ESS neutrino Super Beam for CP violating precision measurements - design and performance

Report at the RICH2022 Workshop on
the achievements of the ESSνSB Design Study 2018-2022 and on
the recently approved EU grant for continued studies 2023-2026

Funded by the Horizon 2020 Framework Programme of the European Union

ESSnuSB Design Study ESSνSB January 2018 - March 2022

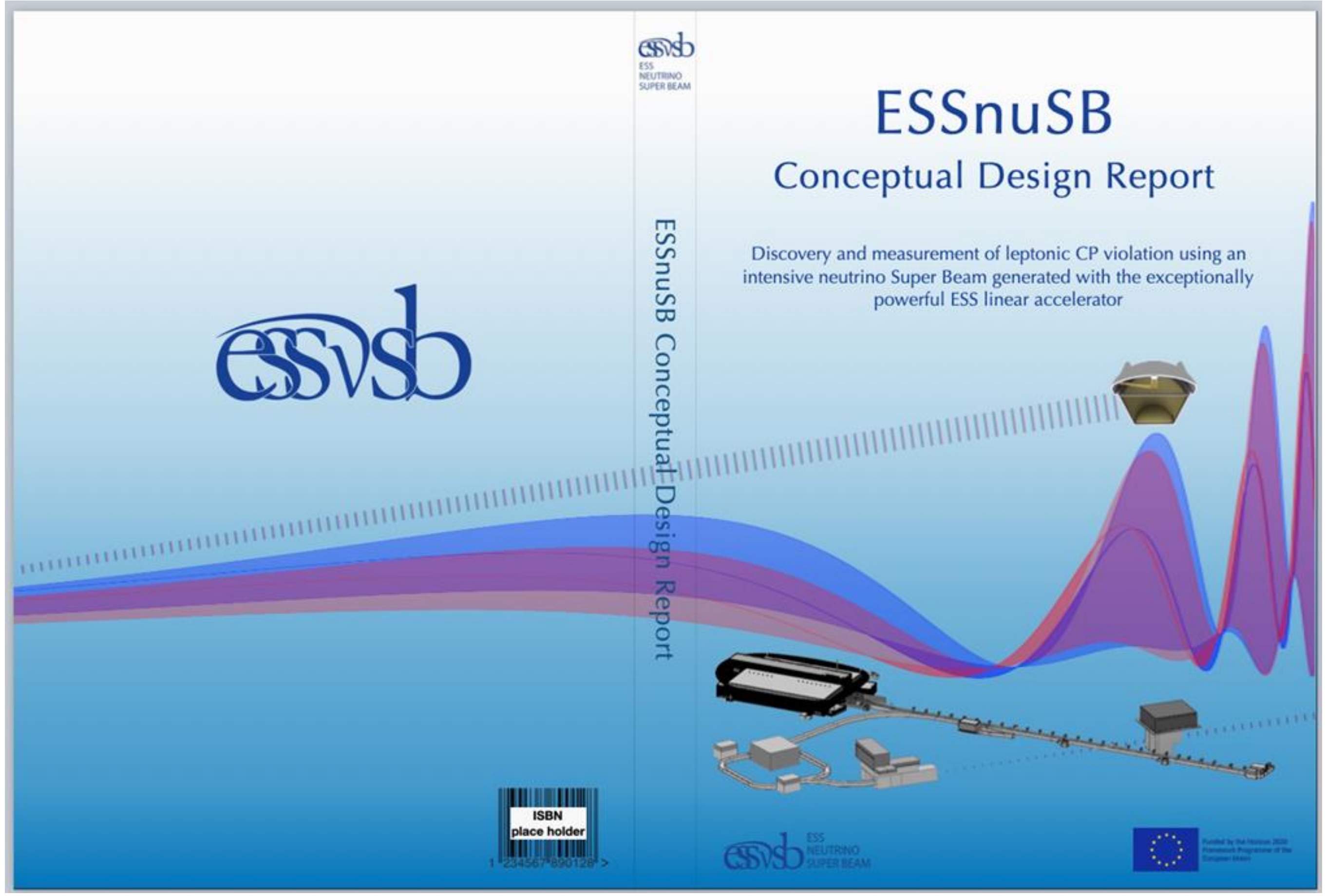
Call:	H2020-INFRADEV-2017-1
Funding scheme:	RIA
Proposal number:	777419
Proposal acronym:	ESSnuSB
Duration (months):	48
Proposal title:	Feasibility Study for employing the uniquely powerful ESS linear accelerator to generate an intense neutrino beam for leptonic CP violation discovery and measurement.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

EU application submitted in 2017
3 M€ granted for the period 2018-2022

All results published in an ESSnuSB CDR On 6 June 2022

More information on the ESSnuSB site: http://essnusb.eu/



CDR published on arXive 6 June 2022:
https://arxiv.org/abs/2206.01208
To appear in European Physical Journal

CDR outline:
1. ESS linac upgrade
2. An linac-pulse compressing accumulator ring
3. A target station and 50 m decay tunnel
4. A near water 1 kton Cherenkov detector placed in the neutrino beam some 250 m downstream of the target statio
5. A far 540 kton water Cherenkov detector 360 km from the target station consisting of 2 large underground tansk filled each with 270’000 m^3 of water
6. Performance for ν CP violation measurments

The European Spallation Source neutrino Super Beam
White Paper to be submitted to the Snowmass 2021
USA Particle Physics Community Planning Exercise
arXiv:2203.08803v1 [physics.acc-ph] 15 Mar 2022

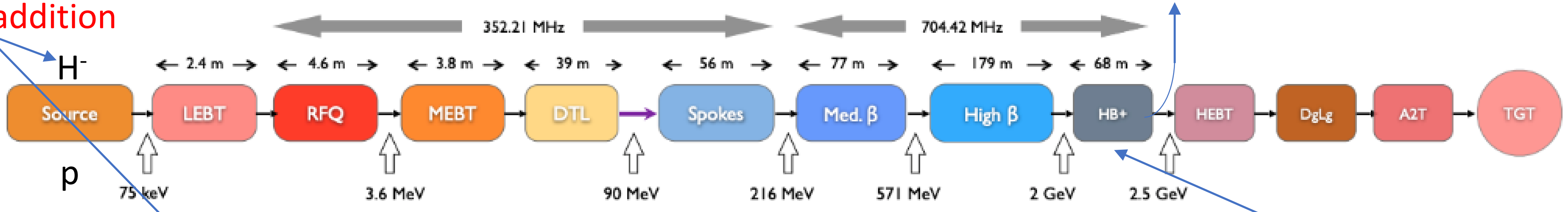
https://arxiv.org/abs/2203.08803

The ESS linac

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

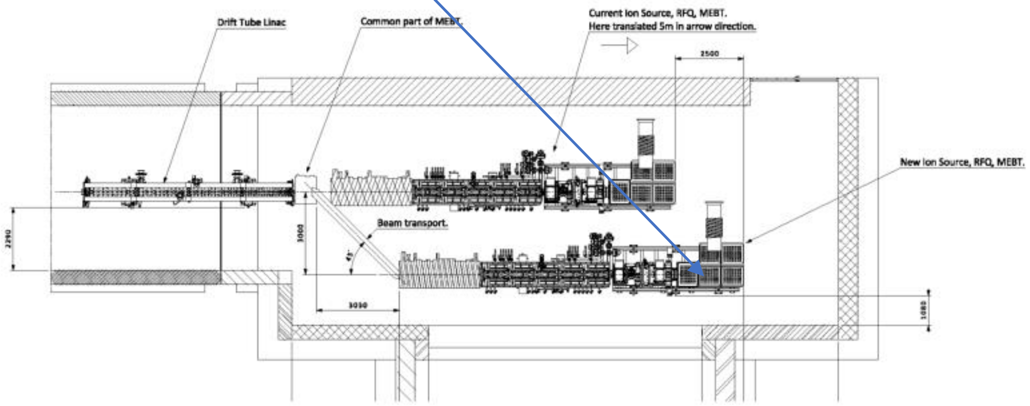
Transfer Line to Accumulator addition

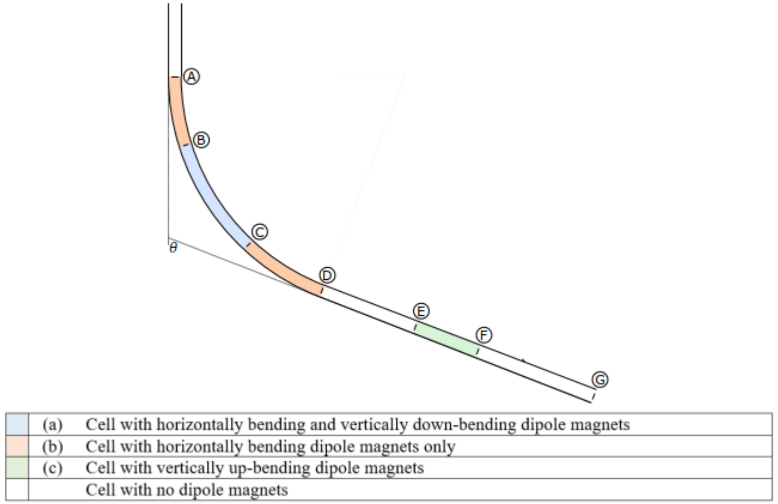
ESSnuSB addition



ESSnuSB addition

The linac Normalconducting part Superconducting part

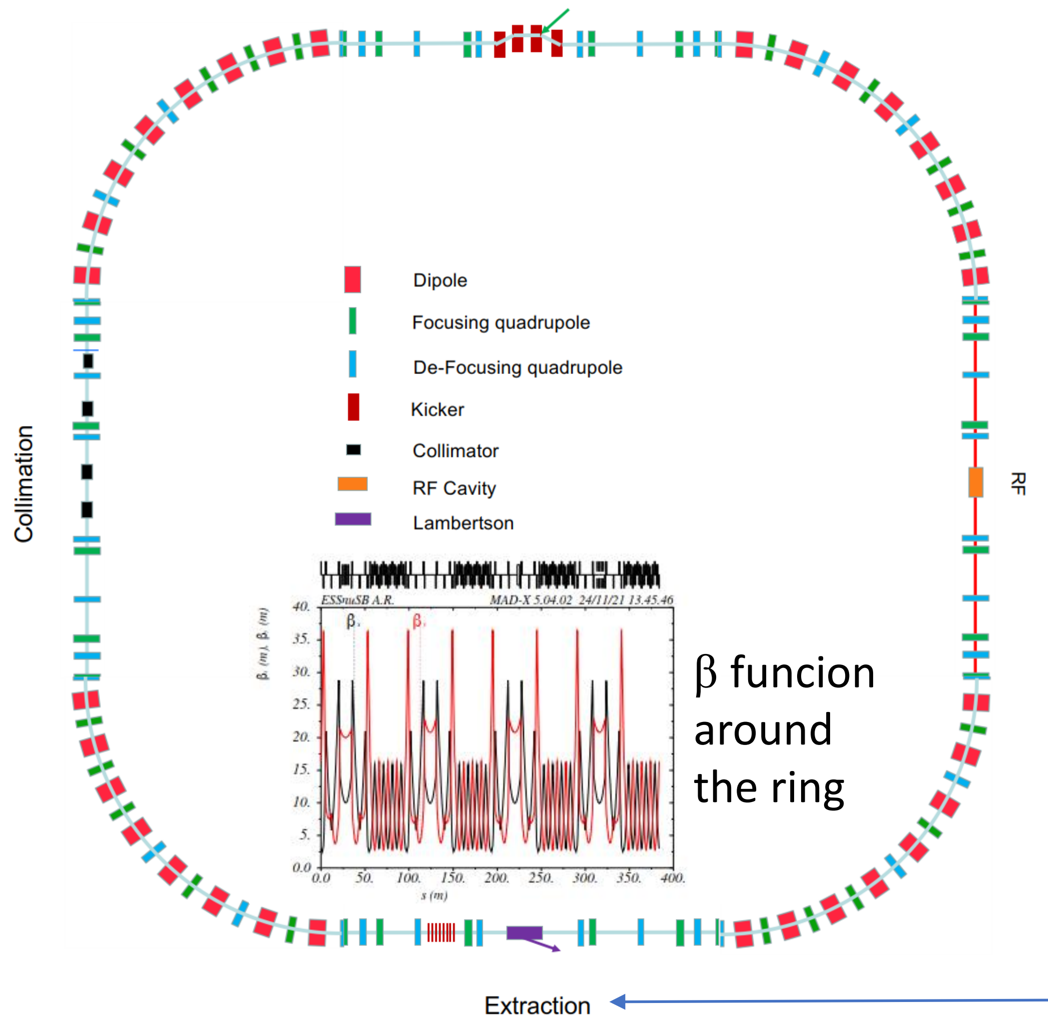




The merging of the H+ and the H- beams in the MEBT

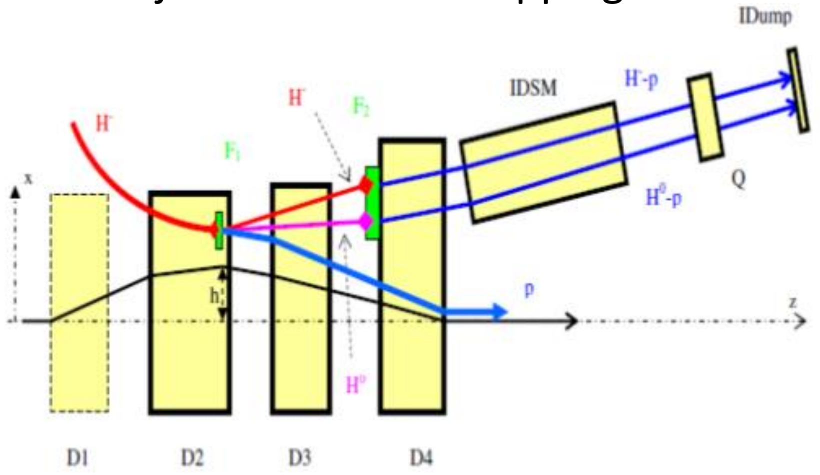
Transfer Line with bending limited by H^- Lorenz stripping

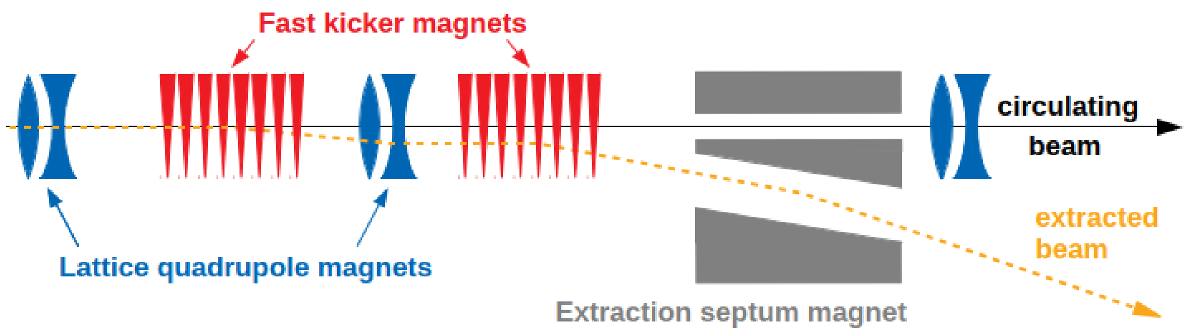
The Accmulator ring



β funcion around the ring

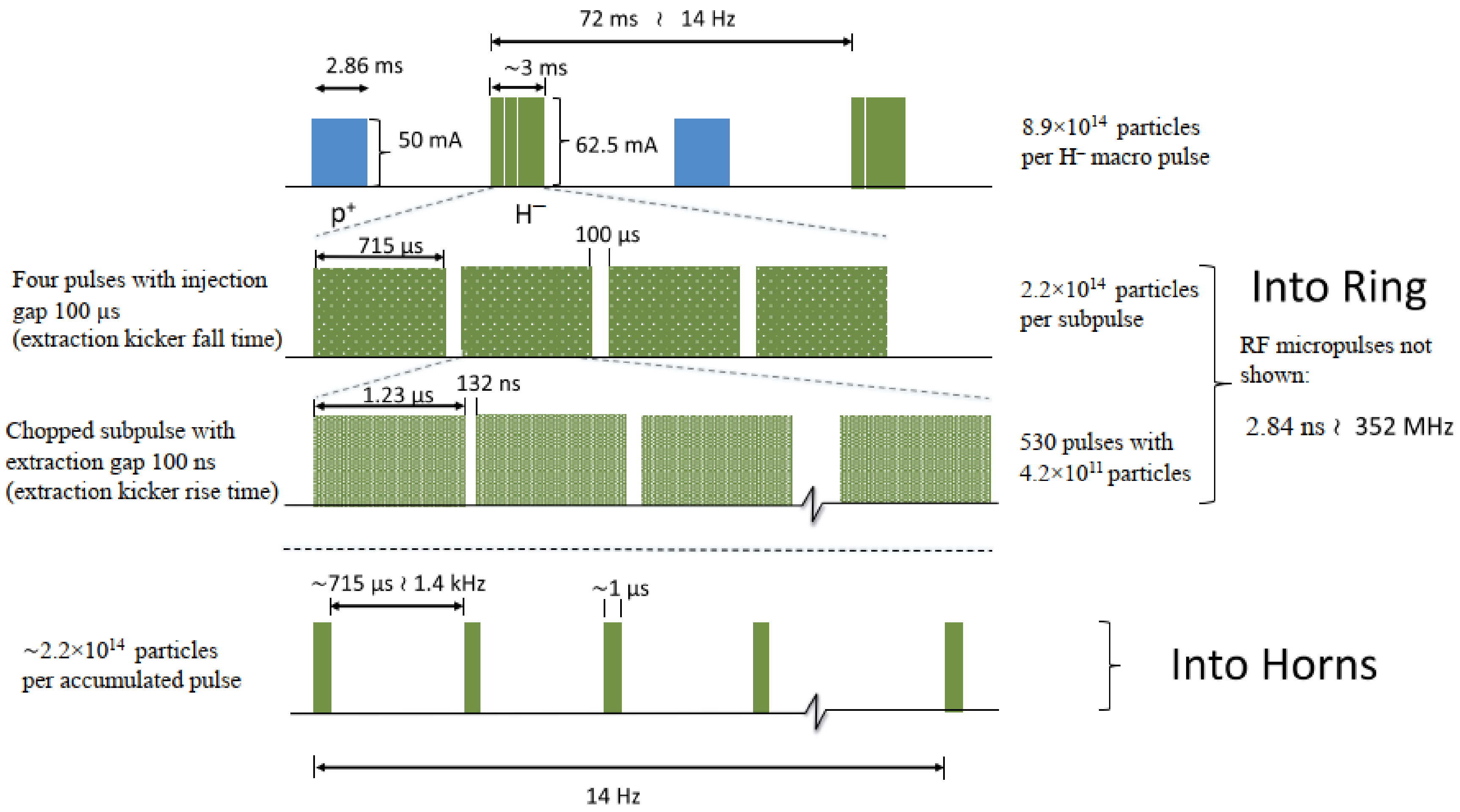
Injection with H- stripping



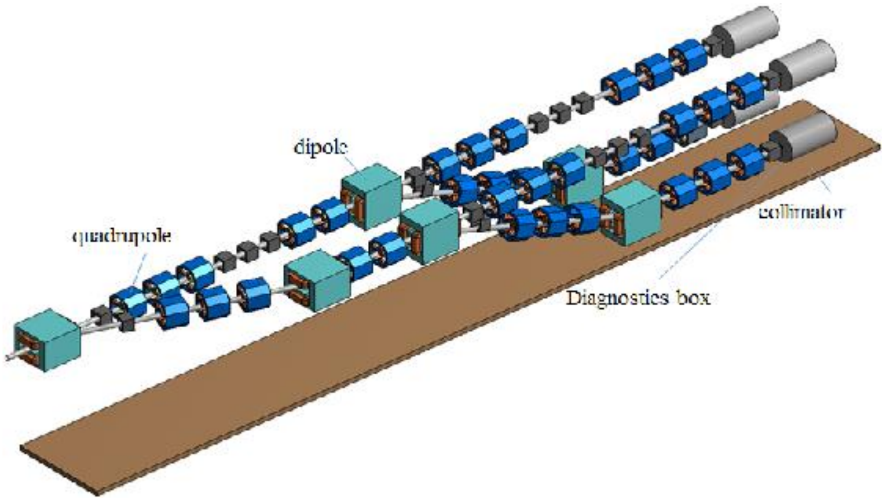


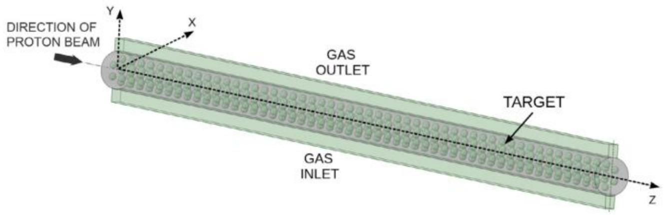
Extraction

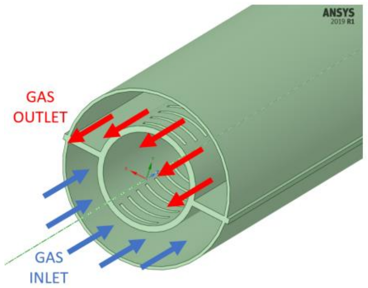
Detailed schematic of the ESSvSB pulsing scheme

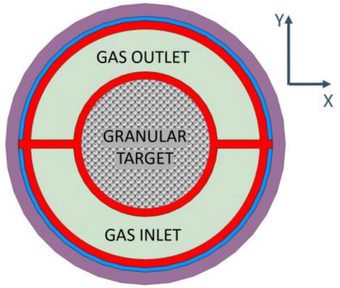


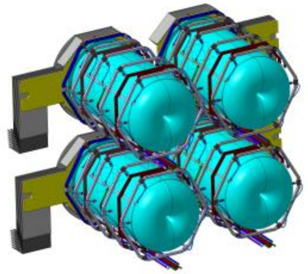
Beam switch-yard and the target station



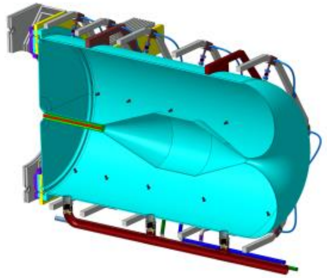




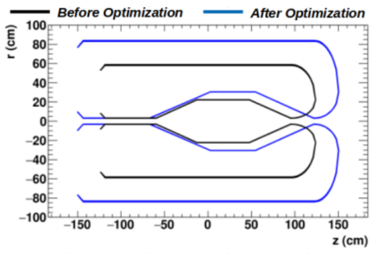




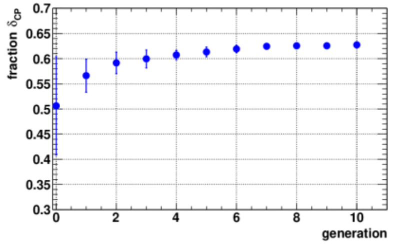
(a) The four-horn system.



(b) Transverse view of one horn.



(a) Evolution of the horn profile.



(b) Genetic algorithm convergence throughout the iterative process.

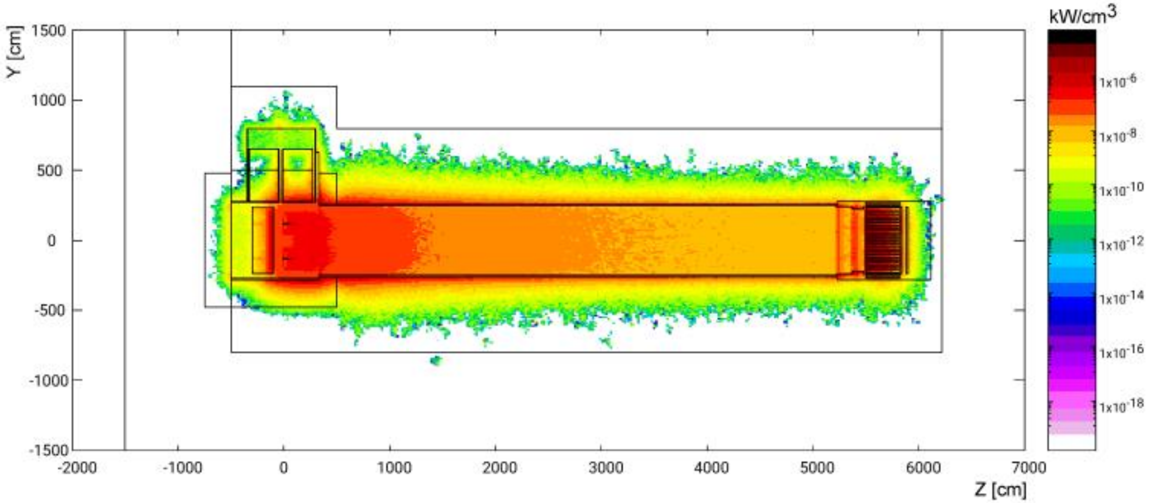
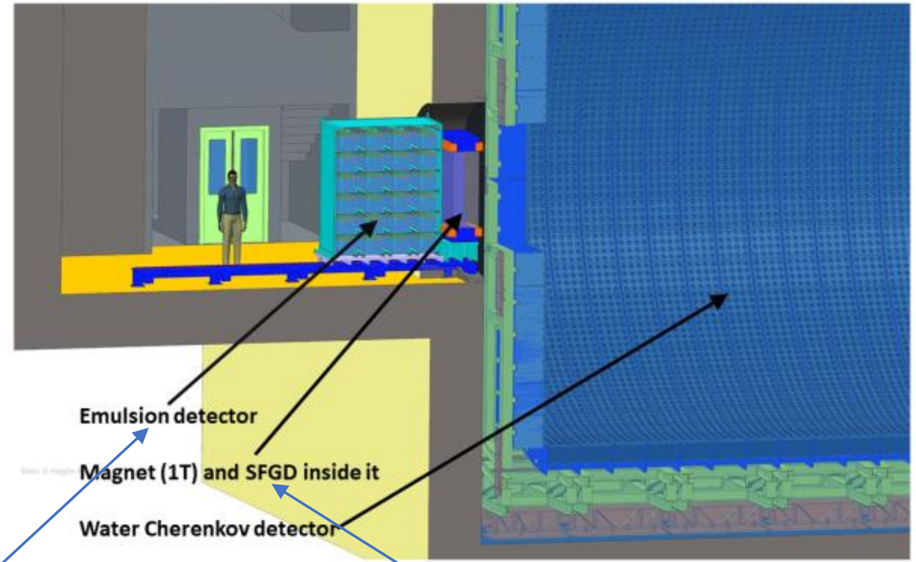
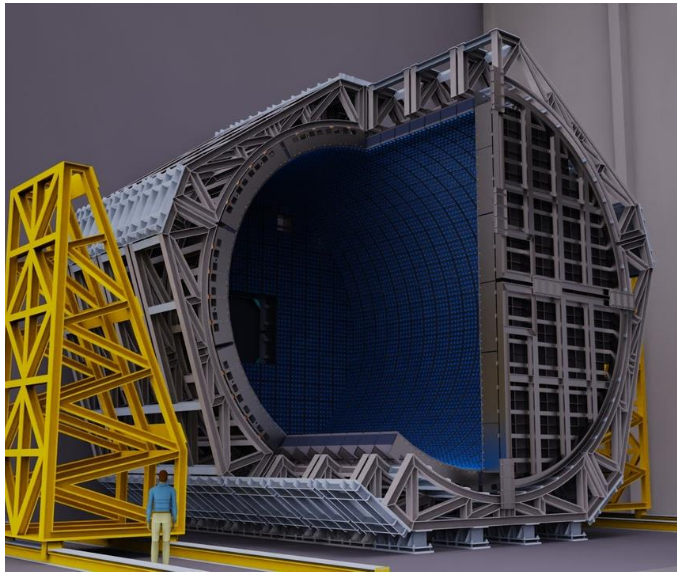


Figure 5.46: Energy deposition distribution in the target station facility.

The Near Detector



Near Detector underground station



A 1 kton water Cherenkov detector

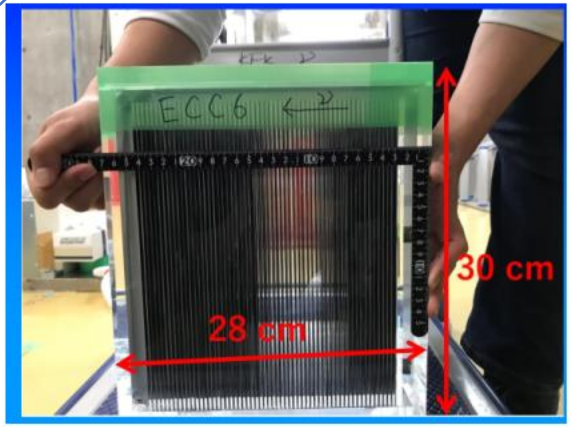
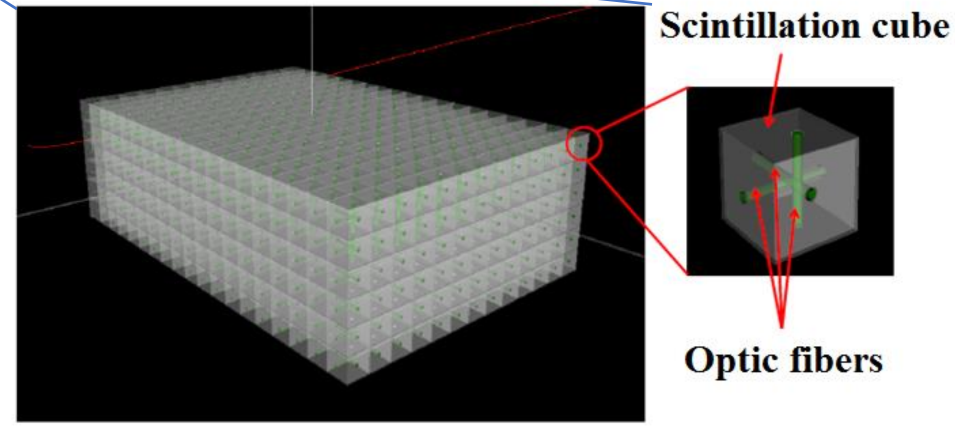
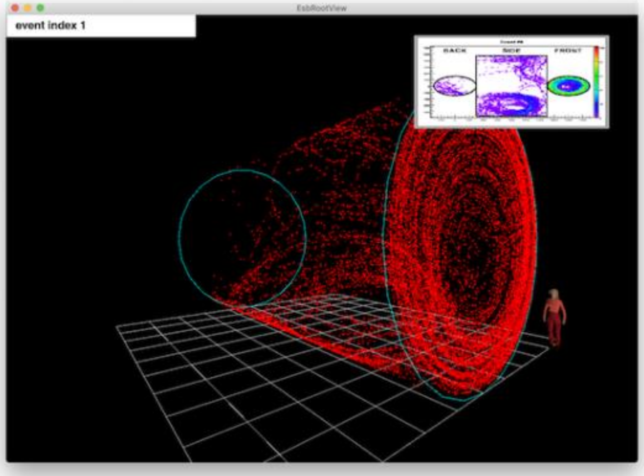


Figure 6.42: A photograph of the NINJA ECC element using water as target.

NINJA emulsion detector



The super Fine-Grained Detector sFDG



A muon Cherenkov ring

The Far Detector

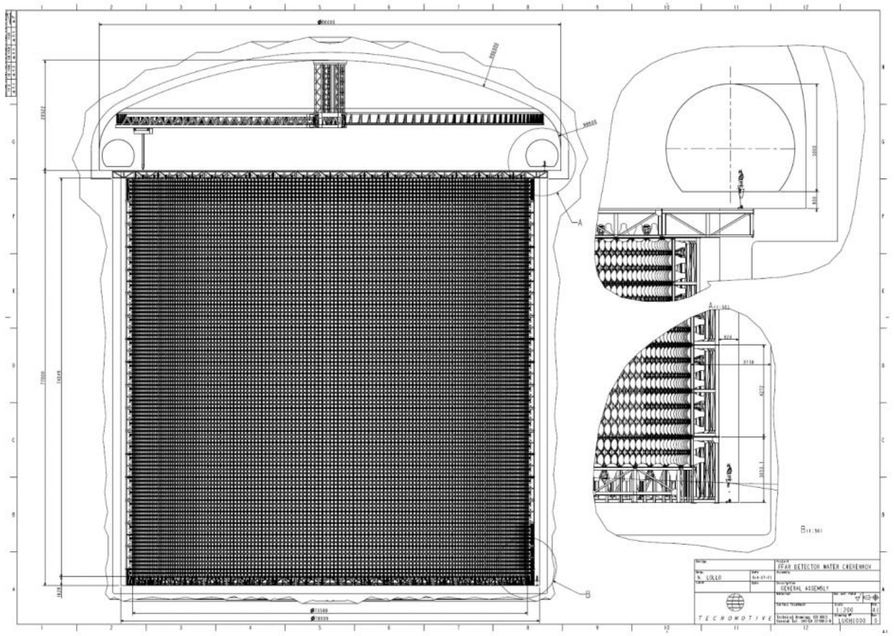
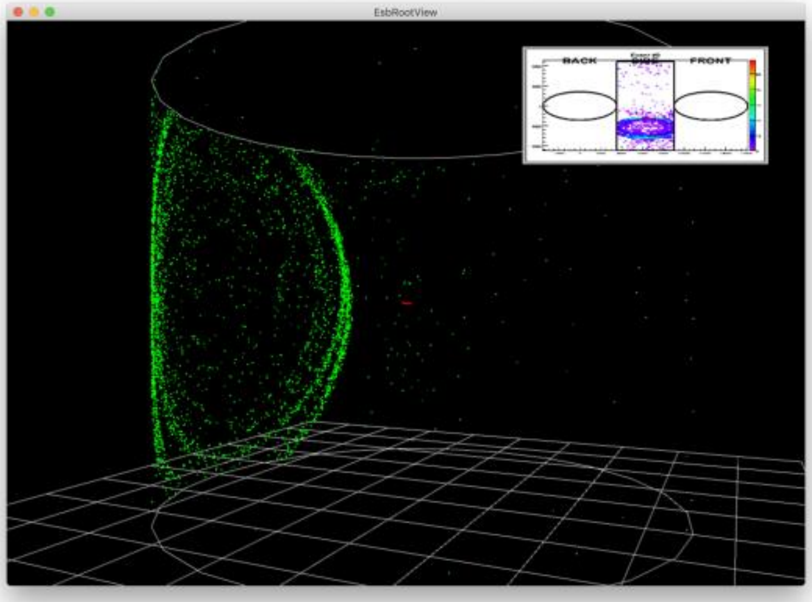


Figure 6.48: Overall view of a single far-detector tank with indicated dimensions.

Two 270 kton fiducial voume water Cherenkov detector



A muon Cherenkov ring

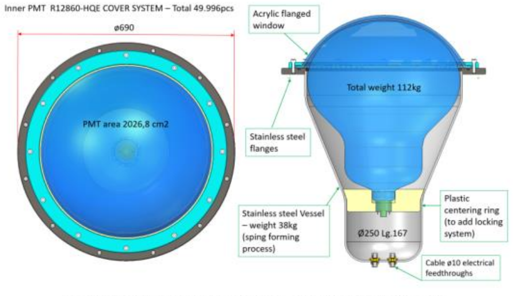
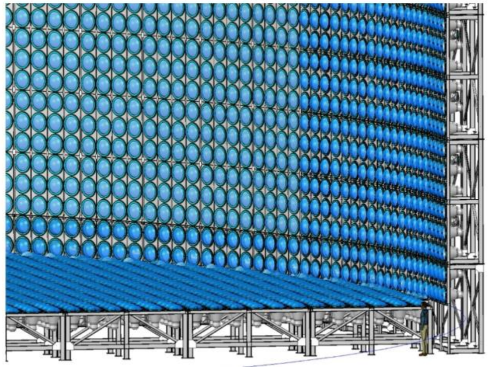
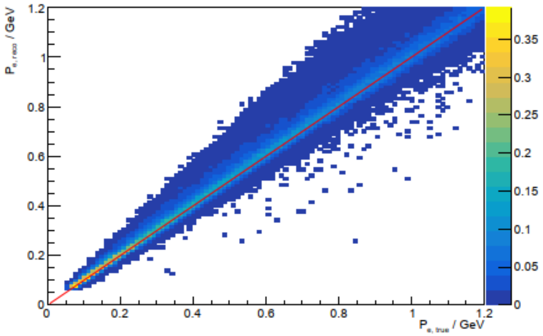


Figure 6.50: A schematic view of an inward-facing 20 inch PMT embedded in a protective cover.

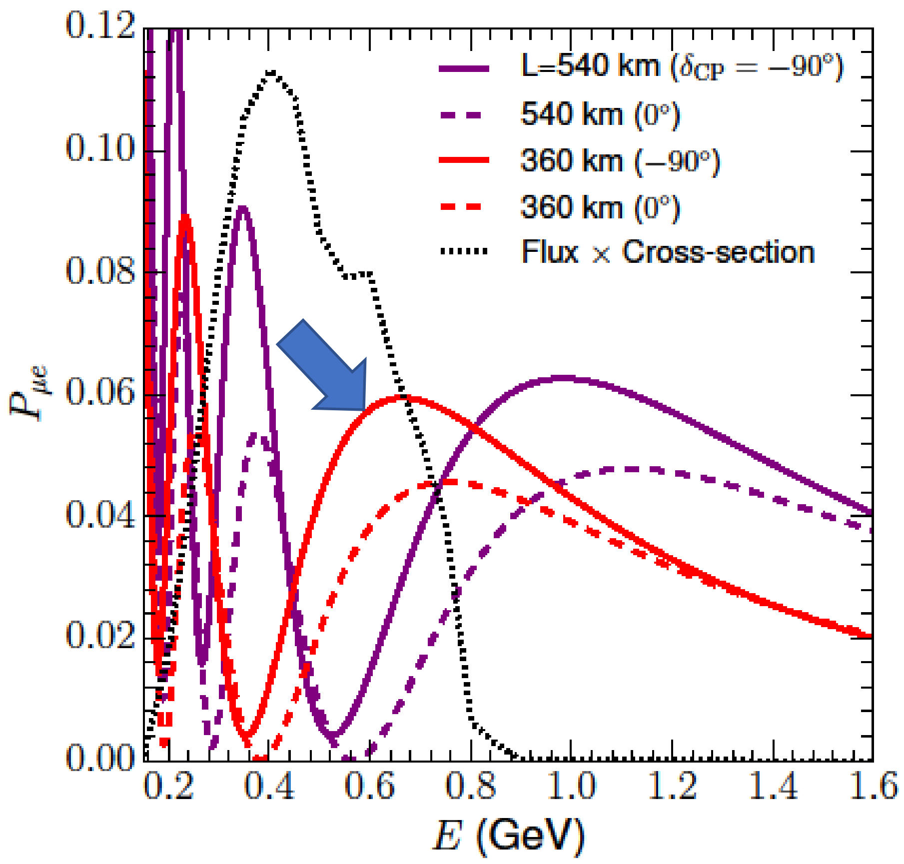




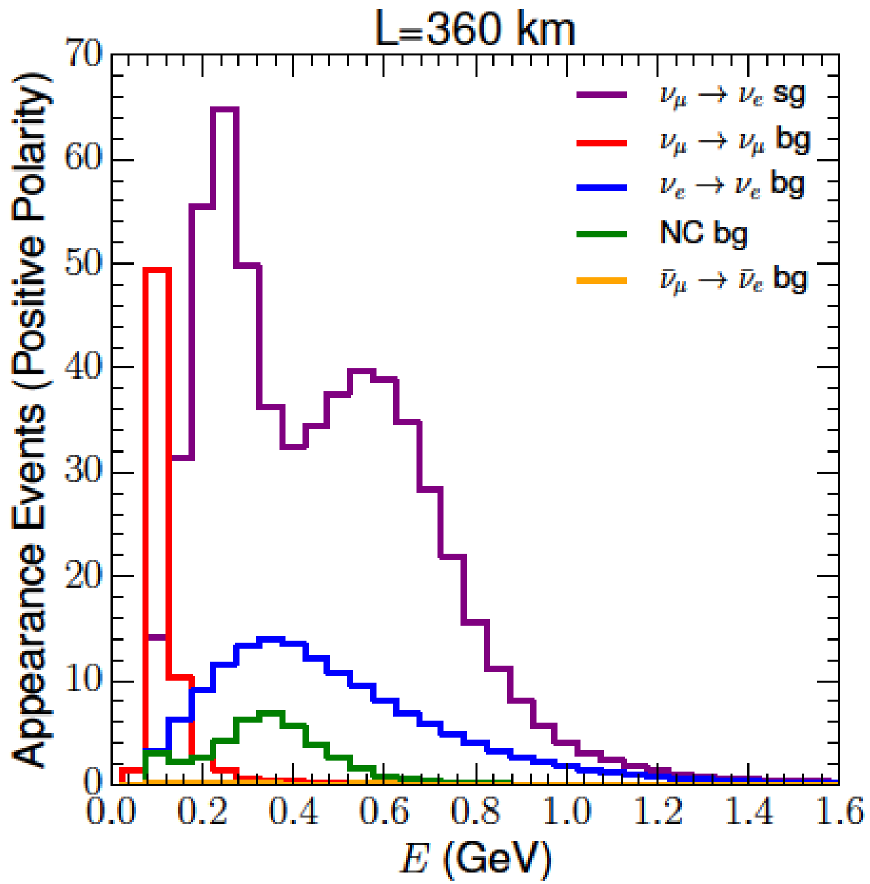
(a) Electrons

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

ESSnuSB at the second neutrino oscillation maximum

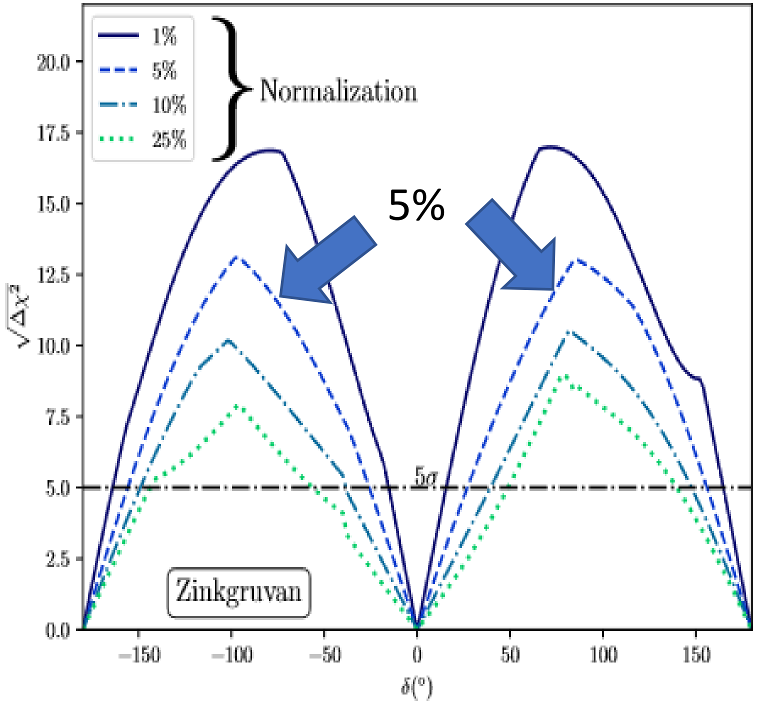


Coverage of the second oscillation maximum

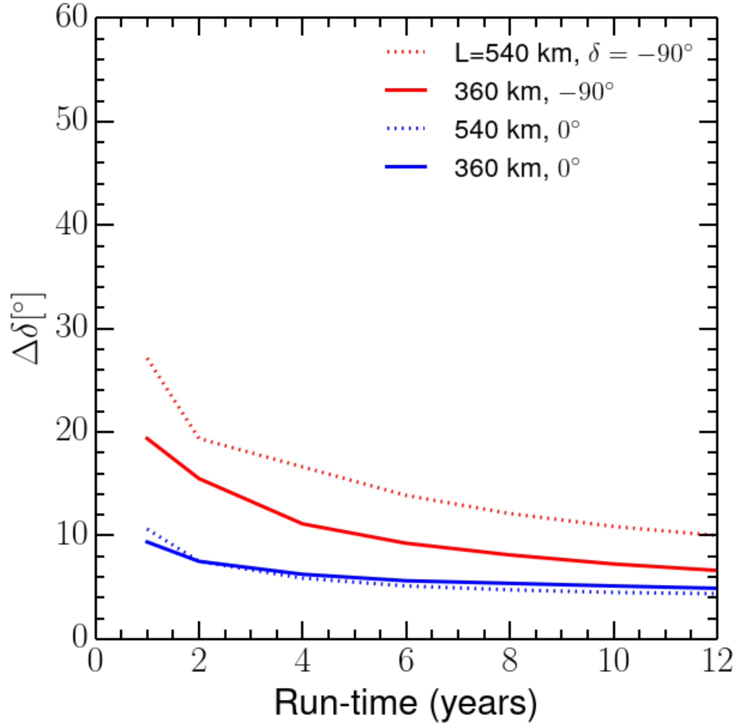


Signal (ν_e) and background energy distributions

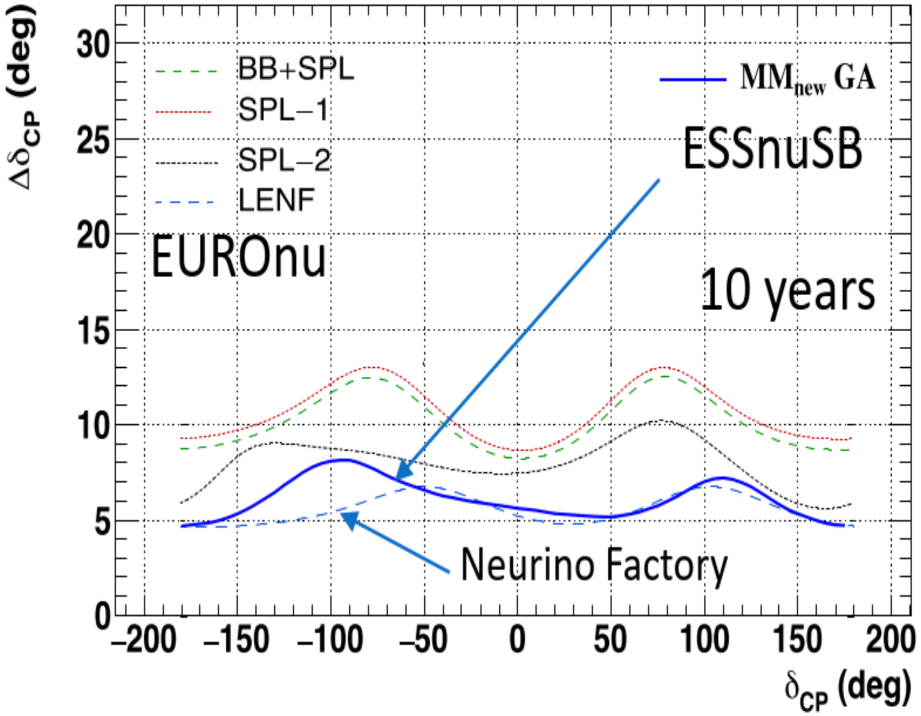
Performance for CPV discovery and δ_{CP} measurement



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

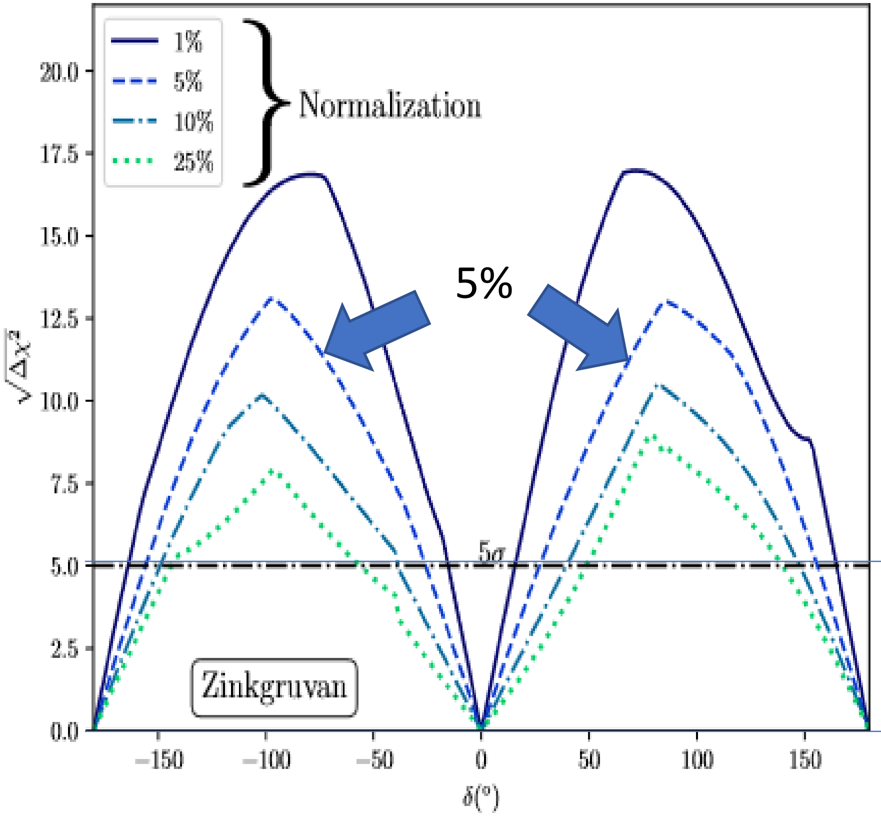


Error in δ_{CP} angle vs run time with 5% normalization error

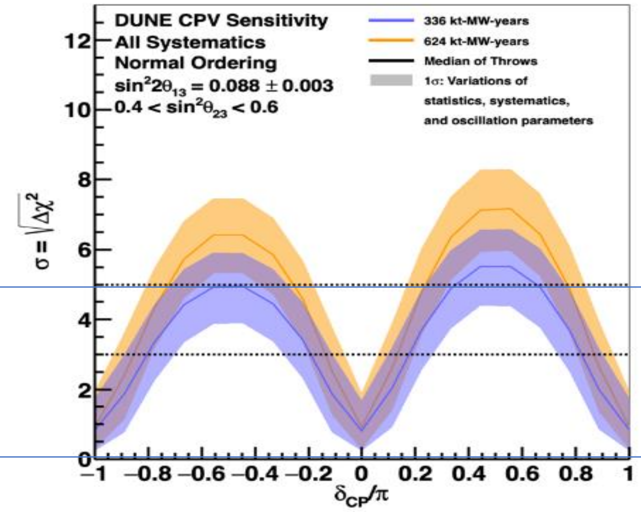


Error in δ_{CP} angle vs δ_{CP} angle after 10 years with 5% normalization error

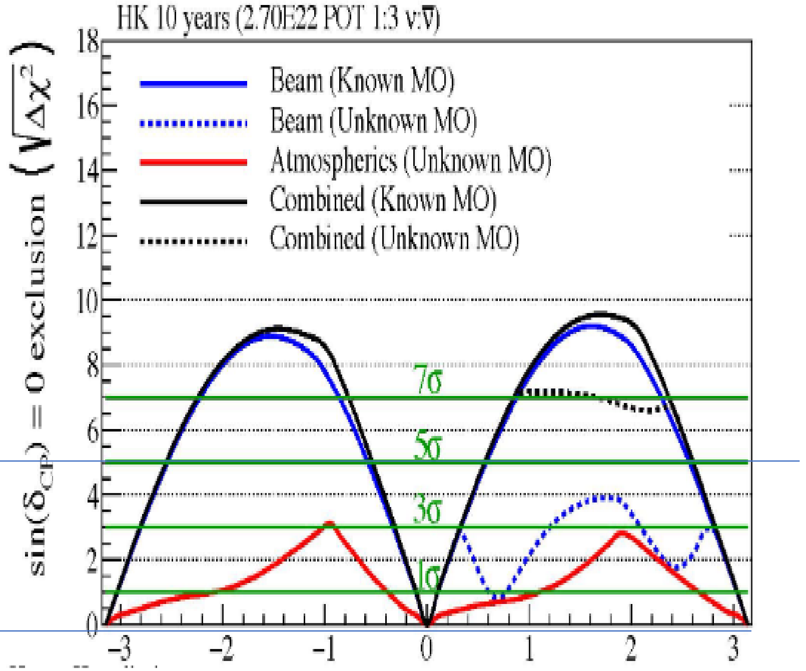
ESSnuSB in the international context – CPV discovery



ESSnuSB March 2022 with 5% normalization error

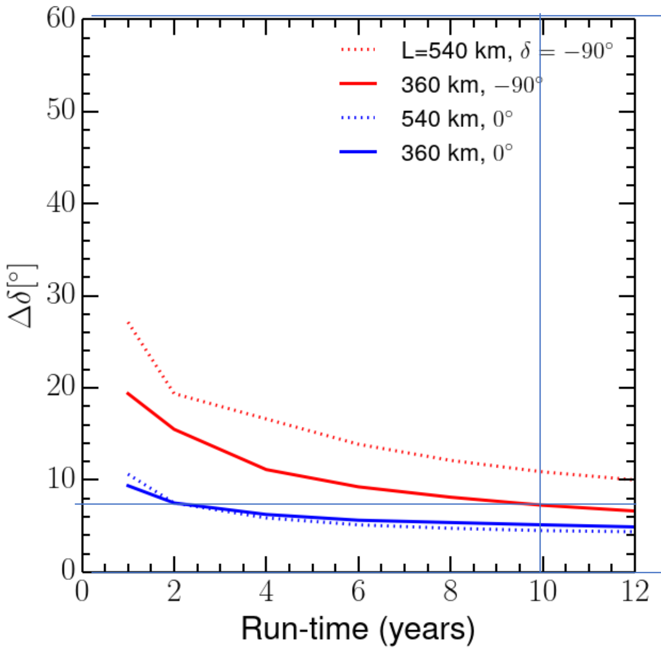


DUNE Snowmass March 2022

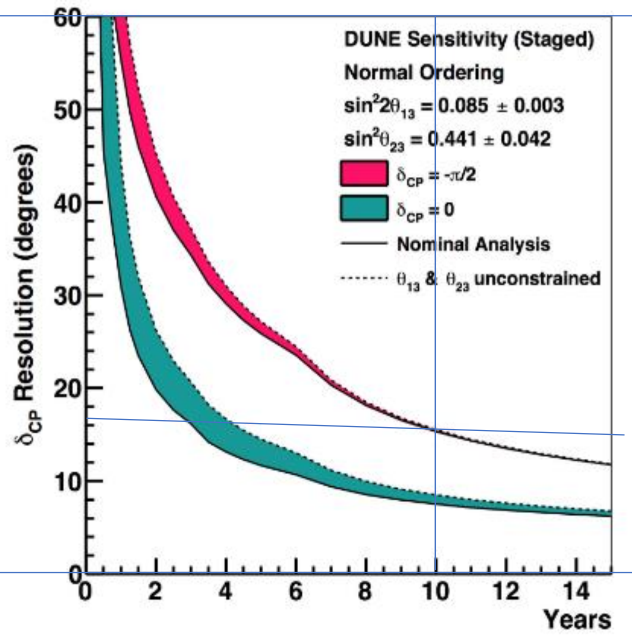


HyperKamokande Snowmass March 2022

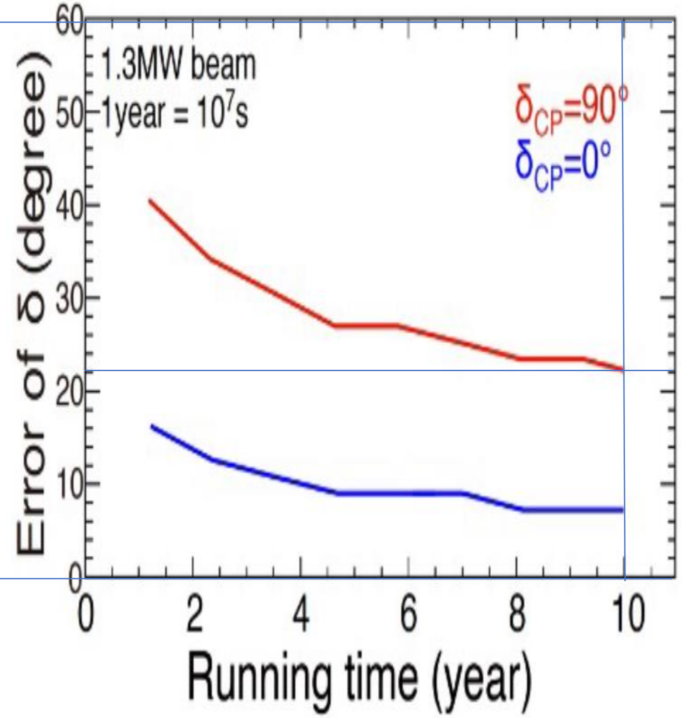
ESSnuSB in the international context – CPV resolution



ESSnuSB March 2022 with 5% normalization error

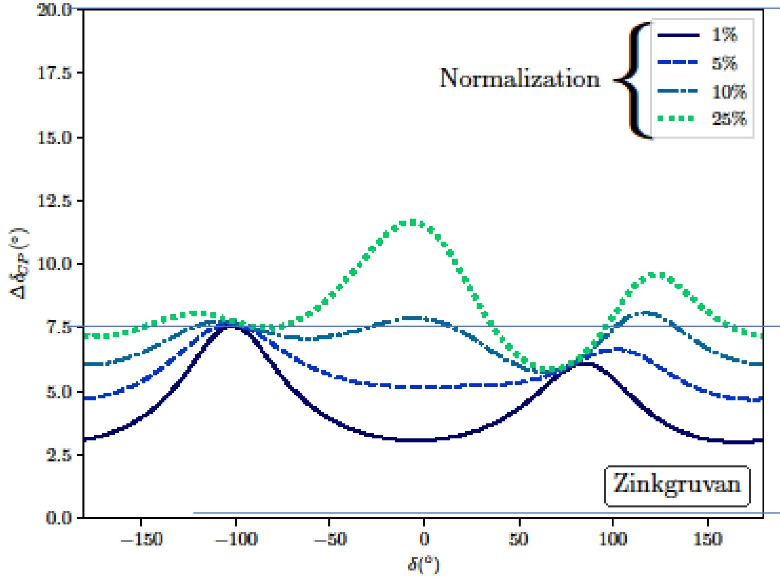


DUNE Snomass March 2022

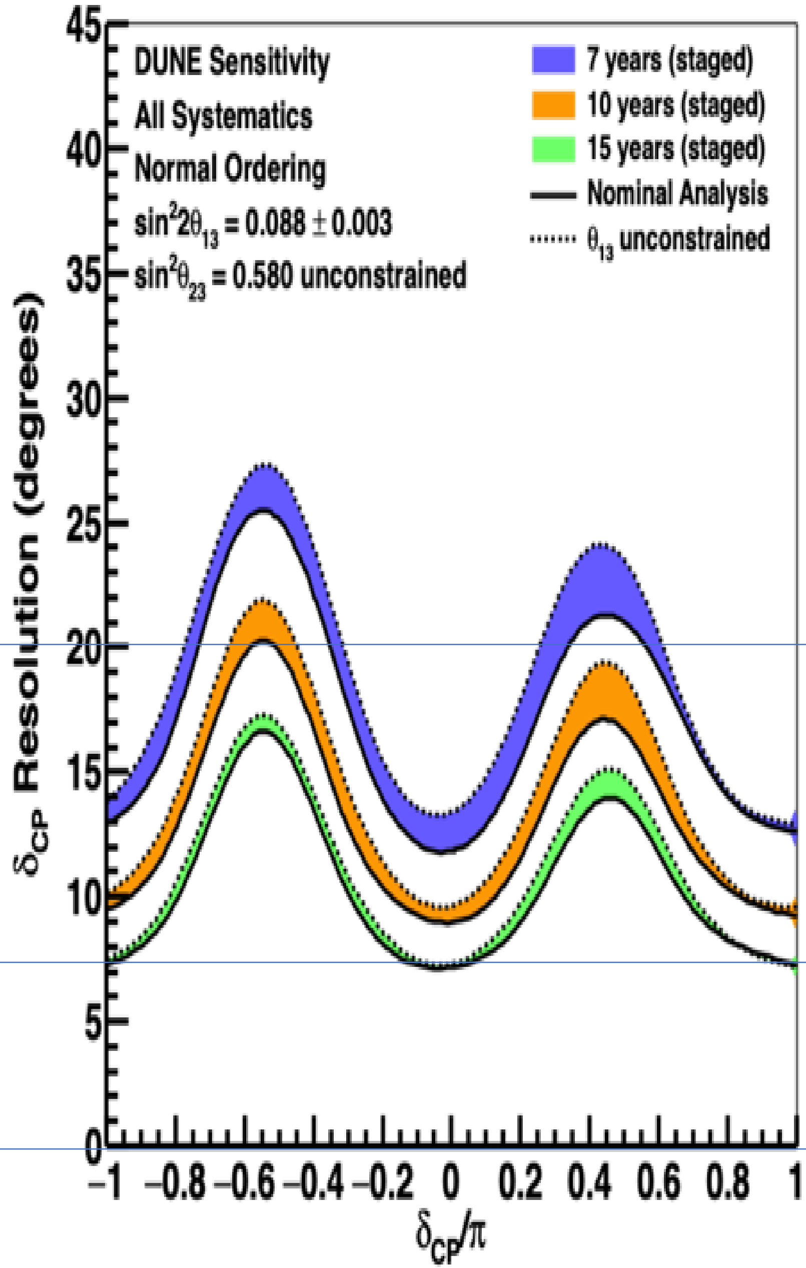


HyperKamokandeSnowmass March 2022

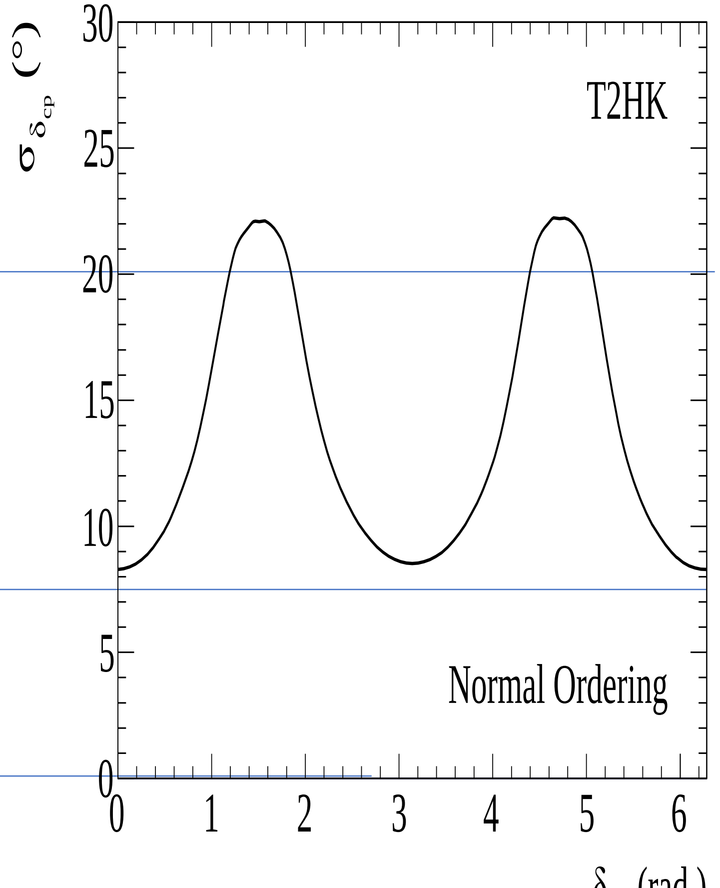
ESSnuSB in the international context – precision in δ_{CP}



ESSnuSB 10 years



DUNE 10 years yellow curve



HyperKamiokande 10 years

ESSnuSB Cost Esimate

Total Cost 1’382 M€

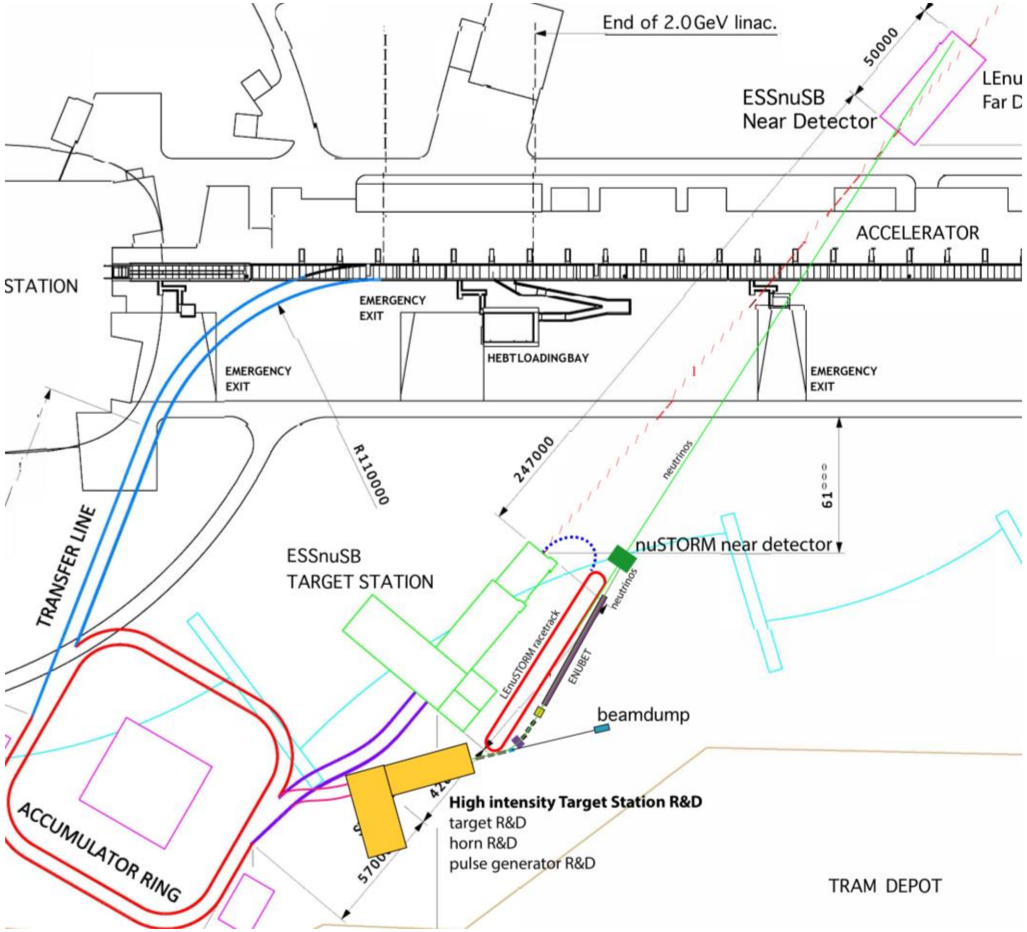
The ca 75’000 20 inch PMTs and the excavation of the cavern for the two Far Detectors represents 67% of the total cost.

The cost of civil engineering on the ESS site is not included. A cost estimate of this 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%**

Continuation of design studies 2023-2026

ESSnuSB+ proposal granted by EU 26/07/2022 with 3 M€



Cross-section measurements with:

- Low Energy nuSTORM: $\pi \longrightarrow \mu \longrightarrow e + \nu_\mu + \nu_e$
- Low Energy ENUBET: $\pi \longrightarrow \mu + \nu_\mu$

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 ESSνSB ring-to-switchyard transfer line to the **nuSTORM target**.
4. Design an **injection scheme** for the racetrack storage ring
5. Design a **Monitored Neutrino Beam** (low energy ENUBET)
6. **Optimize the performance** of the ESSνSB accelerator complex

ESSνSB+

26/07/2022

Title of Horizon Europe EU 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.

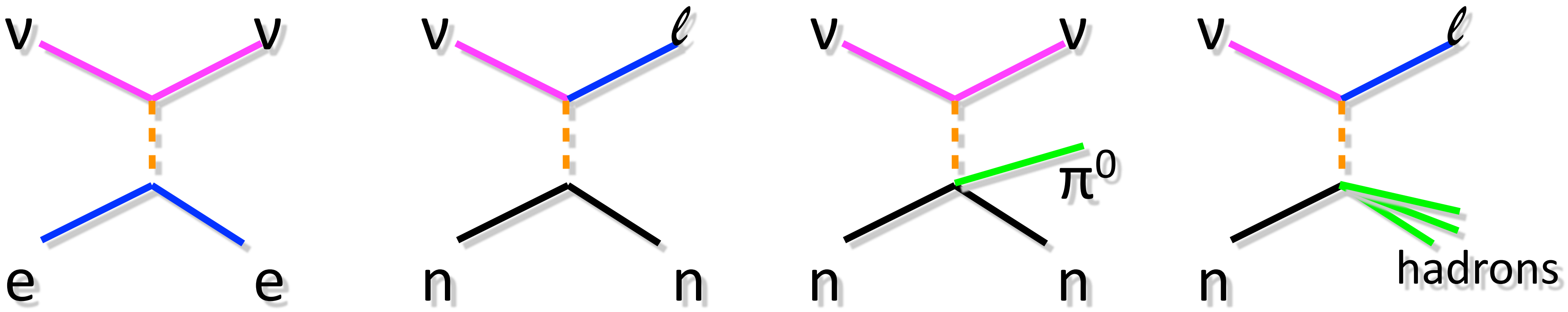
Acronym of Proposal: ESSνSB+

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

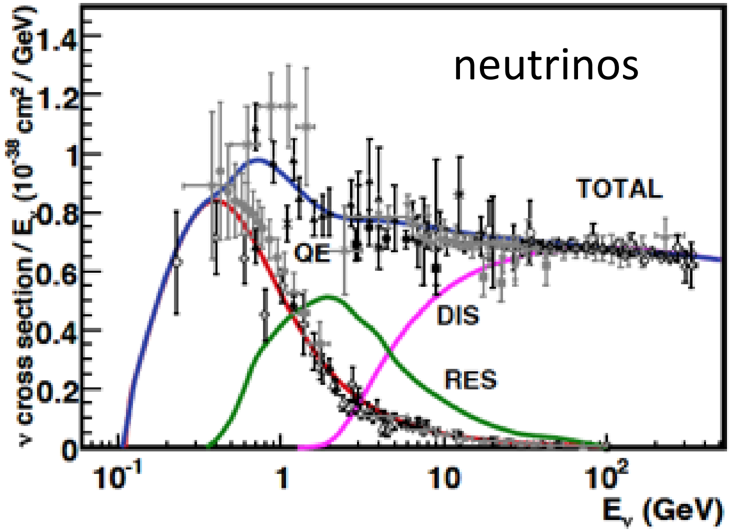
[1] Affiliated Partner
[2] Associated Institute
[3] International European Interest Organisation

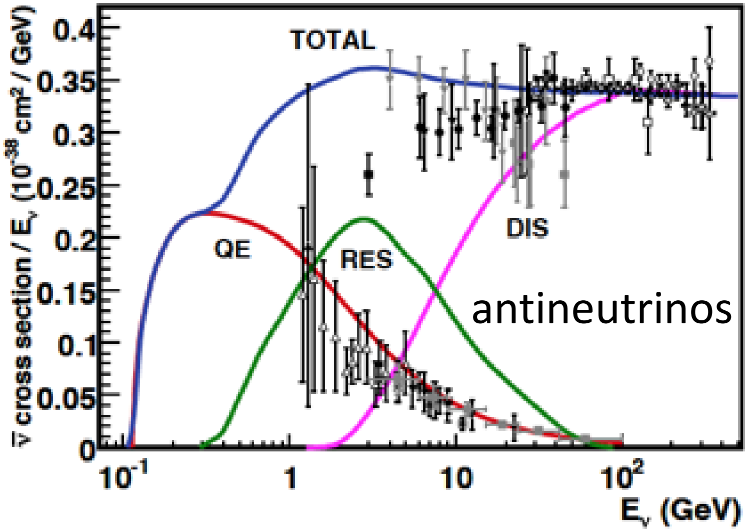
Excellent supporting letter from the ESS director

ESSνSB+ main motivation: neutrino cross-section measurements



Elastic | Quasi-Elastic (QE) | Resonant (RES) | Deep inelastic (DIS)





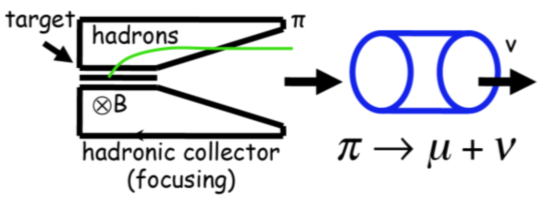
Missing measurements at the ESSνSB region: below 500 MeV

The ESSνSB+ Work Packages

WP2 Engineering and Infrastructures

Civil engineering studies for the proposed installations at the ESS site and the far Detector Zinkgruvan site, including licensing, safety, radiation protection

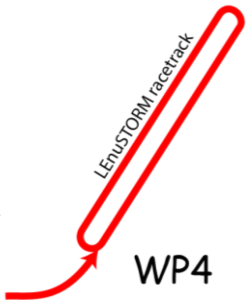
WP3 Target Station

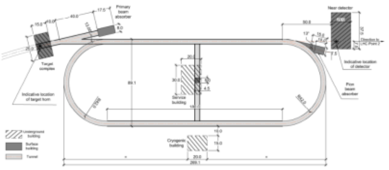


A study will be made of how the target station already designed for the ESSnuSB neutrino beam need to be complemented to suit also for pion collection for LEnuSTORM and LEMNB projects.

WP4 Low Energy nuSTORM

The design of the Low Energy nuSTORM racetrack ring will be made making use of and adapting ideas from designs of nuSTORM rings already made for higher energies. The design will include the transfer and injection of the pion beam from the ESSnuSB complex.



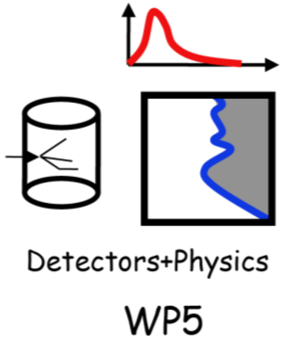


"High Energy" nuSTORM

The ESSνSB+ Work Packages

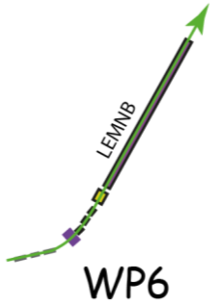
WP5 Detector and physics performance

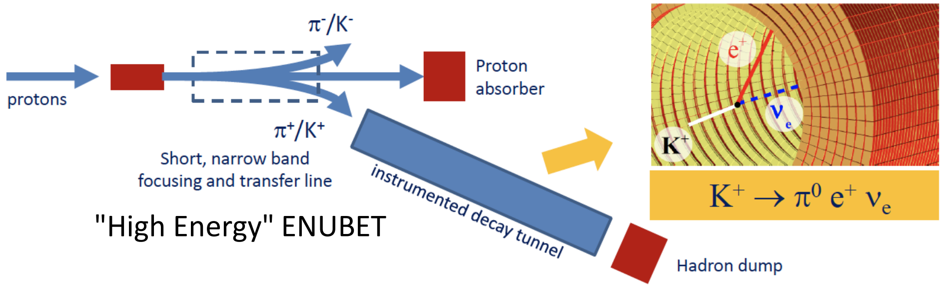
Design of an additional Very Near Detector which will be used by LEnuSTORM and LEMNB for cross-section measurements. This detector will also be used as LEnuSTORM near detector for sterile neutrino searches for which the ESSnuSB Near Detector will be used as a far detector. The use of the information gained on neutrino cross-section using LEnuSTORM and LEMNB to improve the CPV measurements will be evaluated. The potential of the ESSνSB far detector doped with Gadolinium for non-beam related physics (relic neutrinos, proton life-time) will be studied.



WP6 Low Energy Monitored Neutrino BeamNB

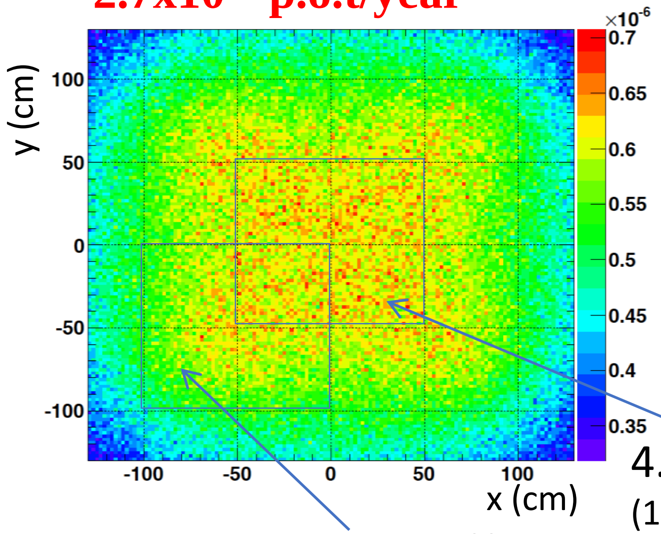
The ideas behind the existing design of ENUBET (Enhanced NeUtrino BEams from kaon Tagging) will be used to design a Low Energy Monitored Neutrino (LEMNB) beam. With this will be studied, instead of decays of kaons, decays of pions and muons, that will be monitored at the single-particle level using sampling calorimeters on the inner walls and end-wall of a ca 30 m long LEMNB decay tunnel for muon/pion separation. In this way the ENUBET together with the Very Near Detector will enable measurements of electron neutrino and muon neutrino cross-sections below 1 GeV.





For each muon-neutrino produced there is also a muon….

2.7x10^{23} p.o.t/year



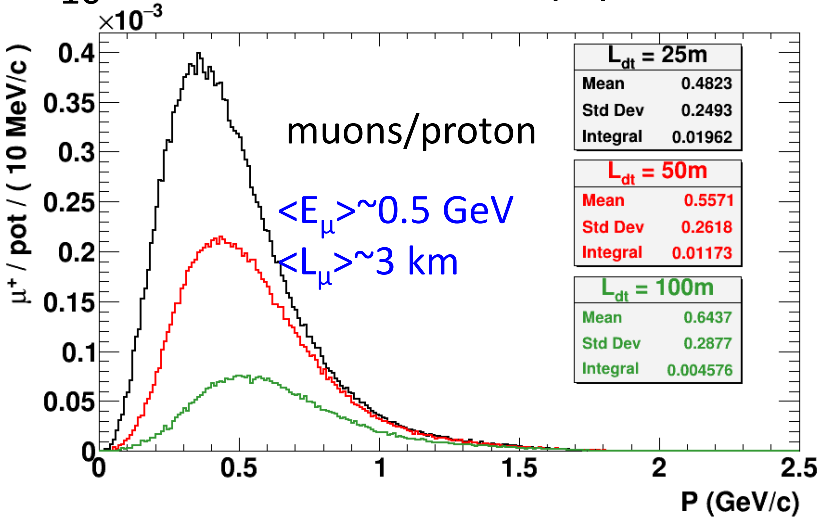
muons at the level of the beam dump (per proton)

4.2x10^{20} μ/year
(16.3x10^{20} for 4 m^2)

4.1x10^{20} μ/year

more than 4x10^{20} μ/year from ESS compared to 10^{14} μ used by all experiments up to now (10^{18} μ for COMET in the future).

10^{-3}

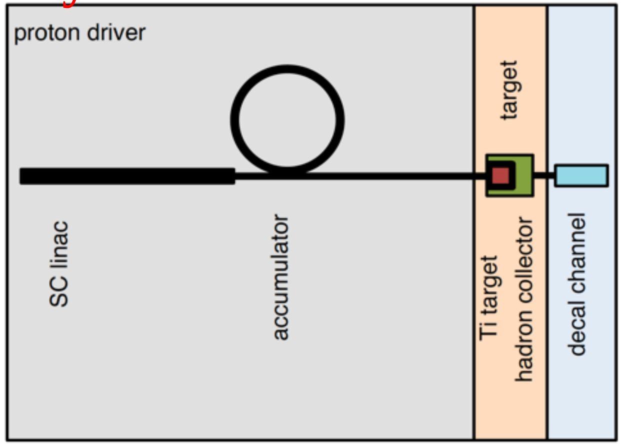


- input beam for future 6D μ cooling experiments (for muon collider),
- low energy nuSTORM,
- Neutrino Factory,
- **Muon Collider**.

ESSνSB and (R&D) synergies

2.7×10^{23} p.o.t/year

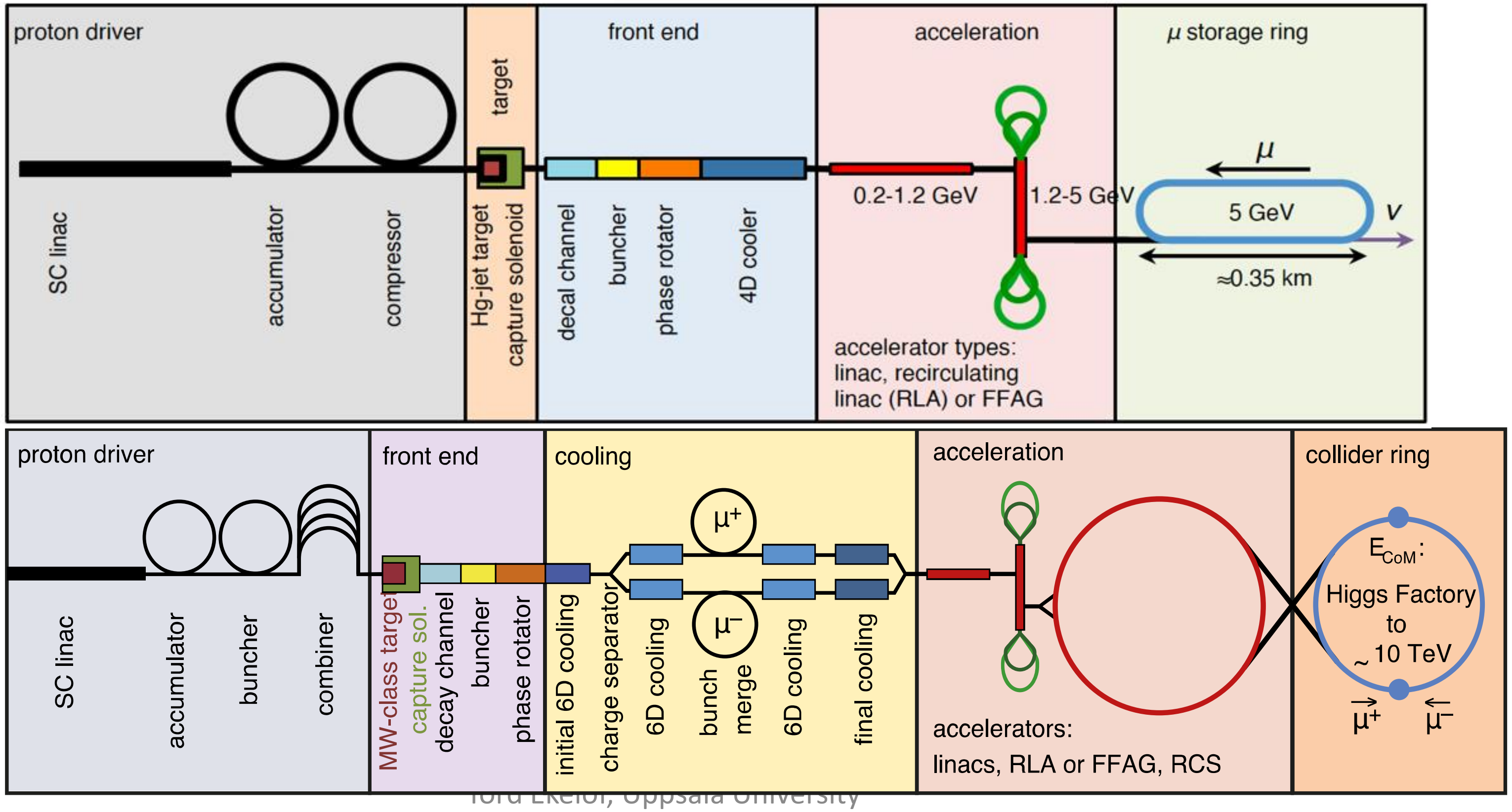
Super Beam ESSνSB



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

Neutrino Factory

Muon Collider ESSμSB



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

2012: Inception of the project

Nucl. Phys. B 885 (2014) 127

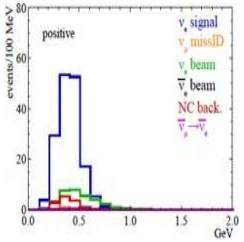
2016-2019: Beginning of COST Action EuroNuNet

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

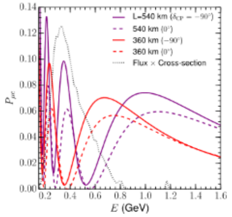
2022: End of ESSνSB Design Study, preliminary costing and CDR

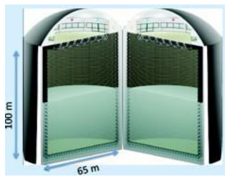
2023-2026: Continuation of Design Study, final costing and an TDR to ESFRI

2027-2028: Preconstruction Phase, International Agreements



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





2036-: Start of data taking

Summary

- The ESS neutron spallation source currently under construction can be the basis also for a world-unique neutrino facility, ESSνSB, which in a first conceptual design study has been proven to have very high physics performance and potential.
- With ESSνSB 5σ discovery potential for CP violation can be reached over 70% of the δ_{CP} range and δ_{CP} can be measured with an error less than 8° independently of its value.
- Complementary studies of this project will be made in a second Design Study 2023-2026 enabling in particular:
  - -Precise neutrino cross-section measurements
  - -Sterile neutrino searches
  - -SuperNova and relic neutrinos measurements, proton life-time…
- Potential for muon studies for Neutrino Factory and Muon Collider
- Application for EU support to ESSnuSB+ accepted 26/07/2022

Thank you