Search for the leptonic CP violation with the ESSnuSB(+) project

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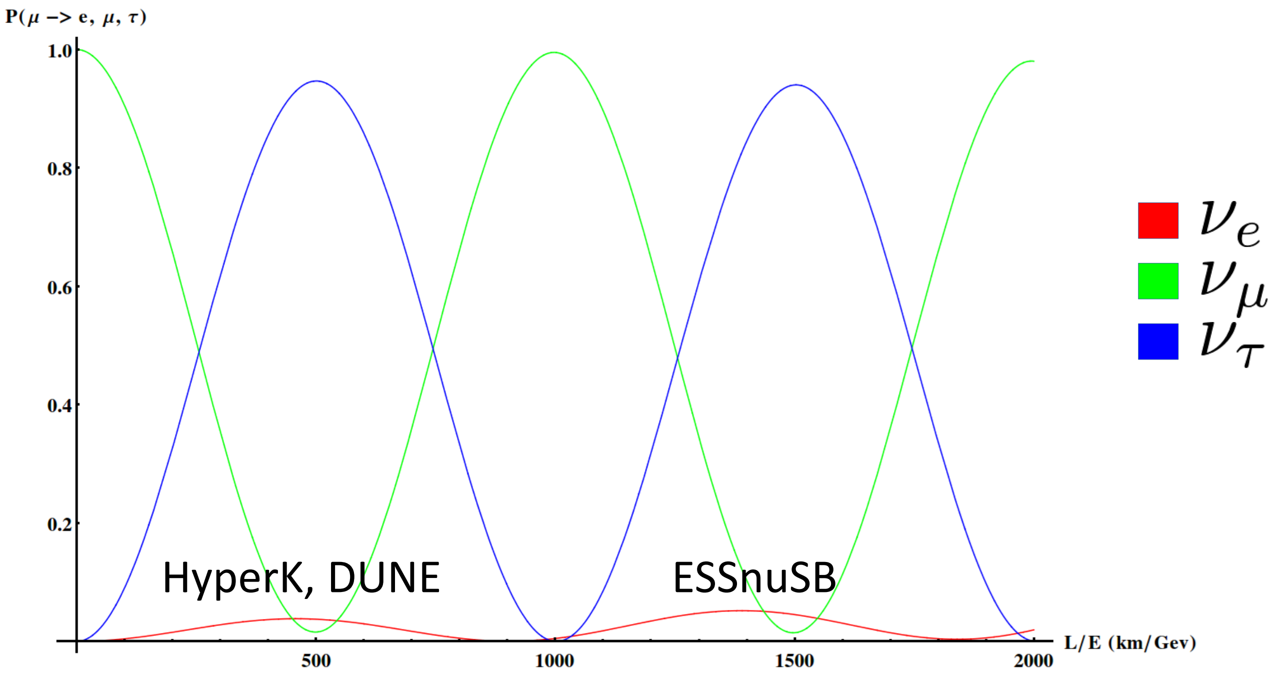
ESSnuSB

(European Spallation Source neutrino Super Beam)

A proposed 2nd generation long-baseline experiment to measure the CP violation in the leptonic sector at 2nd neutrino oscillation maximum



δ_{CP} and Matter-Antimatter Asymmetry Magnitude

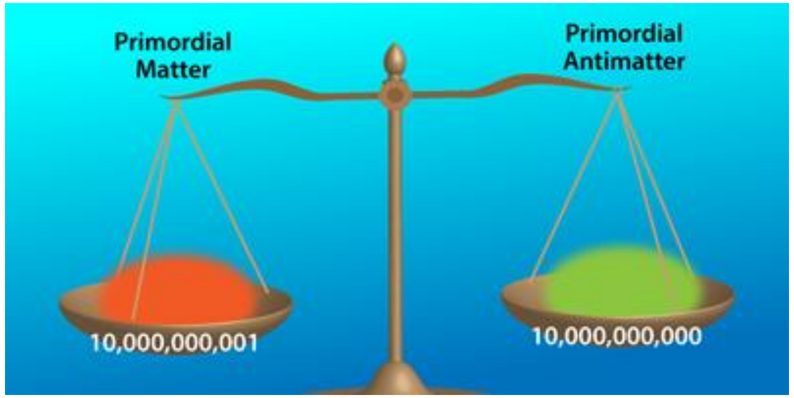
- The observed universe is dominated by matter only!
- The amount of Charge-Parity violation (CPV) needs to be large enough to explain this matter/anti-matter Asymmetry
- CPV has been observed in the hadronic sector (in the neutral *K*-meson decay), but not confirmed yet in the leptonic sector

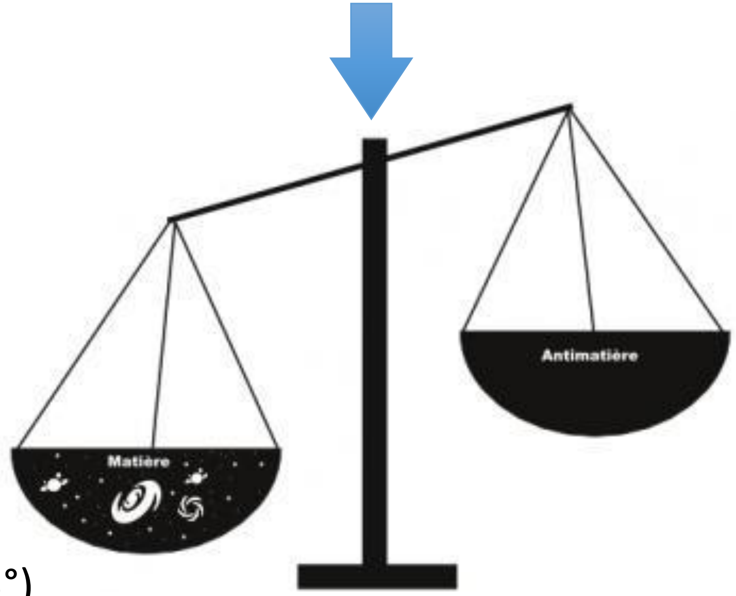
$$A_{\alpha\beta}^{CP} = P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$$
$$= J_{CP}^{PMNS} \cdot \sin\delta_{CP} \quad \text{(Jarlskog invariant)}$$

with: $J_{CP}^{PMNS} \sim 3\times 10^{-3}$

(for hadrons: $J_{CP}^{CKM} \sim 3\times 10^{-5}$, not enough even if $\delta_{CP} \sim 70^\circ$)

(from the already observed CP violation in the hadronic sector)





- Theoretical models predict that if $|\sin\delta_{CP}| \gtrsim 0.7$ ($45^\circ < \delta_{CP} < 135^\circ$ or $225^\circ < \delta_{CP} < 315^\circ$)

  ➔ This could be enough to explain the observed asymmetry (Nucl.Phys.B774:1-52,2007, arXiv:hep-ph/0611338)

- δ_{CP} needs to be measured with the highest precision to decide on the Leptogenesis models

Neutrino oscillations

- Neutrinos do have mass and oscillate.
- It can be expressed as a transformation relating the flavor and mass eigenstates through a unitary matrix, the Pontencorvo–Maki–Nakagawa–Sakata *(PMNS)* matrix. $|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle$

$|\nu_\alpha\rangle$ Neutrino with defined flavor α = e, μ or τ
$|\nu_i\rangle$ Neutrino with defined mass m_i, i = 1, 2, 3

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta_{23} & sin\theta_{23} \\ 0 & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} cos\theta_{13} & 0 & sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -sin\theta_{13}e^{i\delta_{CP}} & 0 & cos\theta_{13} \end{pmatrix} \begin{pmatrix} cos\theta_{12} & sin\theta_{12} & 0 \\ -sin\theta_{12} & cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \text{Two additional phases} \\ \text{for Majorana} \\ \text{neutrinos} \end{pmatrix}$$

Oscillation in the 23/atmospheric sector | Oscillation in the 13 sector | Oscillation in the 12/solar sector | Doesn't influence neutrino flavor oscillations

- The neutrino-flavor oscillation probability, $P(\nu_\alpha \to \nu_\beta)$,

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(A_{ij}^{\alpha\beta}\right)\sin^2\frac{\Delta m_{ij}^2 L}{4E} \pm 2\sum_{i>j} \mathrm{Im}\left(A_{ij}^{\alpha\beta}\right)\sin\frac{\Delta m_{ij}^2 L}{4E}$$

$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$

$A_{ij}^{\alpha\beta} \equiv U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*$

$s_{ij} \equiv \sin\theta_{ij}$

$c_{ij} \equiv \cos\theta_{ij}$

➔ three mixing angles, θ_{12}, θ_{23} and θ_{13}	Known
➔ two independent squared mass splittings, Δm_{12}^2 and Δm_{13}^2	
➔ **one CP-violating phase factor, δ_{CP}**	Unknown/Hint!!

CP violation in neutrino oscillations

Oscillation probability for neutrinos (for $\nu_\alpha \rightarrow \nu_\beta$) is different than the oscillation probability for anti-neutrinos (for $\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta$) in vaccum (same for oscillation in matter for the 2nd oscillation maximum)

probability of oscillation

$$P_{\nu_\alpha \rightarrow \nu_\beta} \neq P_{\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta}$$

neutrino flavour at production

neutrino flavour at detection

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Neutrino Oscillations (Leptonic CP-Violation)

ESS neutrino Super Beam plus

$\nu_\mu \rightarrow \nu_e$ oscillation probability:

$$P(\nu_\mu \rightarrow \nu_e) = sin^2\theta_{23} sin^2 2\theta_{13} sin^2\left(\frac{\Delta m_{31}L}{2}\right)$$
$$+cos^2\theta_{23} sin^2 2\theta_{12} sin^2\left(\frac{\Delta m_{21}L}{2}\right)$$
$$+\bar{J} cos\left(\delta_{CP} - \frac{\Delta m_{31}L}{2}\right) sin\left(\frac{\Delta m_{21}L}{2}\right) sin\left(\frac{\Delta m_{31}L}{2}\right)$$

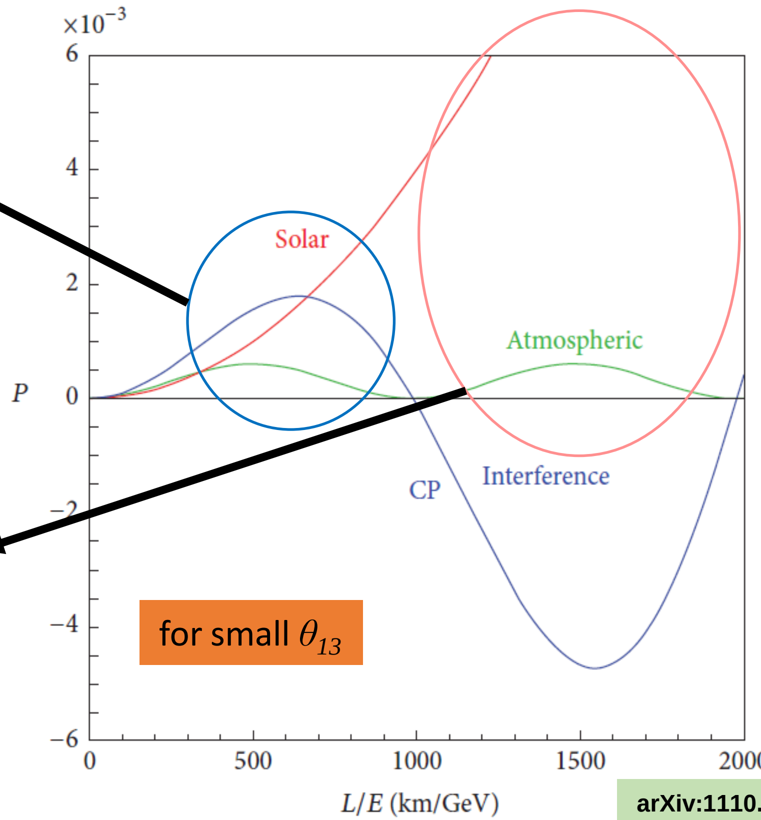
where $\bar{J} \equiv cos\theta_{13} sin2\theta_{12} sin2\theta_{23} sin2\theta_{13}$ and $\Delta_{ij} \equiv \Delta m^2_{ij}/2E_\nu$.
E_ν is the neutrino energy, L is the source-to-detector distance, the *baseline*.
The sign of δ_{CP} is the opposite for antineutrinos.

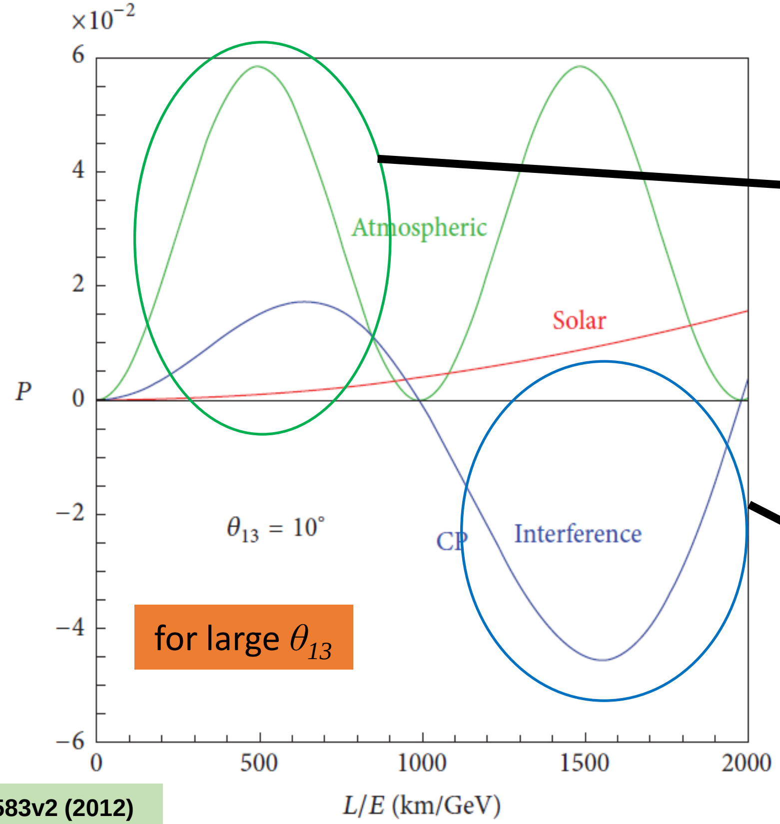
Important for CPV in leptonic sector

θ_{13} plays a significant role in evaluating the performance when planning "future" long baseline neutrino experiments

@ 1st oscillation max.
CP-interference dominates

@ 2nd oscillation max.
Solar term dominates





arXiv:1110.4583v2 (2012)

@ 1st oscillation max.
Atm. term dominates

@ 2nd oscillation max.
CP-interference dominates

Neutrino Oscillations (Leptonic CP-Violation)

$\nu_\mu \rightarrow \nu_e$ oscillation probability:

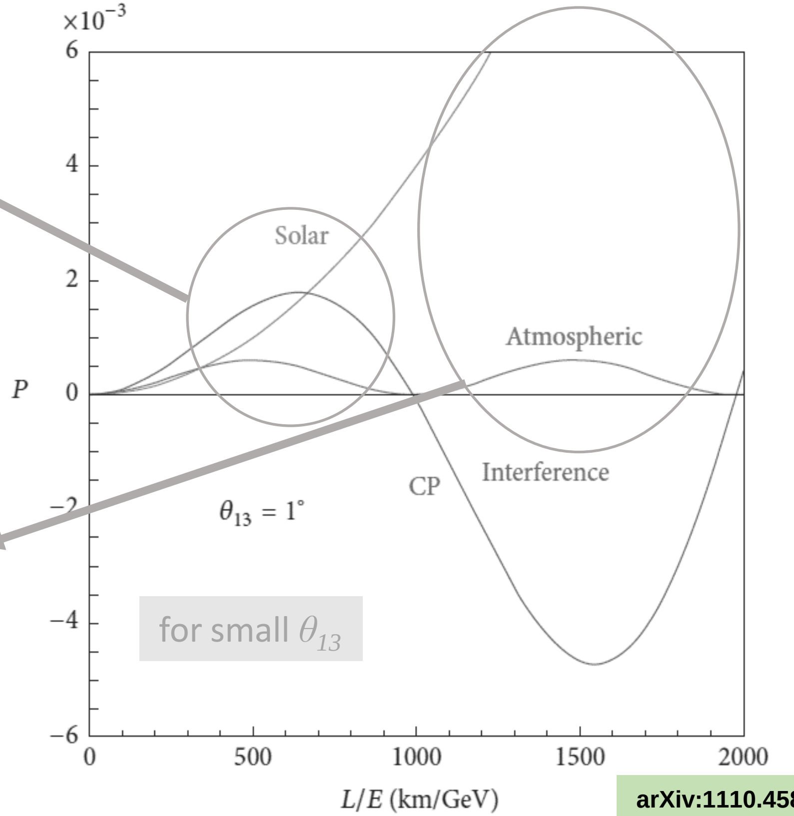
$$P(\nu_\mu \rightarrow \nu_e) = sin^2\theta_{23} sin^2 2\theta_{13} sin^2\left(\frac{\Delta m_{31} L}{2}\right)$$
$$+ cos^2\theta_{23} sin^2 2\theta_{12} sin^2\left(\frac{\Delta m_{21} L}{2}\right)$$
$$+ \bar{J} cos\left(\delta_{CP} - \frac{\Delta m_{31} L}{2}\right) sin\left(\frac{\Delta m_{21} L}{2}\right) sin\left(\frac{\Delta m_{31} L}{2}\right)$$

θ_{13} found to be at higher values ~ **8°**

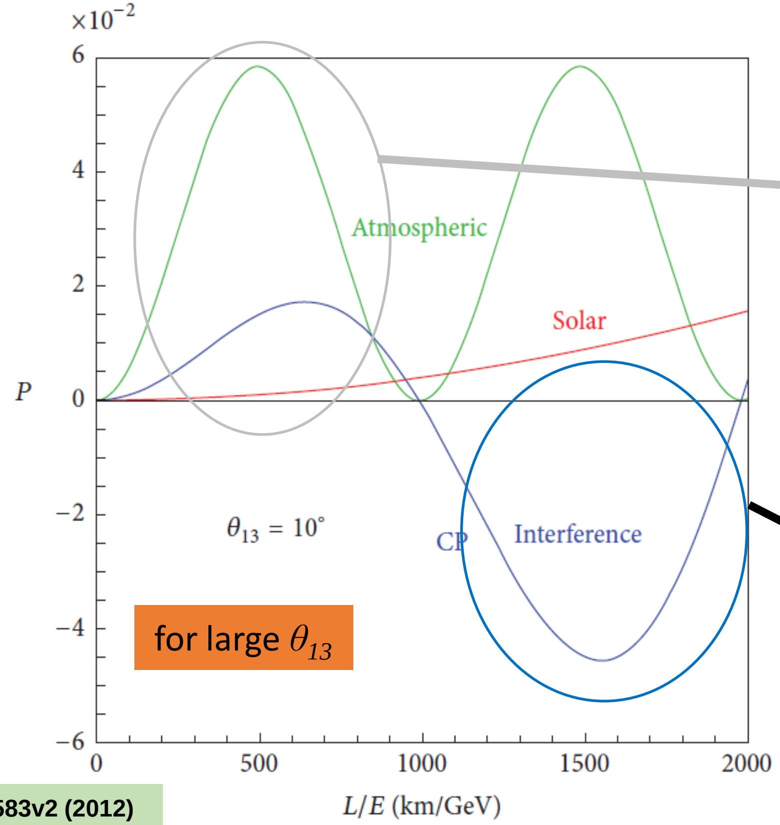
CPV is best studied at 2nd Oscillation maximum

@ 1st oscillation max.
CP-interference dominates

@ 2nd oscillation max.
Solar term dominates



for small θ_{13}



for large θ_{13}

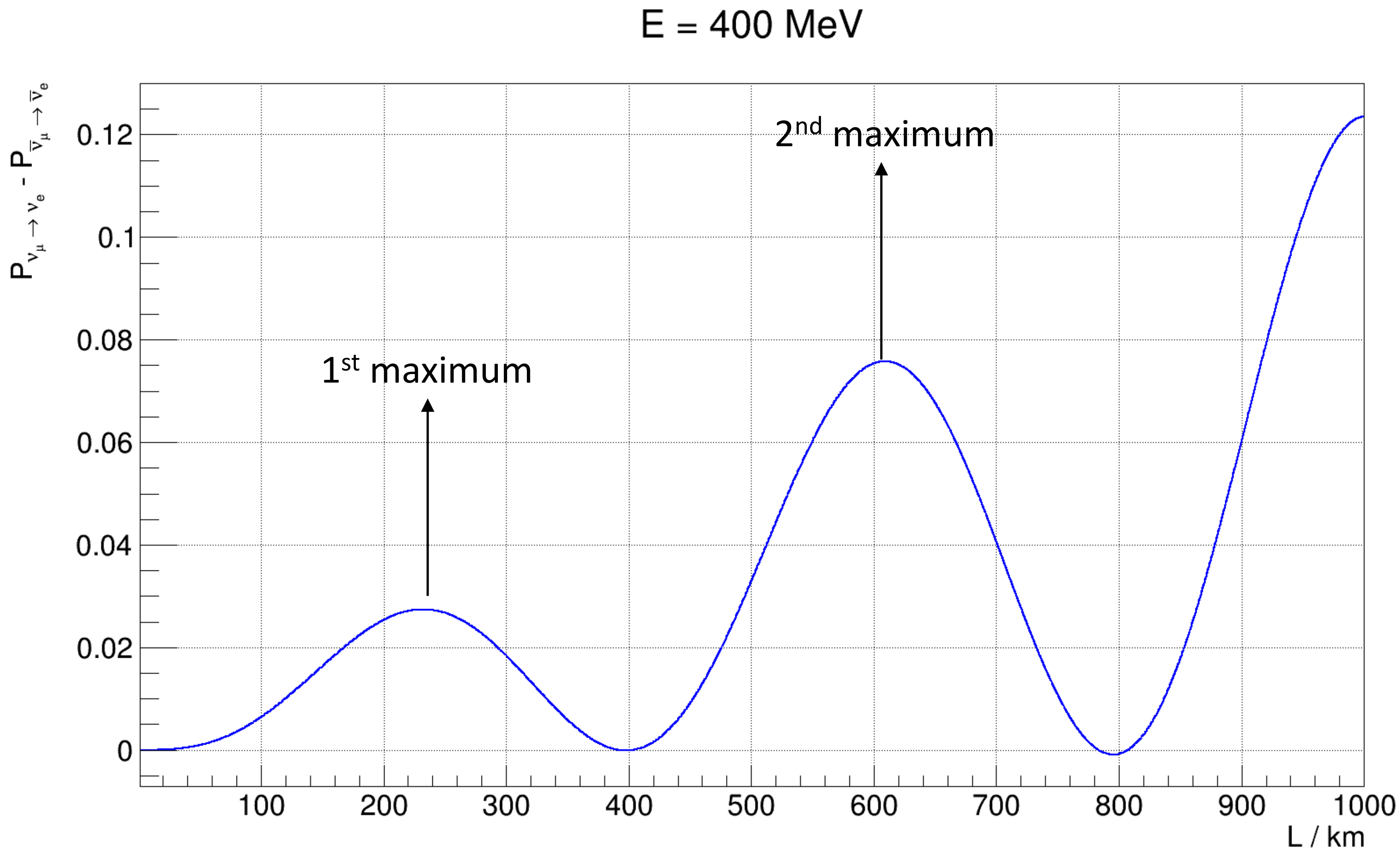
@ 1st oscillation max.
Atm. term dominates

@ 2nd oscillation max.
CP-interference dominates

arXiv:1110.4583v2 (2012)

Neutrino Oscillations (Leptonic CP-Violation)

$$A_{CP} \equiv P_{\nu_\mu \to \nu_e} - P_{\overline{\nu}_\mu \to \overline{\nu}_e} = -16J \sin\frac{\Delta m^2_{31} L}{4E} \sin\frac{\Delta m^2_{32} L}{4E} \sin\frac{\Delta m^2_{21} L}{4E}$$



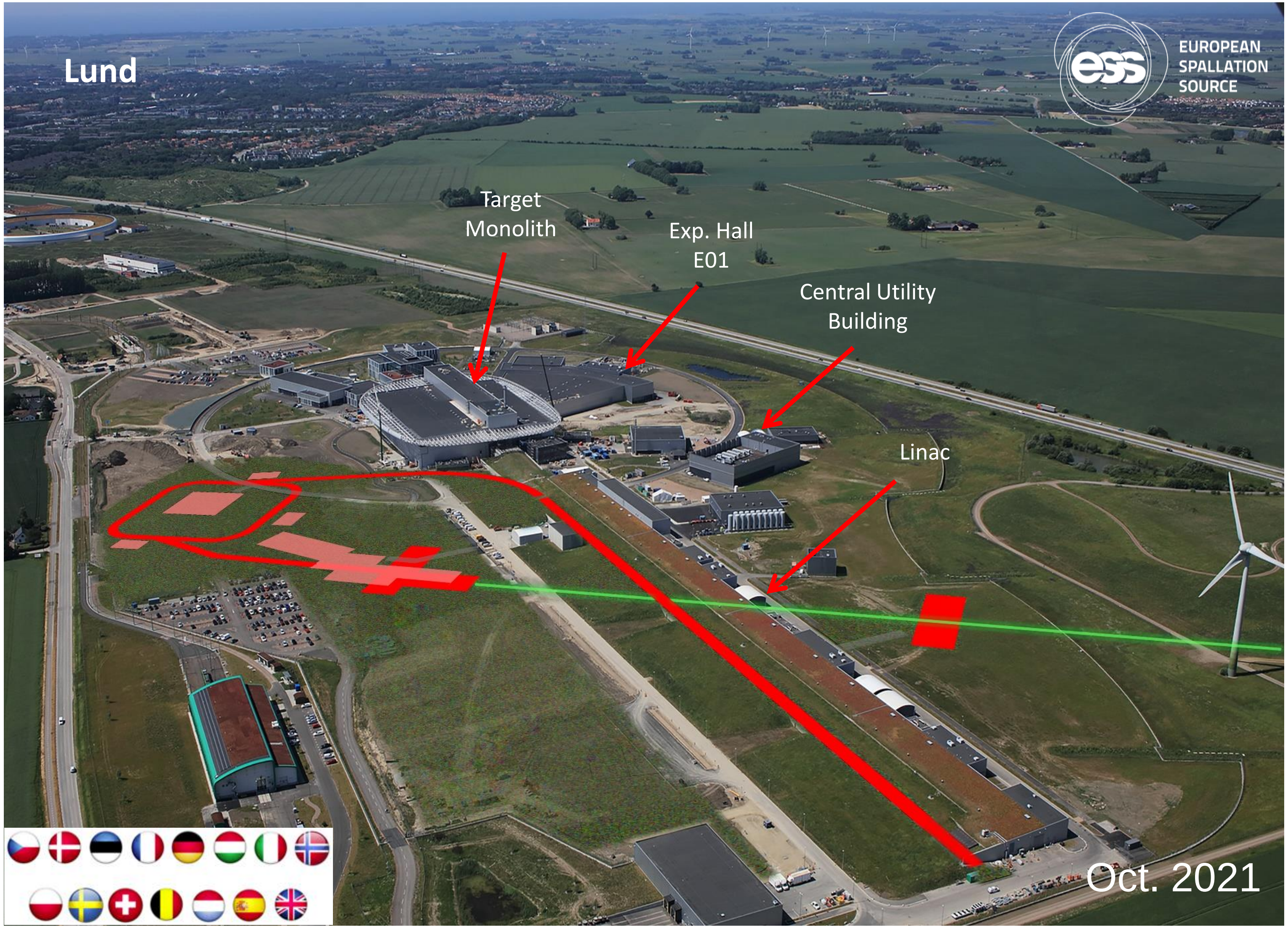
$$s_{ij} \equiv \sin\theta_{ij}$$
$$c_{ij} \equiv \cos\theta_{ij}$$
$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$
$$A^{\alpha\beta}_{ij} \equiv U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}$$

$$\frac{A_{CP} \text{ @ 2nd max}}{A_{CP} \text{ @ 1st max}} \sim 2.7$$

- Does not depend on *J*, i.e. PMNS matrix elements
- Depends only on mass splittings

The European Spallation Source (ESS) layout

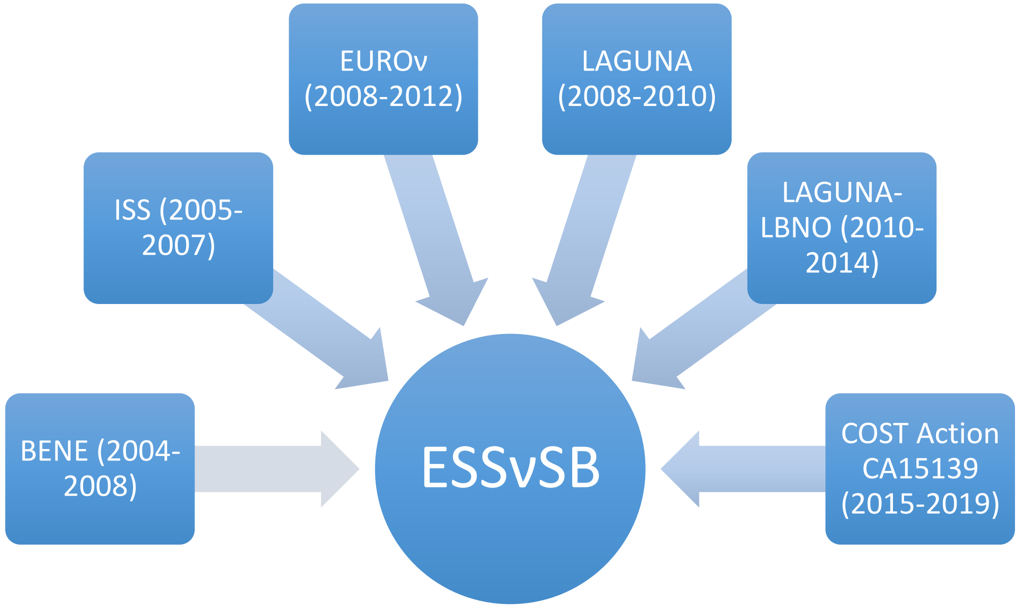
- The ESS facility is under construction in Lund, Sweden
- The most powerful proton linear accelerator ever built, with beam kinetic energy of 2 GeV and power of 5 MW
- The world's most powerful neutron source (ca. 40×10^{15} $n\cdot cm^{-2}\cdot s^{-1}$)



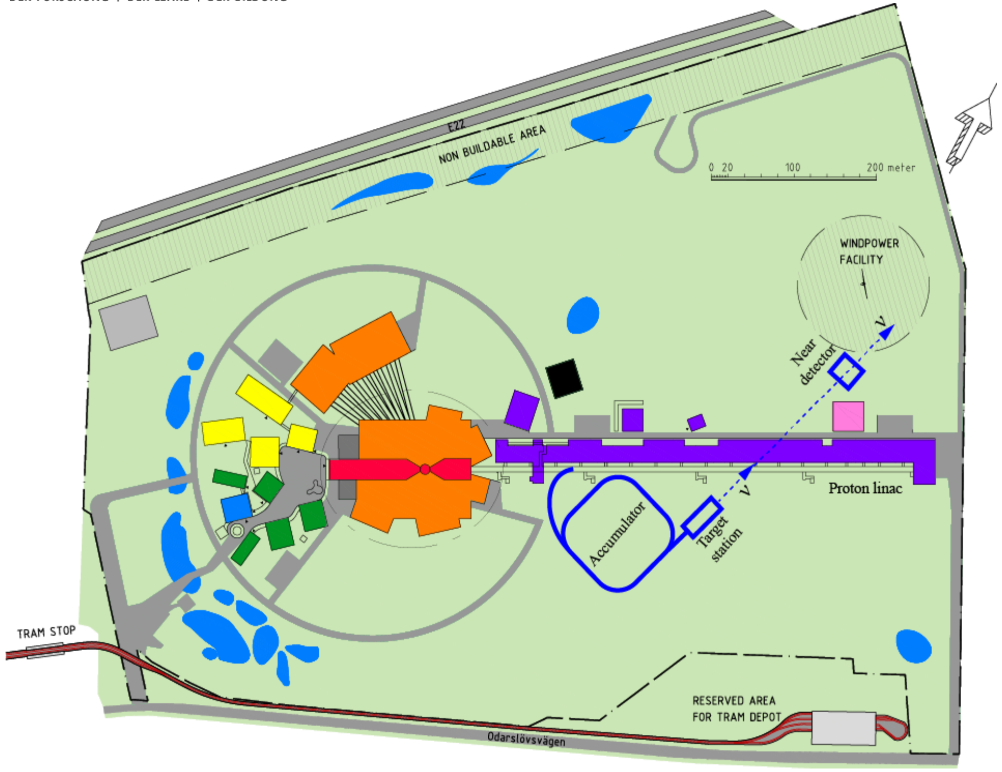
ESSνSB at the European Level

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**

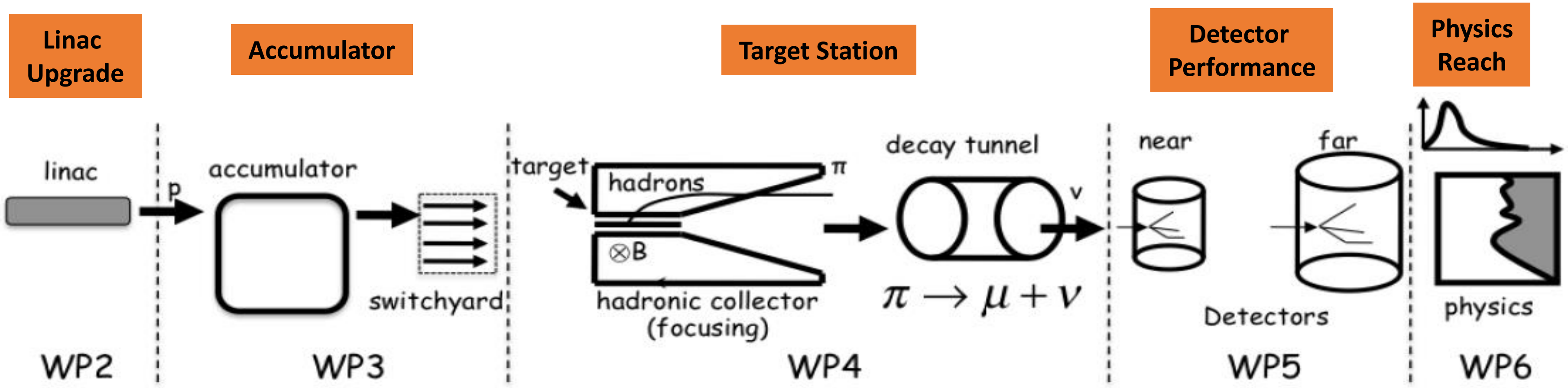


The European Spallation Source neutrino Super Beam (ESSνSB)



- It will benefit from the powerful proton beam of the ESS LINAC to produce intense neutrino beam.
- Aims at searching and measuring, with precision, for CP-violation in the leptonic sector, at 5σ significance level in more than 70% of the leptonic Dirac CP violating phase range,
- The neutrino source-to-detector distance, the baseline, is set at the **second oscillation maximum.**

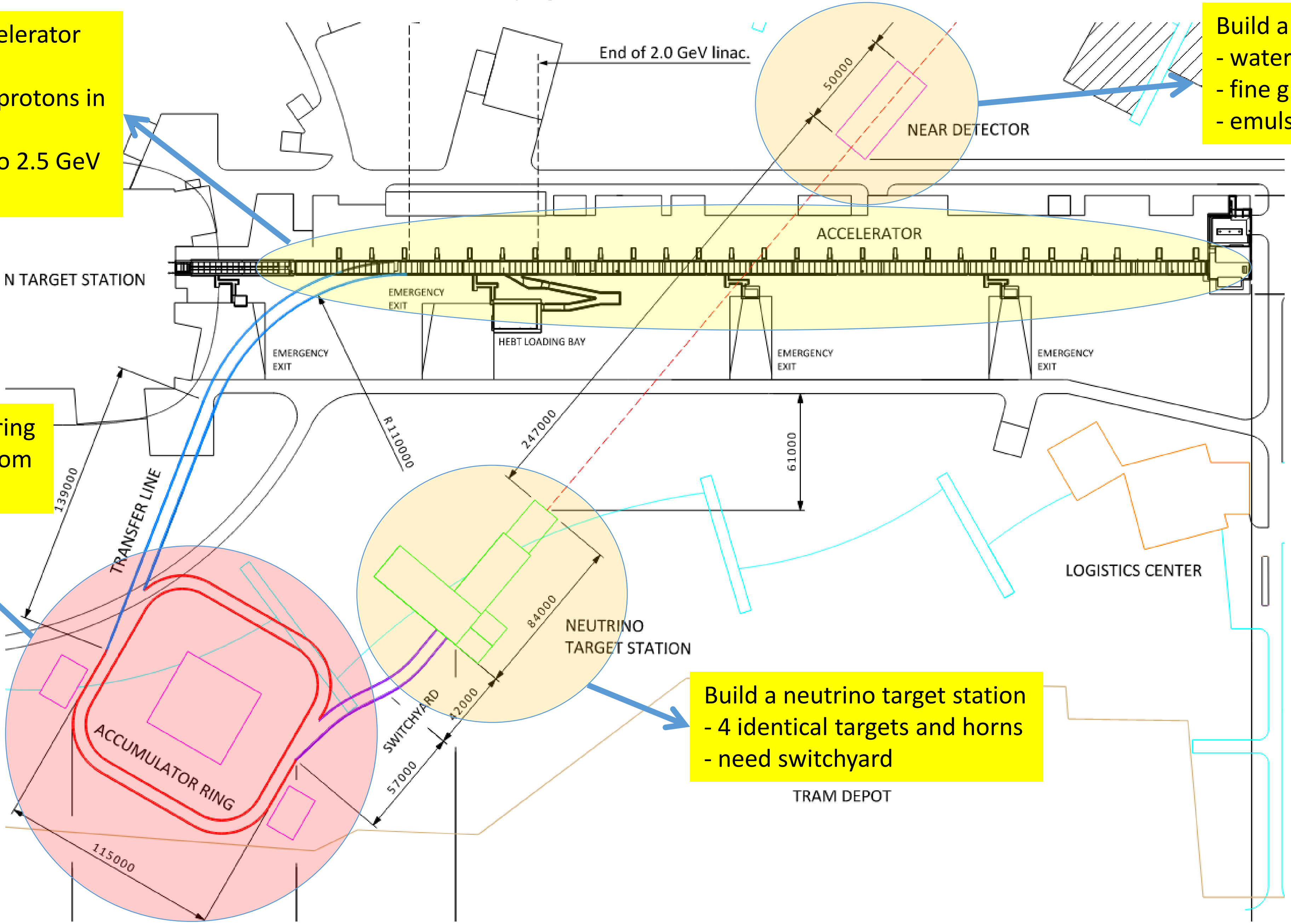
A schematic overview of the main work packages (WP) within the ESSνSB project



Upgrades to the ESS site

Upgrade of the accelerator
- 14 Hz to 28 Hz
- use H^- instead of protons in ESSnuSB cycles
- increase energy to 2.5 GeV kinetic

Build a near detector site
- water Cherenkov detector
- fine grained scintillator
- emulsion detector



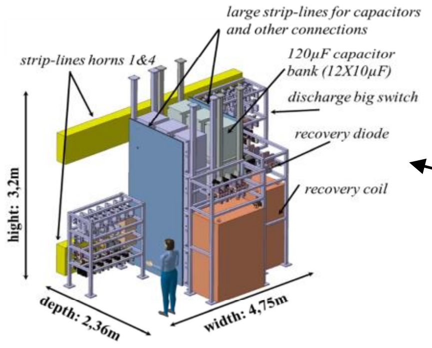
Build an accumulator ring
- shorten ESS pulses from 2.86 ms to ≈ 1 µs

Build a neutrino target station
- 4 identical targets and horns
- need switchyard

ESSνSB Target Station Facility

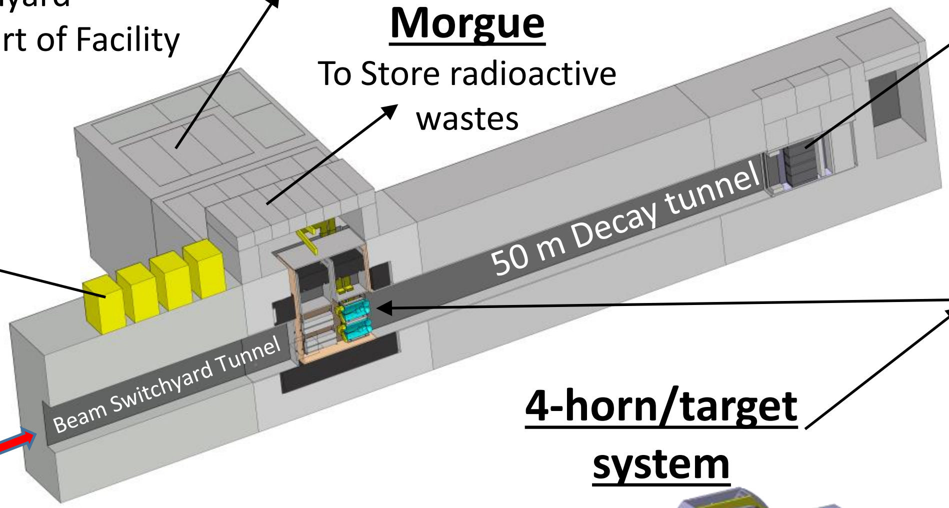
To produce $\nu_\mu(\bar{\nu}_\mu)$ beam and to withstand the energy deposition from the 5 MW proton beam on the 4-horn/target system

Power Supply Unit
- 16 modules (350 kA, 1.3 μs)
- Located above the switchyard
- Outside of radioactive part of Facility

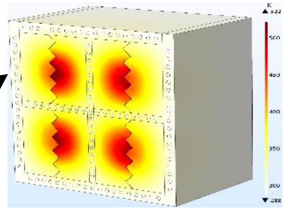


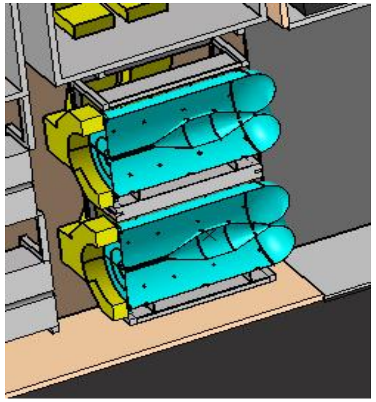
Hot Cell
- Able to manipulate/repair hadronic collector
- Work under Radioactive Environment

Morgue
To Store radioactive wastes

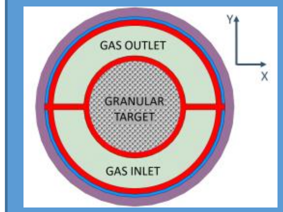


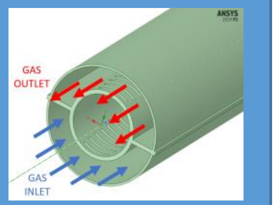
Beam dump

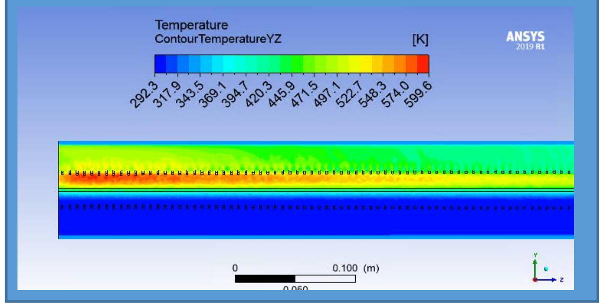




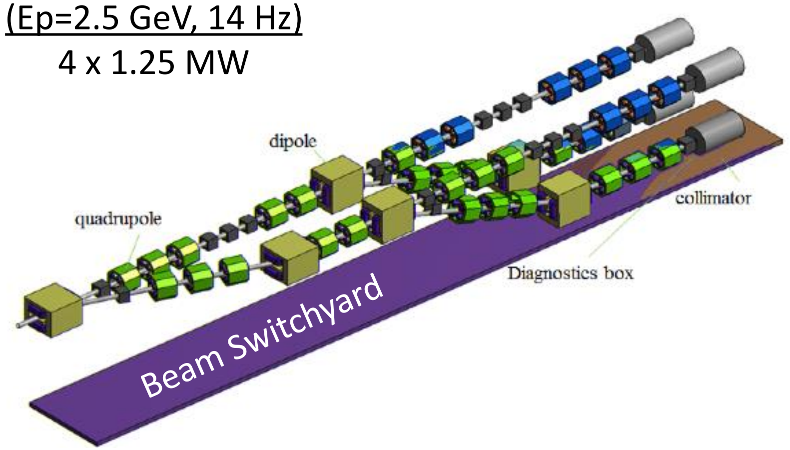
Granular Target Concept
- Target made of 3 mm titanium spheres cooled by transverse helium gas cooling



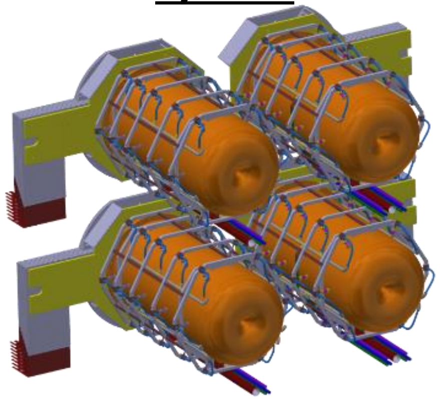




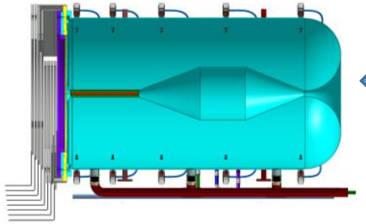
Proton Beam
(Ep=2.5 GeV, 14 Hz)
4 x 1.25 MW



4-horn/target system

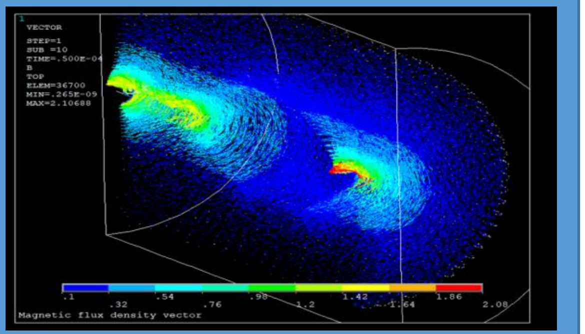


Hadronic Collector



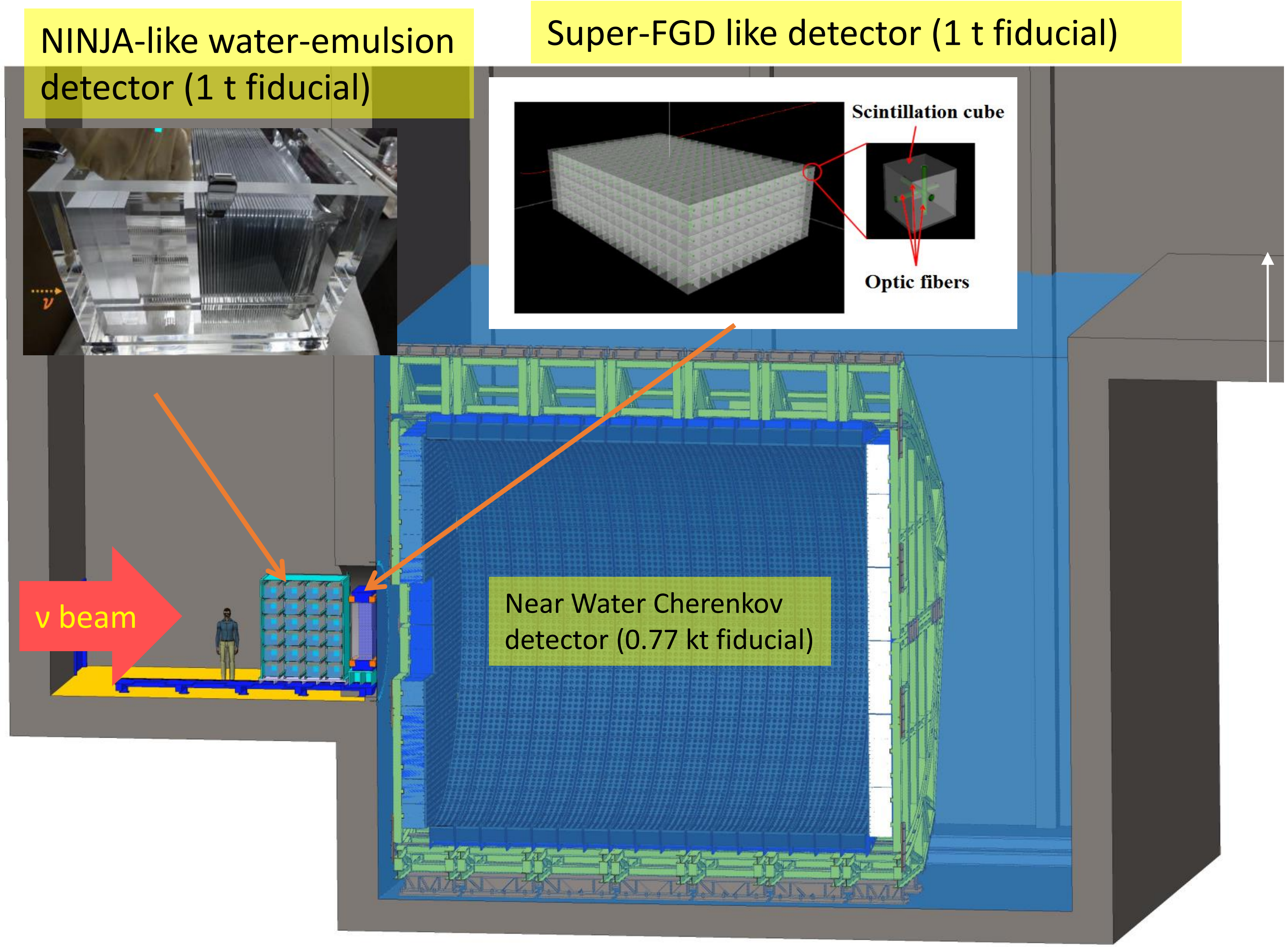
Horn
Shape optimized with genetic algorithm

Magnetic field (350 kA; 1.3 μs pulse)

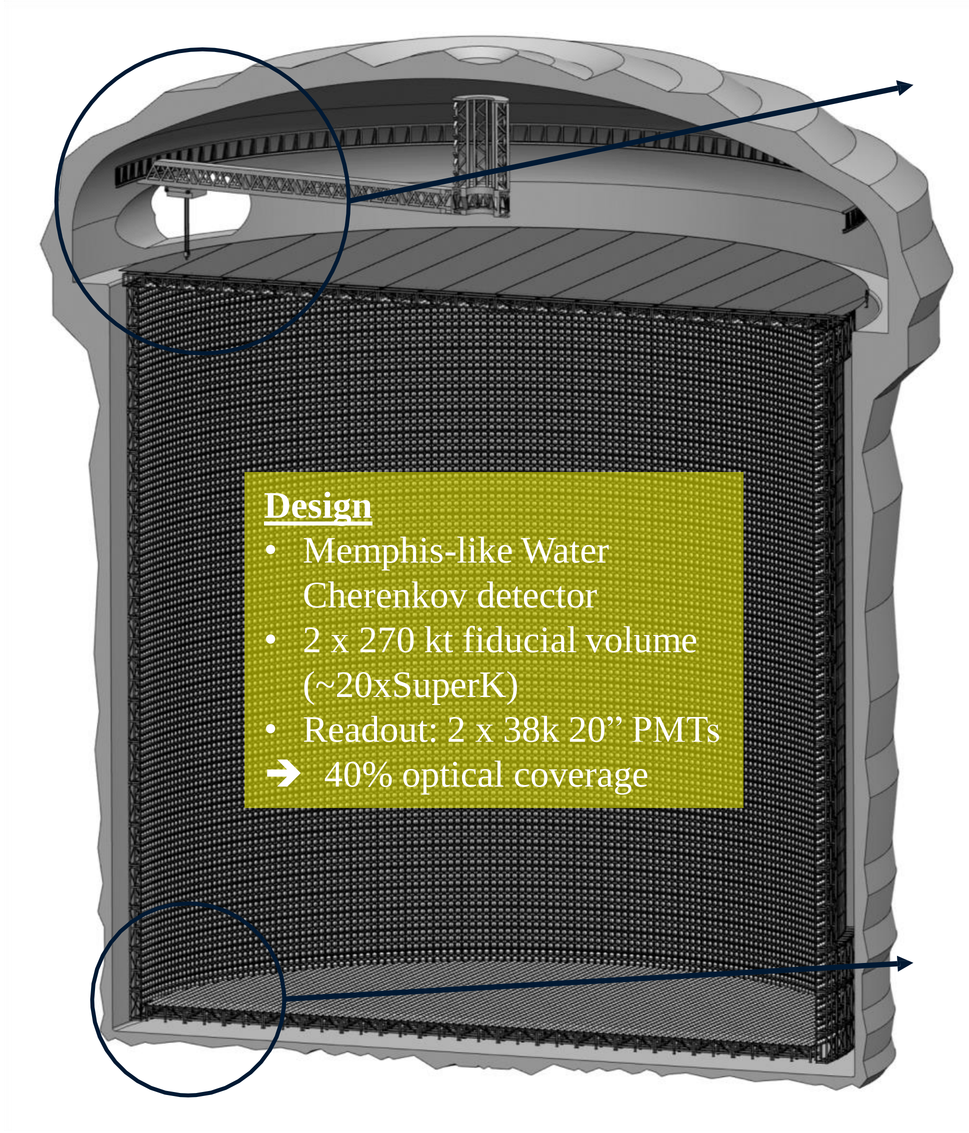


ESSνSB Near Detector

- Baseline ~ 250 m
- Water-Emulsion neutrino detector for flux and cross sections measurements.
- A 1t Super Fine-grained (SFGD) Scintillator Tracker inside a magnetic field for cross-section measurements.
- A 0.5 kt “fiducial volume” Water Cherenkov detector, for event rate measurements, flux normalization and event reconstruction.

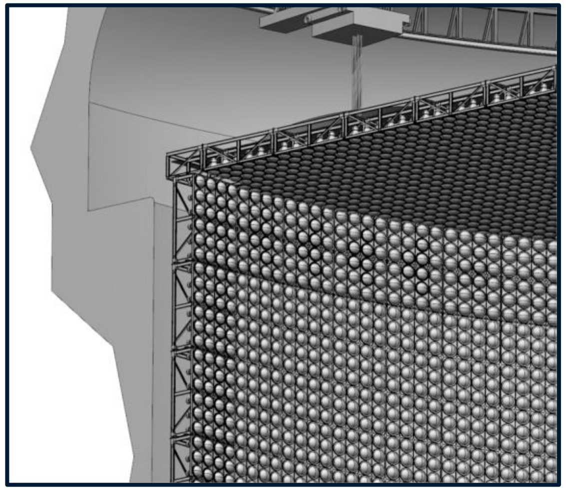


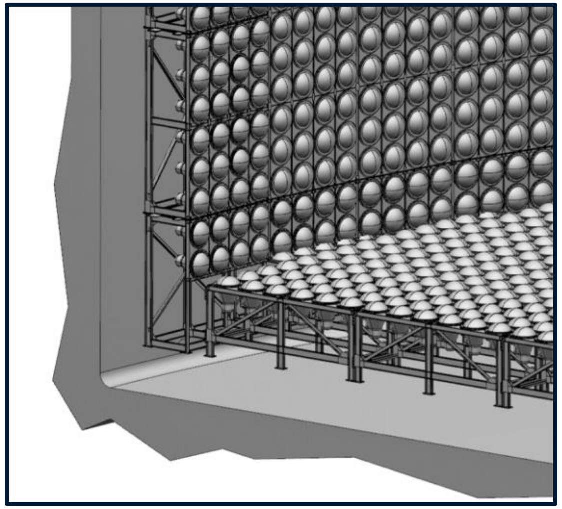
ESSνSB Far Detector



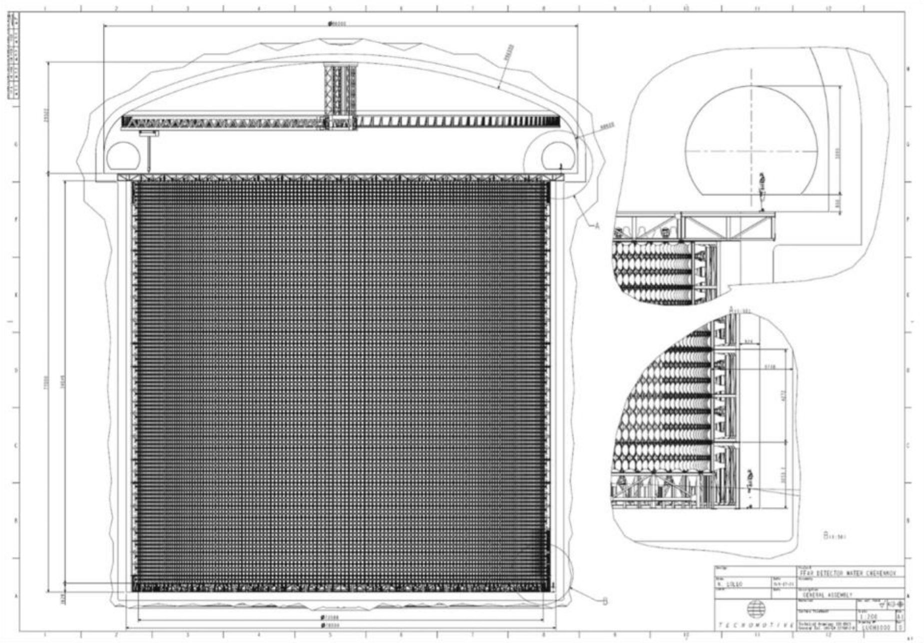
Design
- Memphis-like Water Cherenkov detector
- 2 x 270 kt fiducial volume (~20xSuperK)
- Readout: 2 x 38k 20" PMTs

➔ 40% optical coverage



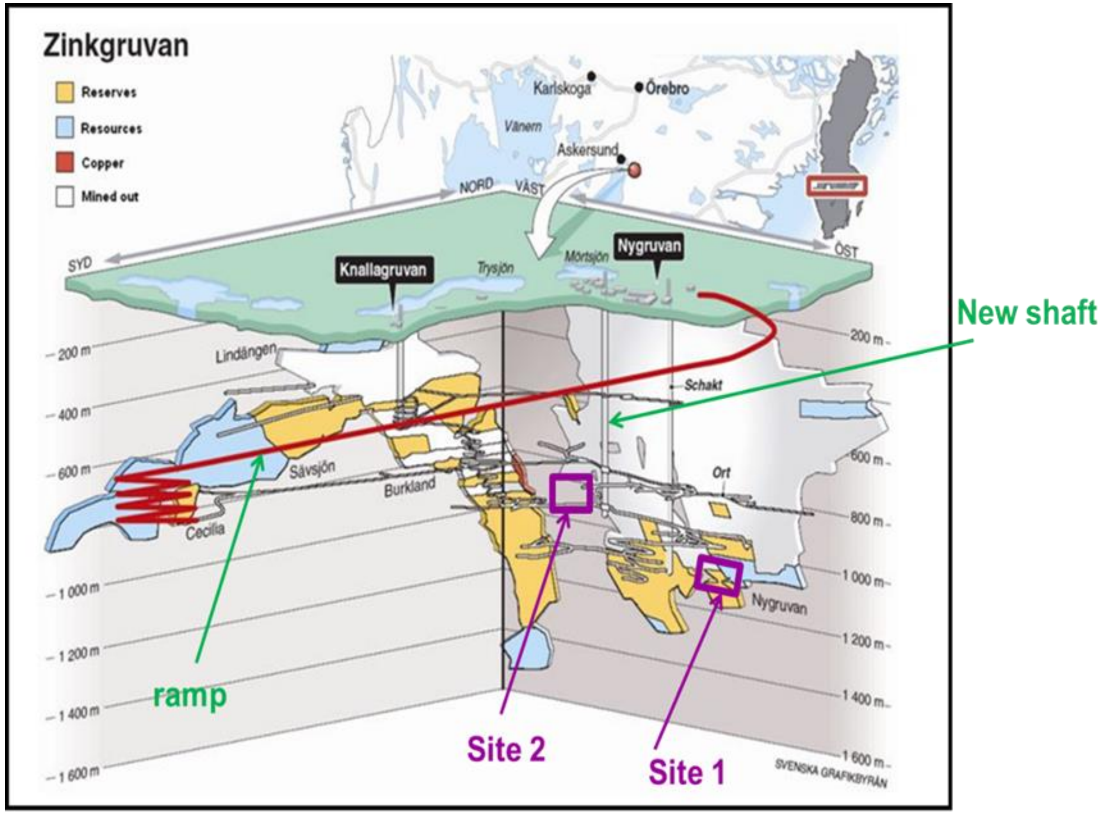


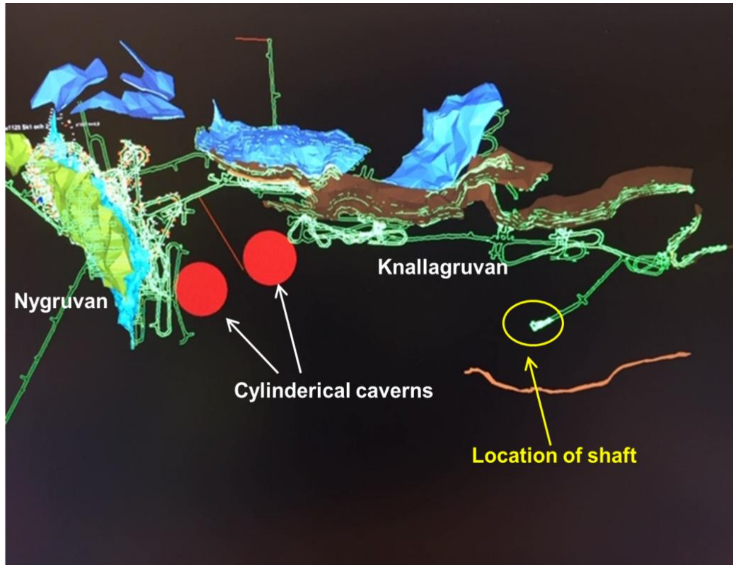
- Baseline 360km (Zinkgruvan mine, Sweden)
- Total Length (external): 86.00m
- Total Width (external): 86.00m
- Height (external) : 97.52m
- Depth (w.r.t.) ground level : 1000.00 m
- Detector Radius 73.60 m (Internal)-78.00 m (external)



ESSνSB Far Detector site

Zinkgruvan mine





Site 2 in Zinkgruvan mine is considered as best considering access to main transport infrastructure and located in an area less disturbed by mining activities

ESSνSB Neutrino Beam

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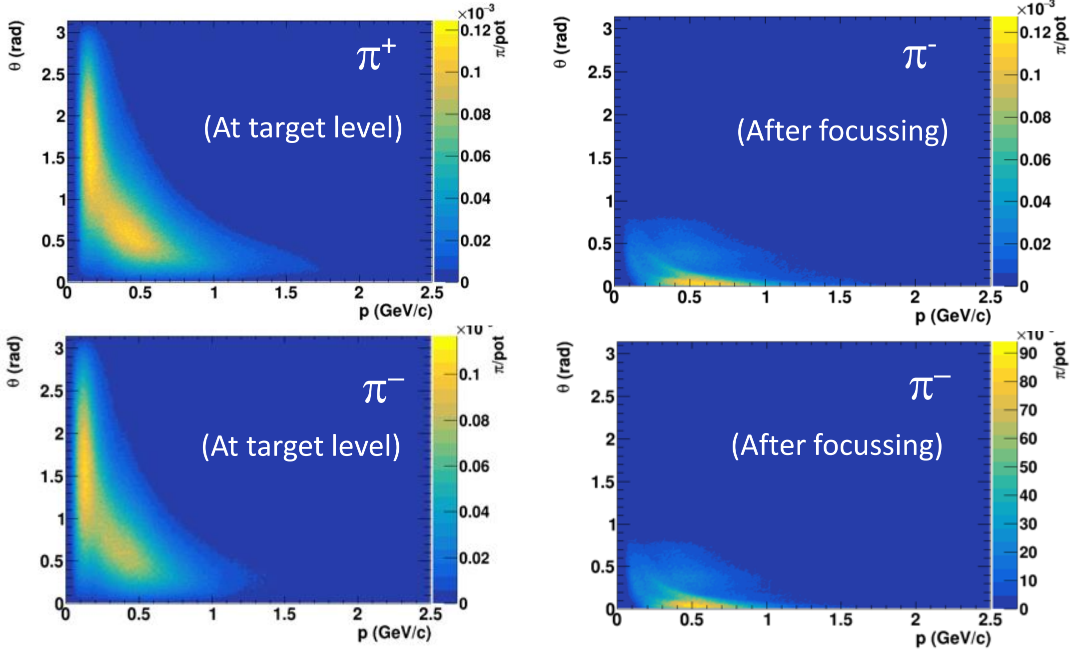
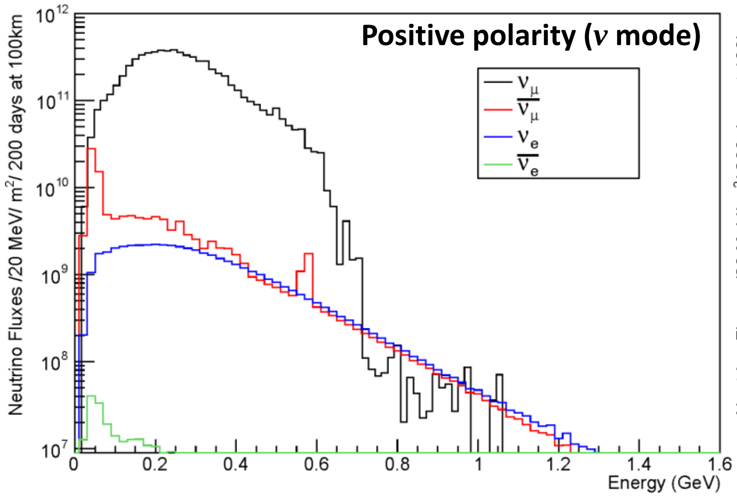
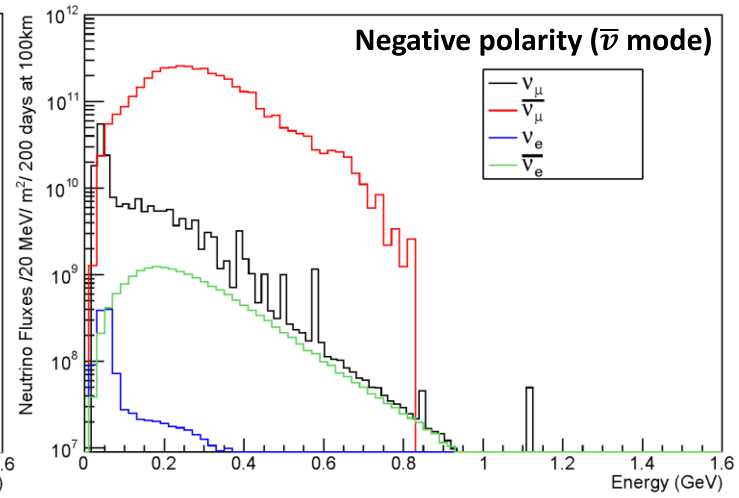
$\pi^+ \rightarrow \mu^+ + \nu_\mu$
(Positive polarity)

$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
(Negative polarity)







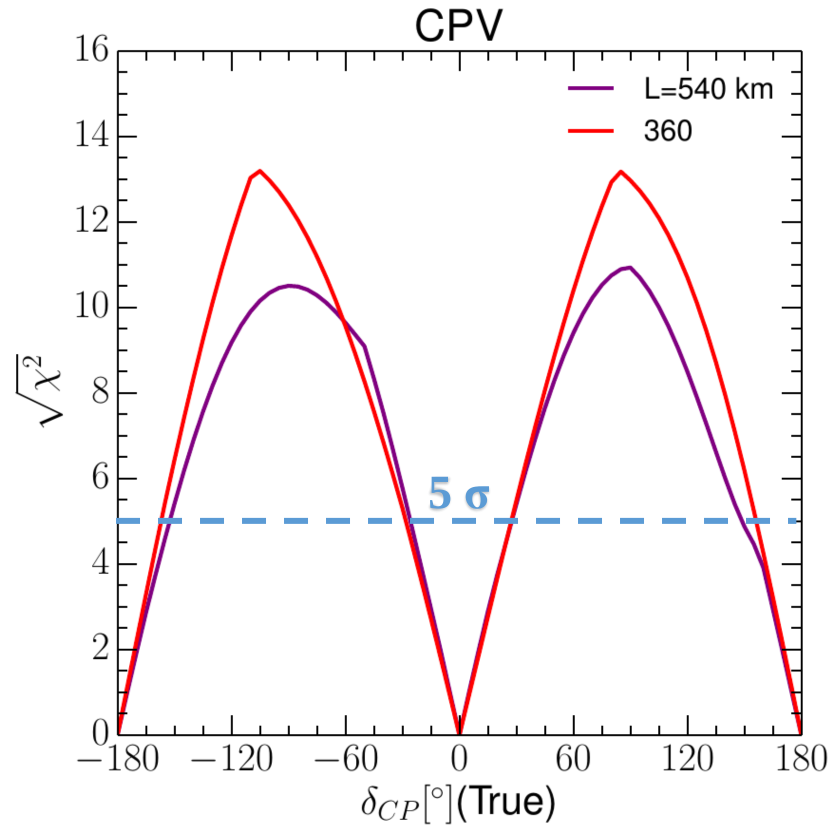
Neutrino flux at 100 km from the target per year (in absence of oscillations)

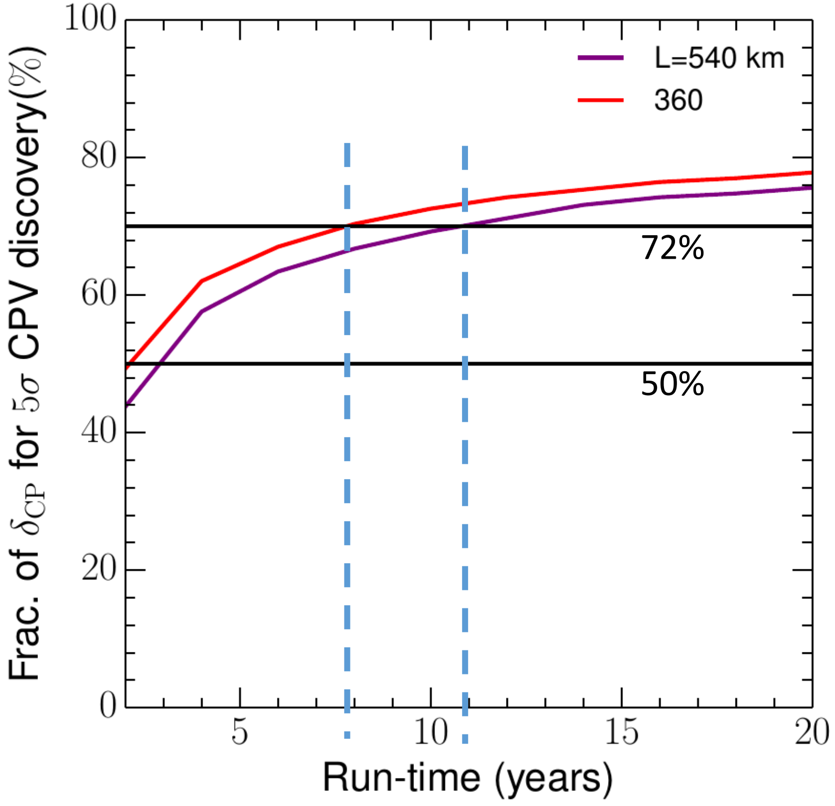
- Almost pure ν_μ beam
- Small ν_e contamination which could be used to measure ν_e cross-sections in the near detector

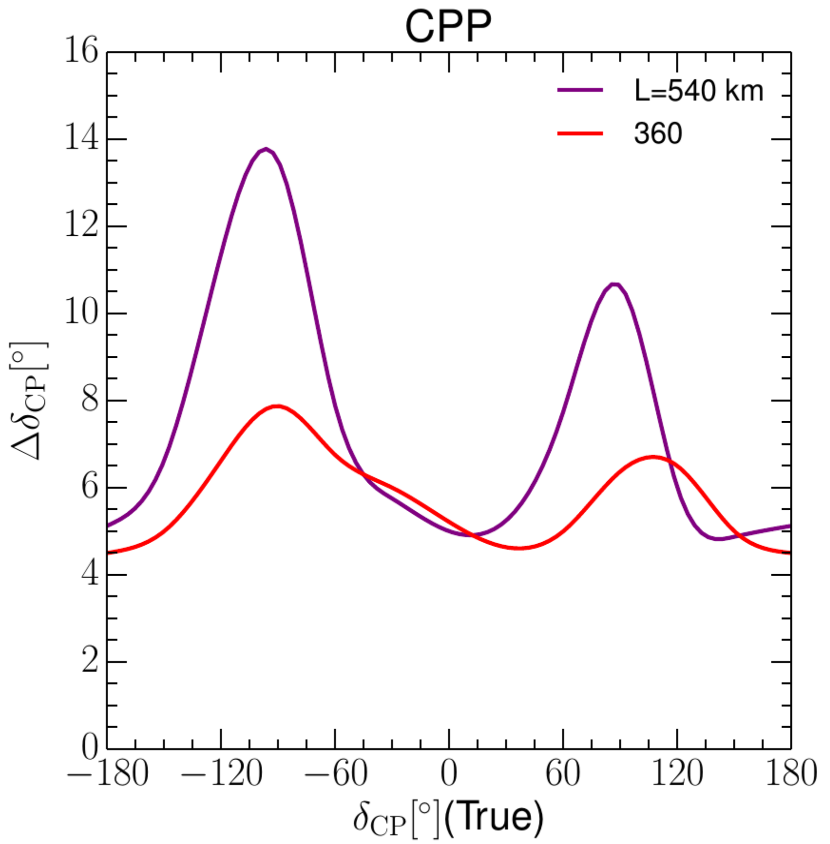
Flavor	ν Mode		$\overline{\nu}$ Mode	
	$N_\nu(10^{10}/\text{m}^2)$	%	$N_\nu(10^{10}/\text{m}^2)$	%
ν_μ	674	97.6	20	4.7
$\overline{\nu}_\mu$	11.8	1.7	396	94.8
ν_e	4..76	0.67	0.13	0.03
$\overline{\nu}_e$	0.03	0.03	1.85	0.43

ESSνSB Physics Reach

[A. Alekou *et al.*, *“Updated physics performance of the ESSnuSB experiment”* Eu. Phys. J. C 81, (2021) 1130]







Sensitivity for $\delta_{CP} = \pm \pi/2$:
11 σ (540 km)
13 σ (360 km)

72% δ_{CP} coverage @ 5 σ:
11 years (540 km)
8 years (360 km)

High precision of δ_{CP} measurement

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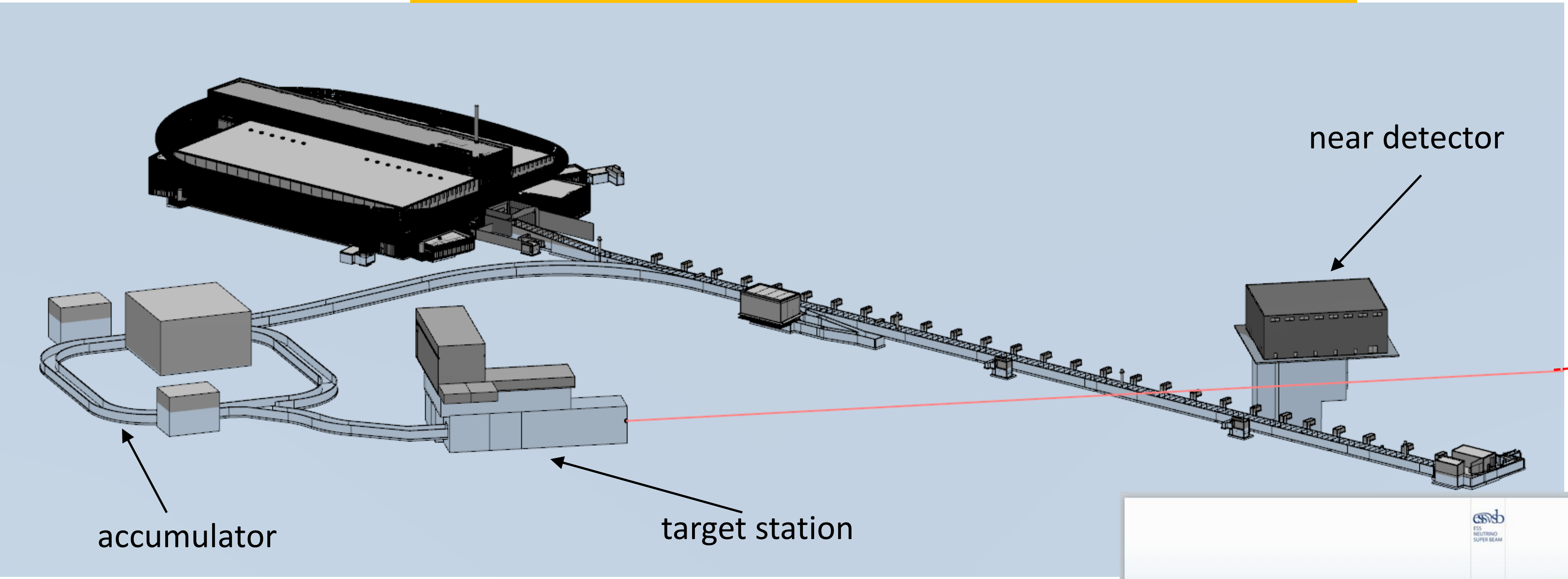
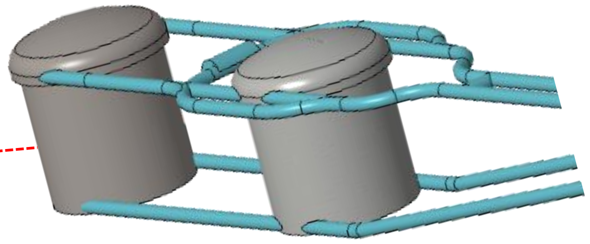
ESSνSB Final Facility Configuration

ESSνSB phase-I has been concluded in March 2022

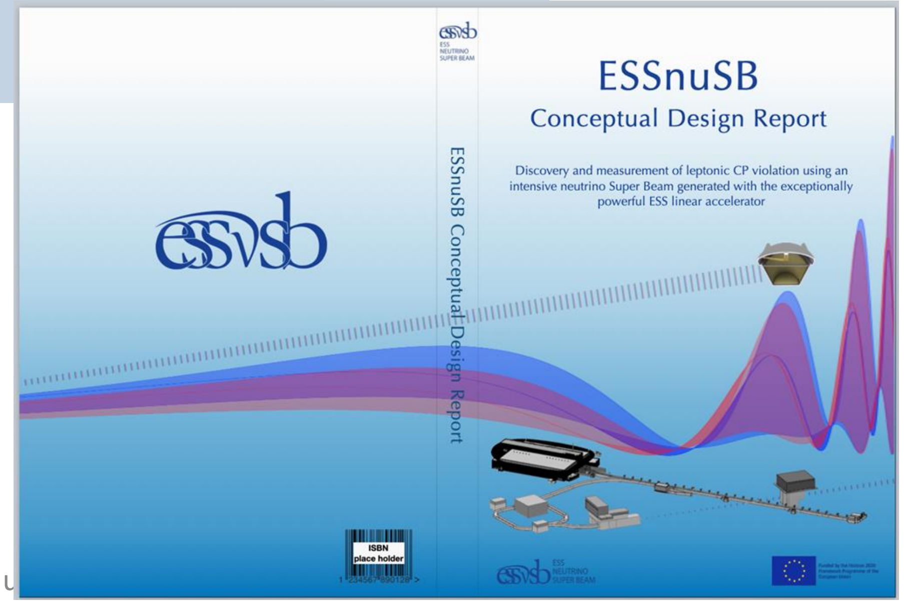


far detector

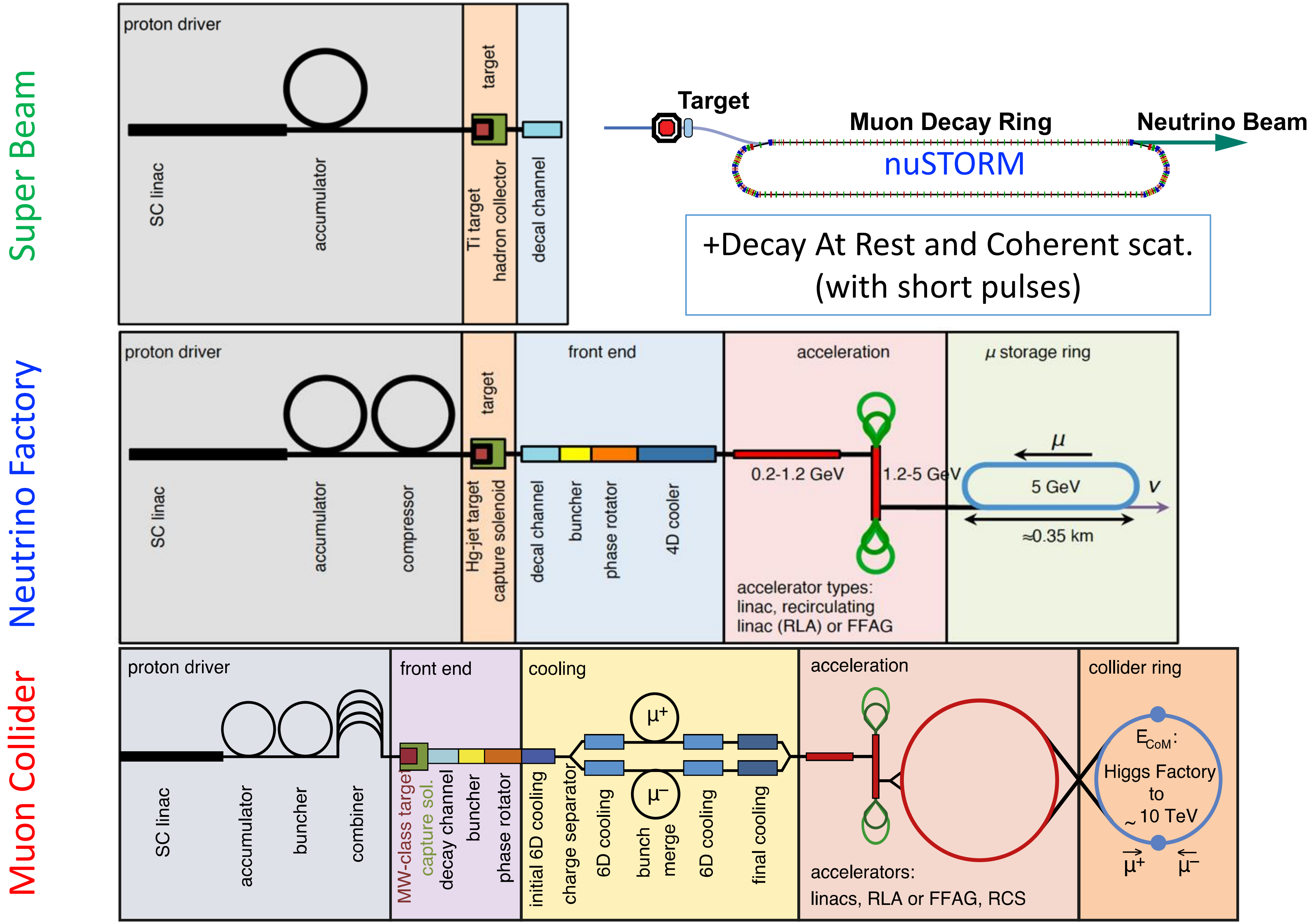


Conceptual Design Report

Eur. Phys. J. ST. 231 (21), (2022) 3779



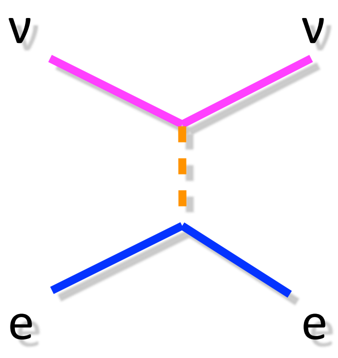
ESSνSB Future Opportunities



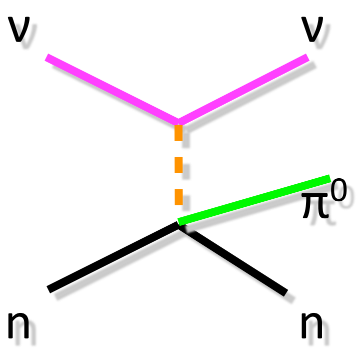
+Decay At Rest and Coherent scat.
(with short pulses)

ESSνSB…Systematic Uncertainities

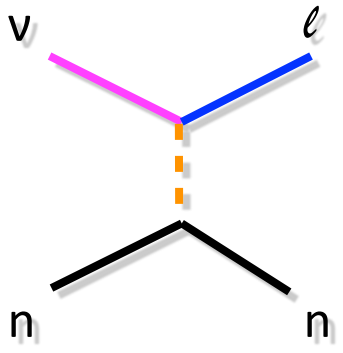
- The influence on δ_{CP} of the systematic errors will be close to three times smaller as compared to other experiments
- Even so, it is of vital importance to measure the neutrino cross-sections in this energy range as precisely as possible for precise measurements of the δ_{CP}, especially since data on neutrino cross-sections in the neutrino energy range of ESSvSB, 0.2-0.6 GeV, is currently very scarce



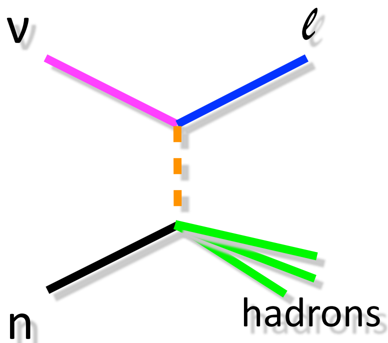
Elastic



Resonant (RES)

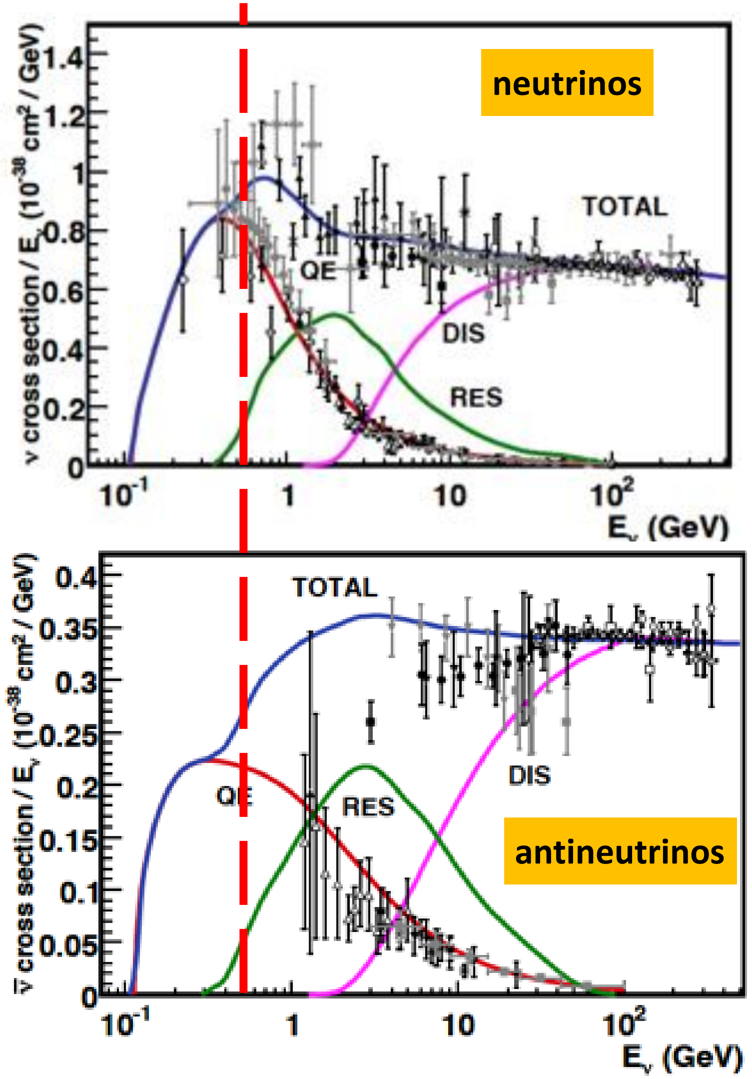


Quasi-Elastic (QE)



Deep inelastic (DIS)

Missing measurements at the ESSvSB region: below 500 MeV



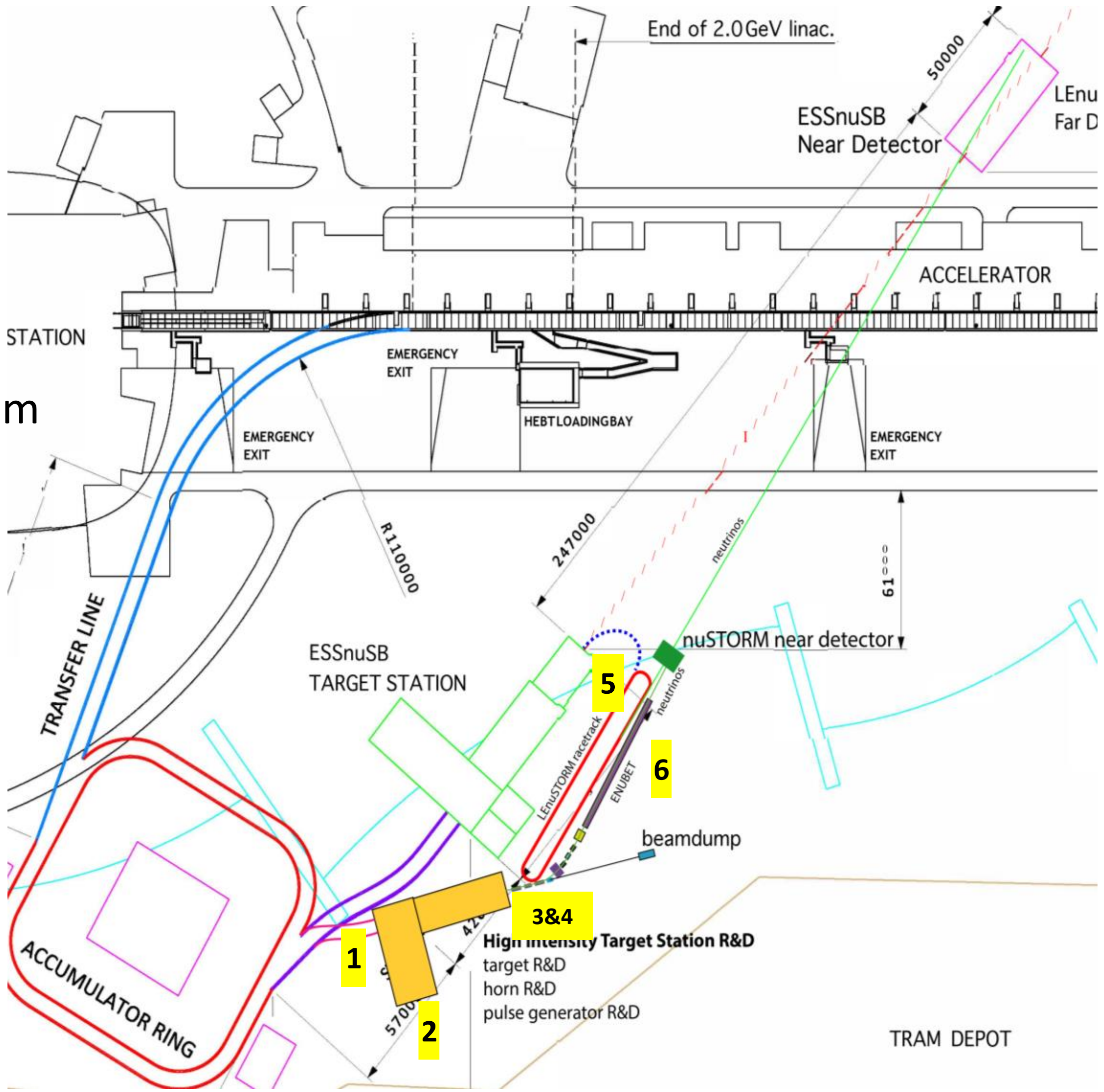
From eV to EeV: Neutrino cross sections across energy scales, *Rev. Mod. Phys. 84, 1307 – Published 24 September 2012*

Upcoming Studies
(mainly cross-section measurements)

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 a **transfer line** from the ESSνSB accumulator ring to the target
2. Design a **special target facility** that depends on one horn-target system
3. Design a pion **extraction and deflection system**
4. Design an **injection scheme** for the extracted pions to the racetrack storage ring, where the pions will decay to muons
5. Design a **storage ring** for the low energy nuSTROM (for cross section measurements and sterile neutrino searches)
6. Design a **Monitored Neutrino Beam** (low energy ENUBET for cross section measurements)
7. **Optimize the performance** of the ESSνSB detectors



The European Spallation Source neutrino Super Beam plus

Research and Innovation actions

Innovation actions

And the EU decision arrived earlier than expected… 26/07/2022

Design Study

HORIZON-INFRA-2022-DEV-01

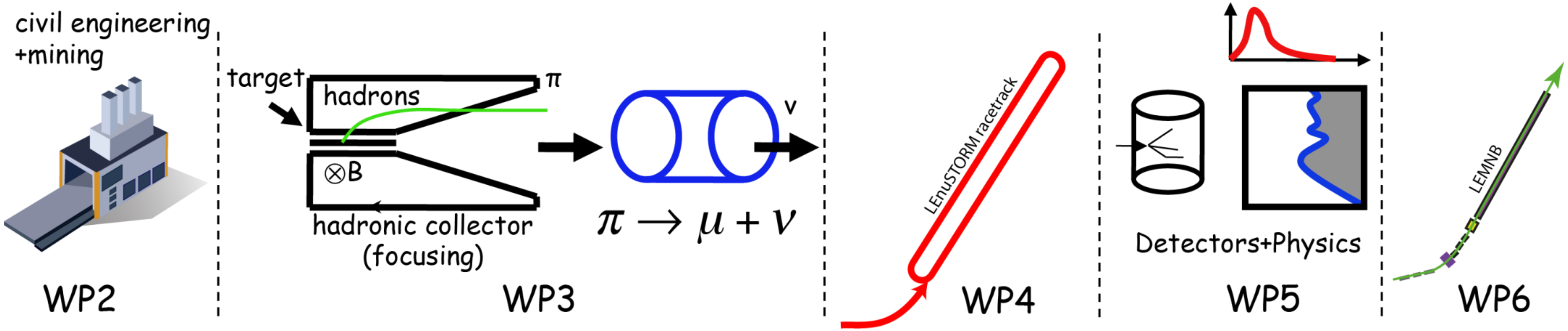
3 M€

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+

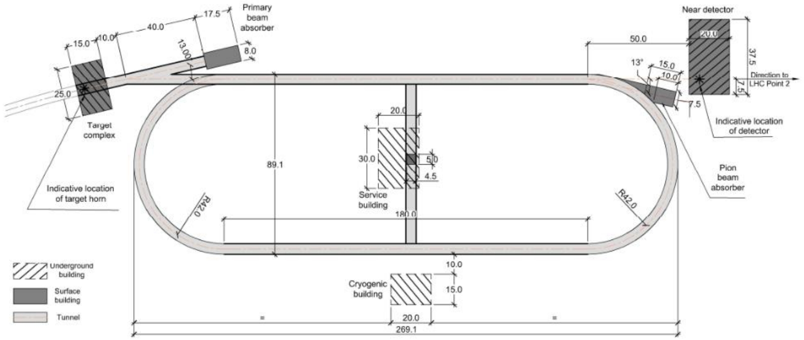

ESS neutrino Super Beam plus
Co-funded by the European Union
CERN CONTROL CENTRE
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
ÇUKUROVA UNIVERSITY 1973
CERN
LULEÅ UNIVERSITY OF TECHNOLOGY
ess
Université de Strasbourg
ROMA TRE UNIVERSITÀ DEGLI STUDI
UNIVERSITÀ DEGLI STUDI DI PADOVA
ARISTOTLE UNIVERSITY OF THESSALONIKI
UPPSALA UNIVERSITET
LUNDS UNIVERSITET
KTH VETENSKAP OCH KONST
名古屋大学 NAGOYA UNIVERSITY
cnrs
INFN Istituto Nazionale di Fisica Nucleare
IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG
AGH
UNIVERSITEIT GENT
ESS bilbao
UH Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG
HELLENIC OPEN UNIVERSITY
RB

The European Spallation Source neutrino Super Beam plus

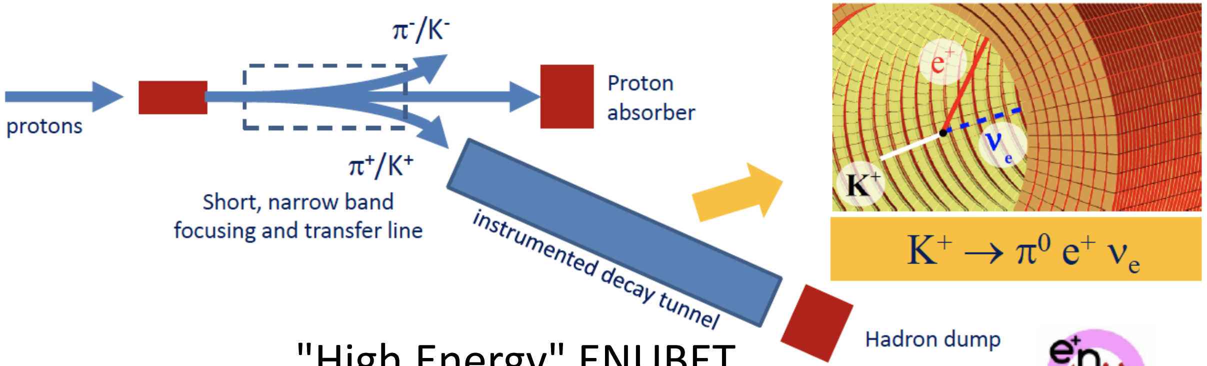


- cross-sections
- sterile neutrinos

- cross-sections



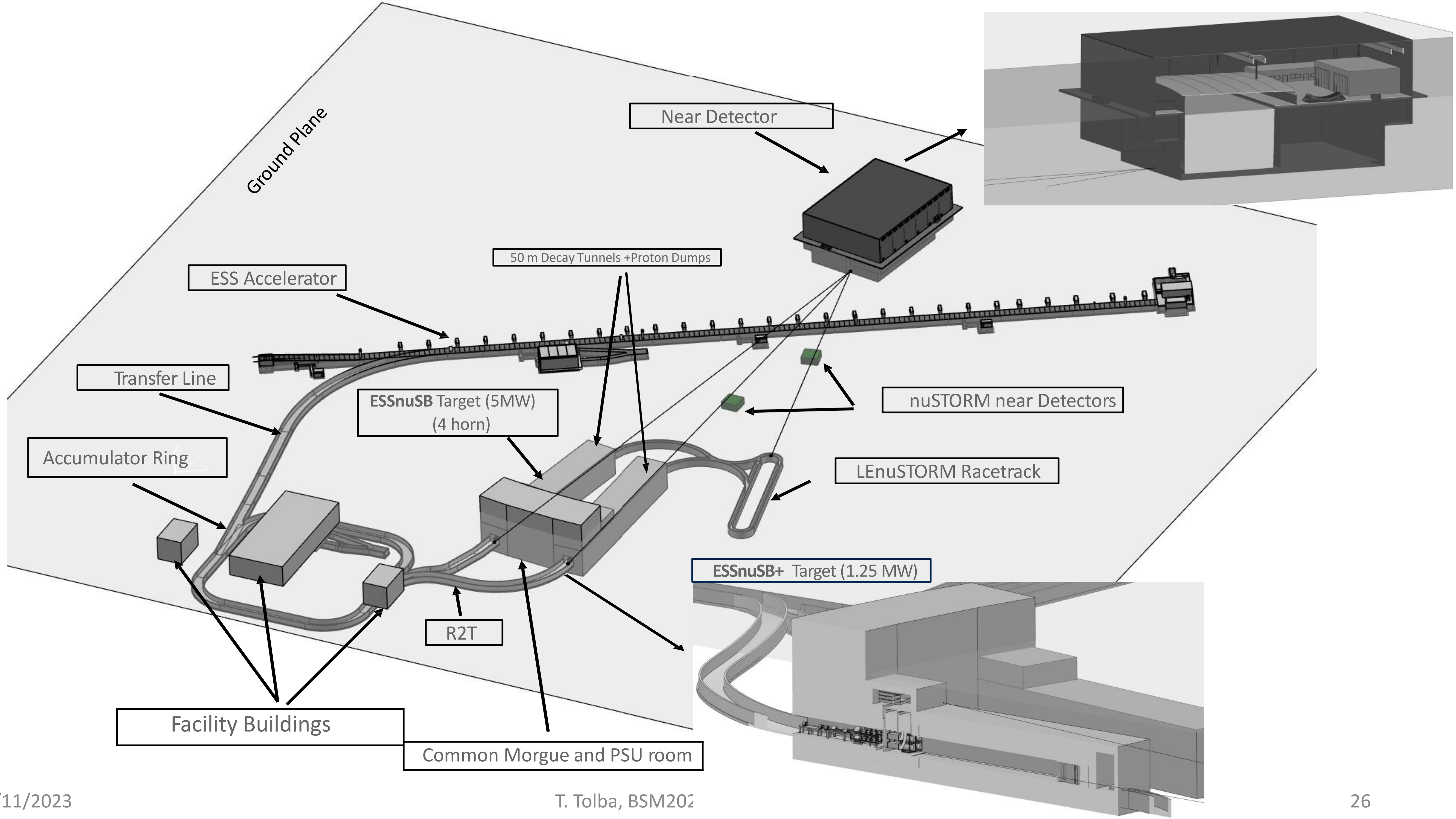
"High Energy" nuSTORM



"High Energy" ENUBET

build a "Low Energy" version

ESS and *ESSvSB and ESSvSB+ site layout*



Conclusion and Outlook

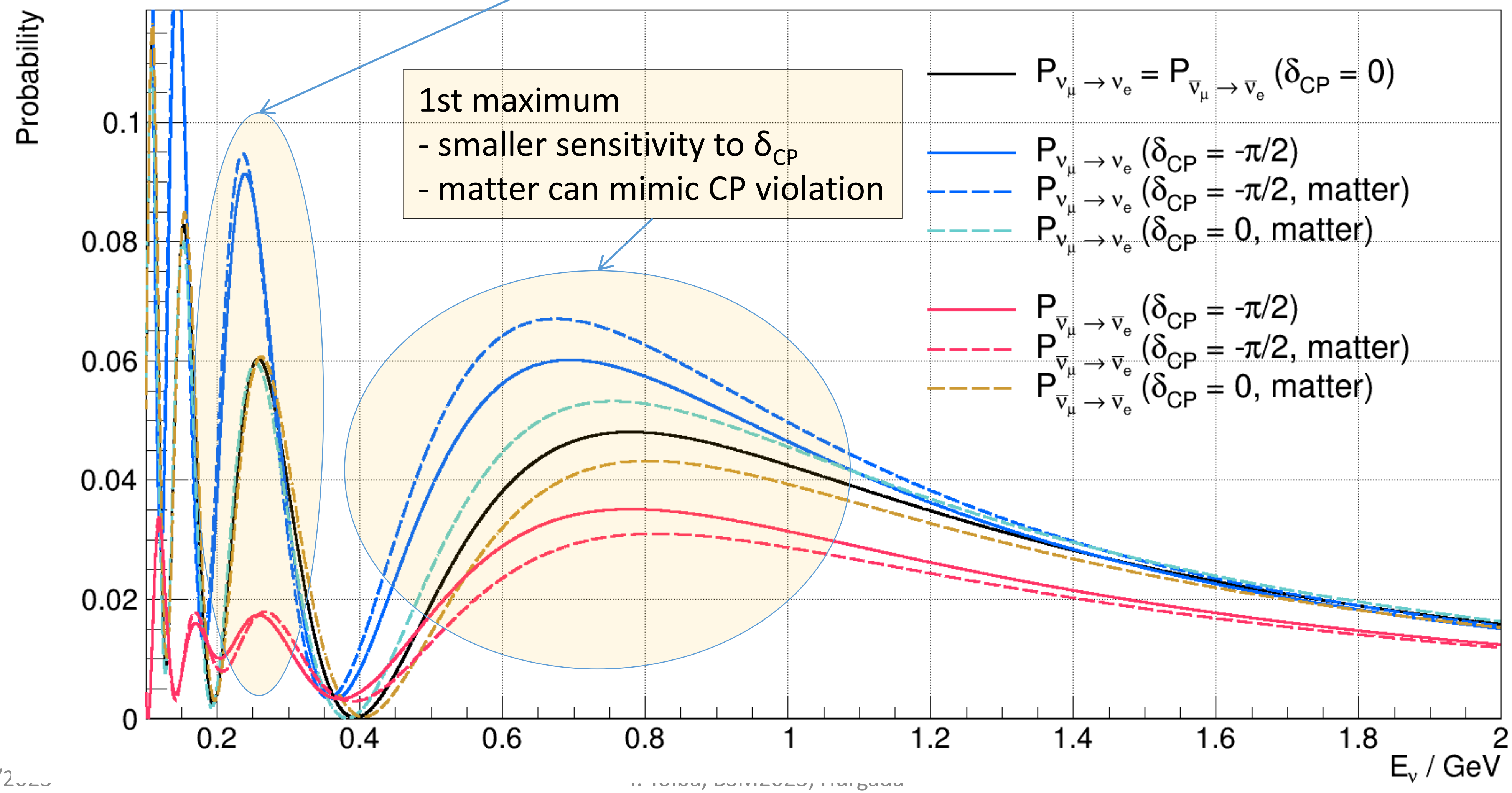
- The ESS proton linac will be soon the most powerful linac in the world, something which cannot be ignored.
- ESS can also become a neutrino facility (ESSνSB) with enough protons to go to the 2nd oscillation maximum and increase significantly the CPV sensitivity and precise measurement of δ_{CP}.
- CPV: 5 σ could be reached over 70% of δ_{CP} range by ESSνSB with large physics potential with less than 8° precision.
- The European Spallation Source will be ready by 2025, upgrade decisions by this moment.
- Conceptual Design Report published.
- Rich muon program for future ESS upgrades.
- **New application now accepted by EU: ESSnuSB+ already started!**

Spare slides

Matter effects

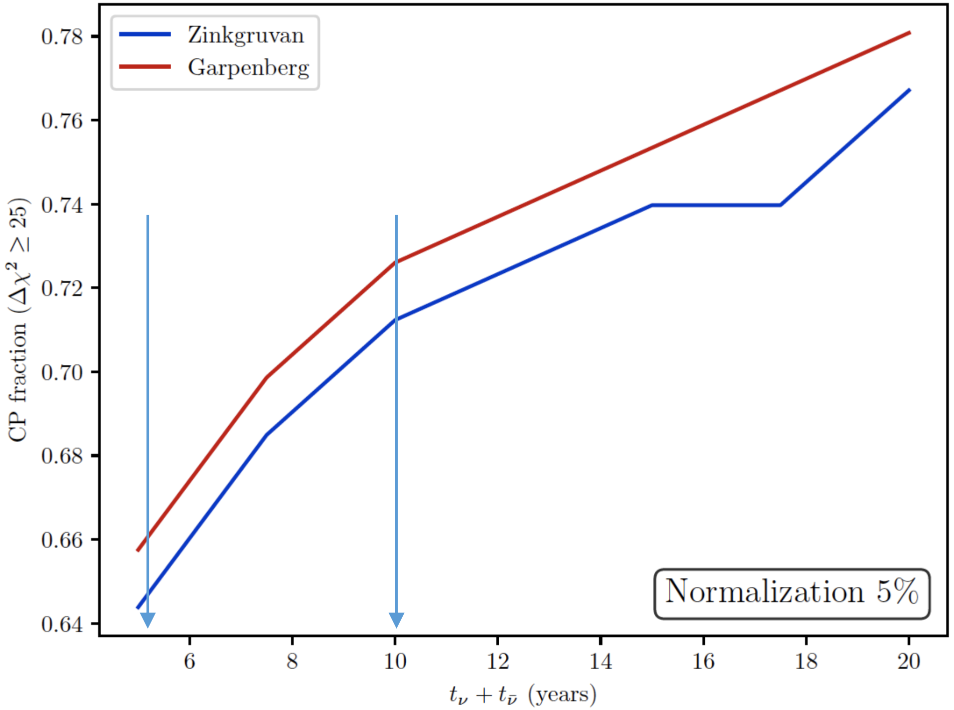
2nd maximum
- larger sensitivity to δ_{CP}
- matter doesn't matter

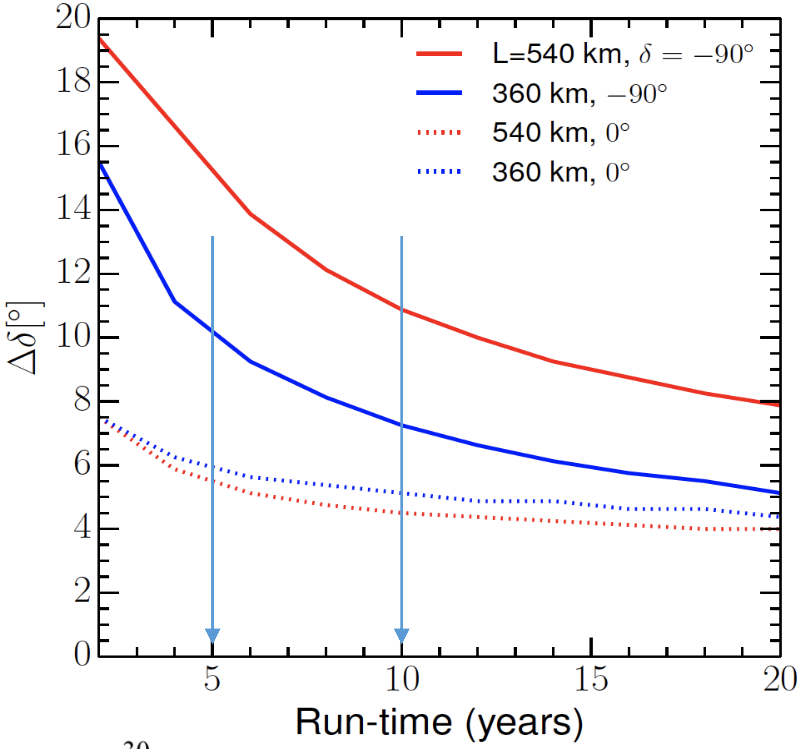
(L = 360 km)



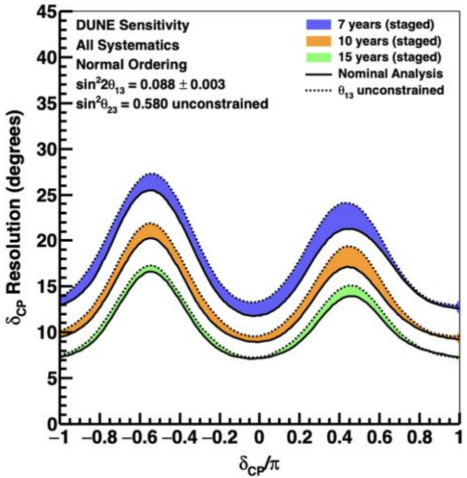
Performance Comparison with Other Experiments

Already after 5 years very competitive performance

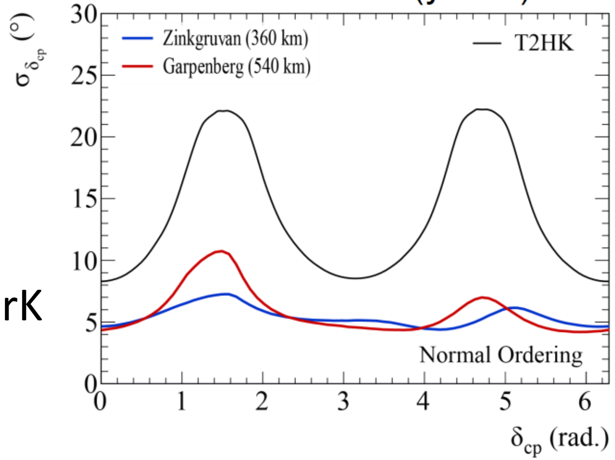




DUNE



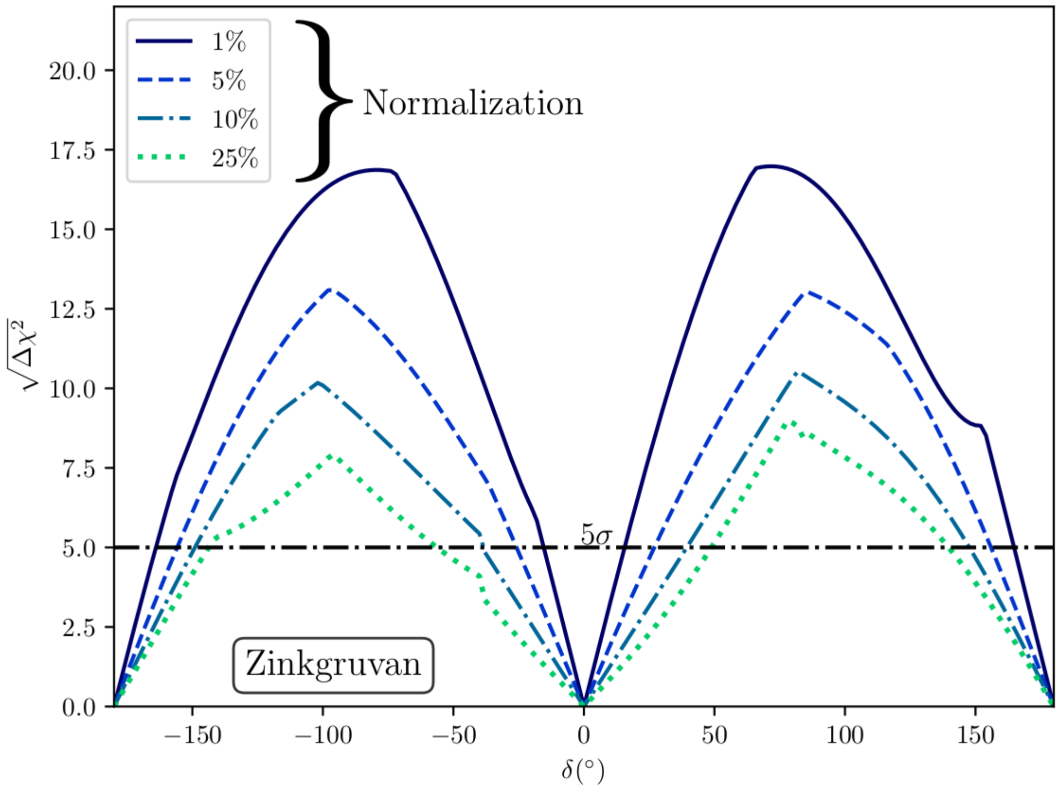
HyperK



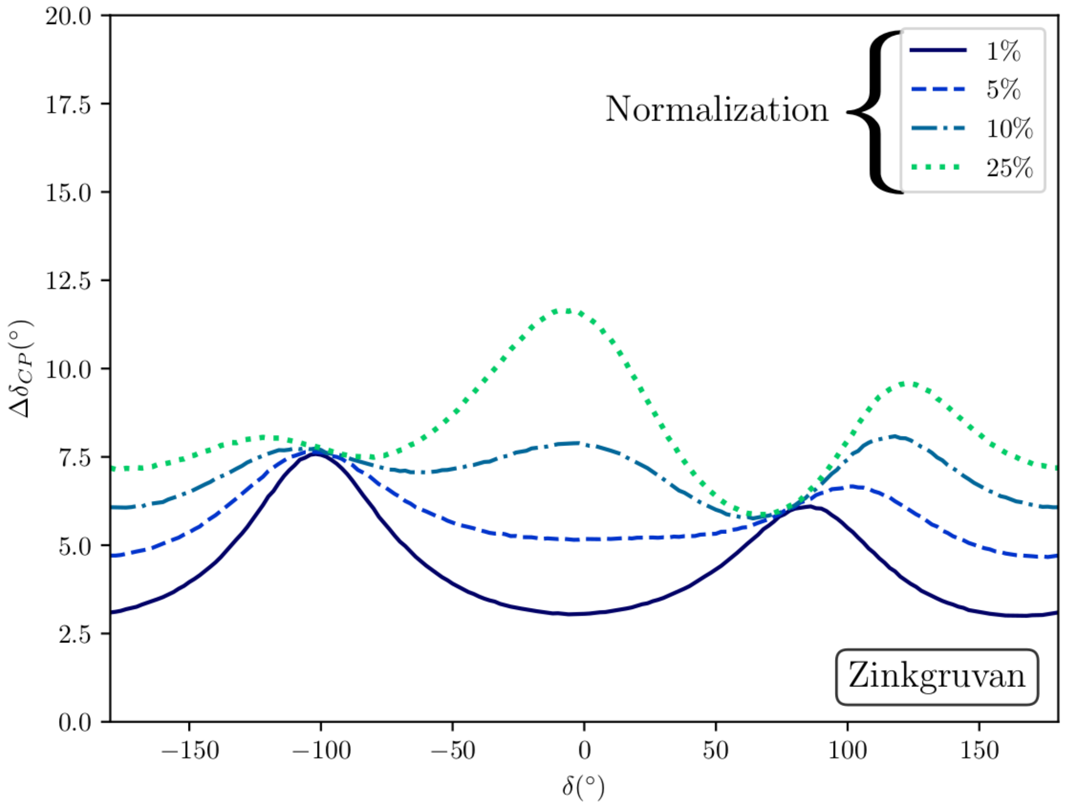
Effect of normalization uncertainty
Future Opportunities

<u>ESSnuSB</u>
- θ_{12} = 33.44°
- θ_{13} = 8.57°
- θ_{23} = 49.2°
- Δm^2_{21} = 7.42e-5
- Δm^2_{31} = +2.52e-3
- 2nd osc. max.
- 507 ktons far detector

Sensitivity

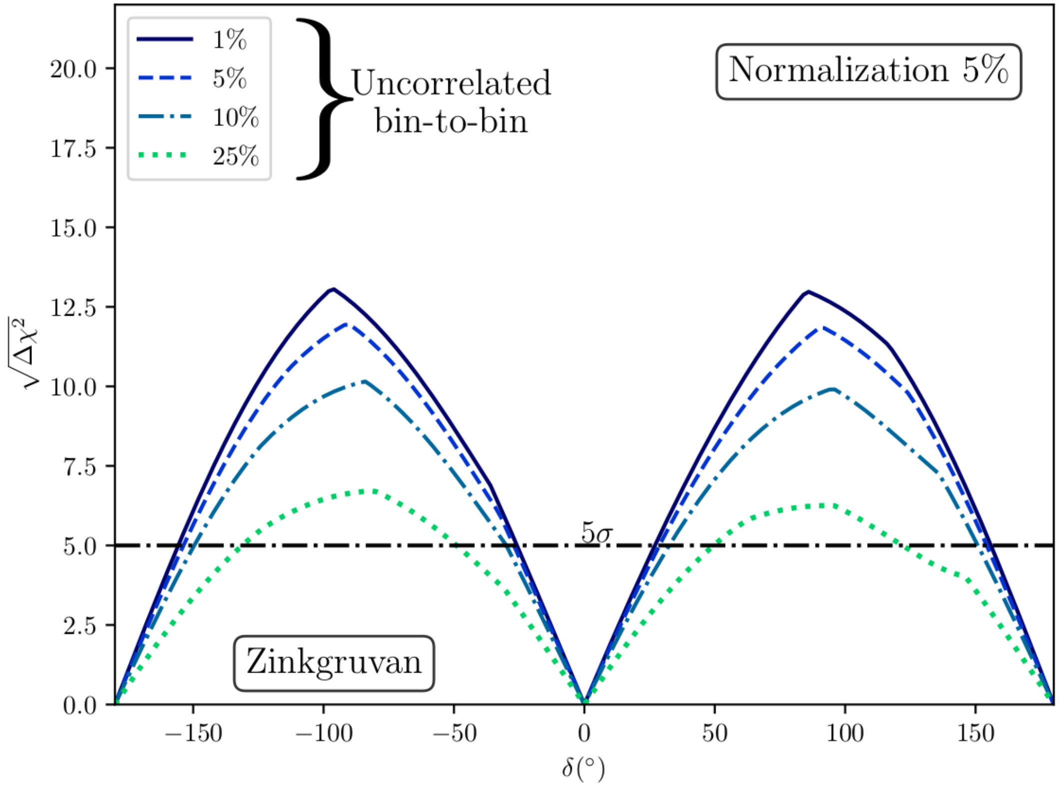


Precision

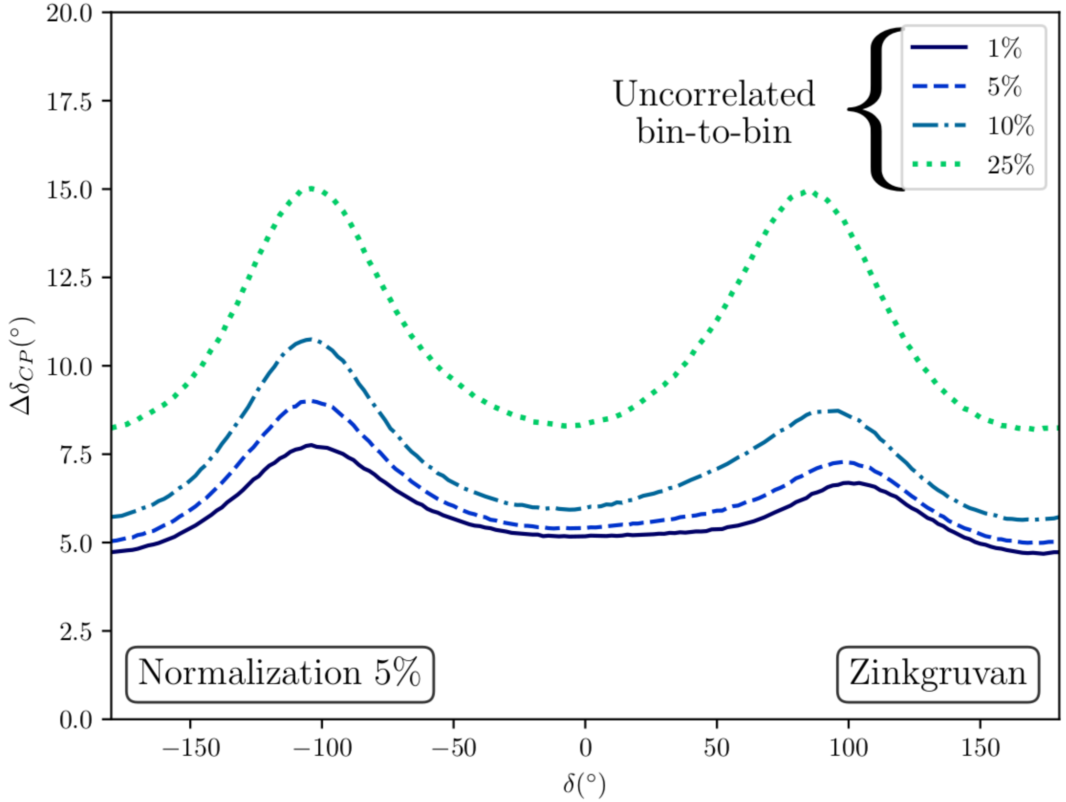


Effect of bin-to-bin uncorrelated uncertainty

Sensitivity



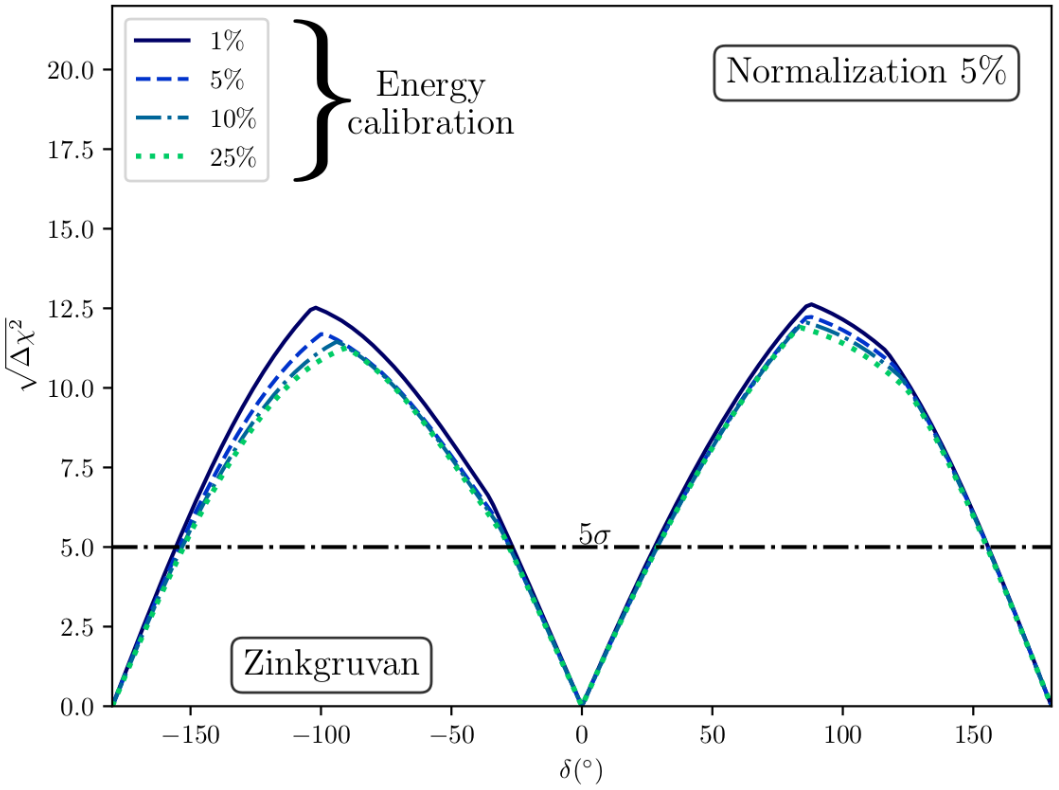
Precision



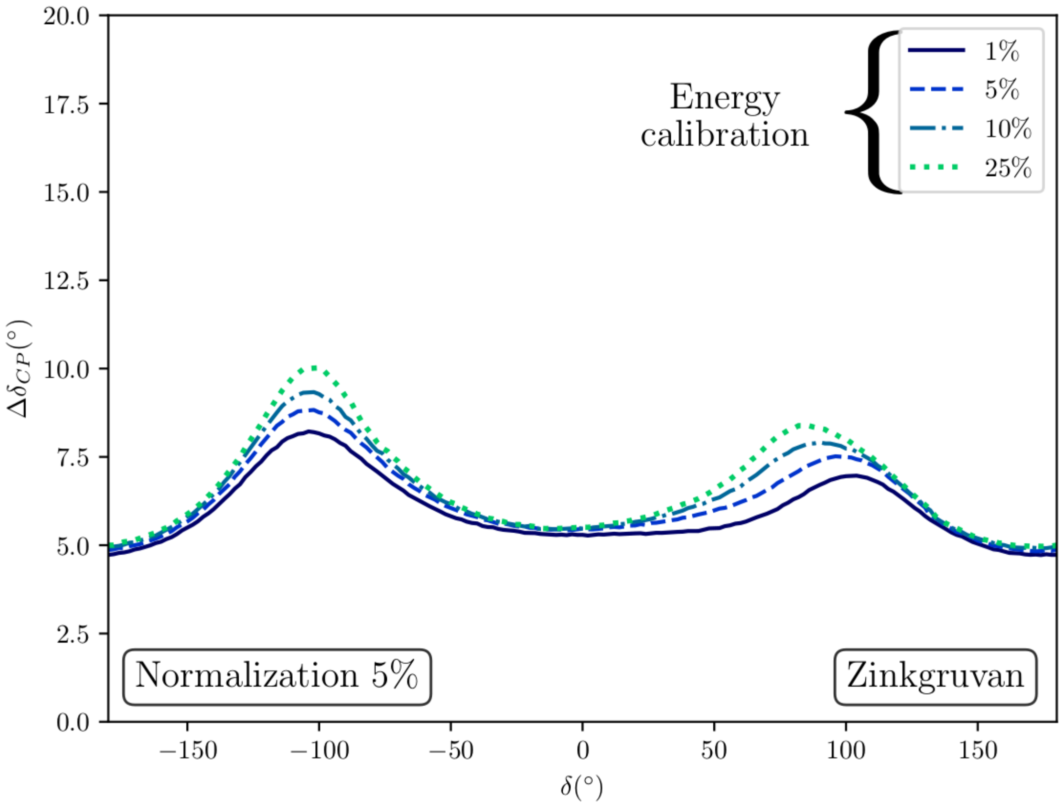
Effect of energy calibration uncertainty

<u>ESSnuSB</u>
- θ_{12} = 33.44°
- θ_{13} = 8.57°
- θ_{23} = 49.2°
- Δm^2_{21} = 7.42e-5
- Δm^2_{31} = +2.52e-3
- 2nd osc. max.
- 507 ktons far detector

Sensitivity



Precision



Systematic errors

Systematics	SB Opt.	SB Def.	SB Cons.	BB Opt.	BB Def.	BB Cons.	NF Opt.	NF Def.	NF Cons.
Fiducial volume ND	0.2%	0.5%	1%	0.2%	0.5%	1%	0.2%	0.5%	1%
Fiducial volume FD (incl. near-far extrap.)	1%	2.5%	5%	1%	2.5%	5%	1%	2.5%	5%
Flux error signal ν	5%	7.5%	10%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background ν	10%	15%	20%	correlated			correlated		
Flux error signal $\bar{\nu}$	10%	15%	20%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background $\bar{\nu}$	20%	30%	40%	correlated			correlated		
Background uncertainty	5%	7.5%	10%	5%	7.5%	10%	10%	15%	20%
Cross secs × eff. QE†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs × eff. RES†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs × eff. DIS†	5%	7.5%	10%	5%	7.5%	10%	5%	7.5%	10%
Effec. ratio ν_e/ν_μ QE*	3.5%	11%	–	3.5%	11%	–	–	–	–
Effec. ratio ν_e/ν_μ RES*	2.7%	5.4%	–	2.7%	5.4%	–	–	–	–
Effec. ratio ν_e/ν_μ DIS*	2.5%	5.1%	–	2.5%	5.1%	–	–	–	–
Matter density	1%	2%	5%	1%	2%	5%	1%	2%	5%

Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]]

ESSνSB Project Time Evolution

ϑ_{13} measurement

Nobel prize:
T. Kajita &
A. McDonald

2015

2008-2012: EUROν Design Study (FP7)

2012: inception of the ESSnuSB project

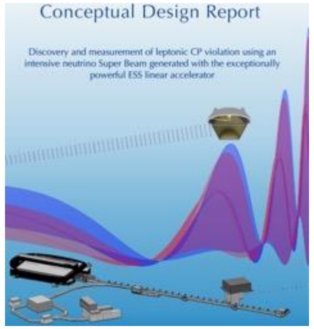
Nucl. Phys. B 885 (2014) 127

COST
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

2016-2020: COST Action EuroNuNet

ESS NEUTRINO SUPER BEAM

2018-2022: ESSνSB Design Study, CDR (EU-H2020)



ESSνSB CDR

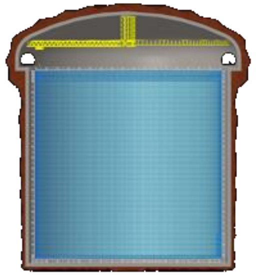
ESFRI

EUROPEAN SPALLATION SOURCE

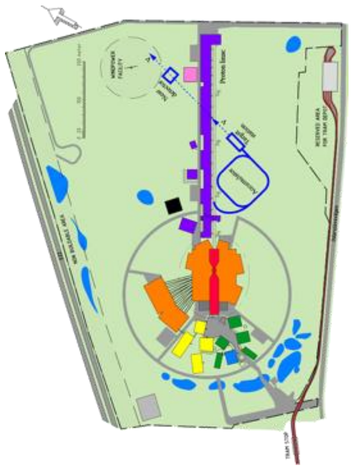
ESS neutrino Super Beam plus

2023-2026: ESSνSB+ Design Study, CDR (EU-HE) and preparatory phase

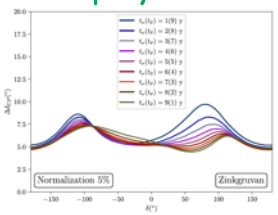
2026-2028: TDR Phase, International Agreement



2028-2037: Construction of the facility and detectors, including commissioning



physics



Data Taking

ESSνSB Future Opportunities

- The large underground water Cherenkov detector of ESSnuSB will have the largest volume in the world, it will also be the most sensitive detector for measuring neutrinos from **galactic supernova explosions**, enabling tests of different models for the time evolution and mechanism of such explosions.

- It would also be possible to make sensitive measurements of the amount and energy distribution of neutrinos in the Universe that remain from all **earlier supernova explosions**.

- Furthermore, ESSnuSB would enable the most sensitive search for **proton decay**, the detection of which would be a direct proof of the baryon-number non-conservation that is required by leptogenesis theories.

- The Far Detector will also be sensitive to the **Solar Neutrinos** and **Atmospheric Neutrinos**.