Status of the ESSnuSB neutrino beam and detector project

Particle Physics with Neutrino Telescopes
Uppsala 7 October 2019

Tord Ekelöf
Uppsala University

Why is there only matter and no antimatter in Universe?

**The Sakharov conditions (necessary but not sufficient)
to explain the Baryon Asymmetry of the Universe (BAU):**

1. At least one B-number violating process.
2. C- and <u>CP-violation</u>
3. Interactions outside of thermal equilibrium

Grand Unified Theories can fulfill the Sakharov conditions. However, in each m^3 of the Universe there are on average ca 10^9 photons, one proton and *no* antiproton. The CP violation measured in the quark sector is far too small (by a factor 10^9) to explain this 10^9 photon to baryon ratio.

Now, <u>neutrino CP-violation, so far not observed,</u> may very well be large enough to permit an explanation of BAU through the *leptogenesis* mechanism which relates the matter-antimatter asymmetry of the universe to neutrino properties: decays of heavy Majorana neutrinos generate a lepton asymmetry which is partly converted to a baryon asym

Three neutrino mixing

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, *and* $s_{ij} = \sin\theta_{ij}$

$$P_{\nu_\mu \to \nu_e (\bar{\nu}_\mu \to \bar{\nu}_e)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right)$$ atmospheric

Non-CP terms

$$+c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$ solar

$$+\tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{\tilde{B}_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\tilde{B}_\mp L}{2}\right) \cos\left(\pm\delta_{CP} - \frac{\Delta_{13} L}{2}\right)$$ interference

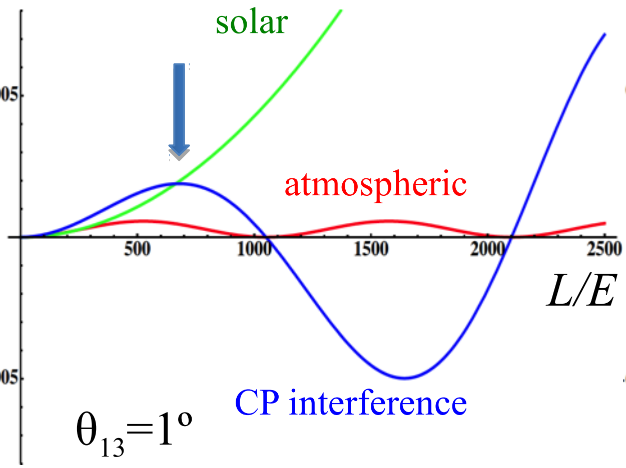
CP violating

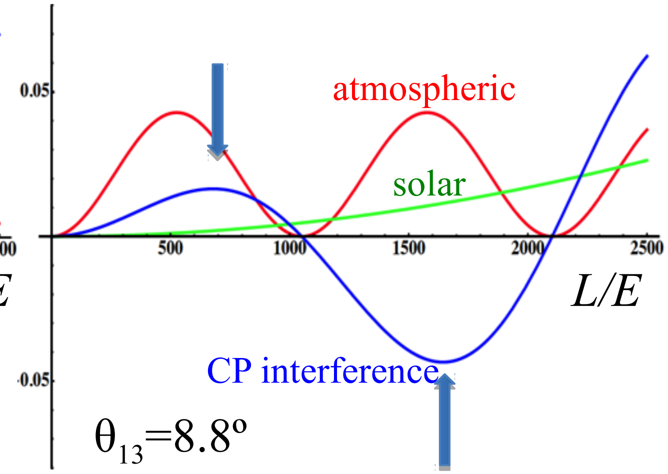
$$\tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}, \ \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu}, \ \tilde{B}_\mp \equiv |A \mp \Delta_{13}|, \ A = \sqrt{2} G_F N_e$$

Neutrino Oscillations with "large" θ_{13}

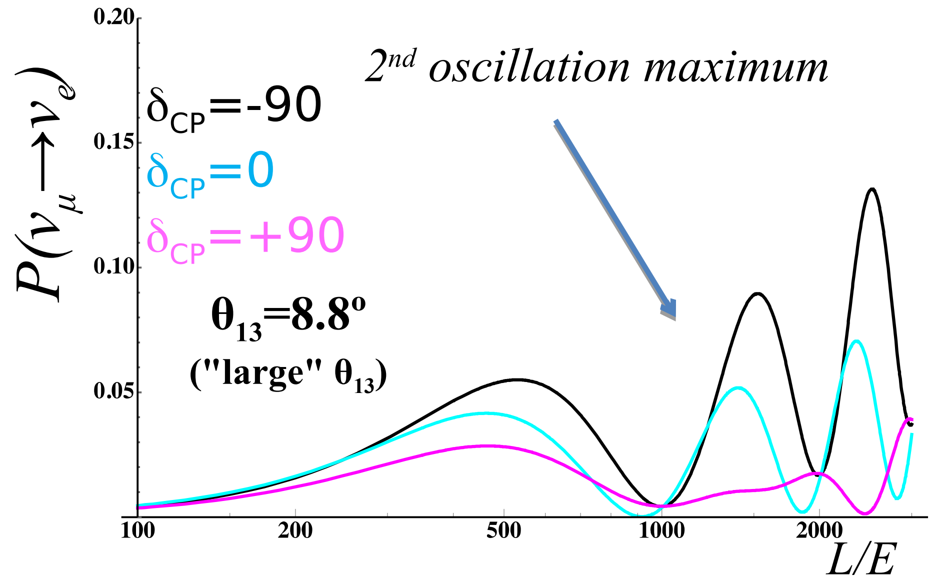
for small θ_{13} 1[st] oscillation maximum is better

(arXiv:1110.4583)





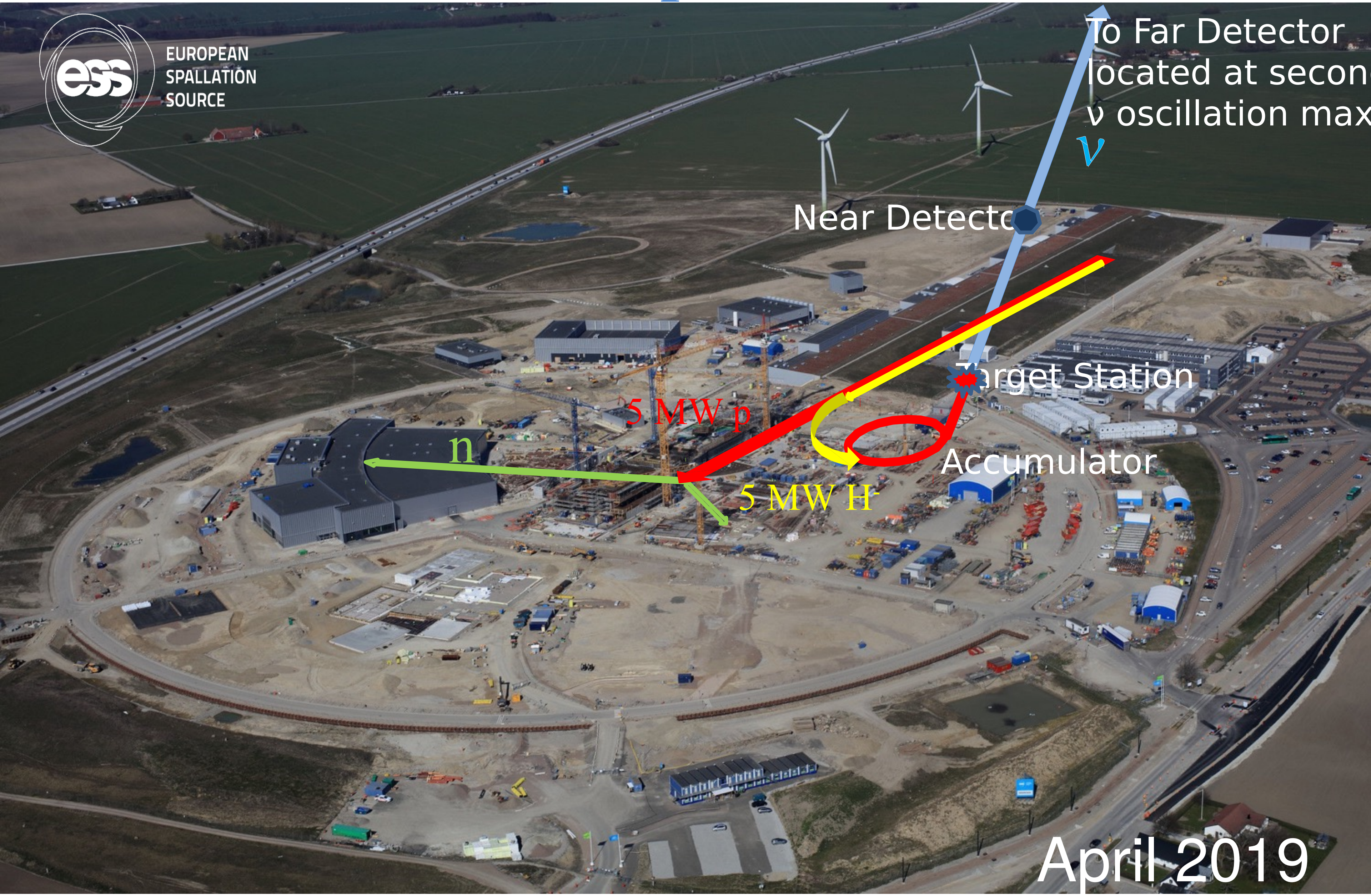
for "large" θ_{13} 1[st] oscillation maximum is dominated by atmospheric term



- 1[st] oscillation max.: $A=0.3\sin\delta_{CP}$
- 2[nd] oscillation max.: $A=0.75\sin\delta_{CP}$
  (see arXiv:1310.5992 and arXiv:0710.0554)

→ more sensitivity at 2[nd] oscillation max.

ESS ν Super Beam



Required modifications of the ESS accelerator architecture for ESSnuSB

F. Gerigk and E. Montesinos **CERN-ACC-NOTE-2016-0050 8 July 2016**

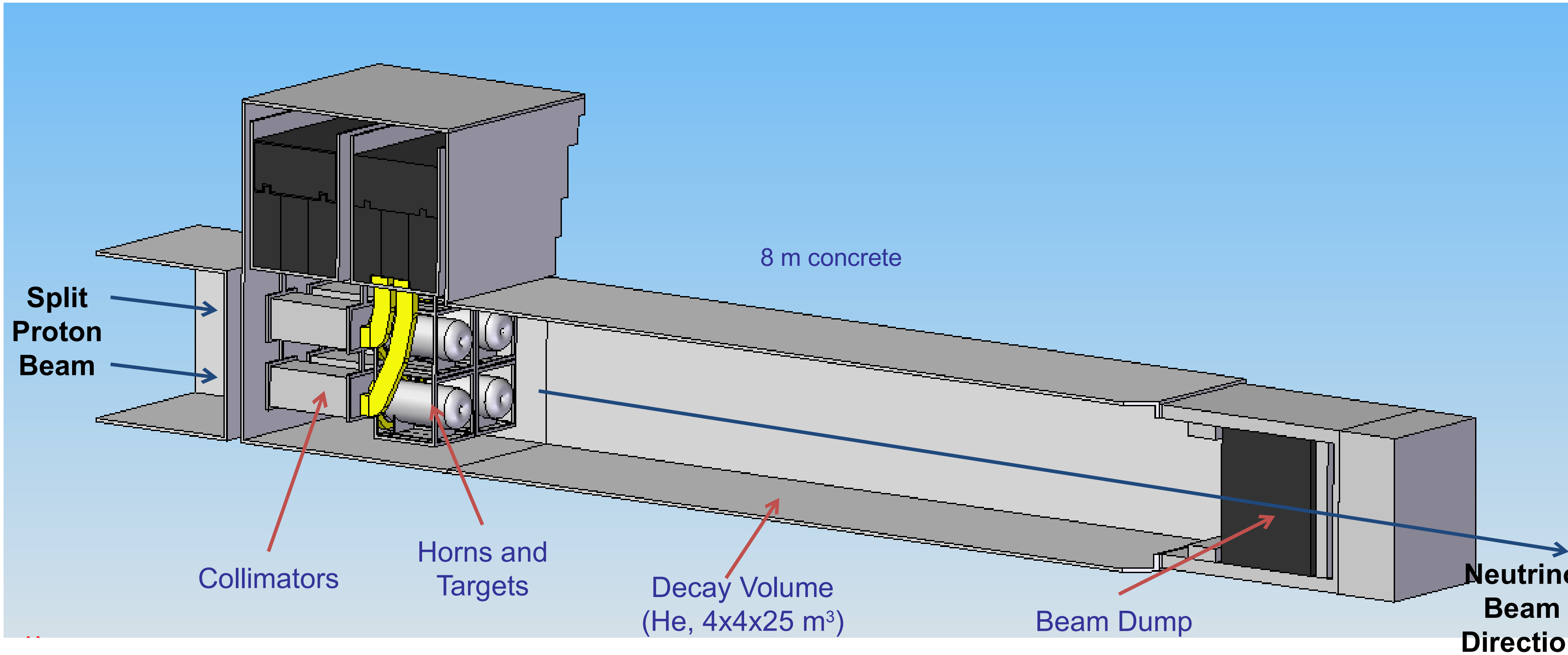
- The identified major modifications for the doubling of the beam power via a higher repetition rate and higher beam energy are (in no particular order):
  - Three new electrical substations along the RF gallery.
  - A third main electrical station, alongside the 2 existing ones.
  - HV cable trenches and pulling of additional HV cables from the main station towards the new substations. New HV cables between the substations and the modulators in the RF gallery.
  - Installation of 8 new cryo modules and associated RF stations.to accelerate to 2.5 GeV
  - Change of klystron collectors, so that 60% more average power can be produced. If klystrons are at the end of their lifetime, they could be exchanged against more powerful models.
  - Installation of additional capacitor chargers to allow faster pulsing of the modulators. This is only possible if the modular design developed in-house is adopted.
  - Installation of a H- source + RFQ + MEBT + beam funnel alongside the existing protons source.
  - Exchange trim magnets and associated power supplies against pulsed versions

“No show stoppers have been identified for a possible future addition of the capability of a 5 MW H- beam to the 5 MW H+ beam of the ESS linac built as presently foreseen. Its additional cost is roughly estimated at 250 MEuros.”

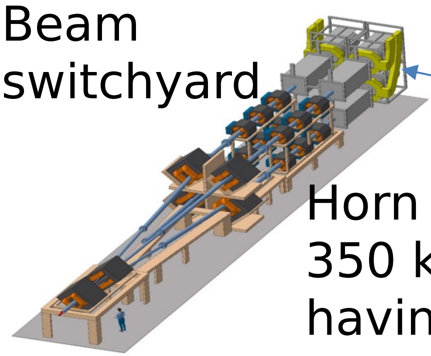
Cf total cost of the ESS 5 MW linac of ca 1000 MEuros

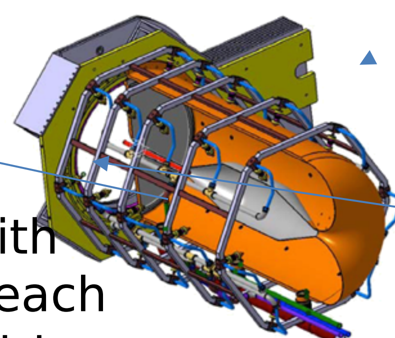
General Layout of the 5 MW target station

The proton beam is split up om 4 targets, each receiving a 1.25 MW beam

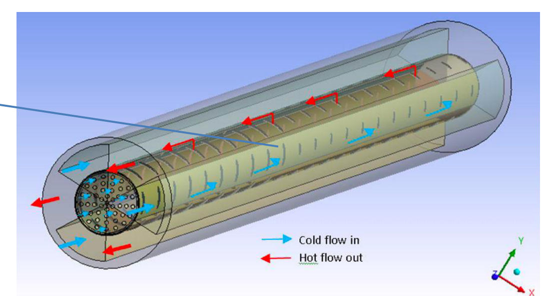


Beam switchyard





Granular Ti target with He gas cooling for a 1.25 MW beam

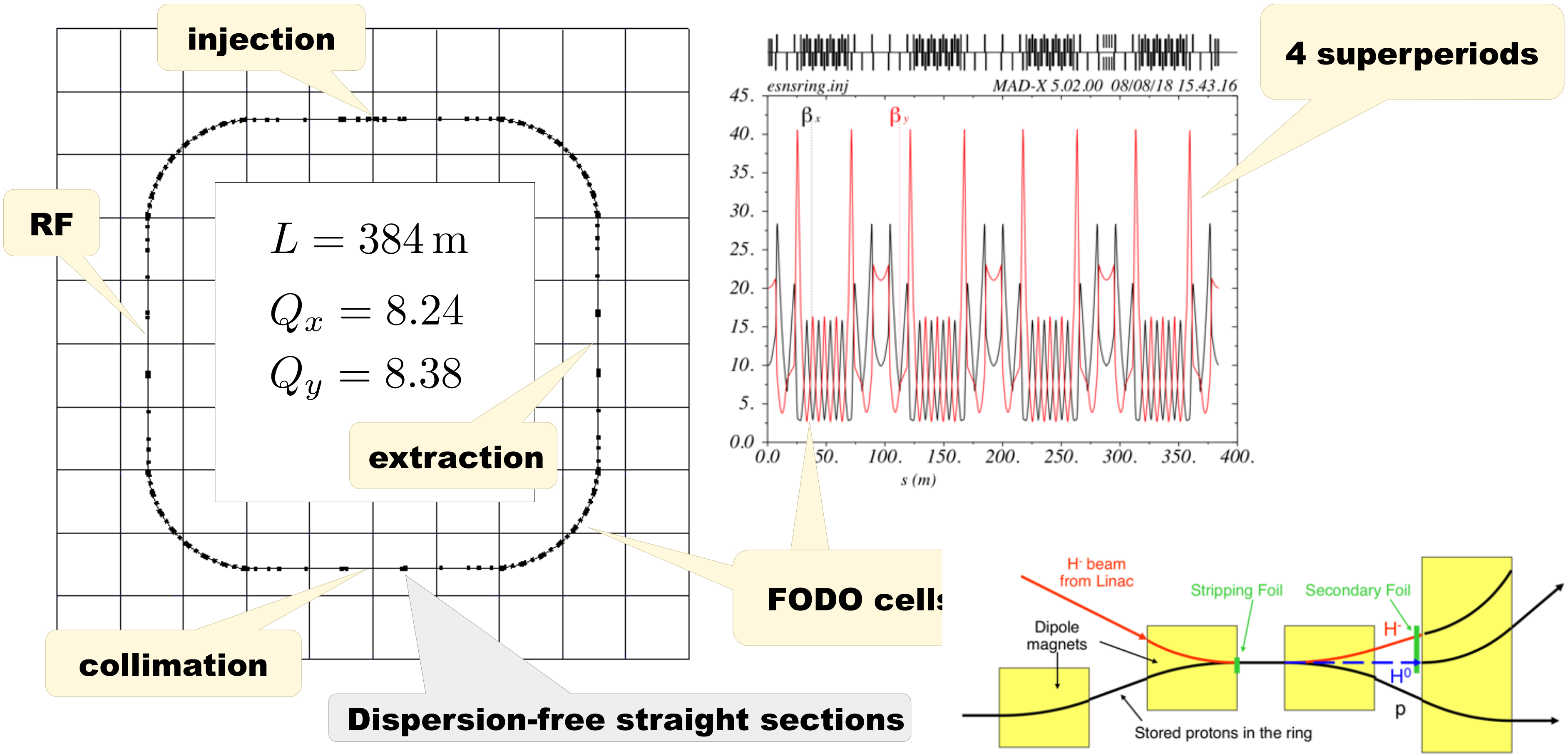


Horn excided with 350 kA pulses, each having a 1.3 flat top

The Accumulator Ring

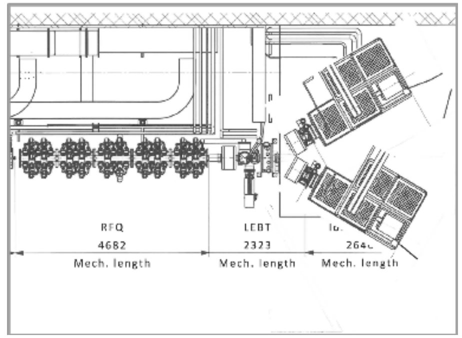
which compresses each 0.65 ms pulse of 2.5×10^{14} protons from the ESS linac to 1.3 µs

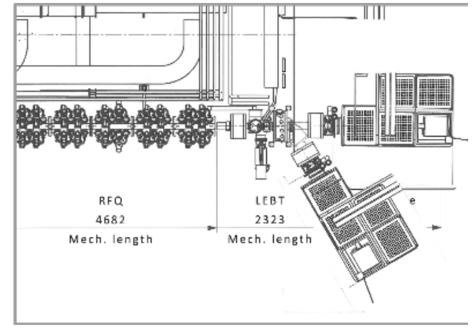
To inject such a high charge in the accumulator ring, H^- injection with stripping is required

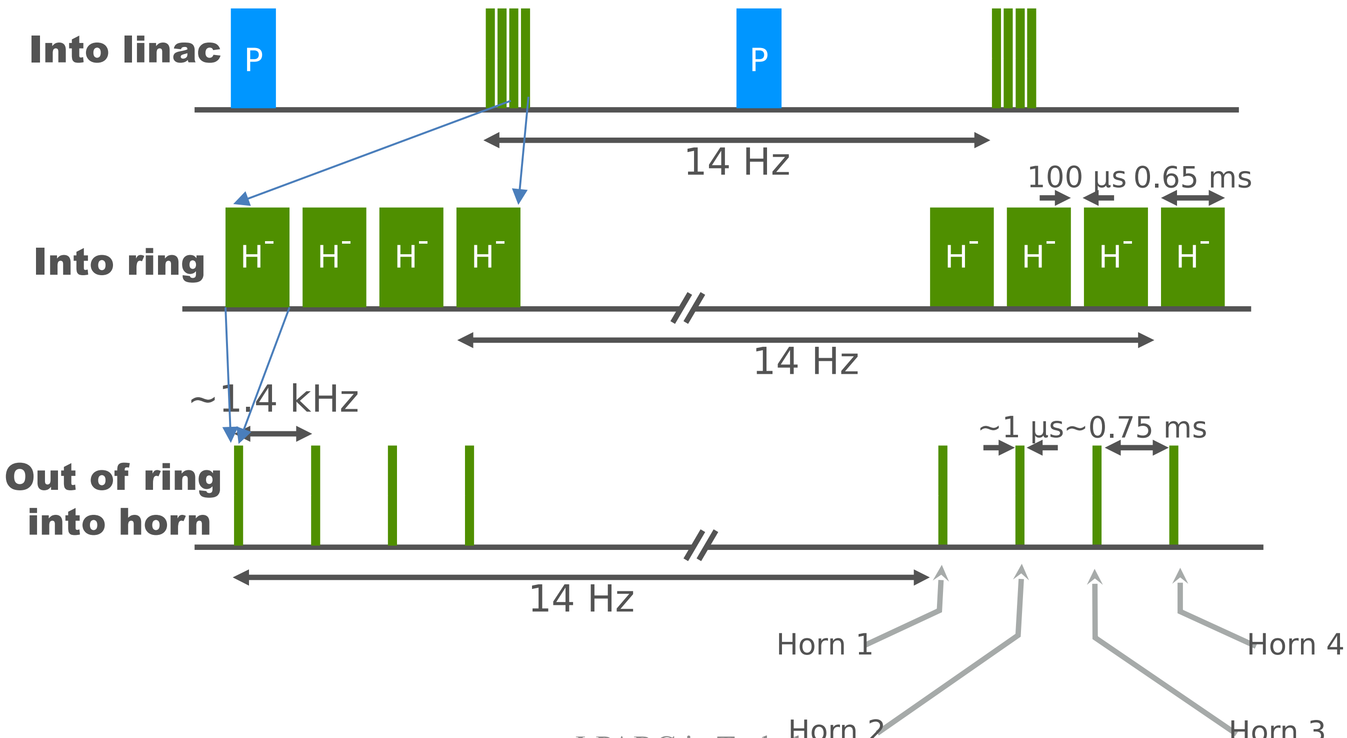


The Linac modifications and operation

H^- source options





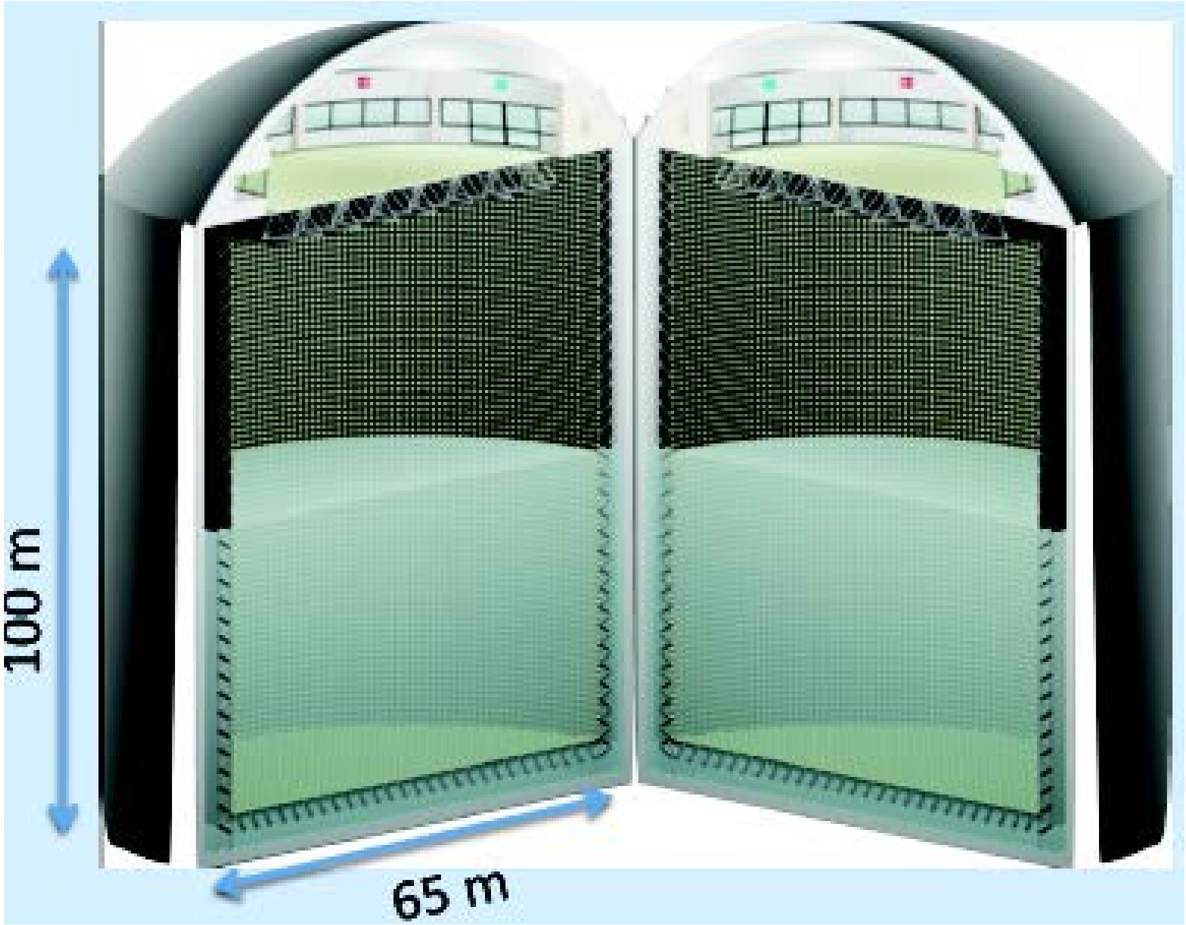


The Megaton Water Cherenkov neutrino detector

MEMPHYS like Cherenkov detector(MEgaton Mass PHYSics studied by LAGUNA

•Two cylindrical tanks
•Total fiducial volume 500 kt (~20xSuperK)
• Readout: ~240k 8” PMTs
• 30% optical coverage

(arXiv: hep-ex/0607026)



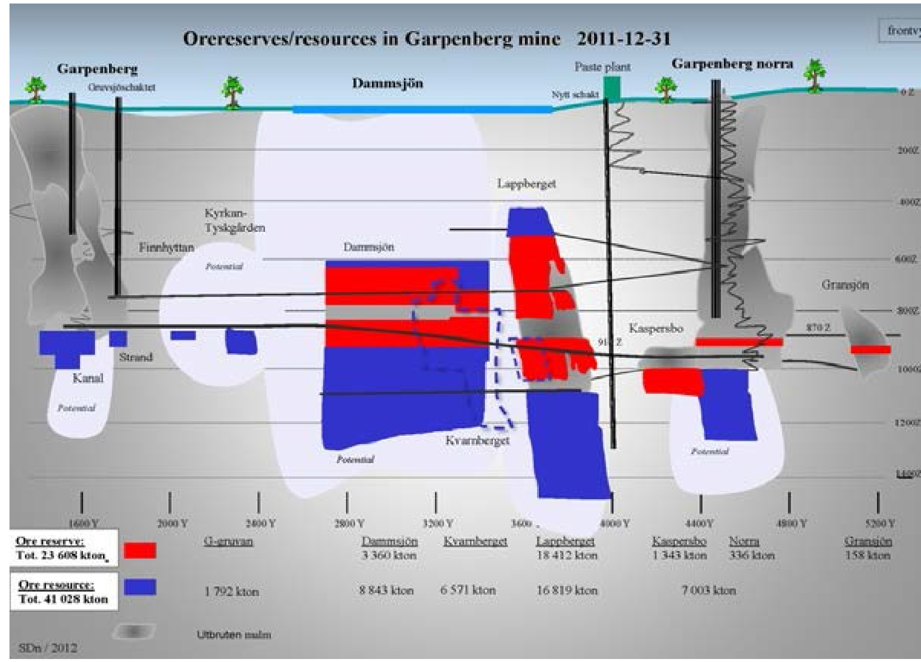
Garpenberg Mine 540 km from ESS

The MEMPHYS type detector to be located 1000 m down in a mine

Garpenberg mine depth 1200 m

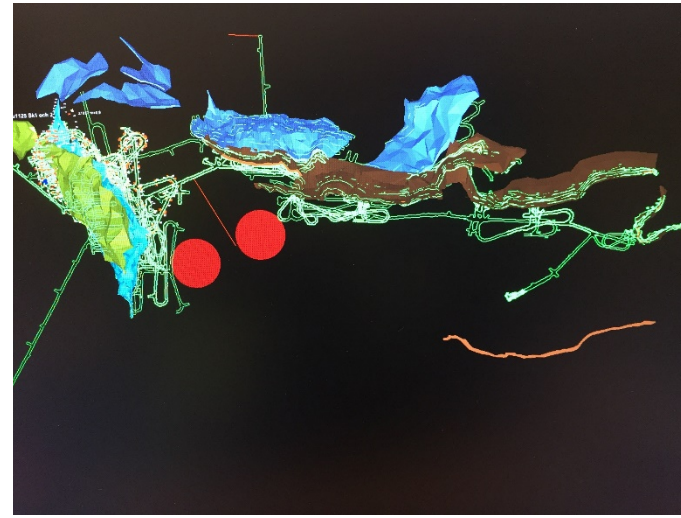
Truck access tunnel

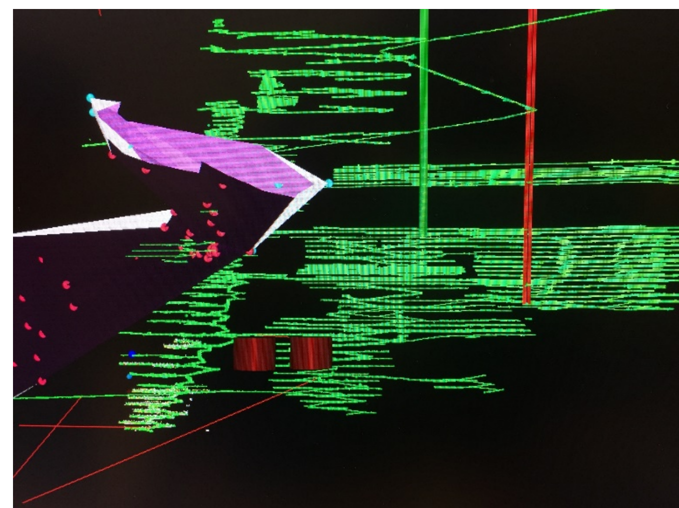
A new ore-hoist shaft has been taken into operation,
leaving an older shaft free to use for transport of ESSnuSB-detector cavern excavation-



Granite drill cores

Zinkgruvan Mine 360 km from ESS



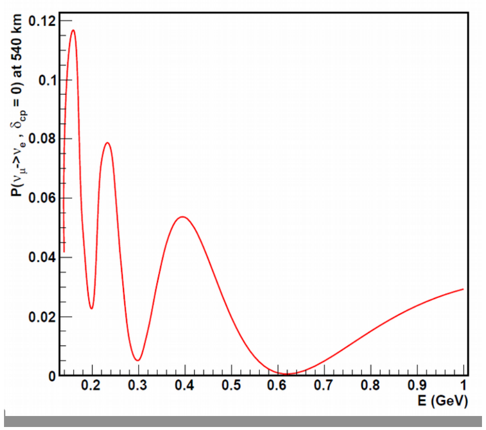


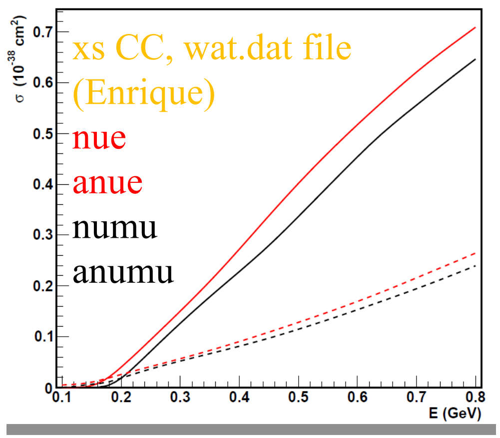
Zinggruvan mine depth 1500 m

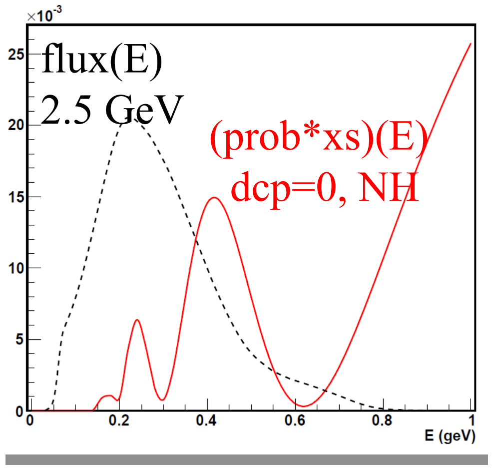
Truck access tunnel

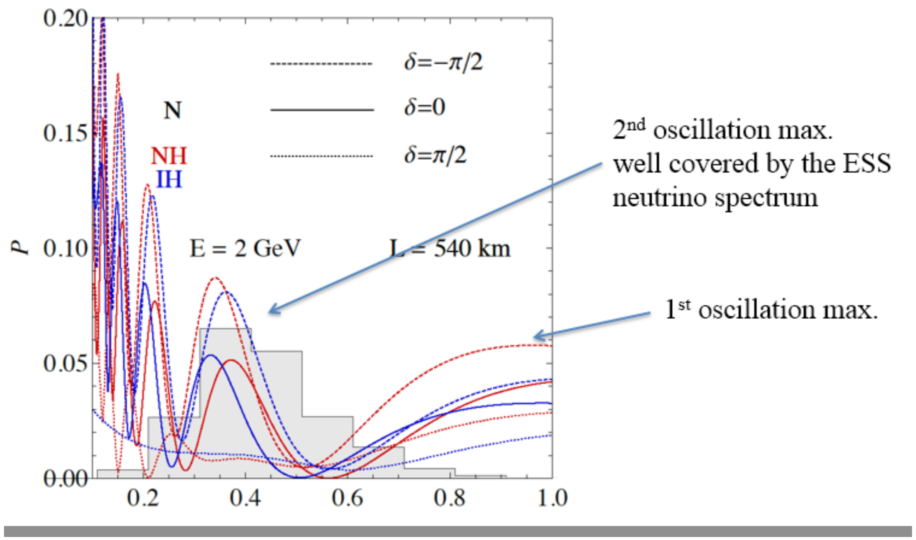
The main ore transport-shaft hoist has a capacity of 6000 tons per 24 hours of which only 2/3 is used. **To bring up the**

The effect of the sharply decreasing ν detection cross-section



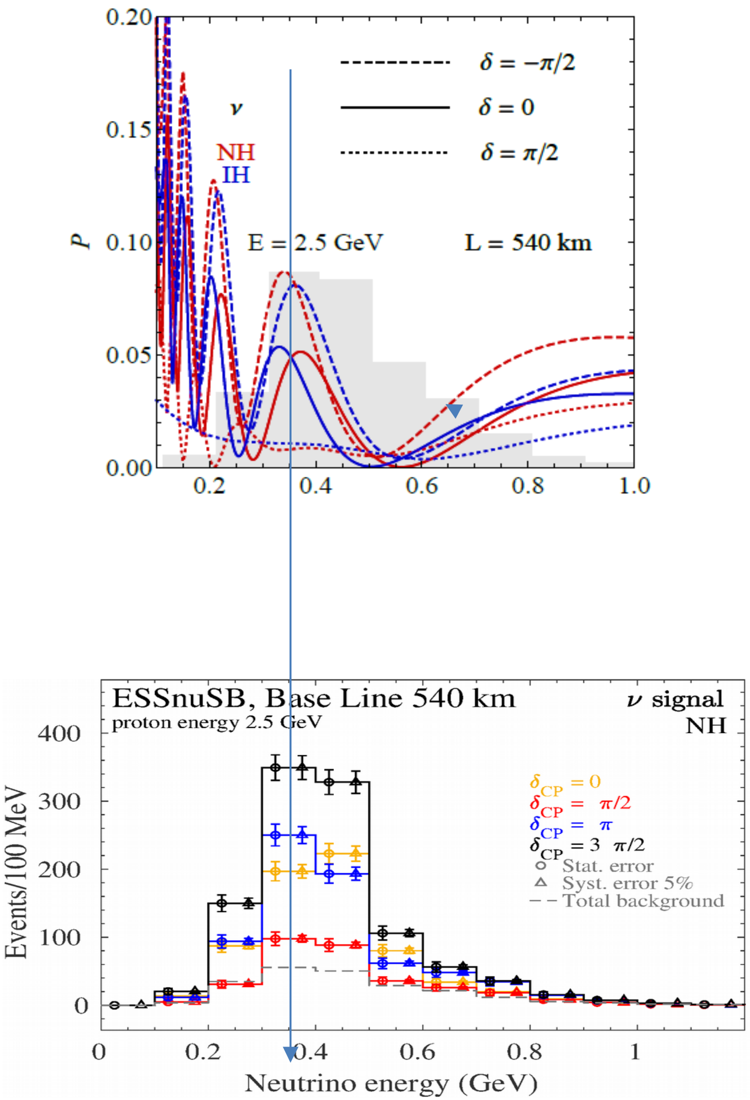




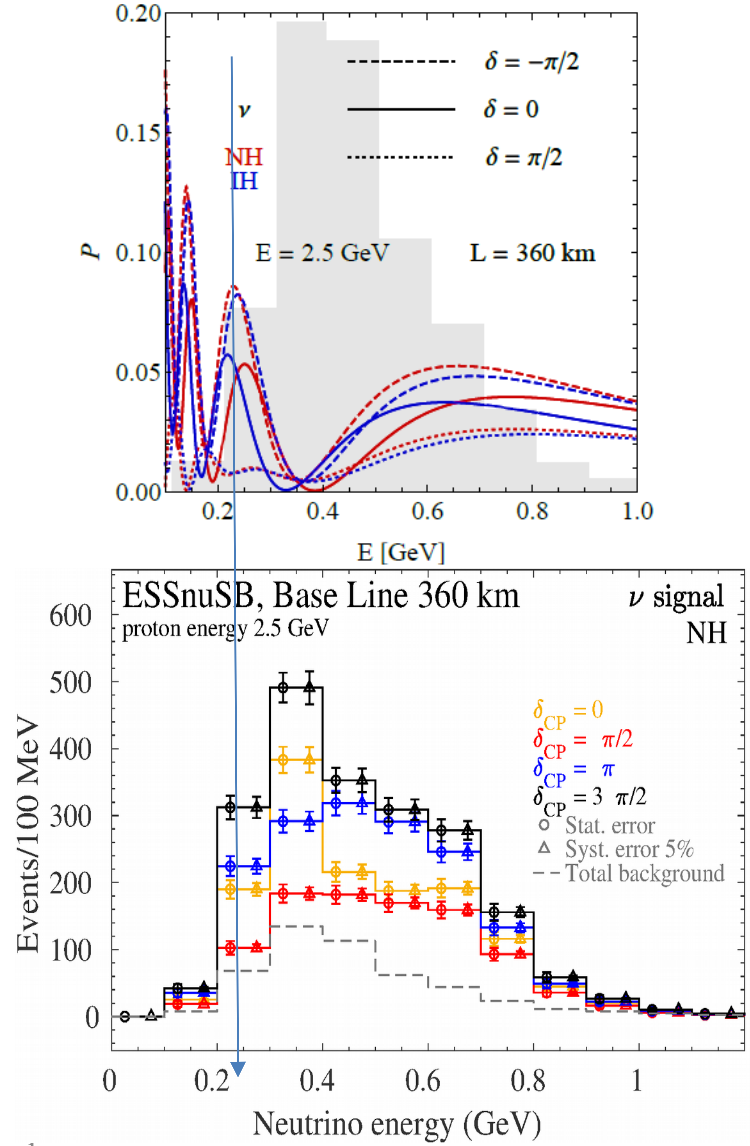


Comparison of the two mines

Garpenberg



Zinkgruvan



The interest of measuring δ_{CP} precisely

Test of flavor models Baryon Asymmetry of the Univers

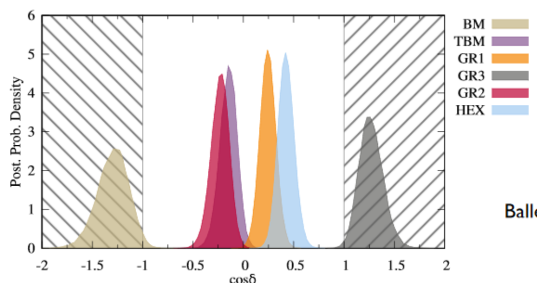
Tests of flavour models

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.:

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

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



Ballet at al., 1410.7573

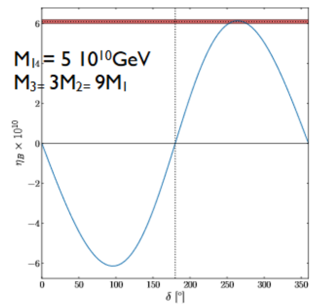
@Silvia Pascoli

Does observing low energy CPV imply baryon asymmetry?

In see-saw type I, let's consider the case of low energy CPV, for instance delta (R real). An approximate formula:

$$|Y_B| \cong 2.4\times 10^{-11}\,|\sin\delta|\left(\frac{s_{13}}{0.15}\right)\left(\frac{M_1}{10^{11}\,\mathrm{GeV}}\right)$$

SP, Petcov, Riotto, PRD and NPB 2007; SP 2014



Intermediate flavour regime: $10^9\mathrm{GeV} < M_1 < 10^{12}\mathrm{GeV}$

$$\epsilon_{\tau\tau}^{(1)} = (0.515 - 3.94 c_{13})\, s_{13}\times 10^{-8}\sin\delta$$

$$\epsilon_{\tau\tau}^{(1)} = 3.14\times 10^{-7}\cos\frac{\alpha_{21}}{2}$$

Moffat, SP, Petcov, Turner, 1804.05066, 1809.08251

A full study shows that delta can give an important (even dominant) contribution to the baryon asymmetry. For Majorana CPV, effects enhanced by a factor of ~10.

See Silvia Pascoli's talk at this workshop from which these two slides are taken

ESSnuSB organization and time plan

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

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:	

Partners: Oslo U, IHEP, BNL, SCK•CEN, SNS, PSI, RAL

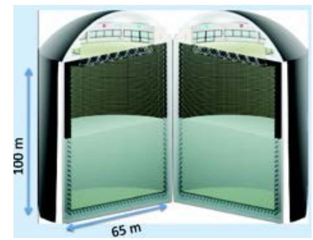
- EU grant 3 MEUR/4 years
- Kick-off meeting in January 2018.
- ESSνSB has about 60 members of which 10 are full-time EU-financed postdocs.
- Next ESSnuSB and EuroNuNet annual meeting to be held in Zagreb 21-24 October 2019 – newcomers are most welcome to attend

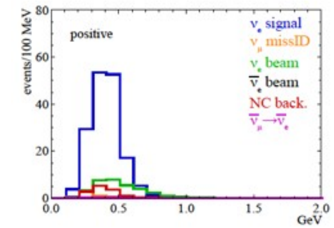
More information at: http://essnusb.eu/

ESSnuSB organization and time plan

A 2nd generation neutrino Super Beam

ESFRI





EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

ESS NEUTRINO SUPER BEAM

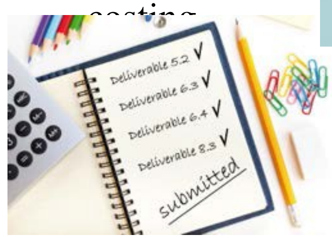
2012: Θ_{13} measurement published - inception of the ESSnuSB project

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



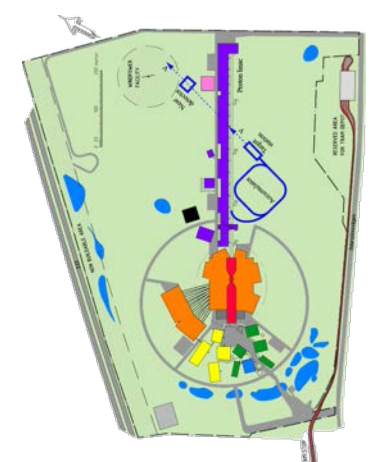
2024:End Preparatory Phase, TDR

2-5 years, International Agreement

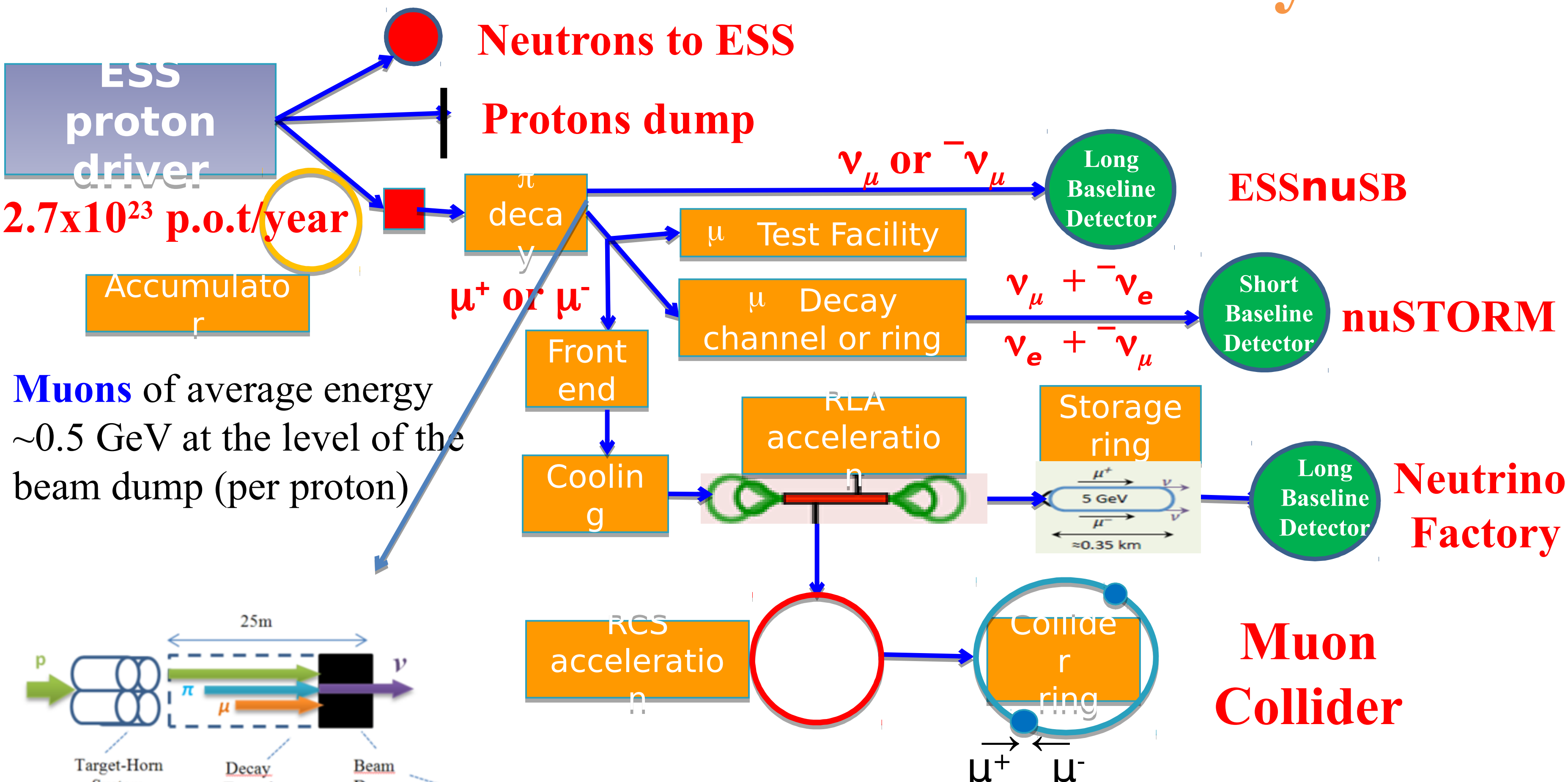
EUROPEAN SPALLATION SOURCE

7 years Construction of the facility and detectors, including commissioning

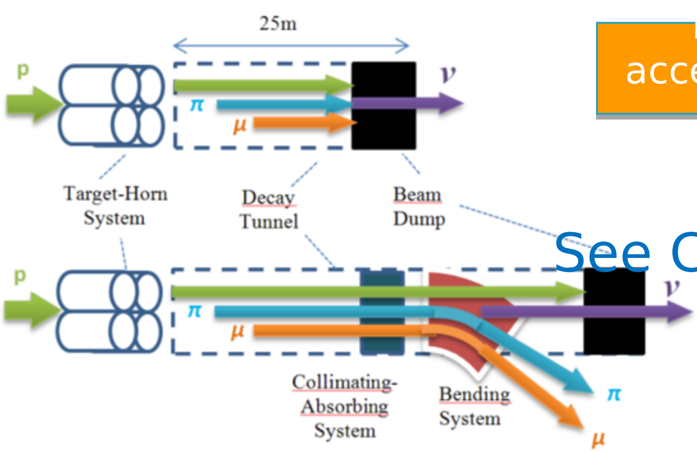
2033-2036: Start Data taking



Future further option form a ESS neutrino and muon facility



Muons of average energy ~0.5 GeV at the level of the beam dump (per proton)



See Carlo Rubbias talk at the NeuTel2019 worksh

more than 4×10^{20} μ/year from ESS

Workshop ‘Prospects for Intensity Frontier Physics with Compresses Pulses from the ESS Linac’ to be held at the Ångström Laboratory at Uppsala University, Sweden 2-3 March 2020.

Monday 2 March 2020
14:00–14:05 Welcome & Introduction to the Workshop/ Tord Ekelof
14:05–14:45 The use of the ESS linac to create a Muon Collider/ Carlo Rubbia
14:45–15:15 The ESS neutrino Super Beam Design Study/ Marcos Dracos
15:15–15:30 Discussion
15:30–16:00 Coffee break
16:00–16:30 The prospects for nuSTORM at ESS/ Alan Bross
16:30–17:00 The prospects for an ESS based Neutrino Factory/ Jaroslaw Pasternak
17:00–17:30 The possibilities of Decay-at-Rest experiments at ESS/ Janet Conrad
19:00–23:00 Conference dinner

Tuesday 3 March 2020
09:00–09:30 Coherent scattering experiments possible at ESS/Kate Scholberg
09:30–10:00 Short Pulses for neutron Physics at ESS/ Ken Andersen
10 :00–10:30 The ESS Linac Modifications required for the Different Proposals/ Natalia Milas
10:30–11:00 Coffee break
11:00–11:30 Design of the ESSnuSB accumulator/ Ye Zou
11:30–12:00 Accumulator Synergies and Differences for the Different Proposals/ Maja Olvegard
12:00–12:30 Discussion
12:30–14:00 Lunch
14:00–14:30 Target Synergies and Differences for the Different Proposals/ Eric Baussan
14:30–15:00 Space available at the ESS site for the new installations/ Karin Wennerholm
15:00–15:30 Discussion & Closing

Concluding remarks

ESSnuSB, the design of which is currently being studied, is complementary to other existing and planned super beam experiments by the fact

1. that it focusses at the second maximum where the sensitivity to systematic errors is 3 times lower than at the first maximum,

2. the correlation with other parameter of the ν mixing matrix is different and

3. that the neutrino energy is low enough for the resonant and deep inelastic backgrounds to be strongly suppressed.

If and when the current experimental hints of CP violation will have been confirmed on the level of 5σ, the next important step will be to make an accurate measurement of the CP violating angle δ_{CP} , which will require the CP violation signal to maximized. Accurate measurement of δ_{CP} has the potential to provide decisive information on flavour models and on the baryon asymmetry.

The use of the ESS linac for the producing a world-uniquely intense neutrino beam can pave the way for making use of the concurrent production of an equally intense muon beam to realize the Muon Collider or Neutrino Factory project.

Thank you