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gSeaGen: a GENIE-based code for neutrino telescopes

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Outline

Introduction to GENIE

Why GENIE for neutrino telescopes?

Present limits and extension to VHE

The gSeaGen code

gSeaGen application within ANTARES and KM3NeT

Conclusions

What is GENIE?

<u>Generates Events for Neutrino Interaction Experiments</u>

A Neutrino Monte Carlo Generator (and extensive toolkit)

Validity:
from few MeV to many hundreds of GeV / handles all nuclear targets

Large scale effort:
110,000 lines of C++

Modularity / Flexibility / Extensibility:
Models can be swapped in/out. Models can be easily reconfigured. All done consistently.

Licensed:
To ensure <u>openness</u> and synergies between experiments

State of the art physics:
GENIE has lots of developers & support. Draws heavily from many people's expertise

Official GENIE web site: http://www.genie-mc.org/

Who is using GENIE now?

Primary clients are the current / near future medium energy expts:

- T2K
  - nd280
  - SK
  - ingrid
- MINOS
- NovA
- MINERvA
- MicroBooNE
- EU LAr R&D projects
- ...

After ~4 yrs of development (from scratch)
now have a nearly universal neutrino physics MC
(an important tool for physics exploitation for the next decade++)

NEUTRINO EXPT.
SYNERGIES !!

GENIE already interfaced to most of these expts & used in physics MC prod.

Could trivially extend GENIE in new kinematical regimes (reactor expts. / neutrino telescopes)
if there is avail. manpower from these communities.

Why GENIE for underwater neutrino telescopes?

- migration to C++ → use of modern neutrino interaction codes/libraries
- it is continually maintained
- it is "canonical" Monte Carlo for neutrino interaction physics, used by experiments at different energy ranges → data comparison

Using GENIE for neutrino telescopes requires the extension to VHE:

- present certified limit up to ~1 TeV
- extension planned and already in progress (in contact with GENIE developers)

Meanwhile, writing of gSeaGen: a GENIE-based code to simulate an underwater neutrino telescope environment (e.g. ANTARES/KM3NeT) in order…

- to have a comparison with our standard generator at the present GENIE validity range
- to be ready to simulate ANTARES and KM3NeT-ARCA, when the extension will be done
- to simulate KM3NeT-ORCA

gSeaGen main features

- It simulates neutrino-induced events detectable by an underwater neutrino detector.
- It simulates the neutrino interaction taking into account the density and the composition of the target media.
- It is able to simulate all neutrino flavours, taking into account topological differences between track-type and shower-like events.
- It is written in C++.
- External dependencies:
  - ✓ GENIE: neutrino interaction
  - ✓ MUSIC: muon propation

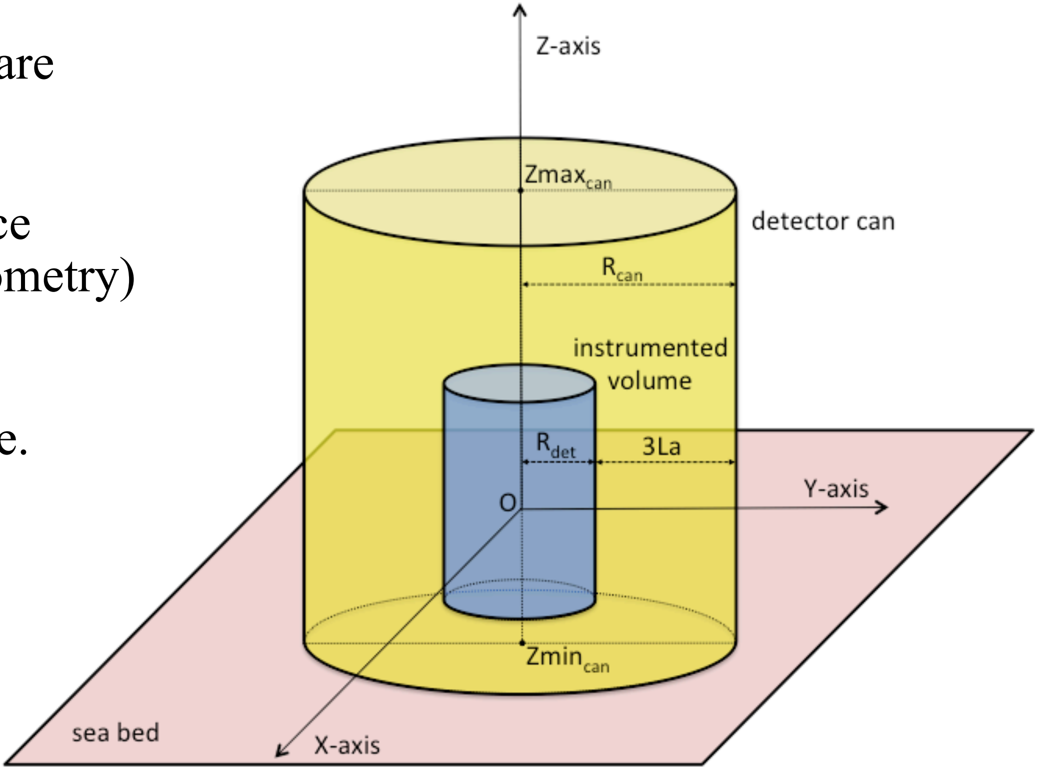
GENIE http://www.genie-mc.org/
MUSIC P. Antonioli et al. Astrop. Phys. 7, 357, 1997

The *detector can* represents the detector horizon, i.e. the volume sensitive to the light.

It is the volume within the Cherenkov light is generated in the Monte Carlo simulation to determine the detector response.

The neutrino-induced particles are stored in the output file only if they are generated inside the can or propagate up to its surface (no dependence on detector geometry)

Detector can size:
set by input or from detector file.



The target media

Four different target media are defined: **Seawater**, **Rock** (GENIE interaction volume), **Mantle** and **Core** (calculation of P_{Earth}).

Default compositions and densities for target media (below) but the user has the possibility to change them → systematics due to medium compositions, simulation of under-ice detectors…

Seawater (Density= 1.04 g/cm^3):

Element	Mass percentage	Element	Mass percentage
Oxygen	85.84	Sulfur	0.091
Hydrogen	10.82	Calcium	0.04
Chloride	1.94	Potassium	0.04
Sodium	1.08	Bromine	0.0067
Magnesium	0.1292	Carbon	0.0028

Rock (Density= 2.65 g/cm^3):

Element	Mass percentage	Element	Mass percentage
Oxygen	46.30	Sodium	2.36
Silicon	28.20	Magnesium	2.33
Aluminum	8.23	Potassium	2.09
Iron	5.63	Titanium	0.57
Calcium	4.15	Hydrogen	0.14

Mantle (Density= PREM model):

Element	Mass percentage	Element	Mass percentage
Oxygen	45.22	Iron	5.97
Magnesium	22.83	Aluminum	2.25
Silicon	21.49	Calcium	2.24

Core (Density= PREM model):

Element	Mass percentage	Element	Mass percentage
Iron	90.0	Nickel	10.0

Cross section and Probability scale

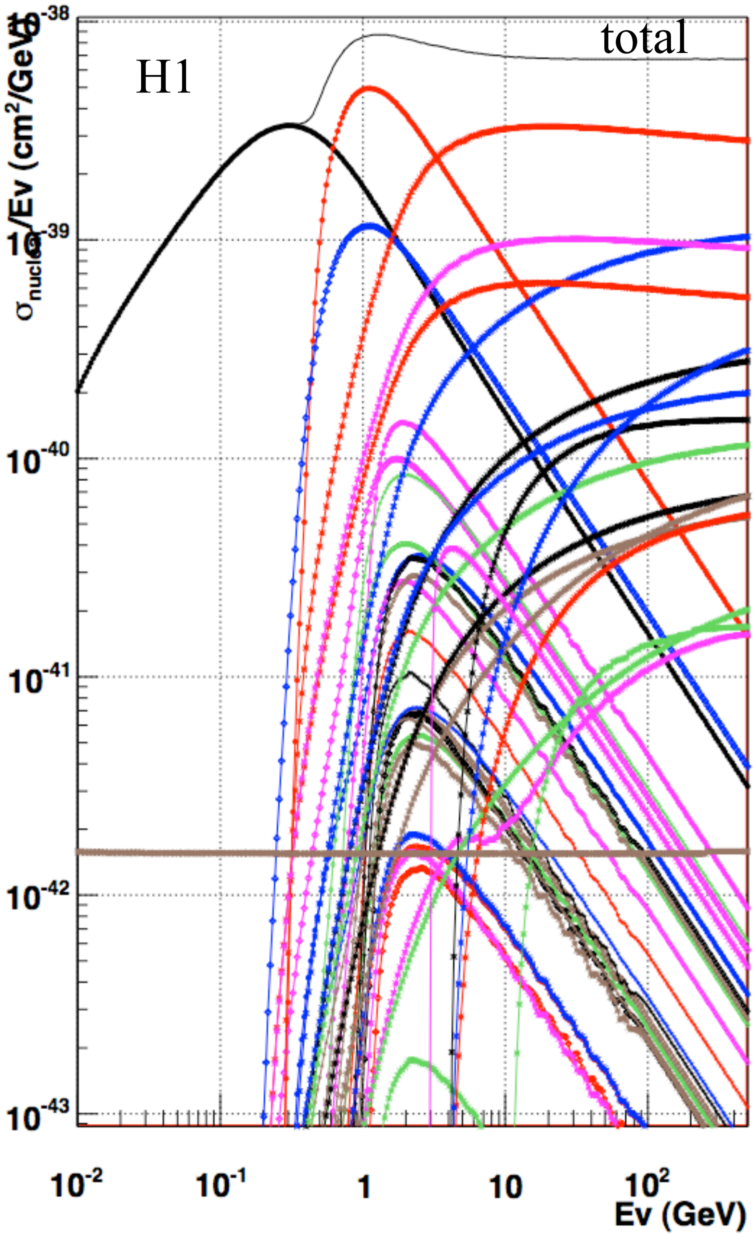
- Cross section calculation is very CPU-intensive because of the fine numerical integration stepping and the large number of processed involved…
- …but it's possible to use pre-computed cross section splines file generated with the GENIE utility - ***gmkspl***

GENIE validity range: up to ~1 TeV
Splines have been computed for nuclei used to define the target media: **Al, Br, C, Ca, Cl, Fe, H, K, Mg, N, Na, Ni, O, S, Si, Ti** (choosing the most abundant isotopes)

Interaction probability are very small numbers

Probabilities are scaled-up to reduce the number of trials

Probability scale is the maximum interaction probability (i.e. probability at maximum energy --so, max cross section– and for the maximum possible path length) **summed over initial states**



The neutrino interaction volume

- The interaction volume is the volume where a neutrino interaction could produce detectable particles (i.e. inside or reaching the *detector can*).

- The interaction volume is defined as a cylinder surrounding the detector and made by the two target media: **SeaWater** and **Rock**.

- The size of the interaction volume and the amount of each medium depend on the type of the probe neutrinos and on of the interaction.

Shower-like events
In case of electron neutrinos and muon or tau neutrinos interacting only in NC, the interaction produces shower-like events.

Such events may be detected only if they are generated inside the light sensitive volume.

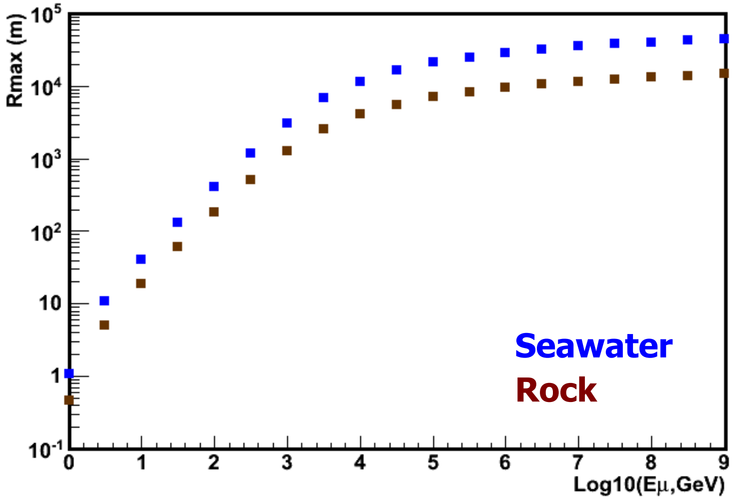
The interaction volume is therefore defined as a cylinder coincident with the detector can and entirely made by seawater.

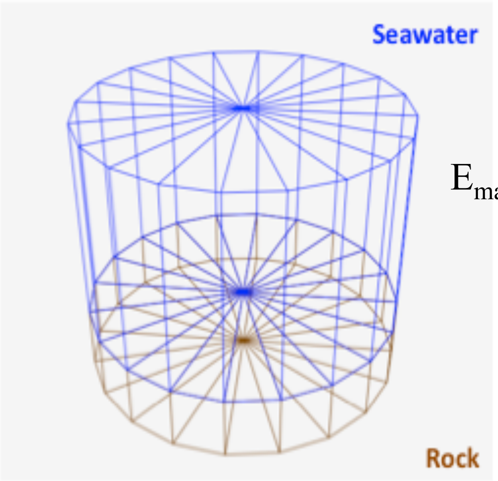
Track-type events

Muons, produced by the neutrino interaction (muon and tau neutrinos in CC), may be detected also if the interaction vertex is outside the can.

The interaction volume is here built taking into account the muon maximum range in water and in rock, evaluated at the highest energy of simulated neutrinos.

The volume is a cylinder made by a layer of rock and a layer of seawater surrounding the can.





E_{max}=500 GeV

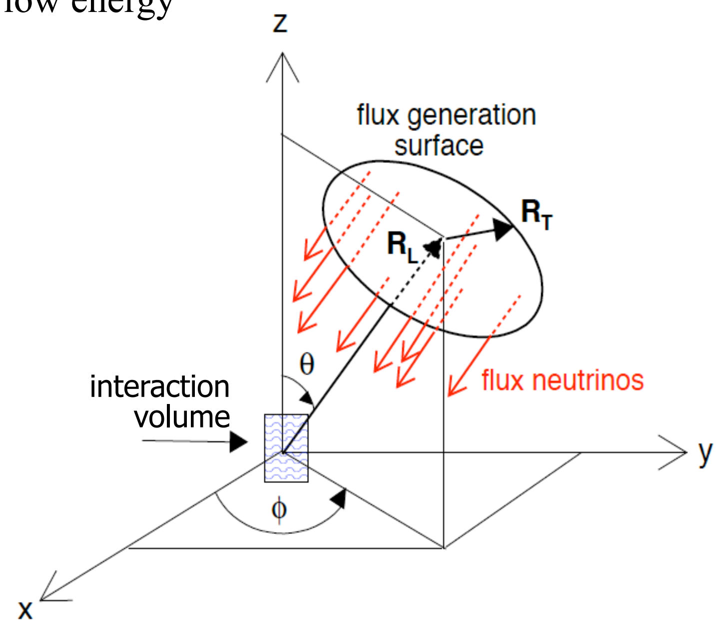
Muon propagation up to the can simulated with MUSIC

P. Antonioli et al. Astrop. Phys. 7, 357, 1997

- The neutrino direction is randomly simulated with a flat distribution in the generation solid angle (diffuse fluxes).
- The track vertex is drawn on a circular surface (outside the interaction volume and covering its projection onto a plane perpendicular to each neutrino direction).
- The neutrino energy is simply drawn according to a power-law energy spectrum E^{-X} , where X is the input spectral index.
- Spectrum binned in equal divisions in Log10(E_ν):
  - Probabilities are scaled-up at each bin (P_{scale}) -> higher stat. at low energy
  - For muons: scaled volumes and number of events
- Weighted generation
  - **Generation weight:**

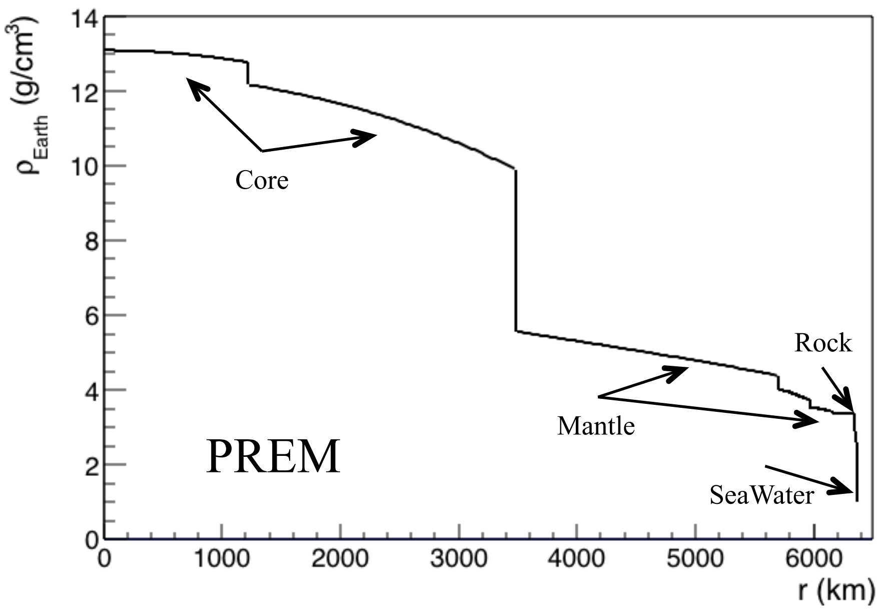
$$w_{gen} = \frac{I_E \cdot I_\vartheta \cdot T_{gen} \cdot A_{gen} \cdot P_{Scale} \cdot E^X \cdot P_{Earth}(E,\vartheta)}{N_{Tot}}$$

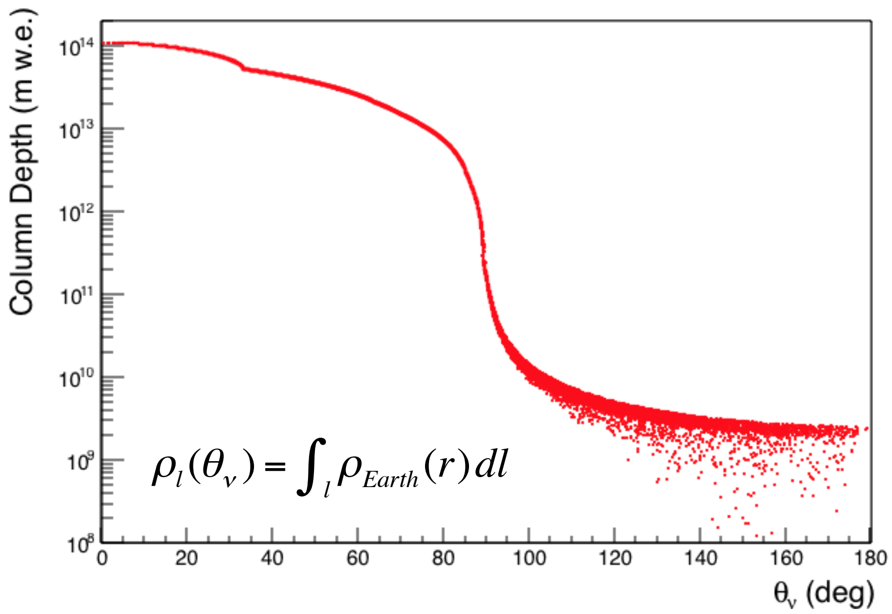
  - **Physical flux:** Bartol or Fluka fluxes, energy function

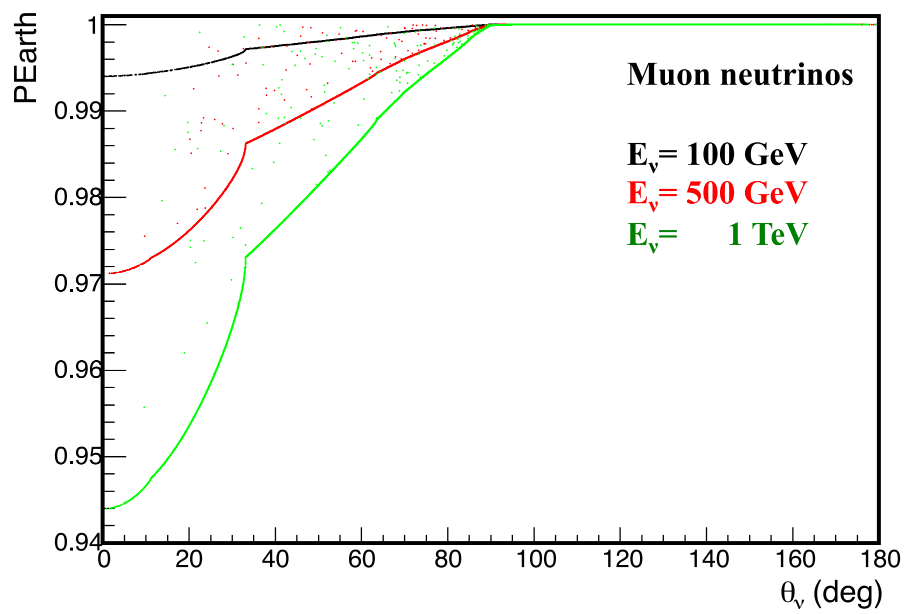


$$P_{Earth}(E_\nu, \cos\theta_\nu) = e^{-N_A \cdot \sigma_l(E_\nu,\theta_\nu)\cdot \rho_l(\theta_\nu)}$$

where $\sigma_l(E_\nu,\theta_\nu)$ is the average cross section per nucleon along the neutrino path $\rho_l(\theta_\nu)$ (i.e. taking into account the different layer compositions).







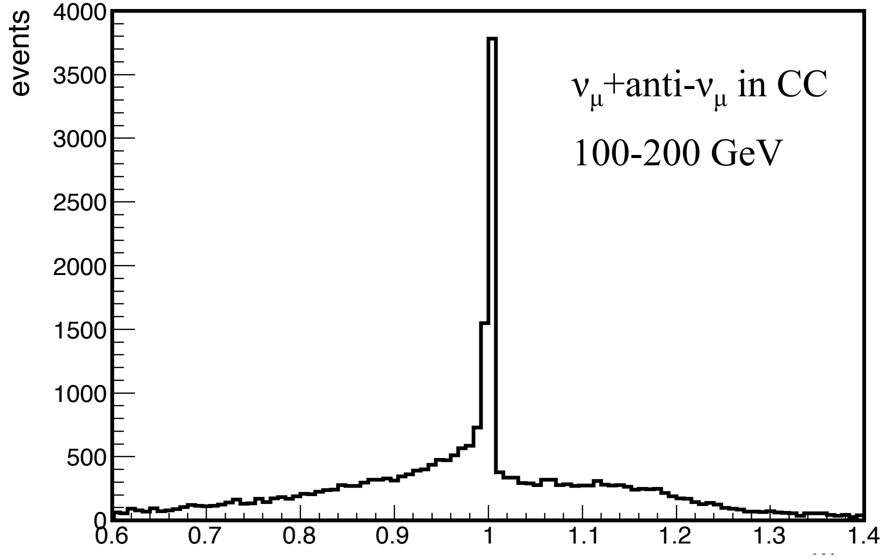
GENIE knows the accuracy of the input simulation parameters and it is able to propagate neutrino interaction uncertainties.

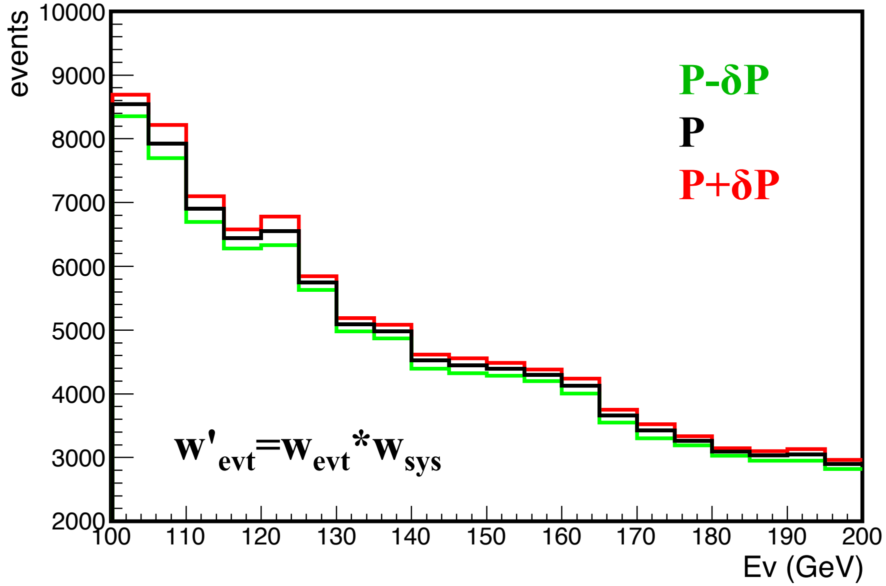
Event reweighting strategy: use one sample to emulate another (i.e. we don’t need to repeat the simulation but just reweighted the events).

Systematics available for cross sections but also for hadronization, resonance-decays….

Implementation of the systematics in **gSeaGen:** possibility to set more than one systematic parameters → GENIE will evaluate the global systematic weights (under check).

Pion mean free path for intranuclear rescattering





Comparison with GenHen

Comparison with the standard ANTARES neutrino generator: cross checking.

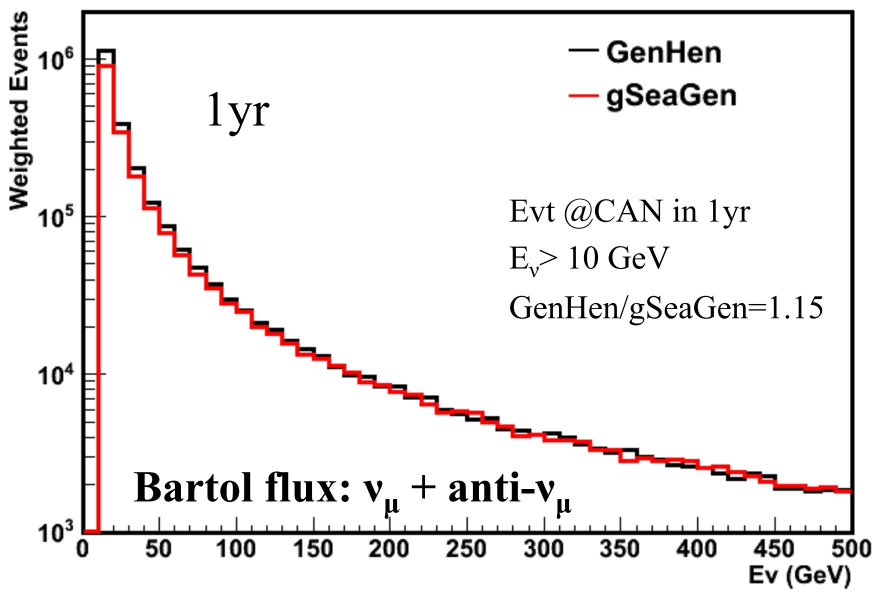
gSeaGen:

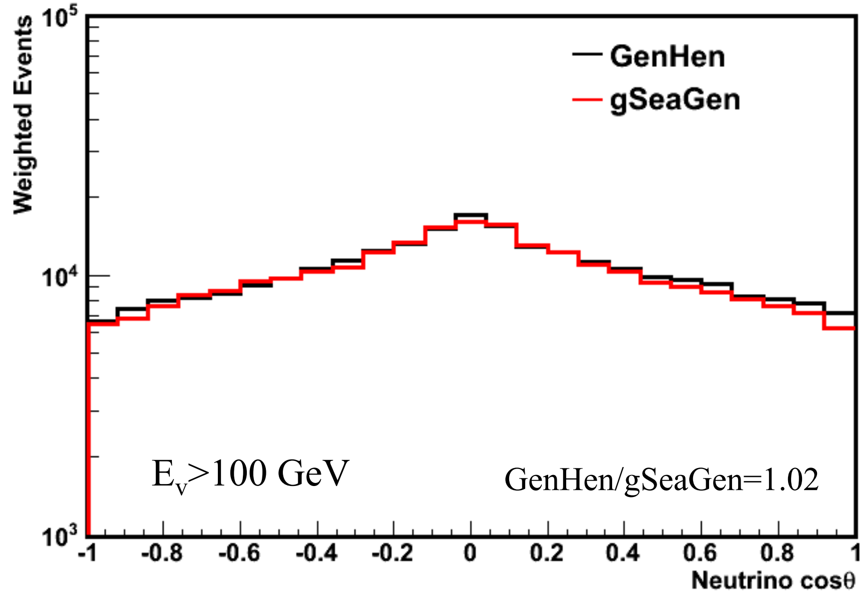
- full simulation of neutrino interaction (probability scale)
- xsec calculated at each neutrino energy
- interaction in seawater and rock as defined in the geometry
- Energy range: 0.01 - 1000 GeV

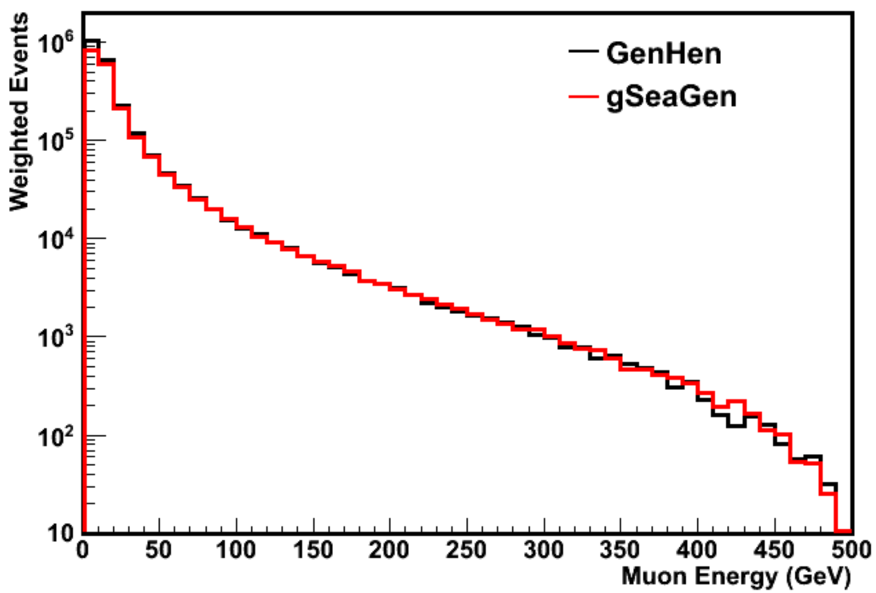
GenHen:

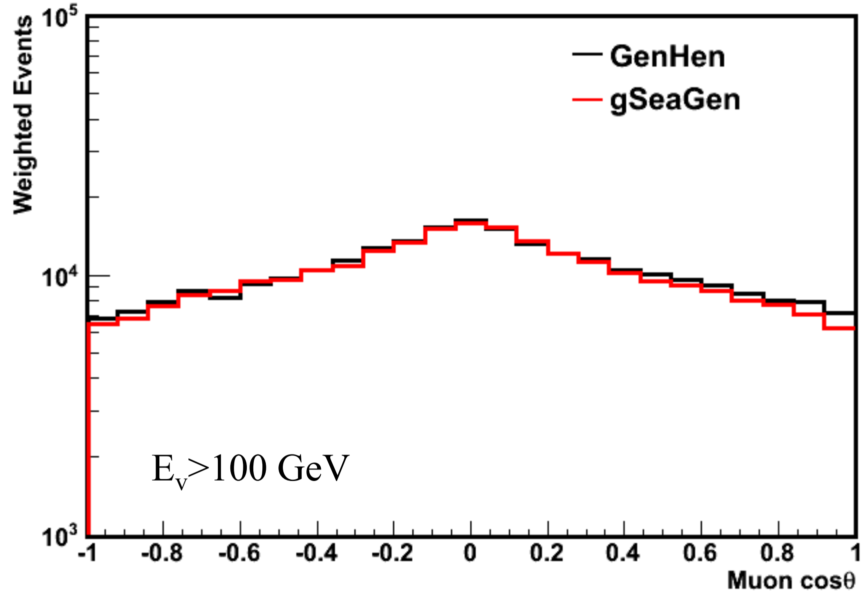
- all neutrinos interact
- xsec calculated at the centre of energy bins
- interaction with iso-scalar nuclei in water equivalent media
- Energy range: 10 – 10^9 GeV

Generation of muon neutrinos



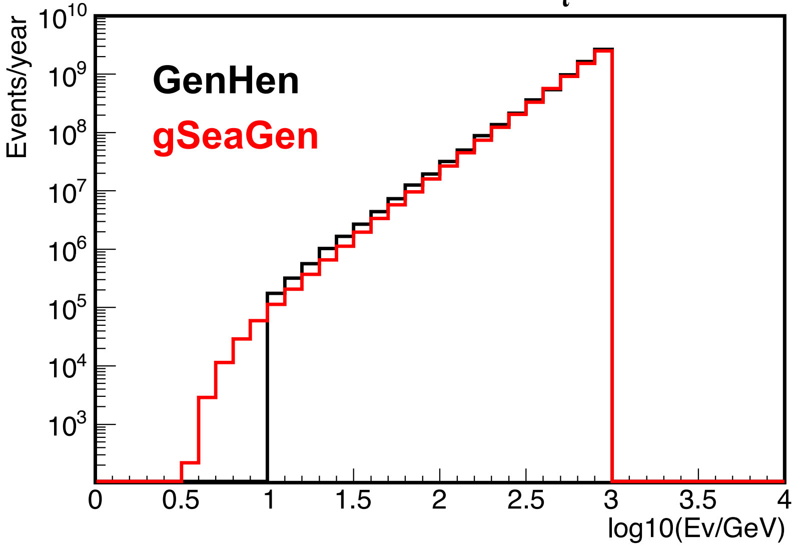




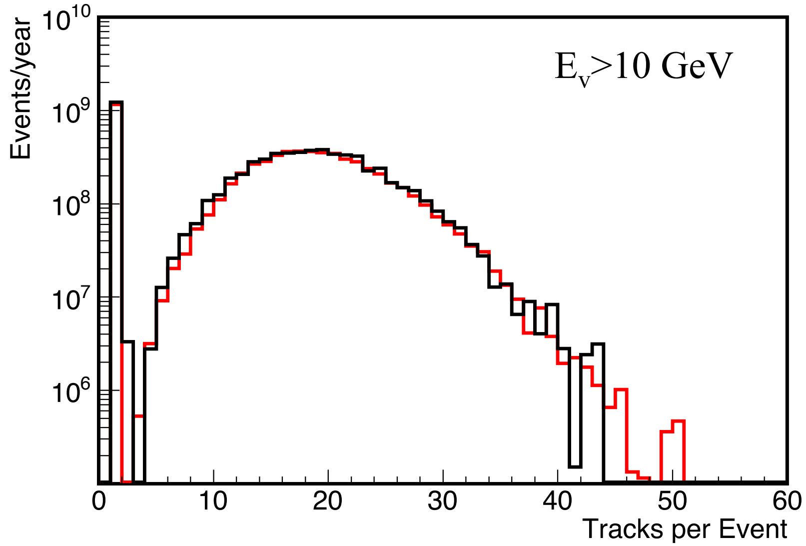


Generation of tau neutrinos

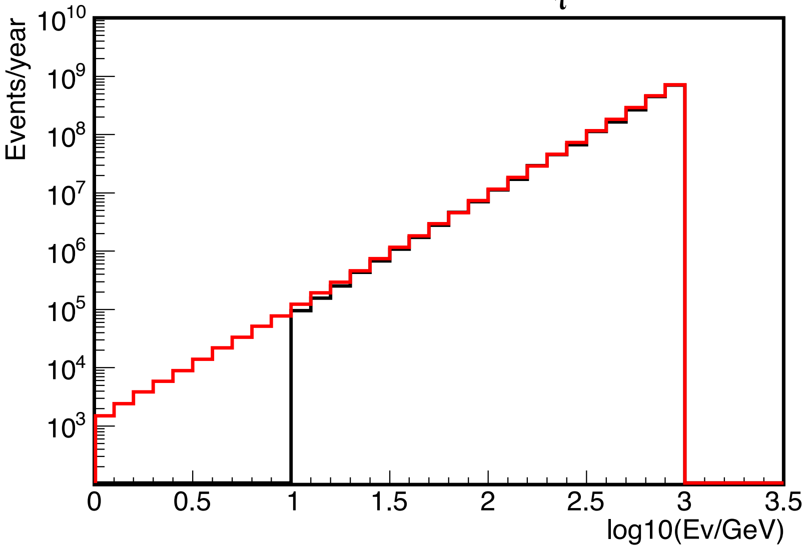
Generated events: anti-ν_τ in CC



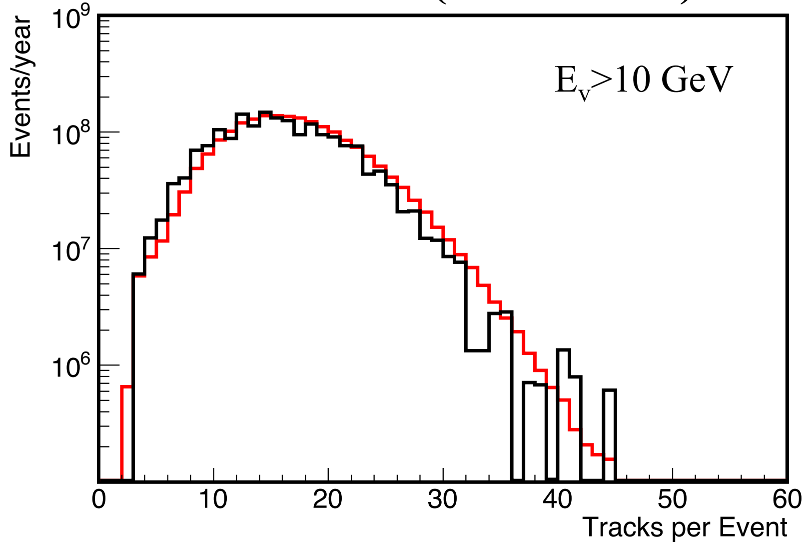
Reference flux: $1/(\mathrm{Gev}\ m^2\ s\ sr)$



Generated events: anti-ν_τ in NC

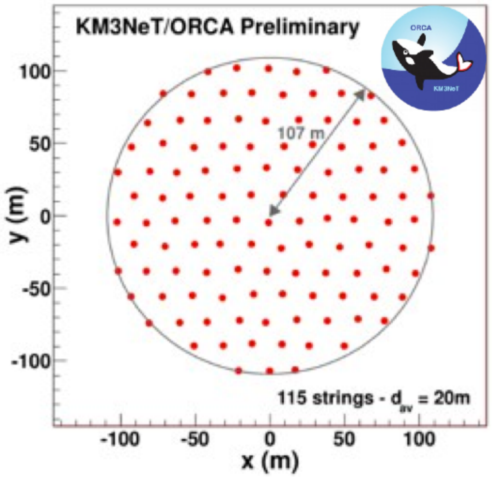


Reference flux: $1/(\mathrm{Gev}\ cm^2\ s\ sr)$



Cross check and code debugging still in progress

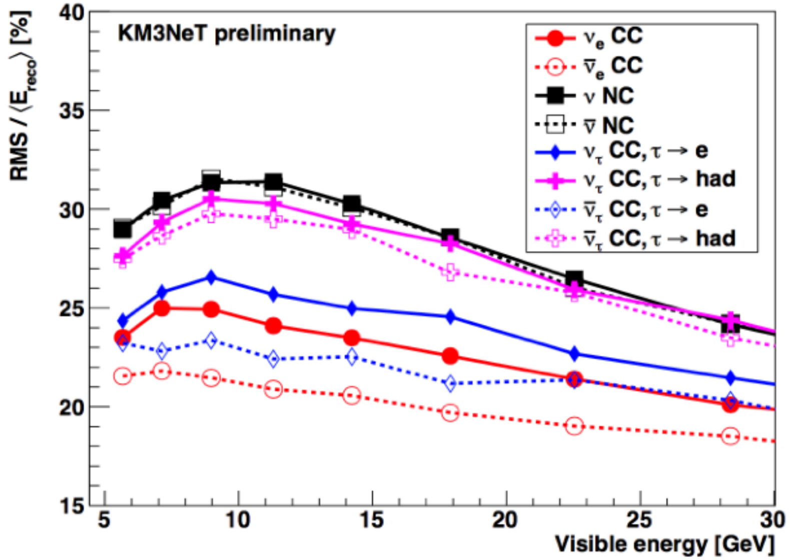
KM3NeT/ORCA: measuring the Neutrino Mass Hierarchy with a deep-sea telescope



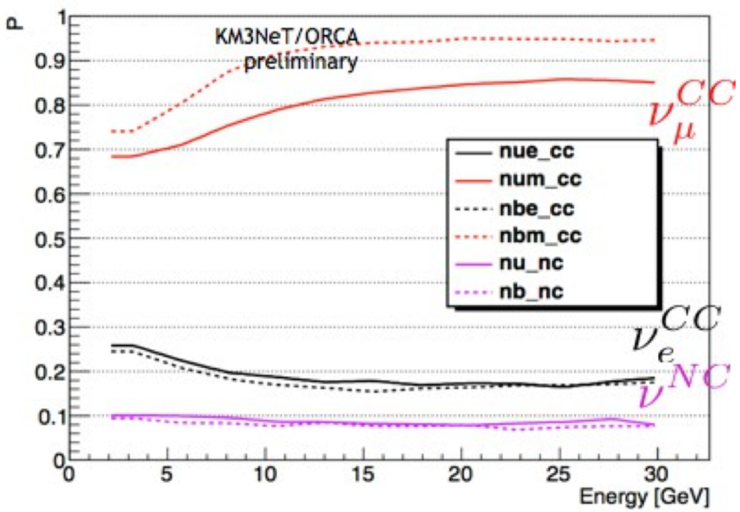
115 lines, 20m spaced,
18 OM/line 6m spaced
Instrumented volume ~3.8 Mt, 2070 OM
3/2 more photocathode area than PINGU

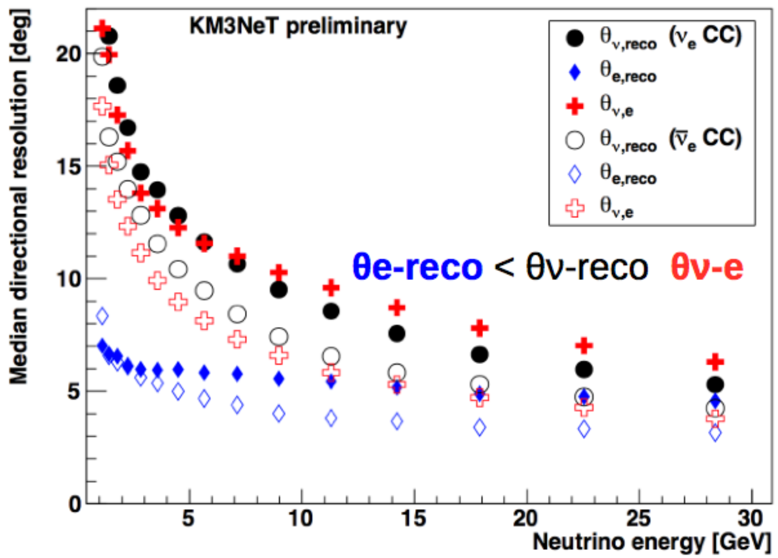
Optical background: 5kHz single rate / PMT & 500 Hz coincidence rate

Optimised layouts still under study



Probability to classify as track-like





See D. Samtleben's talk

Conclusions and Outlook

GENIE is "canonical" Monte Carlo for neutrino interaction physics, used by experiments at different energy ranges.

We wrote the gSeaGen code: a GENIE-based code to generate neutrinos for underwater/ice telescopes.

The code is able to generate events induced by all neutrino flavours, taking into account topological differences between track-type and shower-like events.

The neutrino interaction is simulated taking into account the density and the composition of the media surrounding the detector.

Weighted generation of diffuse fluxes: Bartol, Fluka, analytical function of neutrino energy

Planned:

other atmospheric neutrino fluxes, simulation of point-like sources, propagation through the Earth, …

Present application:

- cross check with GenHen, the standard ANTARES code
- reference code for KM3NeT/ORCA (E_ν<10 GeV)

In the future:

- using the code to test the extension to VHE (in contact with GENIE people)
- using in KM3NeT/ARCA when the extension to VHE will be completed