ESS NEUTRINO SUPER BEAM

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

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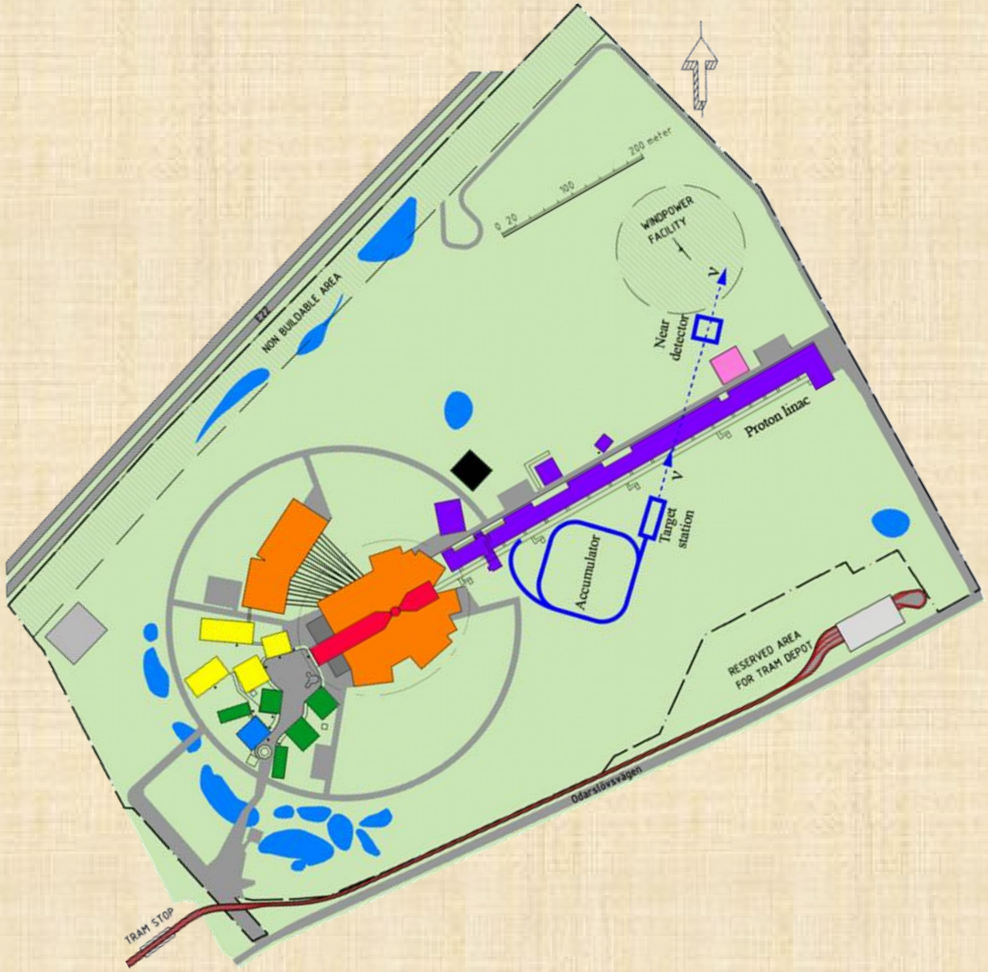
Why ESSνSB?

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

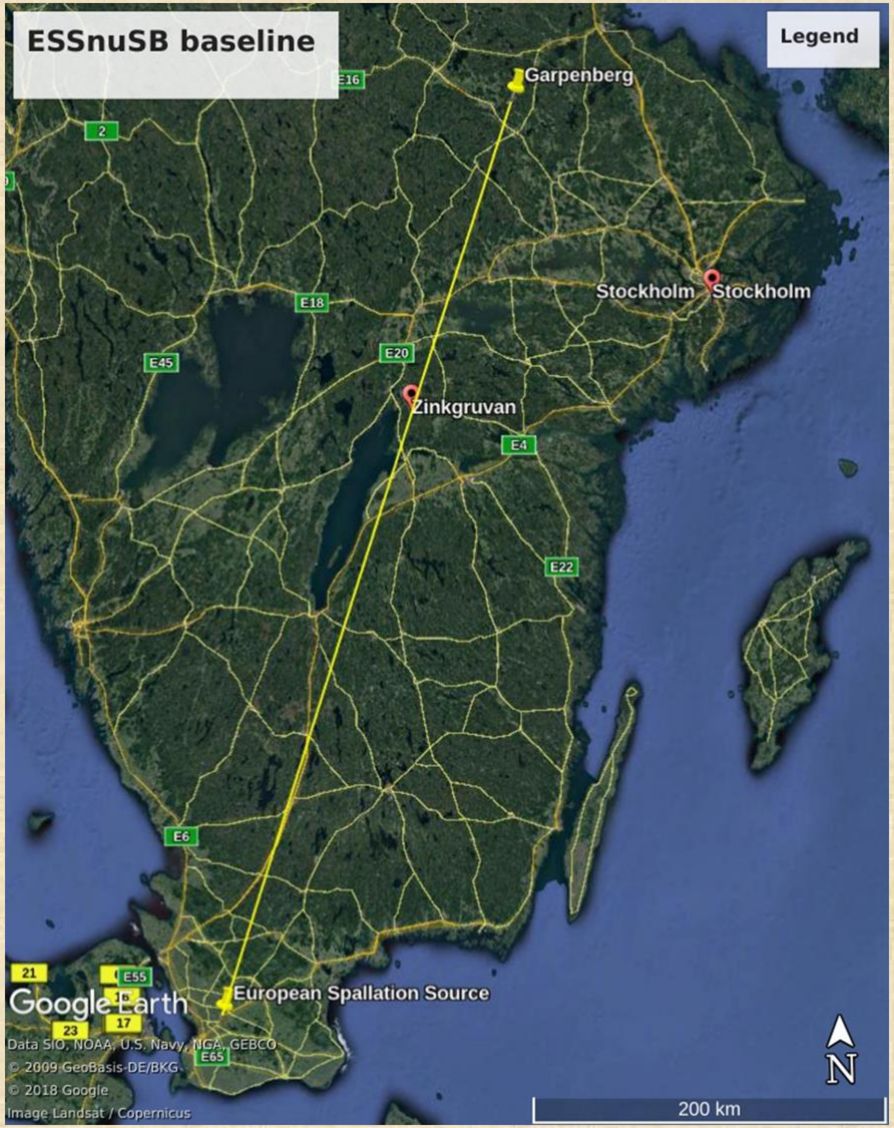
*A Horizon 2020 EU Design Study Project: grant agreement No 777419; start: 2018, end: 2022

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

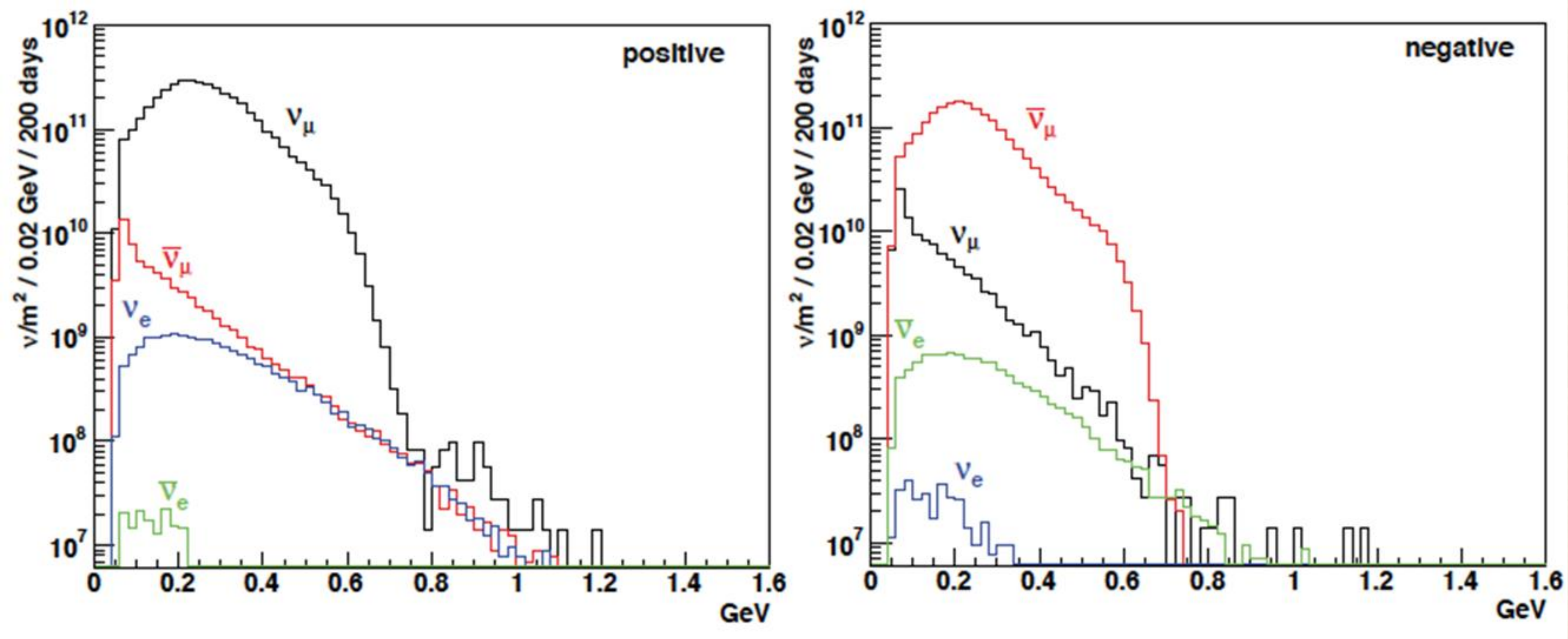
- Alternative:
  - Zinkgruvan mine, 340 km from source
  - depth 1500 m

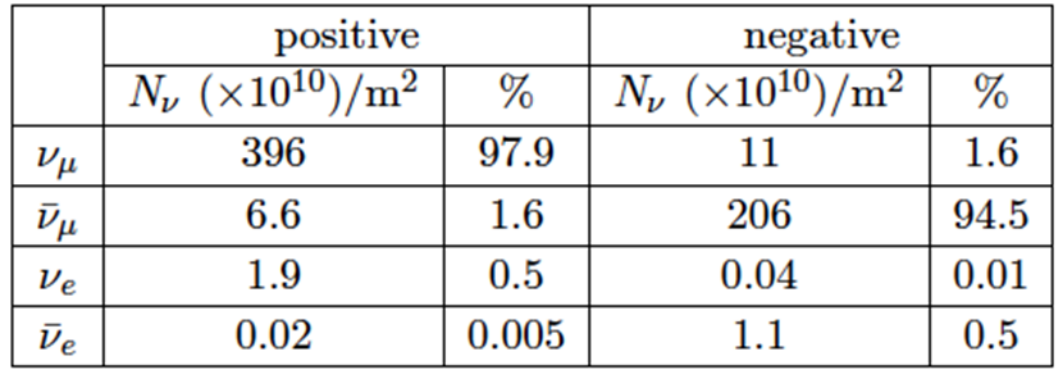
Aim of detectors

- **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 $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ oscillation channel

Neutrino energy distributions

(without optimisation)



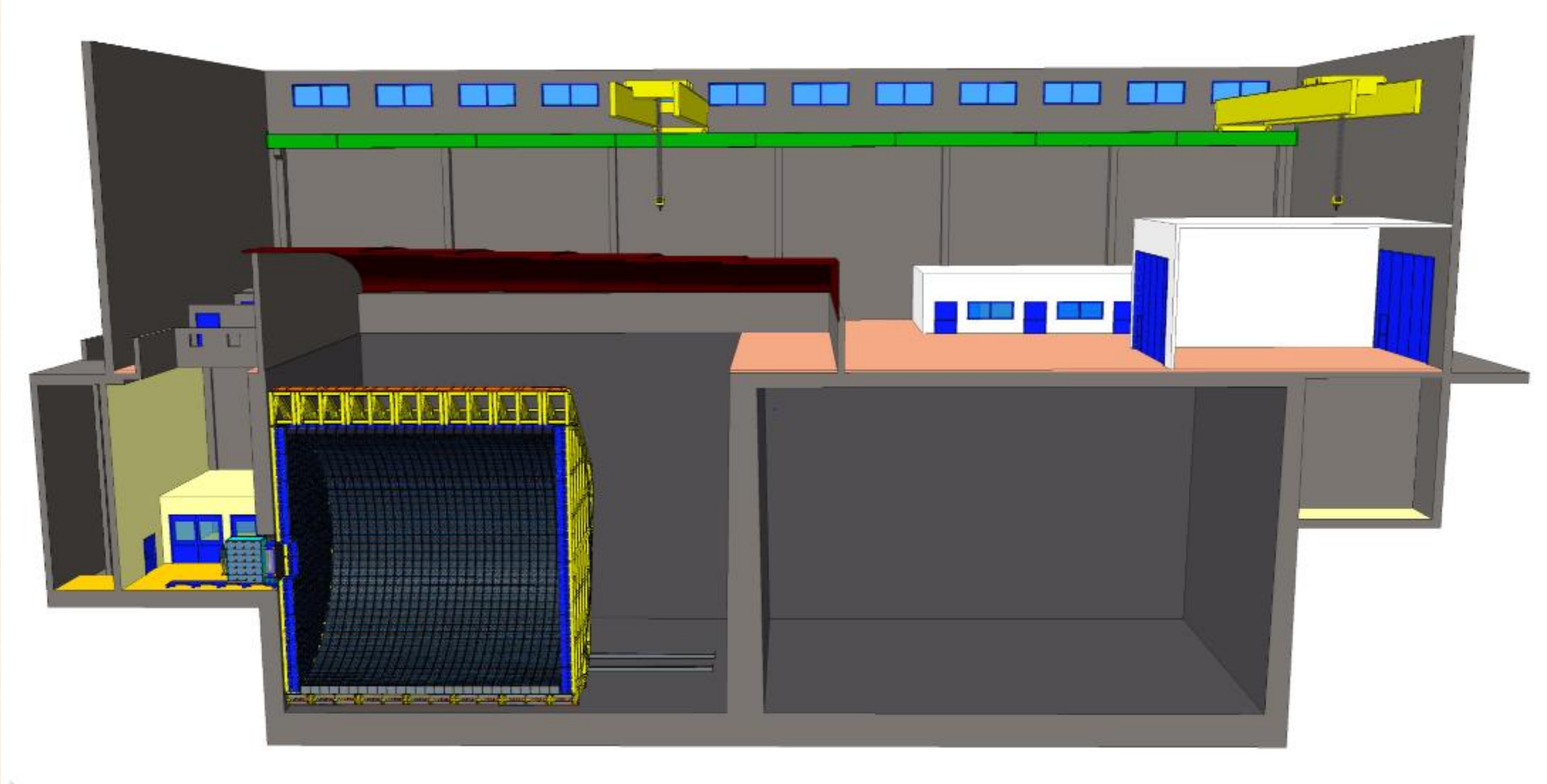


	positive		negative	
	N_ν $(\times 10^{10})/\mathrm{m}^2$	%	N_ν $(\times 10^{10})/\mathrm{m}^2$	%
ν_μ	396	97.9	11	1.6
$\bar{\nu}_\mu$	6.6	1.6	206	94.5
ν_e	1.9	0.5	0.04	0.01
$\bar{\nu}_e$	0.02	0.005	1.1	0.5

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

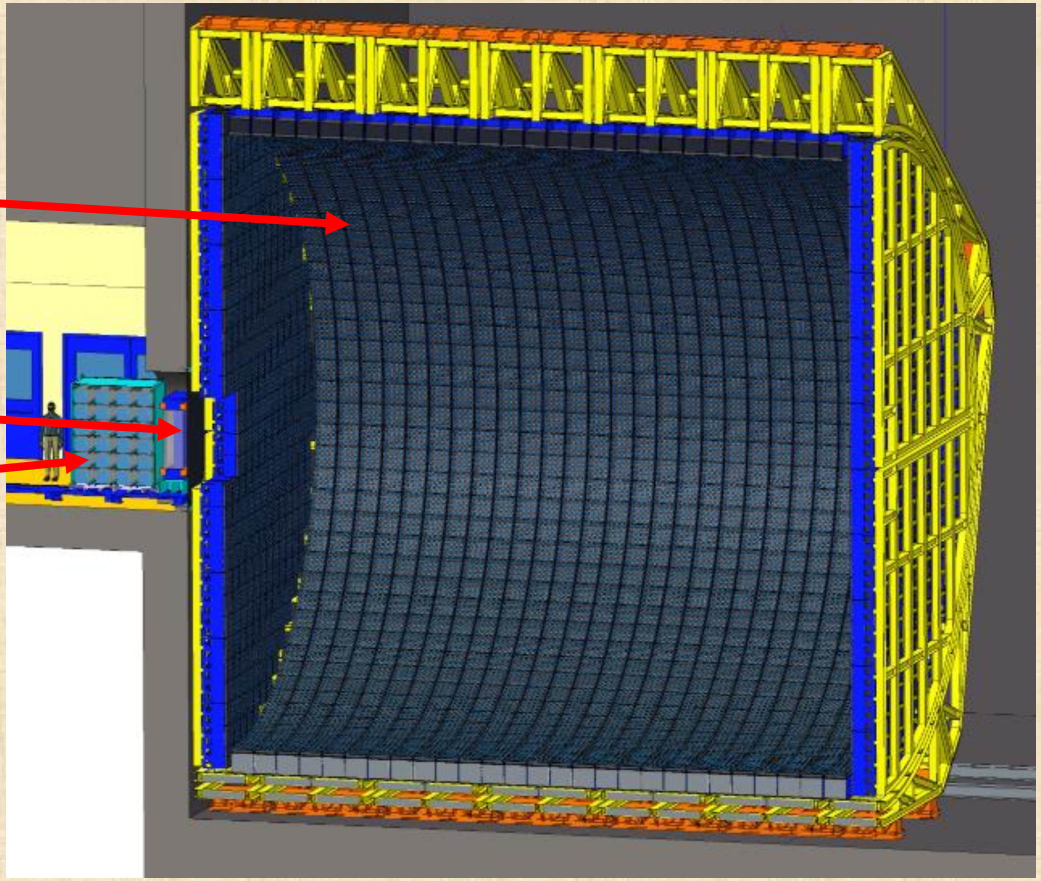
(Nucl. Phys. B 885 (2014) 127)

Near Detectors



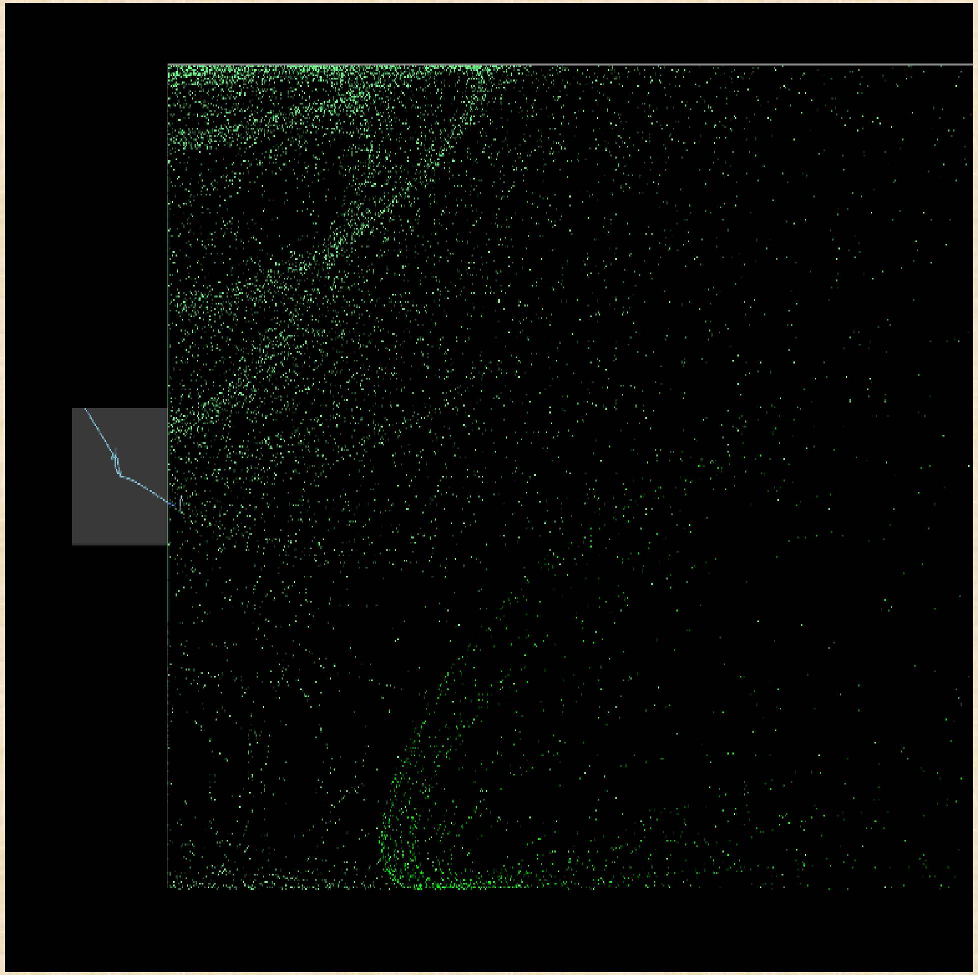
Near detectors

- **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 ton
  - 130 Emulsion Cloud Chambers (ECC)

Near Water Cherenkov detector



Water Cherenkov detector is used for:

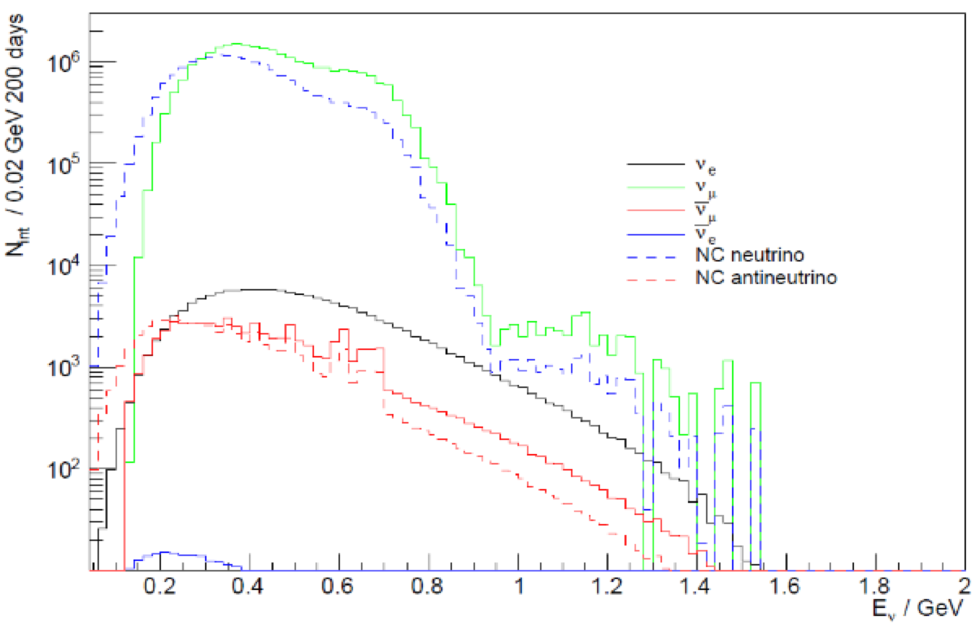
- event rate measurement
- flux normalization
- event reconstruction comparison with the far detector.

➢ **Some figures:**

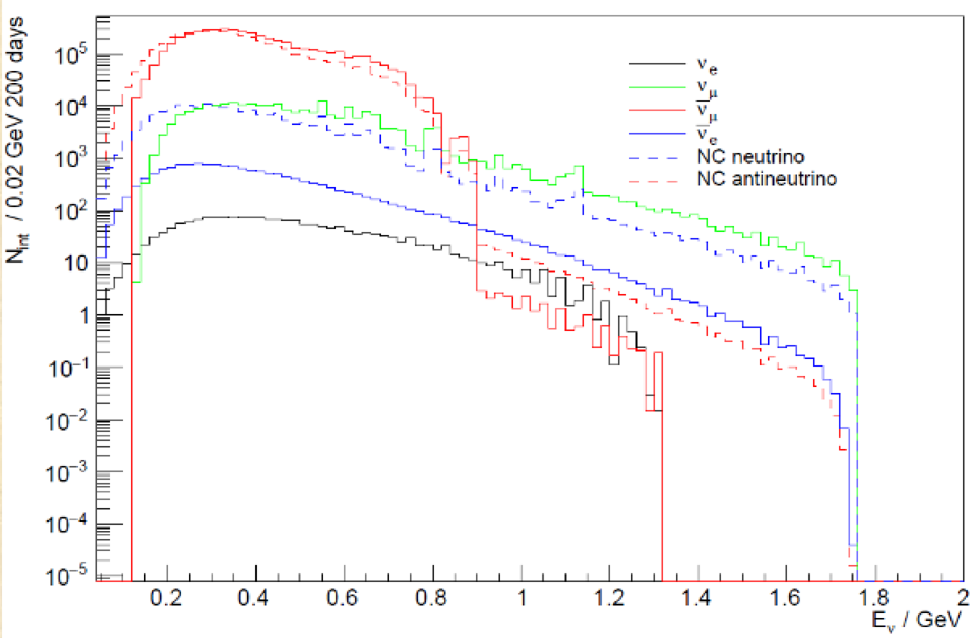
- radius R = 7 m, length L = 11 m
- 1725 m^3 total volume
- ~1000 m^3 fiducial volume
- Readout: 40% PMT coverage

Interaction rates in Near Water Cherenkov

Neutrino mode



Antineutrino mode

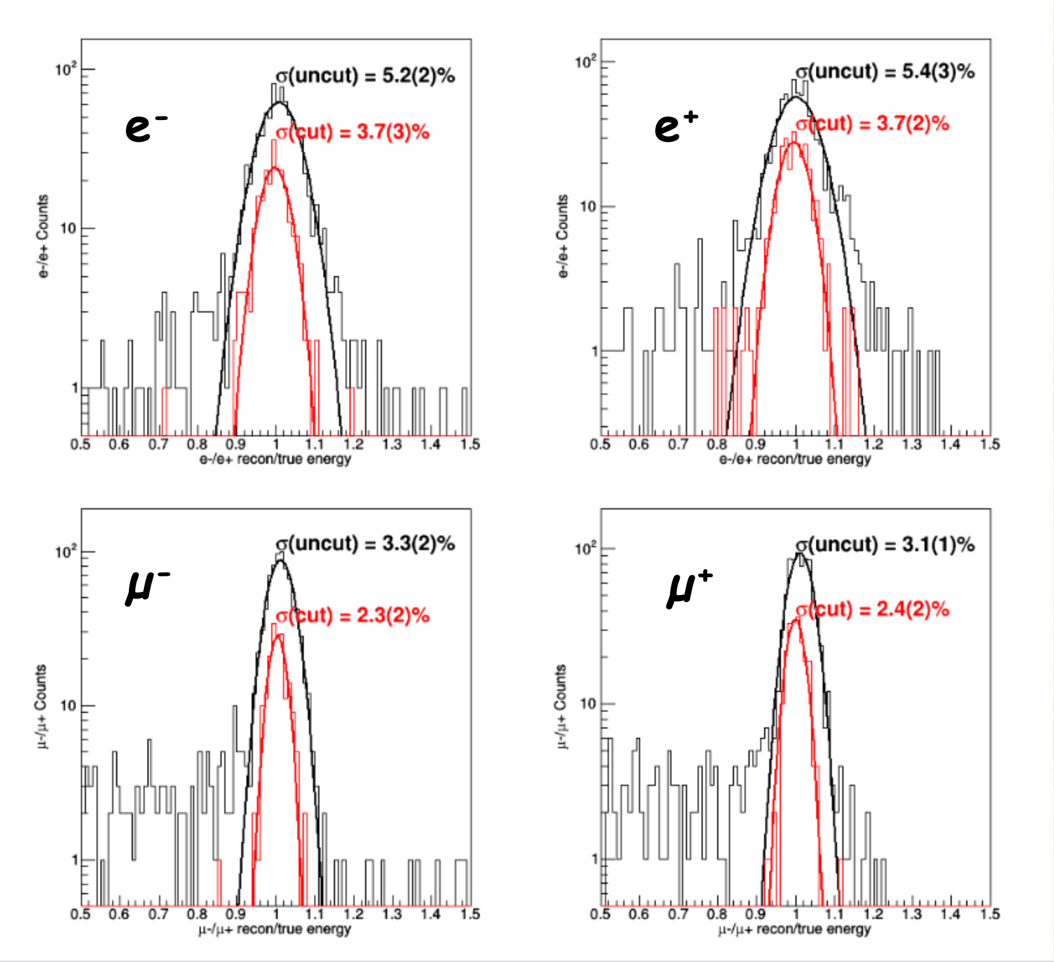


Expected number of interactions at 250 m in 500 t of water for 2.16 x 10^{23} p.o.t. (effective year):

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

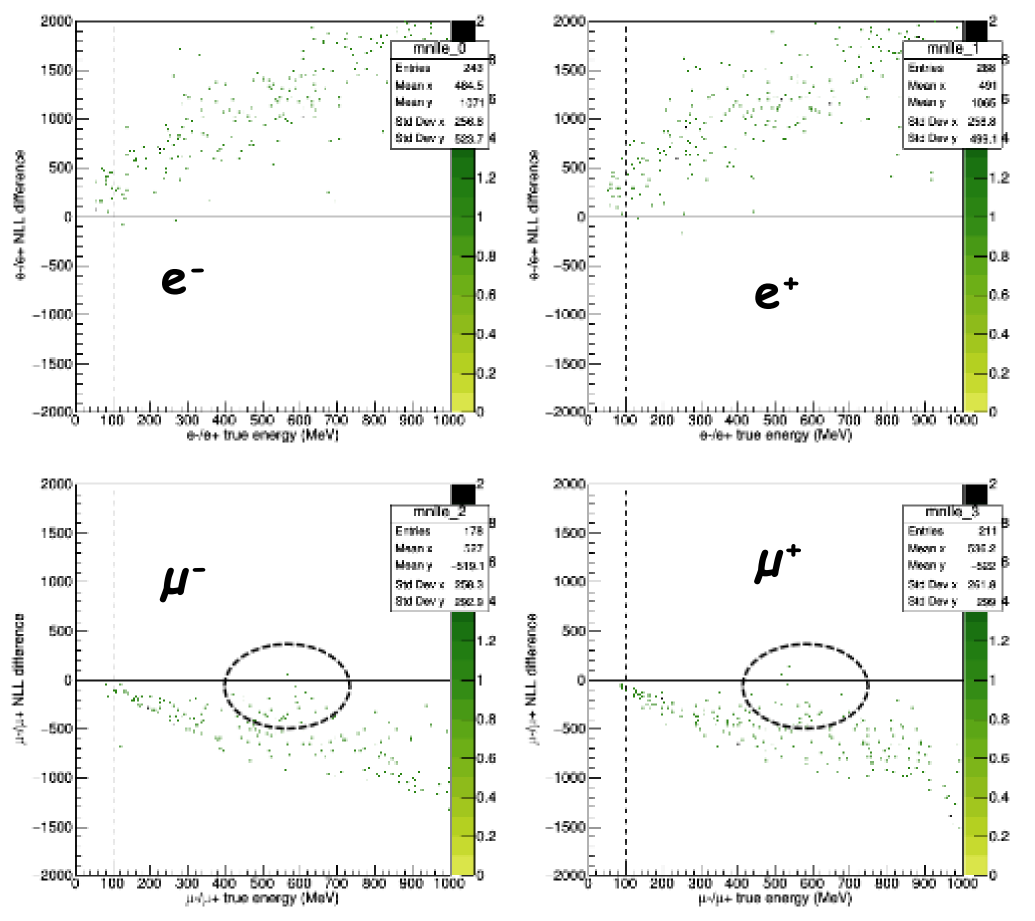
Neutrino	Expected number
ν_μ	265 k
$\bar{\nu}_\mu$	4.7 M
ν_e	1.8 k
$\bar{\nu}_e$	15 k

Near Water Cherenkov performance



Charged lepton energy reconstruction

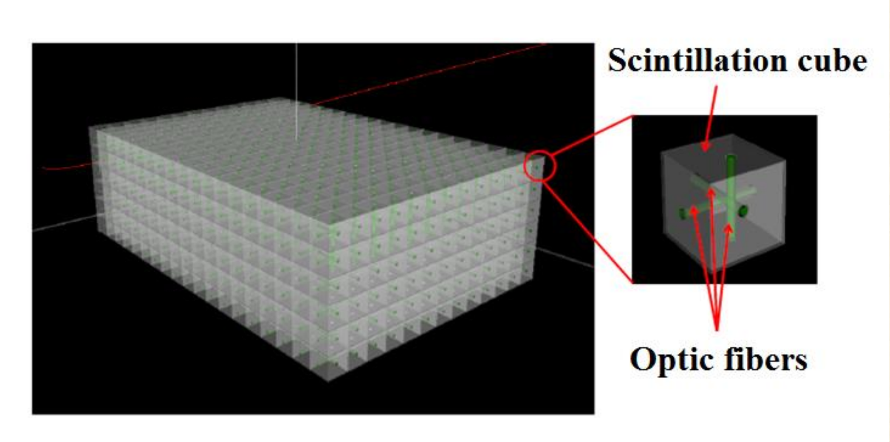
Fiducial cut – 2m



Charged lepton identification

Fiducial cut – 2m

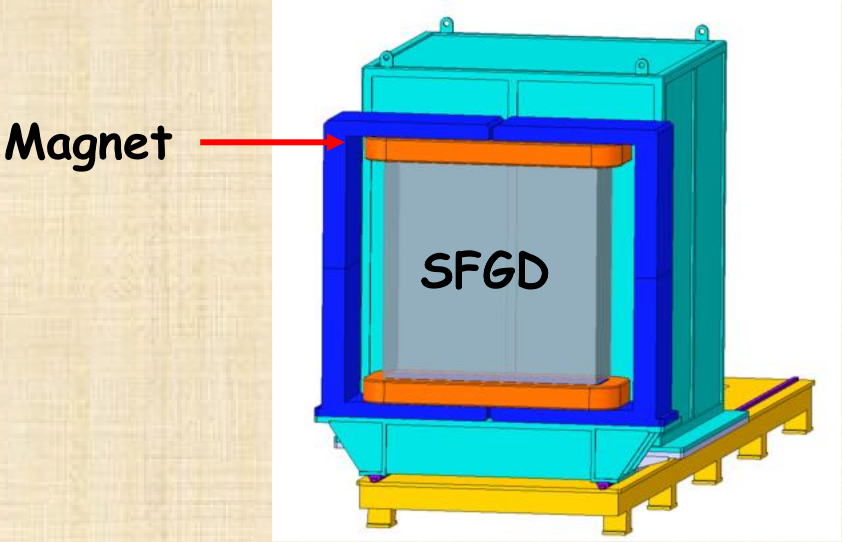
Super Fine-Grained Tracker (SFGD)



SFGD MC geometry

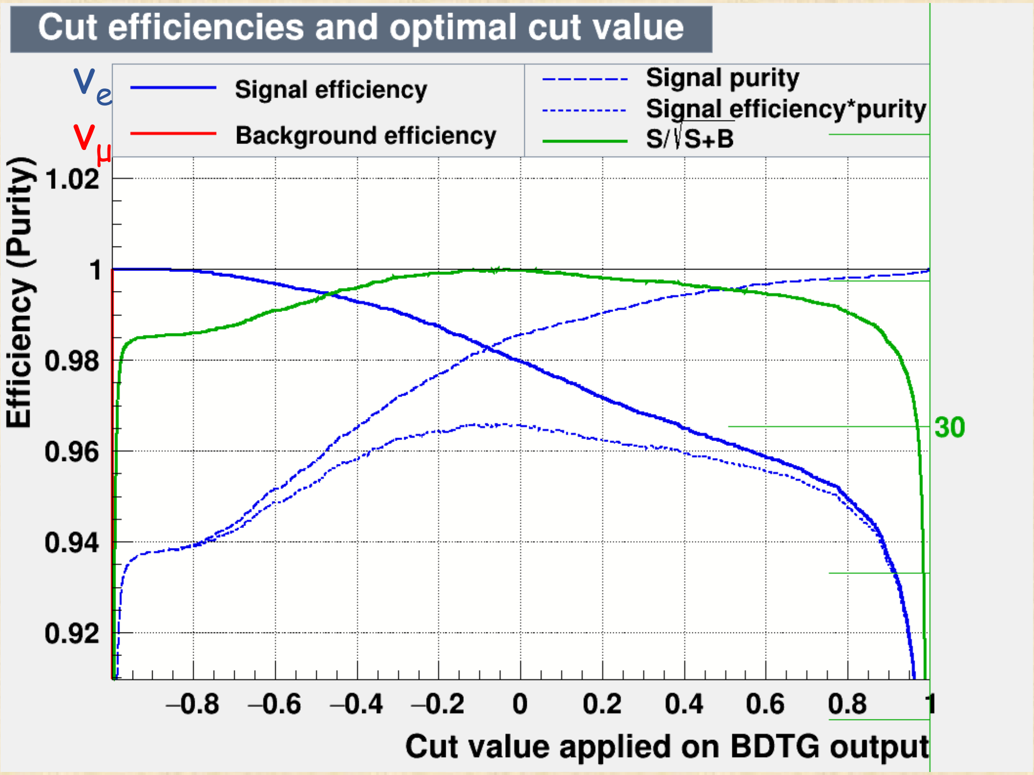
SFGD detector is used for measurements of neutrino cross-sections in energy region (60–600 MeV).

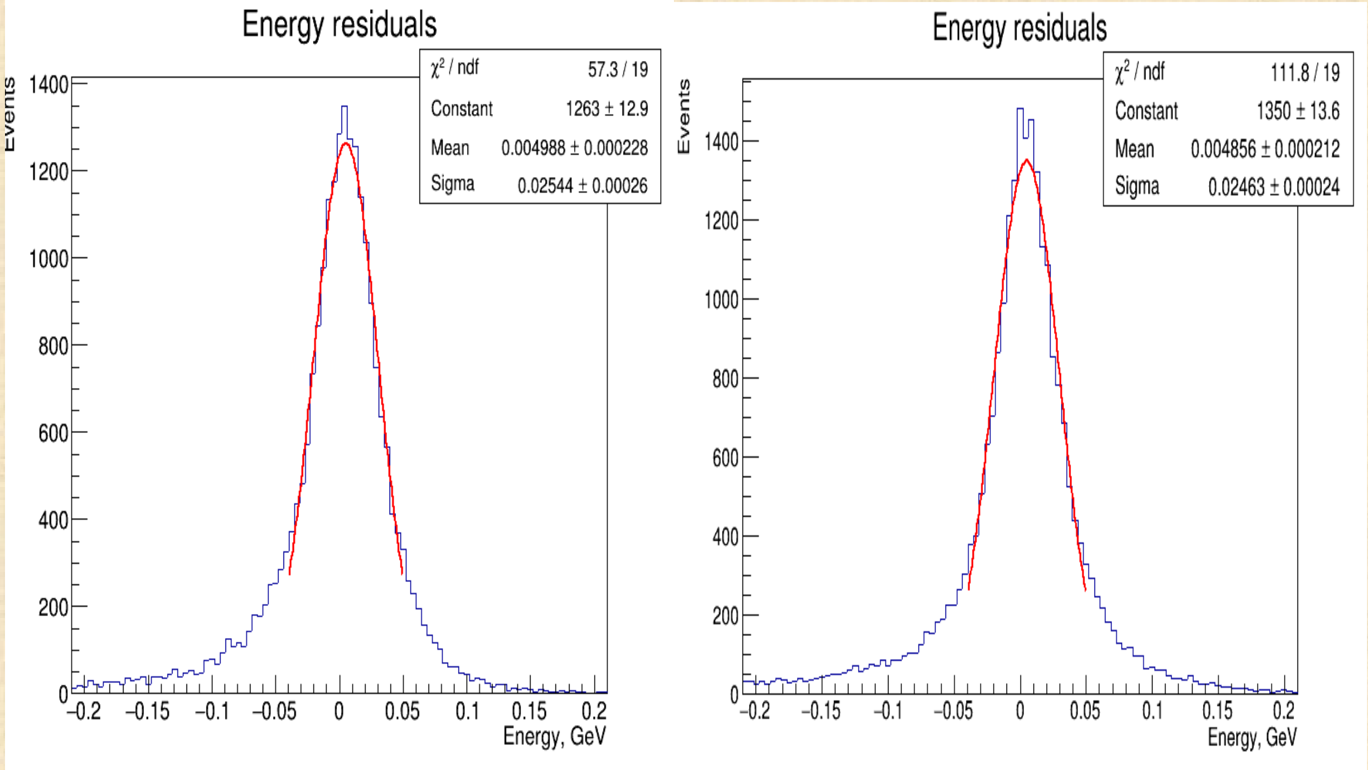
- **Some figures:**
  - scintillating cubes 1x1x1 cm^3
  - WLS fibers in three dimensions
  - overall dimensions 1.4x1.4x0.5m^3
  - Dipole magnetic field up to 1 T
  - Readout MPPCs



SFGD prototype tested at CERN 2018

Super Fine-Grained Tracker performance



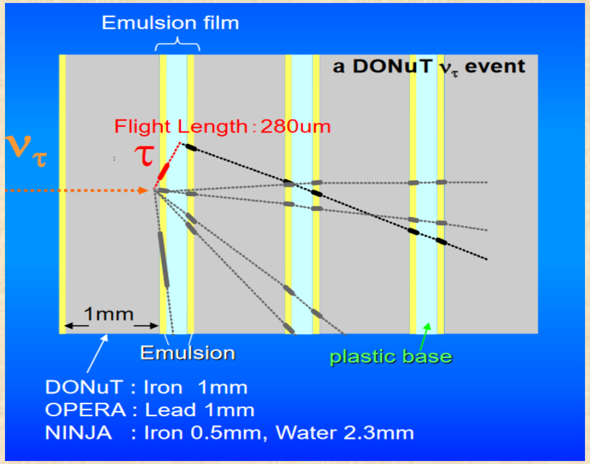


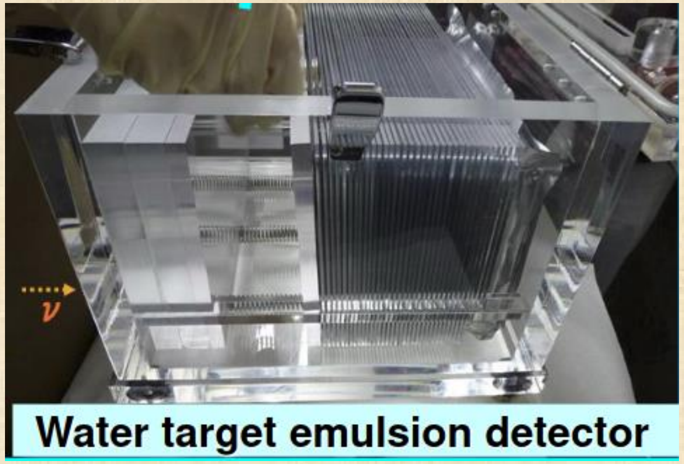
- **Separation ν_e/ν_μ CC events** with machine learning methods (TMVA):
  - signal efficiency of 95,5%
  - signal purity of 99,8%

- **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

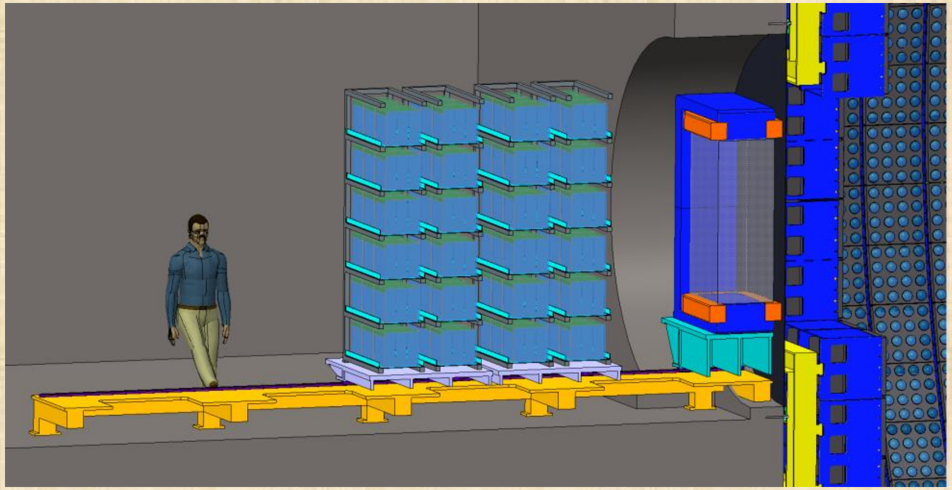
Emulsion detector NINJA-like

- **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

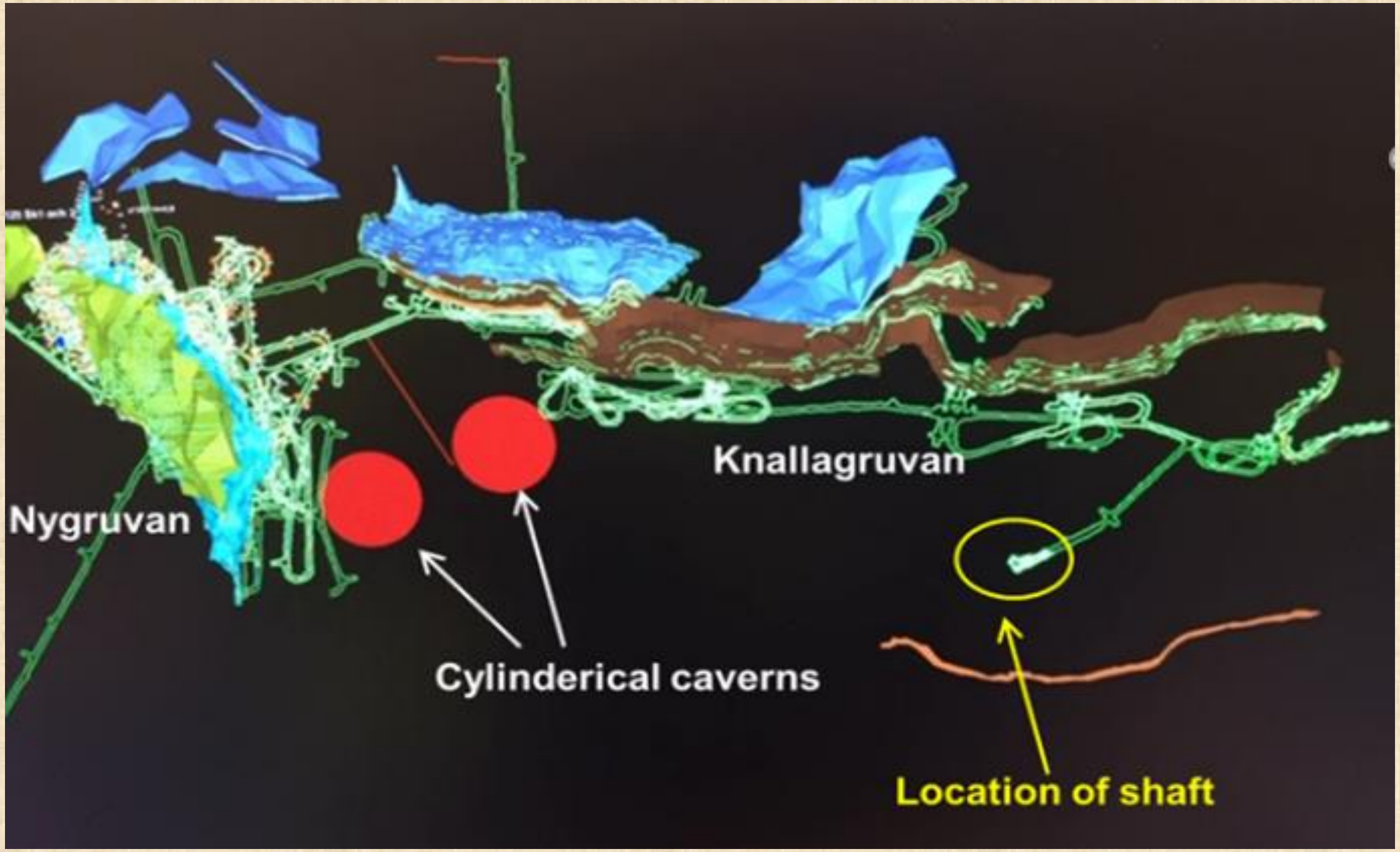
Cross-section measurements

- **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:
      - v - e scattering has a very forward single electron in the final state.

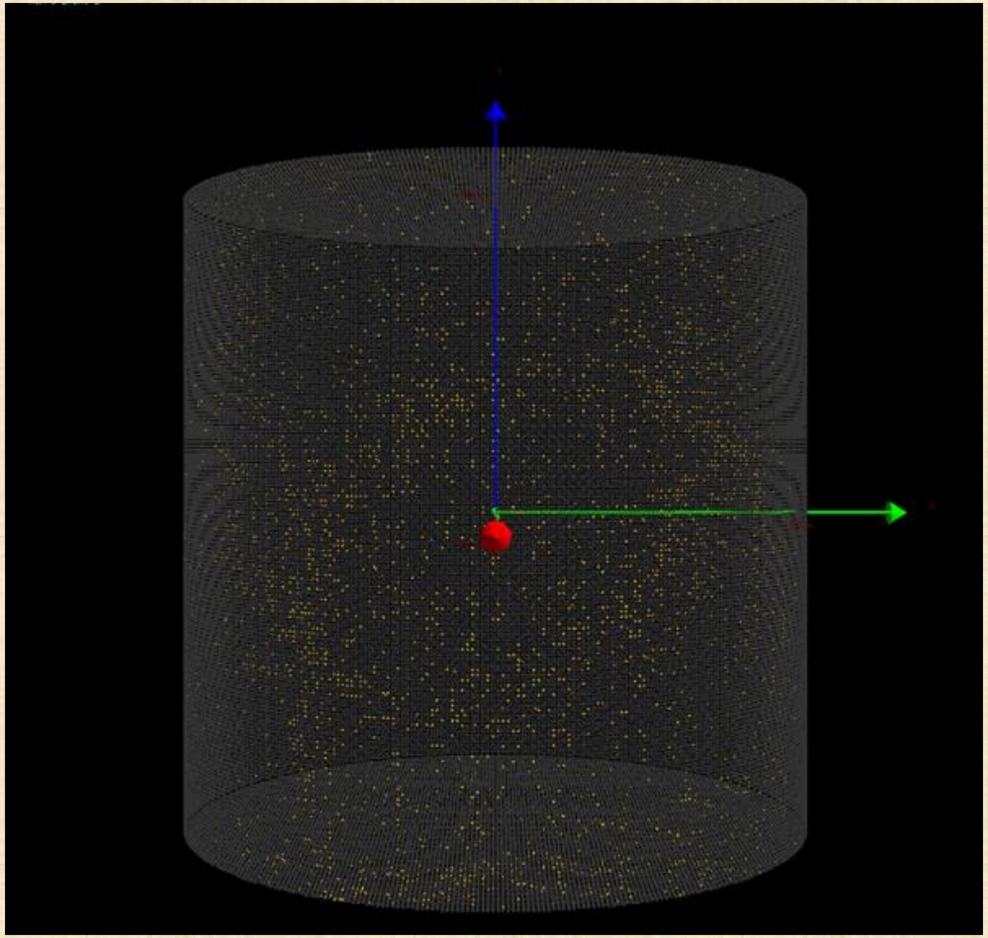
  - Having constraint on the flux, we can measure interaction cross-sections in all Near Detectors:
    - WCkov, Super FGD, emulsion

Far Detector



Far Detectors

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

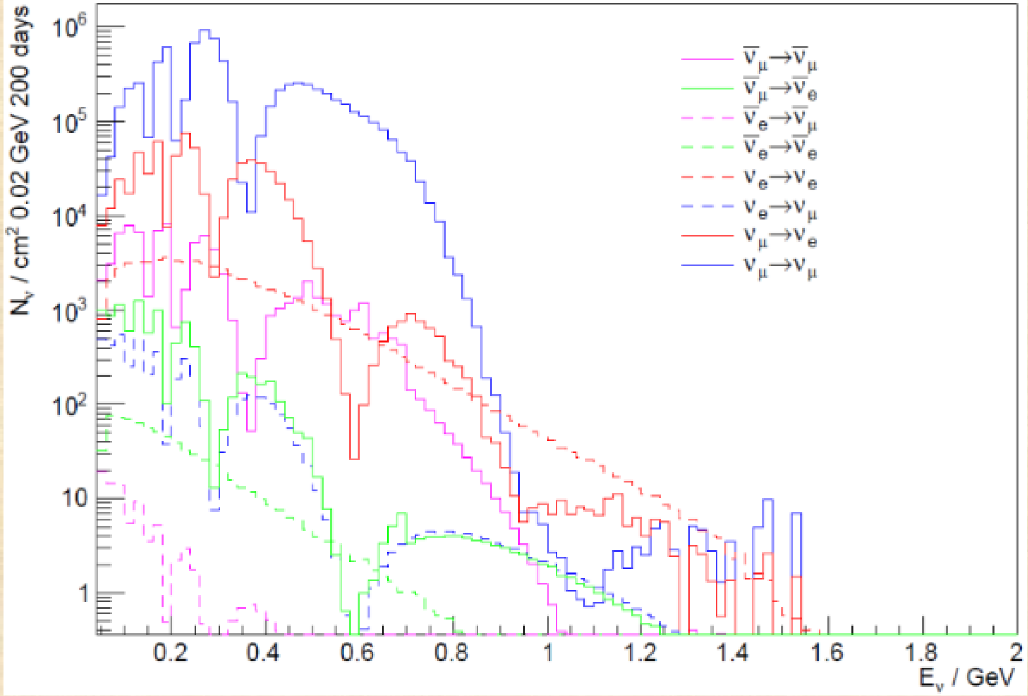


- **Two identical water Cherenkov detectors.**
- **Each module is a standing cylinder:**
  - diameter D = 78 m, height h = 78 m
  - 373k m^3 total volume
  - 270k m^3 fiducial volume (~10xSuperK)
  - Readout: 38k 20" PMTs
  - 30% optical coverage

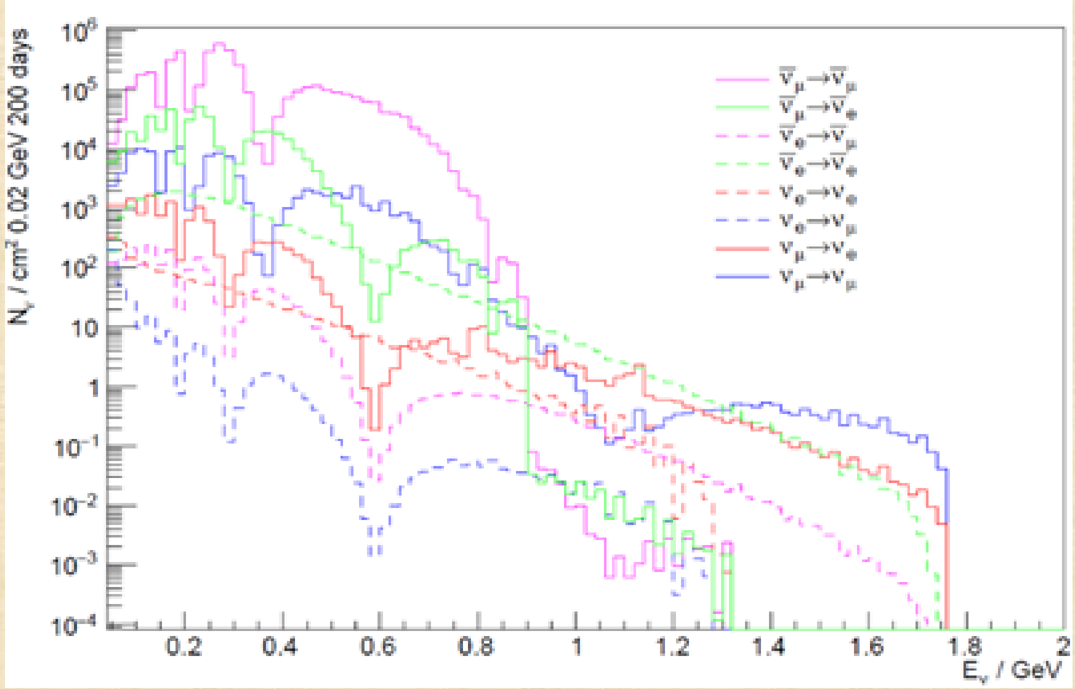
- **Can also be used for other purposes:**
  - **Proton decay**
  - **Astroparticles**
  - **Galactic SN ν**
  - **Supernovae "relics"**
  - **Solar Neutrinos**
  - **Atmospheric Neutrinos**

Interaction rates in Far Detectors

Neutrino mode



Antineutrino mode



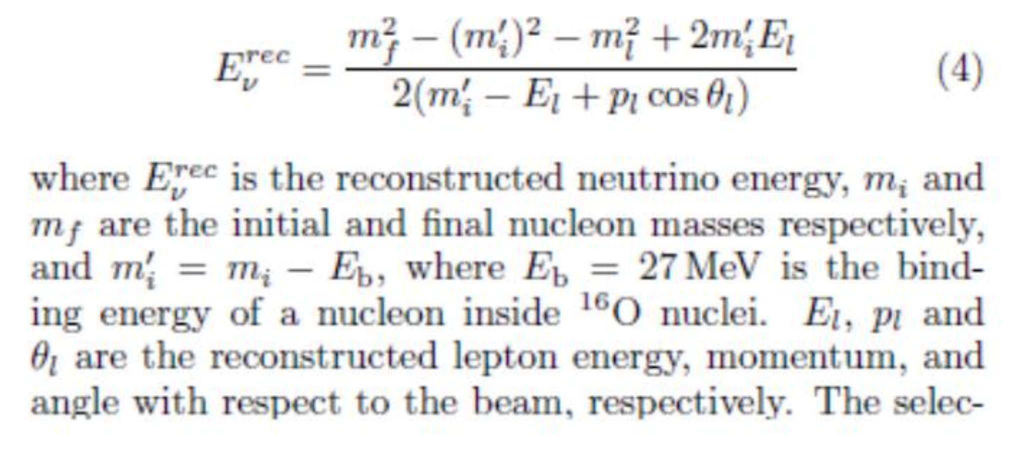
Expected number of interactions at 540 km in 540 kt of water for 2.16 x 10^{23} p.o.t. (effective year), assuming $\delta_{CP} = 0$:

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

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

Neutrino energy reconstruction

Kinematical neutrino energy reconstruction formula



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

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

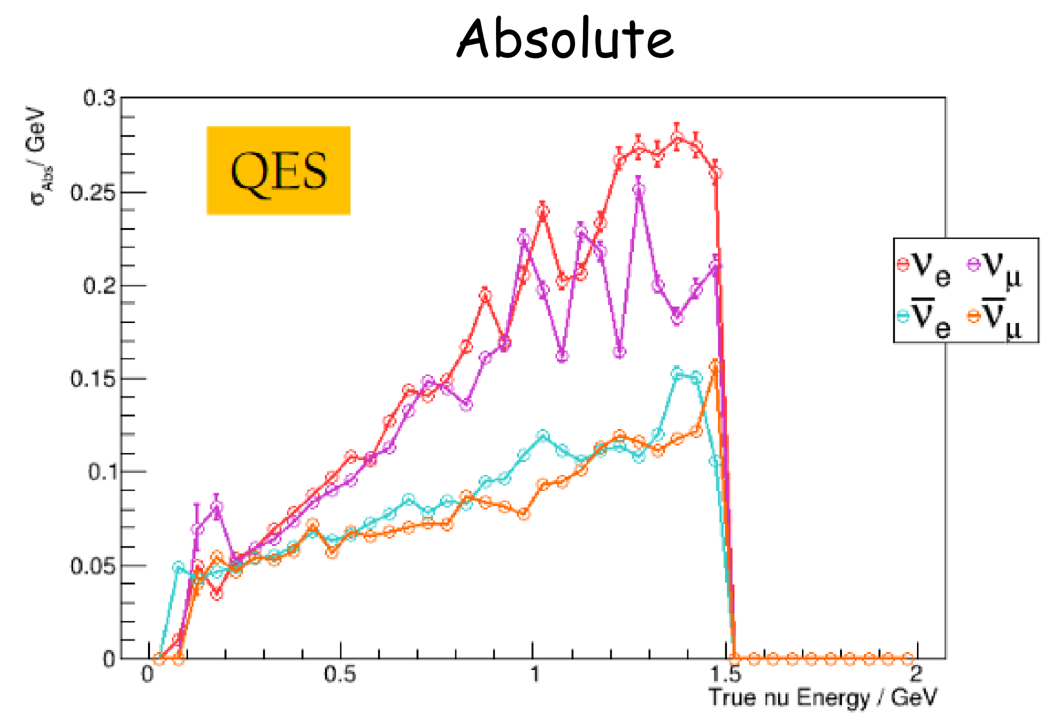
- **Given that you know:**
  - momentum of the outgoing charged lepton
  - its angle w.r.t. incoming neutrino
  - that it is a quasielastic interaction
  - which nucleus neutrino interacted with (^{16}O)

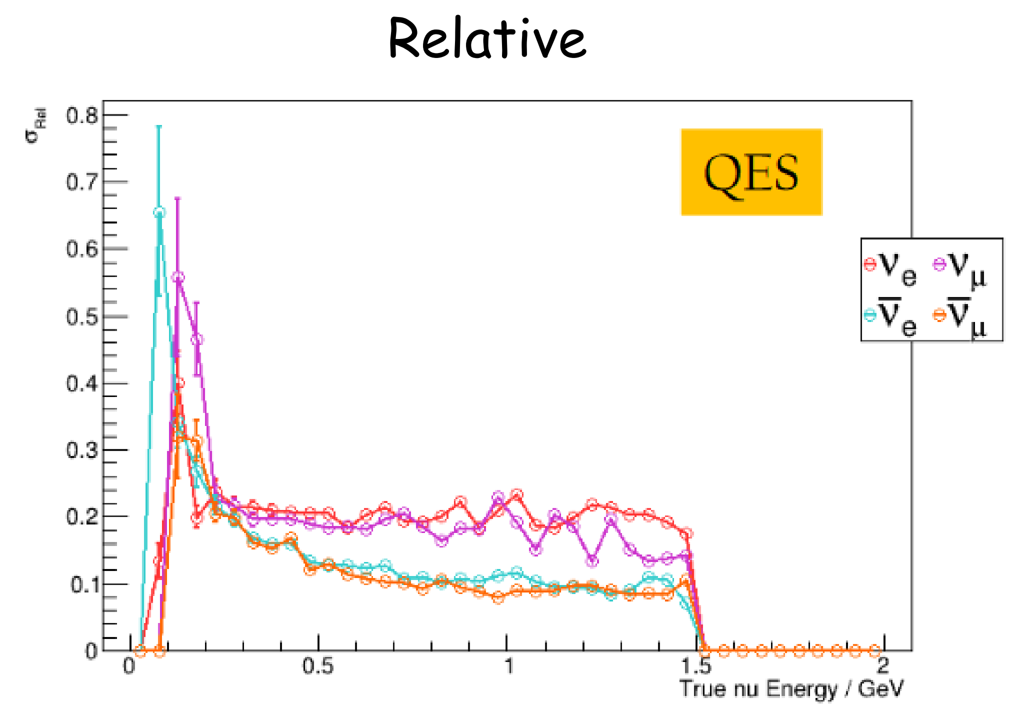
you can **approximately** calculate neutrino energy.

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)