ESSnuSB(+) Far Detector

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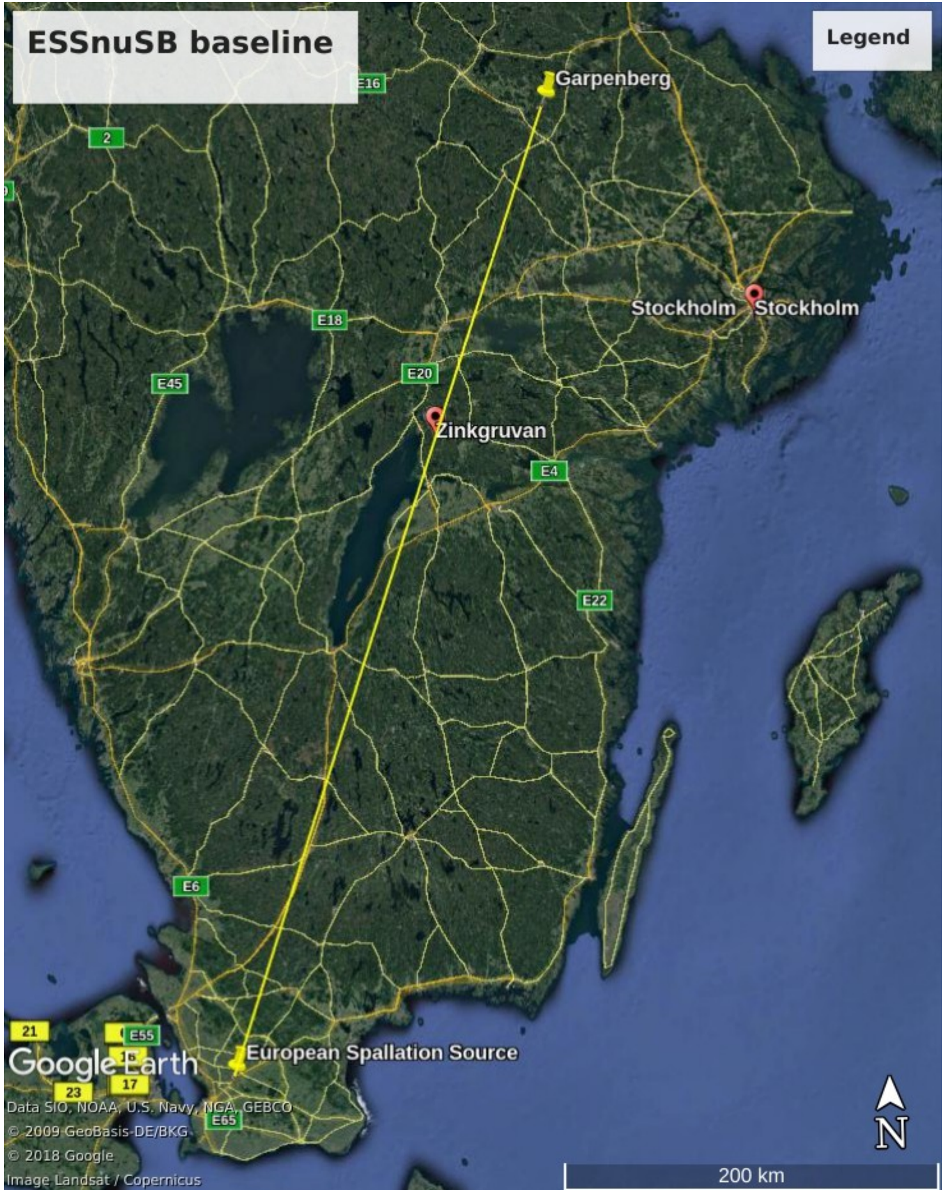


Far detector position

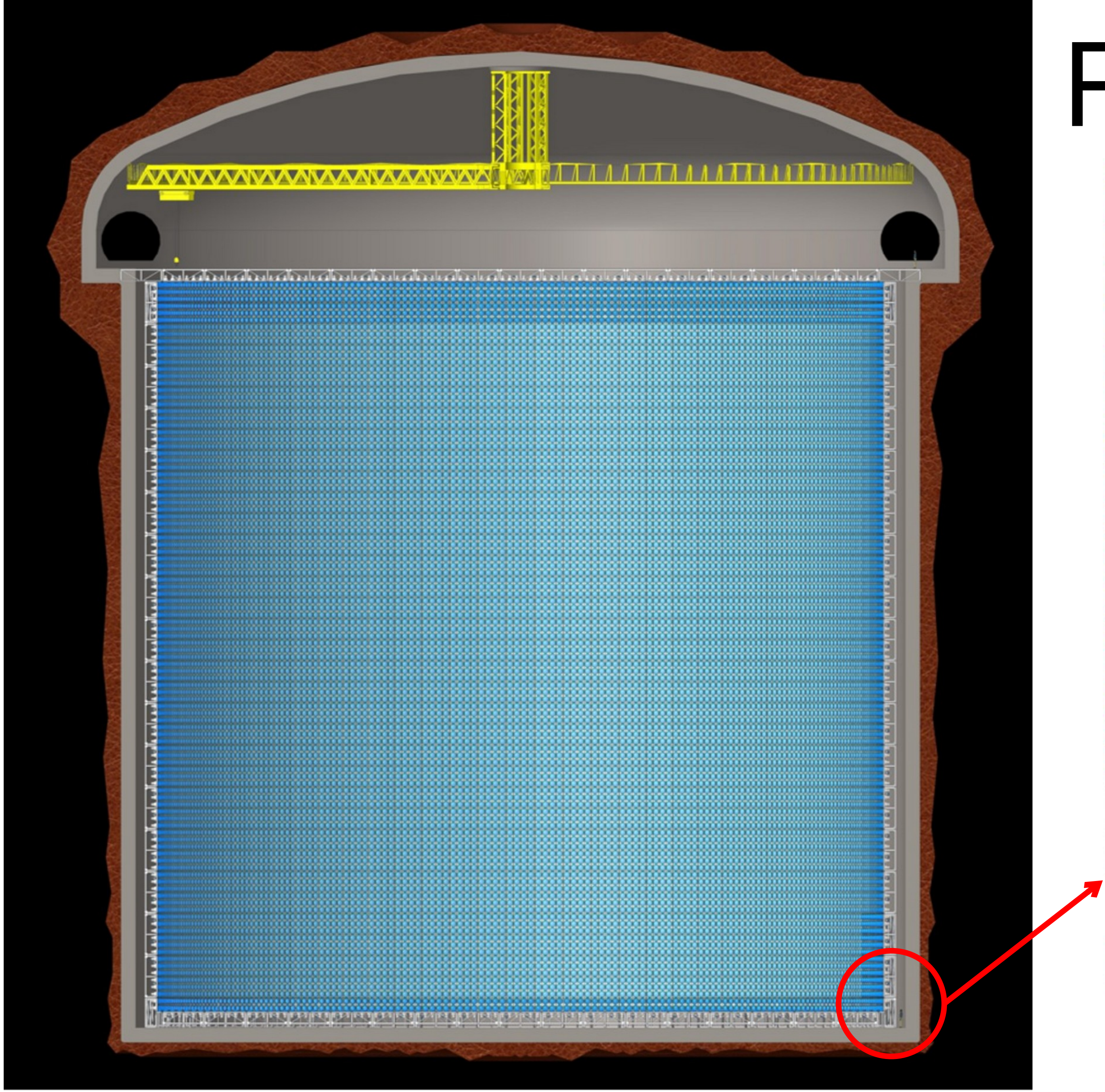
Selected baseline:

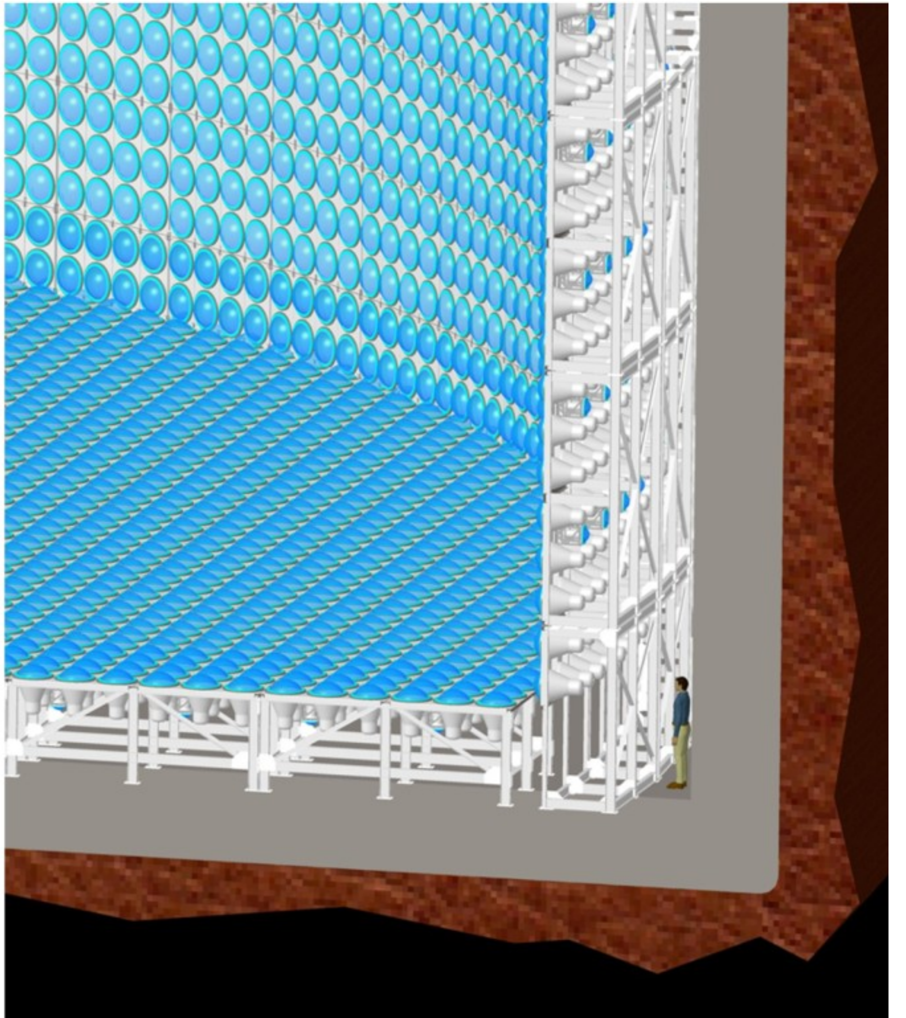
- Zinkgruvan mine, 360 km from the source, partly covernig 1st and 2nd maximum
  - Number of interactions at 2nd maximum similar to Garpenberg

Alternative (not selected)

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

Far detector





Far detectors

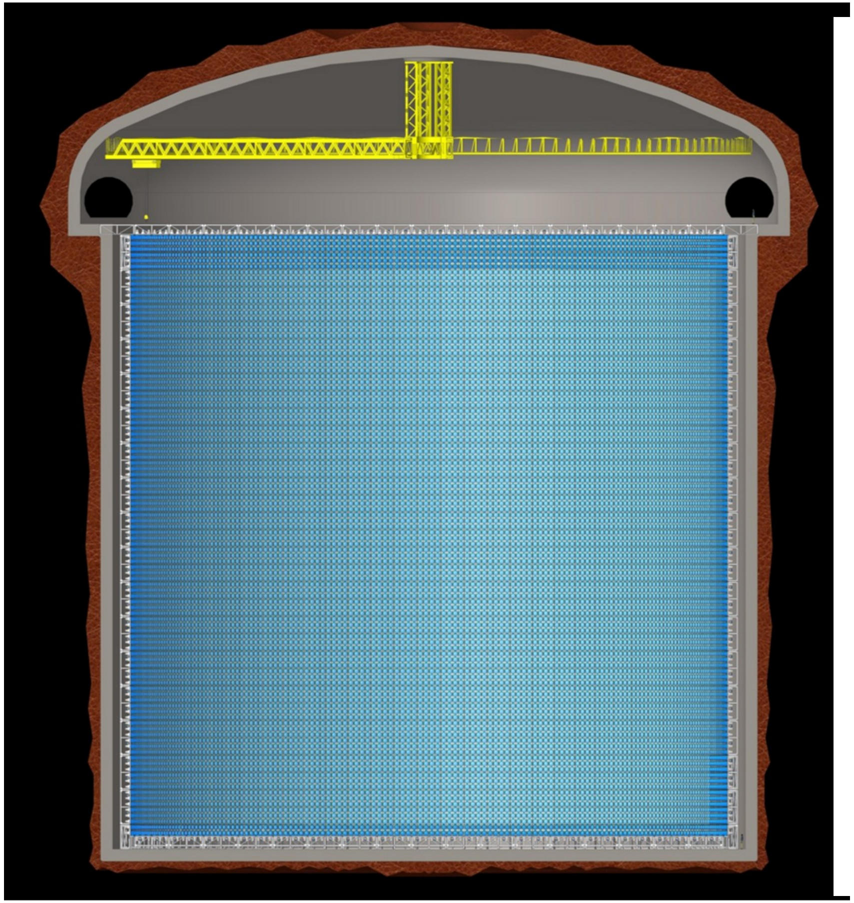
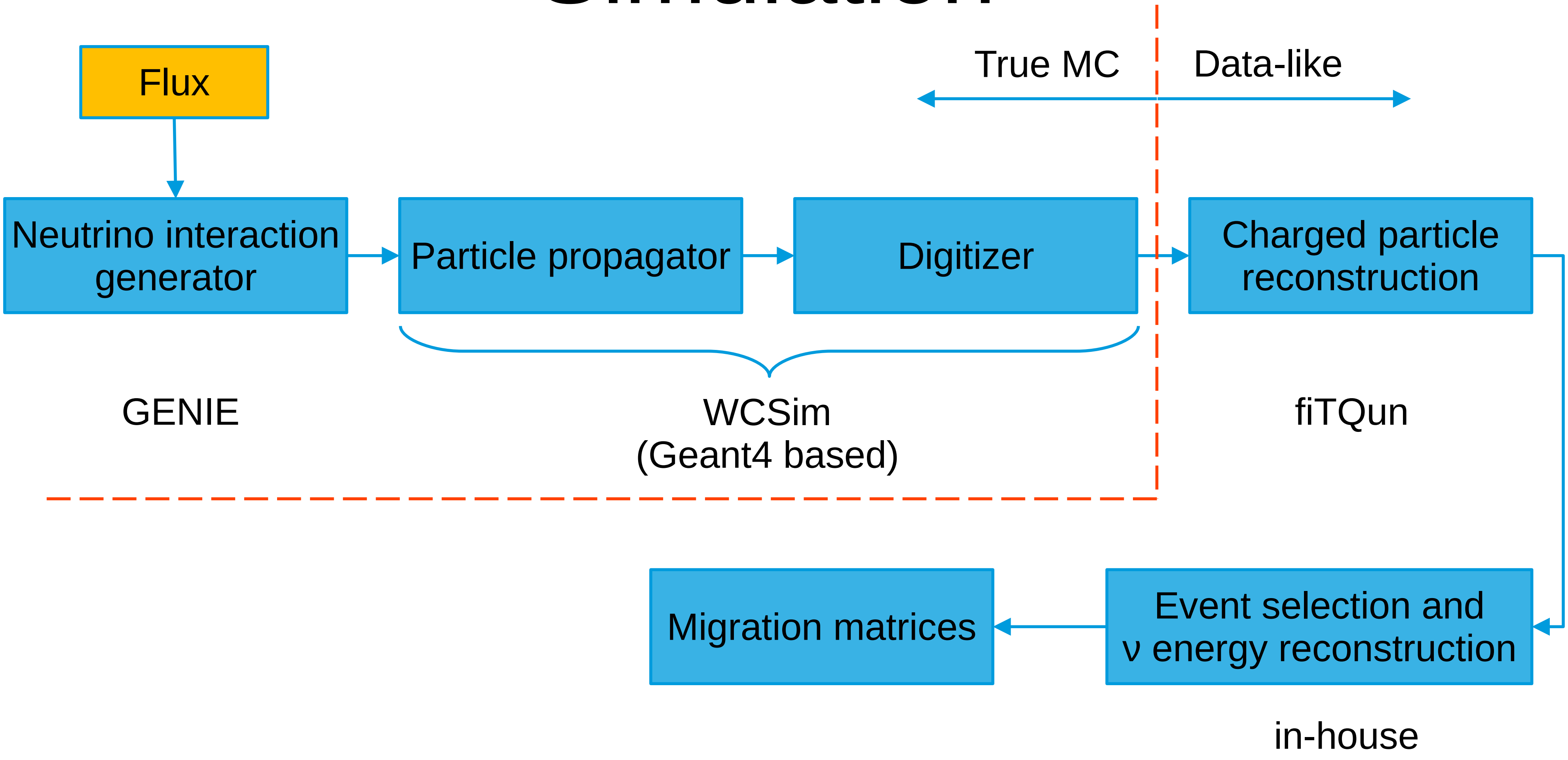


Table 6.15: Parameters of the ESSνSB far detector

Parameter	Value
Type	Cylindrical water Cherenkov
Tank geometry	Standing cylinder
Number of tanks	2
Tank diameter	78 m
Tank height	78 m
Inner detector diameter	74 m
Inner detector height	74 m
Target water mass	318 kt per tank (636 kt total)
Inner detector PMT coverage	30%
Inner PMT diameter	20 inch
Number of inner PMTs	37,830 per tank (75,660 total)
Fiducial volume cut	2 m inwards from inner detector walls
Fiducial water mass	269 kt per tank (538 kt total)
Outer (veto) PMT size	8 inch
Number of outer (veto) PMTs	8226 per tank (16452)

Depth: ~ 1000 m

Simulation


True MC
Data-like
Flux
Neutrino interaction generator
Particle propagator
Digitizer
Charged particle reconstruction
GENIE
WCSim
(Geant4 based)
fiTQun
Migration matrices
Event selection and
ν energy reconstruction
in-house

Neutrino energy from lepton momentum

Scatternig angle needed

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

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-

This formula assumes the QES scattering.

Event selection

- Every beam event in positive (negative) polarity is exclusively classified as:
  - ν_e ($\bar{\nu}_e$) CC candidate
  - ν_μ ($\bar{\nu}_\mu$) CC candidate
  - ν NC ($\bar{\nu}$ NC) candidate (new)
  - not selected
- ν_e / ν_μ discrimination is based on
  - Michel electron detection
  - fiTQun PID
- NC rejection is based on
  - charge collected by PMTs used by fiTQun (noise not included)
  - pi0 detection

Discrimination variables

- **Number of subevents**
  - 1st subevent is the earliest detector trigger that happened within beam on window (BOW)
  - 2nd and higher subevents are subsequent triggers within the BOW and a period after it
- **fiTQun particle id (PID)**
  - maximum likelihood based PID
- **Total collected charge at PMTs**
  - filtered for noise by fiTQun
- **pi0 identification**
  - maximum likelihood based PID coupled with free fit for pi0 mass
- **Reconstructed momentum of electrons**
  - used to reject dark muons
    - muon that is not detected but Michel electron is

Muon decay videos

ν_e selection

- Sequential rejection algorithm
  - Fiducial cut assuming charged lepton is an electron
  - Subevents > 1 → not ν_e
  - PID favours muon over electron → not ν_e
  - Total used PMT charge < 1000 → not ν_e
  - PID strongly favours pi0 over electron (max(llh(pi0)) - max(llh(e))) > 150) **and** fit pi0 mass between 55 MeV and 205 MeV → not ν_e
  - charged lepton momentum assuming electron < 70 MeV → not ν_e
  - it is a ν_e

ν_μ and NC selection

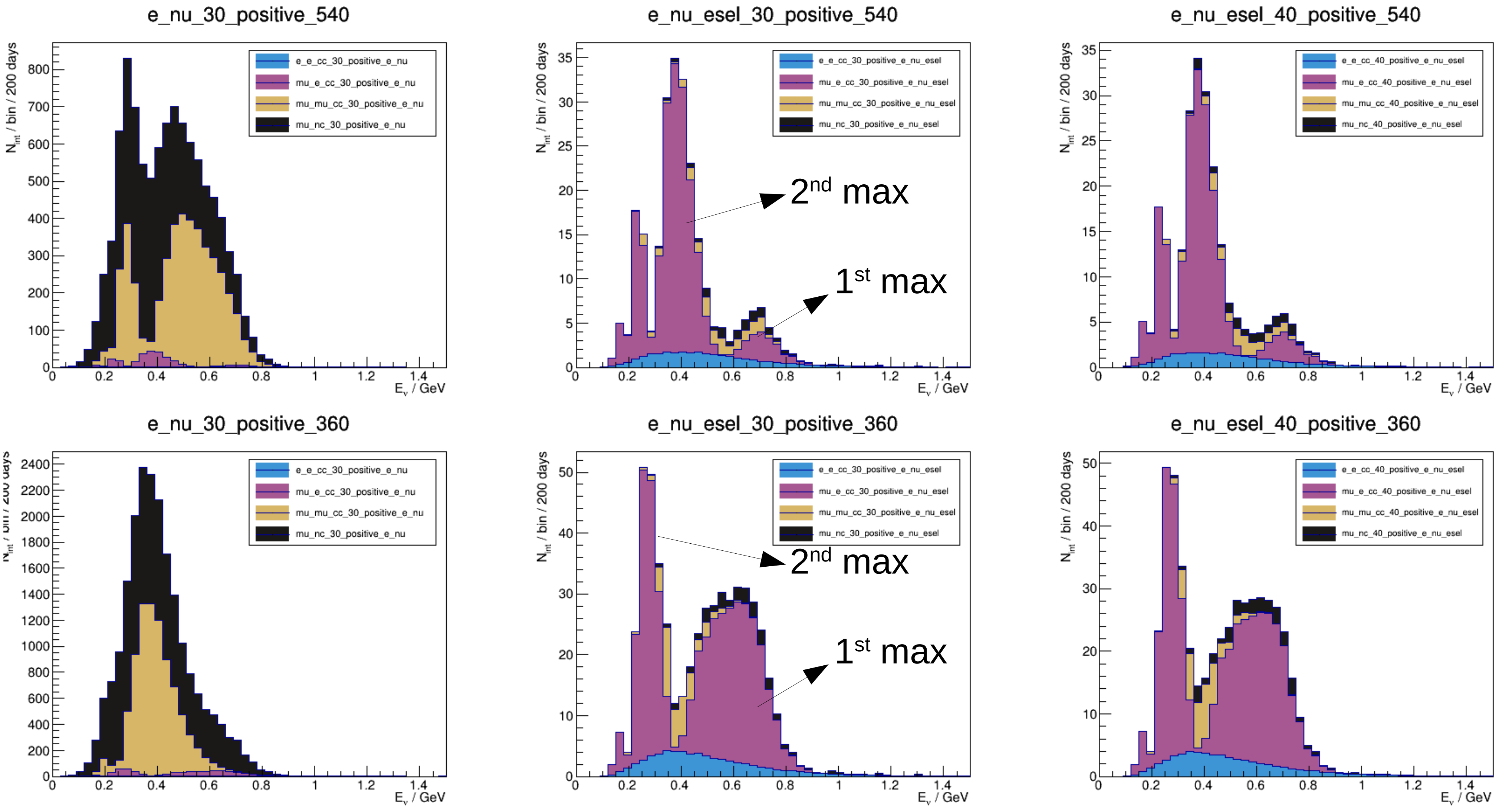
- ν_μ selection
  - selected as ν_e → not ν_μ
  - fiducial cut (assuming muon as charged lepton)
  - subevents < 2 → not ν_μ
  - it is ν_μ
- NC selection
  - selected as ν_e or ν_μ → not NC
  - total used PMT charge between 5 and 800 → it is NC

Before we continue

- Fluxes in following plots are not the latest (CDR) version
  - still good enough for illustration
- Everything is normalized to 1 year (200 days) of operation
  - “expected events” means expected events in a year
- Event selection is the same for positive and negative polarity
  - all events in positive (negative) polarity are assumed to come from neutrinos (antineutrinos) by the selection algorithm
- Migration matrices are different for neutrinos and antineutrinos

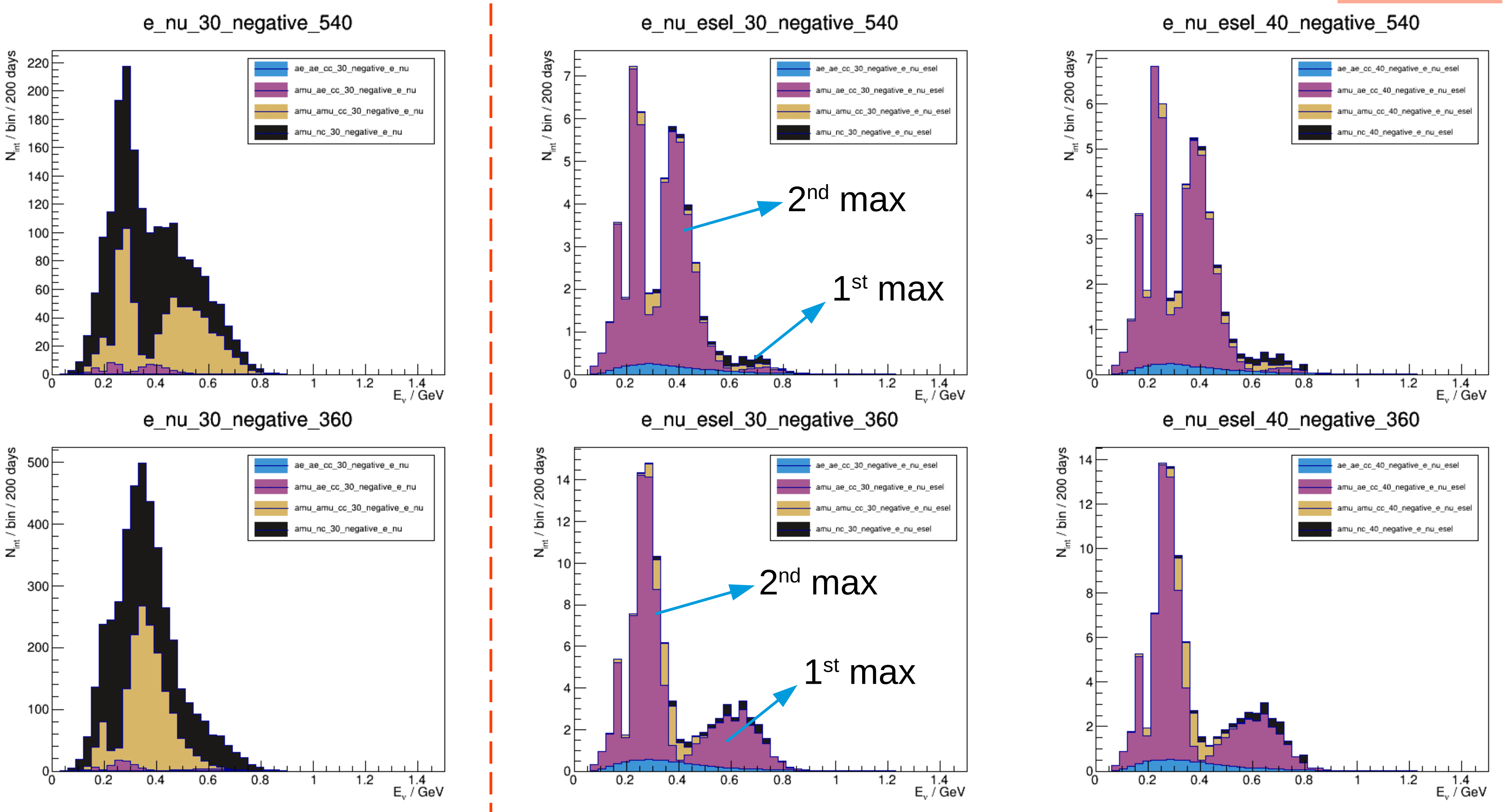
ν_e-like selection – true energy spectrum, positive polarity

True MC



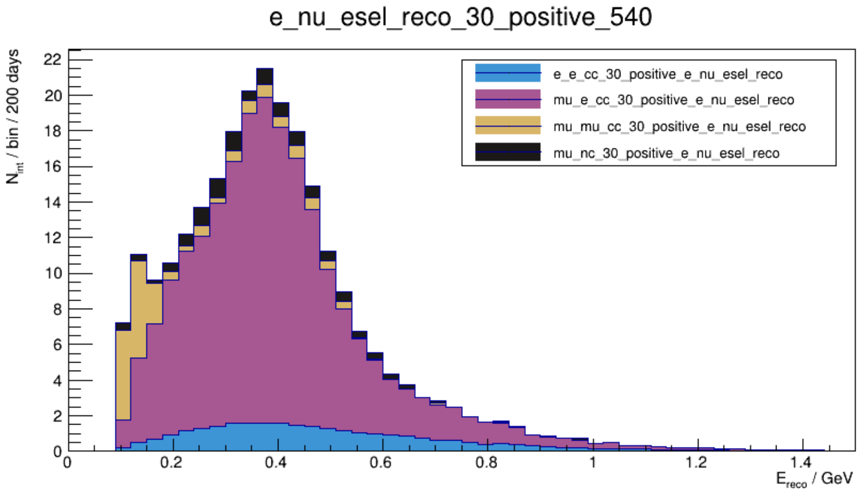
ν_e-like selection – true energy spectrum, negative polarity

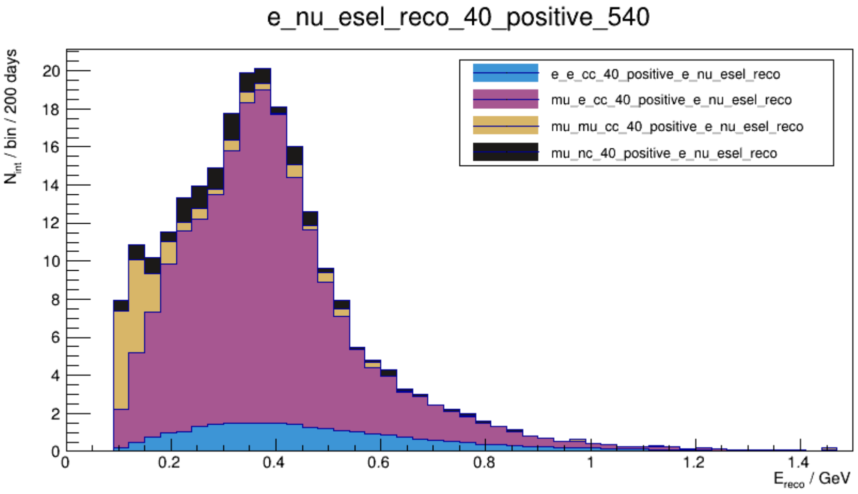
True MC

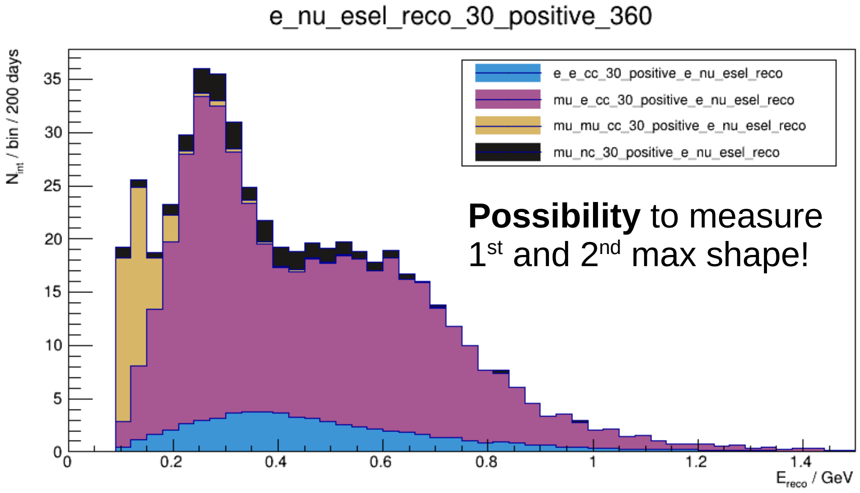


ν_e-like measured spectrum, positive polarity

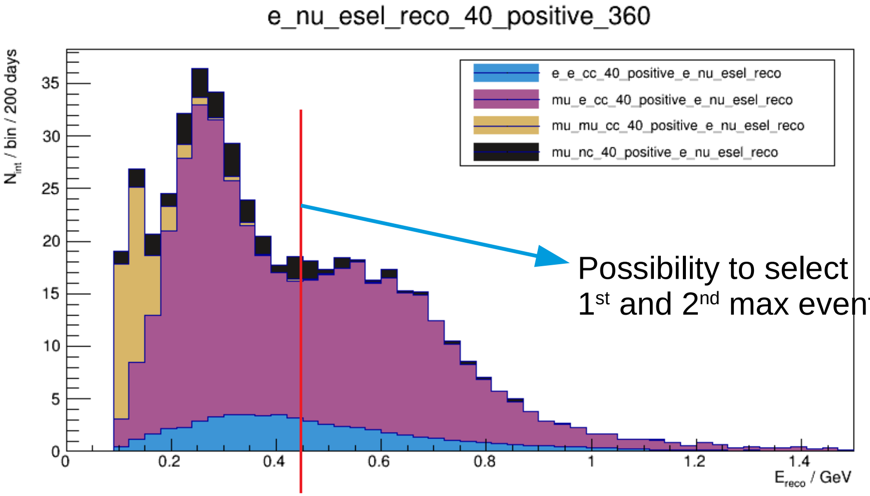
Data-like







Possibility to measure 1st and 2nd max shape!

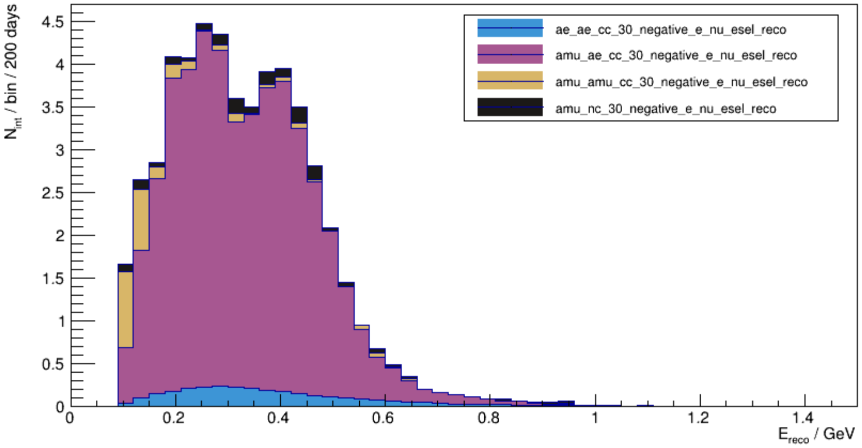


Possibility to select 1st and 2nd max events?

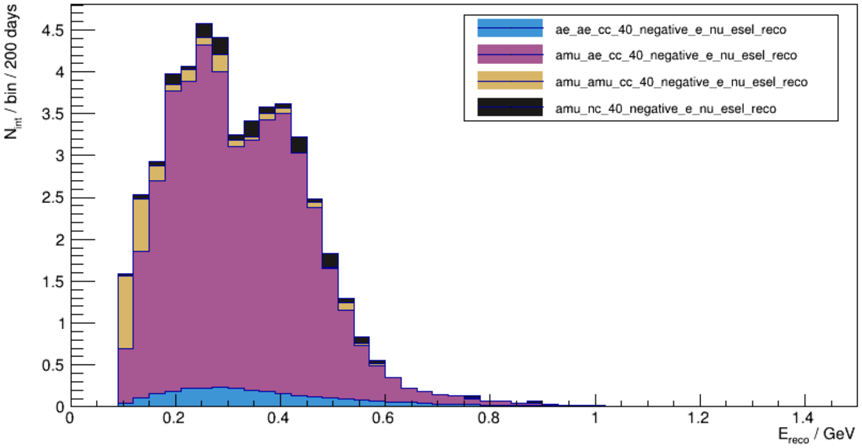
ν_e-like measured spectrum, negative polarity

Data-like

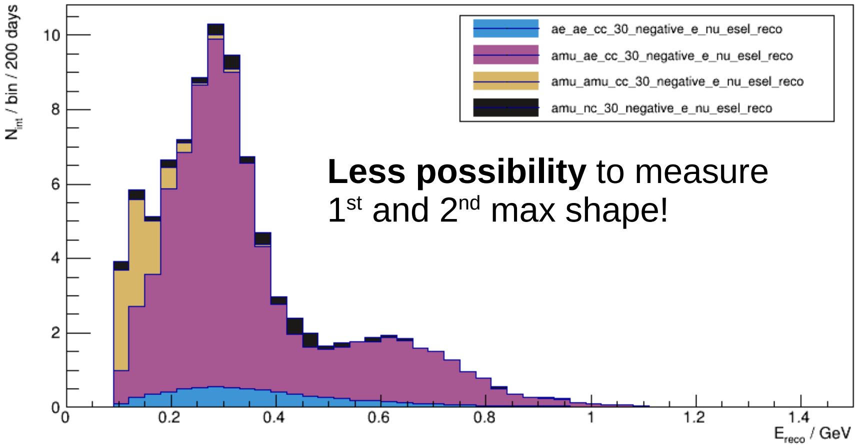
e_nu_esel_reco_30_negative_540



e_nu_esel_reco_40_negative_540

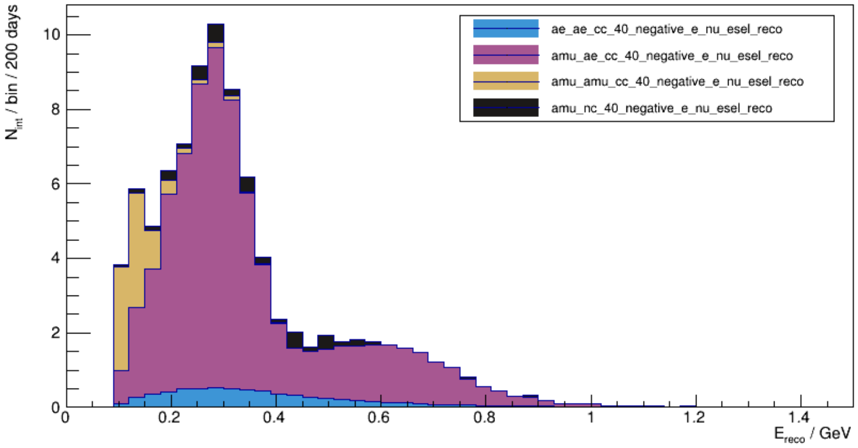


e_nu_esel_reco_30_negative_360

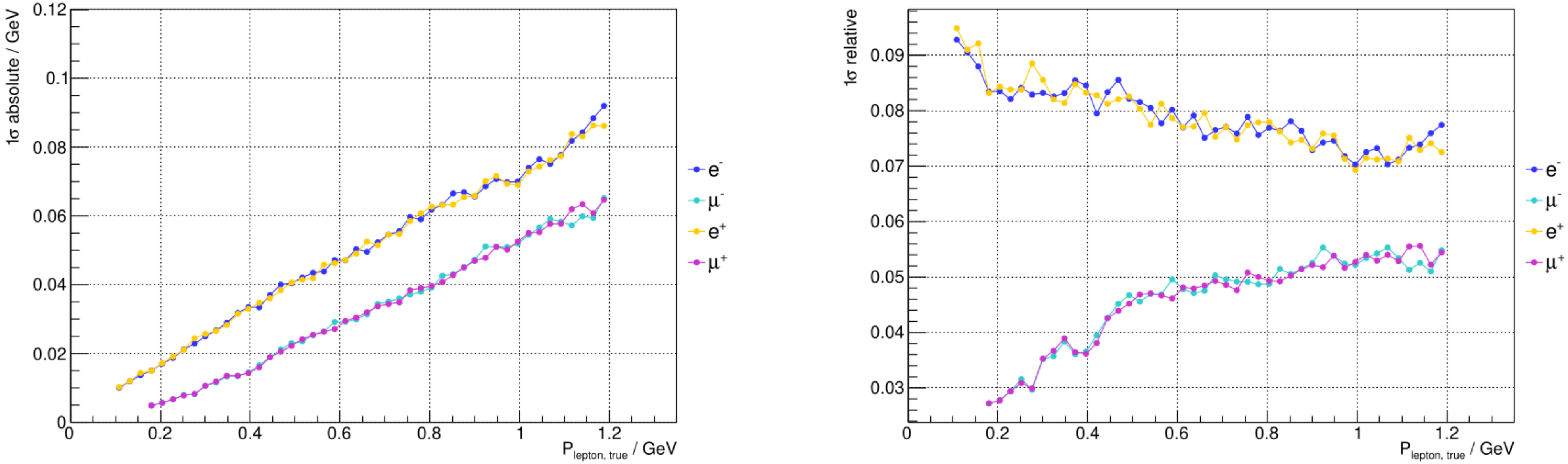


Less possibility to measure 1st and 2nd max shape!

e_nu_esel_reco_40_negative_360



Charged lepton mom. resolutions

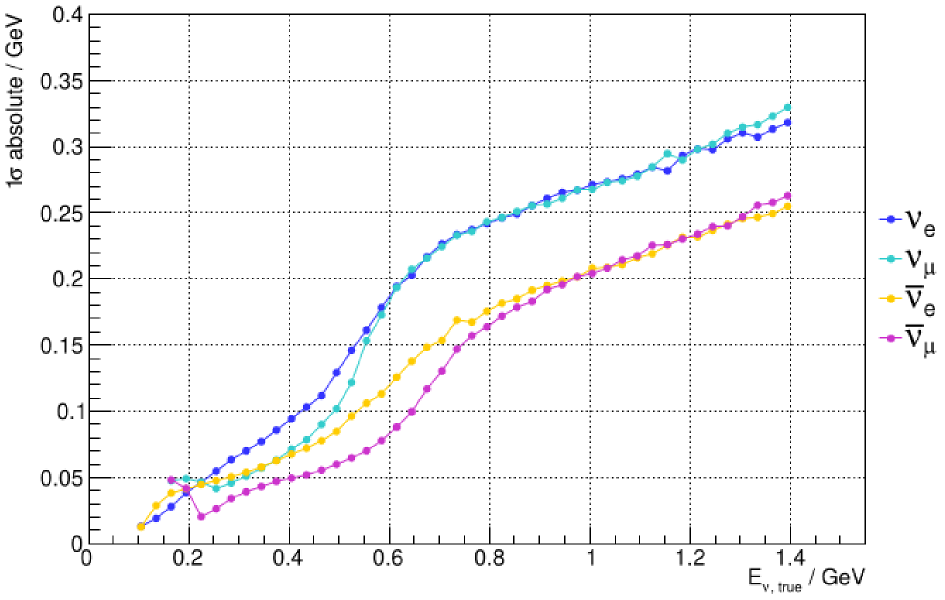


(a) Absolute momentum resolution

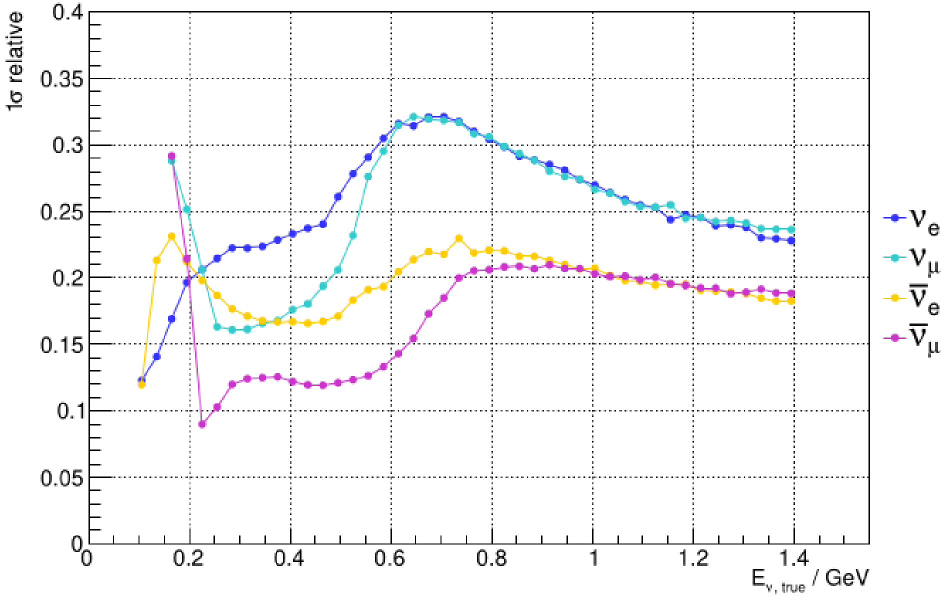
(b) Relative momentum resolution

Figure 6.59: Momentum reconstruction performance for a pure charged lepton flux. $1\,\sigma$ absolute resolution of reconstructed produced lepton momentum as a function of true lepton momentum is shown in Fig. 6.59a. $1\,\sigma$ relative resolution of reconstructed produced lepton momentum as a function of true lepton momentum is shown in Fig. 6.59b

Neutrino energy resolution

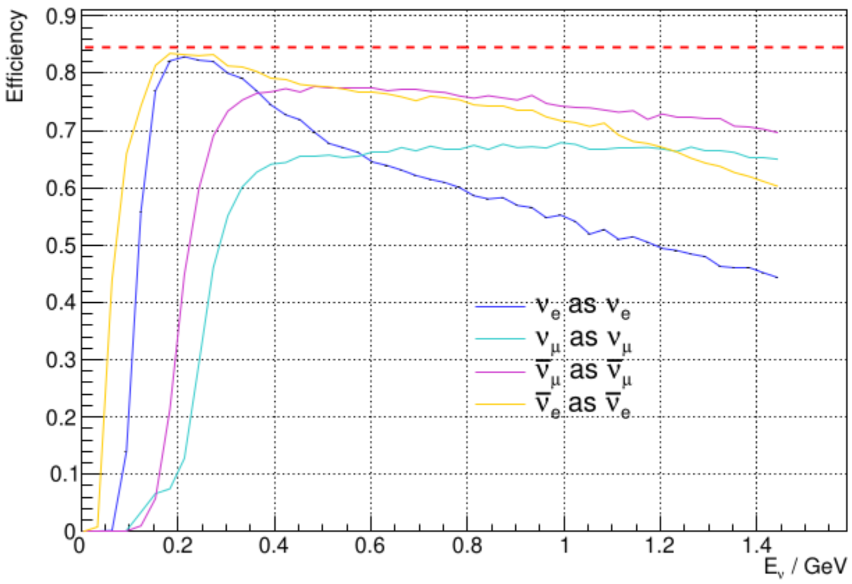


(b) Absolute energy resolution – all events.

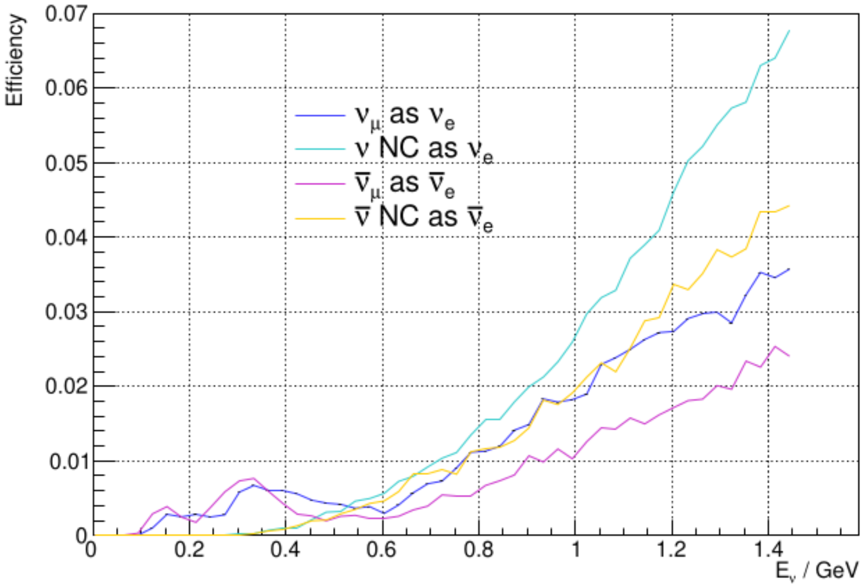


(d) Relative resolution – all events.

Efficiency / rejection



(a) Diagonal



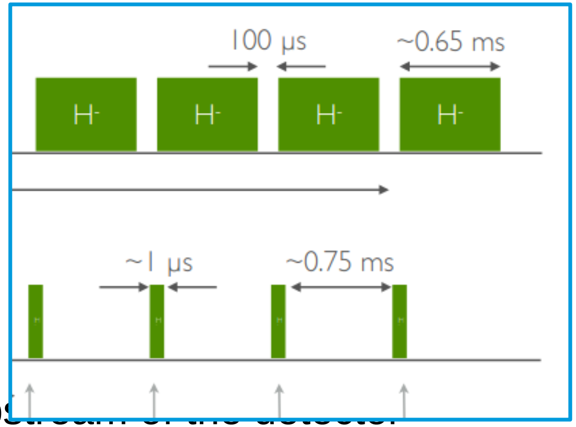
(b) Off-diagonal

Figure 6.69: Efficiency of the selection algorithm. Figure 6.69a shows the diagonal selection – the neutrinos that were selected correctly. Figure 6.69b shows off-diagonal efficiency – the neutrinos that were selected incorrectly. The red dashed line represents the fiducial volume cut. Off-diagonal efficiency is shown only for the most important cases, the physics reach determination is made using all possible selected/true combinations.

Can be further improved, but do we need it?

External background to FD

- Beam time window (BTW) – time during which beam is on **and** time to wait for muon decay (~50 us)
  - time between two ¼ pusles is about 750 us
- Atmospheric muons entering the detector
  - completely negligible during BTW
    - 1000 m rock overhead
- Atmospheric neutrinos interacting in the detector and rock around it
  - interactions in the detector negligible during BTW
  - rock has not been studied, but I'm not worried (veto, short BTW)



- Rock muons – muons produced by **beam neutrinos** interacting in rock upstream of the detector
  - BTW rejection not possible
  - we have low energy neutrino beam - muon range in water < 2 m
    - not many of them will exit the rock and those that do will stop in veto water volume
    - also, we have veto
- **No beam time window rejection possible for non-beam physics!**

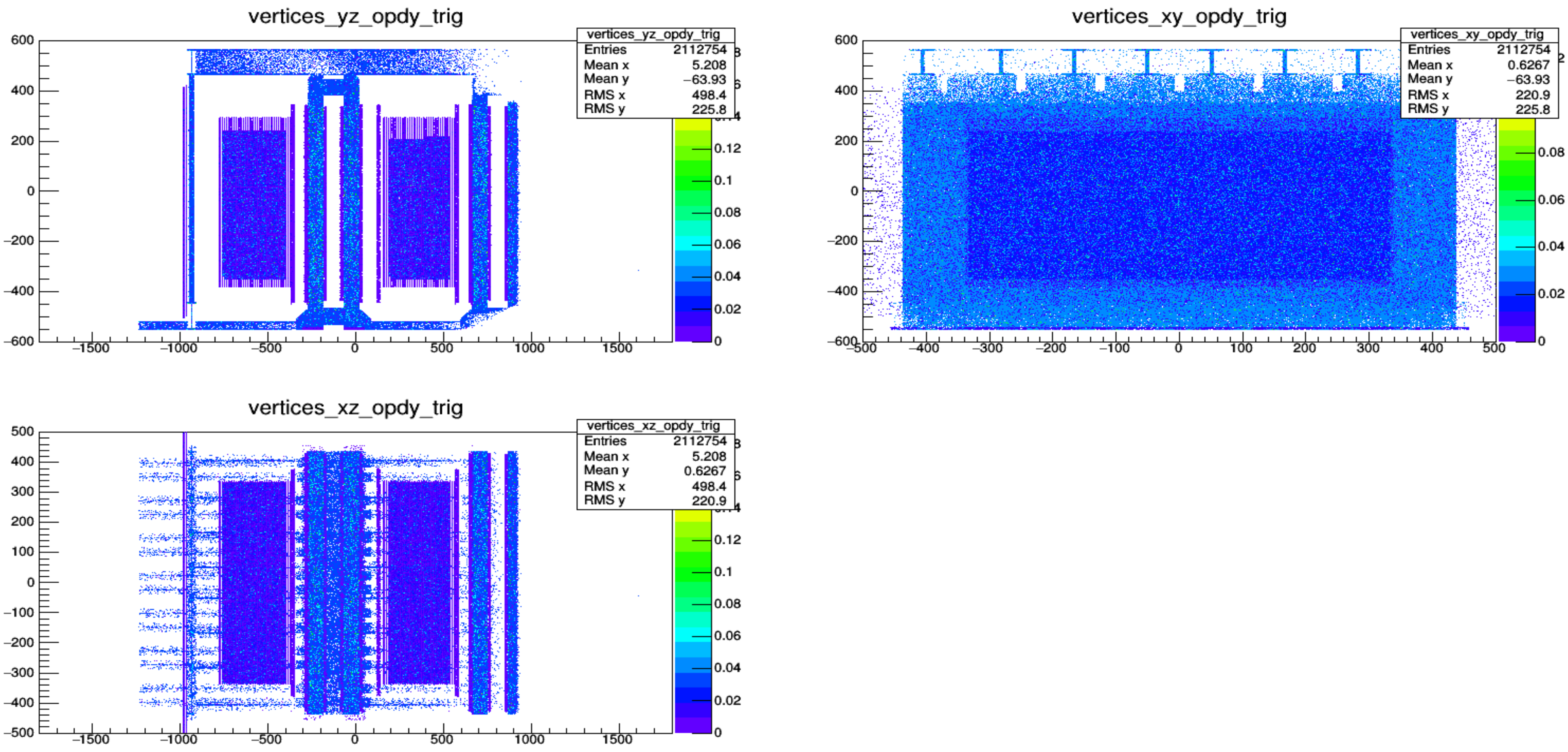
The future

- Create a full simulation framework
  - include full geometry (detector + rock)
    - needed to study neutrino interactions in the rock
  - implement multiple neutrino flux drivers in GENIE
    - needed to study different non-beam fluxes
- simulate Gd doping
- improve/replace WCSim
- better/faster reconstruction – machine learning, ...
  - need to implement a “MC independent” reconstruction as a benchmark

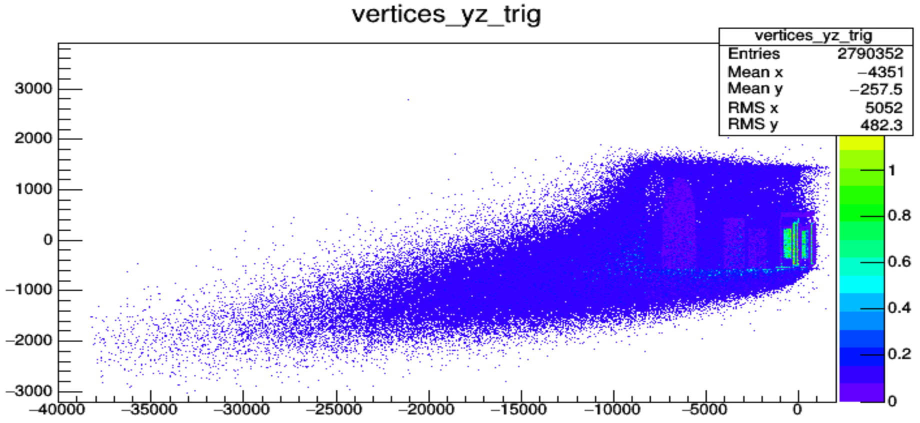
Far detector studies

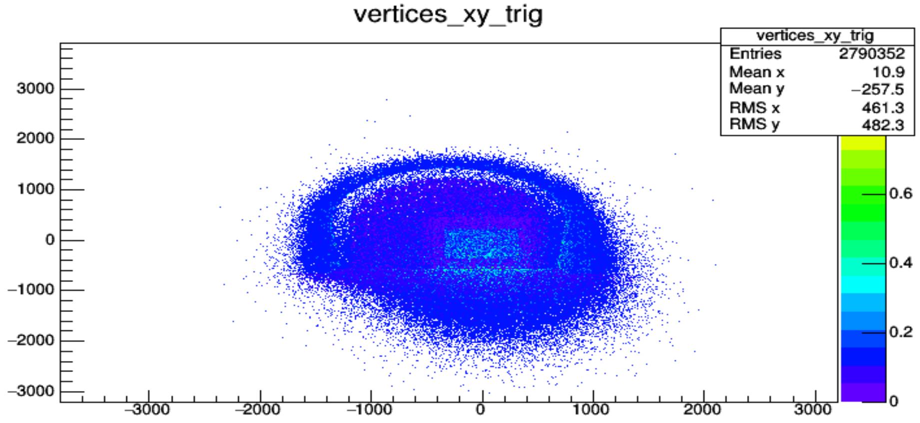
- **atmospheric neutrinos**
  - ν / $\bar{\nu}$ components
  - energy ~ 0.1–100 GeV
  - spherical source – use Honda 2-D fluxes
  - rock muons must be studied too
- **atmospheric muons**
  - correlated time of arrival (muon bundles) – needs full CORSIKA sumulation
  - muon tomography of the mine
- **supernova neutrinos**
  - mostly $\bar{\nu}$, smaller ν component
  - point source – known scattering angle
  - enregy ~ 0.5–100 MeV

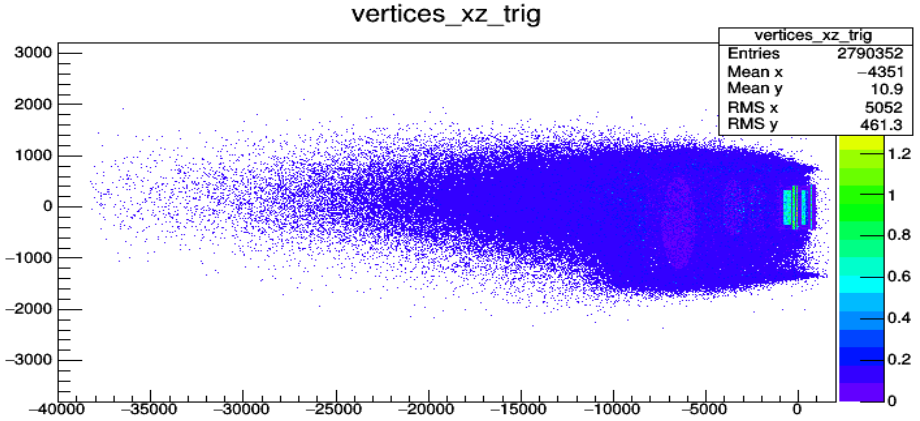
OPERA, beam MC vertices, trigger, no beam rock muons



OPERA, beam MC vertices, trigger, with beam rock muons



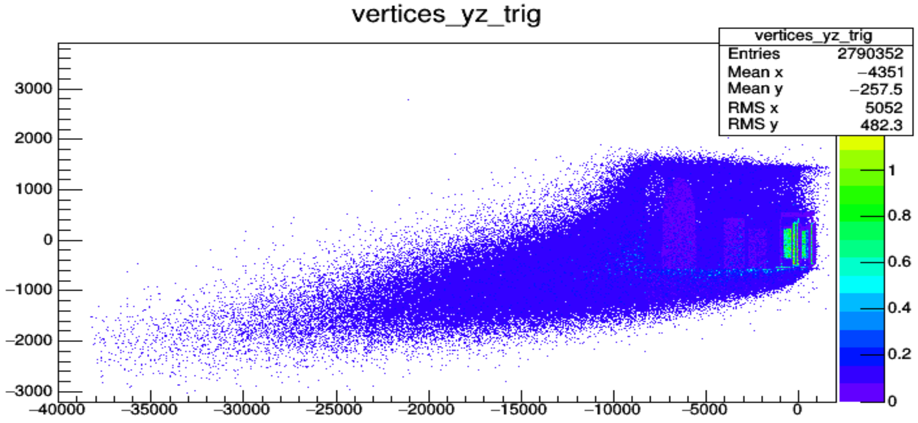


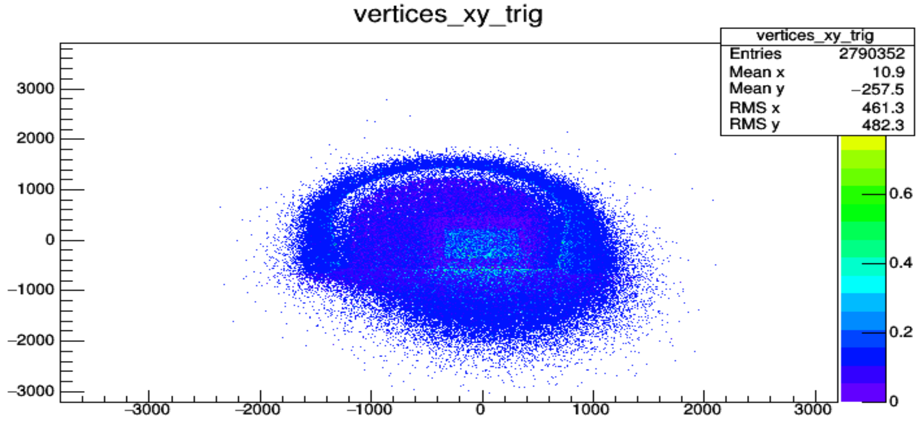


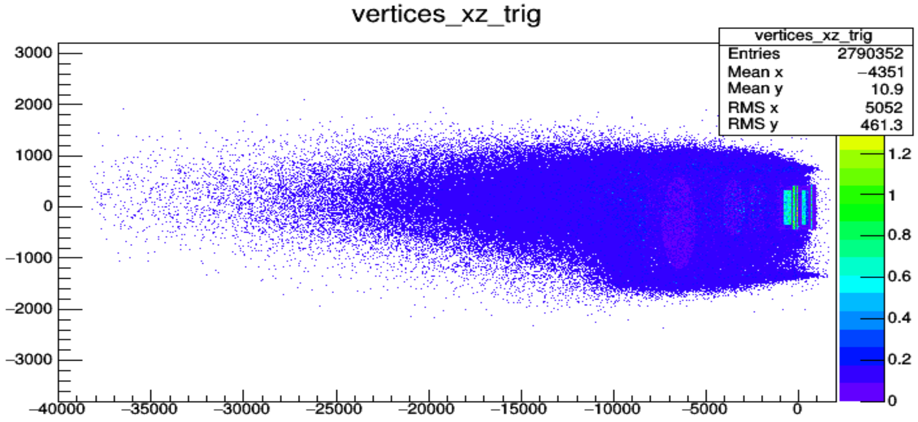
OPERA: $\mathrm{E}_\nu \sim 15\mathrm{GeV}$

ESSnuSB: $\mathrm{E}_\nu \sim 300\mathrm{MeV}$

OPERA, beam MC vertices, trigger, with beam rock muons







OPERA: $E_\nu \sim 15\mathrm{GeV}$

ESSnuSB: $E_\nu \sim 300\mathrm{MeV}$

Muon range scales with energy.

Beam rock muons negligible in ESSnuSB, atmospheric neutrino rock muons probably not.

Far detector studies

- **diffuse supernova neutrinos**
  - isotropic source
  - energy to be figured out
- **solar neutrinos**
  - direction known
  - energy ~0-20 MeV
- **reactor neutrinos**
  - antineutrinos
  - multi-point source
  - energy ~ 1.8-8 MeV
- **geoneutrinos**
  - antineutrinos
  - from below?
  - energy ~ 1.8-3 MeV

Conclusions

- Far detector optimized enough for ESSnuSB beam physics
- Need further work and improvements for non-beam physics