LENA Monte Carlo Simulation User Documentation

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Contents

1 Installation

The code of the LENA Monte Carlo Simulation is hosted by a SVN repository[1]. You can checkout the latest version with the command '**svn checkout https://129.187.186.17/svn/LenaSimulation/trunk**'[2]. In order to run the simulation, you will need Geant4 (Version 4.9.3 or 4.9.4, including all DATA packages) and ROOT (Version 5.20 or later). After you downloaded the code, just compile it with **make**.

2 Tutorial

The LENA simulation is controlled by a command line interface. It is also possible to run the simulation in the batch mode, where the simulation is controlled by a macro[3]. To run the tutorial you should start the simulation with the command:

"lena *path_to_Lena_Directory*/doc/userdoc/Tutorial/Tutorial.mac"

The parameter is the path to the tutorial macro, which is automatically executed. You can find the results of the tutorial in the folder "./doc/userdoc/Tutorial".

2.1 Monoenergetic Events

At the beginning of the macro file, the physics list is defined (see Section 4.1).

```
# load the physics list
/Lena/phys/reg G4EmExtra
/Lena/phys/reg G4HadronElastic
/Lena/phys/reg HadronQGSP_BERT_HP
/Lena/phys/reg G4QStopping
/Lena/phys/reg G4Ion
/Lena/phys/reg LenaOP # optical physics including scintillation
/Lena/phys/reg G4Radioactive
```

[1] username:Lena; password:LenaSim001
[2] see http://svnbook.red-bean.com/en/1.7/index.html for details
[3] You can find a list of all valid commands in the folder "./doc/commands"

```
/physics_engine/tailor/MuonNuclear on

/run/initialize # initialize the physics list and the detector

/control/verbose 2
/run/verbose 2
```

Afterwards, the PMT detection mode and the light yield is defined (see Section 4.3 for details).

```
/Lena/det/pmts false # don't simulate individual PMTs
# activate the winston cones, acceptance angle is set to about 50°,
# corresponding to an area increase by a factor of 1.75
/Lena/det/winston_cones true
/Lena/det/light_yield 792
/Lena/det/dark_noise false # don't generate dark counts
/Lena/det/tof true #turn on time of flight correction
/Lena/det/update #update the detector geometry
```

In the next step the simulation type (see Section 3.3 for a description of all available simulation types) and the filename of the results file is set.

```
# use the general simulation type and
# write an entry for every photon hit
/Lena/run/sim_type 2
# set the path, where the result file is written
/Lena/run/setOutputPath ./SimData
# set the output filename
/Lena/run/setOutputFileName Data_Electron1MeV_Pos1_Precise
```

In the last step we define the primary particle, its position and energy, and start the simulation.

```
/gun/particle e- # define the primary particle
/gun/position 0 0 0 m # define the position of the primary particle
/gun/energy 1 MeV # define the energy of the primary particle
/run/beamOn 500 # simulate 500 events
```

The output file contains a root tree (named "TreeLENA"), which has an entry for every detected photon. Figure 1 shows the time distribution of the detected photon hits.

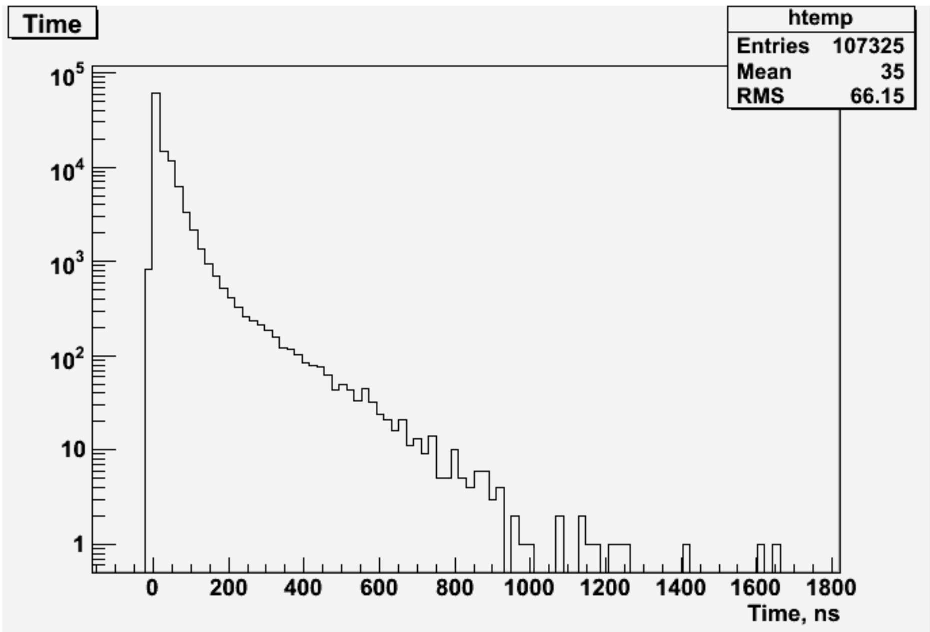

Figure 1: The time distribution of the detected photon hits. A time of flight correction was applied.

In the next simulation we won't save every photon hit, but instead save only general information about the event, like the visible energy. First of all, we will activate the dark noise generation, and set the fast and afterpulse rate.

```
/Lena/det/dark_noise true # generate dark counts
/Lena/det/dark_noise_rate 50 # set the dark count rate to 50 per μs
/Lena/det/after_pulse_prob 0.05 # set the fast afterpulse rate to 5%
/Lena/det/late_pulse_prob 0.05 # set the late pulse rate to 5%
```

```
# only save the number of detected photons
# and calculate the visible energy
/Lena/run/sim_subtype -2
```

In the next step, we define the range of the pulse shape histogramm. Only photon hits within this range will be used for the calculation of the visible energy and the pulse shape parameters.

```
# set the range of the pulse shape histogram,
# only photon hits within this range
# are used for the calculation of the visible energy
/Lena/det/pmt_hist_range_low 0
/Lena/det/pmt_hist_range_up 600

# set the number of bins of the pulse shape histogram
/Lena/det/pmt_hist_num_bins 600
```

To reconstruct the visible energy, we need to define the calibration file. There are several calibration files available, each with different detector properties. It is also possible to generate own calibration files (see Section 3.5 and Section 5.5 for details).

```
# set the calibration file that is used for the calculation
# of the visible energy
/Lena/run/setCalibFile ./Data/Data493/EnergyCalibWinstonConesDN50AP5LP5.dat
```

Finally, we will start two simulations. In the first simulation, the electrons are started in the center of the detector and in the second, they are started at R=12 m.

```
# set the name of the output file
/Lena/run/setOutputFileName Data_Electron1MeV_Pos1
/run/beamOn 10000
```

```
/gun/position 12.0 0 0 m

/Lena/run/setOutputFileName Data_Electron1MeV_Pos2
/run/beamOn 10000
```

The resulting visible energy for the events in the center is shown in Figure 2.

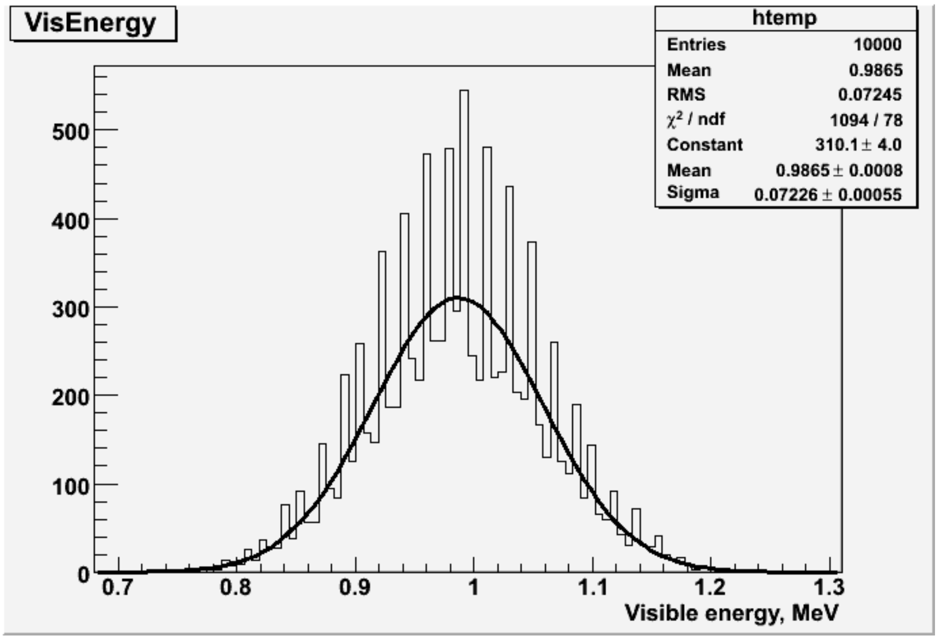

Figure 2: Reconstructed visible energy for 1 MeV electrons in the center of the detector. The spikes are due to a binning effect.

In both simulations the visible energy is reconstructed at 1 MeV, although the number of detected photons is different.
Up to now, we have only simulated electrons at a fixed position. Now we are simulating electrons, which are homogeneously distributed over the fiducial volume. First of all we have to change the gun type (see Section 4.6 for a list of all available gun types) and define our fiducial volume radius.

```
# distribute the events homogeneously in the fiducial volume
/Lena/gun/type 8
# set the radius of the fiducial volume to 11 m
/Lena/gun/SetFiducialVolRadius 11 m
```

Then we need to define the energy of the electrons. In principle we could define an energy spectrum, but for the moment we use monoenergetic electrons. Subsequently we define the output filename and start the simulation.

```
# set the energy to 500 keV
/Lena/gun/SetEnergyRangeLow 500 keV
/Lena/gun/SetEnergyRangeHigh 500 keV

/Lena/run/setOutputFileName Data_Electron500keV_FidVol
/run/beamOn 10000
```

In Figure 3 the radius of the event position is depicted. The rise with the radius is due to the increase of the volume element.

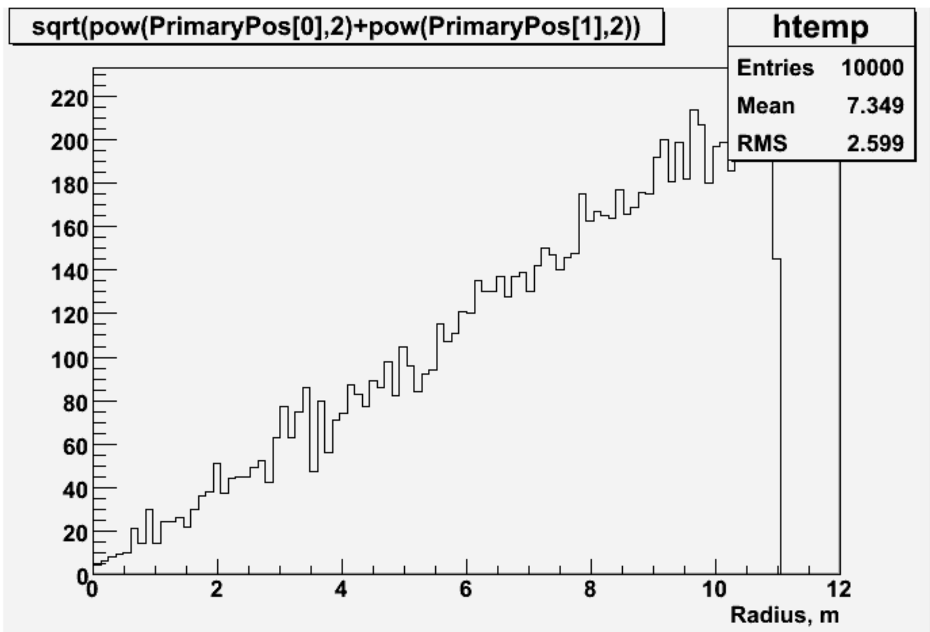

Figure 3: Radius of the event position.

2.2 Energy Spectrum

It is also possible to use a flat energy spectrum. We will set the lower bound to 0.5 MeV and the upper bound to 1.5 MeV.

```
/Lena/run/setOutputFileName Data_Electron500-1500keV_FidVol
# use a flat energy spectrum, ranging from 500 keV to 1500 keV
/Lena/gun/SetEnergyRangeLow 500 keV
/Lena/gun/SetEnergyRangeHigh 1500 keV
/run/beamOn 10000
```

Figure 4 shows the resulting visible energy.

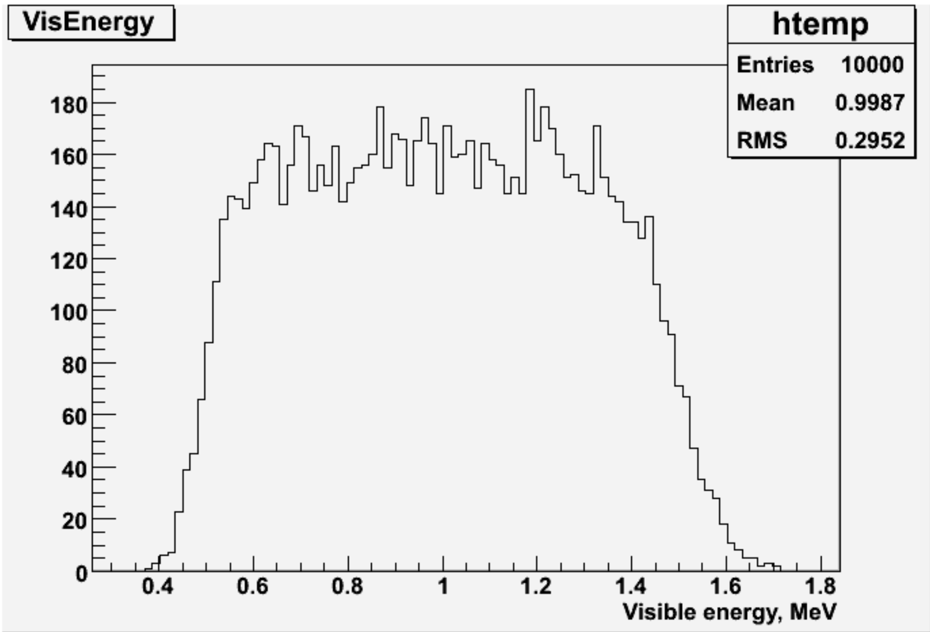

Figure 4: Visible energy of electron events with an energy between 0.5 MeV and 1.5 MeV (flat spectrum), homogeneously distributed over the fiducial volume.

Finally, we will use a linear increasing spectrum (ranging from 1 MeV to 15 MeV), that is defined by a root histogram. With this method it is possible to define arbitrary energy spectra.

```
# use a linear energy spectrum ranging from 1 to 15 MeV
/Lena/gun/SetGeneralSpectrum ./Data/EnergySpectrum_Test.root

/Lena/run/setOutputFileName Data_Electron1-15MeV_spec_FidVol
/run/beamOn 10000
```

Figure 5 shows the resulting visible energy.

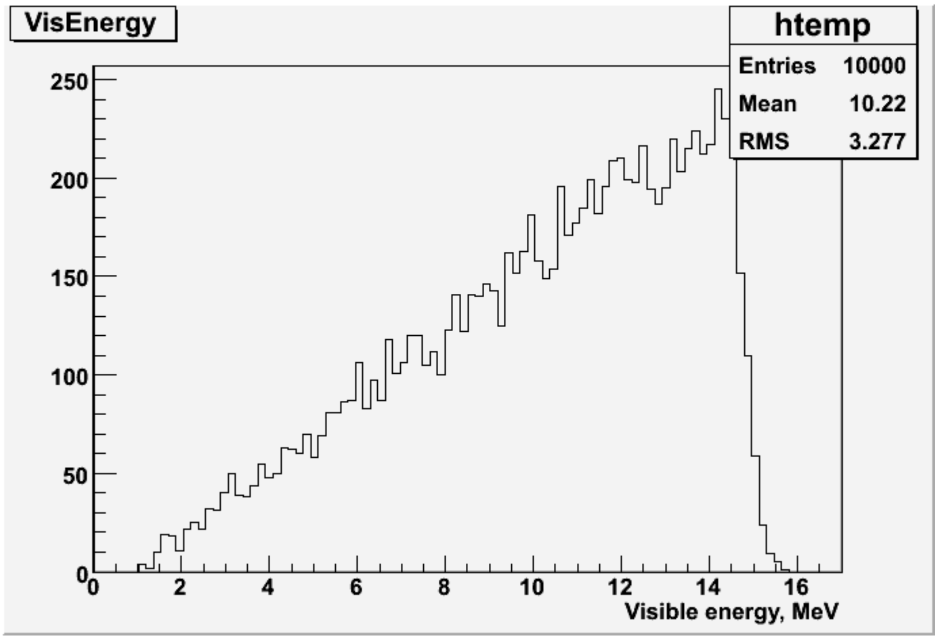

Figure 5: Visible energy of electron events with an energy between 1 MeV and 15 MeV (linear increasing spectrum), homogeneously distributed over the fiducial volume.

2.3 Alpha Background

Next, we will simulate the alpha background from ^{210}Po.

```
# simulate the alpha background from Po210
/gun/particle alpha
/Lena/gun/SetEnergyRangeLow 5300 keV
/Lena/gun/SetEnergyRangeHigh 5300 keV
/Lena/run/setOutputFileName Data_Alpha5300keV_FidVol
/run/beamOn 10000
```

Due to the quenching of the scintillation light, the 5.3 MeV alphas are reconstructed with a visible energy of only 358 keV. Thus, they are a background form the ^{7}Be neutrinos. By comparing the tail-to-total ratio (see Section 3.3) of the alpha events, with the expected distribution from electron recoil events, we can make a pulse shape discrimination. If we set the acceptance of electron events to 97% (ttrCut< 3, see Section 3.3 for details), we can identify about 97% of the alpha events as background.

2.4 Radioactive Decays

In order to simulate radioactive decays, we just need to specify the radioactive nucleus, and set the kinetic energy to 0.

```
# simulate the B12 decay
/gun/particle ion # set the particle type to ion
/gun/ion 5 12 # define the number of protons and nucleons
# activate event start time correction,
# in this mode the start time of the event
# is set to the time when the first scintillation photon was generated.
/Lena/det/start_time_correction true
/Lena/run/setOutputFileName Data_B12_Decay_FidVol
# set the kinetic energy to 0
/Lena/gun/SetEnergyRangeLow 0 keV
/Lena/gun/SetEnergyRangeHigh 0 keV
/run/beamOn 10000
```

Figure 6 shows the resulting visible energy.

3 Simulation Types

There are several simulation types (modi) included into the simulation, which define amongst other things the output format. The results are written to root files, which contain a root tree named 'TreeLENA'[4]. The simulation modus can be set with the command /Lena/run/sim_type, the following modi are valid:

[4] See http://root.cern.ch/drupal/content/documentation for details about the root trees.

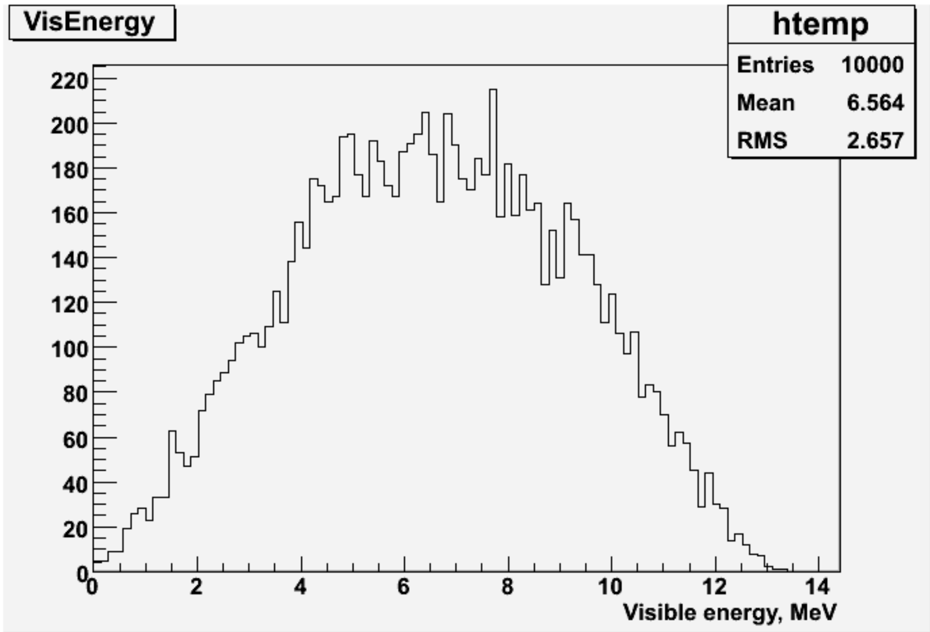

Figure 6: Visible energy of ^{12}B β^{-} decays, homogeneously distributed over the fiducial volume.

3.1 Fast Neutron Background

Simulate the fast neutron background from the surrounding rock (/Lena/run/sim_type 0). The gun type will be automatically set to 0. The output tree has the following branches:

- **EventID**: The number of the event.
- **PrimaryEnergy**: Initial energy of the neutron [GeV].
- **PrimaryMomDir**: Initial direction of the neutron.
- **PrimaryPos**: Initial position of the neutron [m].
- **EnergyDepFidVolume**: Energy that was deposited into the scintillator volume. **Important**: This is not the visible energy!
- **StoppingRadius**: Minimum radius of the neutron (including secondary neutrons).
- **StoppPosZ**: Z position of the neutron's end point (including secondary neutrons).

- **FiducialVolumeHit**: 0: no neutron reached the scintillator volume, 1: the primary neutron reached the scintillator volume, 2: a secondary neutron reached the scintillator volume
- **PMTHits**: Number of PMT hits in the inner detector (ID)
- **PMTHitsVeto**: Number of PMT hits in the outer detector (OD)
- **NumNCaptureIV**: Number of neutrons that were captured by a hydrogen or carbon nucleus in the scintillator
- **VisEnergy**: Visible energy
- **ttr**: Difference between the tail-to-total ratio of this event and the expected tail-to-total ratio for a $\bar{\nu}_e$ event (The tail-to-total ratio is calculated as the ratio between the tail interval (starting at 90 ns) and the whole pulse interval).
- **ttrCut**:
  - **0**: Event can not be identified as a background event by pulse shape discrimination (PSD), using the tail-to-total (ttr) method
  - **1**: Event can be identified as a background event by PSD (ttr) with about 50% $\bar{\nu}_e$ acceptance
  - **2**: Event can be identified as a background event by PSD (ttr) with about 83% $\bar{\nu}_e$ acceptance
  - **3**: Event can be identified as a background event by PSD (ttr) with about 97% $\bar{\nu}_e$ acceptance
  - **4**: Event can be identified as a background event by PSD (ttr) with about 99.6% $\bar{\nu}_e$ acceptance
  - **5**: Event can be identified as a background event by PSD (ttr) with about 99.9% $\bar{\nu}_e$ acceptance
- **gatti**: Difference between the gatti parameter of this event and the expected gatti parameter for a $\bar{\nu}_e$ event (the gatti parameter depends on the particle, thus it can be used for pulse shape discrimination).
- **gattiCut**:
  - **0**: Event can not be identified as a background event by pulse shape discrimination (PSD), using the gatti method

  - **1**: Event can be identified as a background event by PSD (gatti) with about 50% $\bar{\nu}_e$ acceptance
  - **2**: Event can be identified as a background event by PSD (gatti) with about 83% $\bar{\nu}_e$ acceptance
  - **3**: Event can be identified as a background event by PSD (gatti) with about 97% $\bar{\nu}_e$ acceptance
  - **4**: Event can be identified as a background event by PSD (gatti) with about 99.6% $\bar{\nu}_e$ acceptance
  - **5**: Event can be identified as a background event by PSD (gatti) with about 99.9% $\bar{\nu}_e$ acceptance

- **ttrSigma**: The σ of the gaussian tail-to-total ratio distribution for $\bar{\nu}_e$ events.

- **gattiSigma**: The σ of the gaussian gatti parameter distribution for $\bar{\nu}_e$ events.

For every neutron that reaches the scintillator volume, the pulse shape is recorded and written to a seperate root file, with the following branches:

- **EnergyDeposit**: Energy of the detected photon. If the value is smaller than 0, the hit was either dark noise (-1), a late pulse (-2) or an afterpulse (-3).

- **ChamberNb**: Number of the PMT that detected the photon (0 if /Lena/det/pmts is set to false).

- **Time**: The detection time.

- **Pos**: The exact position where the photon was detected.

- **EventID**: The number of the event.

- **TailTotalRatio**: Ratio between the tail interval (starting at 90 ns) and the whole pulse interval. You can use this value for pulse shape discrimination between different particle types.

- **Direction**: The photon direction.

- **PhotonPMTAngle**: The angle between the photon direction and the surface normal of the PMT.

- **PhotonScatter**: If true, the photon was scattered in the scintillator before it was detected.

3.2 Fast Neutron Production

Simulate the production of fast neutrons by cosmic muons in the surrounding rock (/Lena/run/sim_type 1). 300 GeV muons (corresponding to the mean muon energy at 4000 m w.e. depth) are tracked trough 15 m of rock. For every produced neutron, an entry to the root tree is writte. The root tree has the following branches:

- **EventID**: The number of the event.
- **Energy**: The initial energy of the produced neutron.
- **MomDir**: The initial direction of the produced neutron.
- **Pos**: The initial position of the produced neutron.
- **Time**: The production time of the neutron.
- **ParentParticle**: The particle that produced the neutron (in PDG code[5]).
- **ProcessType**: The sub type of the creator process.
  - -1: No sub type defined
  - 121: Inelastic process
  - 151: Absorption (e.g. π^- absorption)
  - 121: Decay (e.g. Λ decay)

Additionally, for every simulated muon event an entry to a second root tree is written. The root tree has the following branches:

- **EventID**: The number of the event
- **NumNeutron**: The number of produced neutrons
- **Energy**: The energy of the muon at the end of its track

[5]See pdg.lbl.gov/2011/reviews/rpp2011-rev-monte-carlo-numbering.pdf for a description of the PDG codes

3.3 General Simulation Type

This is the default simulation modus (/Lena/run/sim_type 2). For every event, the detected photons are written to a root tree. There are two options. In the first one, for every detected photon an entry is written to a root tree, that contains the following branches:

- **EventID**: The number of the event.
- **Time**: The detection time.
- **PhotonPMTAngle**: The angle between the photon direction and the surface normal of the PMT [rad].
- **PhotonScatter**: If true, the photon was scattered in the scintillator before it was detected.
- **EnergyDeposit**: Energy of the detected photon. If the value is smaller than 0, the hit was either dark noise (-1), a late pulse (-2) or an after-pulse (-3).
- **ChamberNb**: Number of the PMT that detected the photon (0 if /Lena/det/pmts is set to false).
- **Pos**: The exact position where the photon was detected.
- **TailTotalRatio**: Ratio between the tail interval (starting at 90 ns) and the whole pulse interval. You can use this value for pulse shape discrimination between different particle types.
- **Direction**: The photon direction.
- **VertexDirection**: The initial direction of the photon when it was generated.
- **VertexPosition**: The position where the photon was generated.
- **TotalTrkLength**: The total track length of the photon from its vertex to its detection point.
- **TotalTrkTime**: The difference between the detection time and the creation time of the photon.

In the second option, only one entry per event is written to the root tree, which contains the following branches:

- **EventID**: The number of the event.
- **PrimaryPos**: Initial position of the primary particle.
- **PMTHits**: Number of detected photons.
- **NHits**: Number of PMTs that detected one or more photons.
- **VisEnergy**: Reconstructed visible energy.
- **ttr**: Difference between the tail-to-total ratio of this event and the expected tail-to-total ratio for the signal event (The tail-to-total ratio is calculated as the ratio between the tail interval (starting at 90 ns) and the whole pulse interval).
- **ttrCut**:
  - **0**: Event can not be identified as a background event by pulse shape discrimination (PSD), using the tail-to-total (ttr) method
  - **1**: Event can be identified as a background event by PSD (ttr) with about 50% signal acceptance
  - **2**: Event can be identified as a background event by PSD (ttr) with about 83% signal acceptance
  - **3**: Event can be identified as a background event by PSD (ttr) with about 97% signal acceptance
  - **4**: Event can be identified as a background event by PSD (ttr) with about 99.6% signal acceptance
  - **5**: Event can be identified as a background event by PSD (ttr) with about 99.9% signal acceptance
- **gatti**: Difference between the gatti parameter of this event and the expected gatti parameter for the signal event (the gatti parameter depends on the particle, thus it can be used for pulse shape discrimination).
- **gattiCut**:
  - **0**: Event can not be identified as a background event by pulse shape discrimination (PSD), using the gatti method
  - **1**: Event can be identified as a background event by PSD (gatti) with about 50% signal acceptance

- **2**: Event can be identified as a background event by PSD (gatti) with about 83% signal acceptance
- **3**: Event can be identified as a background event by PSD (gatti) with about 97% signal acceptance
- **4**: Event can be identified as a background event by PSD (gatti) with about 99.6% signal acceptance
- **5**: Event can be identified as a background event by PSD (gatti) with about 99.9% signal acceptance

- **ttrSigma**: The σ of the gaussian tail-to-total ratio distribution for the signal events.
- **gattiSigma**: The σ of the gaussian gatti parameter distribution for the signal events.
- **PulseShape**: Root histogram of the photon detection time distribution.

3.3.1 High Energy Neutrino Events

If the interface to the GENIE neutrino generator (/Lena/gun/type 5) is used, additional information about each event are written to a second root tree (contained in a different file), with the following branches:

- **EventID**: The number of the event.
- **HitNucl**: The PDG code of the nucleon that interacted with the neutrino
- **NucleusExcitation**: 1: nucleus was in an excitated state after the neutrino interaction (e.g. a neutron was emitted from the $S_{1/2}$ shell). At the moment GENIE does not include the deexcitation of nucleii. Therefore, the deexcitation was simulated with TALYS[6] and included into the simulation.
- **ResNuclZ**: The number of protons in the residual nucleus (before deexcitation).
- **ResNuclA**: The number of nucleons in the residual nucleus (before deexcitation).

[6] See http://www.talys.eu/ for details

- **ResNuclDeexZ**: The number of protons in the residual nucleus, after the deexcitation was performed.
- **ResNuclDeexA**: The number of nucleons the residual nucleus, after the deexcitation was performed.
- **NeutrinoEnergy**: Energy of the incident neutrino [MeV].
- **LeptonEnergy**: Energy of the final state lepton [MeV].
- **PosVertex**: The position of the vertex [m].
- **NumN**: The number of neutrons that were emitted from the nucleus.
- **NumP**: The number of protons that were emitted from the nucleus.
- **NumChargedPions**: The number of $\pi^{+/-}$ that were produced.
- **NumPi0**: The number of π^0 that were produced.
- **NumMuonDecays**: The number of muon decays that were detected (it is assumed that every muon decay in the scintillator which occurs later than 200 ns after the neutrino interaction will be detected).
- **NeutronEnergy**: The accumulated kinetic energy of all emitted neutrons.
- **ProtonEnergy**: The accumulated kinetic energy of all emitted protons.
- **Interaction**: The type of the neutrino interaction. The following types are defined:
  - **1**: Quasi-elastic scattering (qel)
  - **2**: Resonance pion production (res)
  - **3**: Deep-inelastic scattering (dis)
  - **0**: other
- **PMTHits**: The number of PMT hits.
- **ttr**: Difference between the tail-to-total ratio of this event and the expected tail-to-total ratio for the signal event (The tail-to-total ratio is calculated as the ratio between the tail interval (starting at 90 ns) and the whole pulse interval).

- **ttrCut**:
  - **0**: Event can not be identified as a background event by pulse shape discrimination (PSD), using the tail-to-total (ttr) method
  - **1**: Event can be identified as a background event by PSD (ttr) with about 50% signal acceptance
  - **2**: Event can be identified as a background event by PSD (ttr) with about 83% signal acceptance
  - **3**: Event can be identified as a background event by PSD (ttr) with about 97% signal acceptance
  - **4**: Event can be identified as a background event by PSD (ttr) with about 99.6% signal acceptance
  - **5**: Event can be identified as a background event by PSD (ttr) with about 99.9% signal acceptance
- **gatti**: Difference between the gatti parameter of this event and the expected gatti parameter for the signal event (the gatti parameter depends on the particle, thus it can be used for pulse shape discrimination).
- **gattiCut**:
  - **0**: Event can not be identified as a background event by pulse shape discrimination (PSD), using the gatti method
  - **1**: Event can be identified as a background event by PSD (gatti) with about 50% signal acceptance
  - **2**: Event can be identified as a background event by PSD (gatti) with about 83% signal acceptance
  - **3**: Event can be identified as a background event by PSD (gatti) with about 97% signal acceptance
  - **4**: Event can be identified as a background event by PSD (gatti) with about 99.6% signal acceptance
  - **5**: Event can be identified as a background event by PSD (gatti) with about 99.9% signal acceptance
- **ttrSigma**: The σ of the gaussian tail-to-total ratio distribution for the signal events.

- **gattiSigma**: The σ of the gaussian gatti parameter distribution for the signal events.
- **NumNCaptureIV**: Number of neutrons that were captured by a hydrogen or carbon nucleus in the scintillator
- **VisEnergy**: Visible energy.
- **IBNeutrinoEnergy**:

  The neutrino energy (Visible energy + 0.8 MeV) assuming that the event is reconstructed as an inverse beta decay event (e.g. one neutron was emitted by a neutral current interaction, and captured in the scintillator).
- **PulseShape**: Root histogram of the photon detection time distribution.
- **iev**: The original event number in the GENIE root file. You can use this number to look up additional information about the neutrino interaction.

3.4 Gamma Background

Simulate the gamma background from the tank or the PMTs (/Lena/run/sim_type 4). To save computation time, the simulation is split into two parts. In the first part the gammas are started either at the tank or at the PMTs. You can simulate gammas from the U238, Th232 chain, as well as monoenergetic gammas (e.g. 1.4 MeV gammas from ^{40}K decays). The root tree has the following branches:

- **EventID**: The number of the event.
- **PrimaryEnergy**: Energy of the gamma at the start of the event.
- **PrimaryMomDir**: Momentum direction of the gamma at the start of the event.
- **PrimaryPos**: Position of the gamma at the start of the event.
- **IVMomDir**: Momentum direction of the gamma when it entered the scintillator volume.
- **IVPos**: The position where the gamma entered the scintillator volume.

- **EnergyAtBuffer**: The energy of the gamma when it entered the buffer volume.
- **EnergyAtFidVolume**: The energy of the gamma when it entered the scintillator volume.
- **EnergyDepFidVolume**: The energy that the gamma deposited into the scintillator volume (**Important**: This is not the visible energy!).
- **StoppingRadius**: The minium radius of the gamma [m].
- **FiducialVolumeHit**: 1: The gamma reached the scintillator volume.
- **StoppPosZ**: Z position of the gammas end point [m].

In the second part the gammas are started at the edge of the scintillator volume, using the results from the first part. The root tree has the following branches:

- **EventID**: The number of the event.
- **PrimaryEnergy**: Energy of the gamma at the start of the event.
- **PrimaryMomDir**: Momentum direction of the gamma at the start of the event.
- **PrimaryPos**: Position of the gamma at the start of the event.
- **EnergyDepRad12**: The energy that the gamma deposited into a fiducial volume with r < 12 m.
- **EnergyDepRad115**: The energy that the gamma deposited into a fiducial volume with r < 11.5 m.
- **EnergyDepRad11**: The energy that the gamma deposited into a fiducial volume with r < 11 m.
- **EnergyDepRad10**: The energy that the gamma deposited into a fiducial volume with r < 10 m.
- **EnergyDepRad9**: The energy that the gamma deposited into a fiducial volume with r < 9 m.
- **EnergyDepRad8**: The energy that the gamma deposited into a fiducial volume with r < 8 m.

- **EnergyDepFidVolume**: The energy that the gamma deposited into the scintillator volume (**Important**: This is not the visible energy!).
- **StoppingRadius**: The minium radius of the gamma [m].
- **StoppPosZ**: Z position of the gammas end point [m].

3.5 Energy Calibration

Due to the cylindrical shape and the large dimensions, the photo electron yield and the pulse shape depend on the event position. Thus, a calibration at different positions is necessary. In the energy calibration mode (/Lena/run/sim_type 5), the events are started at different positions that are homogenously distributed over the detector mode (you can set the distance between two points with the command /Lena/gun/CalibPrec). The root tree has the following branches:

- **EventID**: The number of the event.
- **PrimaryPos**: The position of the event.
- **PMTHits**: The number of detected photons (including dark noise, late pulses and after pulses).
- **NHits**: The number of PMTs that detected at least one photon (including dark count background).
- **PMTHitsAvg**: The number of photons per MeV (dark count corrected).
- **DarkCounts**: The number of dark counts.
- **ttr**: Difference between the tail-to-total ratio of this event and the expected tail-to-total ratio for the signal event (The tail-to-total ratio is calculated as the ratio between the tail interval (starting at 90 ns) and the whole pulse interval).
- **ttrCut**:
  - **0**: Event can not be identified as a background event by pulse shape discrimination (PSD), using the tail-to-total (ttr) method
  - **1**: Event can be identified as a background event by PSD (ttr) with about 50% signal acceptance

  - **2**: Event can be identified as a background event by PSD (ttr) with about 83% signal acceptance
  - **3**: Event can be identified as a background event by PSD (ttr) with about 97% signal acceptance
  - **4**: Event can be identified as a background event by PSD (ttr) with about 99.6% signal acceptance
  - **5**: Event can be identified as a background event by PSD (ttr) with about 99.9% signal acceptance

- **gatti**: Difference between the gatti parameter of this event and the expected gatti parameter for the signal event (the gatti parameter depends on the particle, thus it can be used for pulse shape discrimination).

- **gattiCut**:

  - **0**: Event can not be identified as a background event by pulse shape discrimination (PSD), using the gatti method
  - **1**: Event can be identified as a background event by PSD (gatti) with about 50% signal acceptance
  - **2**: Event can be identified as a background event by PSD (gatti) with about 83% signal acceptance
  - **3**: Event can be identified as a background event by PSD (gatti) with about 97% signal acceptance
  - **4**: Event can be identified as a background event by PSD (gatti) with about 99.6% signal acceptance
  - **5**: Event can be identified as a background event by PSD (gatti) with about 99.9% signal acceptance

- **ttrSigma**: The σ of the gaussian tail-to-total ratio distribution for the signal events.

- **gattiSigma**: The σ of the gaussian gatti parameter distribution for the signal events.

- **VisEnergy**: Reconstructed visible energy.

- **PulseShape**: Root histogram of the photon detection time distribution.

4 User Interface

In this Section a short overview of all valid commands will be presented. You can get a list of all valid commands with the geant4 command "help". Additionally, all general geant4 commands[7] are valid. If you run the simulation in the interface mode, the vis2.mac macro file is loaded at the start of the simulation to do necessary initialisations. To use the batch mode, you just start the simulation and pass the macro file as an argument, e.g. 'Lena test.mac'.

4.1 Physics List commands

At the beginning of the macro file (this is done automatically in the interface mode), you need to specify the physics list. The **G4EmStandardPhysics** and the **G4DecayPhysics** modules are included per default, every other modules needs to be included into your physics list by a command. So if you don't include any additionals models, no scintillation photons will be generated! In most cases the best option is to load all available modules (see Table 1 for a list of the recommand models)[8], but for some special simulations it might be necessary to exclude some modules, in order to gain CPU speed[9]. You can load a module with the command

/Lena/phys/reg ModuleName.

So the optical photons module is e.g. included with the command

/Lena/phys/reg LenaOP.

The Cherenkov process is not included in the LenaOP module. If you need this process you should use the LenaOPCherenkov module. To include Muon-Nuclear processes you must additinally use the command `/physics_engine/tailor/MuonNuclear on`. After you include all necessary modules you should intialize the run with the command **/run/initialize**.

[7]see http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/ForApplicationDeveloper /html/index.html for details

[8]This will built the QGSP-BERT-HP physic list with additional optical photon physics. See http://geant4.web.cern.ch for a detailed description of this physic list

[9]e.g. If you are not interested in the generated optical photons, turning the LenaOP module off will save lots of CPU time

G4EmExtra	Gamma and Muon nuclear processes
G4HadronElastic	Elastic hadron processes (without neutrons)
`HadronPhysicsQGSP_BERT_HP`	Inleastic hadron processes (including elastic processes for neutrons)
G4QStopping	Capture processes
G4Ion	Physics processes for ions
G4Radioactive	Radioactive decays
LenaOP	optical photon physics (generation of scint. photons, scattering..)

Table 1: Recommanded physic list modules

4.2 Run Commands

- **/Lena/run/sim_type**: Set the Simulation type. The following types are valid:
  - **0**: Simulate the fast neutron background (see Section 3.1 for details).

    The following simulation sub types are valid:
    - **-1**: Don't save individual photon hits.
    - **0**: Save all information about the event, including individual photon hits.
  - **1**: Simulate the production of fast neutron by cosmic muons (see Section 3.2 for details).
  - **2**: General simulation type (see Section 3.3 for details).

    The following simulation sub types are valid:
    - **-2**: Don't save every photon hit, but only the reconstructed energy and the pulse shape as a root histogram (see Section 3.3 for details).
    - **-1**: Don't save the pulse shape.
    - **0**: Save the complete information about every photon hit.
    - **1**: Save only the variables **EventID**, **Time**, **PhotonPMTAngle**, **PhotonScatter** (see Section 3.3 for a description of these variables)
    - **2**: Only save the pulse shape if the event could be a background for the DSNB (valid only for /Lena/gun/type 5)

    * **3**: Only save the detection time of the photon and the number of the PMT that detected it.
  - **4**: Simulate the external gamma background (see Section 3.4 for details).

    The following simulation sub types are valid:

    * **0**: Start the gammas either at the tank or at the PMTs.
    * **1**: Start the gammas at the edge of the scintillator volume.
  - **5**: Make a energy calibration of the LENA detector (see Section 3.5 for details).

    The following simulation sub types are valid:

    * **0**: Standard
    * **1**: Simulate events at positions between the calibration points, to test the precision of the energy reconstruction and the acceptance of the pulse shape analysis for the signal events.

- **/Lena/run/sim_subtype**: Set the simulation sub type
- **/Lena/run/neutron_threshold**: Set the neutron energy threshold. Neutron tracks below this threshold will be killed if they are in the surrounding rock (valid for simulation type 0).
- **/Lena/run/gamma_threshold**: Set the gamma energy threshold. Gamma tracks below this threshold will be killed if the radius of their position is greater than 14.5 m (valid for simulation type 4).
- **/Lena/run/apply_neutron_threshold**: If set to true, neutrons tracks in the surrounding rock will be killed if they are below the energy threshold (use the command /Lena/run/neutron_threshold to set the energy threshold, only valid for simulation type 0).
- **/Lena/run/apply_gamma_threshold**: If set to true, gamma tracks in the surrounding rock will be killed if they are below the energy threshold (use the command /Lena/run/gamma_threshold to set the energy threshold, only valid for simulation type 4).
- **/Lena/run/radius_cut**: Set the radius cut (in m) (valid for sim type 4, default value 13.9 m). If the gamma was stopped at a greater radius than the cut value, the event won't be saved.
- **/Lena/run/energy_dep_cut**: Valid for sim type 4, sub type 1. If set to true, the event will only be saved if the gamma deposited energy at $r < 11.5$ m.

Energy_1 [MeV]	Path to the calibration data (root file)
Energy_2 [MeV]	Path to the calibration data (root file)
Energy_3 [MeV]	Path to the calibration data (root file)

Table 2: File format for the definition of the calibration file.

- **/Lena/run/save_rnd**: If set to true, the status of the rnd engine will be saved at the beginning of an event,
- **/Lena/run/rnd_store_prec**: Set how often the status of rnd engine will be saved. E.g. if you set it to 100, the status will only be saved at the beginning of every 100th event. You can use this option to save computation time.
- **/Lena/run/setCalibFile**: Set the calibration file, that is used to calculate the visible energy. See Table 2 for a description of the file format.

  The calibration data is a root file with the following branches:

  - **PrimaryPos**: The position of the calibration point.
  - **PMTHits**: The average number of photon hits (excluding dark noise) at this position.
  - **DarkCounts**: The average number of dark counts.
  - **AvgTTR**: The average tail-to-total ratio.
  - **TTRCut80**: The one σ tail-to-total ratio (ttr) threshold. If the ttr of an event is above this threshold, it can be excluded as background (about 83% of all signal events should be below this threshold).
  - **AvgGatti**: The average gatti parameter.
  - **GattiCut80**: The one σ gatti parameter threshold. If the gatti parameter of an event is above this threshold, it can be excluded as background (about 83% of all signal events should be below this threshold).
  - **PulseShape**: A root histogram of the average pulse shape of the signal event, which is used for the calculation of the gatti parameter.
  - **PulseShapeBg**: A root histogram of the Average pulse shape of the background event, which is used for the calculation of the gatti parameter.

- **/Lena/run/setOutputPath**: Set the path where the output files will be stored. All folders have to exist!
- **/Lena/run/saveMcData**: If set to true, information about the created particles (except optical photons and electrons below 0.5 MeV) will be saved to an additional tree in the result file. Primary particles are always written. The tree has the following branches:
  - **MCPdgId**: Vector that contains the pdg codes of the created particles.
  - **MCEKin**: Vector that contains the kinetic energies of the particles.
  - **MCTimeOfCreation**: Vector that contains the creation time of the particles.
  - **MCTrackId**: Vector that contains the track id's of the particles.
  - **MCParentId**: Vector that contains the track id's of the parent particles, or 0 if the particle is a primary particle.
  - **MCVertexPosition**: Vector that conatins the initial positions of the particles.
  - **MCVertexDirection**: Vector that contains the initial momentum direction of the particles.
  - **MCCreatorProcess**: Vector that contains the names of the creation processes ("None" means that the particle is a primary particle).

4.3 Detector Commands

In Figure 7 you can see the simulated detector geometry. There are two photon detection modes. You can either simulate every individual PMT (more precise but costs a lot of CPU time), or use the whole tank wall as a photon detector. There are also two options to include Winston Cones[10]. You can either just specify a critical angle for the photon detection. If the photon is detected at a greater angle to the surface normal than this critical angle, the hit will be deleted. The other option is to add a geometrical model of a Winston Cone to every PMT (more precise but time consuming).
Below you will find a list of all valid detector commands. After you changed detector properties you should always use the command **/Lena/det/update**, which rebuilds the detector, to ensure that your changes are included.

[10] See http://scienceworld.wolfram.com/physics/WinstonCone.html for a description of a Winston Cone

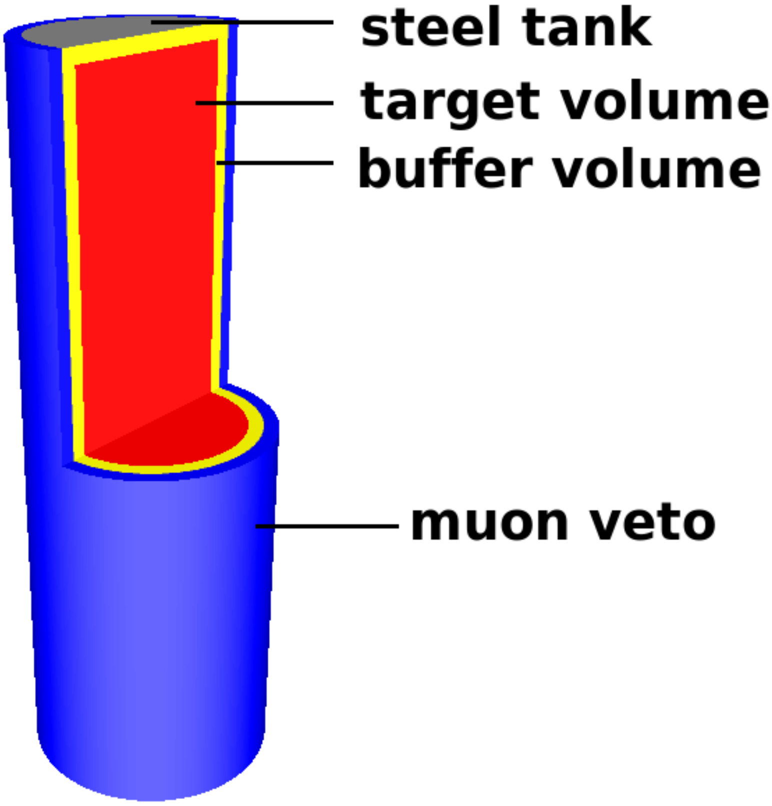

Figure 7: Simulated detector geometry.

$z - value_1$	$radius_1$
$z - value_2$	$radius_2$
$z - value_3$	$radius_3$

Table 3: File format for the definition of the Winston Cone shape.

- **/Lena/det/sensitive_det**: Activate (true) or deactivate (false) the photon detection.
- **/Lena/det/pmts**: If set to true, individual PMTs are simulated. Otherwise the whole tank wall is used for the photon detection.
- **/Lena/det/tof**: If set to true, the detection time of the photons is time of flight corrected (with 1 ns uncertainty, to account for the uncertainty of the position reconstruction). This option is turned on per default.
- **/Lena/det/pmt_sphere**: If set to true, the pmt cathode is simulated as a half sphere. Otherwise it is simulated as a flat disk.
- **/Lena/det/pmt_ncut**: If set to true, the pmt signal is only saved if exactly one neutron is captured. This mode can be used to save disk space if background for the inverse beta decay channel is simulated.
- **/Lena/det/winston_cones**: If set to true, a photon is only detected if the angle to the surface normal of the PMT is less than a certain critical angle (use /Lena/det/wc_crit_angle to set this critical angle).
- **/Lena/det/winston_cones_geo**: If set to true, a geometrical model of the Winston Cone is included into the detector simulation (increases computation time by about 40%). The shape of the winston cone can be set with the command /Lena/det/winston_cones_file.
- **/Lena/det/winston_cones_file**: Set the file that defines the shape of the Winston Cones (sets /Lena/det/winston_cones_geo automatically to true). See Table 3 for a decription of the file format.
- **/Lena/det/wc_crit_angle**: Set the critical angle of the Winston Cones. Photons that hit the PMT with a larger angle to the surface norm than the critical angle are not detected.
- **/Lena/det/start_time_correction**: If set to true, the start time of the event is set to the time when the first scintillation photon was produced. Use this mode e.g. when you simulate radioactive decays.

- **/Lena/det/dark_noise**: If set to true, dark noise PMT hits are generated. The dark noise rate can be defined via the command /Lena/det/dark_noise_rate.
- **/Lena/det/dark_noise_rate**: Set the dark noise rate in the whole detector per μs. If you use this command, the dark noise generation will also be activated.
- **/Lena/det/dark_noise_suppression**: If set to true, hits at a greater distance than 30 m to the event position are discarded, in order to suppress dark noise hits.
- **/Lena/det/late_pulses**: If set to true, pmt late pulses are generated. Time delay and probability of the late pulses can be set via the commands: /Lena/det/late_pulse_prob and /Lena/det/late_pulse_time_delay.
- **/Lena/det/late_pulse_prob**: Set the probability that a late pulse occurs.
- **/Lena/det/late_pulse_time_delay**: Set average the time delay of a PMT late pulse (the uncertainty of the time delay is fixed to 5 ns at the moment).
- **/Lena/det/after_pulses**: If set to true, PMT after pulses are generated. Time delay and probability of the after pulses can be set via the commands: /Lena/det/after_pulse_prob and /Lena/det/after_pulse_time_delay.
- **/Lena/det/after_pulse_prob**: Set the probability that an after pulse occurs.
- **/Lena/det/winston_cones_fov**: Set the radius of the winston cones field of view (in m). From the field of view the critical angle for the photon detection is calculated by the formula $\Theta_{crit} = \sin^{-1}\left(\frac{R_{fov}}{R_{pmt}}\right)$.
- **/Lena/det/light_yield**: Set the light yield (scintillation photons per MeV) for the target volume.
- **/Lena/det/light_yield_buffer**: Set the light yield (scintillation photons per MeV) for the buffer volume.
- **/Lena/det/pmt_hist_range_low**: Set the lower bound of the range for the pulse shape histogram (in ns). This defines also the start point for the generation of dark noise hits (if dark noise hits are activated).

λ_1	Intensity_1
λ_2	Intensity_2
λ_3	Intensity_3

Table 4: File format for the definition of the scintillation spectrum.

- **/Lena/det/pmt_hist_range_up**: Set the upper bound of the range for the pulse shape histogram (in ns). This defines also the end point for the generation of dark noise hits (if dark noise hits are activated).
- **/Lena/det/pmt_hist_num_bins**: Set the number of bins for the pulse shape histogram.
- **/Lena/det/pmt_res**: Set the time resolution of the PMT (σ).
- **/Lena/det/after_pulse_time_delay**: Set average the time delay of a pmt after pulse (the uncertainty of the time delay is fixed to 5 ns at the moment).
- **/Lena/det/scint**: Define the scintillator material ('PXE' or 'LAB' are valid).
- **/Lena/det/tank_material**: Set the tank material to either 'steel' or 'concrete'.
- **/Lena/det/pmt_threshold**: Set the PMT hits threshold. If more hits than the specified threshold are detected, the event will be aborted.
- **/Lena/det/update**: Update Detector geometry. This command MUST be applied before starting a new run if you have changed the detector geometry.

4.4 Material Commands

- **/Lena/det/mat/setsc**: If set to false, no scintillation photons are generated.
- **/Lena/det/mat/spectrum**: Set the file that defines the scintillation spectrum. See Table 4 for a description of the file format. The spectrum will be linearly interpolated between the specified wavelengths.
- **/Lena/det/mat/abs_length**: Set the absorption length. Use this command if you want to have a wavelength independent absorption length.

- **/Lena/det/mat/abs_length_wv**: Set the file that defines the wavelength dependent absorption length. For every specified wavelength in the spectrum file (which can be set via the command '/Lena/det /mat/spectrum'), an absorption length should be specified in this file (format one field per line, value in m). The absorption length will be linearly interpolated between the specified wavelengths.
- **/Lena/det/mat/rayscatter_length**: Set the rayleigh scattering length. Use this command if you want to have a wavelength independent rayleigh scattering length.
- **/Lena/det/mat/rayscatter_length_wv**: Set the file that defines the wavelength dependent rayleigh scattering length. For every specified wavelength in the spectrum file (which can be set via the command '/Lena/det/mat/spectrum'), a rayleigh scattering length should be specified in this file (format one field per line, value in m). The rayleigh scattering length will be linearly interpolated between the specified wavelengths.
- **/Lena/det/mat/isoscatter_length**: Set the absorption-reemission length. Use this command if you want to have a wavelength independent absorption-reemission scattering length.
- **/Lena/det/mat/isoscatter_length_wv**: Set the file that defines the wavelength dependent absorption-reemission length. For every specified wavelength in the spectrum file (which can be set via the command '/Lena/det/mat/spectrum'), an absorption-reemission length should be specified in this file (format one field per line, value in m). The absorption-reemission length will be linearly interpolated between the specified wavelengths.
- **/Lena/det/mat/refractive_index**: Set the refractive index. Use this command if you want to have a wavelength independent refractive index.
- **/Lena/det/mat/refractive_index_wv**: Set the file that defines the wavelength dependent refractive index. For every specified wavelength in the spectrum file (which can be set via the command '/Lena/det /mat/spectrum'), a refractive index should be specified in this file (format one field per line). The refractive index will be linearly interpolated between the specified wavelengths.
- **/Lena/det/mat/set_reflectivity**: Set the reflectivity of the Winston Cones.

- **/Lena/det/mat/set_mat_def**: Set the material properties back to the default values of the specified scintillator (PXE or LAB).
- **/Lena/det/mat/quantum_efficiency**: Set the quantum efficiency of the PMTs. Use this command if you want to have a wavelength independent quantum efficiency.
- **/Lena/det/mat/quantum_efficiency_wv**: Set the file that defines the wavelength dependent quantum efficiency of the PMTs. For every specified wavelength in the spectrum file (which can be set via the command '/Lena/det/mat/spectrum'), a quantum efficiency should be specified in this file (format one field per line). The quantum efficiency will be linearly interpolated between the specified wavelengths.
- **/Lena/det/mat/set_ps**: Set the file that defines the pulse shape parameters in the format KEY = VALUE. The following keys are valid:
  - **NUMCOMPENTS**: Number of decay components
  - **TIMECONSTANTN**: Decay time constant N (default value) [ns]
  - **TIMECONSTANTPARTICLEN**: Decay time constant N (value for the specified particle) [ns]
  - **YIELDRATION**: Relative intensity of the Nth component (default value)
  - **YIELDRATIOPARTICLEN**: Relative intensity of the Nth component (value for the specified particle)
  - **KB**: Birks constant (default value) $\left[\frac{mm}{MeV}\right]$
  - **KBPARTICLE**: Birks constant (value for the specified particle) $\left[\frac{mm}{MeV}\right]$

  For example, to set the default pulse shape parameters for LAB, the following file is used:

```
#Number of decay time constant
NUMCOMPONENTS = 3
#Decay time constant 1 in ns (default value)
TIMECONSTANT1 = 4.6
#Decay time constant 2 in ns (default value)
TIMECONSTANT2 = 18
```

```
#Decay time constant 3 in ns (default value)
TIMECONSTANT3 = 156
#Decay time constant 1 in ns for alpha particles
TIMECONSTANTALPHA1 = 3.2
#Decay time constant 2 in ns for alpha particles
TIMECONSTANTALPHA2 = 18
#Decay time constant 3 in ns for alpha particles
TIMECONSTANTALPHA3 = 190
#Fraction of photons emitted by the first component (default)
YIELDRATIO1 = 0.71
#Fraction of photons emitted by the second component (default)
YIELDRATIO2 = 0.22
#Fraction of photons emitted by the first component (alpha)
YIELDRATIOALPHA1 = 0.44
#Fraction of photons emitted by the second component (alpha)
YIELDRATIOALPHA2 = 0.16
#Fraction of photons emitted by the first component (proton)
YIELDRATIOPROTON1 = 0.68
#Fraction of photons emitted by the second component (proton)
YIELDRATIOPROTON2 = 0.21
```

- **/Lena/det/mat/kb**: Set the birks constant (default value).
- **/Lena/det/mat/kb_proton**: Set the birks constant for protons.
- **/Lena/det/mat/kb_alpha**: Set the birks constant for alphas.

4.5 Detector Geometry Commands

- **/Lena/det/geo/setRadiusTarget**: Set the radius of the target volume.
- **/Lena/det/geo/setHeightTarget**: Set the height of the target volume.
- **/Lena/det/geo/setRadiusBuffer**: Set the radius of the buffer volume.
- **/Lena/det/geo/setHeightBuffer**: Set the height of the buffer volume.

- **/Lena/det/geo/setRadiusTank**: Set the radius of the tank.
- **/Lena/det/geo/setHeightTank**: Set the height of the tank.
- **/Lena/det/geo/setRadiusVeto**: Set the radius of the muon veto.
- **/Lena/det/geo/setHeightVeto**: Set the height of the muon veto.
- **/Lena/det/geo/setRadiusPMT**: Set the radius of the PMT.
- **/Lena/det/geo/setRadiusPMTCurvature**: Set the radius of the PMT curvature (only valid when /Lena/det/pmt_sphere is set to true). This value has to be greater than the PMT radius.
- **/Lena/det/geo/setRadiusPMTEncapsulation**: Set the radius of the PMT encapsulation (the PMT encapsulation is a cylindrical volume). This value has to be greater than the PMT radius.
- **/Lena/det/geo/setHeightPMTEncapsulation**: Set the radius of the PMT encapsulation (the PMT encapsulation is a cylindrical volume).
- **/Lena/det/geo/setDistanceTankPMT**: Set the distance between the tank and the PMTs.
- **/Lena/det/geo/setNumPMTRings**: Set the number of PMT rings in the cylinder (excluding the end caps).
- **/Lena/det/geo/setNumPMTPerRing**: Set the number of PMTs per ring in the cylinder.
- **/Lena/det/geo/setAngleZero**: Set the starting angle (in rad.) for the first PMT position in the cylinder.
- **/Lena/det/geo/setNumPMTRingsCap**: Set the number of PMT rings in the cap of the cylinder.
- **/Lena/det/geo/setPMTRingCapConst**: Set the number of PMT in the first ring of the end cap.
- **/Lena/det/geo/setAngleZeroCap**: Set the starting angle (in rad.) for the first PMT position in the end cap.
- **/Lena/det/geo/setParameters**: Set the file that defines the detector geometry parameters in the format KEY = VALUE (including unit if necessary, e.g. RadiusTargetVolume = 13 m). The following keys are valid:

- RadiusTargetVolume
- HeightTargetVolume
- RadiusBufferVolume
- HeightBufferVolume
- RadiusTank
- HeightTank
- RadiusVeto
- HeightVeto
- RadiusPMT
- RadiusPMTCurvature
- RadiusPMTEncapsulation
- HeightPMTEncapsulation
- DistTankPMT
- NumPMTRings
- NumPMTPerRing
- NumPMTRingsCap
- PMTRingCapConst
- AngleZero
- AngleZeroCap

4.6 Generator Commands

- **/Lena/gun/type**: Define how the Primary Particle will be initialized. The following types are valid:
  - **0**: Generate Primary Particle with a fixed position, energy and momentum.
  - **1**: Generate fast neutrons in the surrounding rock according to a simulated spectrum of the muon induced neutrons (the neutron spectrum can be set with the command /Lena/gun/neutron_spectrum).
  - **2**: Generate gammas with E = 4.44 MeV for the first half of the run, neutrons with E = 10 MeV for the other part.
  - **3**: Generate gammas at a random position in the tank (subtype 0) or at the PMTs (subtype 1), with random momentum direction.

- **4**: Generate gammas at the IV according to a simulated gamma spectrum (the gamma spectrum can be set with the command /Lena/gun/gamma_spectrum).
- **5**: Simulate high energy neutrino events. Use the command /Lena/gun/neutrino_data, to define the GENIE gst file that is used as input.
- **6**: Generate photons at the aperture of a Winston Cone with a uniform incident angle distribution. Use this type to simulate the transmission curve of the Winston Cone (type is only valid if /Lena/det/winston_cones_geo is set to true).
- **7**: Use this type to calibrate the detector. The primary particle will be started at different positions in the detector (use the command /Lena/gun/CalibPrec to define the distance between the calibration points).
- **8**: Generate the primary particle at a random position in the fiducial volume, with a flat energy distribution. The commands /Lena/gun/SetFiducialVolRadius, /Lena/gun/SetEnergyRangeLow and /Lena/gun/SetEnergyRangeHigh can be used to define the fiducial volume and the energy range.
- **9**: Generate two primary particles with fixed position, energy, momentum. Use the commands /Lena/gun/DirectionOfSecondTrack, /Lena/gun/ParticleOfSecondTrack and /Lena/gun/EnergyOfSecondTrack to set the direction, particle type and kinetic energy of the second particle.

- **/Lena/gun/subtype**: Define the particle gun subtype (valid for type 3). Valid are the subtypes 0 (generate gammas at a random position in the tank), 1 (generate gammas in a random PMT).
- **/Lena/gun/UseGeneralSpectrum**: If set to true, an energy spectrum, defined by a root histogram, is used for gun type 0 and 8. Use the command /Lena/gun/SetGeneralSpectrum to set the energy spectrum.
- **/Lena/gun/SetGeneralSpectrum**: Set the general energy spectrum for gun type 0 and 8. The file must be a root file that contains a TH1F histogram named "spectrum".
- **/Lena/gun/CalibNumEv**: Set the number of events that are simulated at each calibration position (valid for gun type 5).

- **/Lena/gun/CalibPrec**: Set the distance [m] between the calibration points (valid for gun type 5).
- **/Lena/gun/part_num**: Define the number of primary particles that are generated in one event.
- **/Lena/gun/decay_chain**: Define the decay chain for the simulation of the gamma background. Valid candidates are **no** (use a single gamma line), **Th232** and **U238**.
- **/Lena/gun/gamma_spectrum**: Set the file that describes the gamma spectrum for gun type 4. The file must contain a root tree (named 'TreeLENA'), with three branches: EnergyAtFidVolume, IVMomDir and IVPos.
- **/Lena/gun/neutron_spectrum** Set the file that describes the neutron spectrumn for gun type 1. The file must contain a root tree (named 'TreeLENA'), with two branches: **Energy** and **MomDir**.
- **/Lena/gun/neutrino_data**: Set the file that is used as input for the simulation of high energy neutrino events. The file needs to be in the GENIE gst format. See http://projects.hepforge.org/genie/manuals/GENIE_PhysicsAndUserManual_20100213.pdf, sec. 6.6.2.1, p. 88 for details.
- **/Lena/gun/neutrino_filter**: Set the filter for the high energy neutrino events (valid for gun type 5). The filter has to be a valid selection for a root tree in the genie gst format. See http://projects.hepforge.org/genie/manuals/GENIE_PhysicsAndUserManual_20100213.pdf, sec. 6.6.2.1, p. 88 for details.
- **/Lena/gun/UseNeutrinoPosVertex**: If set to true, the real position of the high energy neutrino event is used (valid for gun type 5). Otherwise a fixed position for interaction vertex, set by the command gun/position, is used.
- **/Lena/gun/ExProb**: Set the probability that the nucleus is left in an excited state after the neutrino interaction (valid for gun type 5).
- **/Lena/gun/SetEnergyRangeLow**: Set the lower bound of the energy range for gun type 8.
- **/Lena/gun/SetEnergyRangeHigh**: Set the upper bound of the energy range for gun type 8.

- **/Lena/gun/SetFiducialVolRadius**: Set the radius of the fiducial volume (valid for gun type 8).
- **/Lena/gun/DirectionOfSecondTrack**: Set the direction of the second track (valid for gun type 9).
- **/Lena/gun/ParticleOfSecondTrack**: Set the particle type of the second track (valid for gun type 9).
- **/Lena/gun/EnergyOfSecondTrack**: Set the energy of the second track (valid for gun type 9).

5 Examples

The macros for the examples and the results are in the folder "./doc/userdoc /Examples".

5.1 Fast Neutron Background

In this example the fast neutron background from the surrounding rock is simulated. The neutrons are produced in a 2 m thick cylinder around the muon veto. The energy spectrum and the distribution of the momentum direction is loaded from a root file. In this simulation we will use the default file, but you can also use your own spectrum (the generation of the fast neutron spectrum is described in Section 5.2). Neutrons that are not directed towards the detector (2π solid angle) are not simulated, as they have only a minimal chance of reaching the target volume. Thus, you have to consider this, when you calculate the neutron background rate.

```
#load the physics list, radioactive decays are not simulated
/Lena/phys/reg G4EmExtra
/Lena/phys/reg G4HadronElastic
/Lena/phys/reg HadronQGSP_BERT_HP
/Lena/phys/reg G4QStopping
/Lena/phys/reg G4Ion
/Lena/phys/reg LenaOP
/physics_engine/tailor/MuonNuclear on
/run/initialize # initialize the physics list and the detector
/control/verbose 2
/run/verbose 2
```

```
/Lena/det/pmts false # don't simulate individual PMTs
# activate the winston cones, acceptance angle is set to about 50°,
# corresponding to an area increase by a factor of 1.75
/Lena/det/winston_cones true
/Lena/det/light_yield 792
/Lena/det/update # update the detector geometry
# abort events with more than 20.000 photon hits
# as we are only interested in background events
# for the dsnb and geoneutrinos detection
/Lena/det/pmt_threshold 20000
# define the neutron spectrum
/Lena/gun/neutron_spectrum ./Data/NeutronSpectrumHighEnergy494.root
/Lena/run/sim_type 0 # simulate the fast neutron background
/Lena/run/sim_subtype -1 # don't save indvidual photon hits
# set the calibration file that is used for the calculation # of the visible
energy
/Lena/run/setCalibFile ./Data/Data493/EnergyCalibWinstonConesDN50AP5LP5.dat
/Lena/run/setOutputFileName Data_NeutronBackground
/run/beamOn 100000
```

The resulting range of the neutrons is shown in Figure 8. A neutron is only a background for the $\bar{\nu}_e$ detection, when it is captured inside the target volume. Thus, you should check the branch **NumNCapturedIV**, to see how many neutrons were captured.
If more than one neutron is captured, which can happen when the primary neutron produced secondary neutrons, you can also discard this event. A further reduction of the background rate is possibly by a pulse shape discrimination. For this, you can use the branches **ttrCut** and **gattiCut** (see Section 3.1 for details).

5.2 Fast Neutron Production

In this example the fast neutron production from cosmic muons passing through the surrounding rock is simulated. 300 GeV muons, corresponding to the average muon energy at Pyhäsalmi, are tracked through 15 m of rock. For every produced neutron, its energy, momentum direction and production process is saved. Additionally, the number of produced neutrons per event is saved.

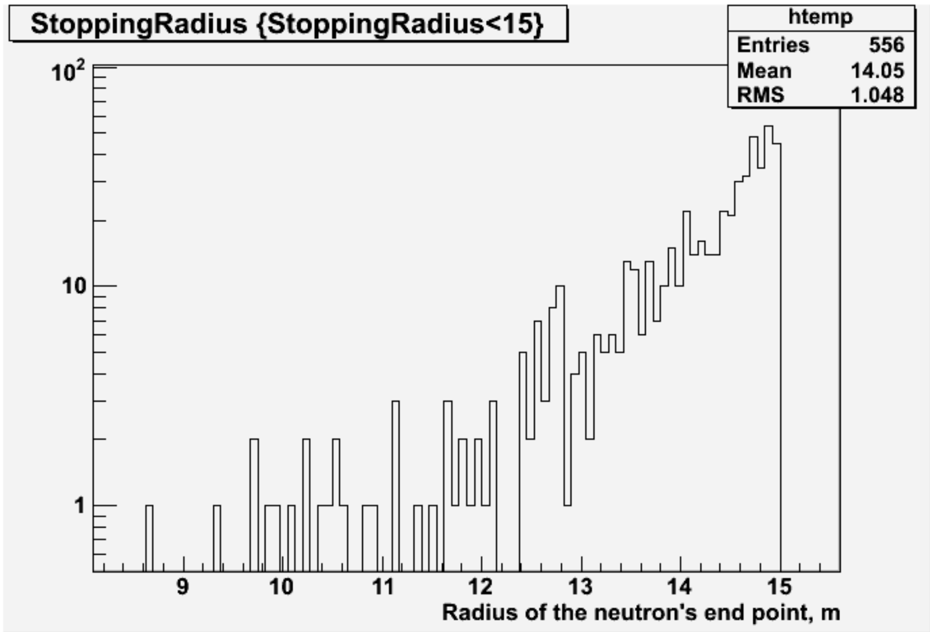

Figure 8: The range of the fast neutrons from the surrounding rock.

```
# load the physics list
/Lena/phys/reg G4EmExtra
/Lena/phys/reg G4HadronElastic
/Lena/phys/reg HadronQGSP_BERT_HP
/Lena/phys/reg G4QStopping
/Lena/phys/reg G4Ion
/Lena/phys/reg G4Radioactive
/physics_engine/tailor/MuonNuclear on
/run/initialize # initialize the physics list and the detector
/control/verbose 2
/run/verbose 2
/Lena/det/pmts false # don't simulate individual PMTs
/Lena/det/update # update the detector geometry
# simulate the production of fast neutrons by cosmic muons # in the
surrounding rock
/Lena/run/sim_type 1
/Lena/run/setOutputFileName Data_FastNeutronProduction
/run/beamOn 10000
```

Figure 9 shows the neutron production along the muon path. You can see that less neutrons are produced at the beginning the track. The reason for this effect is that the neutrons are produced in electromagnetic and hadronic showers. As these showers need some space to develop, you should discard the first 2 m of the muon track.

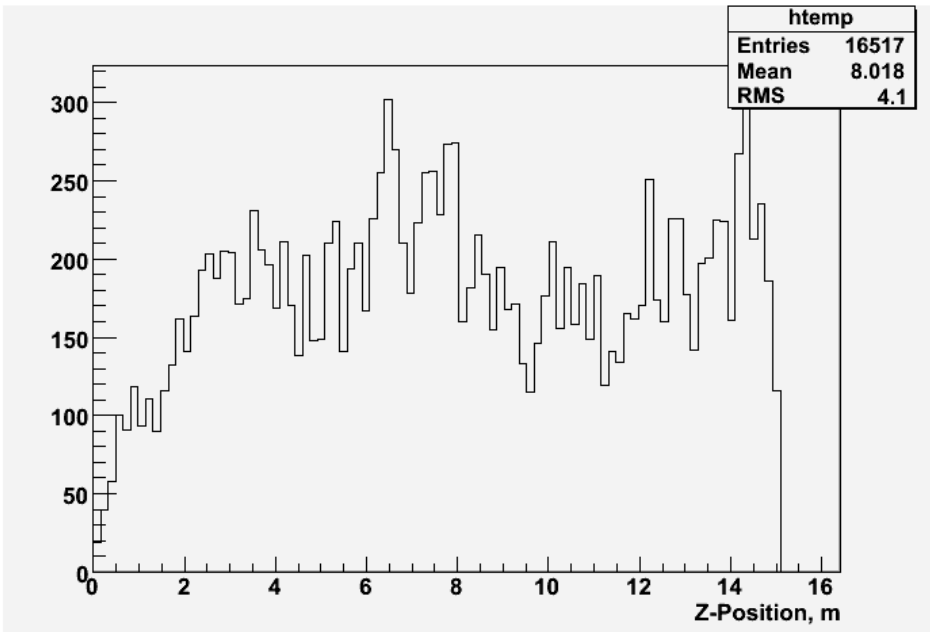

Figure 9: Neutron production along the muon path.

5.3 High Energy Neutrino Events

Neutrino events from a beam, or atmospheric neutrinos, are simulated in two steps. In the first step, the neutrino interaction is simulated with the GENIE[11] neutrino generator. Every produced stable particle ($\tau > 10^{-12}s$) is written to a root file. In the LENA simulation these root file are used to simulate the event. There are files for the simulation of neutrino events from a superbeam from Cern to Pyhäsalmi ("./Data/spl_cn2py_lena_nu_mu.root", "./Data/spl_cn2py_lena_anti_nu_mu.root", "./Data/spl_cn2py_lena_nue.root", "./Data/spl_cn2py_lena_anti_nue.root") and for the simulation of atmospheric neutrinos ("./Data/Lena_atmole_kam050810.root"). First of all, we will simulate quasi-elastic charged current events, from a superbeam. We can specify

[11]see http://www.genie-mc.org/ for details

the type of events that we want with the command /Lena/gun/neutrino_filter, using a selection for the root tree in the genie gst format[12].

```
# load the physics list, radioactive decays are not simulated
/Lena/phys/reg G4EmExtra
/Lena/phys/reg G4HadronElastic
/Lena/phys/reg HadronQGSP_BERT_HP
/Lena/phys/reg G4QStopping
/Lena/phys/reg G4Ion
/Lena/phys/reg LenaOP
/physics_engine/tailor/MuonNuclear on
/run/initialize # initialize the physics list and the detector
/control/verbose 2
/run/verbose 2
/Lena/det/pmts false # don't simulate individual PMTs
# activate the winston cones, acceptance angle is set to about 50°,
# corresponding to an area increase by a factor of 1.75
/Lena/det/winston_cones true
/Lena/det/light_yield 792
/Lena/det/update # update the detector geometry
/Lena/run/sim_type 2 # general simulation
/Lena/run/sim_subtype -2 # don't save individual photon hits
/Lena/det/dark_noise true # generate dark counts
/Lena/det/dark_noise_rate 50 # set the dark count rate to 50 per μs
/Lena/det/after_pulse_prob 0.05 # set the fast afterpulse rate to 5%
/Lena/det/late_pulse_prob 0.05 # set the late pulse rate to 5%
# set the range of the pulse shape histogram,
# only photon hits within this range
# are used for the calculation of the visible energy
/Lena/det/pmt_hist_range_low 0
/Lena/det/pmt_hist_range_up 600
# set the number of bins of the pulse shape histogram
/Lena/det/pmt_hist_num_bins 600
# set the calibration file that is used for the calculation
# of the visible energy
/Lena/run/setCalibFile ./Data/Data493/EnergyCalibWinstonConesDN50AP5LP5.dat
/Lena/gun/type 5 # simulate high energy neutrino events
```

[12]see http://projects.hepforge.org/ genie/manuals/GENIE_PhysicsAndUserManual_20100213.pdf, sec. 6.6.2.1, p. 88 for details

```
# simulate muon neutrinos from a superbeam at cern
/Lena/gun/neutrino_data ./Data/spl_cn2py_lena_nu_mu.root
# only simulate quasi-elastic charged current events
/Lena/gun/neutrino_filter cc==1&&qel==1
/Lena/run/setOutputFileName Data_cn2py_numu_cc_qel
/run/beamOn 500
```

Figure 10 shows the comparison between the visible energy and the neutrino energy. You can see that the visible energy is always less than the neutrino energy. There are several reasons for this. First of all, when nucleons are emitted from the target nucleus, the binding energy (on average about 25 MeV per nucleon) is lost. The emitted nucleons are also quenched, so this leads to another reduction of the visible energy. And as the energy of the

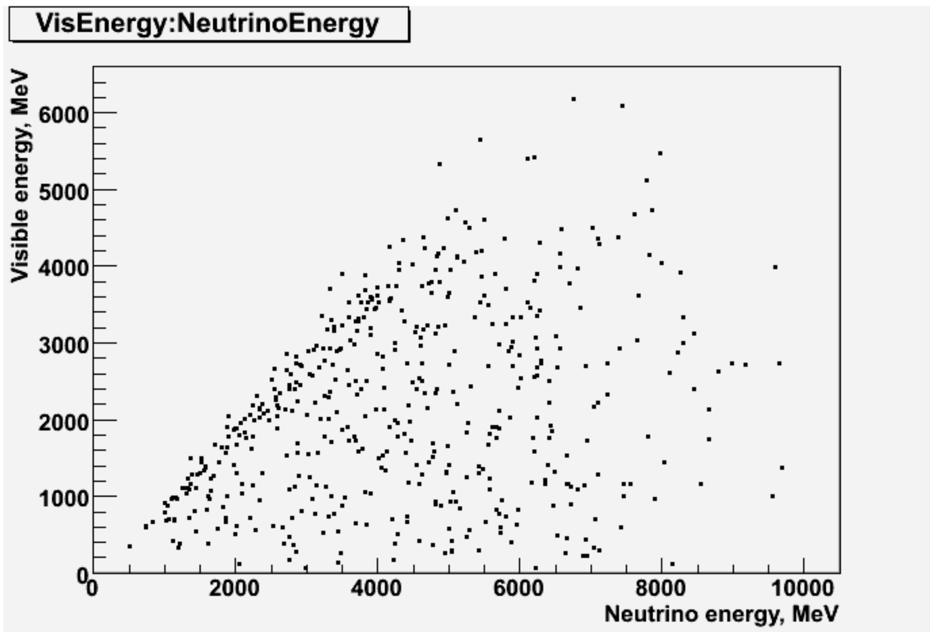

Figure 10: Comparison between the visible and the neutrino energy, for charged current quasi-elastic events from a superbeam.

produced muon is quite high, not every muon track is contained.
Next, we will simulate atmospheric neutrinos. We will only simulate charged current, deep inelastic events.

```
# simulate atmospheric neutrinos
/Lena/gun/neutrino_data ./Data/Lena_atmole_kam050810.root
# simulate deep-inelastic charged current events
/Lena/gun/neutrino_filter cc==1&&dis==1
/Lena/run/setOutputFileName Data_Atmospheric_cc_dis
/run/beamOn 500
```

Figure 11 shows the comparison between the visible energy and the neutrino energy. First of all, you can see that only few neutrino events have more than 2 GeV, although we only considered deep-inelastic events. This is due to the atmospheric neutrino spectrum, which peaks between 100 and 200 MeV.

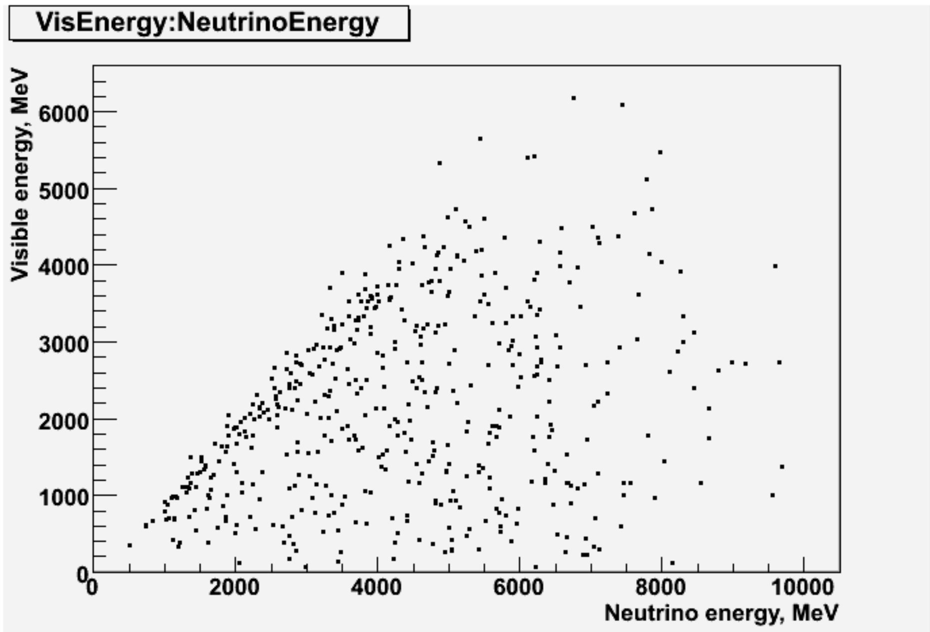

Figure 11: Comparison between the visible and the neutrino energy, for charged current, deep-inelastic atmospheric neutrino events.

Compared to the superbeam events, the energy resolution for the atmospheric neutrino events is better. The reason for this effect, is that the majority of the events are contained in the scintillator volume, due to the different direction of the neutrinos and the lower average energy.

5.4 Gamma Background

The simulation of the external gamma background, coming from the tank or from the PMTs, is divided into two steps, to save computation time. In the first step, the gammas are started either at the tank, or at a PMT. To save computation time, gammas that are not directed to the scintillator volume (2π solid angle) are not tracked, as it is not very likely that they reach the target volume. The energy and the momentum direction of the gammas at the edge of the scintillator volume is saved, and in the next step the gammas are started at the boundary of the scintillator volume. You can either simulate monoenergetic gammas, or gammas from the ^{238}U or ^{232}Th chain. Figure 12 shows the initial energy of the gammas from the ^{238}U chain. Only gammas above 250 keV are simulated, as the lower energetic ones would be below the detection threshold.

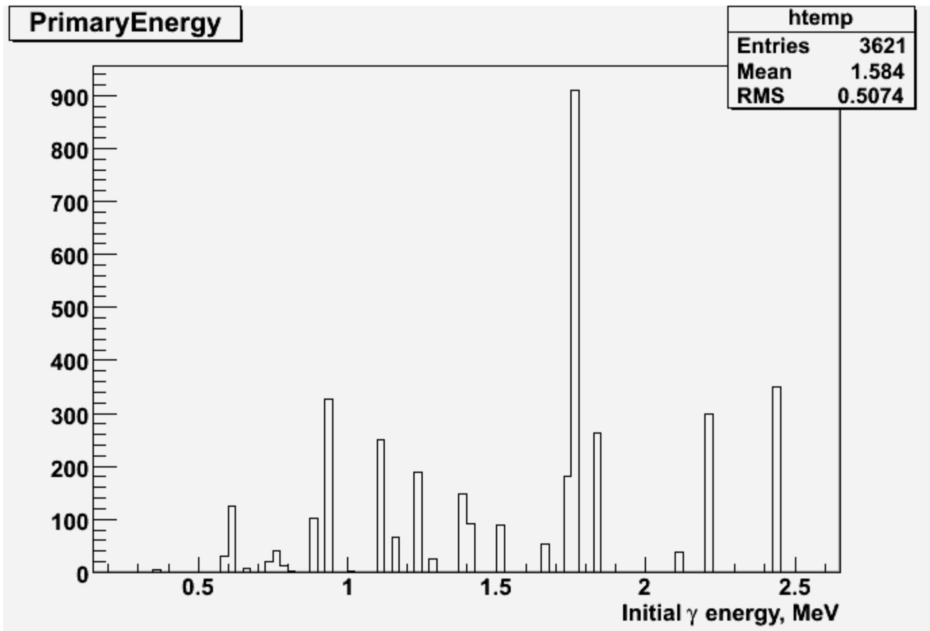

Figure 12: Initial energy of the gammas from the ^{238}U chain.

To save computation time, 10.000 gammas are simulated at every event. This is possible as we only simulate the gamma track, without any detector response. Thus, the gammas don't interfere with each other.

```
# don't generate any scintillation photons
# as we are only generating low energetic gammas,
```

```
# we don't need to include any hadronic models
/run/initialize
/control/verbose 2
/run/verbose 2
/Lena/run/sim_type 4 # simulate the gamma background
/Lena/gun/decay_chain U238 # use gamma energies from the U238
chain above 250 keV
/Lena/gun/subtype 0 # start the gamma at a random PMT
/Lena/run/radius_cut 13.5 # only saved events that reached at least
13.5 m
/Lena/run/setOutputFileName Data_GammaBackground_Step1
/run/beamOn 1000
/Lena/run/setOutputFileName Data_GammaBackground_Final
/Lena/run/sim_subtype 1 # start the gammas at the edge of the target
volume
# use the results from first simulation as input
/Lena/gun/gamma_spectrum ./SimData/Data_GammaBackground_Step1.root
/run/beamOn 1000
```

Figure 13 shows the range of the gammas, after the second simulation step.

5.5 Energy Calibration

In this example we will make four calibrations runs. To reconstruct the visible energy, we need the photon electron yield for two different energies. In order to distinguish between electron and alpha events, we also need two calibration runs for alpha particles. In each run, we will simulate 500 events at every calibration points. The calibration points are distributed homogeneously over the fiducial volume in X and Z direction, with 1 m distance between each point. This is sufficient to consider all position depend effects, as LENA is rotationally symmetric referred to the Z-Axis.

```
# load the physics list
/Lena/phys/reg G4EmExtra
/Lena/phys/reg G4HadronElastic
/Lena/phys/reg HadronQGSP_BERT_HP
/Lena/phys/reg G4QStopping
/Lena/phys/reg G4Ion
```

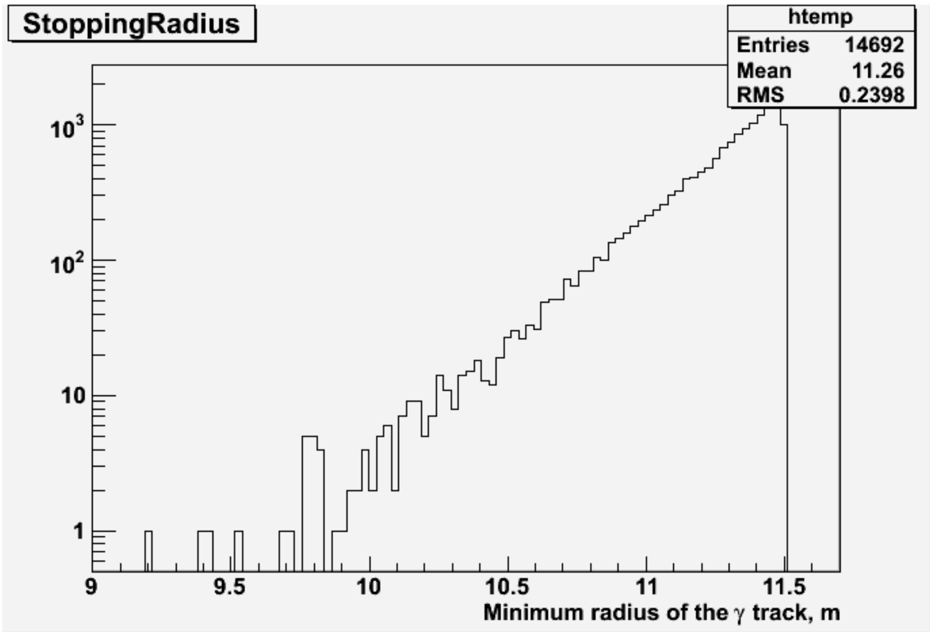

Figure 13: The range of the gammas.

```
/Lena/phys/reg LenaOP
/Lena/phys/reg G4Radioactive
/physics_engine/tailor/MuonNuclear on
/run/initialize # initialize the physics list and the detector
/control/verbose 2
/run/verbose 2
/Lena/det/pmts false # don't simulate individual PMTs
# activate the winston cones, acceptance angle is set to about 50°,
# corresponding to an area increase by a factor of 1.75
/Lena/det/winston_cones true
/Lena/det/light_yield 792
/Lena/det/update # update the detector geometry
/Lena/run/sim_type 5 # make a calibration run
/Lena/det/dark_noise true # generate dark counts
/Lena/det/dark_noise_rate 50 # set the dark count rate to 50 per μs
/Lena/det/after_pulse_prob 0.05 # set the fast afterpulse rate to 5%
/Lena/det/late_pulse_prob 0.05 # set the late pulse rate to 5%
# set the range of the pulse shape histogram,
# only photon hits within this range
```

```
# are used for the calculation of the visible energy
/Lena/det/pmt_hist_range_low 0
/Lena/det/pmt_hist_range_up 600
# set the number of bins of the pulse shape histogram
/Lena/det/pmt_hist_num_bins 600
/Lena/gun/CalibNumEv 500 # 500 events per calibration point
/Lena/gun/CalibPrec 1 # 1m distance between calibration points
/gun/particle e-
/gun/energy 300 keV # simulate 300 keV electrons
/Lena/run/setOutputFileName Data_Calibration_Electron_300keV
/run/beamOn 312000
/Lena/run/setOutputFileName Data_Calibration_Electron_500keV
/gun/energy 500 keV # simulate 500 keV electrons
/run/beamOn 312000
/Lena/run/setOutputFileName Data_Calibration_Alpha_4700keV
/gun/particle alpha
/gun/energy 4700 keV # simulate 4700 keV alphas
/run/beamOn 312000
/Lena/run/setOutputFileName Data_Calibration_Alpha_6400keV
/gun/energy 6400 keV # simulate 6400 keV alphas
/run/beamOn 312000
```

Afterwards, the average photo electron yield (the results are depicted in Figure 14), the average tail-to-total ratio, and the average gatti parameter are calculated for each calibration point. Furthermore, the sigma of the tail-to-total ratio and gatti parameter distribution is calculated (assuming a gaussian distribution). Finally, the average pulse shape for electron and alpha events is determined. These information is written to one root file for each energy (see Section 4.2, command **/Lena/run/setCalibFile** for details). In the last step, we need to create a file, that specifies the energy ([MeV]) and the corresponding calibration file.

```
0.3 ./doc/userdoc/Examples/EnergyCalibration/EnergyCalibration300keV.root
0.5 ./doc/userdoc/Examples/EnergyCalibration/EnergyCalibration500keV.root
```

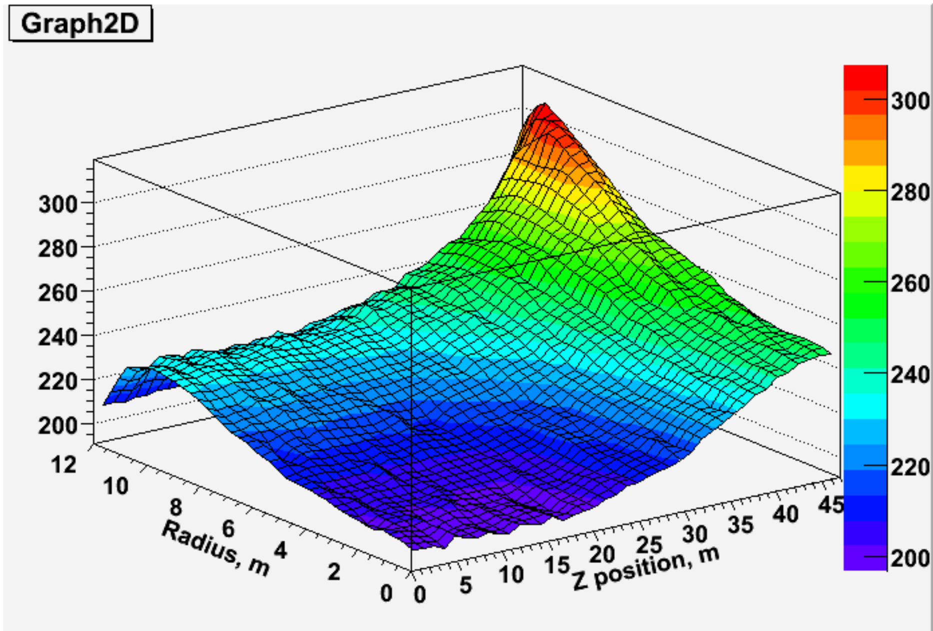

Figure 14: The position dependency of the photo electron yield in LENA.