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for the ANTARES and KM3NeT Collaborations

Confronti tra generatori di interazioni di neutrini usati per i neutrini atmosferici

What Next: Sezioni d'urto dei neutrini
Bologna, Novembre 2015

Outline

GENHEN: ANTARES, KM3NeT-ARCA

ANIS: AMANDA, IceCube

gSeaGen: ANTARES, KM3NeT-ORCA based on

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

Some results and comparisons

GenHen

GENHEN (GENerator of High Energy Neutrinos): designed for the ANTARES Experiment and used in KM3NeT-ARCA.

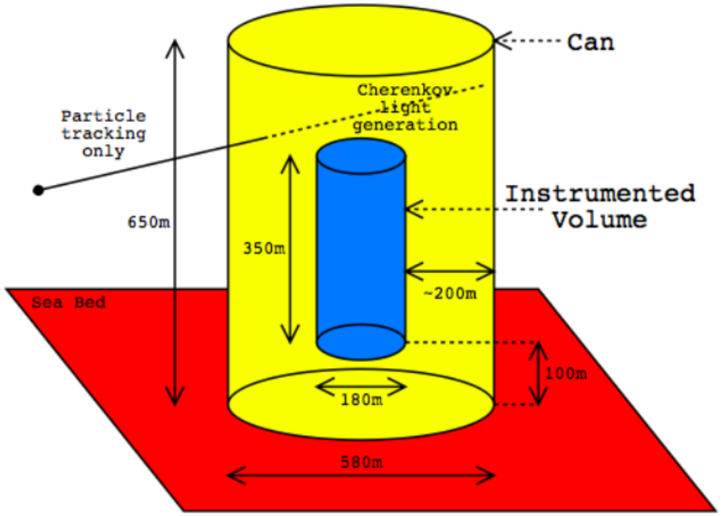
GENHEN is written in FORTRAN

GENHEN simulates neutrino and anti-neutrino interactions with conventional matter for high-energy neutrinos up to 10^9 GeV.

GENHEN simulates one ν or anti-ν at a time; one type of inter. (CC or NC) at a time.

GENHEN simulates QE + RES + DIS events

ANTARES



The ***detector can*** represents the volume sensitive to the light.

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

The ***interaction volume*** is the volume where a neutrino interaction could produce detectable particles.

Shower-like events
The interaction volume is defined as a cylinder coincident with the detector can and entirely made by water.

Track-type events
The volume is a cylinder made by a layer of rock and a layer of pure water surrounding the can, taking into account the muon maximum range in water and in rock, evaluated at the highest energy of simulated neutrinos.

GENHEN generates only interacting neutrinos: interaction probability included in the event weight but full simulation through the Earth can be activated.

GENHEN: simulation algorithm

1. The total interacting neutrino spectrum between E_{min} and E_{max} is divided into equal bins in log10(E) and the number of events N to generated in each bin is calculated.

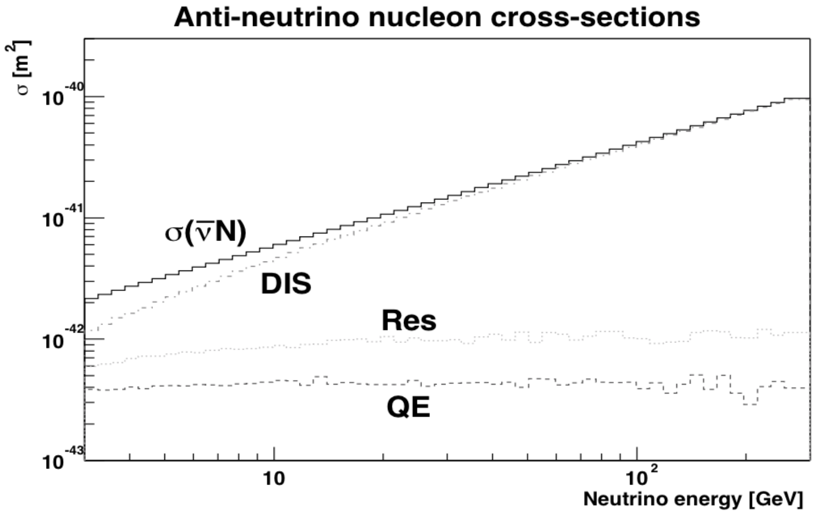
$$N^i(E^i_{min}, E^i_{max}) = N_{total} \times \frac{\int_{E^i_{min}}^{E^i_{max}} E^{-X} dE}{\int_{E_{min}}^{E_{max}} E^{-X} dE}$$

2. For each bin, the interaction volume and the number of events are scaled taking into account the maximum muon ranges in the bin

$$N^i_{scaled}(E^i_{min}, E^i_{max}) = P\left(N^i \times \frac{V_{scaled}}{V_{total}}\right)$$

3. The scaled number of events is generated for each bin

- The vertex is generated inside the scaled interaction volume
- The neutrino energy is sampled from a power law spectrum
- The neutrino direction is sampled from an isotropic distribution
- If muons are produced outside the can, they are propagated up to the can surface (MUM, MUSIC)



The nucleon and Δ resonant events (RES) and the low energy quasi-elastic (QE) parts of the neutrino-nucleon interaction are generated with the program RSQ (Soudan 2).

The Deep Inelasting Scattering (DIS) is simulated with LEPTO.

Both LEPTO and RSQ require an initial choice of the target medium which cannot be changed during the generation because of the time consuming:

- the interaction is simulated with iso-scalar nuclei in water equivalent media;

- the cross-section per nucleon is calculated by summing over individual nucleons and dividing by the total number of nucleons (and hence neglecting nuclear effects):

$$\sigma_N^{total} = \frac{Z}{A}\sigma_p + \frac{(A-Z)}{A}\sigma_n$$

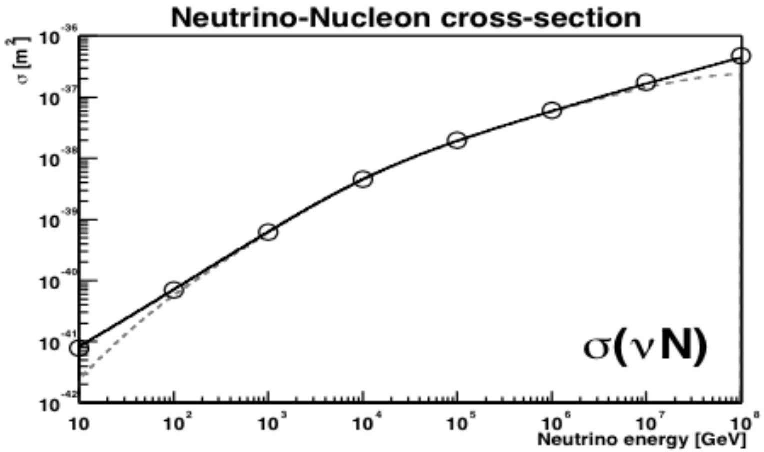
- for each bin, the cross-section is calculated only at the mean log-energy and used to simulate all events in that bin.

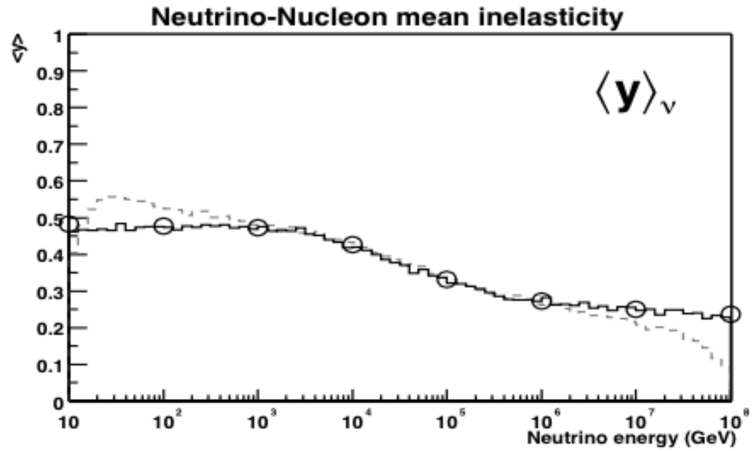
Variable	Description	Default	Adjusted
Bjorken-x	Fraction of the nucleon momentum carried by the struck parton	$10^{-4} < x < 1.$	$10^{-4} < x < 1.$
Bjorken-y	Inelasticity of the interaction. i.e. $E_{\text{lepton}} = (1-y)E_{\text{neutrino}}$	$0 < y < 1$	$0 < y < 1$
Q^2 [GeV^2]	Four momentum transfer	$4 < Q^2 < 10^8$	$0.1 < Q^2 < 10^{10}$
W^2 [GeV^2]	Invariant mass of the hadronic system	$5 < W^2 < 10^8$	$2 < W^2 < 10^{10}$
ν [GeV]	Energy component of the four-momentum transfer	$1 < \nu < 10^8$	$1 < \nu < 10^{10}$
E_l [GeV]	Energy of the scattered lepton	$1 < E_l < 10^8$	$1 < E_l < 10^{10}$

Default limits (kinematics tuned for accelerators) were adjusted for ANTARES.

GENHEN uses various parton density functions of the C-TEQ group, provided by the library PDFLIB for the DIS channel. The recommended (and used) parameterization is the last tested version CTEQ6D.

As the LEPTO program is accurate up to neutrino energies of 10 TeV, GENHEN uses an extrapolation of the model to calculate the neutrino-nucleon cross sections and kinematics to generate DIS interactions up to an energy of 10^9 GeV.





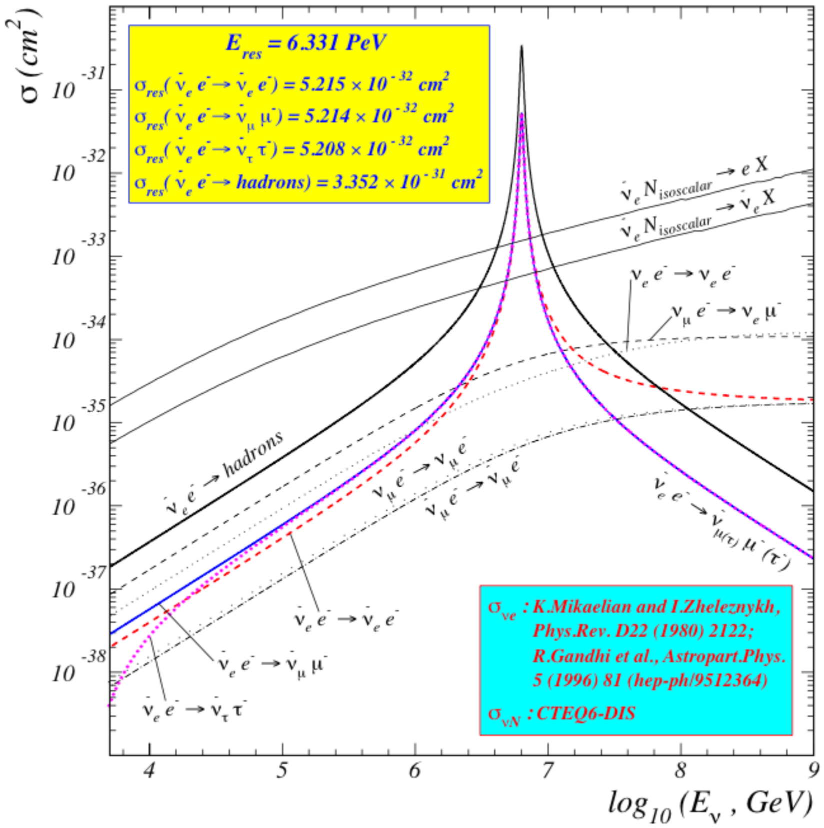
Glashow Resonance in GenHen

Neutrino interactions with electrons are included in the simulation (internal routine)

Activated processes:

$$\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^- \qquad \bar{\nu}_e e^- \rightarrow \bar{\nu}_\tau \tau^-$$

$$\bar{\nu}_e e^- \rightarrow \bar{\nu}_\mu \mu^- \qquad \bar{\nu}_e e^- \rightarrow hadrons$$



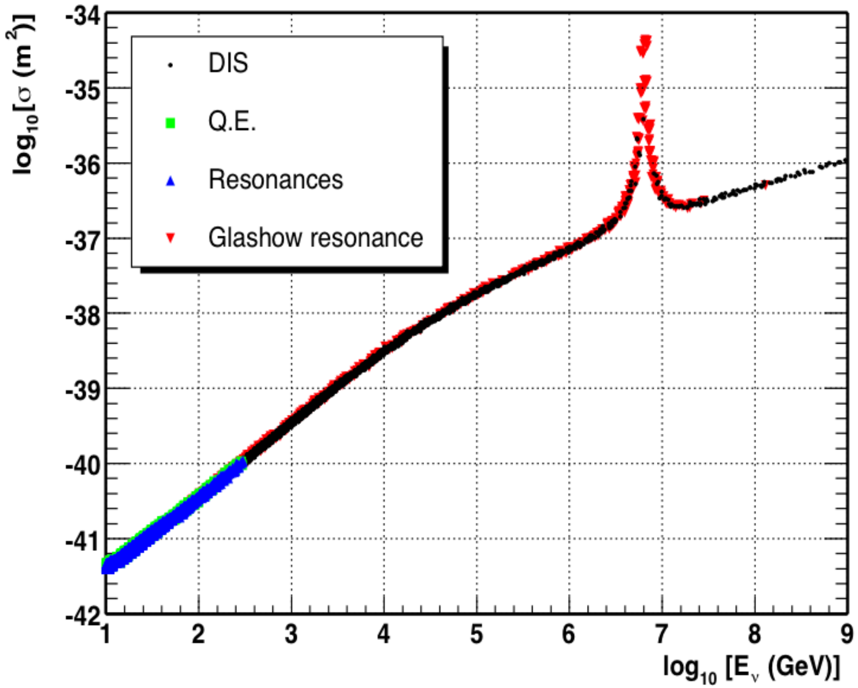
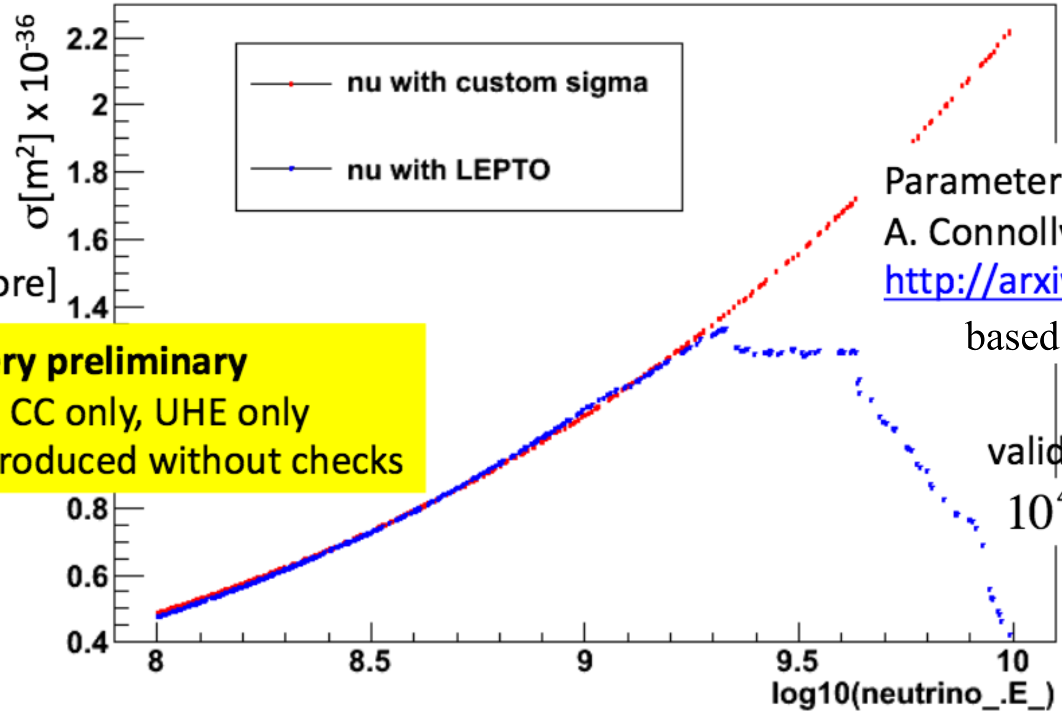


Figure 4: Total cross section for simulated $\bar{\nu}_e$ used in the weight calculation as a function of neutrino energy for events reaching the can. The different colors indicate the occurring of different processes.

…still a problem with Cross Section from LEPTO ?

At the highest energies the behaviour of the cross section as computed by LEPTO starts to fail the expectations and differs from published parameterization. This should not affect the kinematics of the generated event but could have a consequence for the event weight. The proposal is to replace (or complement) the LEPTO computation with a **parameterization taken from selected references → XParam**

[plot by L. Core]

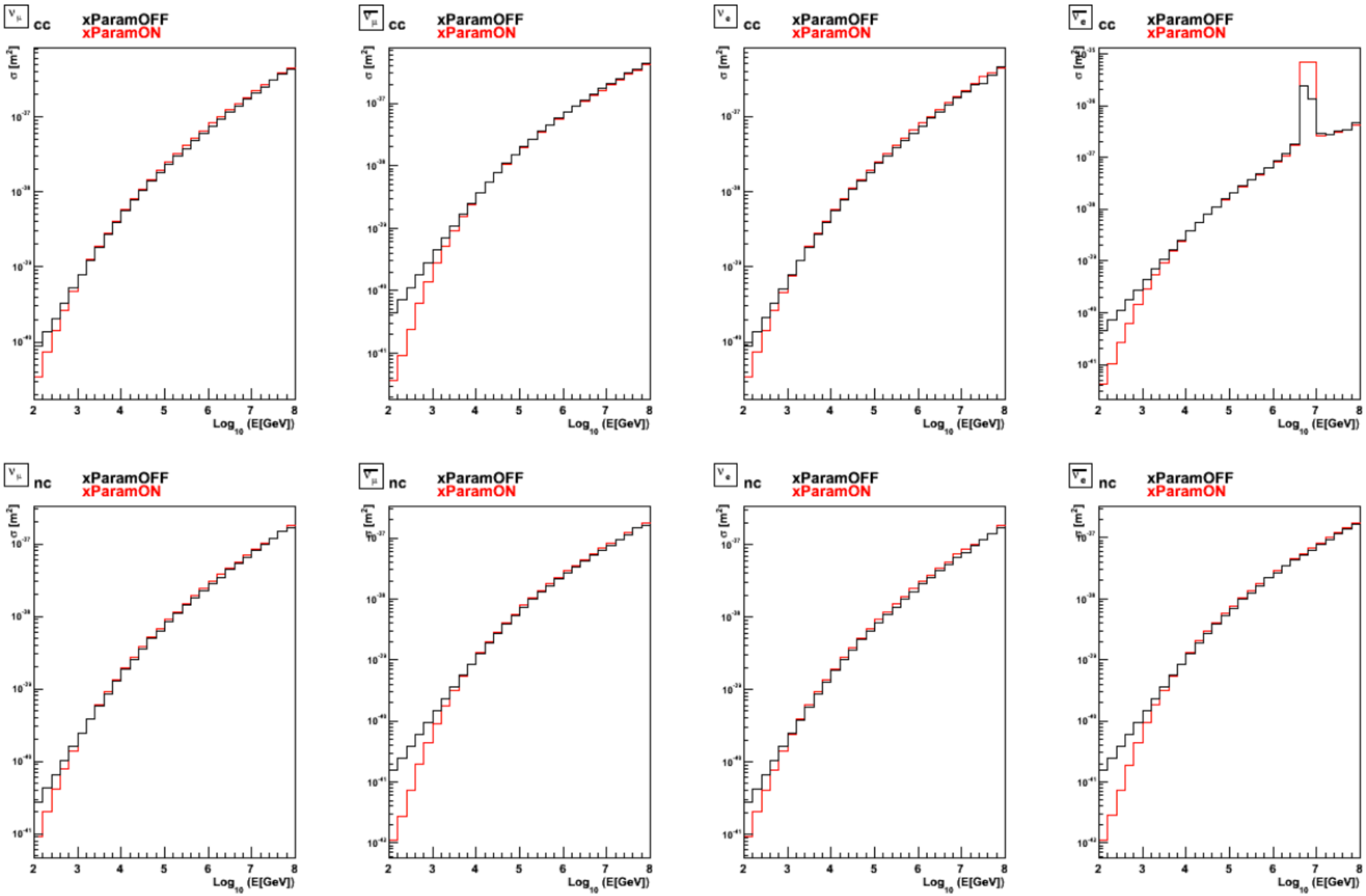


very preliminary
nuMu CC only, UHE only
changes introduced without checks

Parameterization taken from:
A. Connolly et al.,
http://arxiv.org/abs/1102.0691
based on MSTW2008 PDF

valid in the energy range

$$10^4 < E_\nu < 10^{12} GeV$$



cc
xParamOFF
xParamON
σ [m²]
Log10 (E[GeV])
2 3 4 5 6 7 8
nc
xParamOFF
xParamON
σ [m²]
Log10 (E[GeV])
2 3 4 5 6 7 8

ANIS

ANIS (All Neutrino Interaction Simulation) designed for the AMANDA/IceCube Experiments.

ANIS is a Monte Carlo neutrino event generator for high-energy neutrino telescopes. It has been developed by Marek Kowalski and Askhat Gazizov for the AMANDA collaboration.

ANIS is written in C++

ANIS prepares neutrinos, propagates them through the Earth and in a last step simulates a neutrino interaction within a specified volume around the detector.

ANIS can generate neutrinos and anti-neutrinos up to energies of 10^{12} GeV but simulates only DIS interaction.

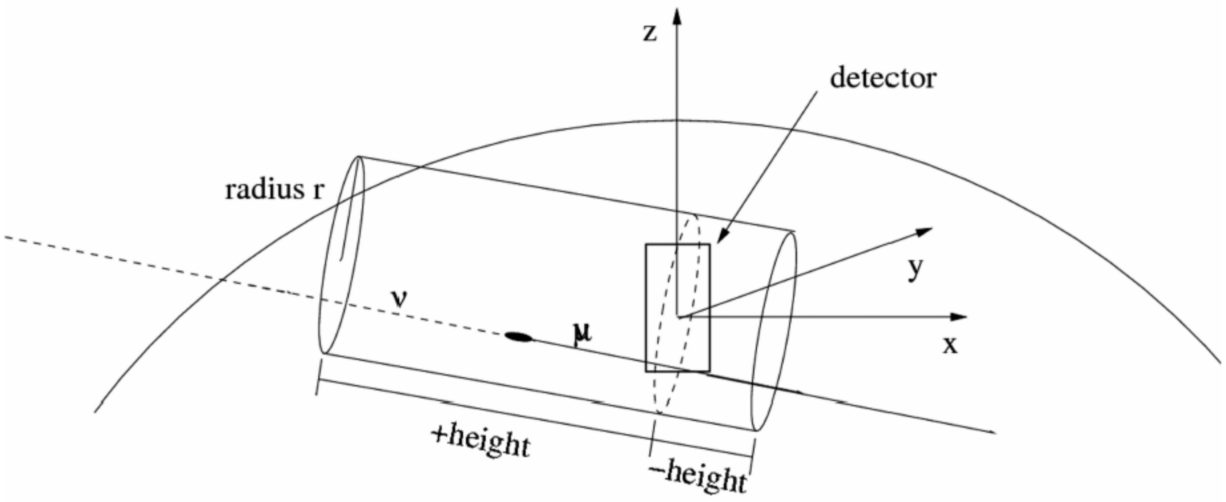
The currently implemented interaction channels include charged current (CC) and neutral current (NC) interactions as well as resonant W− production

Neutrinos are generated uniformly on the surface of the Earth, with an energy is sampled from a power law spectrum.

Neutrinos are propagated through the Earth in small steps towards the telescope (according to the Preliminary Earth Model). In interactions with matter they are either absorbed (CC-case) or regenerated at lower energies (NC-case). The ν_τ regeneration is simulated (using TAUOLA).

Neutrinos that survive the propagation through the Earth are simulated to interact within the Final Volume. Once the detection volume is reached, a final vertex is generated along the neutrino trajectory within the detection volume.

Secondary muons are propagated with MMC (developed for the AMANDA telescope).



ANIS: cross section

At Eν<1×10⁶ GeV, deep inelastic νN-cross-sections is described in the framework of pQCD, choosing the CTEQ5 parameterization for the νN structure.

At Eν>1×10⁶ GeV, two options are presently included in ANIS: smooth extrapolation to low-x and high-Q_2 region of the pQCD CTEQ5 parameterization or Hard Pomeron enhanced extrapolation.

The used cross-section data for CC- and NC-reactions are taken from pre-calculated tables.

The total cross-section is obtained through interpolation between energy bins

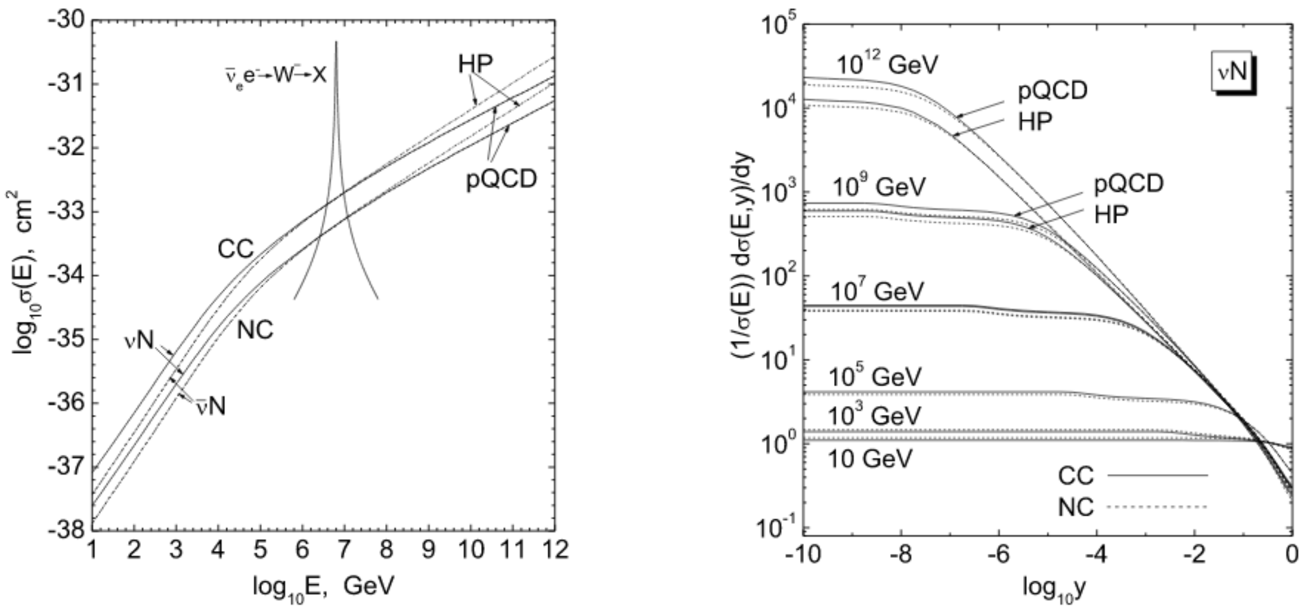


Fig. 1. a) νN- and resonance $\bar{\nu}_e e^-$-cross-sections and b) normalized y-distributions.

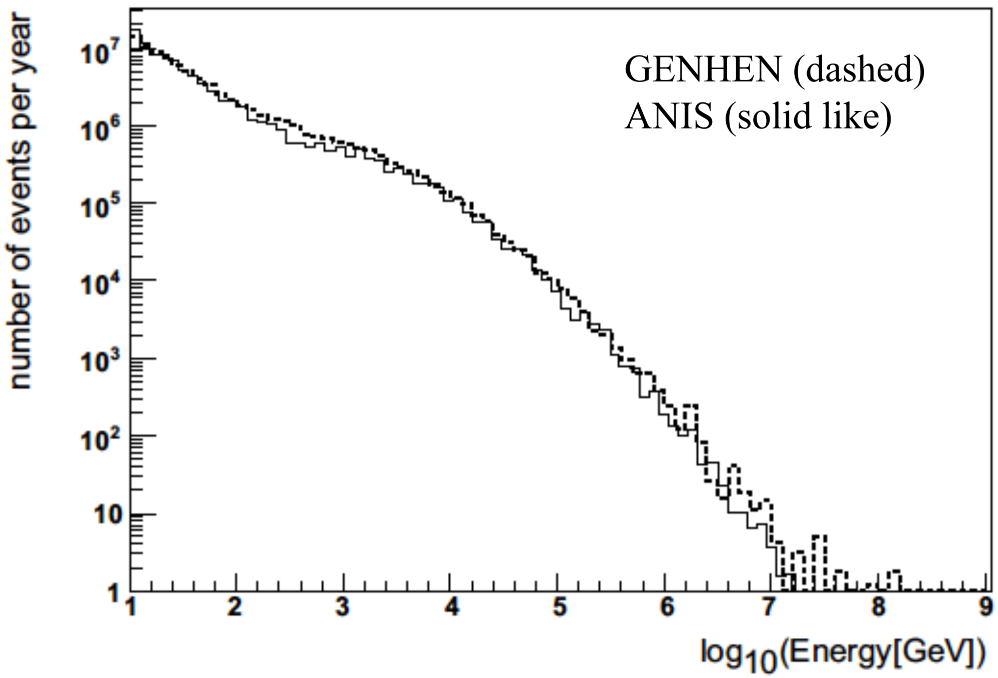
GenHen vs ANIS

	GENHEN	ANIS
Programming Language	FORTRAN	C++.
E_{min} – E_{max} [GeV]	10. – 1.0 x 10^9	10. – 1.0 x 10^{12}
Simulated Generation	one ν or a-ν flavour at a time; one type of inter. (CC or NC) at a time.	50% ν and 50% a-ν and both NC and CC for each run.
Simulated Interaction Channels	QE + RES + DIS (CTEQ6)	DIS only (CTEQ5) [**low energy processes neglected**]
Glashow Resonance	W decay channels: e, μ, τ, hadrons	W decay channels: μ, hadrons
Geometry	**can** [cylinder, **fixed in size and position**, encompassing the instrumented volume] + **Generation Volume**	**Final Volume** [**rotating cylinder**, with axis parallel to the ν direction]
Neutrino Propagation through the Earth	can be deactivated - the **shadowing effect** is included in the event weight as a **transmission probability** (PE)*.	activated

* The PE approximation is reasonable for ν_e and ν_μ; the full propagation has to be activated for ν_τ, to properly account for the regeneration chain

GenHen vs ANIS

Atmospheric muon neutrino rates: Bartol model for GENHEN or the Lipari model for ANIS.



ANIS only simulates DIS neutrino scattering with nuclei as the program focus on high energy neutrinos. Since GENHEN also generates the QE and RES channels, only DIS events have been selected after they were produced for comparison with the results of ANIS.

The small differences are most likely due to the slightly different atmospheric flux model and the generation method used.

What is GENIE?

Generates Events for Neutrino Interaction Experiments

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 openness 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 neutrino telescope?

- migration to C++ → use of modern neutrino interaction codes

External dependencies

A typical GENIE installation[4] requires the following external packages[5]:

- ***ROOT***
- ***LHAPDF***
  The Les Houches Accord PDF interface, a PDFLIB successor.
- ***PYTHIA6***
  The well known LUND Monte Carlo package used by GENIE for particle decays and string fragmentation (for neutrino interactions of high invariant mass).
- ***log4cpp***
  A C++ library for message logging.
- ***libxml2***
  The C XML library for the GNOME project.

- continually maintained

- used by experiments at different energy ranges → data comparison

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

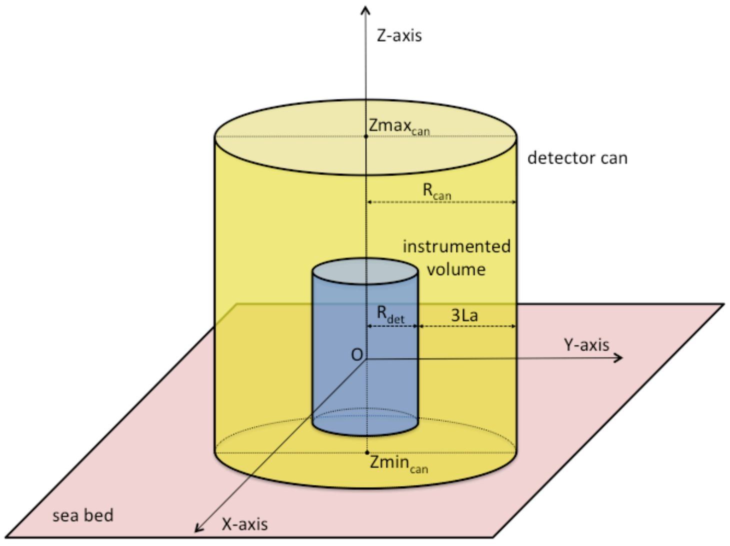
- It simulates neutrino-induced events detectable by an underwater neutrino detector.
- It simulates the neutrino interaction taking into account the density and the composition of the target media.
- It is able to simulate all neutrino flavours, taking into account topological differences between track-type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

GENIE http://www.genie-mc.org/

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

gSeaGen: geometry

As in GENHEN but with a different definition of the target media!!!



The ***detector can*** represents the volume sensitive to the light.

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

The ***interaction volume*** is the volume where a neutrino interaction could produce detectable particles.

Shower-like events
The interaction volume is defined as a cylinder coincident with the detector can and entirely made by **SeaWater**.

Track-type events
The volume is a cylinder made by a layer of **Rock** and a layer of **SeaWater** surrounding the can, taking into account the muon maximum range in water and in rock, evaluated at the highest energy of simulated neutrinos.

gSeaGen: 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

GENIE models – A summary

- **Cross section model**
  - QEL: Llewellyn-Smith with any of Sachs/BBA03/BBA05 elastic f/f
  - RES: Rein-Sehgal
  - COH pi production: Rein-Sehgal / includes updated PCAC
  - DIS: latest Bodek-Yang (GRV98lo)
    - Including parametrization of the longitudinal structure function FL
    - Including NuTeV parameterization of nuclear effects
  - Many other more rare channels: DIS & QEL charm / ve- elastic / inv.mu-decay/...
- **Nuclear model**
  - Fermi Gas model
  - Including high momentum tail due to N-N correlations modelled from eN data
  - "Standard" FG prescription for off-shell kinematics...

Fairly standard at all ν MCs

Careful implementation as MINOS spans a huge kinematical region (E ~ <1 to >100 GeV)

- **Transition region cross section modelling**
  - Non resonance background modelled from DIS & AGKY hadronization
  - Tuned to the world exclusive multi-pion cross section data
- **Neutrino-induced primary hadronic shower modelling**
  - AGKY
  - Effective KNO-based hadronization at low-W
  - Switching gradually to PYTHIA/JETSET at high-W
  - SKAT-type formation zone parametrization
- **Intranuclear hadron transport**
  - INTRANUKE/hA model
  - Anchored to a set of hadron+Fe56
  - Scaled to all nuclei

Unique to GENIE

See Chapter 2 of the Guide

Costas Andreopoulos, *Rutherford Appleton Lab.*

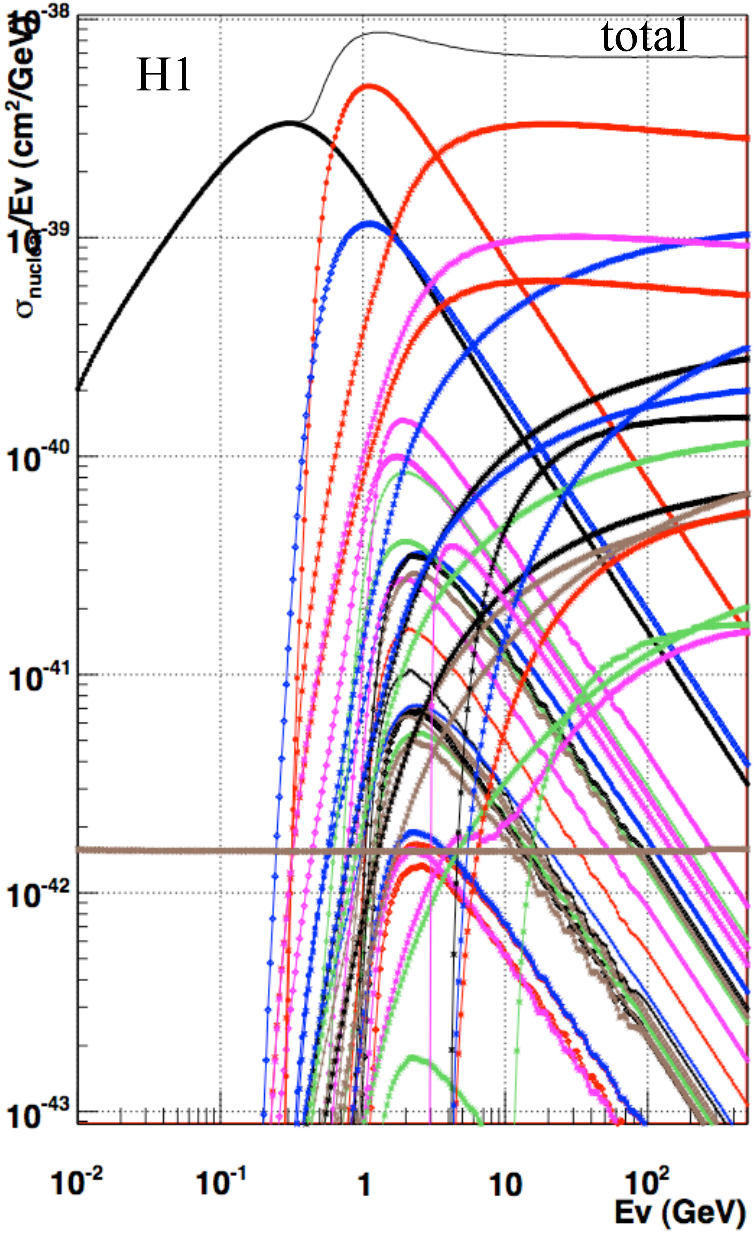
- Cross section calculation is very CPU-intensive because of the fine numerical integration stepping and the large number of processed involved…
- …but it's possible to use pre-computed cross section splines file generated with the GENIE utility - ***gmkspl***

GENIE validity range: up to 5 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**

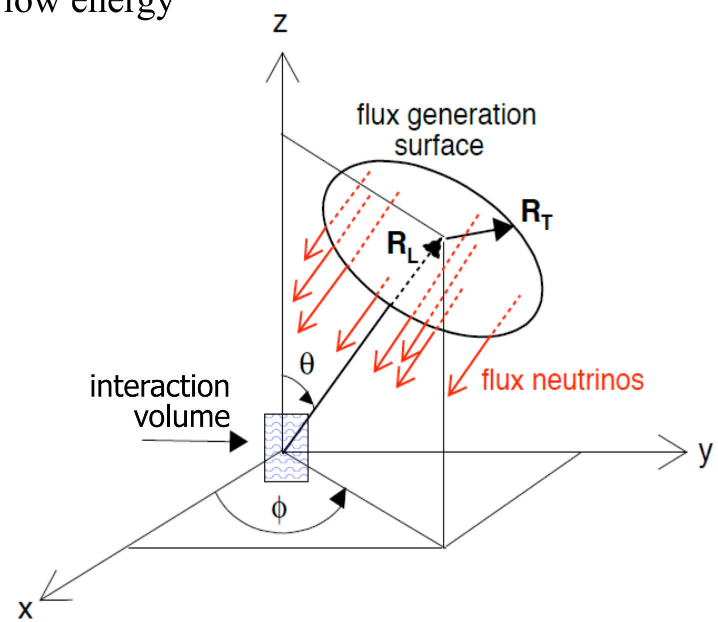


gSeaGen: simulation algorithm

- 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 $Log10(E_\nu)$:
  - 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



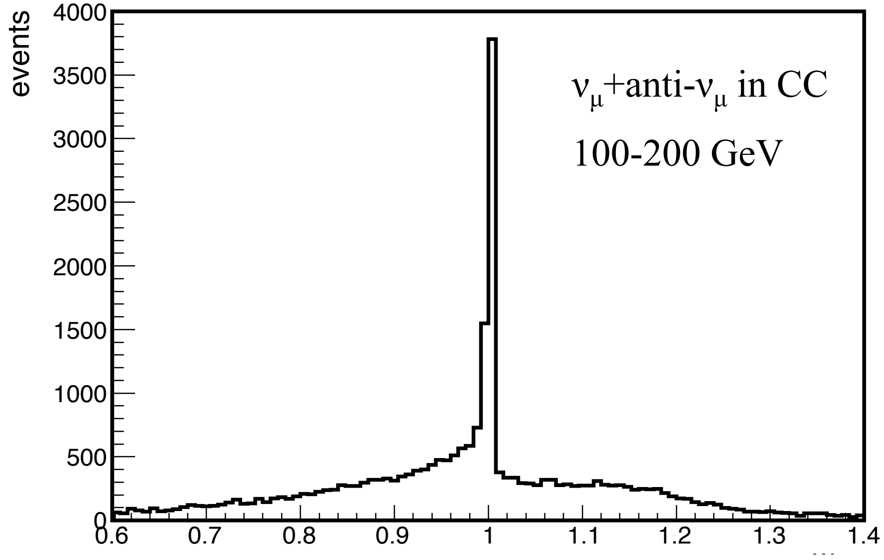
GENIE knows the accuracy of the input simulation parameters and it is able to propagate neutrino interaction uncertainties.

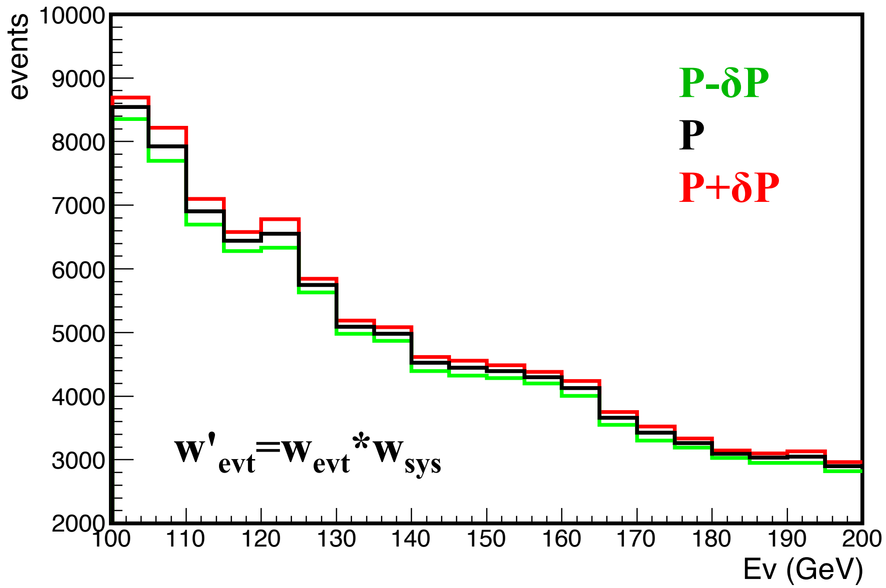
Event reweighting strategy: use one sample to emulate another (i.e. we don't need to repeat the simulation but just reweighted the events).

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





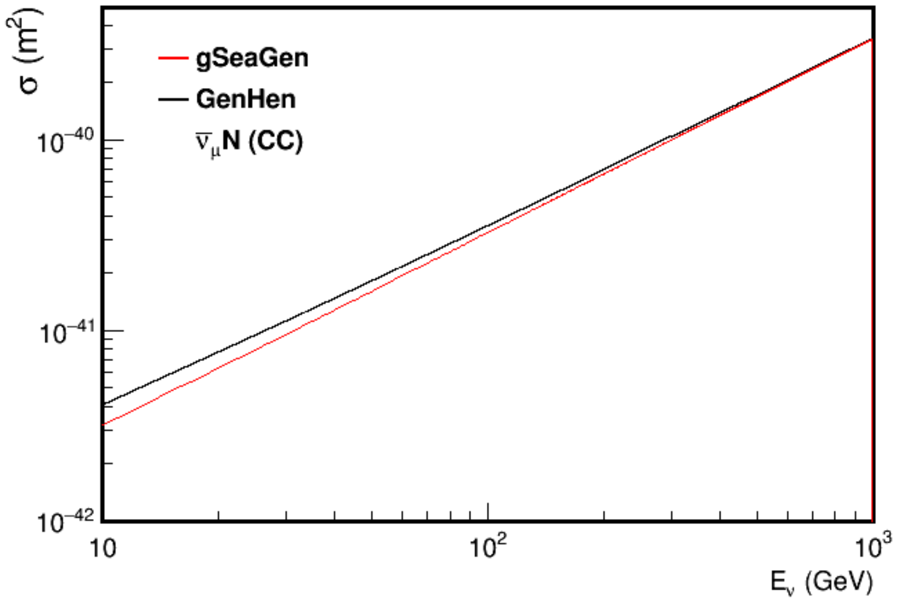
gSeaGen vs GenHen

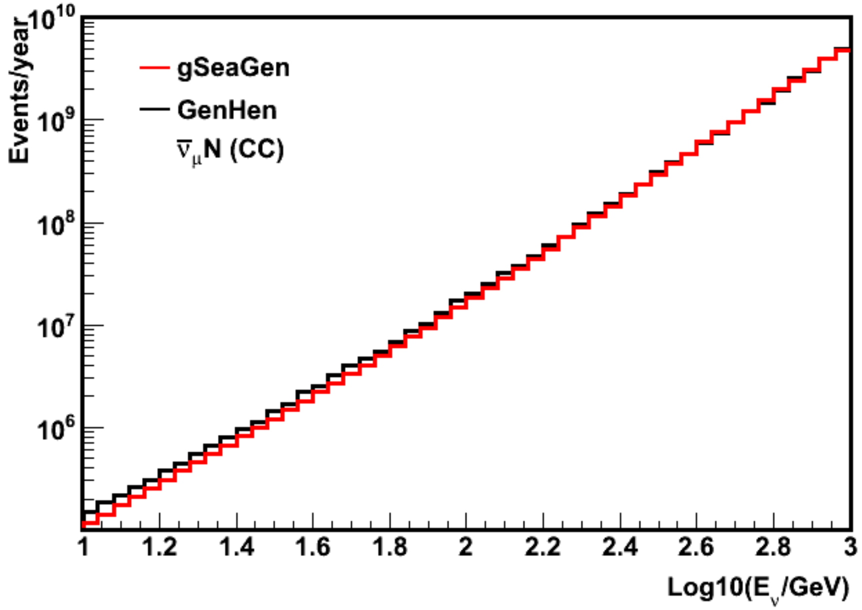
gSeaGen	GENHEN
C++	Fortran
0.01 - 5000 GeV (GENIE)	10 – 10^9 GeV
full simulation of neutrino interaction (probability scale): surface generation	all neutrinos interact (interaction probability included in the event weight): volume generation
xsec calculated at each neutrino energy (pre-computed)	xsec calculated at the centre of energy bins
interaction in seawater and rock as defined in the geometry	interaction with iso-scalar nuclei in water equivalent media
one ν or anti-ν or ν + anti-ν at a time; one type of inter. (CC or NC) or CC+NC at a time.	one ν or anti-ν at a time; one type of inter. (CC or NC) at a time.

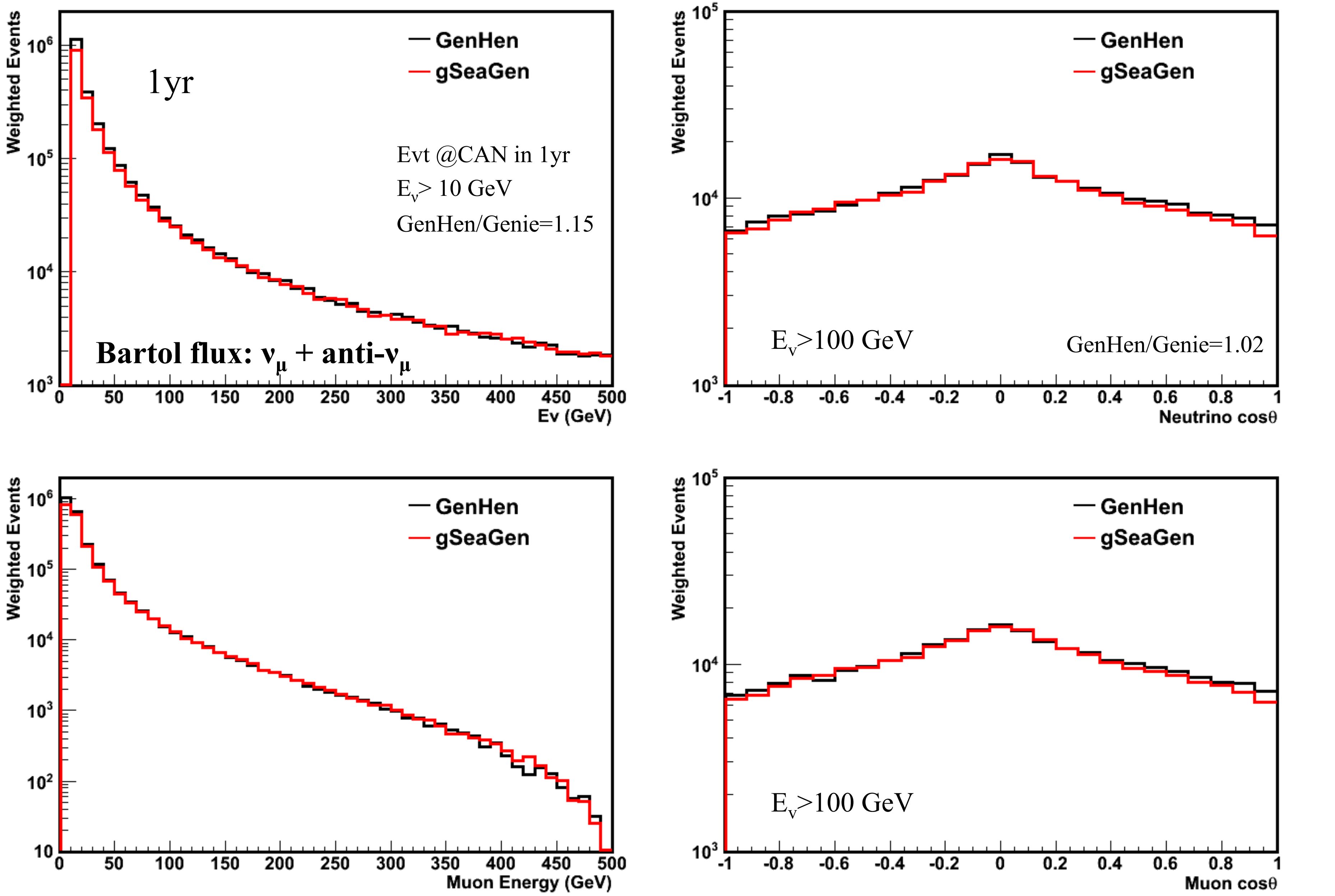
Generation of anti-muon neutrinos

Generated events: anti-ν_μ in CC

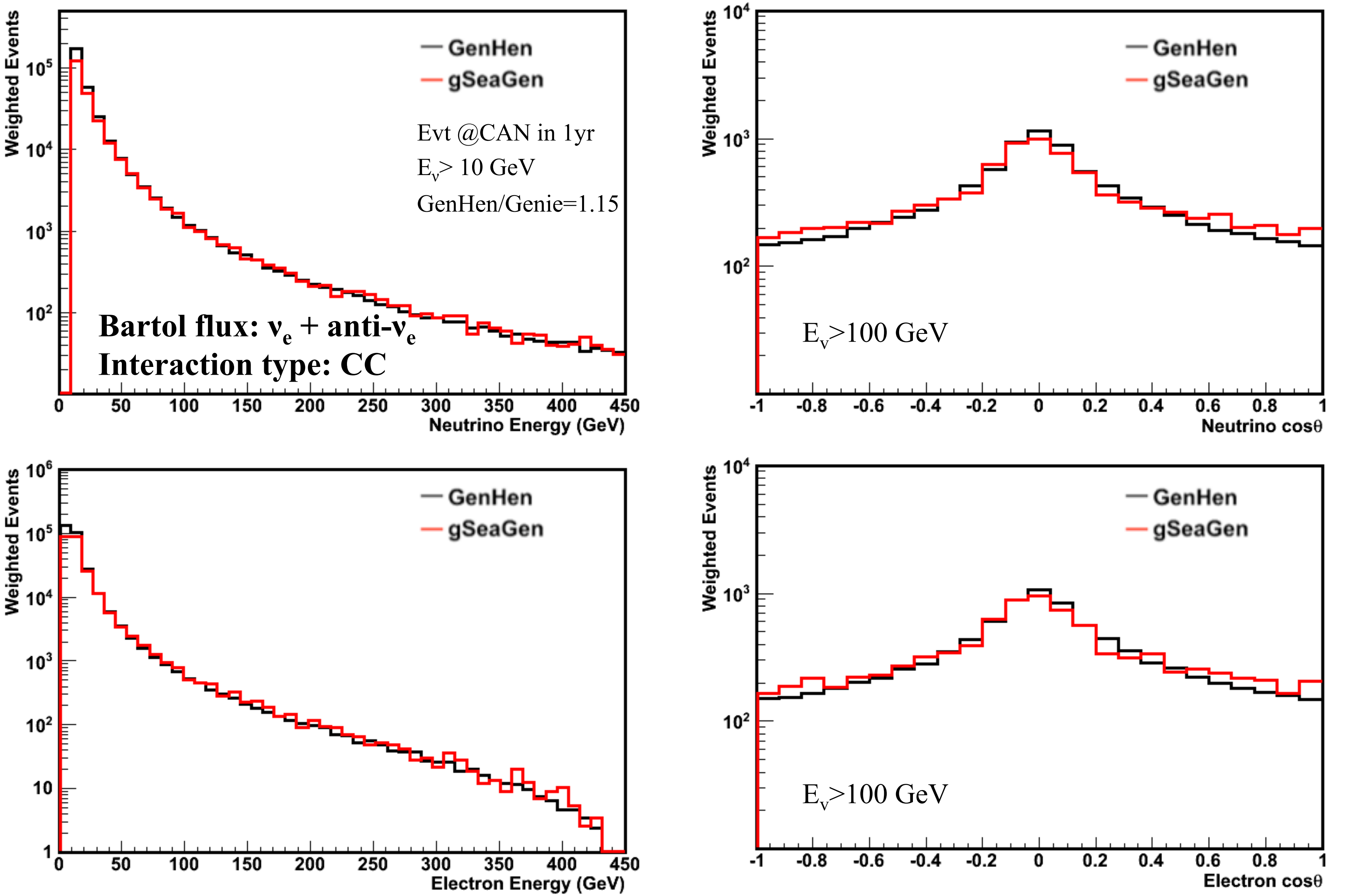
Reference flux: 1/(Gev m² s sr)





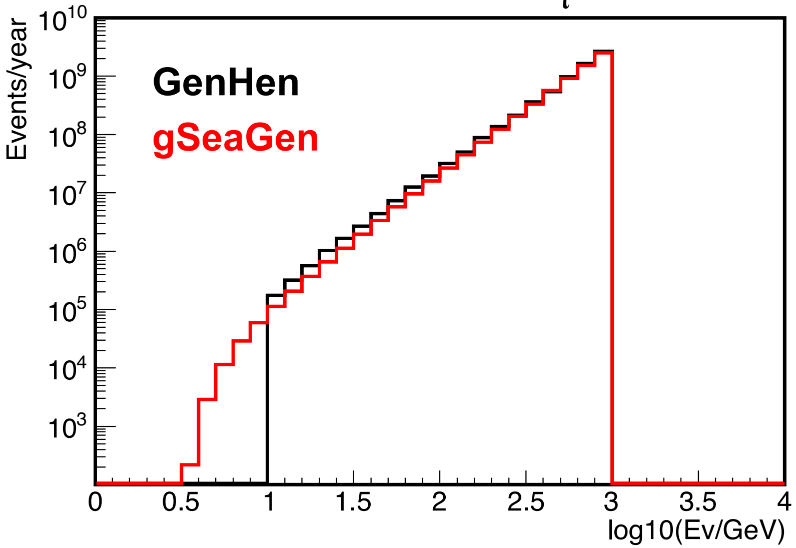

Weighted Events
GenHen
gSeaGen
1yr
Evt @CAN in 1yr
E_ν> 10 GeV
GenHen/Genie=1.15
Bartol flux: ν_μ + anti-ν_μ
Ev (GeV)
E_ν>100 GeV
GenHen/Genie=1.02
Neutrino cosθ
Muon Energy (GeV)
Muon cosθ

Generation of electron neutrinos

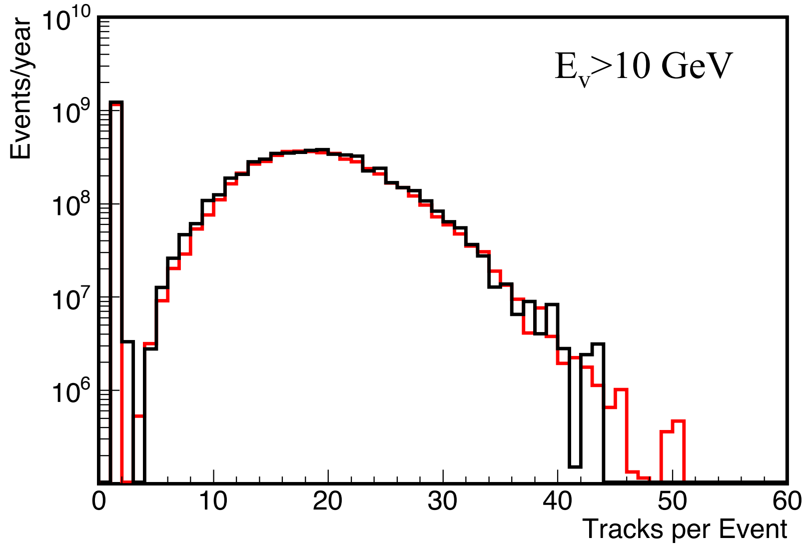


Generation of tau neutrinos

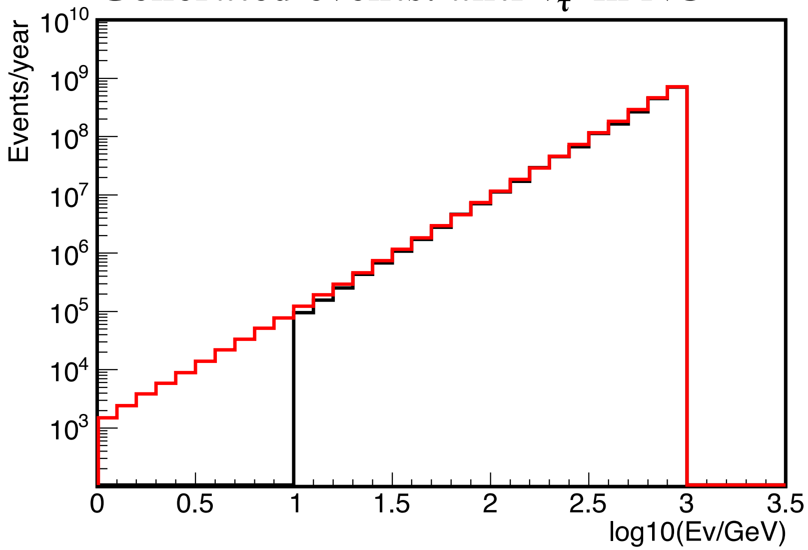
Generated events: anti-ν_τ in CC



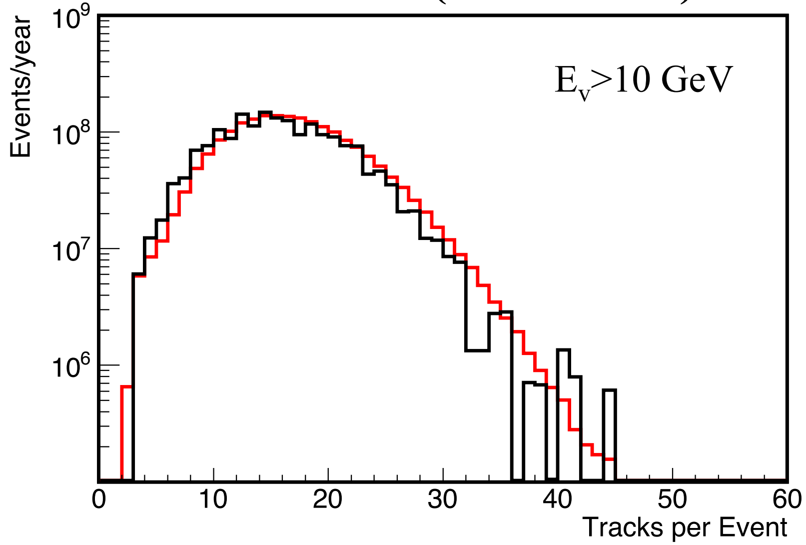
Reference flux: 1/(Gev m^2 s sr)



Generated events: anti-ν_τ in NC



Reference flux: 1/(Gev cm^2 s sr)



Cross check and code debugging still in progress