ESS NEUTRINO SUPER BEAM

Funded by the Horizon 2020 Framework Programme of the European Union

The ESS neutrino Super Beam ESSnuSB and ESSnuSB+

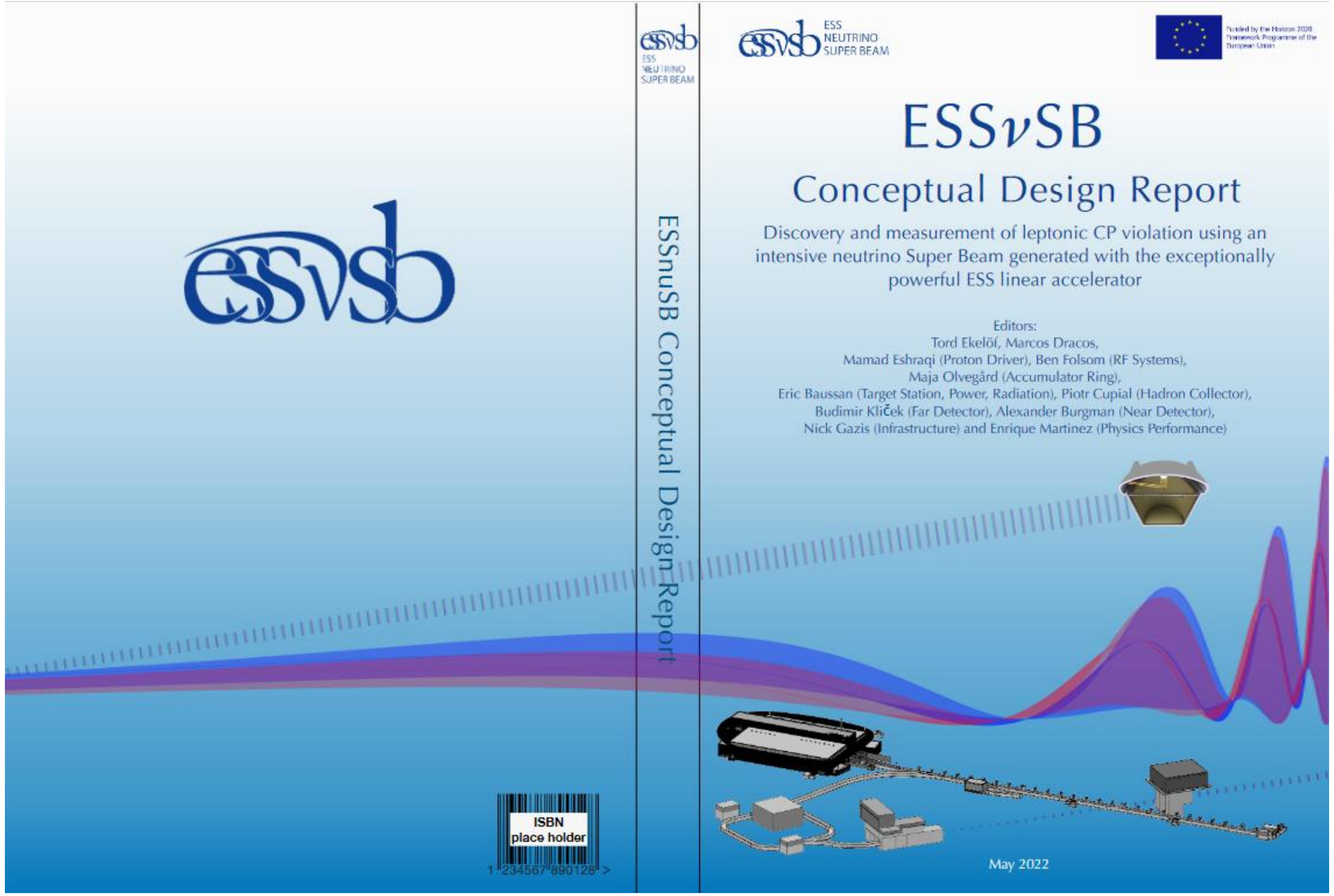
A report on

The achievements of the ESSnuSB Design Study 2018-2022

and on

The preparations for a ESSnuSB+ INFRADEV-1 EU project 2023-2026

Tord Ekelöf
Uppsala university



ESSνSB Conceptual Design Report

Publicly available at
https://arxiv.org/abs/2206.01208

Submitted on 6 June 2022
for publication in
European Physical Journal

The European Spallation Source neutrino Super Beam

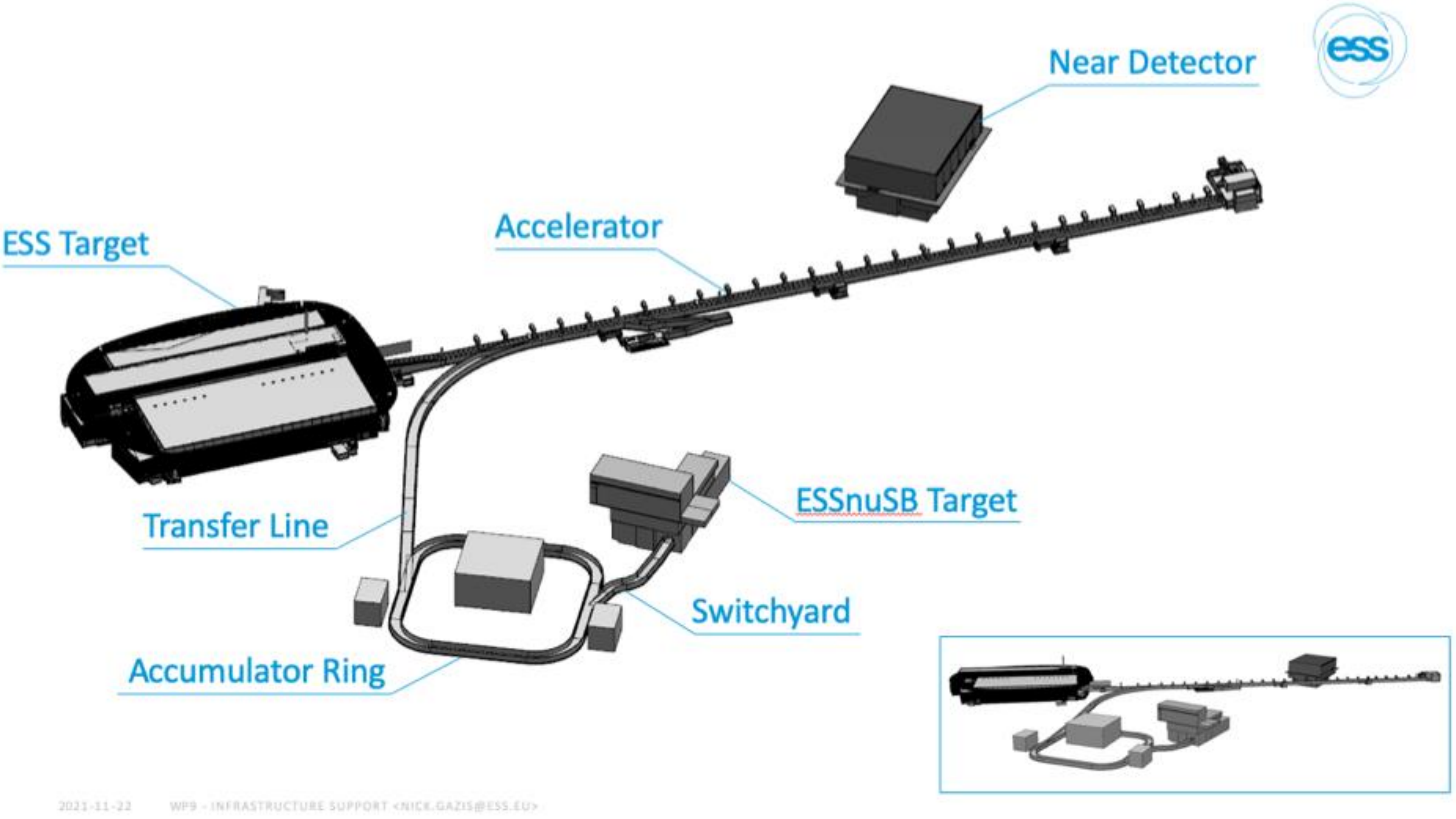
White Paper submitted to the Snowmass 15 March 2022

USA Particle Physics Community Planning Exercise

Publicly available at arXiv:2203.08803v1

https://arxiv.org/abs/2203.08803

ESSnuSB lay-out atthe ESS site in Lund , Sweden

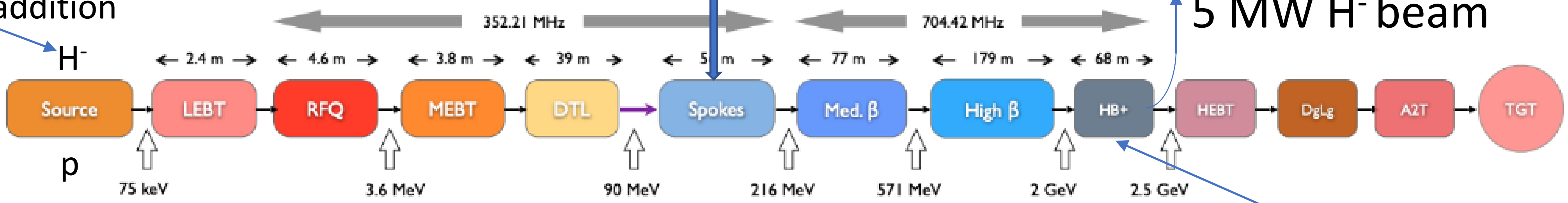


The ESS linac, the accumulator and the switchyard

Currently being tested at FREIA in Uppsala

ESSnuSB addition

5 MW H$^-$ beam

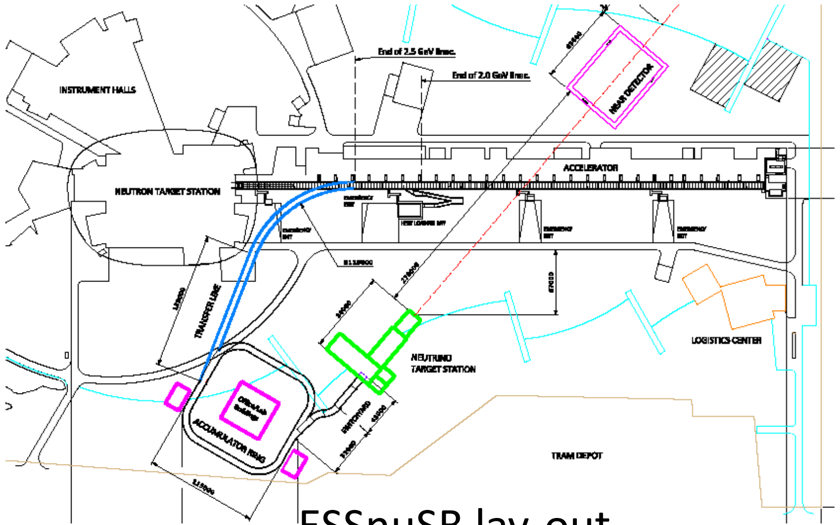


ESSnuSB addition

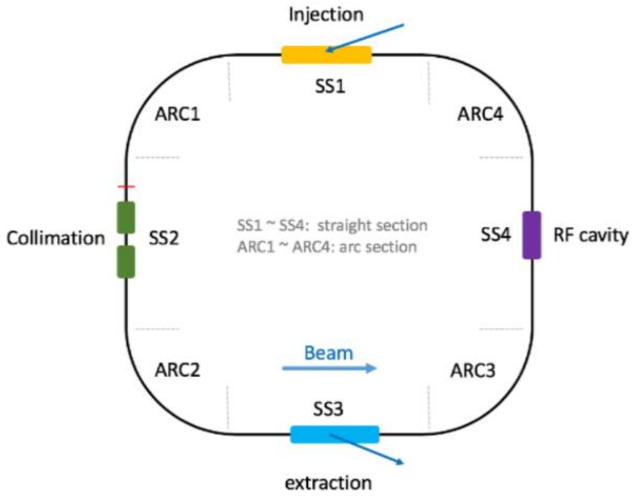
The linac

Normalconducting part

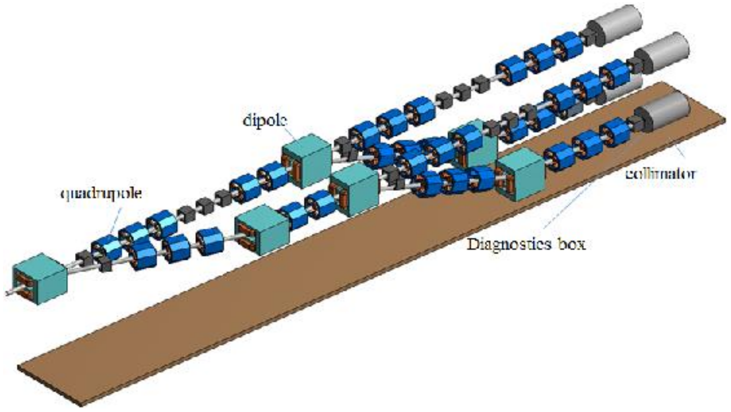
Superconducting part



ESSnuSB lay-out

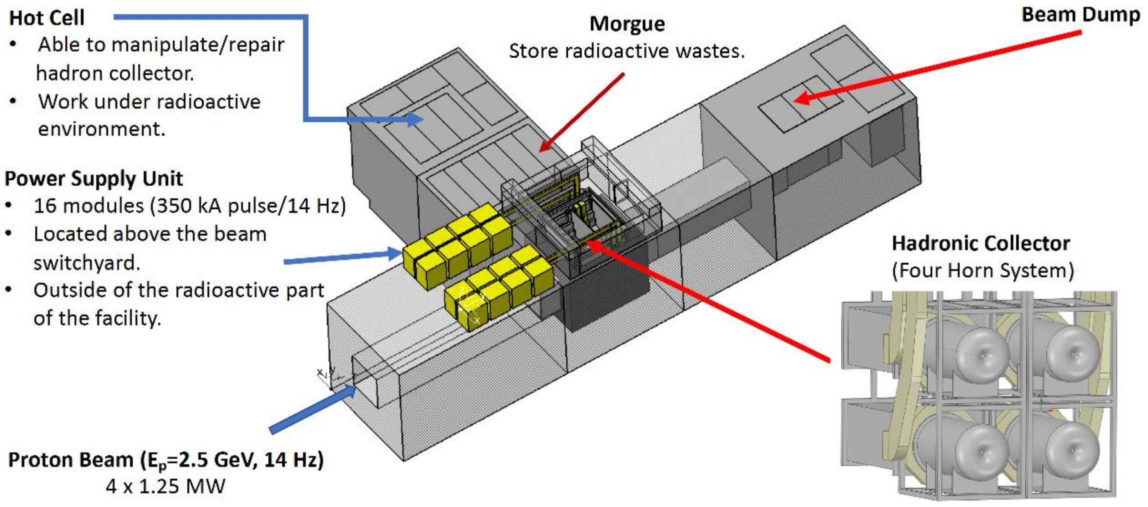


The Accumulator

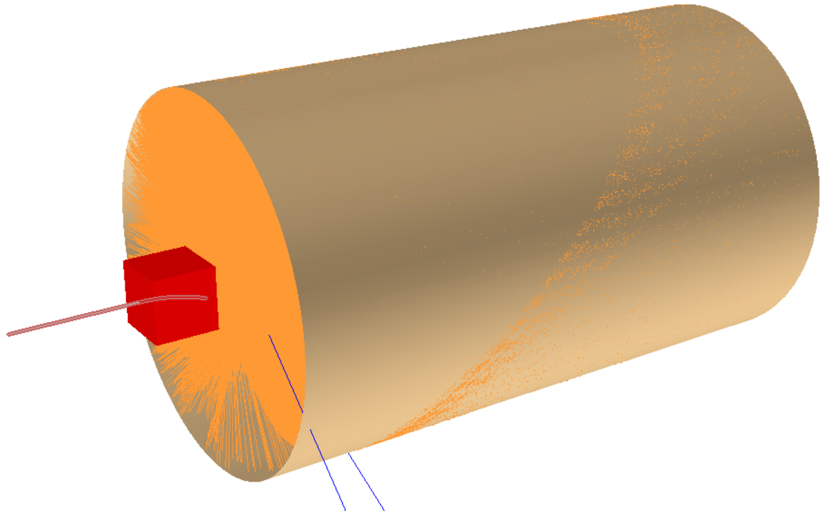


The Switchyard

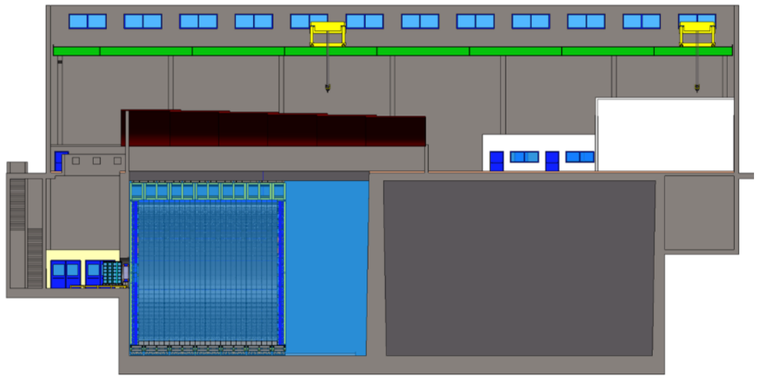
The target station and the near detector



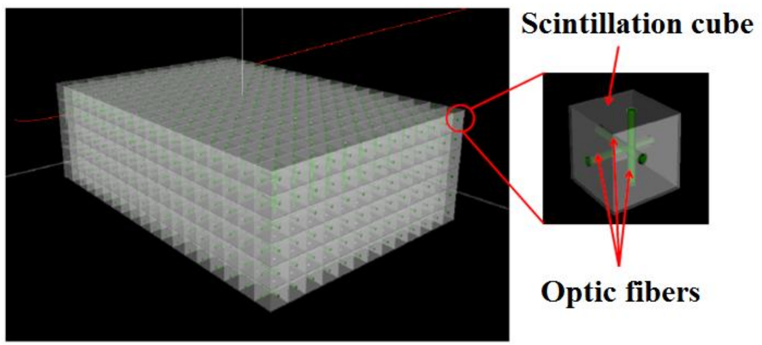
Target underground station



The water Cherenkov near detector and the sFGD

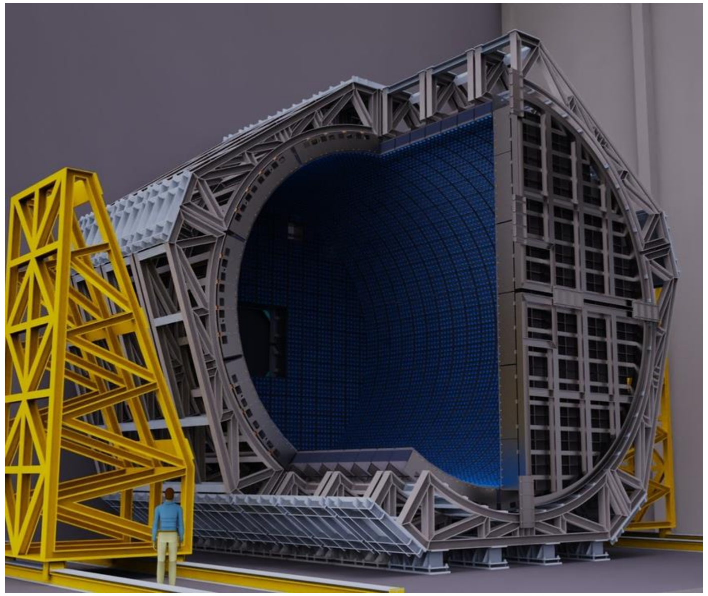


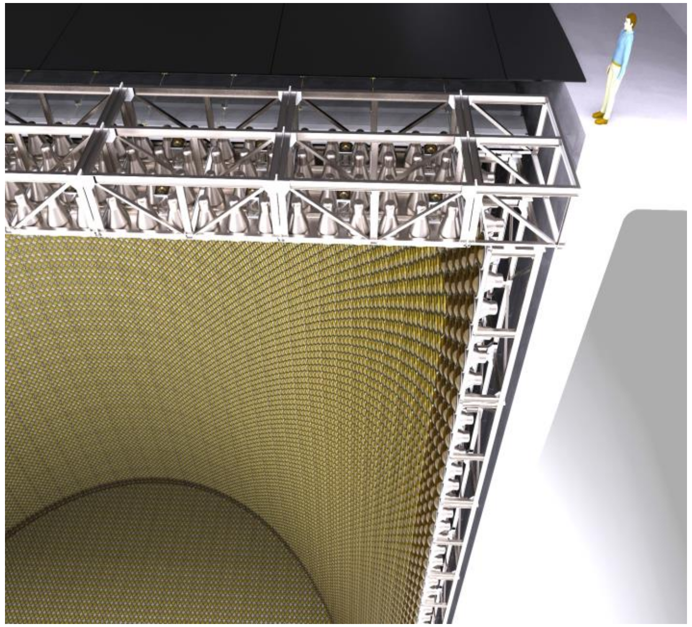
The underground near detector hall



The super Fine-Grained Detector sFDG

The Neard Detector and the Far Detector



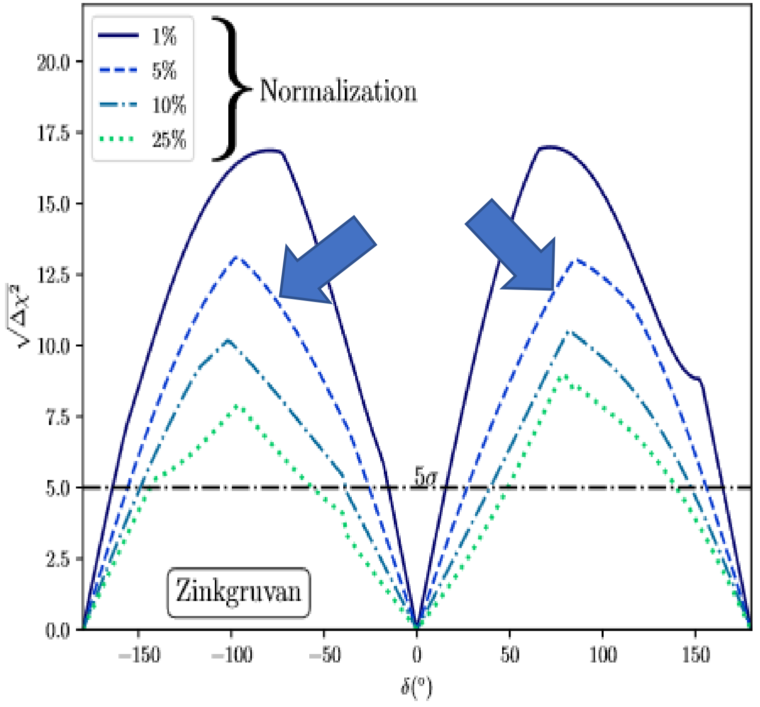


The NeardDetector

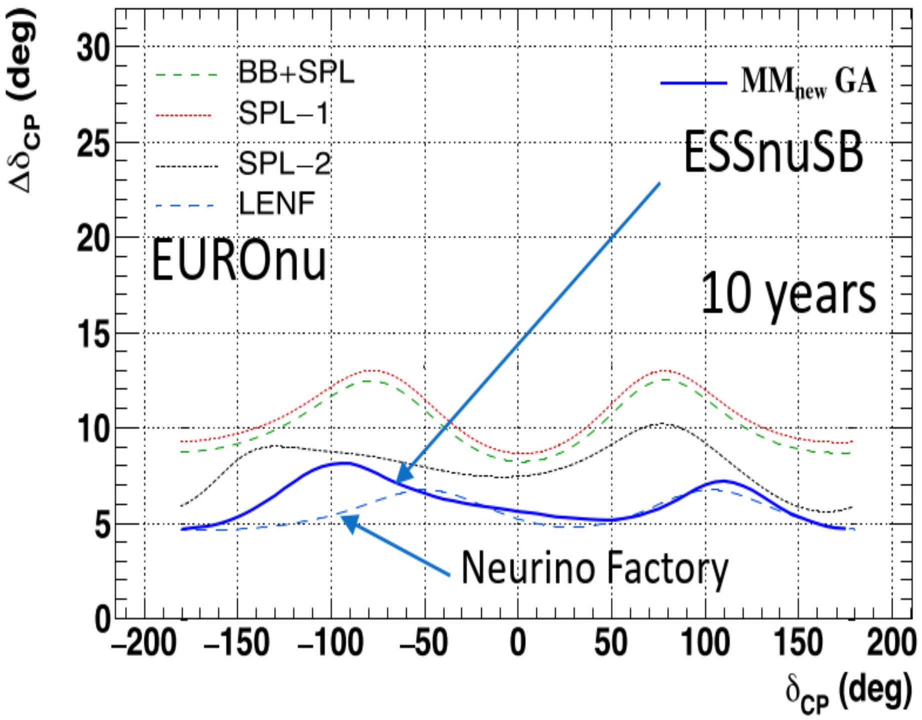
The Far Detector

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

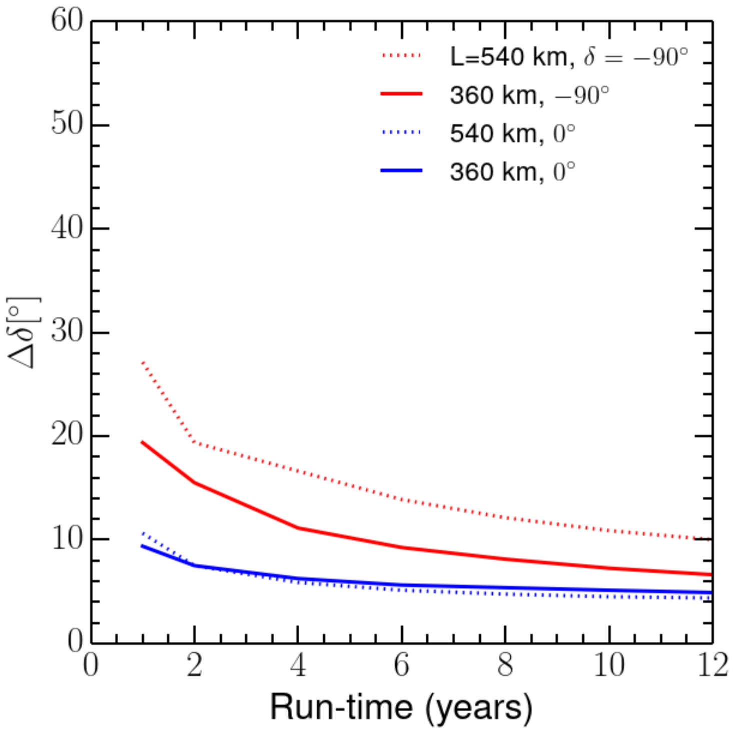
Performance for CV discovery and δ_{CP} measurement



Discovery potential vs δ_{CP} angle after 10 years with 5% normalization error



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



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

Design Study ESSvSB January 2018 - March 2022

Call:	H2020-INFRADEV-2017-1
Funding scheme:	RIA
Proposal number:	777419
Proposal acronym:	ESSnuSB
Duration (months):	48
Proposal title:	Feasibility Study for employing the uniquely powerful ESS linear accelerator to generate an intense neutrino beam for leptonic CP violation discovery and measurement.
Activity:	INFRADEV-01-2017

N.	Proposer name	Country
1	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	FR
2	UPPSALA UNIVERSITET	SE
3	KUNGLIGA TEKNISKA HOEGSKOLAN	SE
4	EUROPEAN SPALLATION SOURCE ERIC	SE
5	UNIVERSITY OF CUKUROVA	TR
6	UNIVERSIDAD AUTONOMA DE MADRID	ES
7	NATIONAL CENTER FOR SCIENTIFIC RESEARCH "DEMOKRITOS"	EL
8	ISTITUTO NAZIONALE DI FISICA NUCLEARE	IT
9	RUDER BOSKOVIC INSTITUTE	HR
10	SOFIISKI UNIVERSITET SVETI KLIMENT OHRIDSKI	BG
11	LUNDS UNIVERSITET	SE
12	AKADEMIA GORNICZO-HUTNICZA IM. STANISLAWA STASZICA W KRAKOWIE	PL
13	EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH	CH
14	UNIVERSITE DE GENEVE	CH
15	UNIVERSITY OF DURHAM	UK
	Total:	

More information on:
http://essnusb.eu/

EU Grant recieved
3 M€

CDR published
6 June 2022
https://arxiv.org/abs/2206.01208

We have submitted on 20 April 2022 an INFRADEV Design Study ESSnuSB+ to EU for the period 2023-2026

- We submitted on 20 April 2022 a proposal for EU Horizon Europe INFRADEV-1 for a design study of **aspects of the ESSnuSB design that have not yet been studied during 2018-2021.**

- The fact that we intend to study new aspects is of great significance as there is **an EU rule that states that for one and the same project only one design-study application can be granted.** CERN's FCC project has shown that a second grant can be obtained if new aspects are to be studied.

- The new aspects to be studied are **building construction, licensing and security** that will be required at ESS and in the Zinkgruvan mine, and design a Low Energy nuSTORM and a Low Energy Monitored Neutrino Beam **for measurement of neutrino cross-sections** and searches for sterile neutrinos.

HORIZON-INFRA-2022-DEV01

Developing European Research Infrastructures to maintain global leadership

Deadline: **20 April 2022**

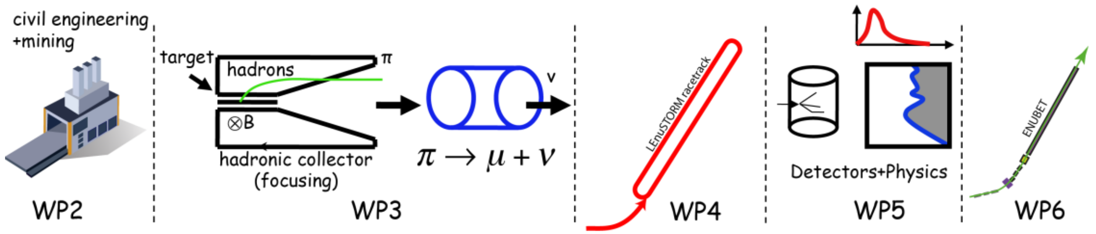
Topics	Type of Action	Budgets (EUR million) 2022	Expected EU contribution per project (EUR million)	Number of projects expected to be funded
Opening: 10 Nov 2021 Deadline(s): 20 April 2022				
HORIZON-INFRA-2022- DEV-01-01	RIA	20.3	1.00 to 3.00	7
Overall indicative budget		20.4		

ESSnuSB+ participants and Work Packages

1	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	France	Coordinator
2	UNIVERSITE DE STRASBOURG	France	Affiliated
3	RUDER BOSKOVIC INSTITUTE	Croatia	Partner
4	TOKAI NATIONAL HIGHER EDUCATION ANDRESEARCH SYSTEM, NATIONAL UNIVERSITY CORPORATION	Japan	Associated
5	UPPSALA UNIVERSITET	Sweden	Partner
6	LUNDS UNIVERSITET	Sweden	Partner
7	EUROPEAN SPALLATION SOURCE ERIC	Sweden	Partner
8	KUNGLIGA TEKNISKA HOEGSKOLAN	Sweden	Partner
9	UNIVERSITAET HAMBURG	Germany	Partner
10	UNIVERSITY OF CUKUROVA	Turkey	Partner
11	NATIONAL CENTER FOR SCIENTIFIC RESEARCH "DEMOKRITOS"	Greece	Partner
12	ARISTOTELIO PANEPISTIMIO THESSALONIKIS	Greece	Affiliated
13	SOFIA UNIVERSITY ST KLIMENT OHRIDSKI	Bulgaria	Partner
14	LULEA TEKNISKA UNIVERSITET	Sweden	Partner
15	ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE	Switzerland	Partner
16	UNIVERSITA DEGLI STUDI ROMA TRE	Italy	Partner
17	UNIVERSITA' DEGLI STUDI DI MILANO-BICOCCA	Italy	Partner
18	ISTITUTO NAZIONALE DI FISICA NUCLEARE	Italy	Partner
19	UNIVERSITA DEGLI STUDI DI PADOVA	Italy	Affiliated
20	**ESS BILBAO**	Spain	Partner

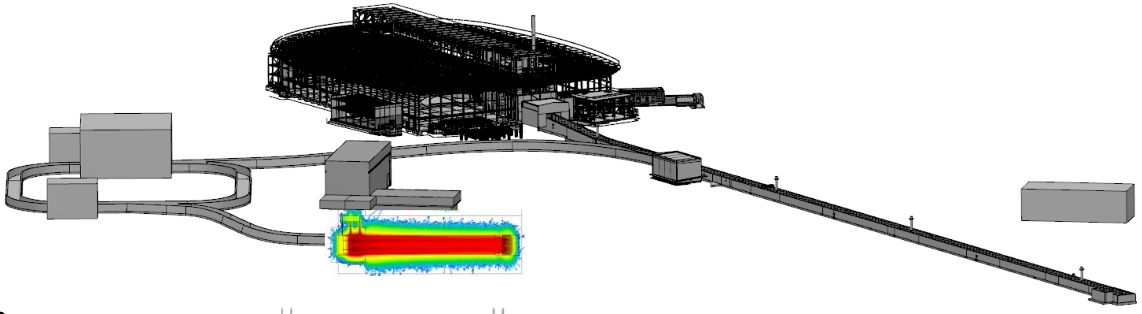
Work Packages

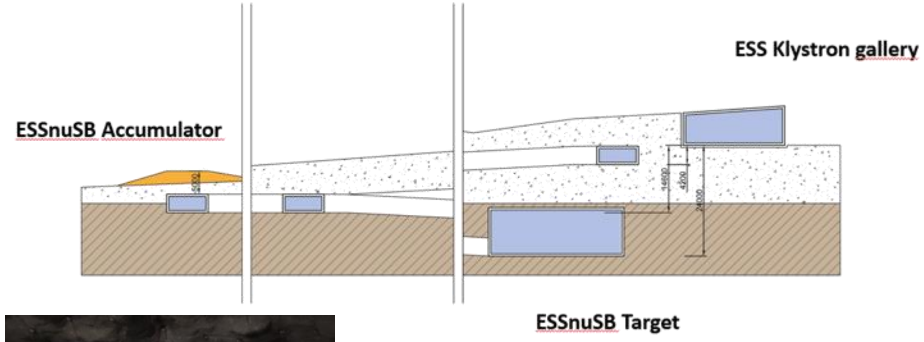
1. Management
2. Civil engineering at ESS and mine sites, safety, licensing and environment preservation.
3. Low Energy nuSTORM (LEnuSTORM) race-track design and adaption to the accelerator complex
4. LEnuSTORM Target Station and pion extraction for Low Energy nuSTORM
5. Detectors and physics performance –expected improvements due to ESSnuSB and LEnuSTORM.
6. Low energy Monitored Neutrino Beam design

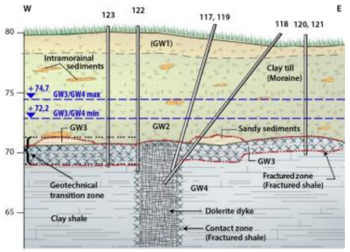


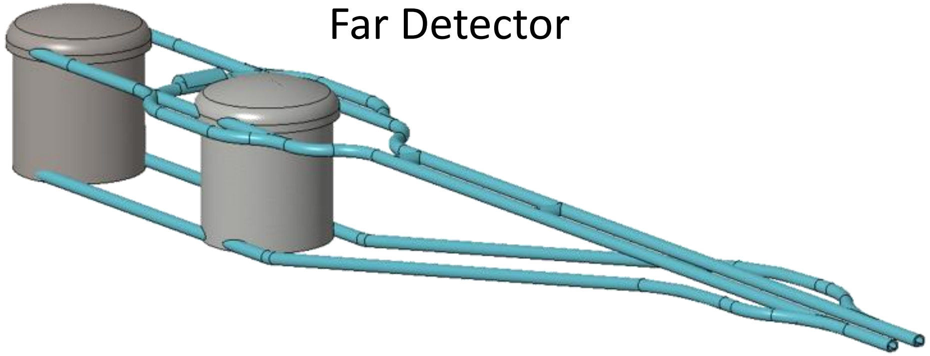
WP2 ESS Site and mine site civil engineering

- **Participants: ESS and Luleå Univ.**
- **Design Study of civil engineering**
  - **ESS site**, all installations are underground
    - **Investigation of bedrock and ground water**
    - **Design of underground tunnels and halls**
    - **Supply of electric power, cooling, ventilation**
  - Cavern constructions at **Zinkgruvan** at 1000 m below ground level
    - **Rock properties**
    - **Stability of the caverns**
    - **Sustainability**
    - **Site layout**
    - **Excavation, reinforcement & ground control**
- **Licencing**
- **Safety**
- **Environment protection**





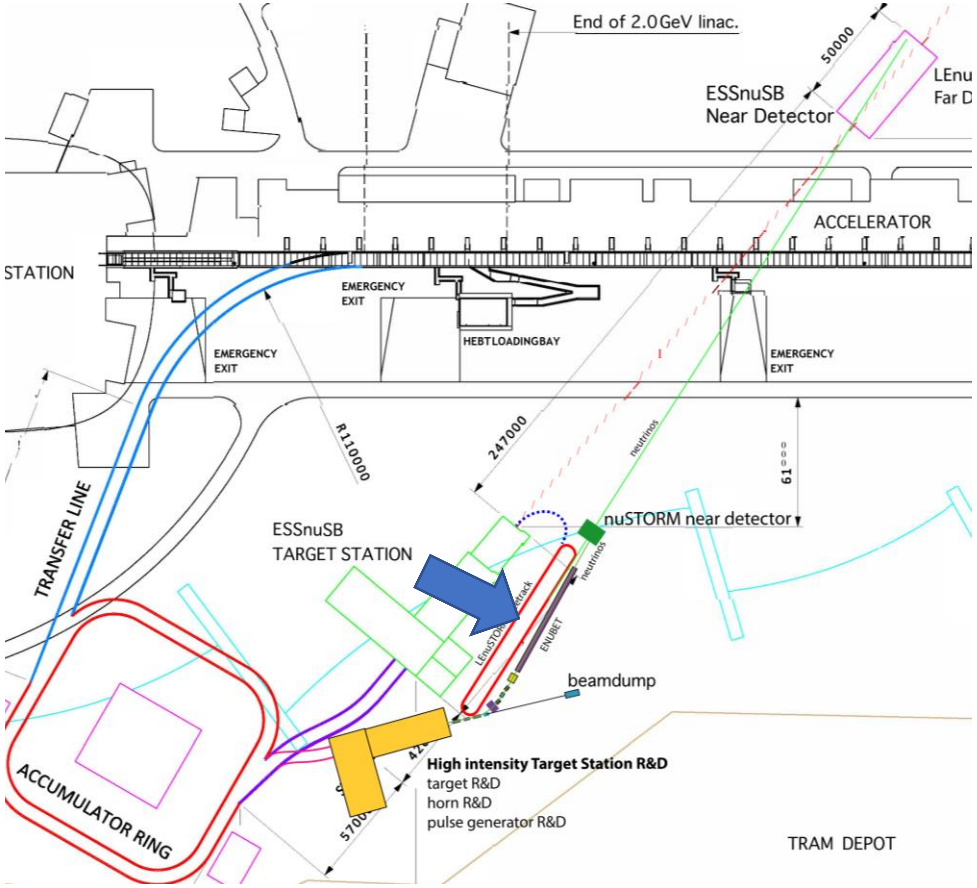


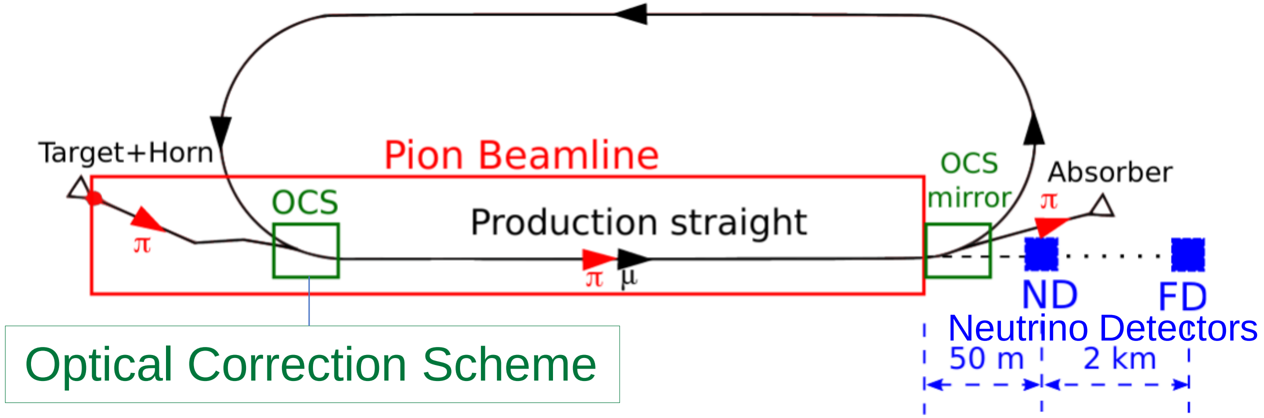


WP4 Low Energy nuSTORM

Participants: CRNS, Hamburg Univ., ESS Bilbao

1. **Design of a racetrack storage** ring for low energy muons produced with a beam from the ESS linac.
2. Design a transfer system from the initial **collection and extraction of pions** behind the target station, up to the injection point.
3. Design a **transfer line** from the ESSnuSB ring-to-switchyard transfer line to the **nuSTORM target**.
4. Design an **injection scheme** for the racetrack storage ring
5. **Optimize the performance** of the ESSnuSB accelerator complex





WP3 Low Energy nuSTORM target station

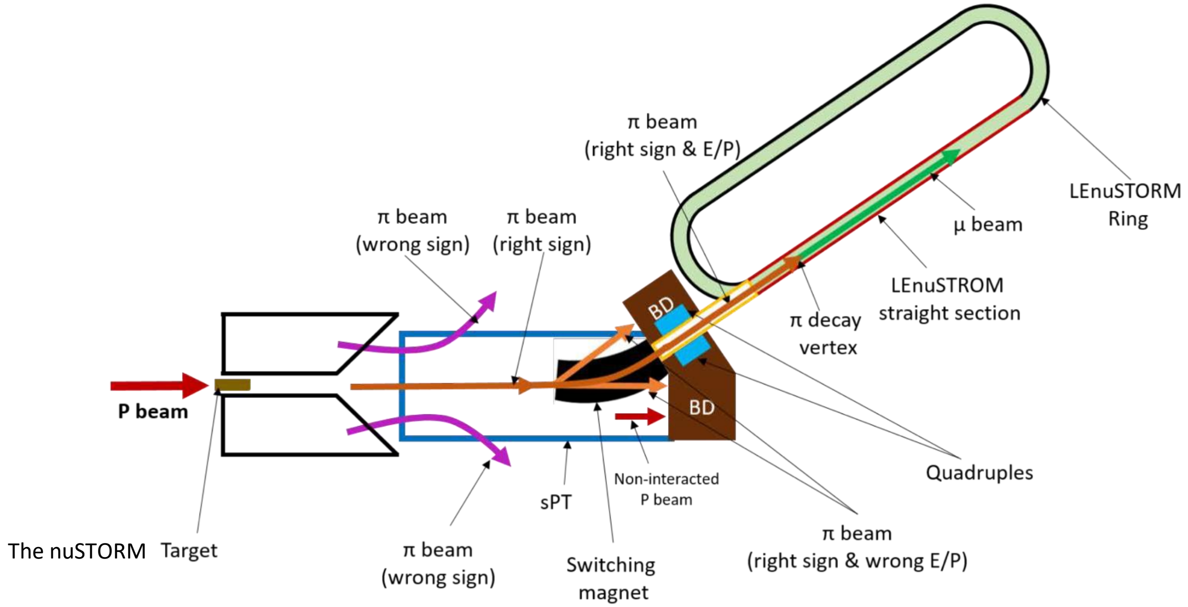
Participants: CRNS, Hamurg univ., Uppsala Univ., ESS, ESS Bilbao

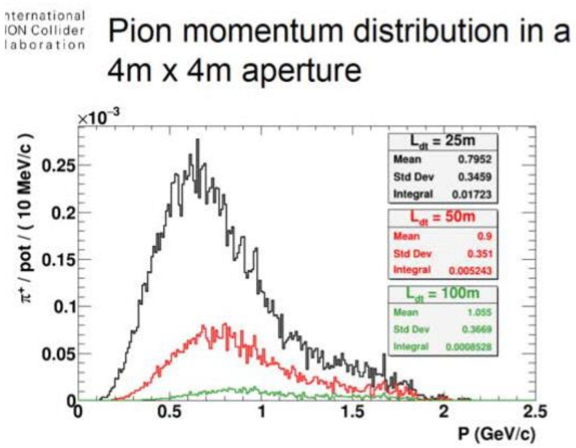
- **Adapt the ESSnuSB Target Station to the muon production requirements.**
  -Target material and horn design optimization for the pion beam production.

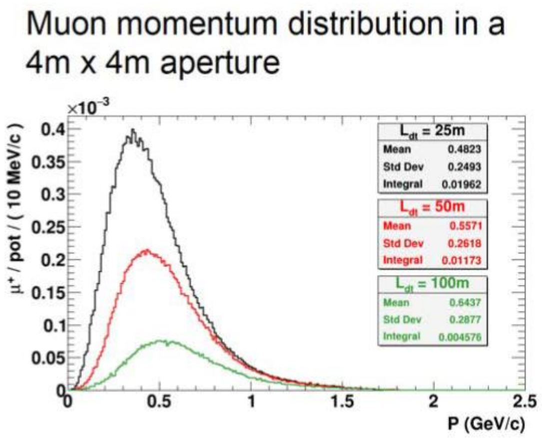
- **Investigate pion extraction and initial focusing system**.
  - Pion extraction short tunnel and deflection+focussing magnet design

- **Power supply unit for the pion extraction and initial focusing system.**
  - Power unit design for the current pulse required

- **Target Station Facility.**
  -Beam window, remote handling, alignement, proton dump







WP5 Physics performance with ESSnuSB including nuSTORM and ENUBET

Participants: CRNS, KTH, Sofia univ., RSI, NCSRD, Cukurova univ.

• Design a single **near detector for LEnuSTORM** and **LEMNB** and optimize its performance.

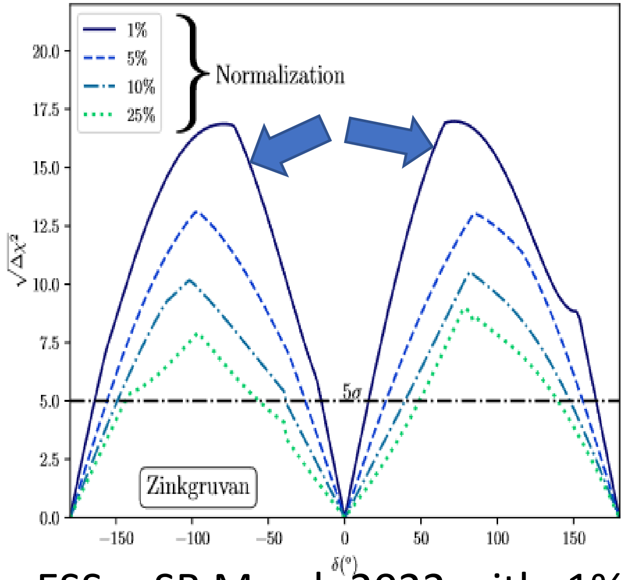
• Determine the expected precision of **neutrino interaction cross section** measurement with the full setup.

• Study the sensitivity of the setup for new physics searches like **sterile neutrinos**.

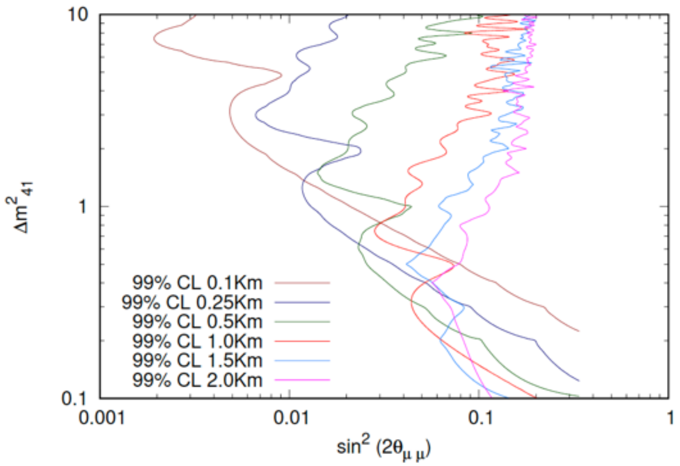
• Study effects of **gadolinium doping** to sensitivity and performance of the ESSnuSB water Cherenkov detectors (near and far).

• Study sensitivity and performance of the ESSnuSB far detectors for **physics not related to the neutrino beam**.

• Develop an advanced analysis for the estimation of physics reach on the above topics **using full MC chain for all detectors** (analysis beyond GLoBES).



ESSnuSB March 2022 with 1% normalization error



Low energy sterile neutrino searches

ESSnuSB support letters from 4 ESS Director Generals:

Jim Jeck in 2014

John Womersly in 2017

Kevin Jones in 2021

Helmut Schober in 2022

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 ESS AB
Visiting address: ESS, Tunavägen 24
P.O. Box 176
SE-221 00 Lund
SWEDEN
www.esss.se

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 ERIC
Visiting address: ESS, Tunavägen 24
P.O. Box 176
SE-221 00 Lund
SWEDEN
www.esss.se

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

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www.ess.eu

EUROPEAN SPALLATION SOURCE

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.

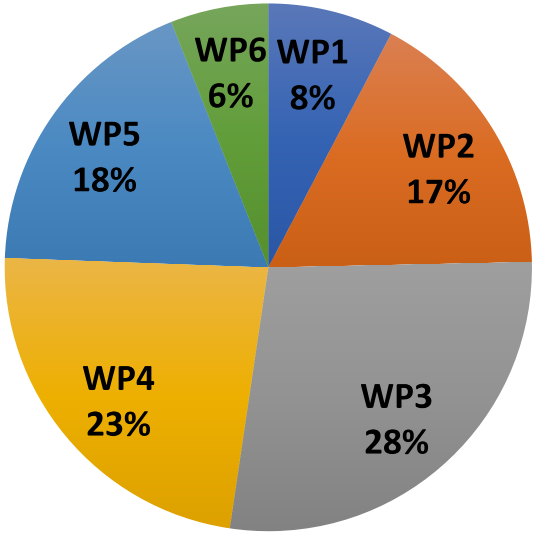
With best regards

Helmut Schober
Director General

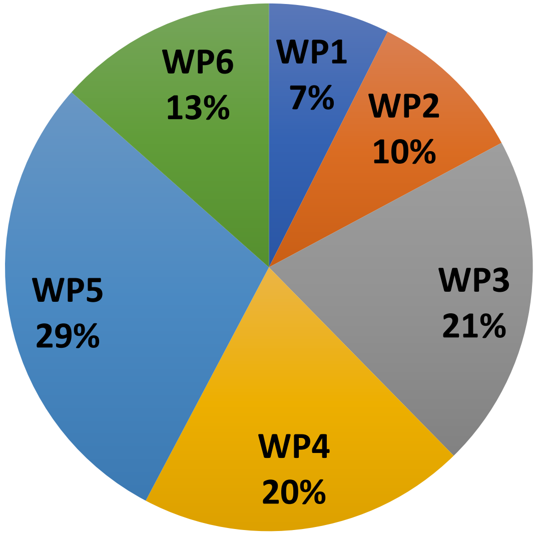
Use of the EU grant of 3 M€ requested for ESSnuSB+

All participants	Cost Category	Total cost € (48 months)
Direct Costs:	Personnel:	
	Senior Staff	2443171
	Post docs	1792891
	Students	0
	Other	0
	Total Personnel:	4236061
	Other Direct Costs:	
	Equipment	0
	Consumables	0
	Travel	431000
	Publications, etc	40000
	Other	0
	Total Other Direct Costs:	471000
	Total Direct Costs:	4707061
Indirect Costs (overheads):	Max 25% of Direct Costs	1176765
Subcontracting Costs:	(No overheads)	9800
Total Costs of project:	(by year and total)	5893627
Requested Grant:	(by year and total)	3000000

WP financial effort



WP person-power effort



Schedule for a 2nd generation ESS-based neutrino Super Beam ESSnuSB

Now

2012: Inception of the project

Nucl. Phys. B 885 (2014) 127

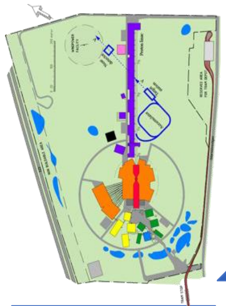
2016-2019: Beginning of COST Action EuroNuNet

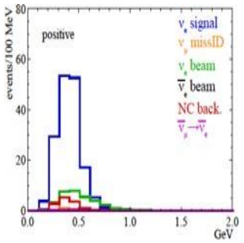
2018: Beginning of ESSνSB Design Study (EU-H2020)

2022: End of ESSνSB Design Study, preliminary costing and CDR

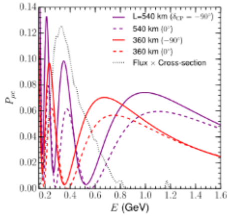
2023-2026: Continuation of Design Study, final costing and an TDR to ESFRI

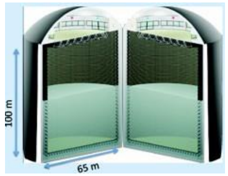
2027-2028: Preconstruction Phase, International Agreements





2029-2035: Construction of the facility and detectors, including commissioning





2036-: Start of data taking

European Particle Physics Strategy

Conclusions:

"**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."

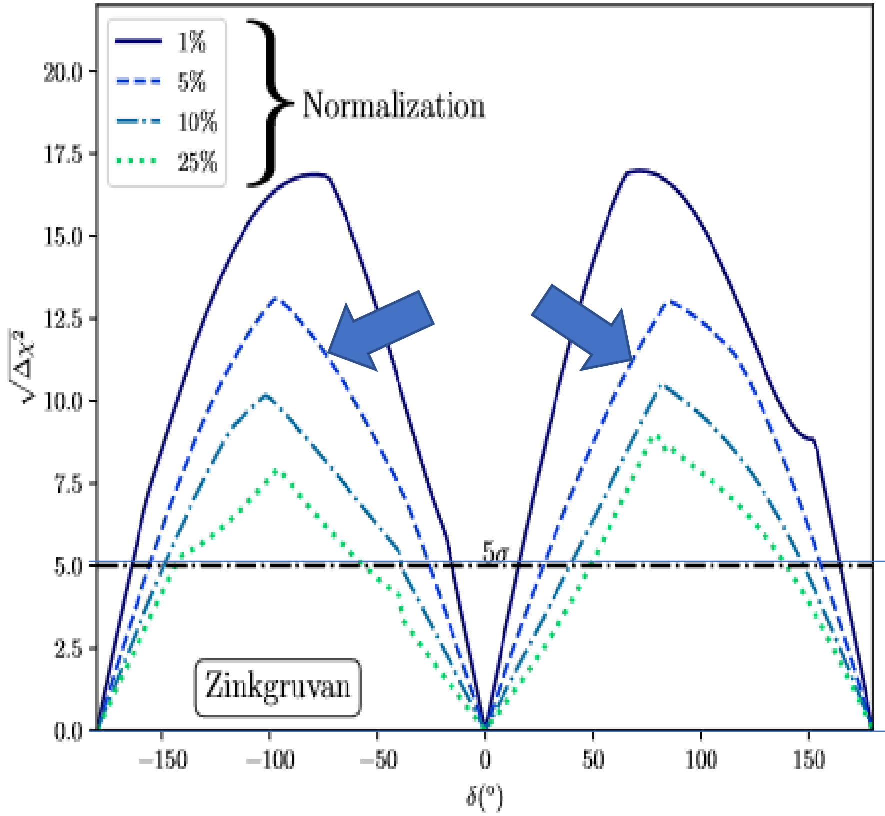
"The European particle physics community should work with the European Commission to shape and establish the funding instruments that are required for the realisation of common R&D projects, e.g. in the Horizon Europe programme."

"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."

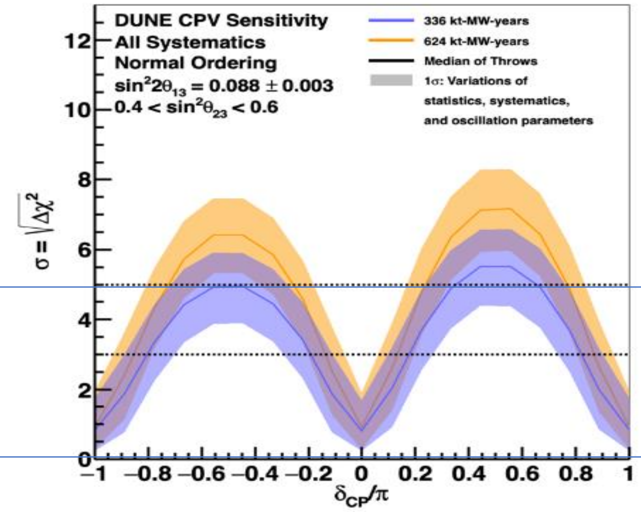
Thank you!

Back-up slides

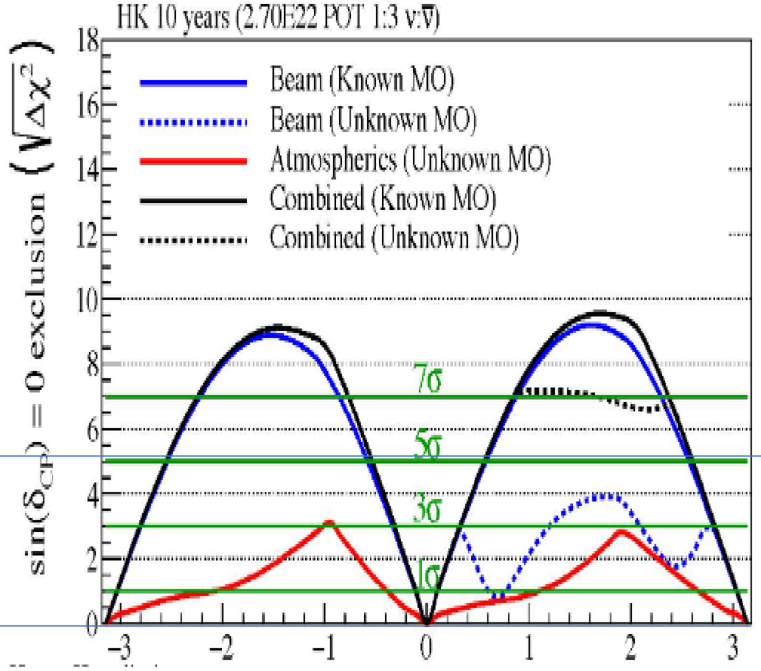
ESSnuSB in the international context – CPV discovery



ESSnuSB March 2022 with 5% normalization error

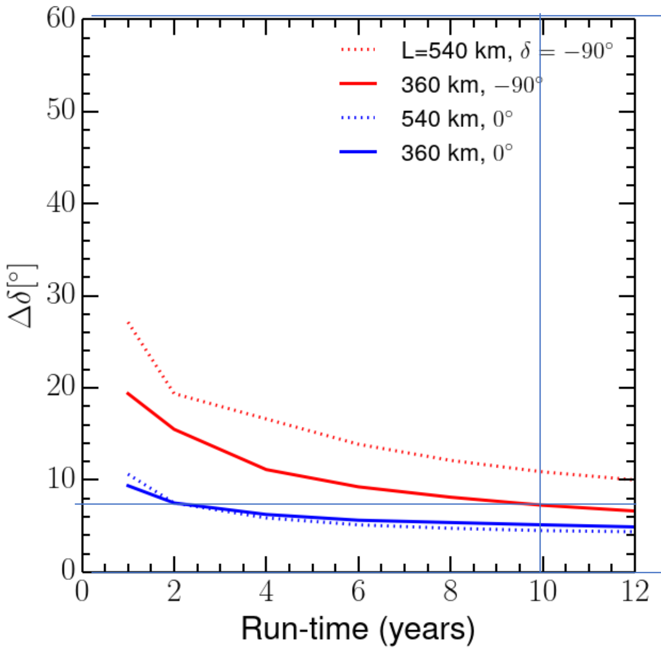


DUNE Snowmass March 2022

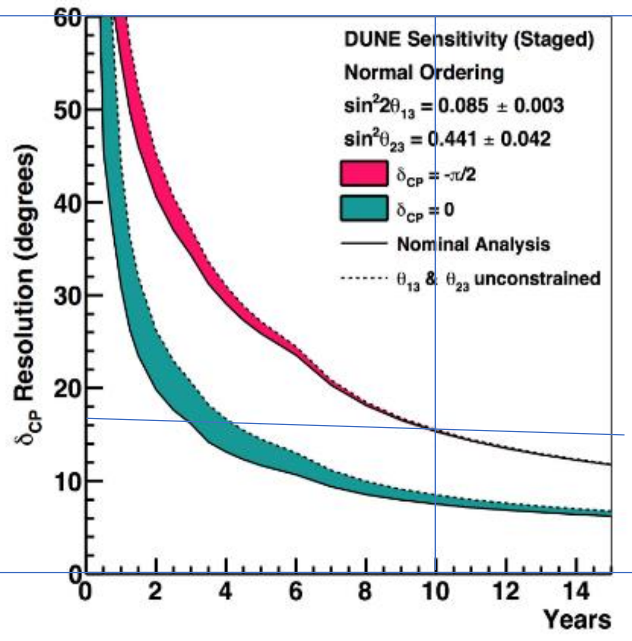


HyperKamokandeSnowmass March 2022

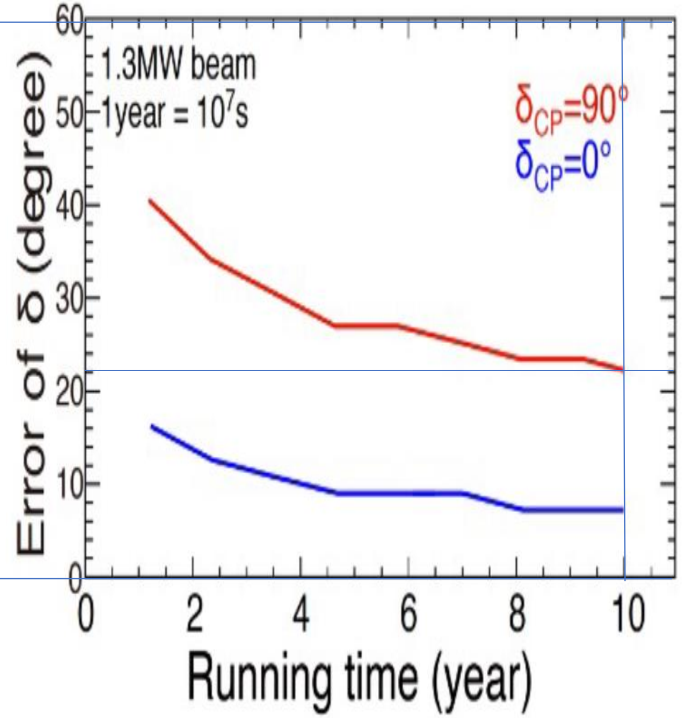
ESSnuSB in the international context – CPV resolution



ESSnuSB March 2022 with 5% normalization error

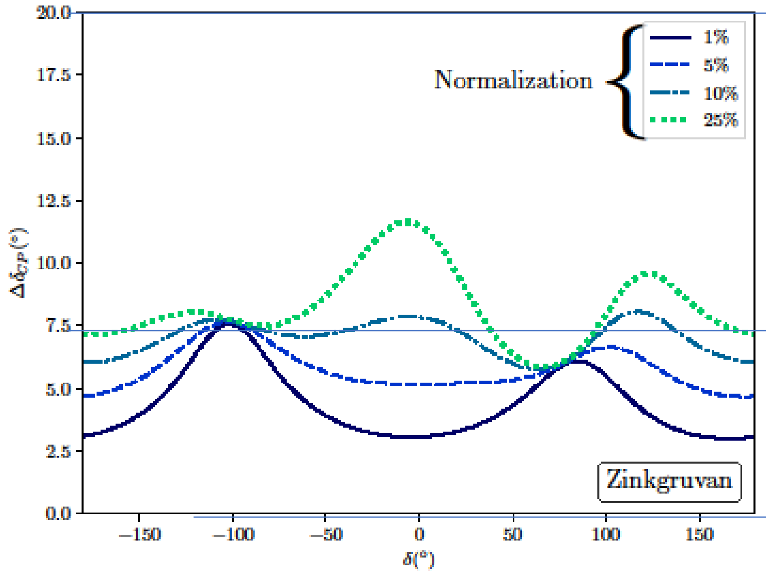


DUNE Snomass March 2022

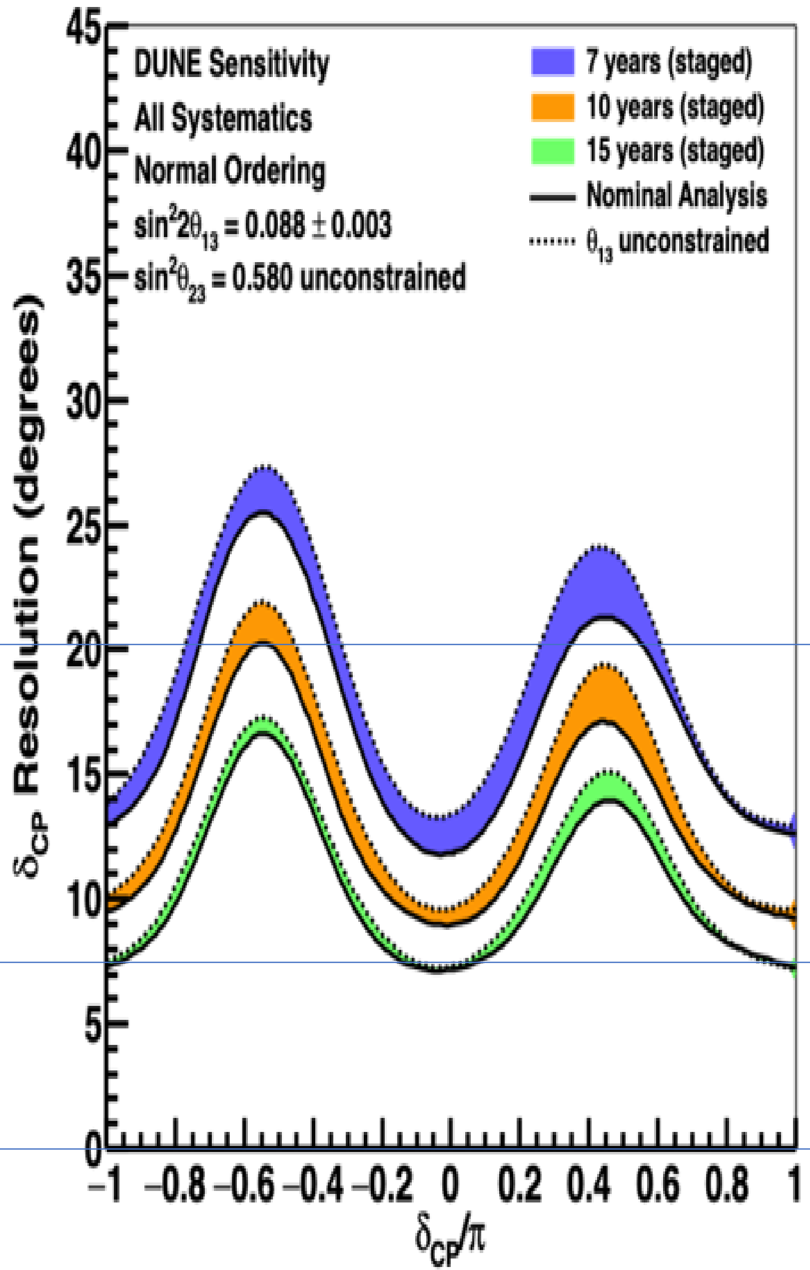


HyperKamokandeSnowmass March 2022

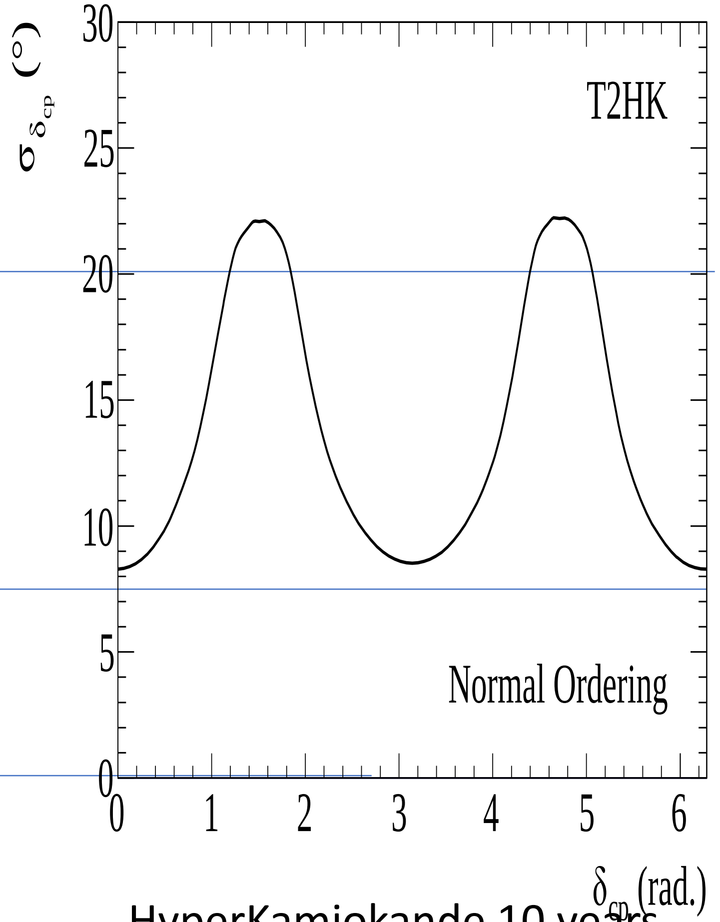
Resolution in degrees of the measurement of δ_{CP}



ESSnuSB 10 years

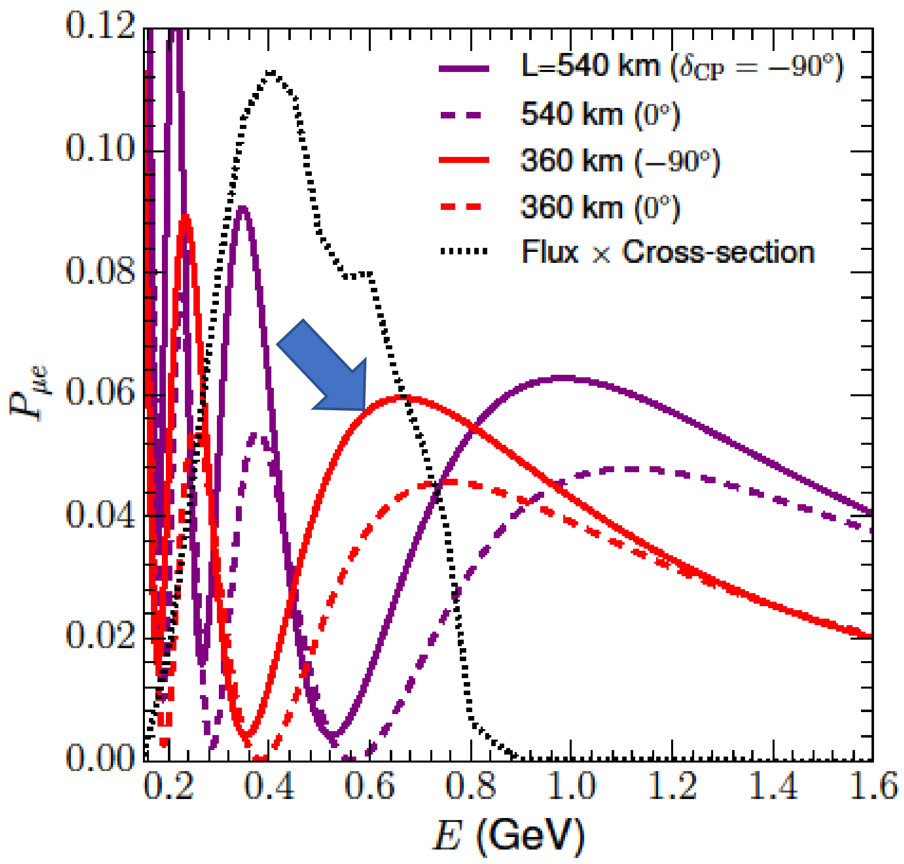


DUNE 10 years yellow curve

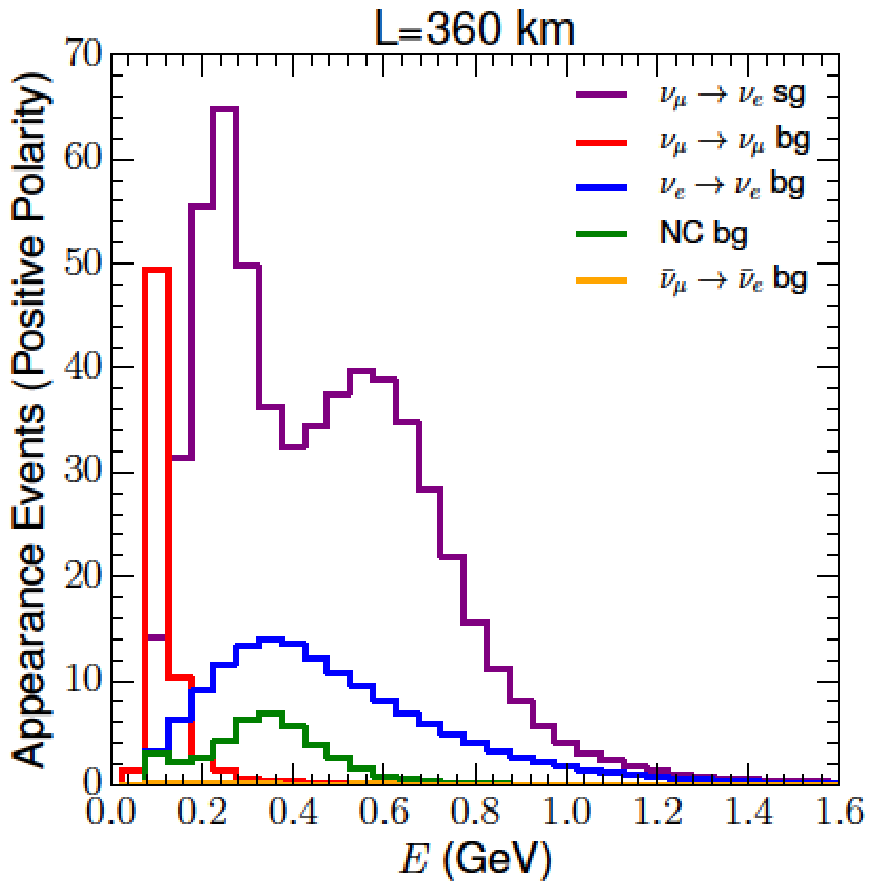


HyperKamiokande 10 years

ESSnuSB at the second neutrino oscillation maximum



Coverage of the second oscillation maximum



Signal (ν_e) and background energy distributions

Preliminary ESSnuSB investment budget

Item	Sub-item	Cost [M€]	Cost [%]
Linac upgrade	Ion Source and Low-Energy Beam Transport (LEBT)	5.00	0.35%
	Radio-Frequency Quadrupole	6.90	0.48%
	Medium Energy Beam Transport (MEBT) Upgrade	3.00	0.21%
	Drift-Tube Linac with BPMs, BCMs	13.40	0.93%
	High-Beta Linac (HBL) Upgrade	10.40	0.72%
	33 Modulator Upgrades	3.50	0.24%
	8 New Modulators	9.00	0.62%
	15 Grid—Modulator Transformers	5.60	0.39%
	11 Grid—Modulator Transformers Retrofitted	0.50	0.03%
	26 Solid State Spoke Amplifiers	26.00	1.79%
	New Klystrons for upgraded HBL	12.10	0.84%
	Remaining Klystron Refurbishment/Replacement	25.20	1.74%
	Cryogenics, Water Cooling, Civil Eng.	12.00	0.83%
	Total	132.60	9.15%
Accumulator	Item	Cost [M€]	
	DC magnets and power supplies	50.00	3.45%
	Injection system	11.00	0.76%
	Extraction system	7.00	0.48%
	RF systems	16.00	1.10%
	Collimation	8.00	0.55%
	Beam instrumentation	19.00	1.31%
	Vacuum system	24.00	1.66%
	Control system	30.00	2.07%
	Total	165.00	11.38%

Target Station	item	Cost [M€]	
	Target Station	30.00	2.07%
	Proton Beam Window System	5.20	0.36%
	PSU + Striplines	5.40	0.37%
	Target and Horn Exchange System	40.42	2.79%
	Facility Building Structure	26.60	1.84%
	General System & Services	9.21	0.64%
	Total	116.83	8.06%
Detectors	item	Cost [M€]	
Emulsion detectors	130 water-emulsion cloud chamber modules	1.00	0.07%
	Detector assembly, installation, air-conditioning, etc	1.00	0.07%
	Total	2.00	0.14%
Super Fine-Grained Detector	Scintillator cubes (980,000, 1x1x1 cm3 each)	1.25	0.09%
	Wavelength shifting fibers	0.22	0.02%
	Multipixel photon counters + optical couplers	0.74	0.05%
	Mechanical structure	0.50	0.03%
	Front-end readout and other electronics	2.10	0.15%
	Data acquisition and calibration systems	0.08	0.01%
	Superconducting magnet and power supply	0.50	0.03%
	Assembly and installation effort (Personnel)	0.10	0.01%
	Total	5.49	0.38%

Near water Cherenkov detector	Detector truss and carbon window	0.50	0.03%
	Detector water storage	0.50	0.03%
	Water pumping and purification plant	10.00	0.69%
	PMT modules, support, power and signal transmission	11.32	0.78%
	Calibration, monitoring and control systems	0.40	0.03%
	Assembly and installation effort (Personnel)	2.50	0.17%
	Total	25.22	1.74%
Far water Cherenkov detector	Two detector tanks and water storage	0.80	0.06%
	PMT modules (PMTs, housing, power, readout)	387.07	26.71%
	PMT module support	15.00	1.04%
	Data logging, processing and transmission	0.50	0.03%
	Calibration, monitoring and control systems	1.50	0.10%
	Water pumping and purification plant	40.00	2.76%
	Counting, testing, assembly, storage rooms (x3)	3.00	0.21%
	Veto detector (smaller PMTs looking outward)	23.20	1.60%
	Assembly and installation effort (Personnel)	10.00	0.69%
	Total	481.07	33.19%
Underground cavern excavations	Civil engineering - excavation of two caverns	507.15	34.99%
	Cranes and other mechanical infrastructure	0.50	0.03%
	Access systems	3.00	0.21%
	Air conditioning and ventilation	5.50	0.38%
	Monitoring systems	2.50	0.17%
	Installation effort (Personnel)	2.50	0.17%
	Total	521.15	35.96%
Grand Total		1449.35	100.000%