ESS NEUTRINO SUPER BEAM

Funded by the Horizon 2020 Framework Programme of the European Union

ESSνSB progress on the design of the near and far neutrino detectors and the simulation of the physics potential

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on behalf of ESSνSB

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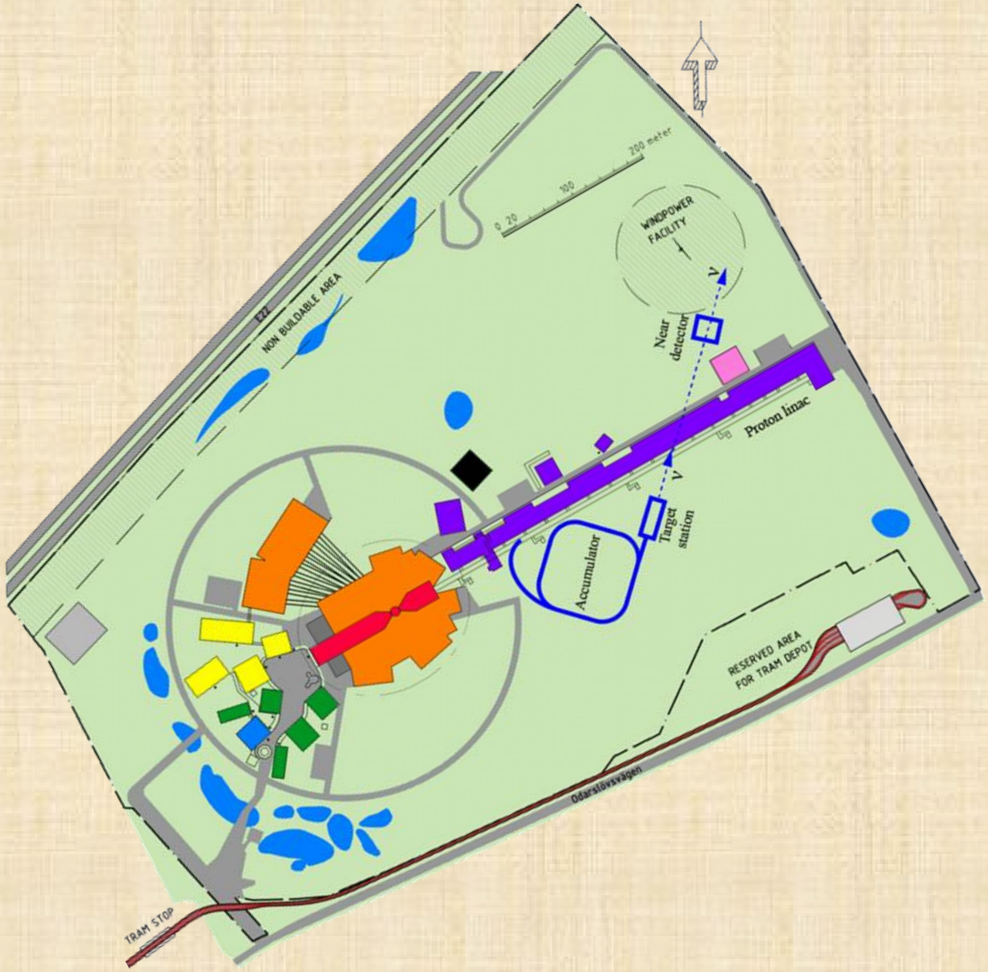
Why ESSνSB?

ESSνSB = European design study* for an experiment to measure CP violation at 2nd neutrino oscillation maximum.

- $$\frac{(P_{\mu\to e} - P_{\overline{\mu}\to\overline{e}}) \text{ @ 2nd osc. max.}}{(P_{\mu\to e} - P_{\overline{\mu}\to\overline{e}}) \text{ @ 1st osc. max.}} \sim 3$$
- 3x signal at 2nd osc. maximum is less obscured by systematics
- But less statistics because:
  - move further than 1st maximum
  - the smaller the energy -> the smaller the cross section
- Intense beam on target -> intense neutrino flux

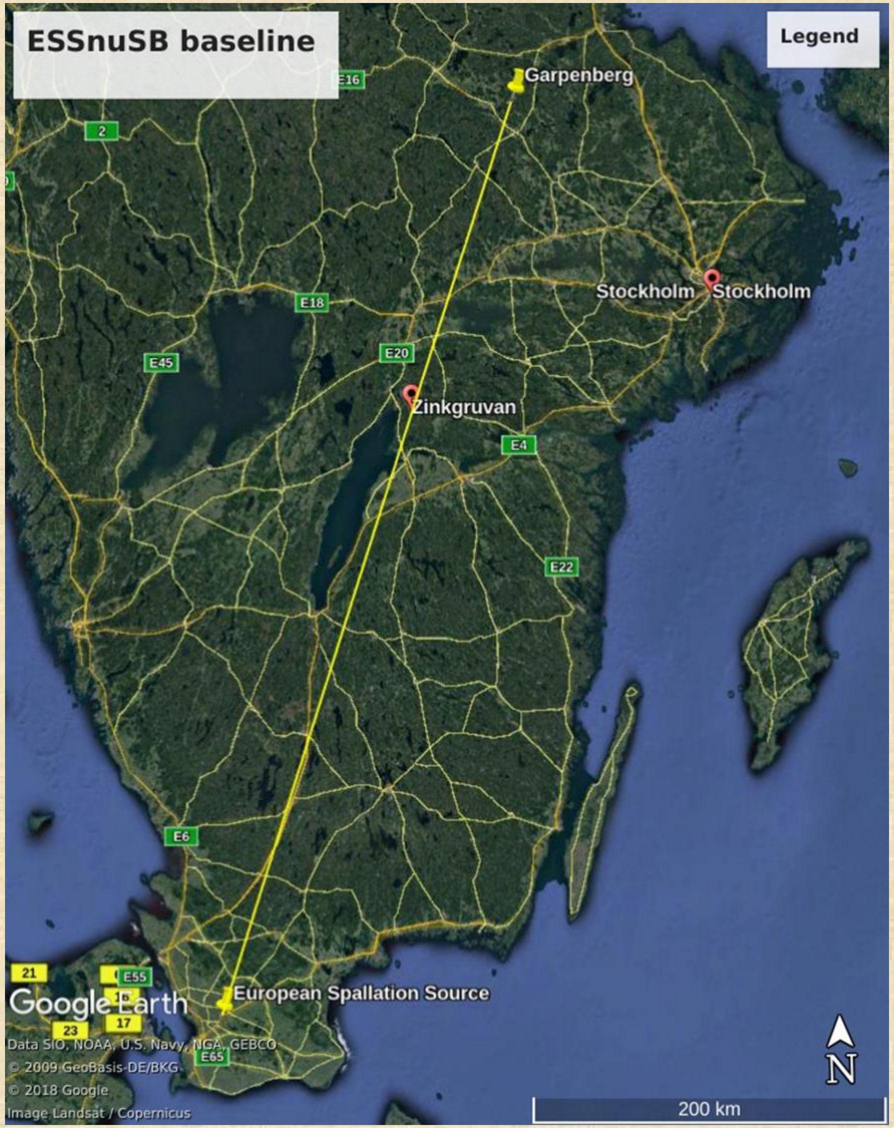
*A H2020 EU Design Study: start:2018, end:2022

Accelerator, accumulator, target and Near Detector site



- ESS proton linac near Lund, Sweden
  - Increase proton kinetic energy to 2.5 GeV
  - Double the linac rate (14 Hz → 28 Hz)
- ESS proton pulse is too long – accumulator ring (C~400 m) needed to compress proton pulses to ~ 1.3 μs, otherwise:
  - magnetic horns would melt
  - atmospheric neutrino background would be too large for CP violation measurement
- Neutrino optimised target station
  - 4 targets made of titanium spheres
- Underground near detector hall
  - Located ~250 m from the target

Far Detector site



- **Baseline:**
  - Garpenberg mine, 540 km from the neutrino source,
  - corresponding to 2nd oscillation maximum.
  - depth 1200 m

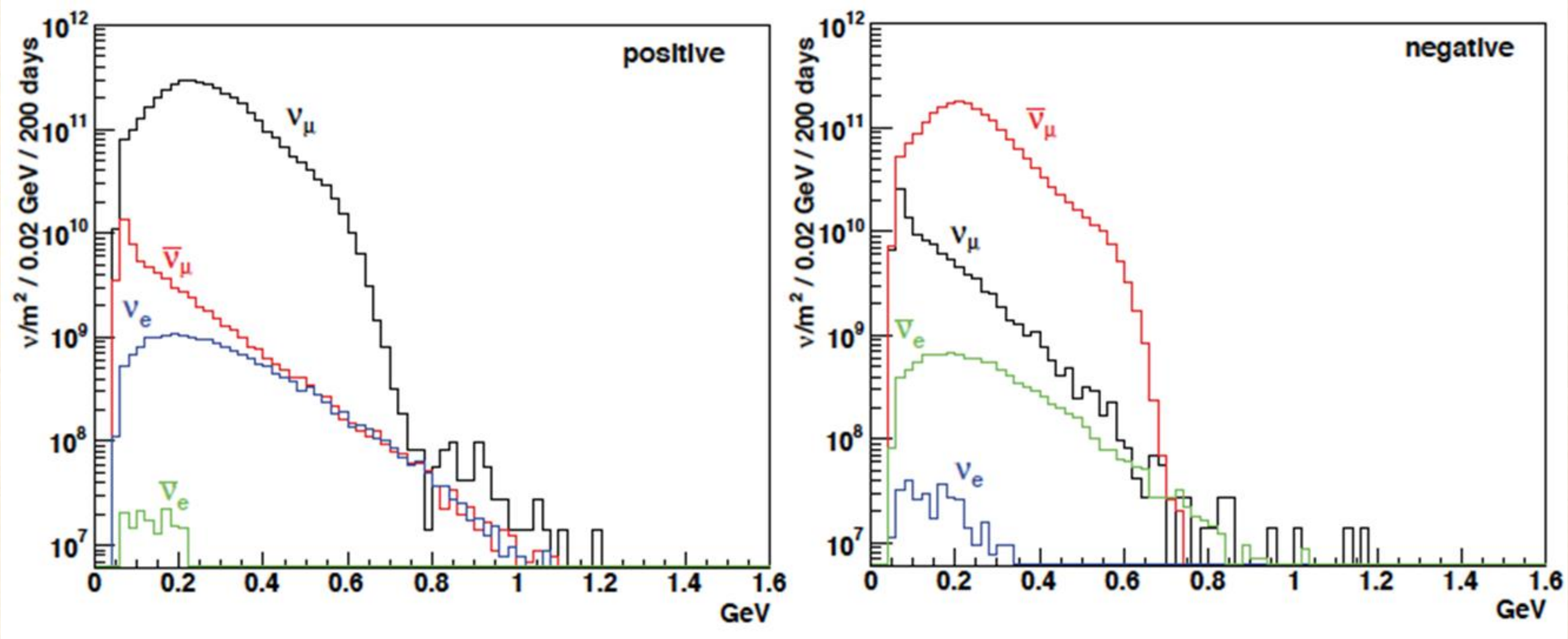
- **Alternative:**
  - Zinkgruvan mine, 340 km from source
  - depth 1500 m

Aim of detectors

- **Near detectors**
  - Constrain the prompt neutrino flux
  - Measure neutrino interaction cross-sections (both inclusive and exclusive)

- **Far detectors**
  - Observe $\overset{(-)}{\nu}_e$ appearance in the $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ oscillation channel

Neutrino energy distributions
(without optimisation)

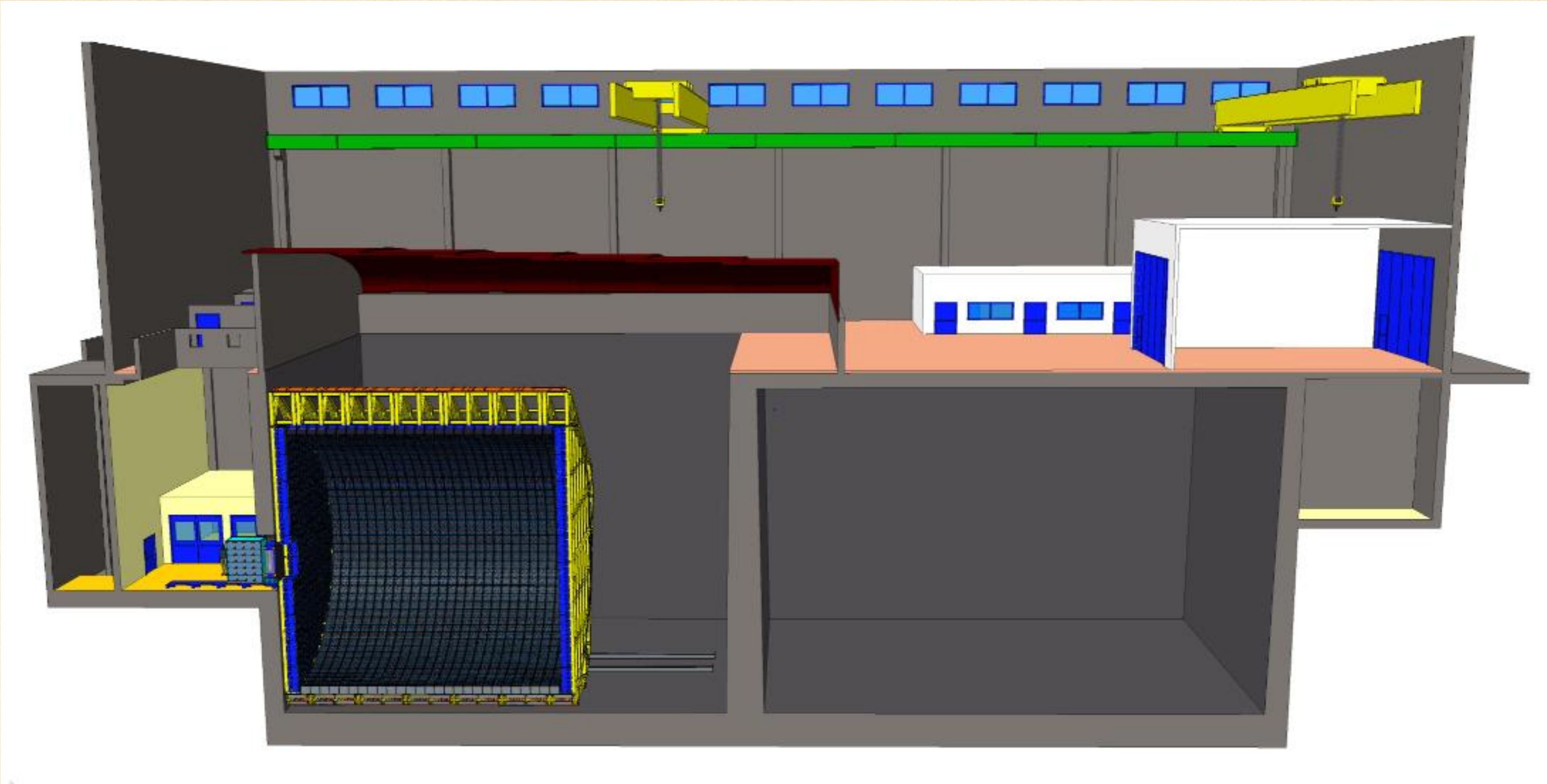


	positive		negative	
	N_ν $(\times 10^{10})/\mathrm{m}^2$	%	N_ν $(\times 10^{10})/\mathrm{m}^2$	%
ν_μ	396	97.9	11	1.6
$\bar{\nu}_\mu$	6.6	1.6	206	94.5
ν_e	1.9	0.5	0.04	0.01
$\bar{\nu}_e$	0.02	0.005	1.1	0.5

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

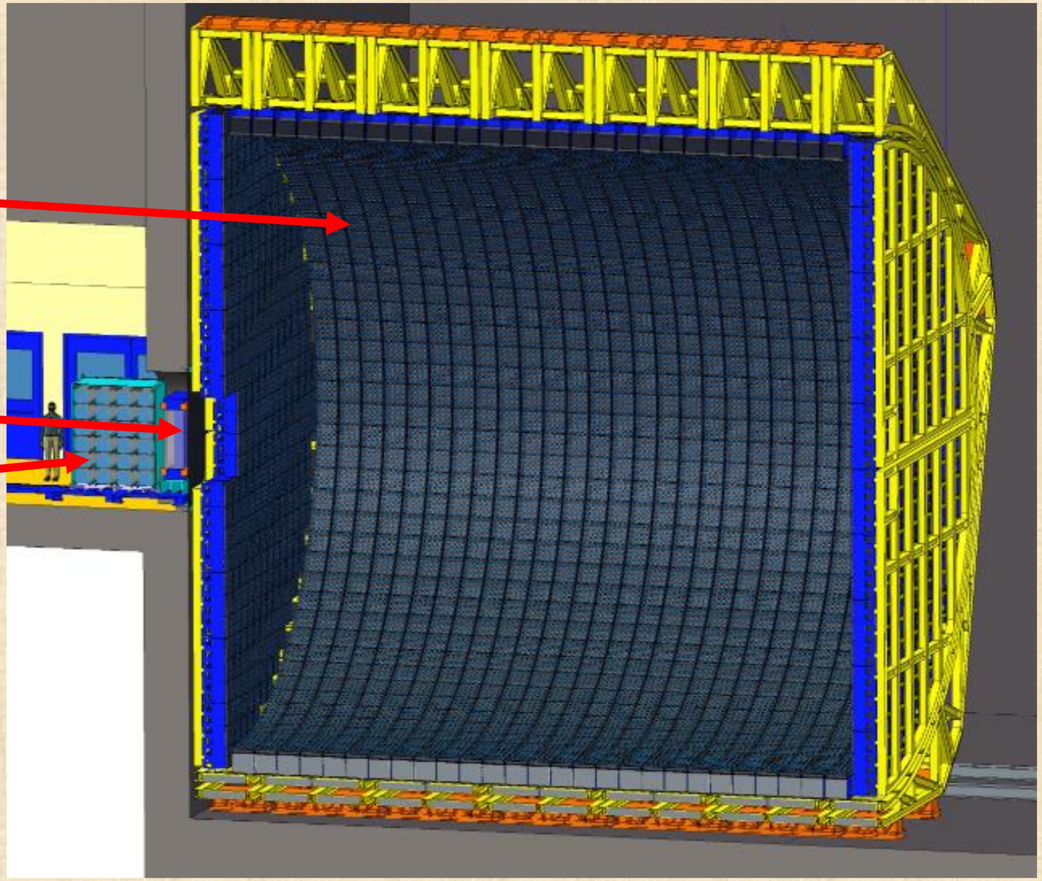
(Nucl. Phys. B 885 (2014) 127)

Near Detectors



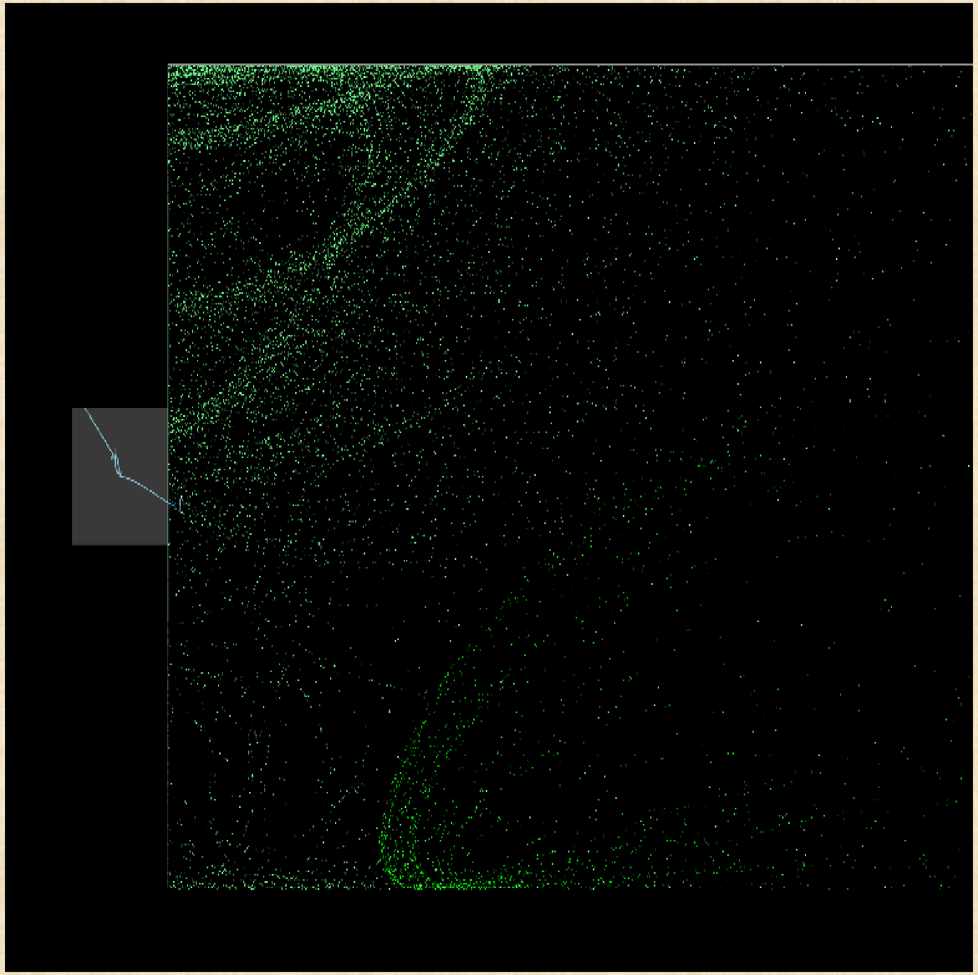
Near detectors

- **Main purposes:**
  - Constrain the prompt neutrino flux
  - Measure neutrino interaction cross-sections (both inclusive and exclusive)



- **A water Cherenkov detector**
- **A magnetized fine-grained tracker (SFGD)**
- **NINJA-like emulsion detector:**
  - water target mass of about 1 t
  - 130 Emulsion Cloud Chambers (ECC)

Near Water Cherenkov detector



Water Cherenkov detector is used for:

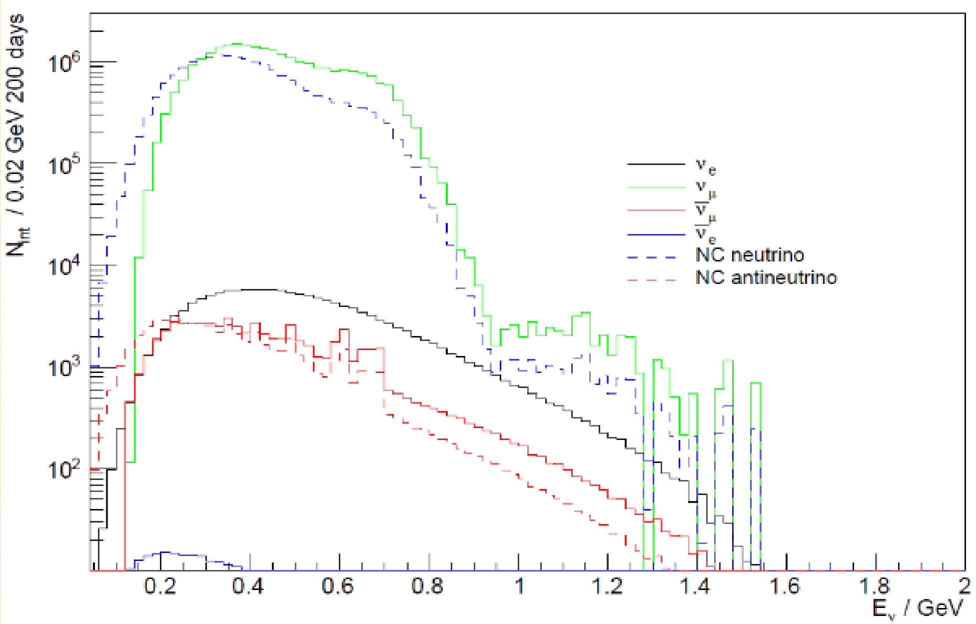
- event rate measurement;
- flux normalization;
- event reconstruction comparison with the far detector.

➢ **Some figures:**

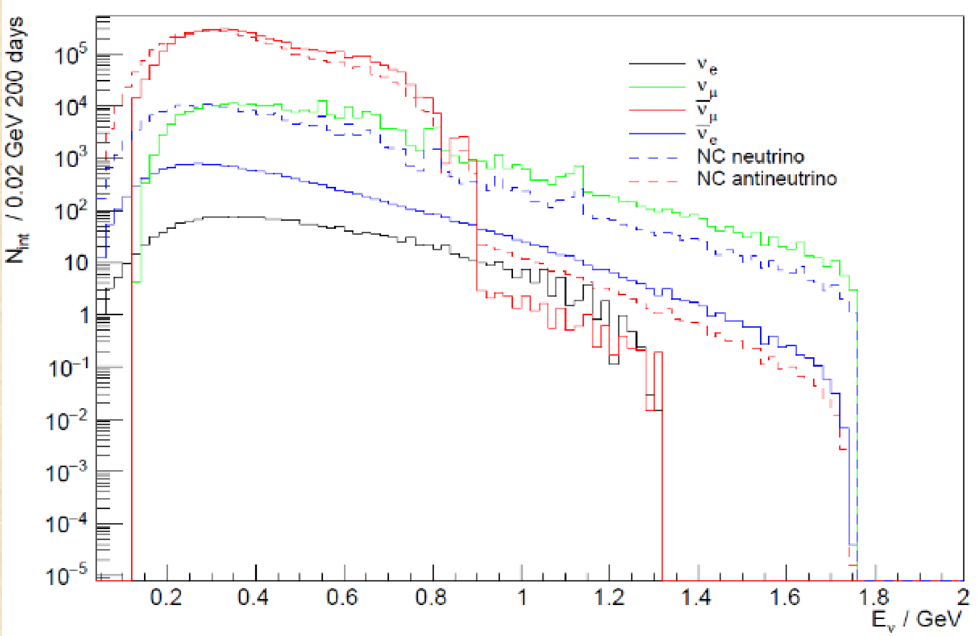
- radius R = 7 m, length L = 11 m
- 1725 m^3 total volume
- ~1000 m^3 fiducial volume
- Readout: 40% PMT coverage

Interaction rates in Near Water Cherenkov

Neutrino mode



Antineutrino mode

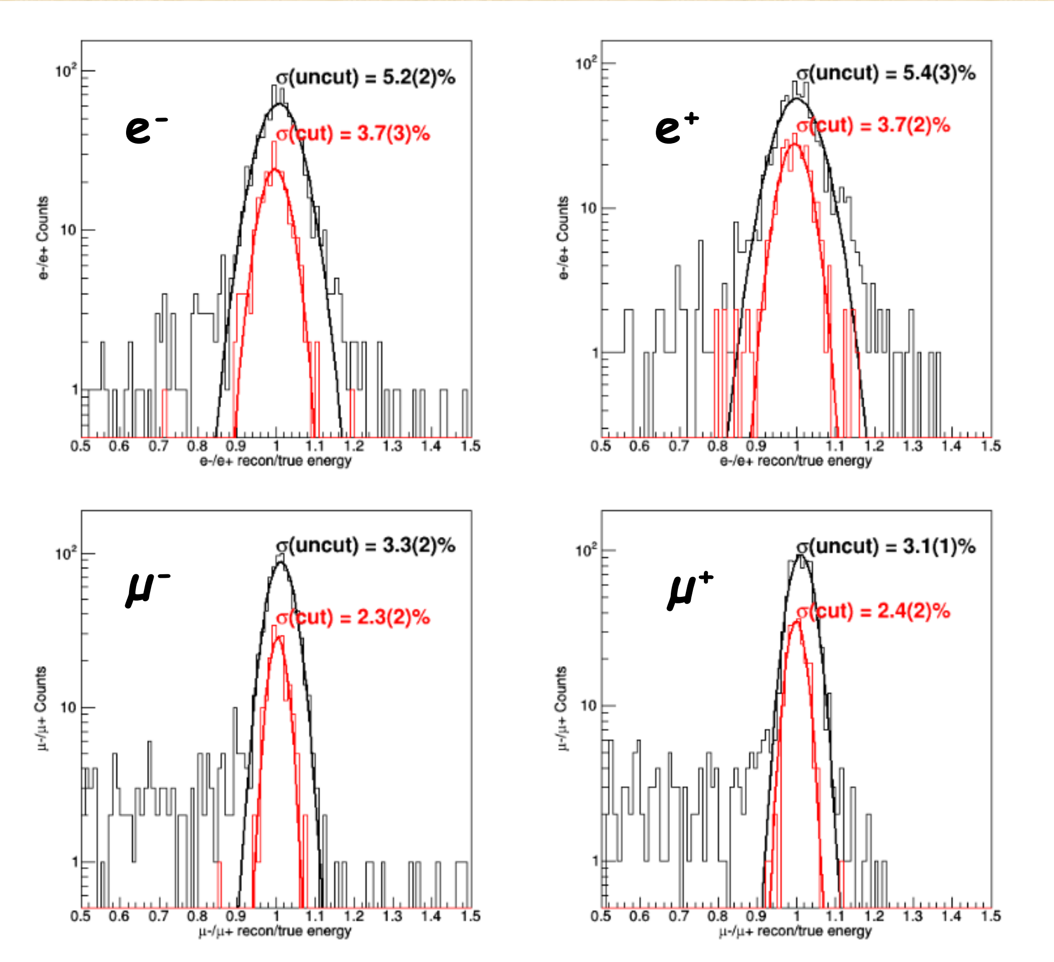


Expected number of interactions at 250 m in 500 t of water for 2.16 x 10^{23} p.o.t. (effective year):

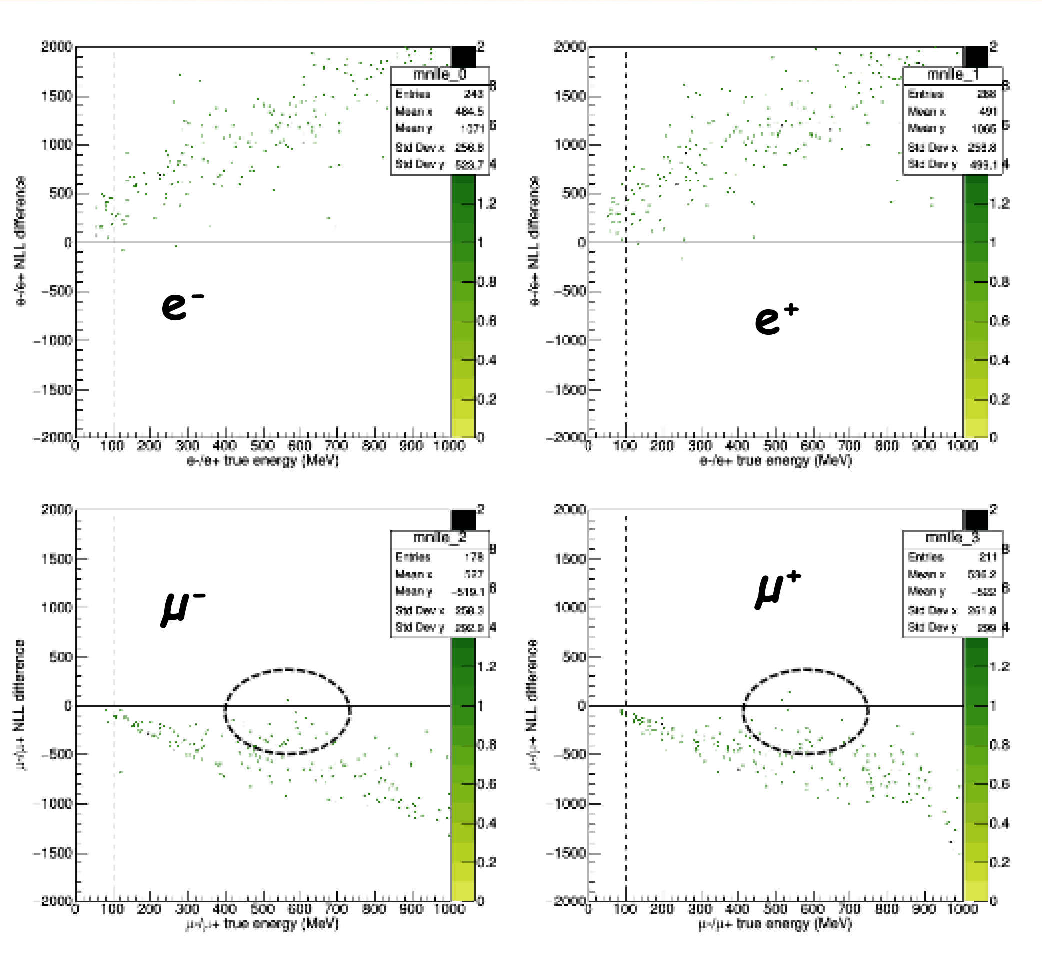
Neutrino	Expected number
ν_μ	27.5 M
$\bar{\nu}_\mu$	66 k
ν_e	150 k
$\bar{\nu}_e$	300

Neutrino	Expected number
ν_μ	265 k
$\bar{\nu}_\mu$	4.7 M
ν_e	1.8 k
$\bar{\nu}_e$	15 k

Near Water Cherenkov performance

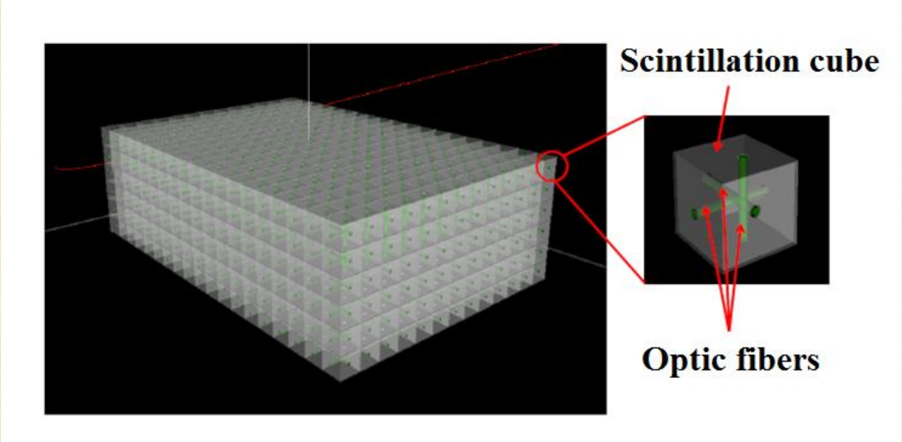


Charged lepton energy reconstruction
Fiducial cut – 2m



Charged lepton identification
Fiducial cut – 2m

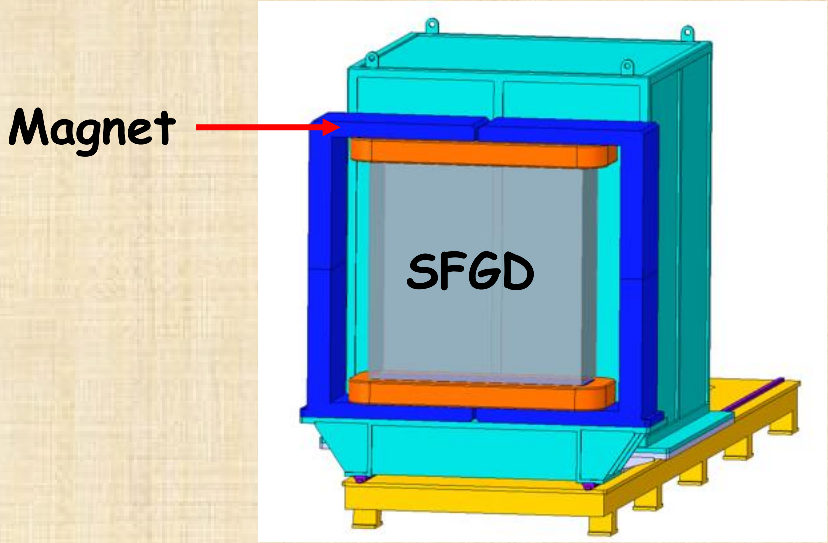
Super Fine-Grained Tracker (SFGD)



SFGD MC geometry

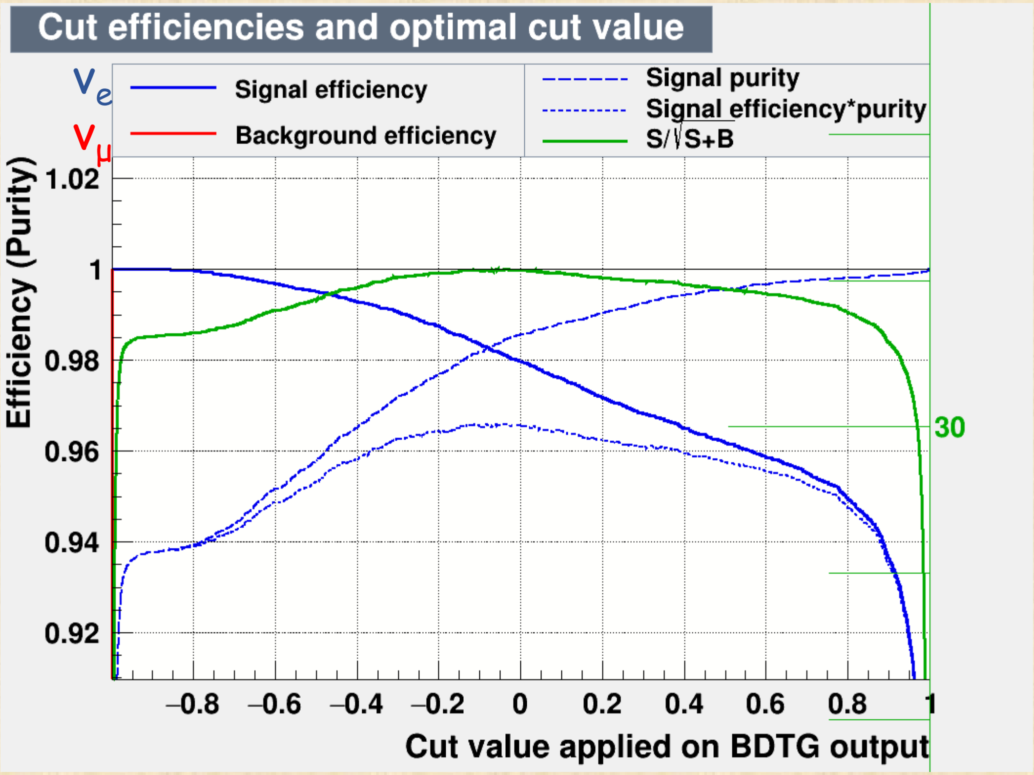
SFGD detector is used for measurements of neutrino cross-sections in energy region (60–600 MeV).

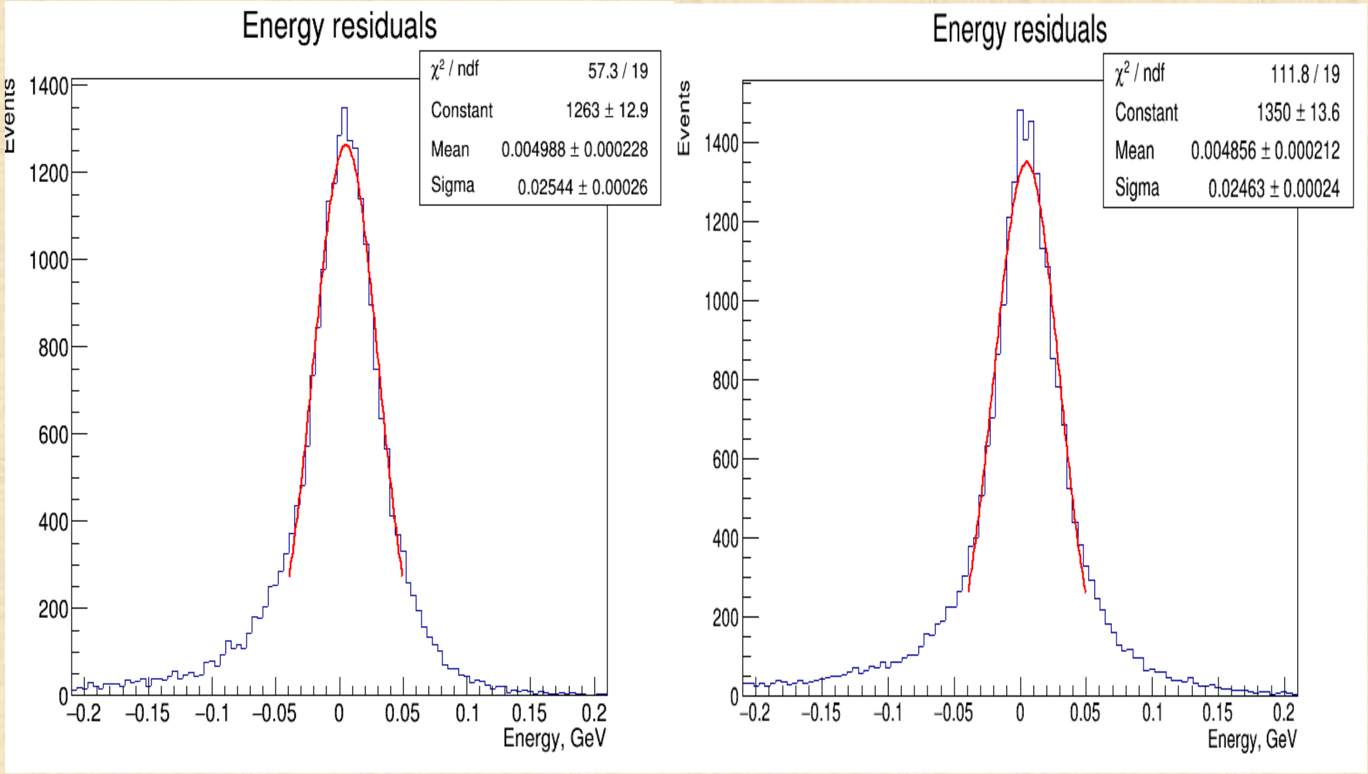
- **Some figures:**
  - scintillating cubes 1x1x1 cm^3
  - WLS fibers in three dimensions
  - overall dimensions 1.4x1.4x0.5m^3
  - Dipole magnetic field up to 1 T
  - Readout MPPCs



SFGD prototype tested at CERN 2018

Super Fine-Grained Tracker performance





- ***Separation ν_e/ν_μ CC events*** with machine learning methods (TMVA):
  - signal efficiency of 95,5%
  - signal purity of 99,8%

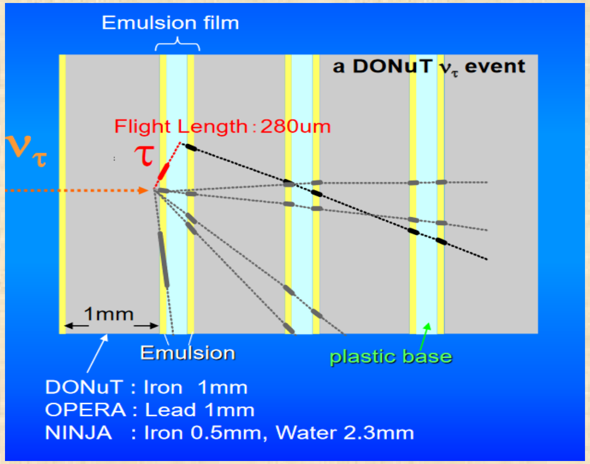
- **Neutrino energy reconstruction** for ν_μ (left) and ν_e (right) with machine learning methods (TMVA):
  - resolution in both cases in the order of 25 MeV
  - assuming true charged lepton momentum

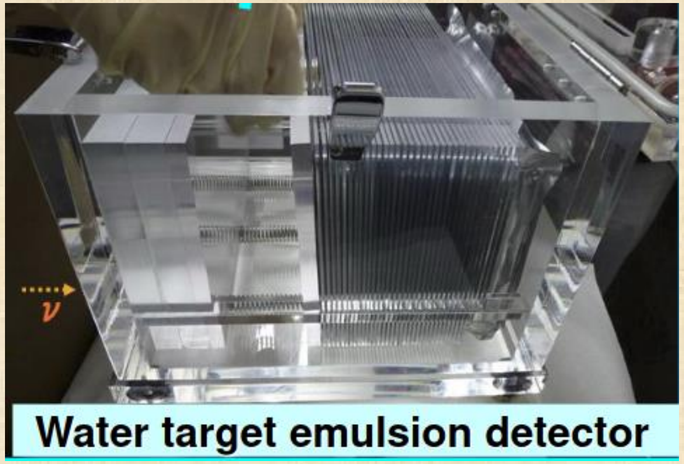
Emulsion detector NINJA-like

- **Usage in ESSnuSB**
  - Study of neutrino interaction topology
  - Measurement of interaction cross-section

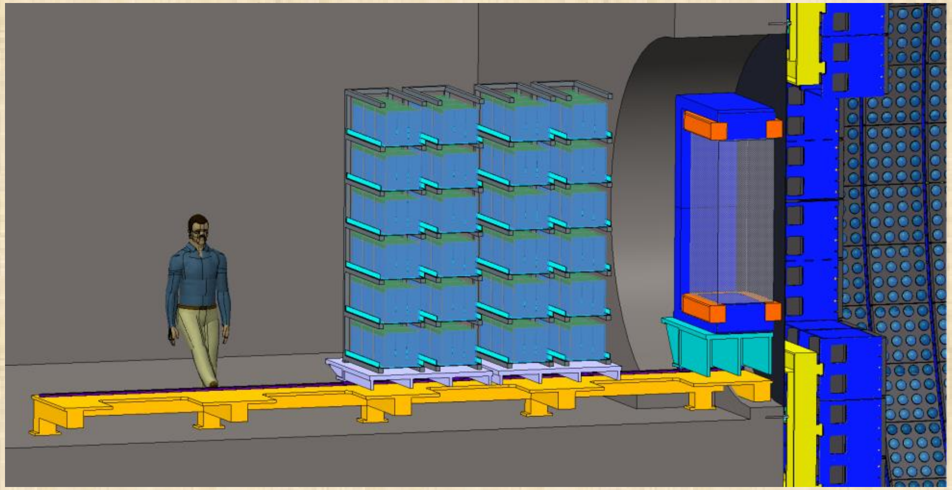
- ***Advantages of the emulsion detector***
  - Can reconstruct all charged particle tracks with high precision
  - Can detect gammas via conversion
  - Good electron/muon/hadron discrimination

- **Disadvantages of the emulsion detectors**
  - No timing information
    - But can be restored by connecting tracks with SFGD
  - Price per mass
  - No online event reconstruction
  - Labour intensive





Courtesy T. Fukuda



Possible configuration in ESSnuSB

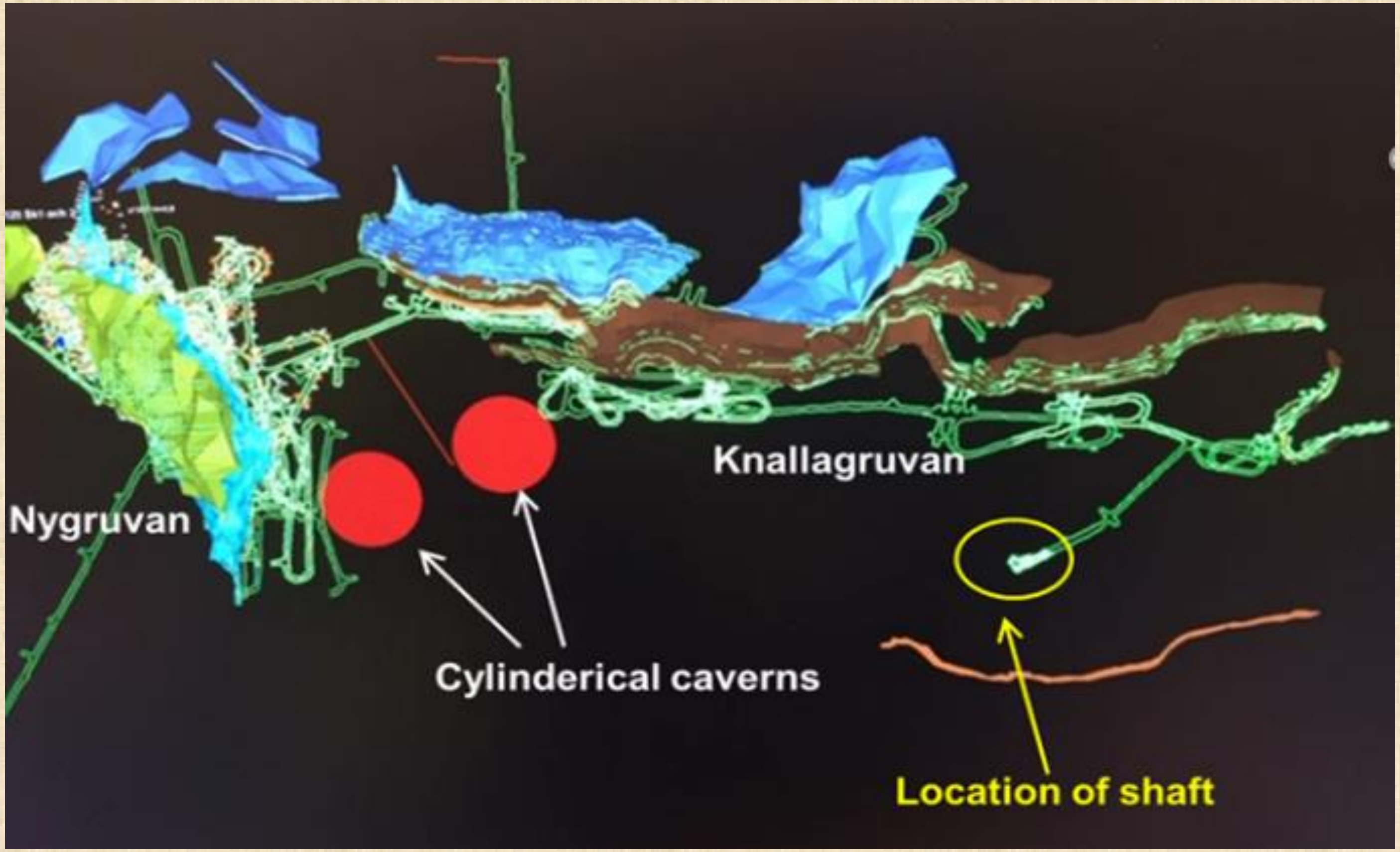
Cross-section measurements

- **Main problem:**
  - Event rate (what we measure) is proportional to **(flux) x (cross-section).**
  - So, we need one to measure the other, if using event rate as observable.

- **Strategies:**
  - Use elastic scattering of neutrinos on electrons (known cross-section) to constrain the flux
    - measured in the Near WC detector;
    - neutrino cross-section scales with target mass:
      - having electron as a target, the cross-section is much smaller than having nucleon as a target
    - Event selection:
      - ν - e scattering has a very forward single electron in the final state.

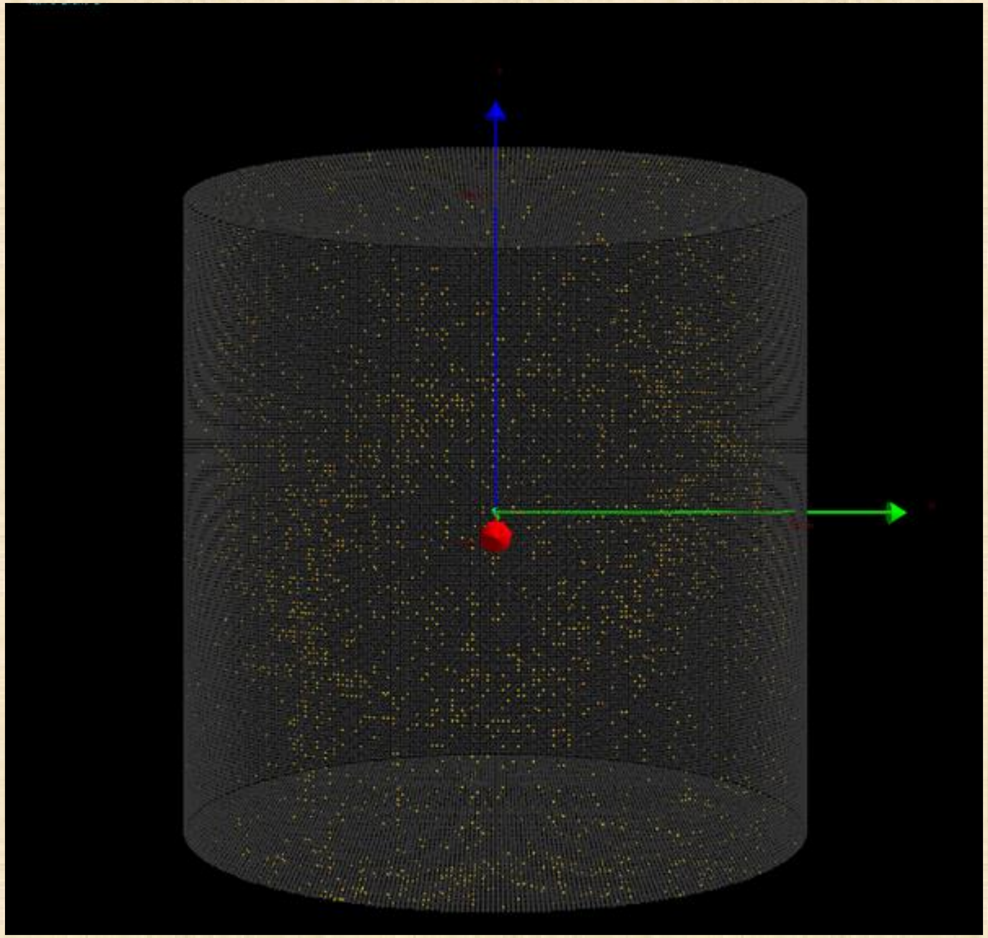
  - Having constraint on the flux, we can measure interaction cross-sections in all Near Detectors:
    - WCkov, Super FGD, emulsion

Far Detector



Far Detectors

Main purpose: observe $\overset{(-)}{\nu}_e$ appearance in the $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ oscillation channel

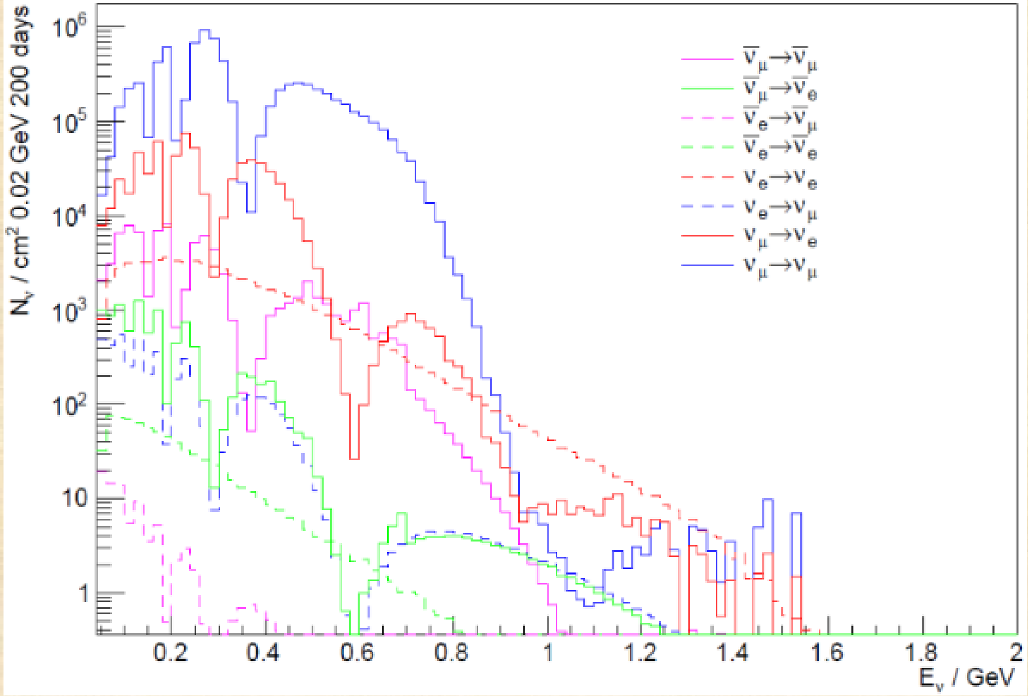


- **Two identical water Cherenkov detectors.**
- **Each module is a standing cylinder:**
  - diameter D = 78 m, height h = 78 m
  - 373k m^3 total volume
  - 270k m^3 fiducial volume (~10xSuperK)
  - Readout: 38k 20″ PMTs
  - 30% optical coverage

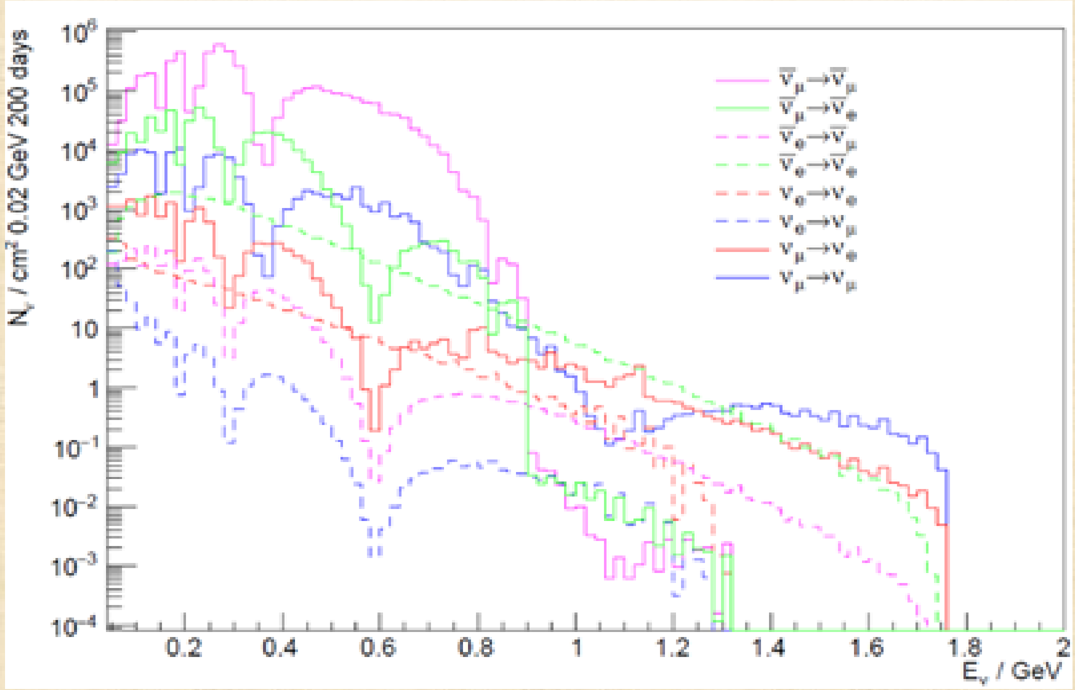
- **Can also be used for other purposes:**
  - **Proton decay**
  - **Astroparticles**
  - **Galactic SN ν**
  - **Supernovae "relics"**
  - **Solar Neutrinos**
  - **Atmospheric Neutrinos**

Interaction rates in Far Detectors

Neutrino mode



Antineutrino mode



Expected number of interactions at 540 km in 540 kt of water for 2.16 x 10^{23} p.o.t. (effective year), assuming $\delta_{CP} = 0$:

Channel	Expected number
$\nu_\mu \rightarrow \nu_e$	200
$\nu_\mu \rightarrow \nu_\mu$	3600
$\nu_e \rightarrow \nu_e$	30

Channel	Expectd number
$\overline{\nu_\mu} \rightarrow \overline{\nu_e}$	40
$\overline{\nu_\mu} \rightarrow \overline{\nu_\mu}$	600
$\overline{\nu_e} \rightarrow \overline{\nu_e}$	3

Neutrino energy reconstruction

Kinematical neutrino energy reconstruction formula

$$E_{\nu}^{rec} = \frac{m_f^2 - (m_i')^2 - m_l^2 + 2m_i' E_l}{2(m_i' - E_l + p_l \cos\theta_l)} \quad (4)$$

where E_{ν}^{rec} is the reconstructed neutrino energy, m_i and m_f are the initial and final nucleon masses respectively, and $m_i' = m_i - E_b$, where $E_b = 27\,\mathrm{MeV}$ is the binding energy of a nucleon inside ^{16}O nuclei. E_l, p_l and θ_l are the reconstructed lepton energy, momentum, and angle with respect to the beam, respectively. The selec-

From: Phys. Rev. D 96, 092006

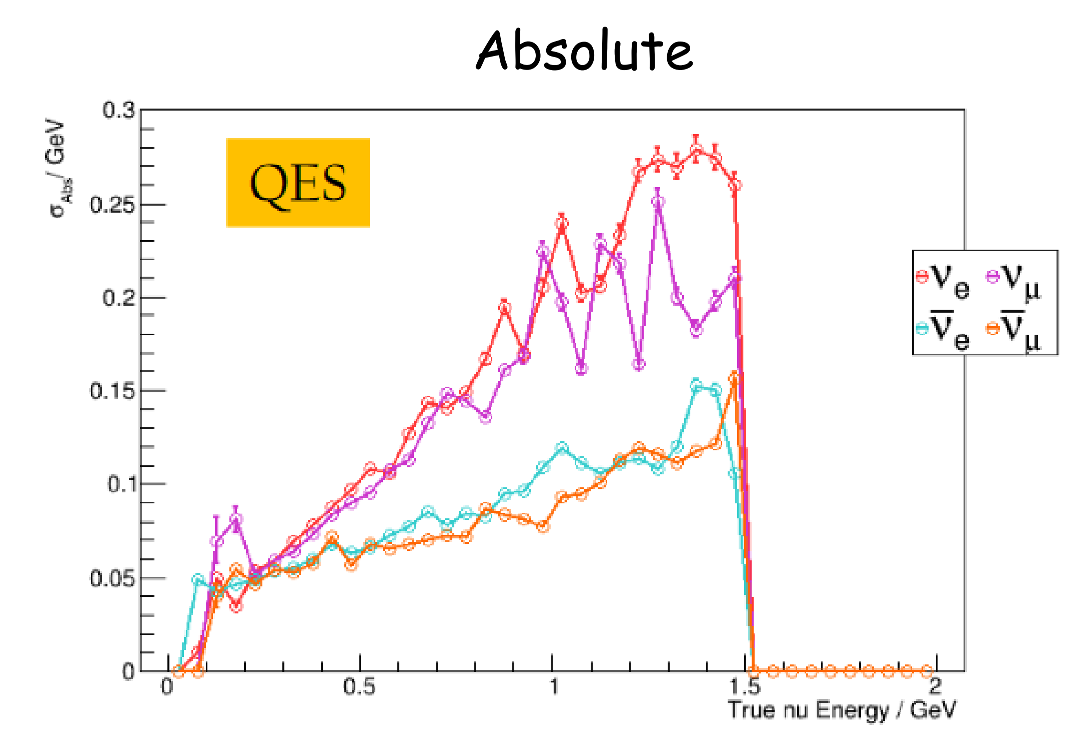
- **Given that you know:**
  - momentum of the outgoing charged lepton
  - its angle w.r.t. incoming neutrino
  - that it is a quasielastic interaction
  - which nucleus neutrino interacted with (^{16}O)

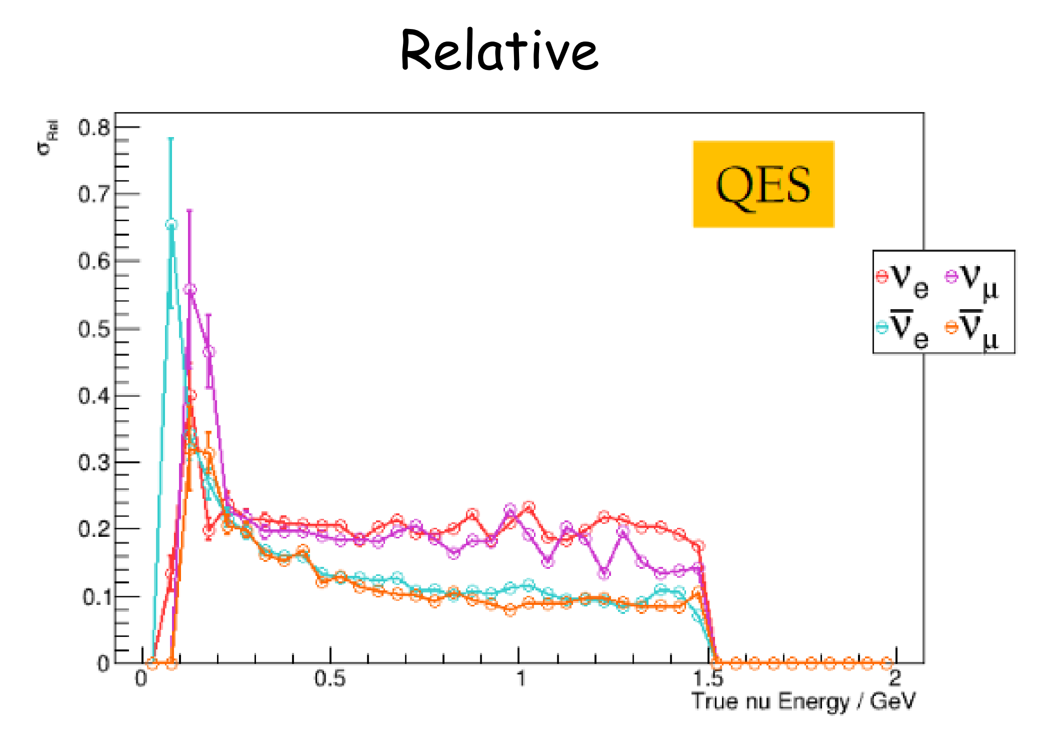
you can **approximately** calculate neutrino energy.

Intrinsic uncertainties come from nuclear effects, most notably **Fermi motion** of nucleons in nuclei.

Neutrino energy resolution

- Quasi-elastic scattering.
- Fiducial volume cut – 2 m from walls.





Neutrino energy resolution: **140 MeV for neutrinos** and **100 MeV for antineutrinos.**

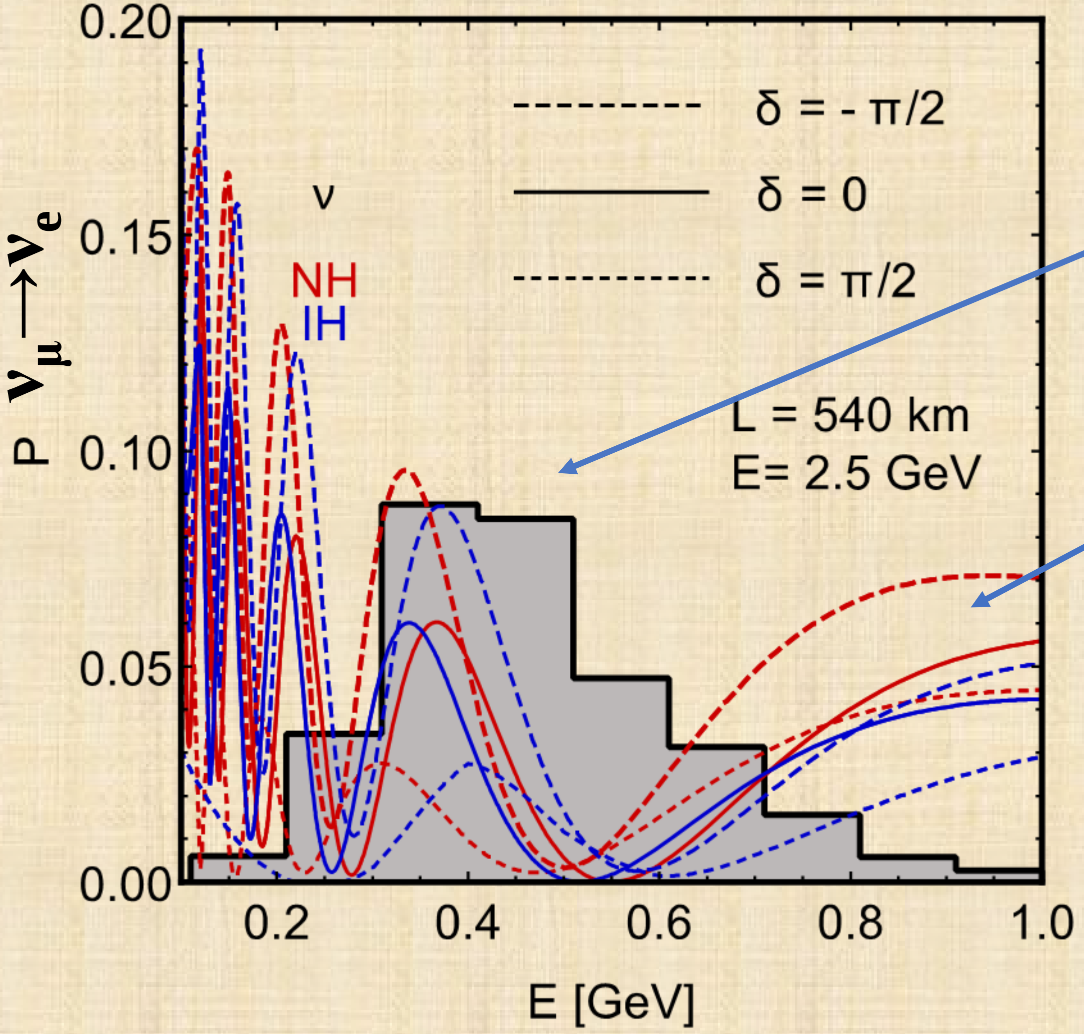
Conclusions

- **The Project ESSnuSB:**
  - aims to observe CP violation in neutrino oscillations at the 2nd oscillation maximum using 500 kt WC detector
  - large associated detectors have a rich astroparticle physics program.
  - a preparatory phase is needed.

- **The detectors:**
  - observe $\overset{(-)}{\nu}_e$ appearance in the $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ oscillation channel
  - constrain the prompt neutrino flux.
  - measure neutrino interaction cross-sections (both inclusive and exclusive).

Backup

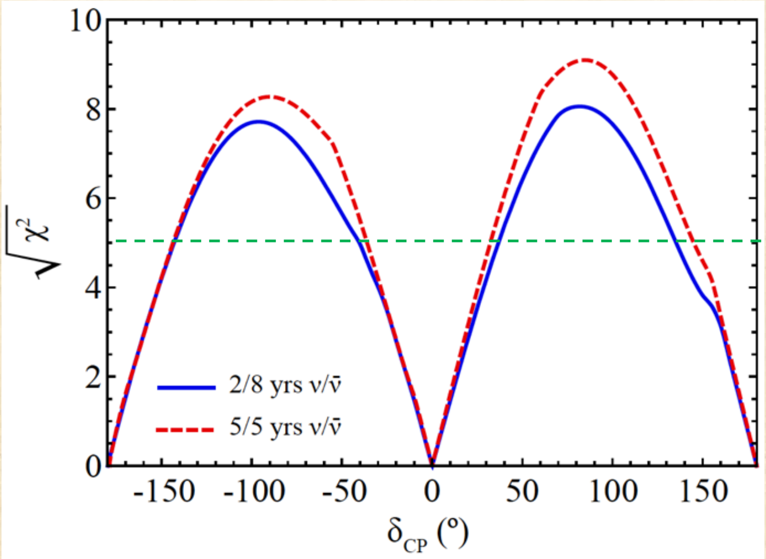
2^{nd} Oscillation maximum coverage

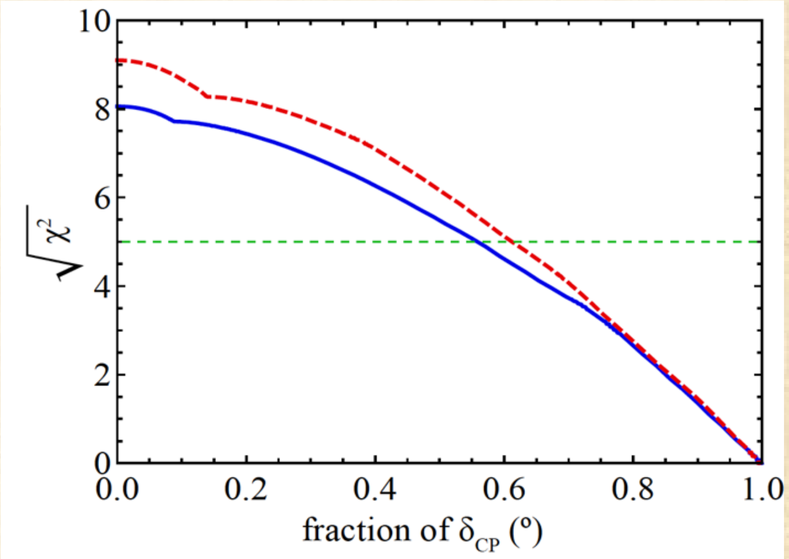


2^{nd} oscillation max. well covered by the ESS neutrino spectrum

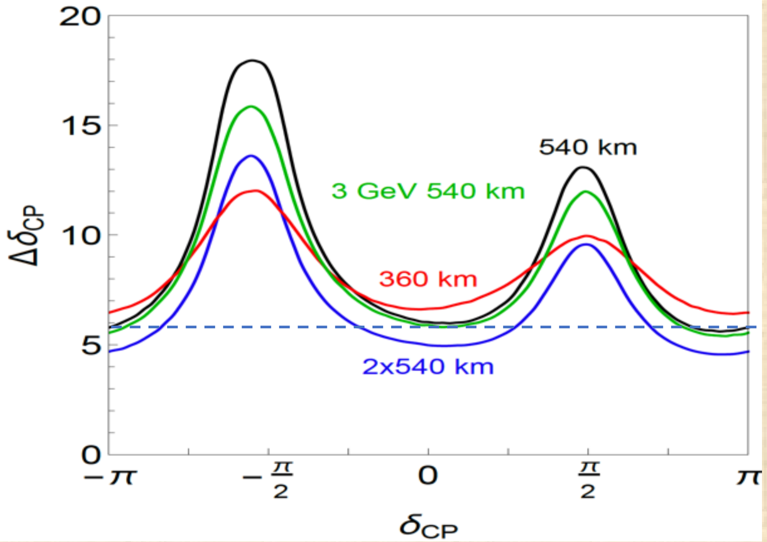
1^{st} oscillation max.

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 fully optimized facility;
- **5/10%** systematic errors on signal/background.

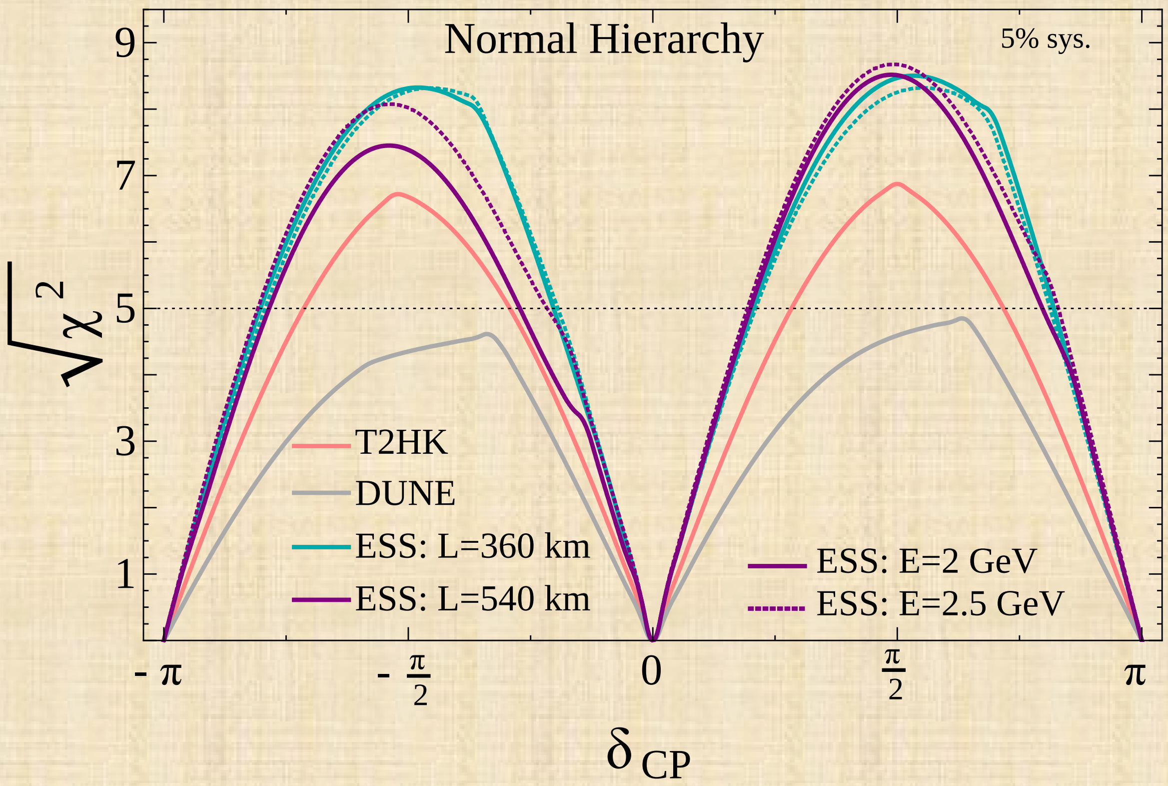


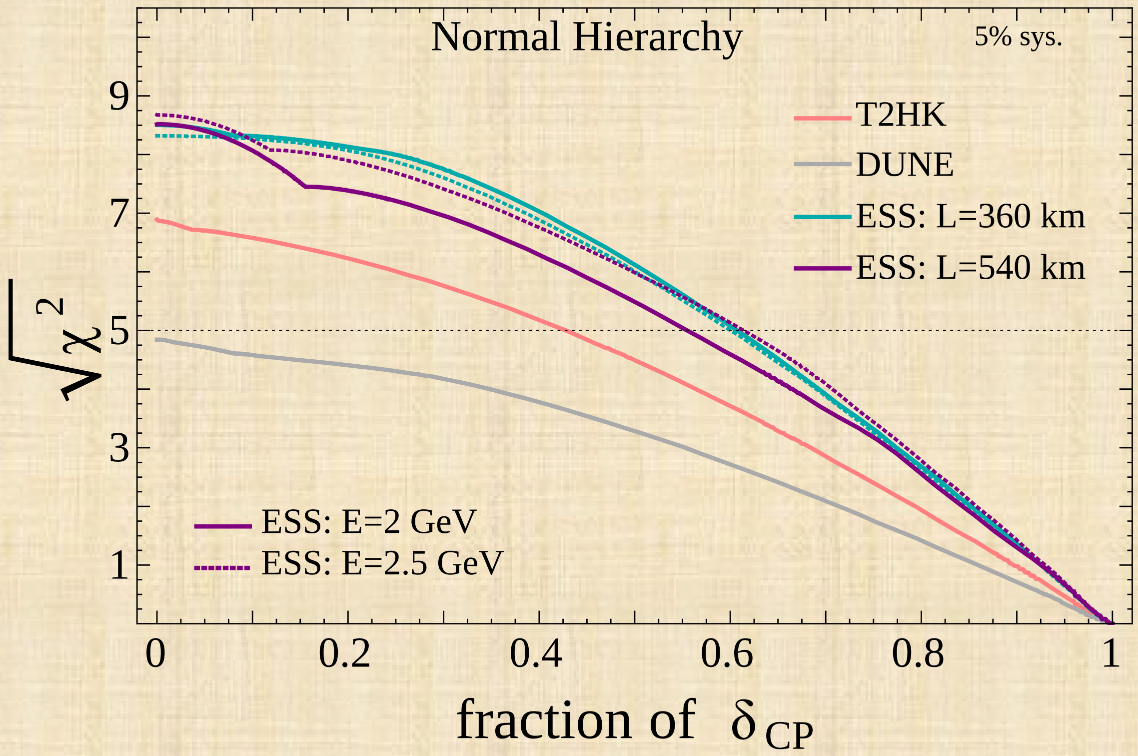
Systematic errors

Systematics	SB			BB			NF		
	Opt.	Def.	Cons.	Opt.	Def.	Cons.	Opt.	Def.	Cons.
Fiducial volume ND	0.2%	0.5%	1%	0.2%	0.5%	1%	0.2%	0.5%	1%
Fiducial volume FD	1%	2.5%	5%	1%	2.5%	5%	1%	2.5%	5%
(incl. near-far extrap.)									
Flux error signal ν	5%	7.5%	10%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background ν	10%	15%	20%	correlated			correlated		
Flux error signal $\bar{\nu}$	10%	15%	20%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background $\bar{\nu}$	20%	30%	40%	correlated			correlated		
Background uncertainty	5%	7.5%	10%	5%	7.5%	10%	10%	15%	20%
Cross secs $\times$ eff. QE†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs $\times$ eff. RES†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs $\times$ eff. DIS†	5%	7.5%	10%	5%	7.5%	10%	5%	7.5%	10%
Effec. ratio ν_e/ν_μ QE*	3.5%	11%	–	3.5%	11%	–	–	–	–
Effec. ratio ν_e/ν_μ RES*	2.7%	5.4%	–	2.7%	5.4%	–	–	–	–
Effec. ratio ν_e/ν_μ DIS*	2.5%	5.1%	–	2.5%	5.1%	–	–	–	–
Matter density	1%	2%	5%	1%	2%	5%	1%	2%	5%

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

Comparisons





Comparison using the same systematic errors

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