ESS Neutrino Super Beam Plus

Co-funded by the European Union

The ESSνSB+ project

E. Baussan on behalf of ESSνSB+ Collaboration
IPHC-IN2P3/CNRS Strasbourg

34th Rencontre de Blois
May 14-19, 2023 Blois Loire Valley France

Neutrino oscillation : sensitivity on CP

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$$P_{\nu_\mu\to\nu_e(\bar\nu_\mu\to\bar\nu_e)} = s^2_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{\tilde B_\mp}\right)^2\sin^2\left(\frac{\tilde B_\mp L}{2}\right)$$ atmospheric

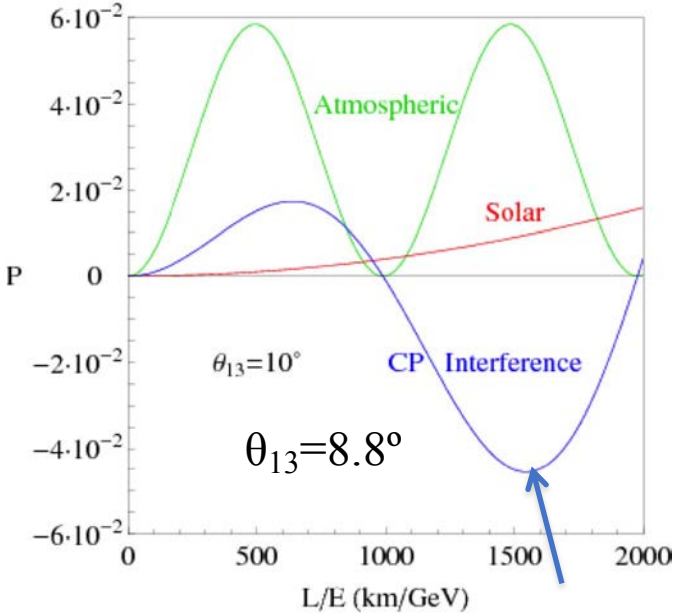
$$+c^2_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\left(\frac{AL}{2}\right)$$ solar

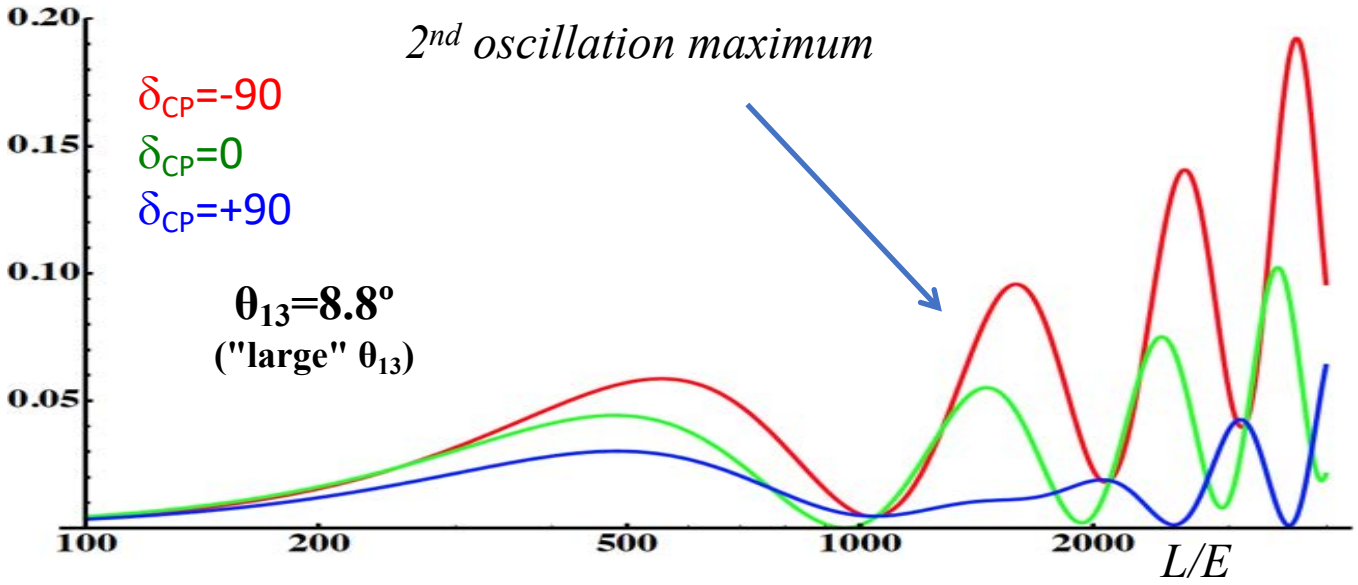
$$+\tilde J\,\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{\tilde B_\mp}\sin\left(\frac{AL}{2}\right)\sin\left(\frac{\tilde B_\mp L}{2}\right)\cos\left(\pm\delta_{CP}-\frac{\Delta_{13}L}{2}\right)$$ CP interference

$$\tilde J \equiv c_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13},\ \Delta_{ij}\equiv\frac{\Delta m^2_{ij}}{2E_\nu},\ \tilde B_\mp \equiv |A\mp\Delta_{13}|,\ A=\sqrt{2}G_F N_e$$

$$\mathcal{A} = \frac{P_{\nu_\mu\to\nu_e} - P_{\bar\nu_\mu\to\bar\nu_e}}{P_{\nu_\mu\to\nu_e} + P_{\bar\nu_\mu\to\bar\nu_e}}$$ ≠0 ⇒ CP Violation

be careful, matter effects also create asymmetry



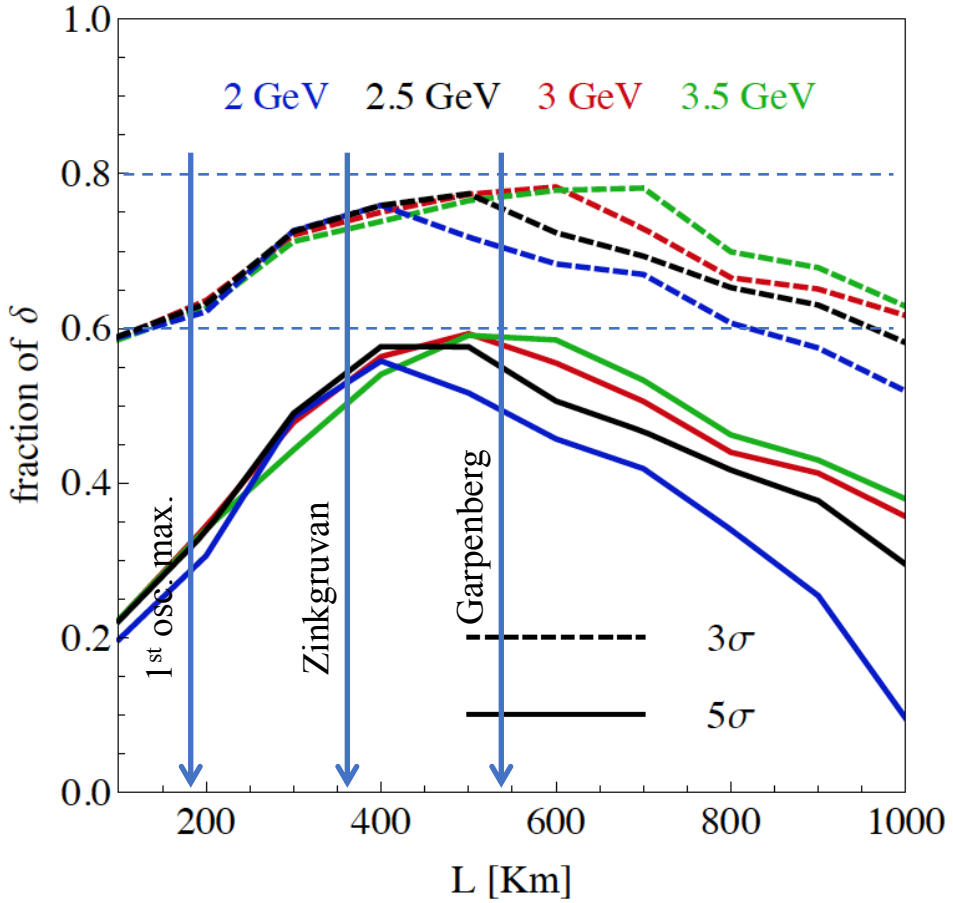


for "large" θ_{13} 1st oscillation maximum is dominated by atmospheric term, 2nd oscillation maximum is better

1st oscillation max. : **A=0.3 sin δ_{CP}**

2nd oscillation max. : **A=0.75 sin δ_{CP}**

Several Baselines Available



- ~60% δ_{CP} coverage at 5 σ C.L.
- >75% δ_{CP} coverage at 3 σ C.L.
- **systematic errors: 5%/10% (signal/backg.)**

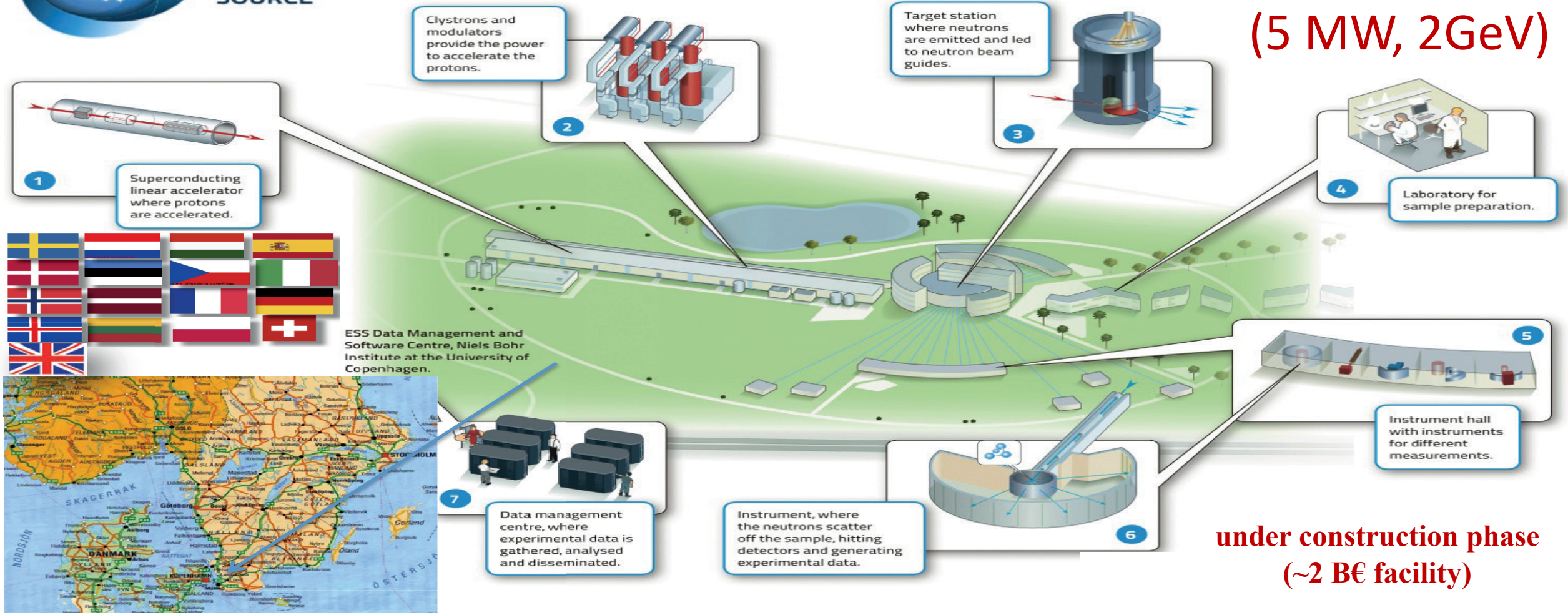
The European Spallation Source

Co-funded by the European Union

EUROPEAN SPALLATION SOURCE

European Spallation Source

(5 MW, 2GeV)



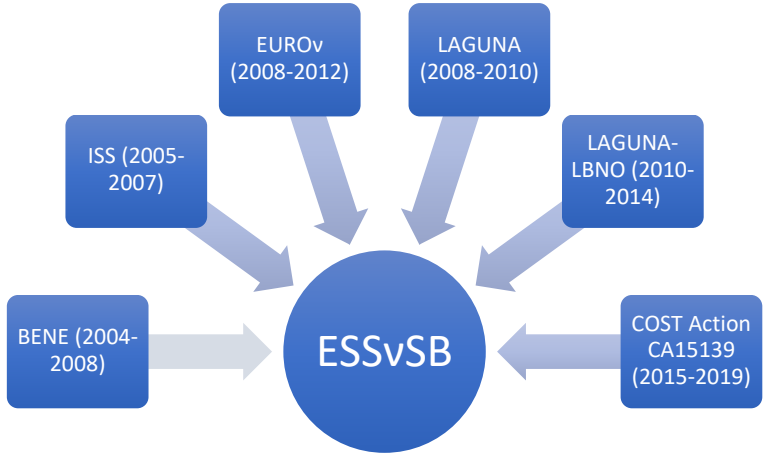
under construction phase (~2 B€ facility)

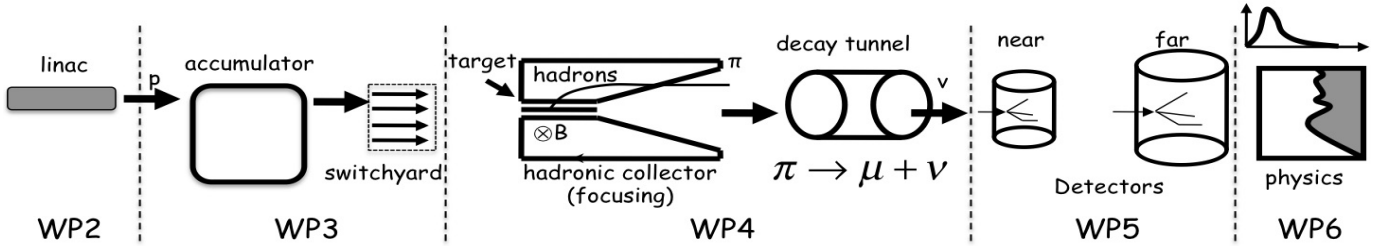
The ESSνSB High Intensity Neutrino Superbeam

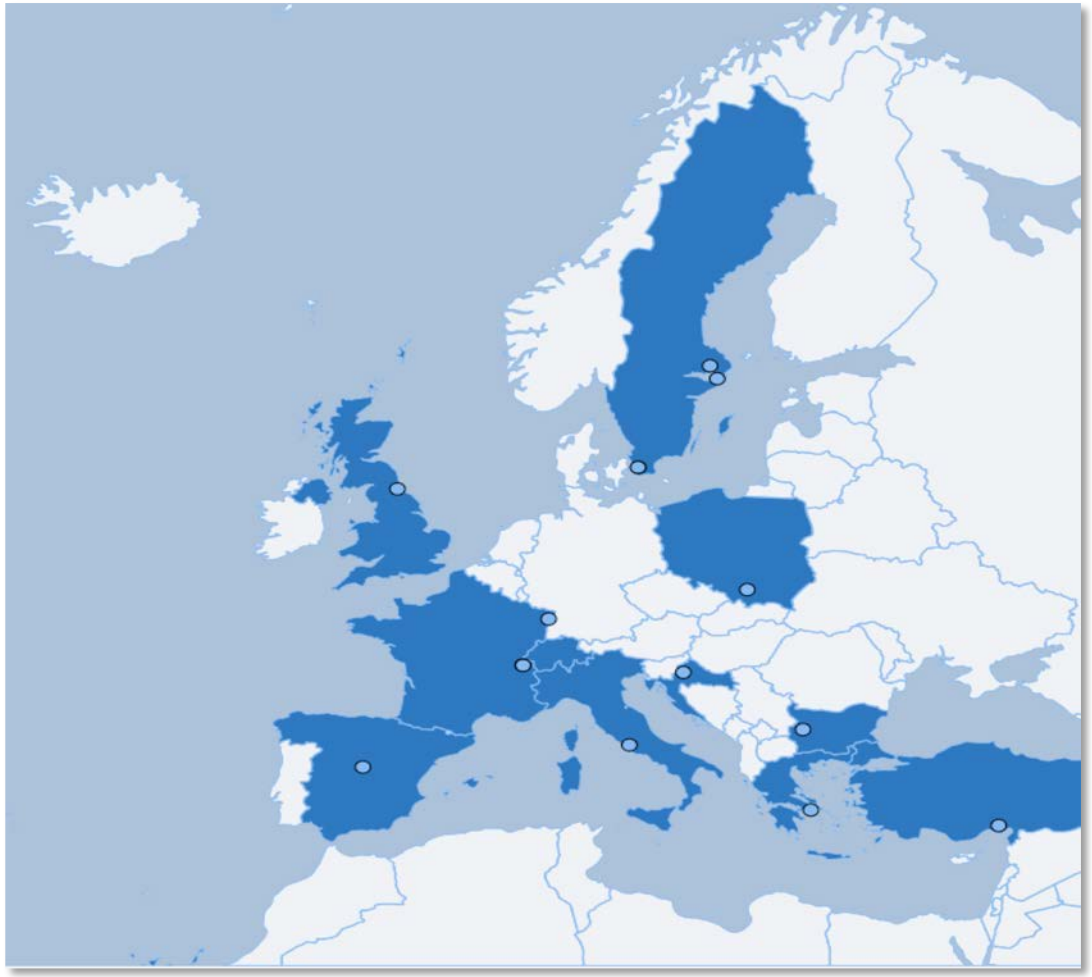
Co-funded by the European Union

A **H2020** EU **Design Study** (Call INFRADEV-01-2017)

- **Title of Proposal**: Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator
- **Duration: 4 years**
- **Total cost: 4.7 M€**
- **Requested budget: 3 M€**
- **15 participating institutes from 11 European countries including CERN and ESS**
- 6 Work Packages
- **Approved end of August 2017**







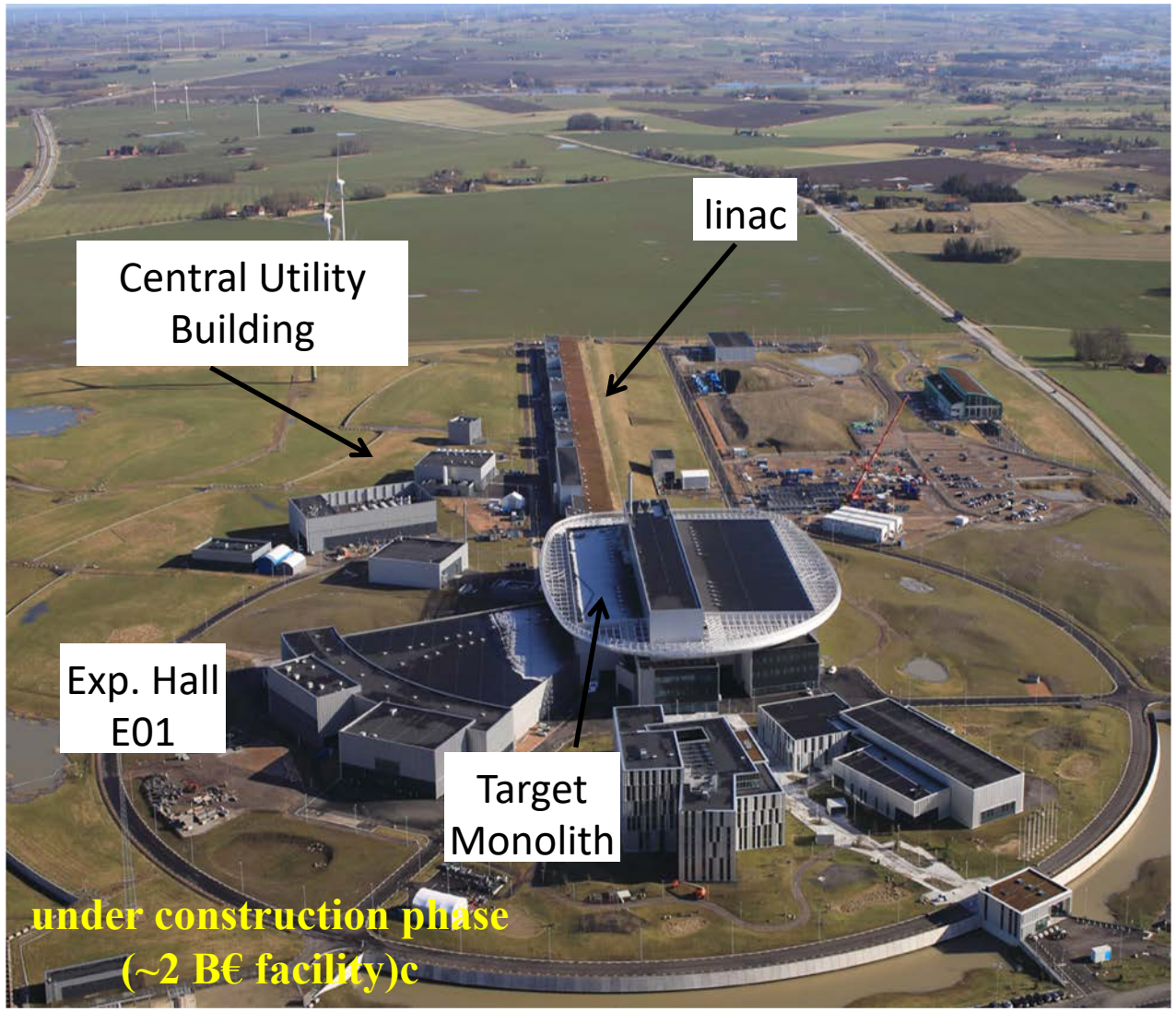
Map of participants

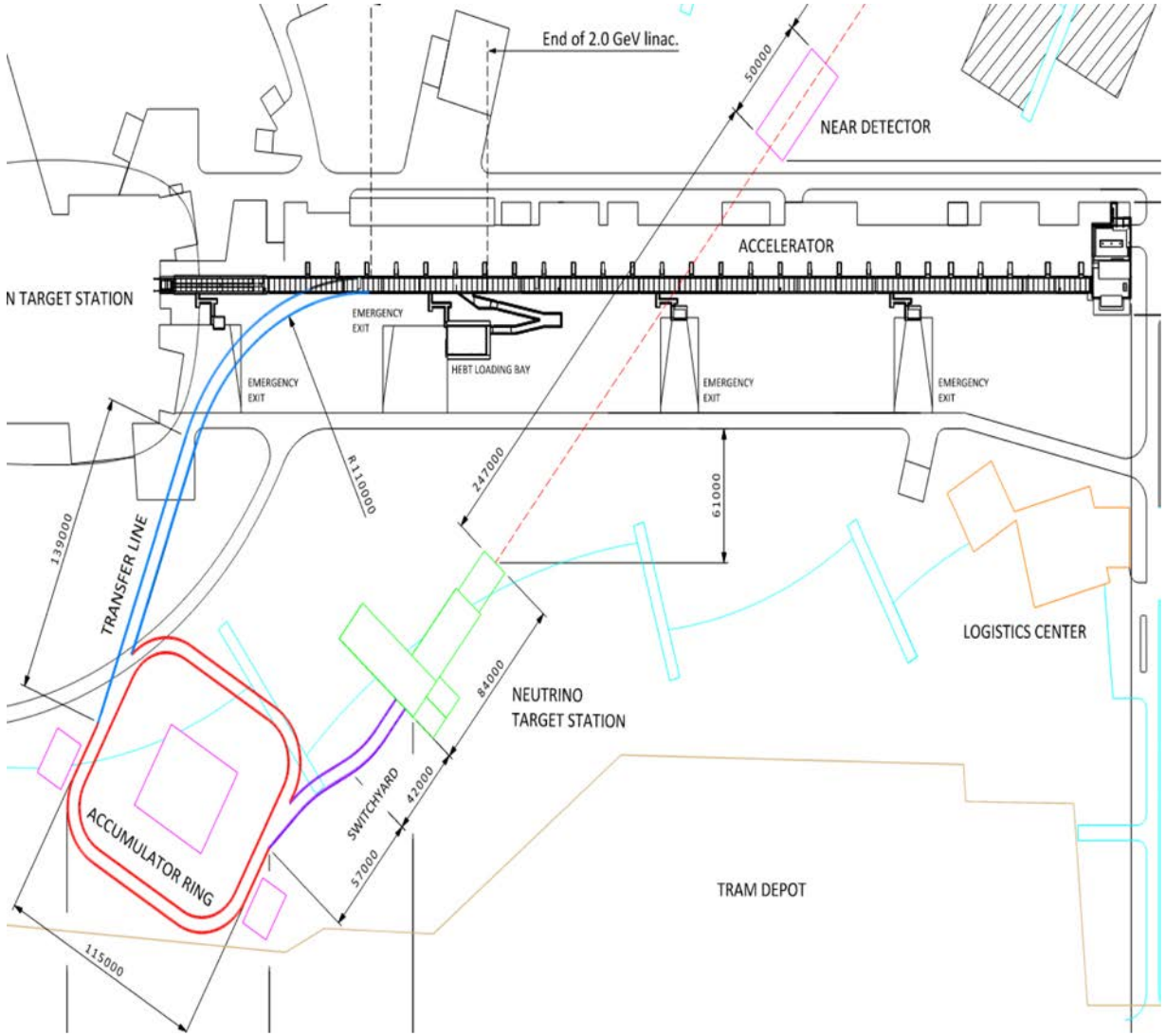
ESSνSB has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 777419

Superbeam Implementation on ESS site

ESS Neutrino Super Beam Plus

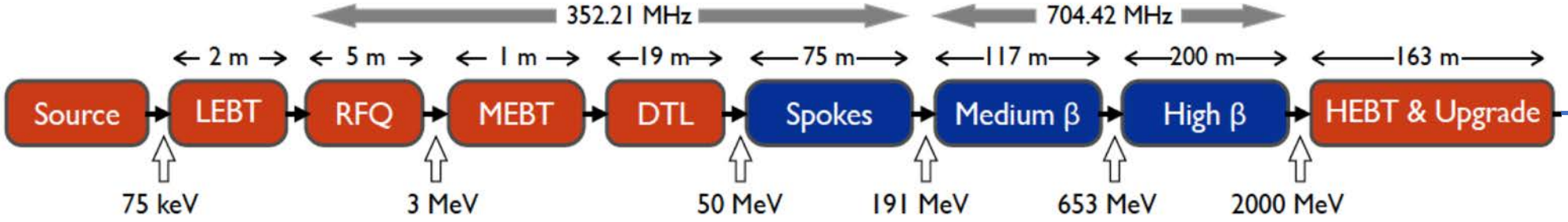
Co-funded by the European Union





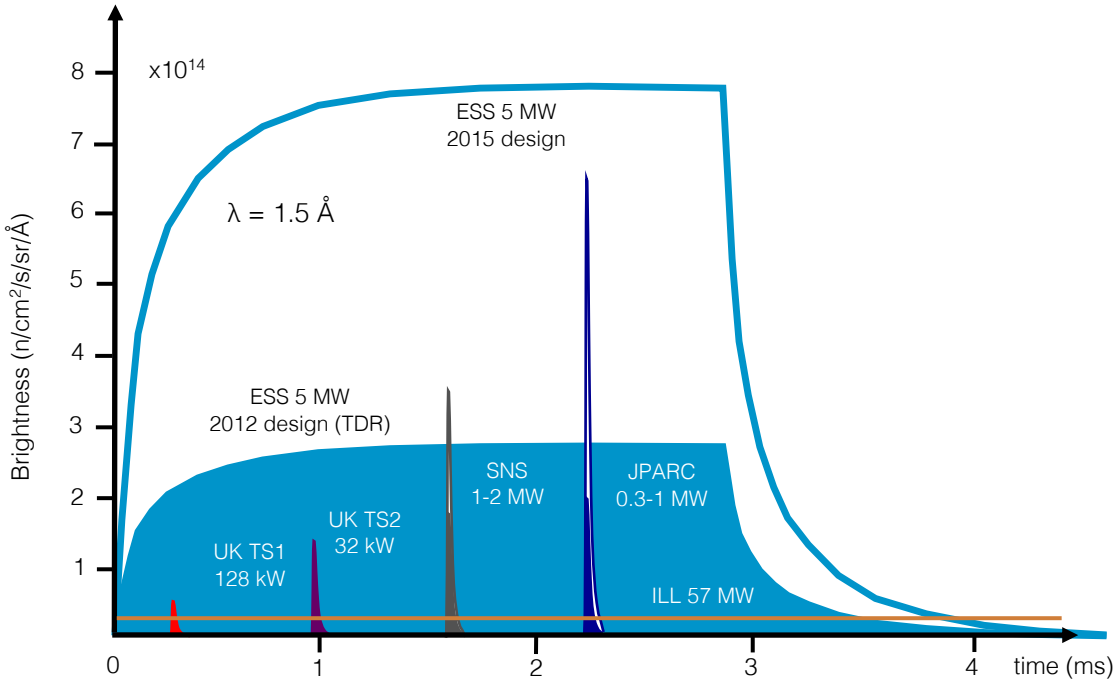
ESS LINAC (5MW)

Co-funded by the European Union



5 MW proton beam for neutron users (2.86 ms pulse width)

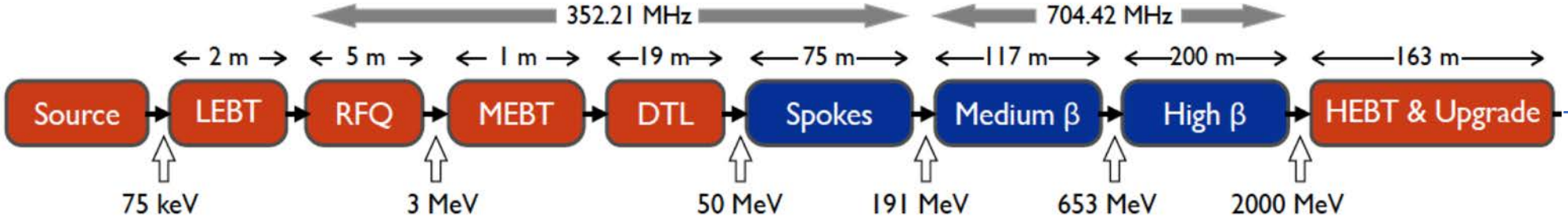
- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV kinetic energy protons
- **>2.7x10^{23} p.o.t/year.**



Linac ready by 2025 (protons on the target)

ESSνSB : LINAC Upgrade (10MW)

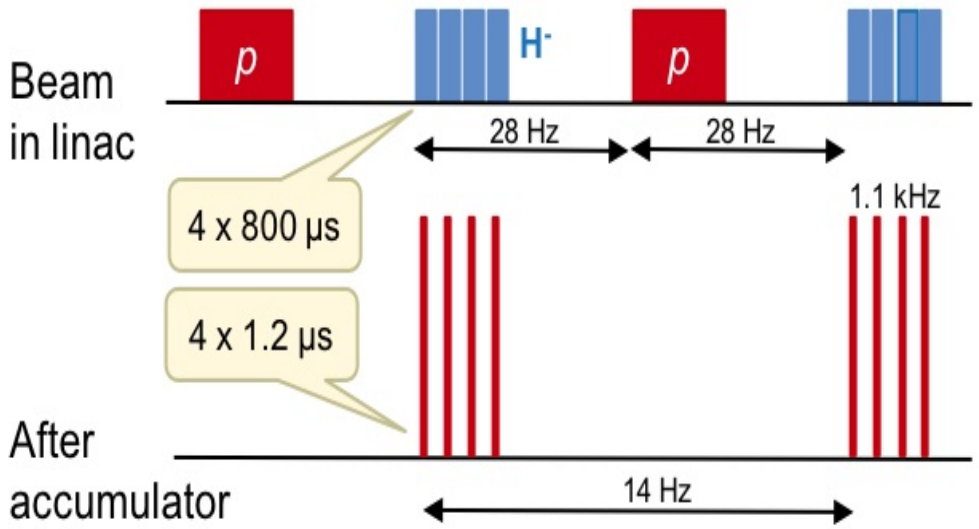
Co-funded by the European Union



5 MW proton beam for neutron users (2.86 ms pulse width)

5 MW proton beam for neutrino users 1 μs pulse width => Accumulator requested

- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power => 10 MW
- 125 MW peak power.
- 28 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4% => Duty cycle 8%
- 2.0 GeV kinetic energy protons => 2.5 GeV
- Accumulator ring to shorten the pulses to μs order for the horn
- Extra H^- source



Proton beam pulses

ESSνSB : Additional Elements

ESS Neutrino Super Beam Plus

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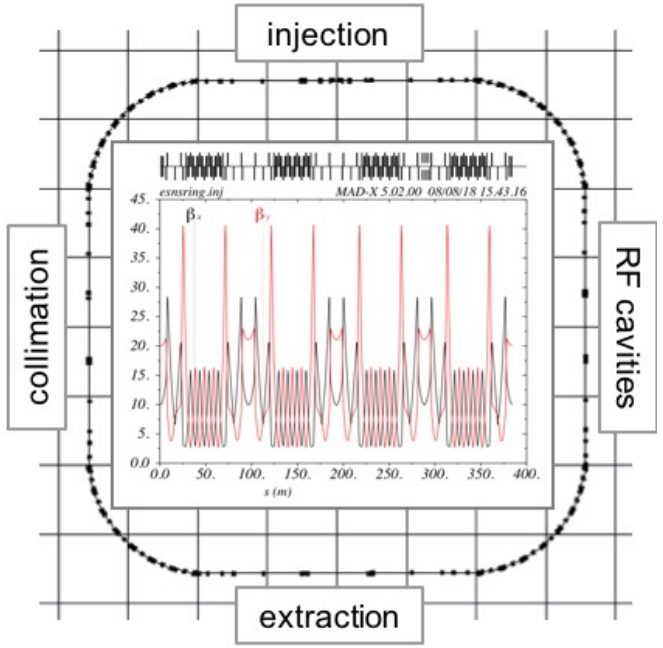
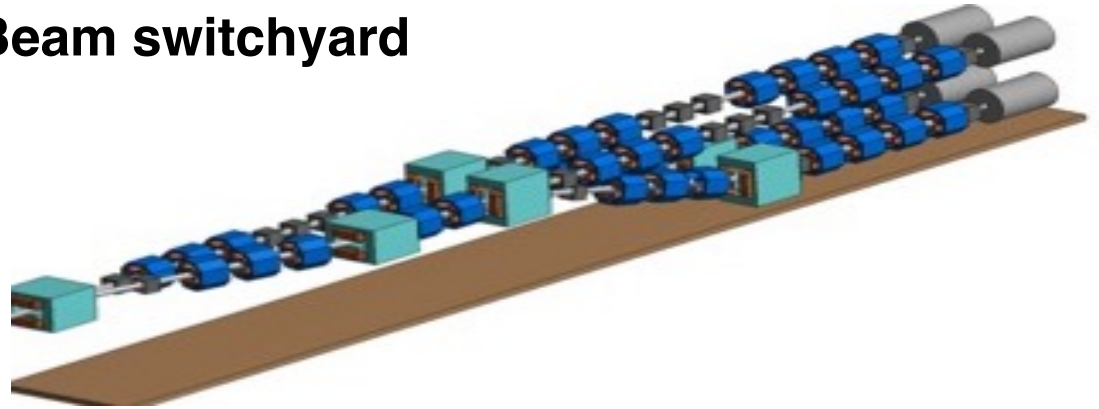
Accumulator

- 384 m circumference (4 arcs, 4 straight sections).
- H- stripping using foil.
- Laser-assisted stripping also considered.
- Correlated and anticorrelated painting of the beam.
- Geom emittance at the switchyard: 70 π mm mrad.

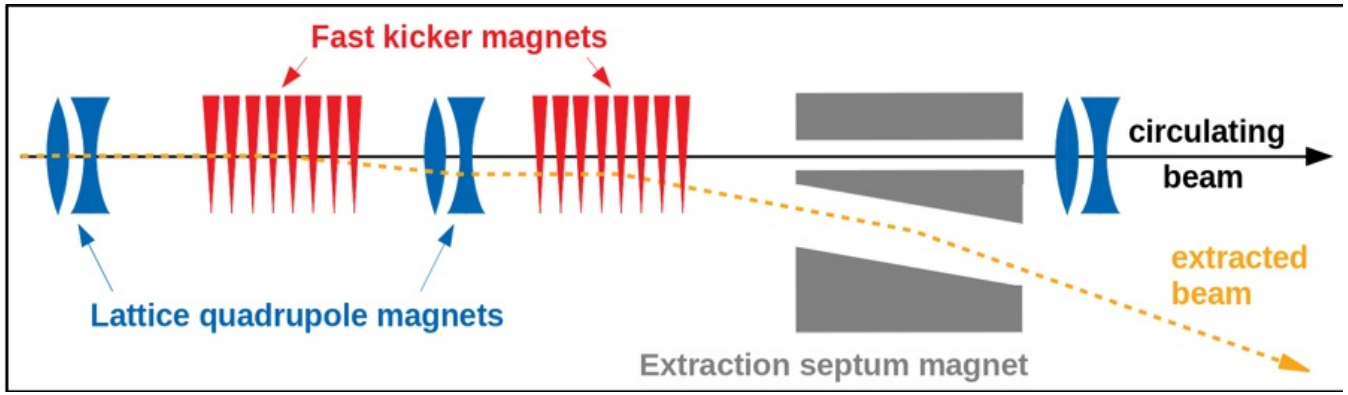


Beam switchyard

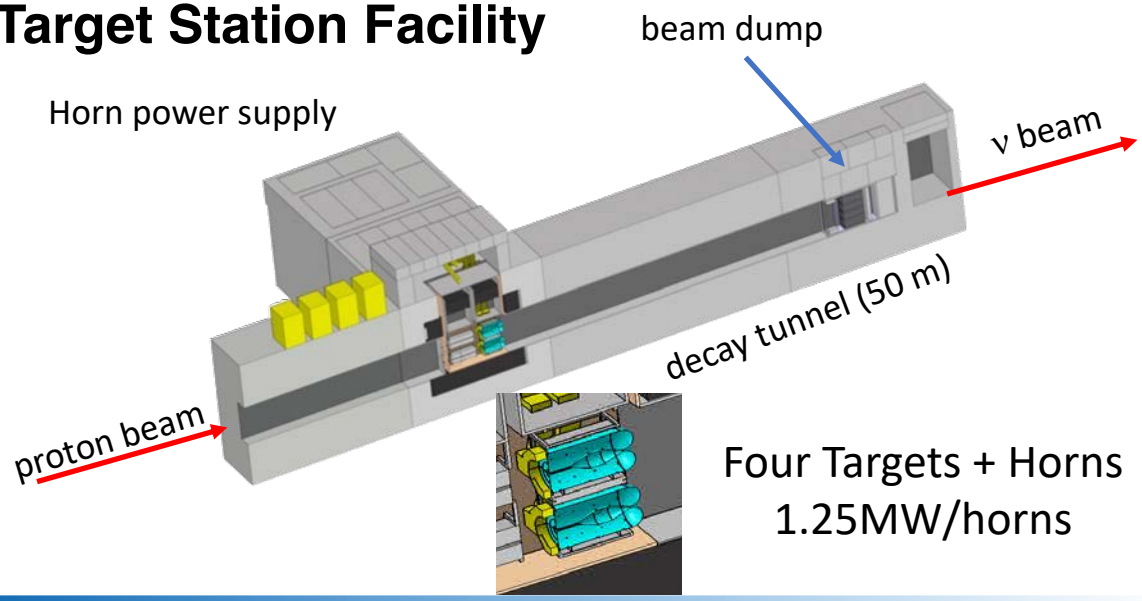


The switchyard splits the 5MW proton beams in four parts

Ring-to-switchyard transfer



Target Station Facility



Four Targets + Horns
1.25MW/horns

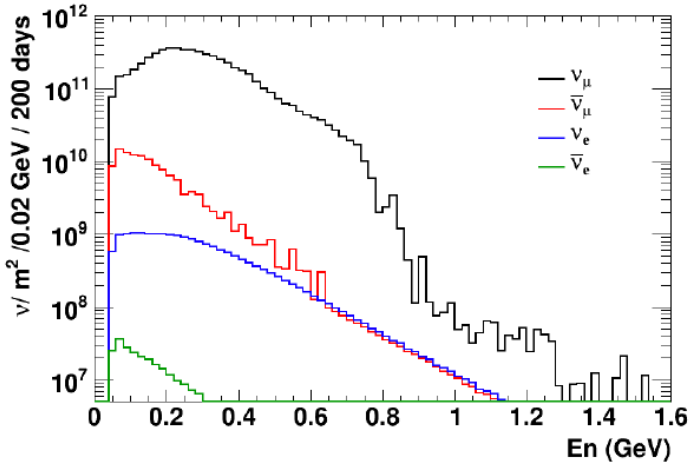
ESSνSB : Neutrino fluxes

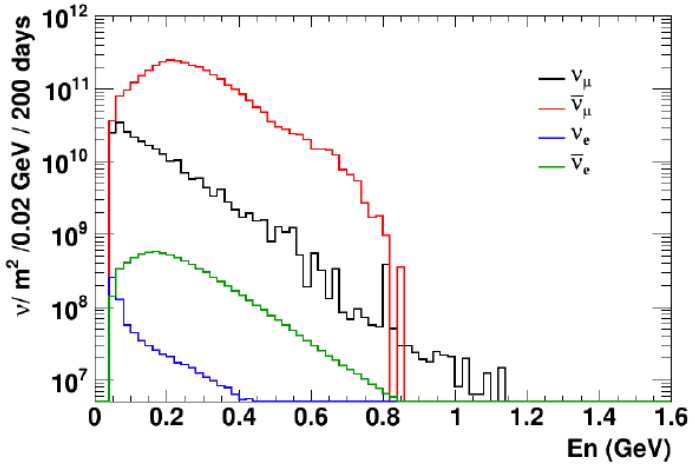
Co-funded by the European Union

What can we do with:

- 5 MW power
- 2,5 GeV energy
- 14 Hz repetition rate
- 10^{15} protons/pulse
- >2.7x10^{23} protons/year

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





	Positive Polarity		Negative Polarity	
	$N_\nu\ (10^{10}/\mathrm{m}^2)$	%	$N_\nu\ (10^{10}/\mathrm{m}^2)$	%
ν_μ	583	98	23.9	6.55
$\bar{\nu}_\mu$	12.8	2.1	340	93.2
ν_e	1.93	0.3	0.08	0.02
$\bar{\nu}_e$	0.03	0.01	0.78	0.21

at 100 km from the target, per year (in absence of oscillations)

ESSνSB : Neutrino detectors

ESS Neutrino Super Beam Plus

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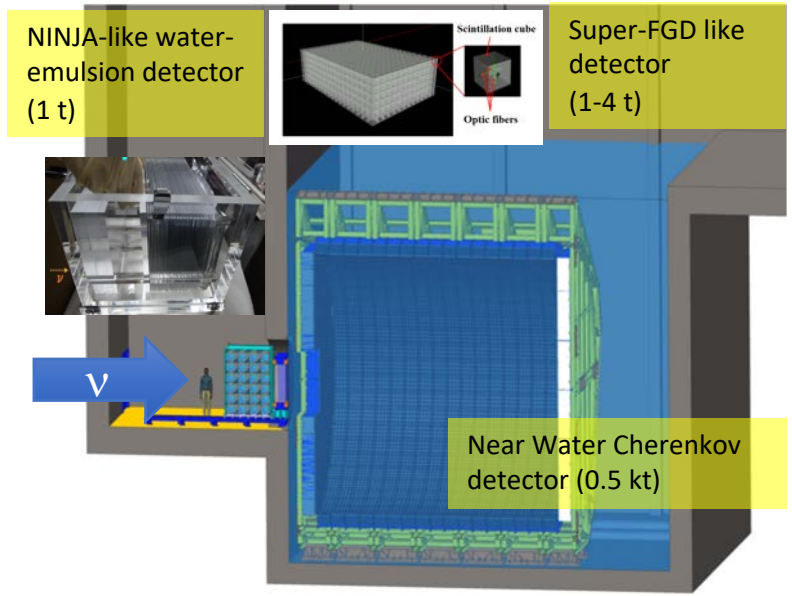
Near Detector

- A magnetized Super Fine Grained Detector (SFGD) for cross-section measurements.
- 1 kton WC detector for event rate measurements, flux normalization and event reconstruction comparison with FD.
- Emulsion setup, similar to NINJA[1] experiment, upstream of the SFGD, for cross-section measurements.



Far Detector

- 538 kt fiducial volume (~10xSuperK)
- Readout 20” PMTs (40% optical coverage)
- Event reconstruction with fiTQun [2,3]
- New migration matrices obtained

Can also be used for other purposes: Proton decay, astroparticles, Galactic SN , Supernovae "relics”, Solar Neutrinos, Atmospheric Neutrinos

WC type detector

[1] A. Hiramoto et al., Phys. Rev. D 102, 072006 (2020), arXiv:2008.03895.
[2] T2K Collaboration, A. D. Missert, J. Phys. Conf. Ser. 888 (2017), no. 1 012066
[3] Super-Kamiokande Collaboration, M. Jiang et al., PTEP 2019 (2019), no. 5 053F01, [arXiv:1901.03230].

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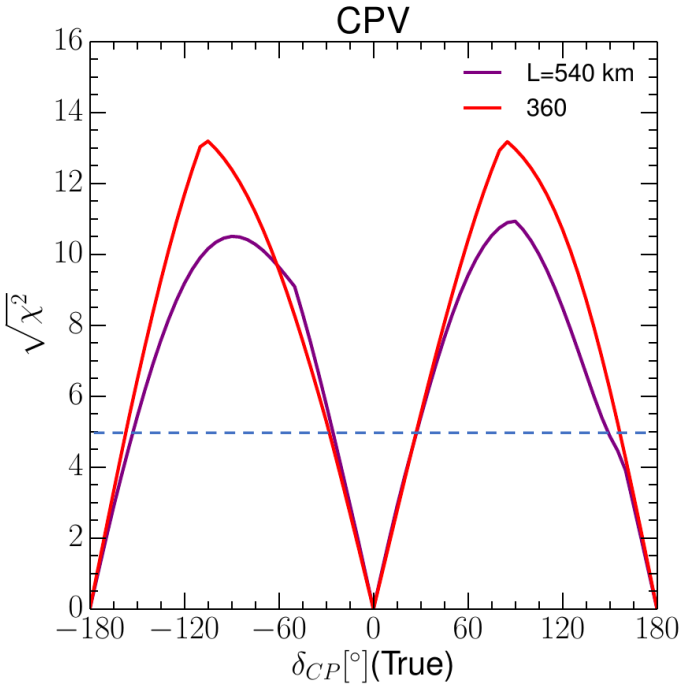
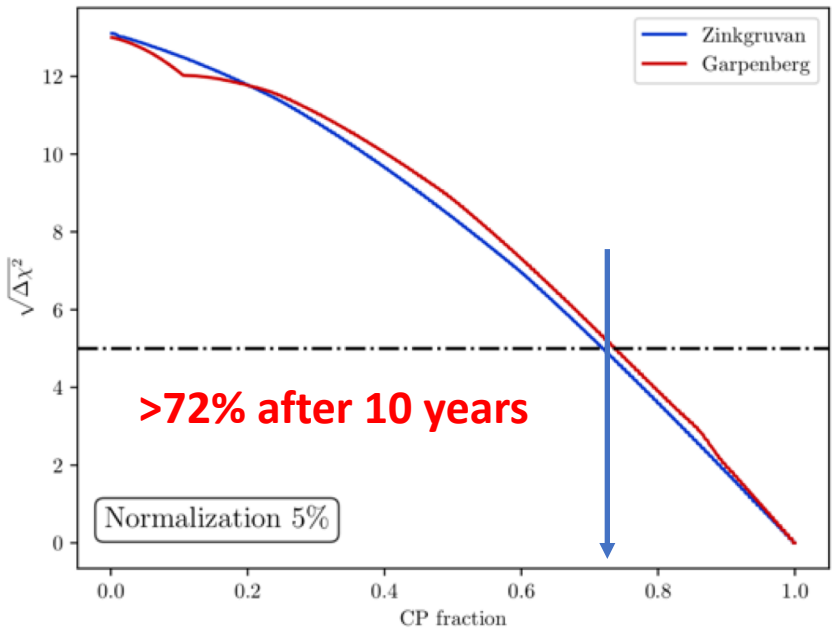
Updated physics performance of the ESSvSB experiment,

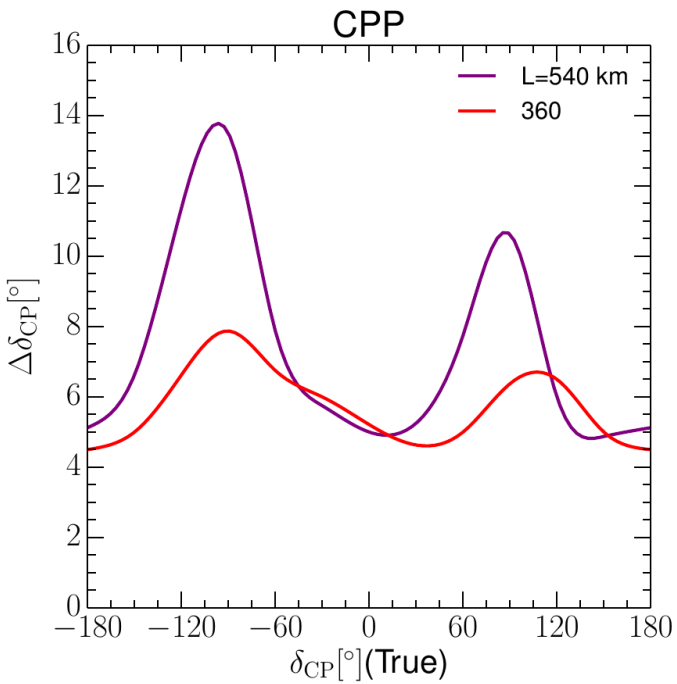
Eur.Phys.J.C 81 (2021) 12, 1130
DOI:10.1140/epjc/s10052-021-09845-8, arXiv:2107.07585



δ_{CP} coverage measurement



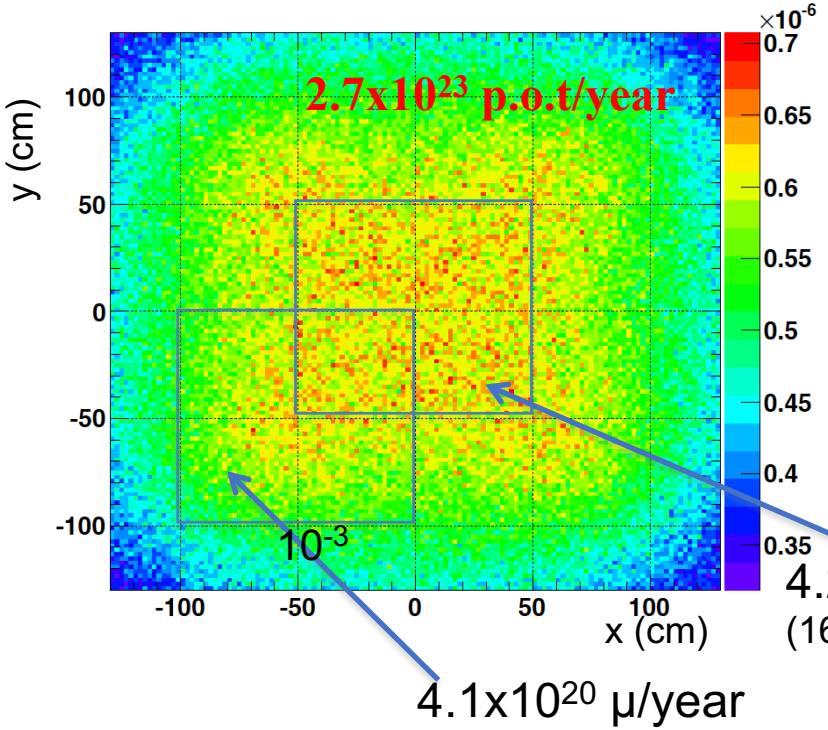
δ_{CP} fraction coverage



Precision measurement

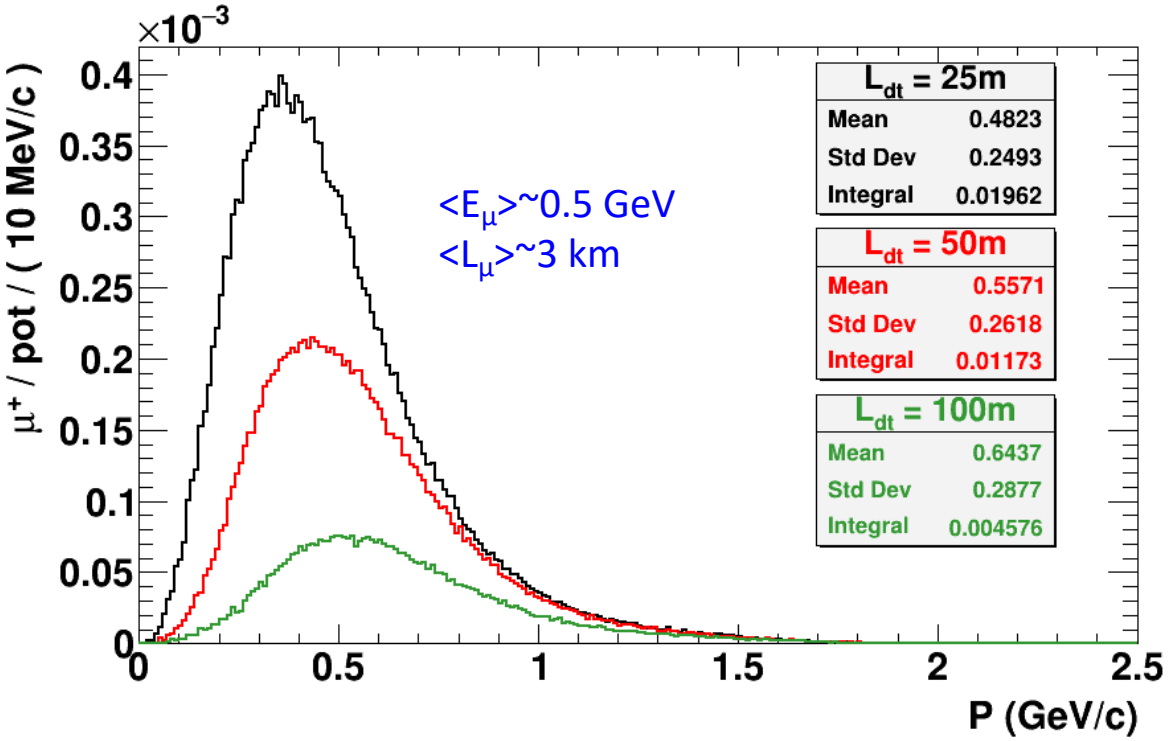
Muons from ESSνSB

Co-funded by the European Union



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

more than 4×10^{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).



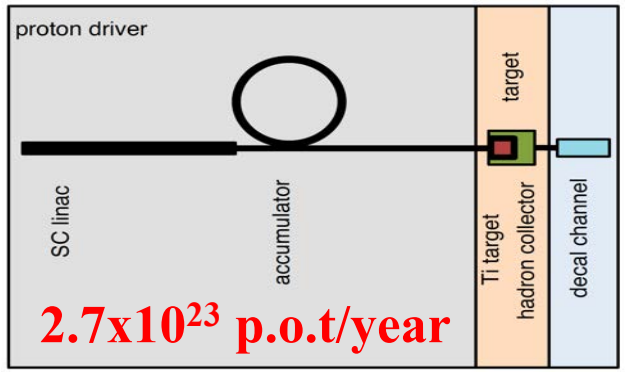
- Input beam for future 6D m cooling experiments (for muon collider),
- Good to measure neutrino x-sections (ν_μ, ν_e), around 200-300 MeV using a near detector,
- Low energy nuSTORM,
- Neutrino Factory,
- **Muon Collider**.

ESSνSB as a platform

Co-funded by the European Union

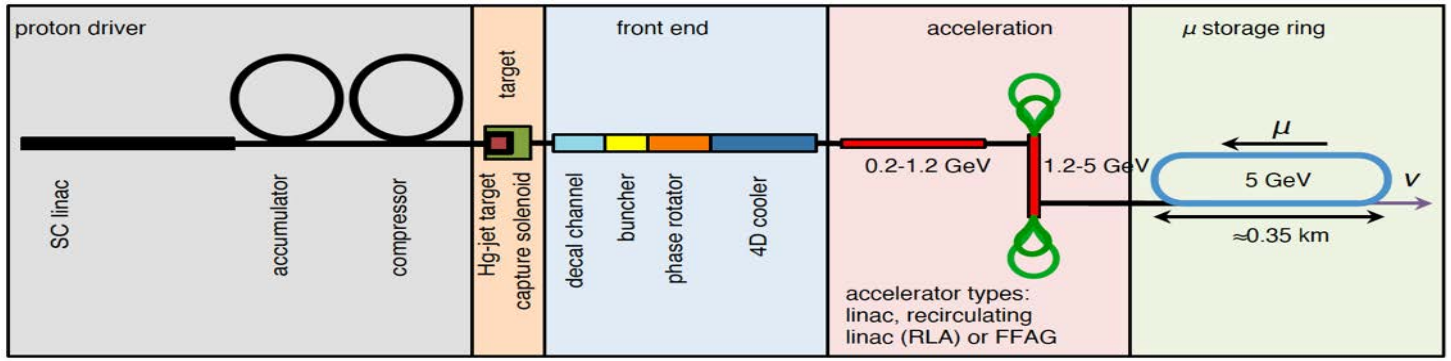
Super Beam

ESSνSB



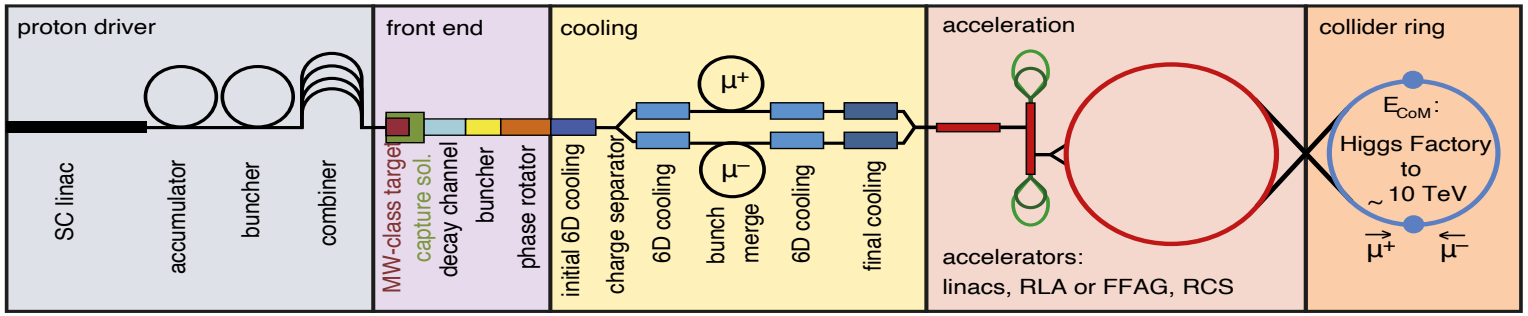
+Decay At Rest and Coherent scat. (with short pulses)

Neutrino Factory



Muon Collider

ESSμSB



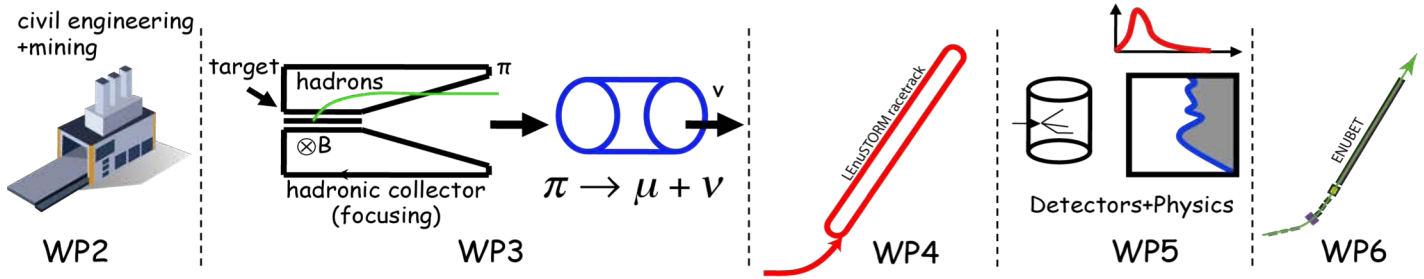
ESSνSB+

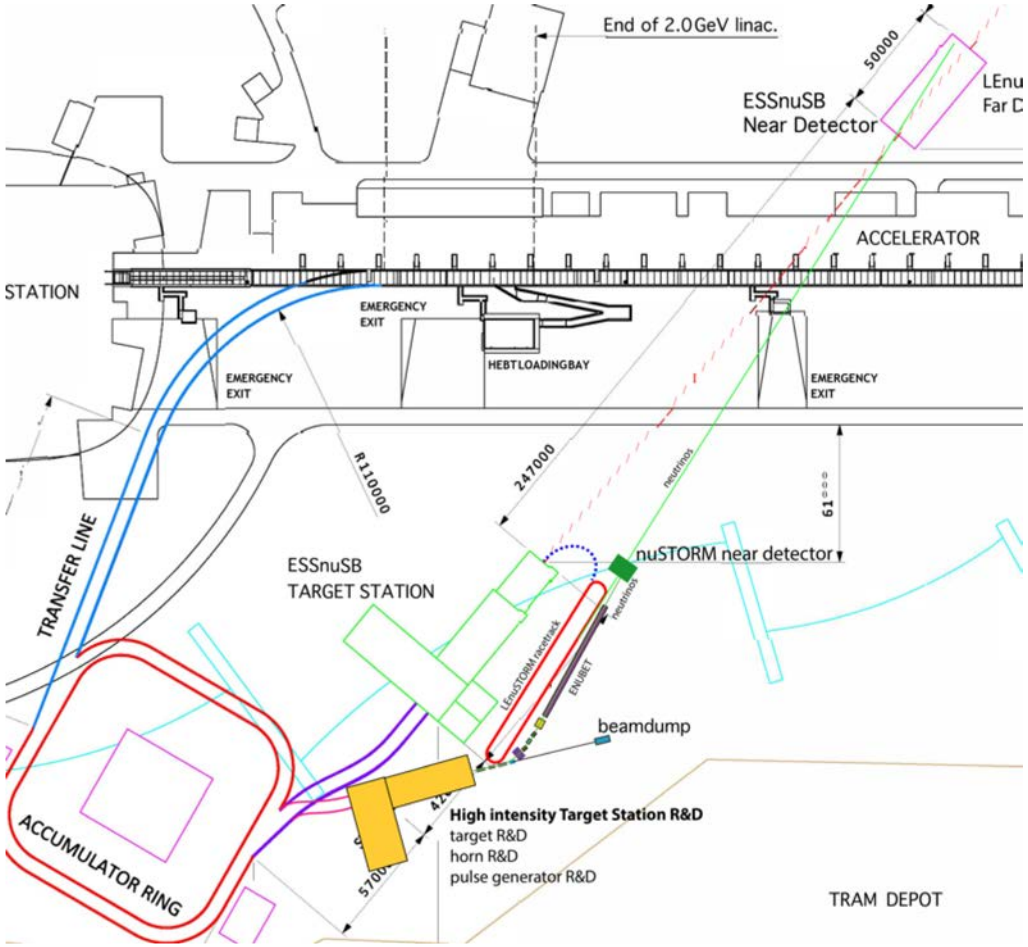
A Synergetic Facility based in Europe

The ESSνSB+ Superbeam

Co-funded by the European Union

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





Implementation of the 2nd Target Station working at 1.25 MW

The ESSνSB+ Superbeam

Co-funded by the European Union

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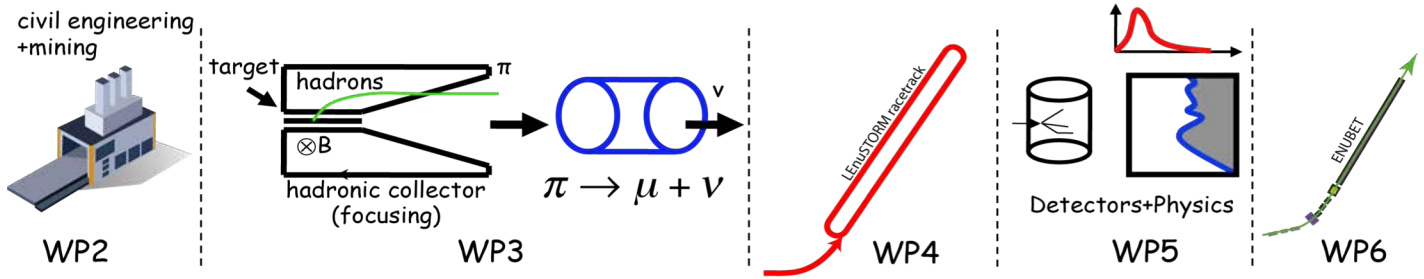
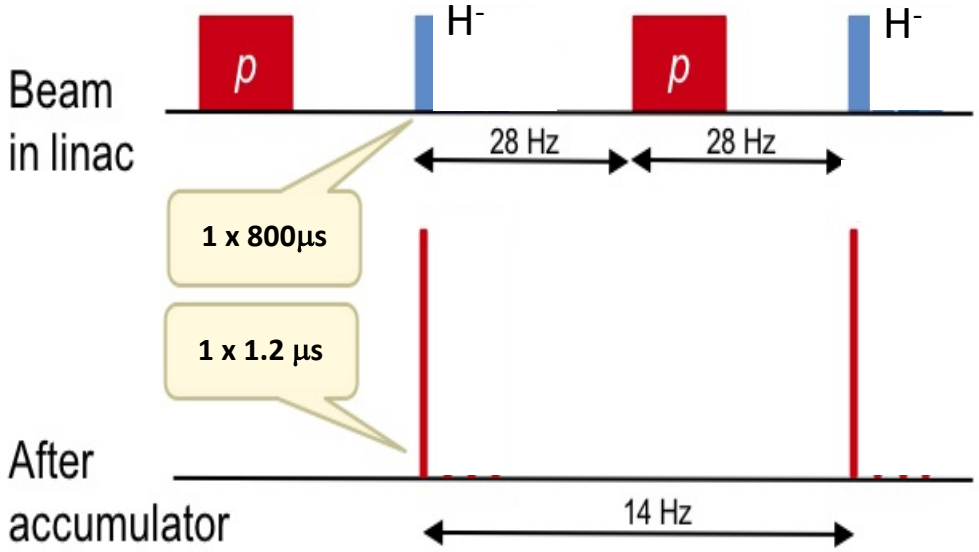
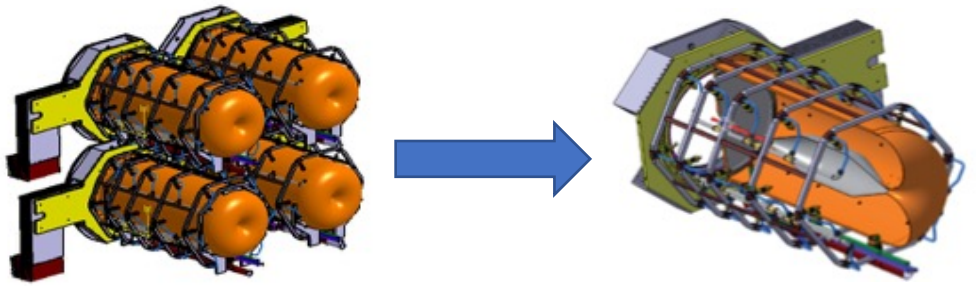




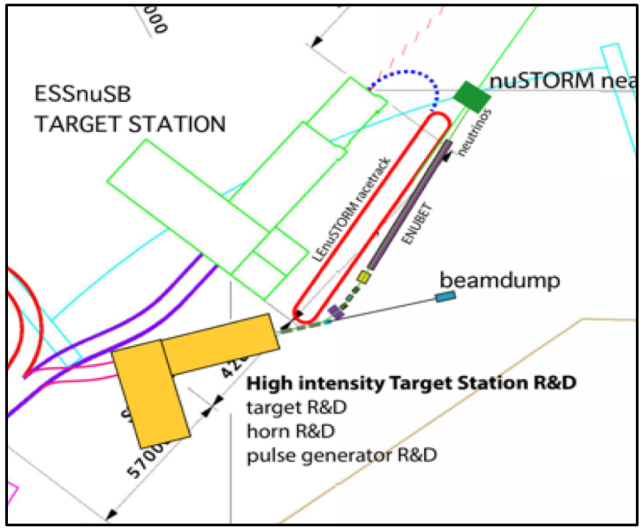


ESSnuSB (5MW)

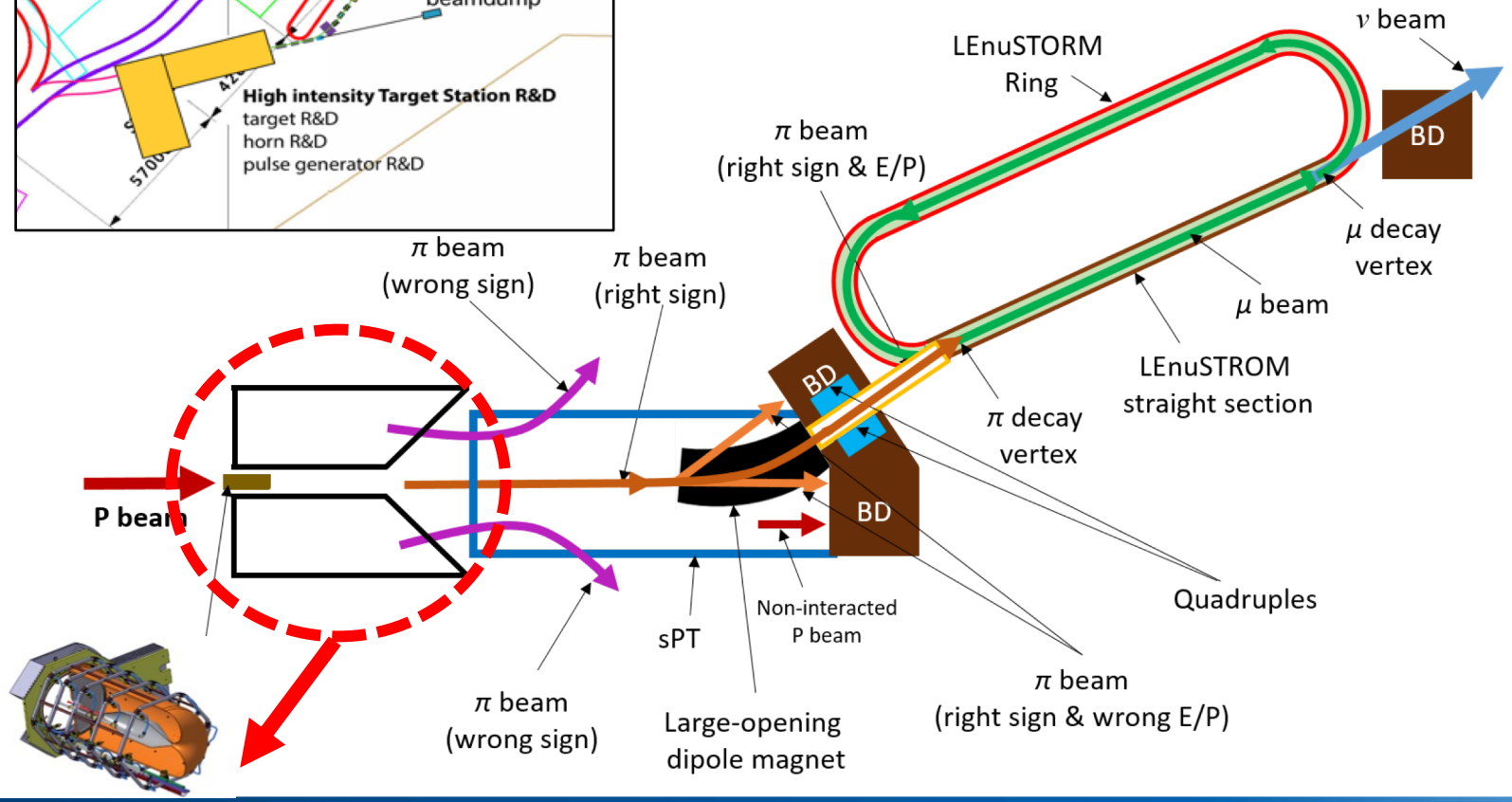
ESSnuSB+ (1.25MW)

The ESSνSB+ Target Station concept

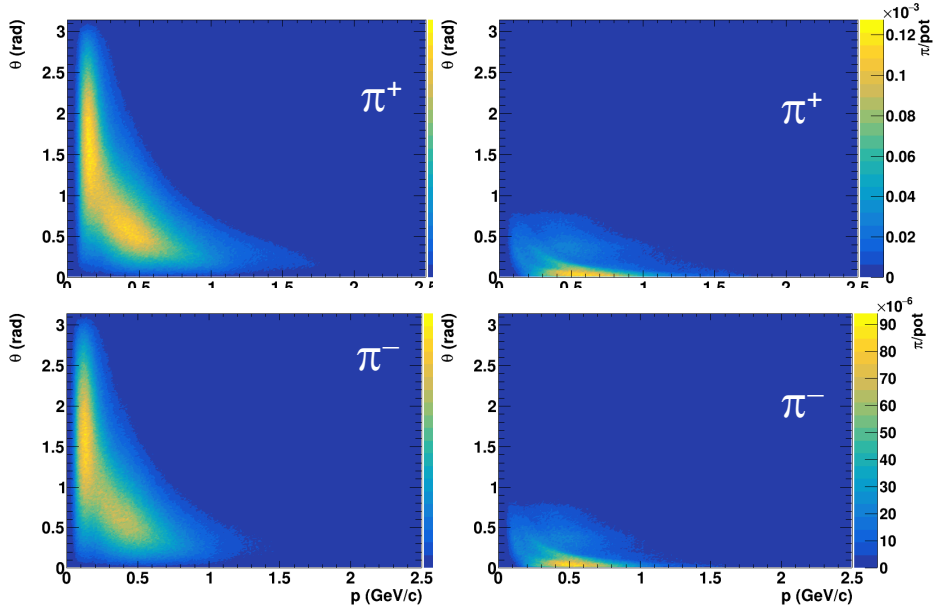
Co-funded by the European Union



Target Station based on a one horn-target system (1.25MW)



ESSnuSB Horn Focusing



Adaptation of the ESSnuSB Target Station to the ESSnuSB+ physics goals

The ESSνSB+ additional facilities

Co-funded by the European Union

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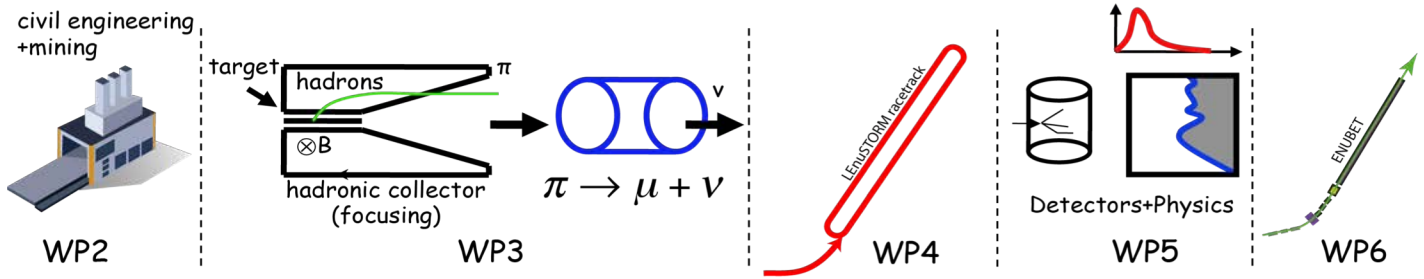
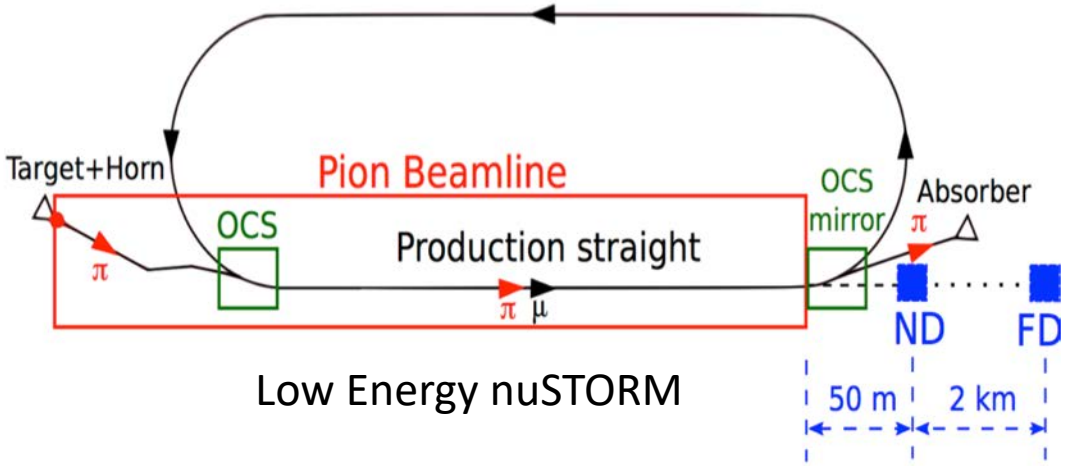
5. Design a **Monitored Neutrino Beam** (low energy ENUBET)
6. **Optimize the performance** of the ESSνSB accelerator complex

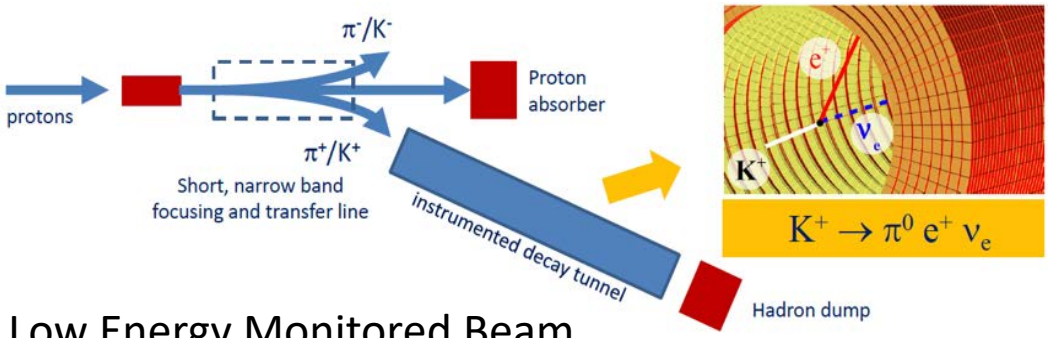


$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$ $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$



Low Energy nuSTORM



Low Energy Monitored Beam

European Commission Approval

Co-funded by the European Union

Research and Innovation actions

Innovation actions

Design Study

HORIZON-INFRA-2022-DEV-01

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

Acronym of Proposal: **ESSvSB+**

Subject: **Horizon Europe (HORIZON)**
Call: HORIZON-INFRA-2022-DEV-01
Project: 101094628 — ESSnuSBplus
GAP invitation letter

July 2022

Dear Applicant,

I am writing in connection with your proposal for the above-mentioned call.

Having completed the evaluation, we are pleased to inform you that your proposal has passed this phase and that we would now like to start grant preparation.

Please find enclosed the evaluation summary report (ESR) for your proposal.

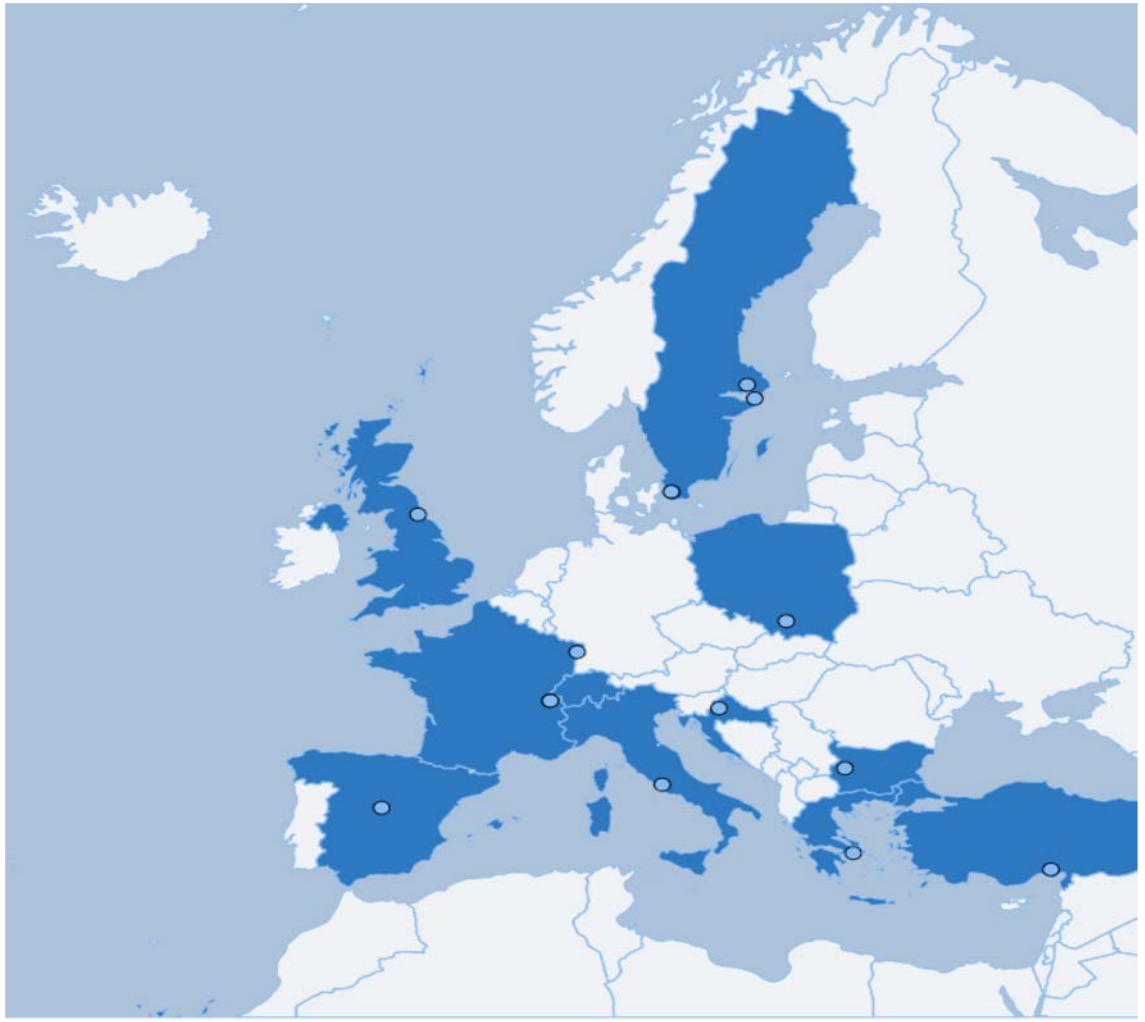
Invitation to grant preparation

- 3 M€
- 4 years

Outlines:

- **ESSνSB** predict that in **10 years of data taking ESSnuSB will be able to reach 5 σ over 72%** of δ_{CP} range and should be able **to measure δ_{CP} in with a precision of 8°**.
- The proposed experiments **ESSνSB & ESSνSB+** represent **an opportunity to have a Neutrino Superbeam in Europe**.
- In addition, the European Spallation Source can offer **a rich complementary program in fundamental physics (arXiv:2211.10396)**.
- A R&D phase is necessary **to solve technical challenges**.

Website : https://essnusb.eu/



Map of the European contributions

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