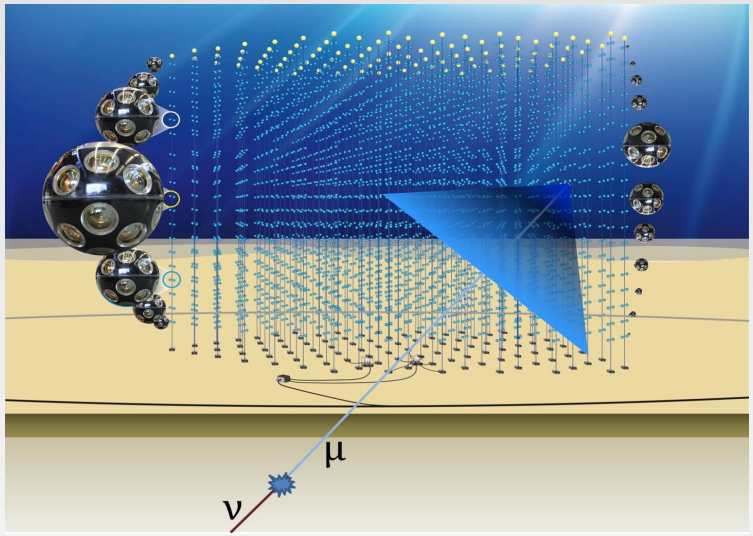
European Union
European Social Fund
OPERATIONAL PROGRAMME
EDUCATION AND LIFELONG LEARNING
investing in knowledge society
MINISTRY OF EDUCATION & RELIGIOUS AFFAIRS
MANAGING AUTHORITY
NSRF 2007-2013
programme for development
EUROPEAN SOCIAL FUND
Co-financed by Greece and the European Union

Muon and Neutrino Energy Reconstruction for KM3NeT

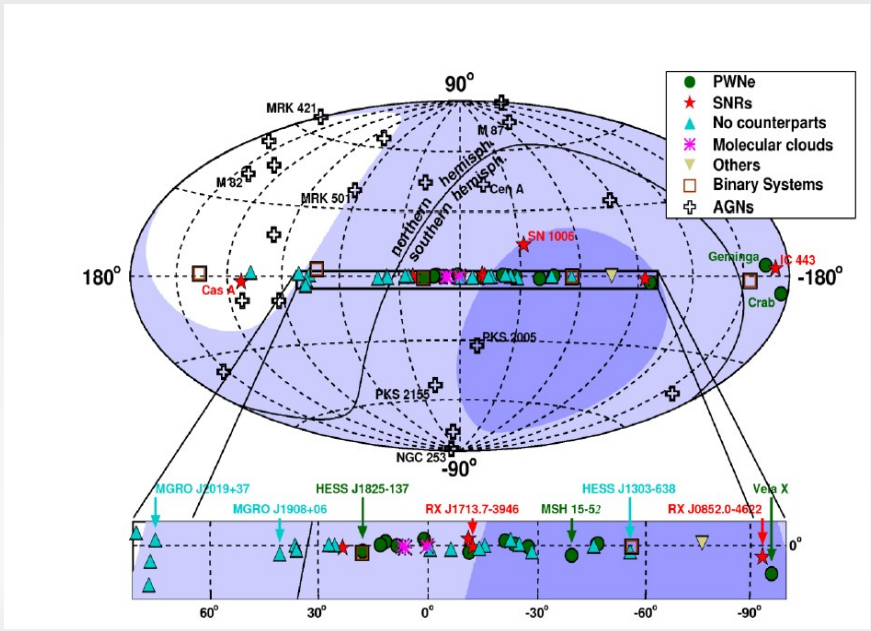


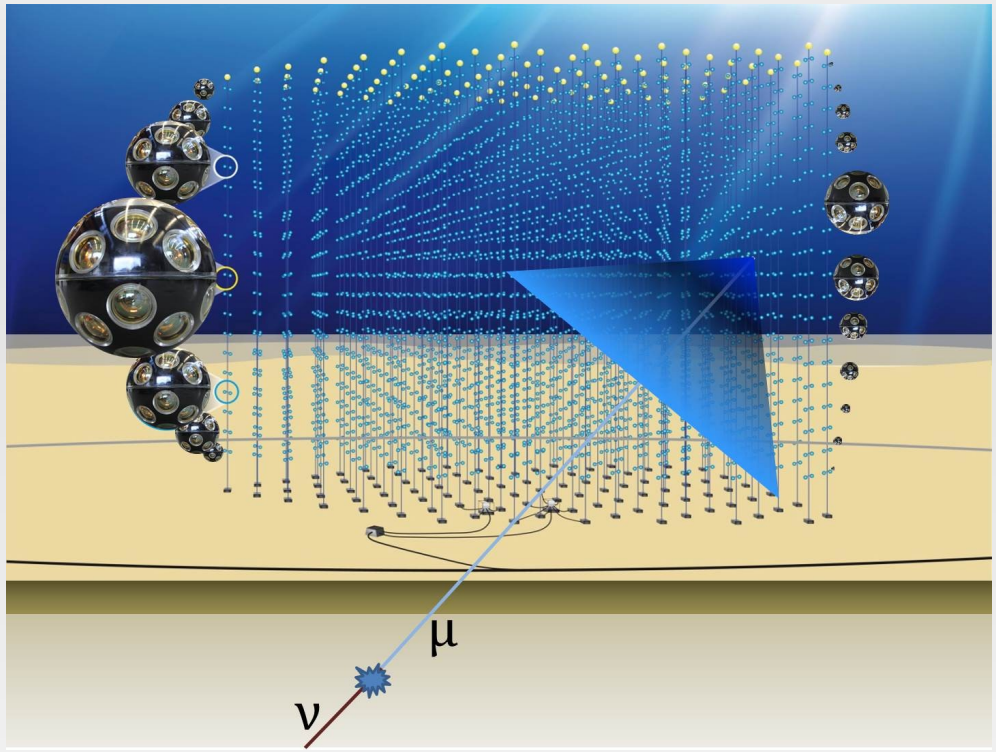
Drakopoulou Evangelia

N.C.S.R. Demokritos

KM3NeT

- **KM3NeT** → Neutrino Telescope with volume of **several km^3** which will be placed in the Mediterranean Sea.
- The telescope will search for **neutrinos** from galactic and extragalactic astrophysical sources (like Gamma Ray Bursts, Supernovae, Colliding Stars).

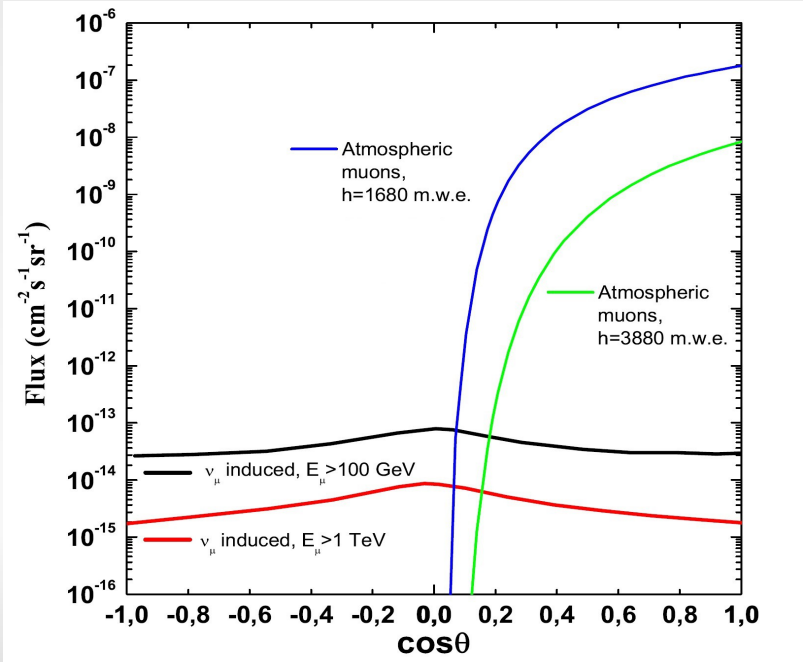


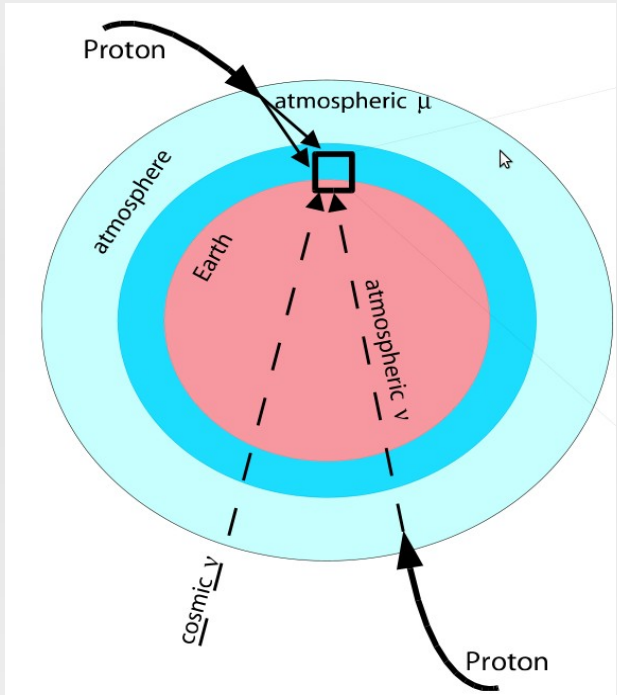


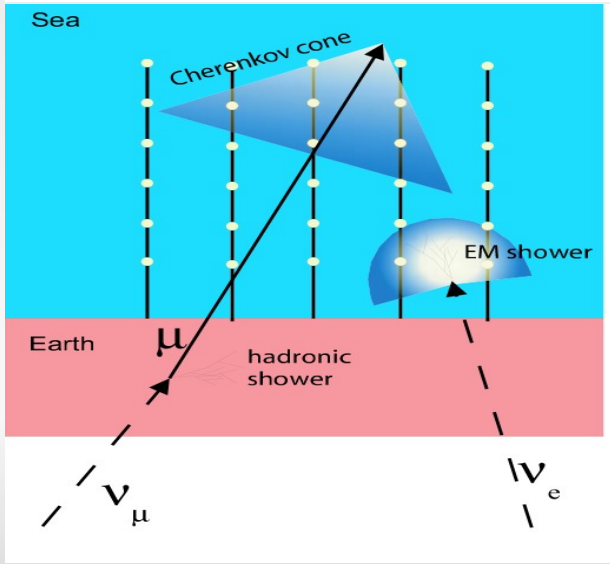
- Sky coverage in galactic coordinates for a detector located in the Mediterranean Sea.
- Dark (light) areas are visible at least 75% (25%) of the time.

KM3NeT - Backgrounds

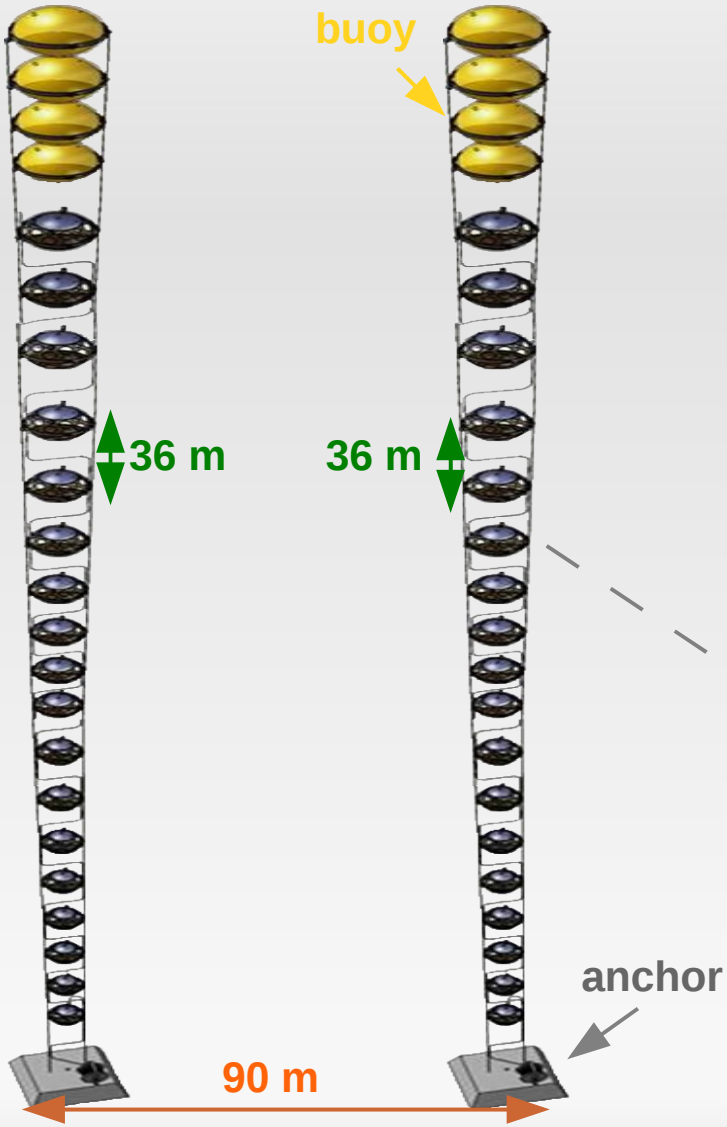
- **Atmospheric Muons :** contained in the extensive air showers produced by cosmic rays in the atmosphere.
- **Atmospheric Neutrinos :** produced by charged kaons or pions in cosmic rays interactions in the atmosphere.
- K^{40} **:** radioactive potassium isotope
- **Bioluminescence :** life forms that inhabit in the deep sea emit light.







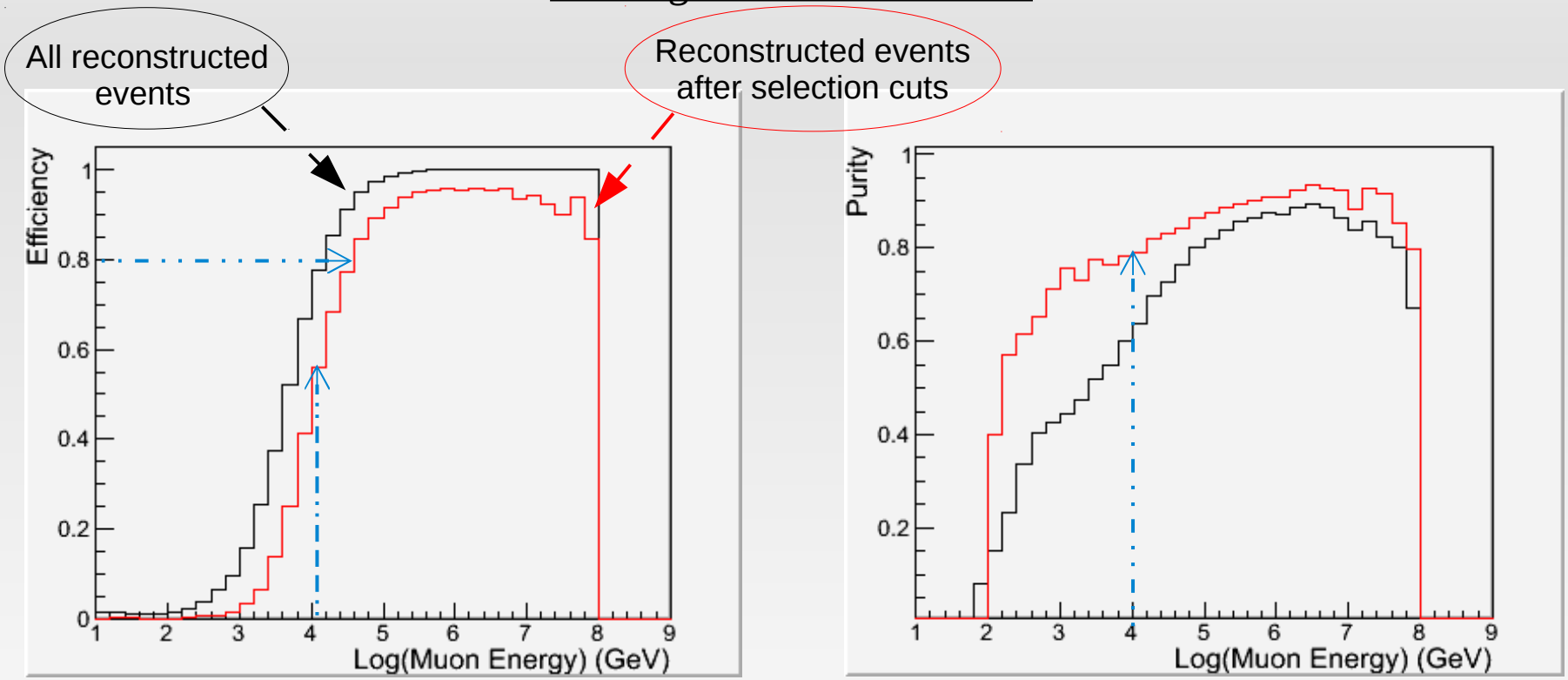
Detector Configuration



- Each of the 6 blocks has an almost hexagonal geometry with **115 strings** at **90m** distance. Each string has **18 floors** and each floor has **1** Optical Module (OM).
- The optical modules are arranged in **vertical strings** with a height of almost **600m**.
- All data are transmitted to shore via an optical fibre network.
- Each optical module consists of a **17" glass sphere**, equipped with **31 3 inches photomultipliers**.

Track Reconstruction

- Muons produced by neutrinos via Charged Current interactions were reconstructed and used for the energy estimation study. Hits from signal and K^{40} background are considered. The muon tracks under consideration are crossing the detector volume.



- A good purity (≥ **80%**) of the reconstructed events for $E_\mu \geq 10\,TeV$ can be attained, with an efficiency of **55%** for $E_\mu \geq 10\,TeV$.
- The efficiency is ≥ **80%** for $E_\mu \geq 40\,TeV$ rising with energy to ~ **95%** for $E_\mu \geq 100\,TeV$.

MultiVariate Analysis

- **Muon and Neutrino Energy Estimation:** a Multi-Layer Percepton (MLP) Neural Network has been trained using information referring to:
  - Number of photomultipliers (PMTs) with signal

    (weighted considering the PMT distance from the reconstructed muon track)
  - Total Time over Threshold (ToT) in PMTs (as a measure of charge in PMTs)
  - Number of OMs with signal

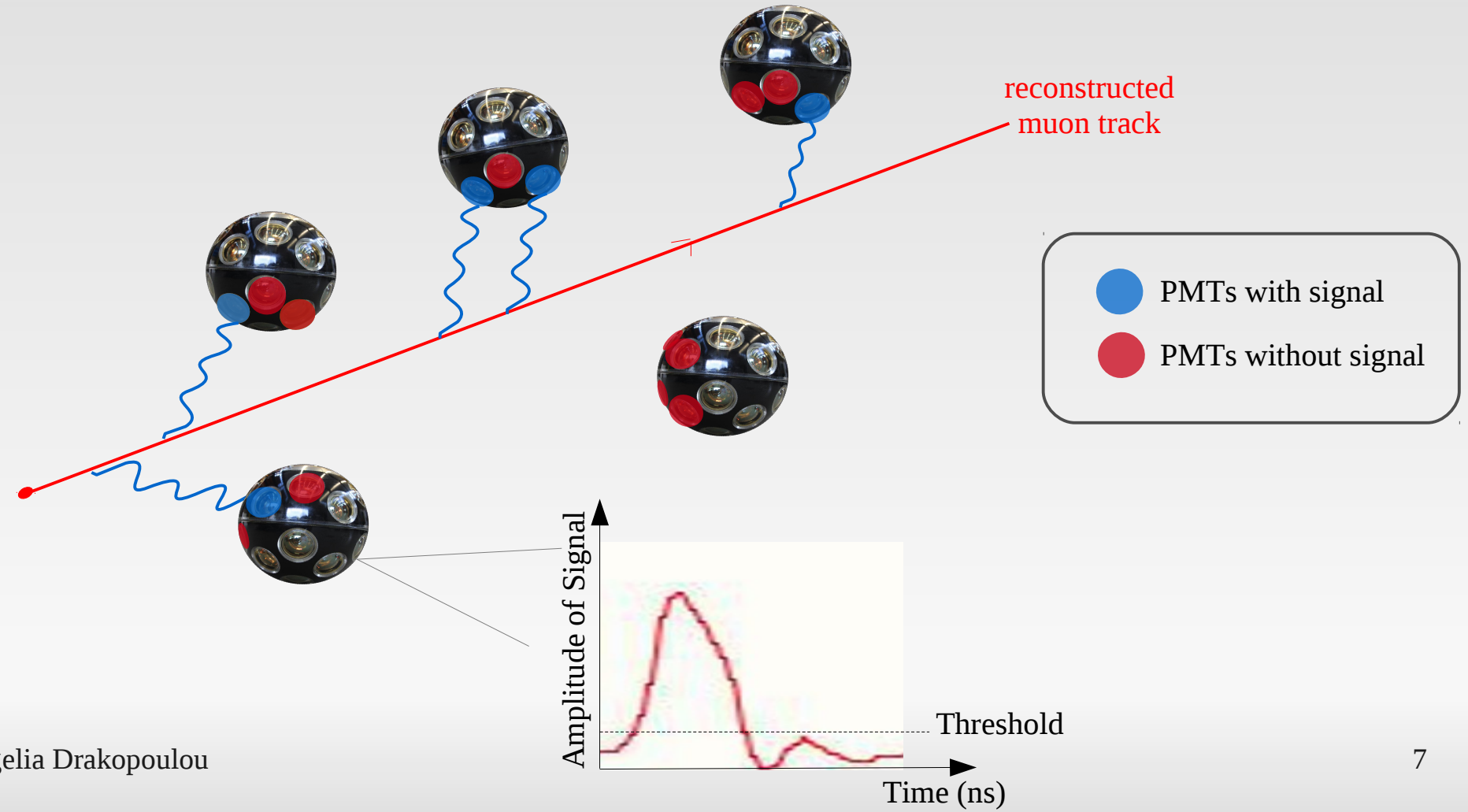
    (weighted taken into account that muons with lower energies travel shorter distances inside the detector than muons with higher energies)
  - Number of PMTs without signal

    (weighted considering that the number of PMTs that have no signal is larger for muons with lower energies)

- A minimum muon track length inside the detector volume is required in order to estimate muon and neutrino energy.

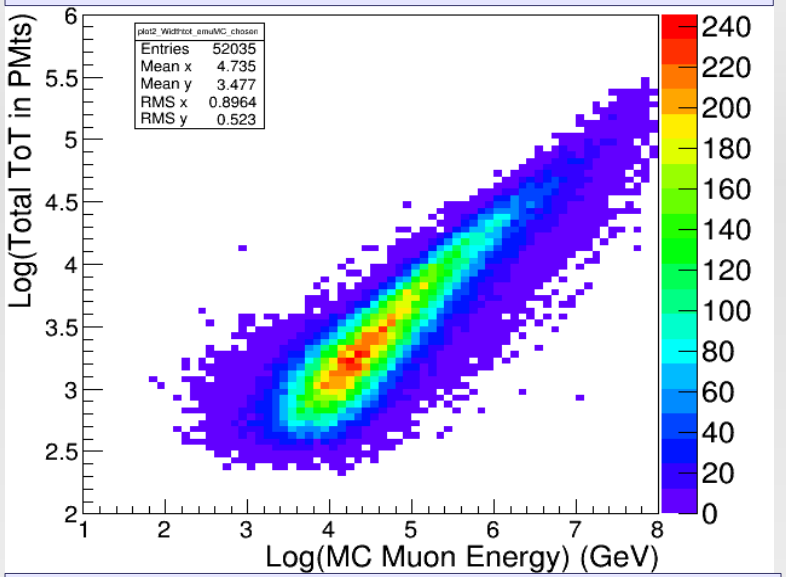
MultiVariate Analysis

We consider the PMTs with signal used by the fitting procedure
→ reduction of K^{40} contribution

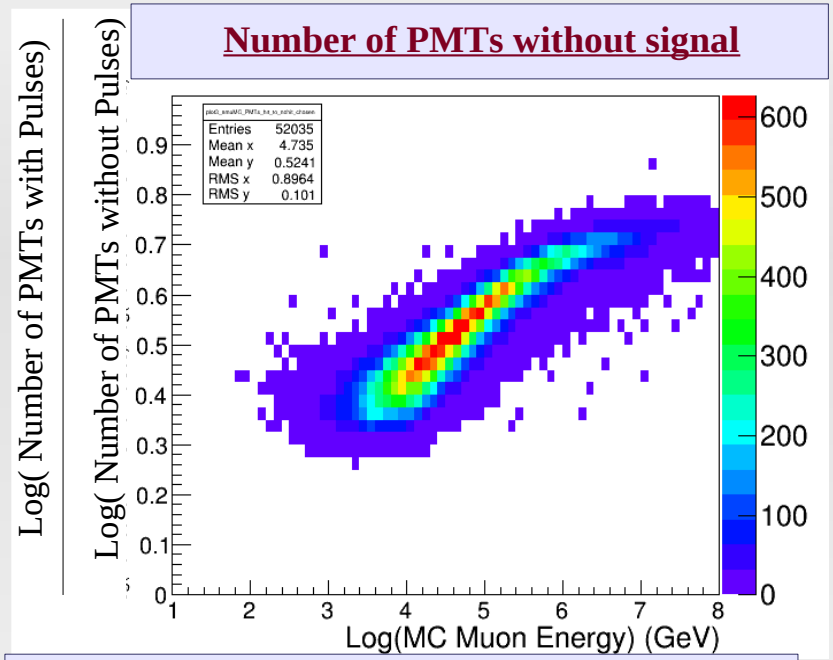


Muon Energy Estimation
Neural Network Input Variables

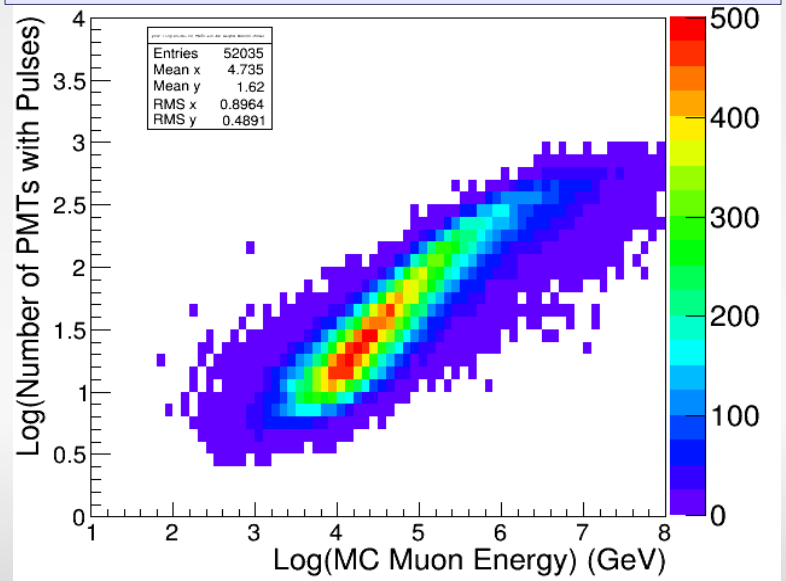
Total Time over Threshold (ToT) in PMTs



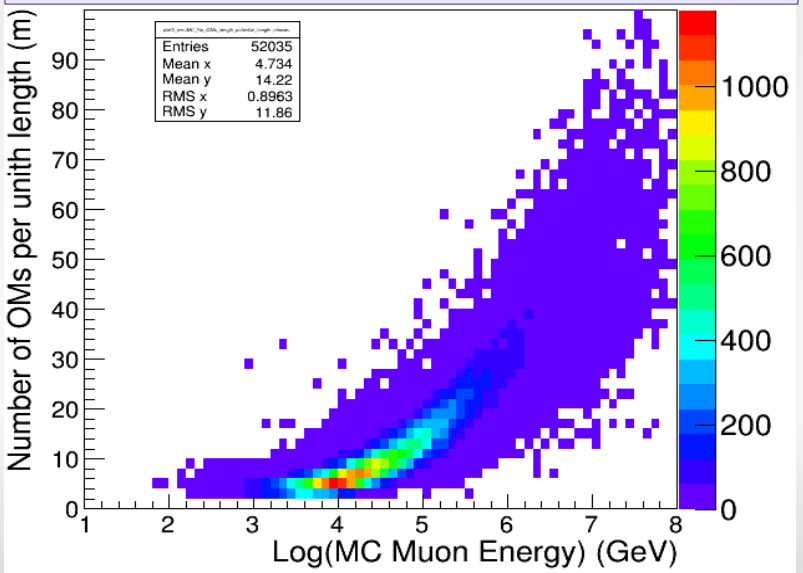
Number of PMTs without signal



Number of PMTs with signal

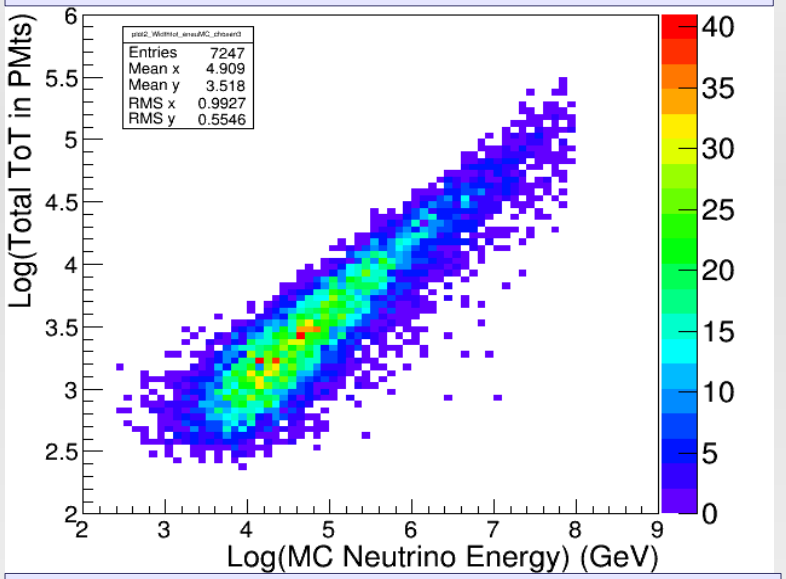


Number of OMs with signal

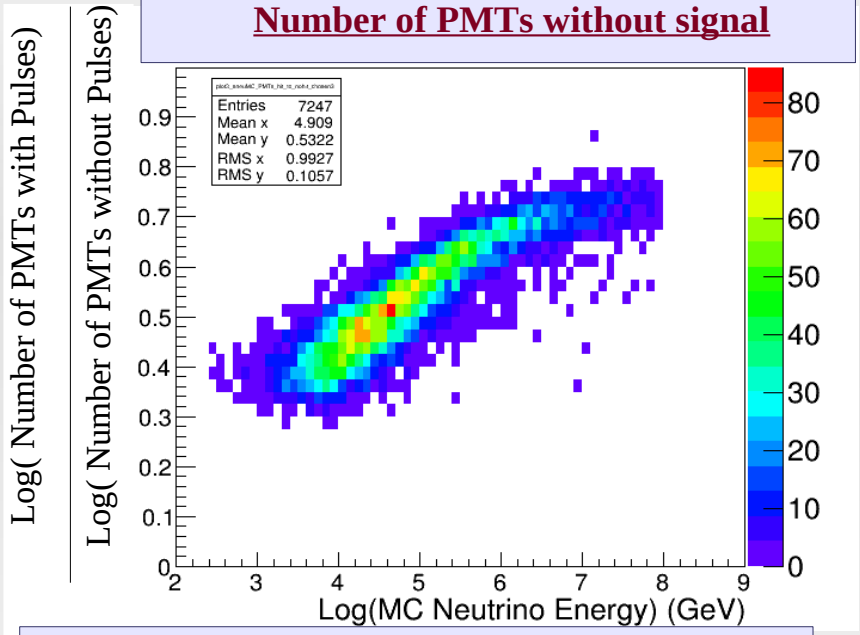


Neutrino Energy Estimation
Neural Network Input Variables

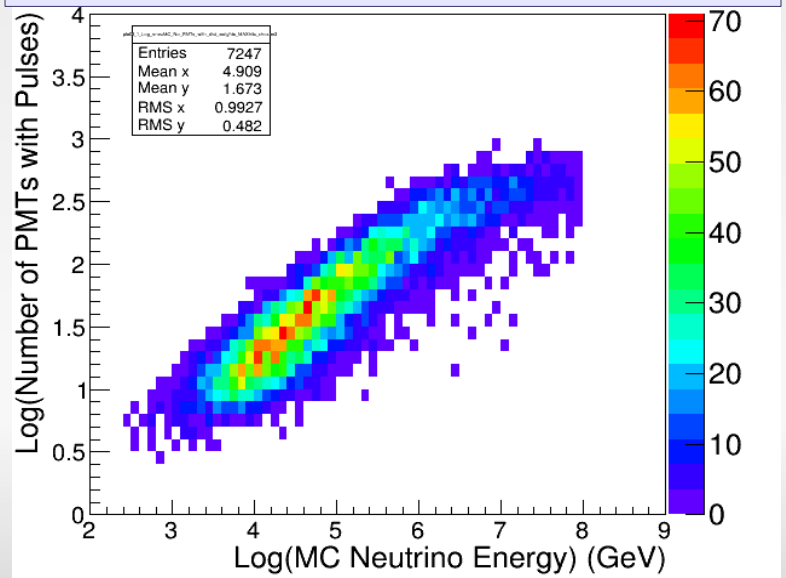
Total Time over Threshold (ToT) in PMTs



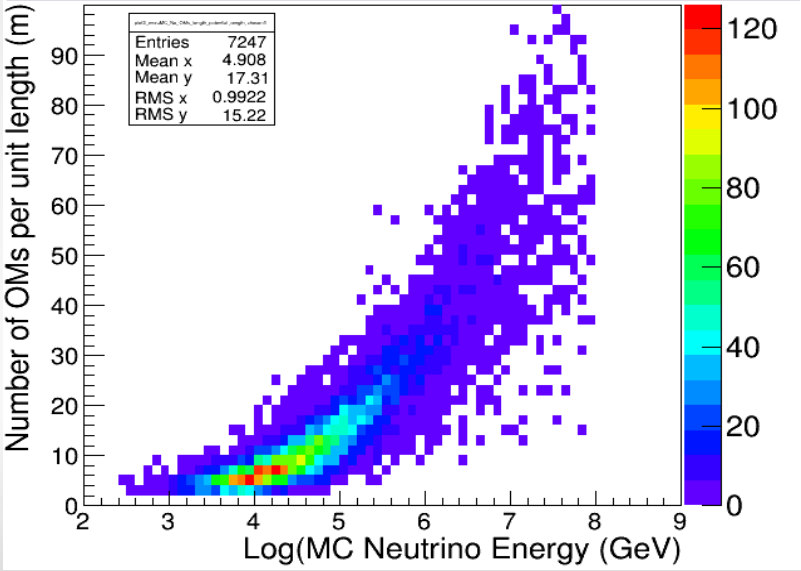
Number of PMTs without signal



Number of PMTs with signal



Number of OMs with signal

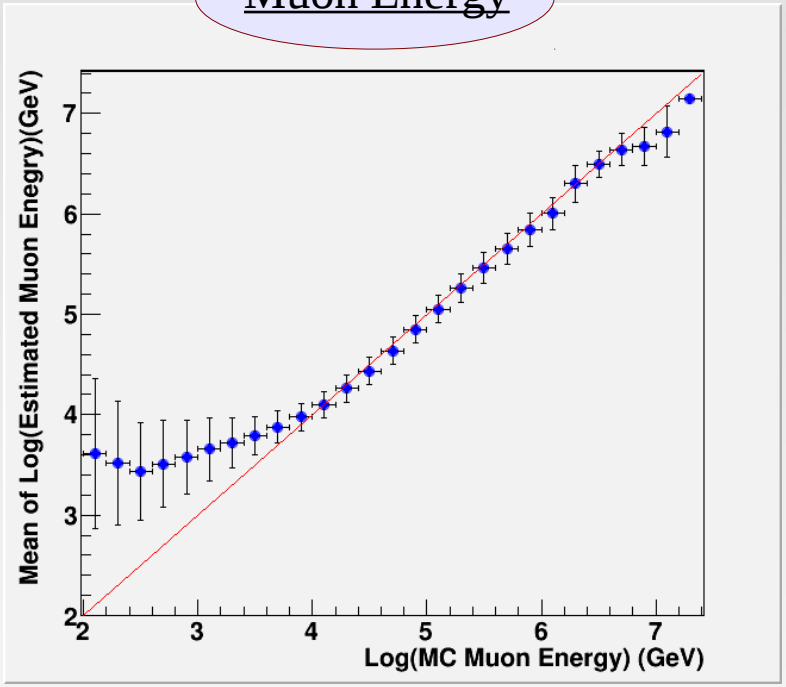


Results in Muon and Neutrino Energy Estimation

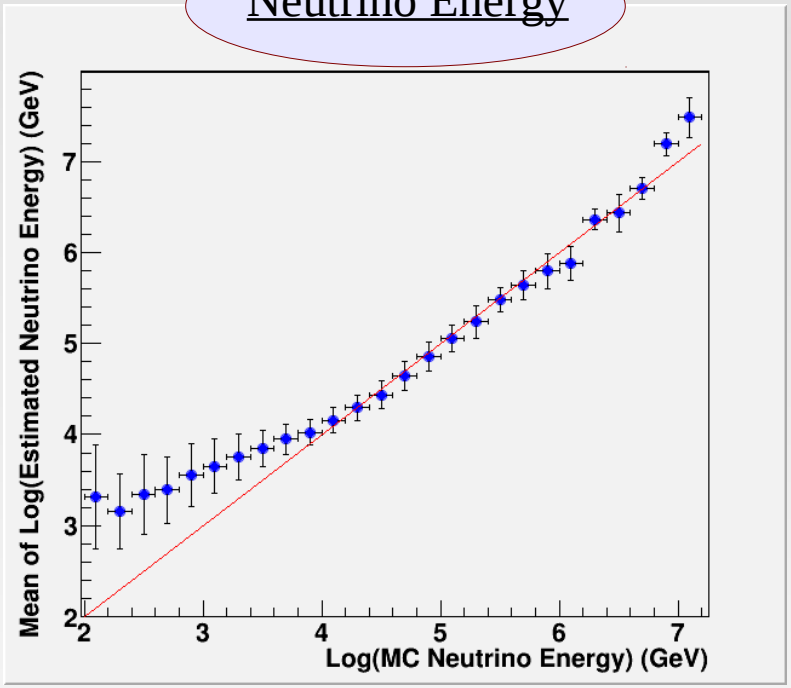
Muons crossing the detector volume

Events with the neutrino vertex close to the detector volume

Muon Energy



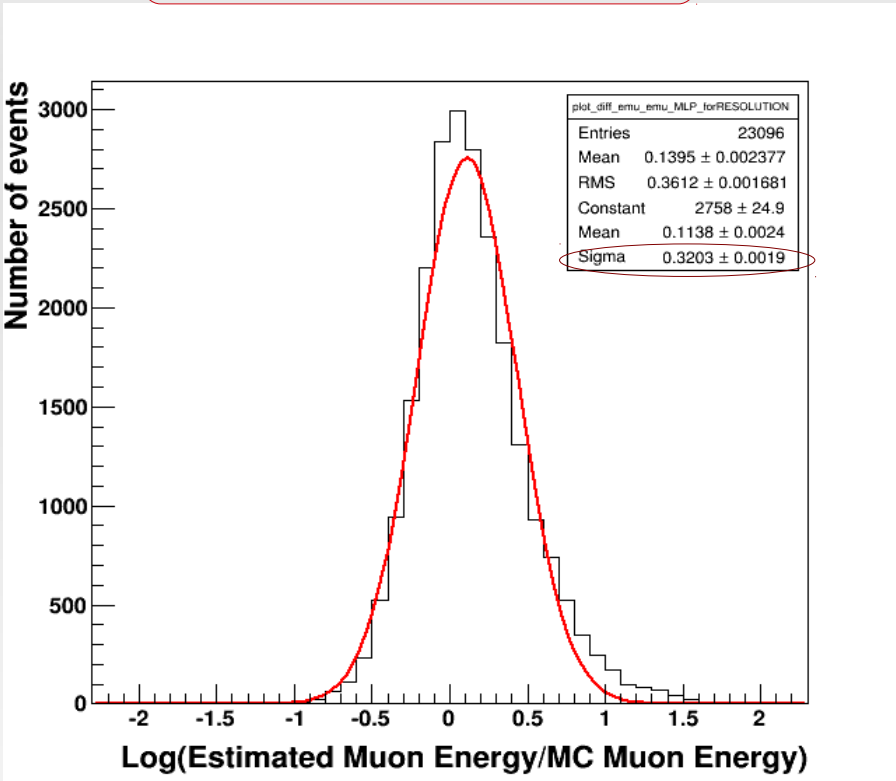
Neutrino Energy



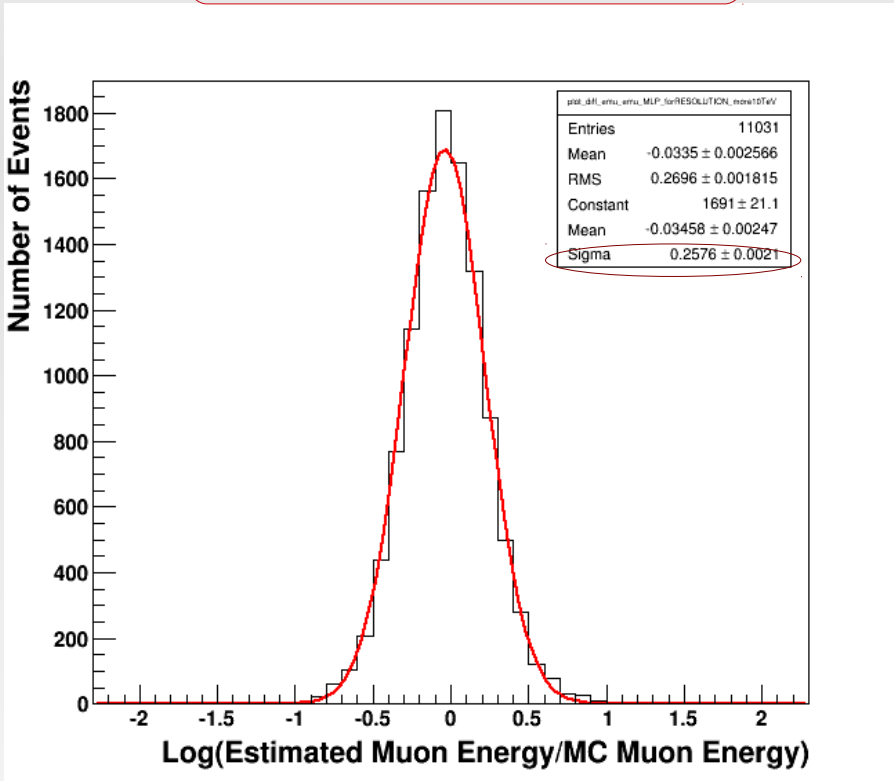
- For muon energies $E_\mu < 1\,TeV$ we overestimate the energy, while there is a very good linear correlation for $E_\mu \geq 10\,TeV$.
- The neutrino energy is better determined (with respect to the muon energy) for the lower energy range. There is also a very good agreement for $E_\nu \geq 10\,TeV$.

Muon Energy Resolution

$100\,GeV \leq E_\mu \leq 20\,PeV$



$10\,TeV \leq E_\mu \leq 20\text{PeV}$

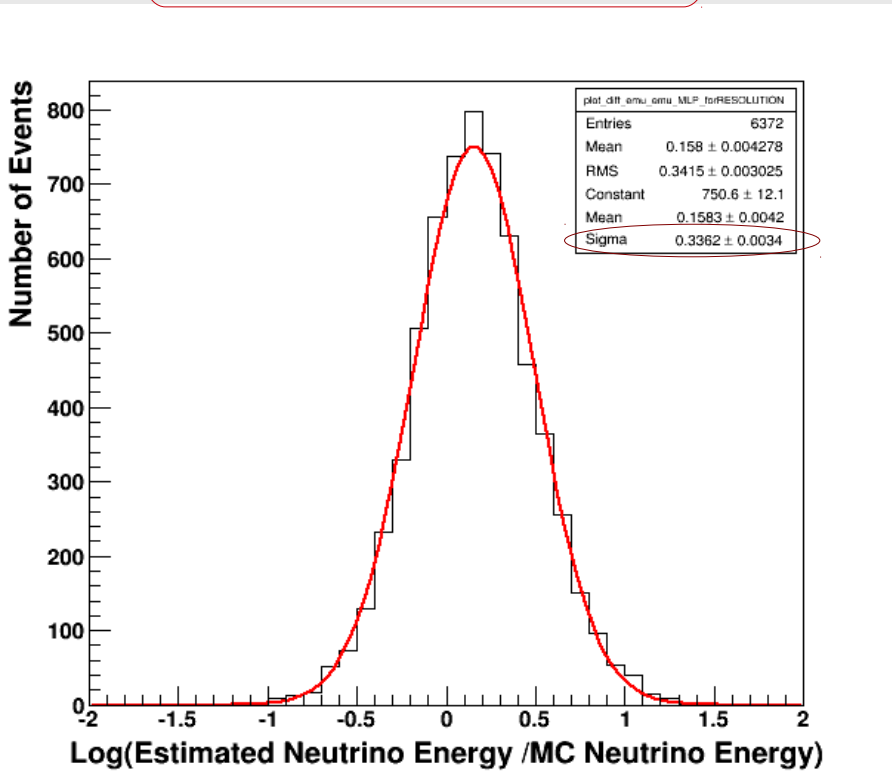


For an E^{-2} spectrum:

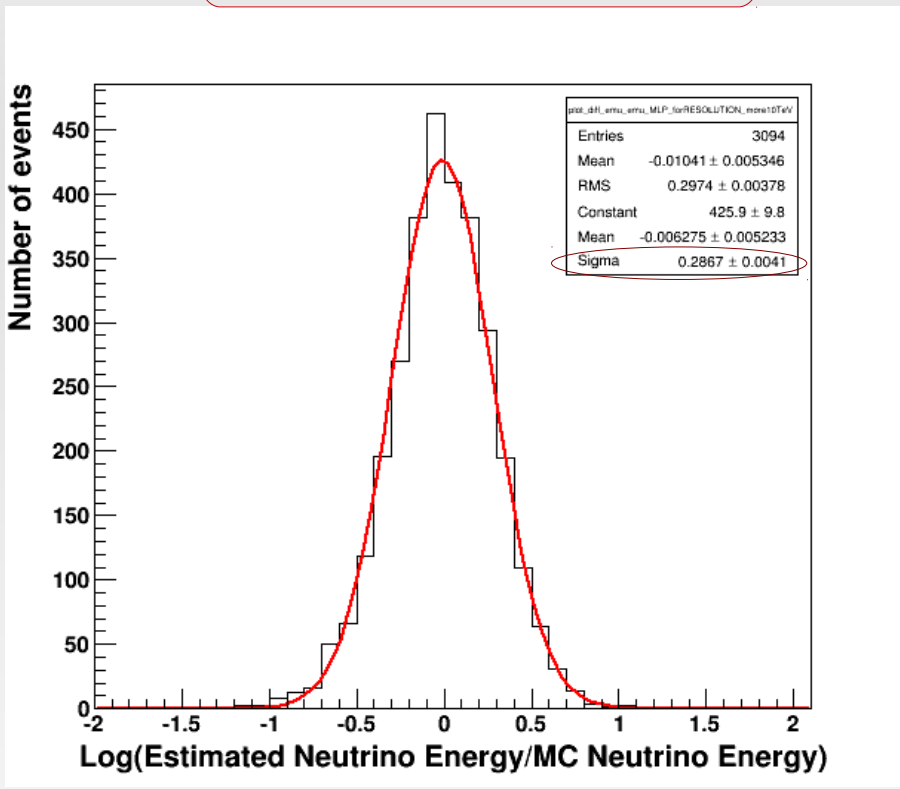
- An energy resolution of ~ 0.32 has been achieved for all events for which the energy was estimated.
- The energy resolution is **~ 0.26** for $E_\mu \geq 10\,TeV$.

Neutrino Energy Resolution

$100\,GeV \leq E_\nu \leq 20\,PeV$



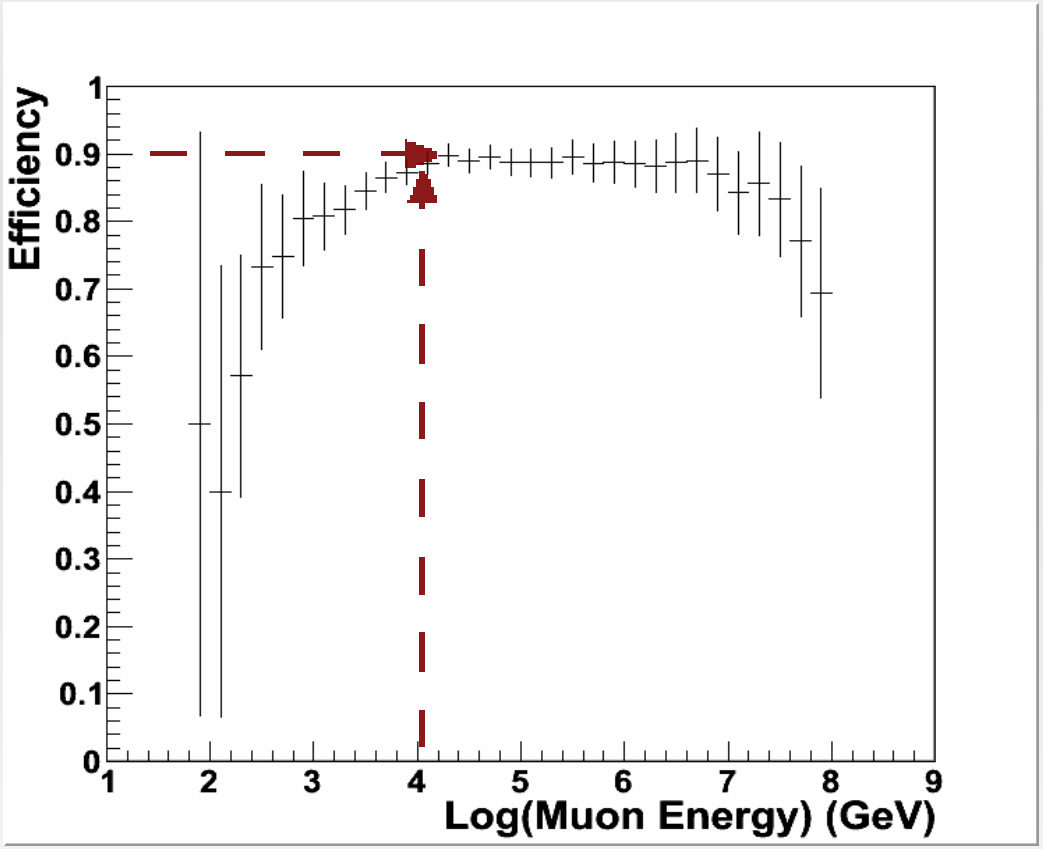
$10\,TeV \leq E_\nu \leq 20\text{PeV}$



For an E^{-2} spectrum:

- An energy resolution of ~ 0.34 has been achieved for all events for which the energy was estimated.
- The energy resolution is **~ 0.29** for $E_\nu \geq 10\,TeV$.

Efficiency of the Energy Reconstruction



- A very high efficiency for the energy reconstruction is achieved of ~ **88%** for all events crossing the detector volume.
- The efficiency is ~ **89%** for $E_\mu \geq 10\,TeV$ peaking at ~ **90%** for $E_\mu \simeq 20\,TeV$.

Conclusions

- A new method for the muon and neutrino energy estimation using a Multi-Layer Percepton Neural Network with appropriate input variables was presented.
- The performance of the energy estimator is very good, particularly in the high energy region ($E_\mu \geq 10\,TeV$) which is the energy regime we are mostly interested in.
- The energy resolution is about 0.32 in $\log_{10} E_\mu$ for muons over all energies and becomes **0.26** for $E_\mu \geq 10\,TeV$.
- The energy resolution is about 0.34 in $\log_{10} E_\nu$ for neutrinos over all energies and becomes **0.29** for $E_\nu \geq 10\,TeV$.

Backup Slides

Energy Reconstruction Selecting Cuts

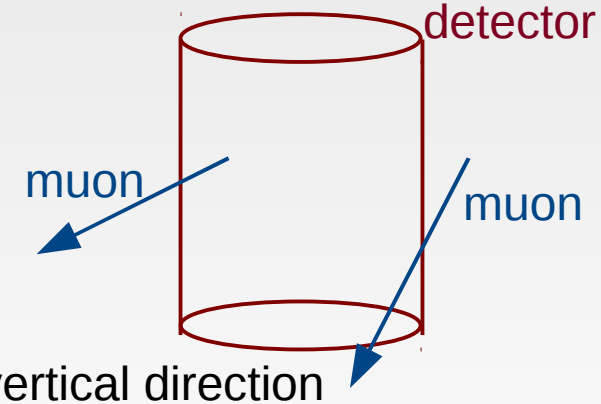
- *Minimum Expected Path* = 0.5*$\mathbf{h}$ + ($\mathbf{R}$ – 0.5*$\mathbf{h}$) * sin ($\boldsymbol{\theta}$**rec**)

  where: **h**: string's height, **R**: detector radius, $\boldsymbol{\theta}$**rec**: reconstructed muon angle

  - For Horizontal Muons Minimum Expected Path is the Detector Radius
  - For Vertical Muons Minimum Expected Path is 0.5*String height

- *PMT Distance* : distance between first and last PMT positions
- The PMT Distance should be more than the half of minimum expected path or at least:

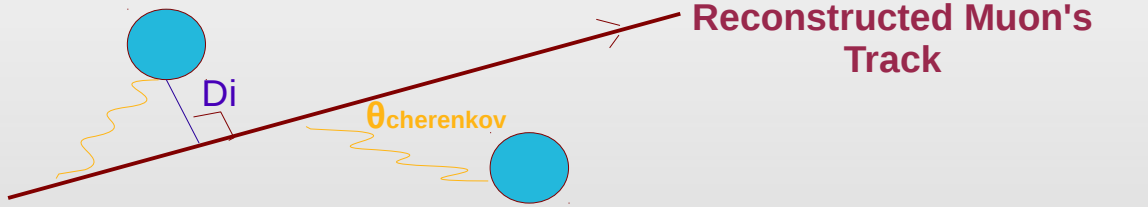
$$\frac{PMT\ Distance}{Minimum\ Expected\ Path} \geq 0.5$$



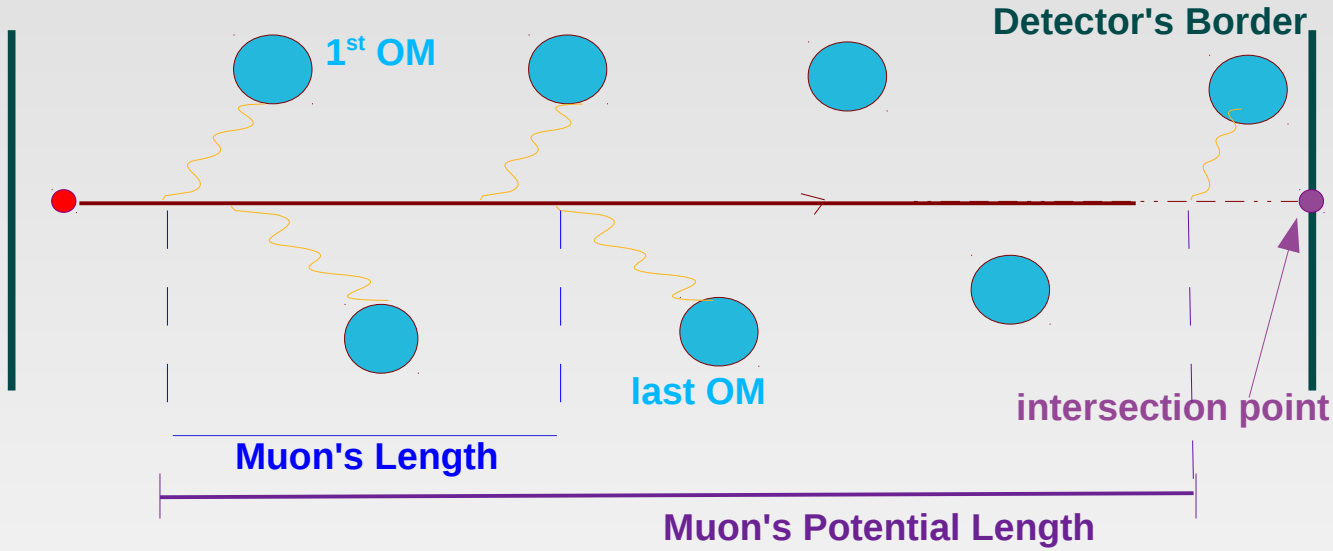
- The distances between OMs are different in horizontal and vertical direction
  - minimum expected path length should change with respect to the muon zenith

Explaining Selection Cuts

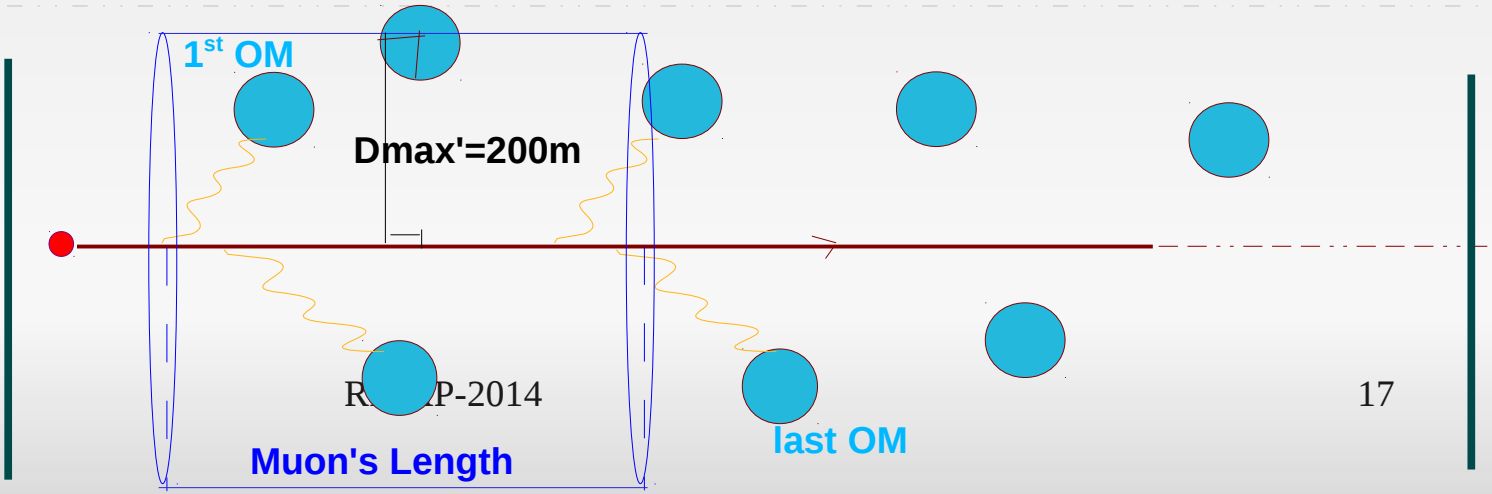
PMTs weight: $\sum \frac{Di}{Dmax}$



$$\frac{Number\ of\ OMs}{muon's\ length} * \left(\frac{muon's\ length}{muon's\ potential\ length}\right)$$

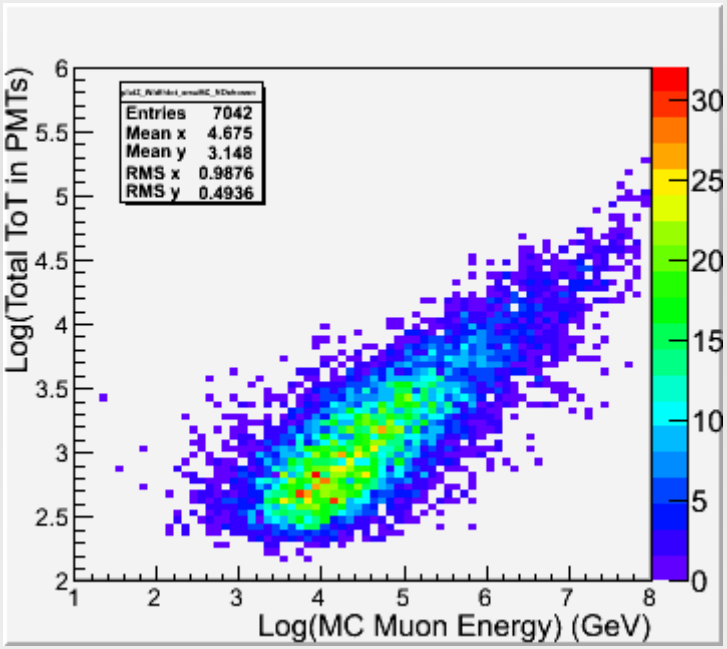


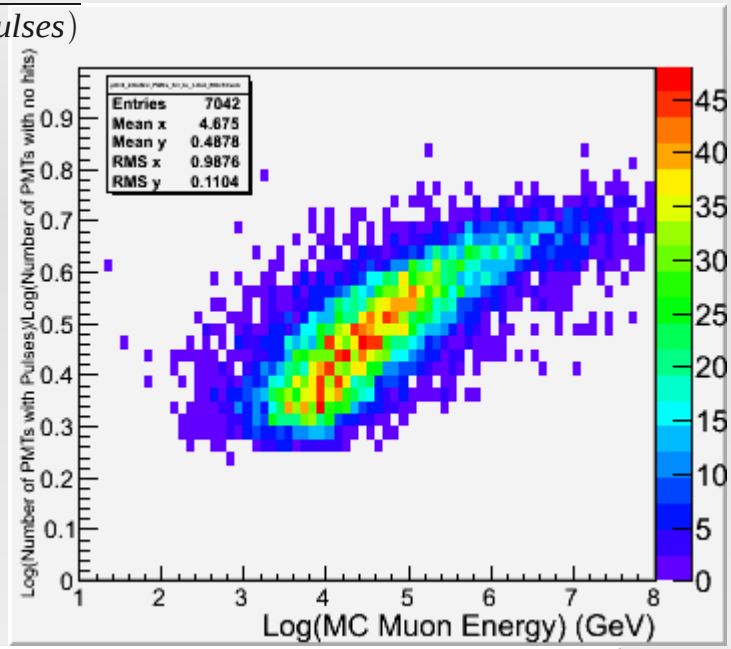
$$\frac{PMTs\ with\ hits}{PMTs\ without\ hits}$$

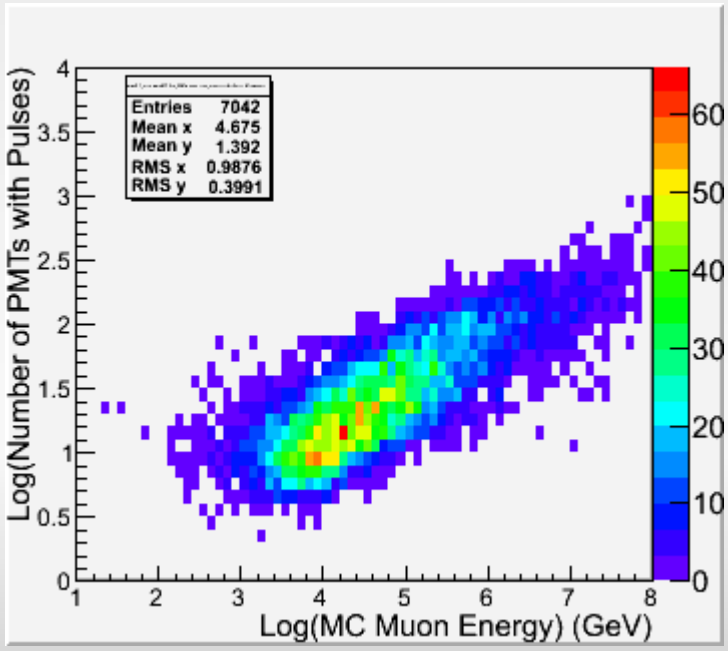


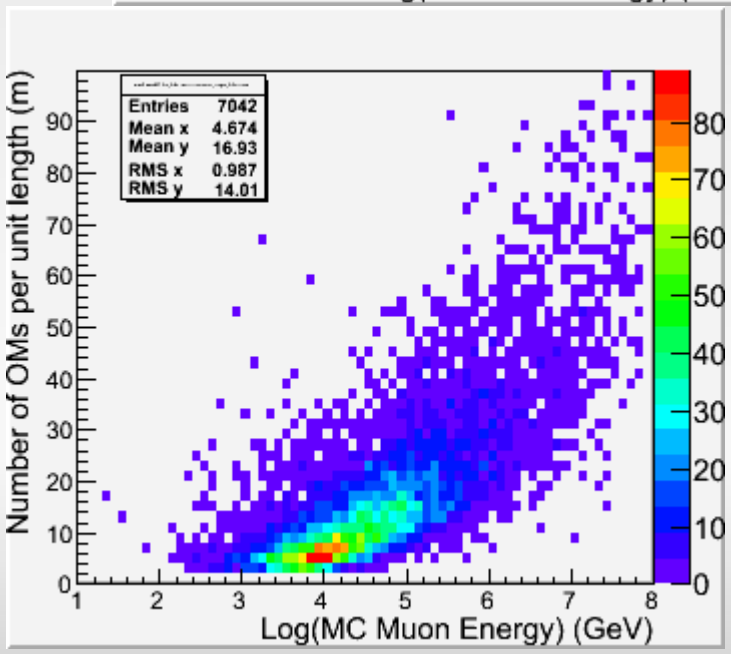
Events that fail to satisfy the selection criteria

$$\frac{\log(\textit{Number of PMTs with Pulses})}{\log(\textit{Number of PMTs without Pulses})}$$

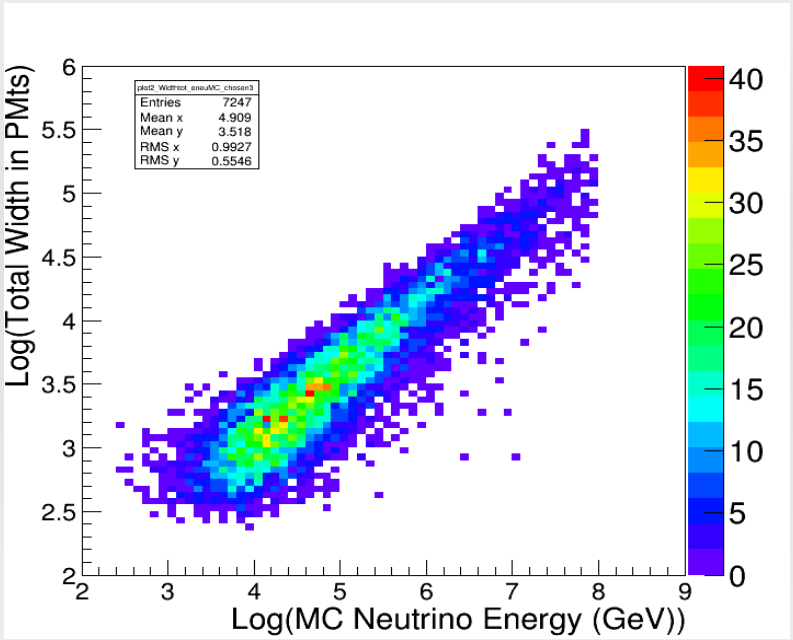




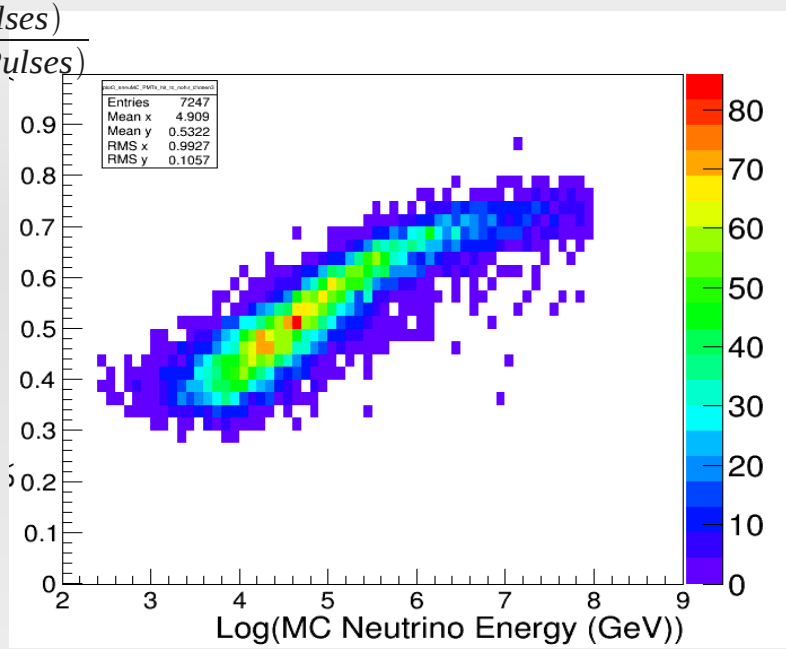


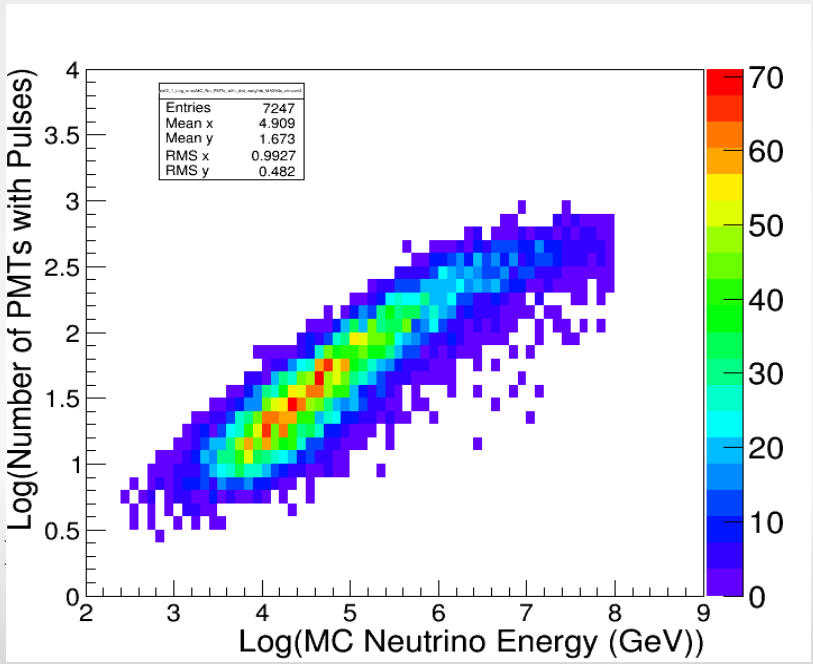


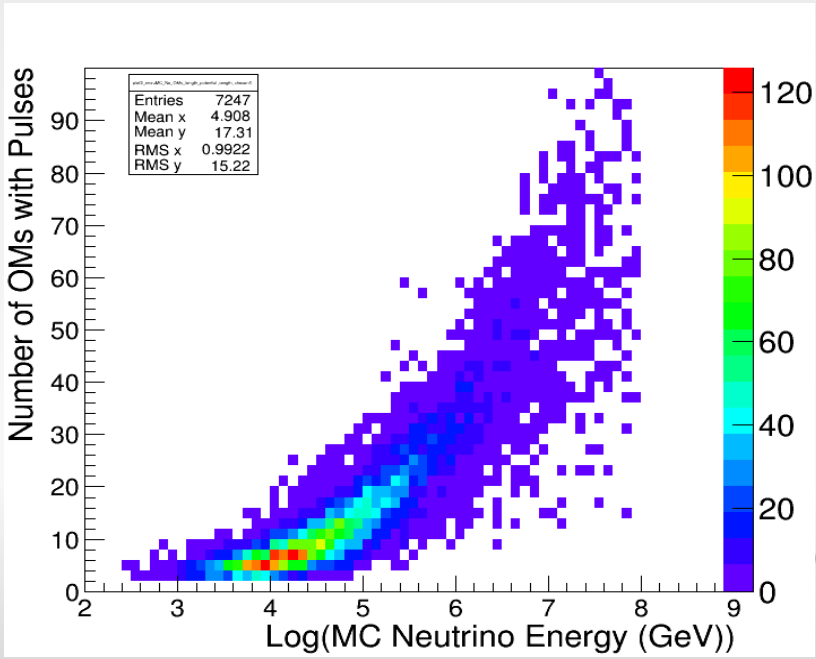
Neutrino Energy Estimation
Neural Network Input Variables



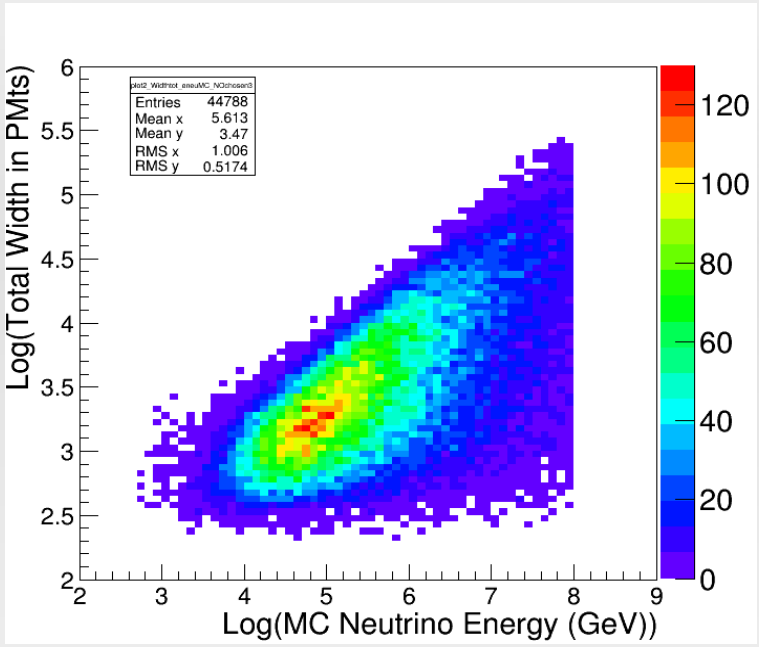
$$\frac{\log(\textit{Number of PMTs with Pulses})}{\log(\textit{Number of PMTs without Pulses})}$$



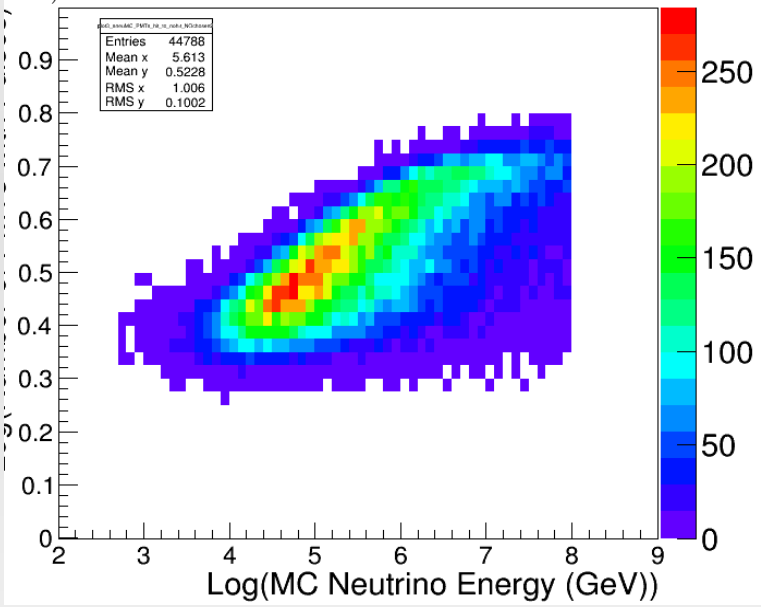


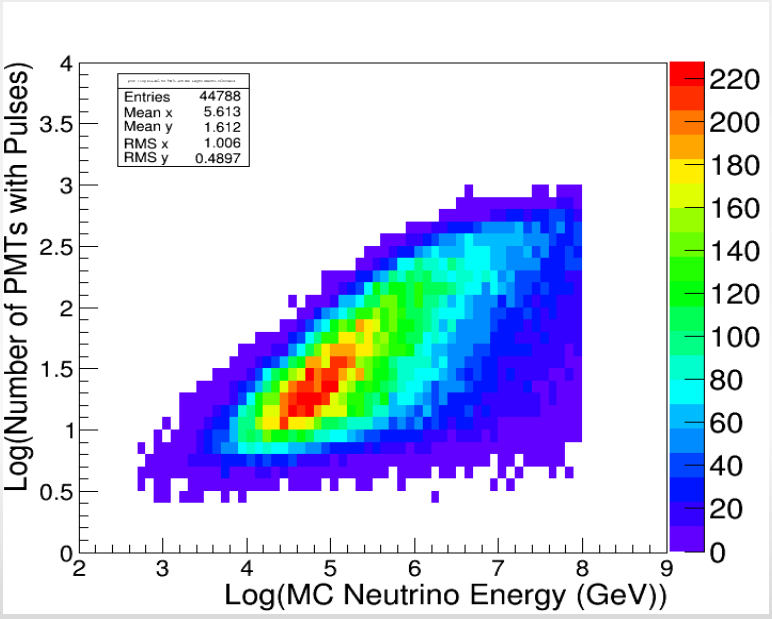


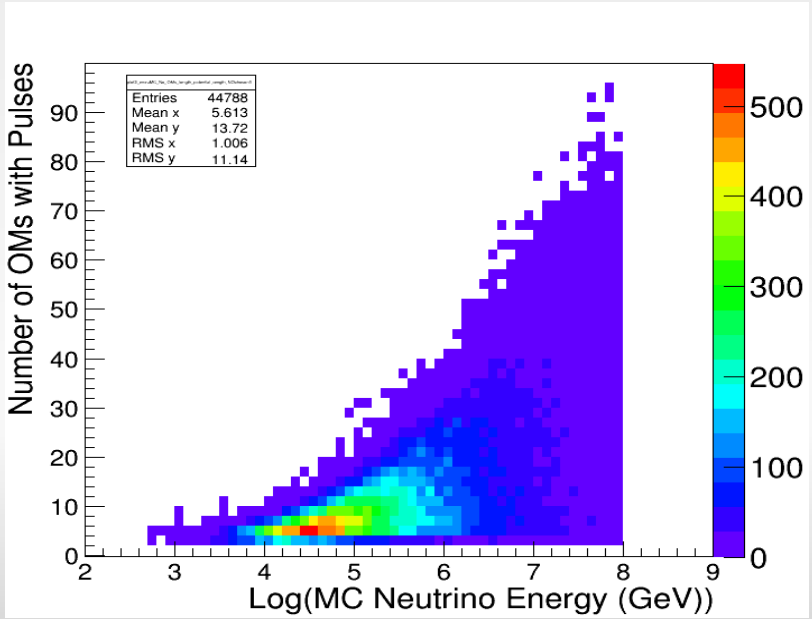
Events that fail to satisfy the selection criteria



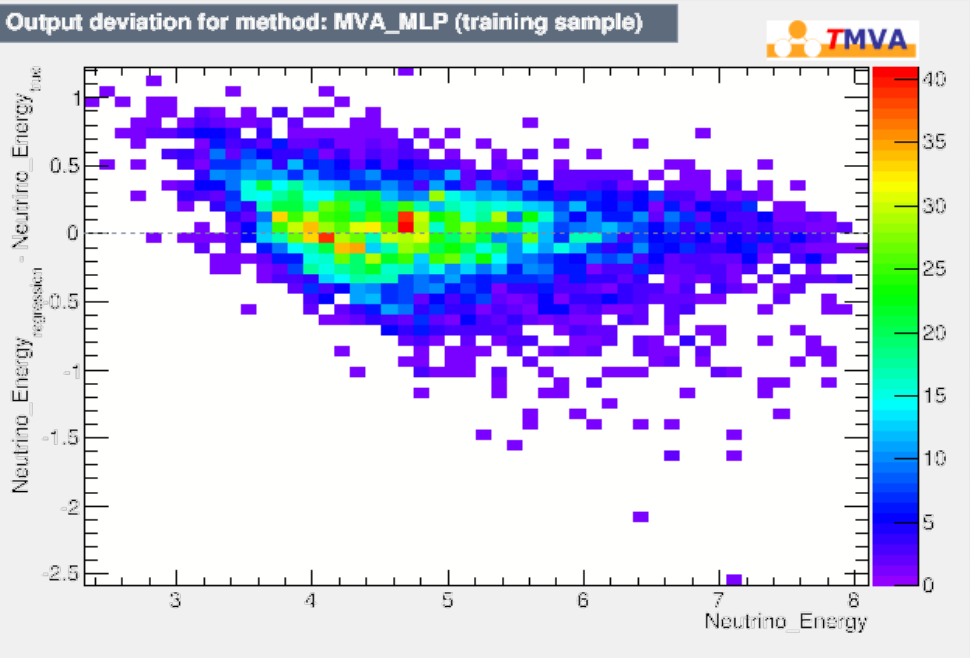
$$\frac{\log(\textit{Number of PMTs with Pulses})}{\log(\textit{Number of PMTs without Pulses})}$$

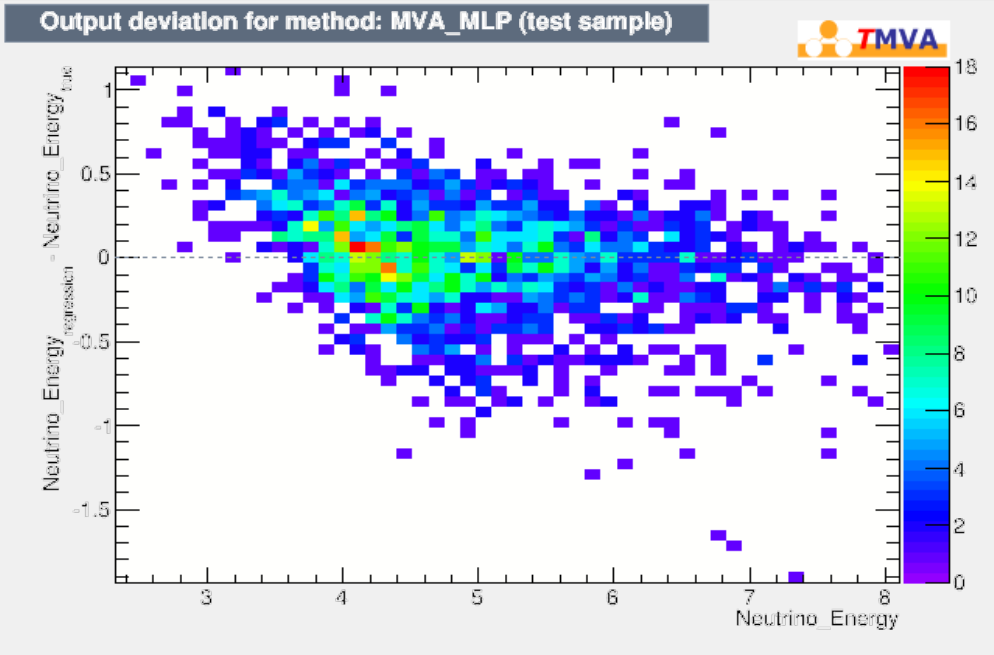


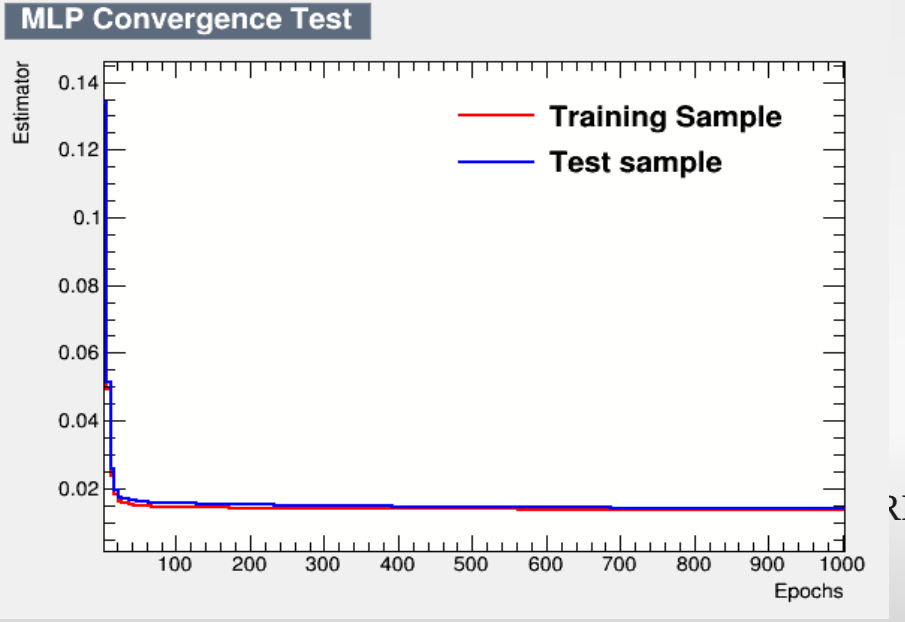


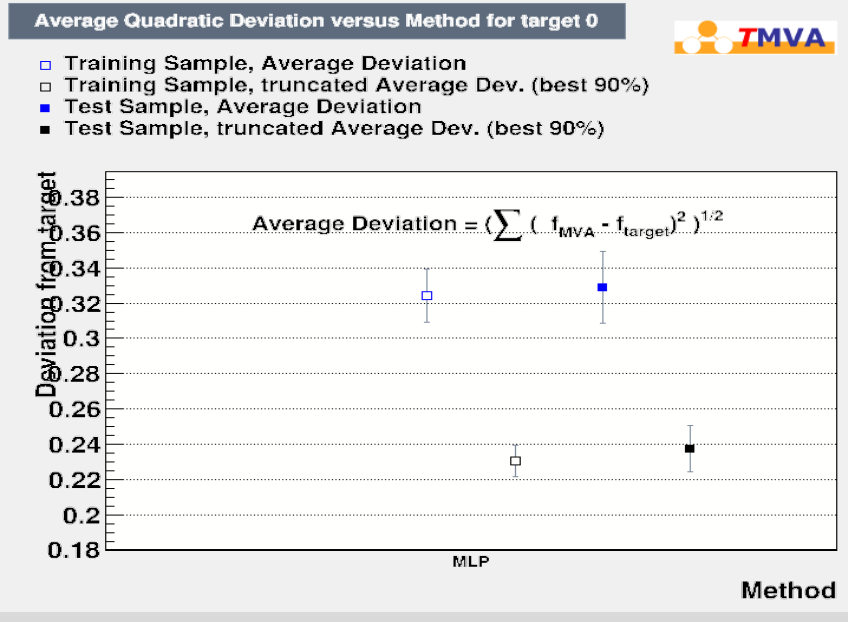


Neutrino Energy Estimation
MLP Performance



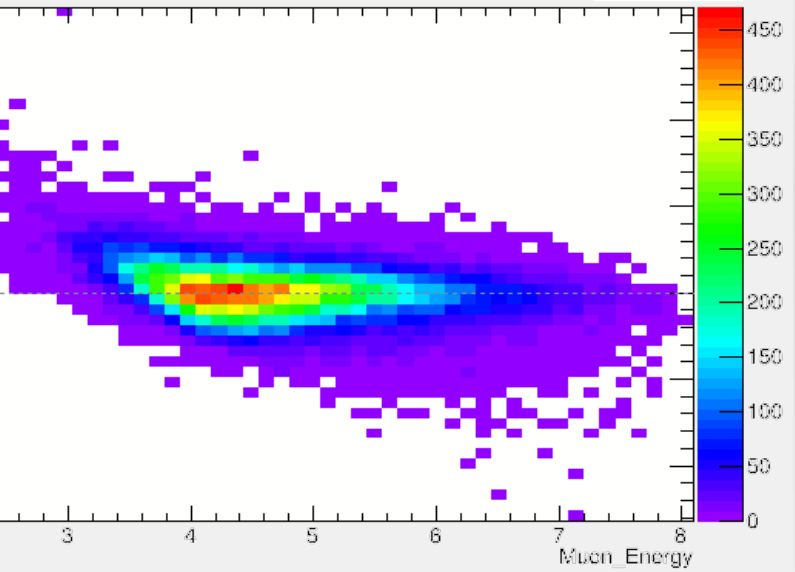


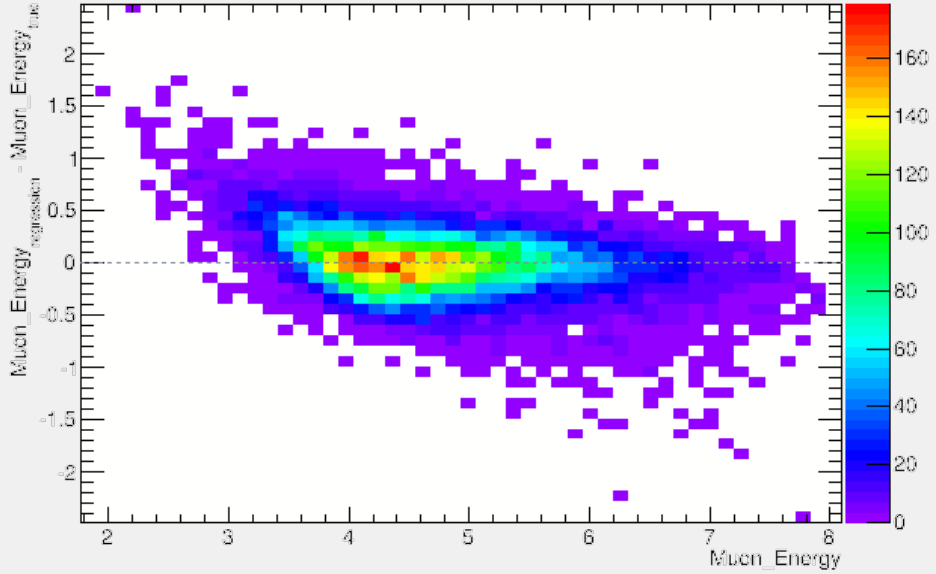


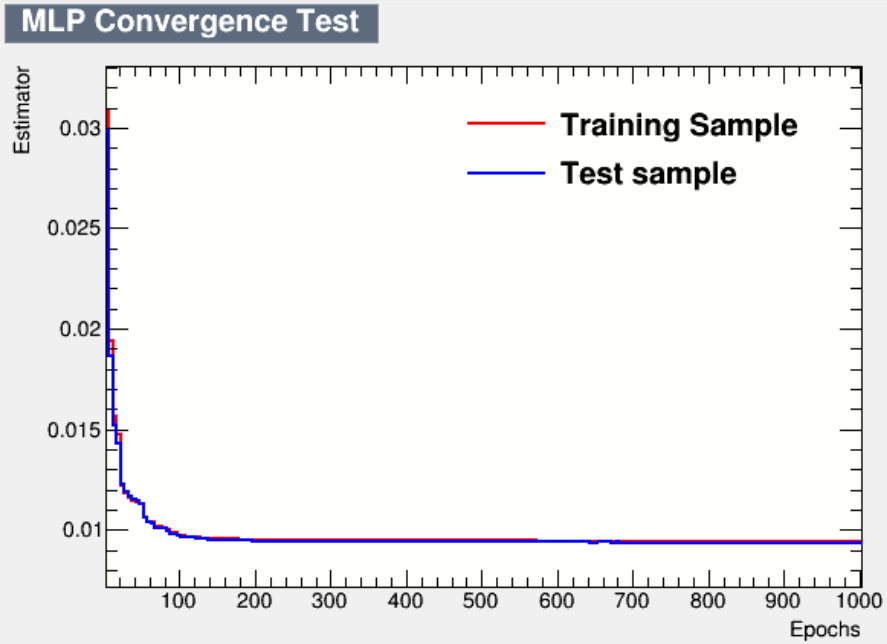


RICAP-2014

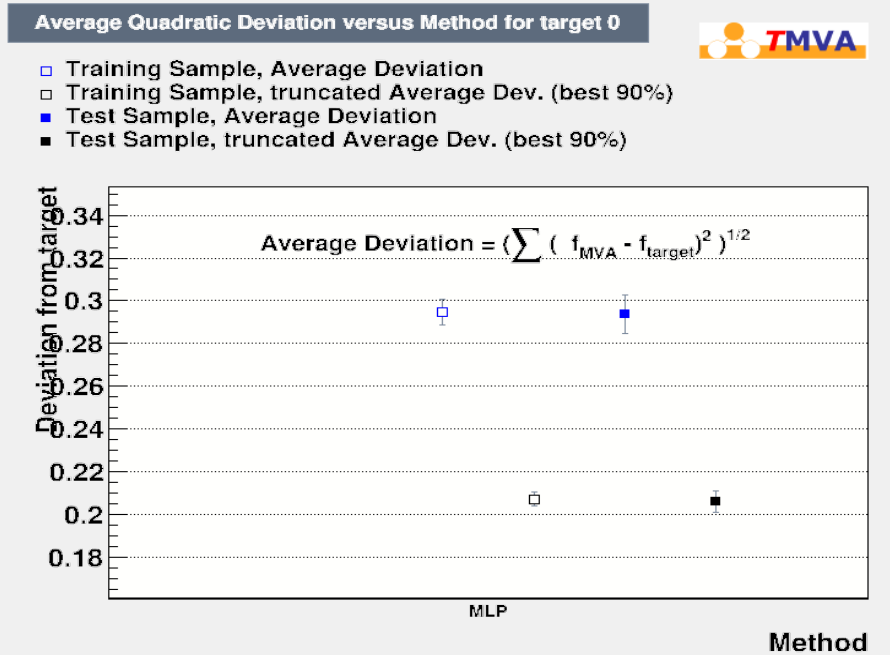
Muon Energy Estimation
MLP Performance





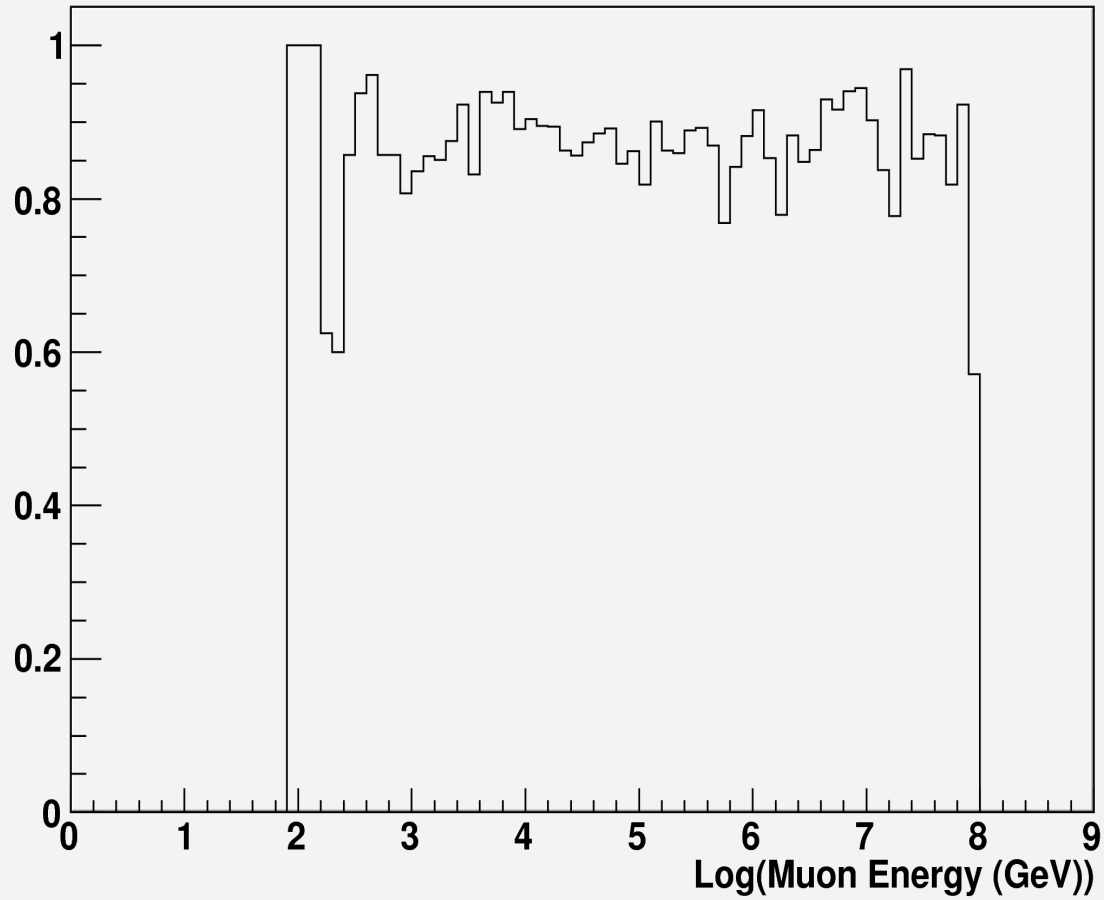


RICAP-2014



Well Reconstructed Events

$$\frac{\text{Selected Well Reconstructed Events for Energy Estimation}}{\text{Well Reconstructed Events}}$$



Motivation

- The energy is one of the most important parameters to discriminate between atmospheric and astrophysical events recorded by neutrino telescopes.

- Muons lose energy via :
  - Ionization
  - Stochastic processes

bremsstrahlung pair production photonuclear interactions

$$\frac{-dE_\mu}{dx} = A(E) + B(E)\,E_\mu$$

where: **A** ≈ 0.274 $GeV\,m^{-1}$ accounts for the energy loss due to ionization, and **B** ≈ 0.000349 m^{-1} is due to the stochastic energy loss.

Muon's Energy Estimation :

- Low Energy Muons
  - muon length

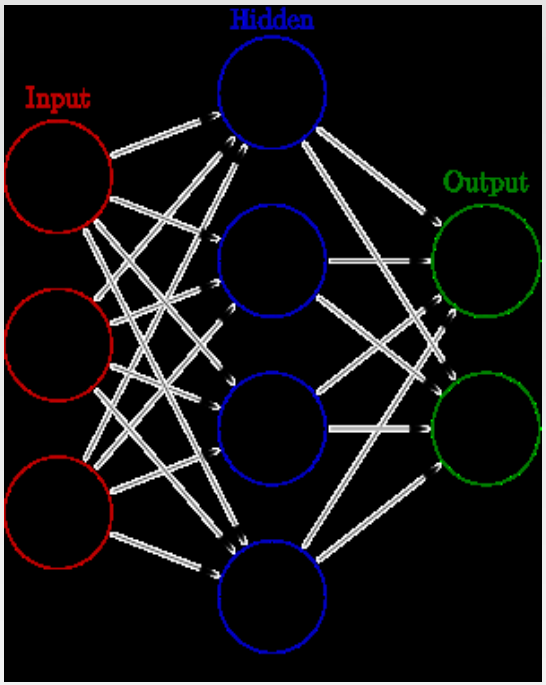
- High Energy Muons
  - light observation in PMTs

Backup Slides – MVA Methods

```
if (Use["MLP"])
factory->BookMethod( TMVA::Types::kMLP, "MLP", "!H:!V:VarTransform=Norm
:NeuronType=tanh:NCycles=1000:HiddenLayers=N+6:TestRate=5:TrainingMethod=BFGS :
!UseRegulator" );

 factory->AddVariable("Widthtot", "Widthtot", "units", 'F');
 factory->AddVariable("PMTs_hit_to_nohit", "PMTs_hit_to_nohit", "units", 'F');
 factory->AddVariable("No_OMs_length_potential_length_chosen",
       "No_OMs_length_potential_length_chosen", "units", 'F');
 factory->AddVariable("Log_No_PMTs_with_dist_weights_MAXhits",
       "Log_No_PMTs_with_dist_weights_MAXhits", "units", 'F');
```

Backup Slides – MVA Methods



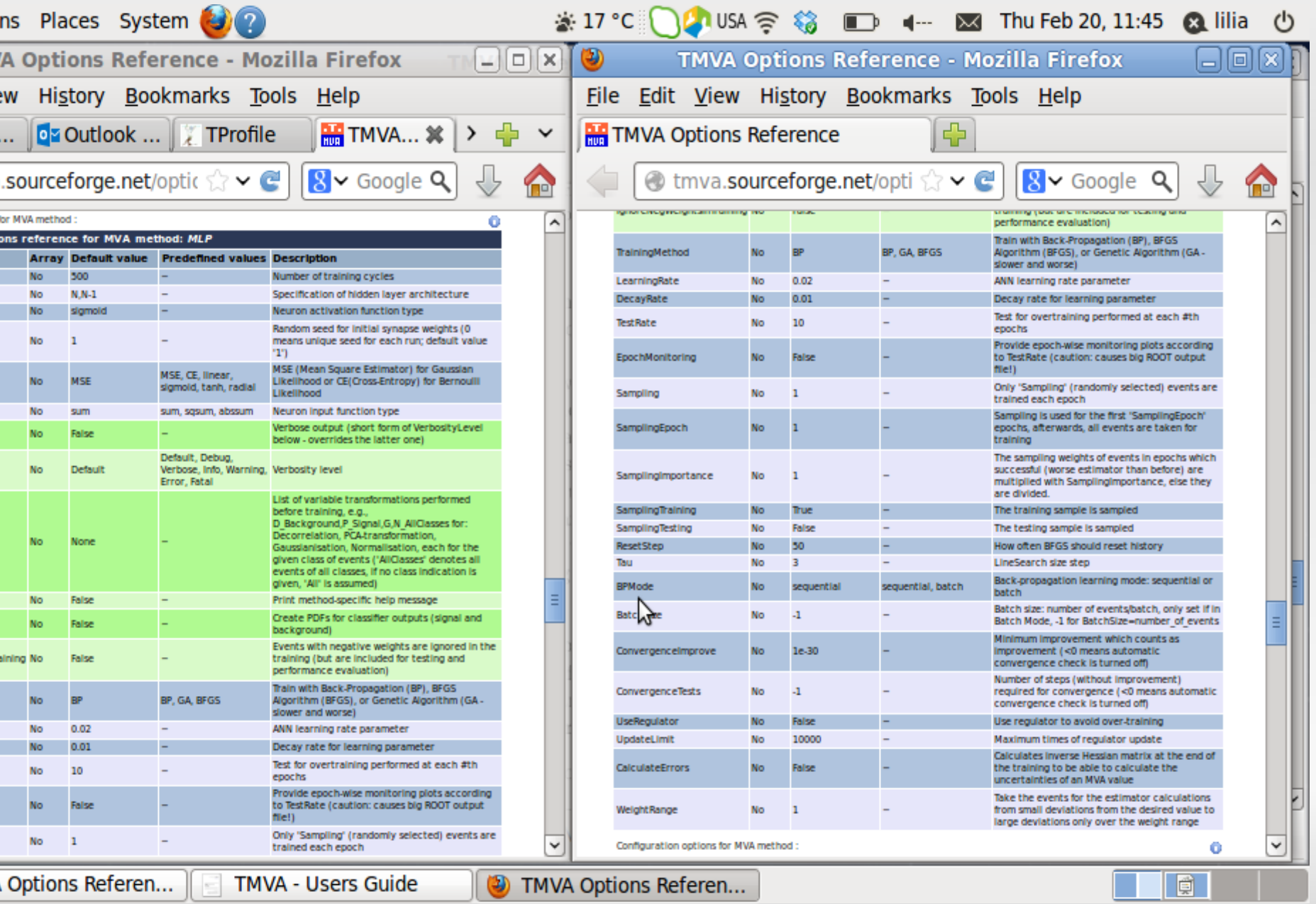
BFGS Training Method at MLP

The Broyden-Fletcher-Goldfarb-Shannon (BFGS) method differs from back propagation by the use of second derivatives of the error function to adapt the synapse weight by an algorithm which is composed of four main steps.

→ During the learning process the network is supplied with N training events x_a = (x1 , . . . , xnvar)$_a$,$_a$ = 1, . . . , N . For each training event $_a$ the neural network output $y_{ANN,a}$ is computed and compared to the desired output y_a. The error function E, is measuring the agreement of the network response with the desired one. The set of weights that minimises the error function can be found using the method of steepest or gradient descent, provided that the neuron response function is differentiable with respect to the input weights.

The advantage of the BFGS method compared to BG is the smaller number of iterations.

Backup Slides – MVA Methods



Counting PMTs that could have hits but they don't → checking only PMTs whose angle between their direction with the reconstructed track is more than 6 degrees and less than 86 degrees