ESS Neutrino Super Beam Plus

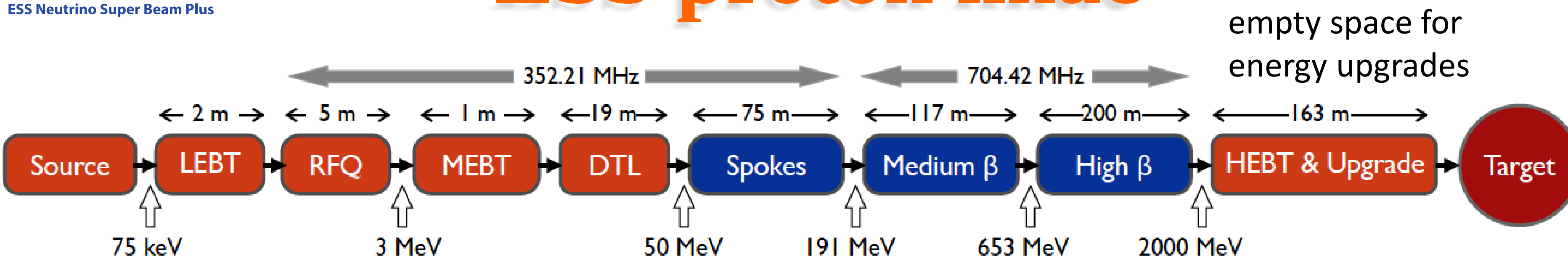
Co-funded by the European Union

Matter-antimatter asymmetry study using the European Spallation Source neutrino Super Beam

Marcos Dracos
IPHC-Strasbourg

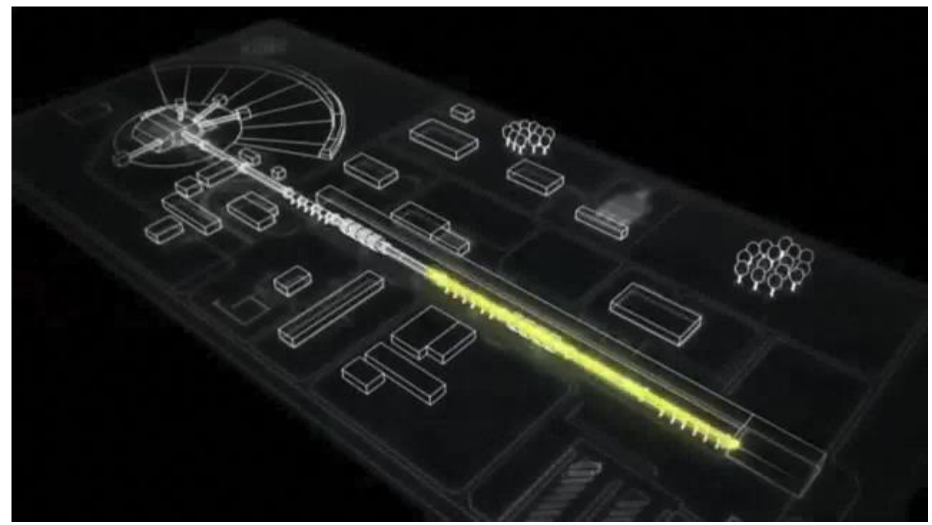
European Spallation Source

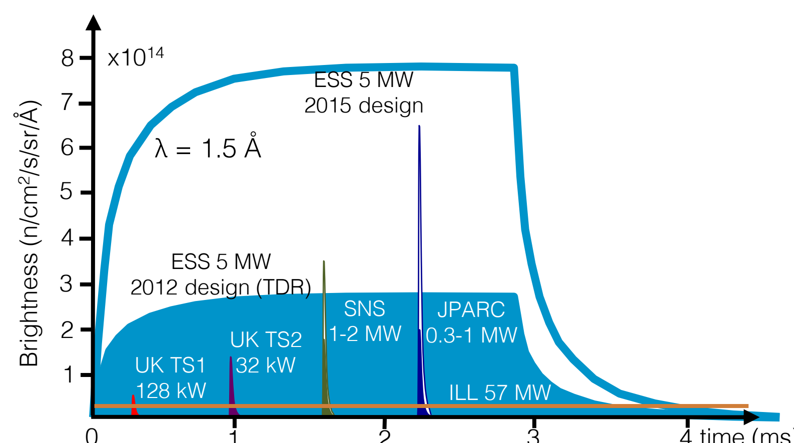
ESS proton linac



- 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 protons
  - up to 3.5 GeV with linac upgrades
- **>2.7x10^{23} p.o.t/year.**

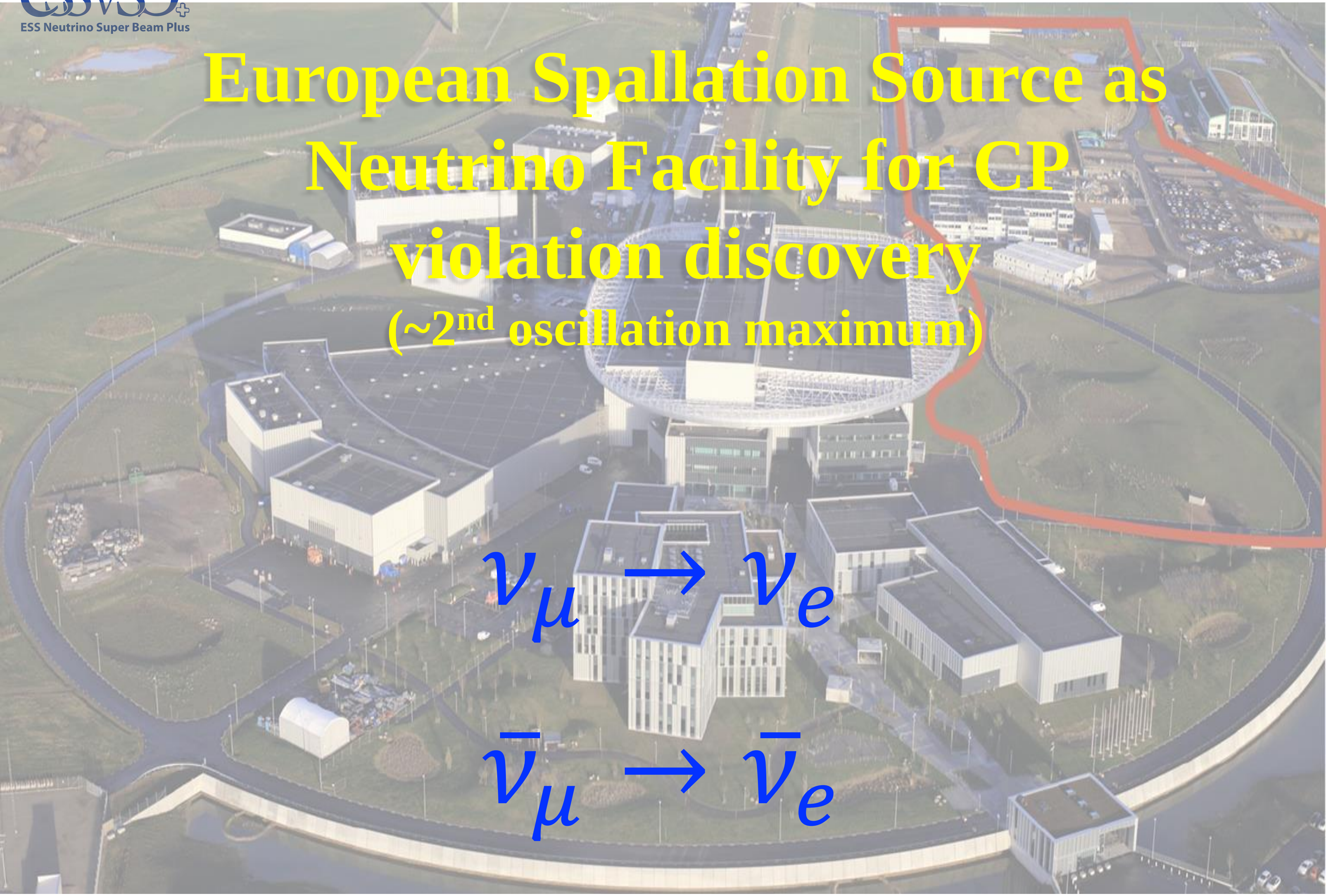
First protons on the target by 2025





European Spallation Source as Neutrino Facility for CP violation discovery

(~2nd oscillation maximum)



$$\nu_\mu \rightarrow \nu_e$$

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

Oscillation probability

(neutrino beams)

$$P_{\nu_\mu\to\nu_e(\overline{\nu_\mu}\to\overline{\nu_e})} \simeq 4 s_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2}\sin^2\frac{(1-r_A)\Delta L}{2}$$ "atmospheric"

$$+8J_r\frac{r_\Delta}{r_A(1-r_A)}\cos\left(\delta_{CP}-\frac{\Delta L}{2}\right)\sin\frac{r_A\Delta L}{2}\sin\frac{(1-r_A)\Delta L}{2}$$ "interference"

$$+4c_{23}^2c_{12}^2s_{12}^2\left(\frac{r_\Delta}{r_A}\right)^2\sin^2\frac{r_A\Delta L}{2}$$ "solar"

$$J_r \equiv c_{12}s_{12}c_{23}s_{23}s_{13},\ \Delta \equiv \frac{\Delta m_{31}^2}{2E_\nu},\ r_A \equiv \frac{a}{\Delta m_{31}^2},\ r_\Delta \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2},\ a = 2\sqrt{2}G_F N_e E_\nu$$

matter effect

- **for antimatter: $\delta_{CP}\to-\delta_{CP}$ and $a\to-a$**
- fake matter/antimatter asymmetry due to matter effect

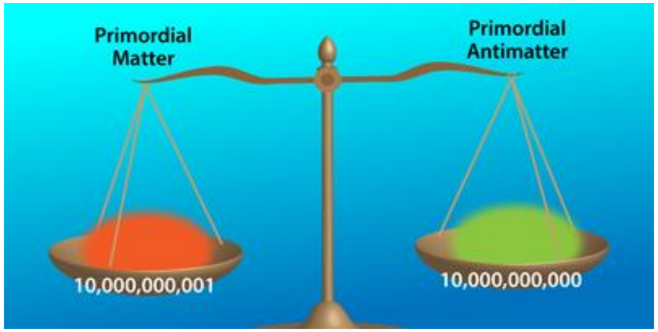
$$\mathcal{A} = \frac{P_{\nu_\mu\to\nu_e} - P_{\bar{\nu}_\mu\to\bar{\nu}_e}}{P_{\nu_\mu\to\nu_e} + P_{\bar{\nu}_\mu\to\bar{\nu}_e}}$$

Matter-antimatter asymmetry

- δ_{CP} dependence,
- sizable matter effect for long baselines

δ_{CP} and Matter-antimatter asymmetry magnitude

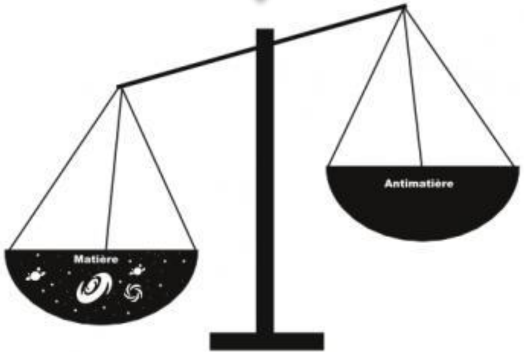
$$A_{\alpha\beta}^{CP} = P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$
$$= J_{CP}^{PMNS} \cdot \sin\delta_{CP}$$



with: $J_{CP}^{PMNS} \sim 3\times10^{-3}$ (Jarlskog invariant)

(for hadrons: $J_{CP}^{CKM} \sim 3\times10^{-5}$, not enough even if δ_{CP}~70°)

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



Theoretical models predict that if |sinδ_{CP}|≳0.7 (45°<δ_{CP}<135° or 225°<δ_{CP}<315°), this could be enough to explain the observed asymmetry.

(Nucl.Phys.B774:1-52,2007, arXiv:hep-ph/0611338)

Neutrino Oscillation probability

$$P_{\nu_\mu\to\nu_e(\overline{\nu_\mu}\to\overline{\nu_e})} \simeq 4 s_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2}\sin^2\frac{(1-r_A)\Delta L}{2}$$ "atmospheric"

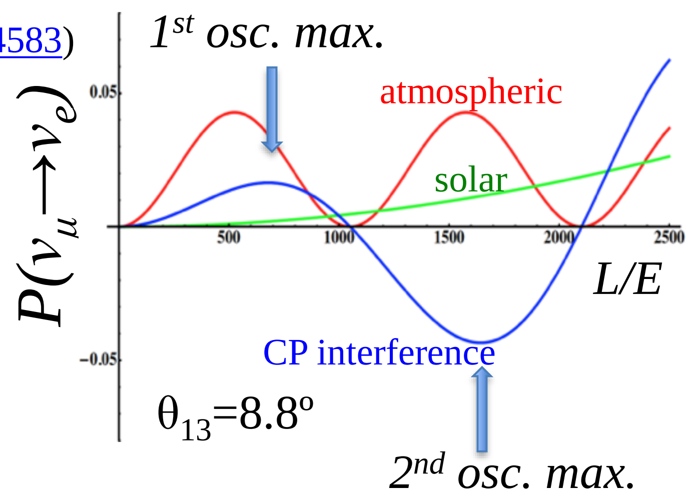
$$+8J_r \frac{r_\Delta}{r_A(1-r_A)}\cos\left(\delta_{CP}-\frac{\Delta L}{2}\right)\sin\frac{r_A\Delta L}{2}\sin\frac{(1-r_A)\Delta L}{2}$$ "interference"

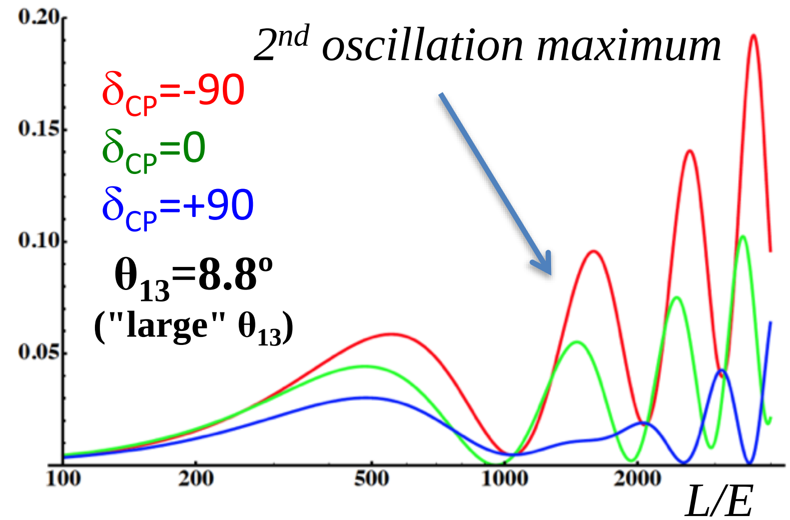
$$+4c_{23}^2 c_{12}^2 s_{12}^2\left(\frac{r_\Delta}{r_A}\right)^2\sin^2\frac{r_A\Delta L}{2}$$ "solar"

$\nu_\mu \to \nu_e$

$\bar{\nu}_\mu \to \bar{\nu}_e$

(arXiv:1110.4583)





- 1st oscillation max.: A=**0.3**$\sin\delta_{CP}$
- 2nd oscillation max.: A=**0.75**$\sin\delta_{CP}$

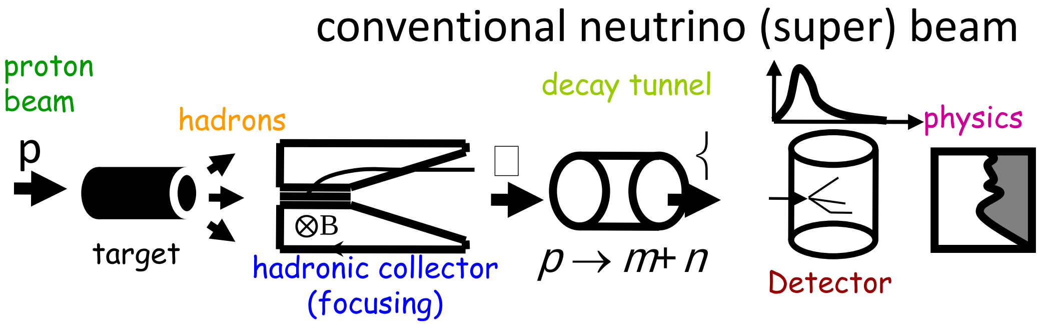
→ more sensitivity at 2nd oscillation max.

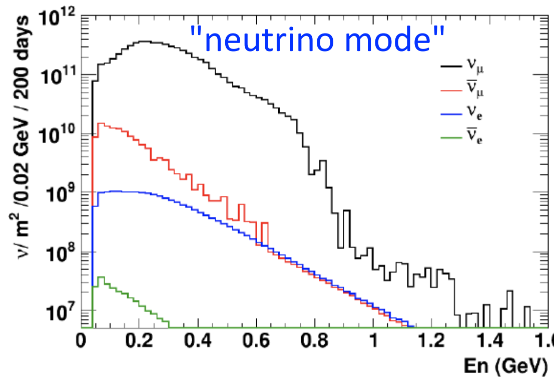
(arXiv:1310.5992, arXiv:0710.0554)

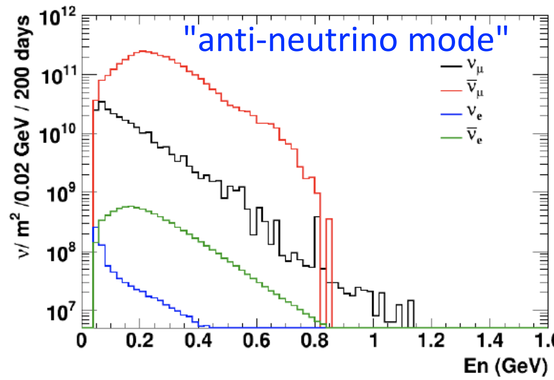
Having access to a powerful proton beam…

What can we do with:

- 5 MW power
- 2 GeV energy
- 14 Hz repetition rate
- 10^{15} protons/pulse
- $>2.7\times10^{23}$ 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

	ν Mode		$\bar{\nu}$ Mode	
	$N_\nu(10^{10}/m^2)$	%	$N_\nu(10^{10}/m^2)$	%
ν_μ	583	97.5	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

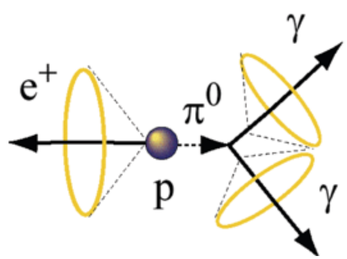
at 100 km from the target, per year (in absence of oscillations)

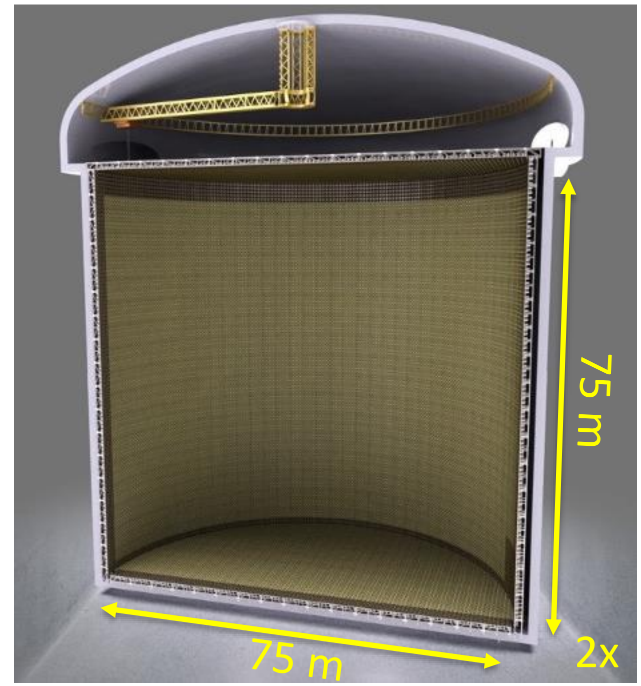
Can we go to the 2nd oscillation maximum using our proton beam?

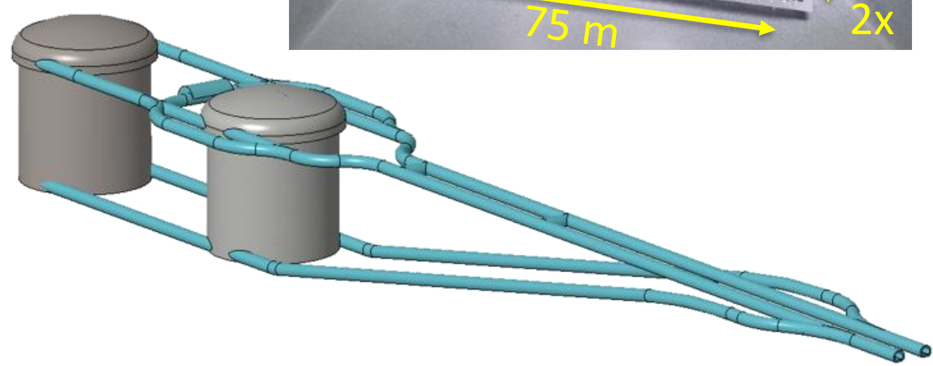
Yes, if we place our far detector at 350- 550 km from the neutrino source.

Megaton Water Cherenkov detector

- **Neutrino Oscillations**
- **Proton decay**
- **Astroparticles**
- Understand the gravitational collapsing: galactic SN ν
- Supernovae "relics"
- Solar Neutrinos
- Atmospheric Neutrinos



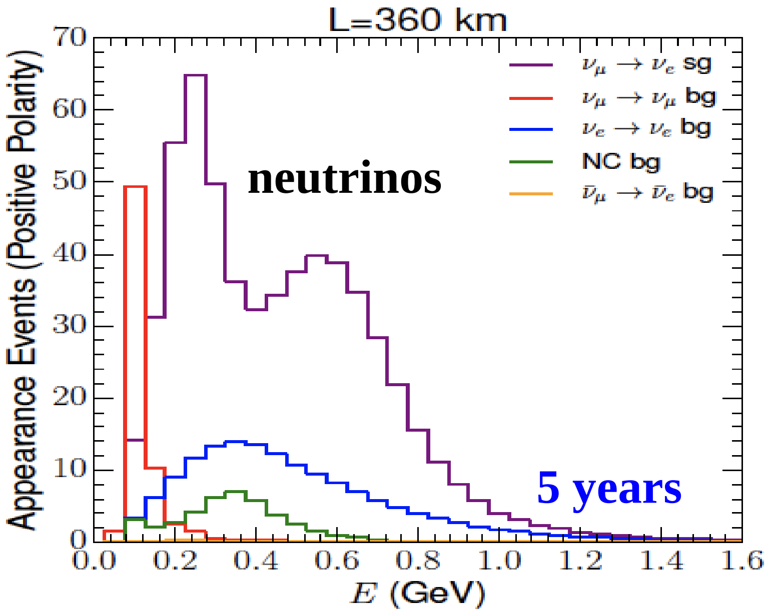


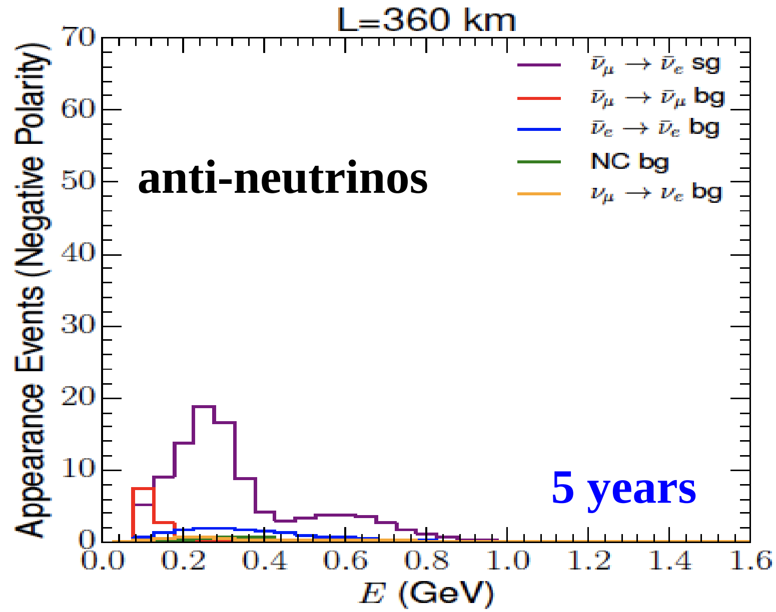


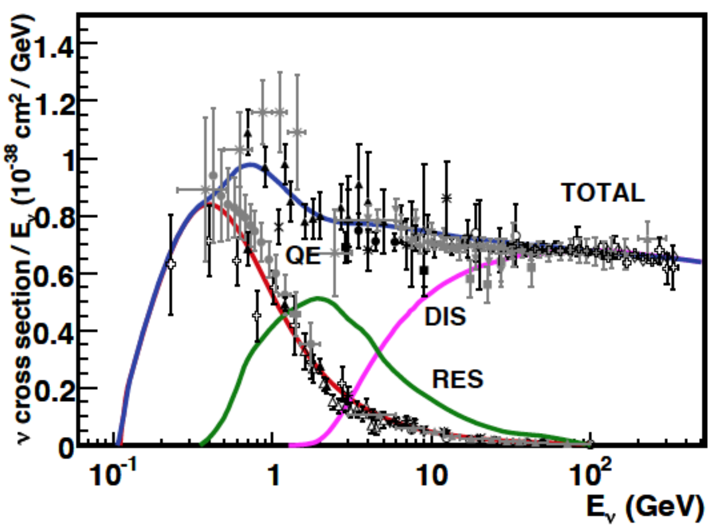
- 500 kt fiducial volume (~20xSuperK)
- Readout: ~20” PMTs
- 30% optical coverage

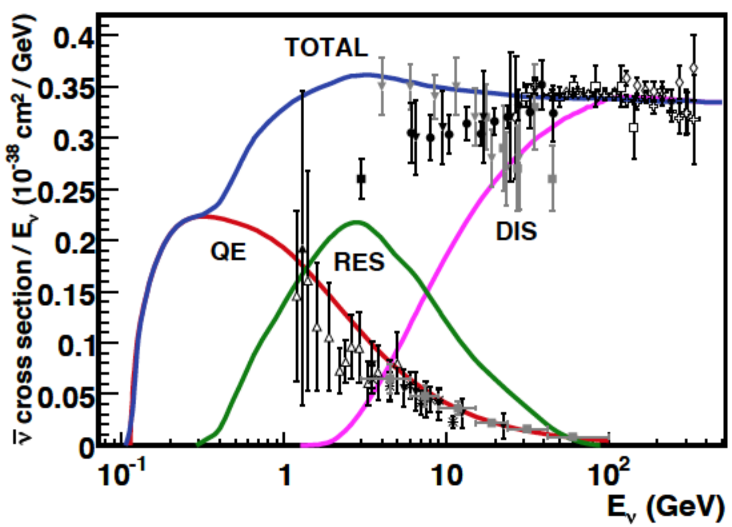
Neutrinos in the Far Detector

$\delta_{CP}=0$







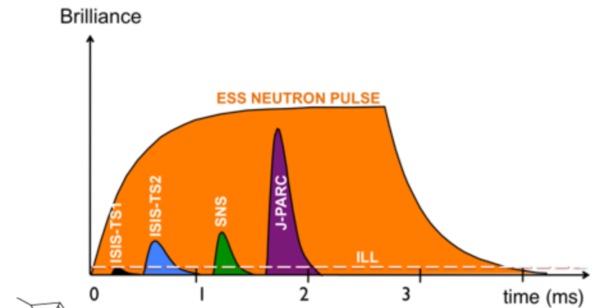


below ν_τ production, almost only QE events, not suffering too much by π^0 background

ESS modifications to produce a neutrino Super Beam

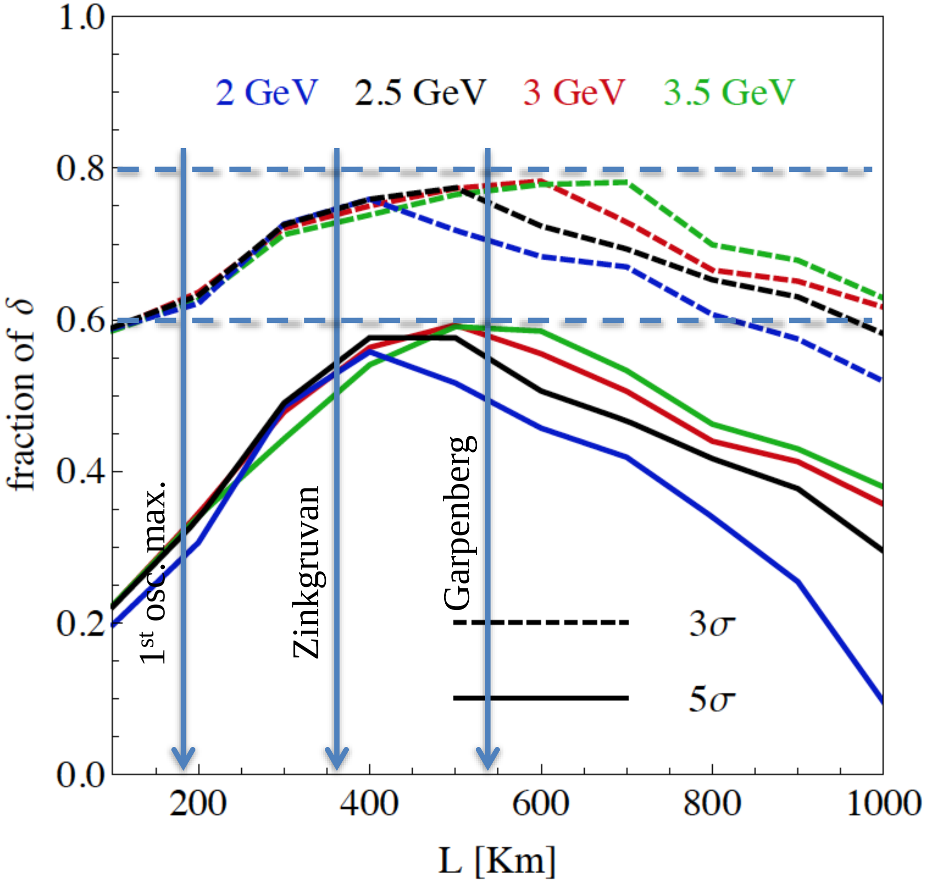
How to add to ESS a neutrino facility?

- The neutron program must not be affected and if possible synergetic modifications.
- Linac modifications: double the rate (14 Hz → 28 Hz), from 4% duty cycle to 8%.
- Accumulator (C~400 m) needed to compress to few μs the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA, power consumption, Joule effect)
    - H^- source (instead of protons),
    - space charge problems to be solved.
- ~300 MeV neutrinos.
- Target station.
- Underground detector.
- Short pulses (~μs) will also allow DAR and coherent scattering experiments (as those proposed for SNS) using the neutron target.



Which baseline?

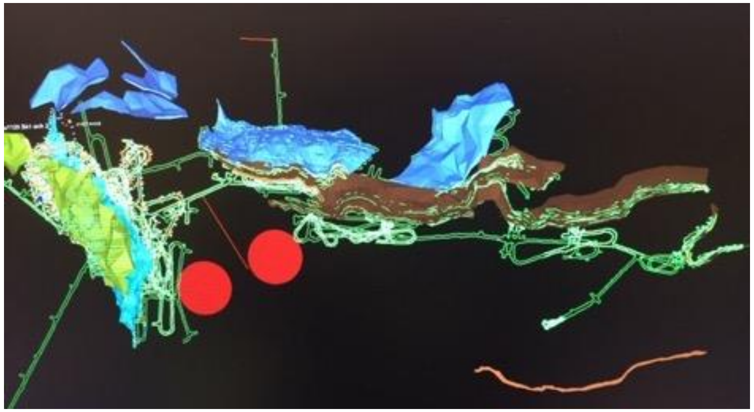
CPV (*Nucl. Phys. B 885 (2014) 127*)



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

Candidate mines

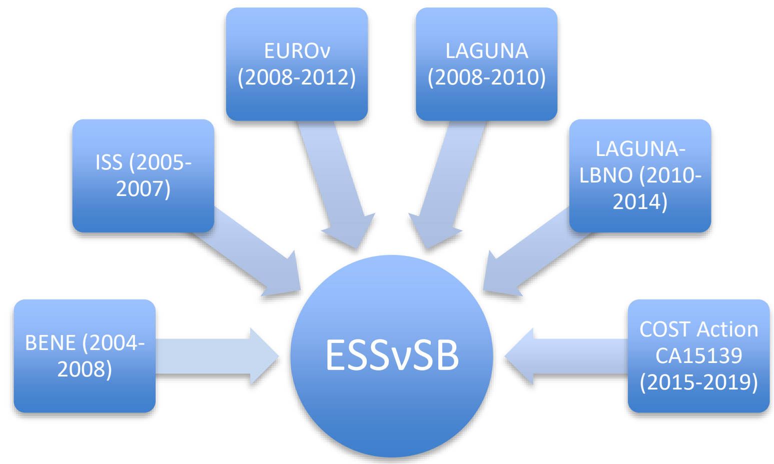
Selected mine: Zinkgruvan

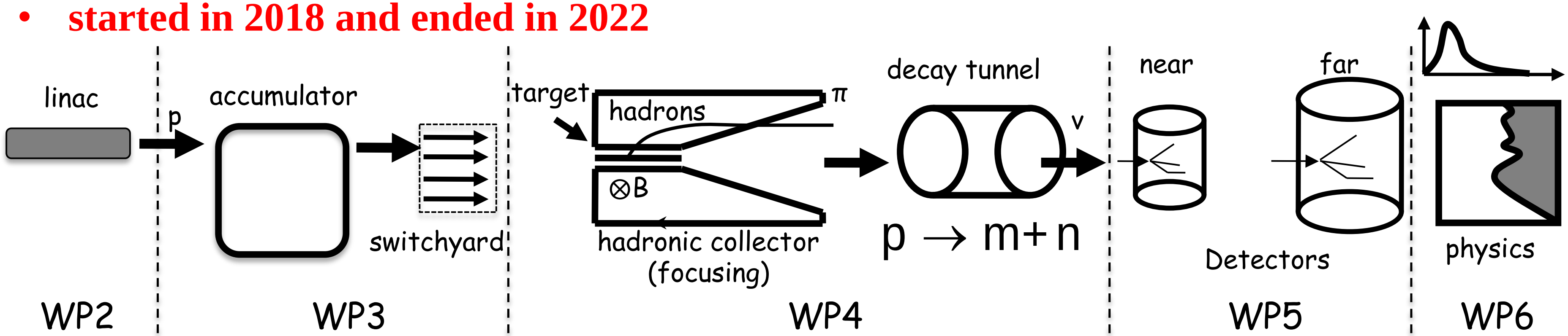


possible location of the detector

ESSνSB at the European level

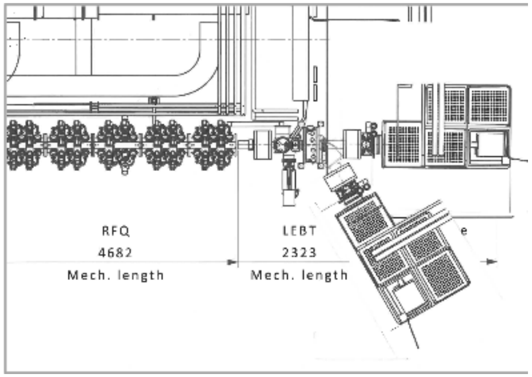
- A **H2020** EU **Design Study** (Call INFRADEV-01-2017)
  - **Title of Proposal**: Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator
  - **Duration: 4 years**
  - **Total cost: 4.7 M€**
  - **Requested budget: 3 M€**
  - **15 participating institutes from 11 European countries including CERN and ESS**
  - 6 Work Packages
  - **started in 2018 and ended in 2022**



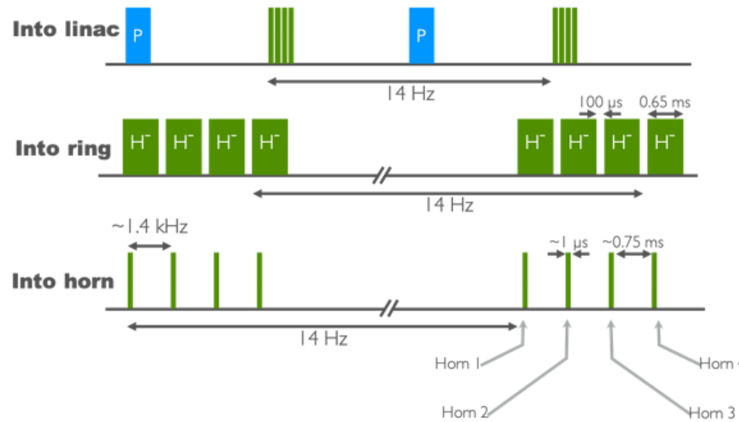


ESS modifications and operation

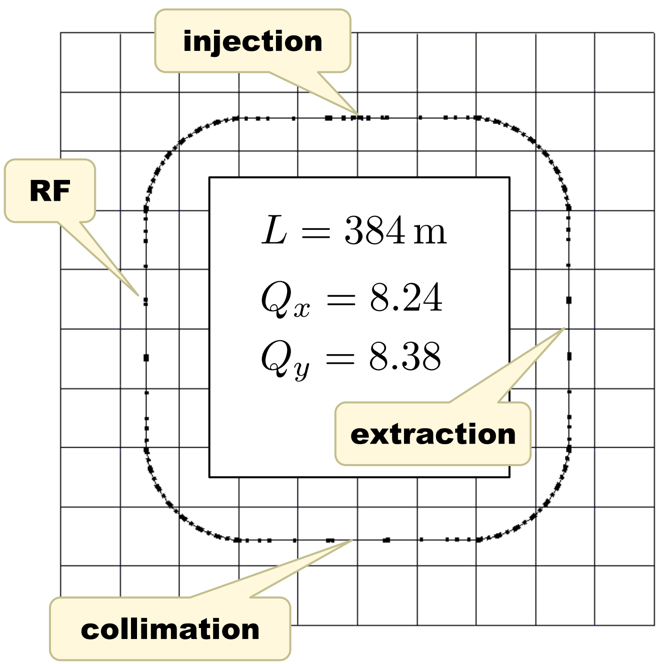
H⁻ source

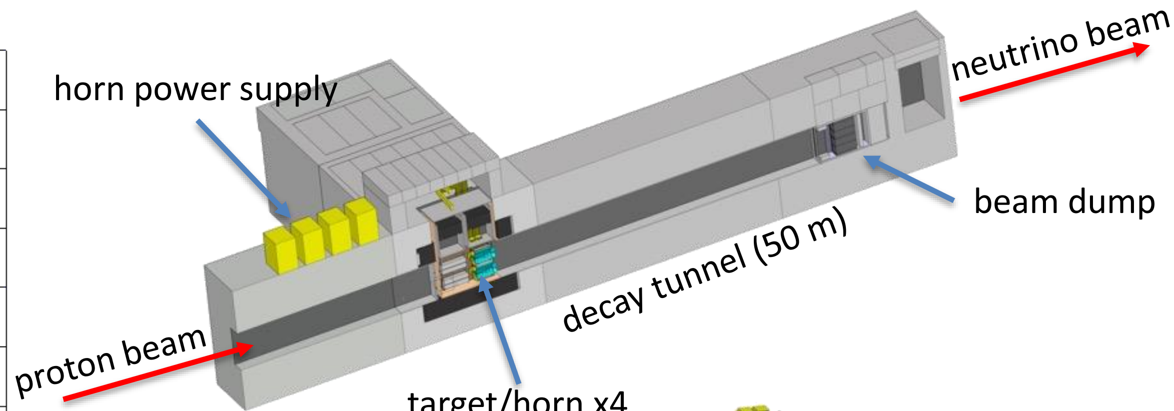


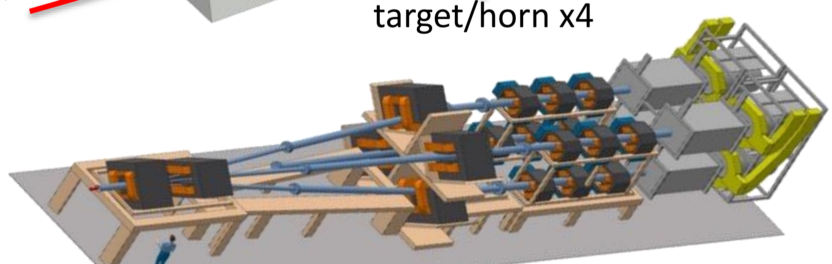
time operation option



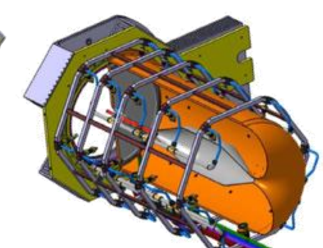
accumulator lattice



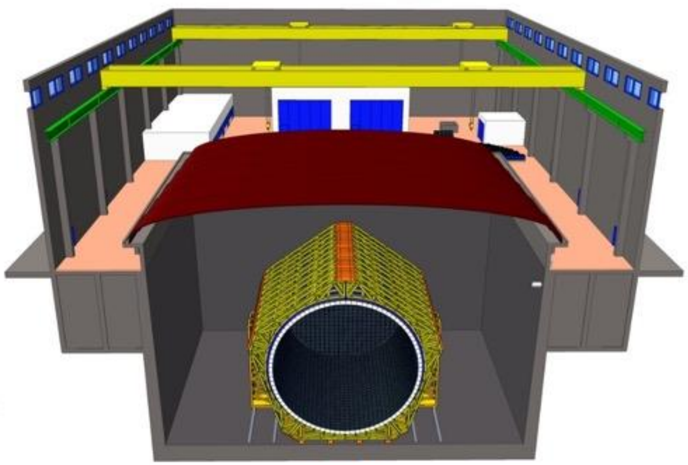




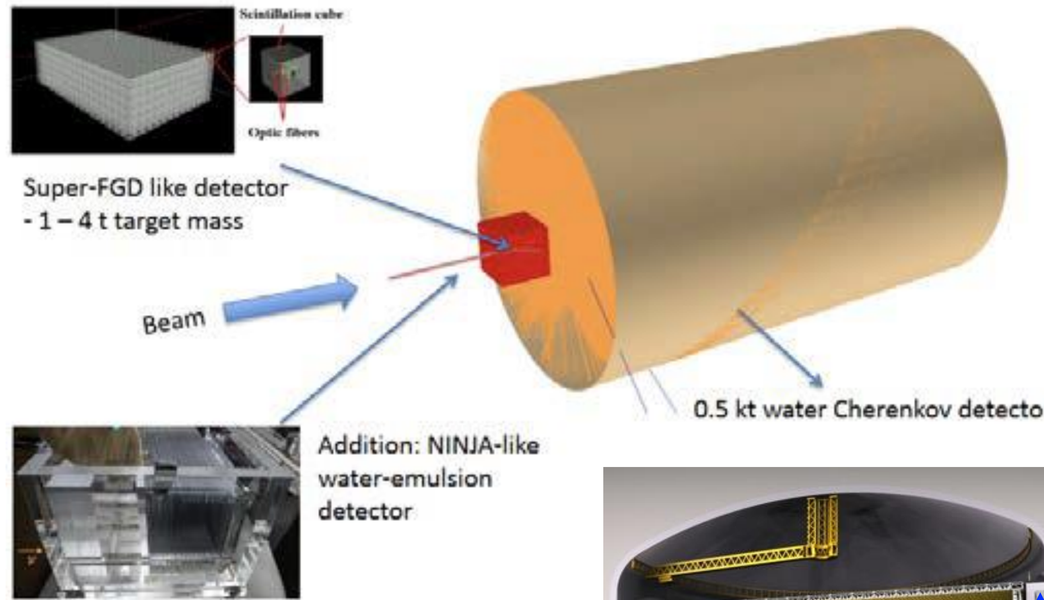
Switchyard



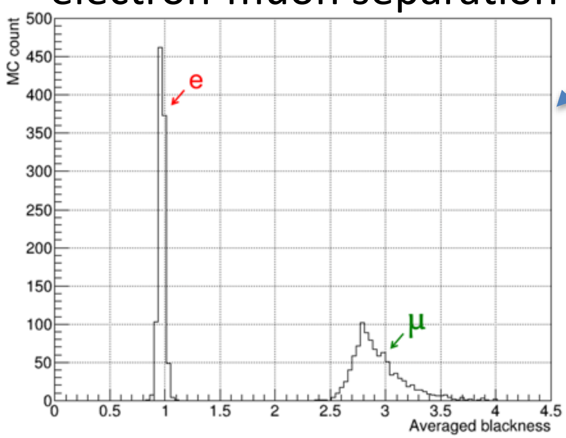
Detectors

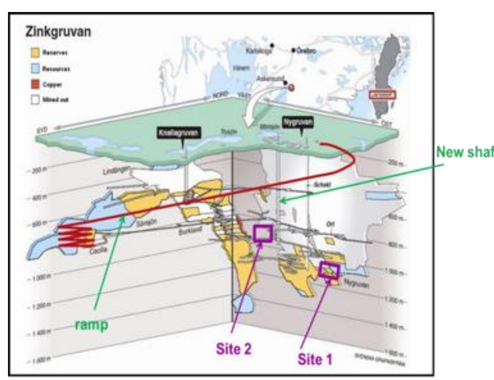


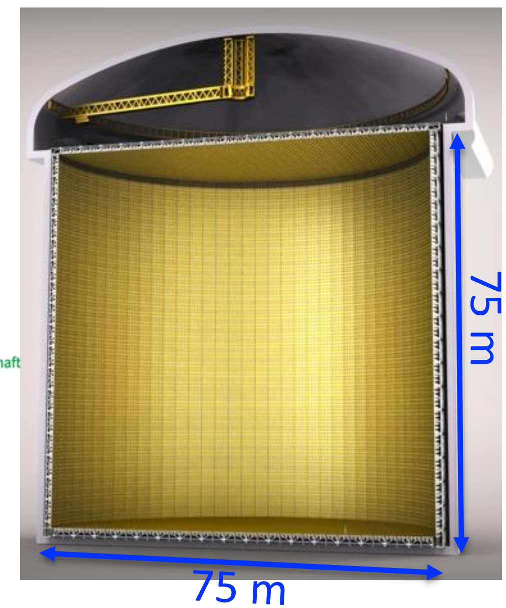
Near detector



electron-muon separation



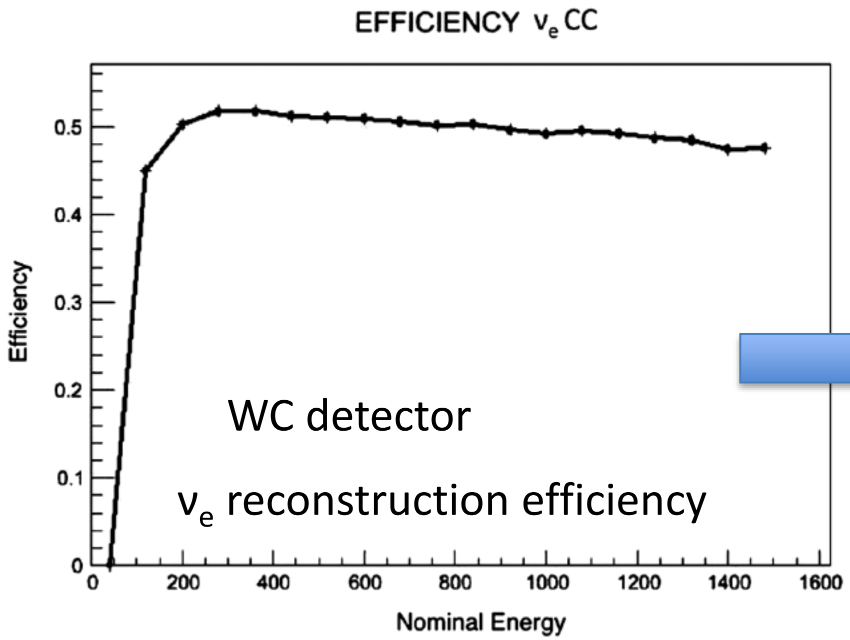


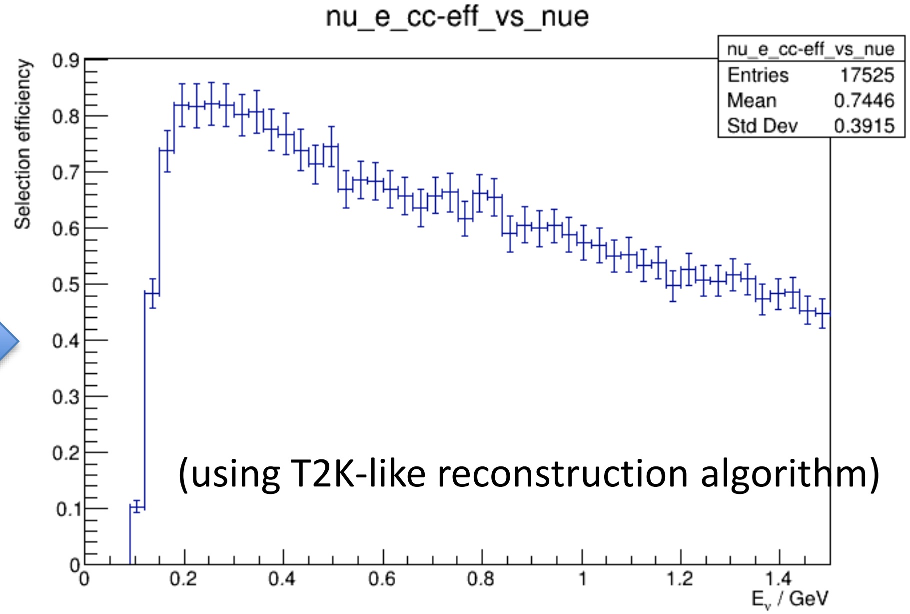


astroparticle physics program with the Far Detector

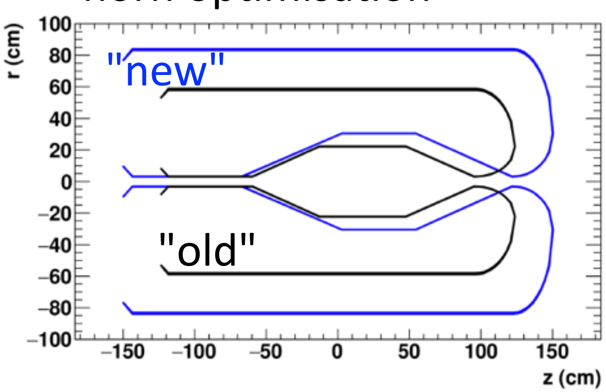
After many Optimisations

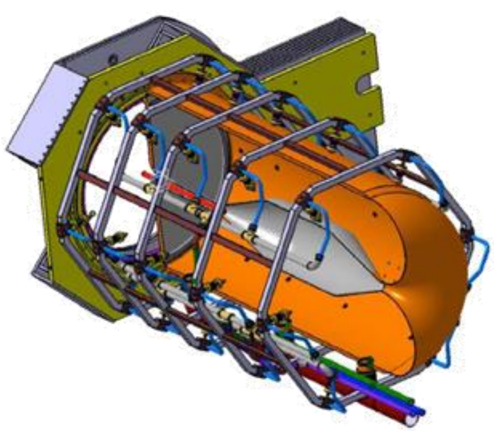
- New Magriation Matrices for the far detector
- Genetic Algorithm for Target Station optimisation



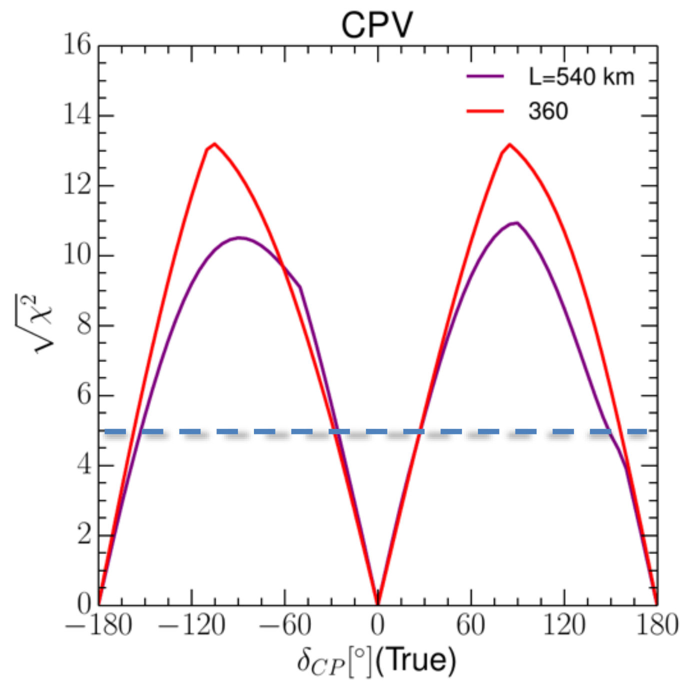


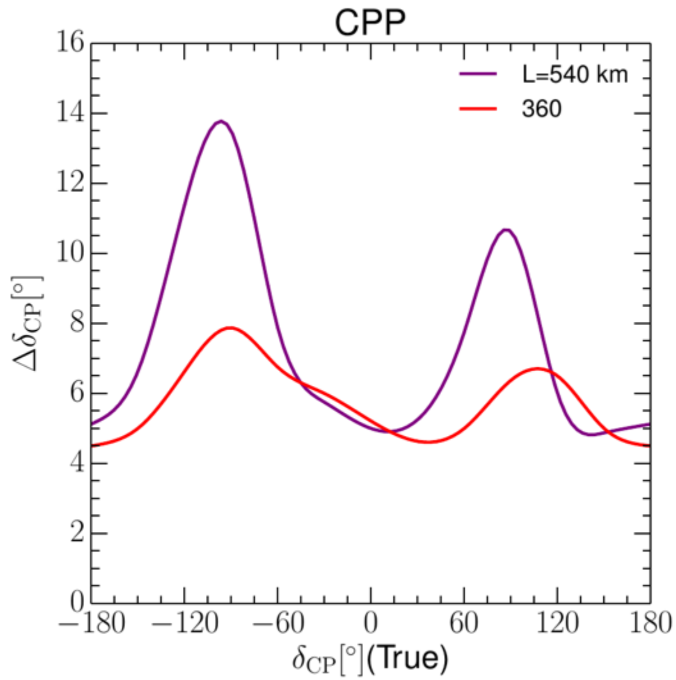
horn optimisation





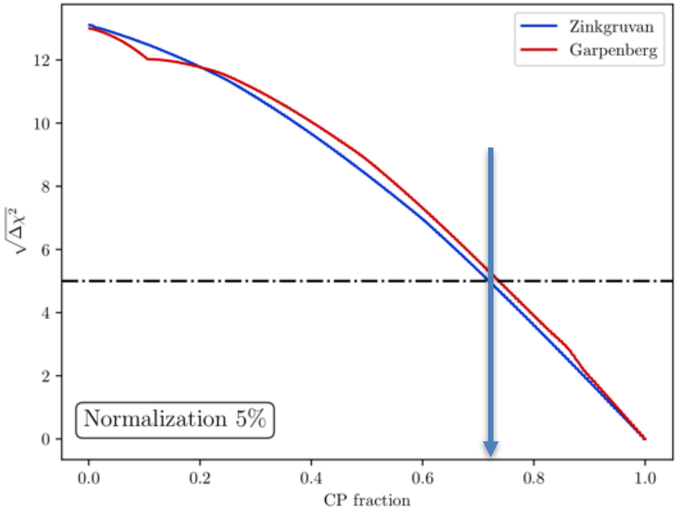
Final results





Precision measurement

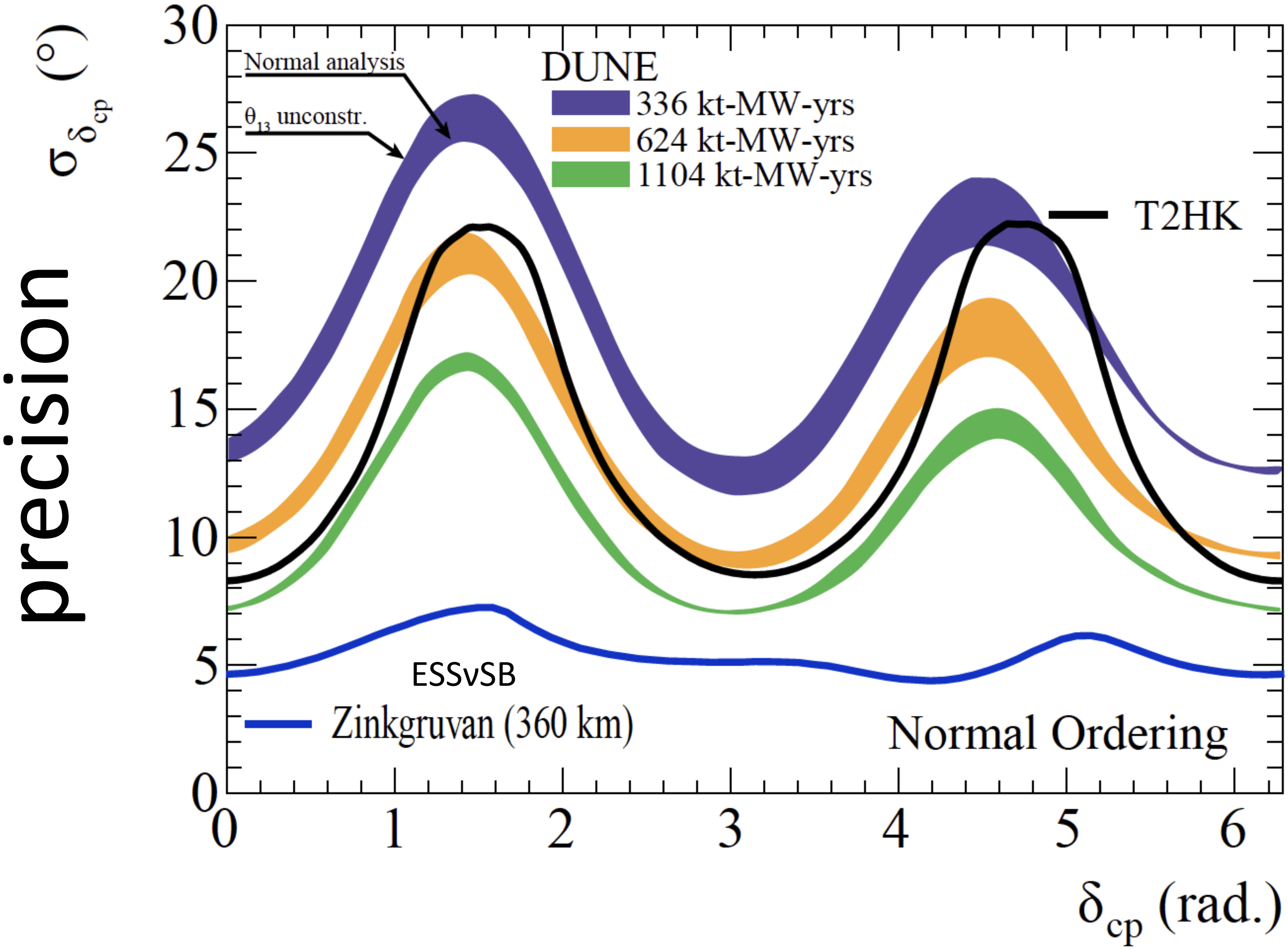
$\Delta\delta_{CP}$<8° for all values



>72% after 10 years

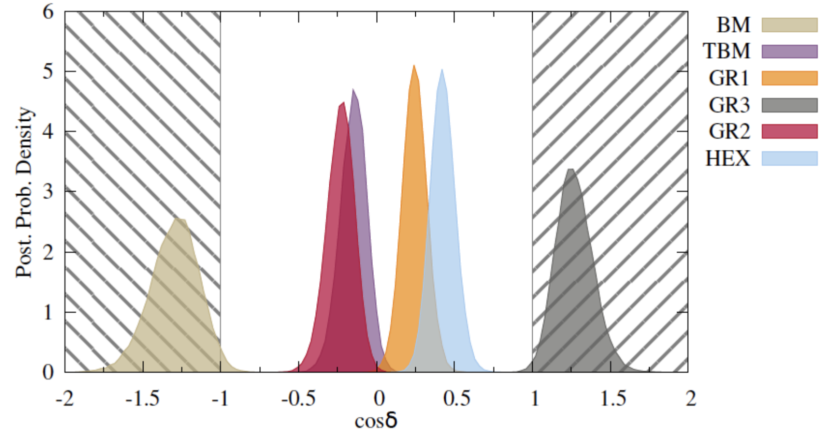
equivalent to Neutrino Factory

Comparison with current projects



δ_{CP} and model predictions

https://arxiv.org/abs/1410.7573



Test of flavour symmetry models:
Typically, the models considered have a reduced number of parameters, leading to relations between the masses and/or mixing angles.
Examples are the so-called **sumrules**, e.g.:

$$\sin\theta_{23} - \frac{1}{\sqrt{2}} = \sin\theta_{13}\cos\delta$$

$$\cos\delta = \frac{t_{23}s_{12}^2 + s_{13}^2 c_{12}^2/t_{23} - s_{12}^{\nu 2}(t_{23} + s_{13}^2/t_{23})}{\sin 2\theta_{12} s_{13}}$$

Figure 3: Posterior probability density functions for $\cos\delta$ for each of the solar sum rules considered in Section 3.1. The patterned regions are unphysical, which shows that the BM and GR3 sum rules could only be consistent with the known data if there is a significant deviation from the current best-fit values.

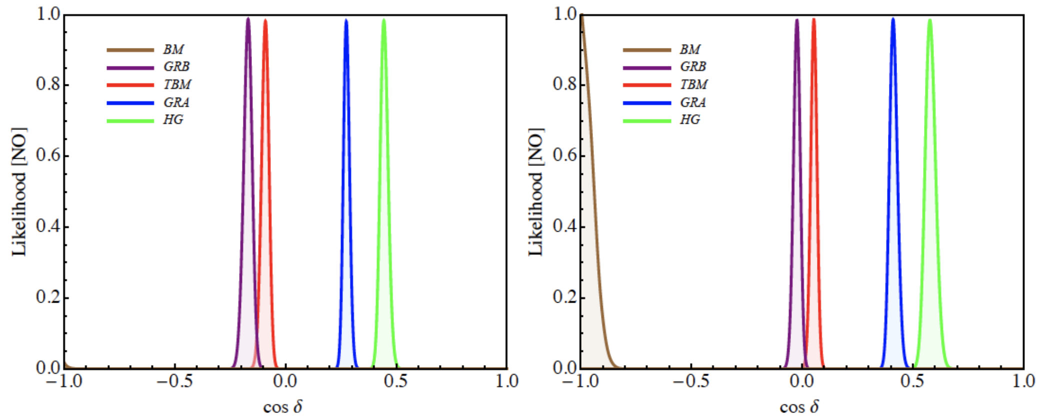
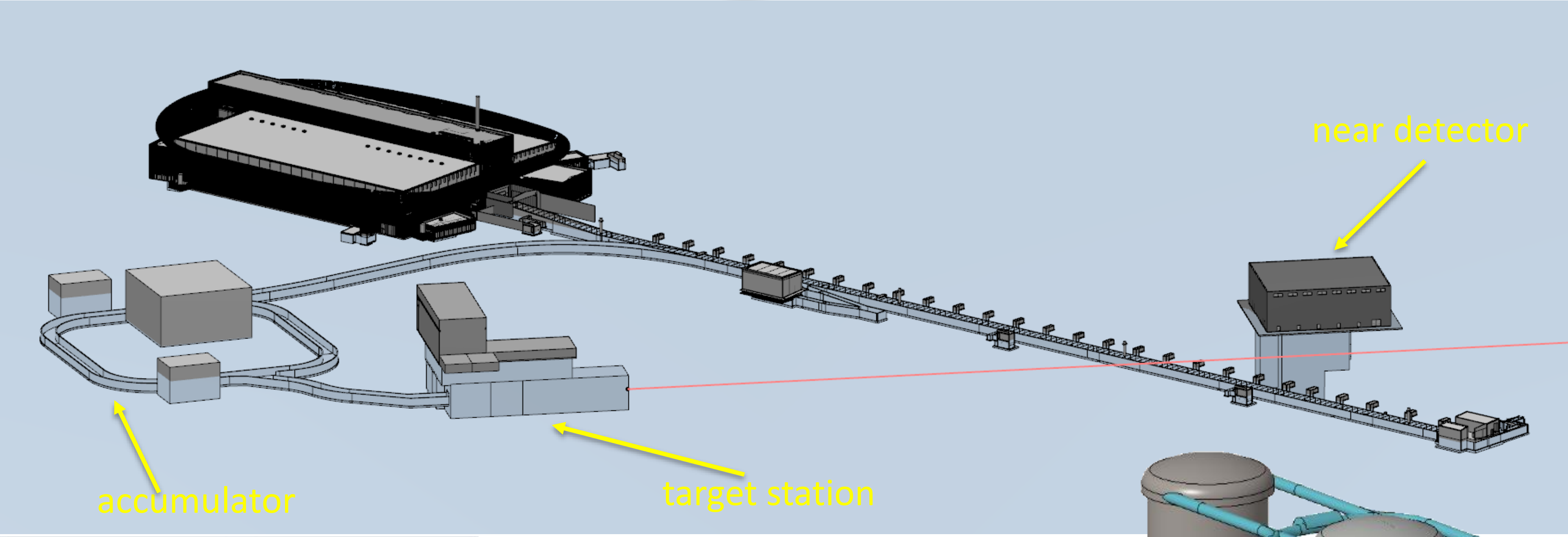
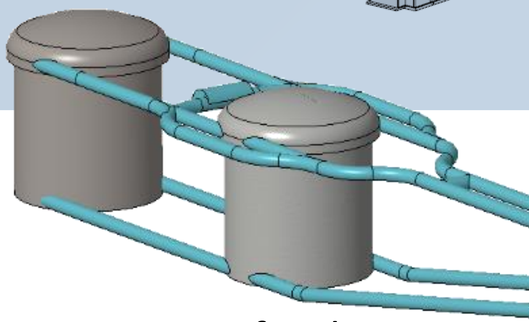


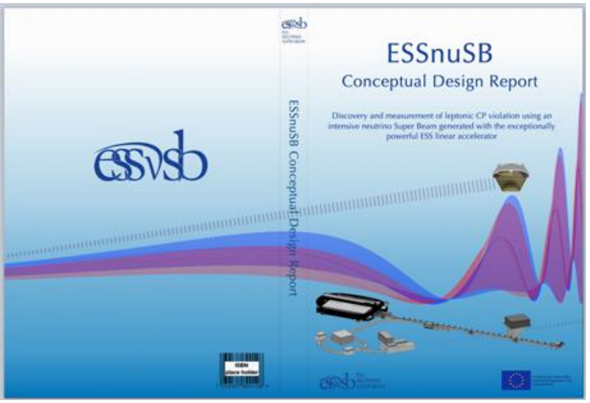
Figure 13: The same as in Fig. 12, but using the prospective 1σ uncertainties in the determination of the neutrino mixing angles within the Gaussian approximation (see text for further details). In the left (right) panel $\sin^2\theta_{12} = 0.308$ (0.332), the other mixing angles being fixed to their NO best fit values.

https://arxiv.org/abs/1410.8056

Final ESSνSB facility configuration







Conceptual Design Report

https://arxiv.org/abs/2206.01208

European Physical Journal Spec. Top. **231**, 3779–3955 (2022).
https://doi.org/10.1140/epjs/s11734-022-00664-w

ESS Neutrino Super Beam Plus

Supporting institutions of ESSνSB

- COST Action EuroNuNet (CA15139): ended March 2020
  - https://euronunet.in2p3.fr
  - video for scientists: https://www.youtube.com/watch?v=PwzNzLQh-Dw
- EU-H2020 Design Study ESSνSB: 2018-2022
  - https://essnusb.eu
  - video for general public: https://www.youtube.com/watch?v=qAnvft0nAlg
- EU-Horizon Europe Design Study ESSνSB+: 2023-2026
  - ongoing

EuroNuNet

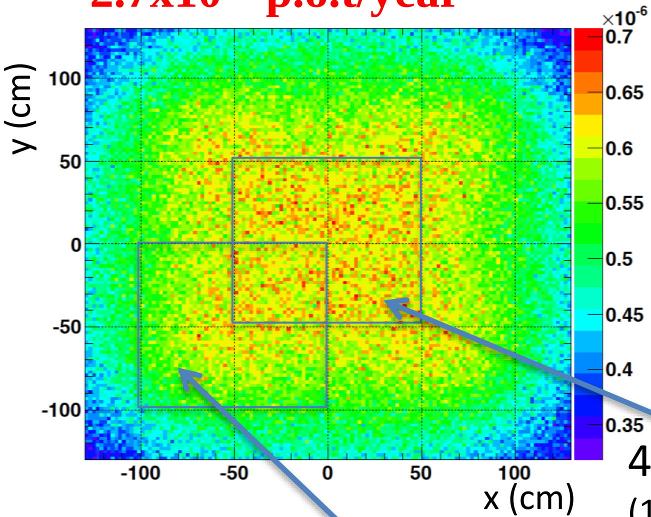
ESSnuSB Design Study Project

ESS NEUTRINO SUPER BEAM

ESSnuSB looking for the answer.

Muons at the level of the beam dump

2.7×10^{23} p.o.t/year



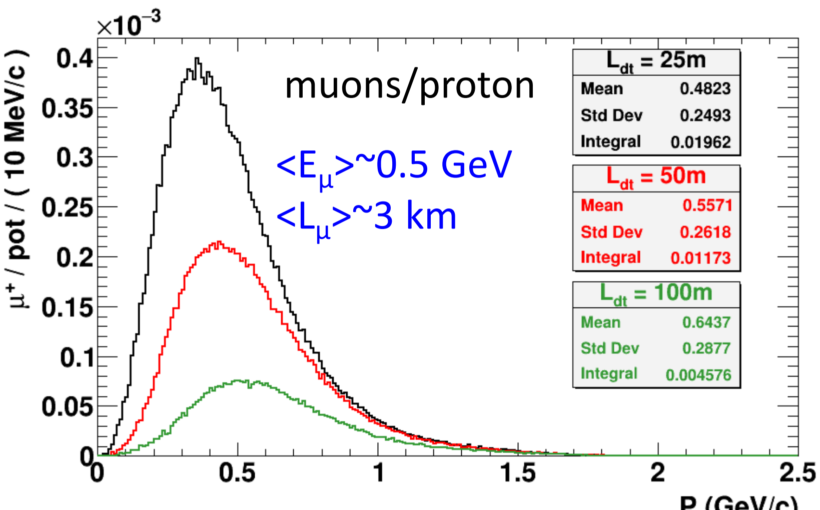
muons at the level of the beam dump (per proton)

4.2×10^{20} μ/year (16.3×10^{20} for 4 m^2)

4.1×10^{20} μ/year

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).

10^{-3}



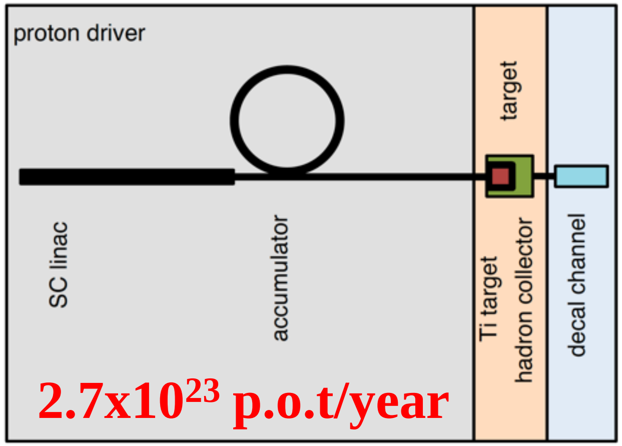
- input beam for future 6D μ cooling experiments,
- low energy nuSTORM,
- Neutrino Factory,
- **Muon Collider**.

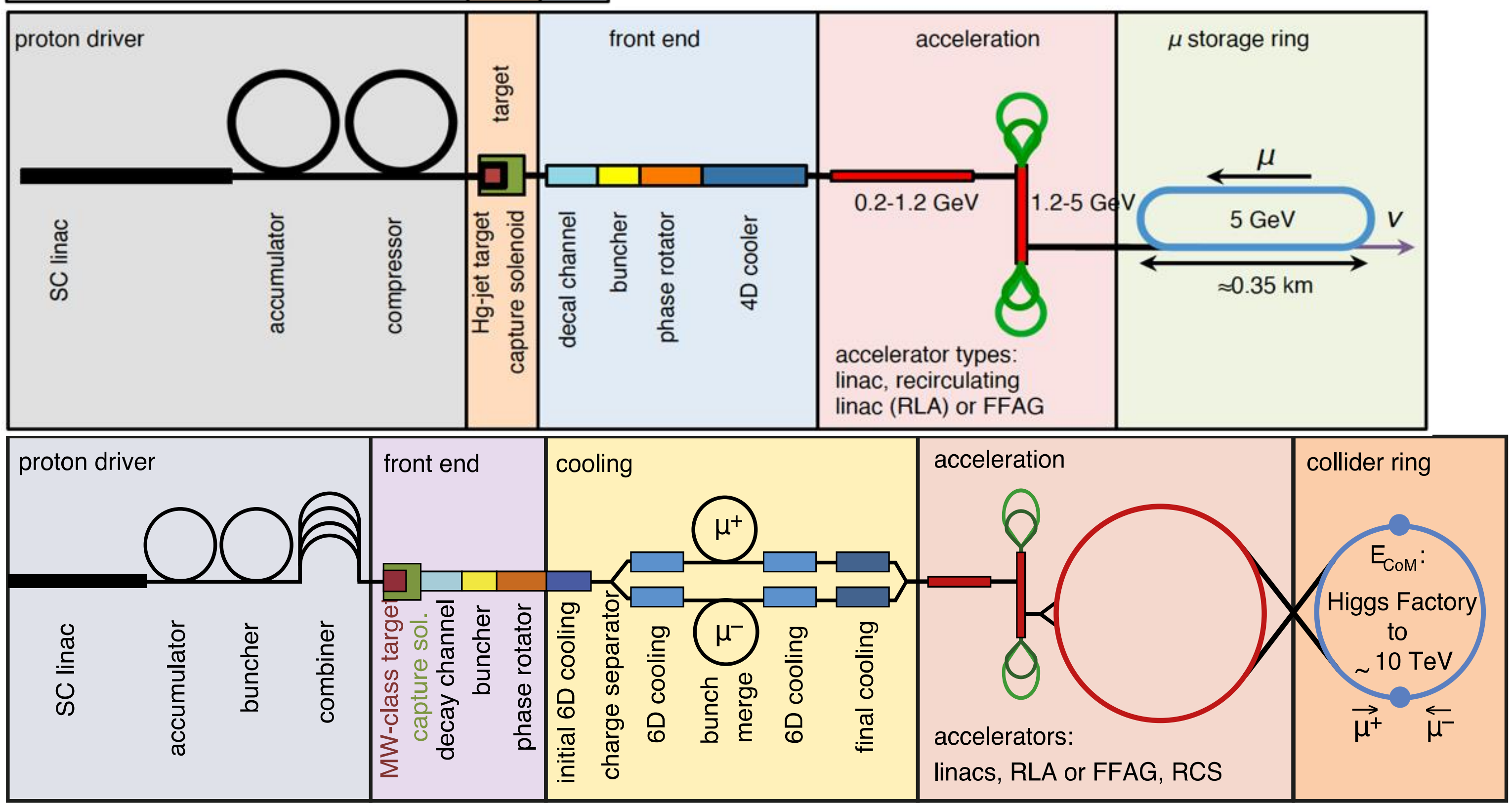
ESSνSB and (R&D) synergies

Super Beam — ESSνSB

Neutrino Factory

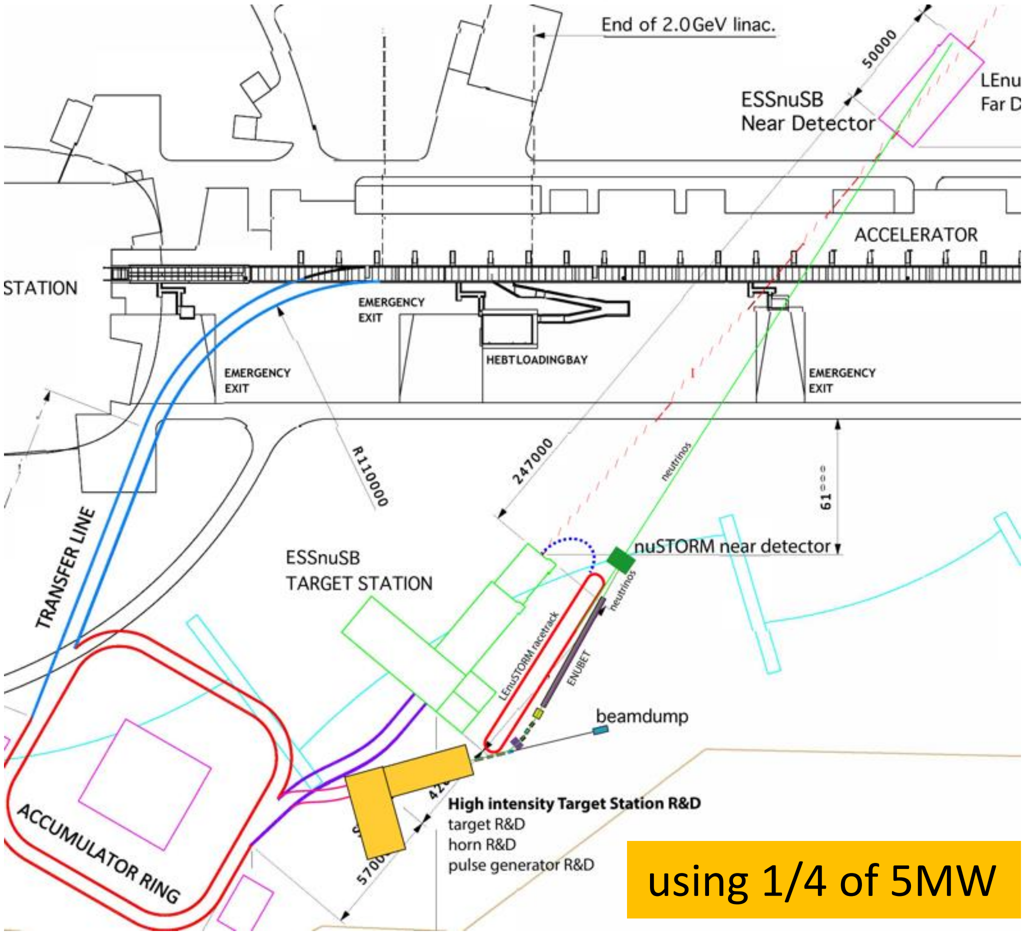
Muon Collider — ESSμSB





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

Further proposed 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 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

ESSvSB+

(Horizon Europe)

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

ESS Neutrino Super Beam Plus

ESSνSB+

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 ESSνSB leptonic CP violation measurements and to perform sterile neutrino searches and astroparticle physics.

Acronym of Proposal: ESSνSB+

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

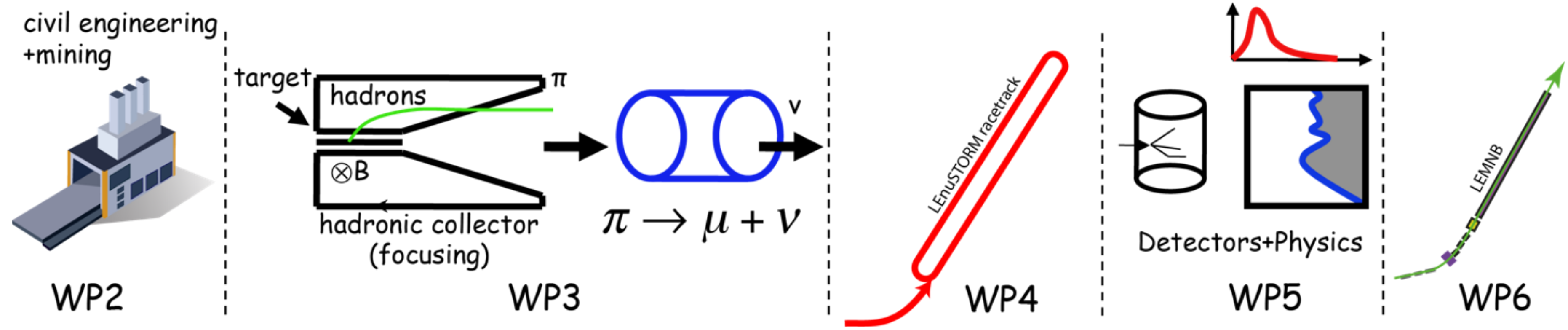
- 3 M€
- 4 years (2023-2026)

2nd ESSνSB+ annual meeting

(Hamburg Uni, Sep. 2024)

ESSνSB+ WP

ESS Neutrino Super Beam Plus



Civil engineering | Target Station |

- cross-sections
- sterile neutrinos

cross-sections

Staged Implementation

Stage 1
LEMNB

- Proton beam from ESS linac, up to 2.86 ms pulses, long-pulses up to 10^{14} protons/pulse,
- ~300kW target station, pion capture using conventional magnets, instrumented decay tunnel
- Beam to near detector LEMMOND at ~40-50 m from the target

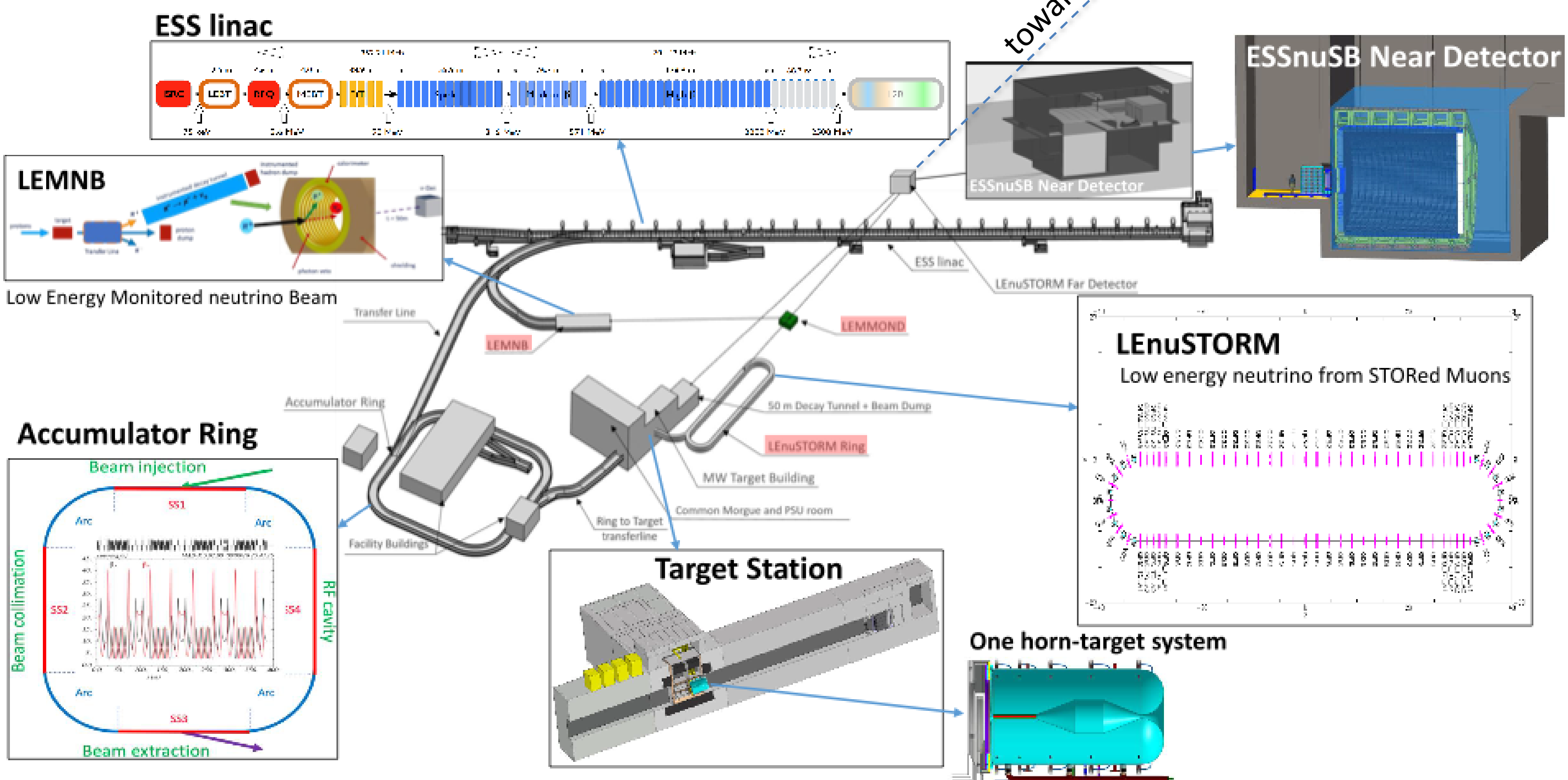
Stage 2
LENUSTORM

- H^- source, and transfer line to accumulator
- Accumulator ring, 1.25 MW target station, horn for pion capture, transfer line and injection to LEnuSTORM ring
- LENUSTORM ring, beam to near detector LEMMOND at ~10-15 m from ring, and to END at 290 m from target

Stage 3
ESSnuSB CPV LBL

- H^- source, and transfer line to accumulator
- Accumulator ring, 5MW target station, horn for pion capture
- Decay tunnel, beam to END at 290 m from target and FD

ESSνSB+ Latest Design

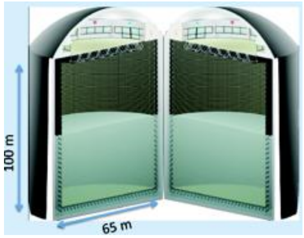


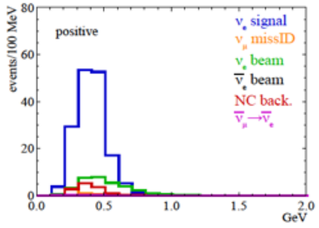
¼ of the total proton power

also able to host the final 4 target/horn system

Possible ESSνSB schedule

(2nd generation neutrino Super Beam)





ESS NEUTRINO SUPER BEAM

ESFRI

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

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, CDR and preliminary costing**

arxiv.org/abs/2206.01208

2022-2026: Preparatory Phase, TDR

2026-2028: Preconstruction Phase, International Agreement

2028-2036: Construction of the facility and detectors, including commissioning

2037-: Data taking

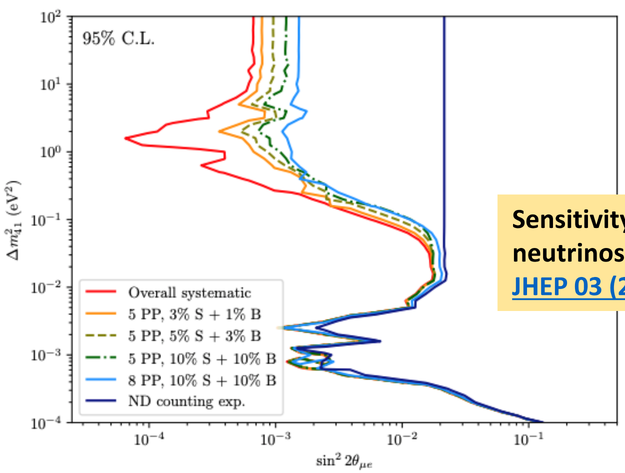
EUROPEAN SPALLATION SOURCE

Conclusion

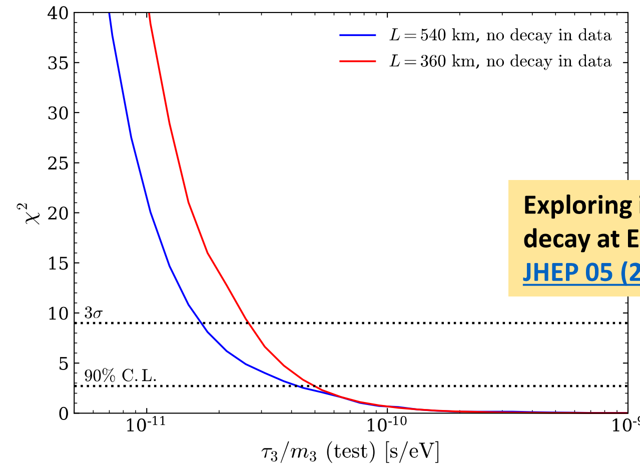
- The ESS proton linac will be soon the most powerful linac in the world.
- ESS can also become a neutrino facility (ESSνSB) with enough protons to go to the 2nd oscillation maximum and increase significantly the CPV sensitivity and make precise measurement of δ_{CP}.
- CPV: 5 σ could be reached over 70% of δ_{CP} range by ESSνSB with large physics potential with less than 8° precision.
- The European Spallation Source (for neutron) will start by 2025, upgrade decisions by this moment.
- Conceptual Design Report published including costing on arXiv.
- Rich muon program for future ESS upgrades.
- New studies for intermediate stages are under way.

Backup

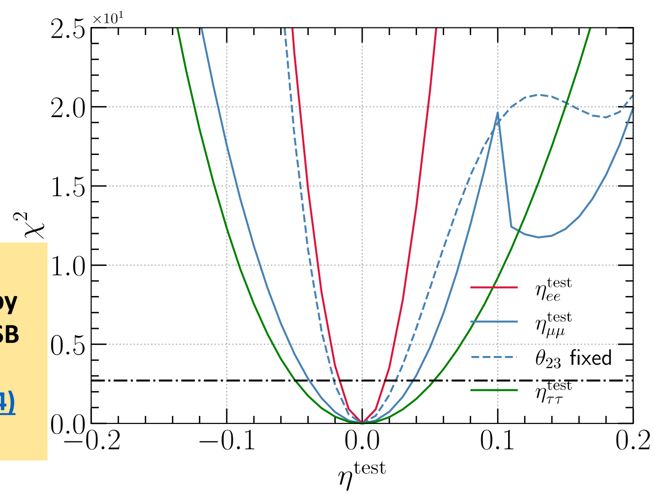
ESSvSB sensitivity to constrain new physics



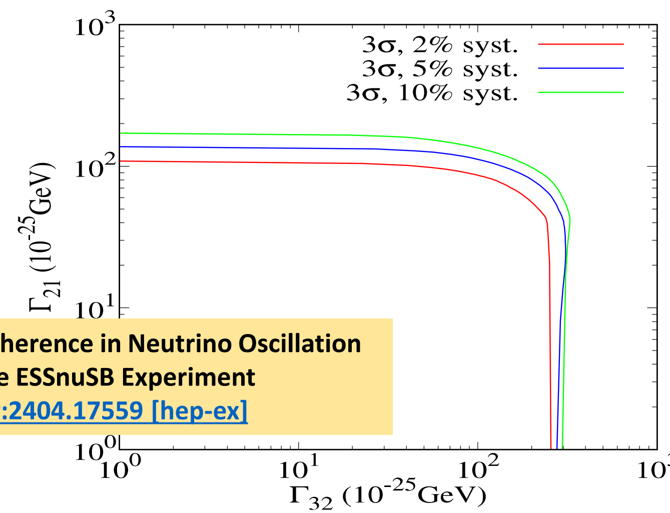
Sensitivity to light sterile neutrinos at ESSnuSB
[JHEP 03 (2020), 026]



Exploring invisible neutrino decay at ESSnuSB
[JHEP 05 (2021), 133]



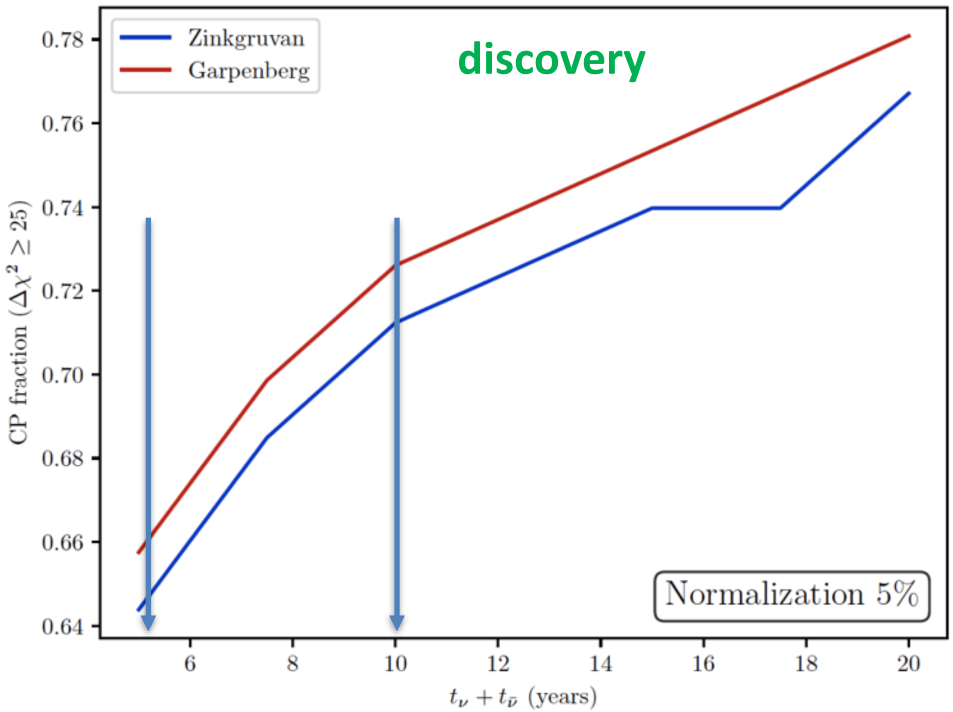
Study of non-standard interaction mediated by a scalar field at ESSnuSB experiment
[Phys. Rev. D 109, (2024) 115010]

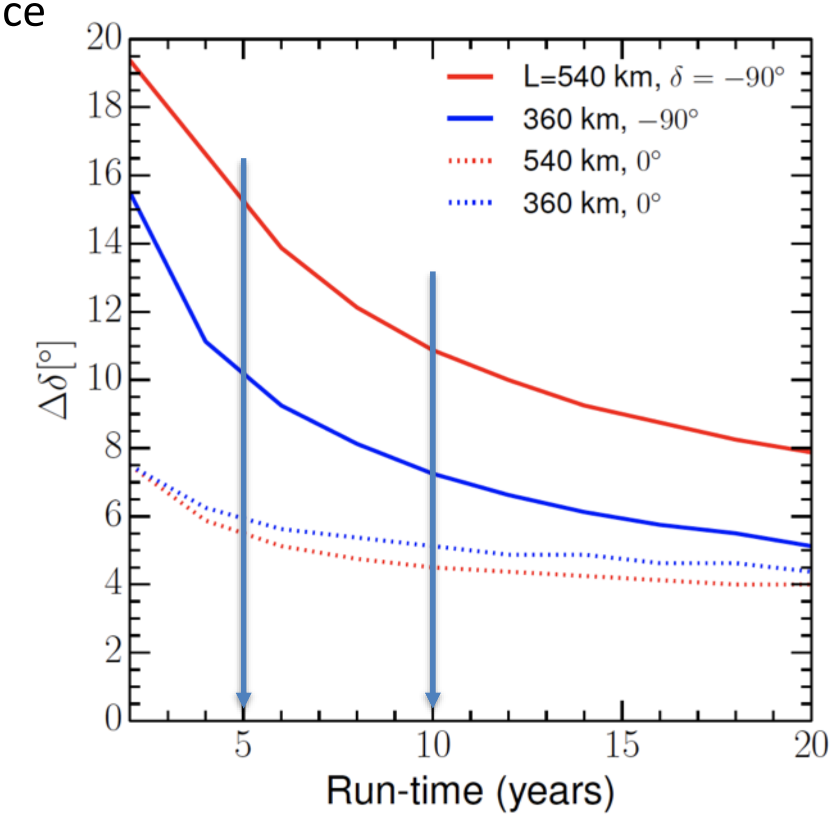


Decoherence in Neutrino Oscillation at the ESSnuSB Experiment
[arXiv:2404.17559 [hep-ex]]

Performance versus time

Already after 5 years very competitive performance





Design Study ESSνSB (2018-2022)

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

Maximum grant amount (proposed amount, after evaluation): **2,999,018.00 EUR**

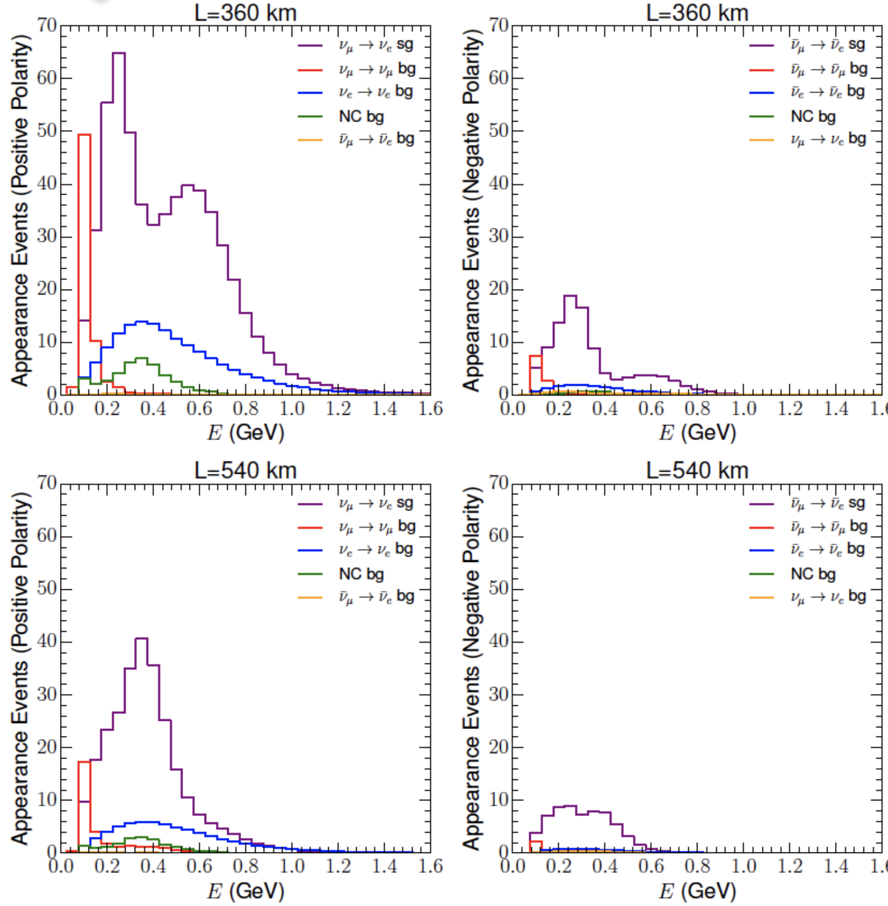
N.	Proposer name	Country
1	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	FR
2	UPPSALA UNIVERSITET	SE
3	KUNGLIGA TEKNISKA HOEGSKOLAN	SE
4	EUROPEAN SPALLATION SOURCE ERIC	SE
5	UNIVERSITY OF CUKUROVA	TR
6	UNIVERSIDAD AUTONOMA DE MADRID	ES
7	NATIONAL CENTER FOR SCIENTIFIC RESEARCH "DEMOKRITOS"	EL
8	ISTITUTO 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:	

now finished end of March 2022

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

partners: IHEP, BNL, SCK•CEN, SNS, PSI, RAL, NU

Physics Performance



during 10 years

	Channel	$L = 540$ km	$L = 360$ km
Signal	$\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$)	272.22 (63.75)	578.62 (101.18)
	$\nu_\mu \to \nu_\mu$ ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)	31.01 (3.73)	67.23 (11.51)
Background	$\nu_e \to \nu_e$ ($\bar{\nu}_e \to \bar{\nu}_e$)	67.49 (7.31)	151.12 (16.66)
	ν_μ NC ($\bar{\nu}_\mu$ NC)	18.57 (2.10)	41.78 (4.73)
	$\bar{\nu}_\mu \to \bar{\nu}_e$ ($\nu_\mu \to \nu_e$)	1.08 (3.08)	1.94 (6.47)

Physics Performance