ESS Neutrino Super Beam Plus

Co-funded by the European Union

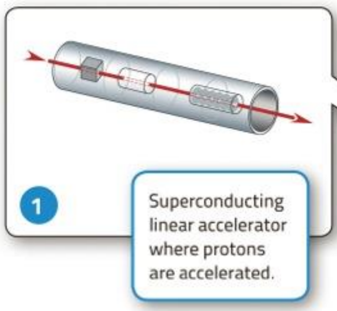
The European Spallation Source neutrino Super Beam and muon synergies

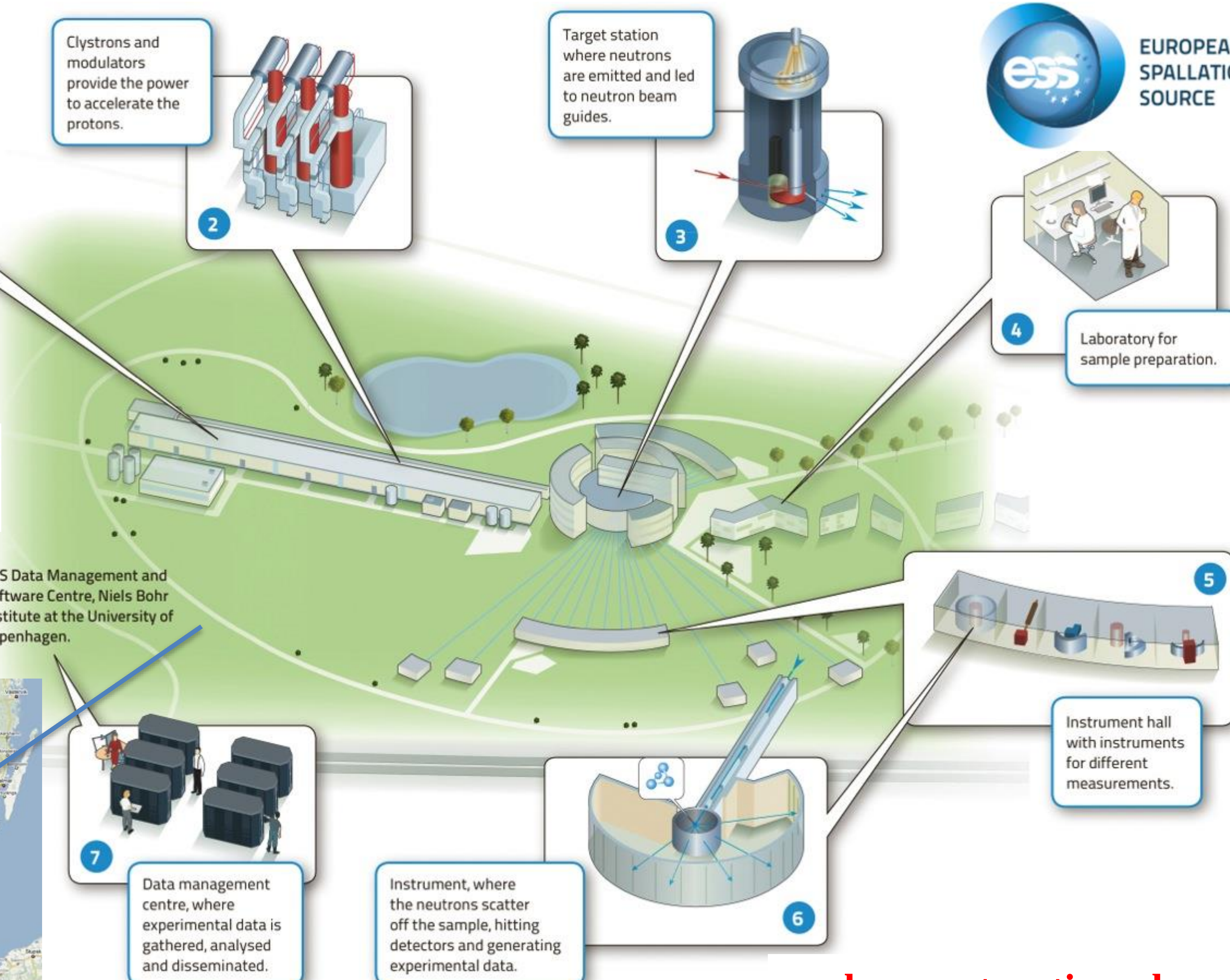
Marcos Dracos
IPHC-Strasbourg

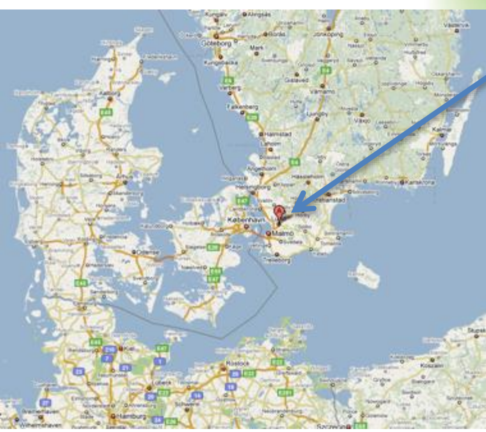
KITP Muon Collider Workshop

European Spallation Source

Neutron facility

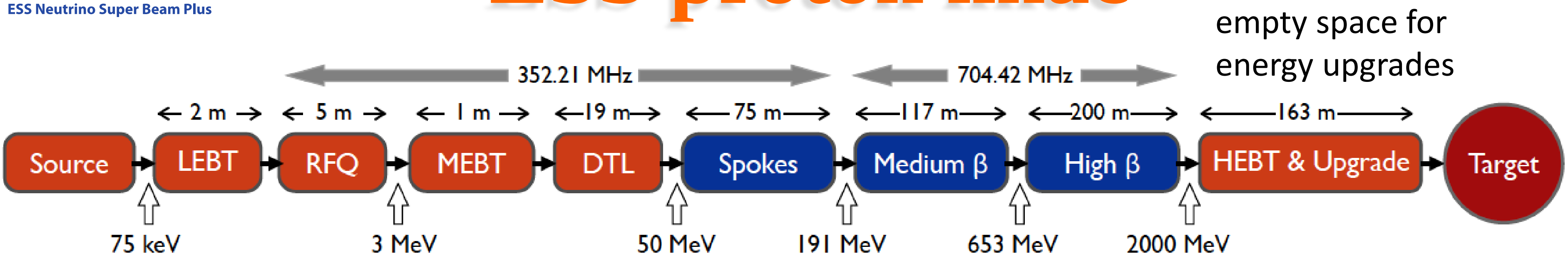




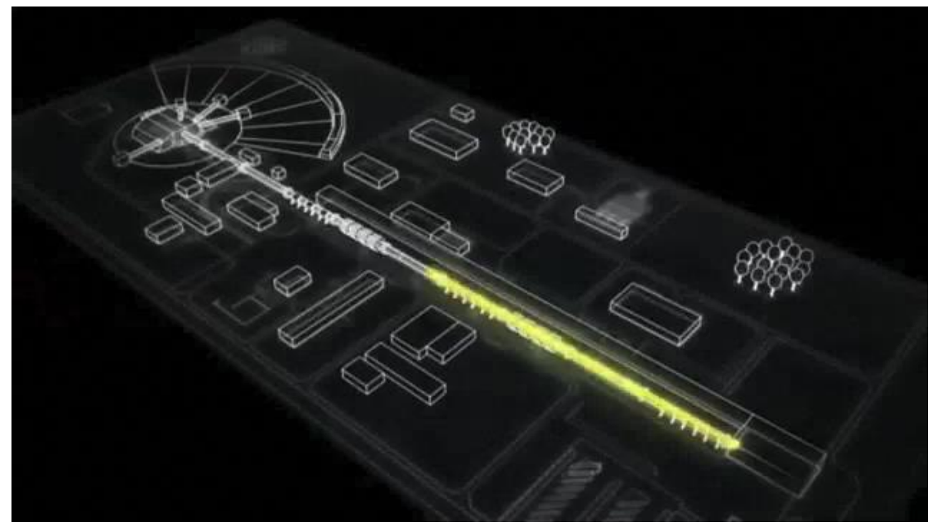


under construction phase
(~2 B€ facility)

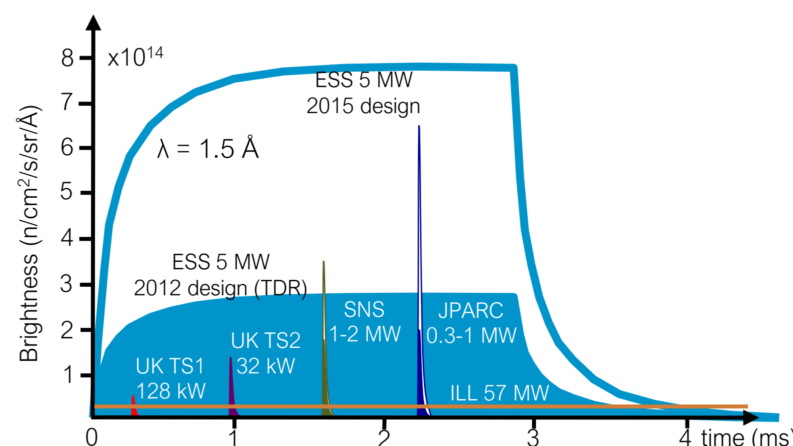
ESS proton linac



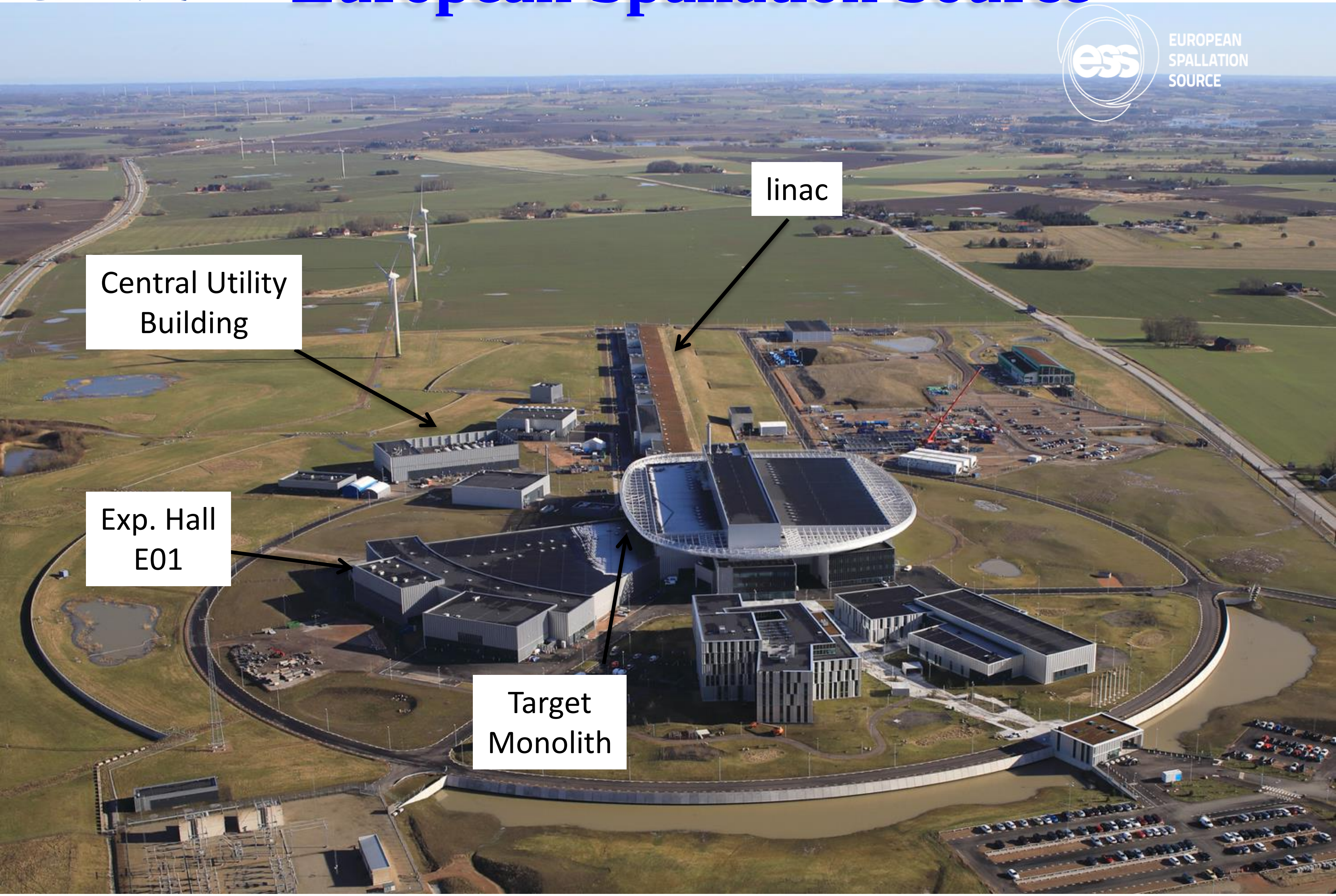
- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power.
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV protons
  - up to 3.5 GeV with linac upgrades
- **>2.7x10^{23} p.o.t/year.**



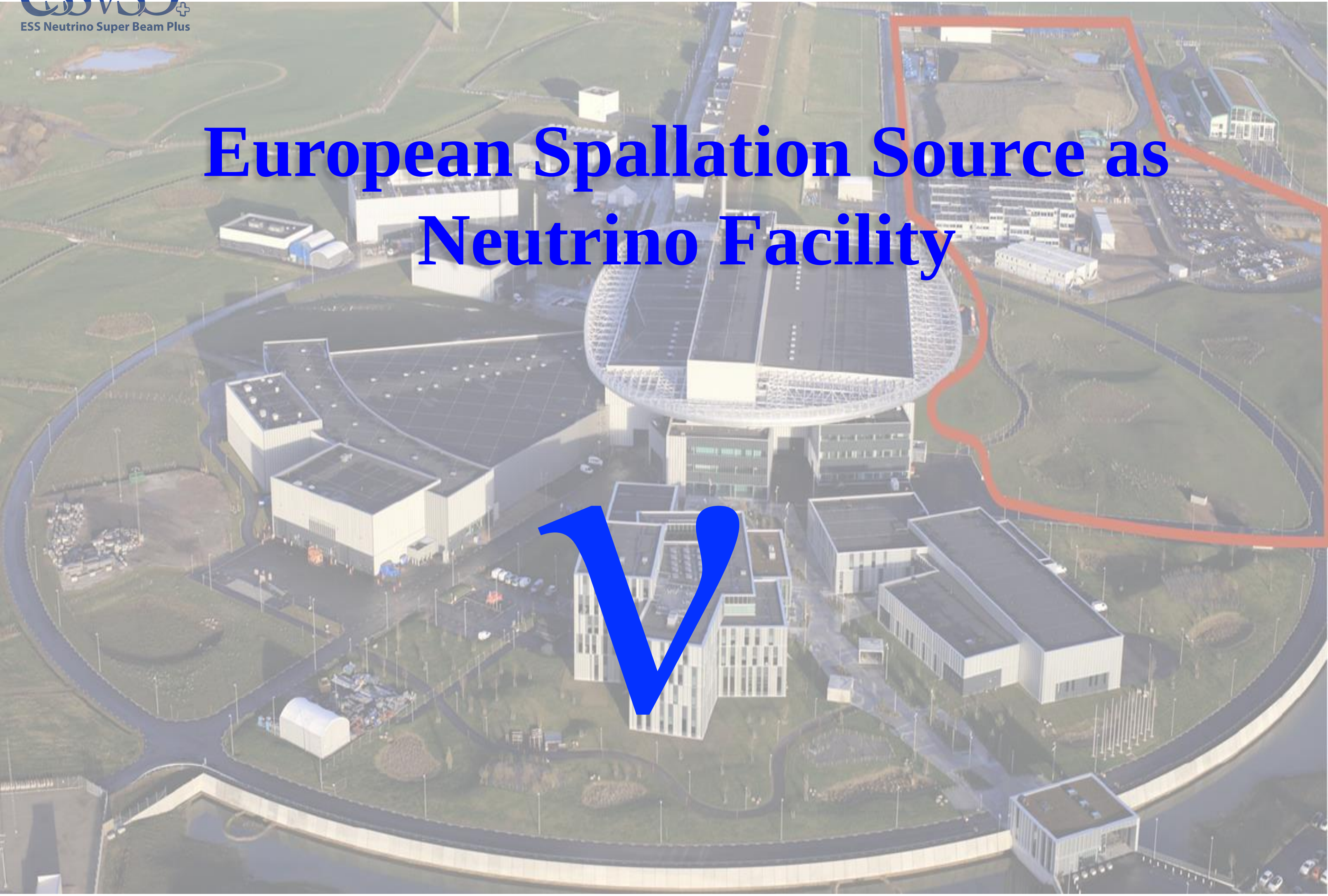
Linac ready by 2025 (protons on the target)



European Spallation Source



European Spallation Source as Neutrino Facility



ν

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"

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

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

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

matter effect

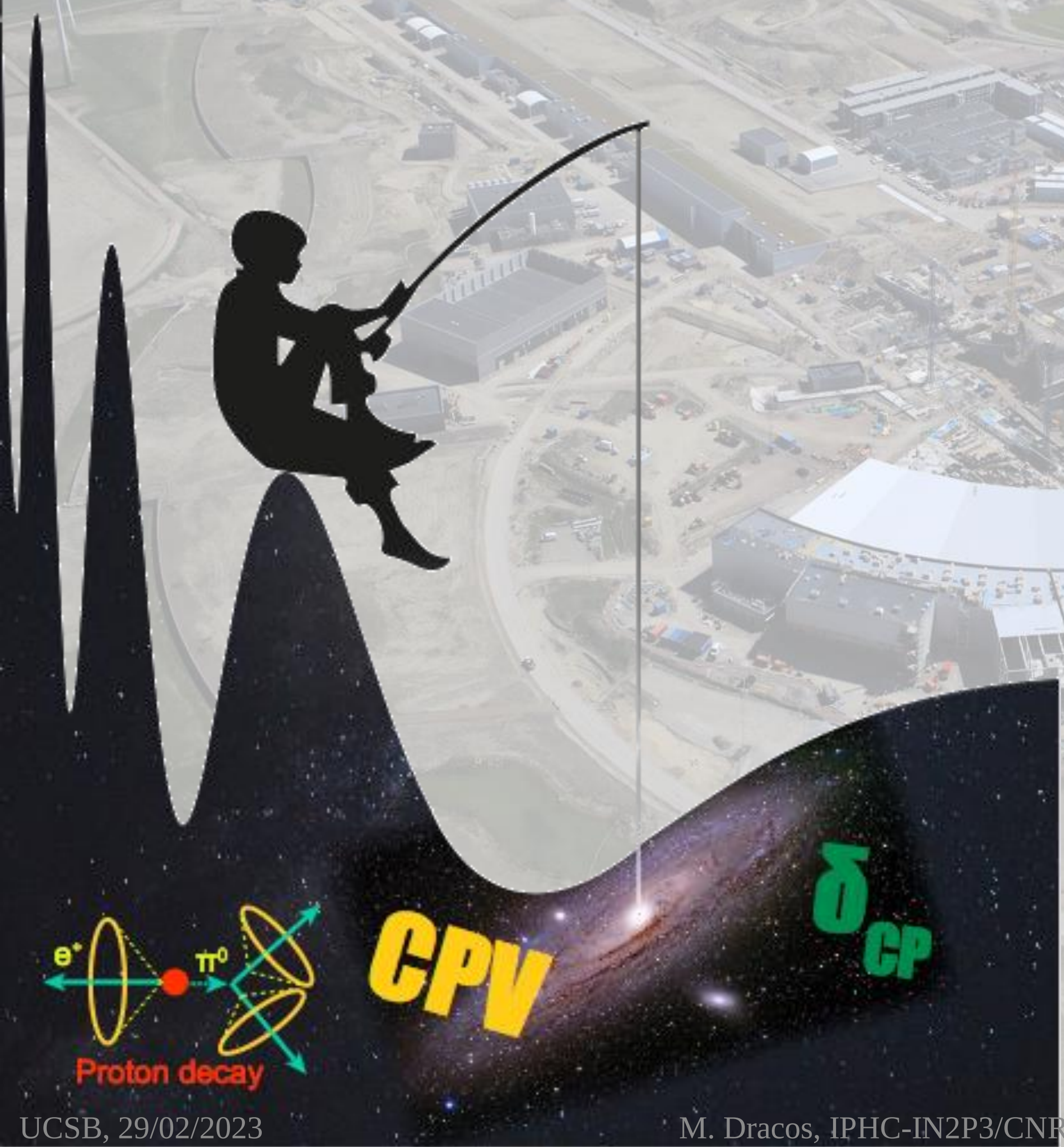
- **for antimatter: $\delta_{CP} \to -\delta_{CP}$ and $a \to -a$**
- fake matter/antimatter asymmetry due to matter effect

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

Matter-antimatter asymmetry

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

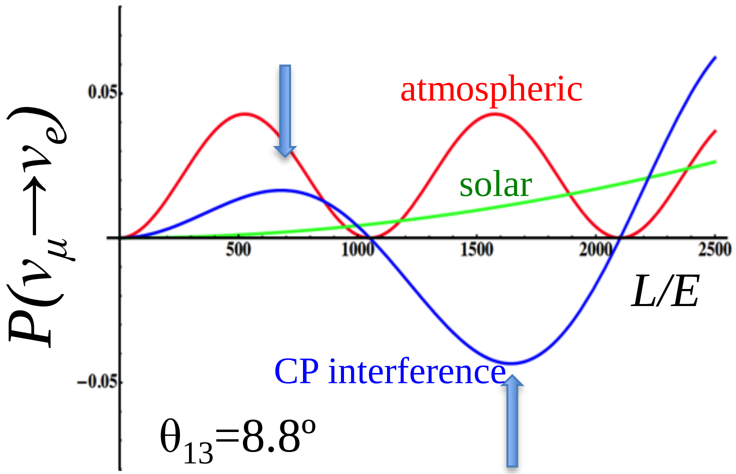
Use all this ESS linac power to go to the 2nd oscillation maximum



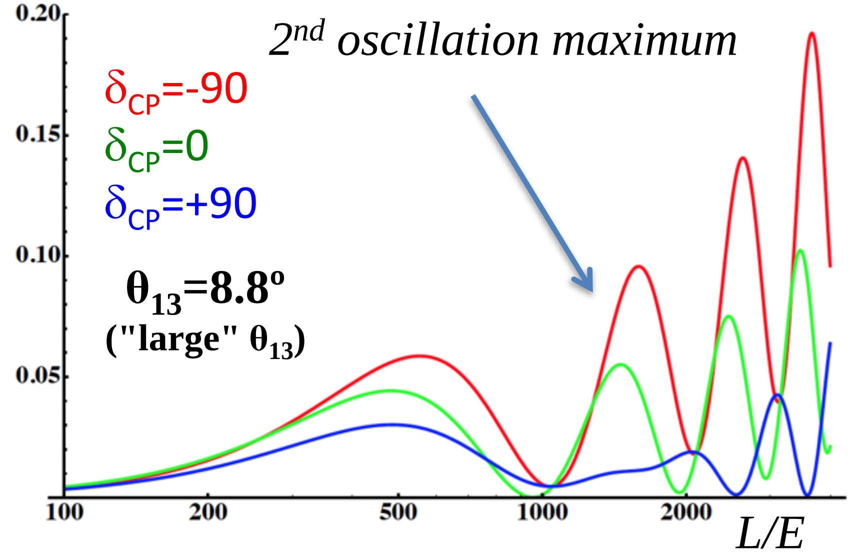
but why?

Neutrino Oscillations with "large" θ_{13}

(arXiv:1110.4583)



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



- 1st oscillation max.: A=**0.3**sinδ_{CP}
- 2nd oscillation max.: A=**0.75**sinδ_{CP}

more sensitivity at 2nd oscillation max.

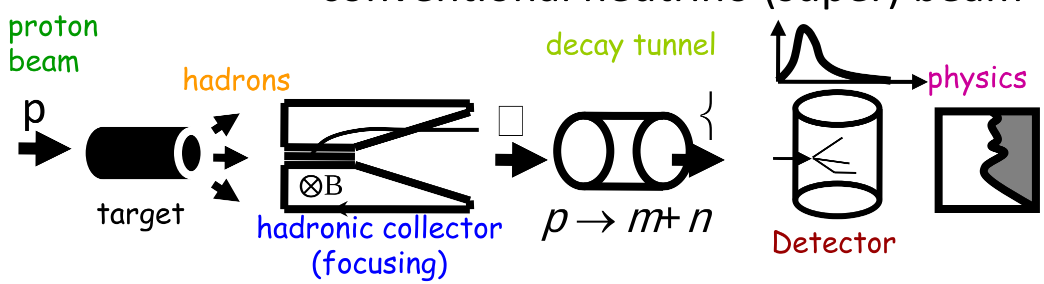
(see arXiv:1310.5992 and arXiv:0710.0554)

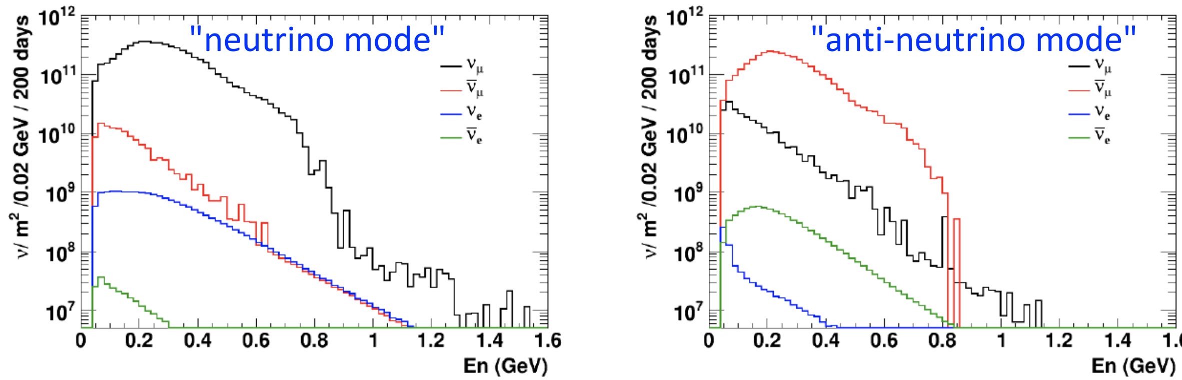
Having access to a powerful proton beam…

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

conventional neutrino (super) beam



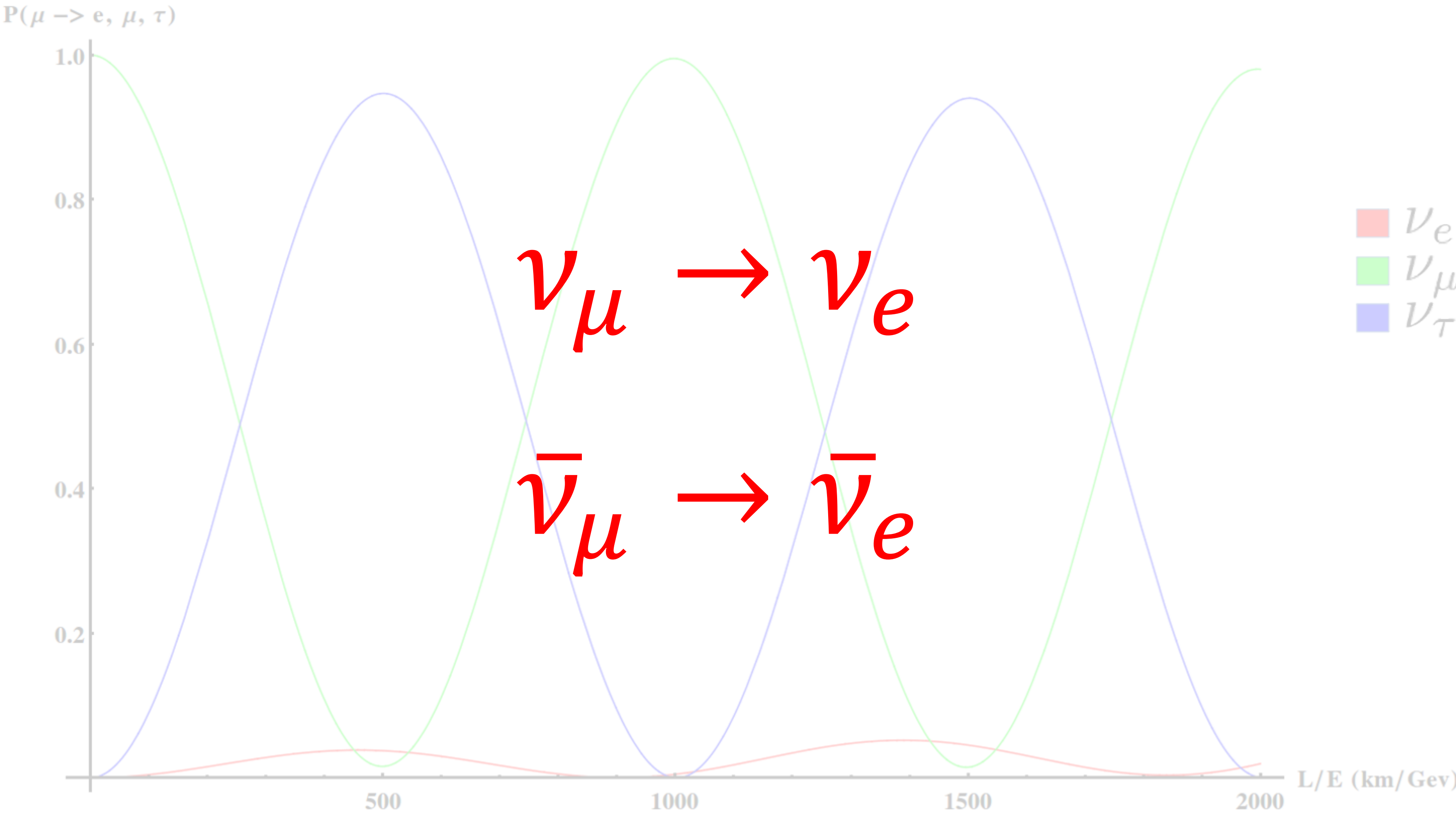


	ν Mode		$\bar{\nu}$ Mode	
	$N_\nu(10^{10}/m^2)$	%	$N_\nu(10^{10}/m^2)$	%
ν_μ	583	97.5	23.9	6.55
$\bar{\nu}_\mu$	12.8	2.1	340	93.2
ν_e	1.93	0.3	0.08	0.02
$\bar{\nu}_e$	0.03	0.01	0.78	0.21

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

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

Oscillations to be studied



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

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

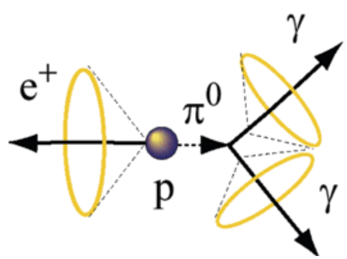
ESS Neutrino Super Beam Plus

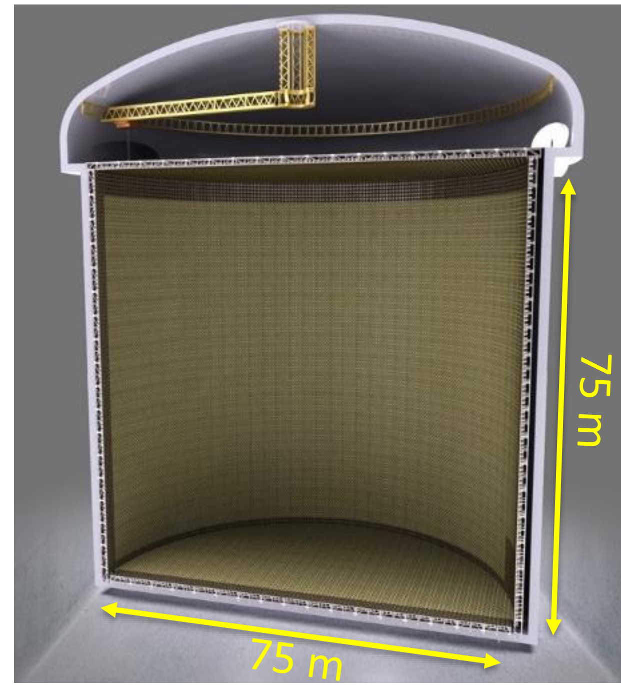
Can we go to the 2nd oscillation maximum using our proton beam?

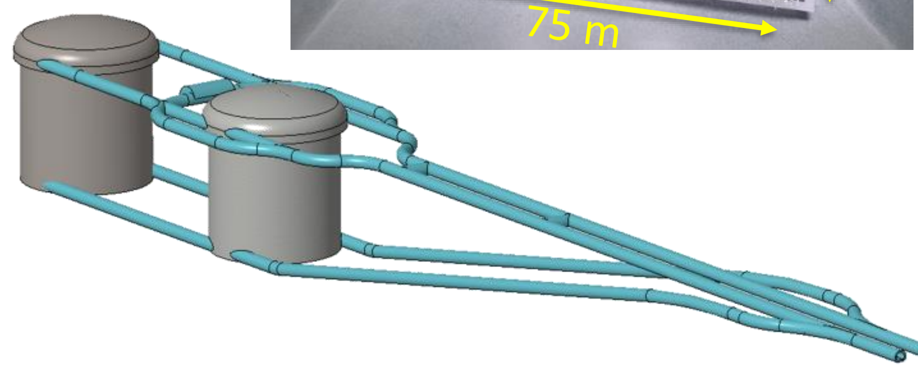
Yes, if we place our far detector at 350- 550 km from the neutrino source.

Megaton Water Cherenkov detector

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





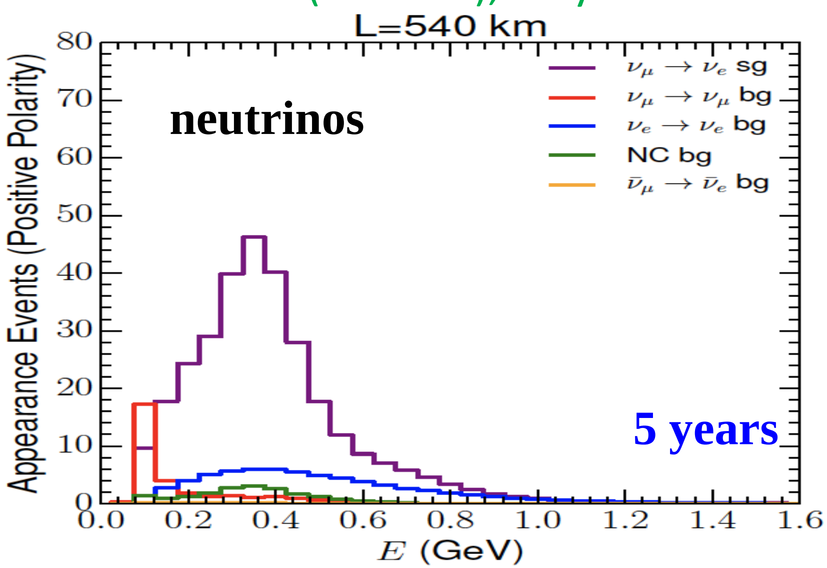


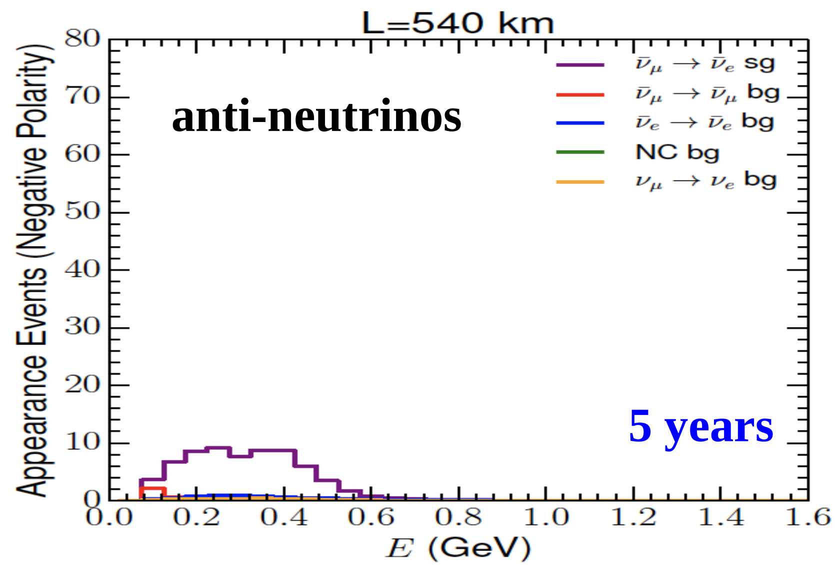
- 500 kt fiducial volume (~20xSuperK)
- Readout: ~20" PMTs
- 30% optical coverage

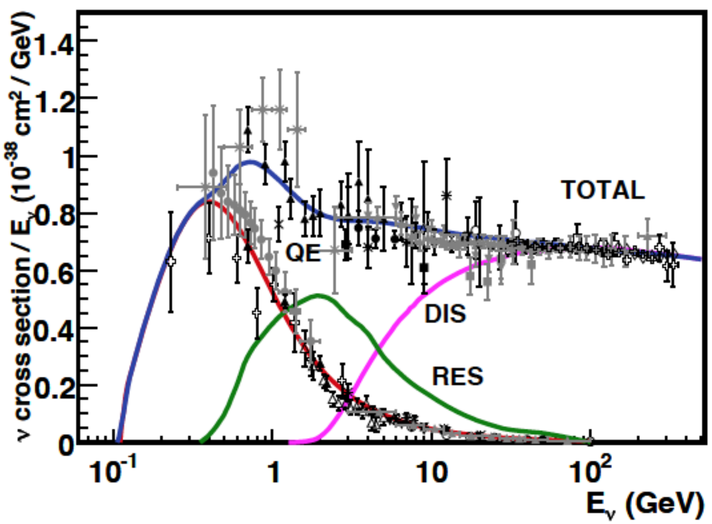
Neutrinos in the far detector

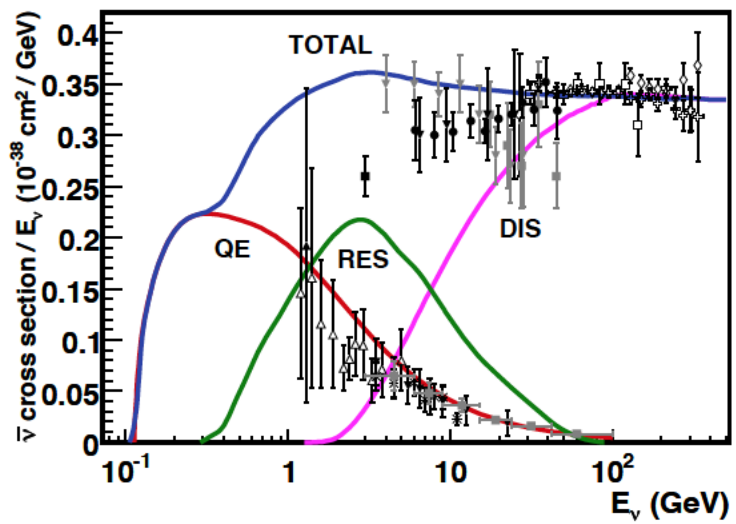
540 km (2.5 GeV), 10 years

$\delta_{CP}=0$





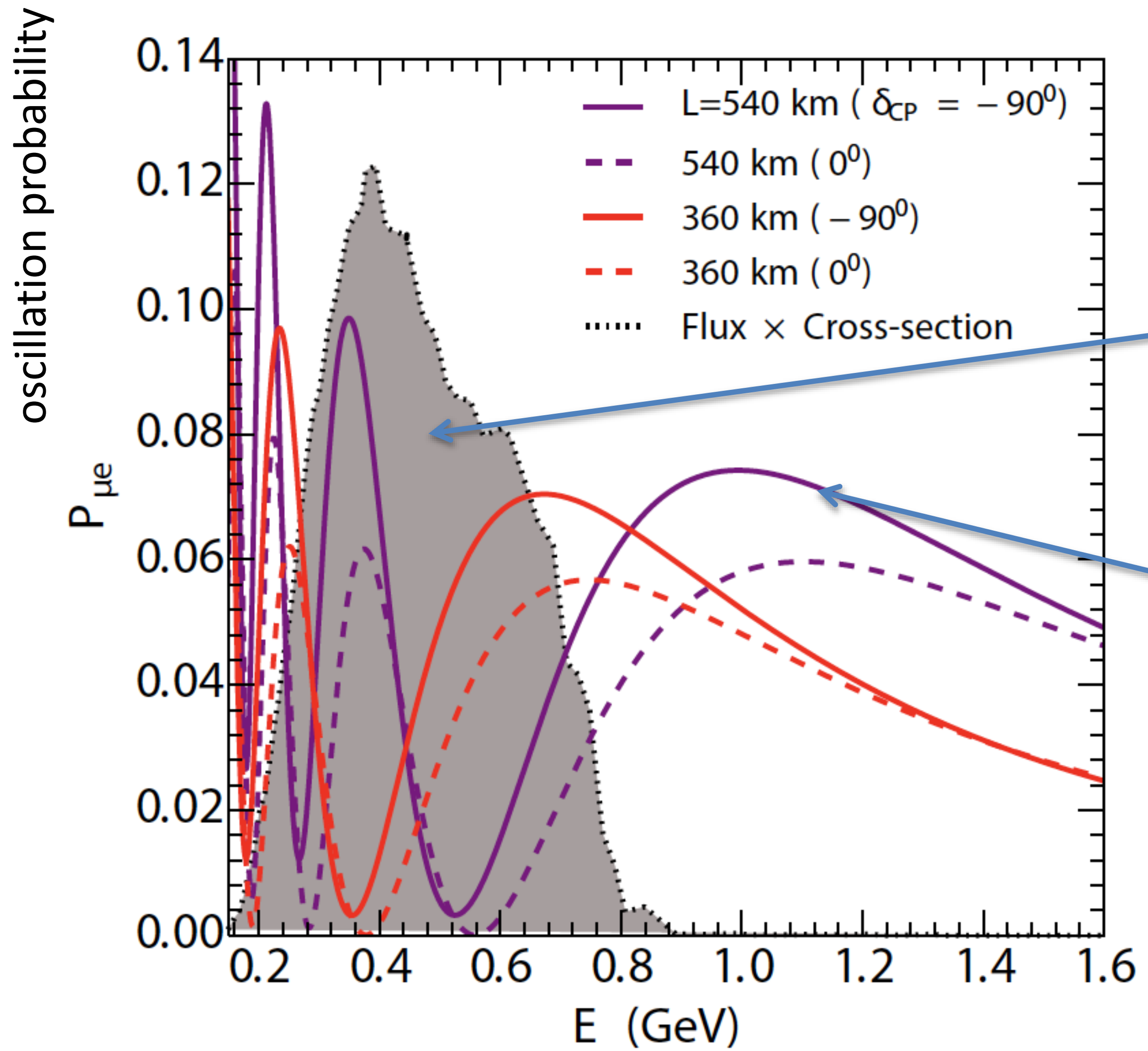




below ν_τ production, almost only QE events, not suffering too much by π^0 background

ESS Neutrino Super Beam Plus

2nd Oscillation max. coverage



2^{nd} oscillation max. well covered by the ESS neutrino spectrum

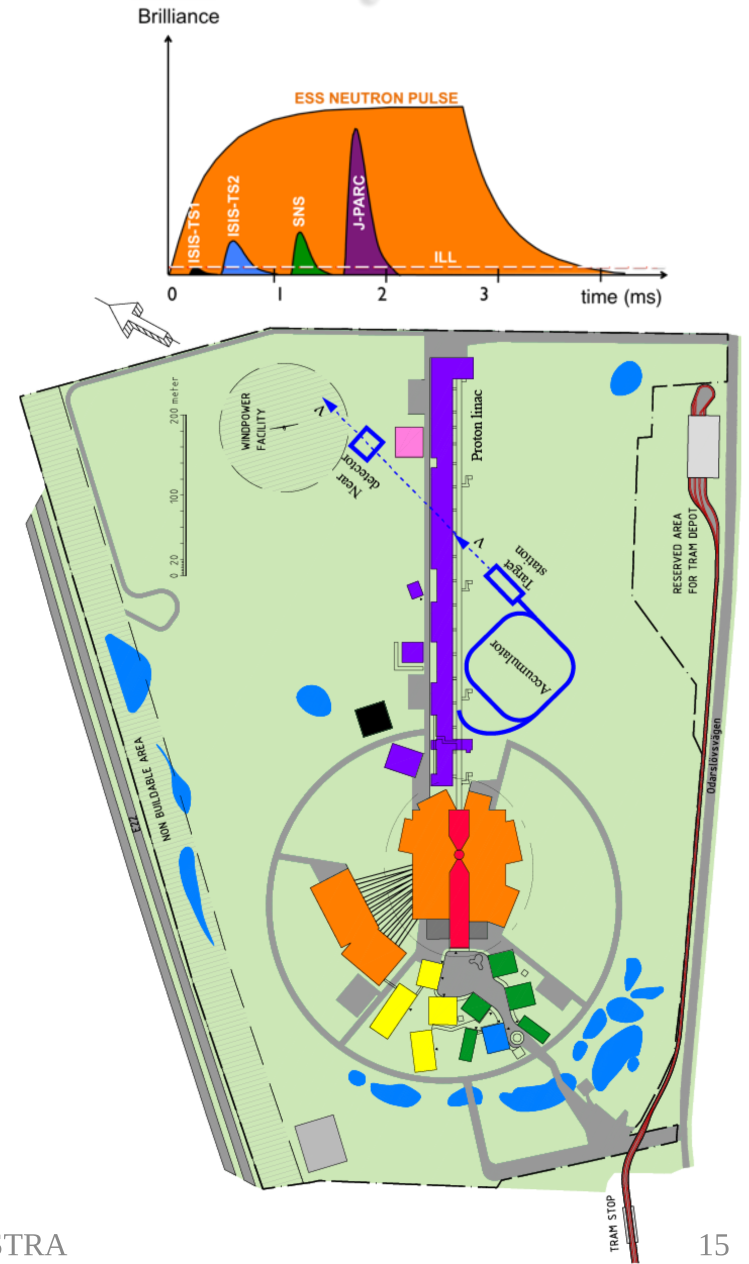
1^{st} oscillation max.

full coverage of the 2^{nd} oscillation max.

ESS modifications to produce a neutrino Super Beam

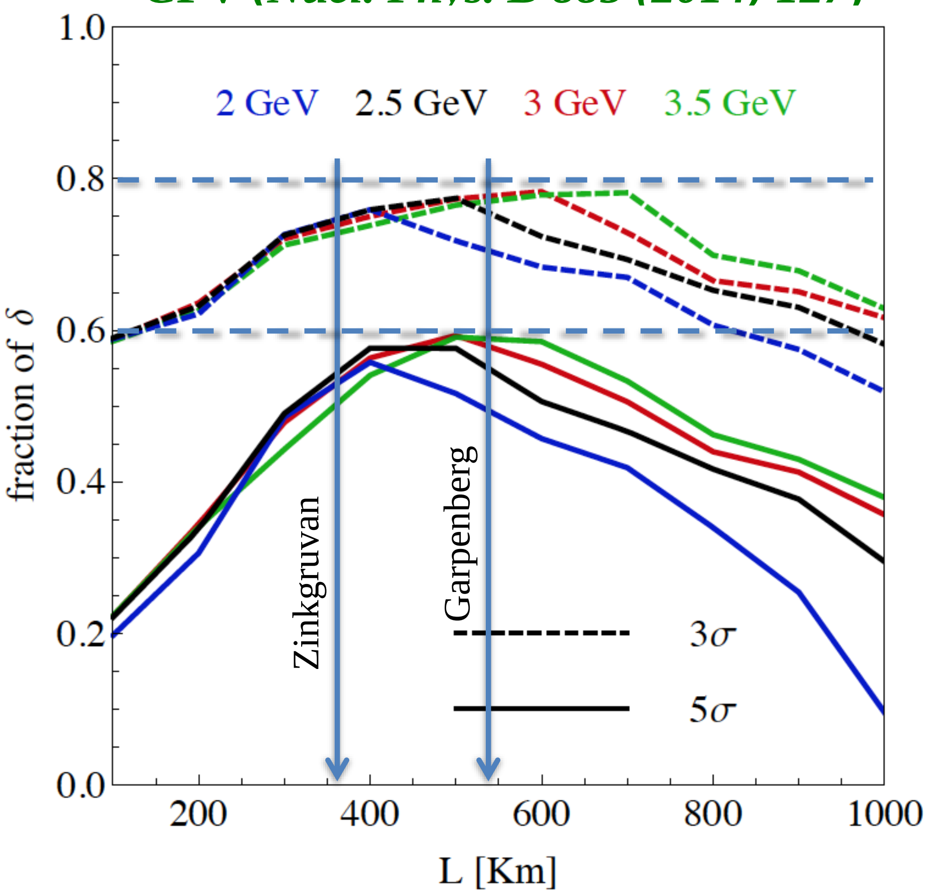
How to add a neutrino facility?

- 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*)

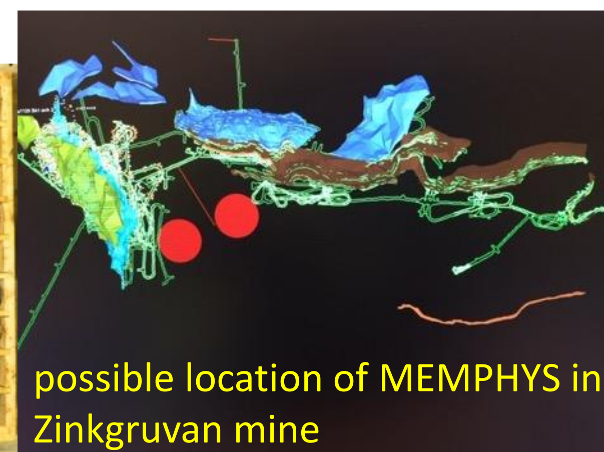


Candidate active mines

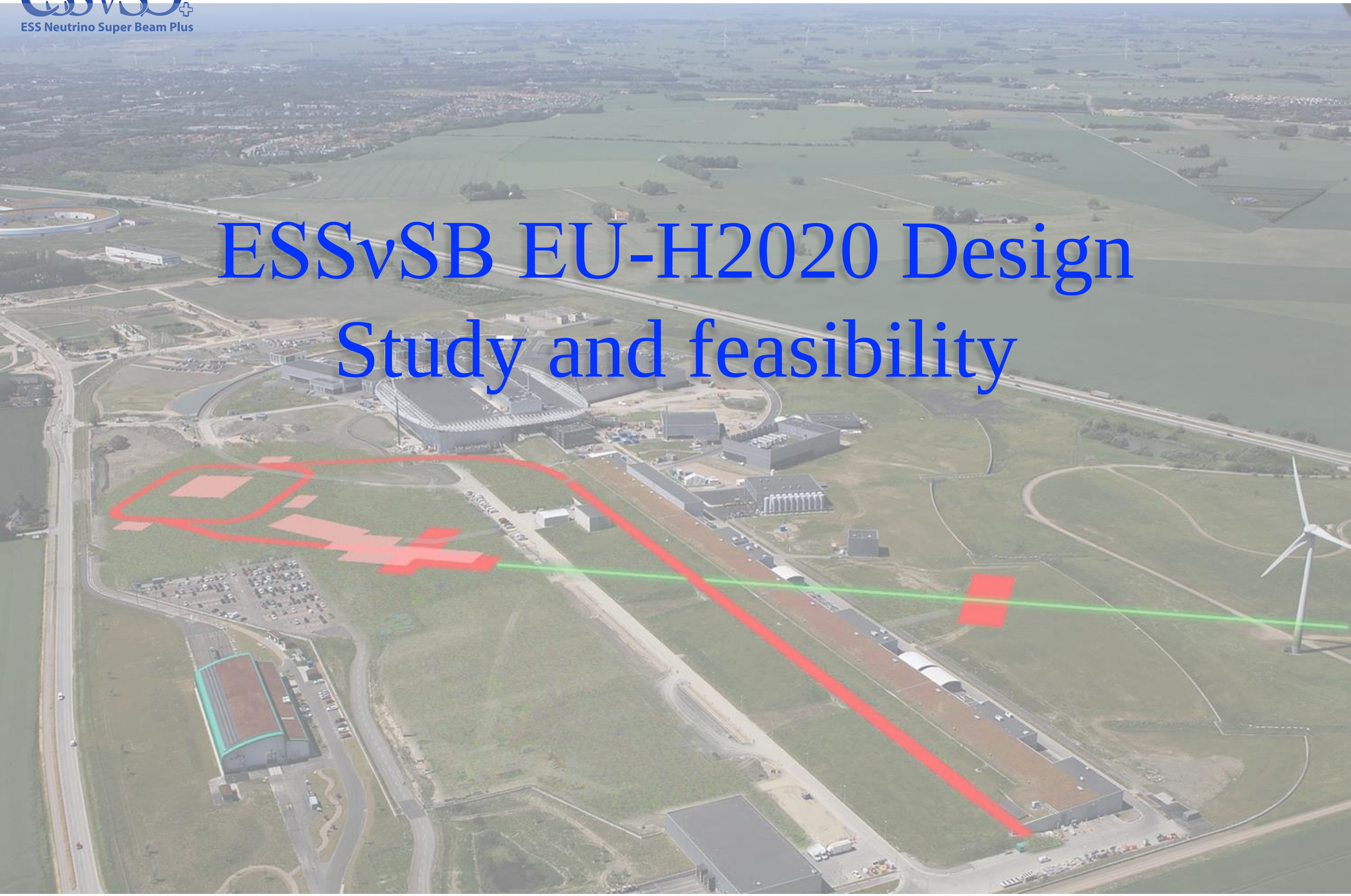
- ~60% δ_{CP} coverage at 5 σ C.L.
- >75% δ_{CP} coverage at 3 σ C.L.
- **systematic errors: 5%/10% (signal/backg.)**

Candidate active mines

- **Garpenberg mine**
  - Distance from ESS Lund **540 km**
  - Depth **1200 m**
  - Truck **access tunnel**
- **Zinkgruvan mine**
  - Distance from ESS Lund **360 km**
  - Depth **1500 m**
  - Truck **access tunnel**



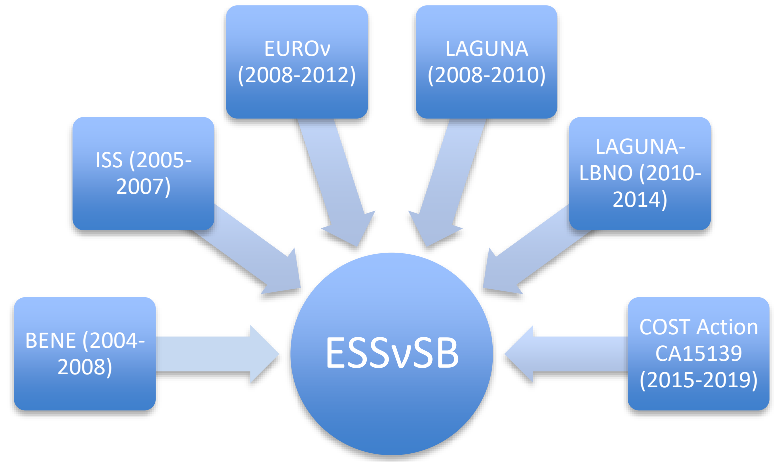
ESSνSB EU-H2020 Design Study and feasibility

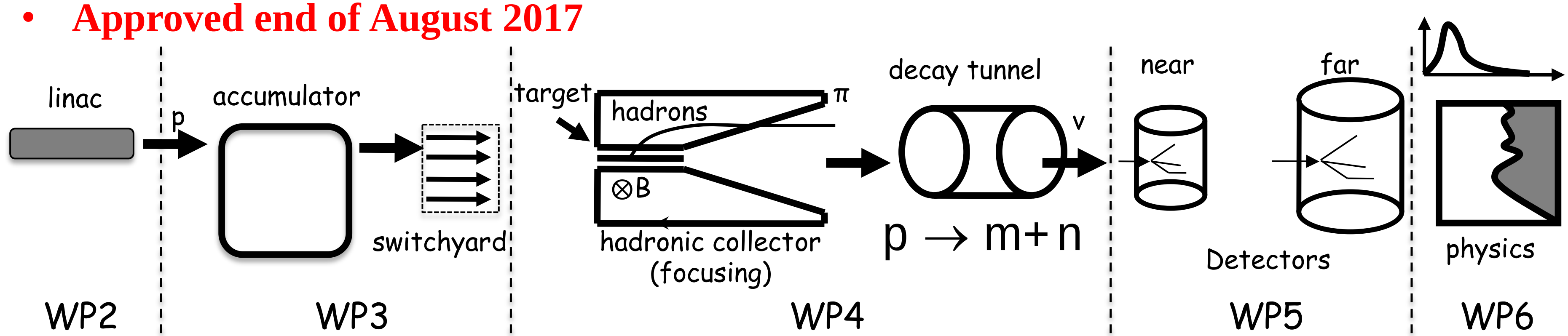


ESSνSB at the European level

- 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**





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:	

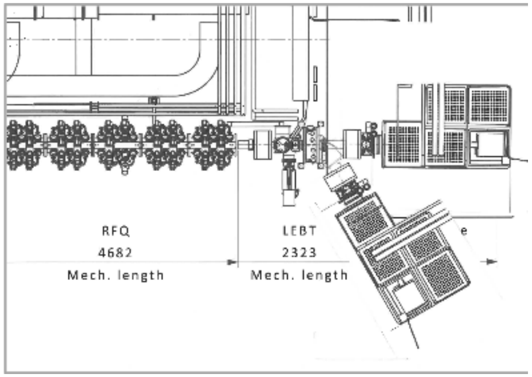
now finished end of March 2022

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

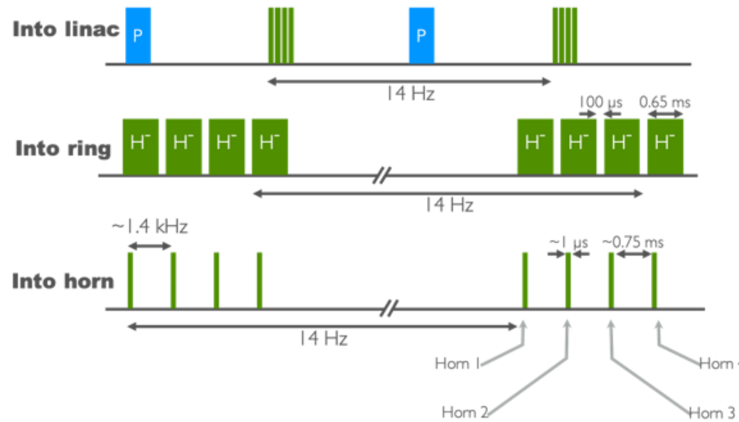
partners: IHEP, BNL, SCK•CEN, SNS, PSI, RAL, NU

ESS modifications and operation

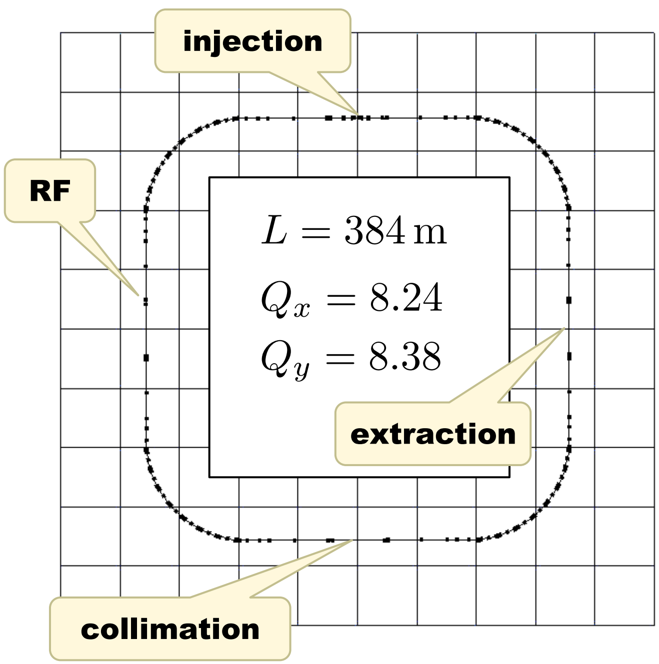
H$^-$ source

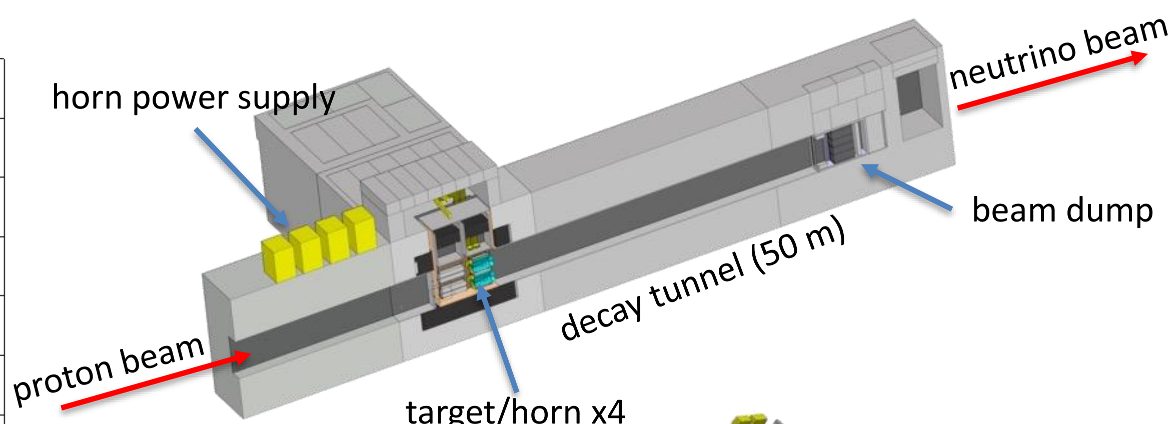


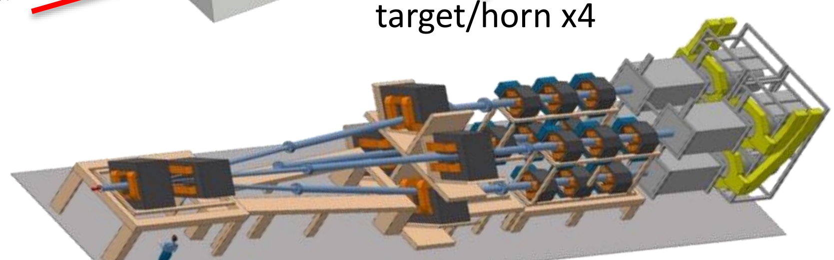
time operation option



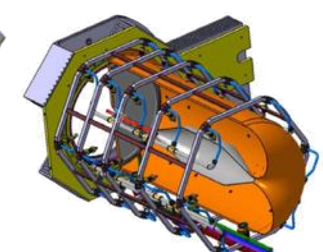
accumulator lattice



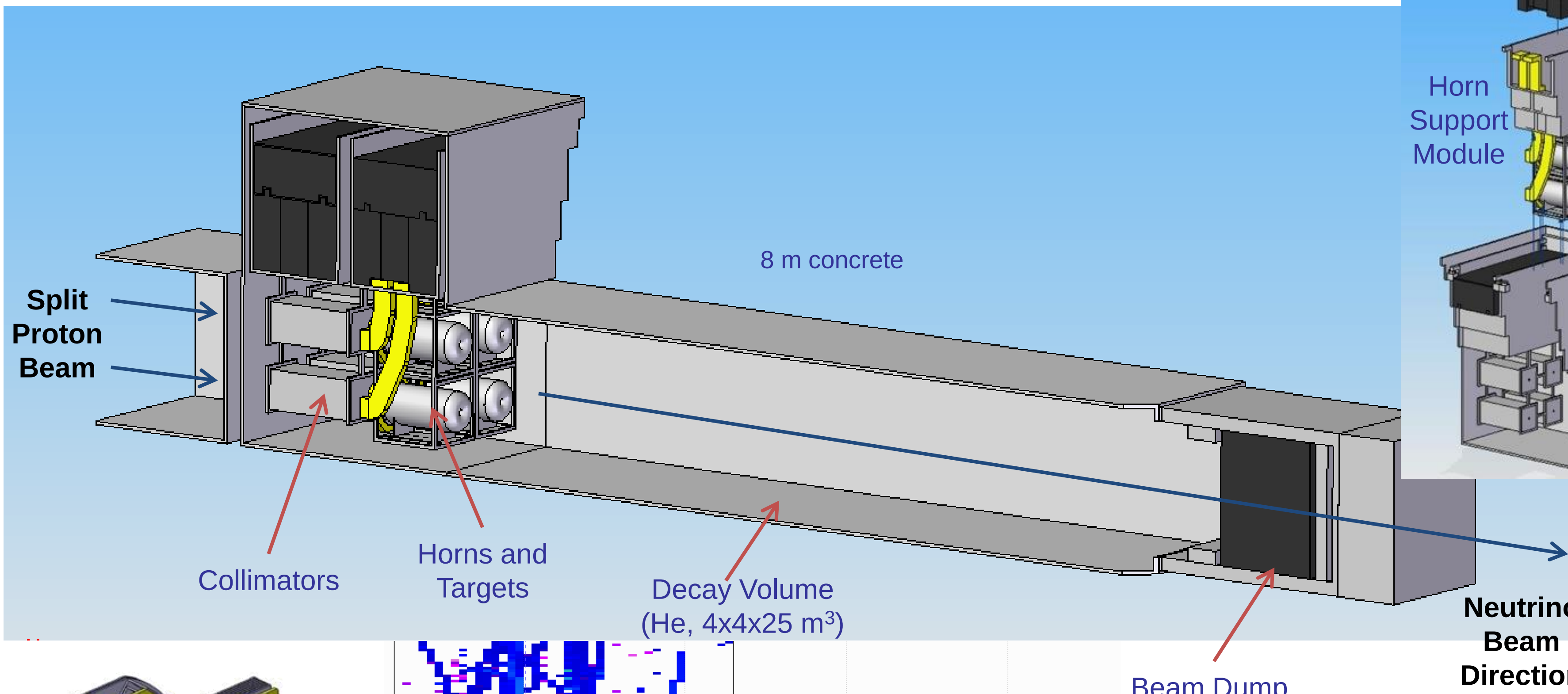


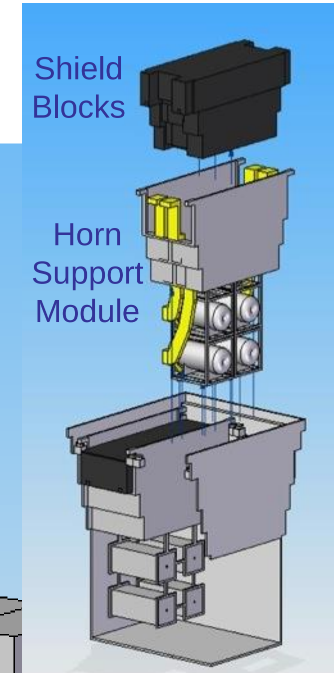


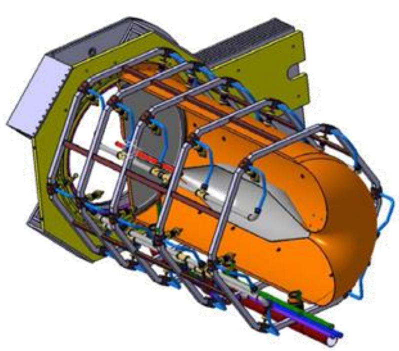
Switchyard

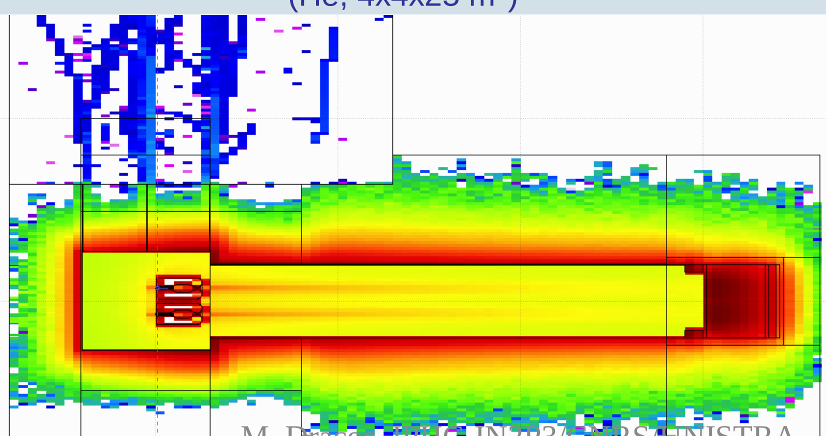


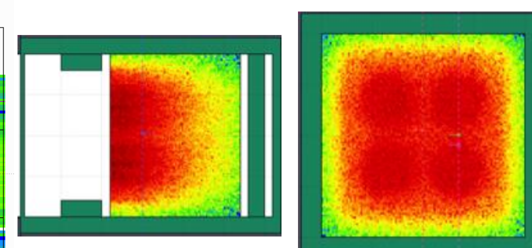
General Layout of the target station
(inspired by J-PARC)



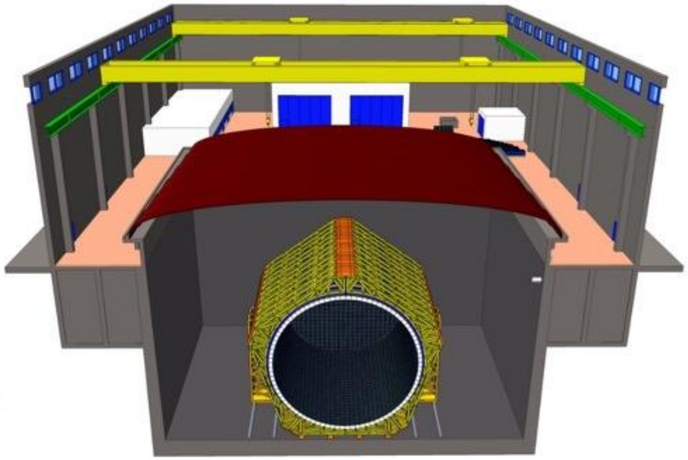




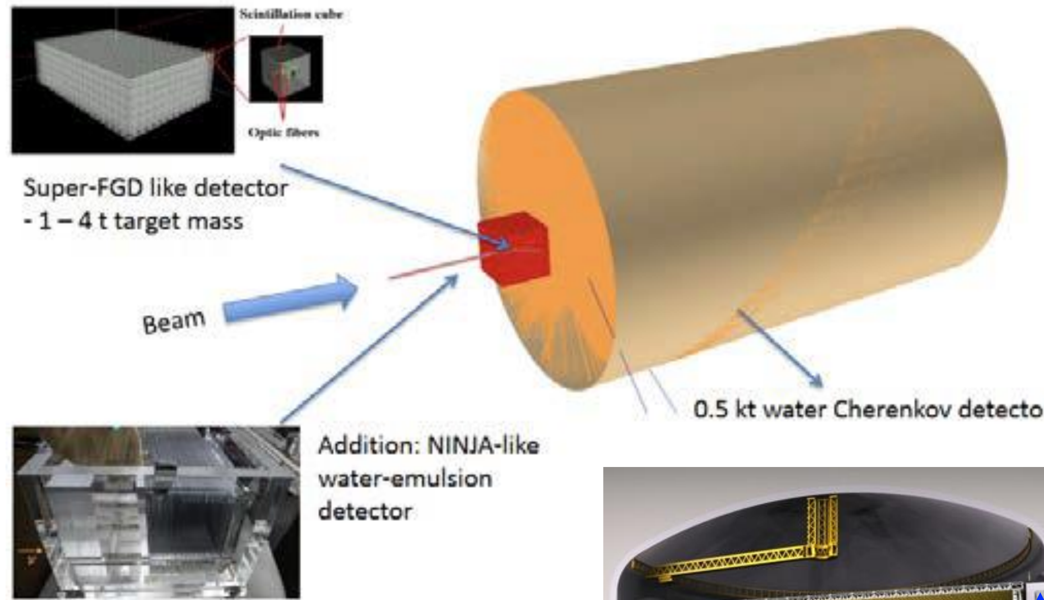




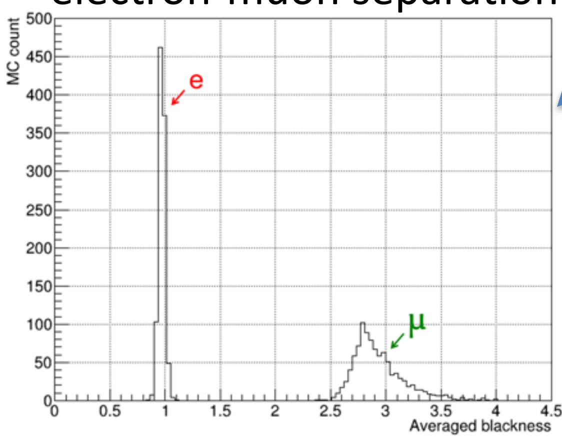
Detectors

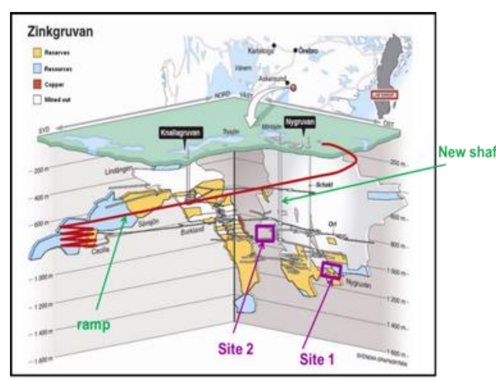


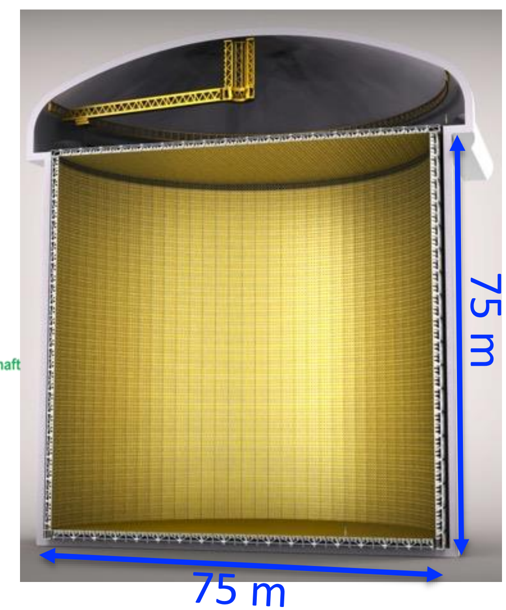
Near detector



electron-muon separation



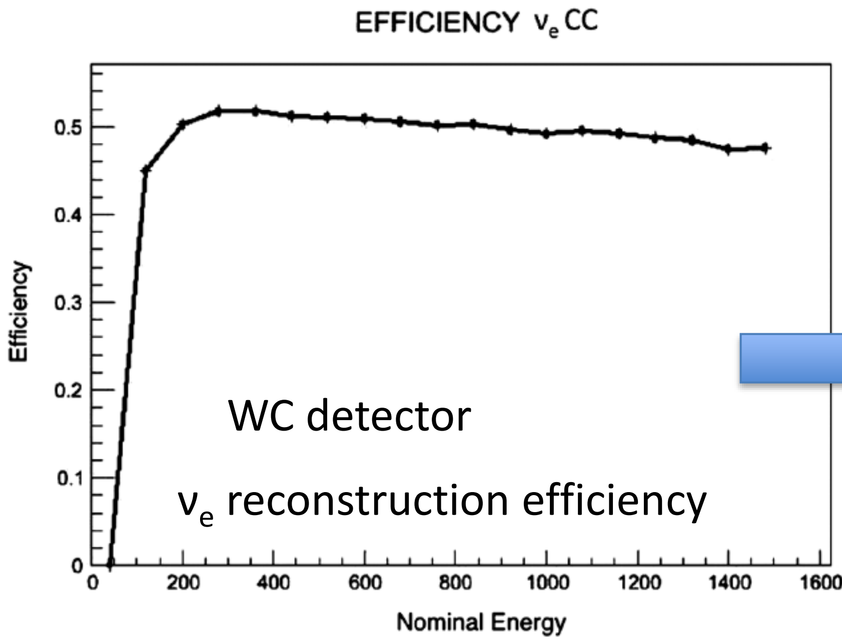


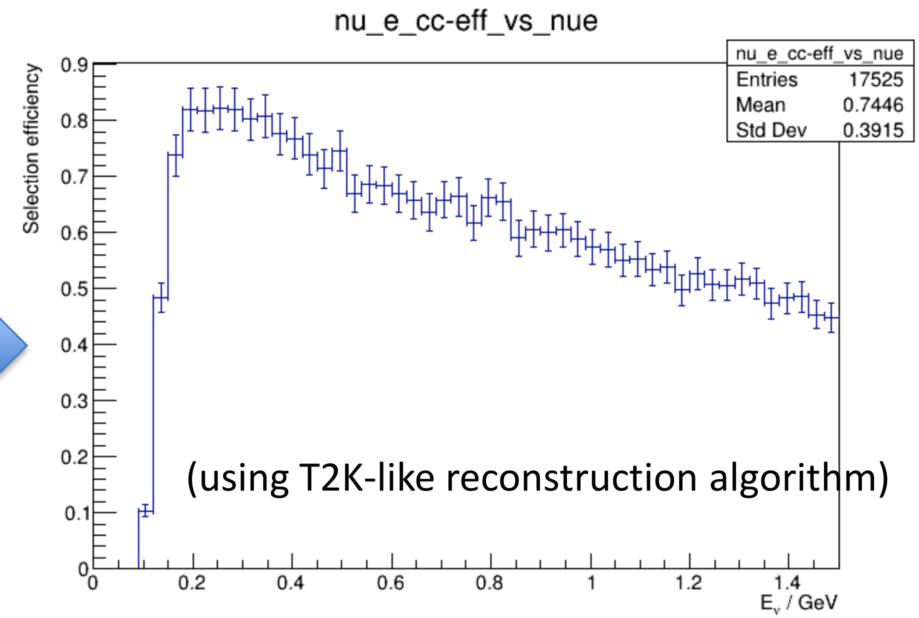


astroparticle physics program
with the Far Detector

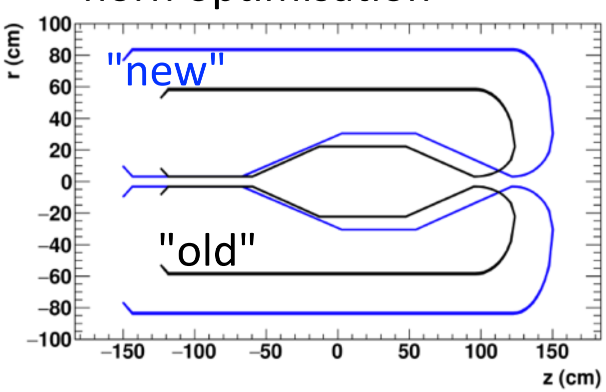
After many Optimisations

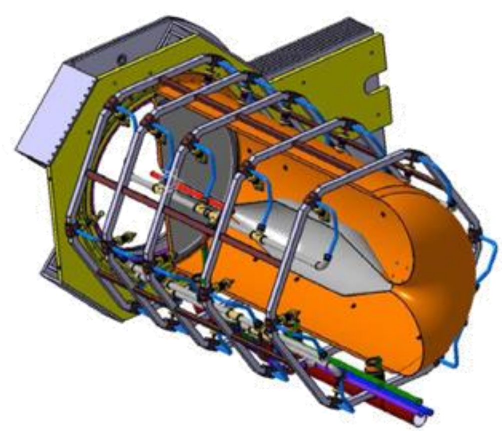
- New Magriation Matrices for the far detector
- Genetic Algorithm for Target Station optimisation





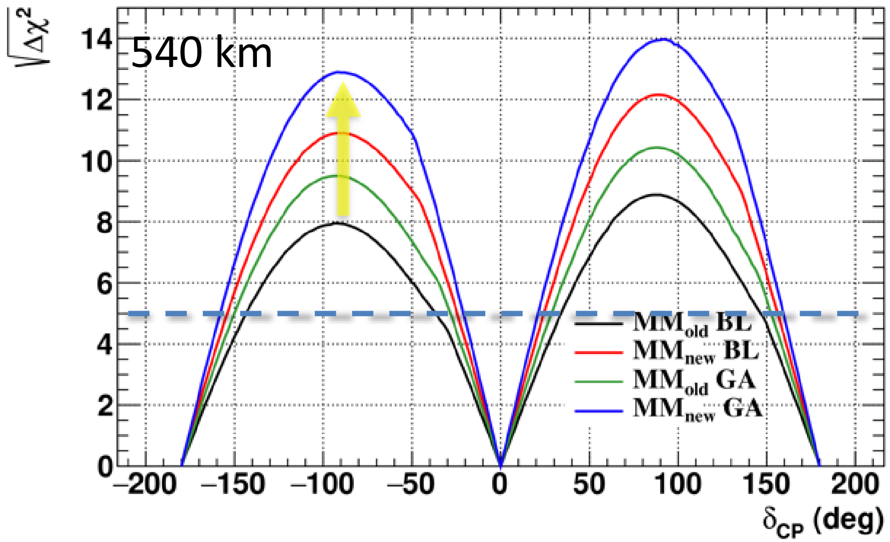
horn optimisation

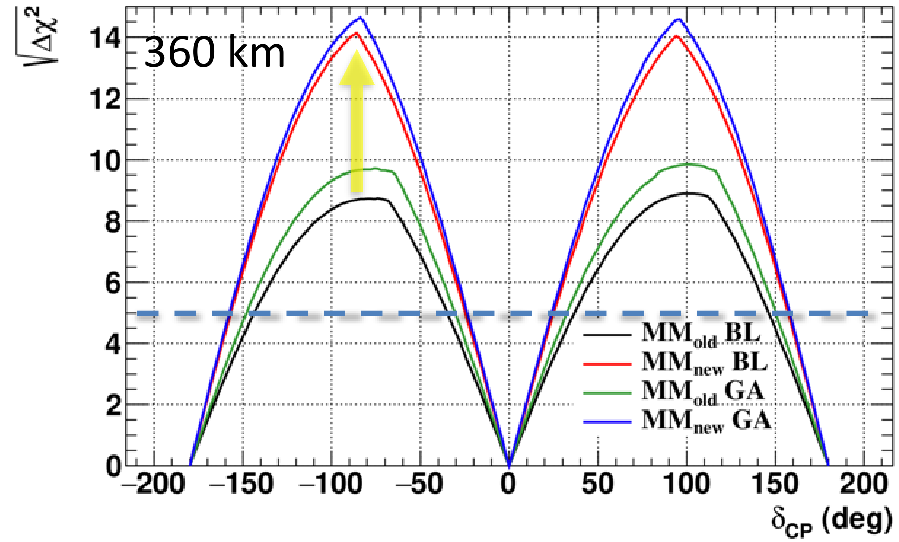




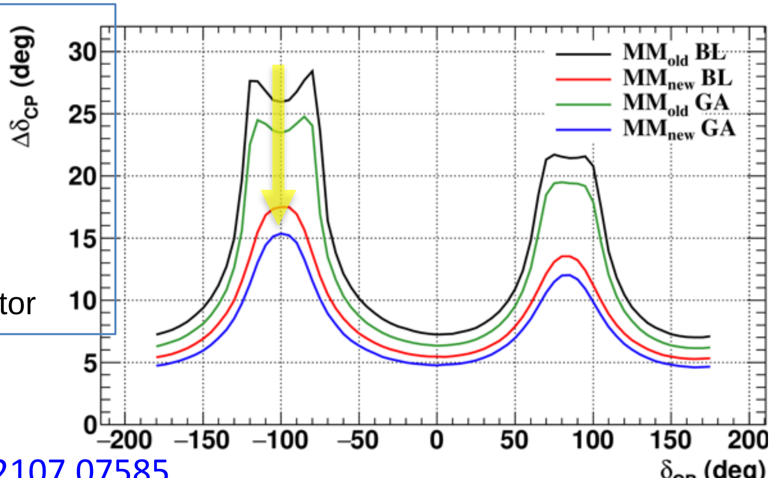
ESS Neutrino Super Beam Plus

Improvements and Optimisations

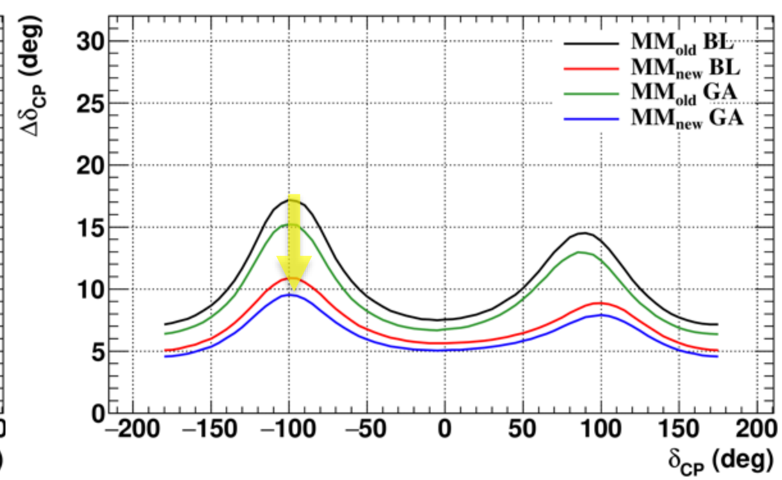




540 km



360 km

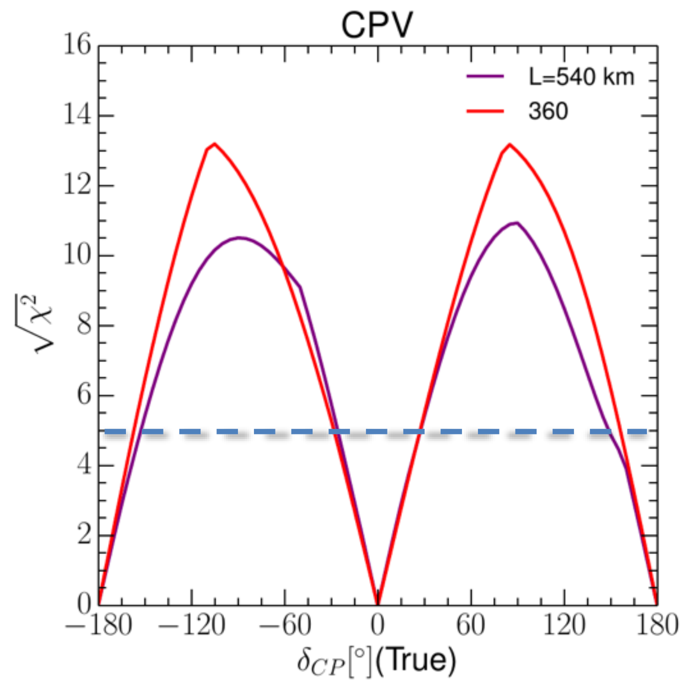


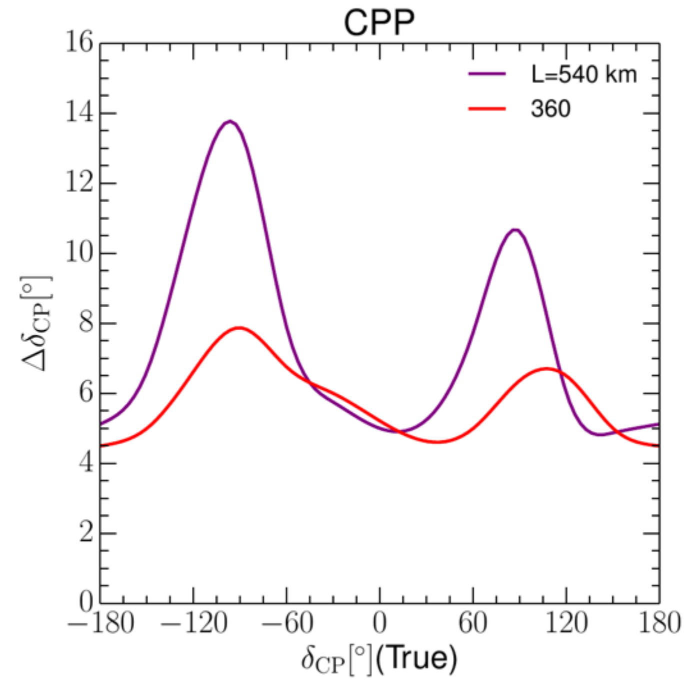
ESSnuSB

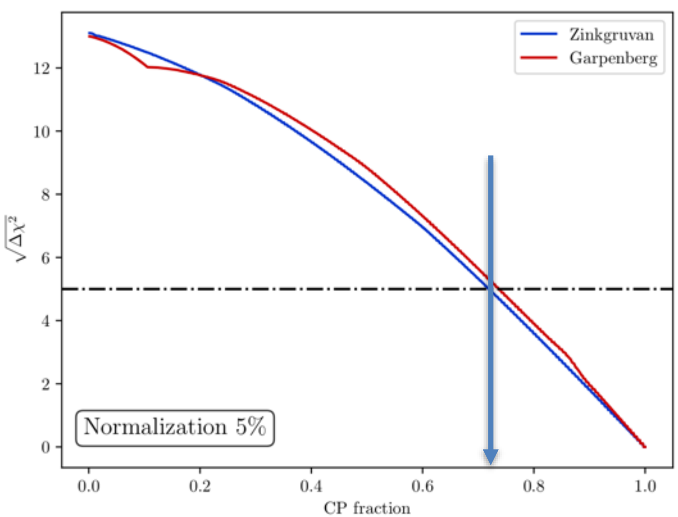
- $\theta_{12} = 33.44°$
- $\theta_{13} = 8.57°$
- $\theta_{23} = 49.2°$
- $\Delta m^2_{21} = 7.42e-5$
- $\Delta m^2_{31} = +2.52e-3$
- 2^{nd} osc. max.
- 507 ktons far detector

https://arxiv.org/abs/2107.07585

Final results







Precision measurement

$\Delta\delta_{CP}$<8° for all values

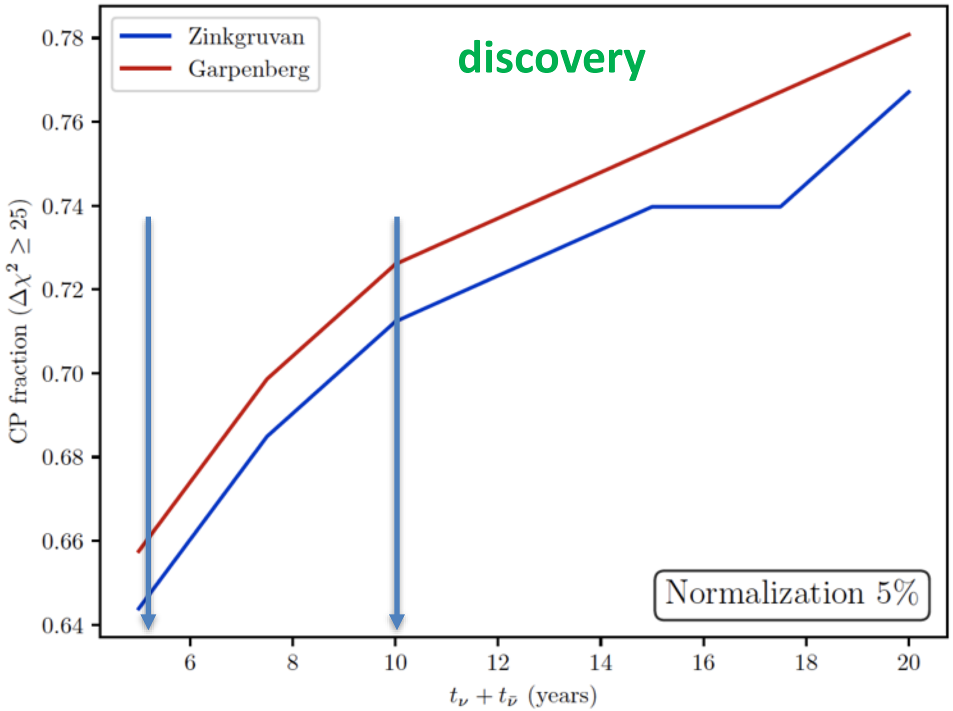
>72% after 10 years

equivalent to Neutrino Factory

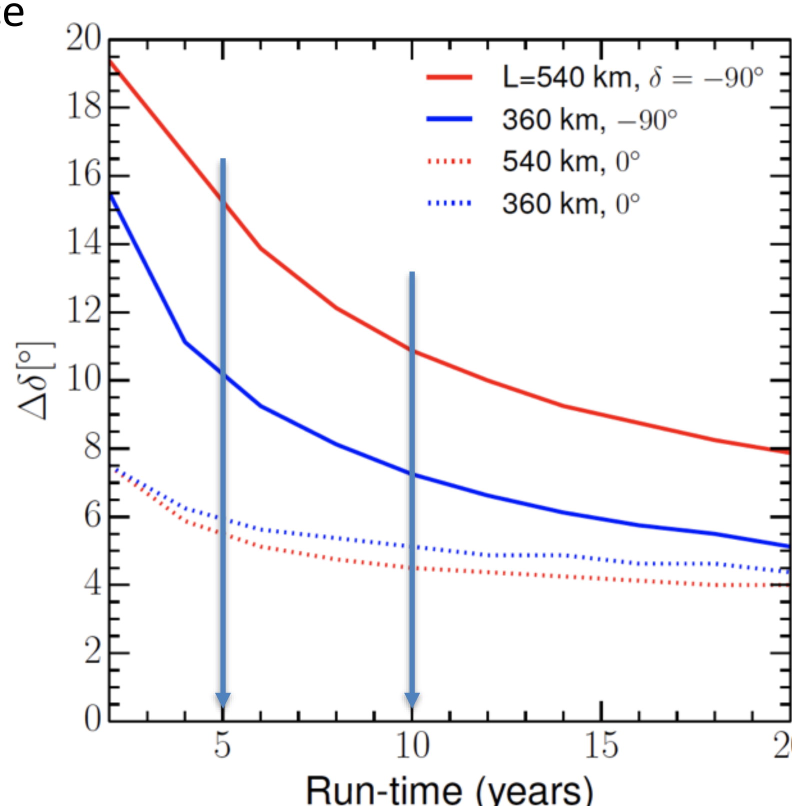
ESS Neutrino Super Beam Plus

Performance versus time

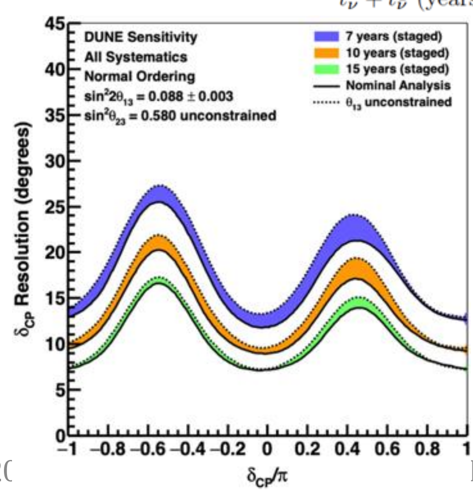
Already after 5 years very competitive performance



discovery

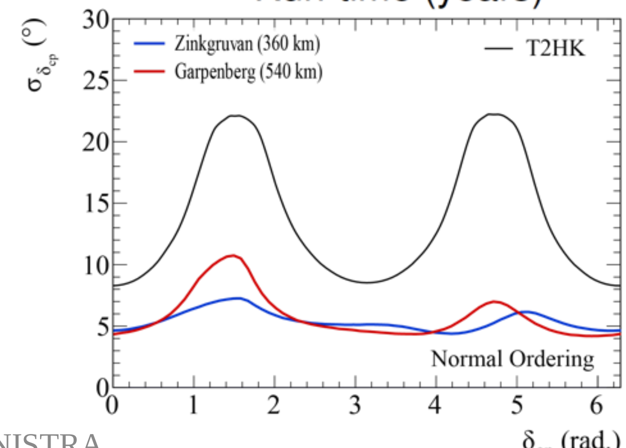


DUNE



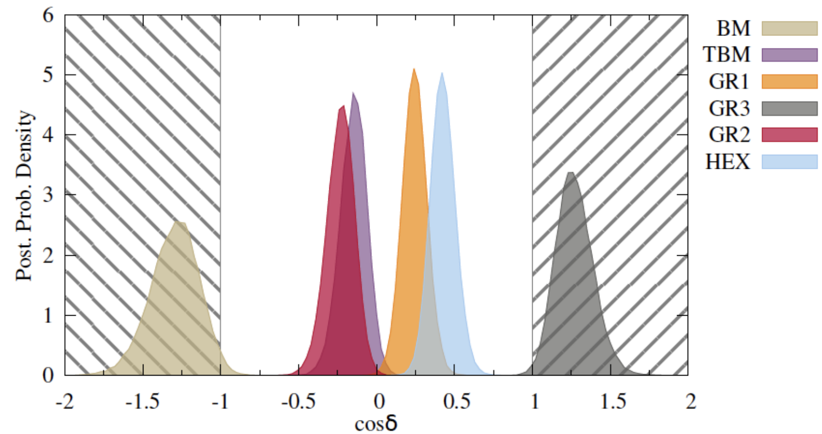
precision

HyperK



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.

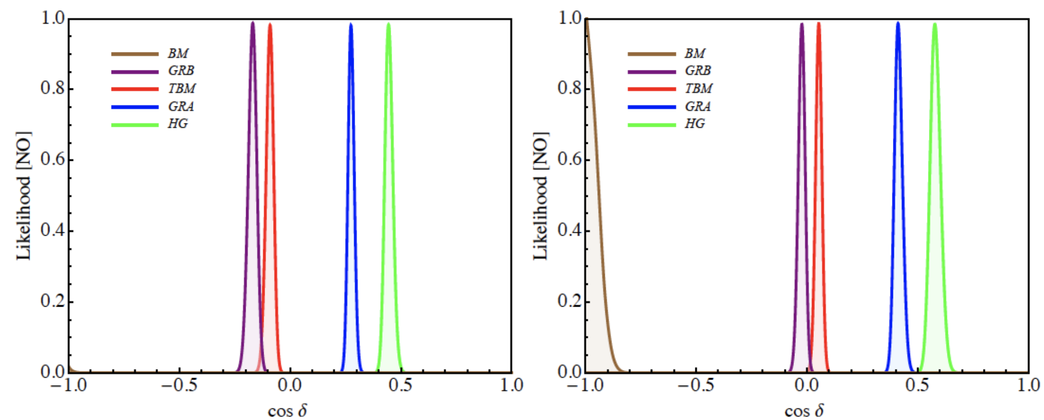
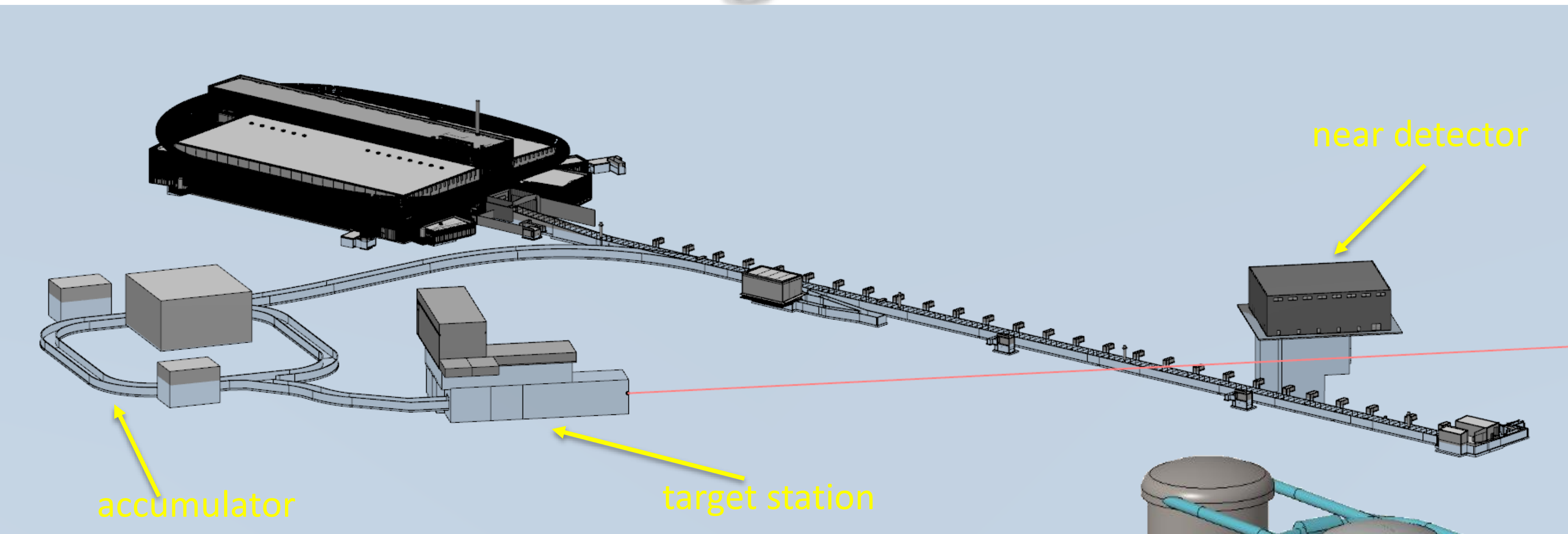
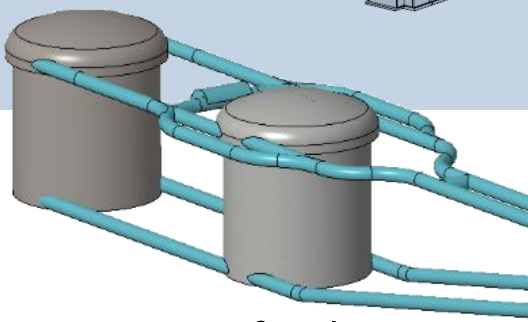


Figure 13: The same as in Fig. 12, but using the prospective 1σ uncertainties in the determination of the neutrino mixing angles within the Gaussian approximation (see text for further details). In the left (right) panel $\sin^2\theta_{12} = 0.308$ (0.332), the other mixing angles being fixed to their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

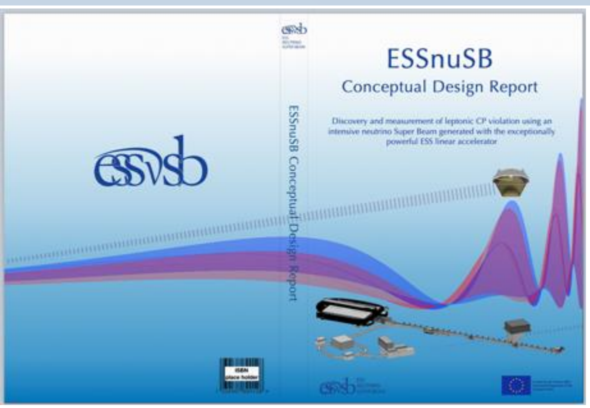
https://arxiv.org/abs/1410.8056

Final ESSνSB facility configuration





far detector



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

Supporting institutions of ESSvSB

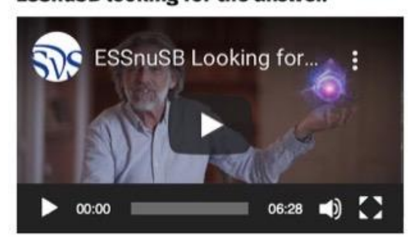
- COST Action EuroNuNet (CA15139): ended March 2020
  - https://euronunet.in2p3.fr
  - video for scientists: https://www.youtube.com/watch?v=PwzNzLQh-Dw

ESSnuSB Design Study Project

- EU-H2020 Design Study ESSvSB: on going up to March 2021 (3 months extension due to COVID19)
  - https://essnusb.eu
  - video for general public: https://www.youtube.com/watch?v=qAnvft0nAlg

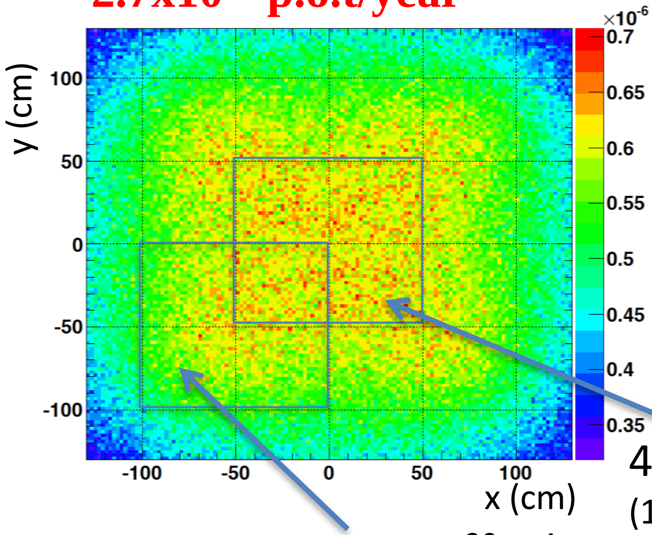
ESS NEUTRINO SUPER BEAM

ESSnuSB looking for the answer.



Muons at the level of the beam dump

2.7x10^{23} p.o.t/year



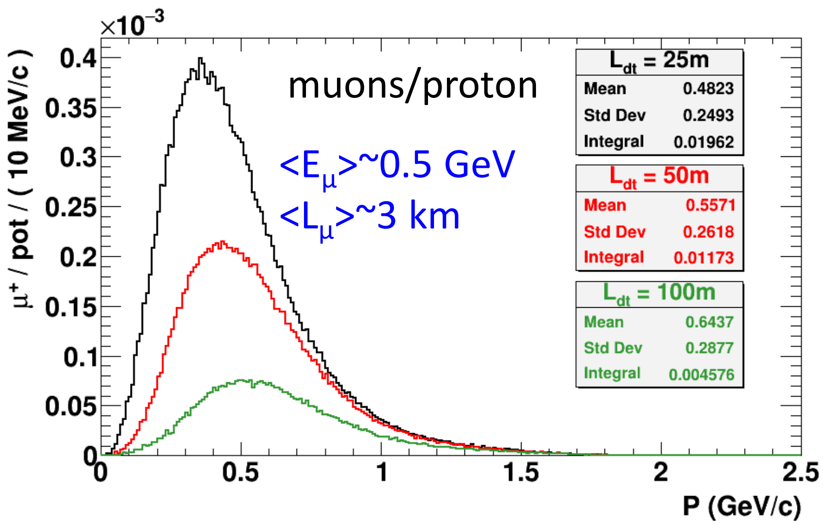
muons at the level of the beam dump (per proton)

4.2x10^{20} μ/year (16.3x10^{20} for 4 m^2)

4.1x10^{20} μ/year

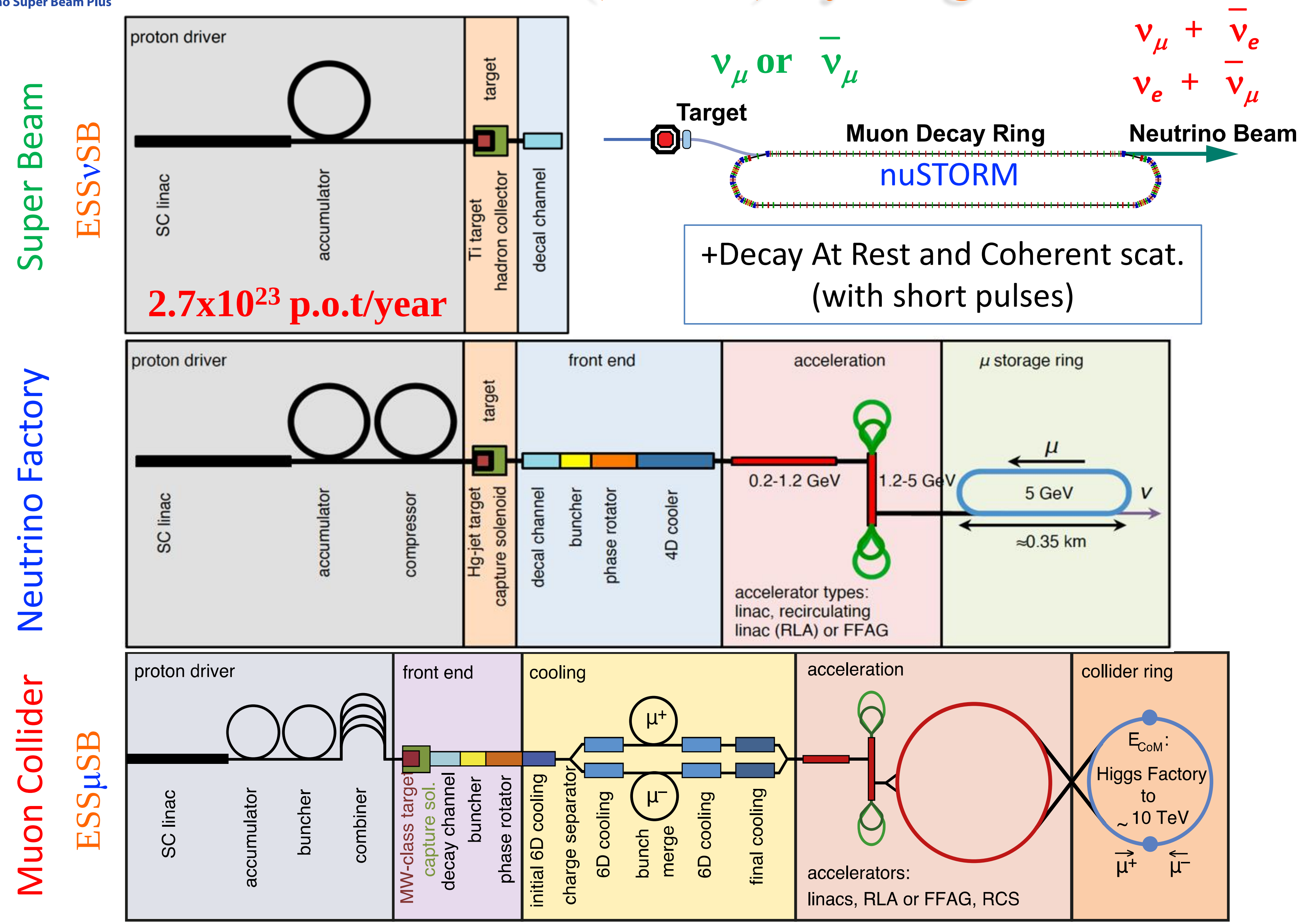
more than 4x10^{20} μ/year from ESS compared to 10^{14} μ used by all experiments up to now (10^{18} μ for COMET in the future).

10^{-3}



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

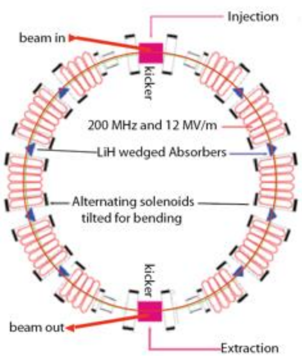
ESSνSB and (R&D) synergies



Muon Collider as Higgs Factory

arXiv:1908.05664

Parametric Resonance Cooling (PIC)



HIFI Uppsala Workshop March 2020

Main future muon Higgs alternatives

- Two adequate Higgs alternatives of a $\mu+\mu-$ collider will be discussed:
  - the s-channel resonance at the Ho mass, to study with ≈ 40'000 fb and L > 10^{32} all decay modes with small backgrounds;
  - A higher energy collider, eventually up to $\sqrt{s}$ ≈ 0.5-1 TeV and L > 10^{34} to study all other Higgs processes of the scalar sector.
- The colliding beams ring can easily fit within existing locations:
  - For $\sqrt{s}$ = 126 GeV the ring *radius is ≈ 50 m* (about 1/2 of the CERN PS or 1/100 of LHC) but with the *resolution ≈ 0.003%*
  - For $\sqrt{s}$ = 0.5 TeV the corresponding ring *radius is ≈ 200 m* (about twice the CERN PS) and the *resolution ≈ 0.1 %*
- Two $\mu+\mu-$ bunches of 2 x 10^{12}ppp can likely be produced by a high pulsing rate of a few GeV protons at ≈ 5 MWatt.

CERN.24March2021 Slide# : 12

Muons at ESS (ESSμSB)

Estimated performance for the H⁰-factory (ESS)

- Two asymptotically cooled μ bunches of opposite signs collide in two low-beta interaction points with $\beta^* = 5$ cm and a free length of about 10 m, where the two detectors are located.
- *With PIC cooling* a peak collider a luminosity of 4×10^{32} cm^{-2} s^{-1} is achieved
  - The bunch transverse rms size is 0.05 mm and the μ–μ tune shift is 0.086.
  - The SM Higgs rate is ≈ 10^5 ev/year (10^7 s) in each of the detectors.
  - An arrangement with at least two detector positions is recommended.

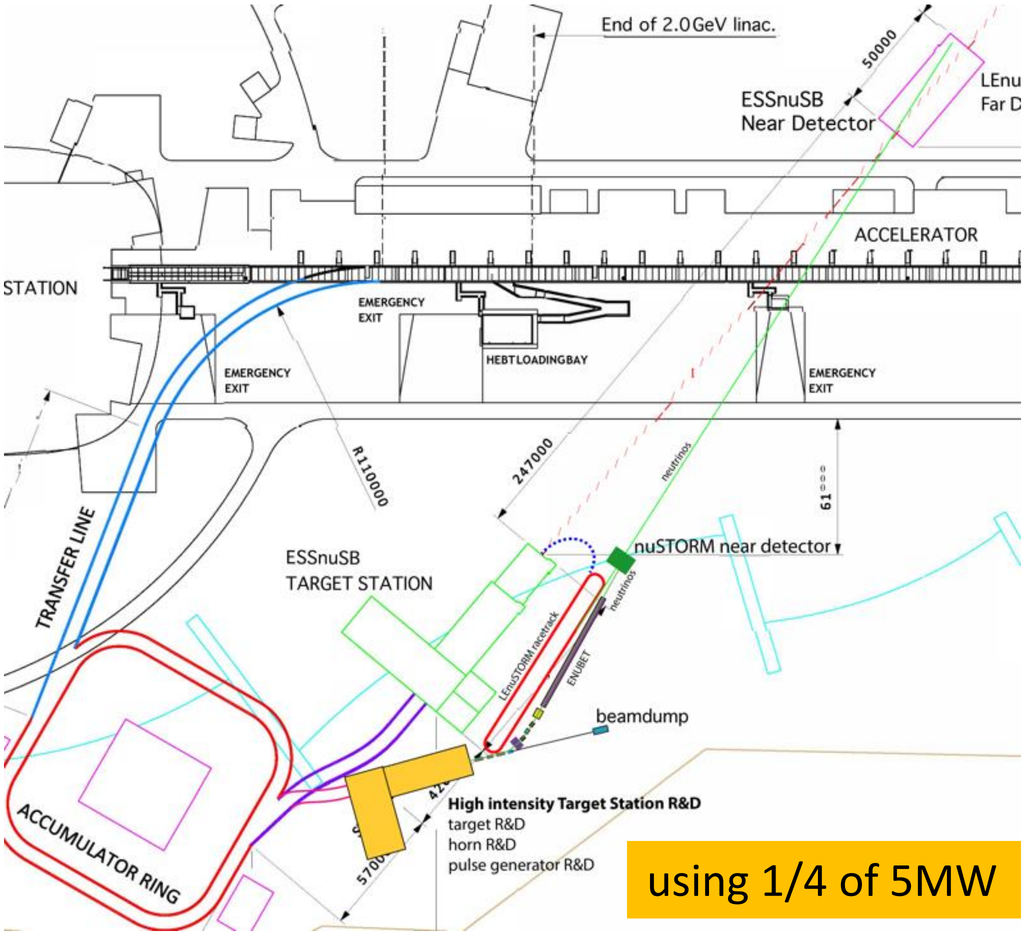
Proton kinetic energy	2.0	GeV
Proton power	5.0	MW
Proton collisions	56 =14x4	ev/s
Timing proton collisions	17.86	ms
Protons/collision	2.5×10^{14}	p/coll
Final muon momentum	62.5	GeV/c
Final muon lifetime	1.295	Ms
Total μ surv. fraction	0.07	
μ+ at collider ring	2.93×10^{12}	μ/coll
μ- at collider ring	1.89×10^{12}	μ/coll
Inv. transv. emittance, ε_N	0.37	π mm rad
Inv. long. emittance	1.9	π mm rad
Beta at collision $\beta_x = \beta_y$	5.0	cm
Circumf. of collider ring	350	m
Effective luminosity turns	555	
Effective crossing rate	29'970	sec-1
Luminosity no PIC	4.24×10^{31}	cm^{-2} s^{-1}
Luminosity + PIC (10 x)	4.2×10^{32}	cm^{-2} s^{-1}
Higgs cross section	3.0×10^{-35}	cm^2
Higgs @10^7 s/y, no PIC	1.2×10^4	ev/y
Higgs @10^7 s/y + PIC	**1.2×10^5**	**ev/y**
Higgs -> γγ, 10^7 s/y + PIC	≈ 2400	ev/y
Tune shift with PIC	0.086	

Without PIC
1.2×10^4 ev/year

CERN March 2021

Slide# : 30

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 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

Excellent supporting letter from the ESS director

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+

ESSνSB+

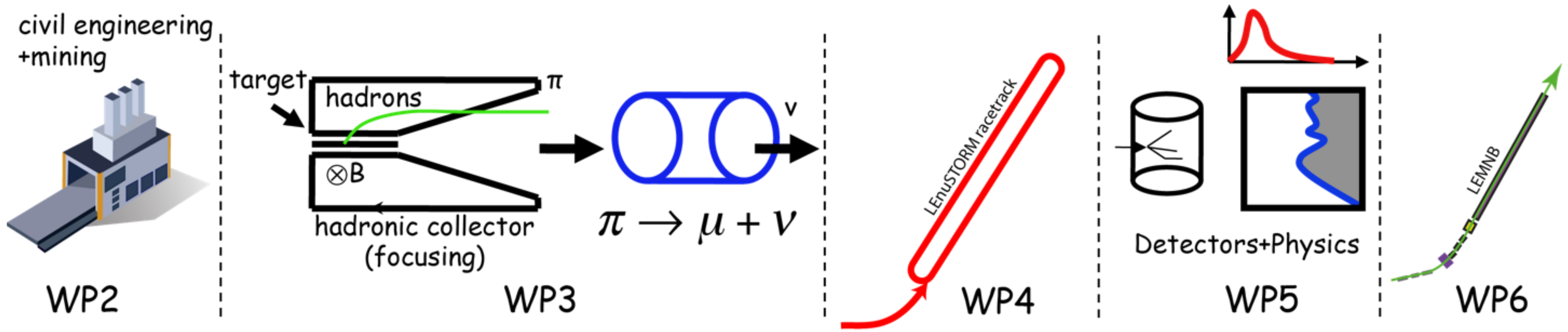
(Horizon Europe)

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

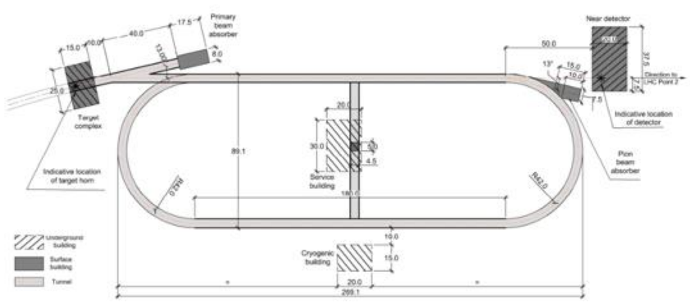
- submitted last April
- decision in September

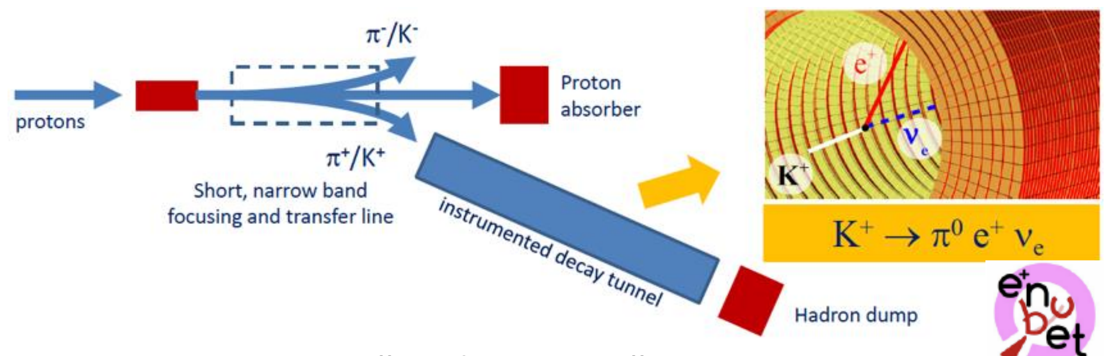
ESSνSB+ WP



- cross-sections
- sterile neutrinos

- cross-sections





"High Energy" nuSTORM "High Energy" ENUBET

build a "Low Energy" version

ESS Neutrino Super Beam Plus

ESSνSB+

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

Marcos DRACOS
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS
RUE MICHEL ANGE 3
75794 PARIS
FRANCE

- 3 M€
- 4 years

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

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

ESSνSB+ kick-off meeting

(ESS, Lund, Jan. 17 2023)

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 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 on arXiv.
- Rich muon program for future ESS upgrades.
- **New application submitted and now accepted by EU**

Backup

Possible ESSνSB schedule

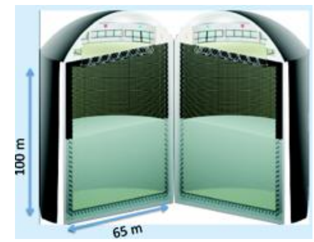
(2nd generation neutrino Super Beam)

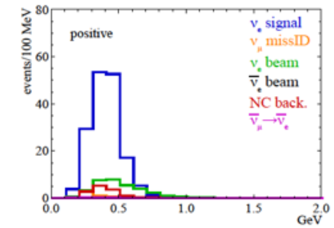
ESS Neutrino Super Beam Plus

cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

ESS NEUTRINO SUPER BEAM

ESFRI





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

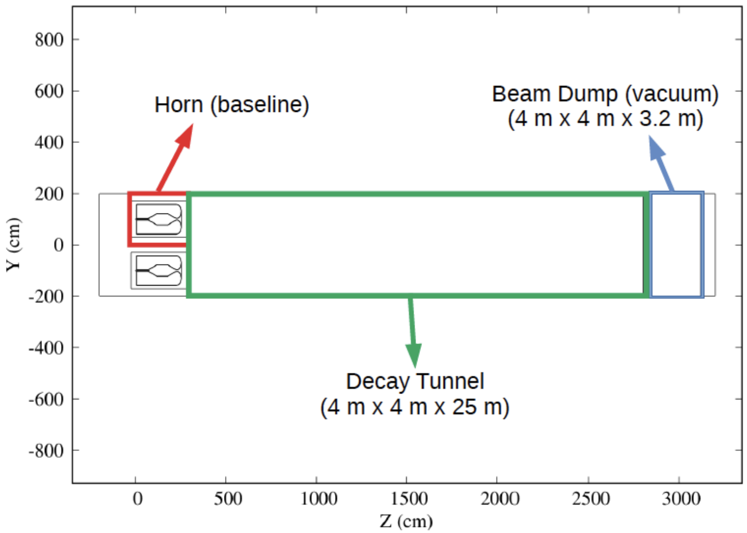
2026-2028: Preconstruction Phase, International Agreement

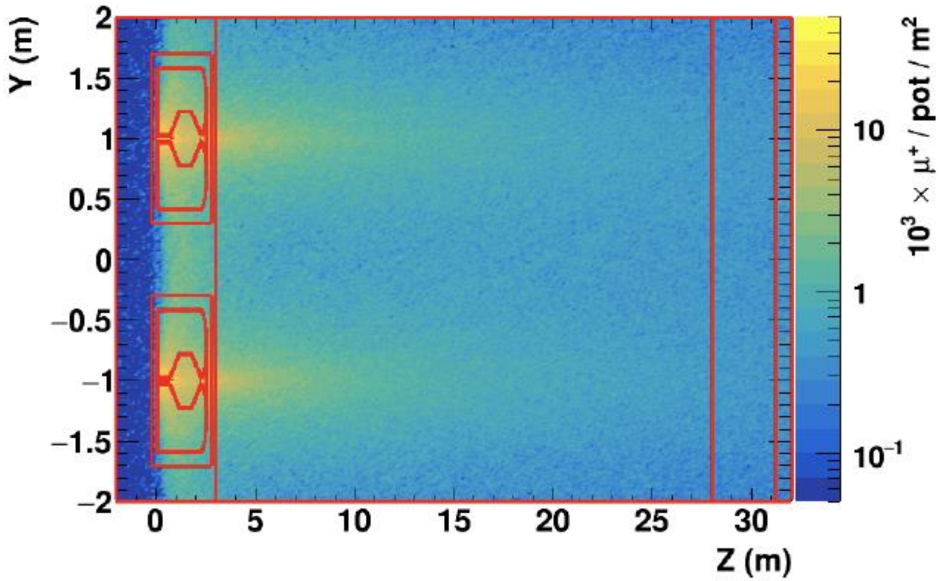
2028-2036: Construction of the facility and detectors, including commissioning

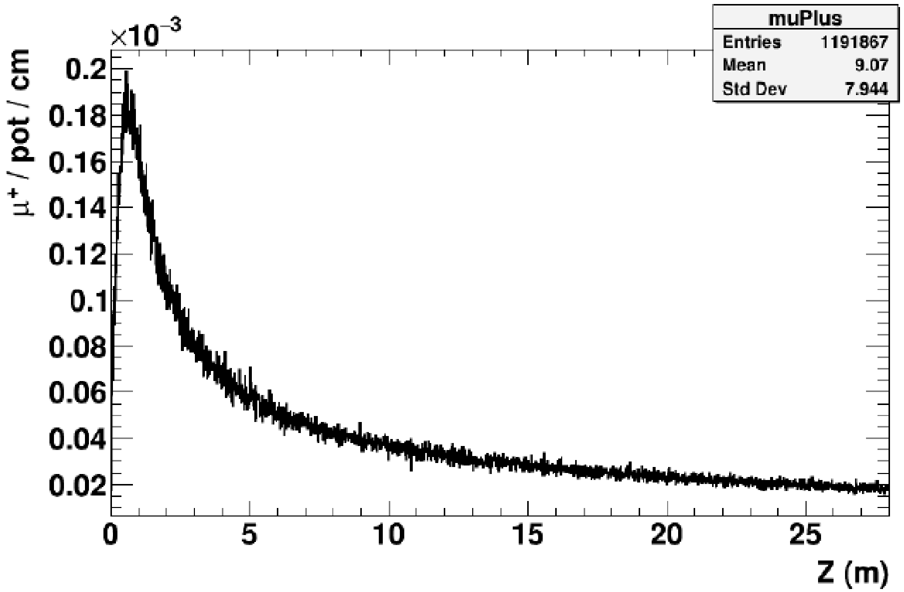
2037-: Data taking

EUROPEAN SPALLATION SOURCE

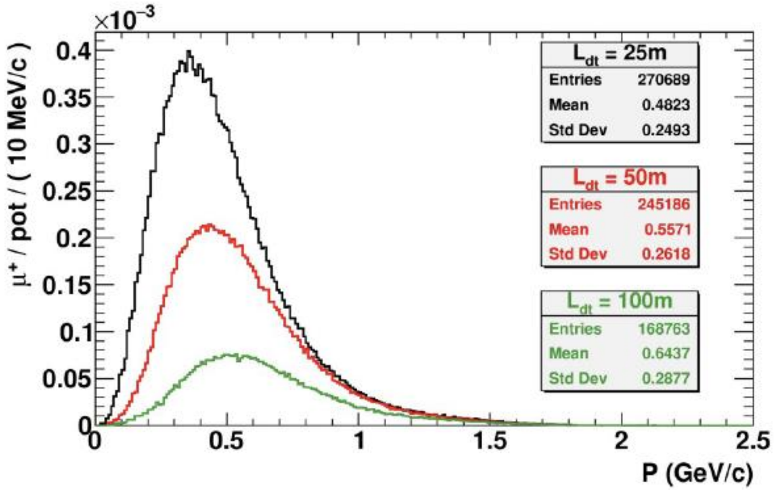
Muon production

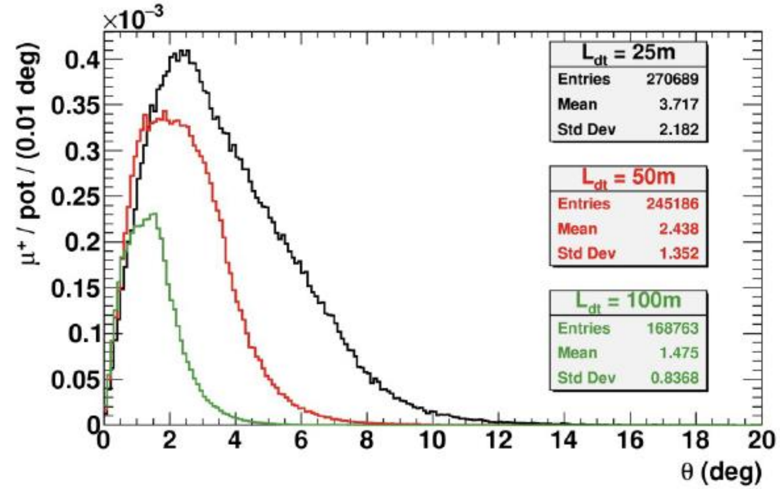






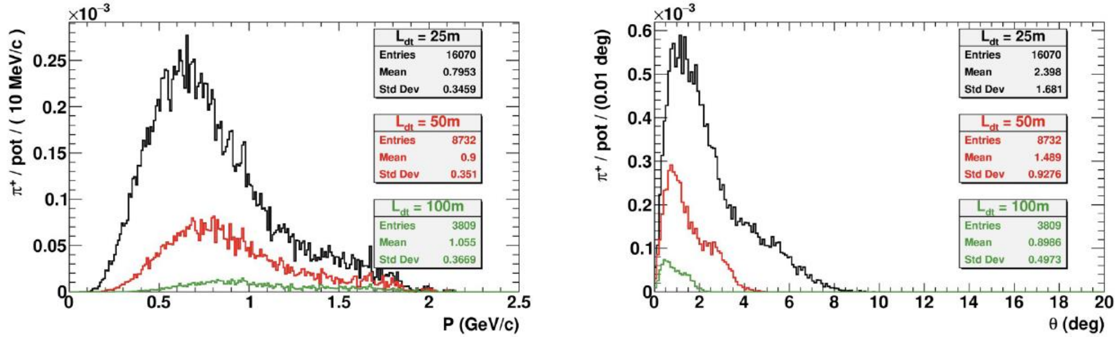
Muon production





- I + reaching the BD:
  - L_{dt} = 25m => N_I = 0.02 I +/pot = 4.3x10^{21} I +/200d
  - Ldt = 50 m => N_I = 0.01 I +/pot = 2.2x10^{21} I +/200d
  - Ldt = 100 m => N_I = 0.0045 I +/pot = 0.97x10^{21} I +/200d

Pion production



- M+ reaching the BD:
  - L_{dt} = 25m => N_M= 0.017 M+/pot = 3.7x10^{21} M+/200d
  - Ldt = 50 m => N_M= 0.005 M+/pot = 1.1x10^{21} M+/200d
  - Ldt = 100 m => N_M= 8.5 x 10^{-4} M+/pot = 1.8x10^{20} M+/200d

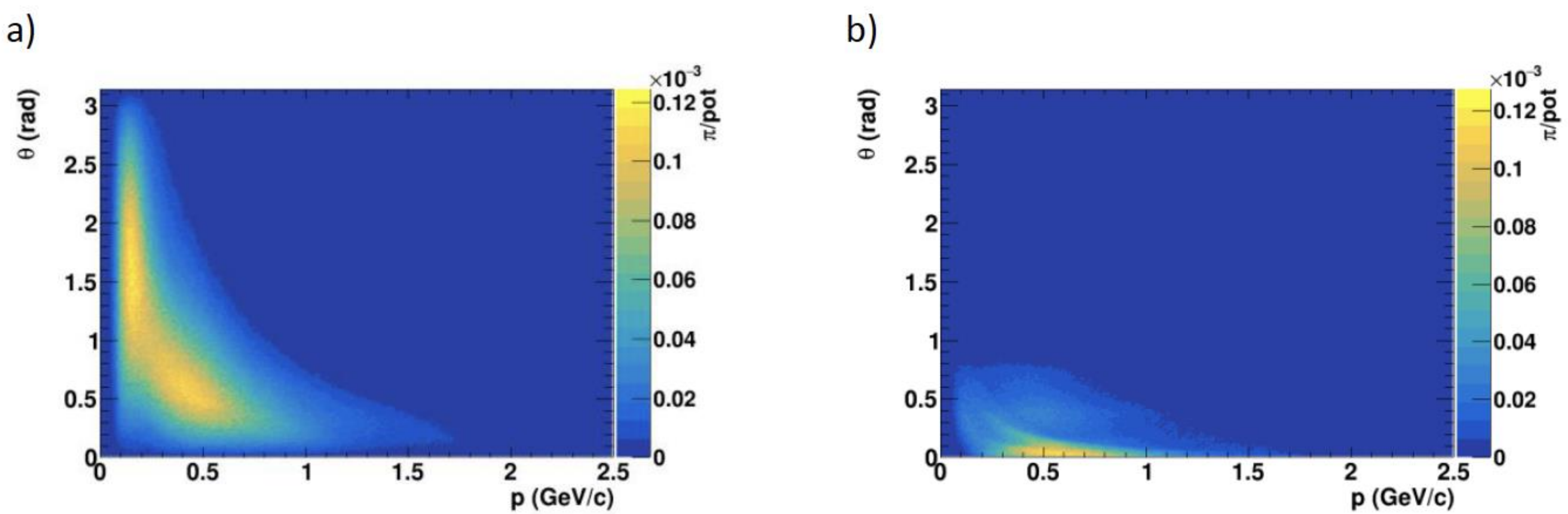
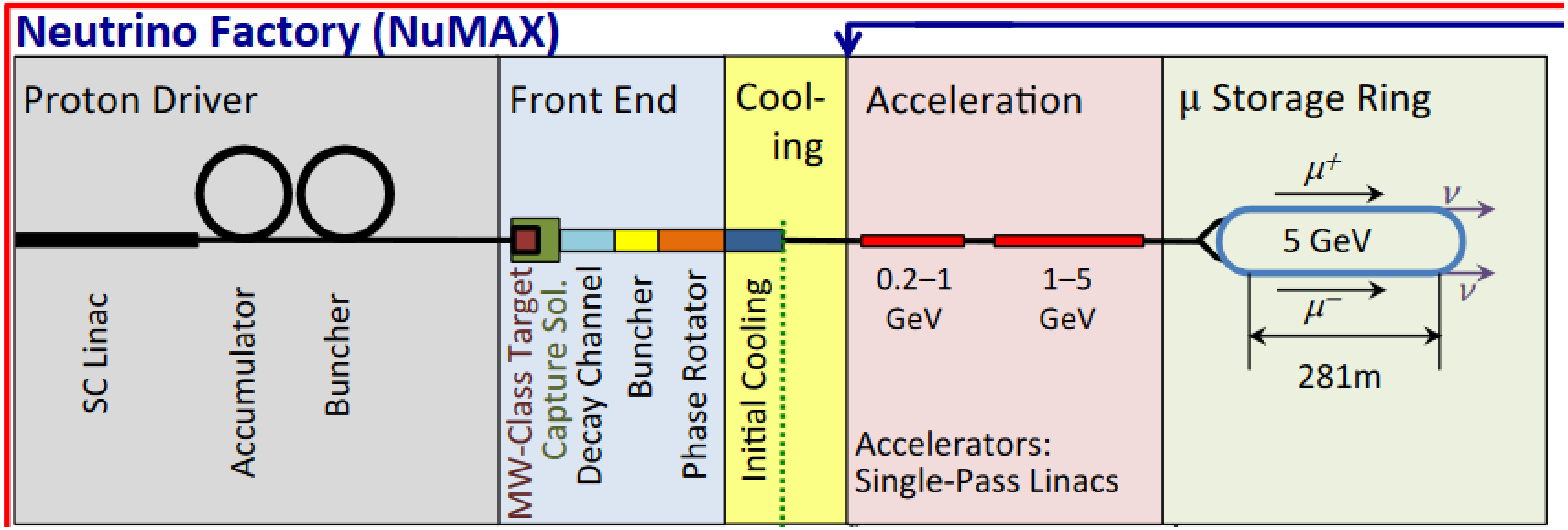
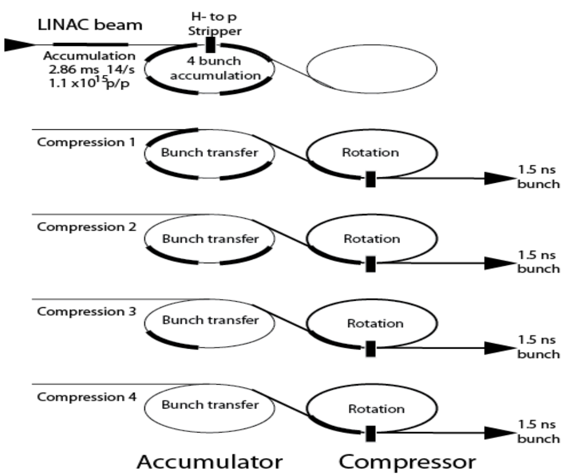


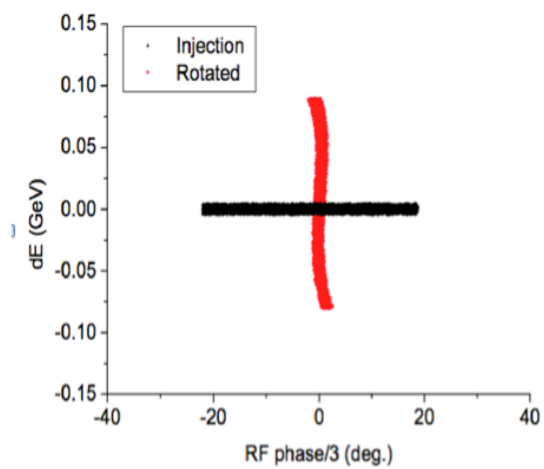
Figure 36: a) Momentum-angular distribution of positive pions exiting the target, b) momentum-angular distribution entering the decay tunnel.

HIFI Neutrino Factory generic layout





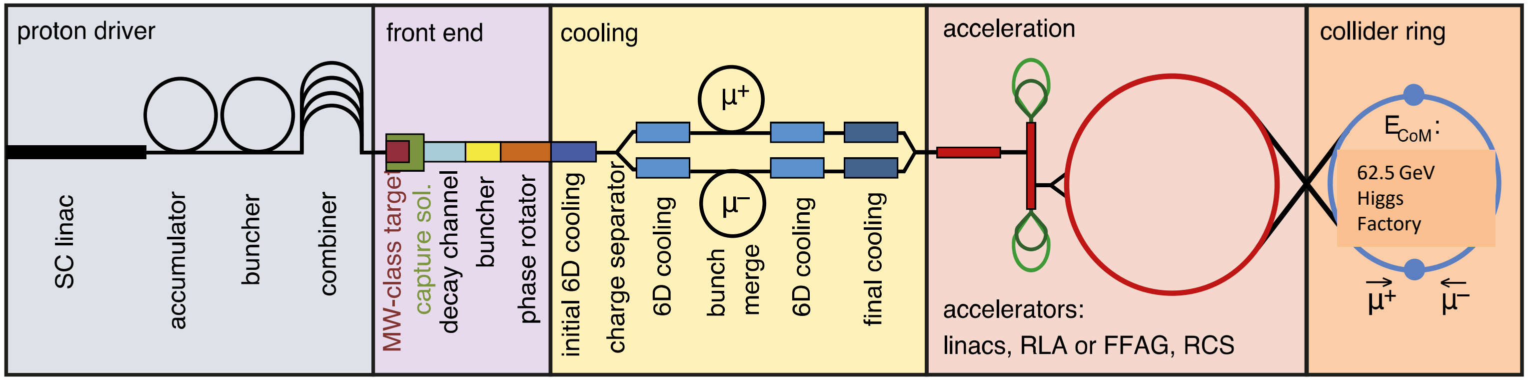
Accumulation and bunching

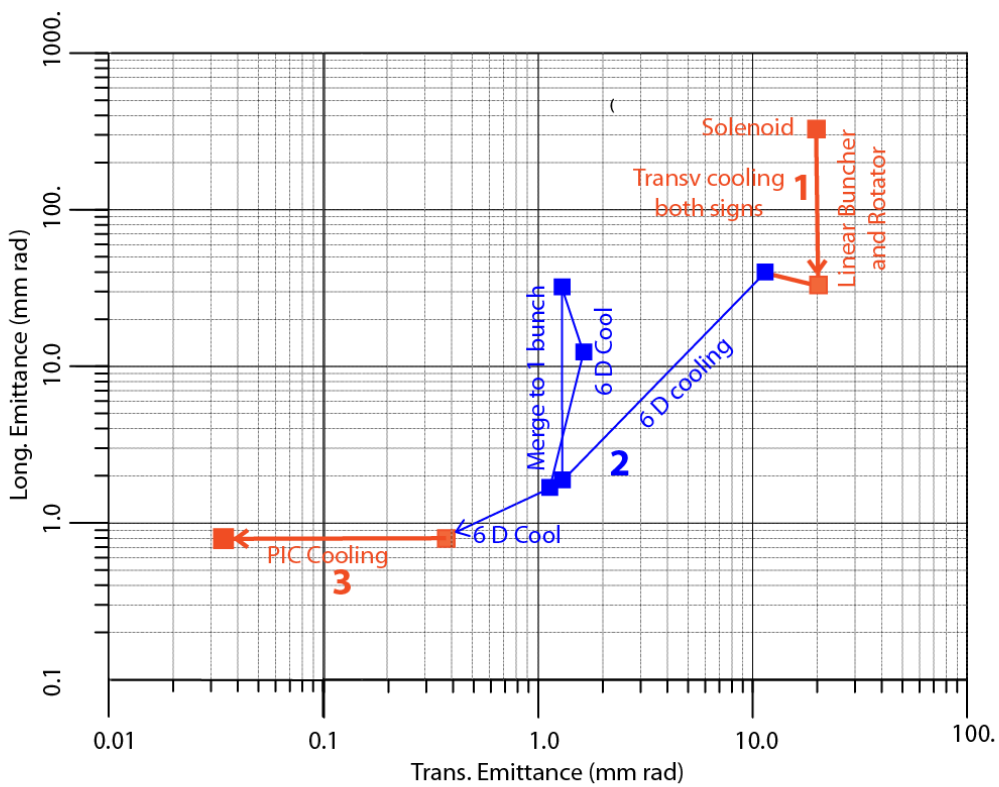


Phase rotation

Then cooling, acceleration and storage in a muon decay ring

Muon Collider Higgs Factory at ESS
(generic layout)





Muon cooling in 3 steps:

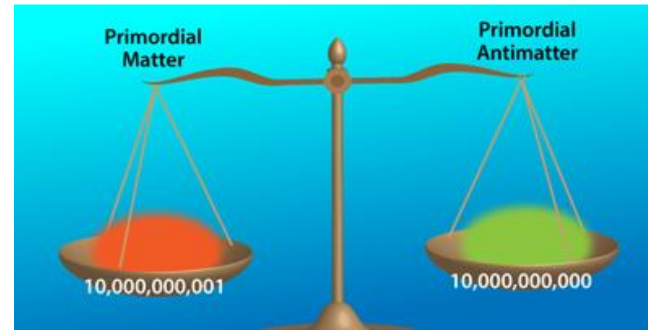
1. Linear transverse cooling
2. 6D cooling
3. Parametric Resonance Cooling

Then acceleration to

62.5 GeV and collisions

δ_{CP} and Matter-antimatter asymmetry magnitude

$$A^{CP}_{\alpha\beta} = P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$$
$$= J^{PMNS}_{CP} \cdot \sin\delta_{CP}$$



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

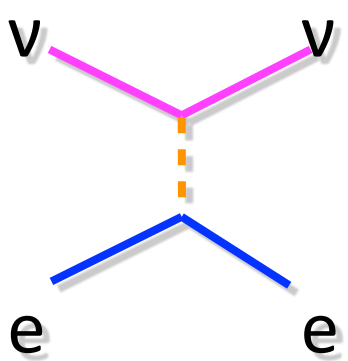
(for hadrons: $J^{CKM}_{CP} \sim 3\times10^{-5}$, not enough even if δ_{CP}~70°)

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

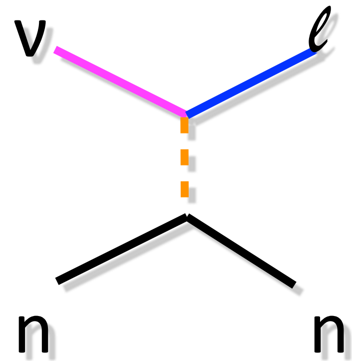
Theoretical models predict that if |sinδ_{CP}|≳0.7 (45°<δ_{CP}<135° or 225°<δ_{CP}<315°), this could be enough to explain the observed asymmetry.

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

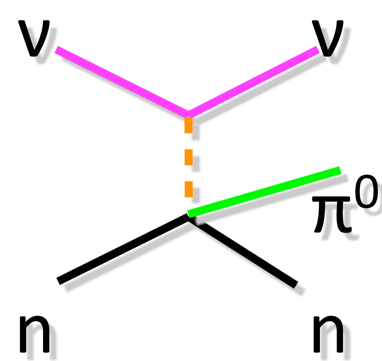
ESSνSB+



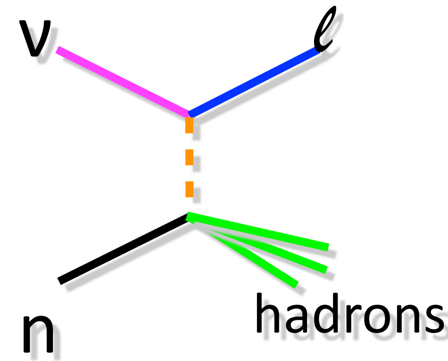
Elastic



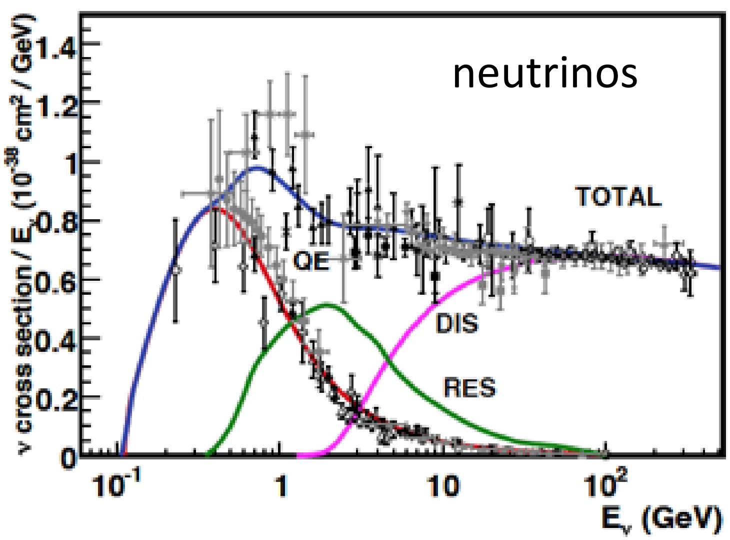
Quasi-Elastic (QE)

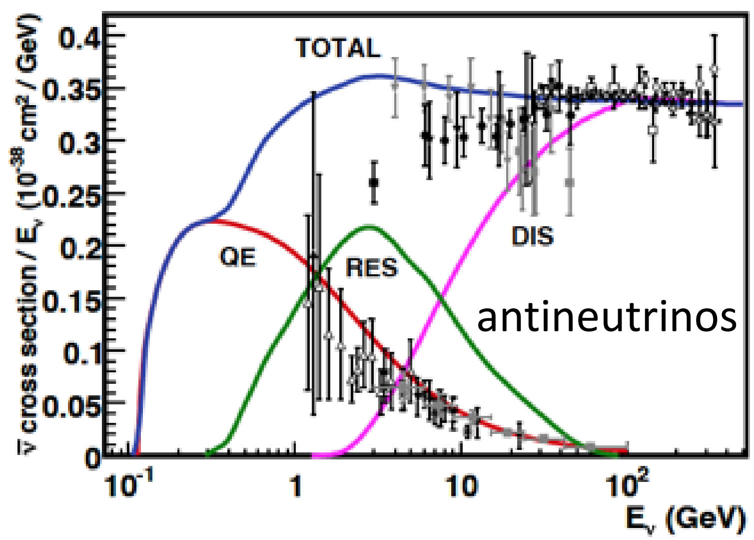


Resonant (RES)



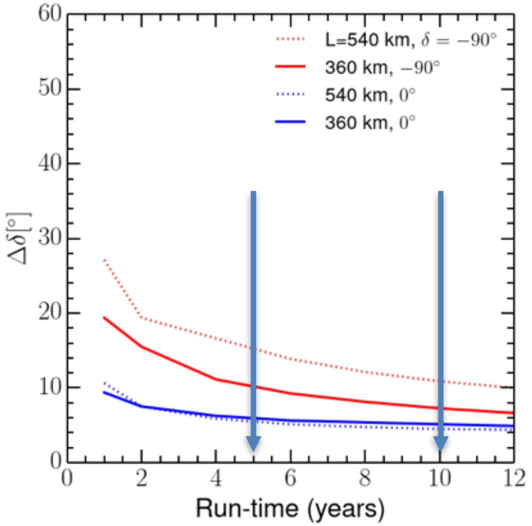
Deep inelastic (DIS)



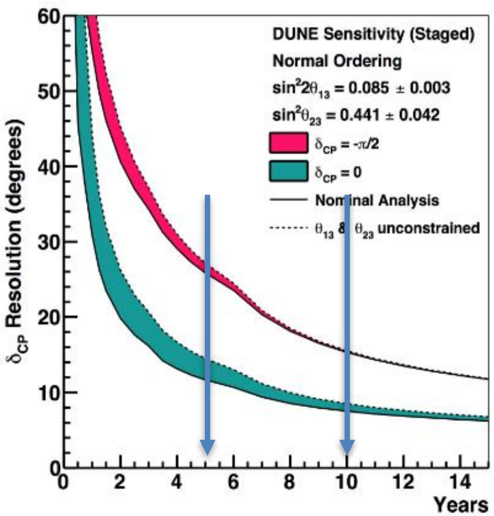


Missing measurements at the ESSνSB region: below 500 MeV

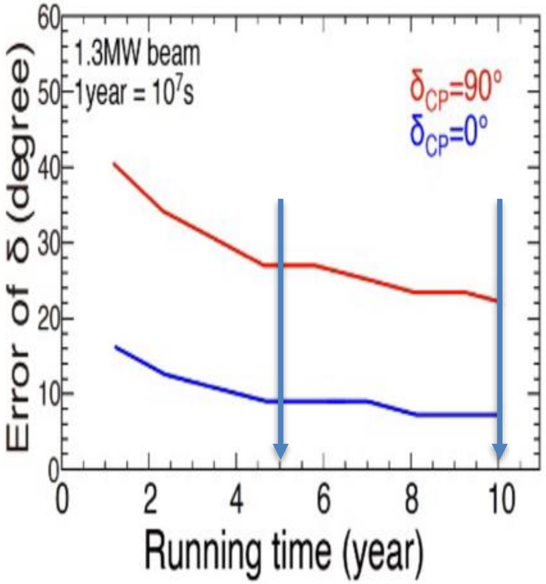
Comparisons



ESSnuSB March 2022 with 5% normalization error

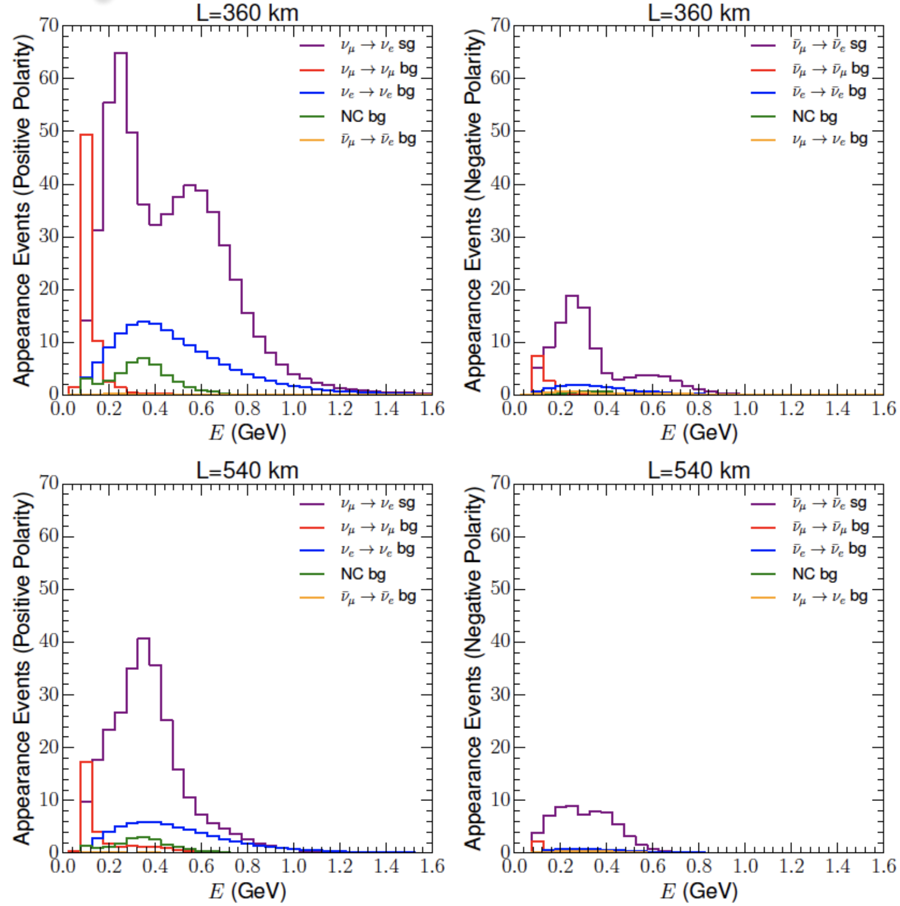


DUNE Snomass March 2022



HyperK Snowmass March 2022

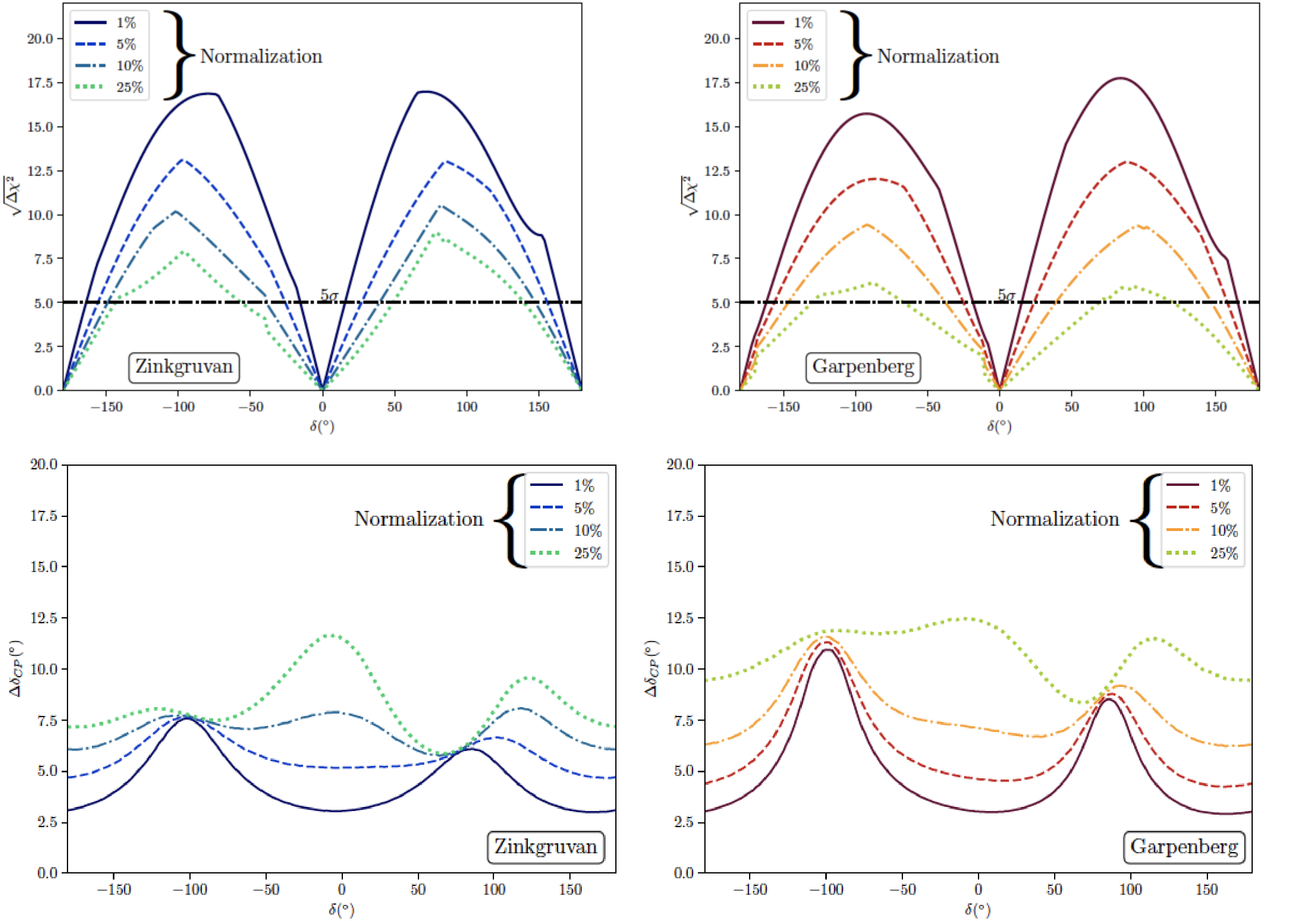
Physics Performance



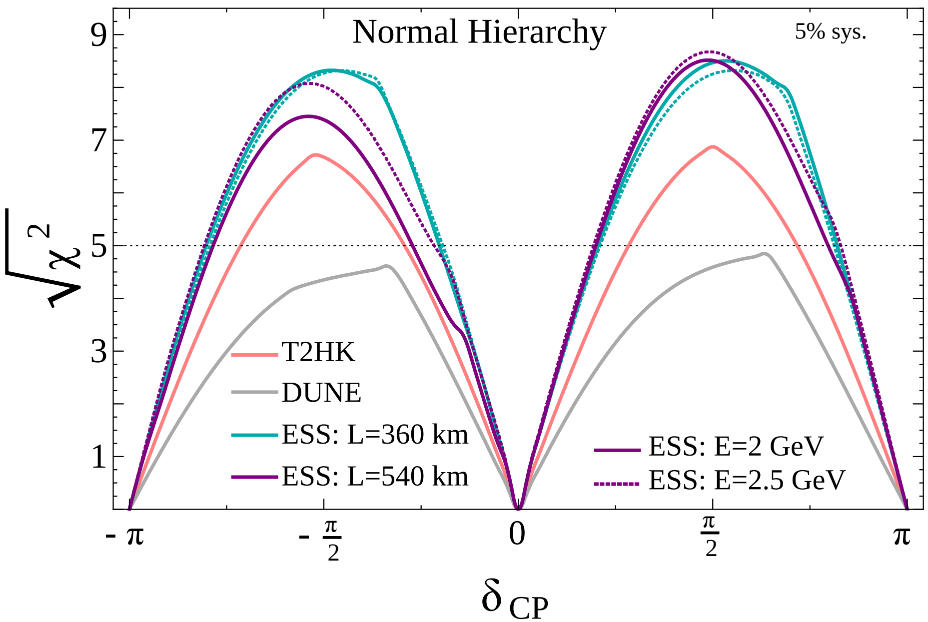
during 10 years

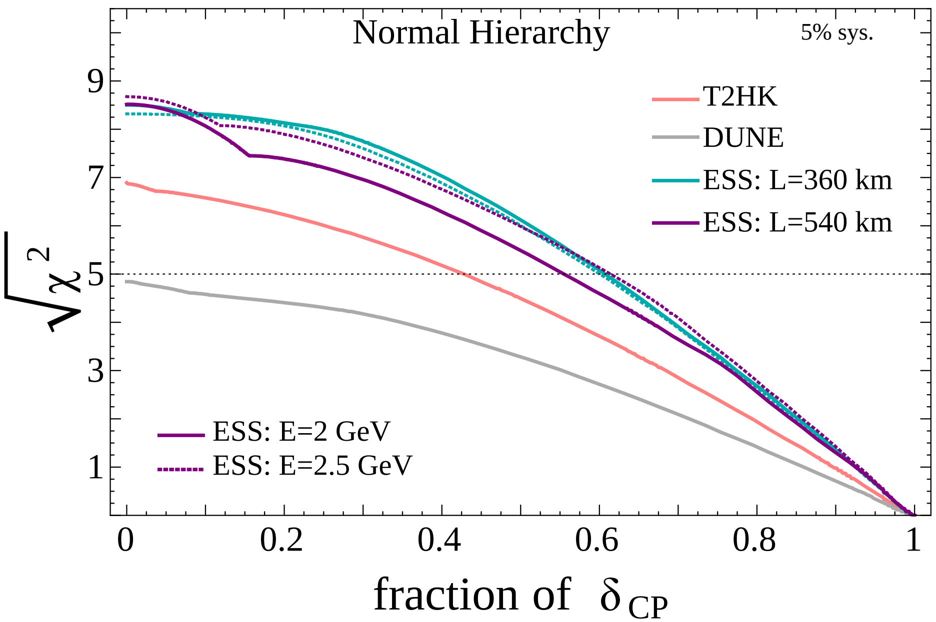
	Channel	L = 540 km	L = 360 km
Signal	$\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$)	272.22 (63.75)	578.62 (101.18)
Background	$\nu_\mu \to \nu_\mu$ ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)	31.01 (3.73)	67.23 (11.51)
	$\nu_e \to \nu_e$ ($\bar{\nu}_e \to \bar{\nu}_e$)	67.49 (7.31)	151.12 (16.66)
	ν_μ 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



Comparisons



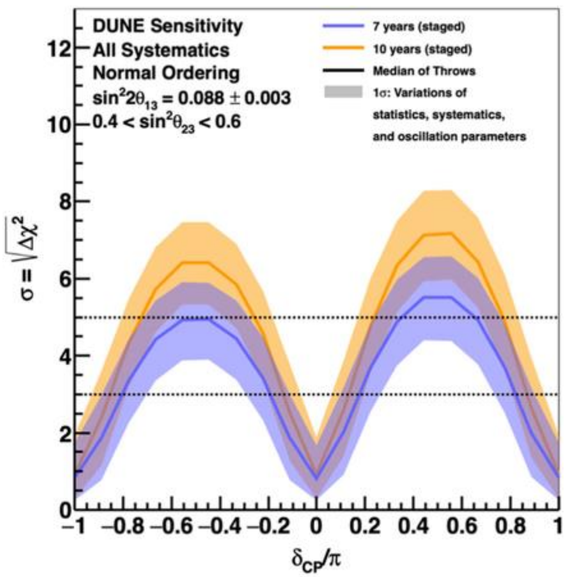


Comparison using the same systematic errors

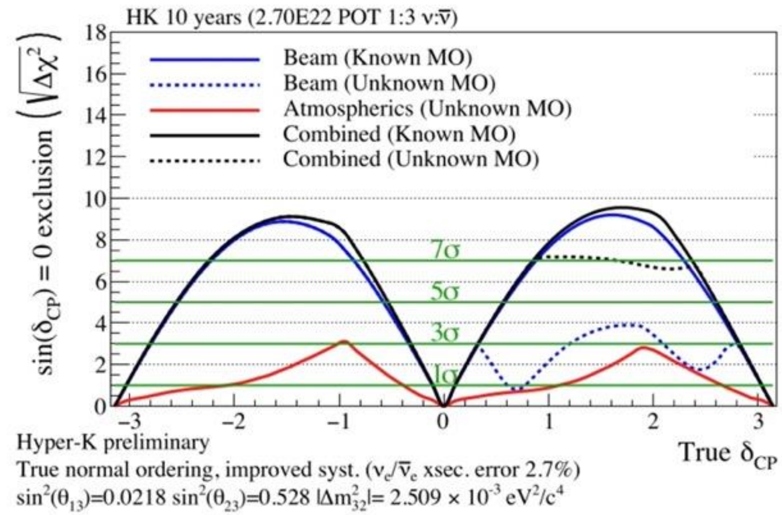
Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]]

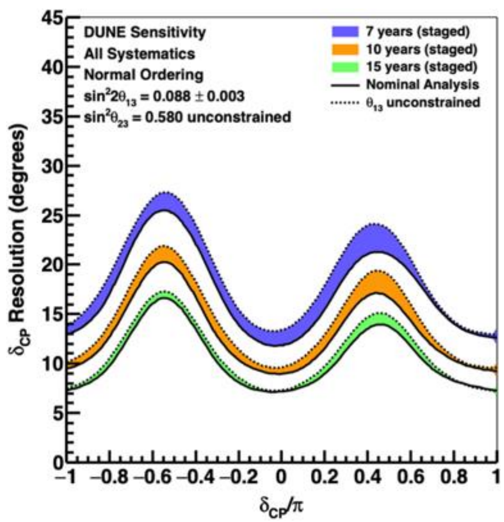
Under construction long baseline projects

DUNE (USA)

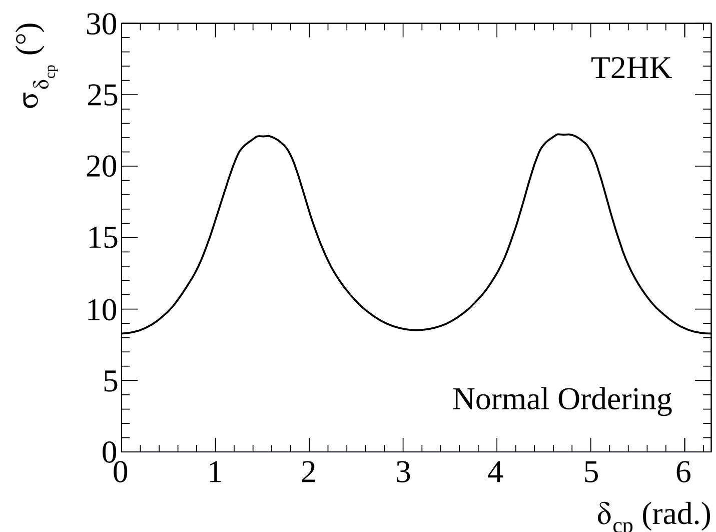


T2HK (Japan)





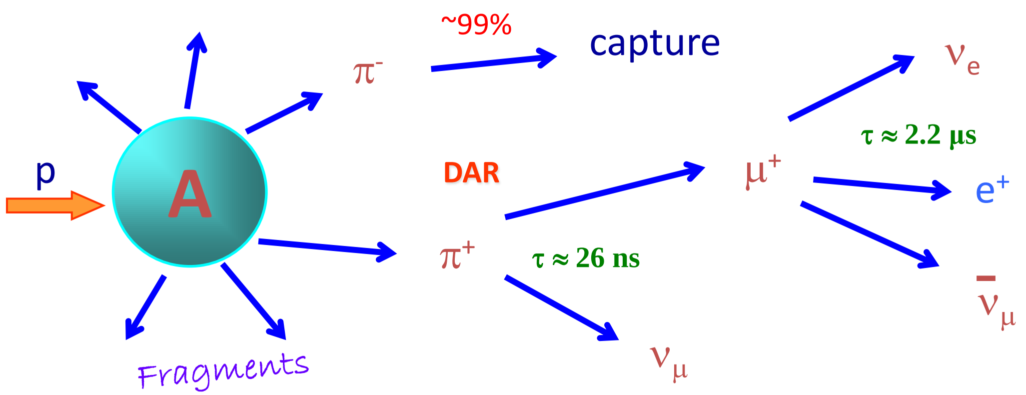
- ~50% of δ_{CP} coverage
- δ_{CP} resolution ~20° at δ_{CP} = 90°
- with low systematic uncertainties assumptions



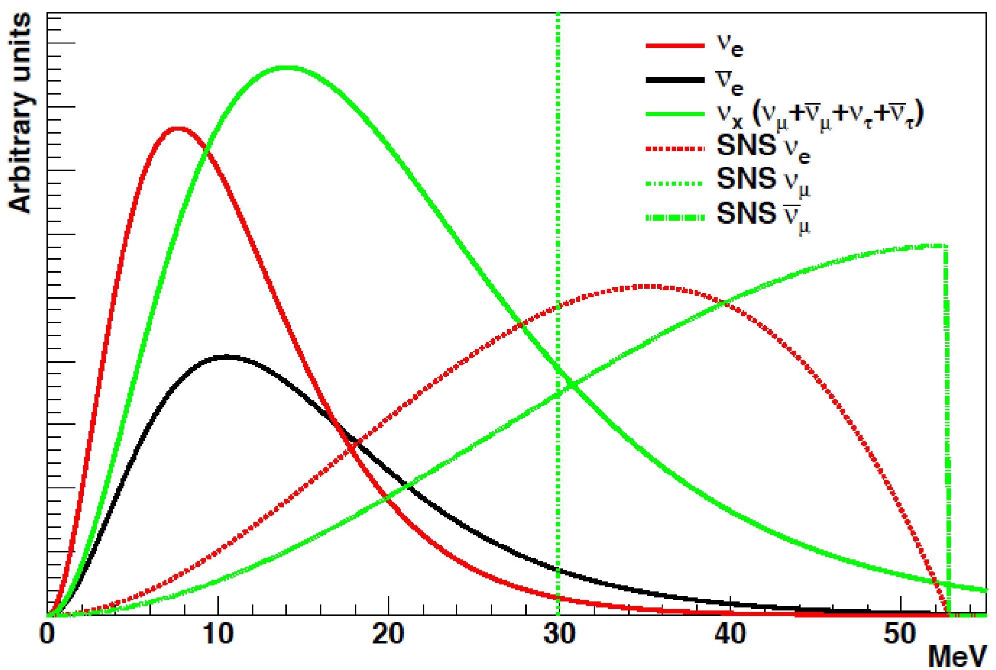
Decay At Rest at ESS

Possible if short pulses (~μs)

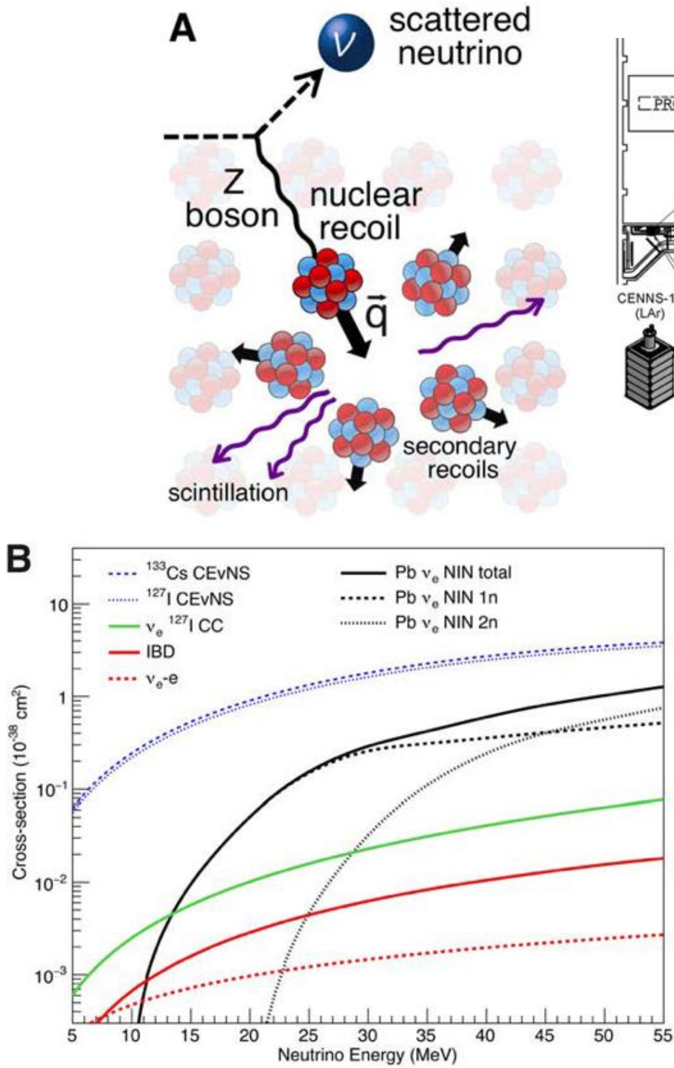
- Well known neutrino spectra (DAR).
- Very high neutrino intensities ~ 5×10^{15} ν/s.
- Separate neutrinos of different flavors by time cut.

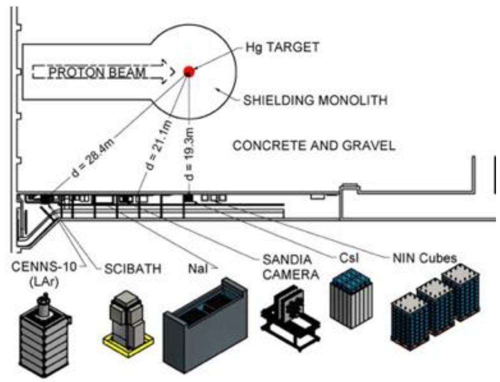


- Role that neutrino-nucleus interactions play in the supernova explosion process and subsequent nucleosynthesis.
- Accurate knowledge of neutrino-nucleus cross sections is important (almost no data exist).
- This lack of knowledge significantly limits our understanding of supernovae and of terrestrial observations of cosmic neutrinos to probe the deepest layer of these powerful explosions.



Coherent Scattering at ESS





- sterile neutrinos,
- neutrino magnetic moment,
- non-standard interactions (NSI) mediated by new particles,
- probes of nuclear structure,
- improved constraints on the value of the weak nuclear charge,
- reduction in neutrino detector mass may lead to a number of technological applications as non-intrusive nuclear reactor monitoring.
- CEνNS is also expected to dominate neutrino transport in neutron stars, and during stellar collapse.
- …

Coherent Scattering at ESS

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Coherent Elastic Neutrino-Nucleus Scattering at the European Spallation Source

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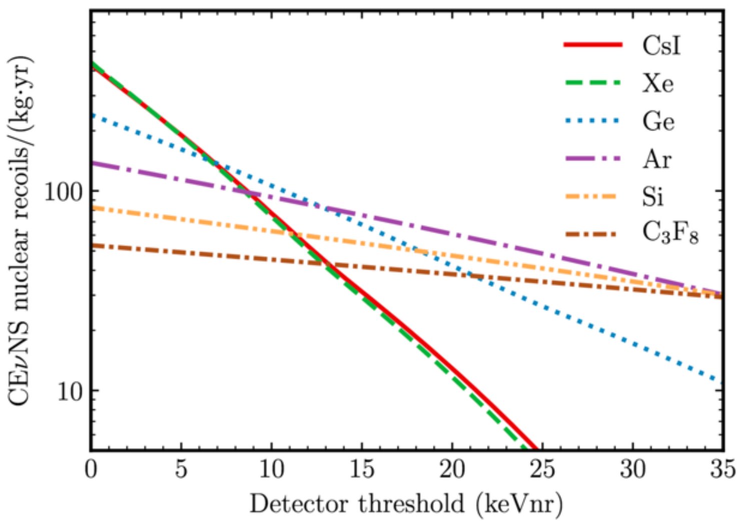
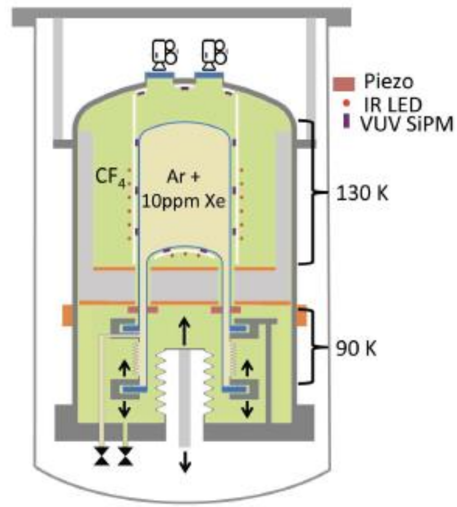
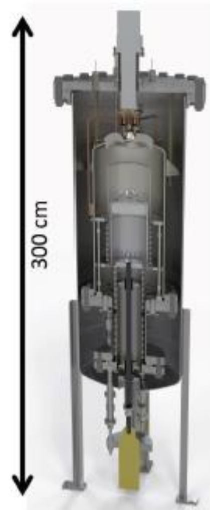
J.J. Gomez-Cadenas,[6,7,¶] M. C. Gonzalez–Garcia,[5,8,9,**] A.R.L. Kavner,[1] C.M. Lewis,[1]
F. Monrabal,[6,7,††] J. Muñoz Vidal,[6] P. Privitera,[1] K. Ramanathan,[1] and J. Renner[10]







- ESS can generate the largest pulsed neutrino flux suitable for the detection of Coherent Elastic Neutrino-Nucleus Scattering (CEνNS).
- Innovative detector technologies able to profit from the order-of-magnitude increase in neutrino flux provided by the ESS, along with their sensitivity to a rich particle physics phenomenology accessible through high-statistics, precision CEνNS measurements, are under study.