

New Physics Opportunities at Neutrino
Facilities (NPN-2026)

**CPV precision measurement using the
European Spallation Source neutrino
Super Beam**

**Marcos Dracos
IPHC-Strasbourg**



European Spallation Source



Neutron facility

linac

Central Utility Building

Exp. Hall E01

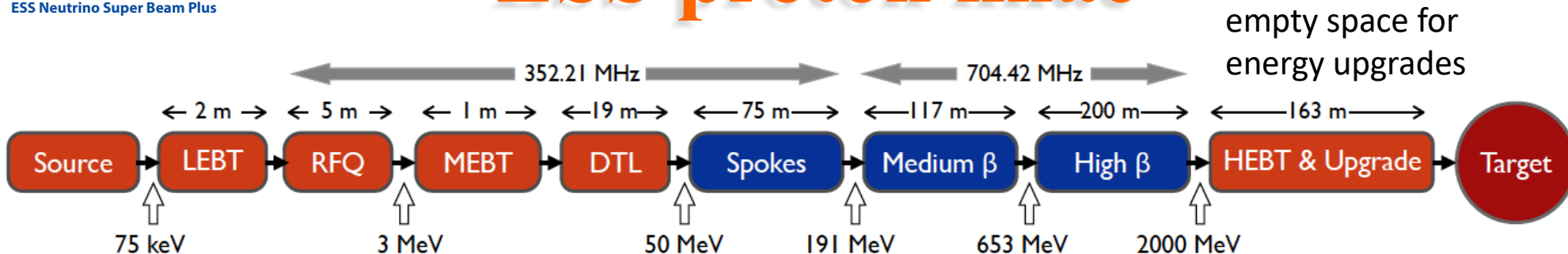
Target Monolith

under construction phase (>2 B€ facility)

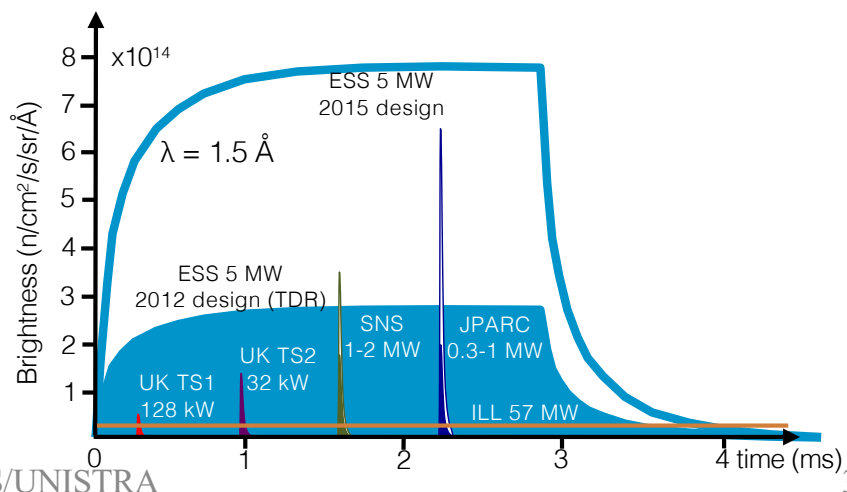
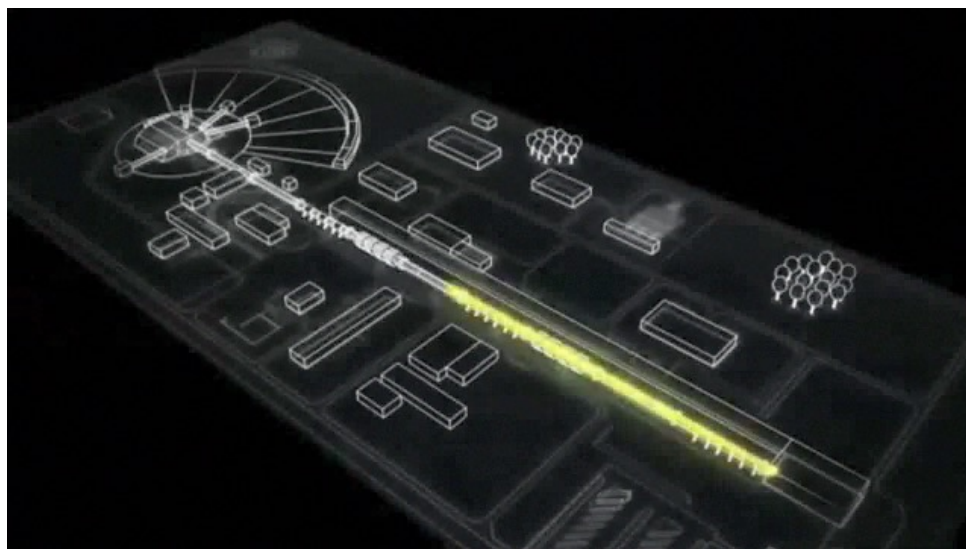
first beam in May 2025
commissioning ongoing

<https://youtu.be/brB3xaQe1xo>

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



European Spallation Source as Neutrino Facility for CP violation discovery ($\sim 2^{\text{nd}}$ oscillation maximum)

$$\nu_{\mu} \rightarrow \nu_e$$

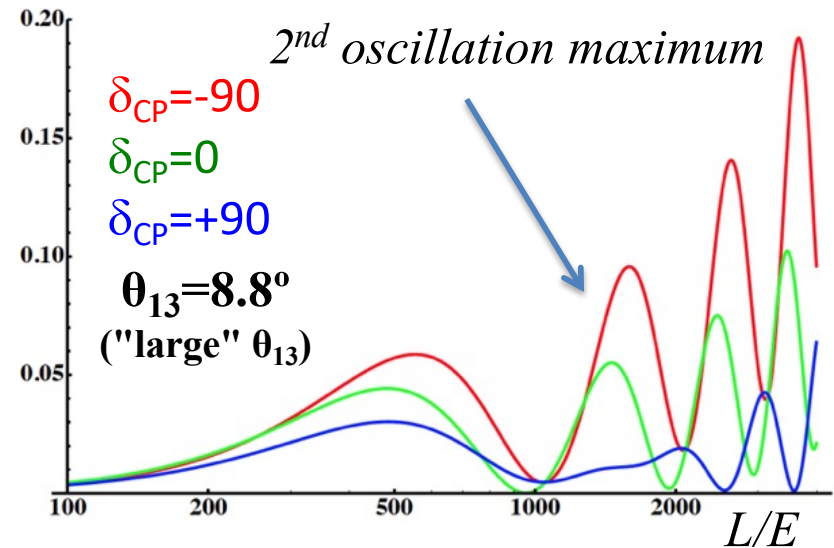
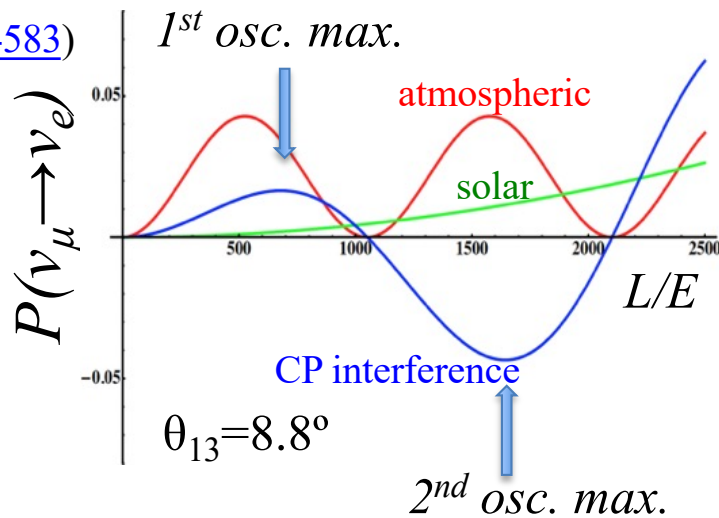
$$\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$$

Neutrino Oscillation probability

$$\begin{aligned}
 P_{\nu_\mu \rightarrow \nu_e} &\simeq 4s_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2} \sin^2 \frac{(1-r_A)\Delta L}{2} && \text{"atmospheric"} \\
 &+ 8J_r \frac{r_\Delta}{r_A(1-r_A)} \cos\left(\delta_{CP} - \frac{\Delta L}{2}\right) \sin \frac{r_A \Delta L}{2} \sin \frac{(1-r_A)\Delta L}{2} && \text{"interference"} \\
 &+ 4c_{23}^2 c_{12}^2 s_{12}^2 \left(\frac{r_\Delta}{r_A}\right)^2 \sin^2 \frac{r_A \Delta L}{2} && \text{"solar"}
 \end{aligned}$$

$$\begin{aligned}
 \nu_\mu &\rightarrow \nu_e \\
 \bar{\nu}_\mu &\rightarrow \bar{\nu}_e
 \end{aligned}$$

(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)

δ_{CP} and Matter-antimatter asymmetry magnitude

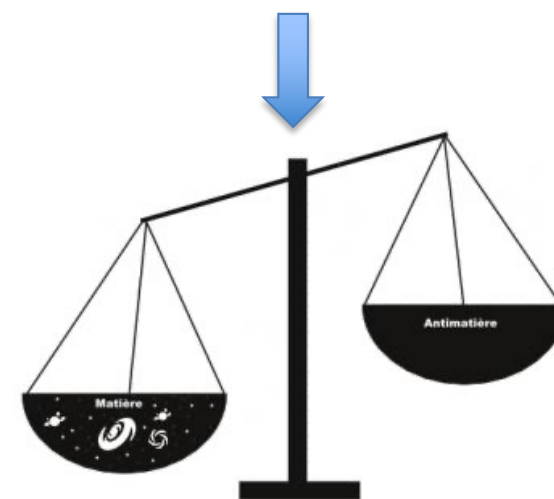
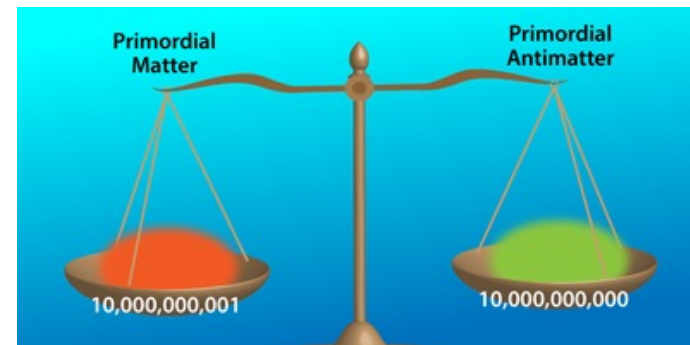
$$A_{\alpha\beta}^{CP} = P(\nu_{\alpha} \rightarrow \nu_{\beta}) - P(\bar{\nu}_{\alpha} \rightarrow \bar{\nu}_{\beta})$$

$$= J_{CP}^{PMNS} \cdot \sin\delta_{CP}$$

with: $J_{CP}^{PMNS} \sim 3 \times 10^{-3}$ (Jarlskog invariant)

(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.

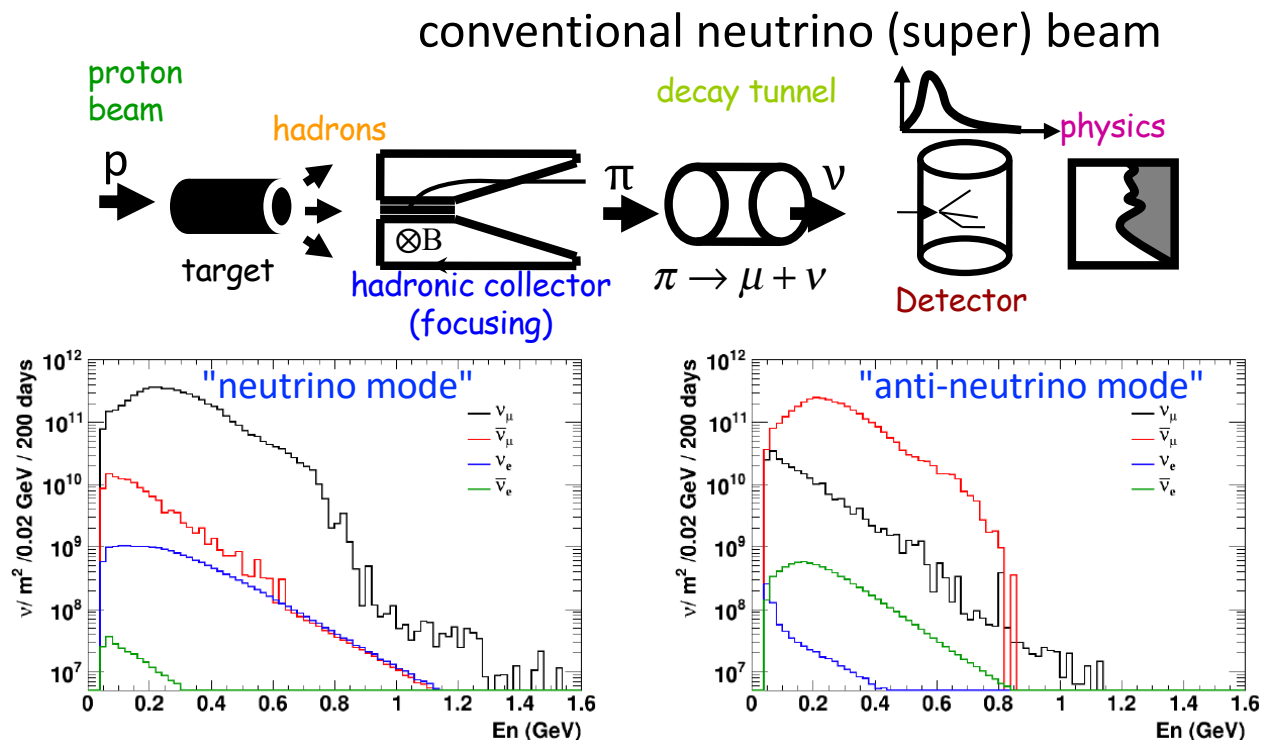
(Nucl.Phys.B774:1-52,2007, [arXiv:hep-ph/0611338](https://arxiv.org/abs/hep-ph/0611338))

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
- $>2.7 \times 10^{23}$ 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

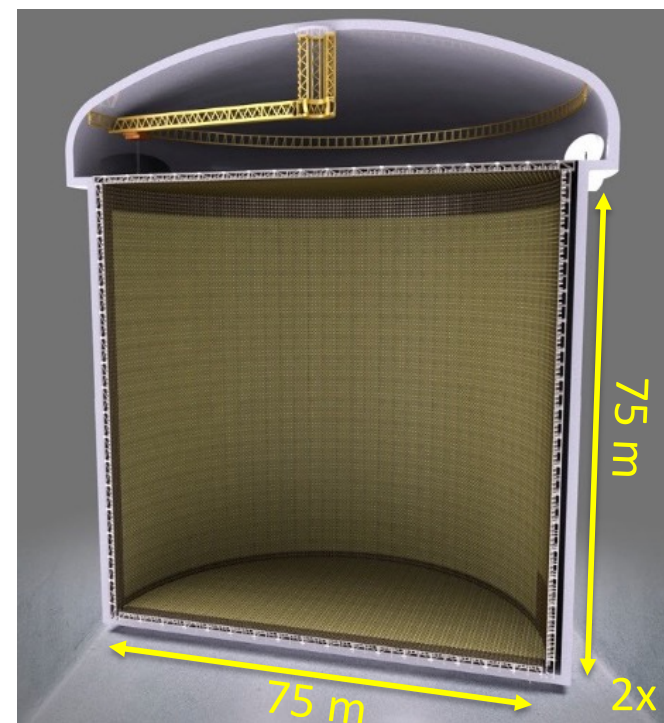
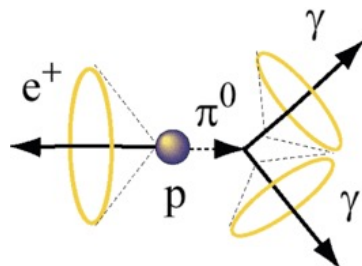
at 100 km from the target, per year (in absence of oscillations)

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

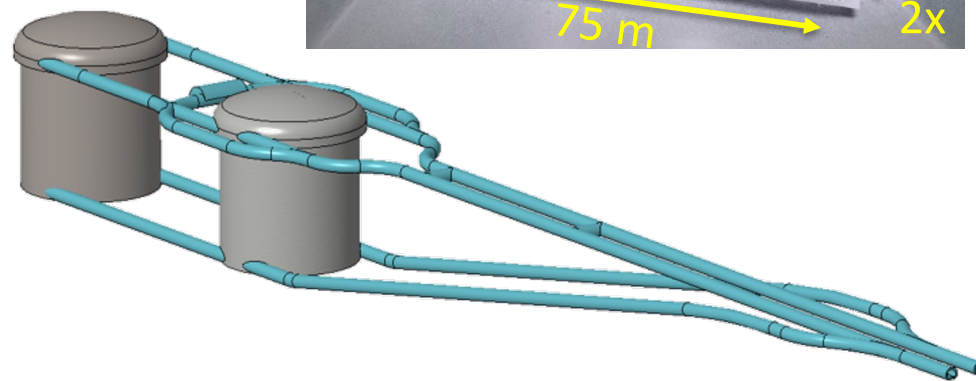
Yes, if we place our far detector at 350- 550 km from the neutrino source.

Megaton Water Cherenkov detector

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

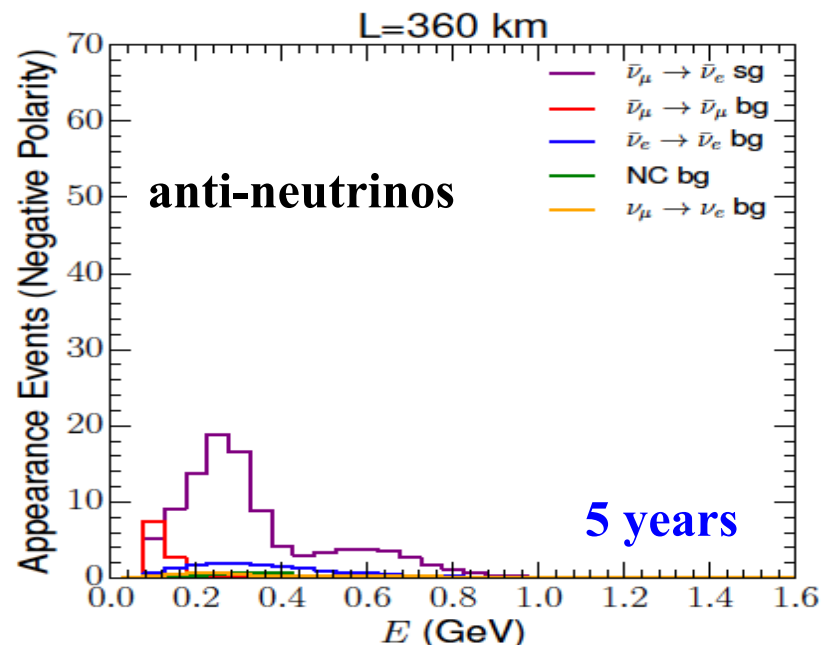
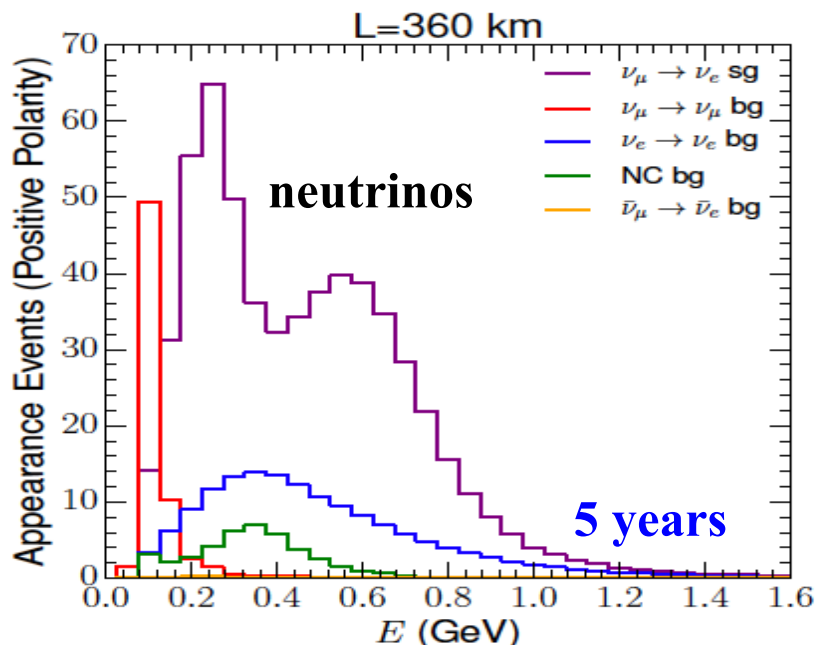


- 560 kt fiducial volume
- Readout: ~20" PMTs
- 30% optical coverage

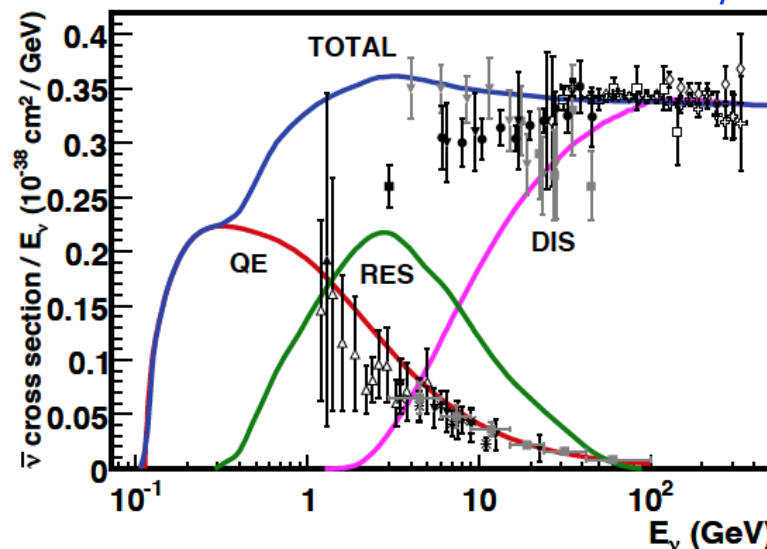
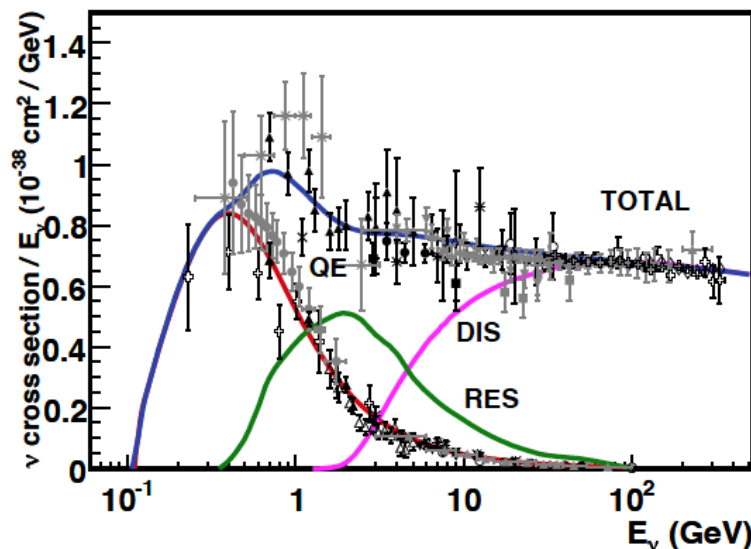


Neutrinos in the Far Detector

$\delta_{CP}=0$



Rev. Mod. Phys. 84 1307



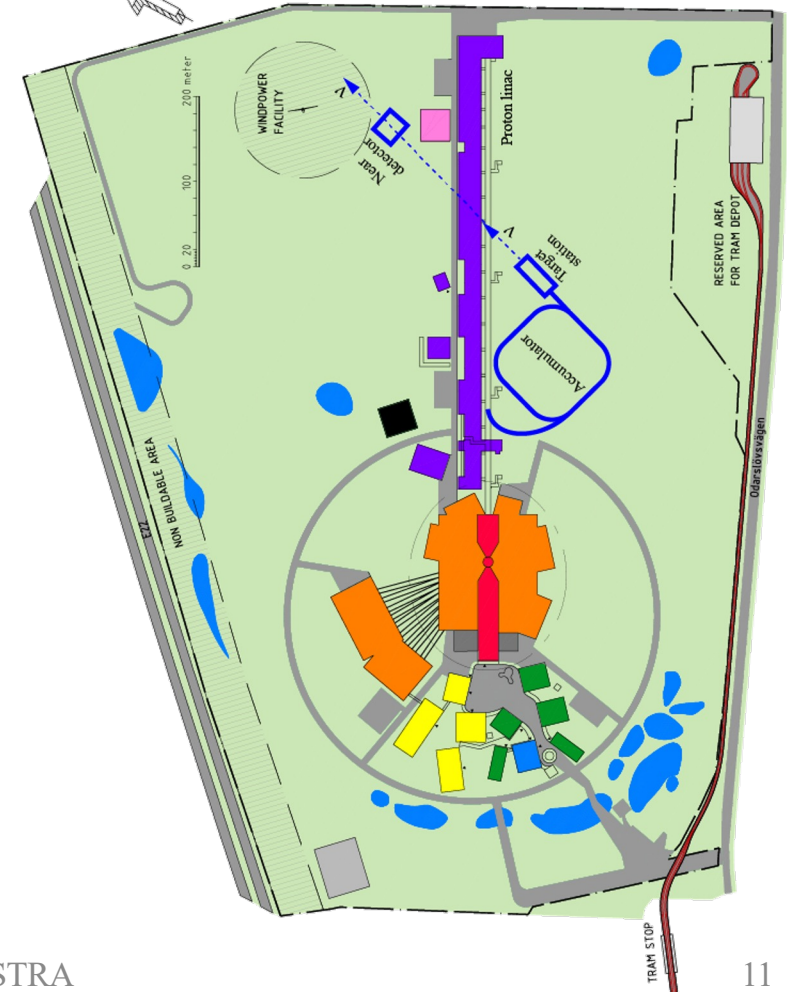
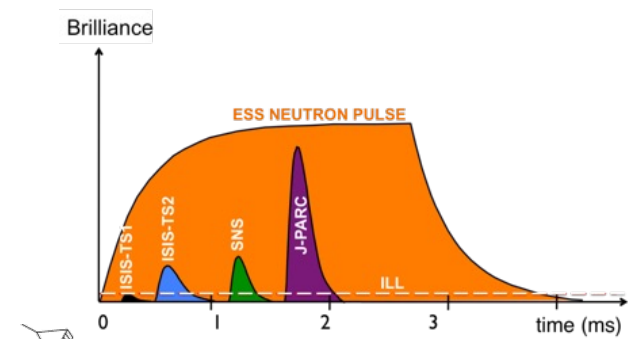
below ν_τ production, almost only QE events, not suffering too much by π^0 background

ESS modifications to produce a neutrino Super Beam

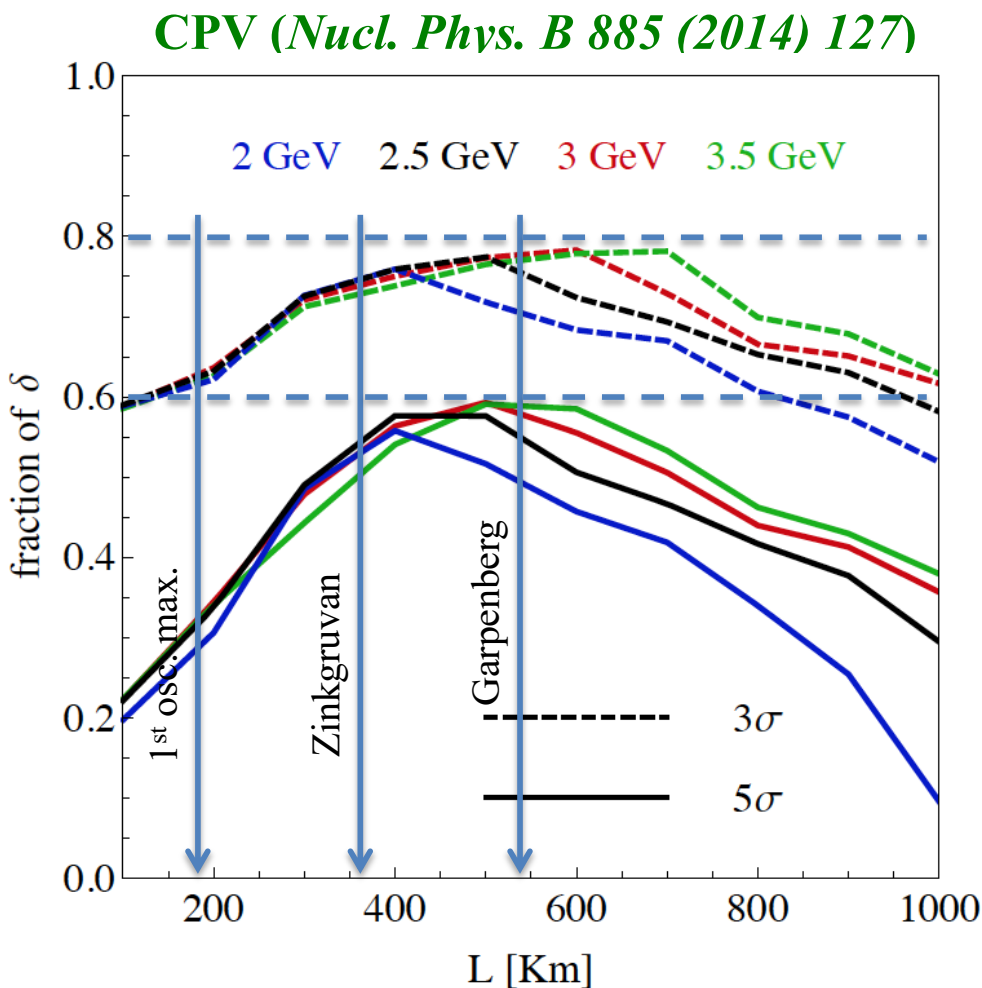
European Spallation Source Linac

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 \rightarrow 28 Hz), from 4% duty cycle to 8%.
- Accumulator (C \sim 400 m) needed to compress to few μ s 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.
- \sim 300 MeV neutrinos.
- Target station.
- Underground detector.
- Short pulses ($\sim\mu$ s) will also allow DAR and coherent scattering experiments (as those proposed for SNS) using the neutron target.



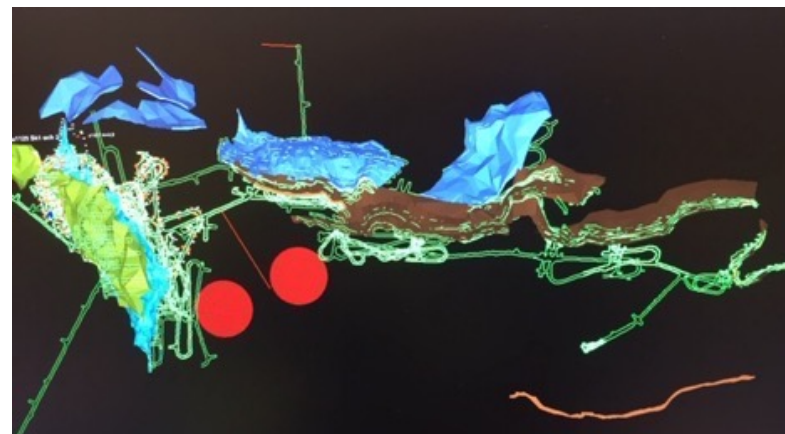
Which baseline?



Candidate mines



Selected mine: Zinkgruvan



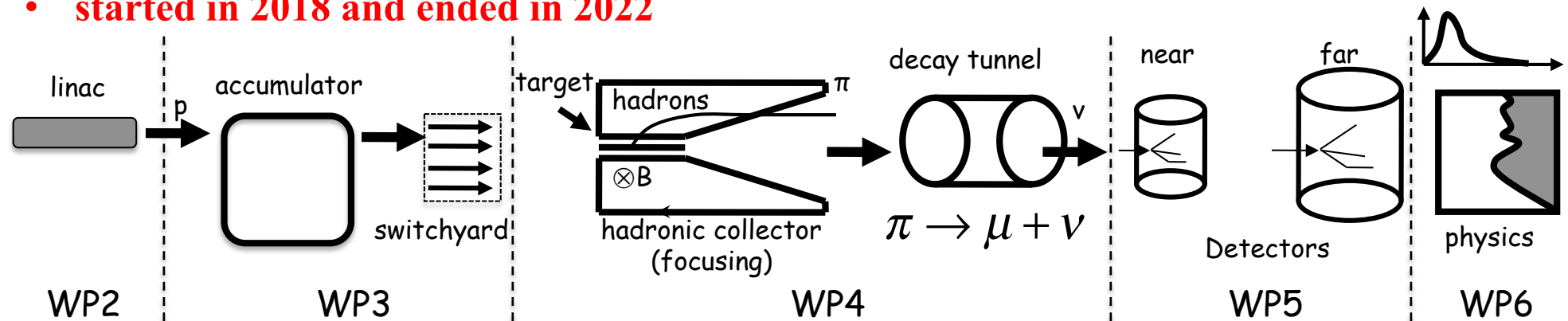
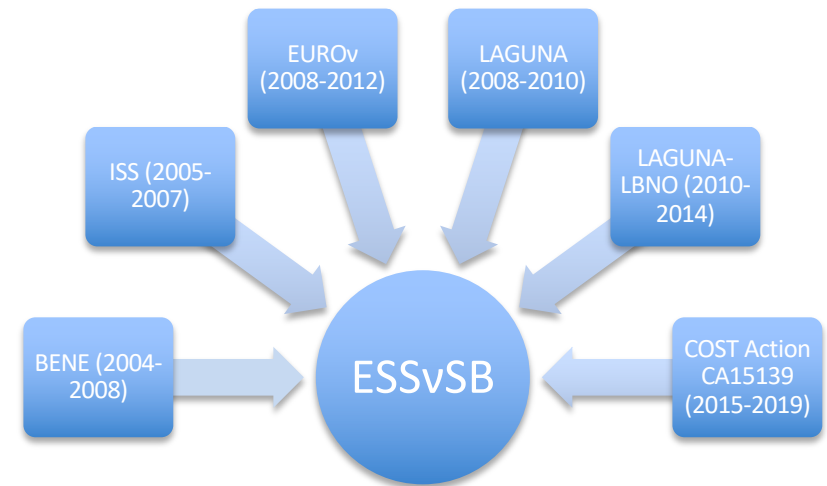
possible location of the detector

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

ESSvSB at the European level

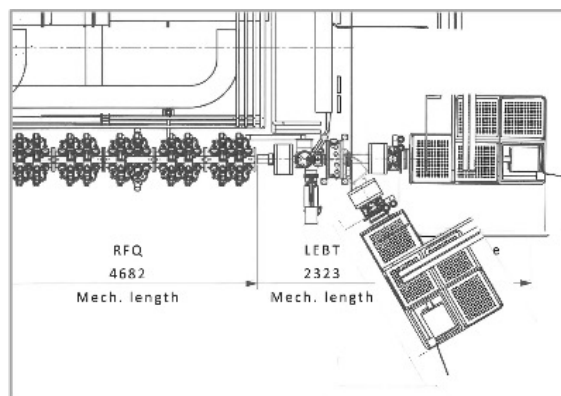


- A H2020 EU Design Study (Call INFRADEV-01-2017)
 - **Title of Proposal:** Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator
 - **Duration:** 4 years
 - **Total cost:** 4.7 M€
 - **Requested budget:**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

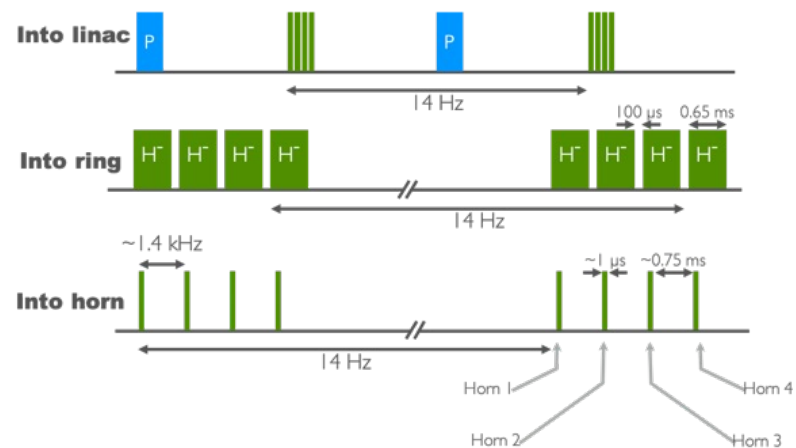


ESS modifications and operation

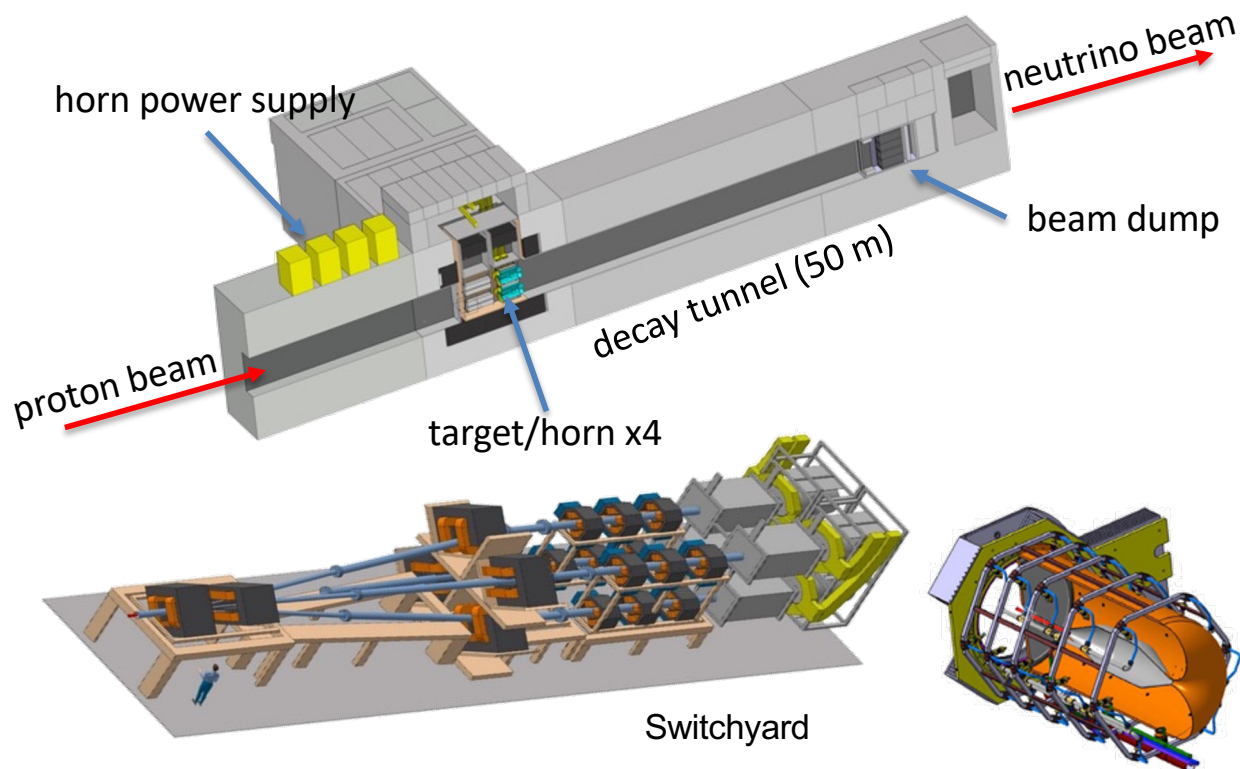
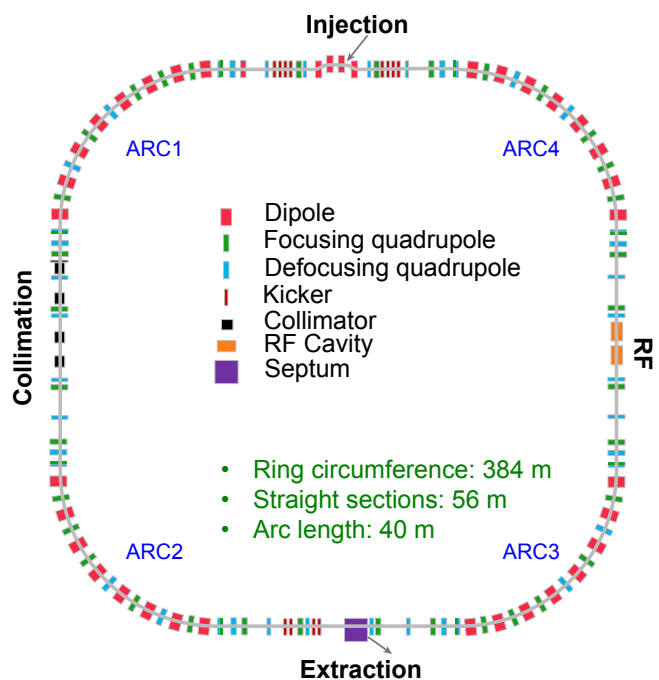
H⁻ source



time operation option

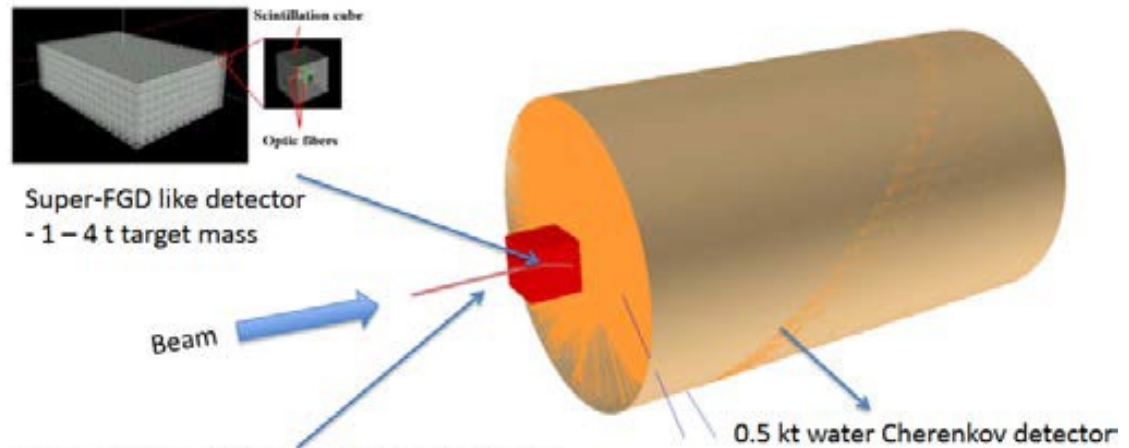
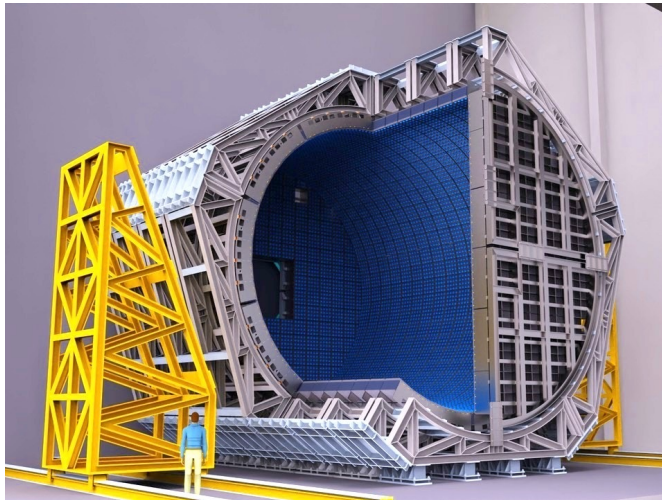


accumulator lattice

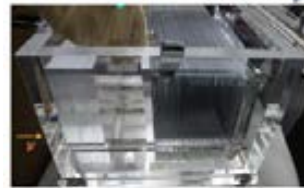


Detectors

Water Cherenkov

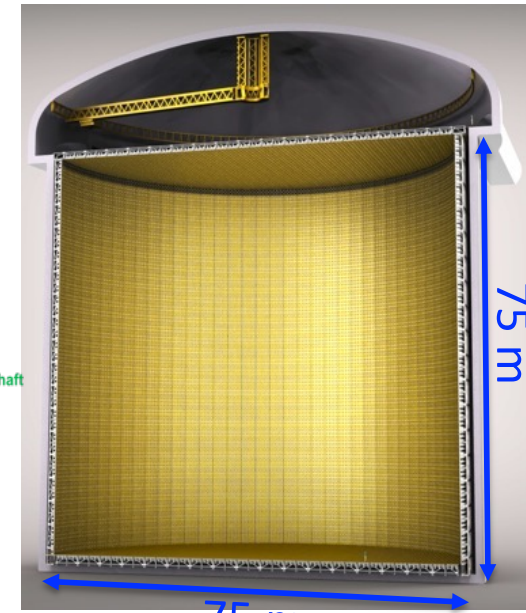
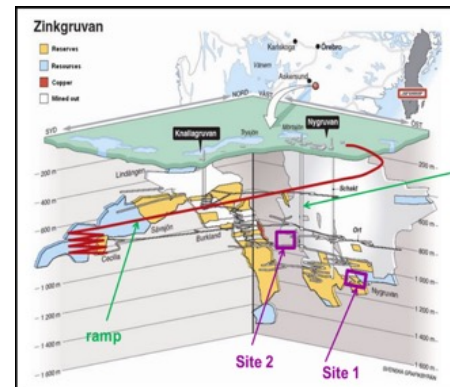
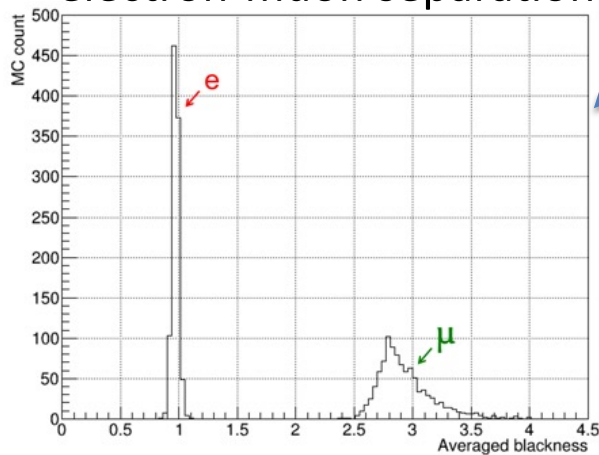


Near detector



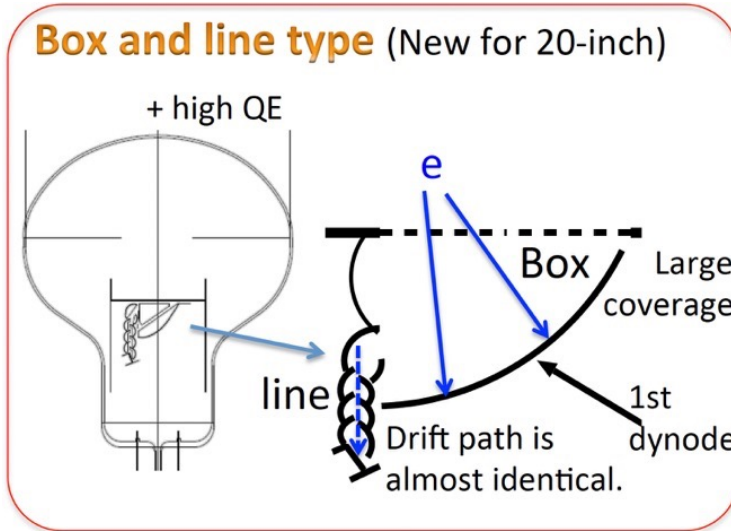
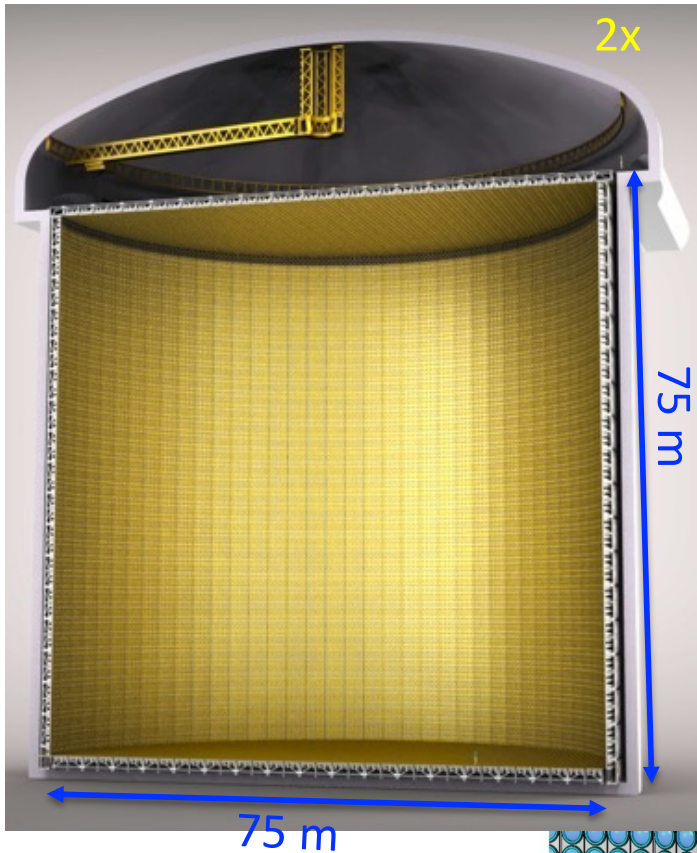
Addition: NINJA-like water-emulsion detector

electron-muon separation

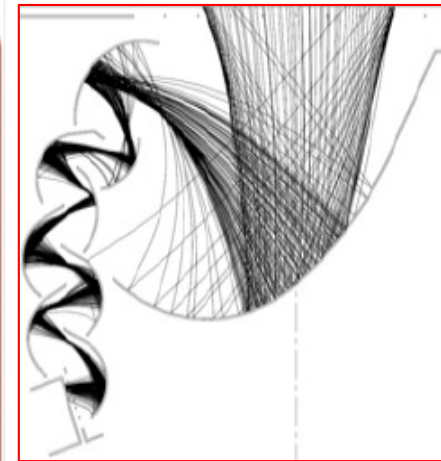


astroparticle physics program with the Far Detector

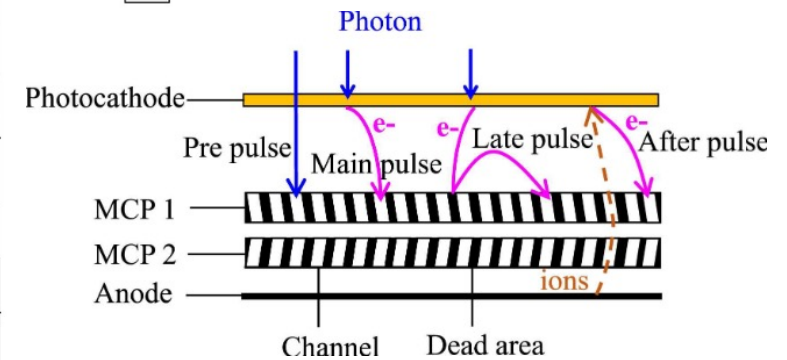
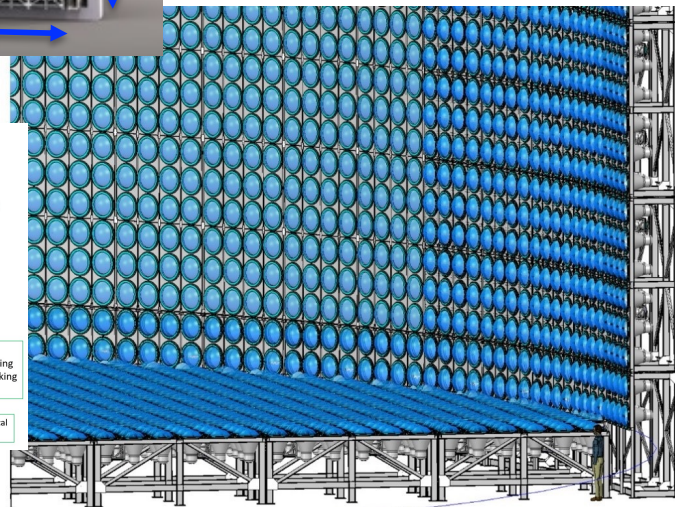
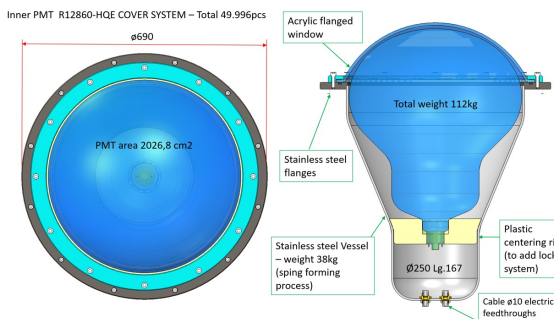
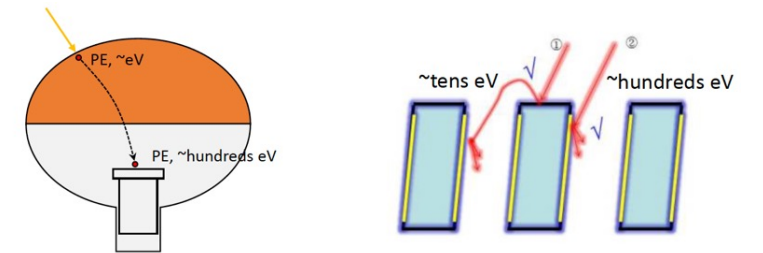
Far Detector



Hamamatsu

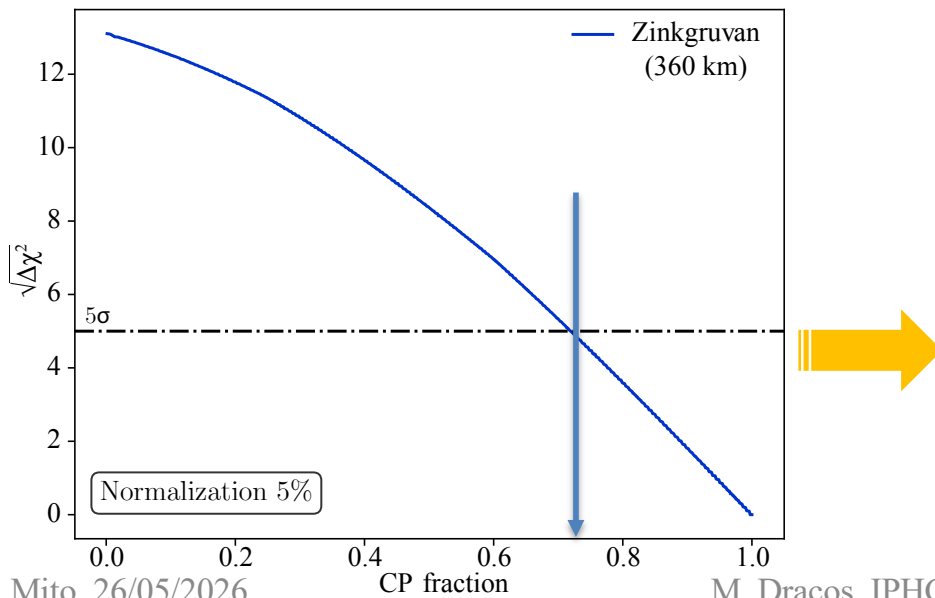
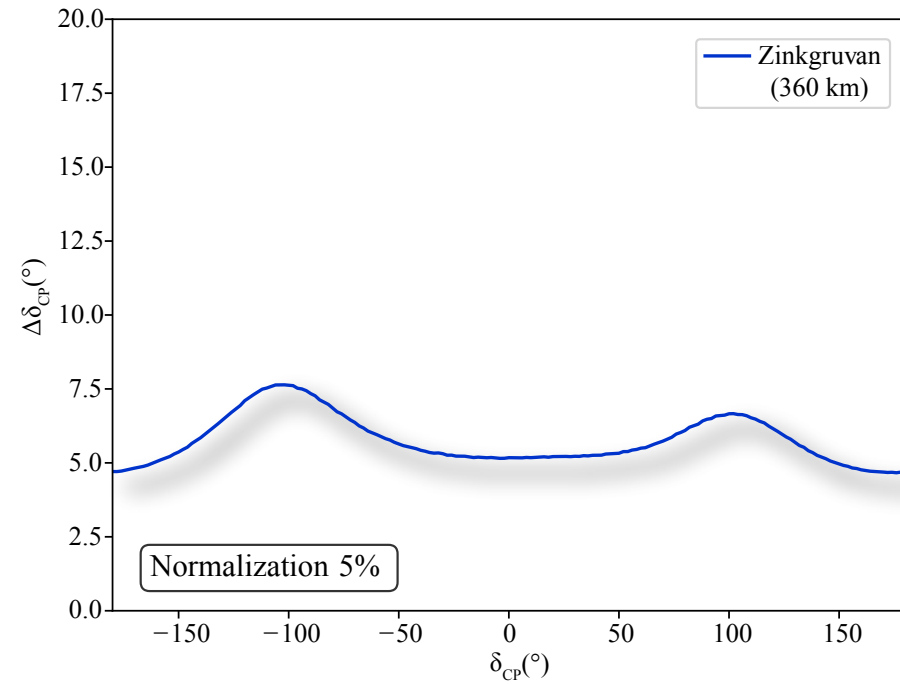
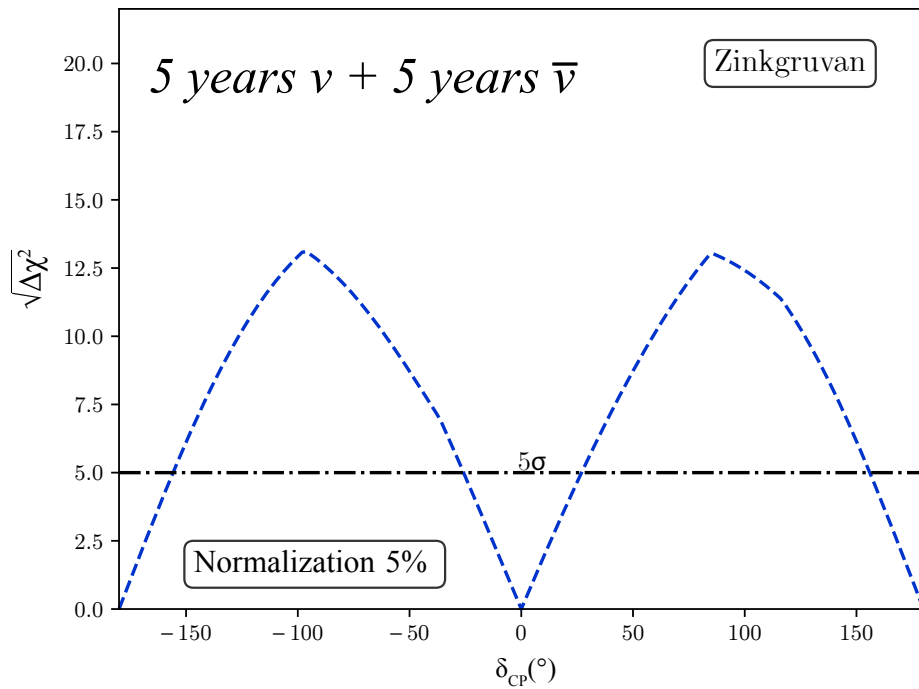


or MCP (NNVT)



still a lot of time before we choose

Final results



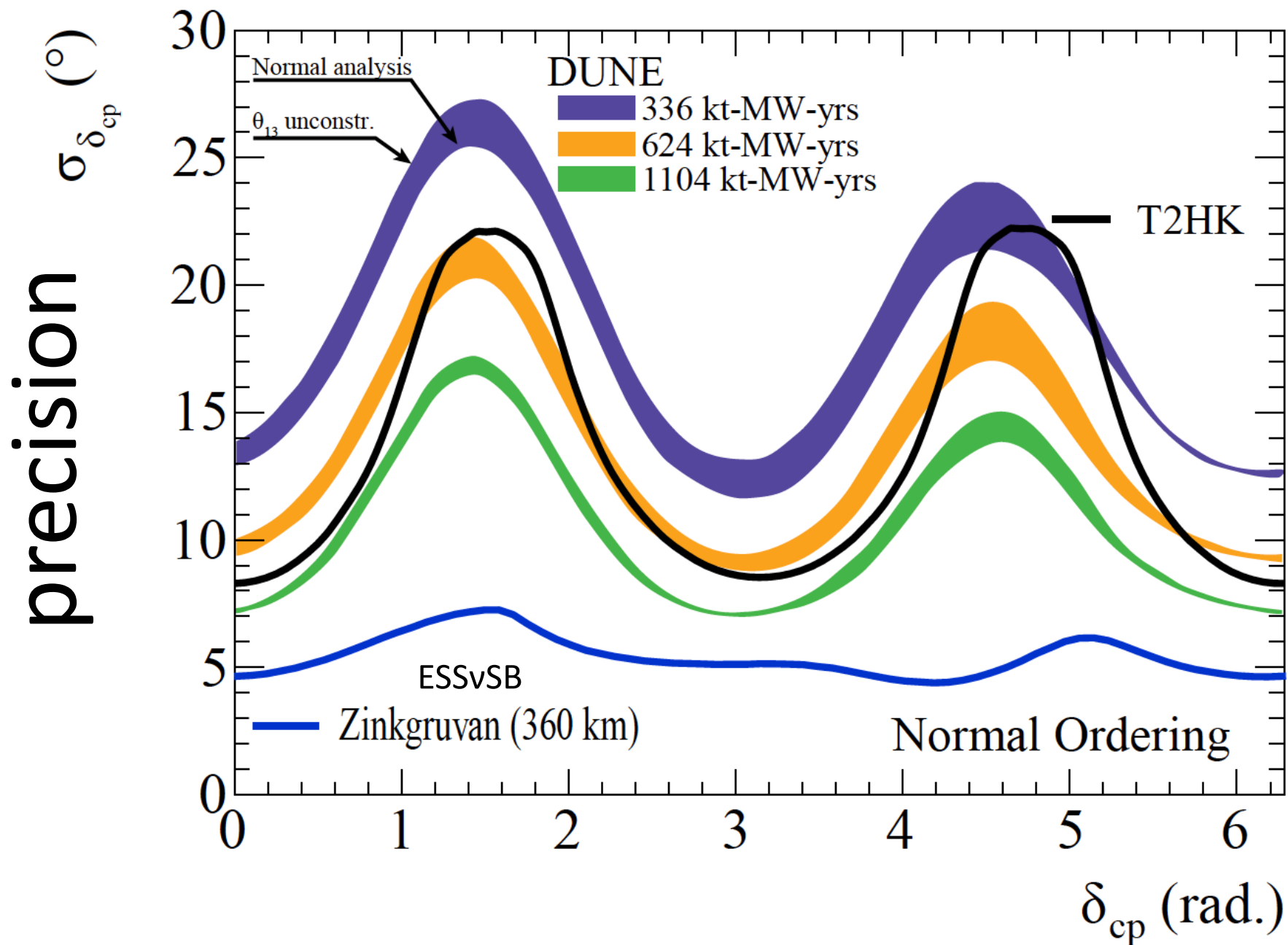
Precision measurement

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

>72% after 10 years

equivalent to Neutrino Factory

Comparison with current projects



δ_{CP} and model predictions

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.:

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

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

<https://arxiv.org/abs/1410.8056>

<https://arxiv.org/abs/1410.7573>

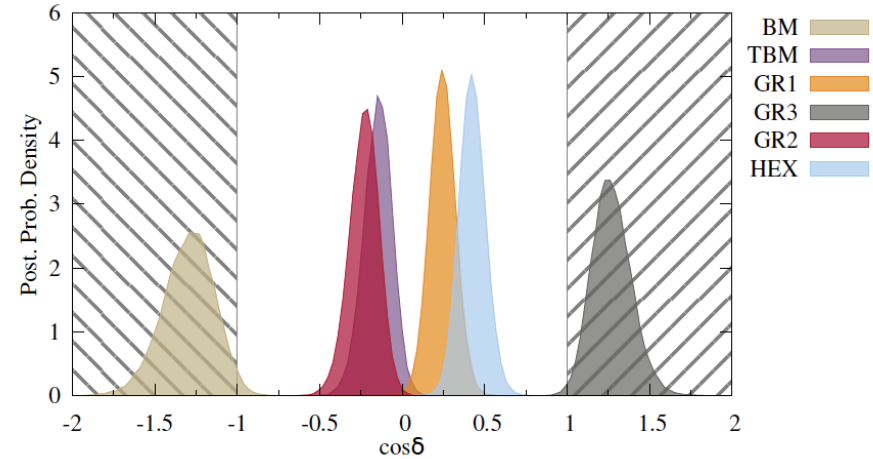


Figure 3: Posterior probability density functions for $\cos \delta$ for each of the solar sum rules considered in Section 3.1. The patterned regions are unphysical, which shows that the BM and GR3 sum rules could only be consistent with the known data if there is a significant deviation from the current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

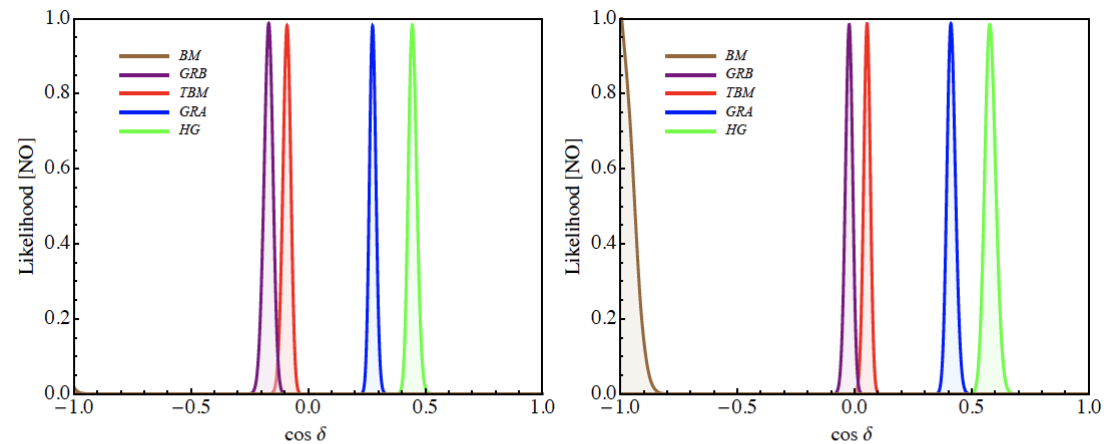
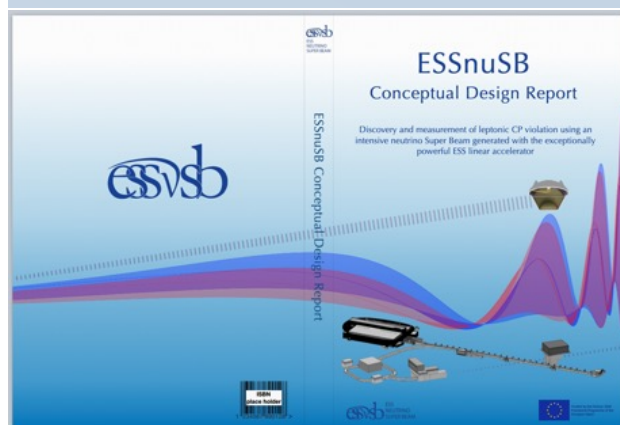
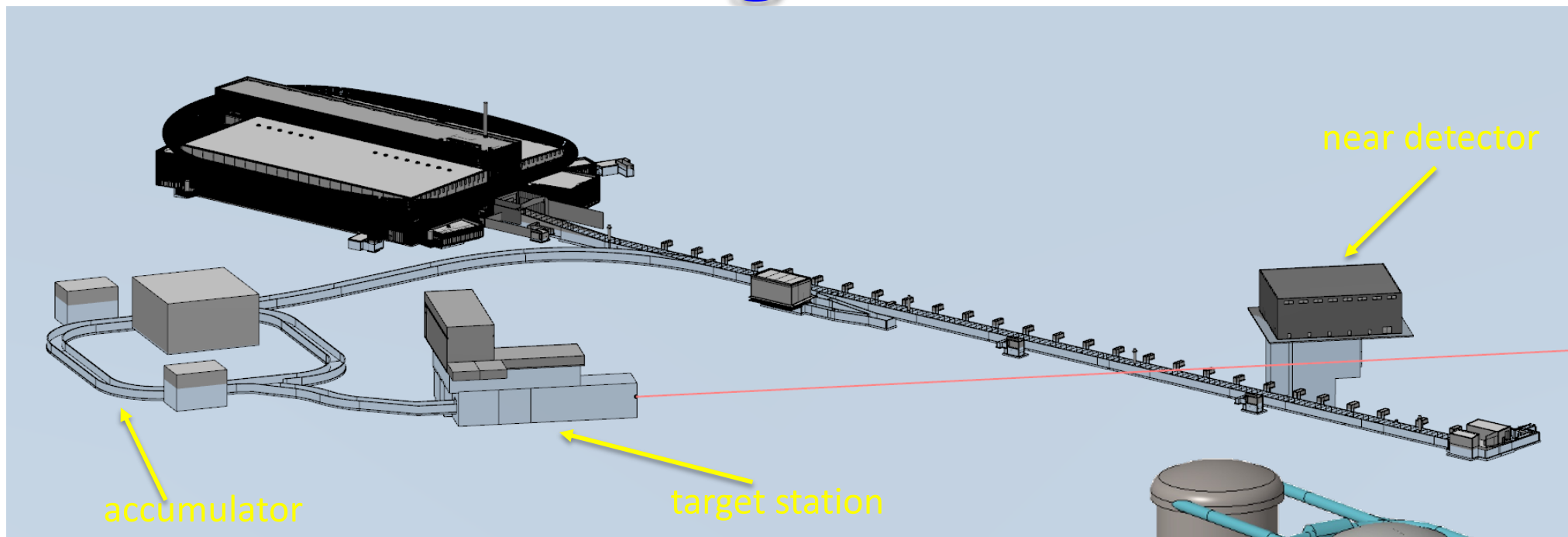


Figure 13: The same as in Fig. 12, but using the prospective 1σ uncertainties in the determination of the neutrino mixing angles within the Gaussian approximation (see text for further details). In the left (right) panel $\sin^2 \theta_{12} = 0.308$ (0.332), the other mixing angles being fixed to their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

Final ESSνSB facility configuration



<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>

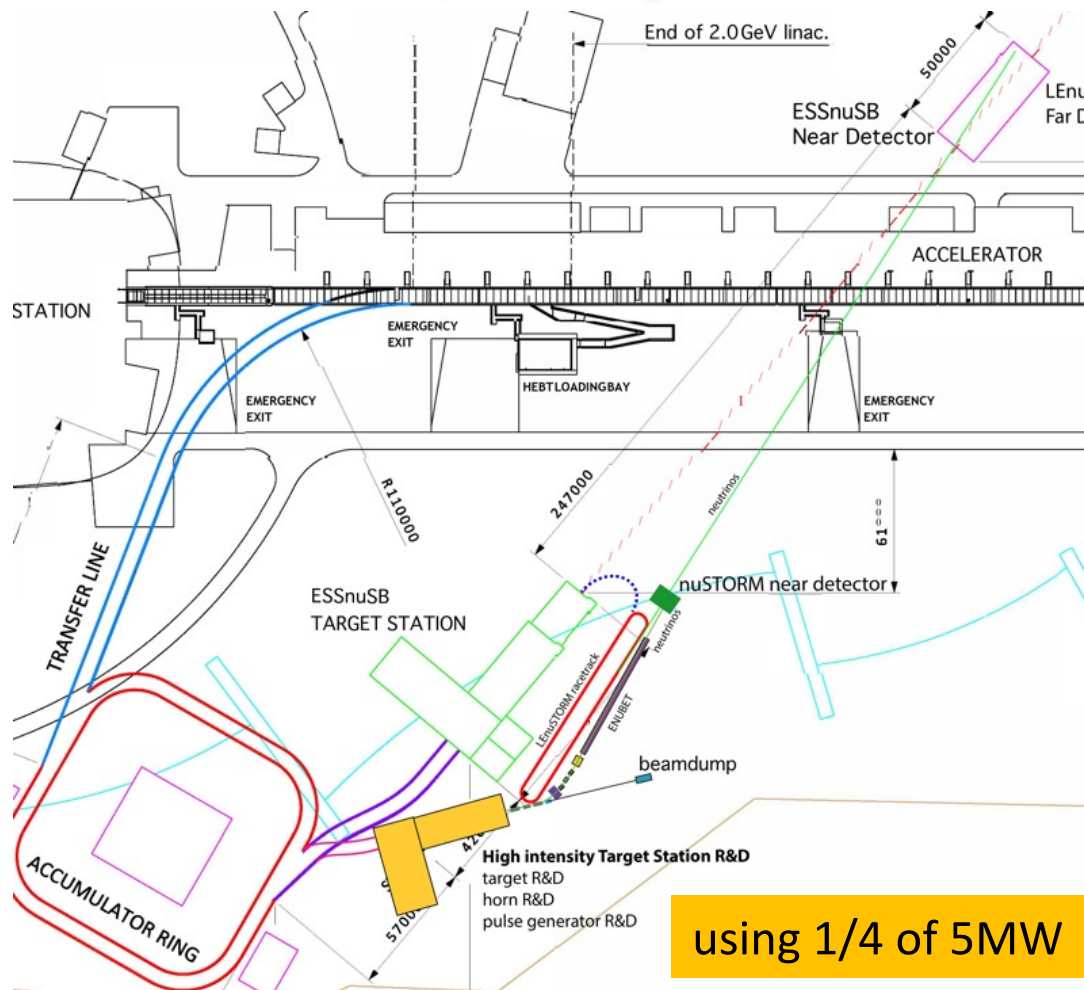
Conceptual Design Report

Mito, 26/05/2026

M. Dracos, IPHC-IN2P3/CNRS/UNISTRA

Further ongoing studies

(mainly cross-section measurements)



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: $\pi \rightarrow \mu + \nu_\mu$

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+

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)

3rd ESSvSB+ annual meeting

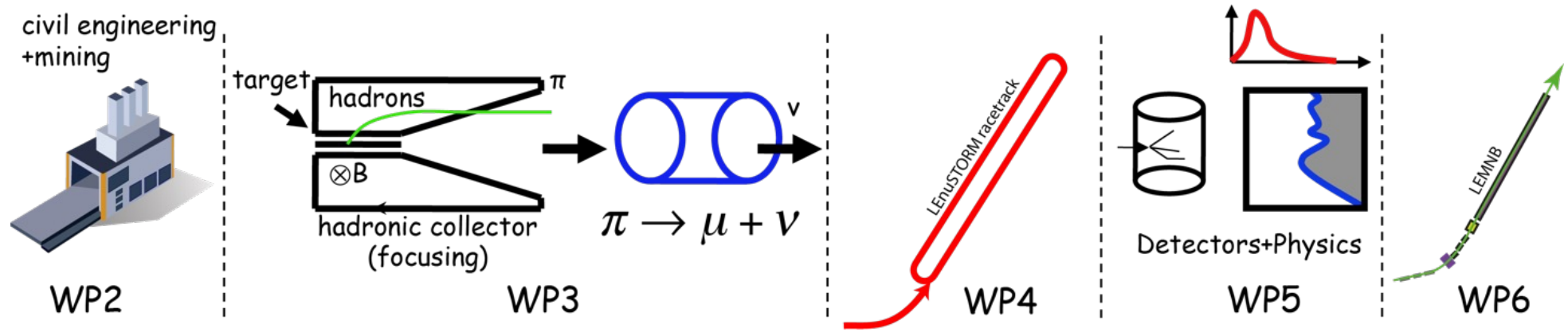
(Milos/Greece, Sep. 2025)



Co-funded by
the European Union



ESSvSB+ WP



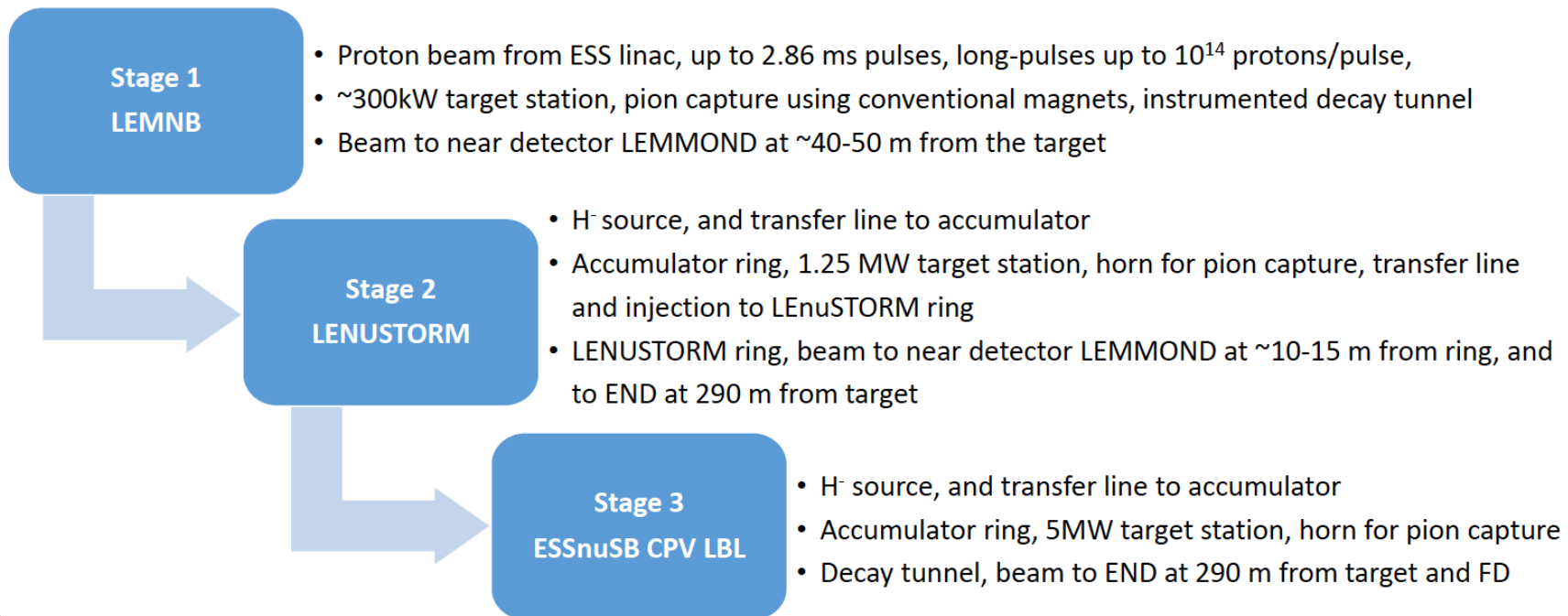
Civil engineering

Target Station

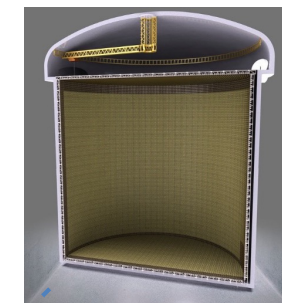
- cross-sections
- sterile neutrinos

cross-sections

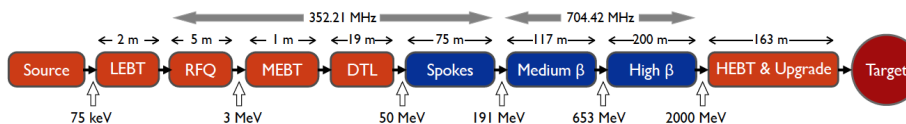
Staged Implementation



ESSvSB+ Latest Design



Far Detector



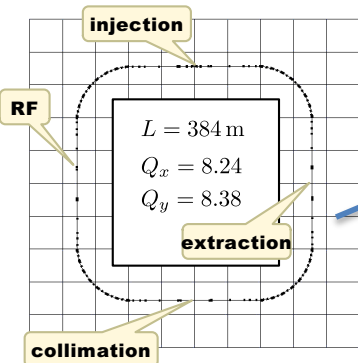
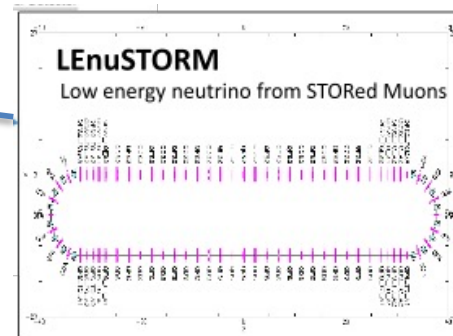
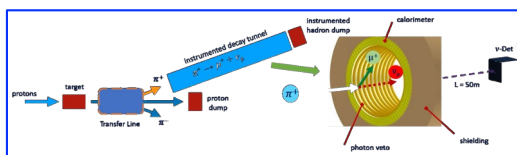
Spallation target

360 km

Near Detector

Monitored ν beam

Near Near Detector (LEMMOND)



Accumulator ring

Neutrino production target

LEnuSTORM

also able to host the final 4 target/horn system

Further proposed studies for Far Detector



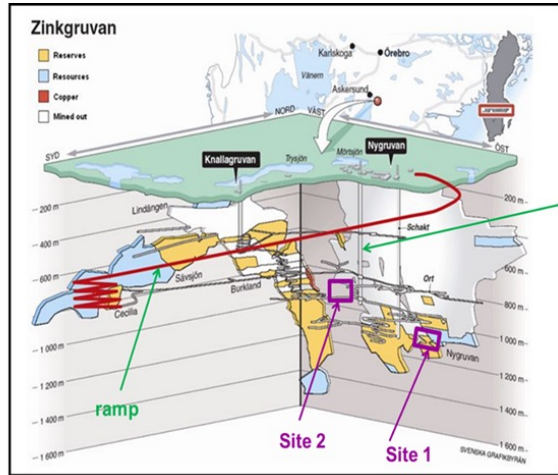
HORIZON-INFRA-2026-01-DEV-03: Consolidation of the Research Infrastructure landscape – Individual support for evolution, long term sustainability and emerging needs of pan-European research infrastructures

Title of Proposal: Design and feasibility study of the engineering of the large underground ESSnuSB Far Detectors for fundamental neutrino oscillation research with as added benefits of their use for mineral exploration and energy-storage

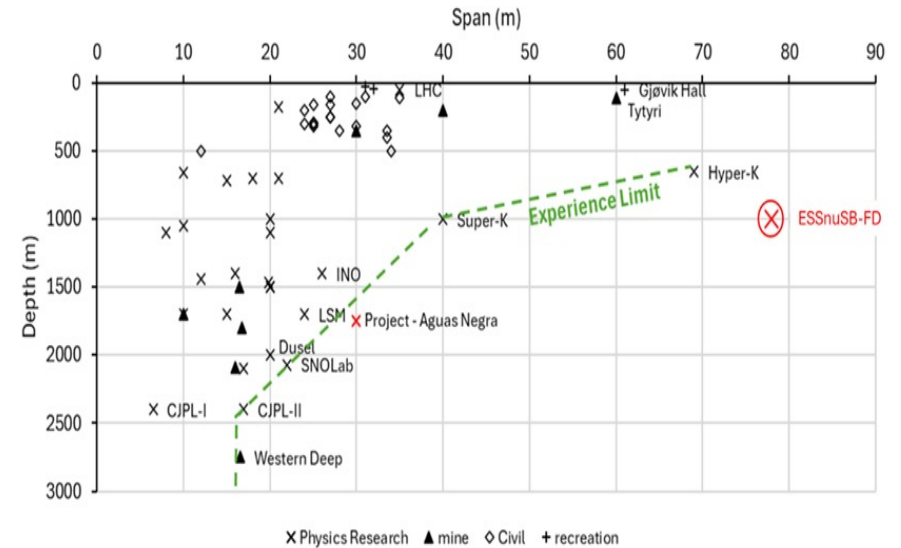
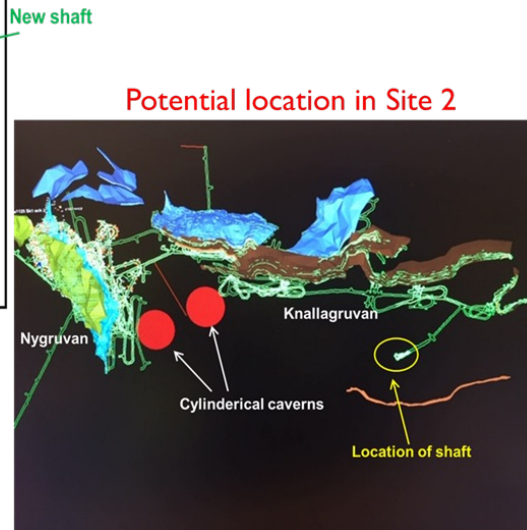
Acronym of Proposal: ESSvSB-FD

Submission to be done before the 16th of June!

Further proposed studies for Far Detector



Two potential sites identified are marked Site 1 and Site 2. Site 2 is considered as best considering access to main transport infrastructure and located in an area less disturbed by mining activities

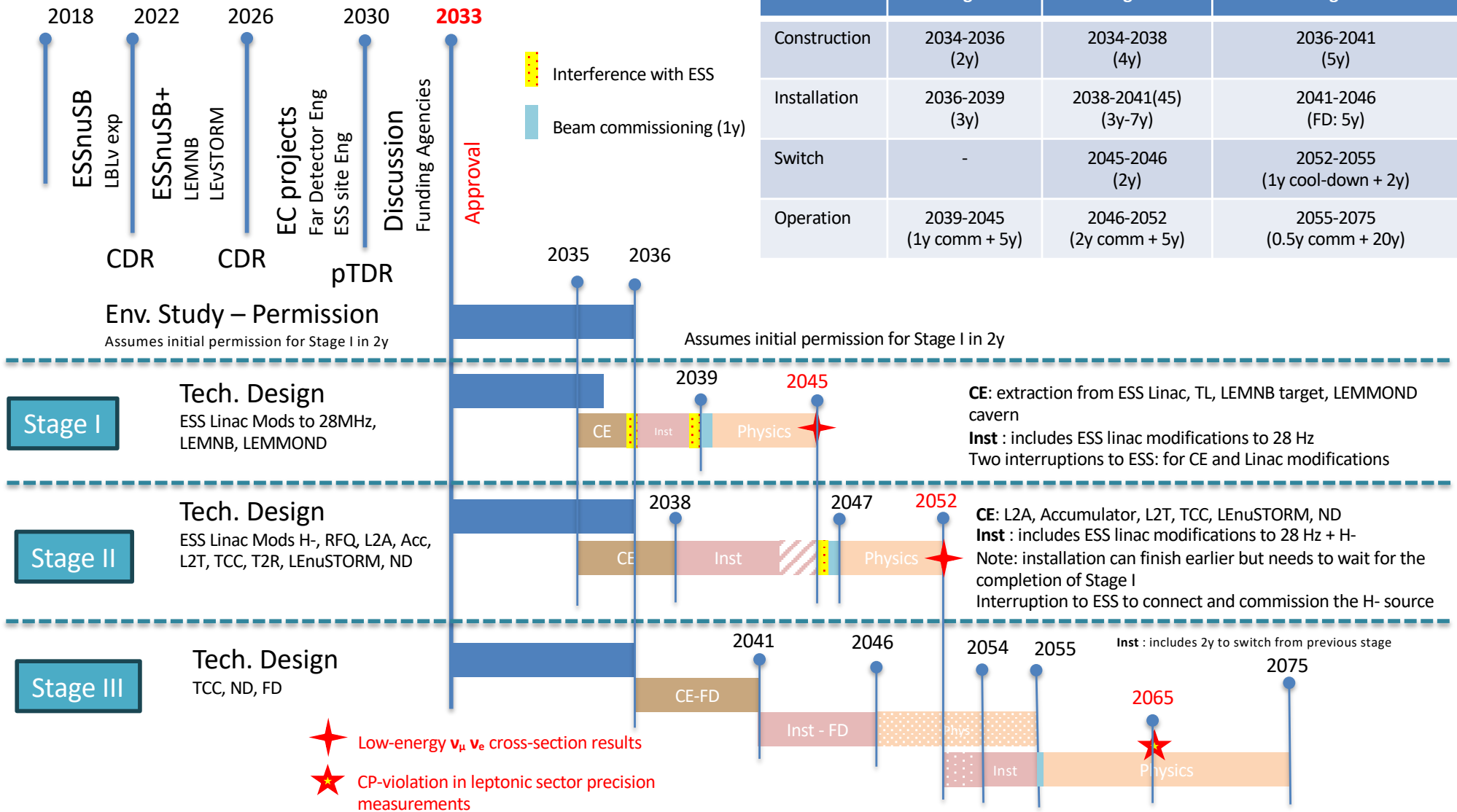


Work Packages		
WP1	Management	LTU, UU,
WP2	Site Characterization	LTU, ZIN/BOL, UNISTRA, KTH, AUTH, RBI
WP3	Engineering design of ESSnuSB-FD Infrastructure	CRD, LTU, ZIN/BOL, ESS, RWTH
WP4	Sustainability, decommissioning and post-closure	OU, LTU, CRD, ZIN/BOL
WP5	The ESSnuSB-FD detector water tanks, photosensors, electronics, data acquisition and computing	UU, UNISTRA, NCSR, AUTH, HOU, RWTH, LU, UI, RBI
WP6	Use of the ESSnuSB infrastructure for other applications	ESS CERN UU KTH UIB

Possible ESSvSB schedule

(2nd generation neutrino Super Beam)

Phase	Stage I	Stage II	Stage III
Construction	2034-2036 (2y)	2034-2038 (4y)	2036-2041 (5y)
Installation	2036-2039 (3y)	2038-2041(45) (3y-7y)	2041-2046 (FD: 5y)
Switch	-	2045-2046 (2y)	2052-2055 (1y cool-down + 2y)
Operation	2039-2045 (1y comm + 5y)	2046-2052 (2y comm + 5y)	2055-2075 (0.5y comm + 20y)



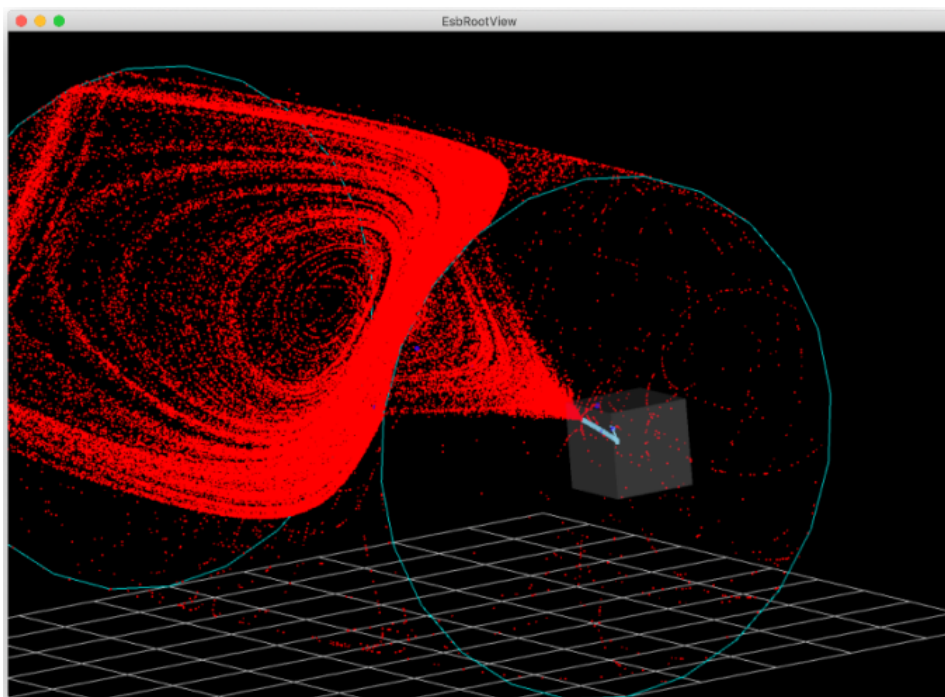
Conclusion

- The ESS proton linac is about to become the most powerful linac in the world.
- ESS can also become a neutrino facility (ESSvSB) with enough protons to go to the 2nd oscillation maximum and increase significantly the CPV sensitivity and make precise measurement of δ_{CP} .
- CPV: 5σ could be reached over 70% of δ_{CP} range by ESSvSB with large physics potential with less than 8° precision.
- Conceptual Design Report published including costing on arXiv.
- Rich muon program for future ESS upgrades.
- New studies for intermediate stages are under way.
- **New proposal to be submitted soon for the Far Water Cherenkov detector.**

Backup



Near Detector



Muon neutrino interaction in the SFGD cube with a secondary muon producing Cherenkov light in the near water Cherenkov detector.

Number of expected events per running year in the SFGD, as well as those entering the water Cherenkov detector and passing the water Cherenkov selection criteria. Listed over the four charged lepton flavours and two horn polarities.

Positive polarity

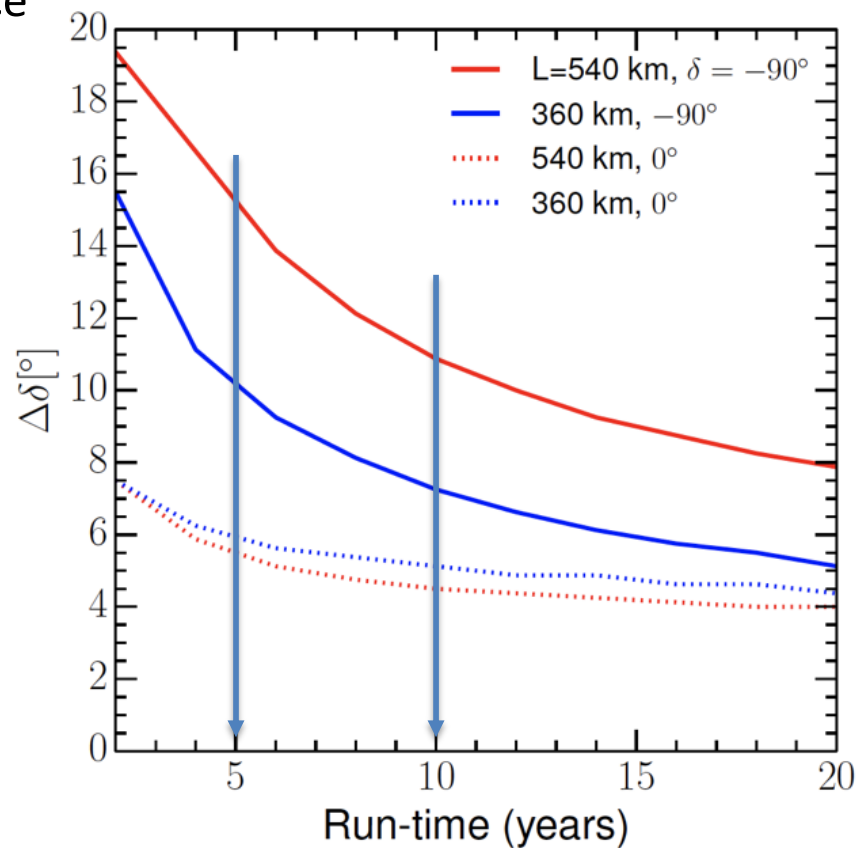
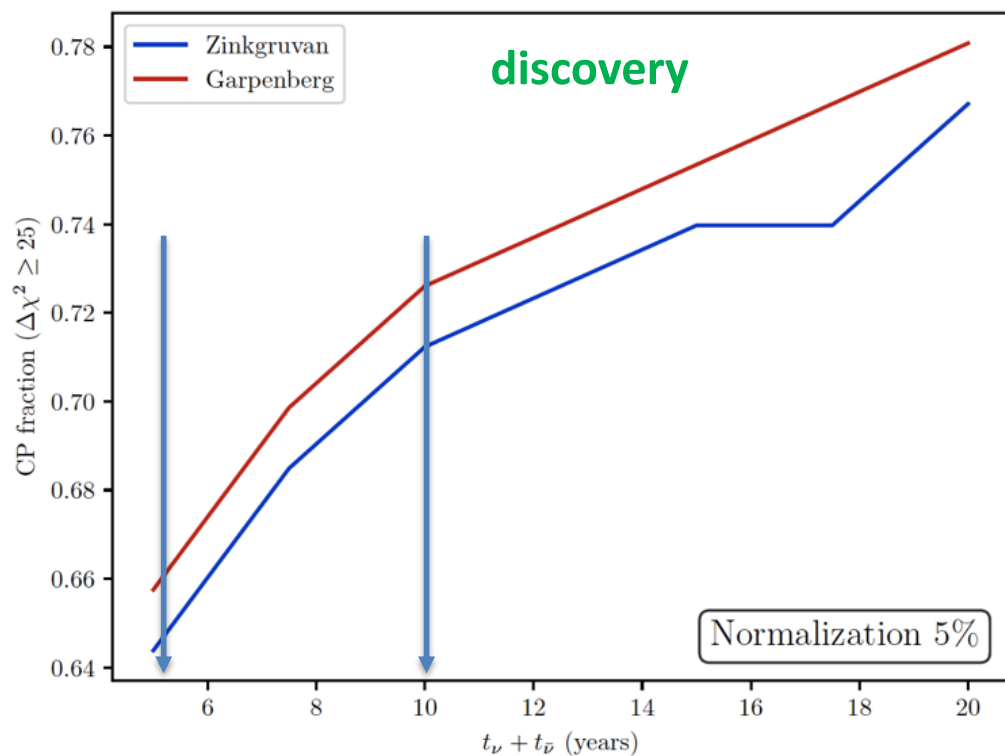
	μ^-	e^-	μ^+	e^+
All events SFGD	9.82×10^4	484	241	1.0
Exiting SFGD (entering water Cherenkov)	1.78×10^4	87.9	39.9	0.2
Trigger	1.18×10^4	60.4	33.6	0.1
Sub-Cherenkov criterion	4100	40.0	12.0	0.1

Negative polarity

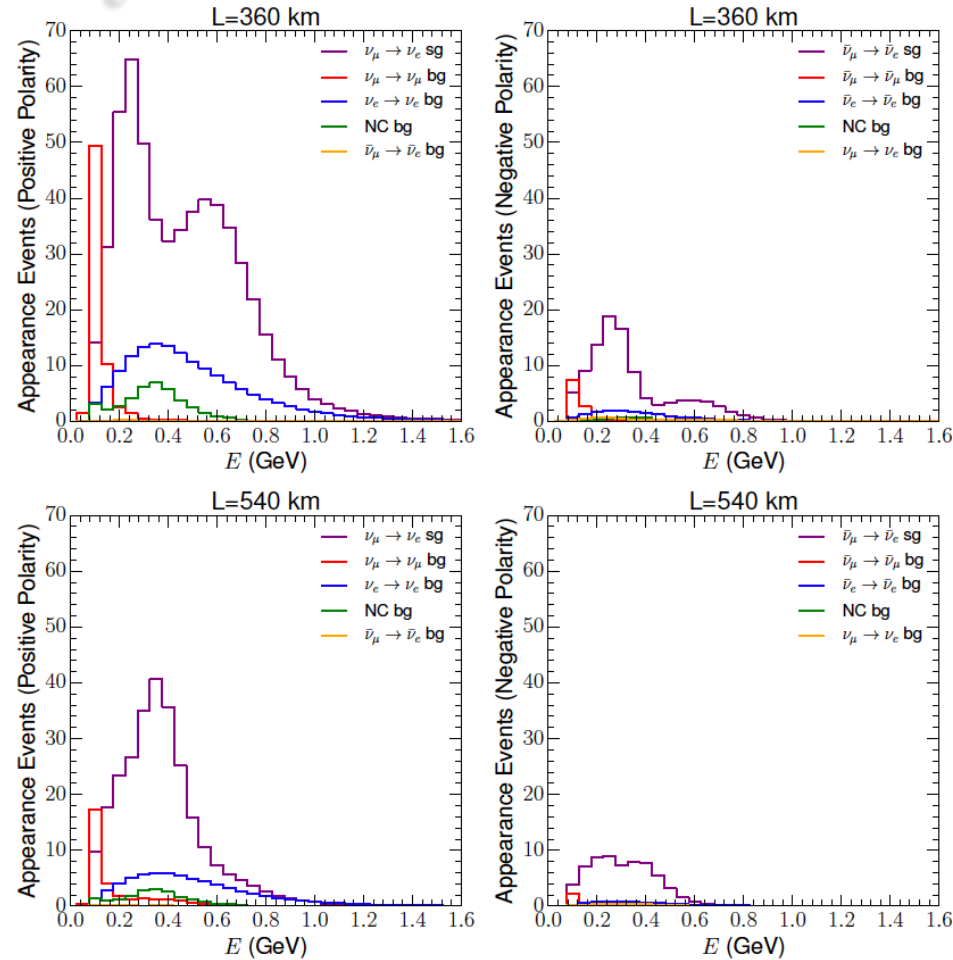
	μ^-	e^-	μ^+	e^+
All events SFGD	929	6.4	1.75×10^4	51.9
Exiting SFGD (entering water Cherenkov)	120	0.6	3890	11.1
Trigger	78	0.4	3350	9.6
Sub-Cherenkov criterion	26	0.2	1210	6.8

Performance versus time

Already after 5 years very competitive performance



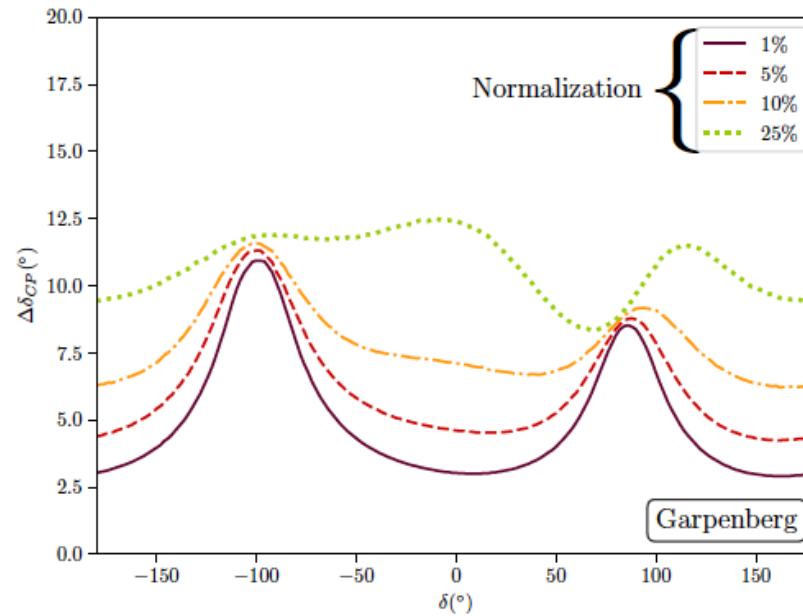
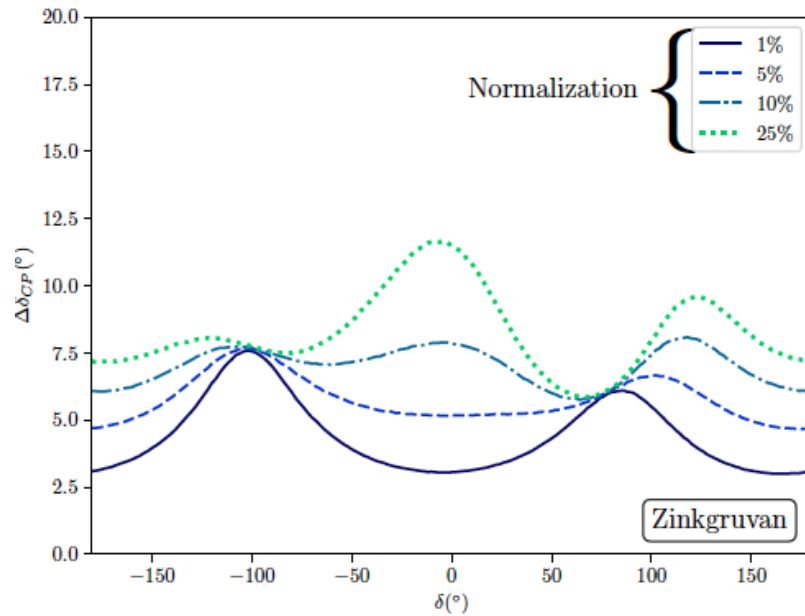
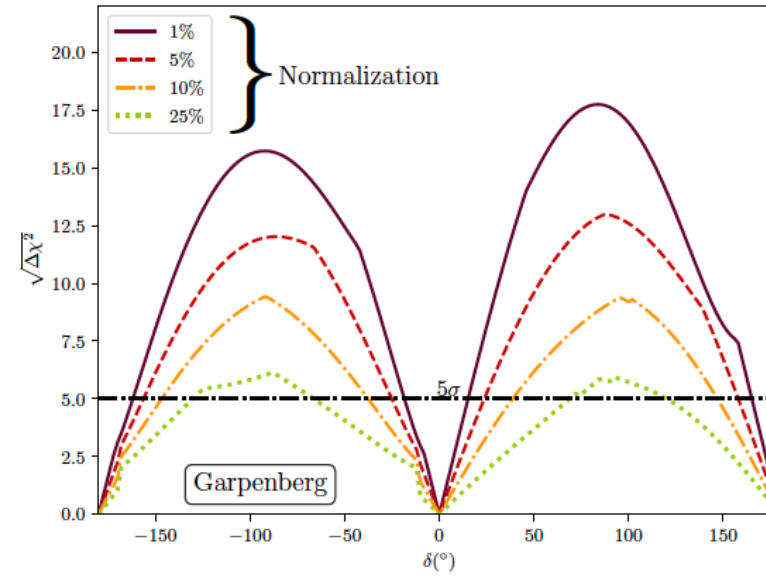
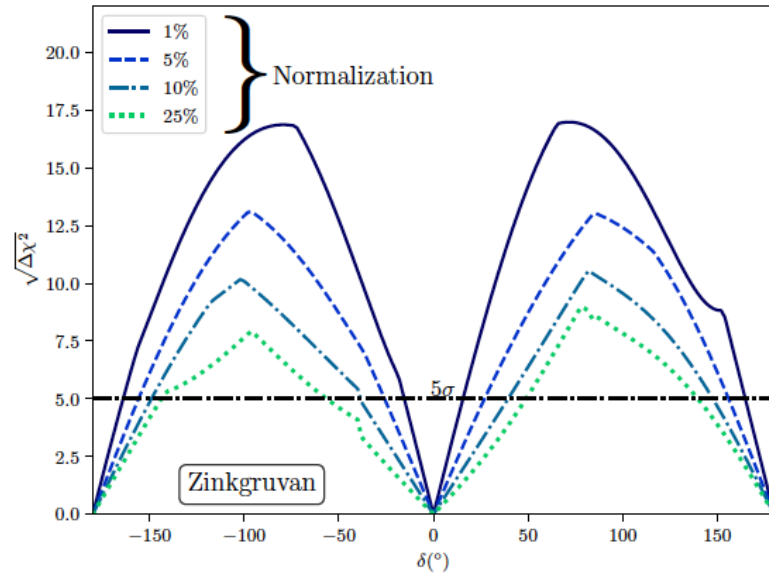
Physics Performance



during 10 years

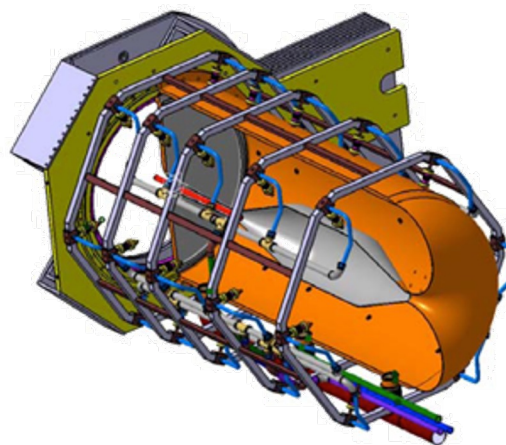
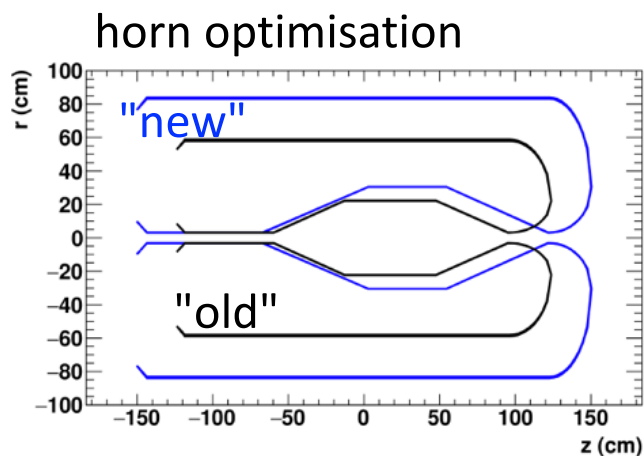
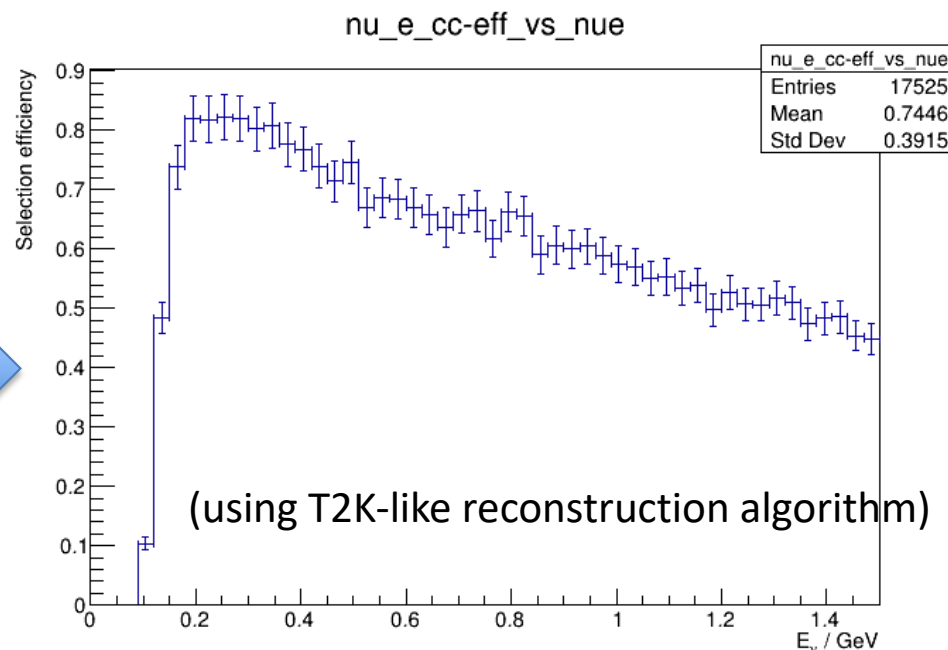
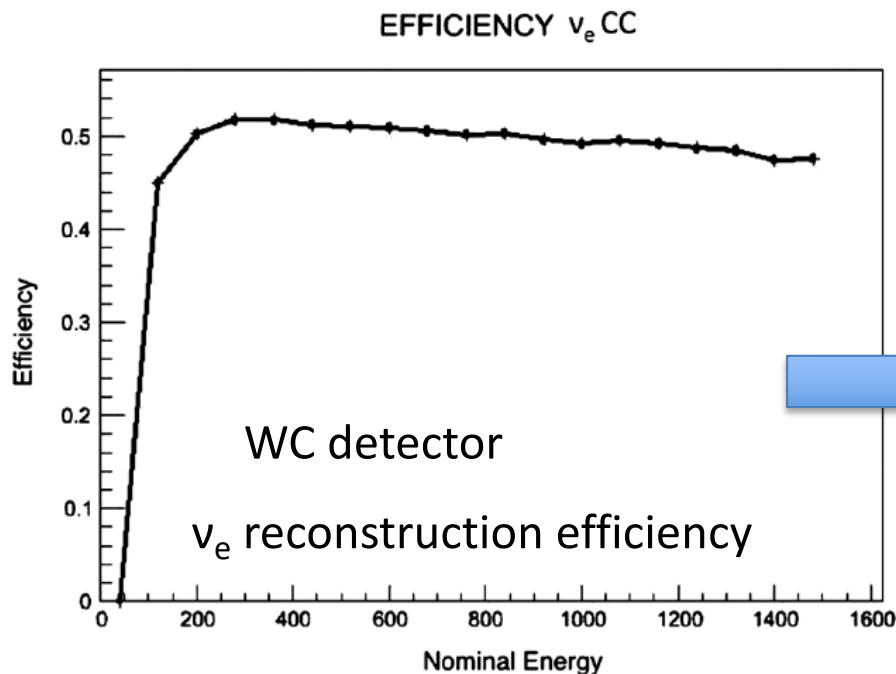
	Channel	$L = 540$ km	$L = 360$ km
Signal	$\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)	272.22 (63.75)	578.62 (101.18)
	$\nu_\mu \rightarrow \nu_\mu$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)	31.01 (3.73)	67.23 (11.51)
Background	$\nu_e \rightarrow \nu_e$ ($\bar{\nu}_e \rightarrow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

Physics Performance



After many Optimisations

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



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"	NCSR	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	Consortio 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



Design Study ESSvSB (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](#)

Supporting institutions of ESSvSB

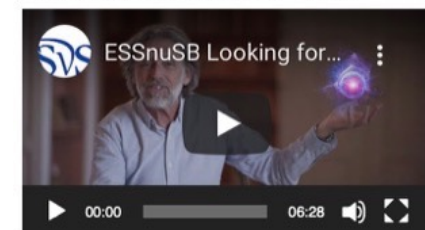
- COST Action EuroNuNet (CA15139): ended March 2020
 - <https://euronunet.in2p3.fr>
 - video for scientists:
<https://www.youtube.com/watch?v=PwzNzLQh-Dw>
- EU-H2020 Design Study ESSvSB: 2018-2022
 - <https://essnusb.eu>
 - video for general public:
<https://www.youtube.com/watch?v=qAnvft0nAlg>
- EU-Horizon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



ESSnuSB Design Study Project

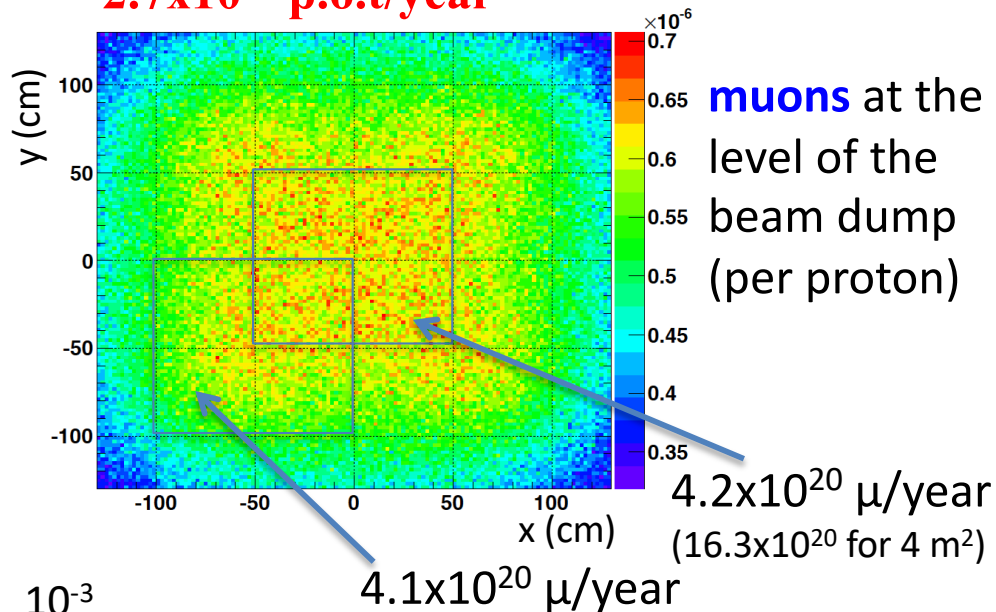


ESSnuSB looking for the answer.

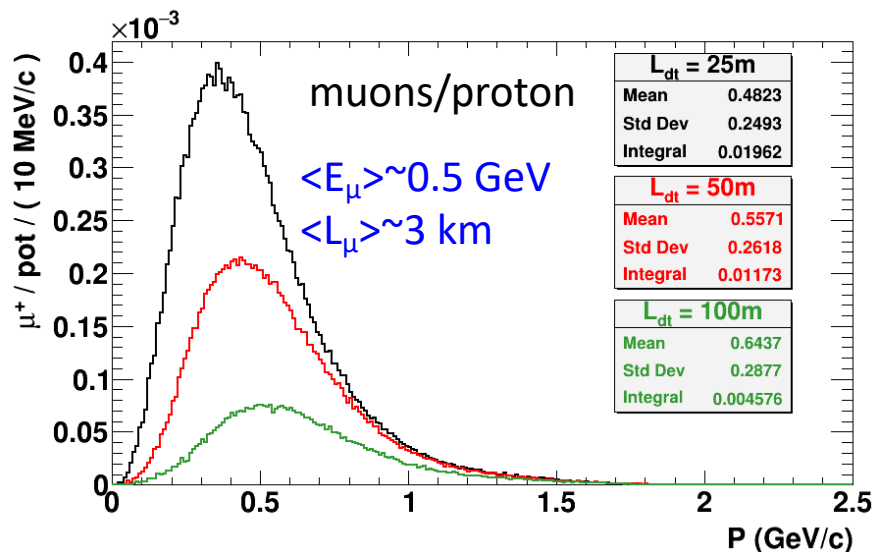


Muons at the level of the beam dump

2.7×10^{23} p.o.t/year



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

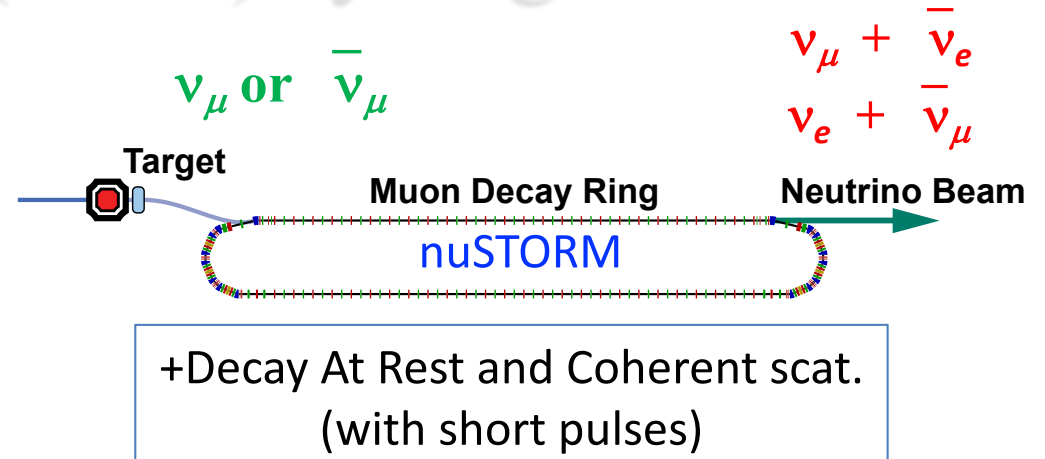
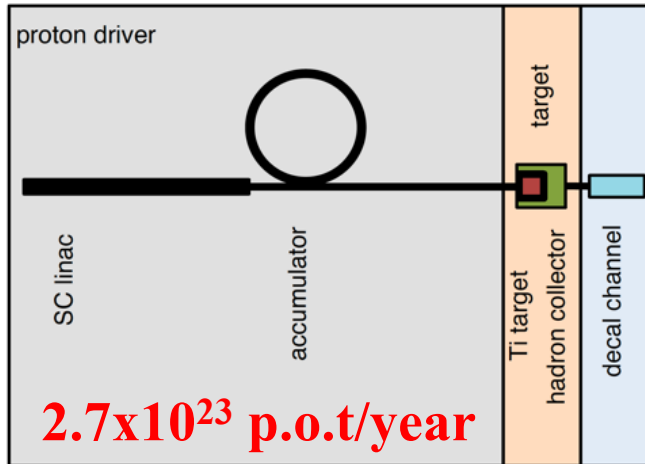


- input beam for future 6D μ cooling experiments,
- low energy nuSTORM,
- Neutrino Factory,
- **Muon Collider.**

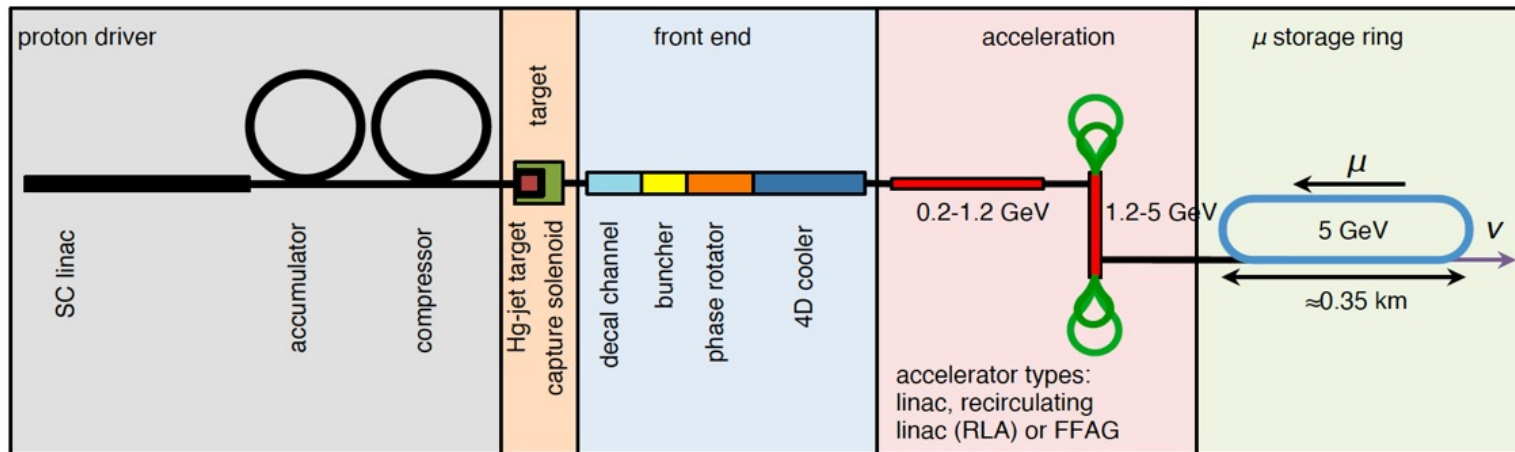
ESSνSB and (R&D) synergies

Super Beam

ESSνSB



Neutrino Factory



Muon Collider

ESSμSB

