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The ESSnuSB project

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on behalf of ESSnuSB

WIN2019 Bari
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ESSnuSB

A design study for an experiment to measure CP violation at 2nd neutrino oscillation maximum.

CP violation in neutrino oscillations

Oscilation probability for neutrinos is different than oscillation probability for anti-neutrinos in vaccum.

probability of oscillation

$$P_{\alpha\rightarrow\beta} \neq P_{\overline{\alpha}\rightarrow\overline{\beta}}$$

neutrino flavour at production

neutrino flavour at detection

CP violation in ESSnuSB

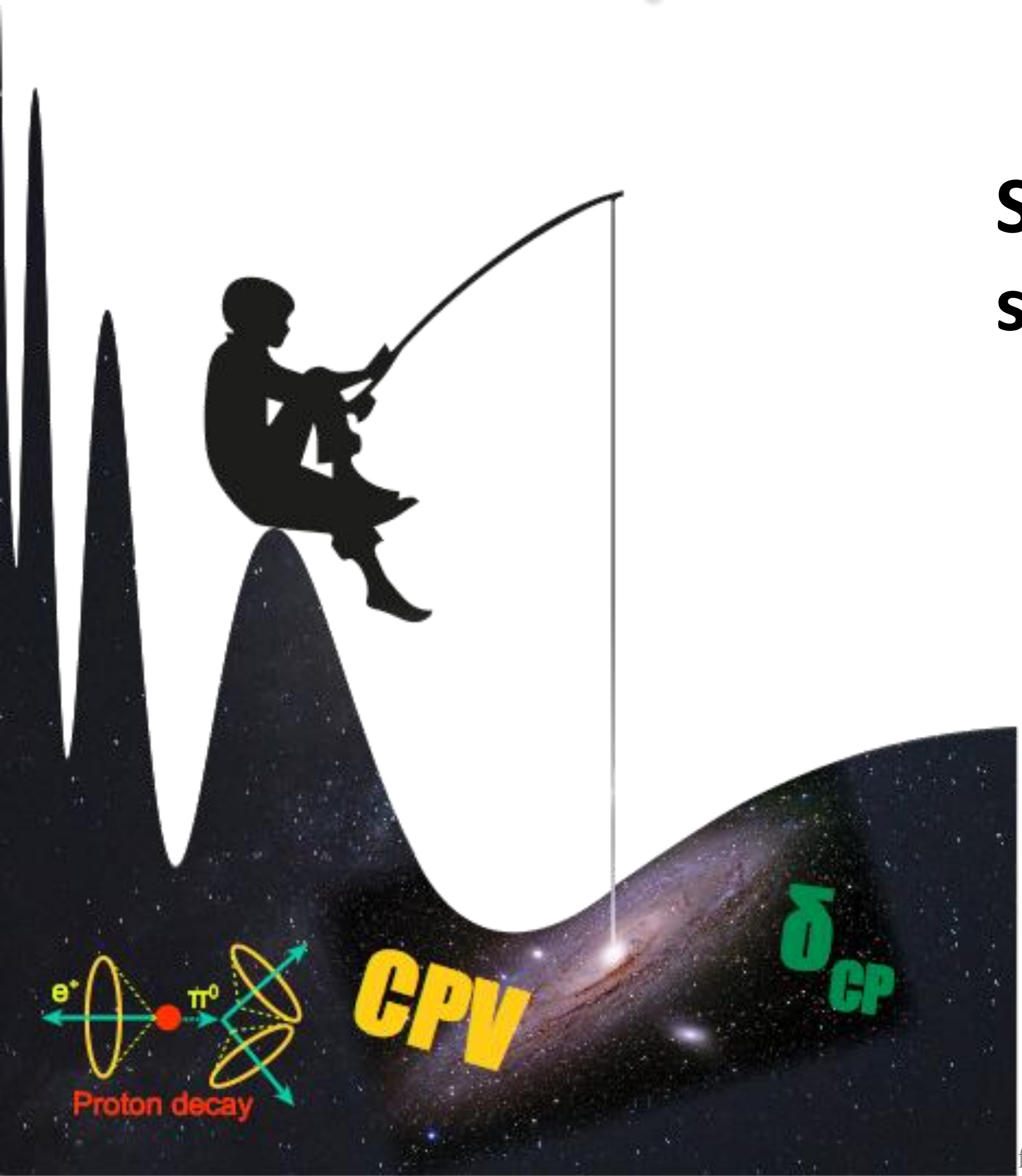
$$P_{\mu\rightarrow e} \neq P_{\overline{\mu}\rightarrow\overline{e}}$$

We will study ν_e and $\bar{\nu}_e$ appearance in ν_μ and $\bar{\nu}_\mu$ beam, respectively

The plan:

1. Run with ν_μ and look at ν_e appearance, then
2. Run with $\bar{\nu}_\mu$ and look at $\bar{\nu}_e$ appearance

Why 2nd maximum?



Statistics vs. systematics

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Why 2nd maximum (hand waving explanation)

The good

$$\frac{(P_{\mu\to e} - P_{\overline{\mu}\to\overline{e}}) \text{ @ 2nd osc. max.}}{(P_{\mu\to e} - P_{\overline{\mu}\to\overline{e}}) \text{ @ 1st osc. max.}} \sim 3$$

In vaccum, this ratio depends only on neutrino mass square differences

The bad

You get less statistics because you have to either:

- Move 3x further than 1st maximum - flux 9x smaller
- Reduce energy 3x – cross-section at least 3x smaller

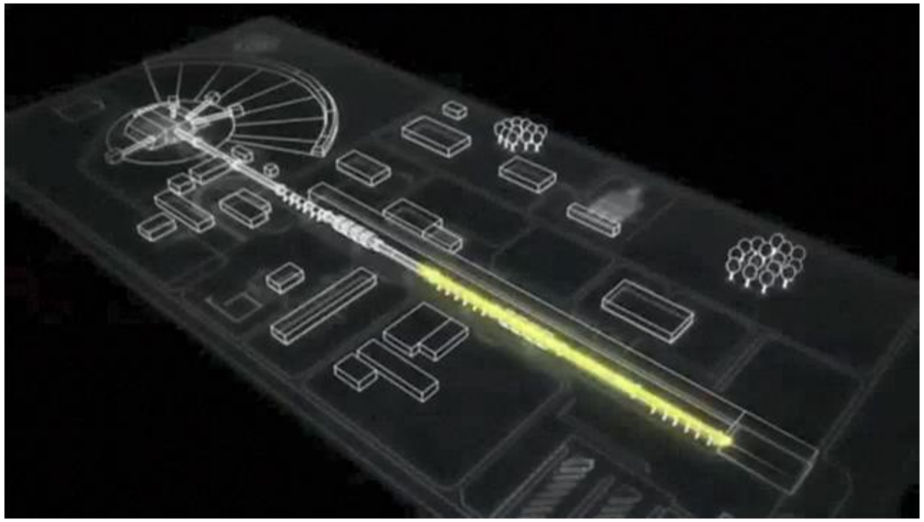
The optimal

- With 0 systematic error, first maximum is better : more statistics, even though the effect is smaller.
- With non-0 systematic error: depends on statistics.
- 3x singal at 2nd osc. maximum is less obscured by systematics, but we have less statistics (measured appearance events).
- If the signal at 2nd maximum is not obscured by larger statistical error, then 2nd maximum is better.
  - Intense beam helps here., as does having larger θ_{13} because $P_{\mu\to e}$ and $P_{\overline{\mu}\to\overline{e}}$ are larger and we get more events.

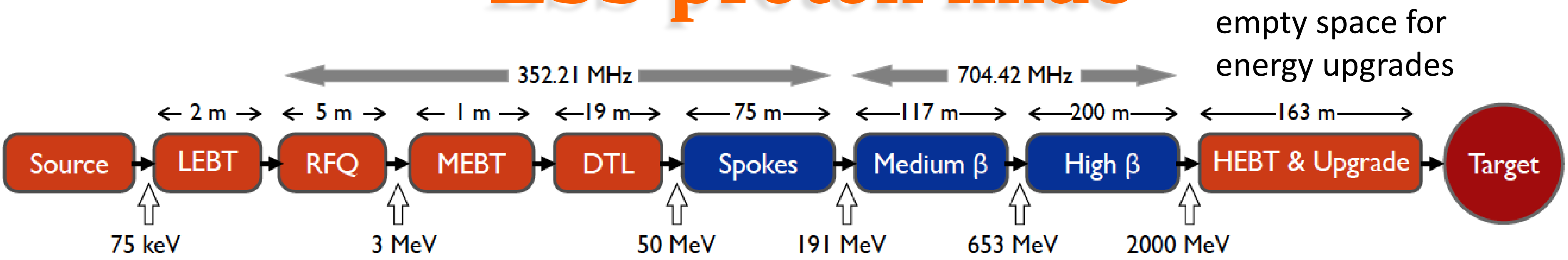
2nd maximum?

As it happens, a very intense proton linac is in construction near Lund, Sweden.

And θ_{13} is large enough.
(According to GLoBES)

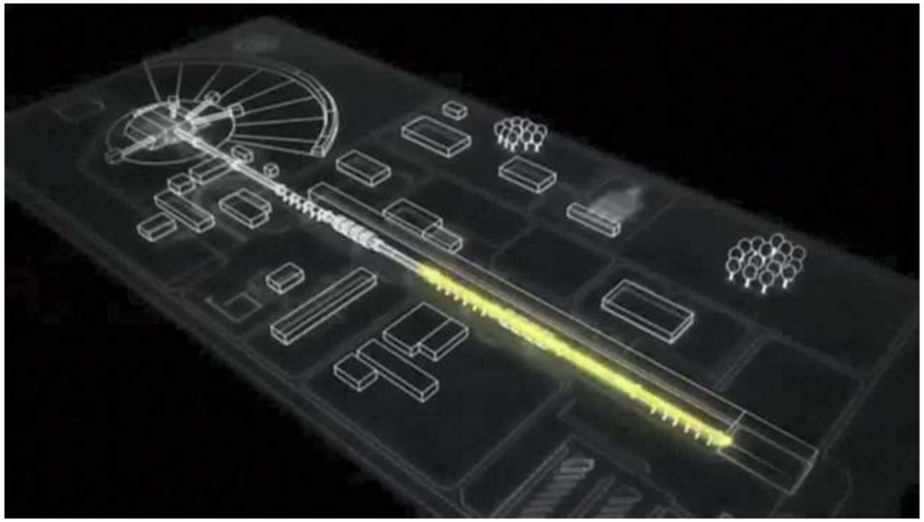


ESS proton linac



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

450 mg of protons/year at 94% speed of light!

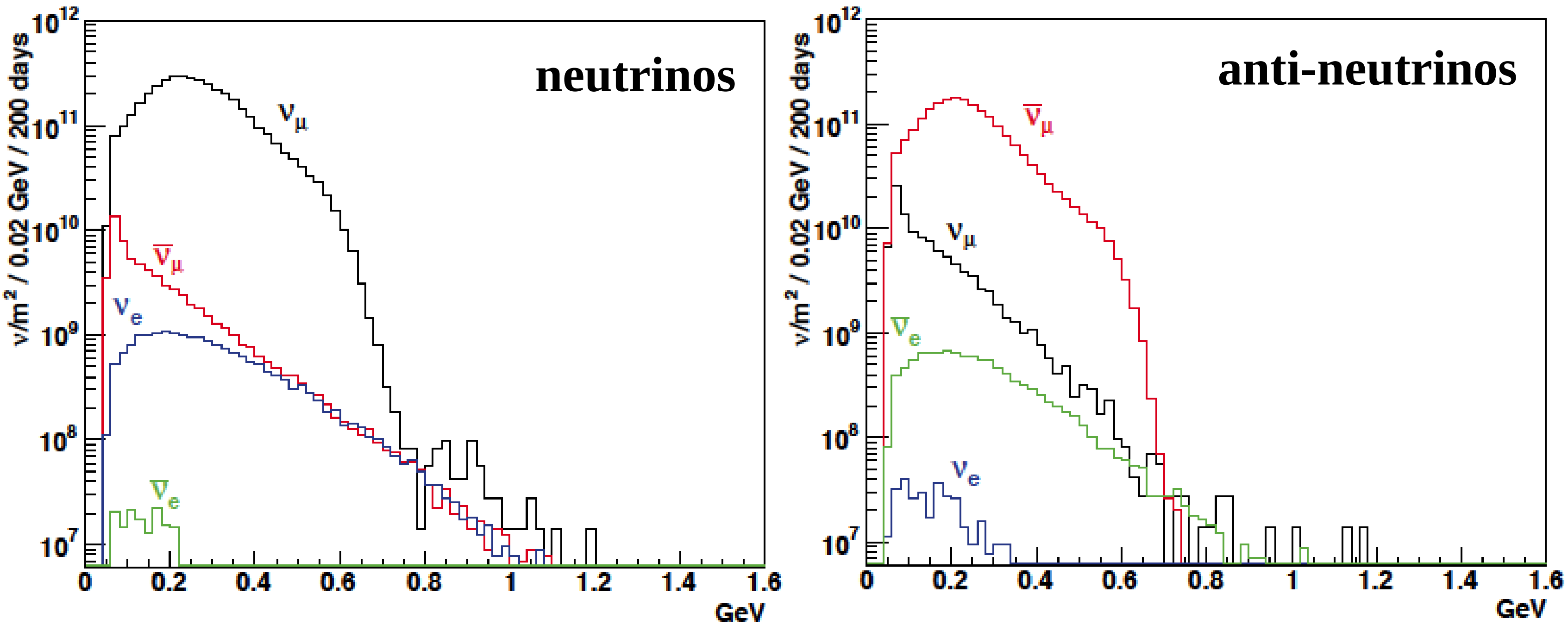


Linac ready by 2023 (full power)

Modifications to ESS linac to produce neutrinos

- Neutrino optimised target station (studied in EUROν).
- Underground near detector (studied in LAGUNA).
- Double the linac rate the rate (14 Hz → 28 Hz), from 4% duty cycle to 8%.
- ESS proton pulse is too long for a conventional magnetic horn – it would melt
  - Accumulator (C~400 m) needed to compress to few μs the 2.86 ms proton pulses,
- The neutron program must not be affected and if possible synergetic modifications.

ESSνSB ν energy distribution (without optimisation)



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

	positive		negative	
	N_ν $(\times 10^{10})/\mathrm{m}^2$	%	N_ν $(\times 10^{10})/\mathrm{m}^2$	%
ν_μ	396	97.9	11	1.6
$\bar{\nu}_\mu$	6.6	1.6	206	94.5
ν_e	1.9	0.5	0.04	0.01
$\bar{\nu}_e$	0.02	0.005	1.1	0.5

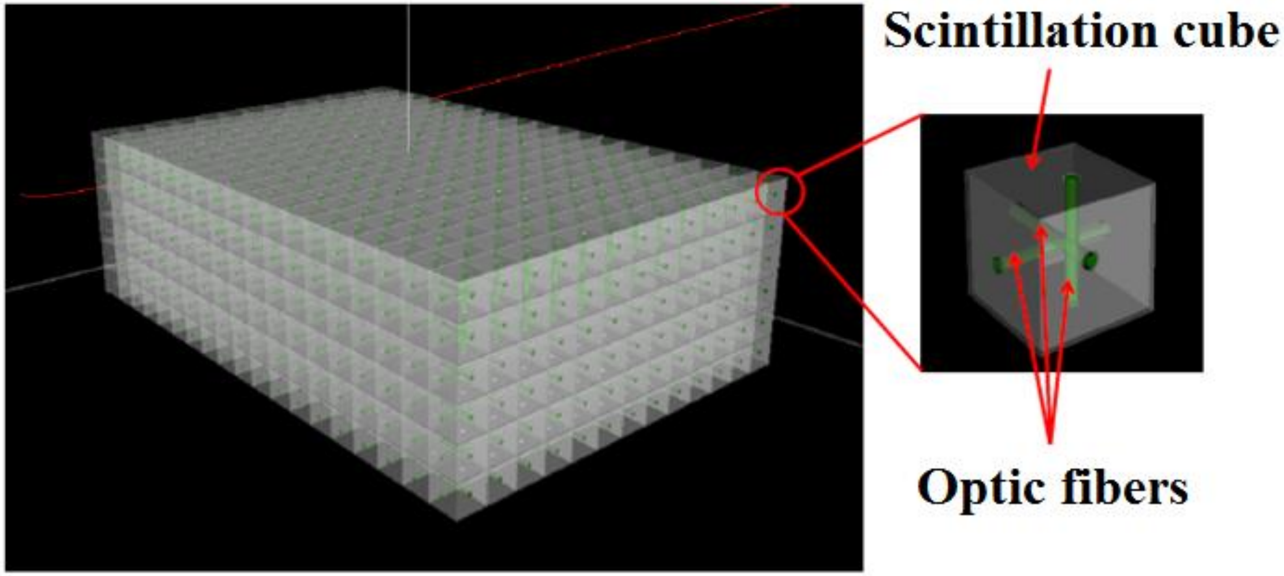
at 100 km from the target and per year (in absence of oscillations)

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

Near detectors

- **Baseline**: SuperFGD-like detector adjacent to upstream end of WC detector 100m from target station
  - WC detector - 250t fiducial
  - SuperFGD-like detector – (1 – 10) t total target
    - Thanks to ND280 upgrade project for support!

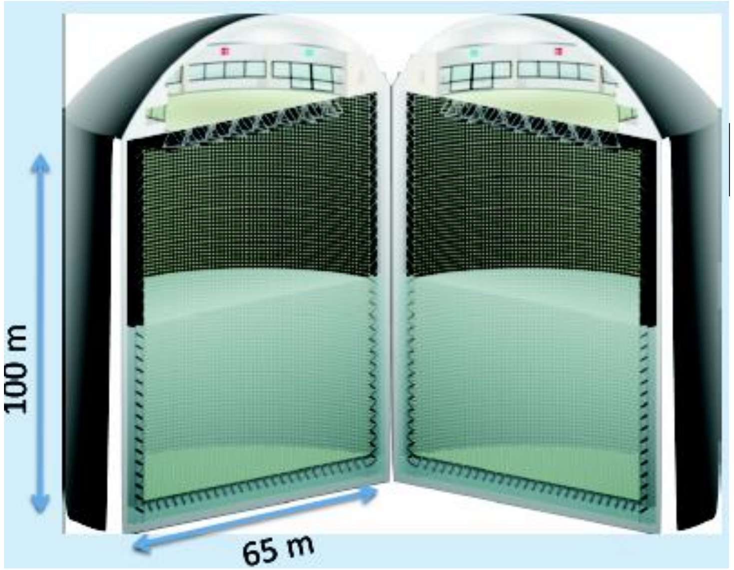
Possible addition – NINJA like emulsion/water detector



Super-FGD like detector

Far detector

MEMPHYS like Cherenkov detector
(MEgaton Mass PHYSics studied by LAGUNA)

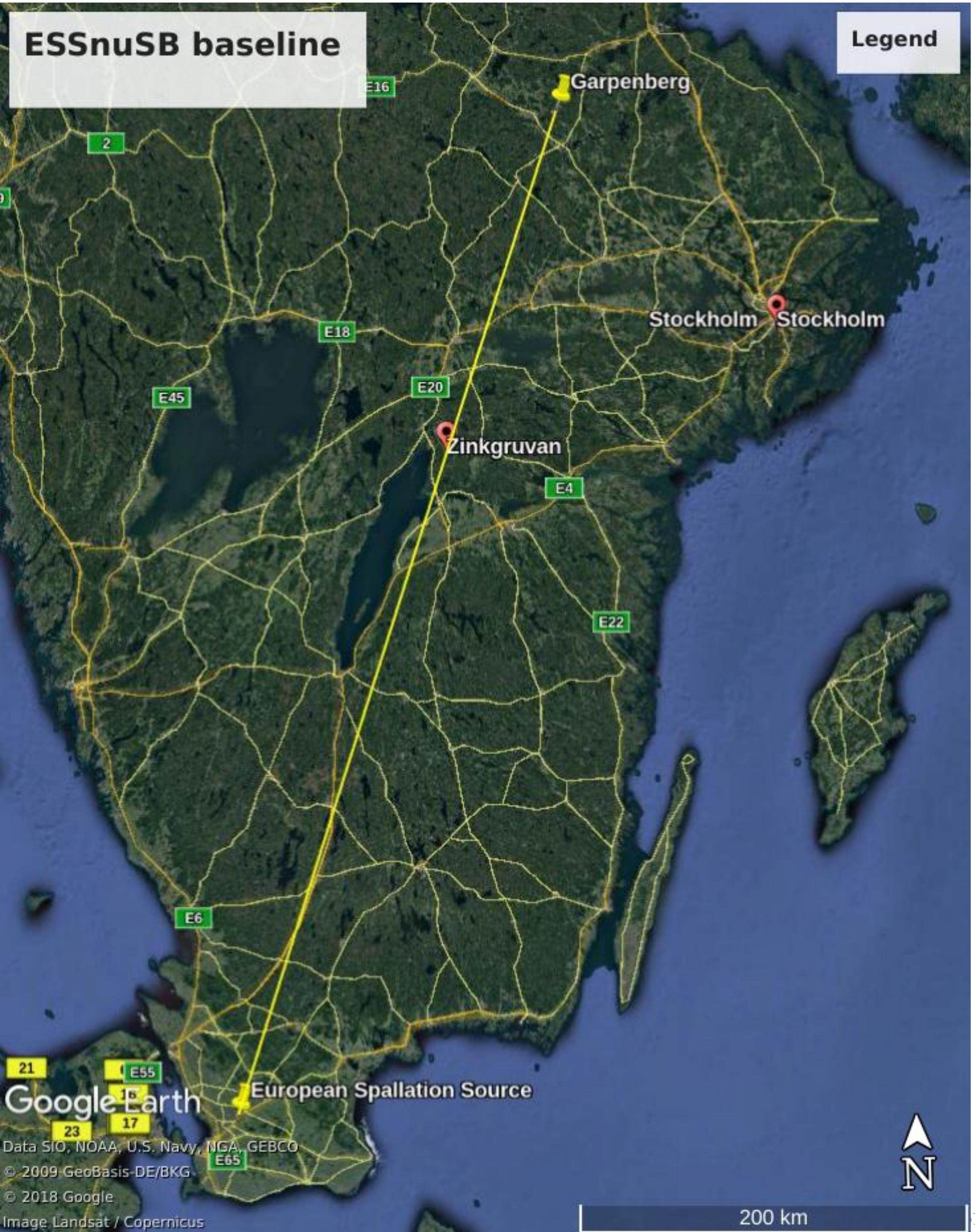


Can also be used for other purposes:

- Proton decay
- Astroparticles
- Galactic SN ν
- Supernovae "relics"
- Solar Neutrinos
- Atmospheric Neutrinos

- 500 kt fiducial volume (~20xSuperK)
- Readout: ~240k 8" PMTs
- 30% optical coverage

New 20" PMTs with higher QE and cheaper (see JUNO), the detection efficiency will improve the detector performance keeping the price constant, not yet taken into account.



Neutrino baseline choice

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Baseline choices

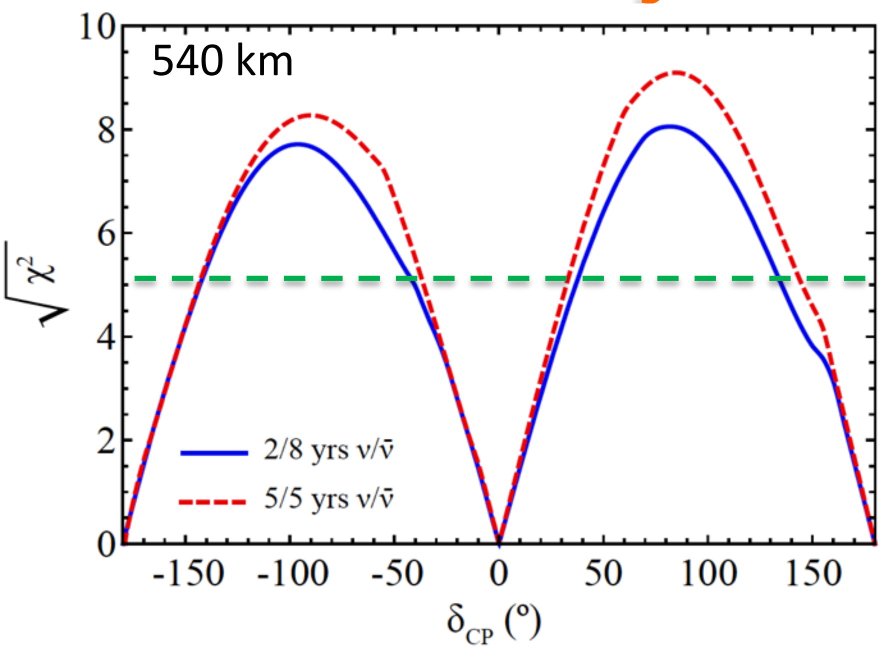
Baseline baseline:

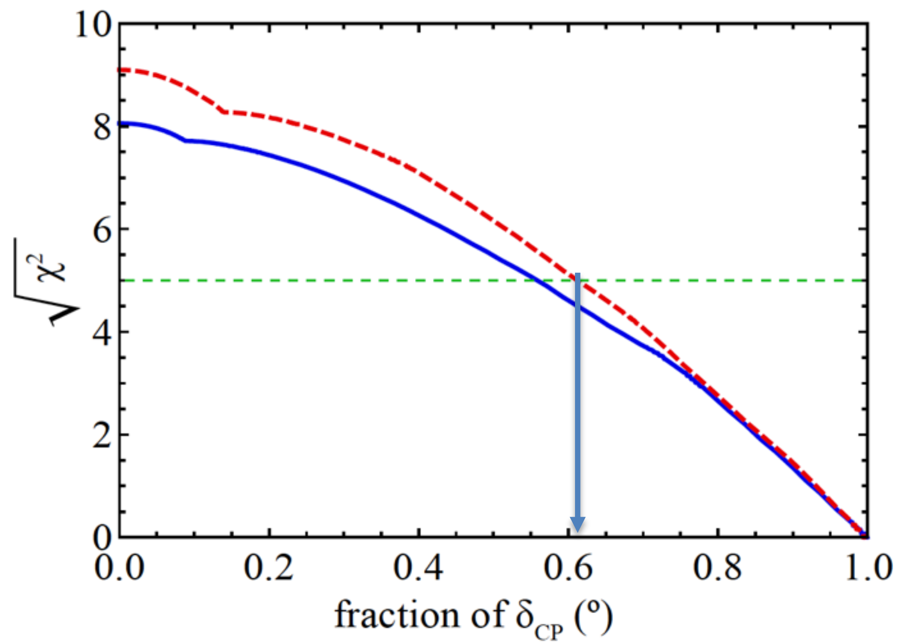
- Garpenberg mine, 540 km from the neutrino source, corresponding to 2nd oscillation maximum.

Alternative baselines:

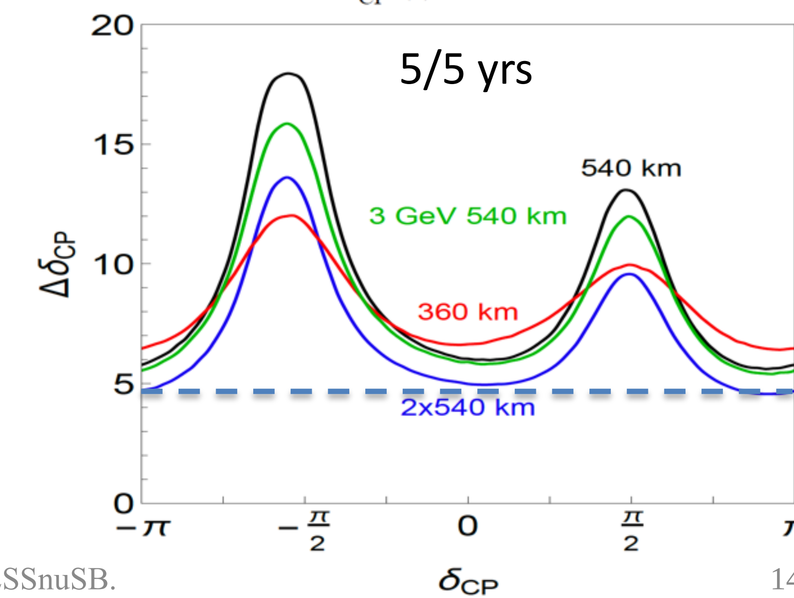
- Zinkgruvan mine, 340 km from source
- Garpenberg and Zinkgruvan, 250 kt each

Physics Performance





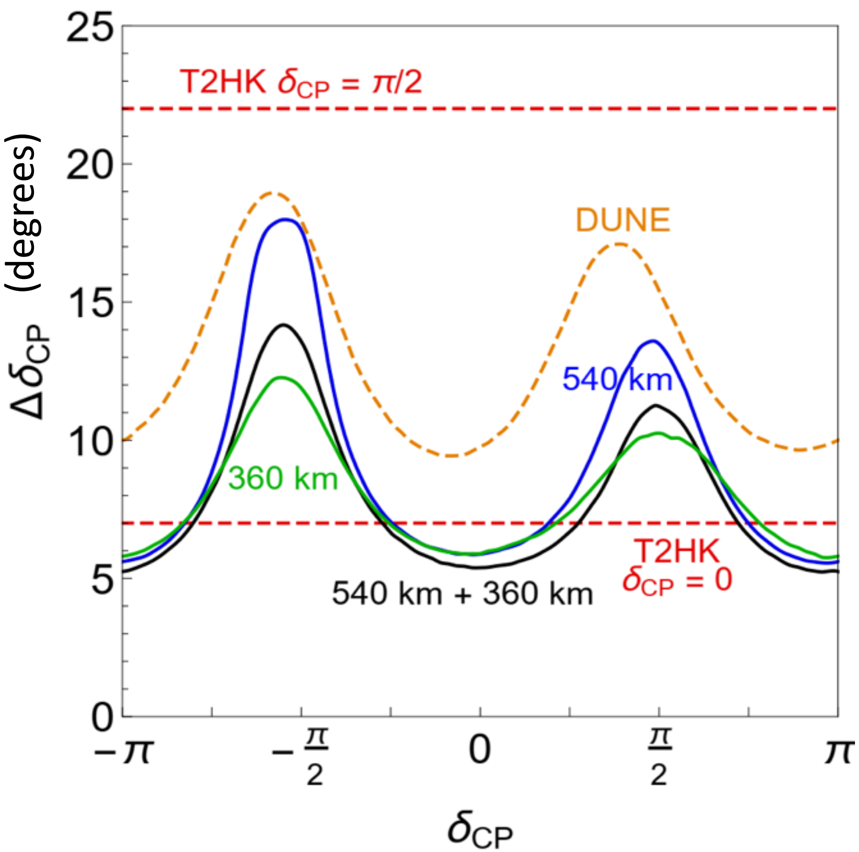
- little dependence on mass hierarchy,
- δ_{CP} coverage at 5 σ C.L. up to **60%**,
- δ_{CP} accuracy down to **6°** at 0° and 180° (absence of CPV for these two values),
- not yet optimised facility,
- **5/10%** systematic errors on signal/background.

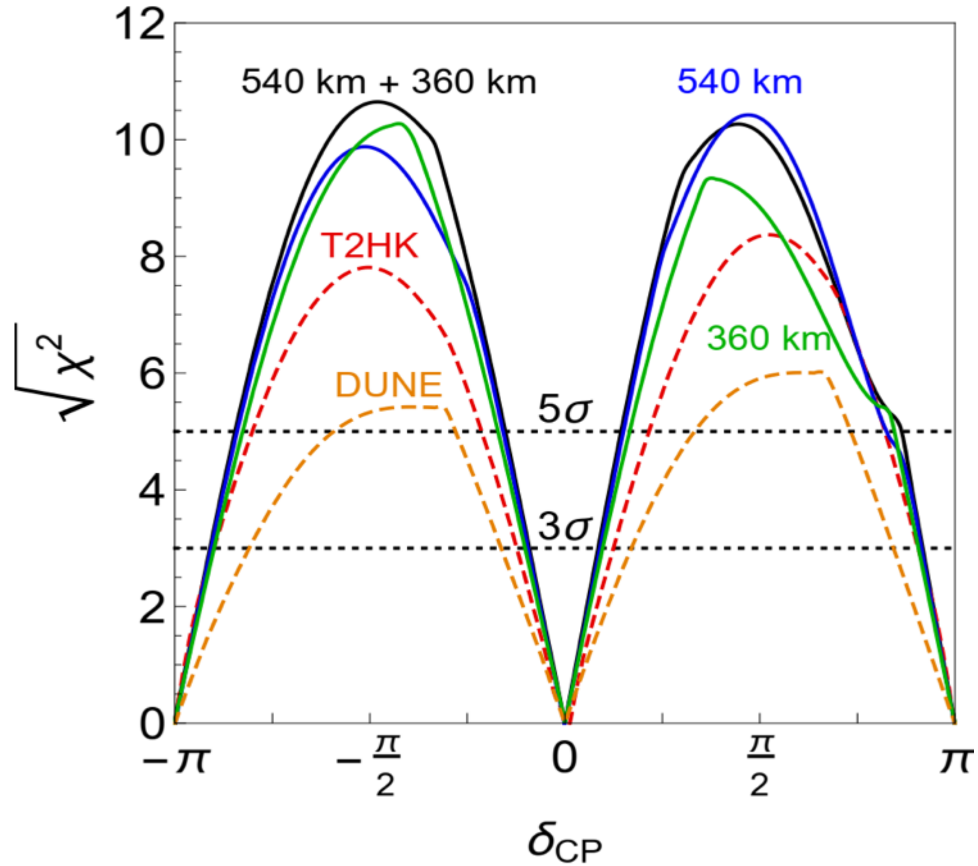


CPV performance comparison between ESSnuSB, DUNE and Hyper-K assuming 3% systematic errors for ESSnuSB in line with the other two.

ESSνSB 500 kt tank at 540 km.

ESSνSB 500 kt tank at 360 km.





ESSνSB 250 kt tank at 540 km and 250 kt tank at 360 km.

Detector simulation

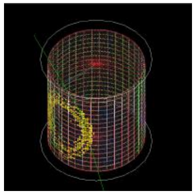
- **EsbRoot** – a framework for ESSnuSB Monte Carlo simulation based on FairRoot
  - FairRoot provides a software infrastructure to fit together various components of the simulation
- The components we use:
  - **GENIE** neutrino interaction generator (thanks to Marco Roda for suport)
    - used as a library from EsbRoot
  - **GEANT4** for particle propagation, via **ROOTVMC**
- **WCSim** as an option for WC detector modeling and digitization
  - plan to merge with in-house WC simulator

Genie UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

GEANT4 A SIMULATION TOOLKIT

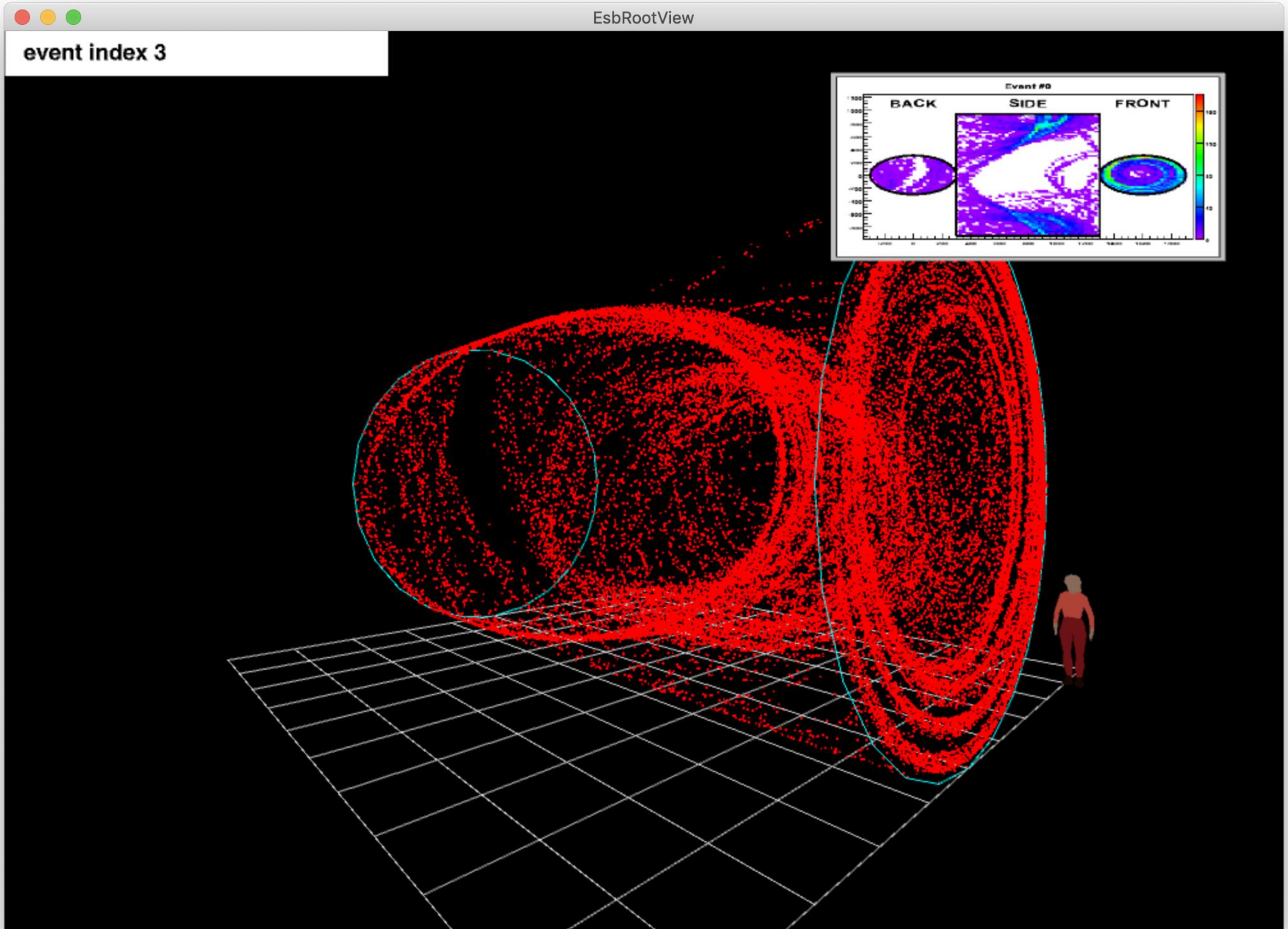
FairRoot

ROOT Data Analysis Framework



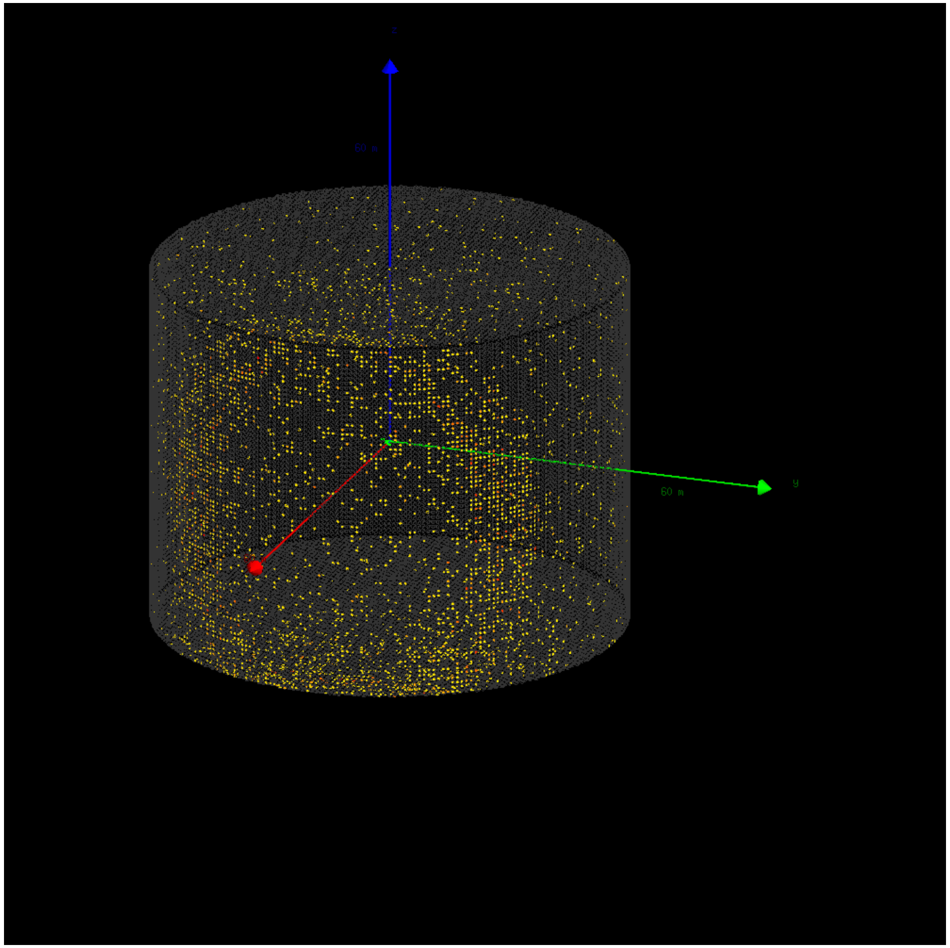
WCSim

EsbRoot visualization (in-house)



Big thanks to Guy Barrand, LAL

Running WCSim



Running vanilla WCSim on HyperK geometry

- We are running preliminary studies on near and far WC detectors using WCSim
- Thanks to Erin O'Sullivan for support!

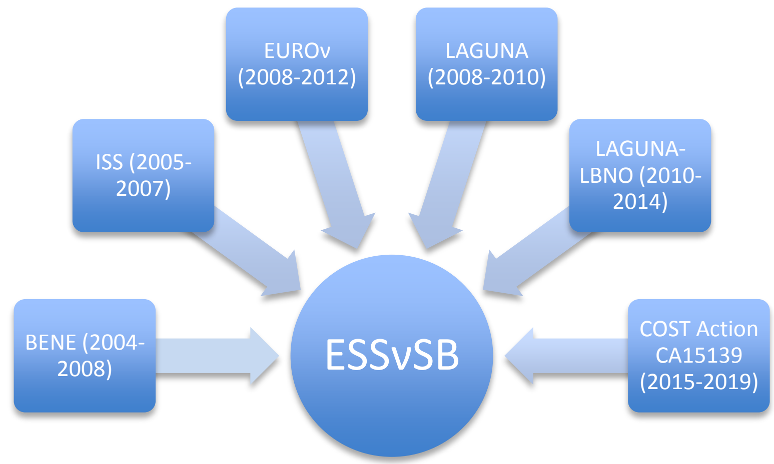
EuroNuNet

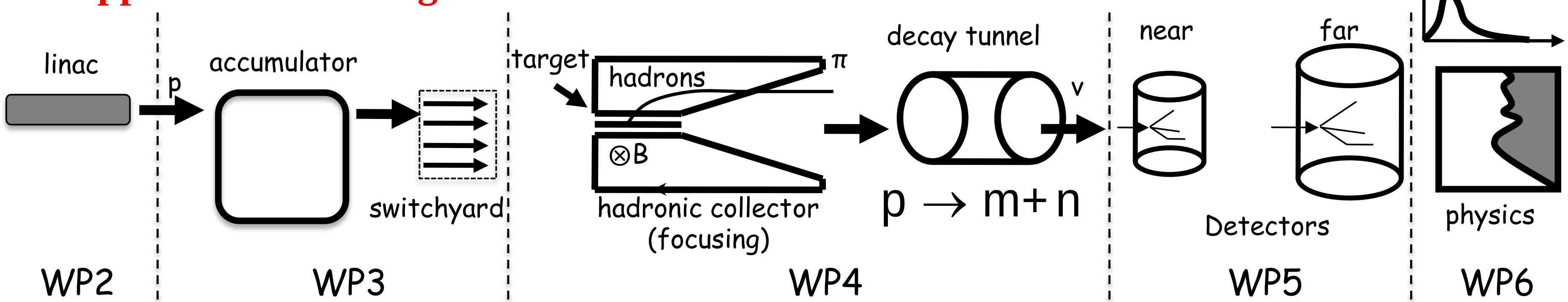
- **COST application for networking: CA15139 (2016-2020)**
  - **EuroNuNet** : *Combining forces for a novel European facility for neutrino-antineutrino symmetry violation discovery* (**http://www.cost.eu/COST_Actions/ca/CA15139**)
  - **Major goals of EuroNuNet**:
    - to aggregate the community of neutrino physics in Europe to study a neutrino long baseline concept in a spirit of inclusiveness,
    - to impact the priority list of High Energy Physics policy makers and of funding agencies to this new approach to the experimental discovery of leptonic CP violation.
    - 13 participating countries (network still growing). http://euronunet.in2p3.fr/

The members are countries which signed the Action MoU

ESSνSB at the European level

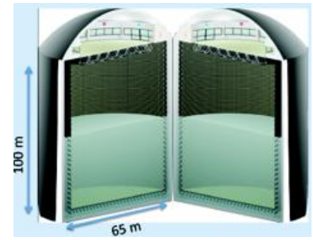
- A **H2020** EU **Design Study** (Call INFRADEV-01-2017)
  - **Title of Proposal**: Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator
  - **Duration: 4 years**
  - **Total cost: 4.7 M€**
  - **Requested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

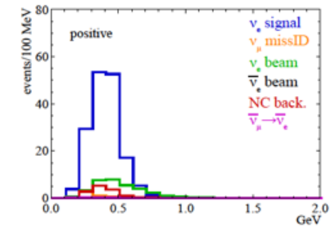




Possible ESSνSB schedule

(2nd generation neutrino Super Beam)





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ESFRI

2012: inception of the project

2016-2020: COST Action EuroNuNet

2018: beginning of ESSνSB Design Study (EU-H2020)

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

2022-2024: Preparatory Phase, TDR

2025-2026: Preconstruction Phase, International Agreement

2027-2034: Construction of the facility and detectors, including commissioning

2035-: Data taking

Nucl. Phys. B 885 (2014) 127

EUROPEAN SPALLATION SOURCE

Conclusions

- **ESSnuSB** aims to observe CP violation in neutrino oscillations at the 2nd oscillation maximum using 500 kt WC detector
  - 5 σ could be reached over 60% of δ_{CP} range
- **ESS linac** will be most powerful proton accelerator in the world
  - Can be used to generate intense neutrino beam to go to 2nd maximum
  - will be ready by 2025, decision on neutrino programme pending
- **Large detector** can also be used for rich astroparticle physics programme
- **COST** network project **CA15139** and the **ESSnuSB EU-H2020** Design Study support this project

The end