END: ESSnuSB near detectors

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Purpose of Near Detectors

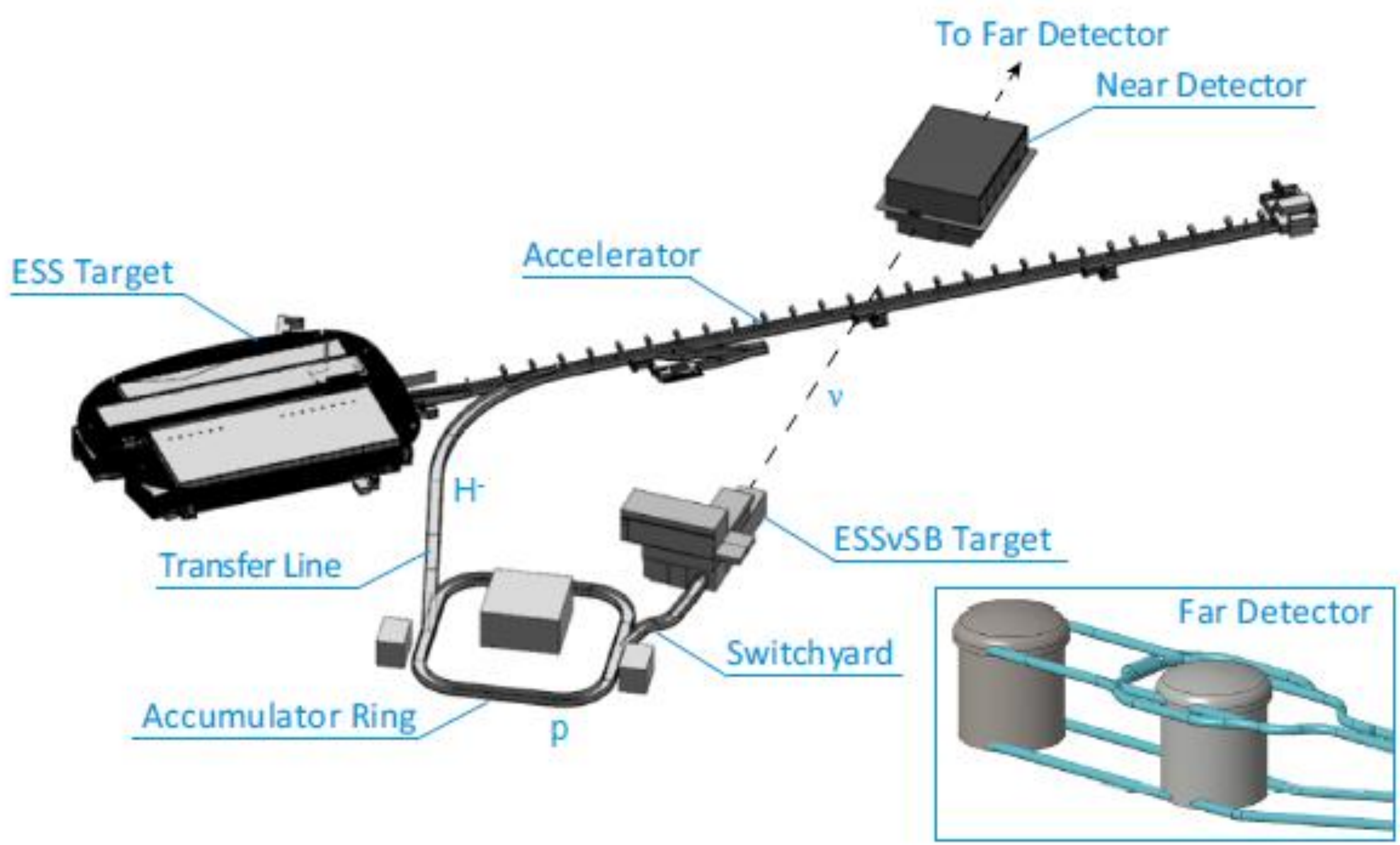
To reduce the systematic uncertainties by measuring:

- The unoscillated flux of neutrinos and, in particular, the electron neutrino contribution.

    electron neutrinos constitute < 1% of the unoscillated neutrino beam

- The neutrino interaction cross section in water for all four neutrino flavors.

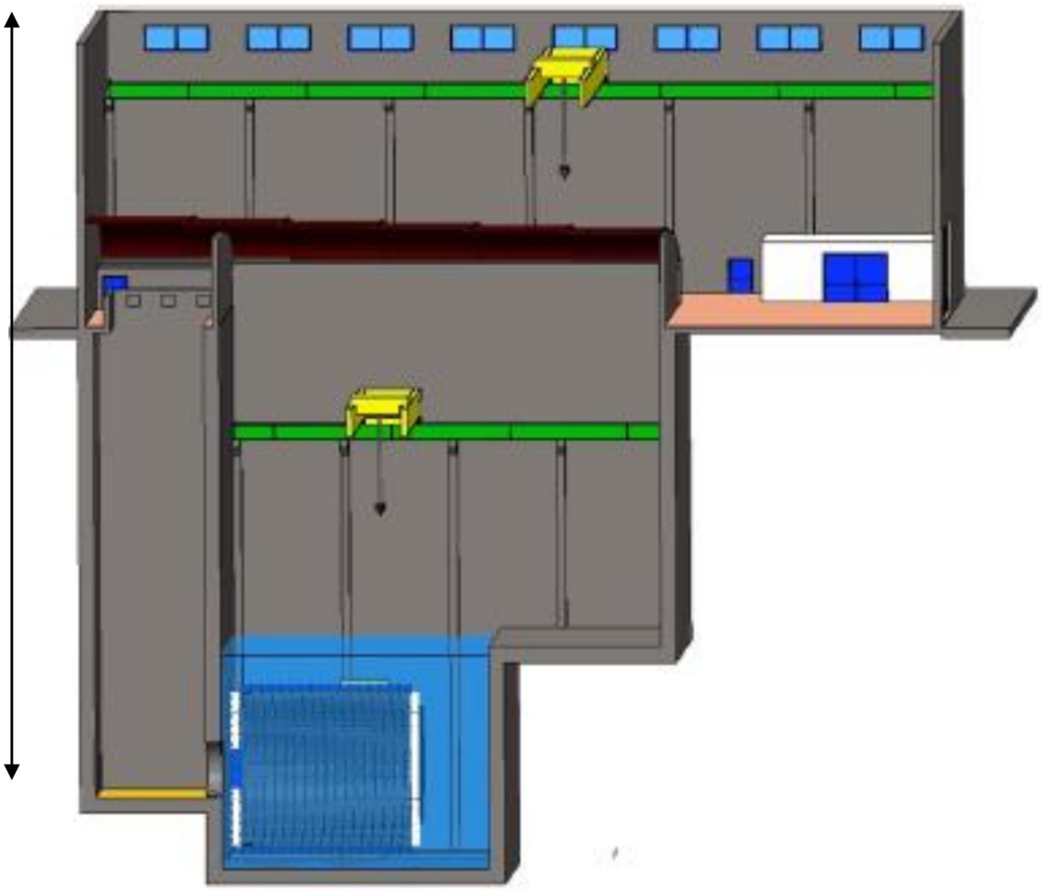
Near Detectors Site



The near detector will be placed at least ~250m from the neutrino target within the ESS campus.

Near Detectors Complex

Near detector building and cavern



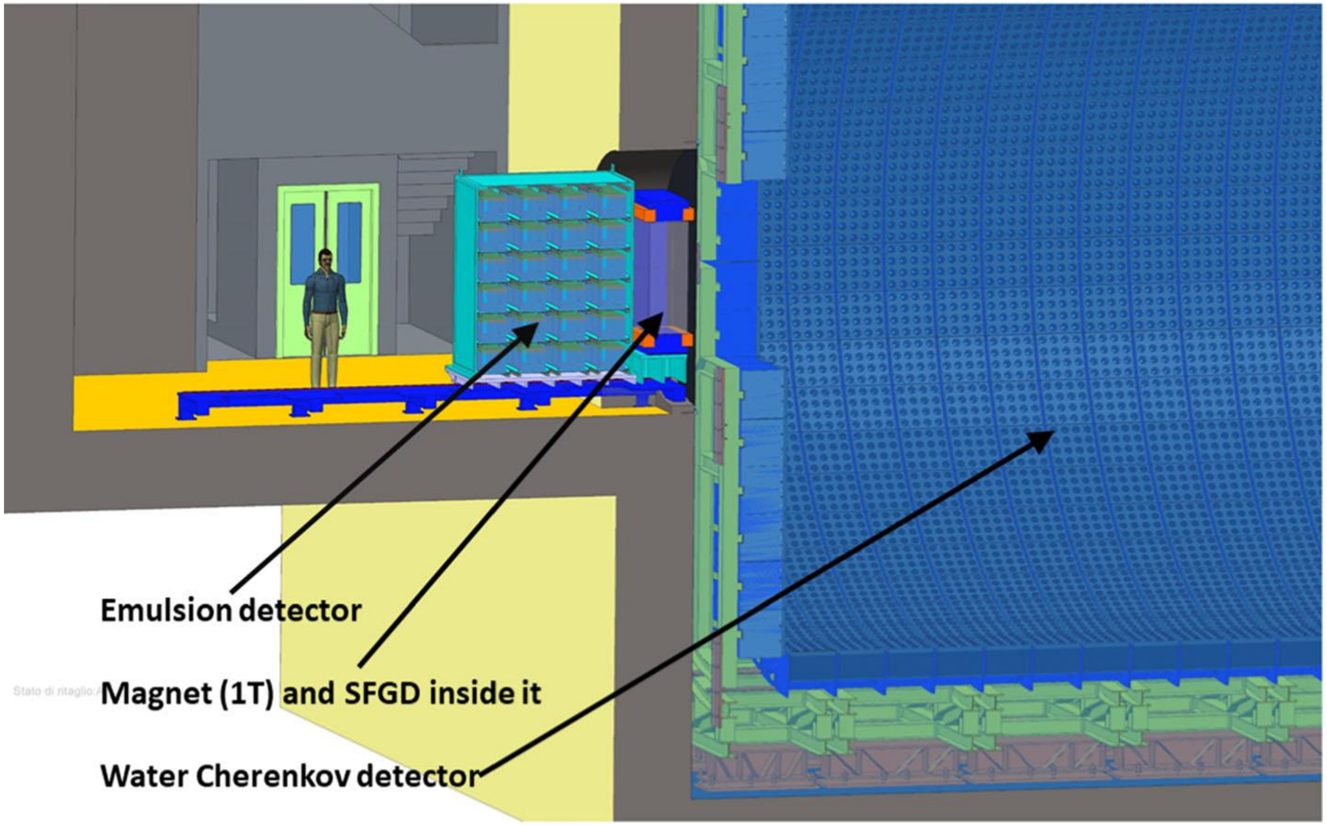
Depth ~ 15 - 20 m

Neutrino beam

Near Detectors

The near detector complex of the ESSνSB will consist of three separate detectors.:

- A kiloton-scale water Cherenkov detector.
- A magnetised super fine-grained detector (SFGD).
- An emulsion detector setup modelled after that of the NINJA experiment



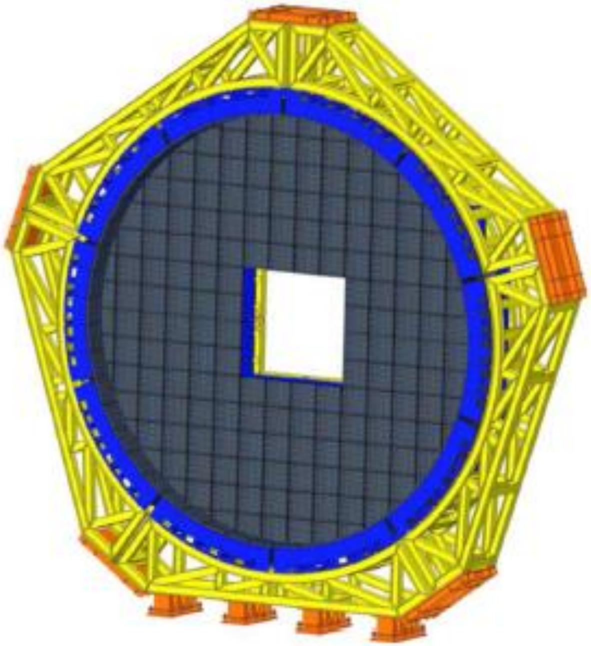
Water Cherenkov

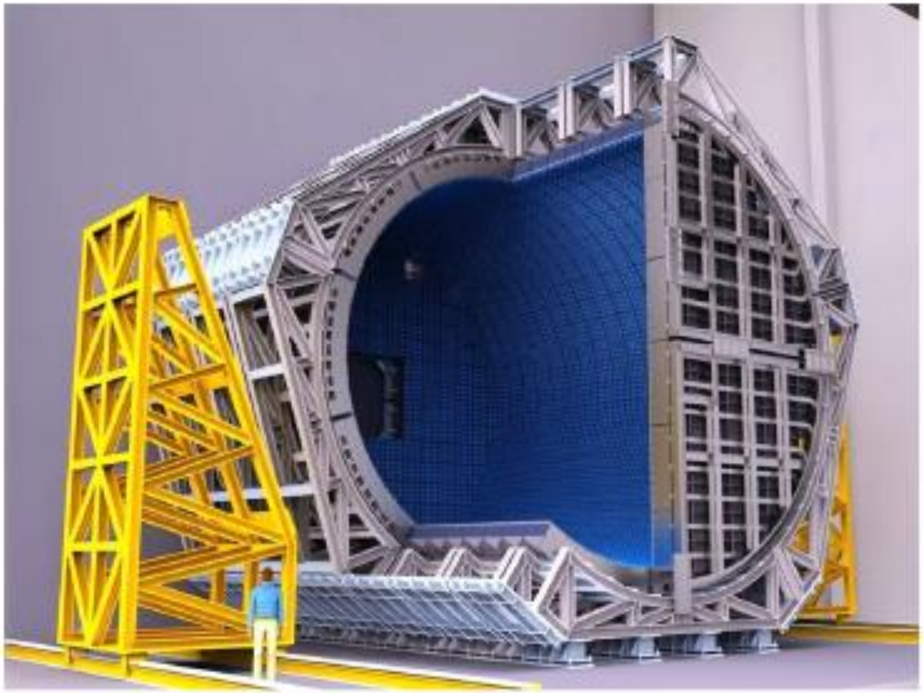
Purposes:

- event-rate measurement and flux normalisation,
- neutrino interaction cross-section measurements in water,
- event reconstruction comparison with the far detector

Geometry:

- horizontally oriented cylinder tank, having the cylinder axis aligned with the neutrino beam direction.
- diameter ~ 9.4 m,
- length ~ 10.8m,
- total detector volume of 750m^3,
- more than 22000 photomultiplier tubes each having a 3.5 inch diameter, and ~30% coverage of the detector cylinder.





Water Cherenkov Software

WCSim - the water Cherenkov simulation software:

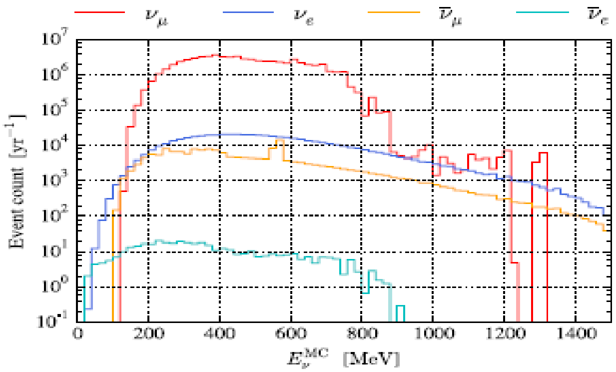
- used for particle transport postvertex,
- simulation of the detector response,
- based on Geant4,
- developed within the Hyper-Kamiokande collaboration.

fiTQun - the water Cherenkov reconstruction software:

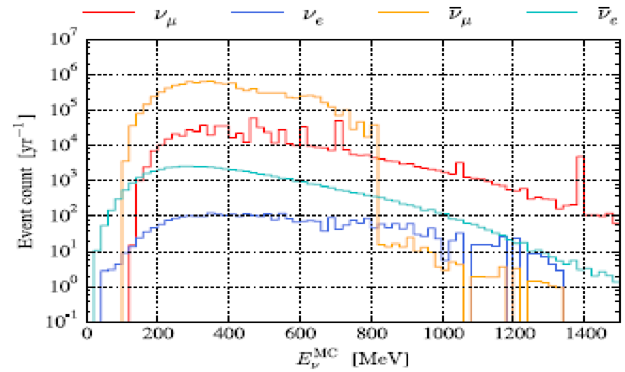
- developed within the Hyper-Kamiokande collaboration,
- fits the detector response to several particle hypotheses, including variations in particle flavor, vertex position, particle direction and momentum

Expected neutrino events in Water Cherenkov

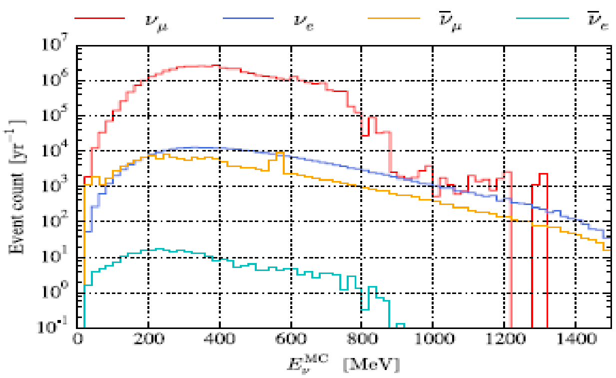
All interactions								
	ν_μ CC	ν_e CC	$\bar{\nu}_\mu$ CC	$\bar{\nu}_e$ CC	ν_μ NC	ν_e NC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ NC
Positive polarity	5.20×10^7	1.07×10^6	9.25×10^4	1.11×10^3	4.42×10^7	6.11×10^5	3.36×10^5	8.72×10^2
Negative polarity	1.06×10^6	8.90×10^3	9.74×10^6	1.89×10^5	8.81×10^5	1.11×10^4	9.65×10^6	1.36×10^5



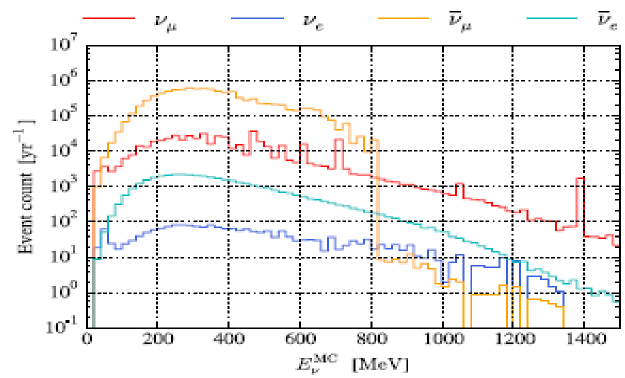
(a) Positive polarity, charged current interaction.



(b) Negative polarity, charged current interaction.



(c) Positive polarity, neutral current interaction.



(d) Negative polarity, neutral current interaction.

Criteria used in analysis

The main objective for the near detector is to select a high-purity sample of electron-neutrino candidate events.

Charged lepton identification and reconstruction. The charged lepton selection criteria:

- The sub-Cherenkov criterion - to reject muon events where the muon has an energy below the Cherenkov threshold.
- The reconstruction quality criteria - the proximity of the event to the detector tank wall and the registered brightness (total registered charge) of the event.
- The Cherenkov-ring resolution criterion

$$\mathrm{NLL}^{\mathrm{FQ}\mu}/\mathrm{NLL}^{\mathrm{FQ}e} \geq 1.01 \;\Rightarrow\; e^{\mathrm{ID}}$$
$$\mathrm{NLL}^{\mathrm{FQ}\mu}/\mathrm{NLL}^{\mathrm{FQ}e} < 1.01 \;\Rightarrow\; \mu^{\mathrm{ID}}.$$

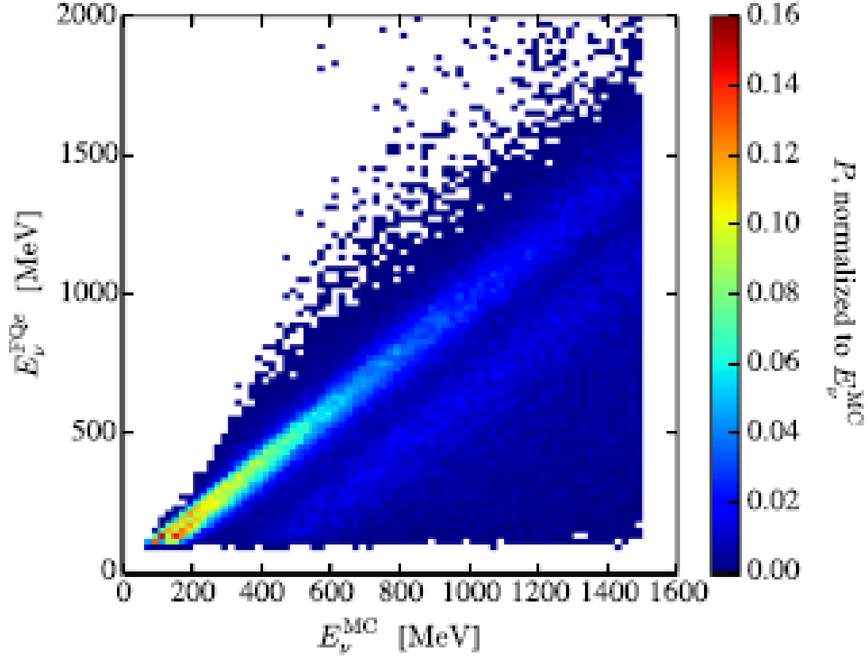
Neutrino identification and reconstruction. The neutrino selection criteria:

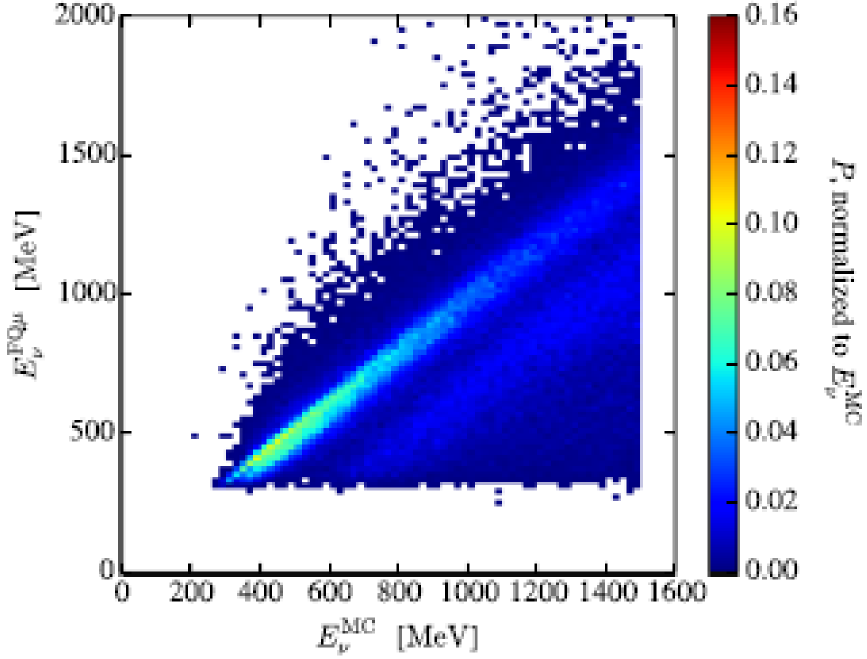
- The pion-like criteria - to reject events that are likely to be caused by a neutral pion
- The multi-sub-event criterion - to reject events where the initial energy reconstruction is too low due to a significant amount of energy being lost to non-primary final-state particles.
- Neutrino energy reconstruction (QES):

$$E_\nu = \frac{m_{\mathrm{F}}^2 - m_{\mathrm{IB}}^2 - m_{\mathrm{l}}^2 + 2m_{\mathrm{IB}}E_{\mathrm{l}}}{2(m_{\mathrm{IB}} - E_{\mathrm{l}} + p_{\mathrm{l}}\cos\theta_{\mathrm{l}})}.$$

** Work performed by Jason Park and Alex Burgman.*

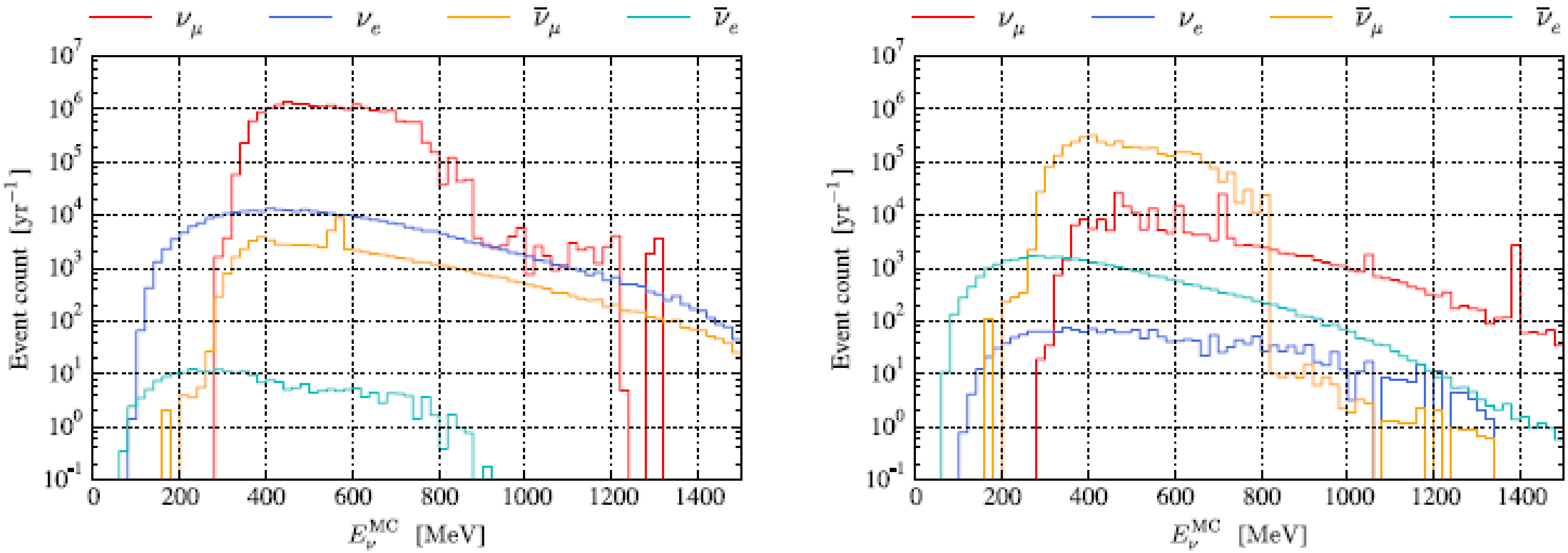
Neutrino energy migration matrices





Migration matrices after all criteria applied.

Expected number of neutrino events

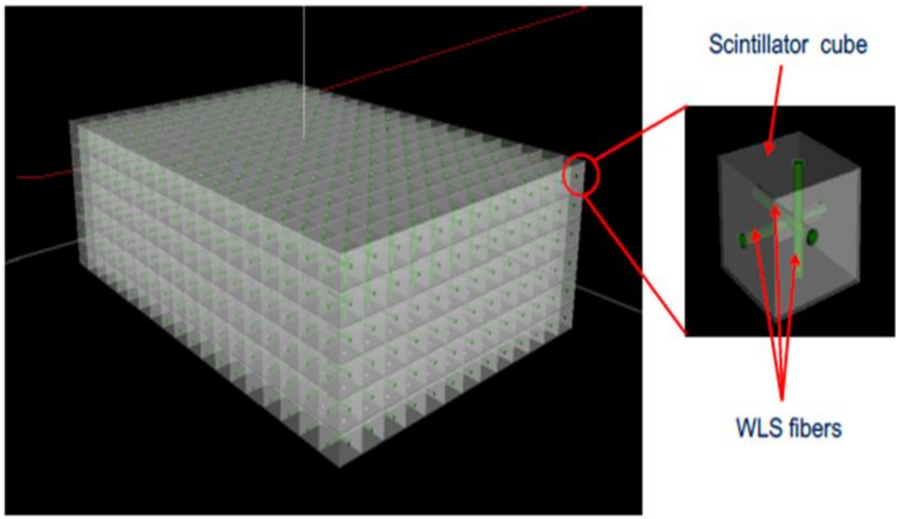


Neutrino distributions after all criteria applied.

Super Fine-Grained Detector SFGD

Purposes:
- To estimate the neutrino energy,
- To identify the flavor of interacted neutrino
- To measure cross-section

Geometry:
- Cube size: $1 \times 1 \times 1$ cm^3
- use $\sim 10^6$ cubes,
- rectangular cuboid with dimensions $1.4 \times 1.4 \times 0.5$ m^3
- The thickness of 0.5 m along the neutrino beam -> more charged leptons penetrate into the water Cherenkov detector tank,
  - around 12% of muons enter the water Cherenkov tank and can be identified there.
  - For the muon antineutrino interactions, the respective percentage is as high as 20%.
- A magnetic field of up to 1 T oriented perpendicular to the beam is applied in the tracker by a dipole

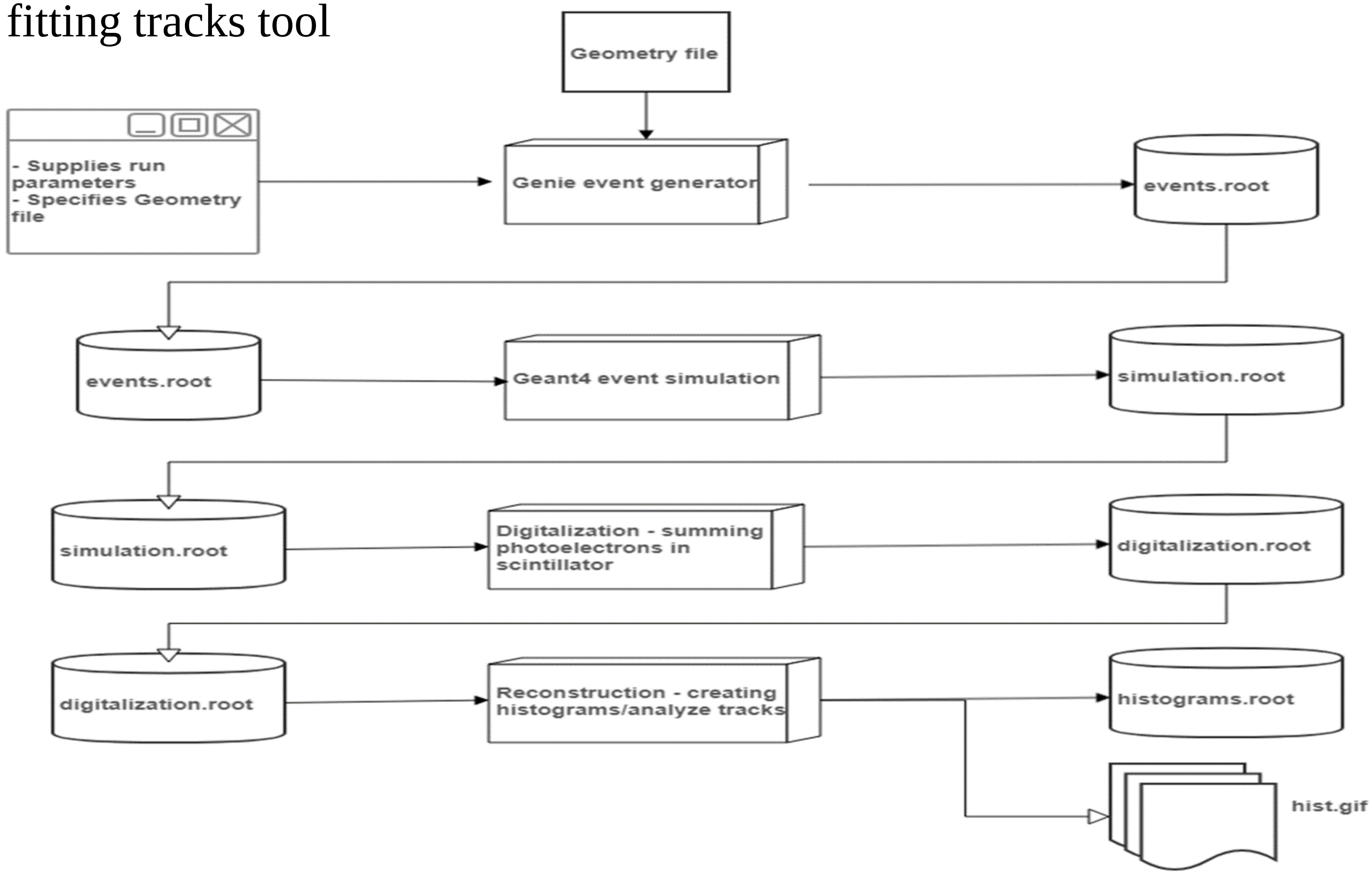


Parameter	Value
Coating thickness	50 μm
Hole diameter	1.5 mm
WLS fiber diameter	1.0 mm

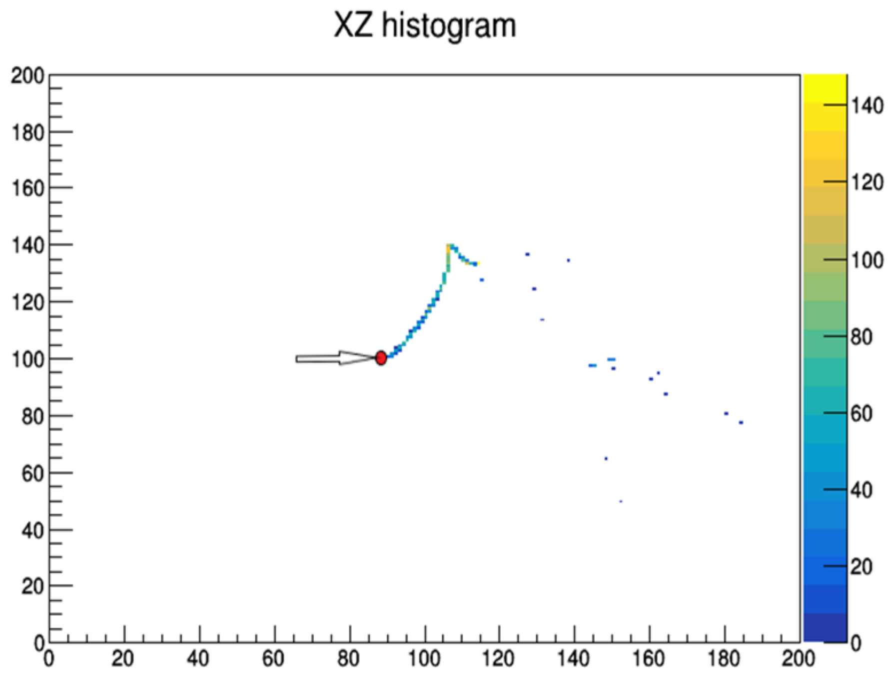
SFGD Software - EsbRoot

EsbRoot - The simulation framework EsbRoot
- developed in-house,
- based on FairRoot

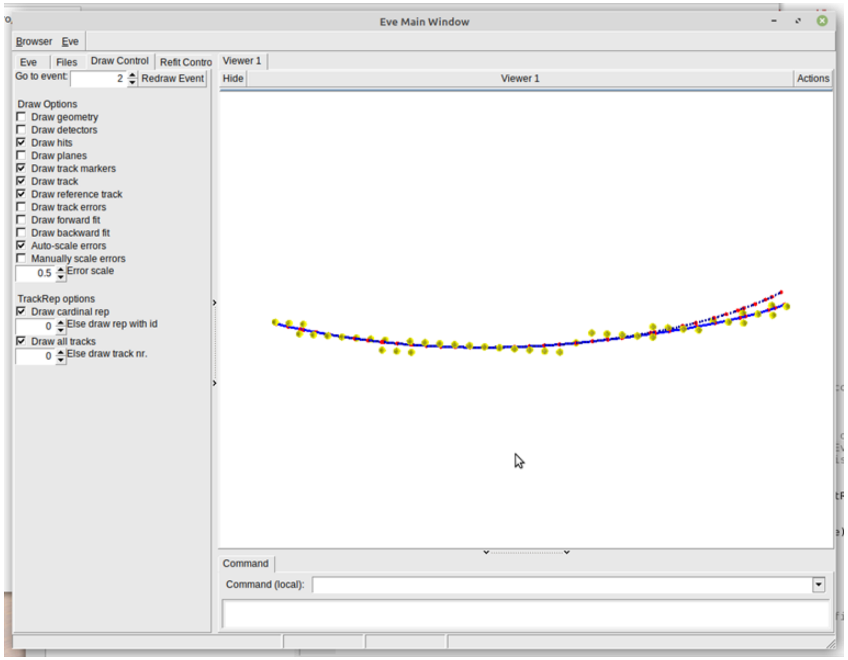
Genie - The neutrino interaction vertex generator
Geant4 - Particle propagation through the detectors
GenFit – fitting tracks tool



Neutrino interactions (example)



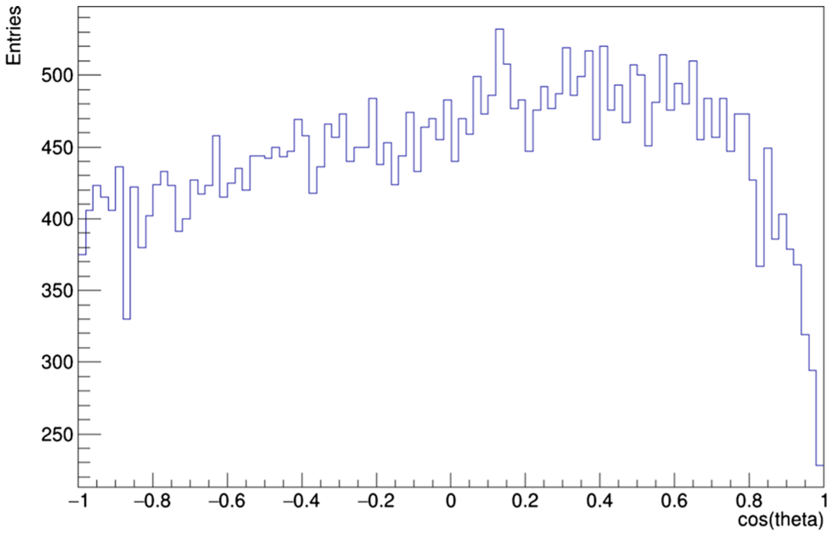
ν_μ interaction



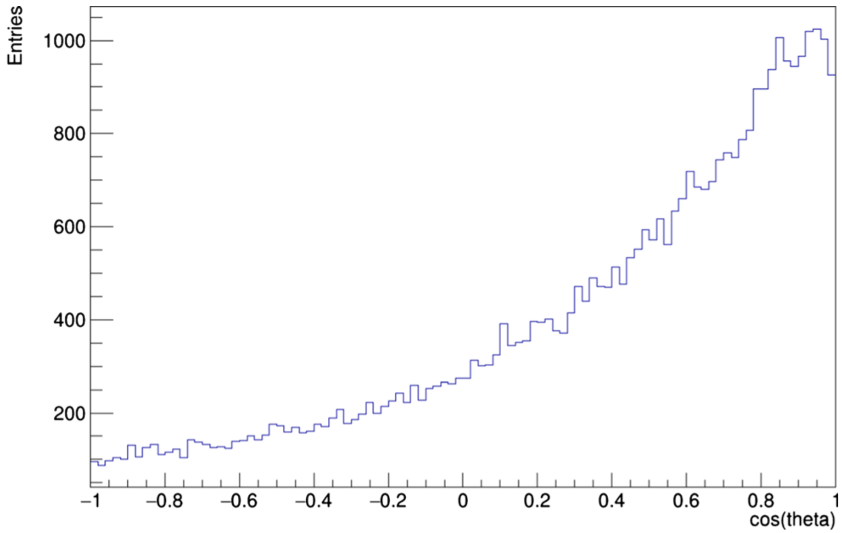
Fit of a muon track

Magnetic field

- The SFGD detector should be magnetized to measure momenta of the outgoing leptons produced by neutrino interactions.
- Distribution of the outgoing charged leptons versus its scattering is flat for negative muons, but a clear trend towards forward angles is seen for the positive muons => the magnetic field should be perpendicular to the neutrino beam.
- Due to technical difficulties to build a relatively large conventional (“warm”) magnet with a field exceeding 1T, a magnetic field strength of 1T is retained.

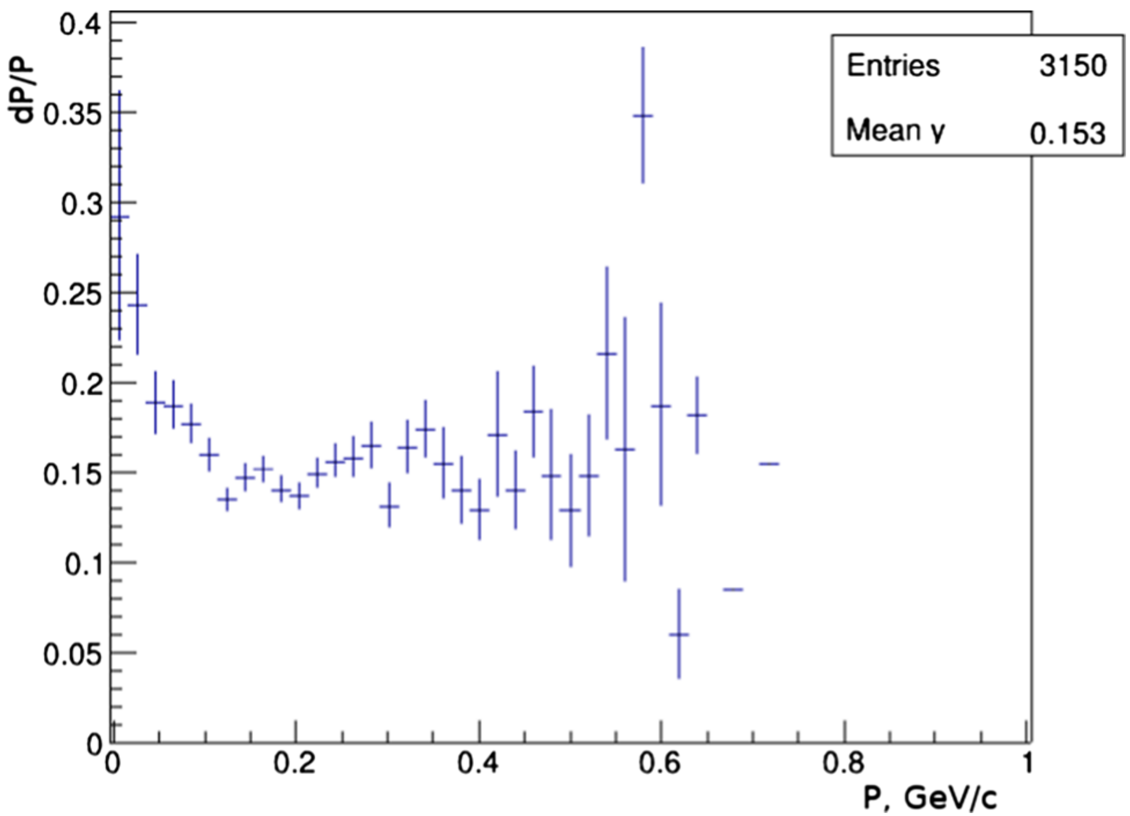


Negative muons



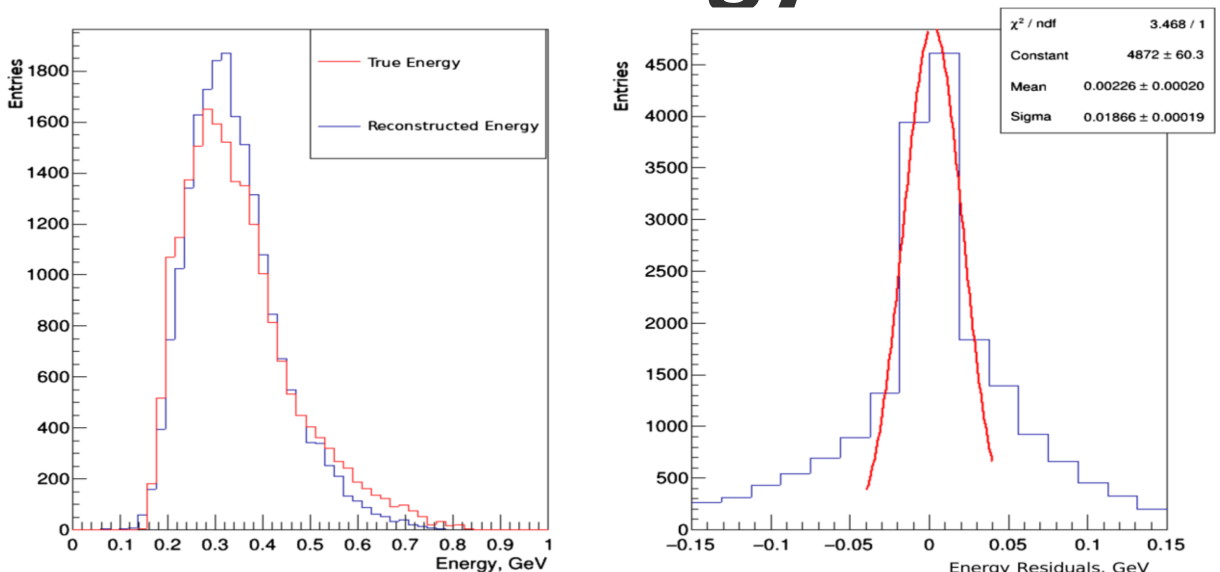
Positive muons

Muon momentum resolution

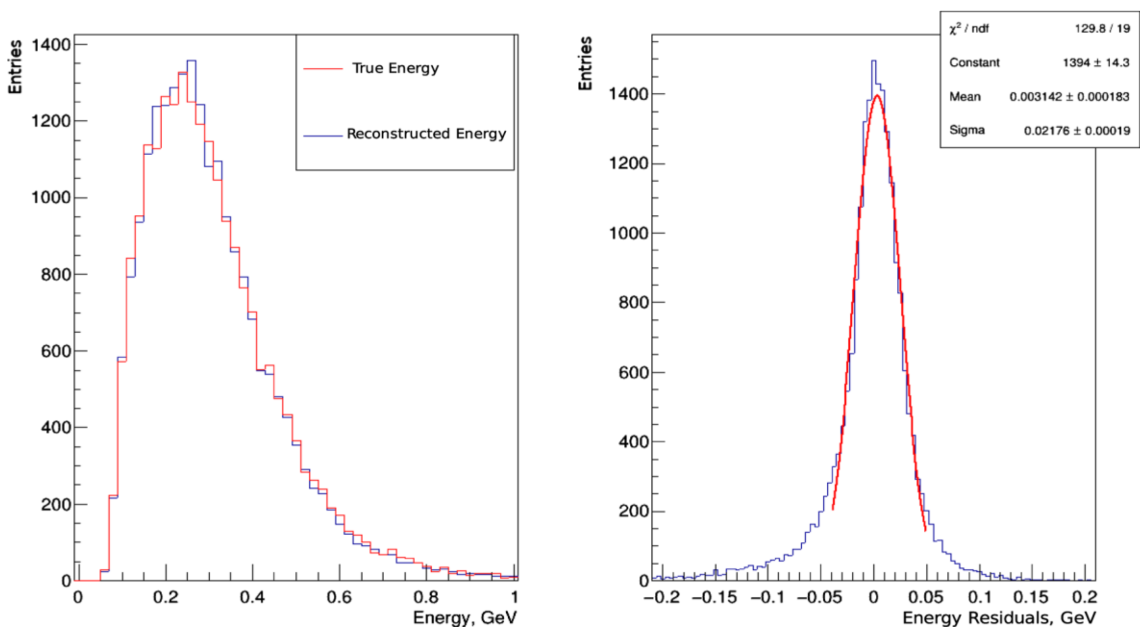


- Mean resolution ~15% for μ- and ~23% for μ+.
- Stronger dependence on track length (if L>30 cm, resolution <10%).
- No strong dependence on momentum and track angle.

Neutrino energy reconstruction



Muon neutrino



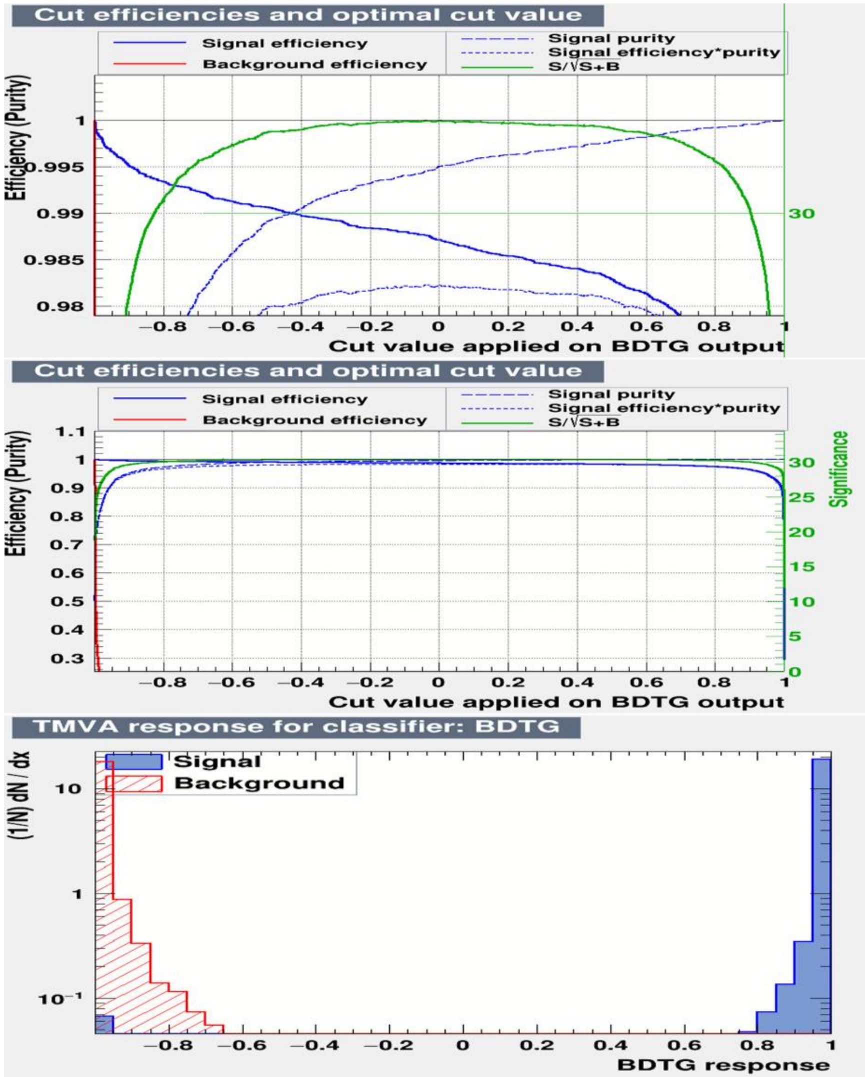
Electron neutrino

- Reconstruction algorithms based on machine-learning methods based on the software package Toolkit for Multivariate Data Analysis with ROOT (TMVA)

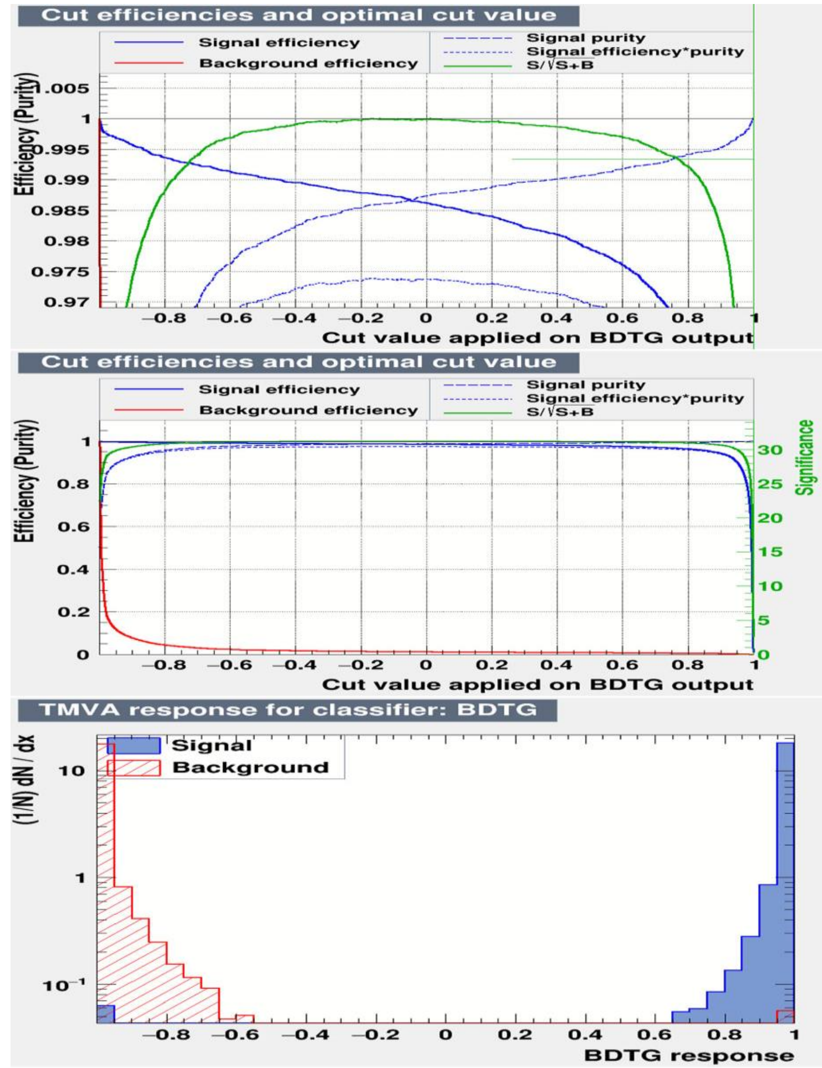
- achieved resolution, integrated over the spectrum, is ~ 20MeV and that the relative one, (Etrue − Erec)/Etrue, is of the order of 6% at 350 MeV

- These are obtained with the fitted muon momentum for muon neutrino interactions and with Monte Carlo truth for the electron momentum

CC and NC event separation



CC/NC separation of muon neutrino interactions



CC/NC separation of electron neutrino interactions

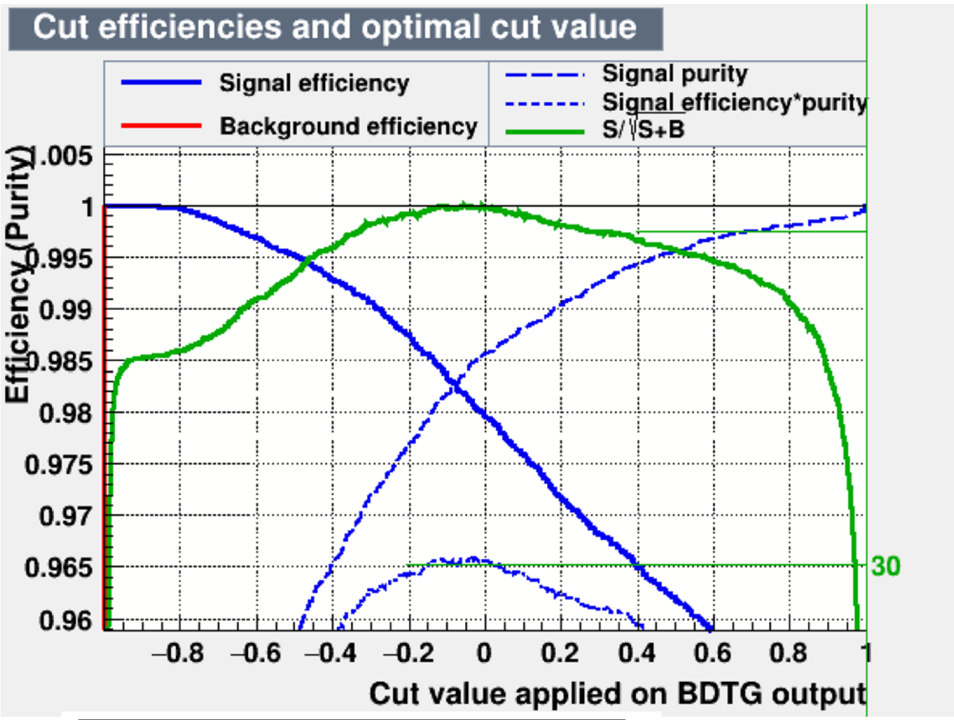
CC and NC event separation

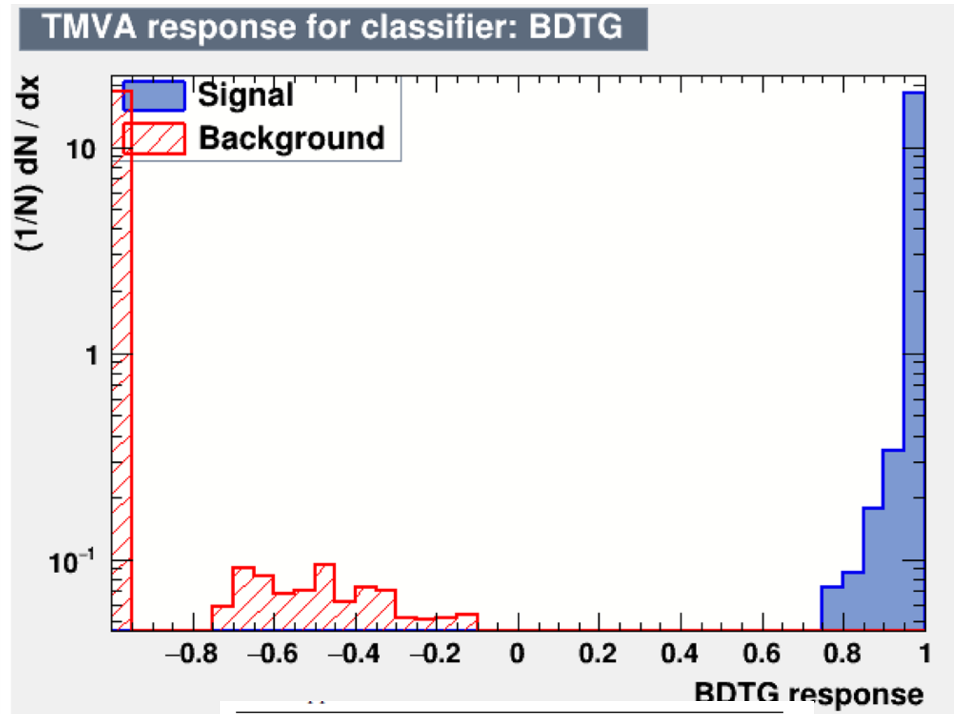
Performance of the SFGD in separation of CC from NC neutrino interactions applying TMVA methods. The best training method is the Boosted Decision Tree with Gradient Boosting (BDTG).

E_ν (GeV)	ν_μ		ν_e		$\bar{\nu}_\mu$		$\bar{\nu}_e$	
	ε (%)	p (%)	ε (%)	p (%)	ε (%)	p (%)	ε (%)	p (%)
0.0–0.2	98.1	99.7	99.1	99.9	99.5	99.9	99.5	100
0.2–0.3	99.3	99.9	99.6	99.9	99.5	99.8	99.5	99.9
0.3–0.4	99.3	99.9	98.8	99.9	99.0	99.9	99.1	99.0
0.4–0.5	98.3	99.5	97.8	98.0	98.5	99.5	98.5	98.2
0.5–0.6	97.0	99.0	97.0	95.4	96.8	99.6	96.8	97.8
0.6–0.8	95.8	98.4	95.2	95.1	98.0	99.8	95.9	98.5
0.8–1.0	95.5	95.5	n/a	n/a	n/a	n/a	n/a	n/a

Neutrino flavour identification

choosing an appropriate cut value, the admixture of the wrong flavour events could be constrained below per mill level, with a signal efficiency well above 90%.





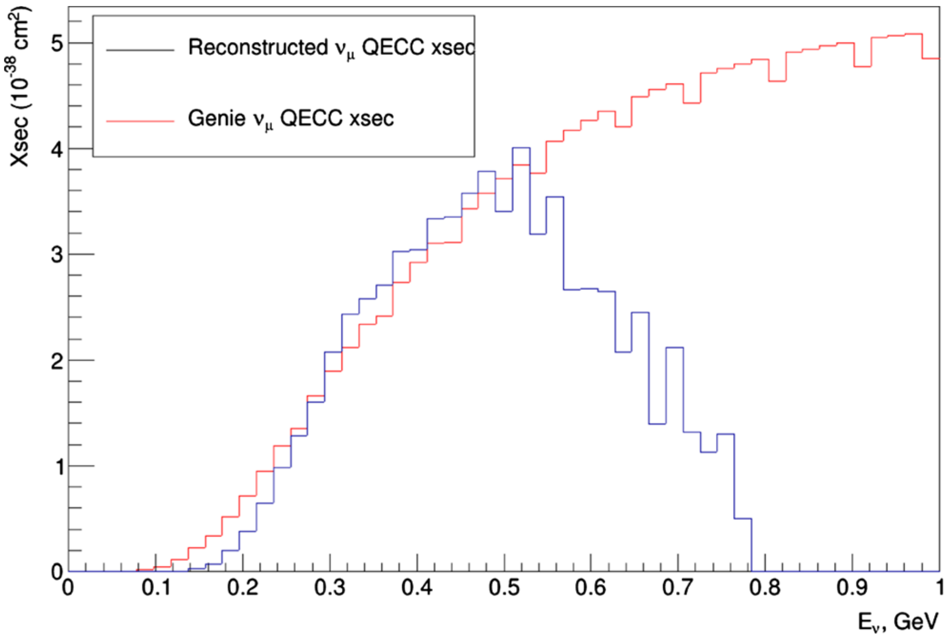
BDTG cut	Efficiency (%)	Purity (%)	
−0.80	100	93.9	
−0.60	99.7	95.2	
−0.40	99.2	96.6	
−0.20	98.7	97.7	
−0.03	98.1	98.5	*Best cut*
0.20	97.2	99.0	
0.40	96.5	99.4	
0.60	95.9	99.7	
0.80	95.0	99.8	
0.95	92.0	99.9	

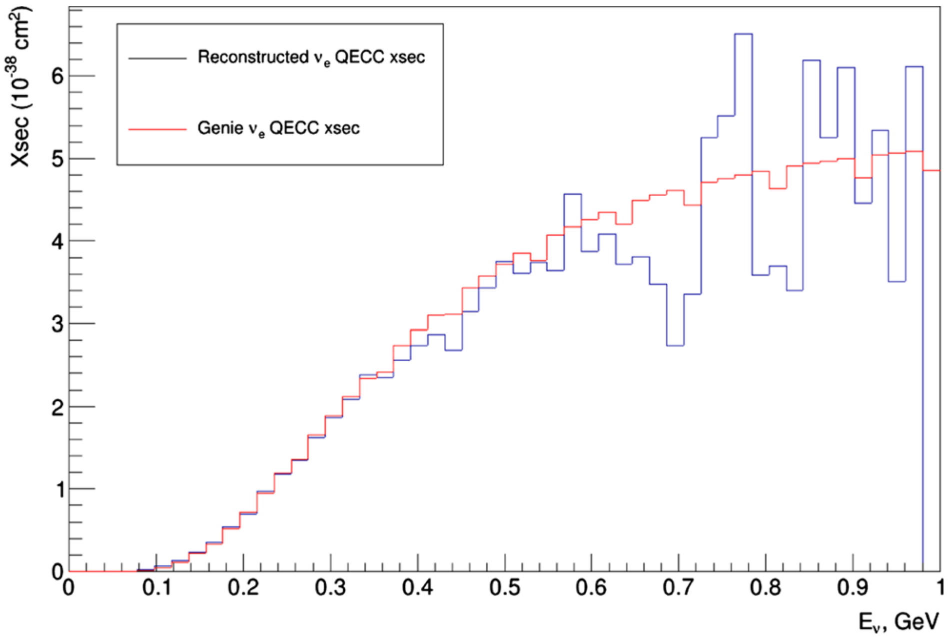
ν_μ and ν_e CC events

BDTG cut	Efficiency (%)	Purity (%)	
−0.80	100	96.5	
−0.60	99.8	96.9	
−0.40	99.6	97.5	
−0.20	99.2	98.1	
0.00	98.8	98.7	
0.26	98.3	99.3	*Best cut*
0.40	97.9	99.4	
0.60	97.3	99.7	
0.80	96.2	99.8	
0.95	93.0	99.9	

anti-$\nu\mu$ and anti-νe CC events

Neutrino cross-section measurement

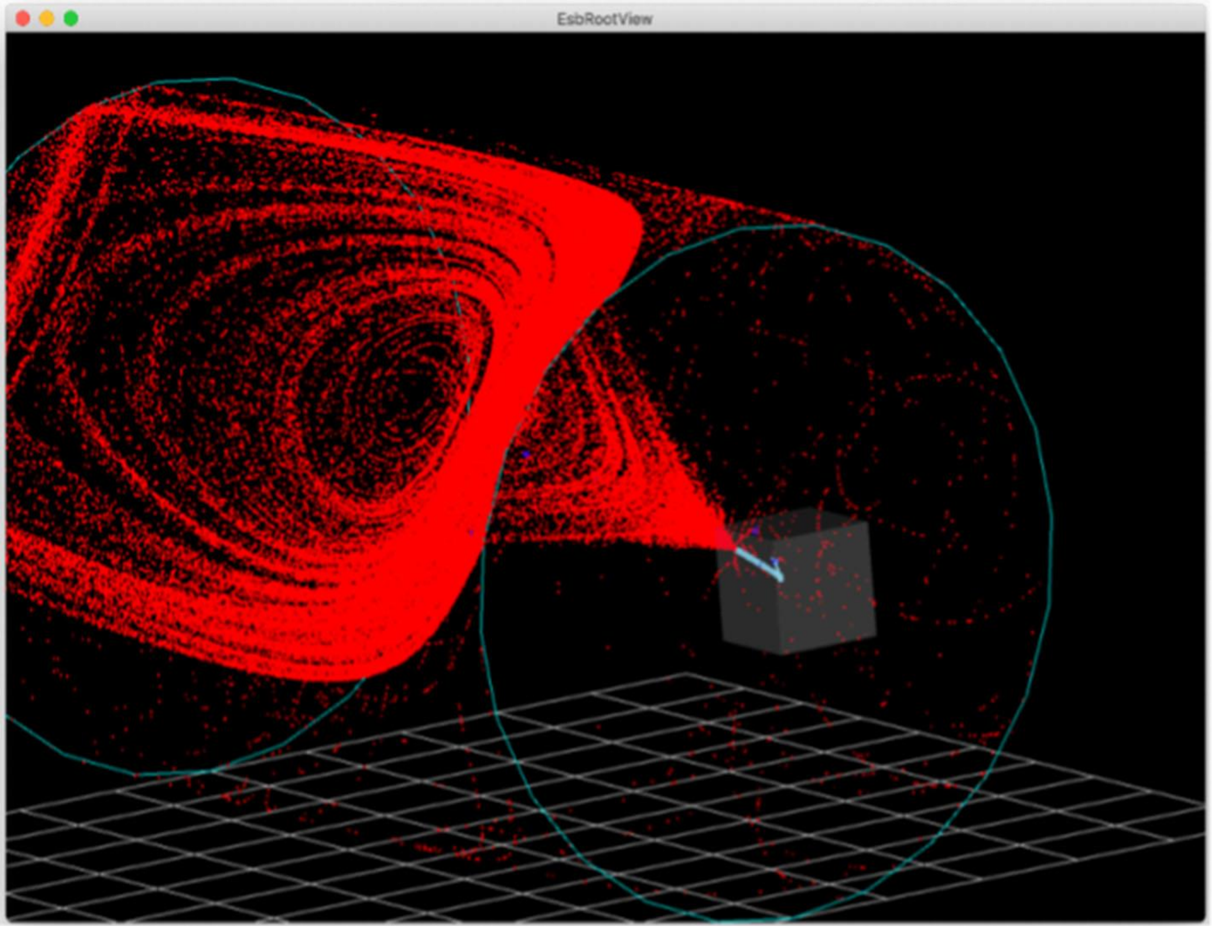




- The "measured" ν_μ and ν_e cross-sections compared with the ones used for simulation of neutrino events.
- Good agreement up to $E_\nu \sim 500$MeV is observed in both cases.
- For higher energies discrepancy becomes substantial, especially in the muon case.
- The higher momentum region suffers from low statistics, which reduces the accuracy of the neural network reconstruction in this region.

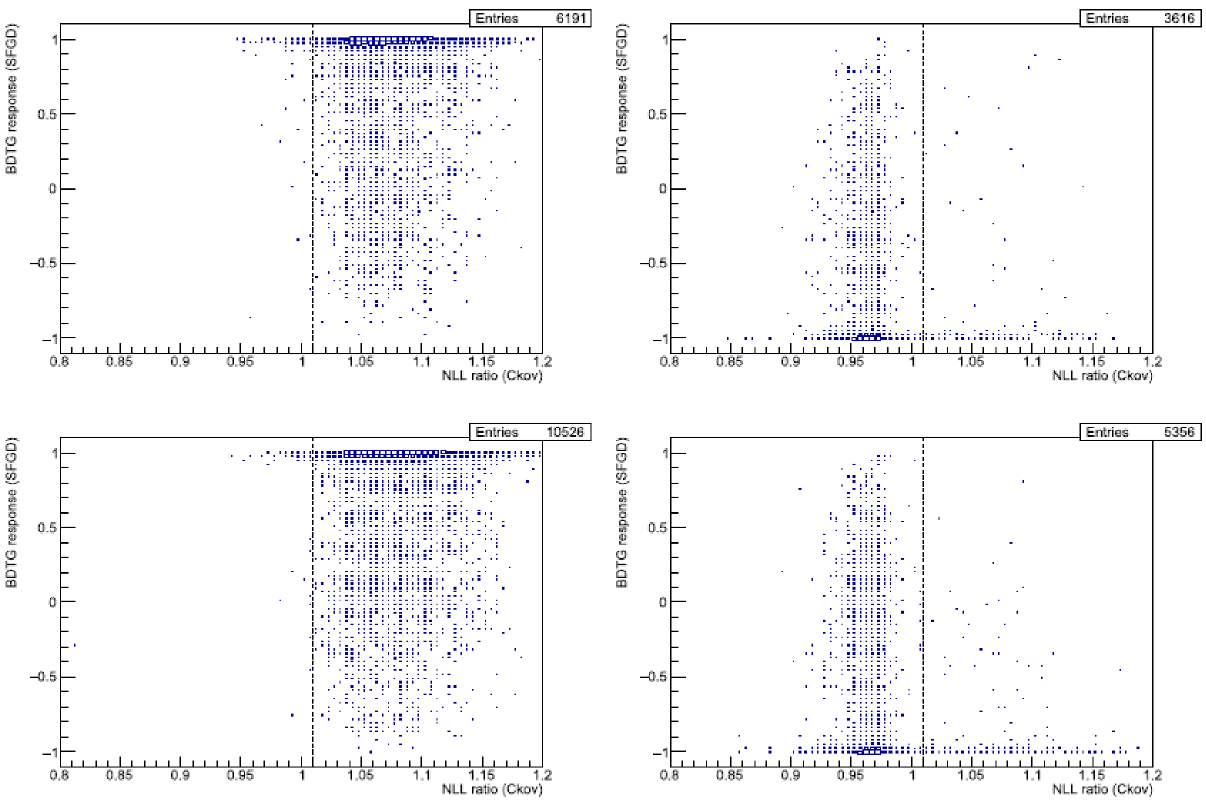
Crossover events

- SFGD and water Cherenkov detector combined analysis - multi-detector-spanning events 'crossover events'.
- Roughly 12% (20%) of positive (negative) muons produced in SFGD will exit the detector in the direction of the water Cherenkov volume having a chance of being detected there.
- The corresponding proportion of electron neutrino events is about 6% of the sample.
- The identification of exiting muon events in the water Cherenkov tank would serve as an additional veto for muon neutrinos, and thus yield a better purity.



Crossover events

- Capability of the two detectors for particle identification in the crossover events using a combined analysis is shown.
- The identification criterion from the water Cherenkov analysis is $NLL^{FQ\mu}/NLL^{FQe}$, along with the BDTG characterisation value of the SFGD.
- The assumption is that the available information from the SFGD is the track momentum and length, number of tracks, and number of photoelectrons.



- Top left: ν_e beam, top right: ν_μ beam, bottom left: anti-νe beam, bottom right: anti-νμ beam.
- Events with $NLL^{FQ\mu}/NLL^{FQe} < 1.01$ are classified as muon-like and events with $NLL^{FQ\mu}/NLL^{FQe} \geq 1.01$ as electron-like

Crossover events

- Number of expected events per running year in the SFGD, as well as those entering the water Cherenkov detector and passing the water Cherenkov selection criteria.
- Listed over the four charged lepton flavours and two horn polarities

	μ^-	e^-	μ^+	e^+
Positive polarity				
All events SFGD	9.82×10^4	484	241	1.0
Exiting SFGD (entering water Cherenkov)	1.78×10^4	87.9	39.9	0.2
Trigger	1.18×10^4	60.4	33.6	0.1
Sub-Cherenkov criterion	4100	40.0	12.0	0.1
Negative polarity				
All events SFGD	929	6.4	1.75×10^4	51.9
Exiting SFGD (entering water Cherenkov)	120	0.6	3890	11.1
Trigger	78	0.4	3350	9.6
Sub-Cherenkov criterion	26	0.2	1210	6.8

Let's go…

- **Task 5.3: Set up a unified MC simulation chain for the ESSνSB near detector (END) site to facilitate LEnuSTORM new physics searches (RBI, UniSofia, CU, NU).**

A unified MC simulation of the END site will be set up. Geometry of the three ESSνSB near detectors (water Cherenkov with addition of Gd, SFGD, emulsion) will be properly placed within the ND site and the geometry of the surrounding structures and rock/soil will be taken into account. This will make it possible to do a detailed study of LEnuSTORM neutrino interactions in all three detectors, including events that pass through multiple detectors. External background by atmospheric muons and similar sources will be simulated, as well as the background coming from LEnuSTORM neutrino interactions in the upstream rock and surrounding structures.

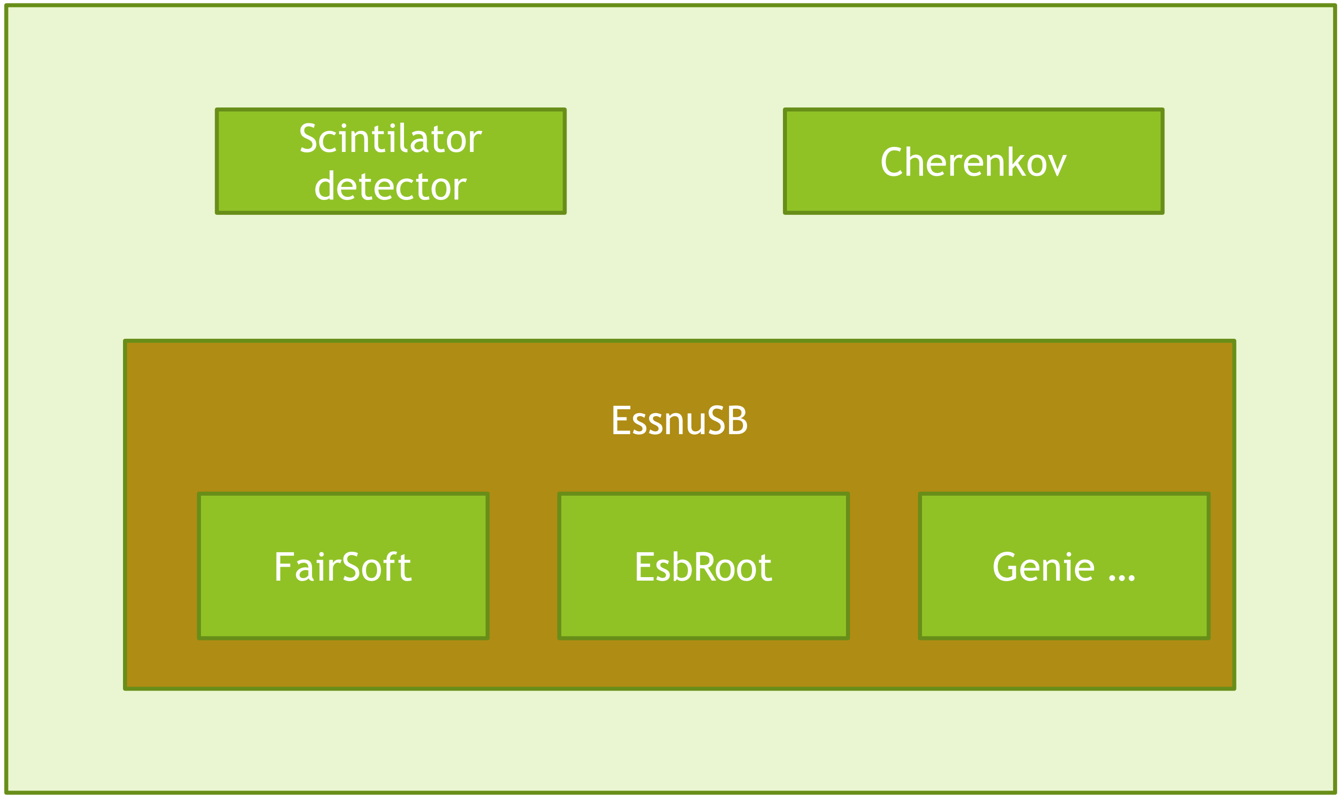
How?

- Operation system?
- EsbRoot as basic framework?
- Include libraries of WCSim and FitQun in EsbRoot possible? Or start from scratch?
- Emulsions simulation? Does it exist in some form?

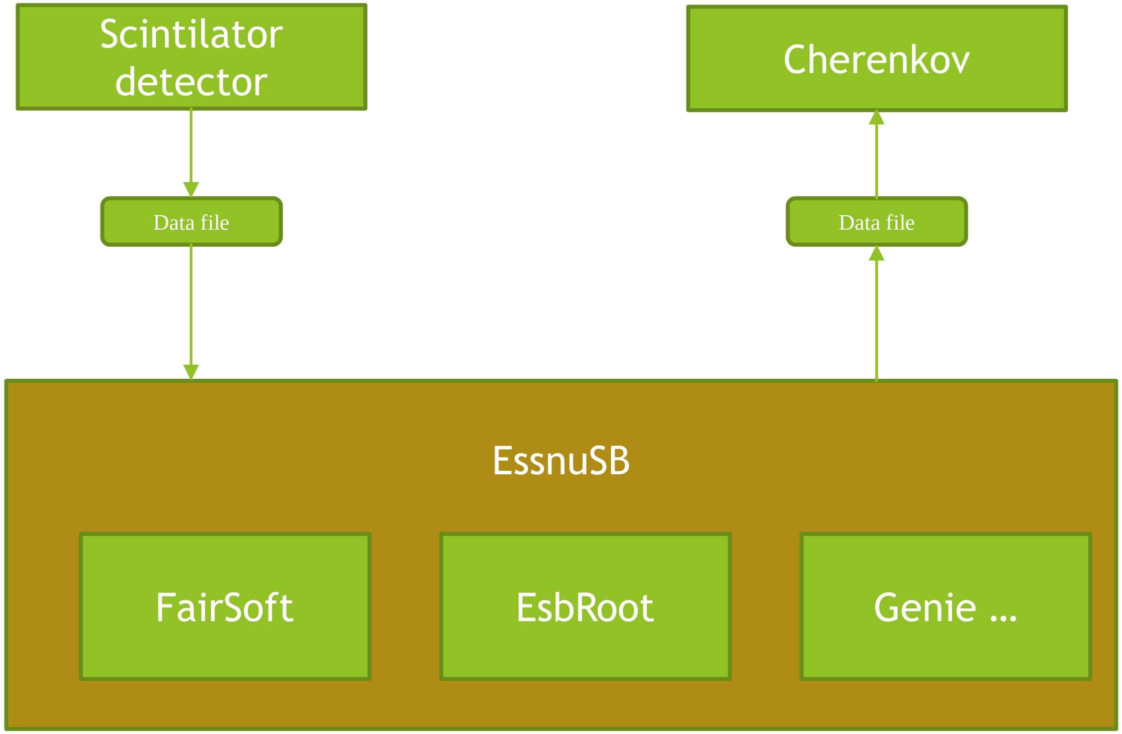
Integration options

Georgi Petkov

Option 1 – Add new geometries to the existing framework



Option 2 – Add intermediate data files. Script files control execution



Option 3 – Communicate via App API (if existing)