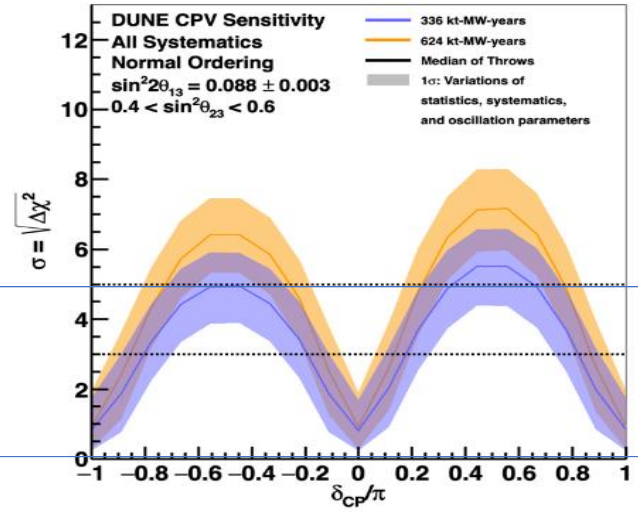


HyperKamokande Snowmass March 2022

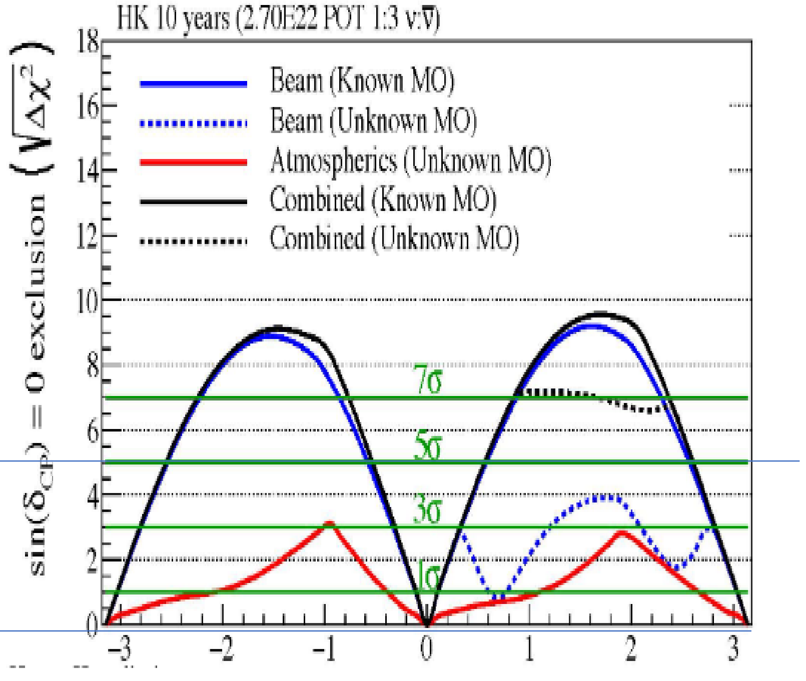
ESSnuSB in the international context – CPV discovery



ESSnuSB March 2022 with 5% normalization error



DUNE Snowmass March 2022



HyperKamokande Snowmass March 2022

EU's longterm support for a major European Neutrino Experiment

EU's Research Directorate has provided support to the project of building a long baseline neutrino facility in Europe since nearly 20 year by funding during this period a long series of design studies: CARE/BENE (FP7), EURONU (FP7), LAGUNA (FP7), LAGUNA-LBNO (FP7), EUCARD (FP7), COST Action CA15139, ESSnuSB (Horizon 2020), and ESSnuSB+ (Horizon Europe) and thereby **appears as well determined to have a major neutrino project realized in Europe**.

ESS management support for a neutrino physics program at ESS

The European Spallation Source (ESS) European Research Infrastructure Consortium (ERIC) is a member of the ESSnuSB Collaboration and supports ESSnuSB strongly as documented in recommendation letters from its four Director Generals since 2014.

EUROPEAN SPALLATION SOURCE

Jim Jeck in 2014

Date: 19 May 2014

To the European Commission's Horizon 2020 Research Infrastructure Office

Subject: Support for the ESSnuSB Conceptual Study

ESS notes that the ESSnuSB collaboration is planning a Design Study of ways to increase the average power of the ESS linear accelerator from 5 MW to 10 MW by doubling the duty cycle from 4% to 8%. This collaboration includes an international group of scientists and engineers from a number of research institutions including the universities of Durham, Krakow, Lund, Madrid, Sofia, Stockholm-KTH, Strasbourg and Uppsala and the laboratories of CERN, ESS, Fermilab and RAL. The goal of the collaboration is to determine the best way to produce the highest flux neutrino-beam in the world. An important boundary condition for the conceptual study, according to the ESSnuSB group, is that the ESS mission for neutron production will not be compromised in any way. An additional ESS boundary condition is that any ESS engagement in the study will not divert our staff from their current priorities, i.e., successful delivery of the ESS baseline linear accelerator.

The stated scientific aim of the Design Study is to specify how the high flux neutrino beam would be produced and how the beam would make possible the discovery of CP violation in the neutrino sector. According to the ESSnuSB group, this scientific goal could be achieved by comparing the rates of appearance of electron neutrinos and electron anti-neutrinos at the second neutrino oscillation maximum. The second maximum for the enhanced ESS parameters is approximately 500 km from the ESS site. My understanding is that at this distance there is an appropriate underground location for a large neutrino detector available. New neutrino measurements, published in 2012, imply that the CP violation signal at the second maximum is significantly larger than at the first maximum. Other planned neutrino experiments in the US and Japan, proposed before 2012, is designed to measure neutrino oscillations at the first maximum and will not have access to the second maximum. Statistically significant measurements at the second, more distantly situated maximum would be made possible only by the use of the exceptionally high proton beam flux of the ESS linear accelerator.

Given the high scientific interest in exploring the possibility of using the future ESS linear accelerator for neutrino physics, interesting additional user communities, and a shared commitment to the above mentioned boundary conditions for the Design Study, ESS management agrees to provide information and general support for the ESSnuSB collaboration's ongoing studies.

James Yeck
Director General and CEO

EUROPEAN SPALLATION SOURCE

John Womersly in 2017

To whom it may concern – ESSnuSB project

The European Spallation Source (ESS) is now well into its construction phase and all indications are positive. The ESS is naturally concentrating on delivering first neutrons and achieving full specification such that we can deliver the transformational science that such a powerful source will enable. This is our top priority. At the same time we are aware of the future potential of the ESS laboratory. There are a number of future pathways and among them is the possibility, being explored by the very imaginative ESSnuSB project to deliver high intensity beams of neutrinos. Neutrinos offer a window to the fundamental structure of the universe which is totally independent and complementary to high energy colliders such as CERN. The ESSnuSB project is coming together around an increasingly credible science case and has assembled a strong international scientific collaboration with members from 12 European countries now organized as a EU COST Association, of which ESS is an associate member.

The ESSnuSB collaboration is currently studying how the average power of the ESS linear accelerator could eventually be increased from 5 MW to 10 MW by doubling the duty cycle from 4% to 8% with the goal of producing the highest flux neutrino-beam in the world. The primary scientific aim of the study is to specify how such a high flux neutrino beam would be produced and explore what new ground breaking neutrino physics would then become possible. The discovery of matter-antimatter asymmetries in the neutrino sector is especially tantalizing, as it could explain the observed preponderance of matter over antimatter in our universe. The exceptionally high power possible in an eventual ESS neutrino beam would allow for the neutrino measurements to be made at the second neutrino oscillation maximum, where the CP signal is three times larger than at the first maximum. This provides a clear advantage over the current generation of neutrino projects planned in US and Japan, respectively. The ESSnuSB project also opens up the possibility, at a future stage, of making use of the intense flux of muons generated concurrently with the neutrinos and to enable the generation of high-brightness short-pulse neutron beams.

It is now important for the ESSnuSB project to embark upon a sustained design phase so that its feasibility can be properly judged when the time comes. For the reasons given above I have no hesitation in fully endorsing the application for INFRADEV support so that a professional Design Report and an outline costing can be available by 2020 when ESS will be operational and its future development pathways can be assessed.

Lund, February 13, 2017

John Womersley
Director General

EUROPEAN SPALLATION SOURCE

Kevin Jones in 2021

Lund, May 25th 2021

Dear Tord,

I was very pleased to hear of the progress that you have made with the ESSnuSB design study and I look forward to reading the Conceptual Design Report (CDR) in due course. The second phase of your work is very innovative and deserves to be supported. It broadens considerably the scientific scope and impact of the proposed upgrade to the ESS linear accelerator (linac). I encourage you to put the considerable energies and expertise of your collaboration into this second phase.

On behalf of the ESS organisation I would like to reiterate our continued strong support for the neutrino and muon physics opportunities presented by the ESSnuSB initiative as previously communicated by John Womersley in 2017.

Please keep me posted on the outcome of the upcoming TIARA meeting and your further progress.

With best regards

Kevin Jones
Acting Director General

EUROPEAN SPALLATION SOURCE

Helmut Schober in 2022

Lund, March 23, 2022

Dear Tord,

I was very pleased to hear of the progress that you have made with the ESSnuSB design study and I look forward to reading the Conceptual Design Report (CDR) in due course. The next phase of your work ESSnuSB+ is very innovative and deserves to be supported. It consolidates and broadens considerably the scientific scope and impact of the proposed upgrade to the ESS linear accelerator (linac). I encourage you to put the considerable energies and expertise of your collaboration into this second phase.

While concentrating all our efforts on realising the current baseline, I would like to reiterate ESS's continued strong support for exploring the use of neutrinos and muons at ESS to create the new physics opportunities presented by the ESSnuSB initiative as previously communicated by ESS Director General in 2017 and 2021.

Please keep me posted on your further progress.

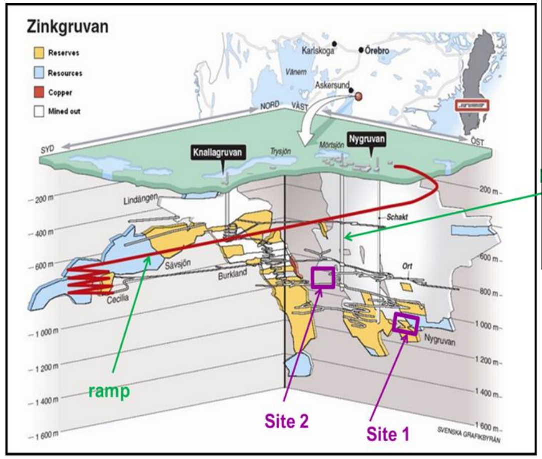
With best regards

Helmut Schober
Director General

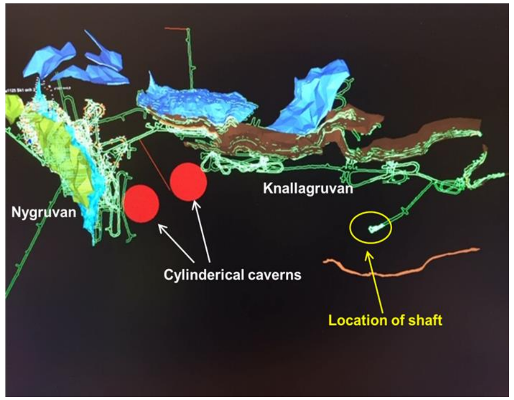
Helmut Schober: ”I would like to reiterate ESS's continued strong support for exploring the use of neutrinos and muons at ESS to create the new physics opportunities by the ESSnuSB initiative as previously communicated by ESS Director Generals in 2014- 2021.”

Zinkgruvan Mine Management support for ESSnuSB

Zinkgruvan Mining AB is a partner of ESSnuSB and its Mine Manager Craig Griffiths attended the ESSnuSB+ Yearly Collaboration meeting at CERN 16-19 Oct 2023



Two potential sites identified are marked Site 1 and Site 2. Site 2 is considered as best considering access to main transport infrastructure and located in an area less disturbed by mining activities



Underground lay-out of Zinkgruvan Mine and photo from one of our visits there

Zinkgruvan Mine Manager Craig Griffiths (pointing upwards) visiting the Hyper-Kamiokande excavation site on 27 Sept 2023

Conclusions

In view of the important scientific mission of long-base neutrino experiments and the long lead times for preparing next generation experiments, there is a need to now plan for the long-term future of such experiments, beyond those that are currently operating and those now starting construction. The ESSnuSB is a second generation ESS-based neutrino super beam for high precision measurements of the CP violating angle.

The first EU-supported phase of the ESSnuSB conceptual design study 2018-2021 has been successfully concluded and the results reported in the European Physical Journal, demonstrating the **feasibility of the use of the ESS 5 MW linac as proton driver** for a long base-line neutrino experiment with **exceptionally high resolution in $\boldsymbol{\delta_{CP}}$** $(8°)$.

A second EU-supported phase of the ESSnuSB design 2023-2026 has started and is focussing on including facilities for **high precision neutrino cross-section measurements at low energy** based on the construction and use of a Low Energy Monitored Neutrino Beam and Low Energy nuSTORM as first stages in the ESSnuSB programme.

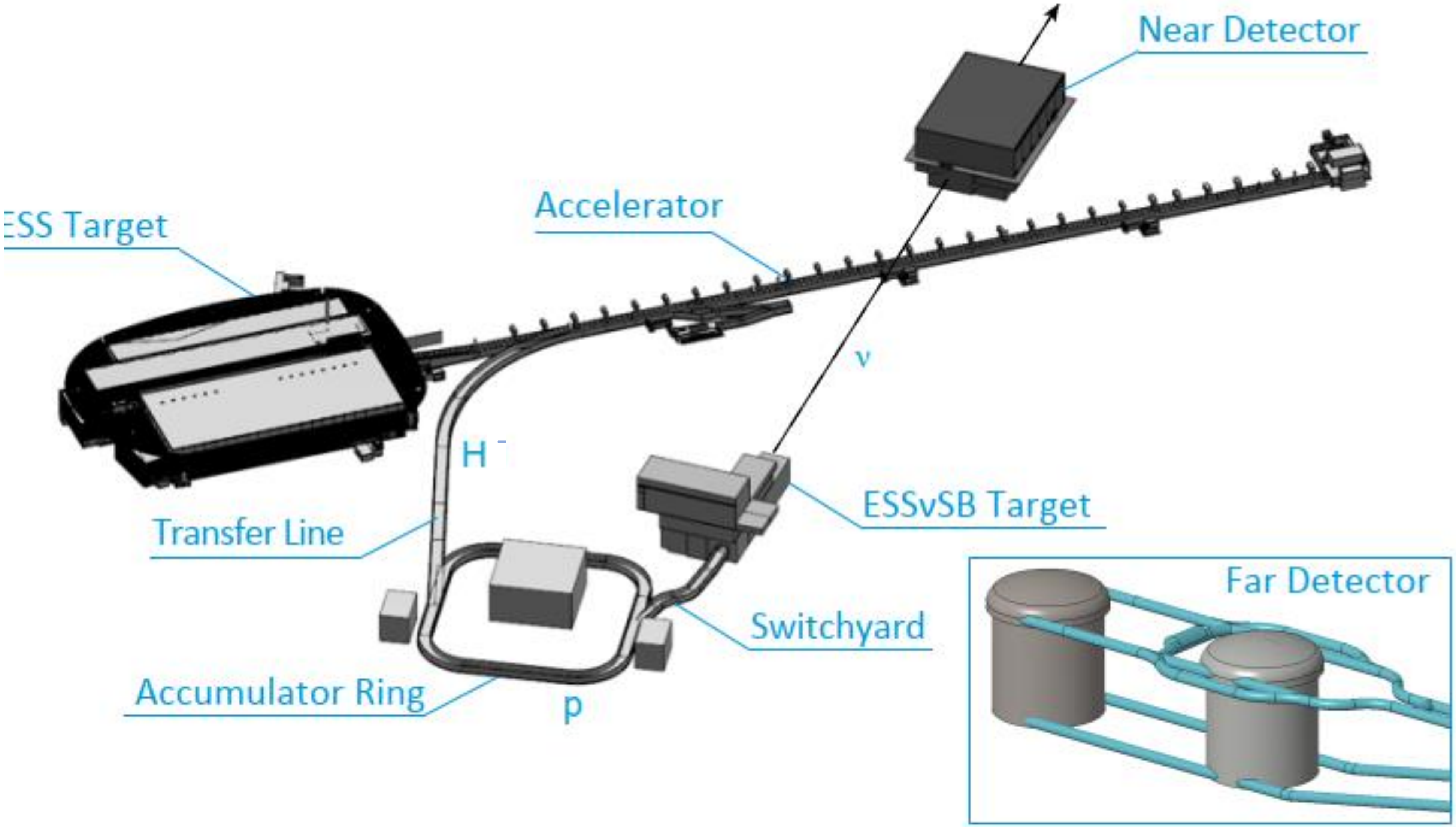
The ESSnuSB Collaboration, currenly consisting of ca 80 members from 20 universities and 11 European countries has had and has **strong support** from the European Union Research INFRADEV Programme (Horison2020 and Horizon Europe), from the ESS Management and from the Zinkgruvan Mine Management.

The current plan for the ESSnuSB long baseline measurements is to **start data taking in 2038**

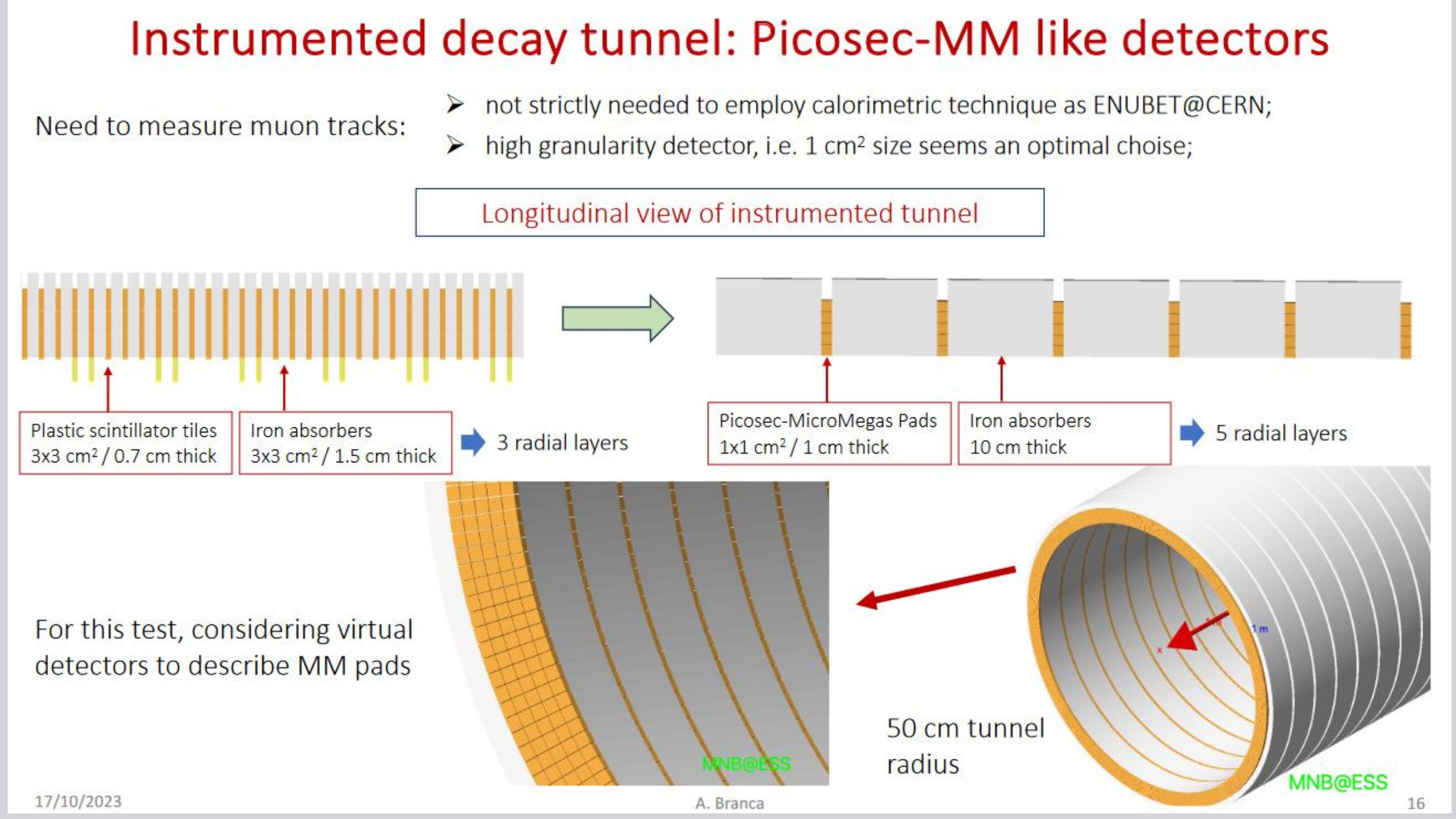
Thank you!

ESSnuSB lay-out

Far detector at Zinkgruvan 360 km distance



Low Energy Monitored Neutrino Beam LEMNB for π decay

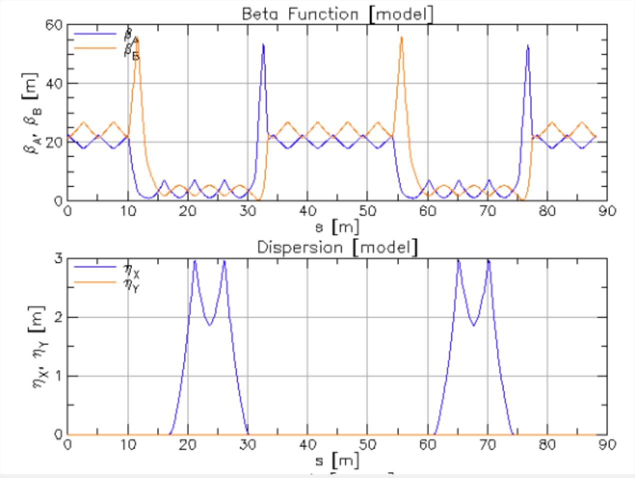


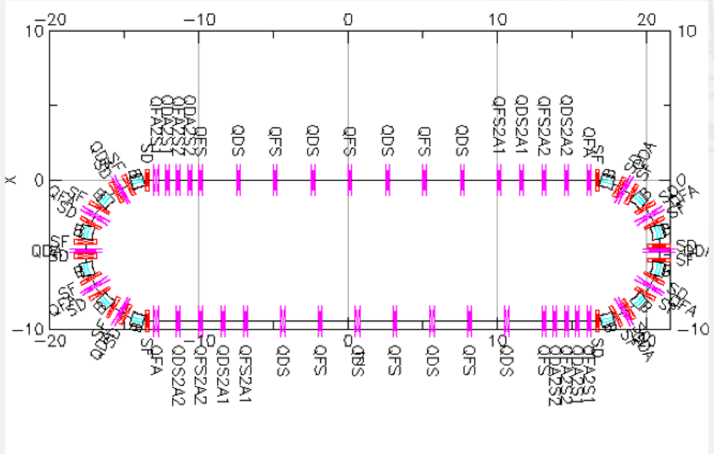
The LEMNB program will be set up as the first stage of the ESSnuSB program

Presented at the ESSnuSB+ Annual Meeting 16-20 Oct 2023 by Antonio Branca – University and INFN of Milano-Bicocca

Low Energy neutrinos from Stored Muons LEnuSTORM

Fodo design of the ring, 88m,
(no chromaticity correction)





	x	y
Q	3.24	2.83
Chrom	- 6.82	- 7.41

~FNAL *normal-conducting*, the survival rate for 100 turns: 50%

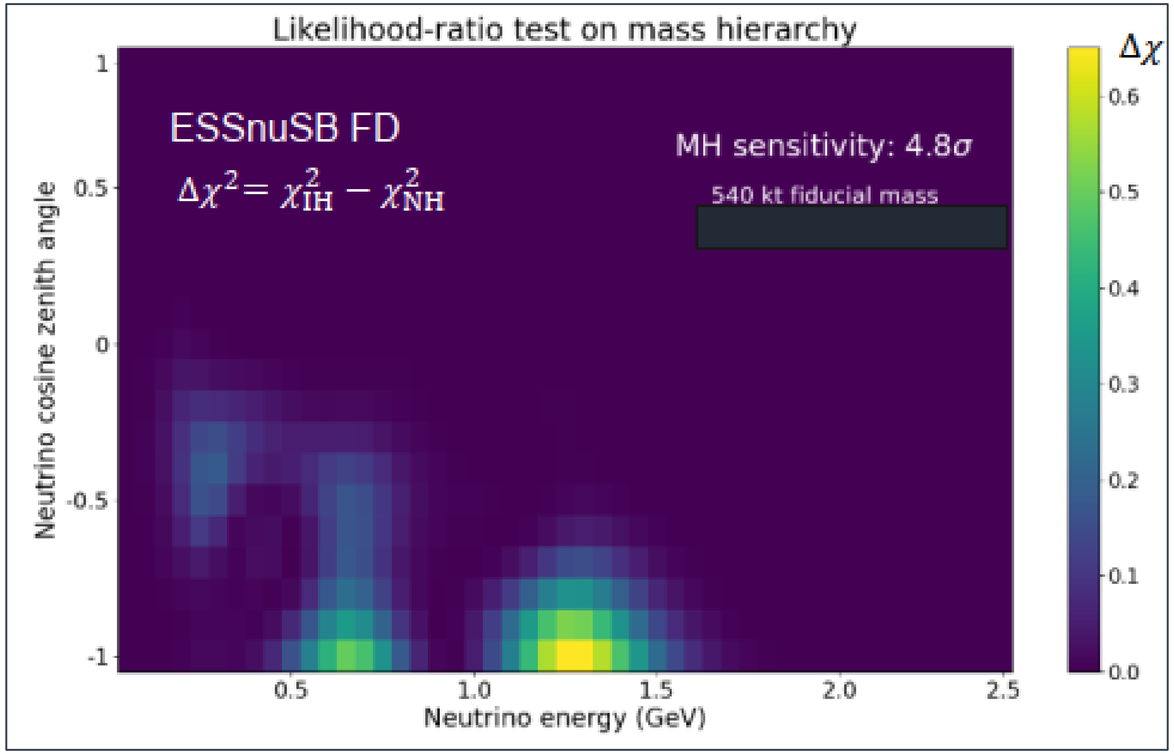
UPPSALA

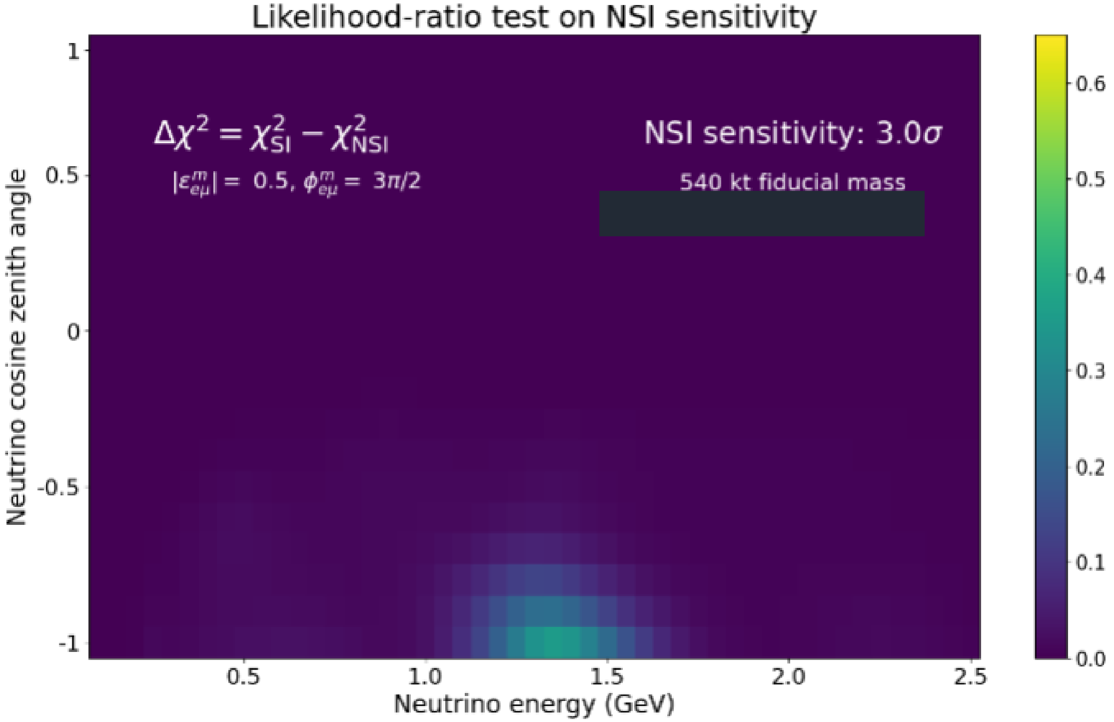
The LEnuSTORM program will be set up as the second stage of the ESSnuSB program

Presented at the ESSnuSB+ Annual Meeting 16-20 Oct 2023 by Ting Wing Choi, Uppsala University

Mass Hierarchy and Non-Standard Interactions with ESSnuSB

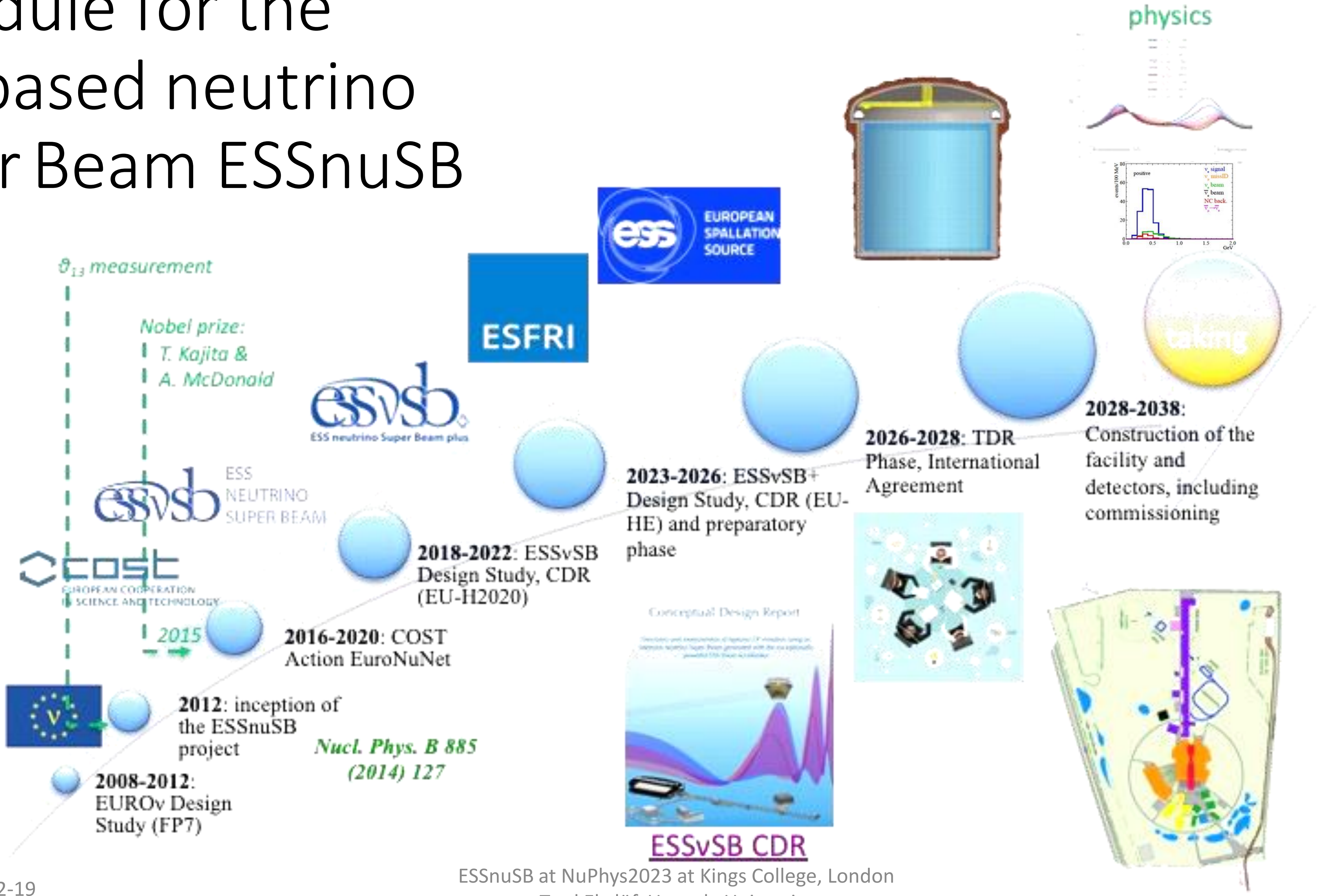
VERY PRELIMINARY RESULT





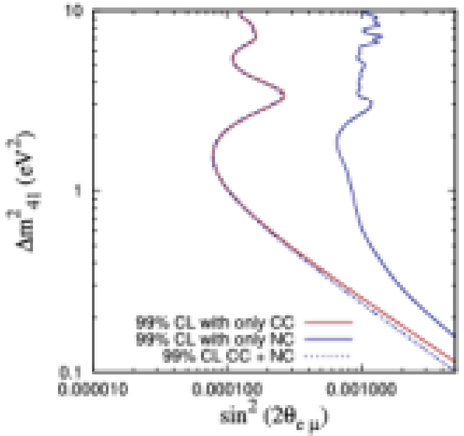
Presented at the ESSnuSB+ Annual Meeting 16-20 Oct 2023 by Sampsa Vihonen, KTH, Stockholm

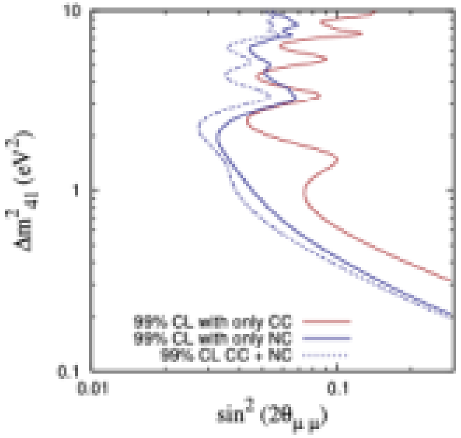
Schedule for the ESS-based neutrino Super Beam ESSnuSB



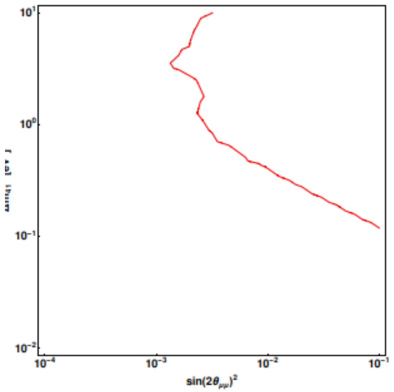
Sterile neutrino searches with ESSnuSB Near Detectors

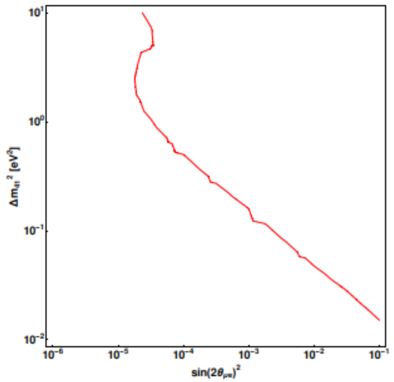
ANALYSIS IN PROGRESS





LEnuSTORM

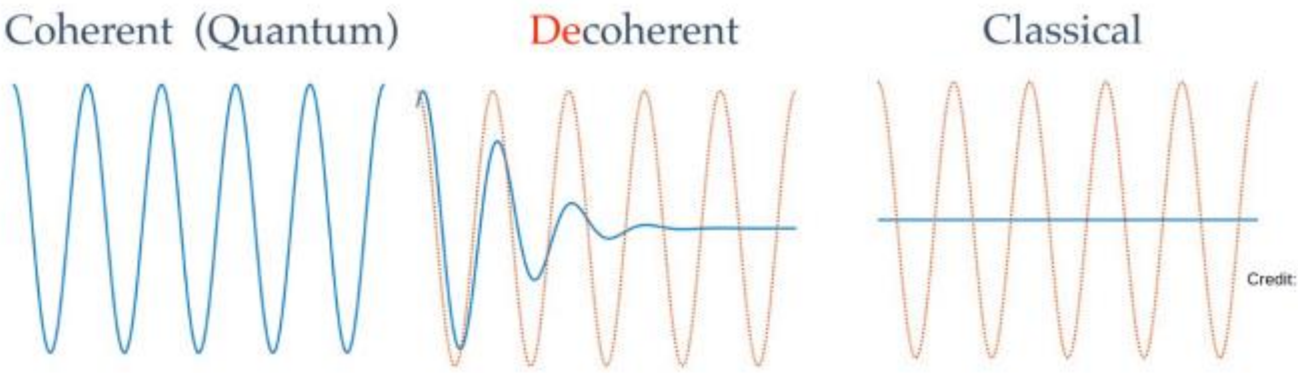




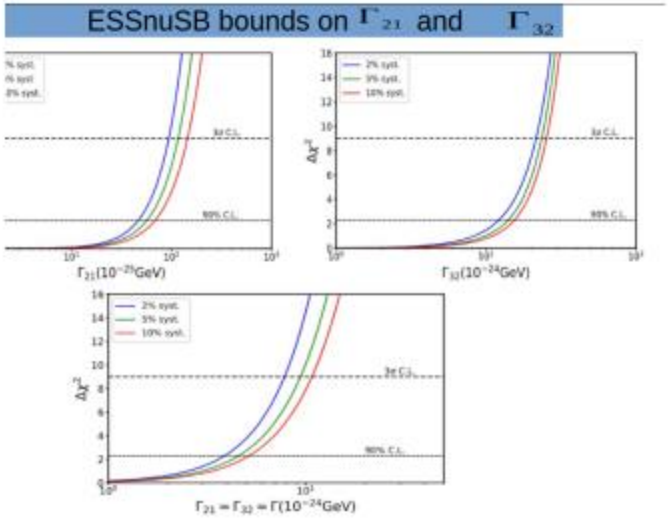
LEMNB

Presented at the ESSnuSB+ Annual Meeting 16-20 Oct 2023 by William Brorsson, KTH, Stockholm

Decoherence in neutrino oscillations



Credit: Ting Cheng



Presented at the ESSnuSB+ Annual Meeting 16-20 Oct 2023 by Aman Gupta, SINP Kolkata, India

Expected bounds on decoh. params.

One of the conclusions:

- The CPV measurement of ESSnuSB is robust in the presence of decoherence.

Test of flavour models

Slide from Serguey Petcov's talk at this conference

For arbitrary fixed θ^{ν}_{12} and any θ_{23} ("minimal" and "next-to-minimal" cases):

$$\cos\delta = \frac{\tan\theta_{23}}{\sin 2\theta_{12}\sin\theta_{13}}\left[\cos 2\theta^{\nu}_{12} + \left(\sin^2\theta_{12} - \cos^2\theta^{\nu}_{12}\right)\left(1 - \cot^2\theta_{23}\sin^2\theta_{13}\right)\right].$$

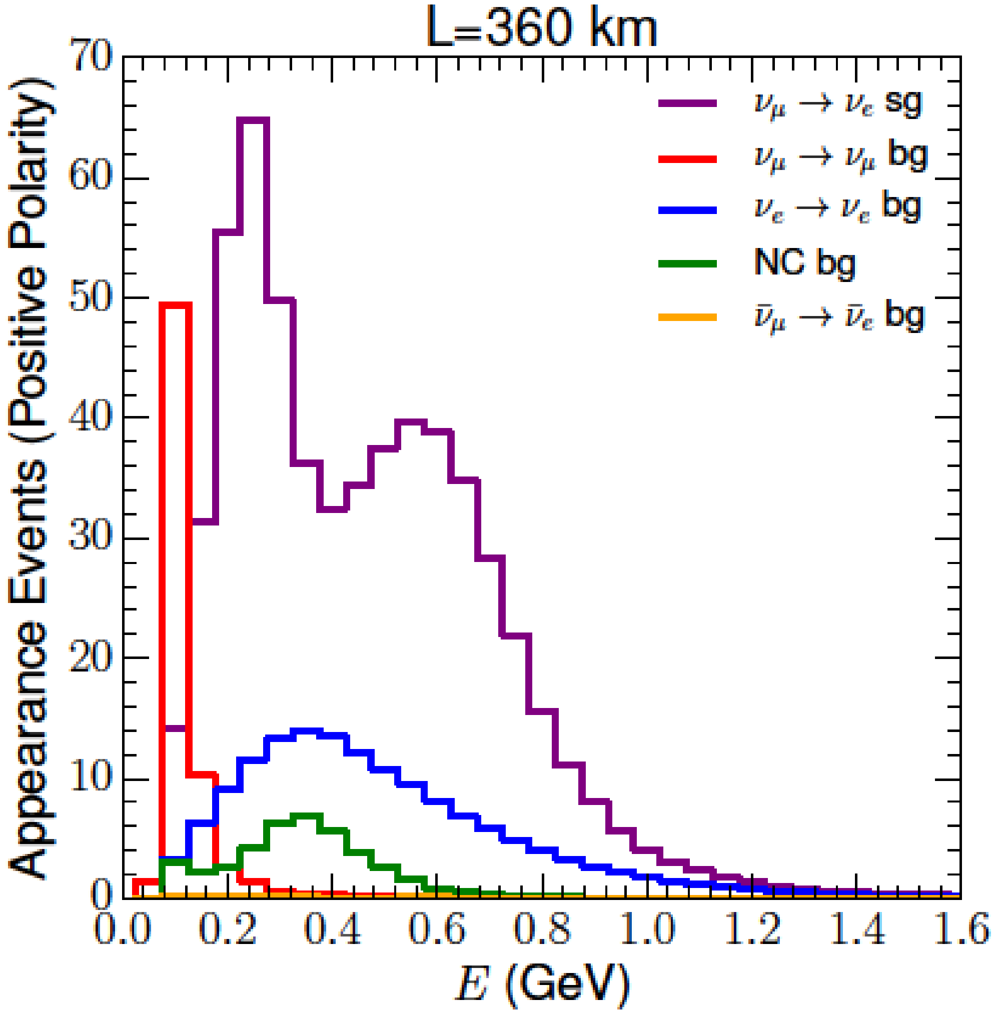
S.T.P., arXiv:1405.6006

This results is exact.

"Minimal" case: $\sin^2\theta_{23} = \frac{1}{2}\frac{1-2\sin^2\theta_{13}}{1-\sin^2\theta_{13}}$.

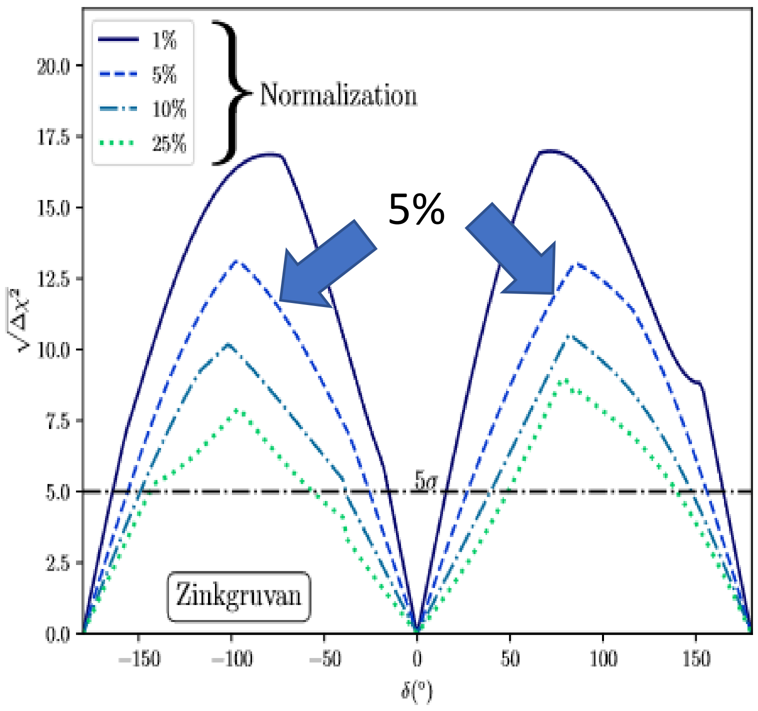
S.T. Petcov, NuTel, Venice 23/10/2023

ESSnuSB at the second neutrino oscillation maximum at the Zingruvan Mine

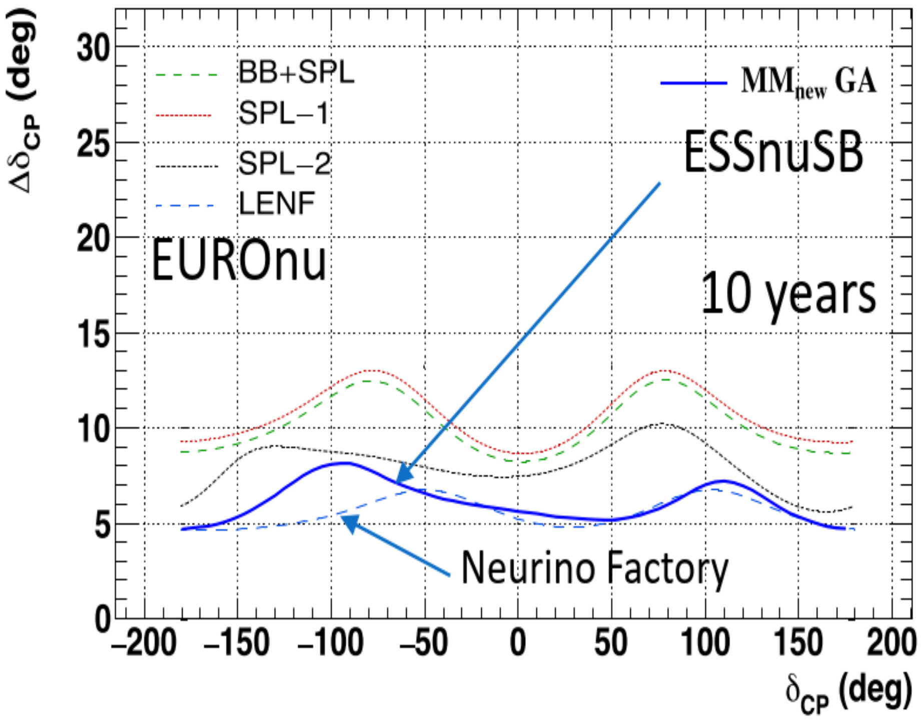


Signal (ν_e) and background energy distributions

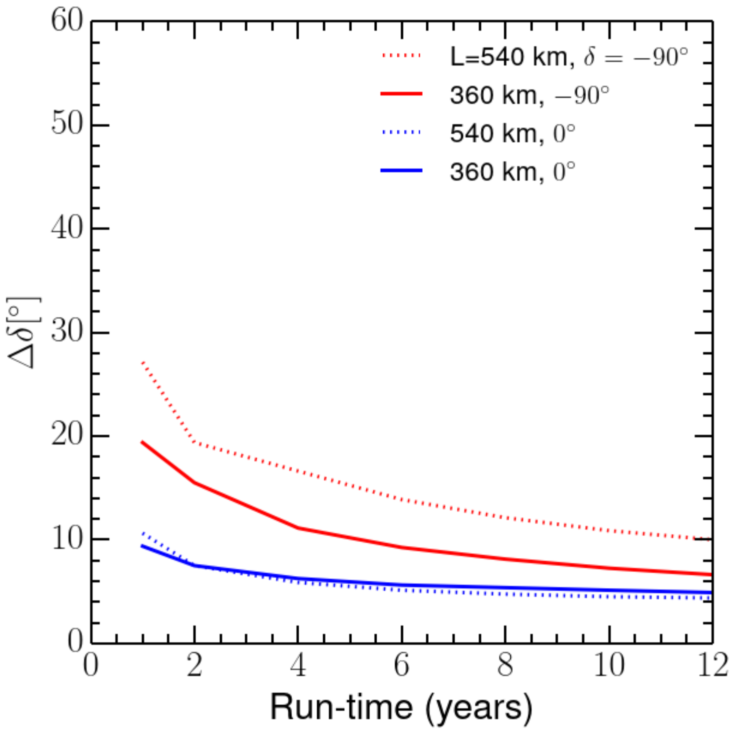
Performance for CPV discovery and δ_{CP} measurement



Discovery potential vs δ_{CP} angle after 10 years with 5% normalization error providing 70% coverage of all δ_{CP} vaues



Error in δ_{CP} angle vs δ_{CP} angle after 10 years with 5% normalization error



Error in δ_{CP} angle vs run time with 5% normalization error

European Particle Physics Strategy

We have taken note of the following recommendations of the CERN European Strategy Council:

"The design studies for next-generation long-baseline neutrino facilities should continue. "

"The first priority is the completion of the programme of measurements of the oscillation parameters, most notably the CP-violating phase of the mixing matrix and the neutrino mass ordering."

"Future European facilities such as FAIR, NICA and ESS envisage research programmes that are of interest to particle physics."

"The European particle physics community should work with the European Commission to shape and establish the funding instruments that are required for the realisation of common R&D projects, e.g. in the Horizon Europe programme."

″A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry."

ESSnuSB Cost Esimate as published in the ESSnuSB Conceptual Design report at arXiv:2203.08803v1

1’382 M€

Work in progress.

The cost of civil engineering on the ESS site is not included. A cost estimate of the civil engineering will require a detailed study of the implementation of the components on the ESS site, that will be made only in the next phase of the study.

Item	Sub-item	Cost (M€)	Cost (%)
Linac Upgrade	Ion Source and Low-Energy Beam Transport (LEBT)	5.00	0.36%
	Radio-Frequency Quadrupole	6.90	0.50 %
	Medium Energy Beam Transport (MEBT) Upgrade	3.00	0.22%
	Drift-Tube Linac with BPMs, BCMs	13.40	0.97%
	High-Beta Linac (HBL) Upgrade	10.40	0.75%
	33 Modulator Upgrades	3.50	0.25%
	8 New Modulators	9.00	0.65%
	15 Grid-Modulator Transformers	5.60	0.41%
	11 Grid-Modulator Transformers Retrofitted	0.50	0.04%
	26 Solid-State Spoke Amplifiers	26.00	1.88%
	New Klystrons for upgraded HBL	12.10	0.88%
	Remaining Klystron Refurbishment/Replacement	25.20	1.82%
	Cryogenics, Water Cooling, Civil Eng.	12.00	0.87%
	Total	**132.60**	**9.59%**
Accumulator	**Item**	**Cost (M€)**	**Cost (%)**
	DC Magnets and Power Supplies	50.00	3.62%
	Injection system	11.00	0.80%
	Extraction System	7.00	0.51%
	RF Systems	16.00	1.16%
	Collimation	8.00	0.58%
	Beam Instrumentation	19.00	1.37%
	Vacuum System	24.00	1.74%
	Control System	30.00	2.17%
	Total	**165.00**	**11.94%**
Target Station	**Item**	**Cost (M€)**	**Cost (%)**
	Target Station	32.00	2.32%
	Proton Beam Window System	5.20	0.38%
	PSU + Striplines	5.40	0.39%
	Target and Horn Exchange System	40.42	2.92%
	Facility Building Structure	26.60	1.92%
	General System and Services	21.80	1.58%
	Total	**131.42**	**9.51%**
Detectors	**Item**	**Cost (M€)**	**Cost (%)**
	Emulsion Detectors	2.00	0.14%
	Super Fine-Grained Detector	5.49	0.40%
	Near Water Cherenkov Detector	25.22	1.82%
	Far Water Detector	399.35	28.89%
	Underground Cavern Excavations	521.15	37.70%
	Total	**953.21**	**68.93%**
Grand Total		**1382.23**	**100.00%**

The ESS linac – status: 2 MW beam on target May 2025

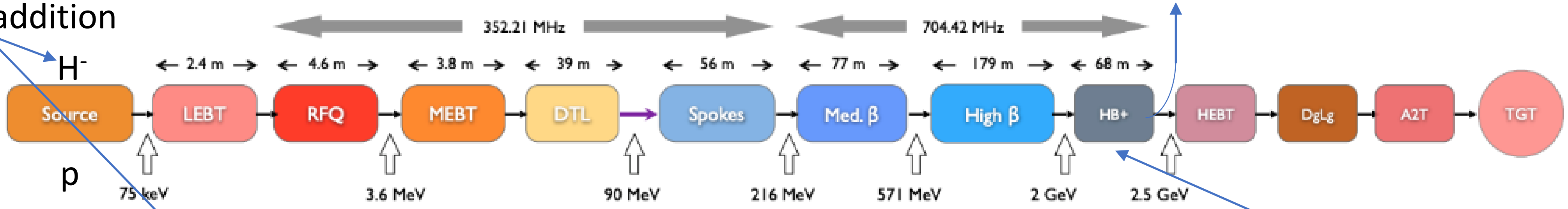
2.86 ms pulses at 14 Hz pulse frequency tah will be increased to 28 Hz, implying an increase of the beam power from 5 MW to 10 MW

Transfer Line to Accumulator

ESSnuSB addition

H^-

p

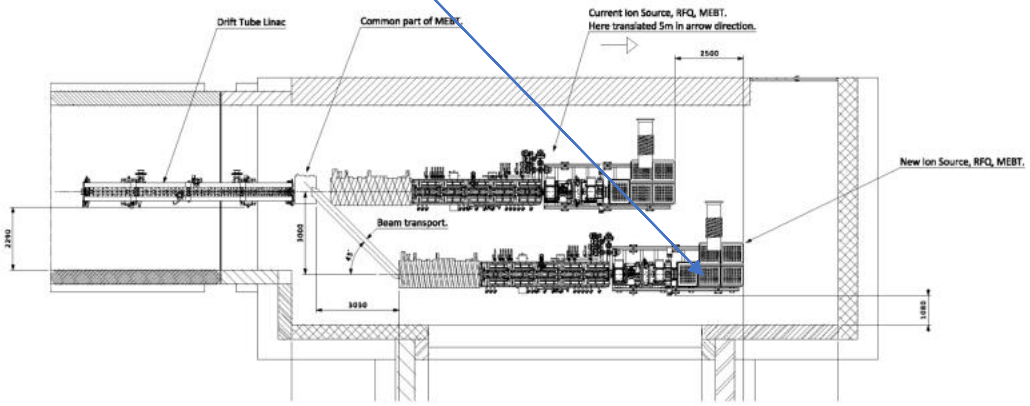


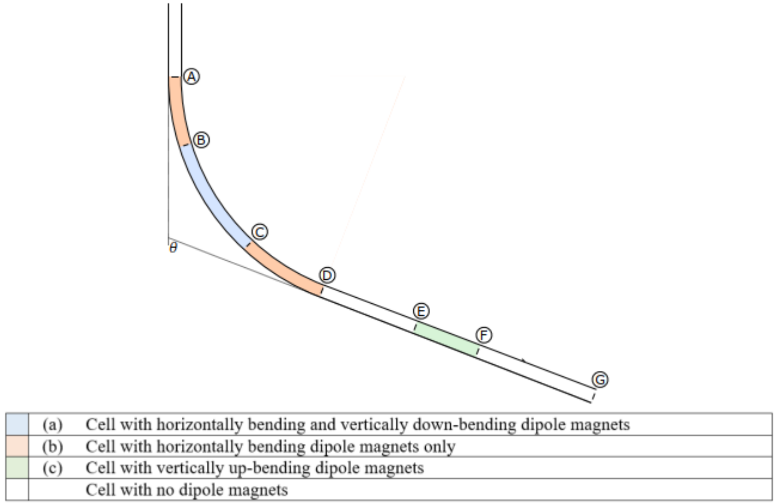
ESSnuSB addition

The linac

Normalconducting part

Superconducting part





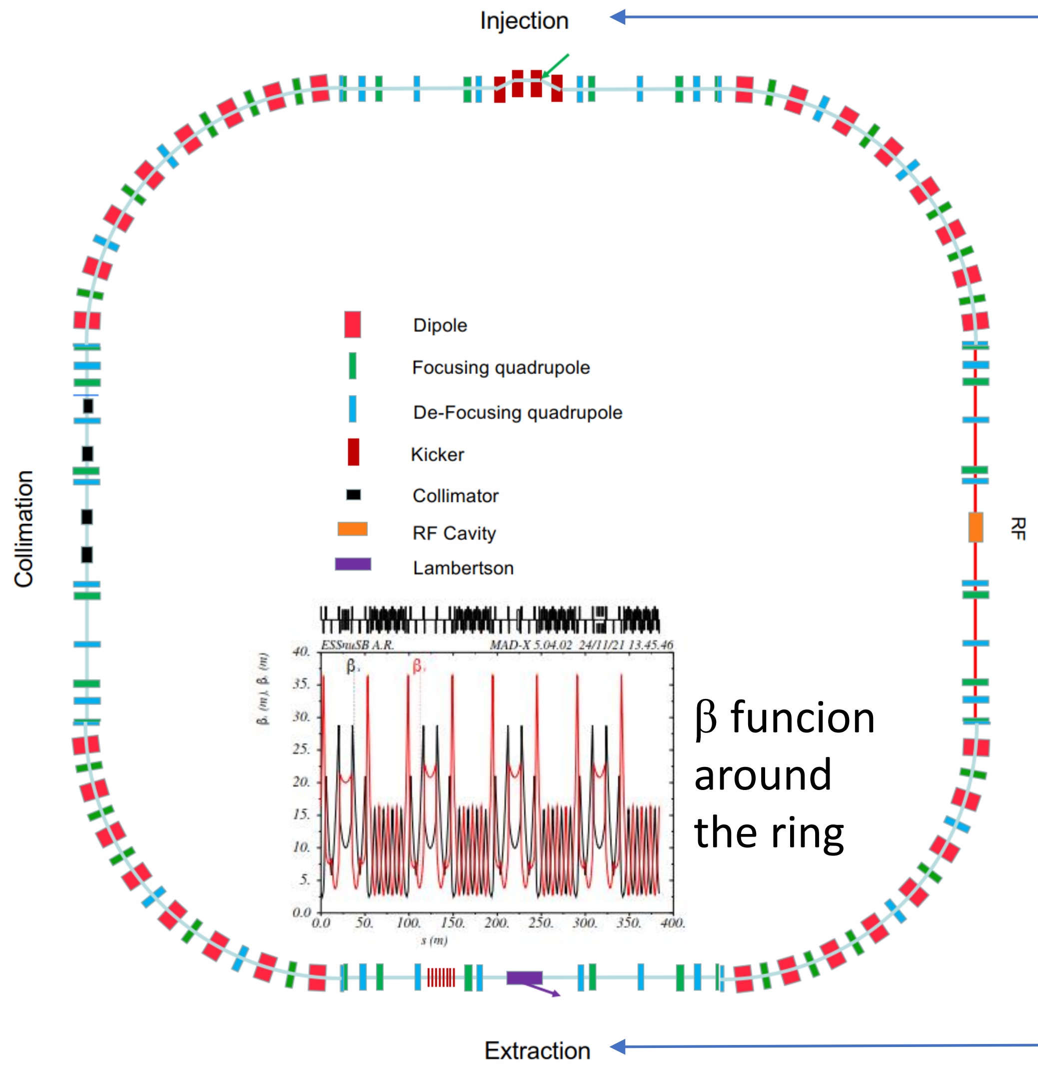
The merging of the H+ and the H- beams in the MEBT

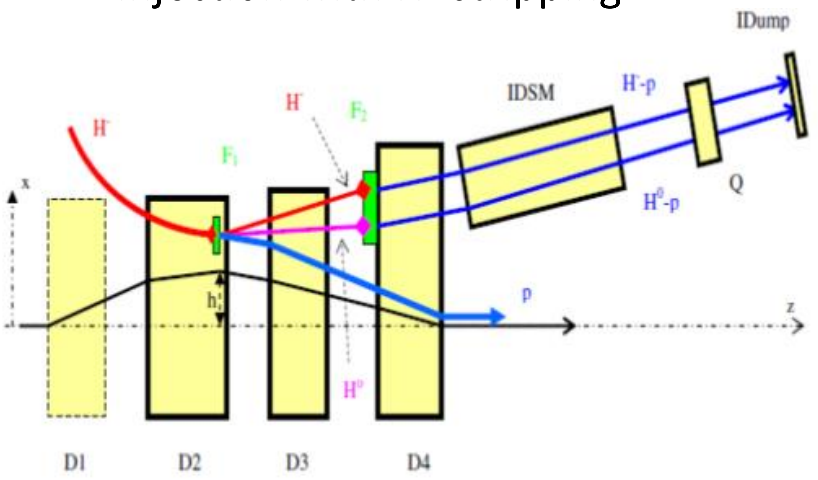
Transfer Line with bending limited by H^- Lorenz stripping

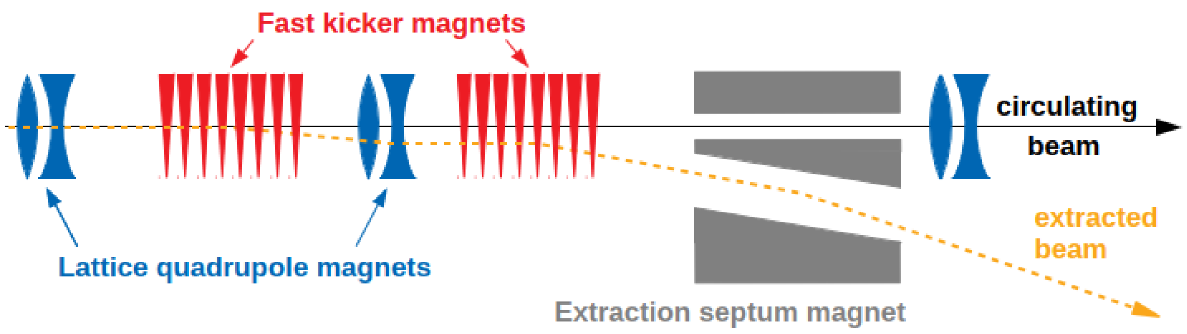
The Accmulator ring

Compresses and divides the 2.86 ms long linac pulse to four 1.2 μs long pulses

Injection with H- stripping



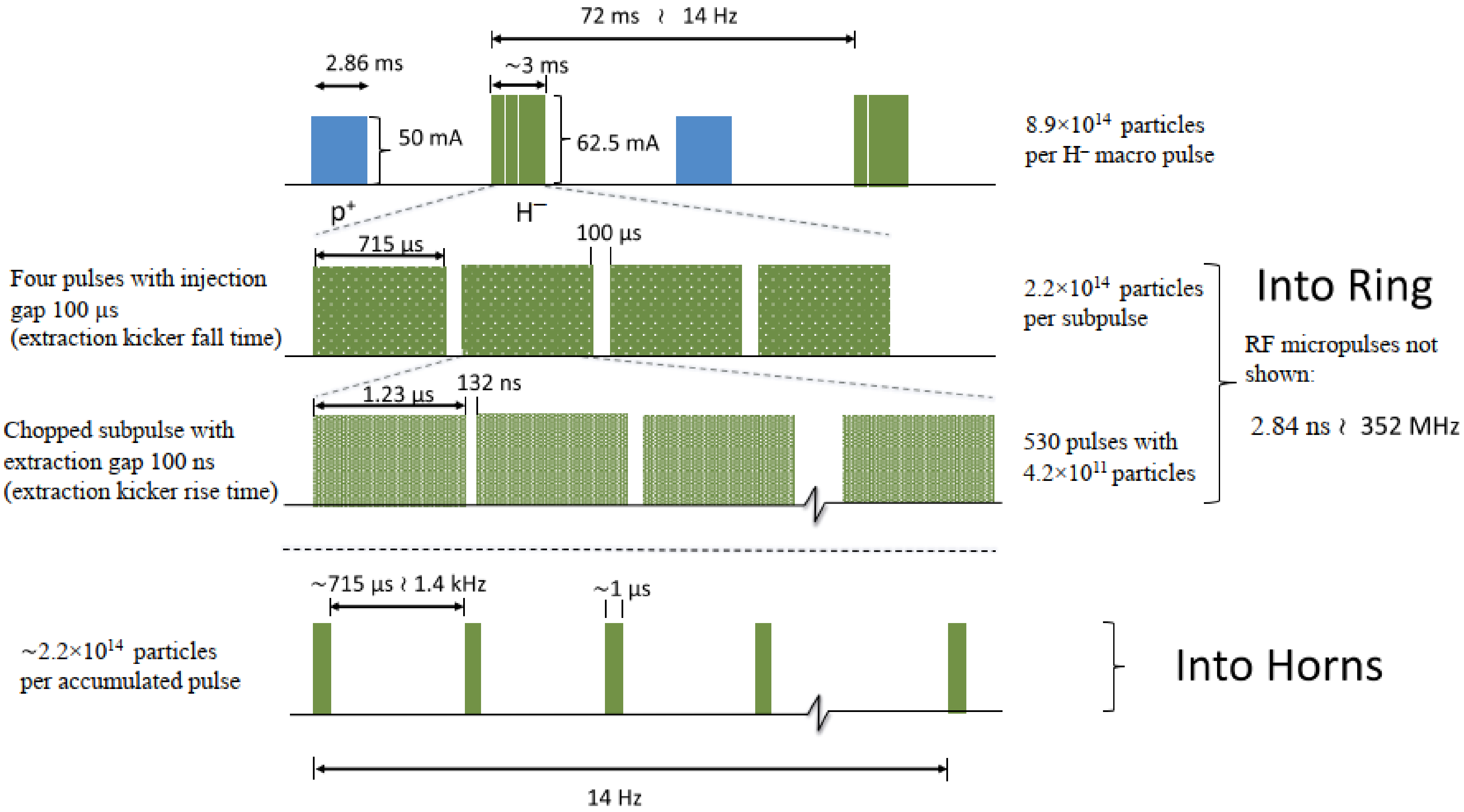




Extraction

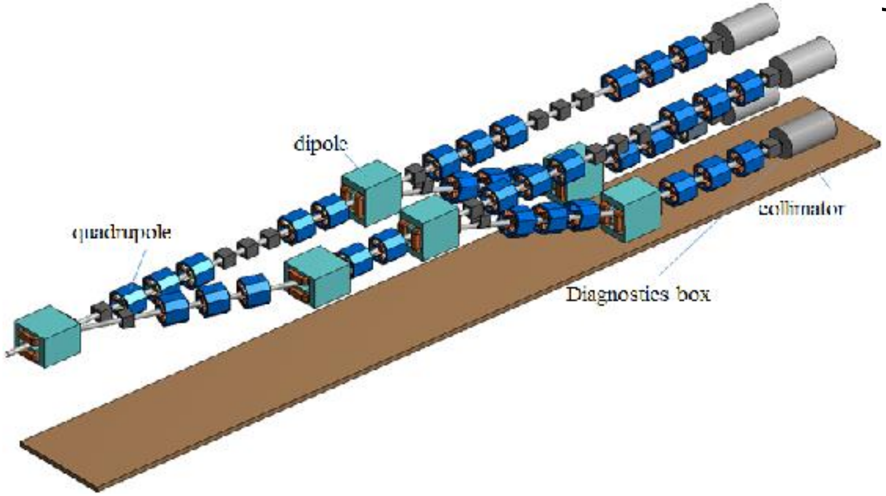
Detailed schematic of the ESSvSB pulsing scheme

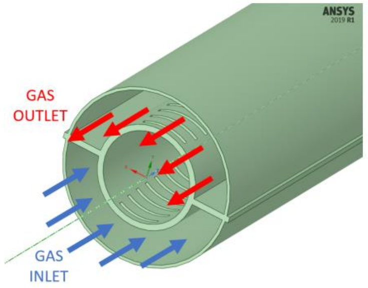
Insertion of 14 extra H^- pulses per second between the proton pulses, chopping each such pulse into four 715 µs pulses that are sequentially injected in the accumulator ring and compressed to 1.2 µs

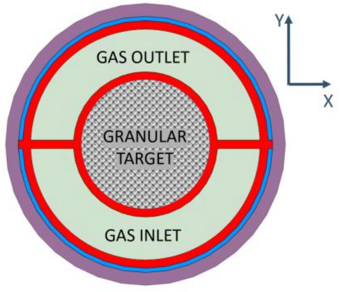


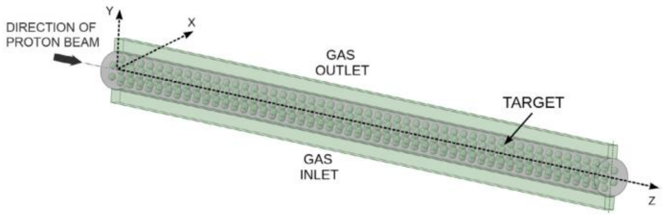
Beam switch-yard and the target station

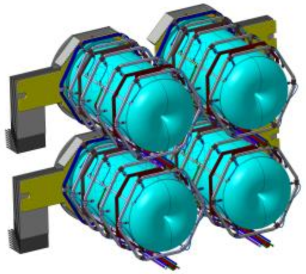
The beam is split into four and made to hit four granular He-gas-cooled targets surrounded by focussing horns



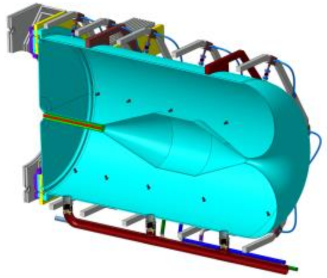




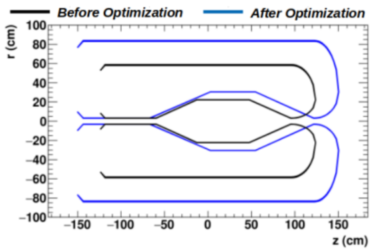




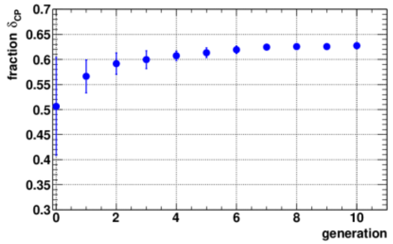
(a) The four-horn system.



(b) Transverse view of one horn.



(a) Evolution of the horn profile.



(b) Genetic algorithm convergence throughout the iterative process.

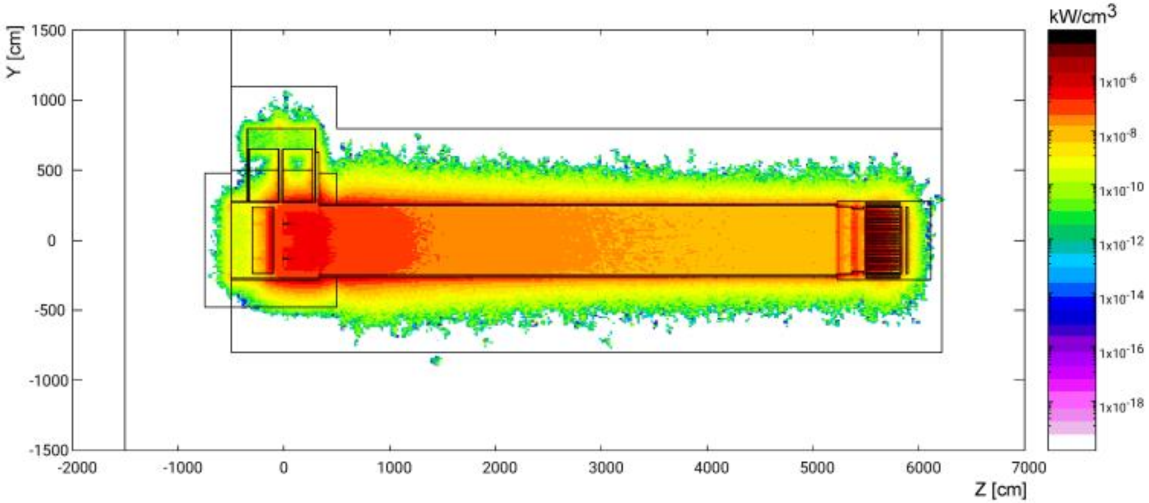
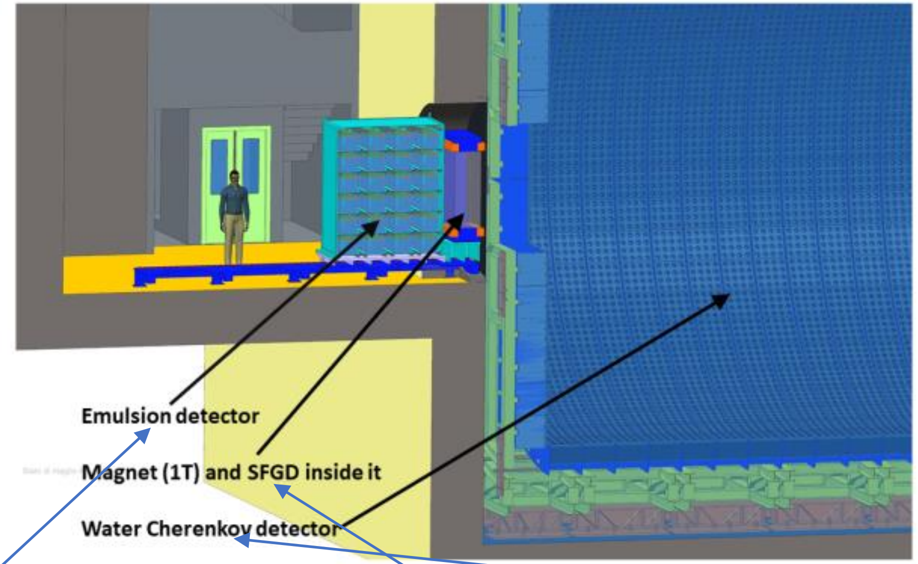
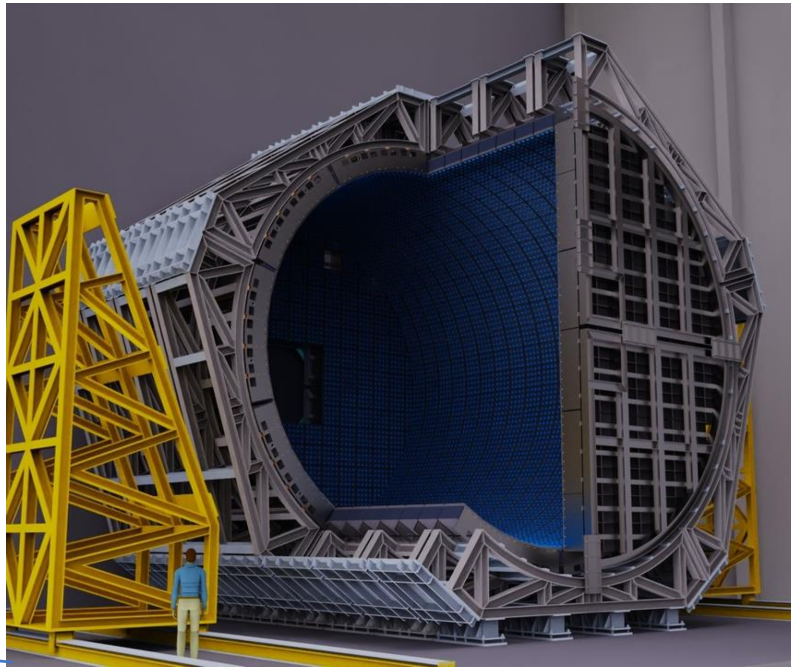


Figure 5.46: Energy deposition distribution in the target station facility.

The Near Detector



Near Detector underground station



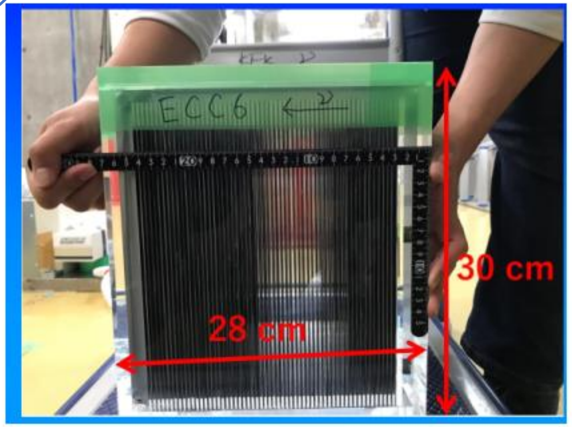
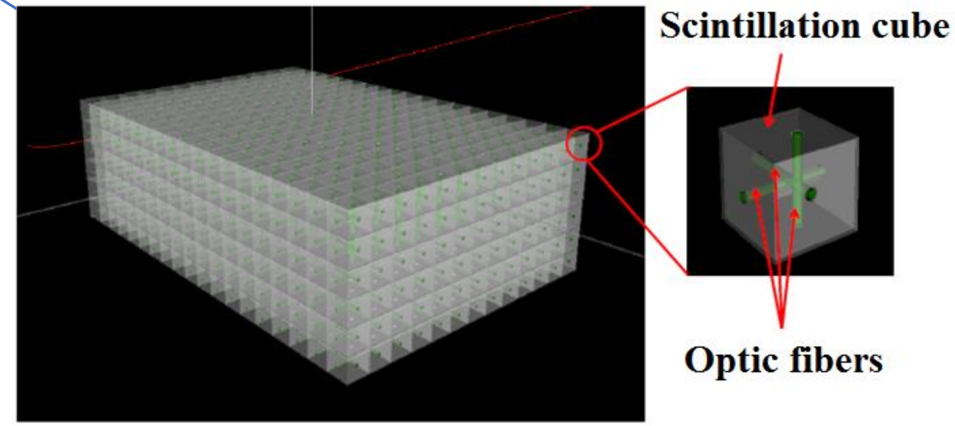
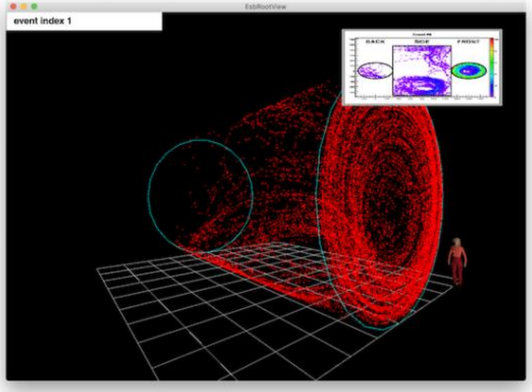


Figure 6.42: A photograph of the NINJA ECC element using water as target.





The super Fine-Grained Detector sFDG

The Far Detector

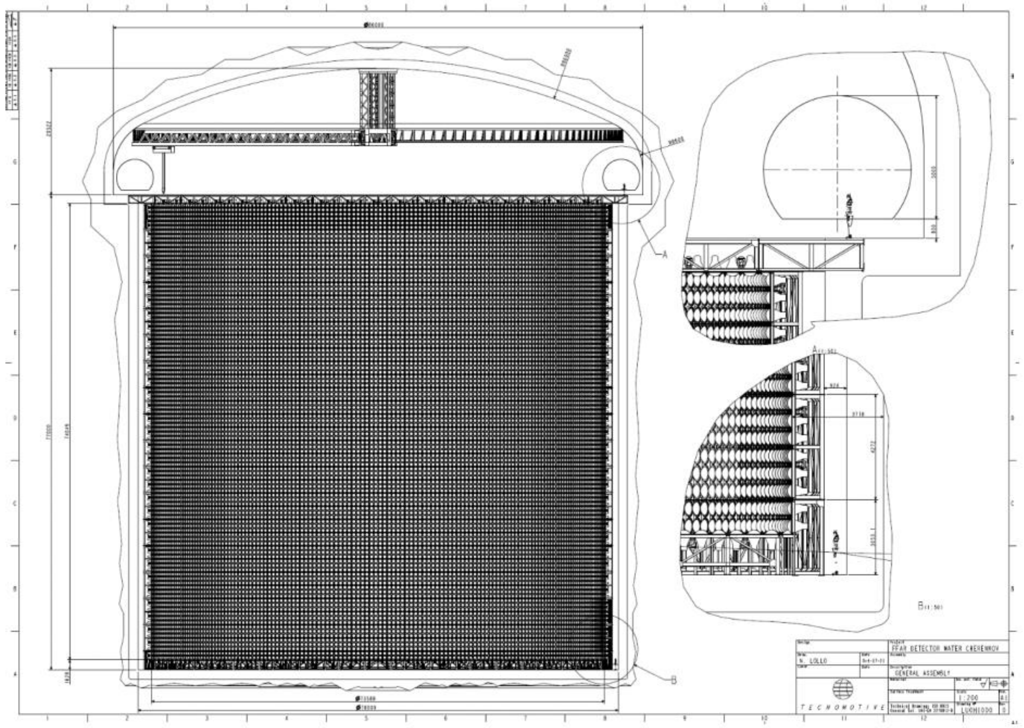


Figure 6.48: Overall view of a single far-detector tank with indicated dimensions.

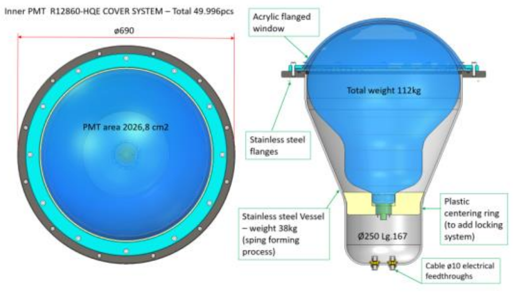
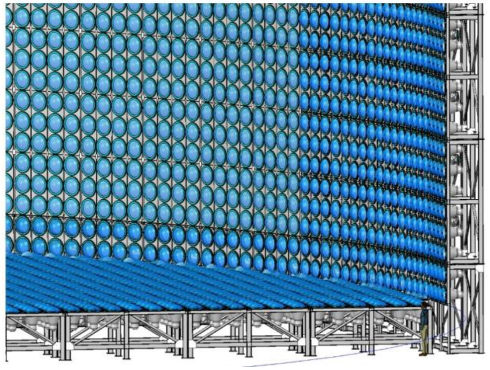
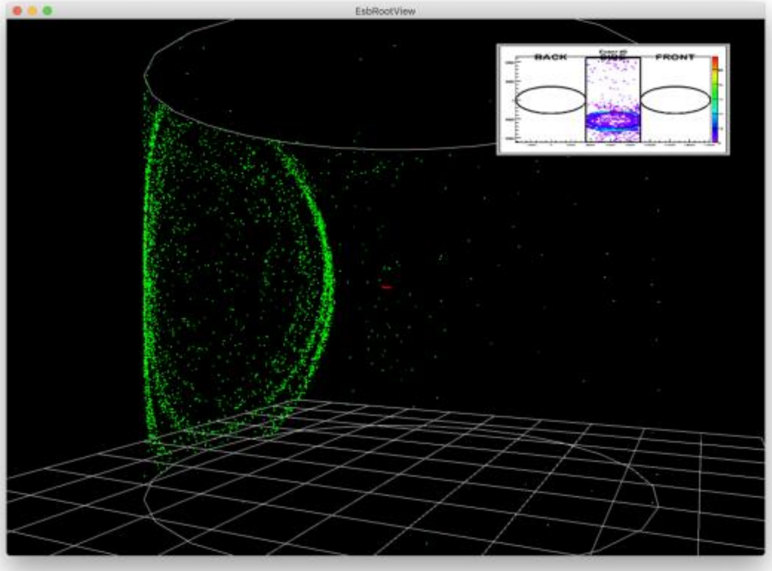


Figure 6.50: A schematic view of an inward-facing 20 inch PMT embedded in a protective cover.





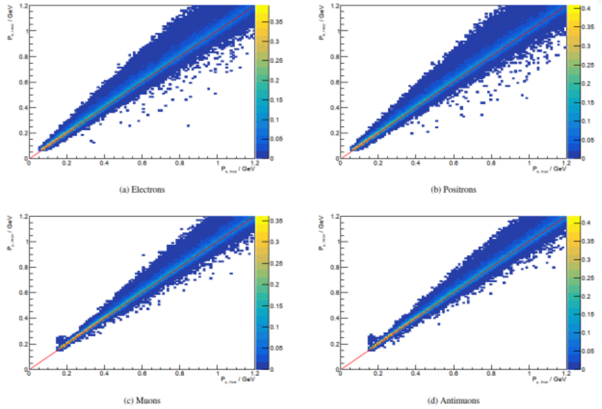


Figure 6.58: Distribution of reconstructed momentum as a function of true momentum for different flavours of charged leptons. These plots were produced using the charged lepton production.

For Cherenkov imagies in the Far Detector see https://drive.google.com/drive/folders/1DidkJRA05GJtm0vFSqpfpCTAooNWAv22

Reference information

Short abstract of the presentation (word text max 250 words): The talk presents, after an introduction recalling the ESSnuSB Conceptual Design Report published in November 2022, the two main additional ESSnuSB installations that will be designed during the second design period, called ESSnuSB+, of the ESSnuSB project: the Low Energy nuSTORM and the Low Energy ENUBET-type Monitored Neutrino beam . It continues by outlining the primary argument for the ESSnuSB project which is it high precision, due to the location of the far detector at near the second oscillation maximum, in the measurement of the CP-violation phase-angle which will be measure with a standard error not exceeding 8 degrees for any value of the phase angle as compared to a standard error not exceeding 22 degrees fore DUNE and Hyper-K. An exposé is made of the significance of this high precision when it comes to deciding in future on the validity of different flavour models and of different leptogenesis models. The ongoing investigations of the sensitivity in the measurement of other features such as the mass hierarchy, non-standard neutrino interactions, sterile neutrinos and neutrino decoherence are also reviewed. The longstanding support from EU for a long-baseline neutrino experiment in Europe is pointed out as well as that from the ESS management and from the Zinkgruvan management.

DOI # if your paper already has one : No, there is no DOI # of this report

Name and Surname of the primary author: Tord Ekelof on behalf of the ESSnuSB+ Collaboration

Name and Surname of co-authors: The ca 70 scientists of the ESSnuSB Collaboration, see the authors of https://link.springer.com/article/10.1140/epjs/s11734-022-00664-w

Eventual identifiers of the author and co-authors (eg.: Orcid #, ISNI, GND, etc.): Tord Ekelof orcid.org/0000-0002-7341-9115

Affiliation of primary author and co-authors and respective role (eg.: researcher, supervisor, project manager, etc.): Tord Ekelof, Uppsala University is the Scientific Leader of the ESSnuSB project

Eventual Organization (eg.: project name, collaboration, etc.): European Spallation Source neutrino Super Beam (ESSnuSB) project and collaboration

Key-word and topic of your presentation (eg.: "cross section", "Neutrino Properties" etc. according to the topics of the Workshop): Long-baseline neutrino-beam design study, precision neutrino cross-sections, second neutrino oscillation maximum, high precision CP violation angle measurement, EU support

Funds (if your work has been funded, please indicate the name of the funder and the grant #): EU Horizon 2020 777419, EU Horizon Europe 101094628 and matching funds from 20 European universities and laboratories

Identifier of the work, if the case (eg.: ARK, arVix, DOI, ISBN, etc.): Not the case

Related work, if the case (eg.: derived from, is cited by, it cites, is referenced by, etc. and relevant identifier, string of reference, etc.): Not the case

Publishing information: (eg.: Journal - with title and ISSN; Imprint – book title and ISBN): "ESSnuSB Conceptual Design Report" in European Physical Journal 6 Nov 2022
Eur. Phys. J. Spec. Top. (2022) **231**: 3779-3955 https://link.springer.com/article/10.1140/epjs/s11734-022-00664-w