ESS NEUTRINO SUPER BEAM

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EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

ESSnuSB near and far detector technology / strategy

Budimir Kliček
Ruđer Bošković Institute Zagreb
on behalf of ESSnuSB

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CP violation in ESSnuSB

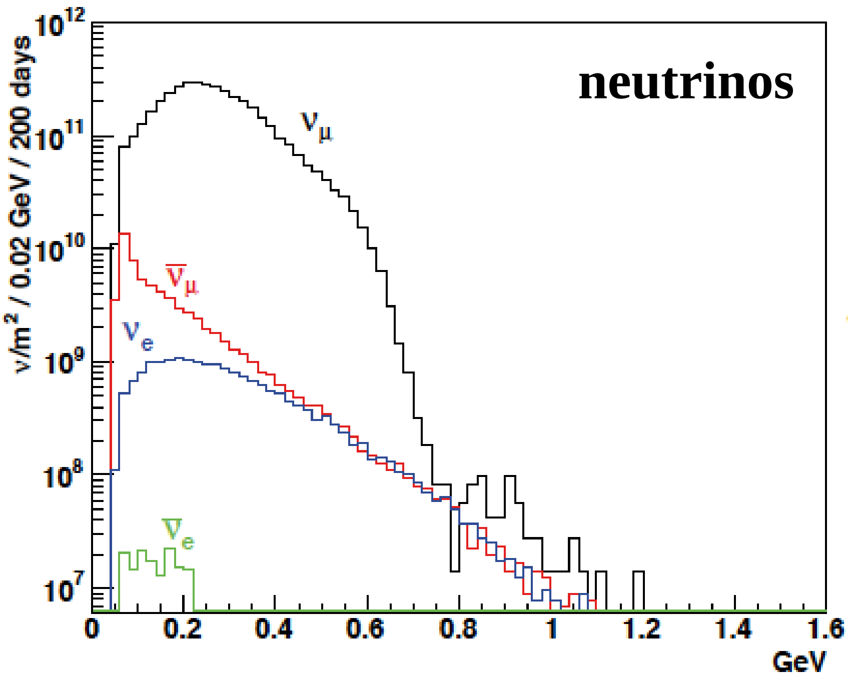
$$P_{\mu \to e} \neq P_{\overline{\mu} \to \overline{e}}$$

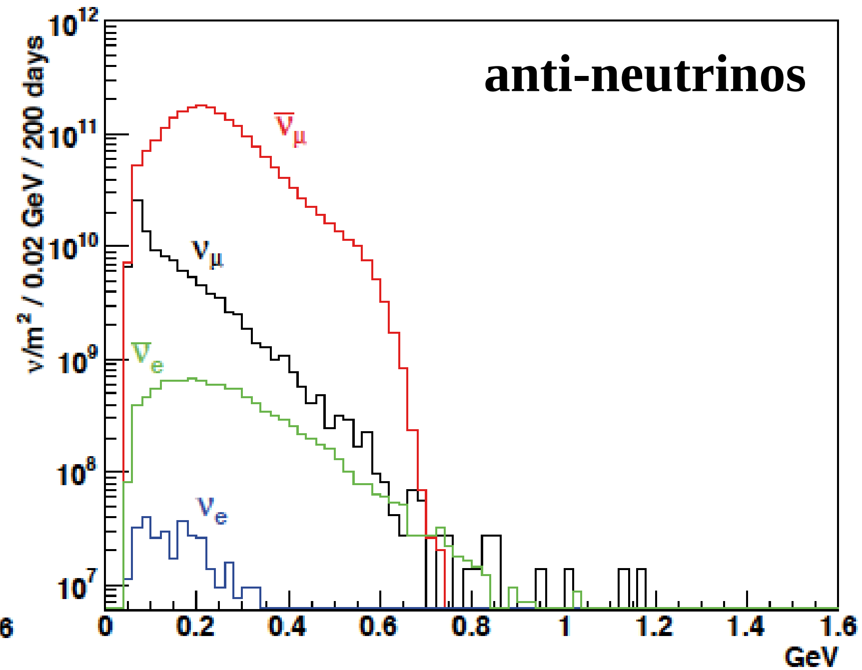
We will study ν_e and $\overline{\nu}_e$ appearance in ν_μ and $\overline{\nu}_\mu$ beam, respectively

The plan:

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

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)

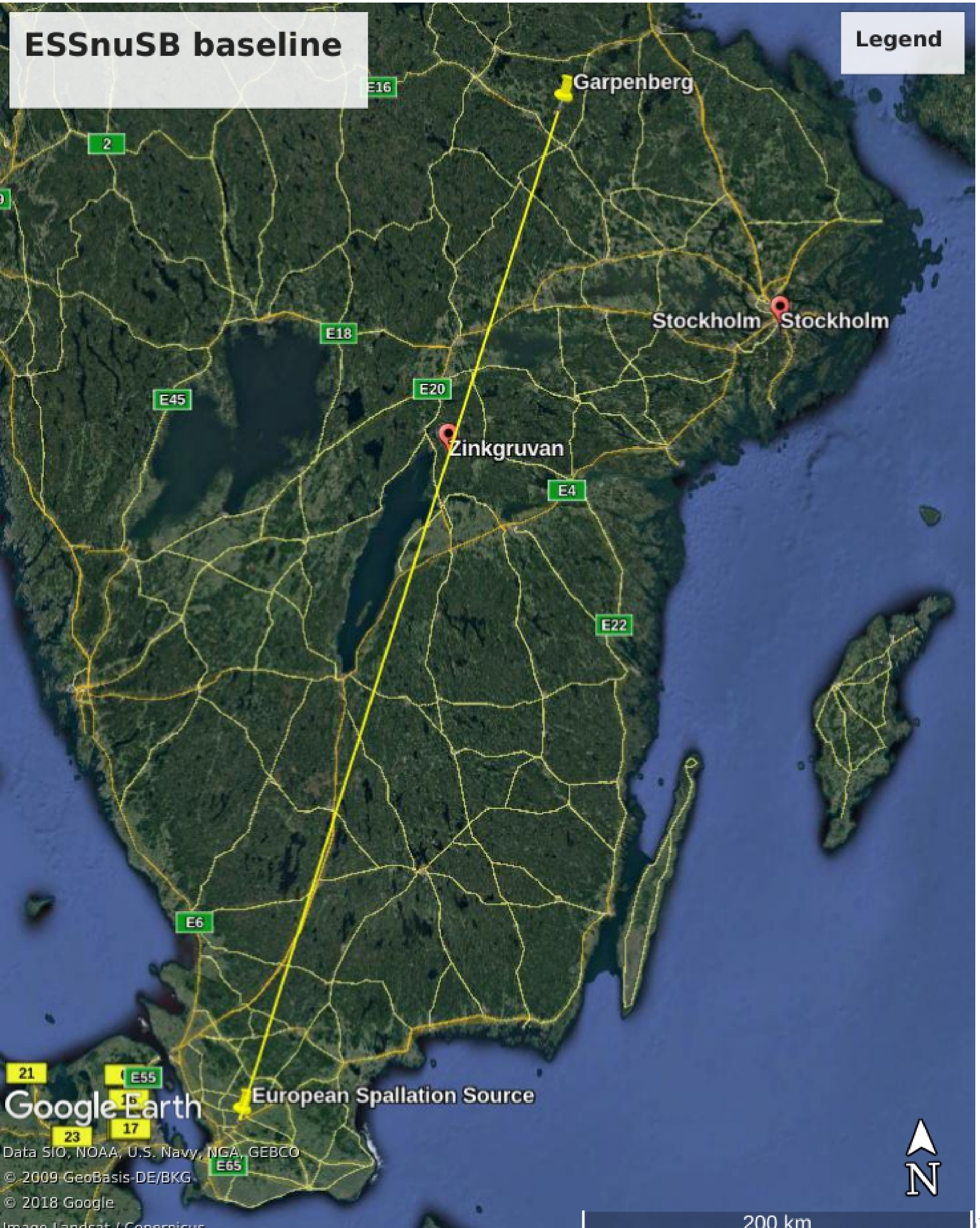
Purpose of the ESSnuSB detectors

Far detectors

- Observe $\overset{(-)}{\nu}_e$ appearance in the $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ oscillation channel

Near detectors

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



Neutrino baseline

Baseline:

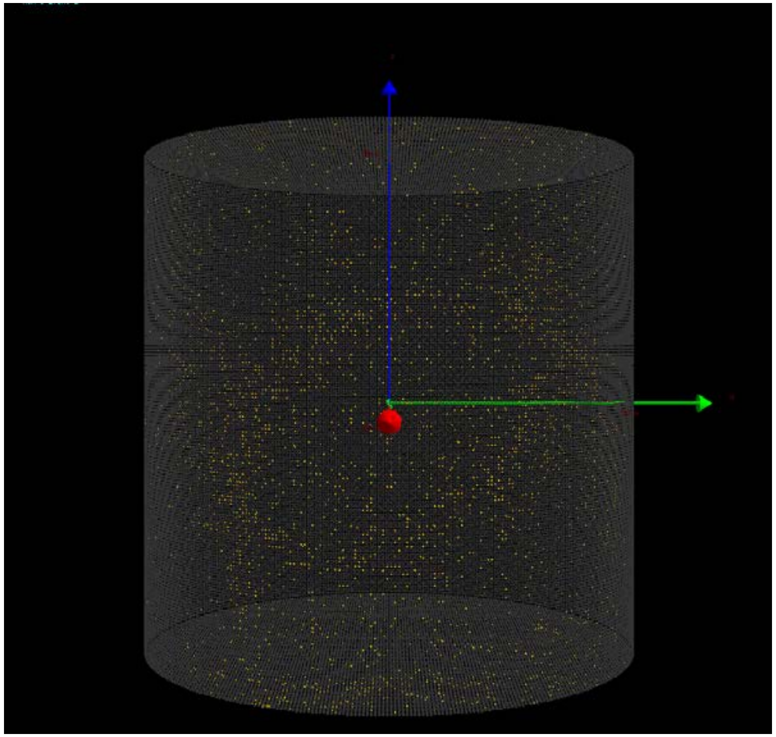
- Garpenberg mine, 540 km from the neutrino source, corresponding to 2nd oscillation maximum.

Alternatives:

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

Far detectors

Far detectors

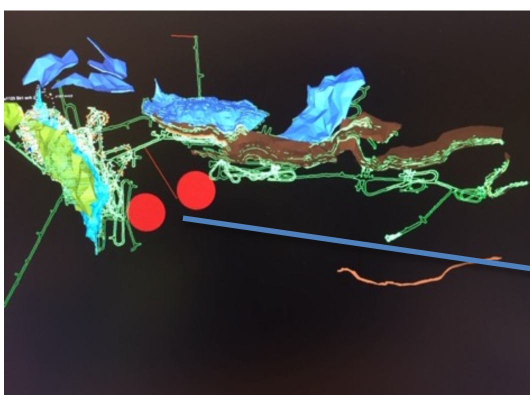


Baseline – two identical modules.

- It would be cheaper to have one larger module, but then we would have a problem with statics of the cave

Each module is a standing cylinder:

- diameter D = 78 m, height h = 78 m
    - D = h minimizes surface/volume ratio
- 373k m^3 total volume
- 270k m^3 fiducial volume (~10xSuperK)
- Readout: 38k 20” PMTs
- 30% optical coverage

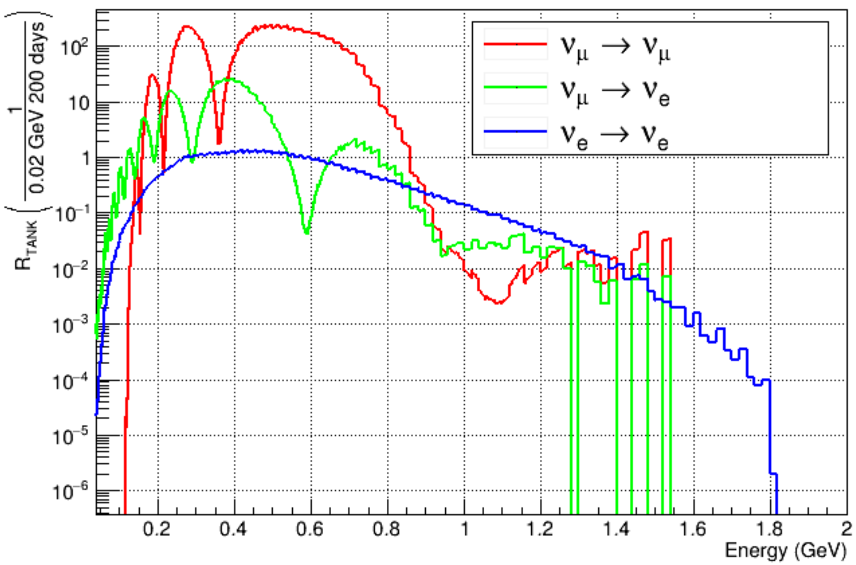


Possible positions at Zinkgruvan mine

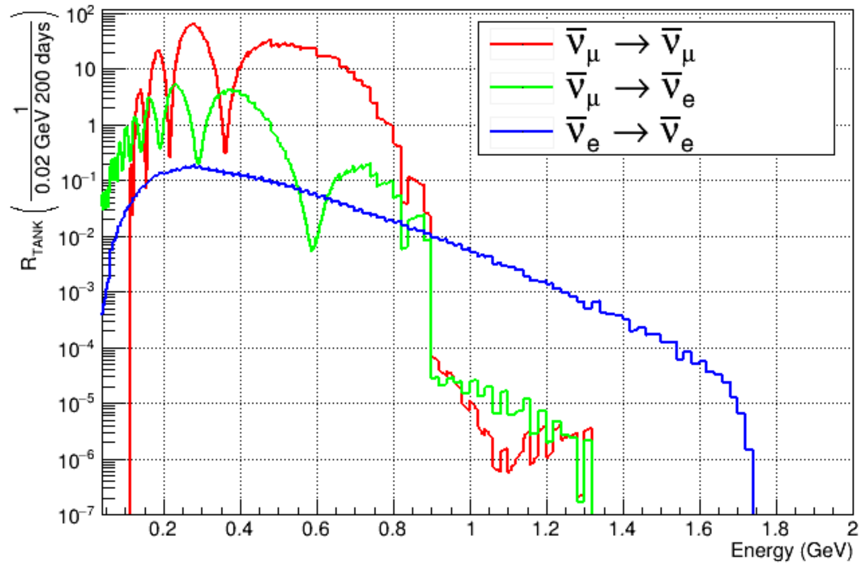
Expected interaction rates in Far Detectors

Plots and numbers by L. Halić

Neutrino mode



Antineutrino mode



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

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

Channel	Expected number
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	40
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	600
$\bar{\nu}_e \rightarrow \bar{\nu}_e$	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

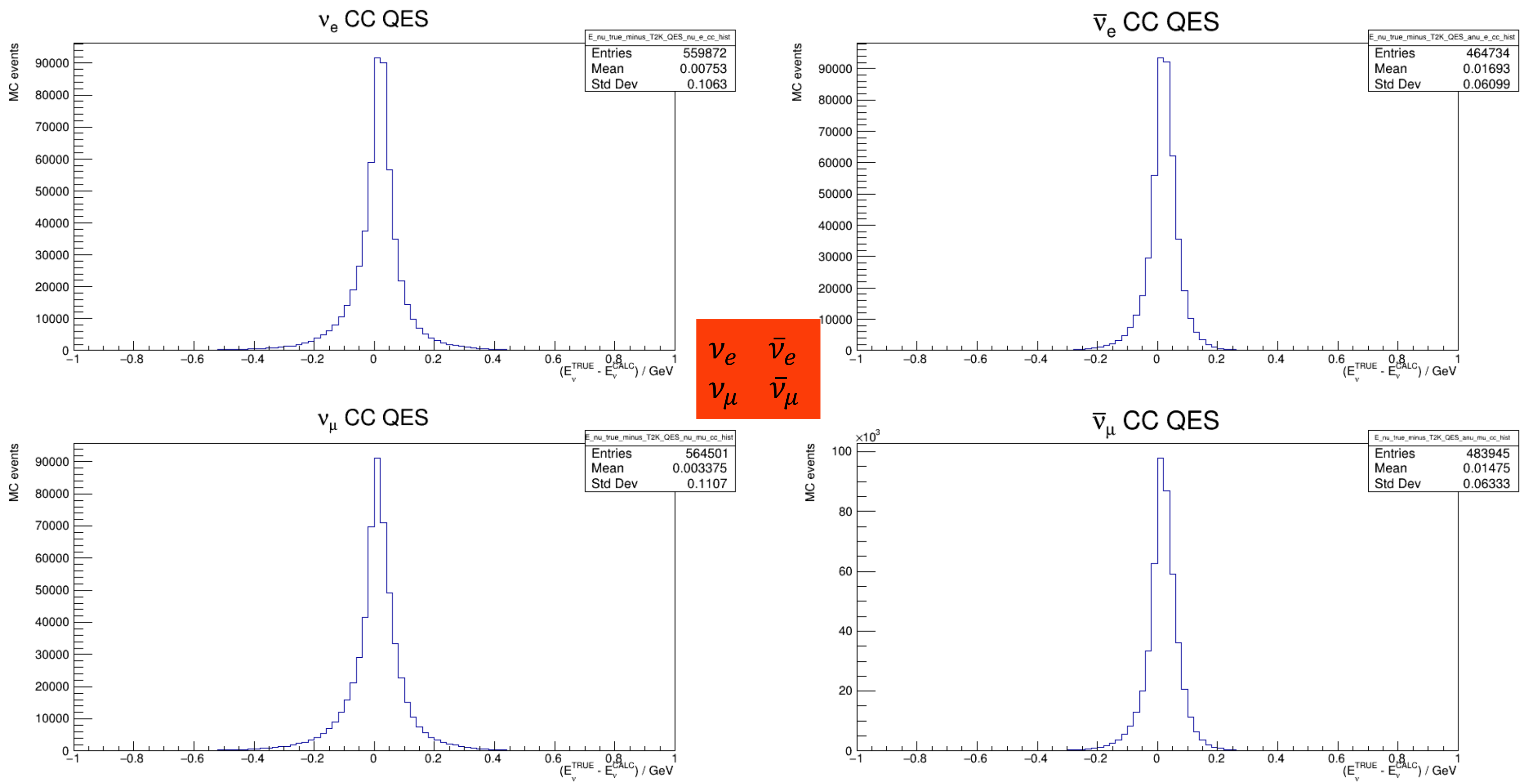
Given that you know:

- magnitude of the outgoing charged lepton momentum
- its angle w.r.t. incoming neutrino
- that it is a quasielastic QES interaction
- which nucleus neutrino interacted with (e.g. oxygen-16)

you can **approximately** calculate neutrino energy.

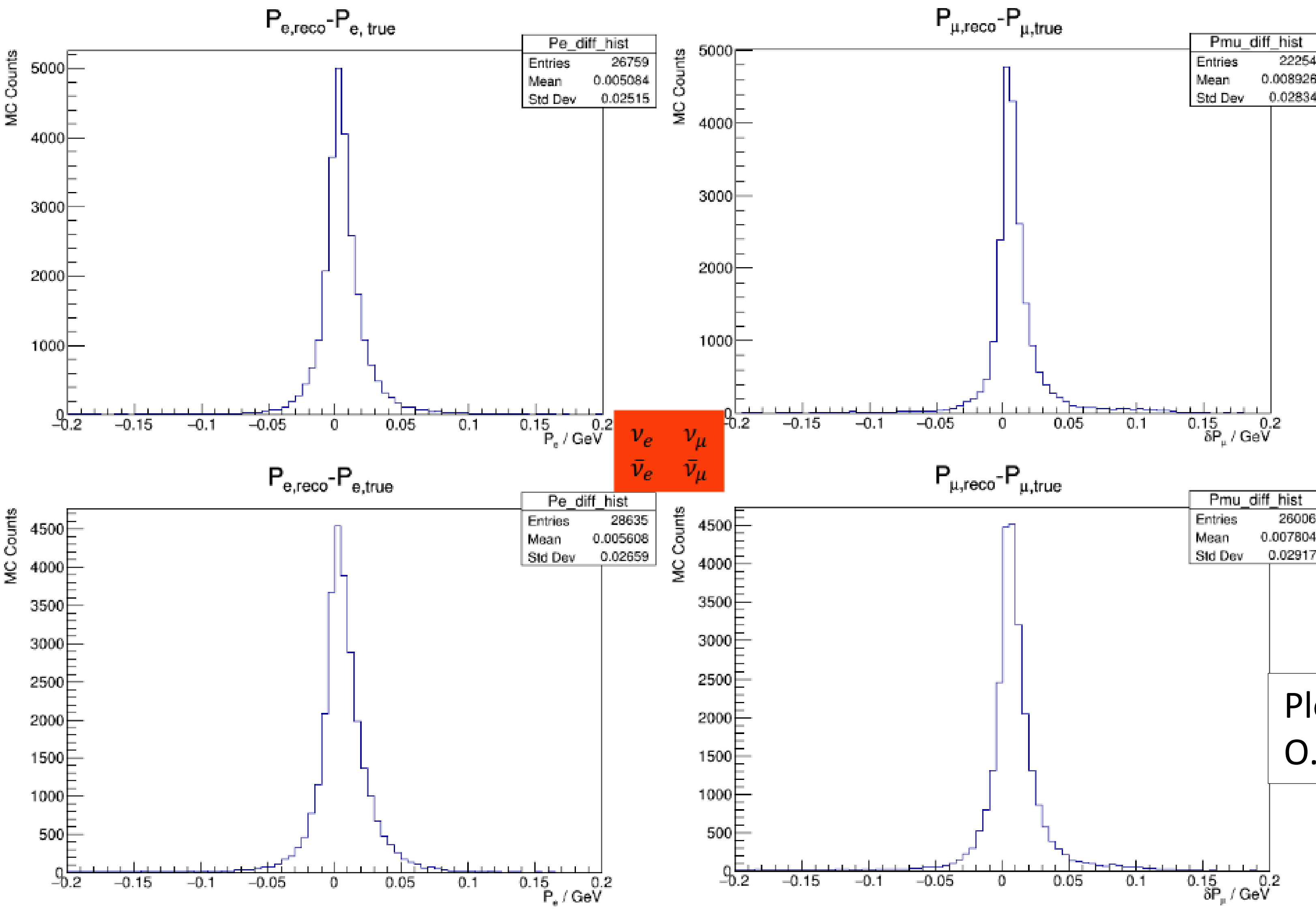
Intrinsic uncertainties come from nuclear effects, most notably **fermi motion** of nucleons in nuclei.

Energy resolution using true MC momenta



Conclusion: with a perfect detector using kinematical reconstruction formula we get energy resolution of about **110 MeV for neutrinos** and **65 MeV for antineutrinos**.

Difference between reconstructed and true lepton momentum

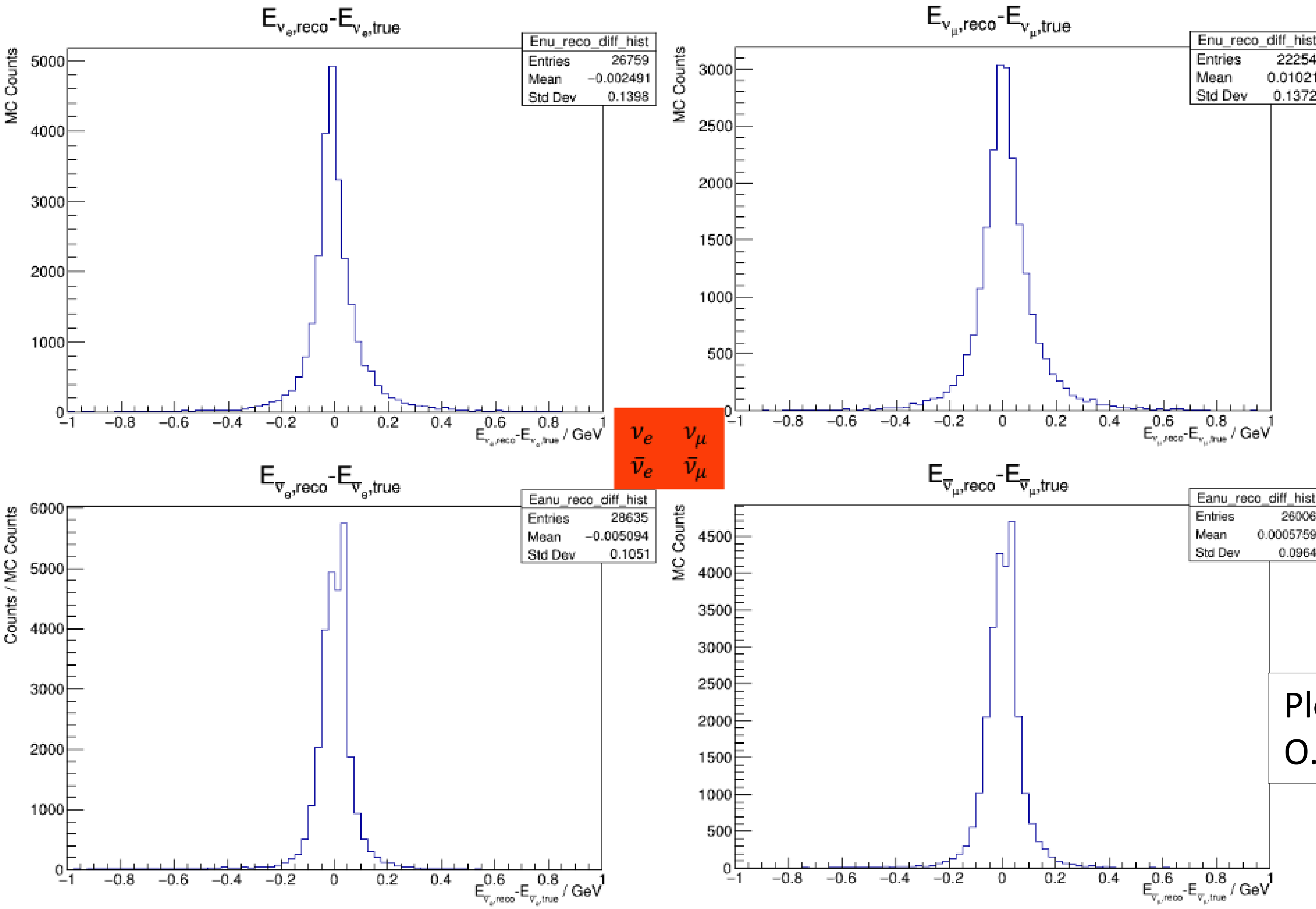


Plots by O. Zormpa

28/09/2020 9

Charged lepton momentum reconstruction resolution in Far Detectors: 25-30 MeV

Difference between reconstructed and true ν energy



Plots by O. Zormpa

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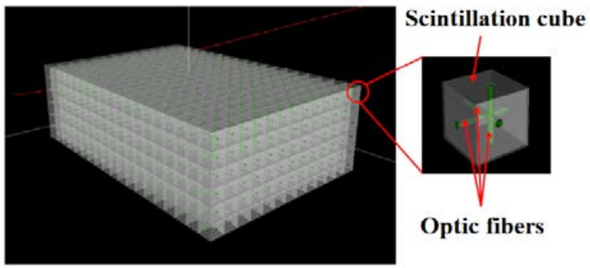
Neutrino energy resolution for QES interactions:
140 MeV for neutrinos and **100 MeV for antineutrinos**

Far detector conclusions / strategy

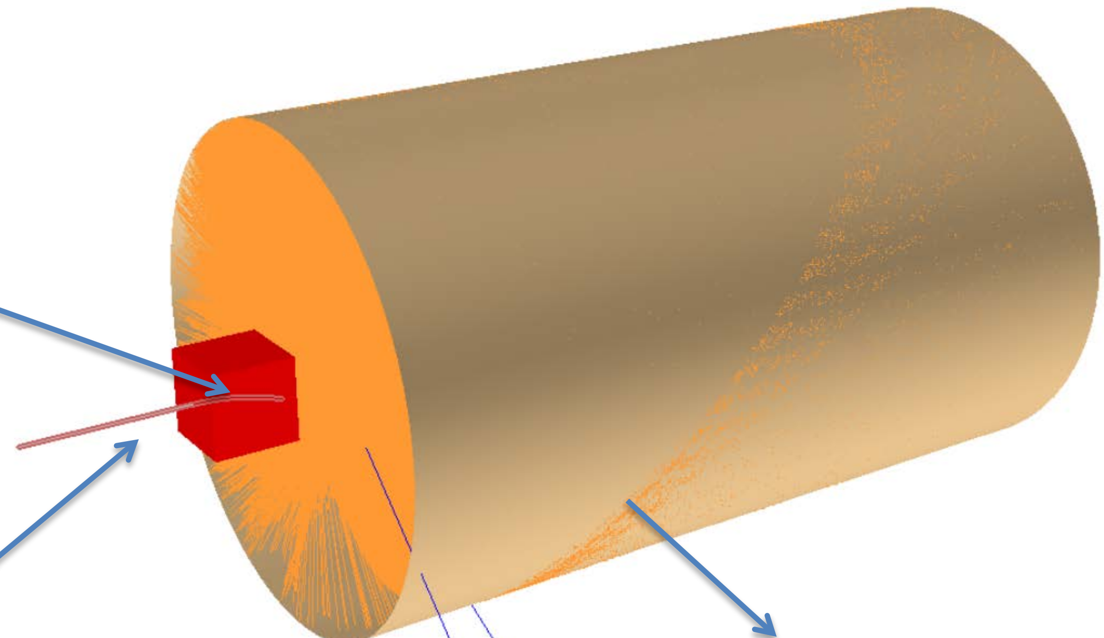
- **Main purpose:** observe $\overset{(-)}{\nu}_e$ appearance in the $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ oscillation channel
- **Energy reconstruction:**
  - Using the kinematical reconstruction formula, there is an intristic resolution of **110 MeV for neutrinos** and **65 MeV for antineutrinos.**
  - Therefore, trying to improve the resolution of charged lepton momentum produces very **diminishing returns** – no reason to improve it further
  - Having calorimetry could significantly improve energy resolution
    - but, you can't have calorimetry in pure WC detector
- **Things that we are optimizing** (but carefully in order not to screw up non-beam physics potential):
  - event tagging (ν_μ CC, ν_e CC, NC discrimination) - work in progress
  - detector geometry w.r.t. the local rock conditions
  - PMT coverage

Near detectors

Near Detectors



Super-FGD like detector
- 1 – 4 t target mass



Beam

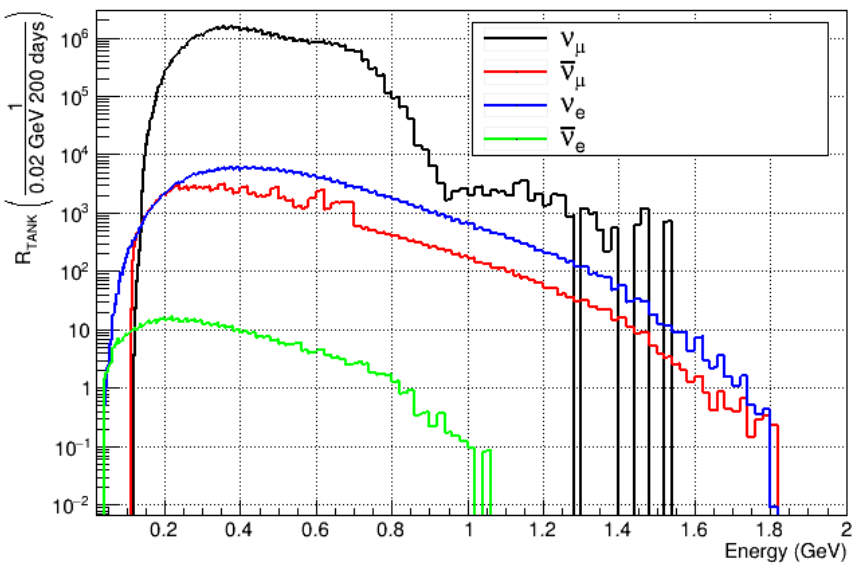
0.5 kt water Cherenkov detector

Addition: NINJA-like water-emulsion detector

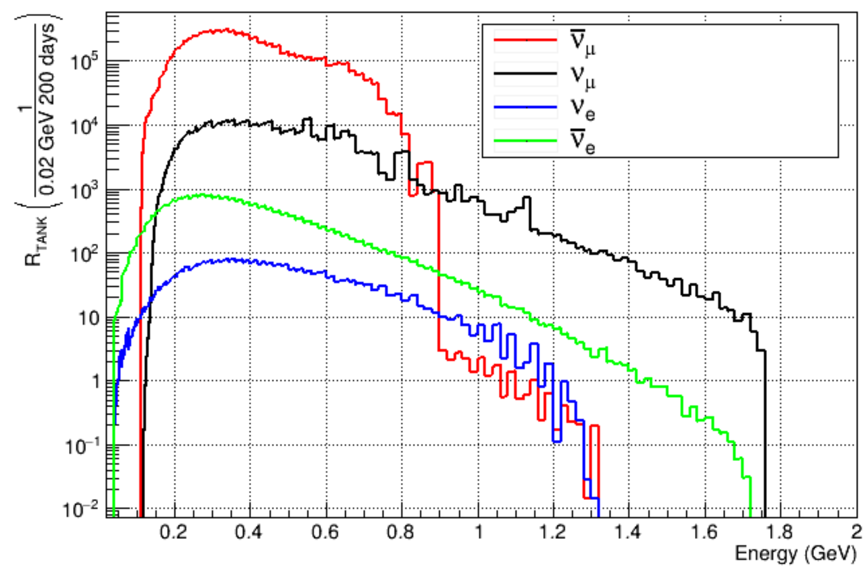
Expected interaction rates inWC Near Detector

Plots and numbers by L. Halić

Neutrino mode



Antineutrino mode



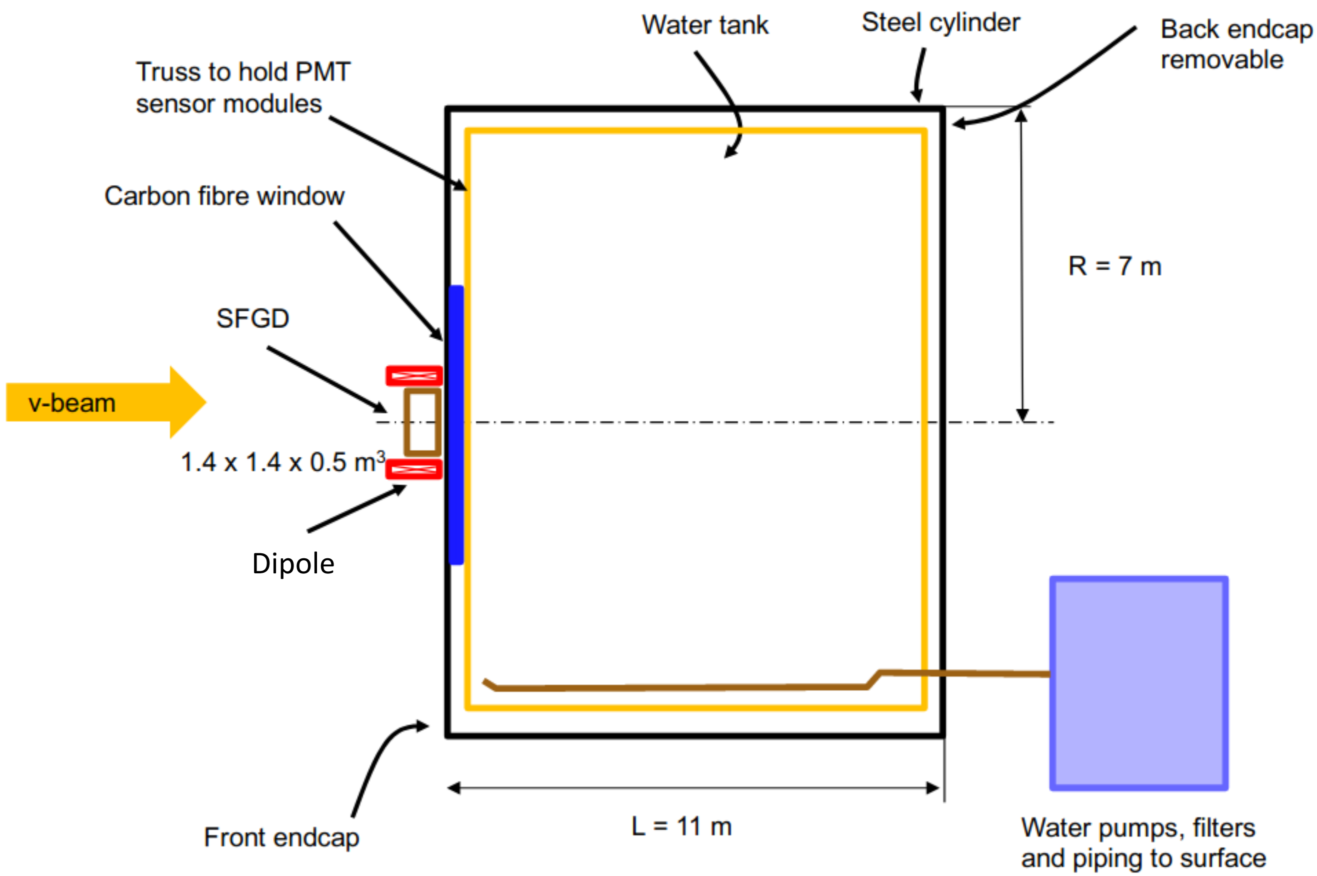
Approximate expected interactions at 250 m in 500 t of water for 2.16 x 10^{23} p.o.t. (effective year):

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

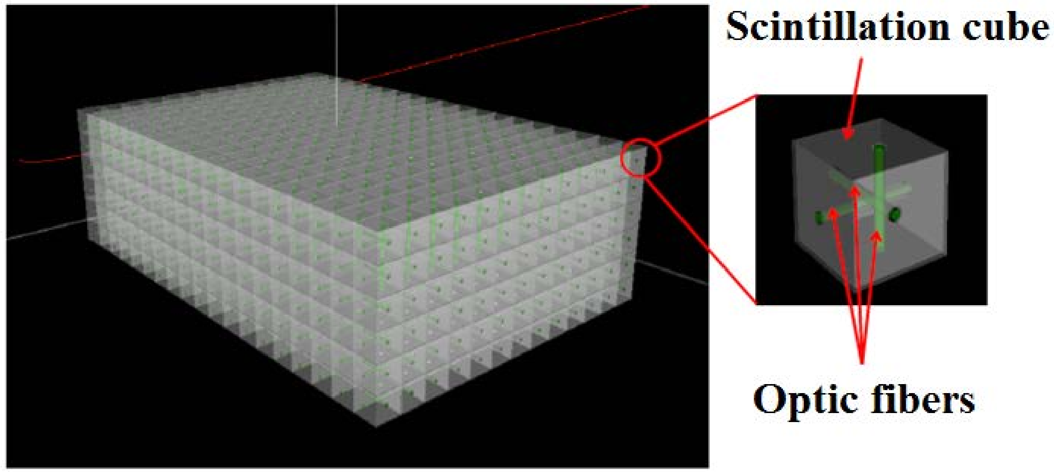
Near WC detector

ND design discussion

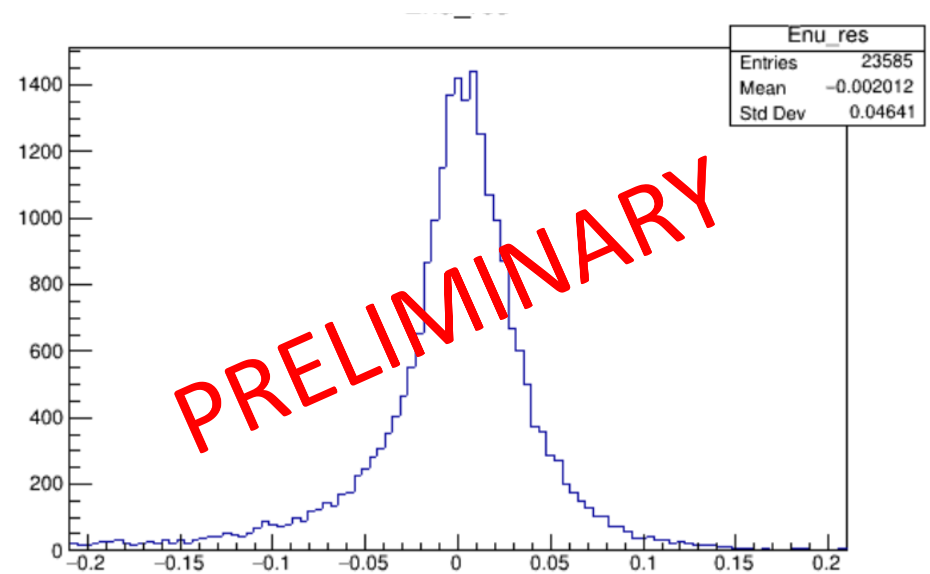


LUND UNIVERSITY

Near SFGD detector



- **Baseline dimensions:**
  - 140 x 140 x 50 cubes
  - each cube 1cm x 1cm x 1cm
- **Possible to do calorimetry**
  - improving neutrino energy resolution
- **Could provide timing to emulstion detector**



Plot by M. Bogomilov

Near emulsion detector

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 FGD
- Price per mass
- No online event reconstruction
- Labour intensive

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

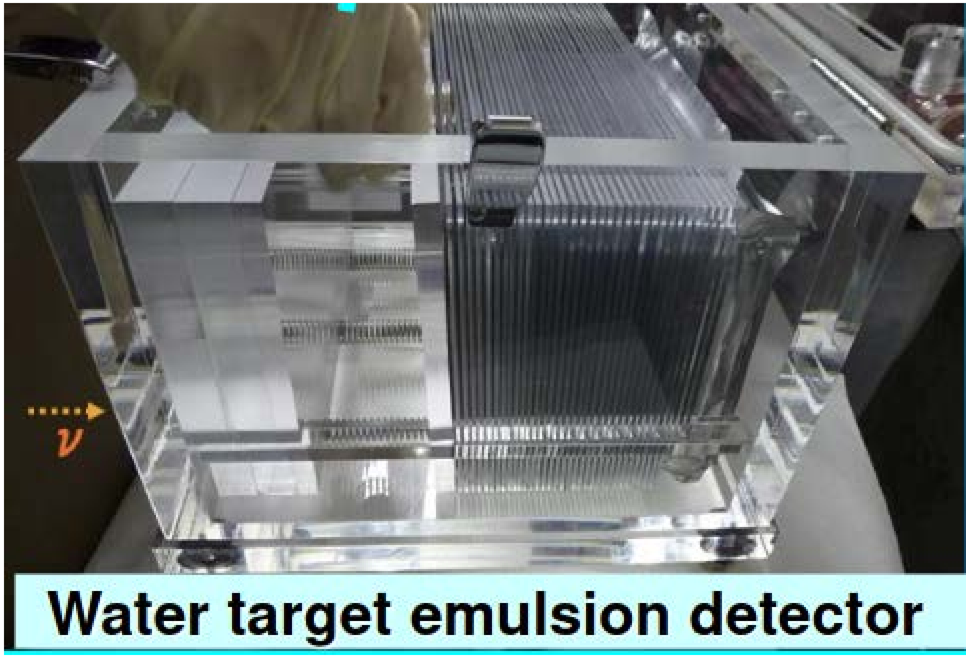
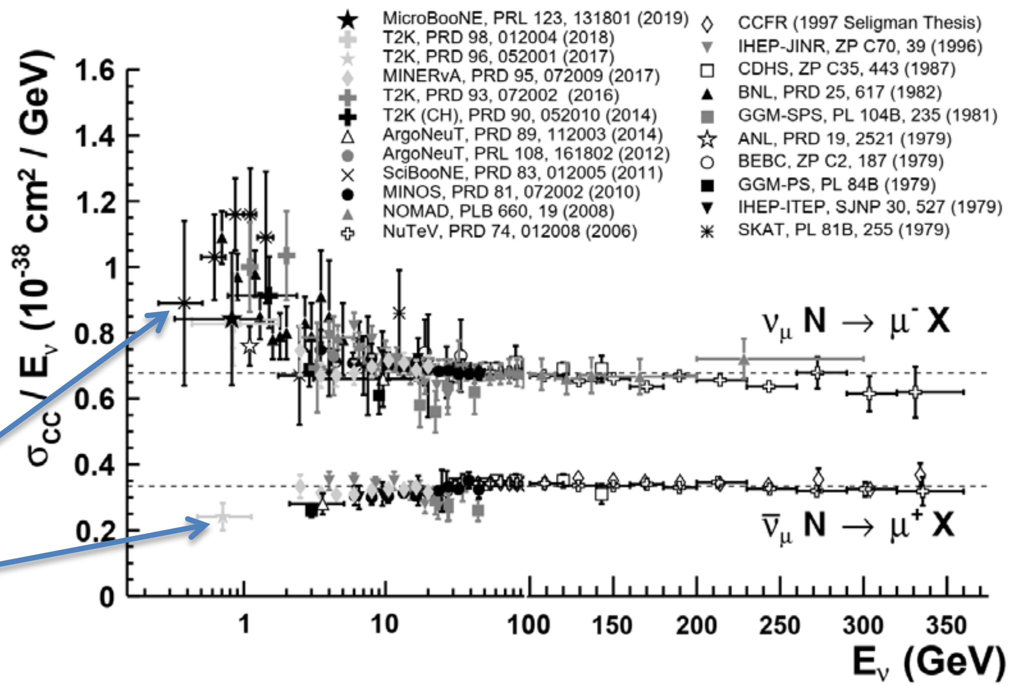


Photo from T. Fukuda of NINJA collaboration

Why measure cross-section?



Two lonely dots in our energy region

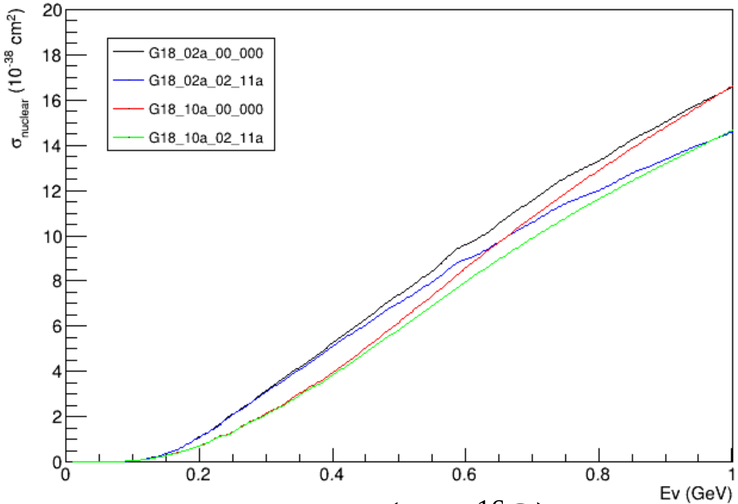
Figure 51.1: Measurements of per nucleon ν_μ and $\overline{\nu}_\mu$ CC inclusive scattering cross sections divided by neutrino energy as a function of neutrino energy. Note the transition between logarithmic and linear scales occurring at 100 GeV. Neutrino cross sections are typically twice as large as their corresponding antineutrino counterparts, although this difference can be larger at lower energies. NC cross sections (not shown) are generally smaller compared to the CC case.

Taken from PDG 2020:
[P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)]

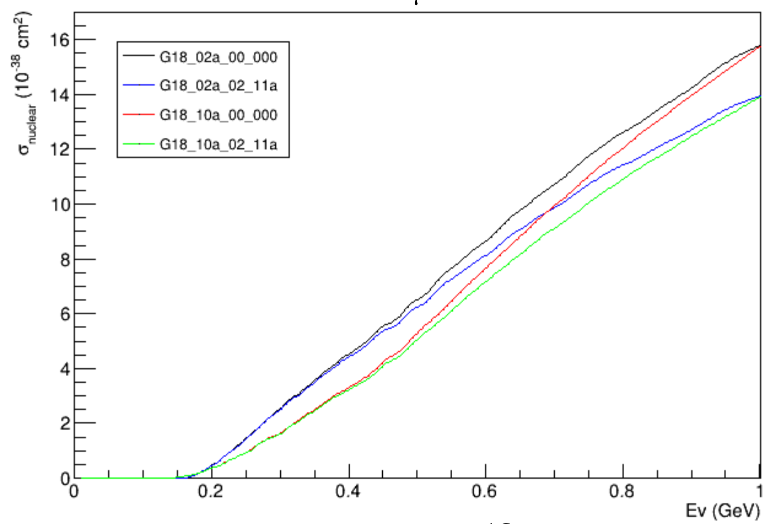
Why measure cross-section?

- 4 different “tunes” of GENIE 4.0.6 produce significantly differen curves

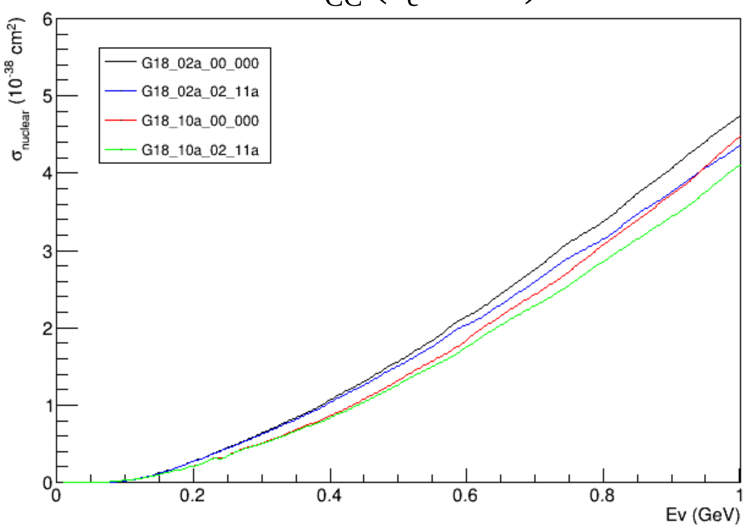
$\sigma_{CC}\ (\nu_e + {}^{16}O)$



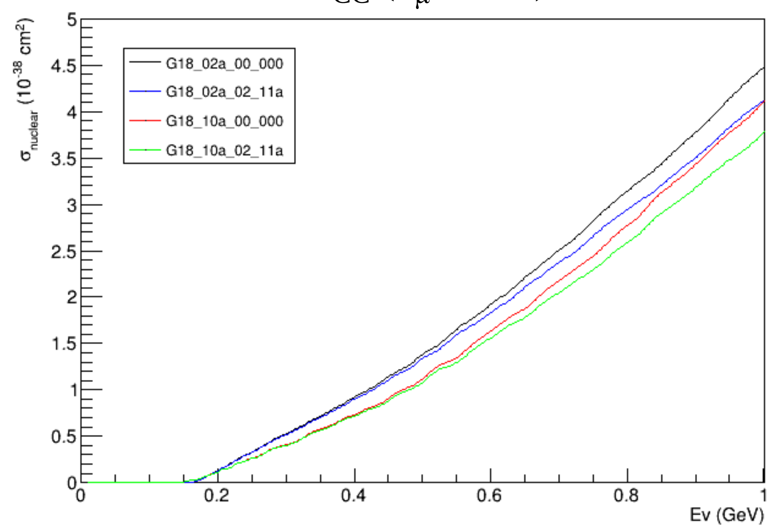
$\sigma_{CC}\ (\nu_\mu + {}^{16}O)$



$\sigma_{CC}\ (\overline{\nu}_e + {}^{16}O)$



$\sigma_{CC}\ (\overline{\nu}_\mu + {}^{16}O)$



Cross-section measurement

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
- Having constraint on the flux, we can measure interaction cross-sections in all Near Detectors:
    - WC, Super FGD, emulsion
- Use current **and future** data from other experiments (e.g. T2K)

Neutrino scattering on electrons

Basic idea:

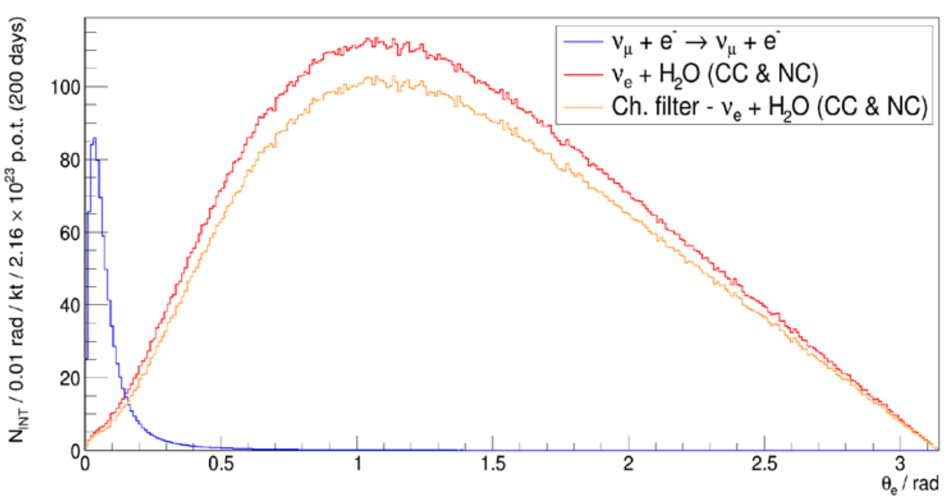
- Cross section for neutrino – electron scattering can be calculated to high precision (NLO seems to be enough for all practical purposes)
- Knowing a cross-section, one can measure the flux at Near Detector site
  - More precisely, **put tight constraints on the flux**

Main problem:

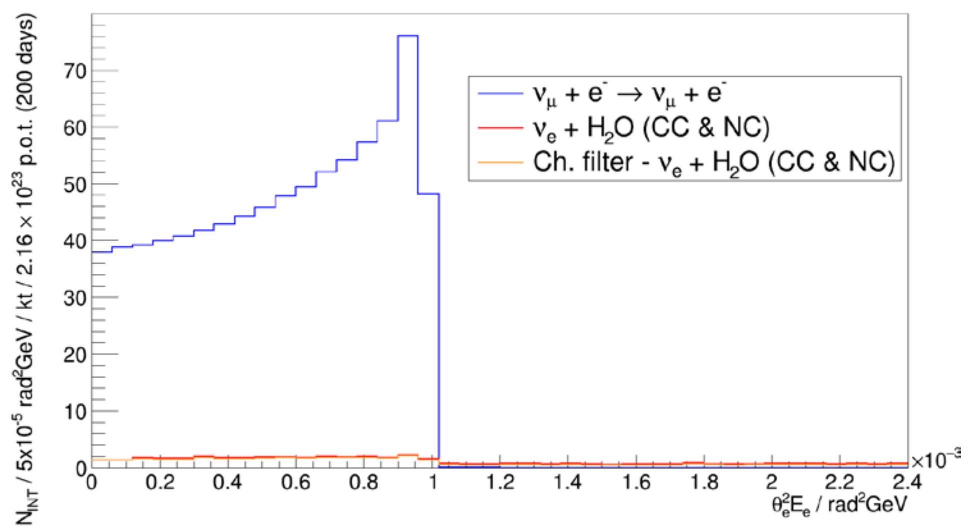
- Neutrino cross-section scales with target mass
  - having electron as a target, the cross-section is much smaller than having nucleon as a target

Event selection:

- ν - e scattering has a very forward single electron in the final state



True MC angular (θ) distribution



True MC distribution of ($\theta^2 E_e$)

Near detectors conclusions / strategy

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

- **Main difficulty:**
  - To disentangle the cross-section from flux

- **Strategy:**
  - Constrain flux by measuring neutrino-electron scattering
  - Use the constrained flux to measure (inclusive and inclusive) cross-sections for interactions of neutrinos with water

The End