Lake Louise Winter Institute 2022

Neutrino CP Violation with the European Spallation Source neutrino Super Beam

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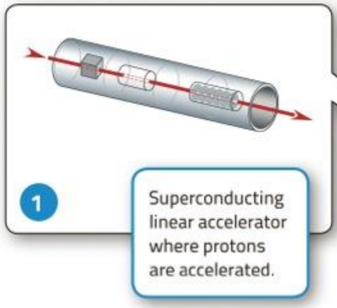
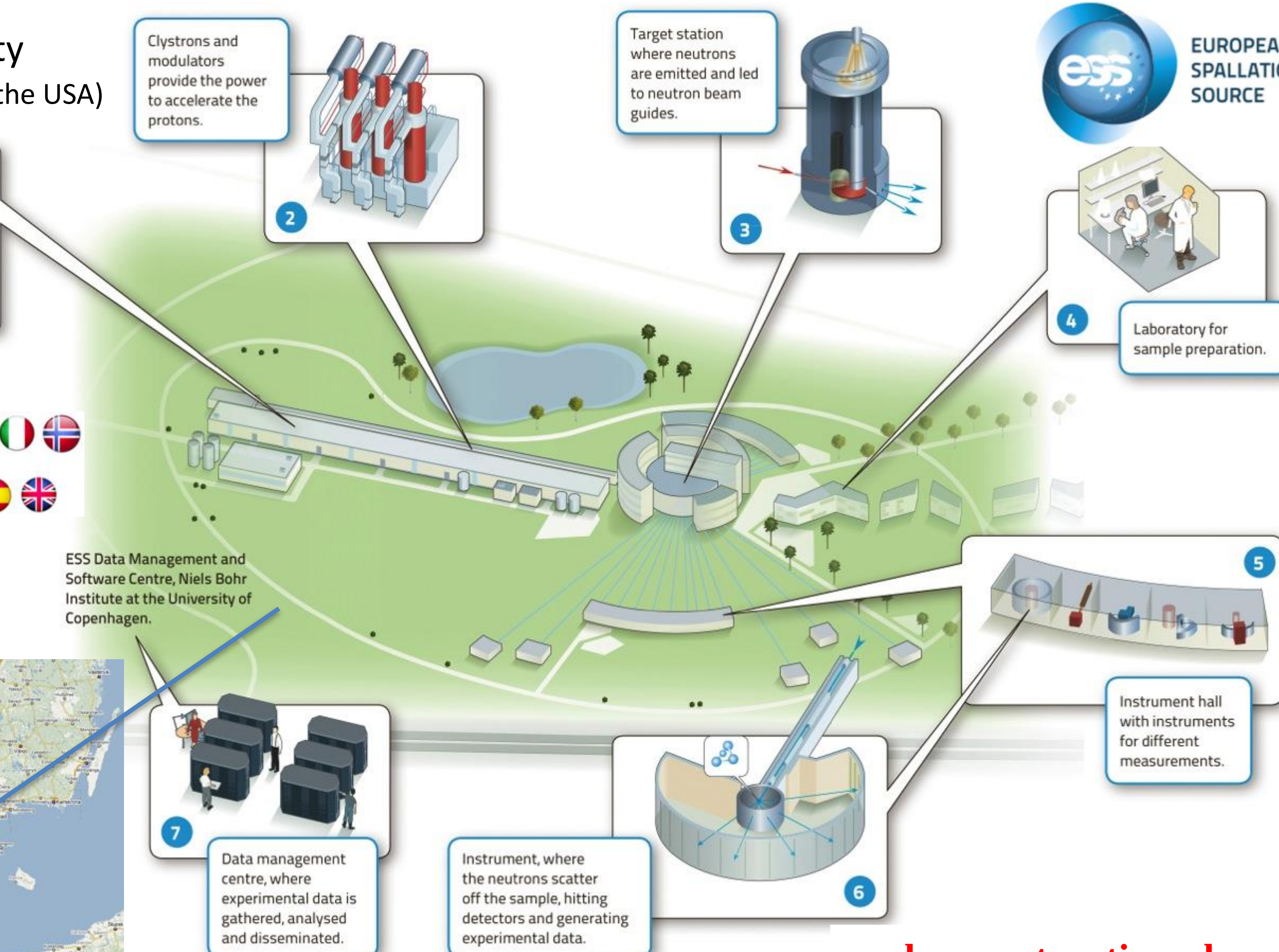
IPHC-Strasbourg

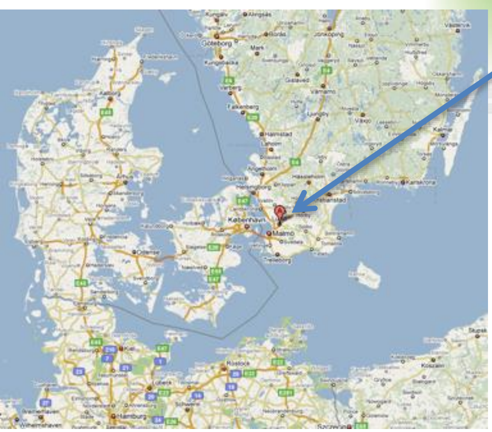
Design Study financed by EU

European Spallation Source

Neutron facility
(equivalent to SNS in the USA)

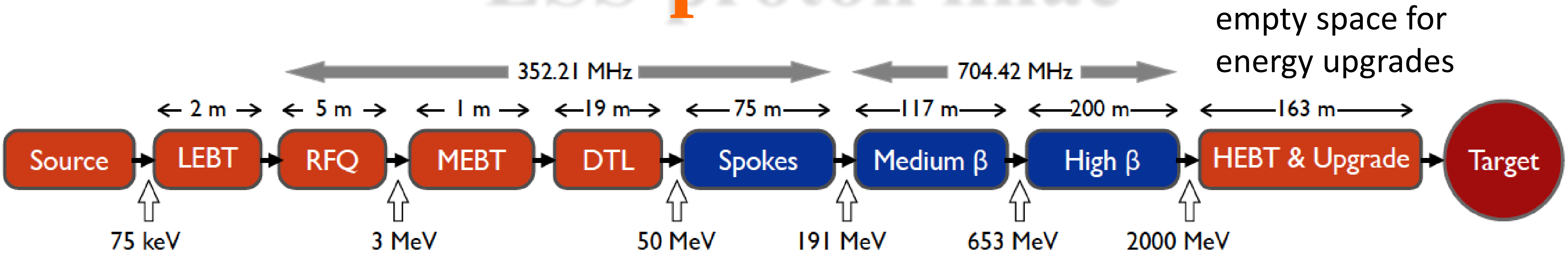






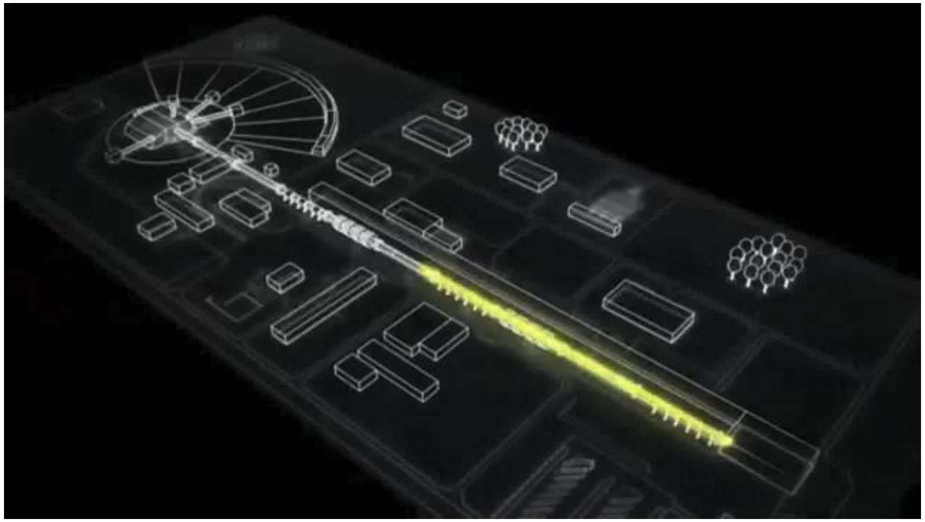
under construction phase
(~2 B€ facility)

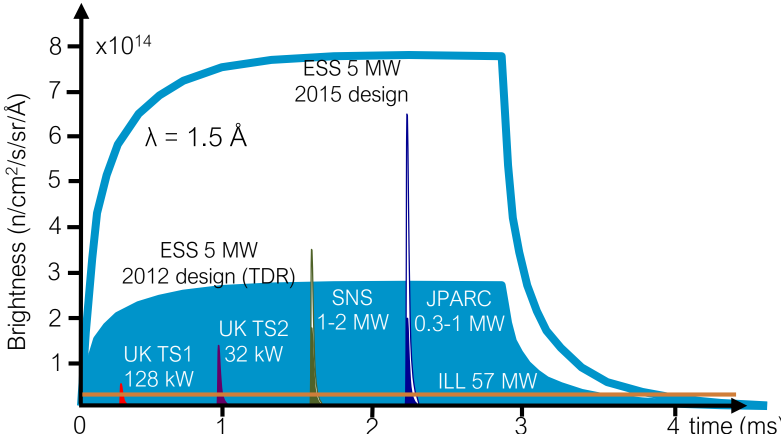
ESS proton linac



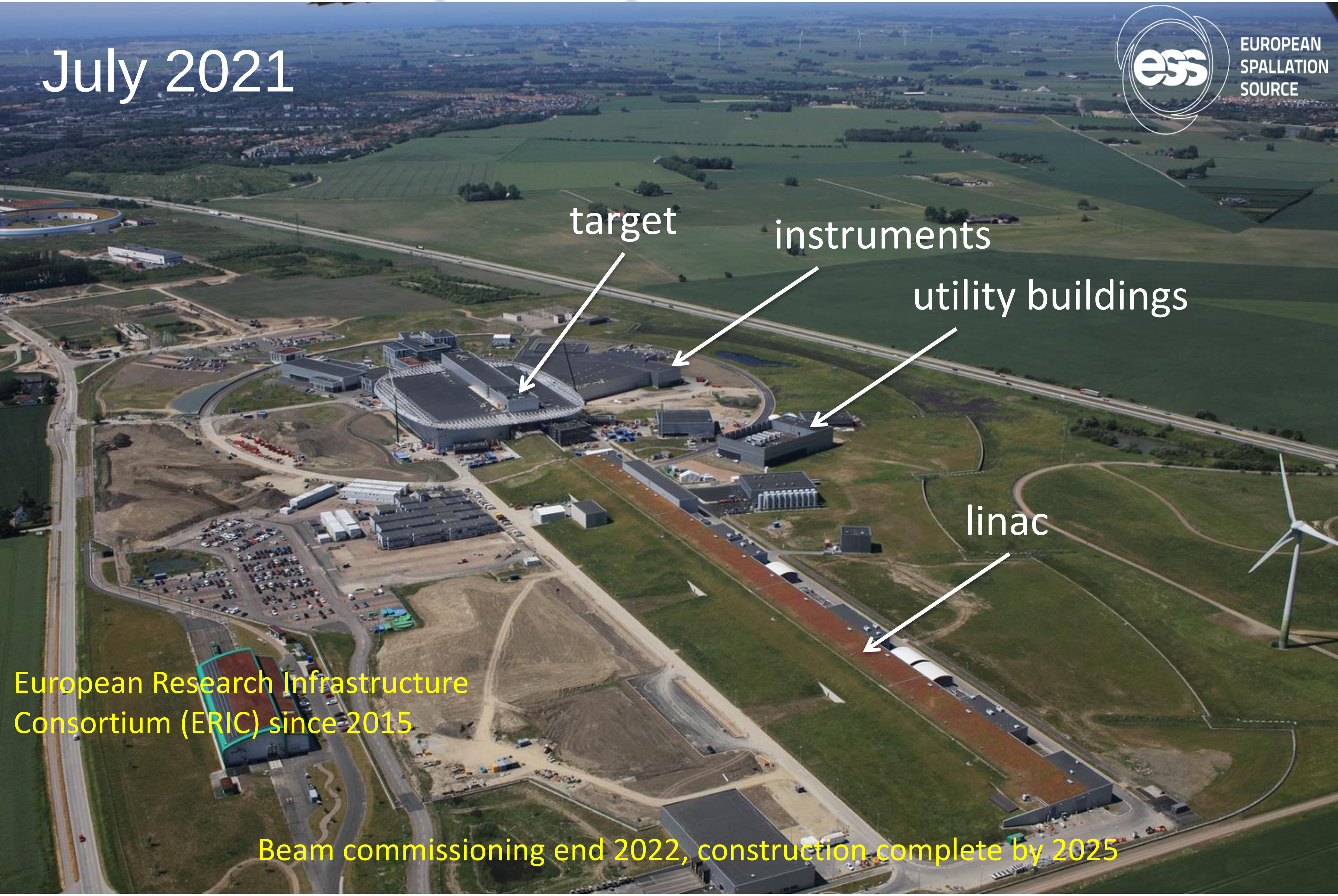
- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power.
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV protons
  - up to 3.5 GeV with linac upgrades
- **>2.7x10^{23} p.o.t/year.**

Linac ready by 2025 (full power)





European Spallation Source



European Spallation Source as Neutrino Facility for CP violation observation (2^{nd} Oscillation maximum)

or, what else can we do with 5 MW proton beam?

$$\nu_\mu \longrightarrow \nu_e$$

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 and high energy

δ_{CP} and matter-antimatter asymmetry magnitude

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

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

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

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

Theoretical models predict that if $|\sin\delta_{CP}| \gtrsim 0.7$ (45°<δ_{CP}<135° or 225°<δ_{CP}<315°), this could be enough, under assumptions, to explain the observed asymmetry.

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

Use all this ESS linac power to go to the second oscillation maximum

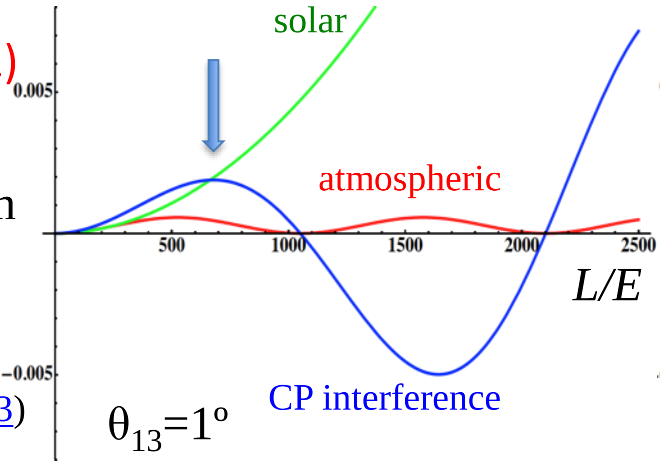
but why?

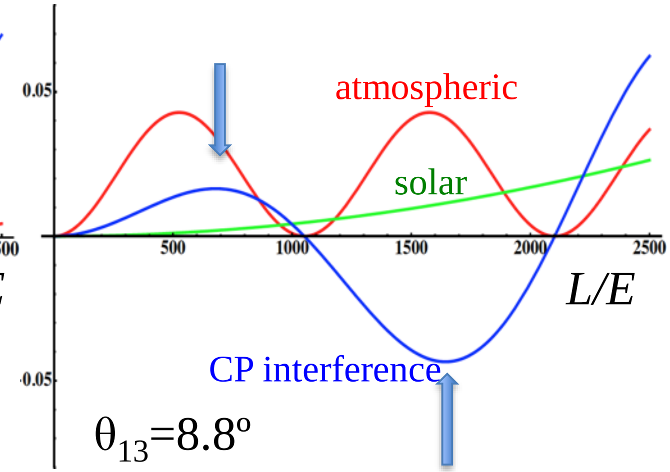
Neutrino Oscillations with "large" θ_{13}

(before 2012)

for small θ_{13} 1st oscillation maximum is better

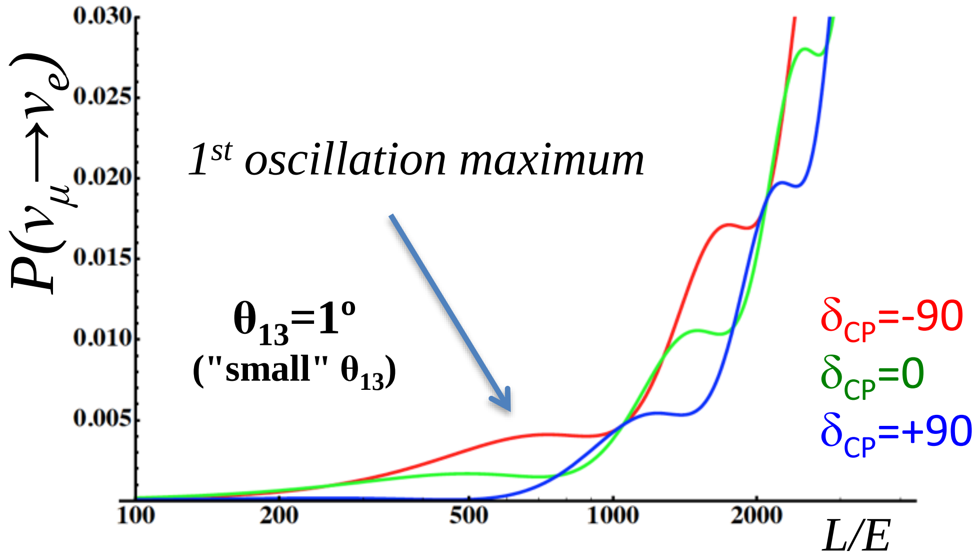
(arXiv:1110.4583)

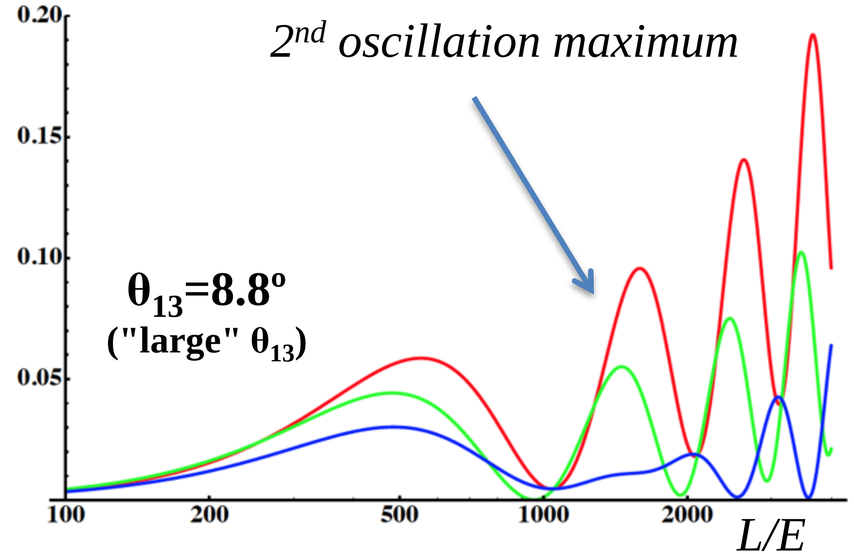




(after 2012)

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





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

more sensitivity at 2nd oscillation max.

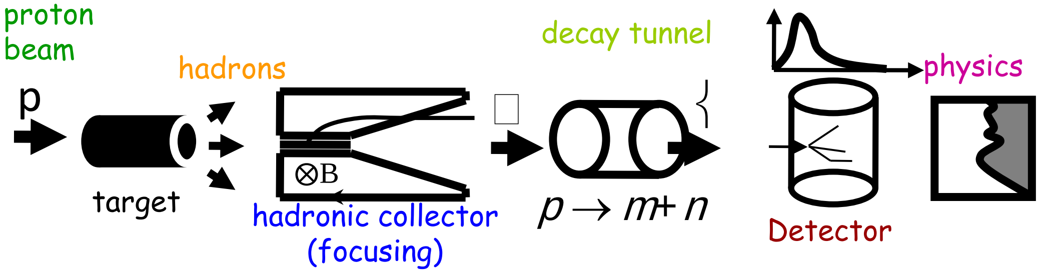
(see arXiv:1310.5992 and arXiv:0710.0554)

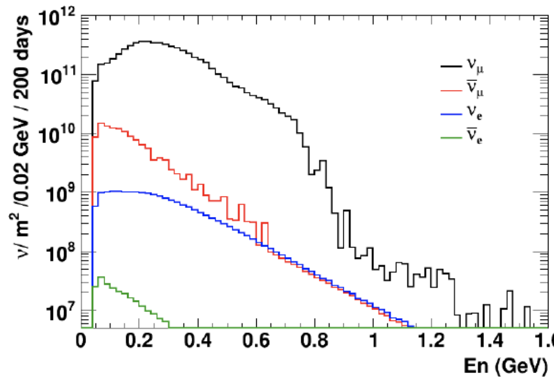
Having access to a powerful proton beam…

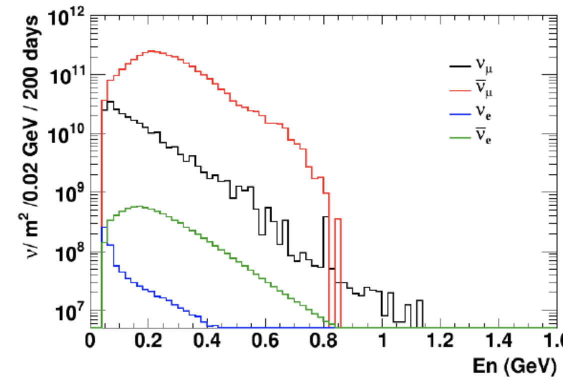
What can we do with:

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

conventional neutrino (super) beam







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

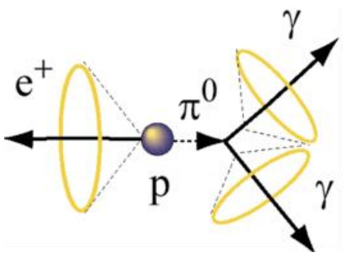
	ν Mode		$\bar{\nu}$ Mode	
	$N_\nu(10^{10}/m^2)$	%	$N_\nu(10^{10}/m^2)$	%
ν_μ	583	97.5	23.9	6.55
$\bar{\nu}_\mu$	12.8	2.1	340	93.2
ν_e	1.93	0.3	0.08	0.02
$\bar{\nu}_e$	0.03	0.01	0.78	0.21

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

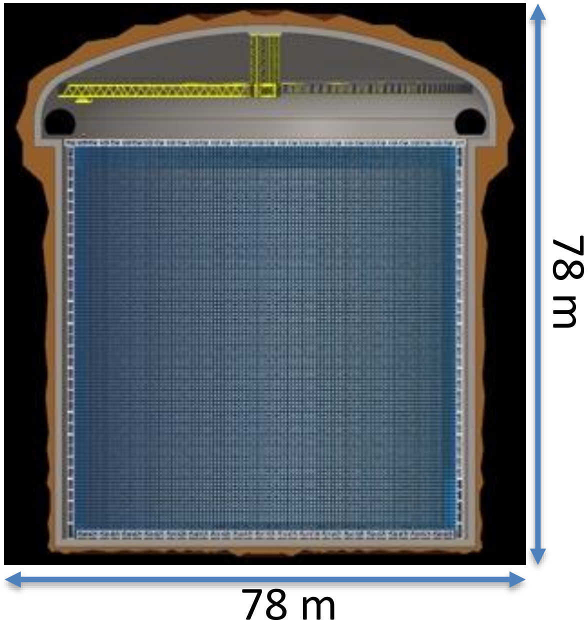
Can we go to the 2nd oscillation maximum using our proton beam?

Yes, if we place our far detector at around 500 km from the neutrino source.

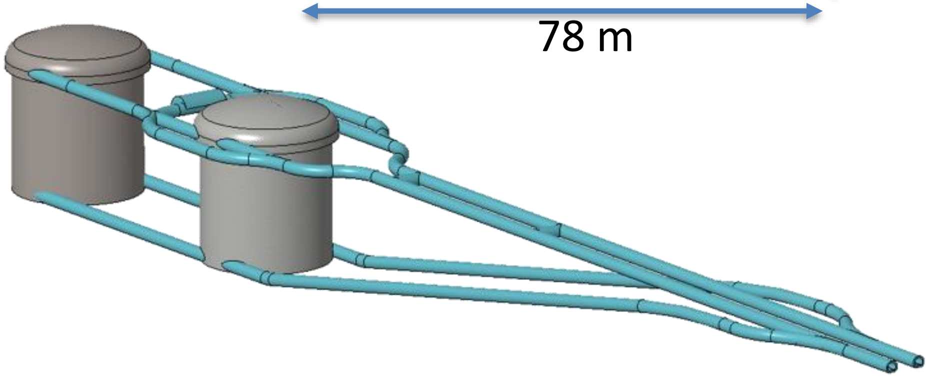
Water Cherenkov detector



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



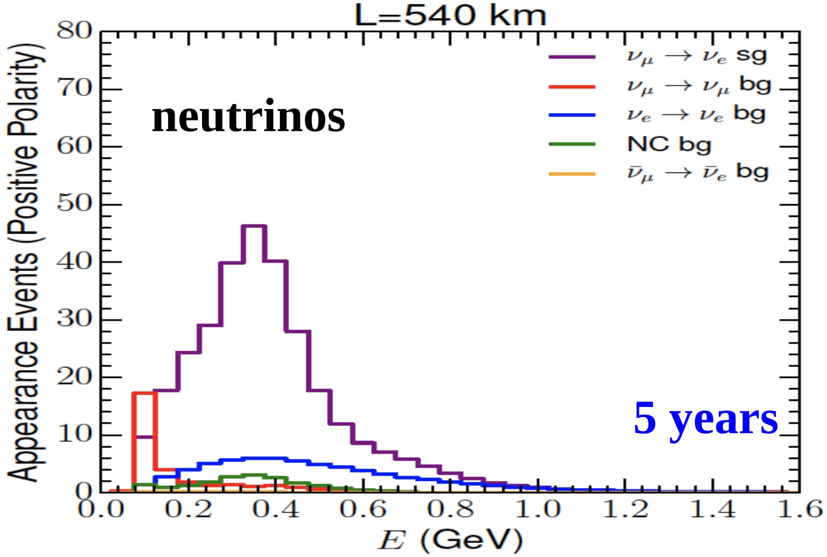
- 500 kt fiducial volume (~20xSuperK)
- Readout: ~20” PMTs
- 30% optical coverage

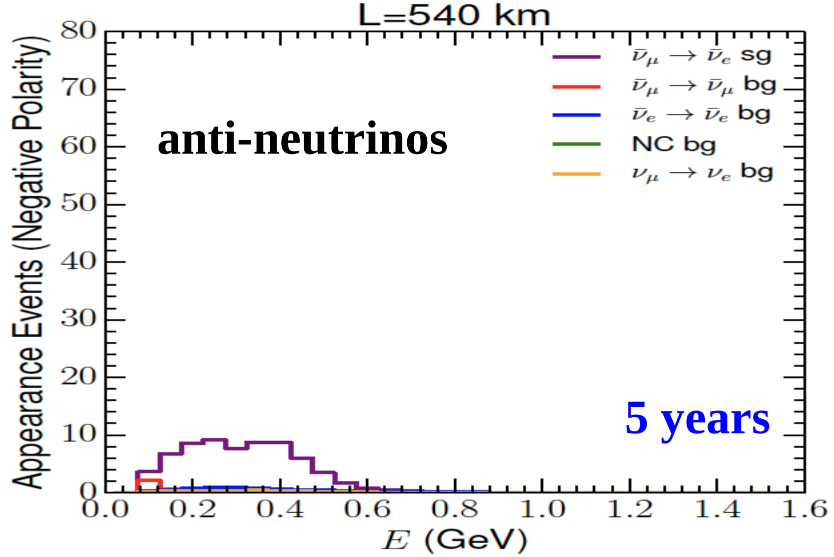


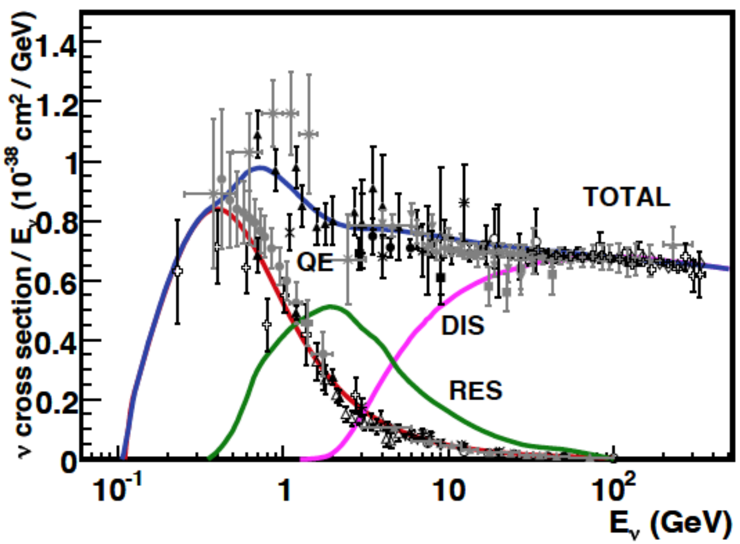
Neutrinos in the far detector

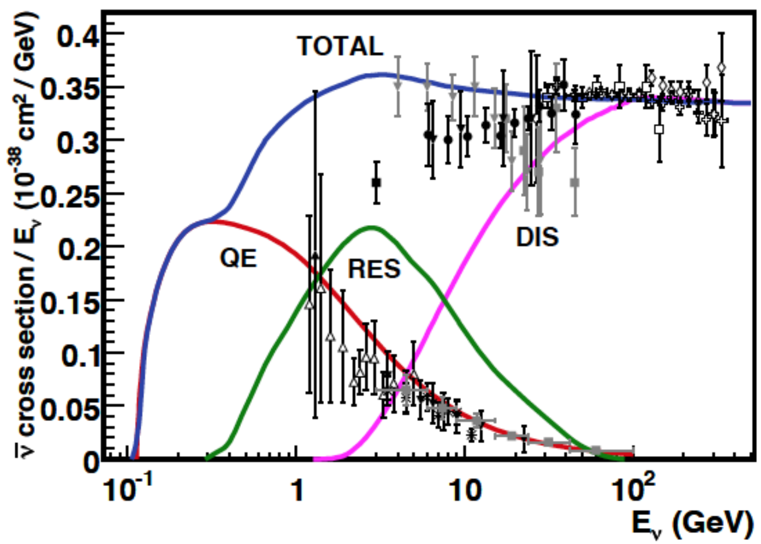
540 km (2.5 GeV), 10 years

$\delta_{CP}=0$



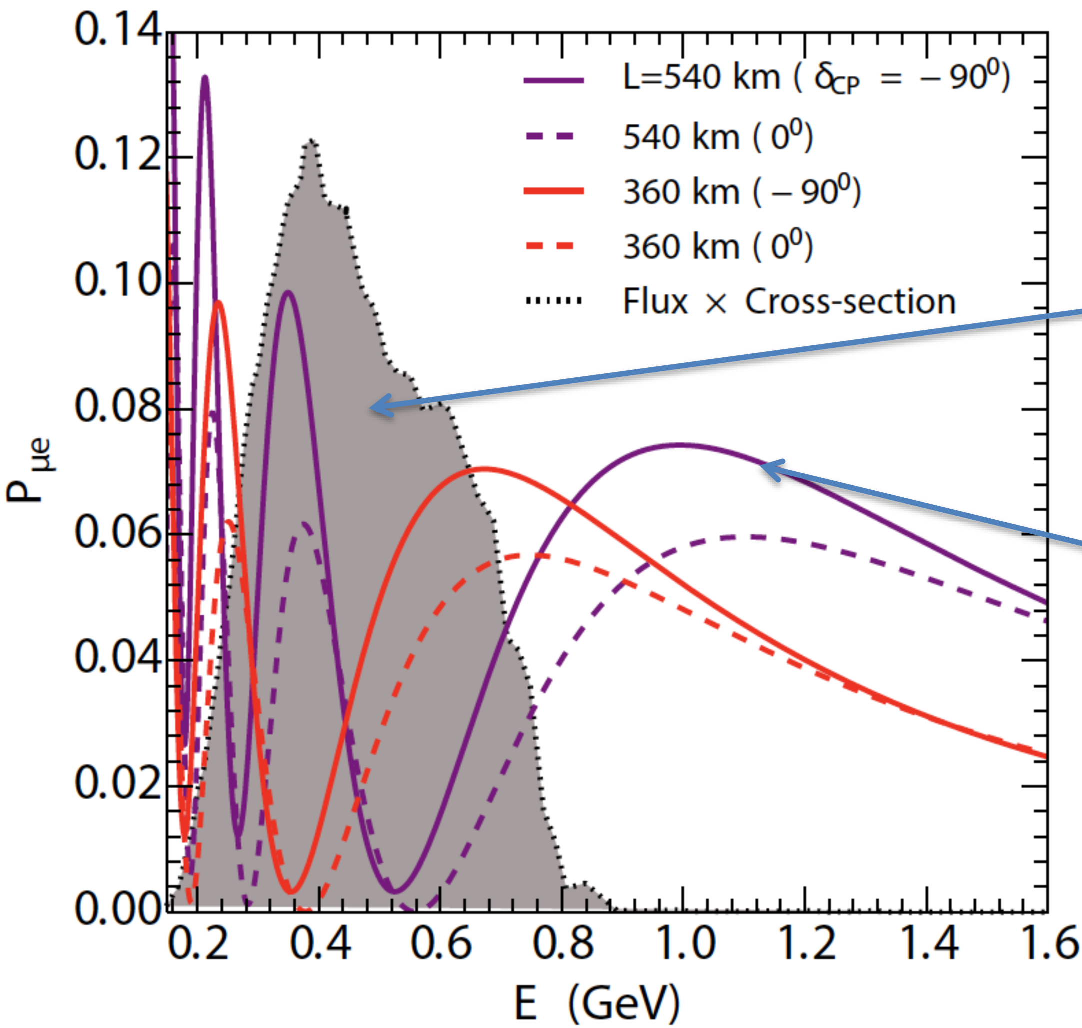






Below ν_τ production, almost only QE events, not suffering too much by π^0 background.

2nd Oscillation max. coverage



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

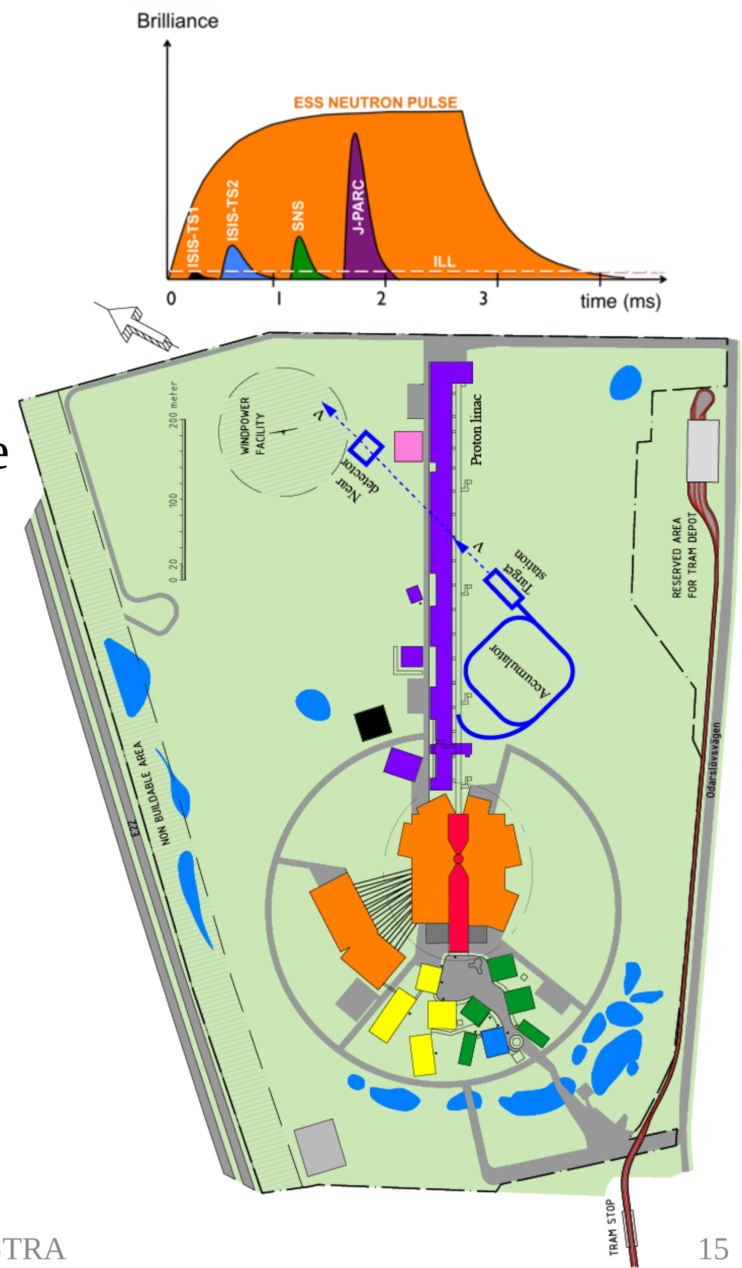
1st oscillation max.

full coverage of the 2nd oscillation max.

ESS Linac modifications to produce a neutrino Super Beam

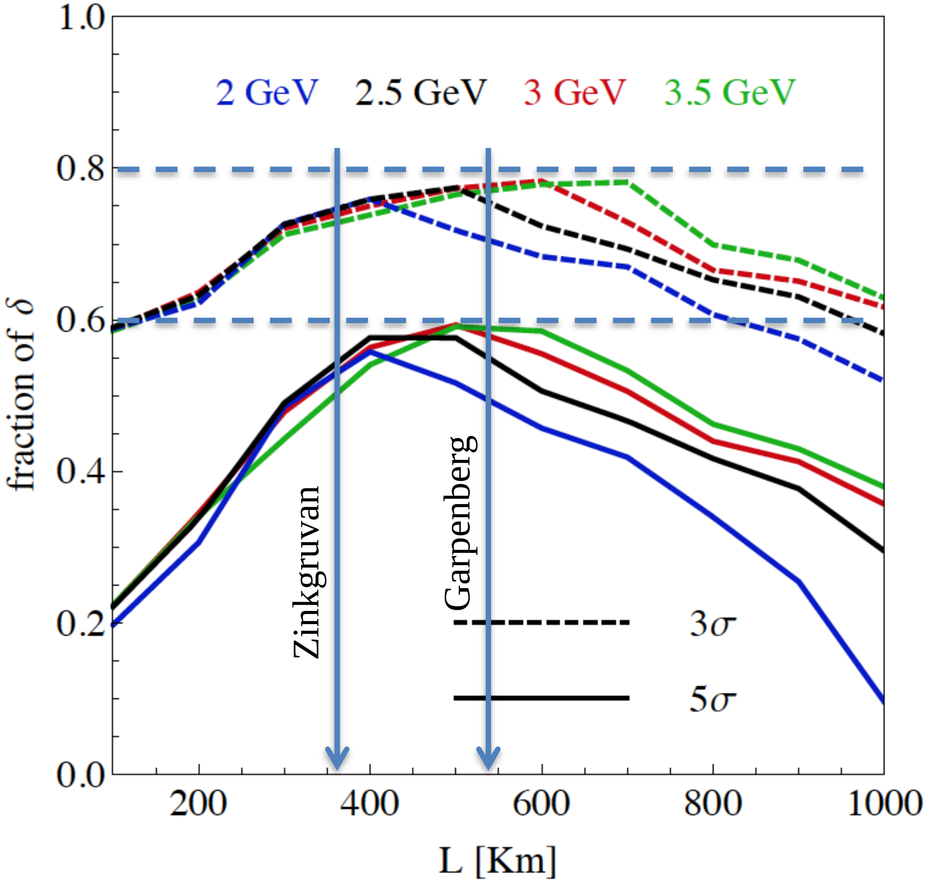
How to add a neutrino facility?

- 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 experiments (as those proposed for SNS) using the neutron target.



Which baseline?

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



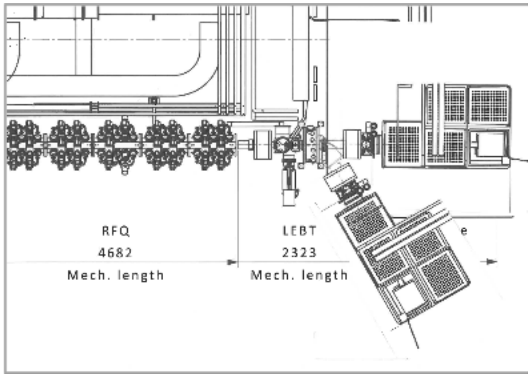
pre-project studies

Candidate active mines

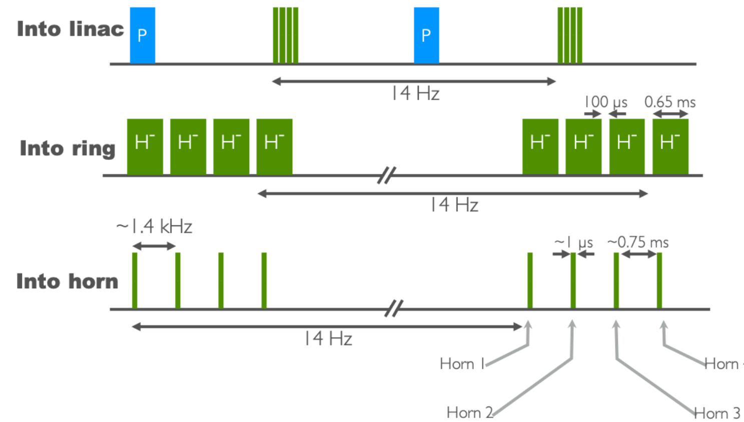
- ~60% δ_{CP} coverage at 5 σ C.L.
- >75% δ_{CP} coverage at 3 σ C.L.
- **systematic errors: 5%/10% (signal/backg.)**

ESS modifications and operation

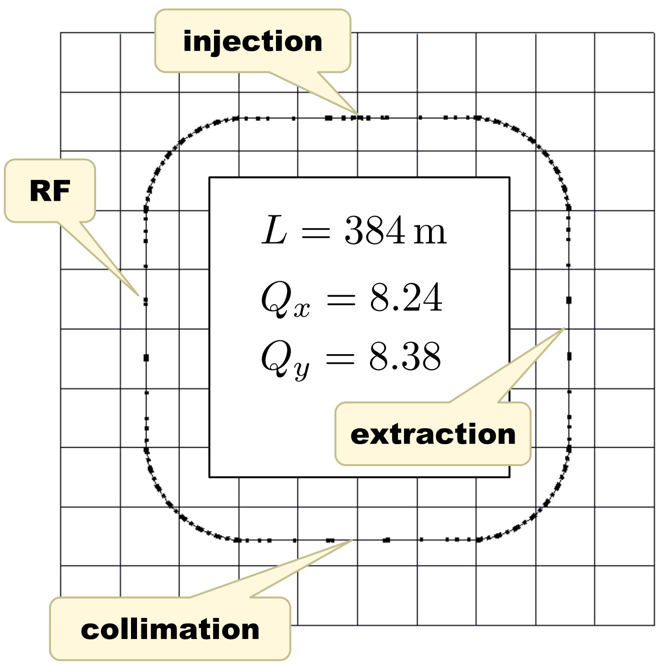
H⁻ source

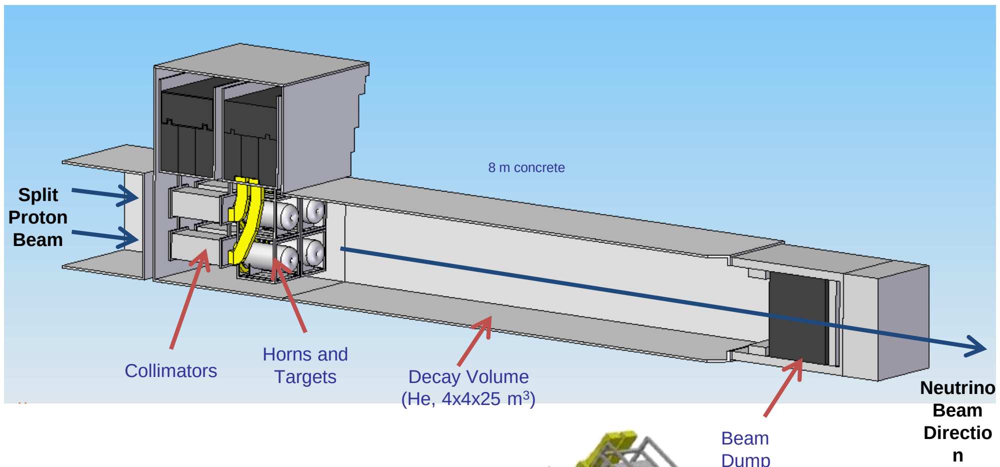


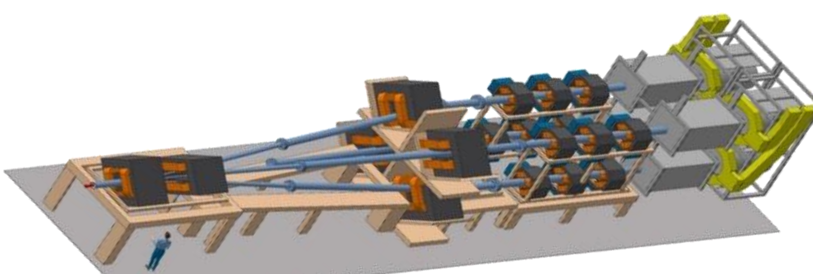
time operation option



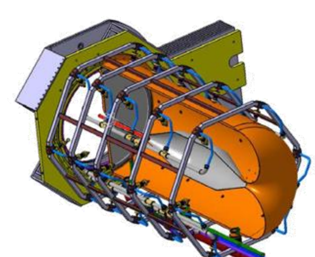
accumulator latice





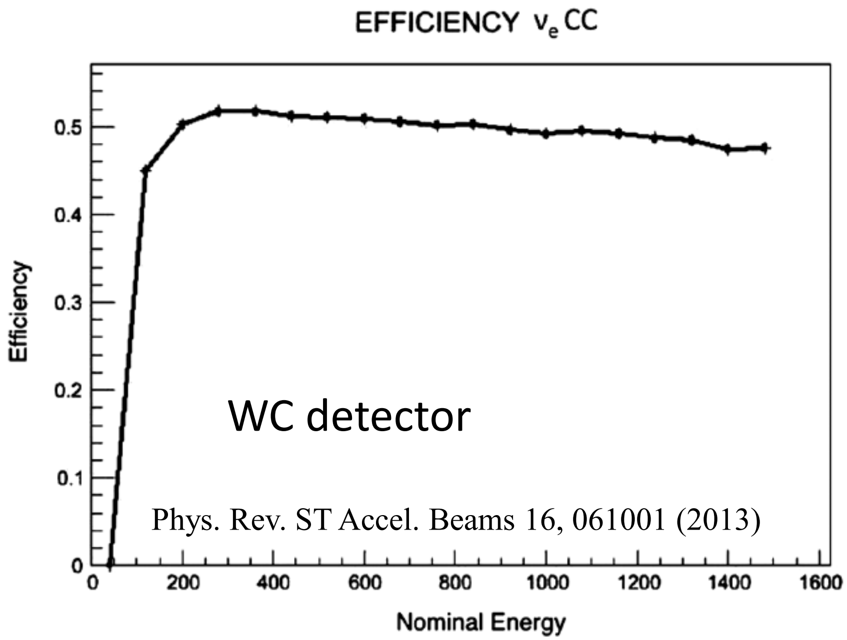


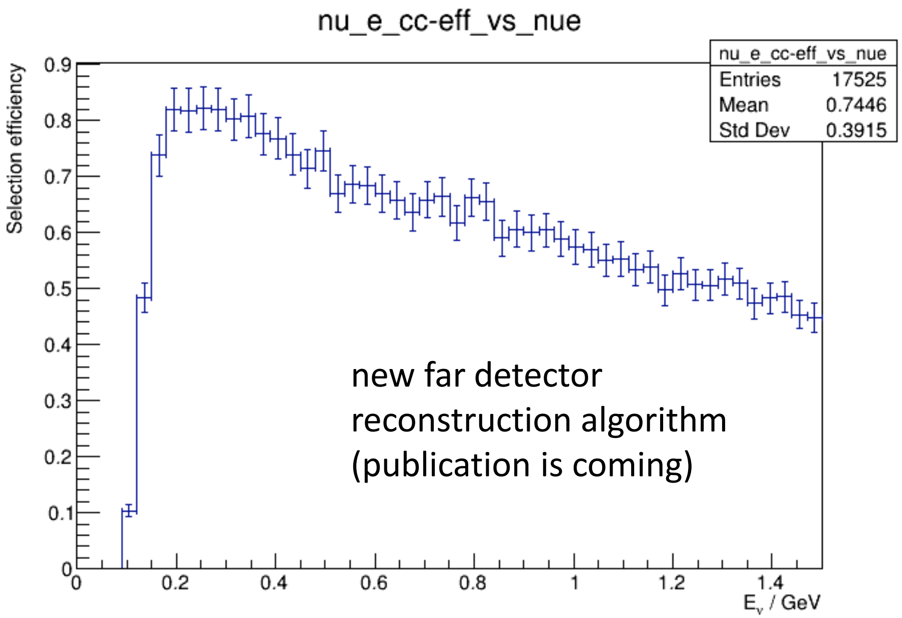
Switchyard



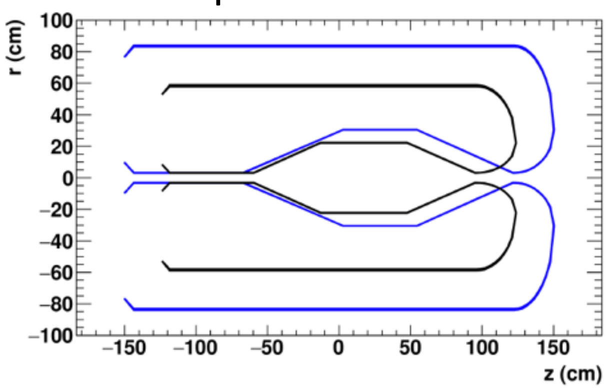
Latest Improvements

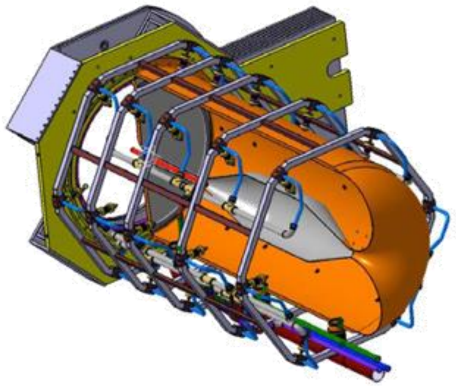
- New Magriation Matrices for the far detector
- Genetic Algorithm for Target Station optimisation





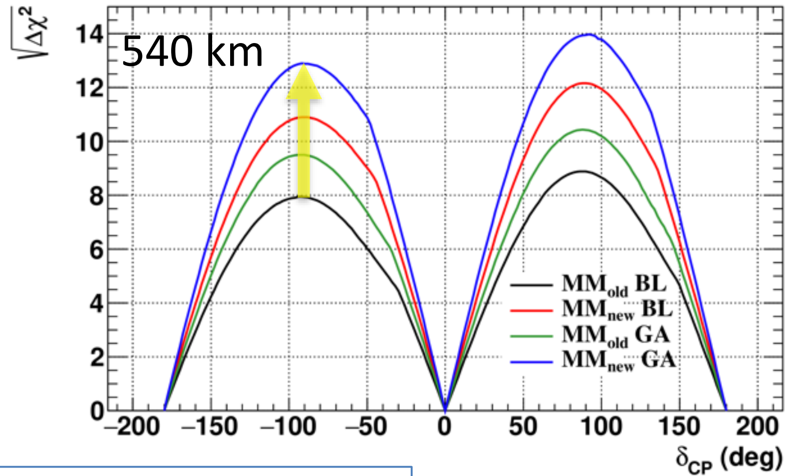
horn optimisation





Improvements and Optimisations

very preliminary
(to be confirmed)



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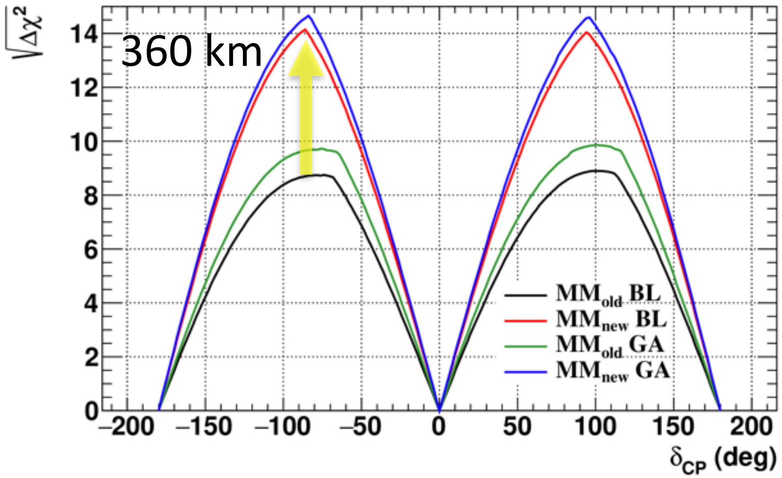


ESSnuSB

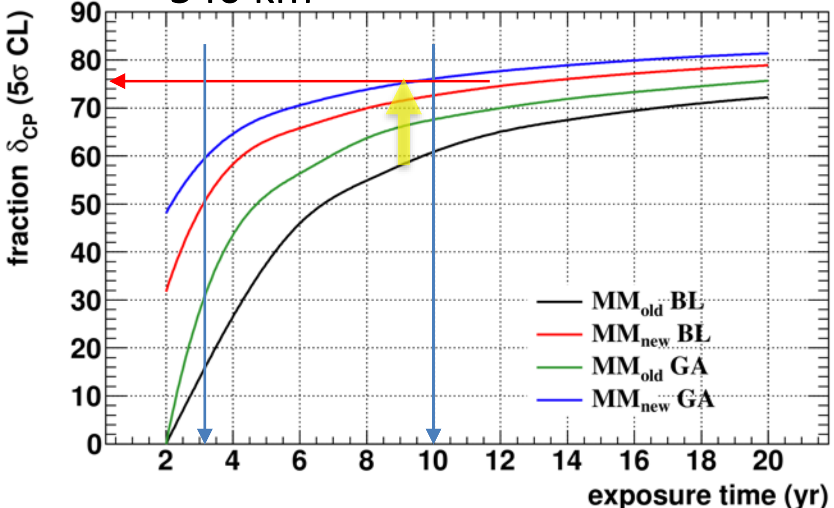
- $\theta_{12} = 33.44°$
- $\theta_{13} = 8.57°$
- $\theta_{23} = 49.2°$
- $\Delta m^2_{21} = 7.42\text{e-}5$
- $\Delta m^2_{31} = +2.517\text{e-}3$
- 2^{nd} osc. max.
- 507 ktons far detector

https://arxiv.org/abs/2107.07585

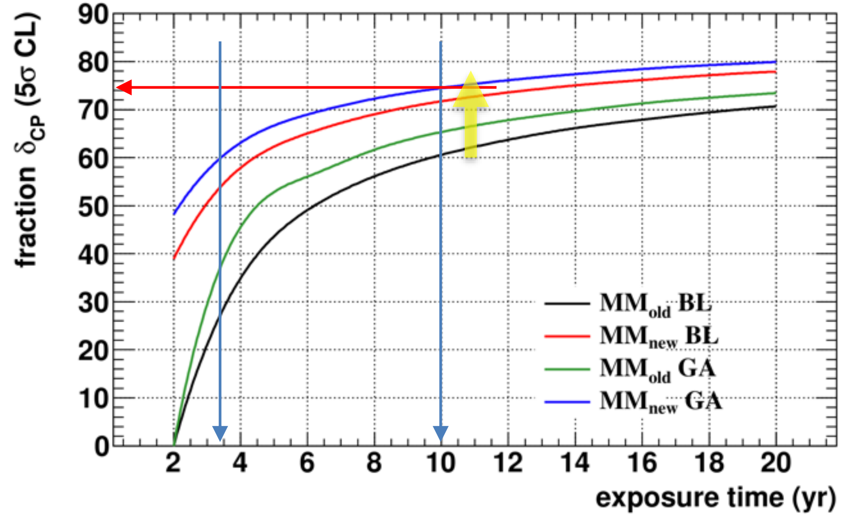
Improvements and optimisations

very preliminary

540 km



360 km

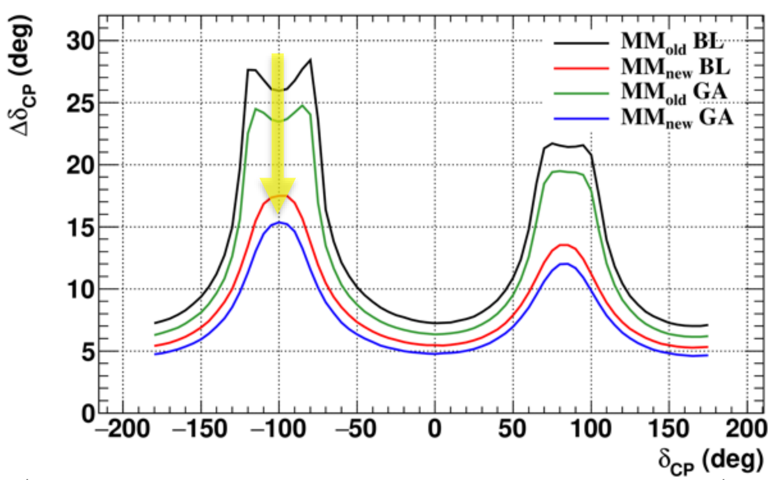


>72% after 10 years

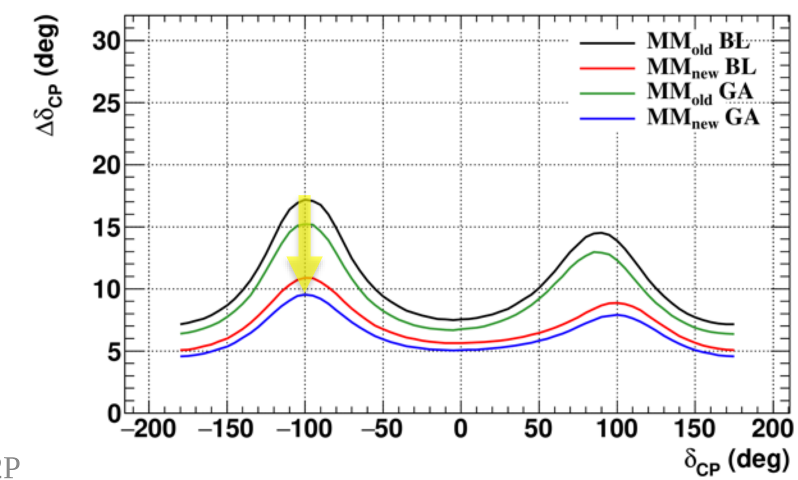
$\Delta\delta_{CP}$<8° for all values

Precision measurements

540 km

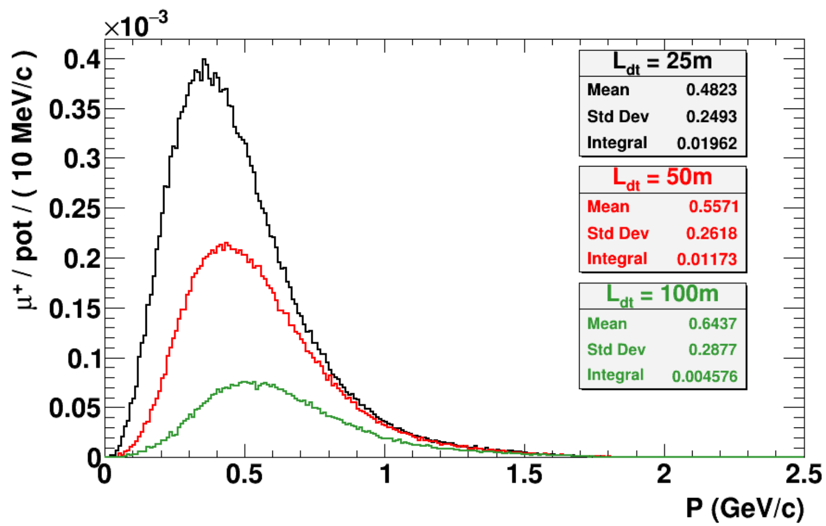


360 km



Muons at the level of the beam dump

<E_μ>~0.5 GeV
<L_μ>~3 km

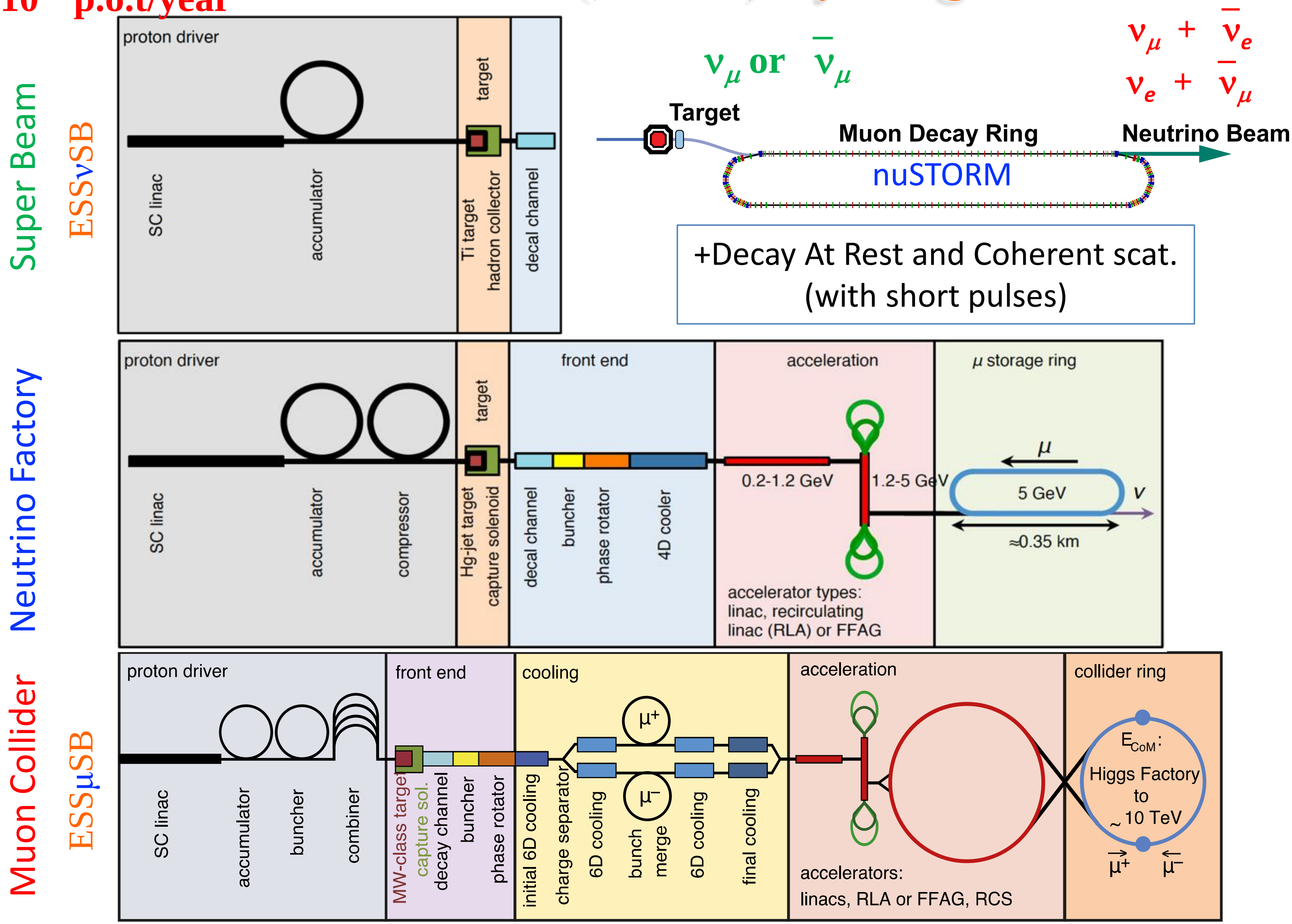


$L_{dt}\,(m)$	$N_\mu\ (\mu^+/pot)$	$N_\mu\ (\mu^+/s)$	$N_\mu\ (\mu^+/200d)$	$\langle P_\mu\rangle\,(GeV/c)$
25	0.02	2.5×10^{14}	4.3×10^{21}	0.48
50	0.01	1.2×10^{14}	2.1×10^{21}	0.56
100	4.5×10^{-3}	0.6×10^{14}	1.0×10^{21}	0.64

decay tunnel length

ESSνSB and (R&D) synergies

2.7×10^{23} p.o.t/year



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

ESSnuSB Design Study Project

- EU-H2020 Design Study ESSνSB: 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

ESSnuSB looking for the answer.

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}.
- The European Spallation Source will be ready by 2025, upgrade decisions by this moment.
- Rich muon program for future ESS upgrades
    - Low energy nuSTORM
    - Muon Collider R&D
- Conceptual Design Report by end of March 2022
- **New applications under preparation**

Backup

Possible ESSνSB schedule

(2nd generation neutrino Super Beam)

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)

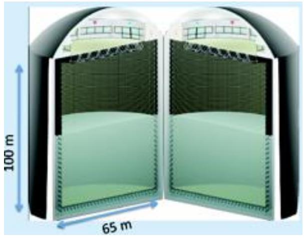
2021: End of ESSνSB Design Study, CDR and preliminary costing

CDR

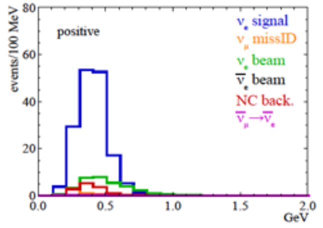
ESFRI

2022-2024: Preparatory Phase, TDR

2025-2026: Preconstruction Phase, International Agreement



2027-2035: Construction of the facility and detectors, including commissioning



2036-: Data taking

ESSνSB at the European level

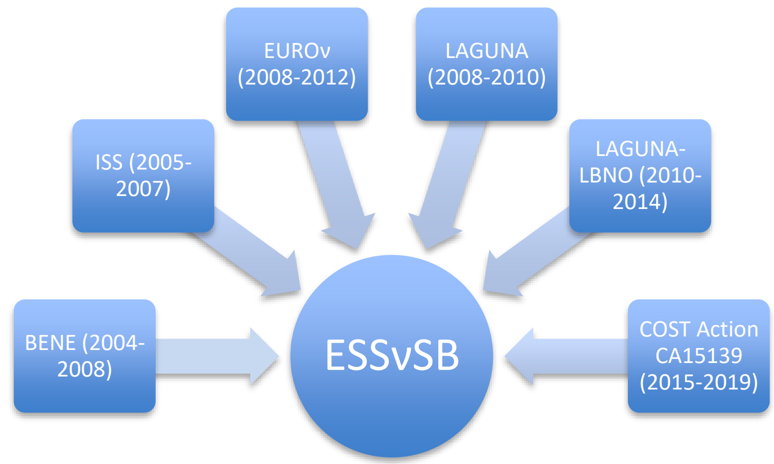
List of ESSnuSB Participating Institutions / Organisations			
#	Institutions / organisations name	Accronym	Country
1	Centre National de la Recherche Scientifique	CNRS	France
2	University of Uppsala	UU	Sweden
3	Kungliga Tekniska Hoegskolan	KTH	Sweden
4	European Spallation Source Eric	ESS	Sweden
5	University of Cukurova	CU	Turkey
6	Universidad Autonoma de Madrid	UAD	Spain
7	National Center for Scientific Research "Demokritos"	DEMOKRITOS	Greece
8	Instituto Nationale di Fisica Nucleare	INFN	Italy
9	Ruder Boskovi Instgitute	RBI	Croatia
10	Sofiiski Universitet Sveti Kliment Ohridski	UniSofia	Bulgaria
11	Lunds Universitet	ULUND	Sweden
12	Akademia Gorniczo-Hutnicza Im. Stanislawa Staszica w Krakowie	AGH / AGH-UST	Poland
13	European Organization for Nuclear Resarch	CERN	Switzerland
14	University of Geneva	UNIGE	Switzerland
15	University of Durham	UDUR	United Kingdom

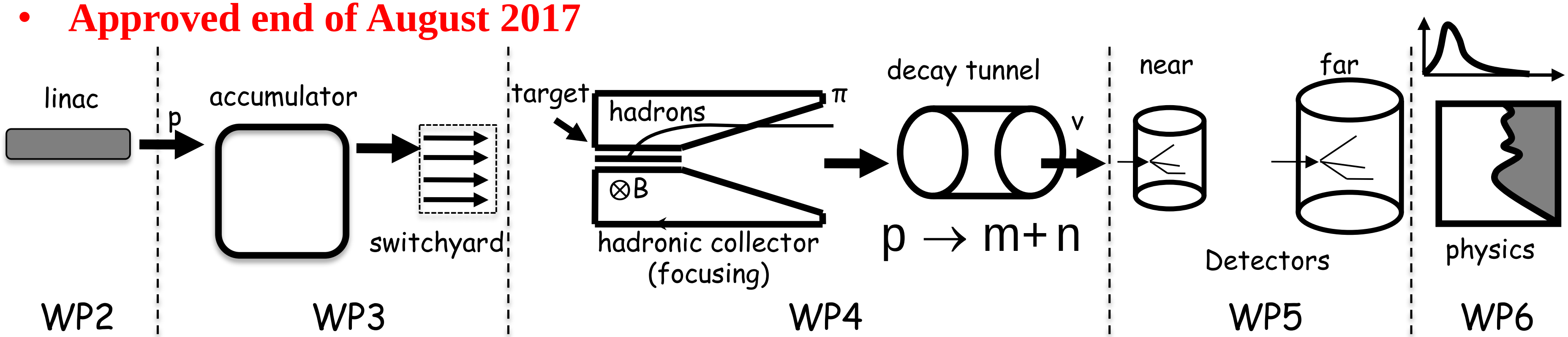
11 countries

- Starting date: 01/01/2018
- Ending date: 31/12/2021 → 31/03/2022,
- Duration: 48+3 Months,
- 3 months extension due to COVID19
- Kick-off meeting: 15 January 2018, Lund (ESS),
- 90% of the budget already received,
- All deliverables and milestones ready on time (some rescheduling due to COVID19 has been arranged with the EU Project Officer)

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**





Muon Collider as Higgs Factory

arXiv:1908.05664

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.

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HIFI Uppsala Workshop
2-3 March 2020

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 β^*= 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

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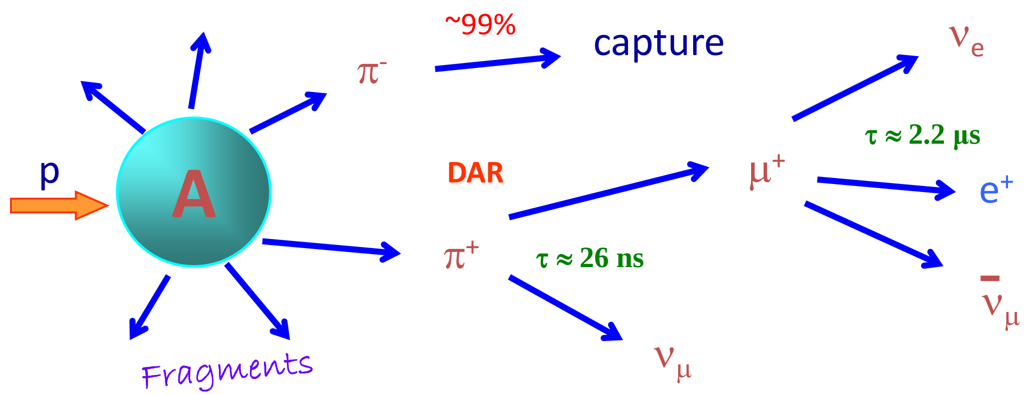
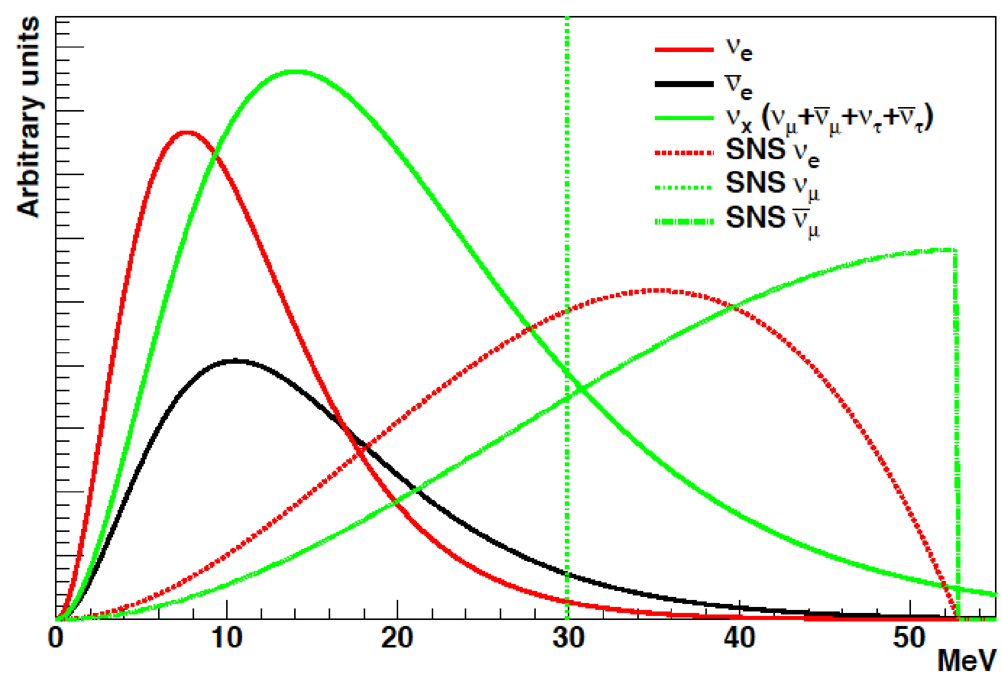
Decay At Rest at ESS

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

JHEP 02 (2020) 123

Coherent Elastic Neutrino-Nucleus Scattering at the European Spallation Source

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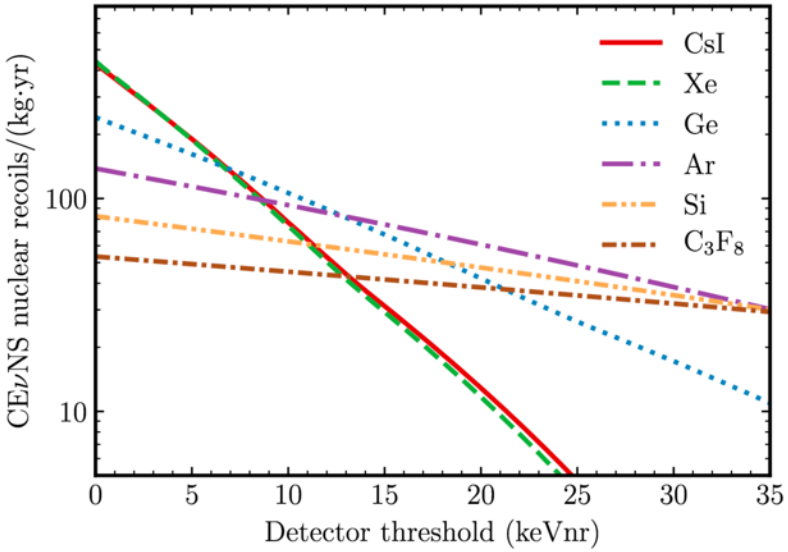
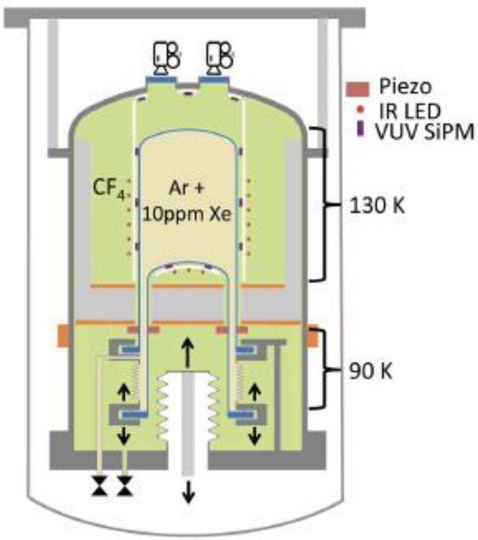
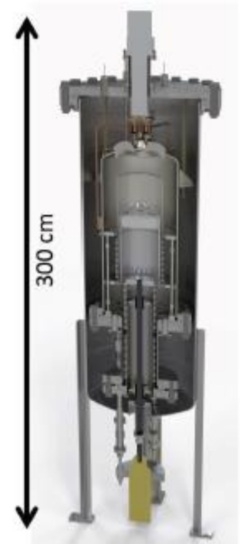
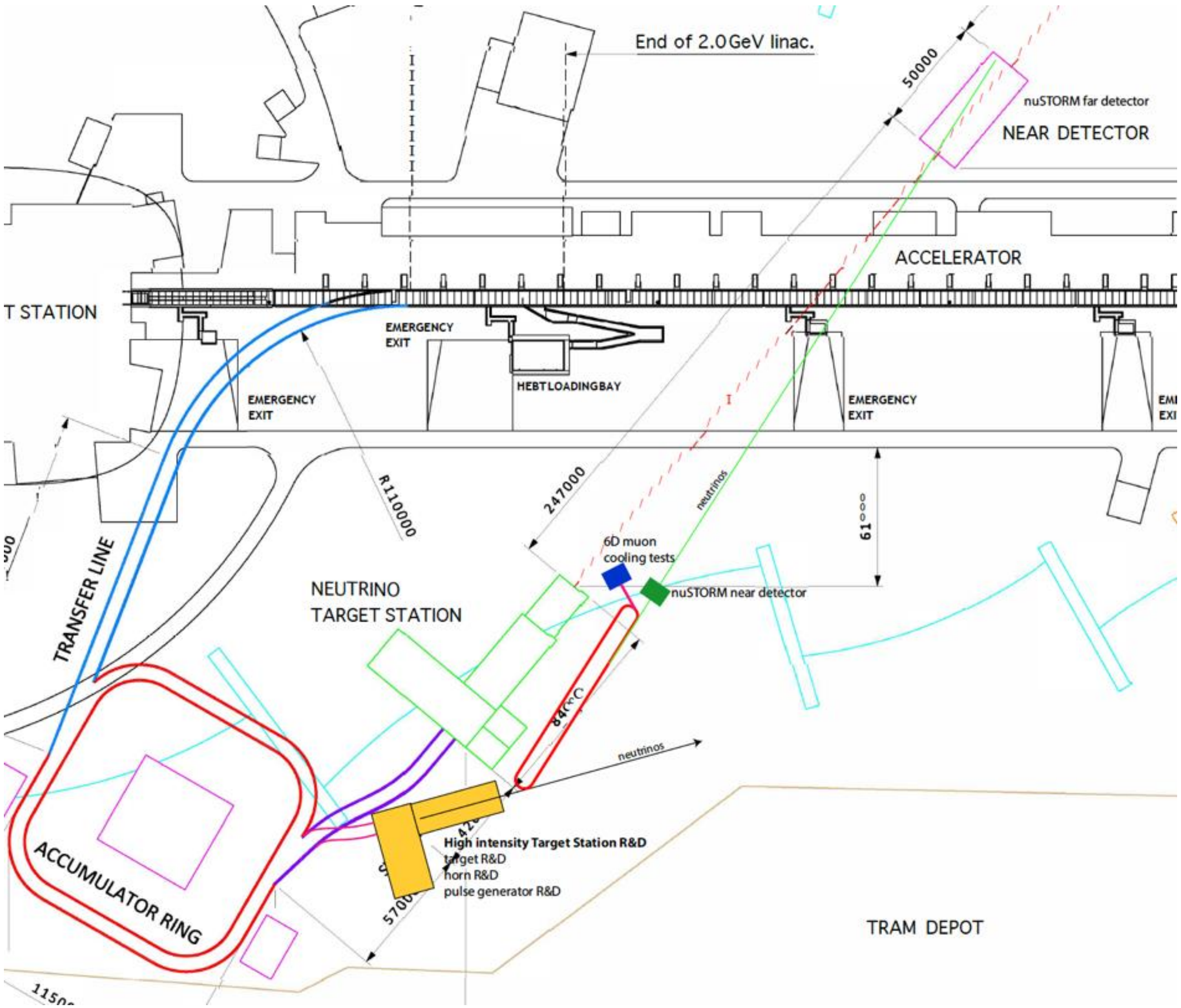






- ESS can generate the largest pulsed neutrino flux suitable for the detection of Coherent Elastic Neutrino-Nucleus Scattering (CEvNS).
- Innovative detector technologies able to profit from the order-of-magnitude increase in neutrino flux provided by the ESS, along with their sensitivity to a rich particle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

Possible scenario for new near future applications

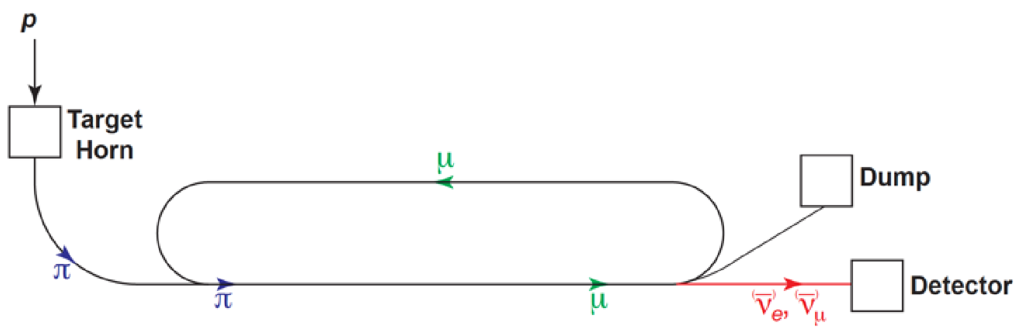


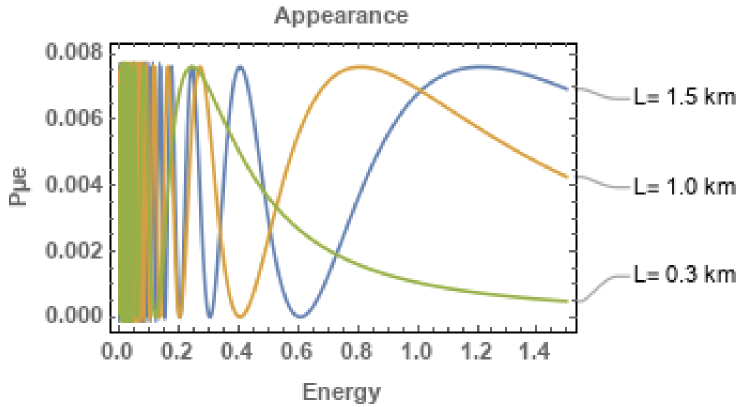
Possible WPs:

- Civil engineering (onsite and offsite) abd safety.
- Linac accumulator and race-track.
- Target Station, hadron/muon production and muon extraction.
- Low Energy nuSTORM.
- Detectors and physics performance (synergy between ESSnuSB and LEnuSTORM).
- Muons for future. applications, including 6D cooling tests (several locations are possible).

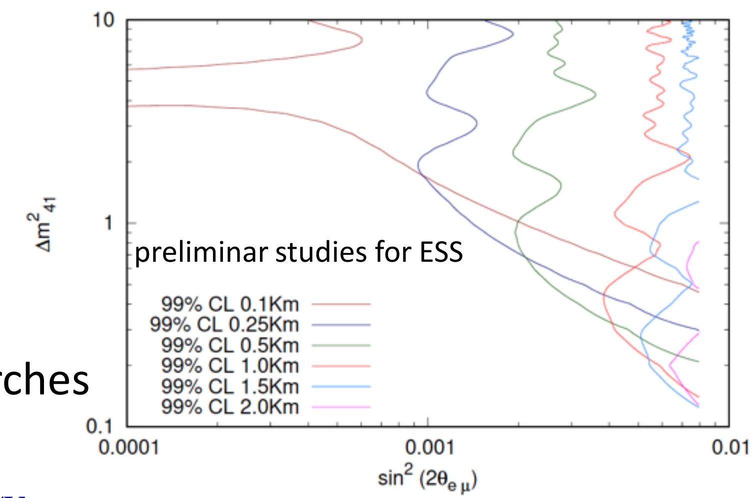
Low Energy nuSTORM at ESS

- Sterile Neutrino searches
- Neutrino cross sections measurements with unprecedented precision
- LBL performance improvement by systematic error mitigation
- To be adapted for lower muon energies (~0.5 GeV)





Proposed at FERMILAB and CERN (~3.8 GeV muons)



sterile neutrino searches