

# 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

# ESSnuSB Design Study ESSvSB January 2018 - March 2022

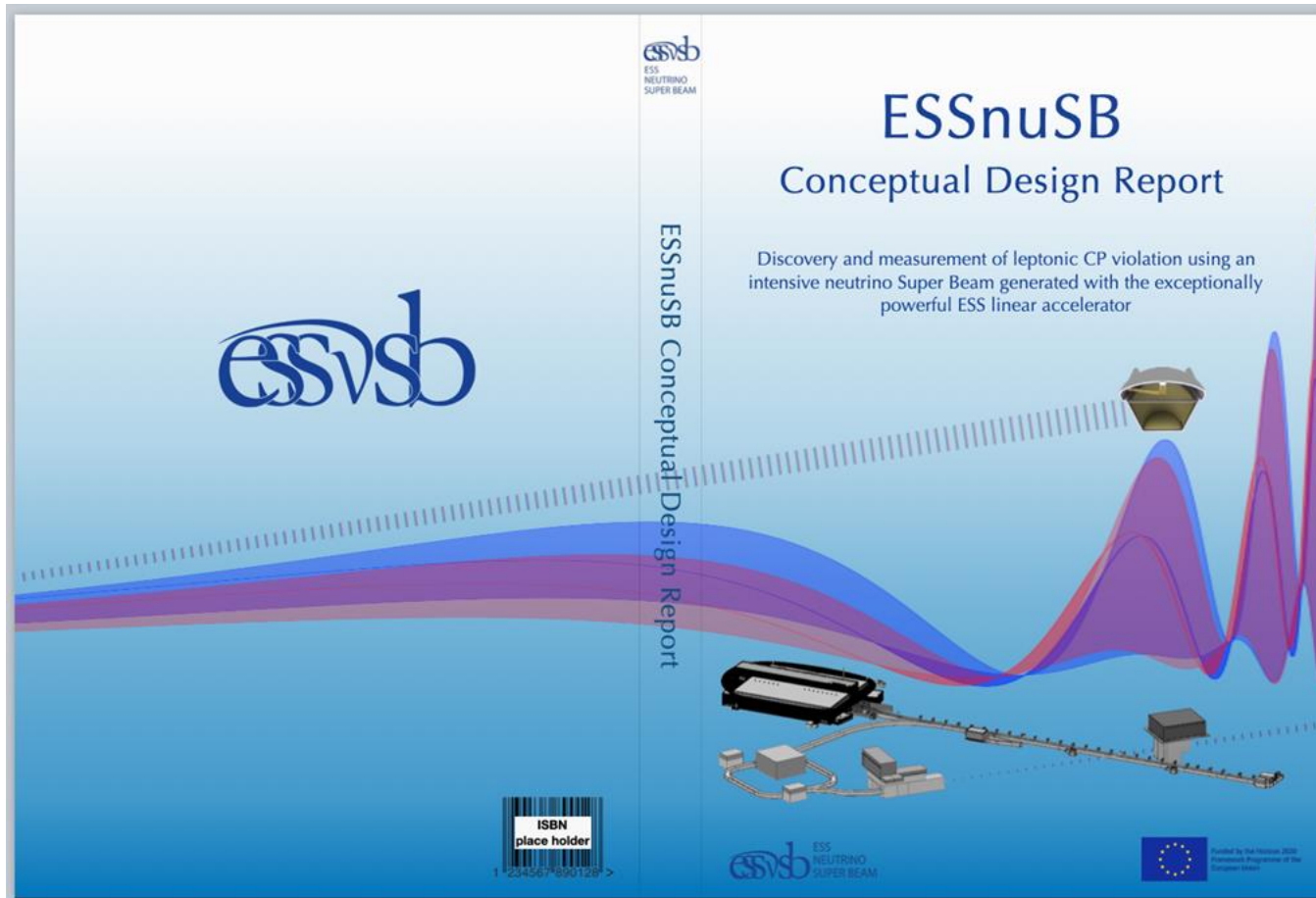
**Call:** H2020-INFRADEV-2017-1  
**Funding scheme:** RIA  
**Proposal number:** 777419  
**Proposal acronym:** ESSnuSB  
**Duration (months):** 48  
**Proposal title:** Feasibility Study for employing the uniquely powerful ESS linear accelerator to generate an intense neutrino beam for leptonic CP violation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

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 station
5. A far 540 kton water Cherenkov detector 360 km from the target station consisting of 2 large underground tanks filled each with 270'000 m<sup>3</sup> of water
6. Performance for  $\nu$  CP violation measurements

## **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

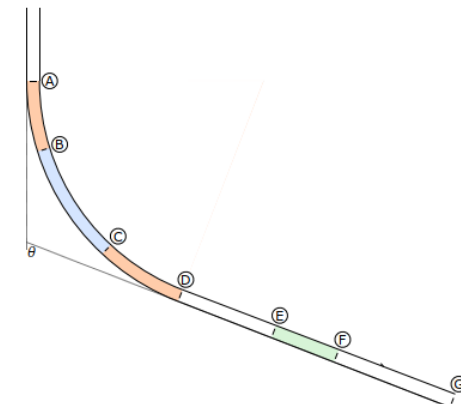
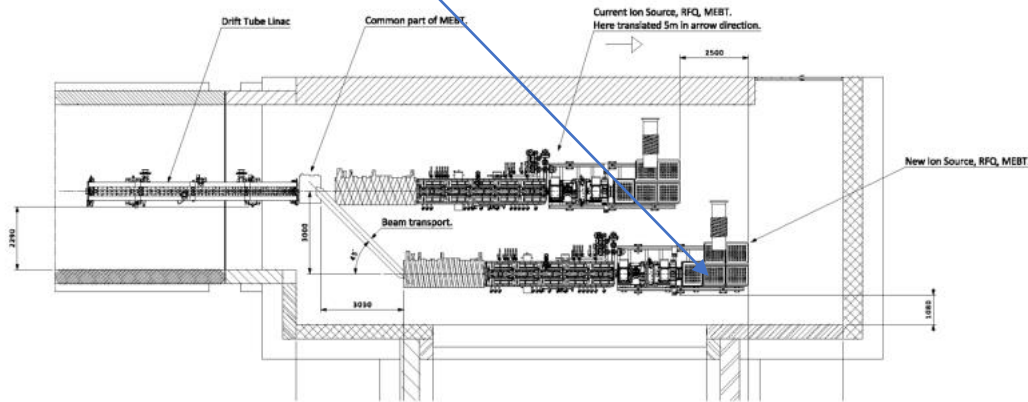
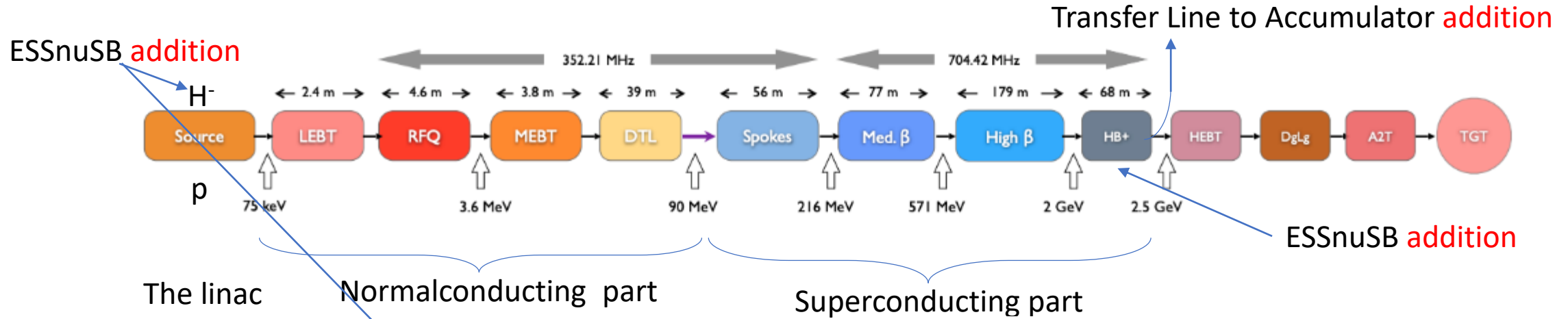
<https://arxiv.org/abs/2203.08803>

ESSnuSB presentation at RICH2022

Tord Ekelöf, Uppsala University

# 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

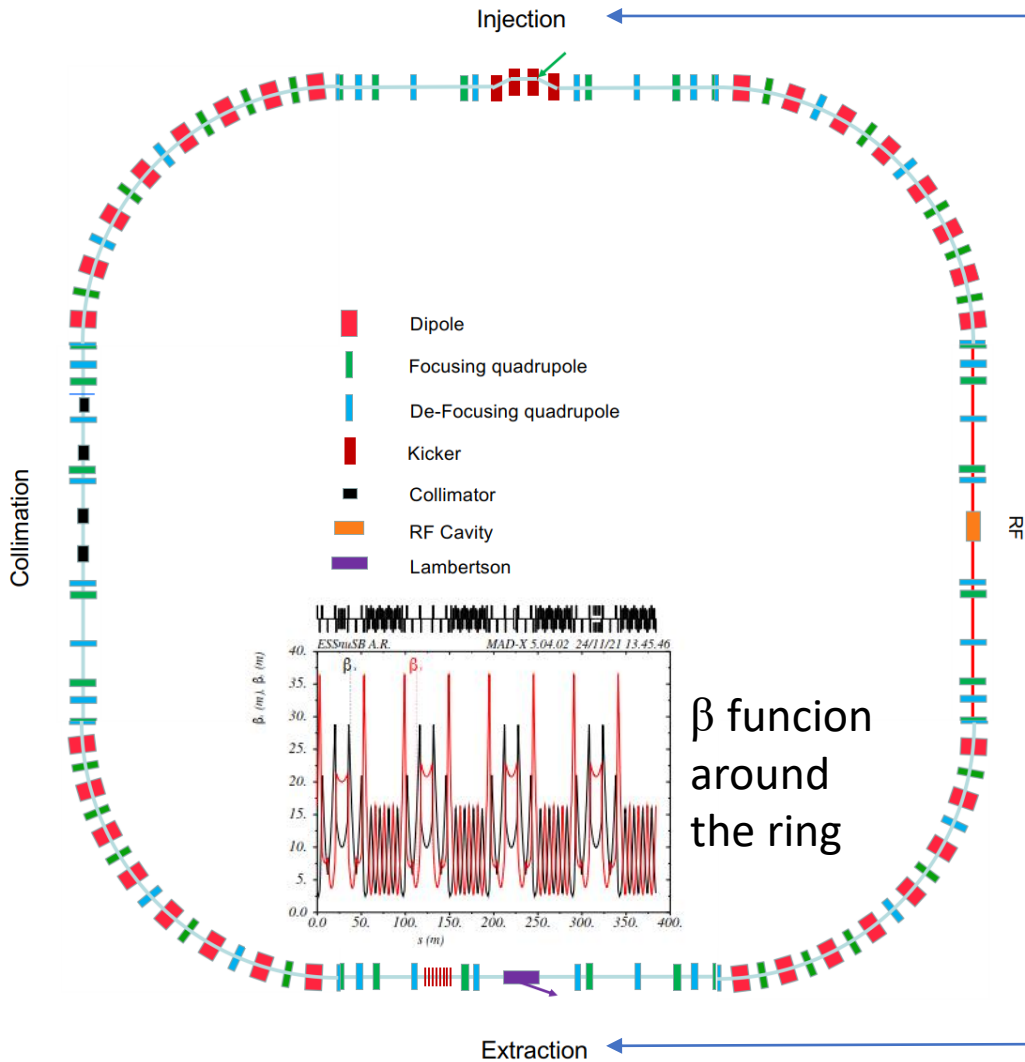


(a)	Cell with horizontally bending and vertically down-bending dipole magnets
(b)	Cell with horizontally bending dipole magnets only
(c)	Cell with vertically up-bending dipole magnets
	Cell with no dipole magnets

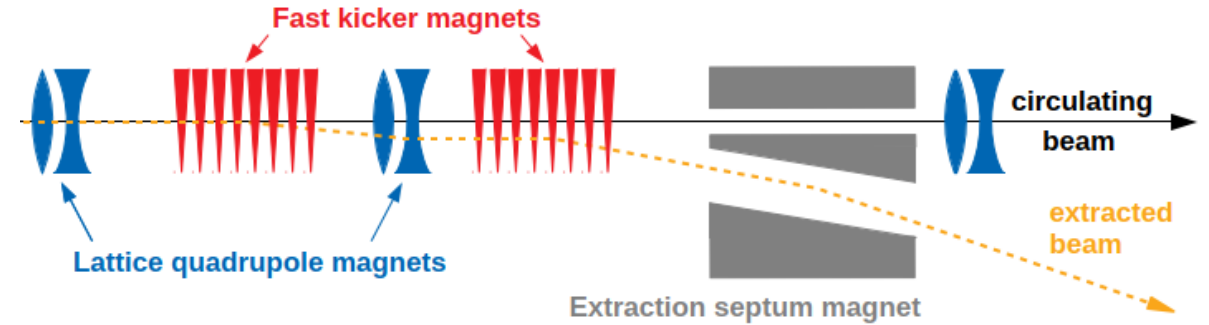
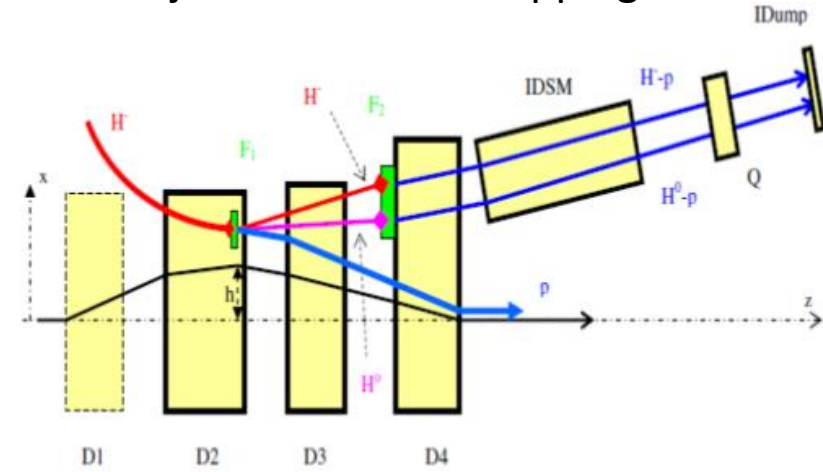
The merging of the H<sup>+</sup> and the H<sup>-</sup> beams in the MEBT

Transfer Line with bending limited by H<sup>-</sup> Lorenz stripping

# The Accmulator ring

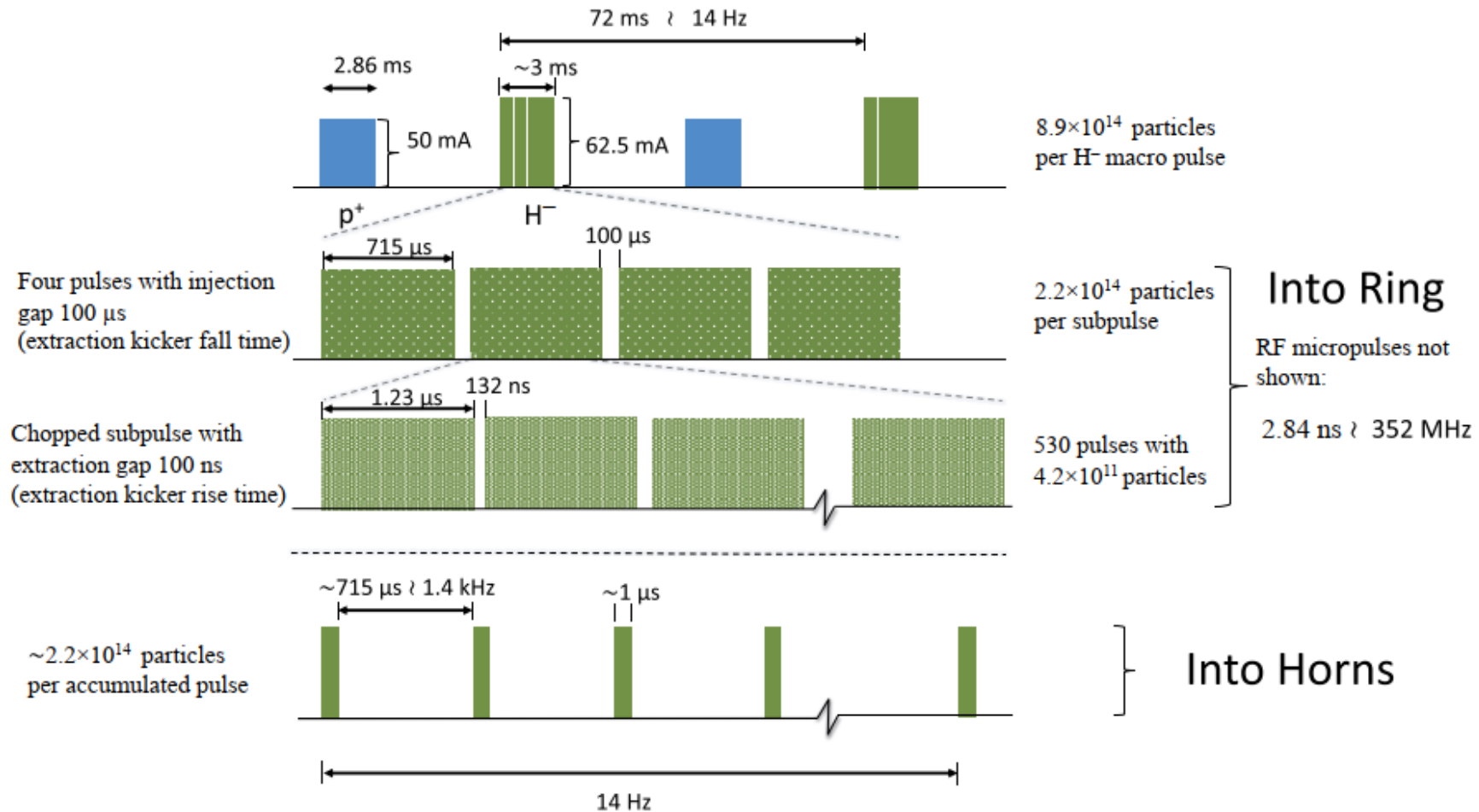


Injection with H- stripping



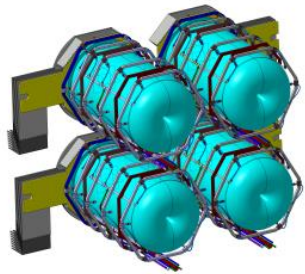
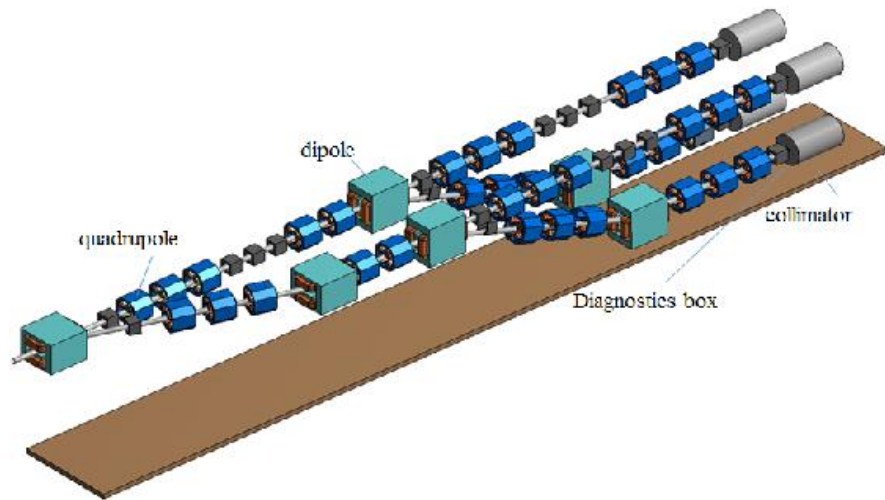
Extraction

# Detailed schematic of the ESSvSB pulsing scheme

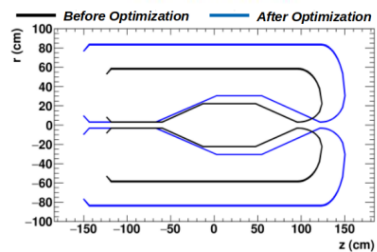




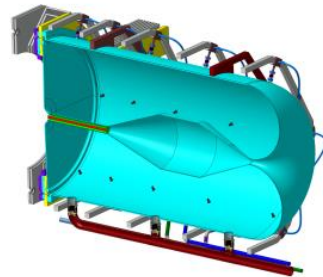
# Beam switch-yard and the target station



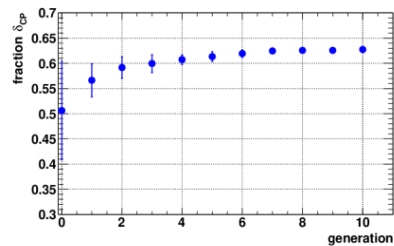
(a) The four-horn system.



(a) Evolution of the horn profile.



(b) Transverse view of one horn.



(b) Genetic algorithm convergence throughout the iterative process.

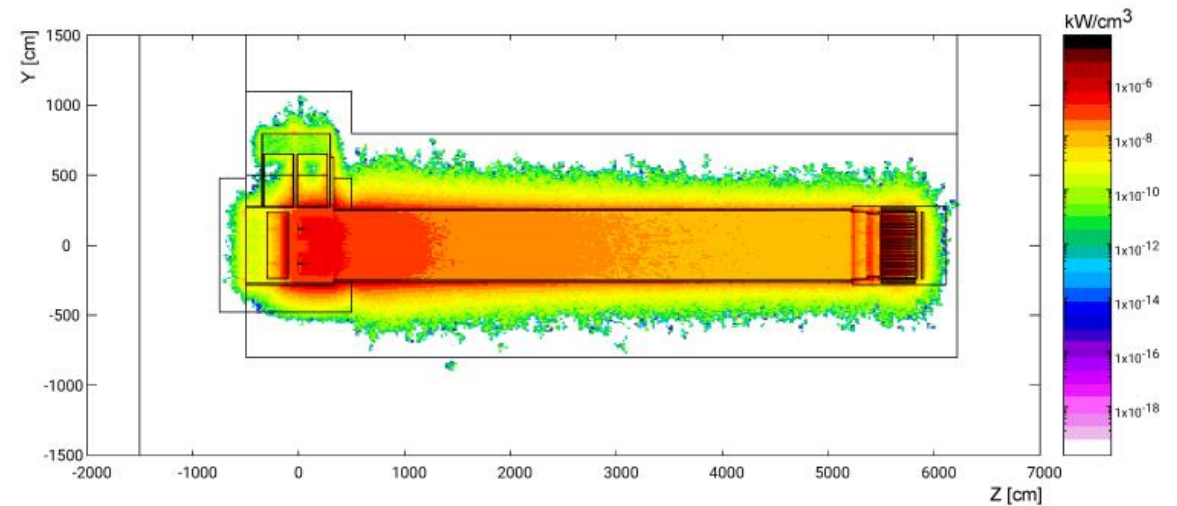
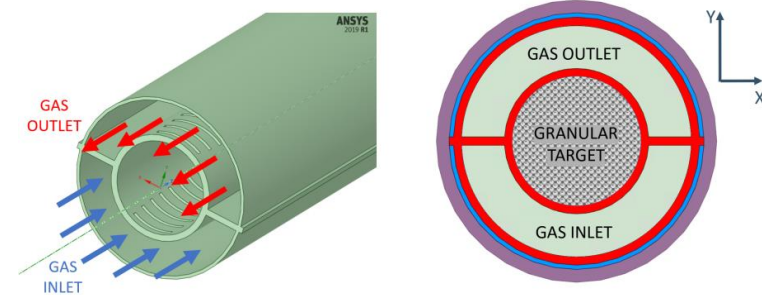
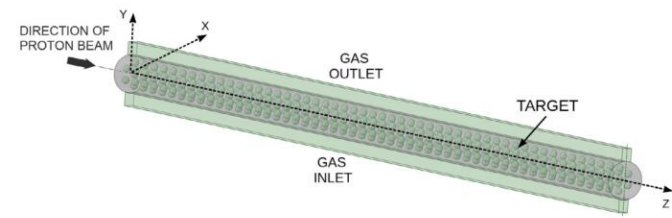
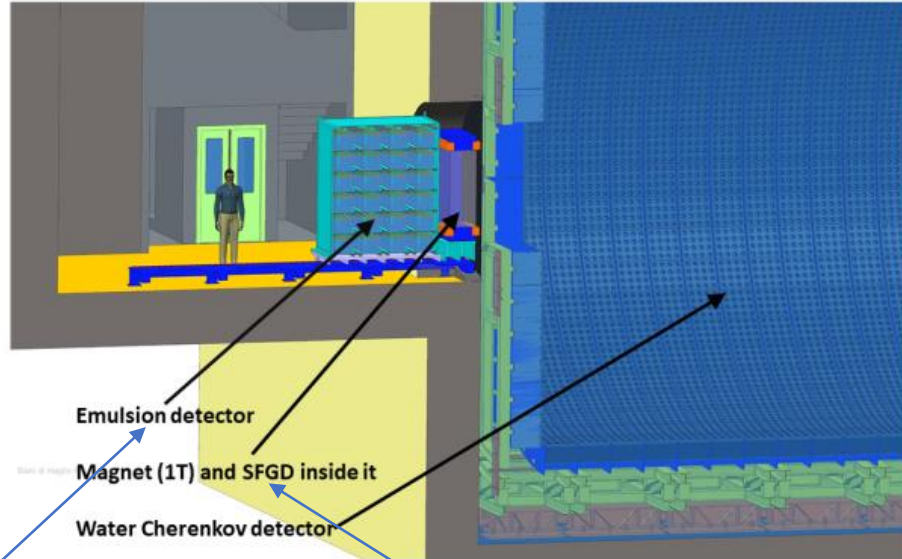
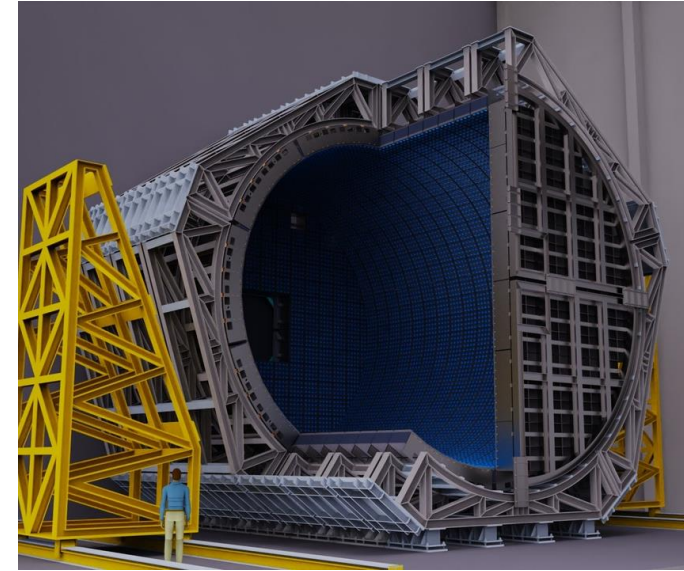


Figure 5.46: Energy deposition distribution in the target station facility.

# The Near Detector



**Near Detector underground station**



**A 1 kton water Cherenkov detector**

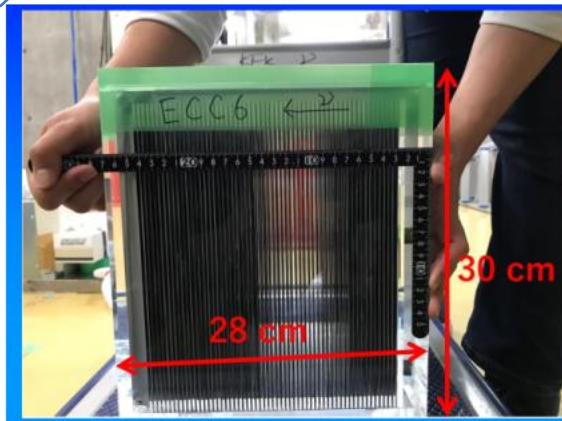
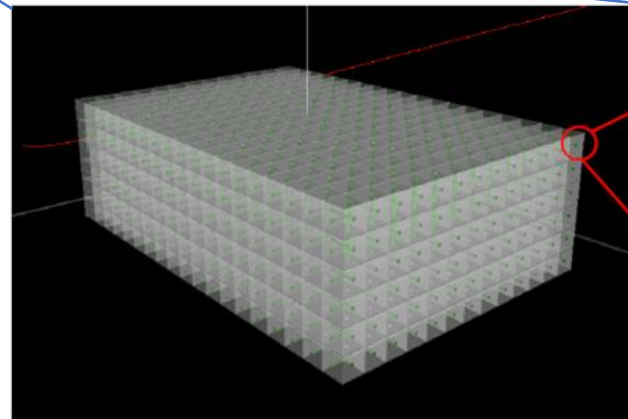
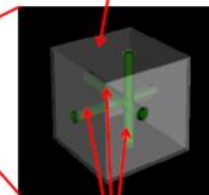


Figure 6.42: A photograph of the NINJA ECC element using water as target.

**NINJA emulsion detector**

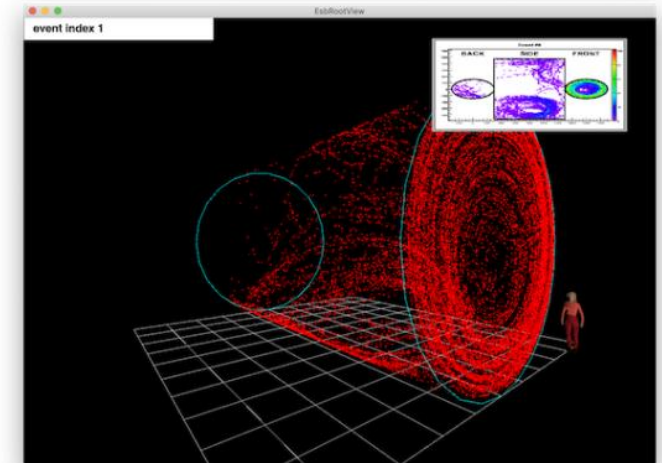


**Scintillation cube**



**Optic fibers**

**The super Fine-Grained Detector sFDG**



**A muon Cherenkov ring**



# The Far Detector

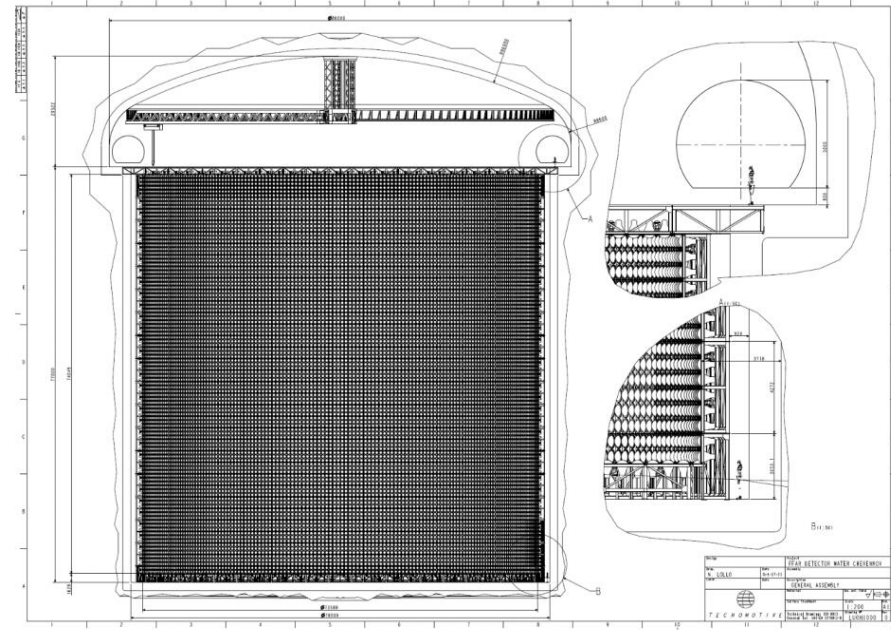
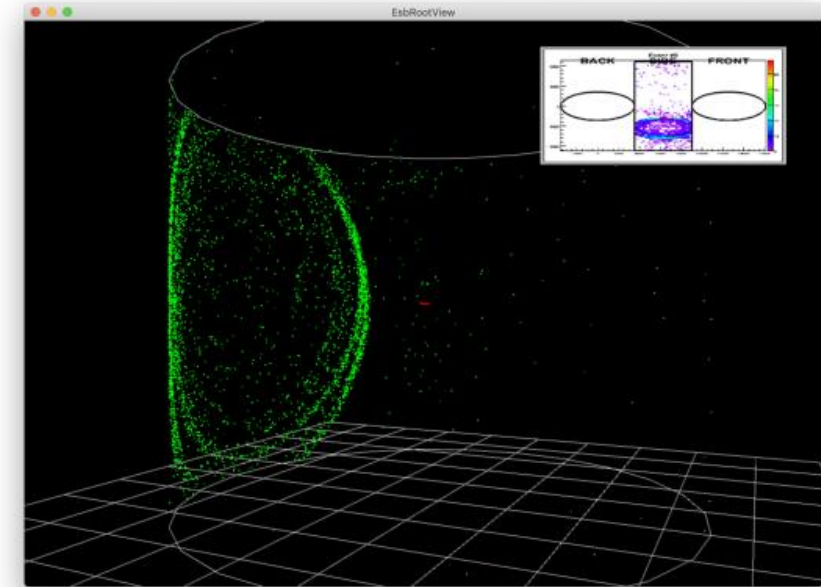


Figure 6.48: Overall view of a single far-detector tank with indicated dimensions.



## Two 270 kton fiducial volume water Cherenkov detector

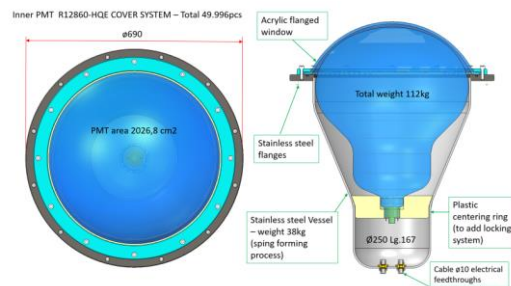
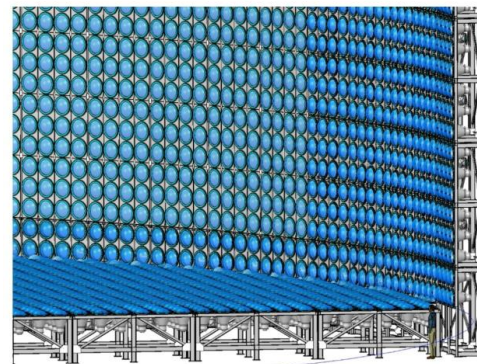
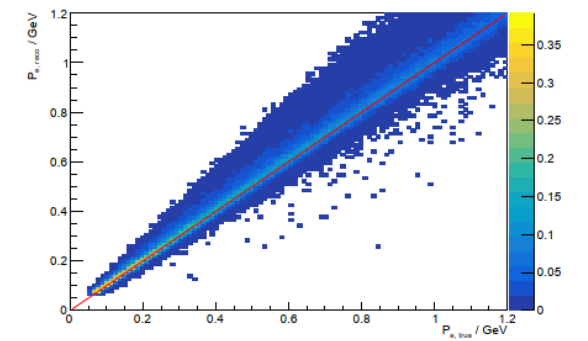


Figure 6.50: A schematic view of an inward-facing 20 inch PMT embedded in a protective cover.



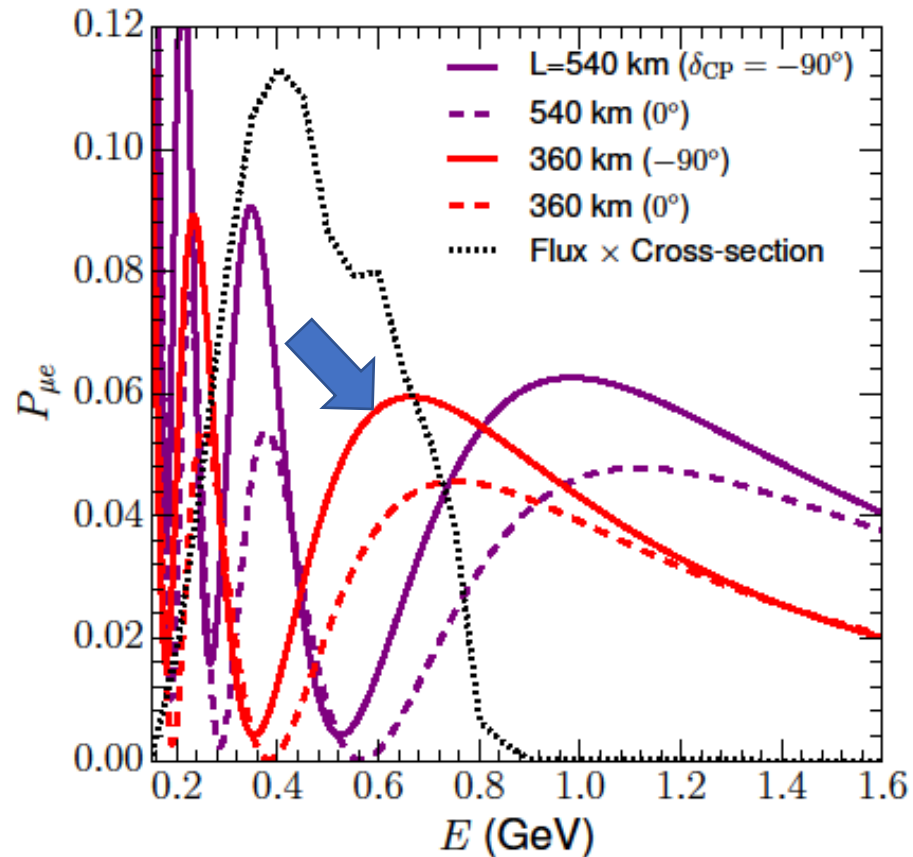
## A muon Cherenkov ring



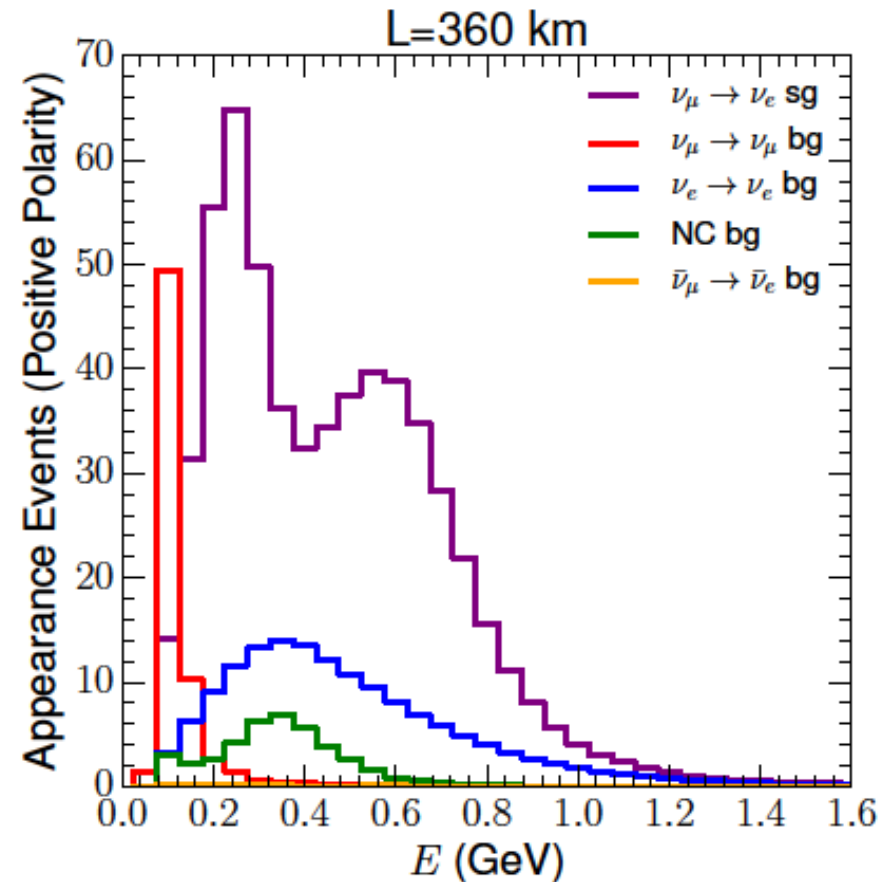
(a) Electrons

For Cherenkov images in the Far Detector see <https://drive.google.com/drive/folders/1DidkJRA05GJtm0vFSqpfpCTAooNWA22>

# ESSnuSB at the second neutrino oscillation maximum

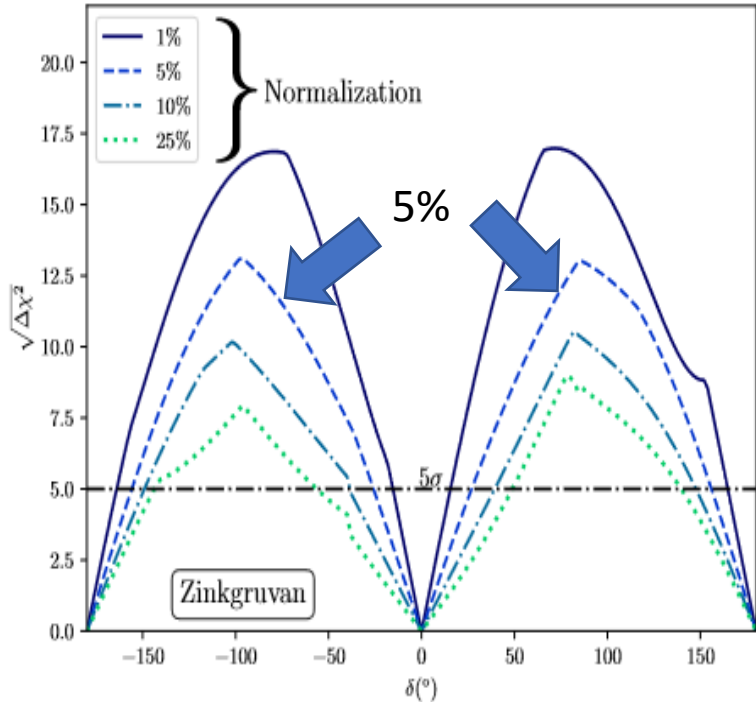


Coverage of the second oscillation maximum

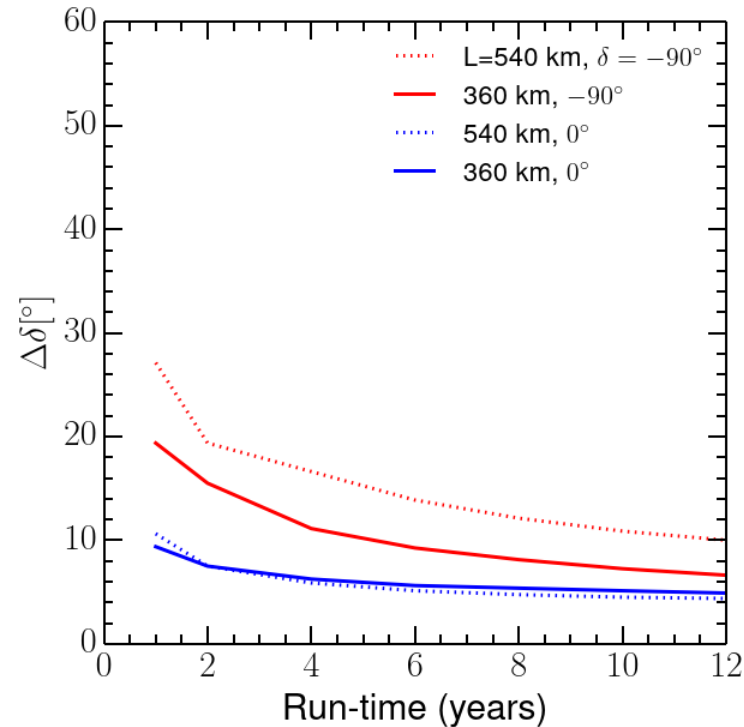


Signal ( $\nu_e$ ) and background energy distributions

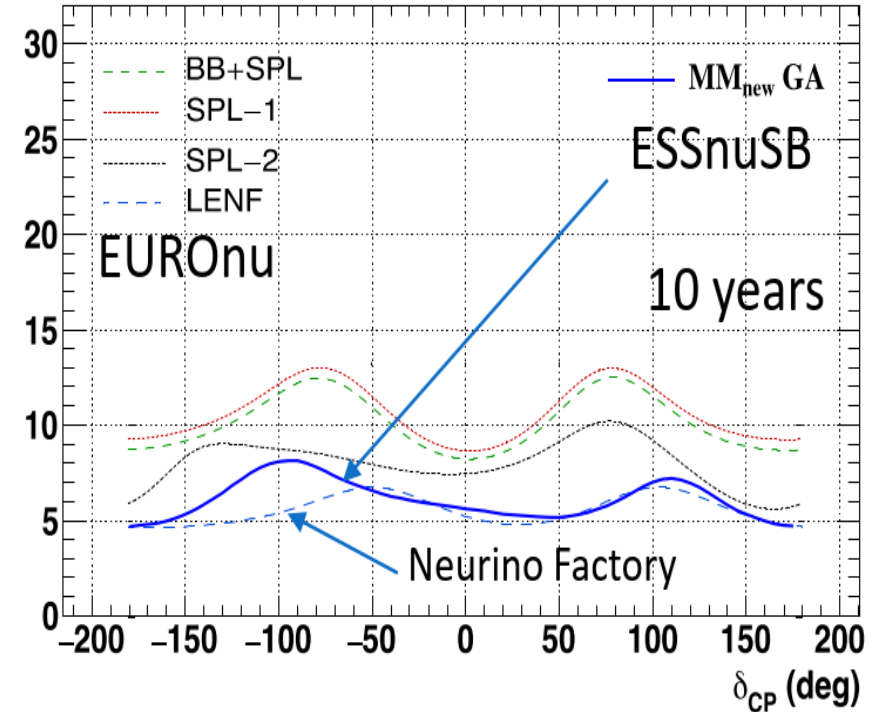
# Performance for CPV discovery and $\delta_{CP}$ measurement



Discovery potential vs  $\delta_{CP}$  angle after 10 years with 5% normalization error providing 70% coverage of all  $\delta_{CP}$  values



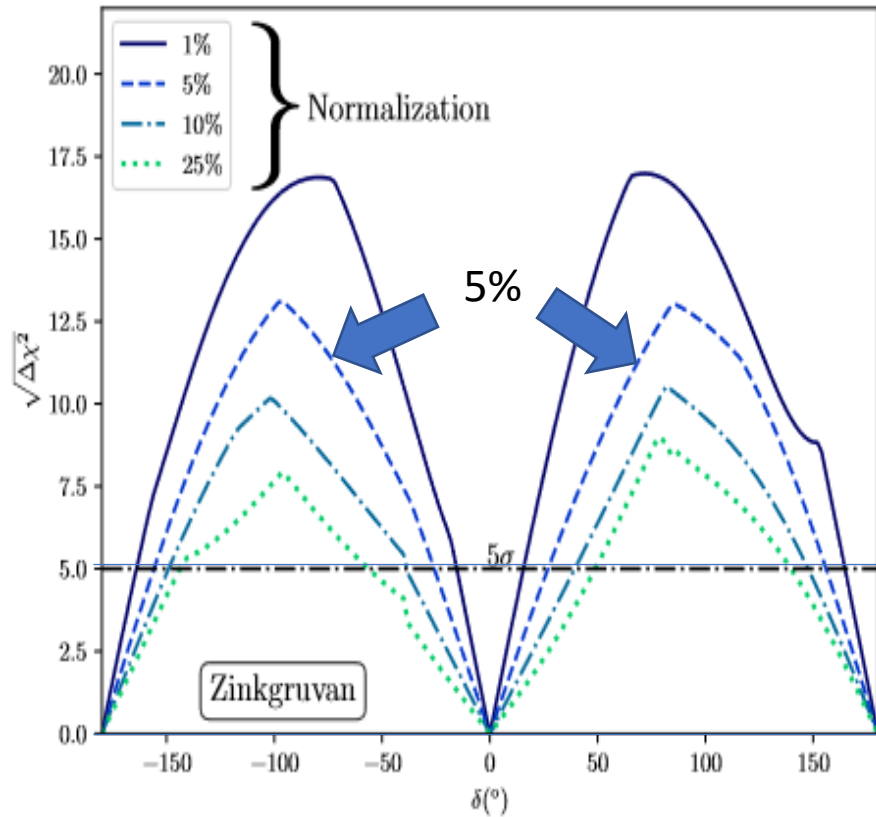
Error in  $\delta_{CP}$  angle vs run time with 5% normalization error



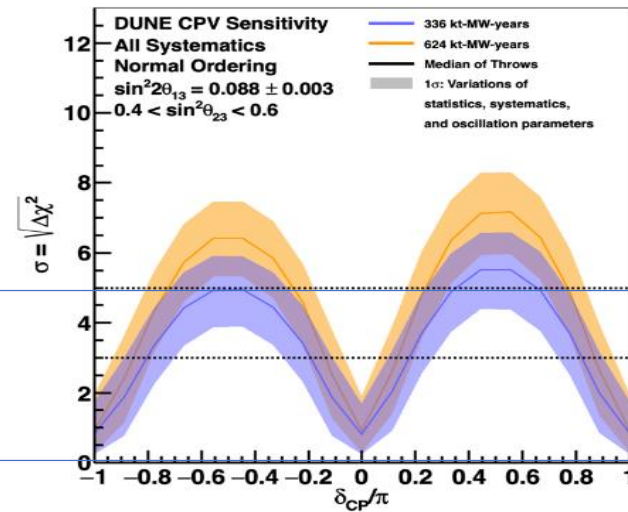
Error in  $\delta_{CP}$  angle vs  $\delta_{CP}$  angle after 10 years with 5% normalization error



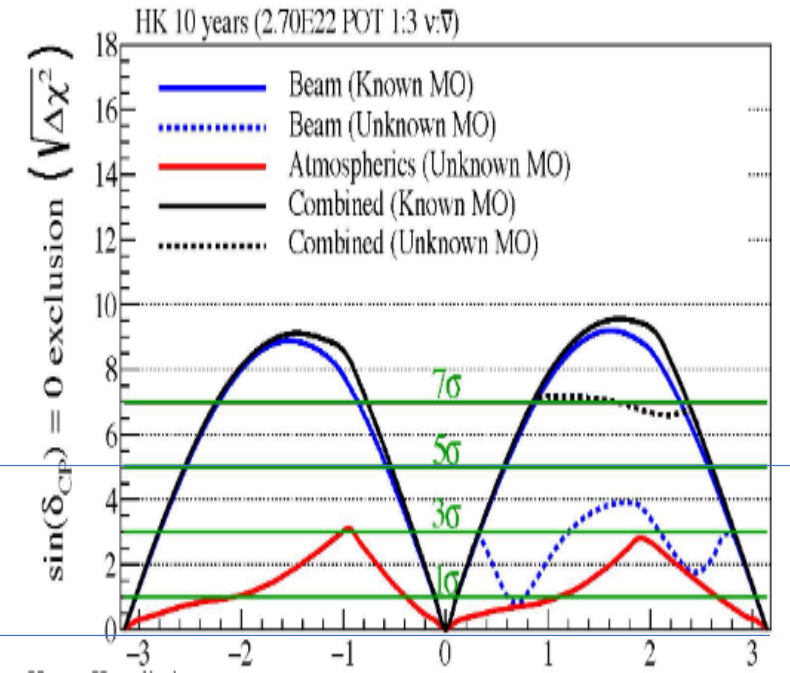
# ESSnuSB in the international context – CPV discovery



ESSnuSB March 2022 with 5% normalization error



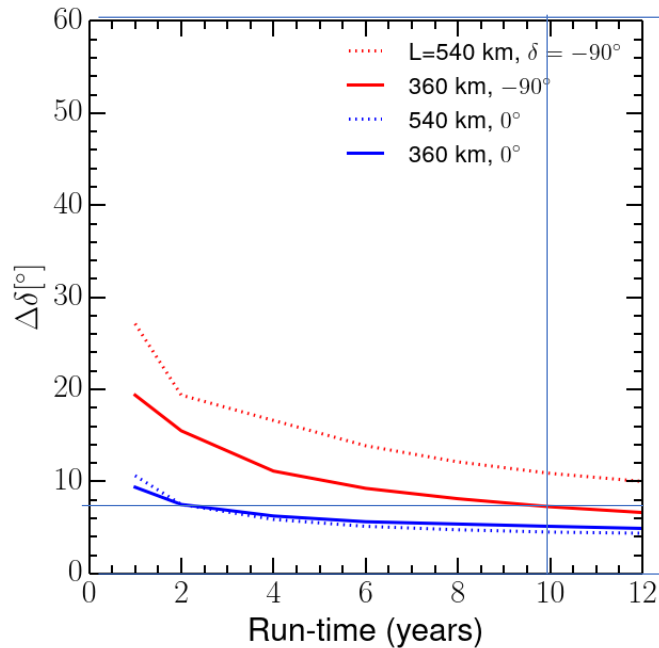
DUNE Snowmass March 2022



HyperKamokande Snowmass March 2022

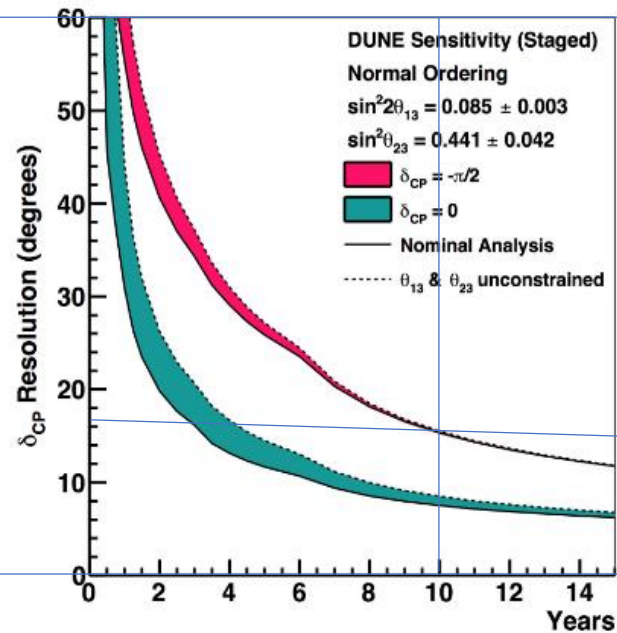


# ESSnuSB in the international context – CPV resolution



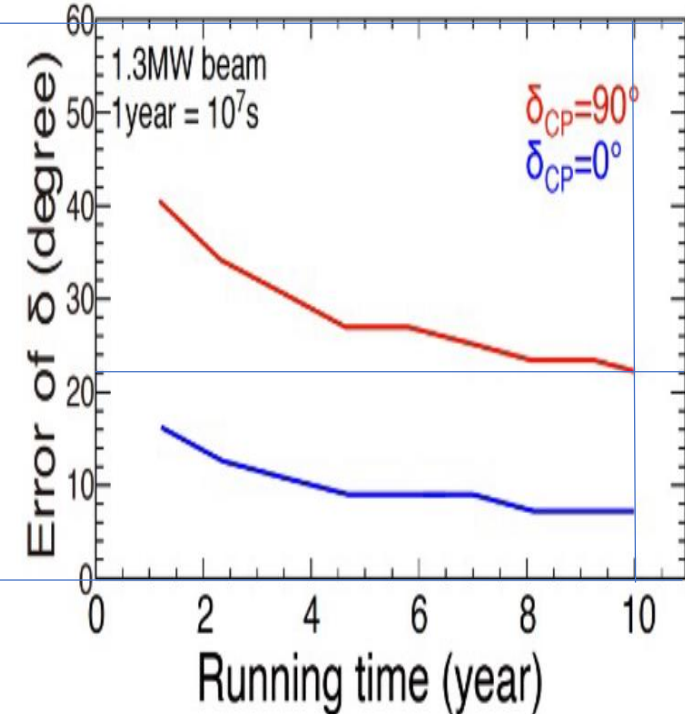
ESSnuSB March 2022 with 5% normalization error

2022-09-13



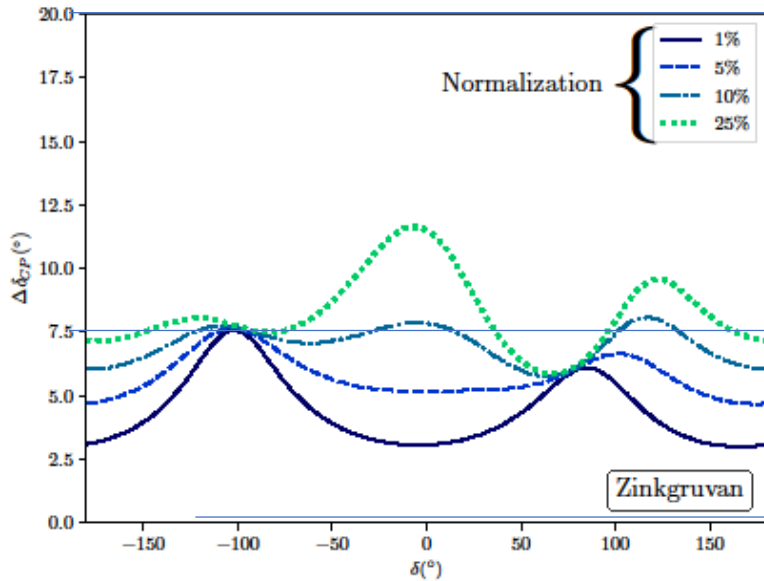
DUNE Snomass March 2022

ESSnuSB presentation at RICH2022  
Tord Ekelöf, Uppsala University



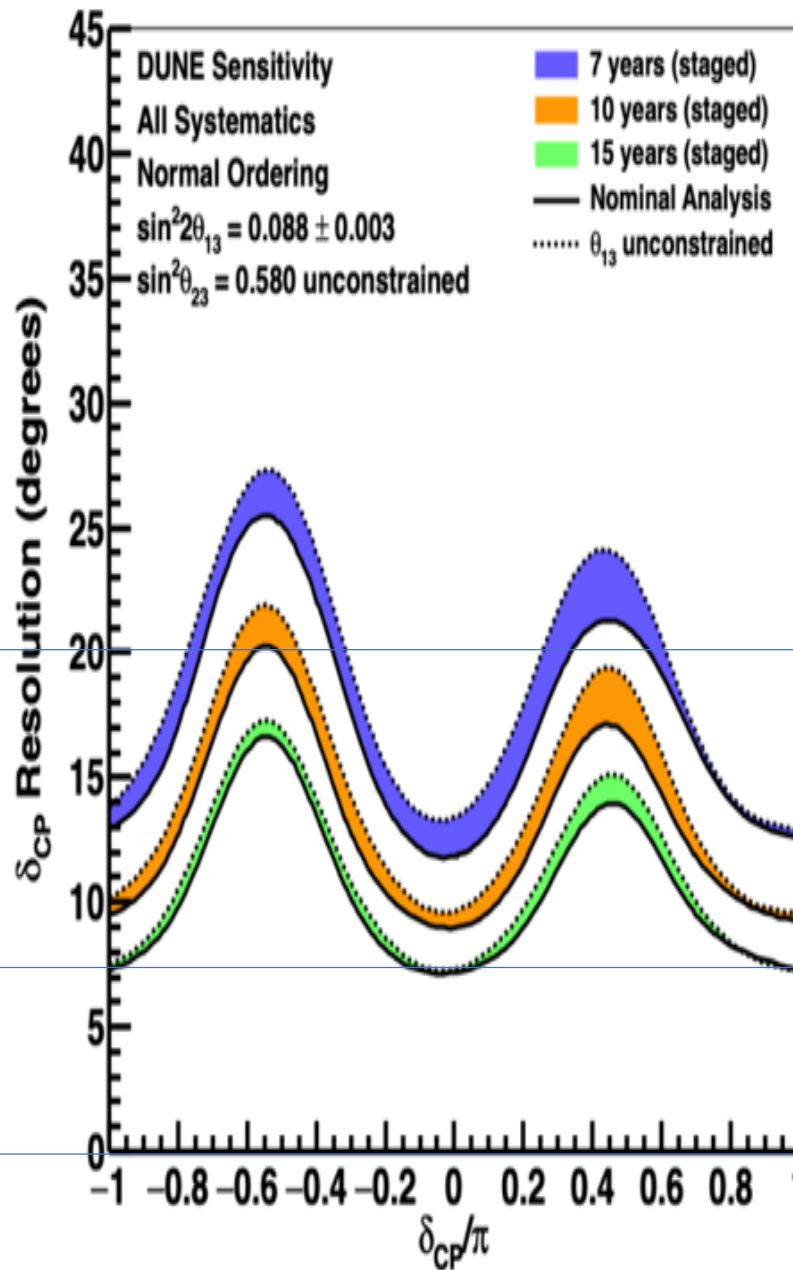
HyperKamokandeSnowmass March 2022

# ESSnuSB in the international context – precision in $\delta_{CP}$



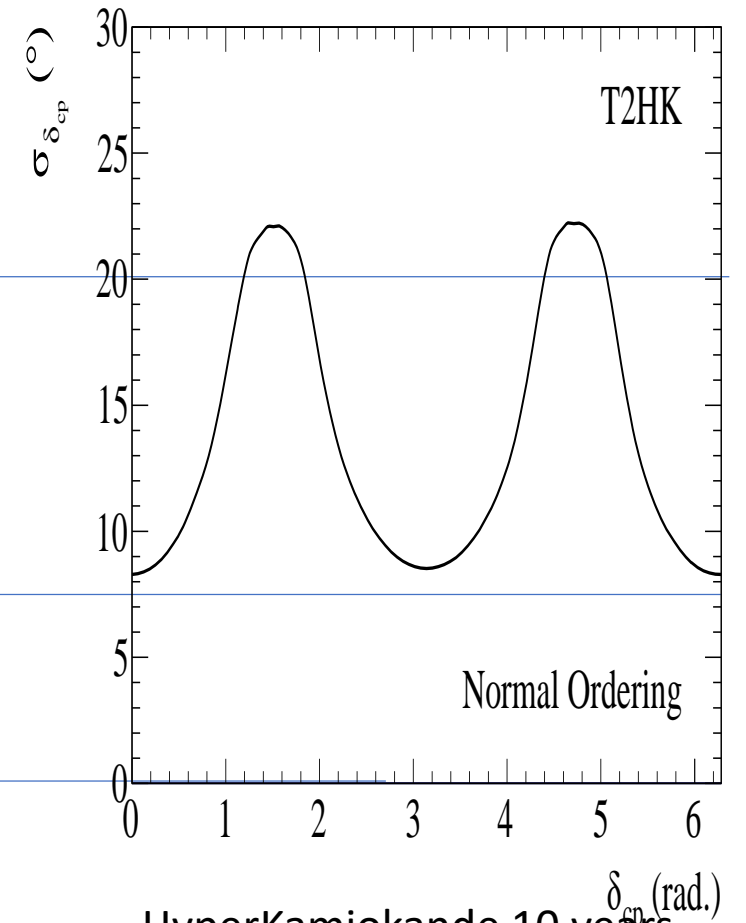
ESSnuSB 10 years

2022-09-13



DUNE 10 years yellow curve

ESSnuSB presentation at RICH2022  
Tord Ekelöf, Uppsala University



HyperKamiokande 10 years

# ESSnuSB Cost Estimate

Total Cost 1'382 M€

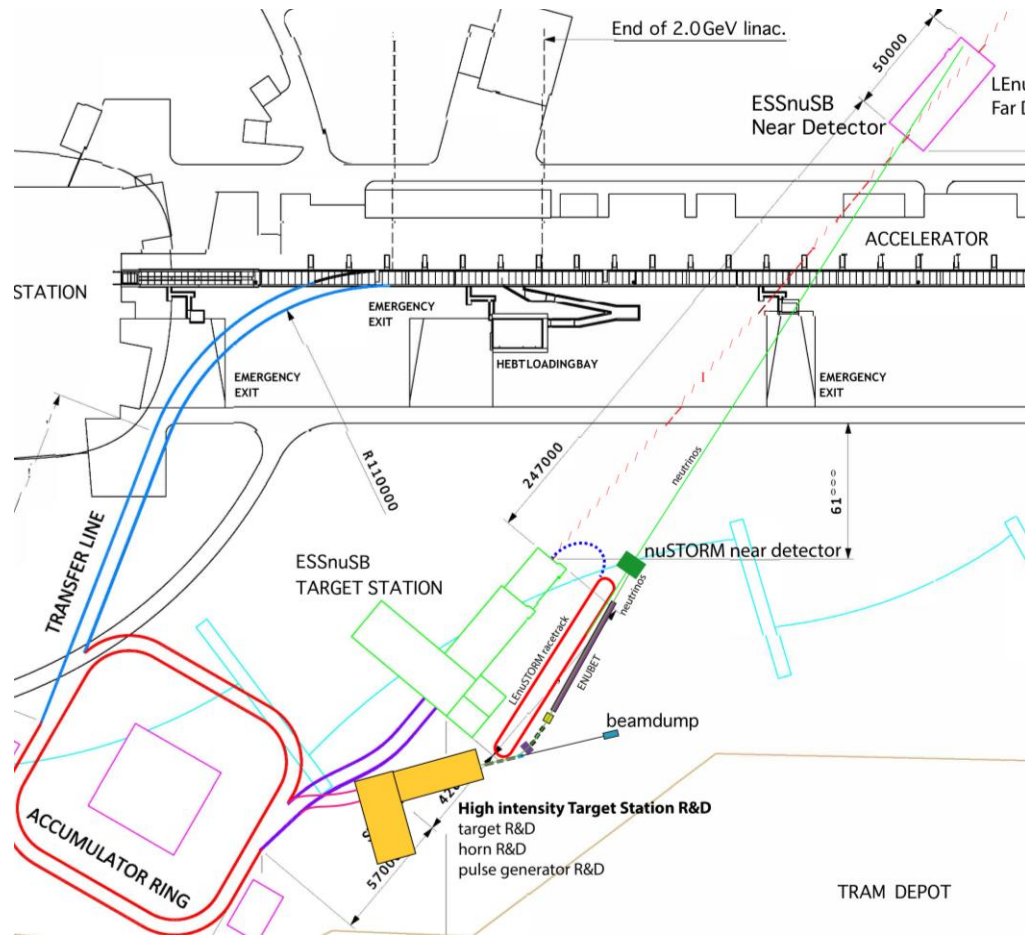
The ca 75'000 20 inch PMTs and the excavation of the cavern for the two Far Detectors represents 67% of the total cost.

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 (%)
<b>Linac Upgrade</b>	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%
<b>Total</b>		<b>132.60</b>	<b>9.59%</b>
<b>Accumulator</b>	<b>Item</b>	<b>Cost (M€)</b>	<b>Cost (%)</b>
	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%
	<b>Total</b>	<b>165.00</b>	<b>11.94%</b>
<b>Target Station</b>	<b>Item</b>	<b>Cost (M€)</b>	<b>Cost (%)</b>
	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%
<b>Total</b>	<b>131.42</b>	<b>9.51%</b>	
<b>Detectors</b>	<b>Item</b>	<b>Cost (M€)</b>	<b>Cost (%)</b>
	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%
<b>Total</b>	<b>953.21</b>	<b>68.93%</b>	
<b>Grand Total</b>		<b>1382.23</b>	<b>100.00%</b>

# Continuation of design studies 2023-2026

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



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 ESSvSB 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 ESSvSB accelerator complex

Cross-section measurements with:

- Low Energy nuSTORM:  $\pi \rightarrow \mu \rightarrow e + \nu_{\mu} + \nu_e$
- Low Energy ENUBET:  $\pi \rightarrow \mu + \nu$

ESSnuSB presentation at RICH2022



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

### Acronym of Proposal: ESSvSB+

Participant no.	Participant organisation name	Part. short name	Country
1 (Coordinator)	Centre National de la Recherche Scientifique	CNRS	France
2	Université de Strasbourg	UNISTRA <sup>1</sup>	France
3	Rudjer Boskovic Institute	RBI	Croatia
4	Tokai National Higher Education and Research System, National University Corporation	NU <sup>2</sup>	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"	NCSR	Greece
12	Aristotelio Panepistimio Thessalonikis	AUTH <sup>1</sup>	Greece
13	Sofia University St. Kliment Ohridski	UniSofia	Bulgaria
14	Lulea Tekniska Universitet	LTU	Sweden
15	European Organisation for Nuclear Research	CERN	IEIO <sup>3</sup>
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 <sup>1</sup>	Italy
20	Consorcio para la construccion, equipamiento y explotacion de la sede espanola de la fuente Europea de neutrones por espalacion	ESSB	Spain

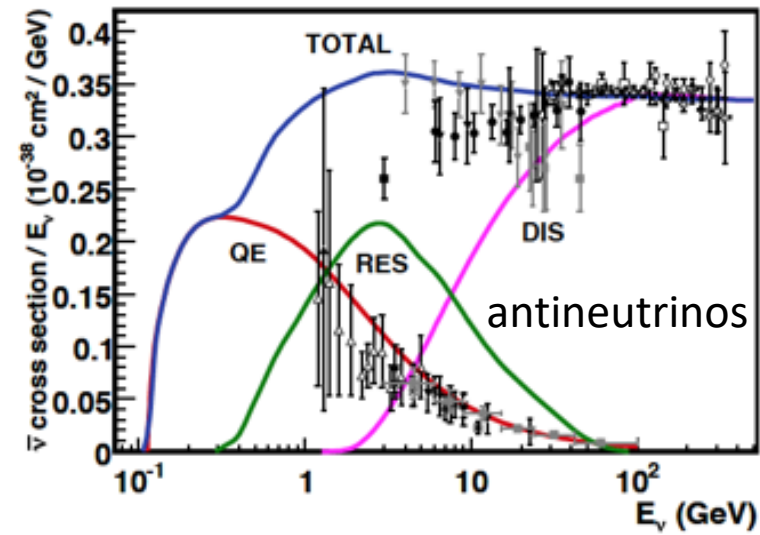
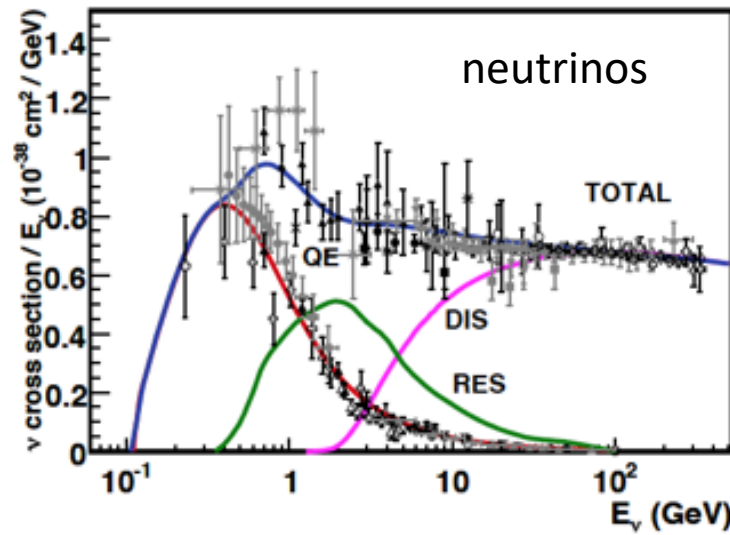
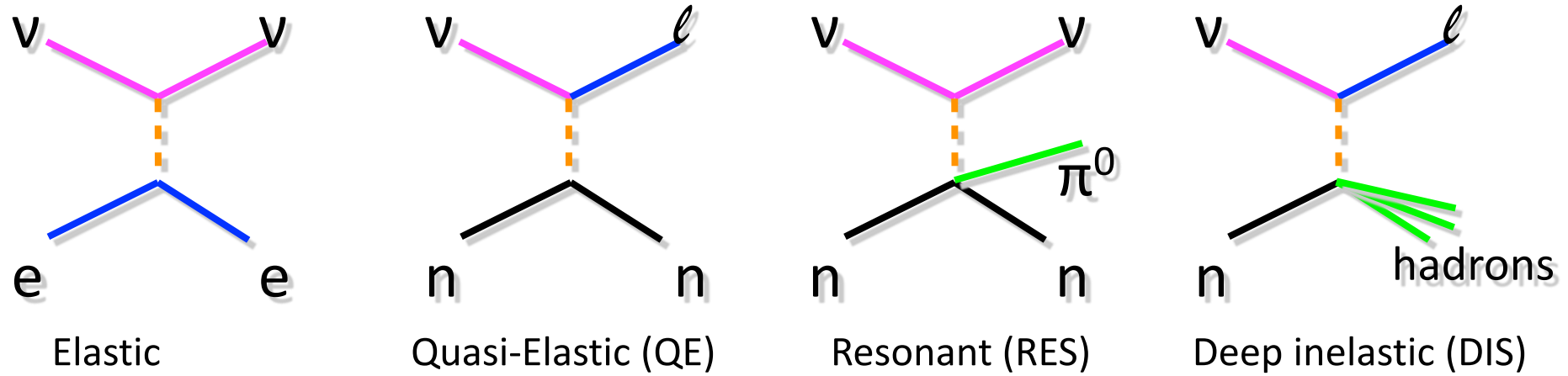
<sup>1</sup> Affiliated Partner

<sup>2</sup> Associated Institute

<sup>3</sup> International European Interest Organisation

**Excellent supporting letter from the ESS director**

# ESSvSB+ main motivation: neutrino cross-section measurements



Missing measurements at the ESSvSB region: below 500 MeV

# The ESSvSB+ Work Packages

## WP2 Engineering and Infrastructures

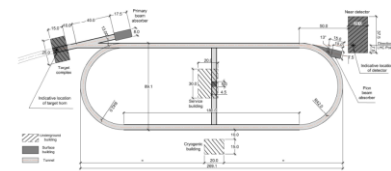
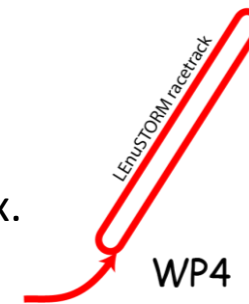
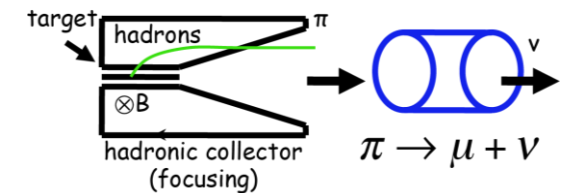
Civil engineering studies for the proposed installations at the ESS site and the far Detector Zinkgruvan site, including licensing, safety, radiation protection

## 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.

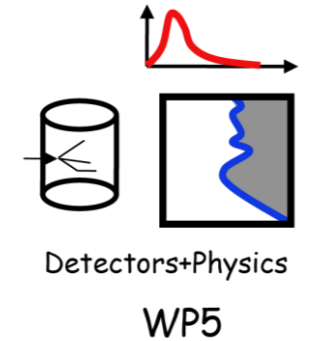


"High Energy" nuSTORM

# The ESSvSB+ Work Packages

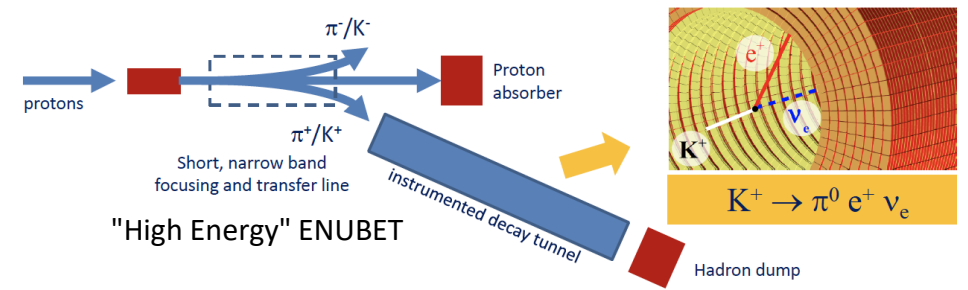
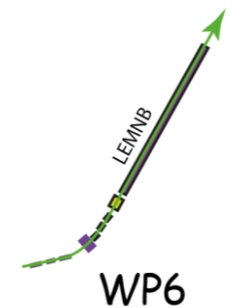
## WP5 Detector and physics performance

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 ESSvSB far detector doped with Gadolinium for non-beam related physics (relic neutrinos, proton life-time) will be studied.



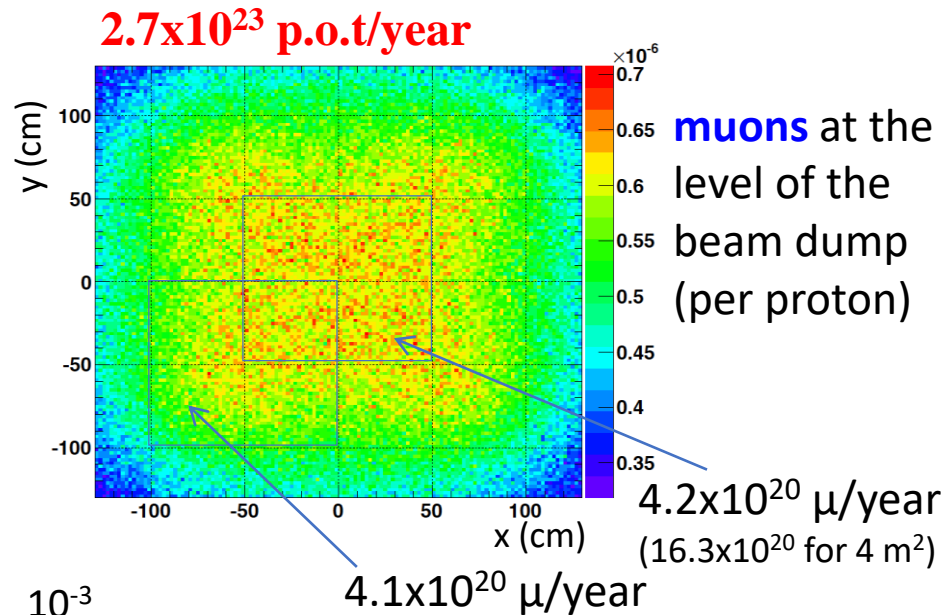
## WP6 Low Energy Monitored Neutrino BeamNB

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.

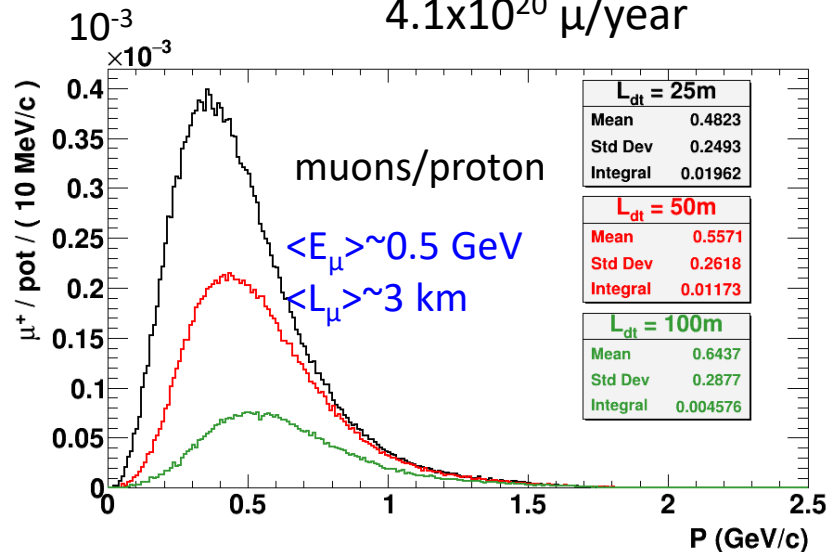




# For each muon-neutrino produced there is also a muon....



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



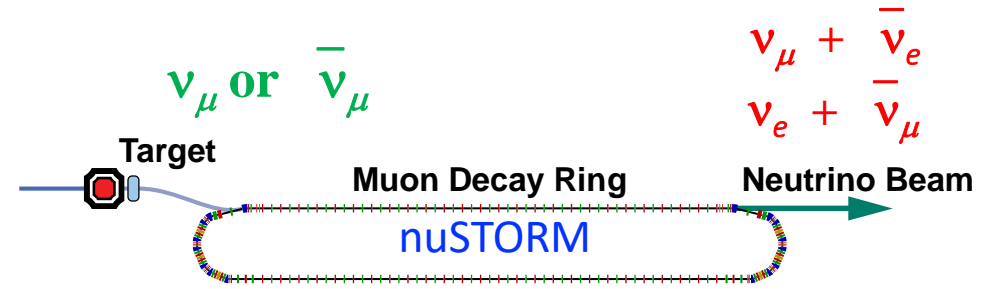
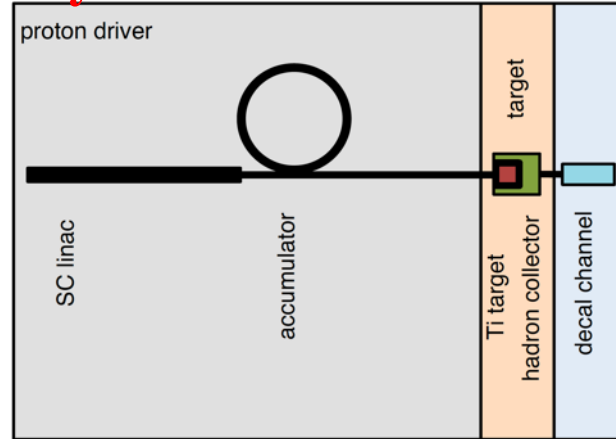
- input beam for future 6D  $\mu$  cooling experiments (for muon collider),
- low energy nuSTORM,
- Neutrino Factory,
- **Muon Collider.**

# ESSvSB and (R&D) synergies

$2.7 \times 10^{23}$  p.o.t./year

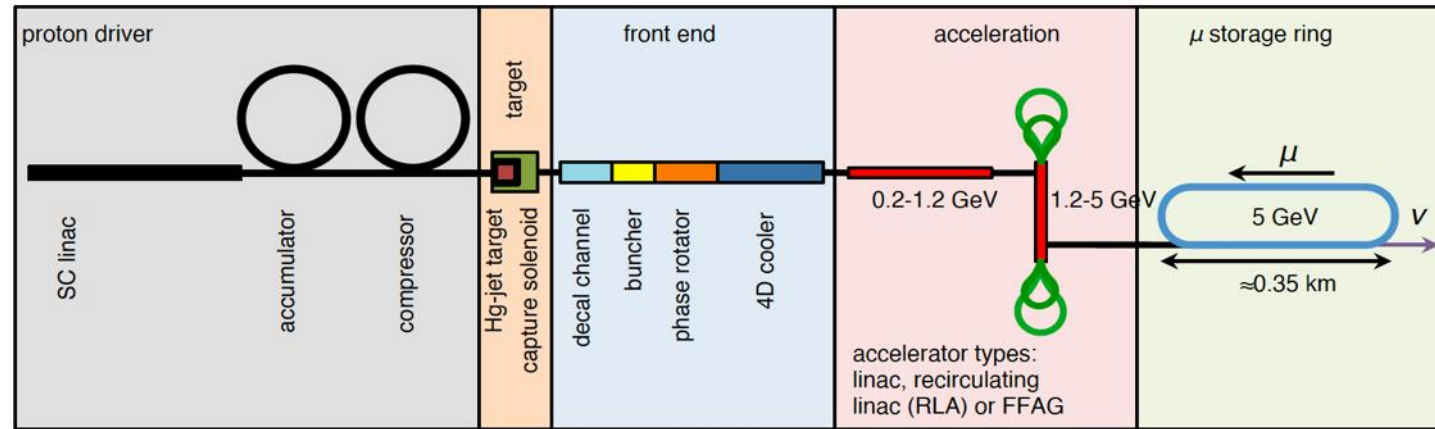
Super Beam

ESSvSB



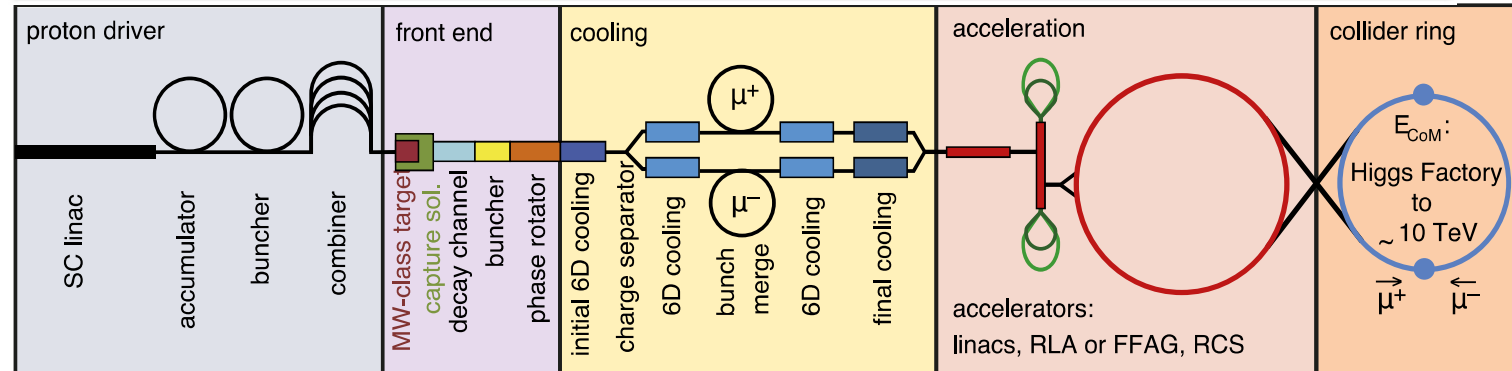
+Decay At Rest and Coherent scat.  
(with short pulses)

Neutrino Factory



Muon Collider

ESS $\mu$ SB



# Schedule for a 2<sup>nd</sup> 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 ESSnuSB  
Design  
Study (EU-  
H2020)



**2022:** End of  
ESSnuSB  
Design Study,  
preliminary  
costing and  
CDR



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

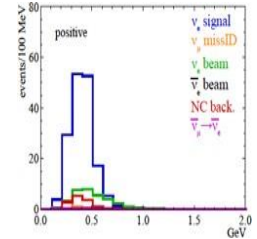
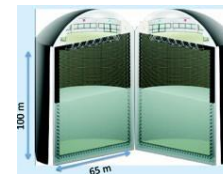


**2027-2028:**  
Preconstructi  
on Phase,  
International  
Agreements

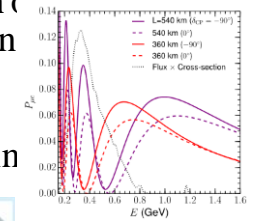


**2029-2035:**

Construction o  
f the facility an  
detectors,  
including  
commissionin



**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, ESSvSB, which in a first conceptual design study has been proven to have very high physics performance and potential.
- With ESSvSB  $5\sigma$  discovery potential for CP violation can be reached over 70% of the  $\delta_{CP}$  range and  $\delta_{CP}$  can be measured with an error less than  $8^\circ$  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