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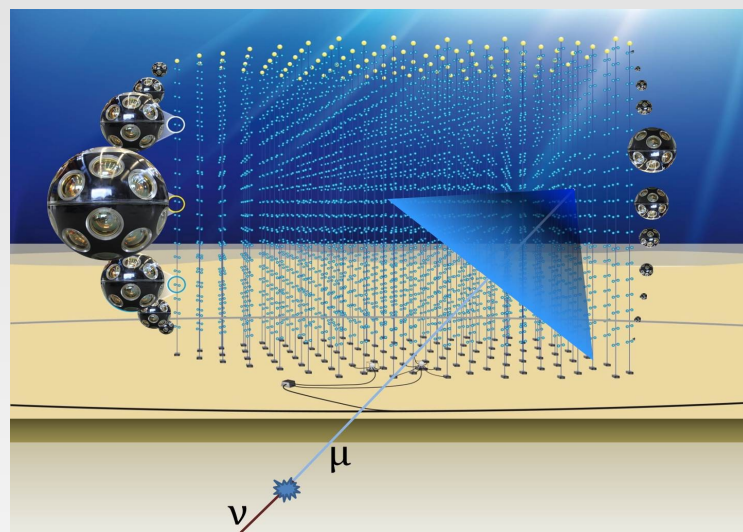


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MANAGING AUTHORITY

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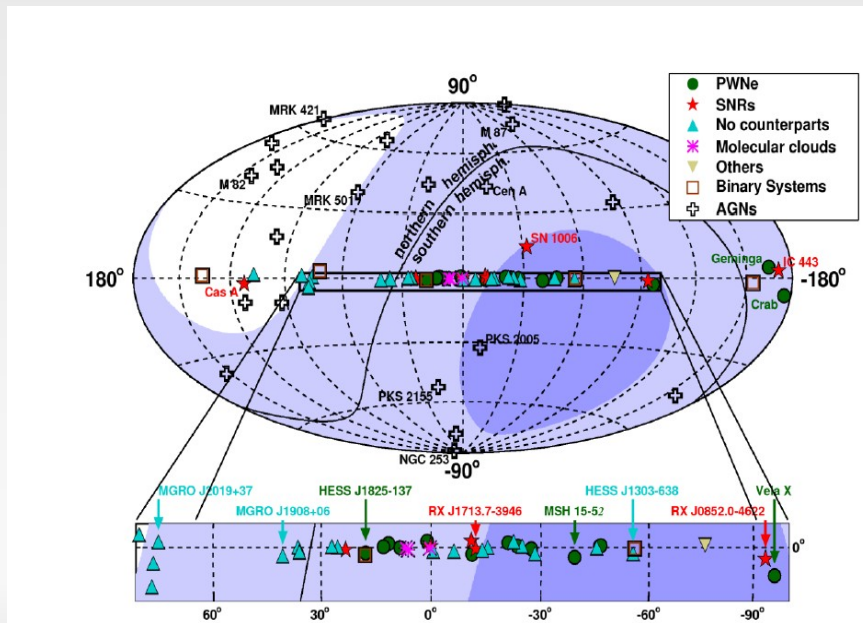


Muon and Neutrino Energy Reconstruction for KM3NeT

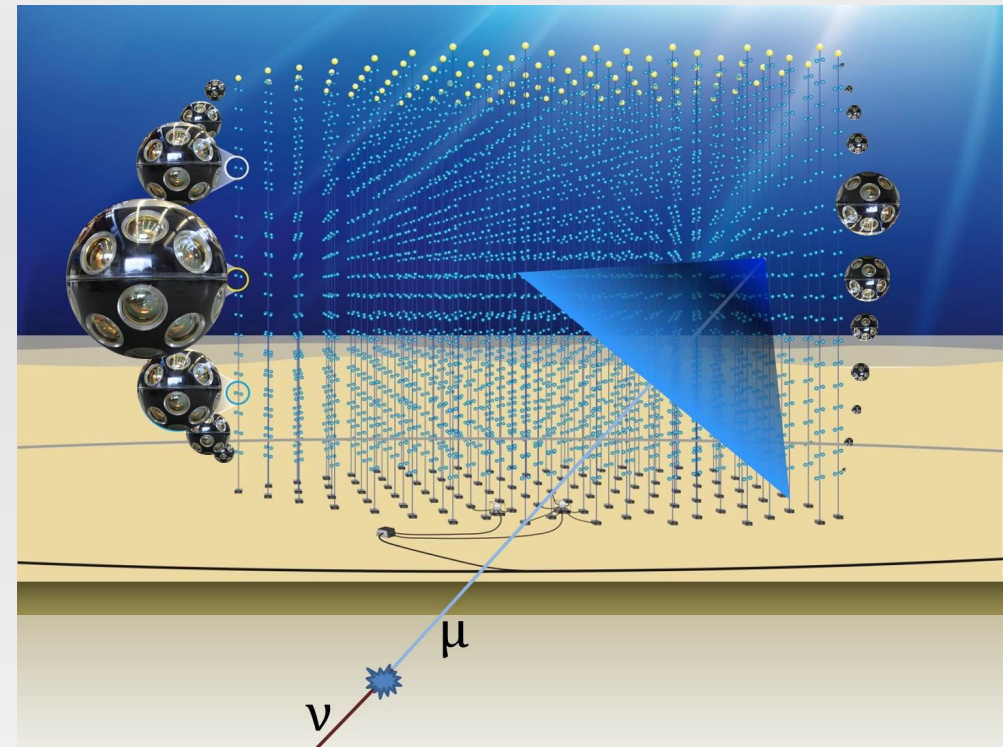


Drakopoulou Evangelia
N.C.S.R. Demokritos

- **KM3NeT** → Neutrino Telescope with volume of **several km³** 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).

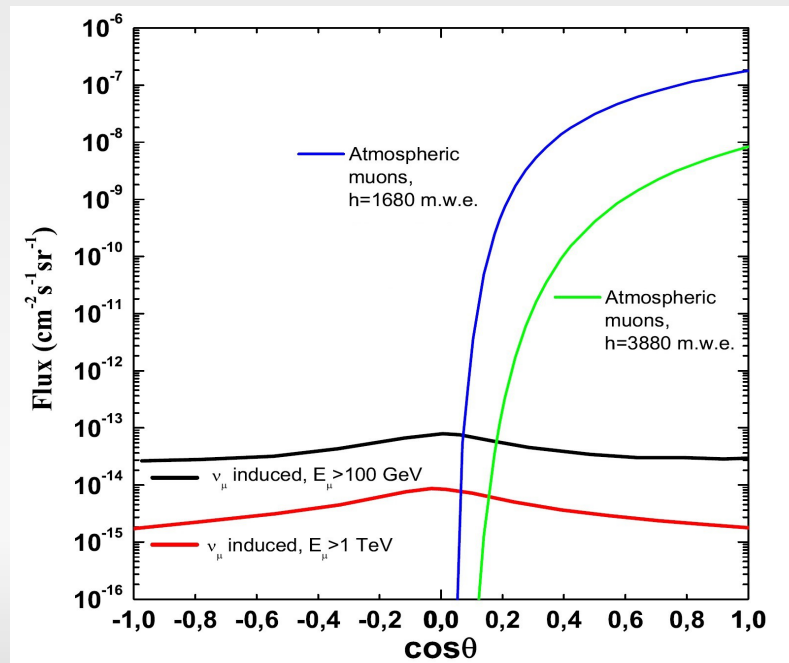


Evangelia Drakopoulou

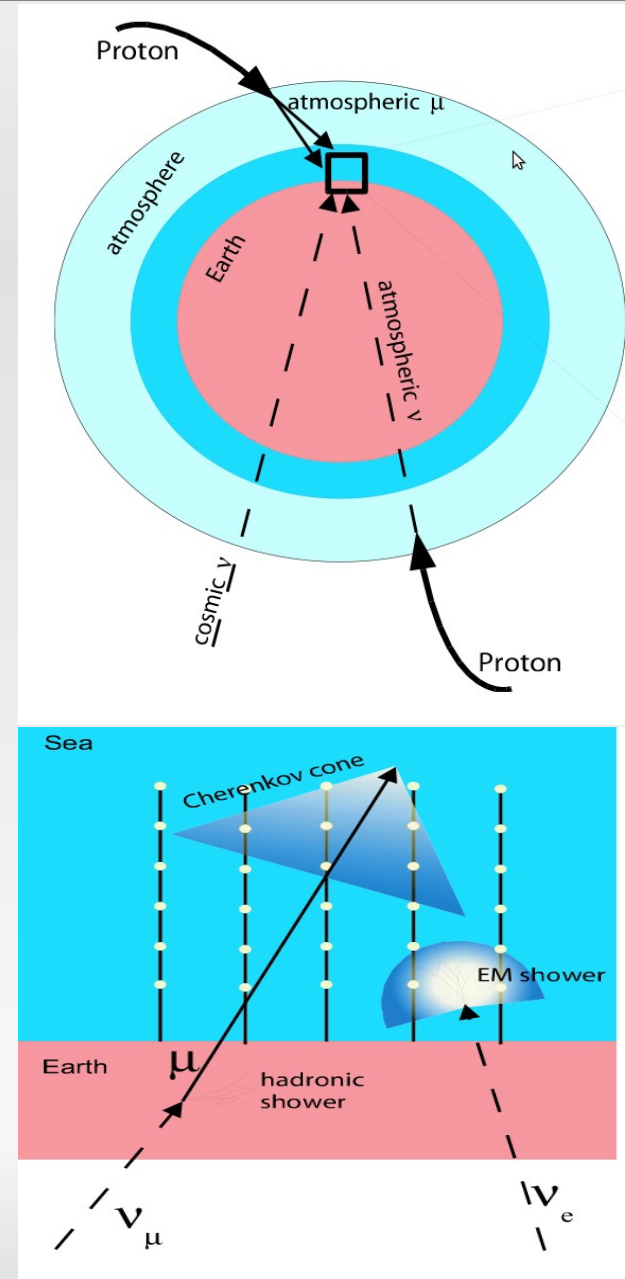


- Sky coverage in galactic coordinates for a detector located in the Mediterranean Sea.
- Dark (light) areas are visible at least 75% (25%) of the time.

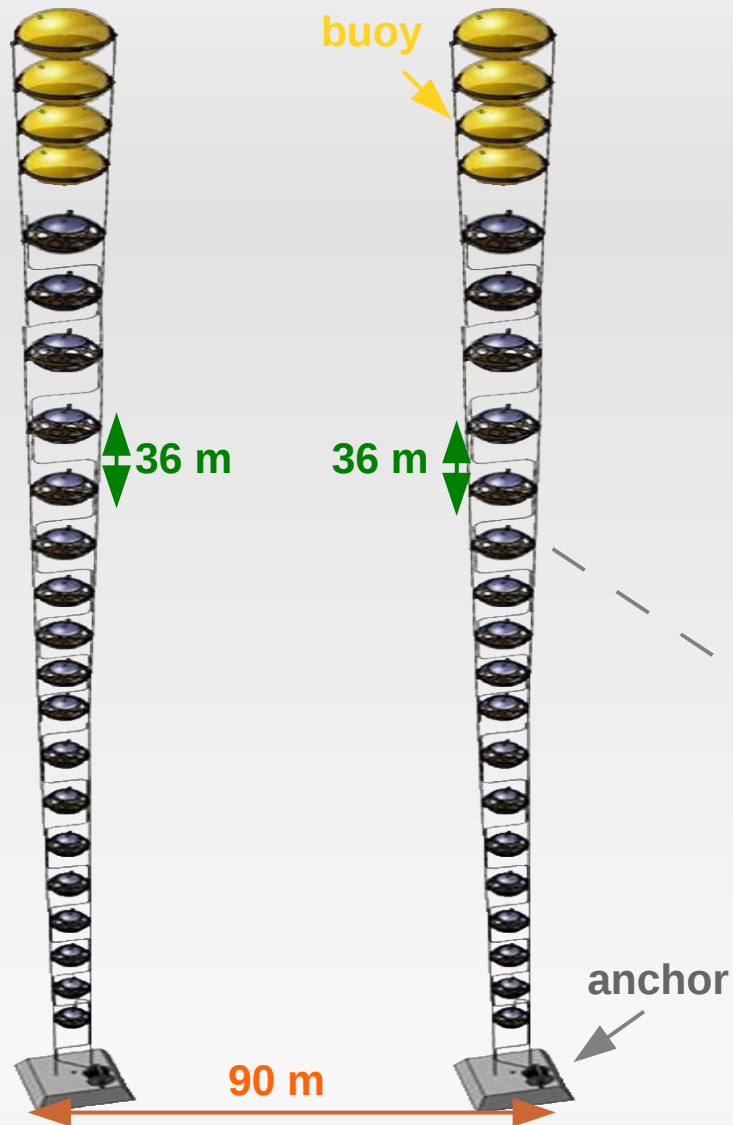
- **Atmospheric Muons** : contained in the extensive air showers produced by cosmic rays in the atmosphere.
- **Atmospheric Neutrinos** : produced by charged kaons or pions in cosmic rays interactions in the atmosphere.
- K^{40} : radioactive potassium isotope
- **Bioluminescence** : life forms that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



Evangelia Drakopoulou



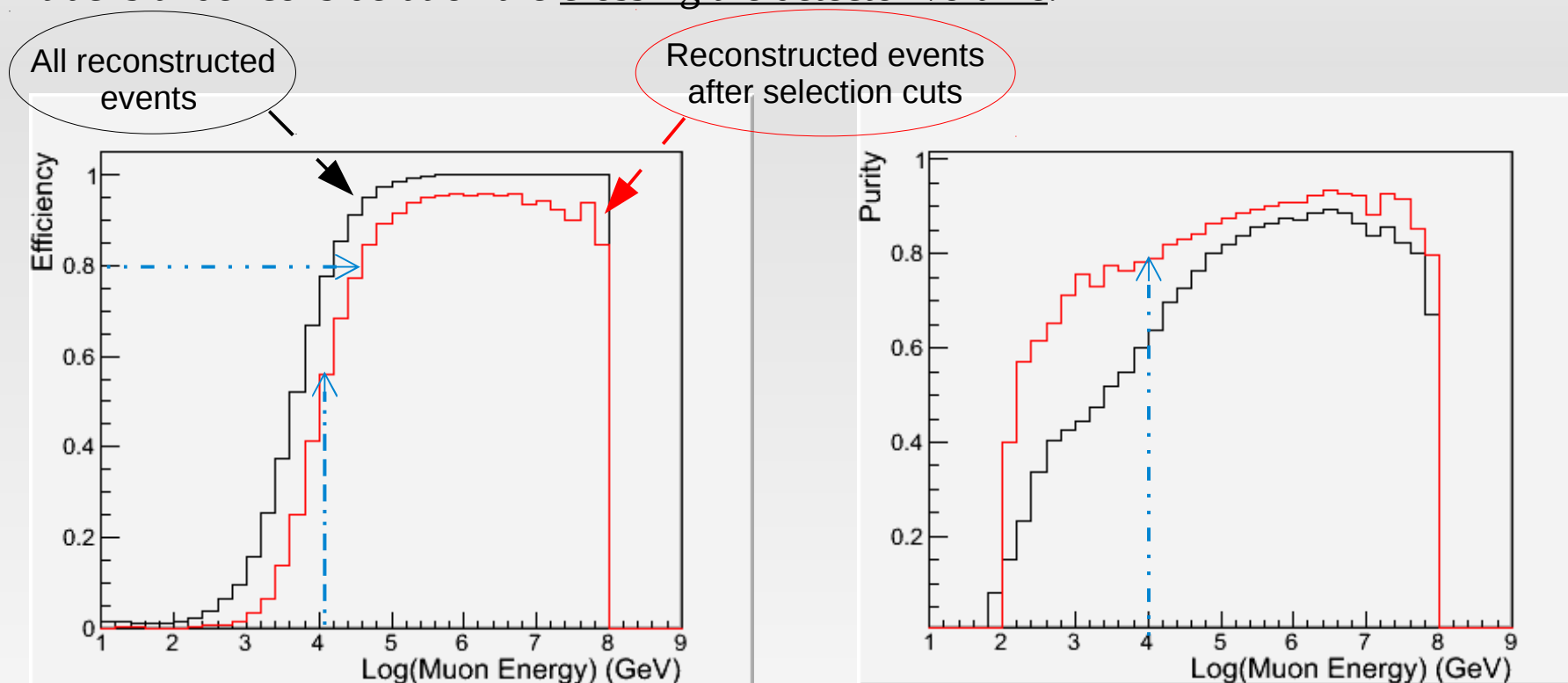
Detector Configuration



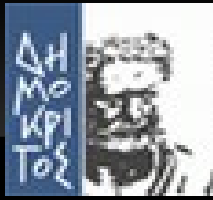
- Each of the 6 blocks has an almost hexagonal geometry with **115 strings** at **90m** distance. Each string has **18 floors** and each floor has **1 Optical Module (OM)**.
- The optical modules are arranged in **vertical strings** with a height of almost **600m**.
- All data are transmitted to shore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



- 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 ($\geq 80\%$) of the reconstructed events for $E_\mu \geq 10 \text{ TeV}$ can be attained, with an efficiency of 55% for $E_\mu \geq 10 \text{ TeV}$.
- The efficiency is $\geq 80\%$ for $E_\mu \geq 40 \text{ TeV}$ rising with energy to $\sim 95\%$ for $E_\mu \geq 100 \text{ TeV}$.



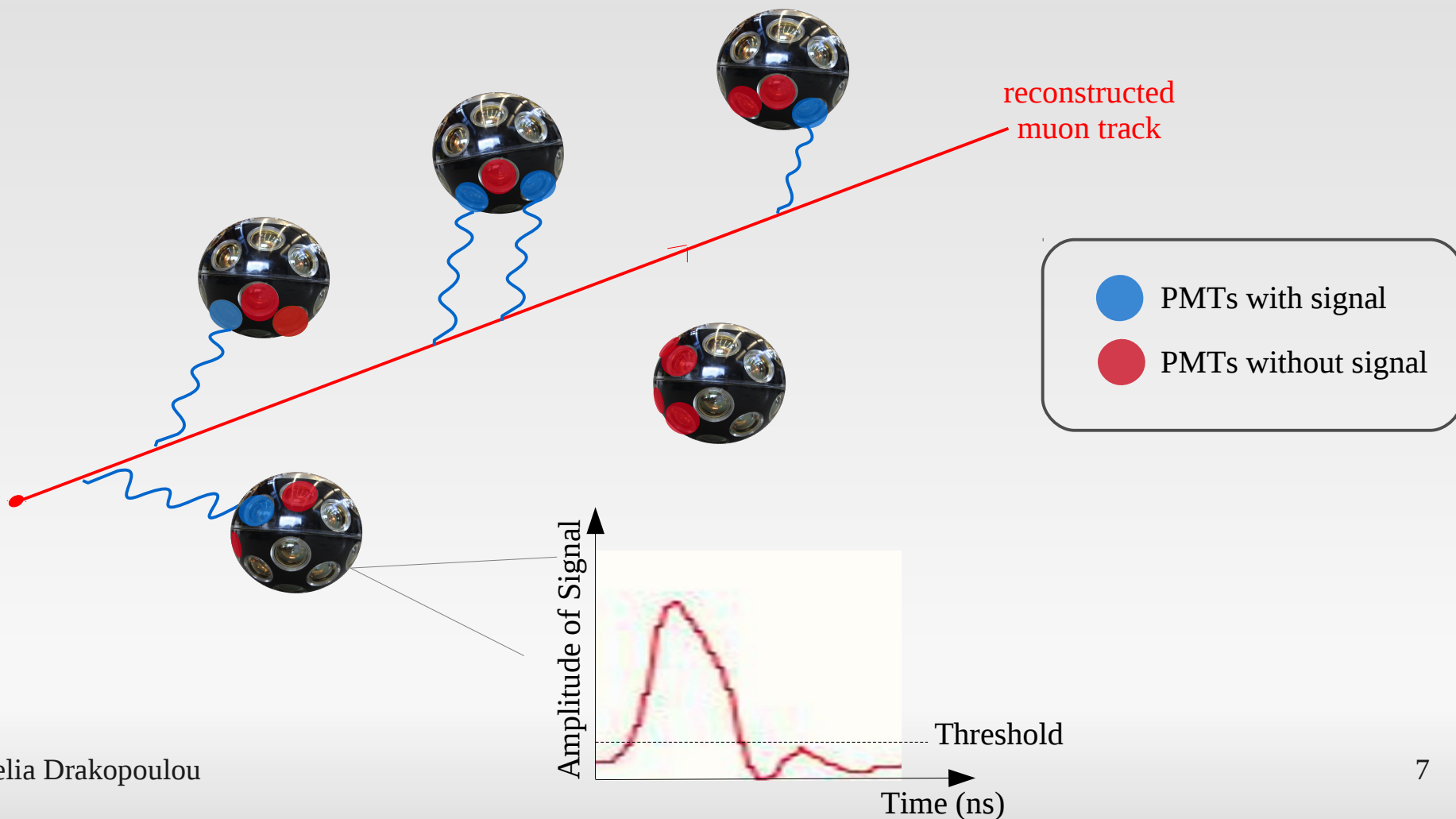
MultiVariate Analysis



- **Muon and Neutrino Energy Estimation:** a Multi-Layer Perceptron (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

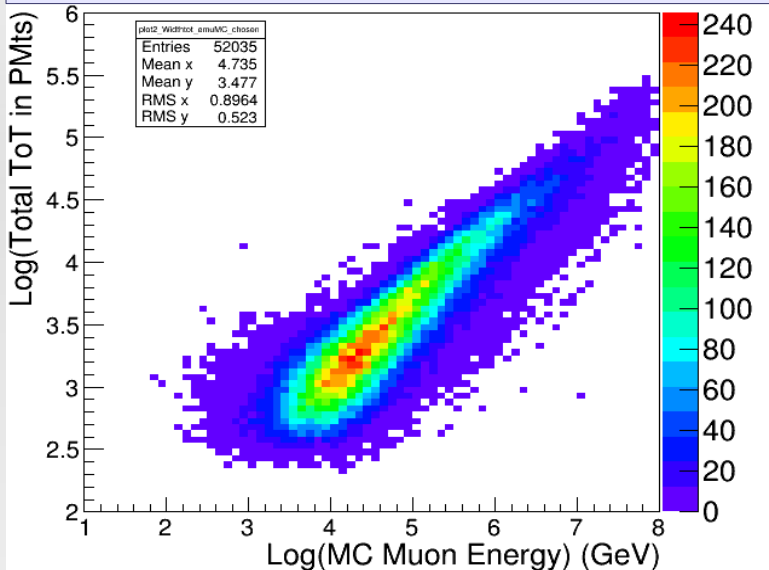




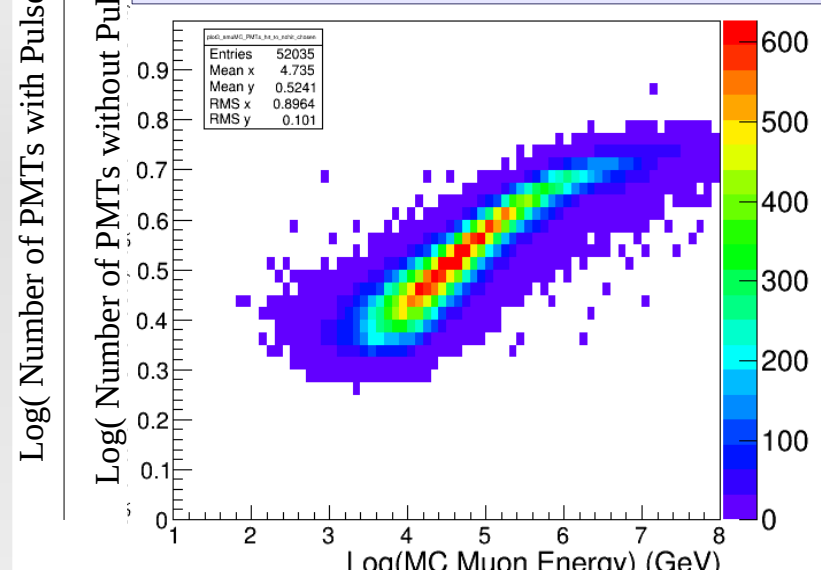
Muon Energy Estimation Neural Network Input Variables



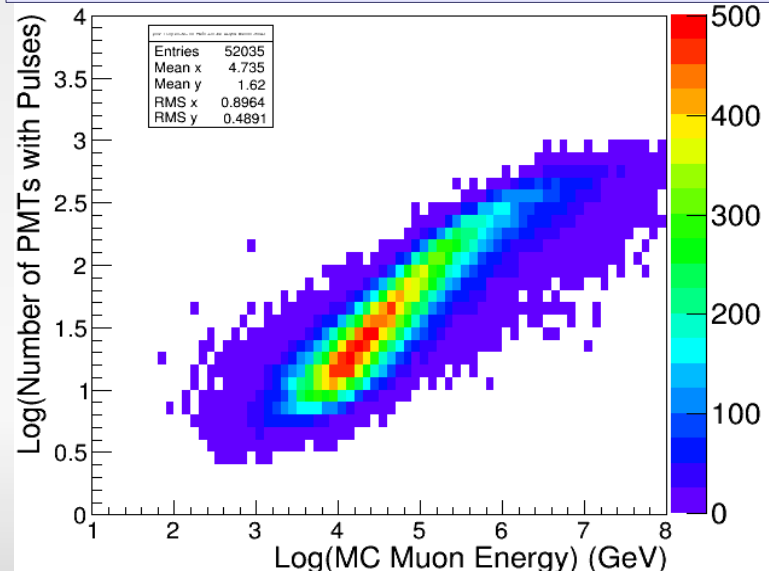
Total Time over Threshold (ToT) in PMTs



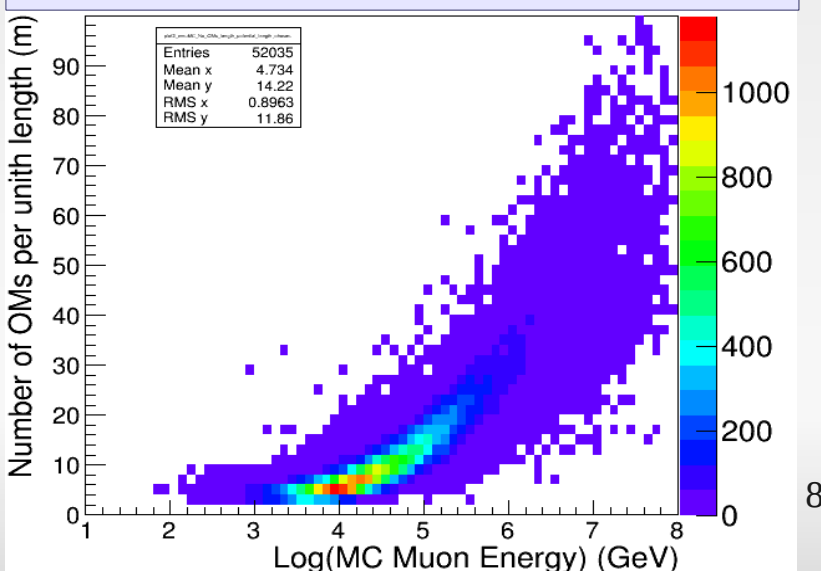
Number of PMTs without signal



Number of PMTs with signal



Number of OMs with signal

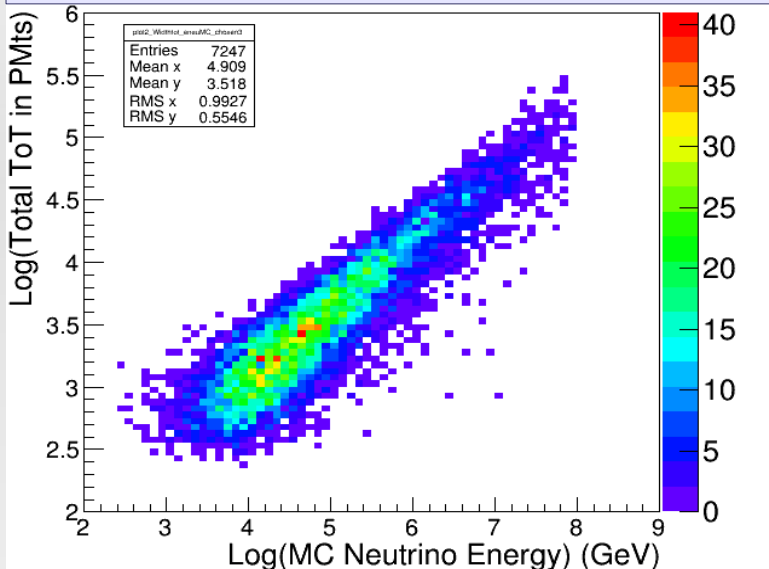




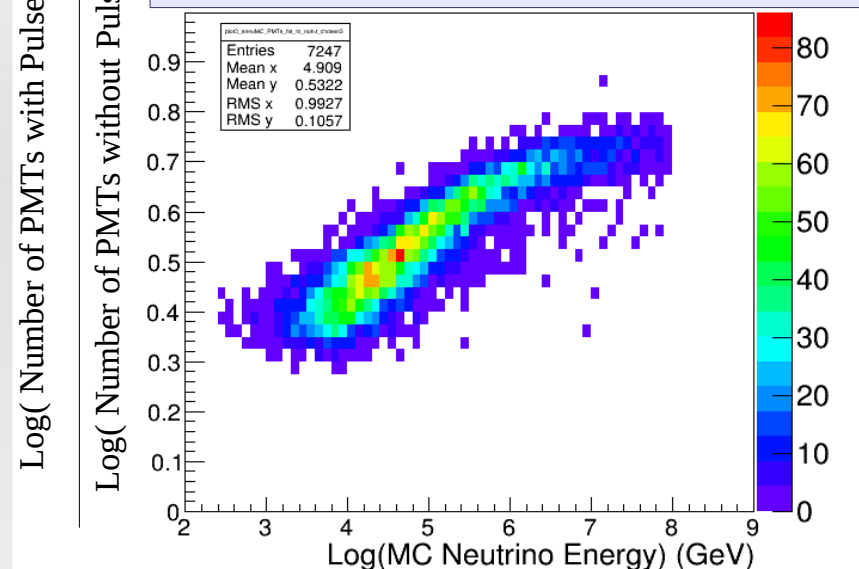
Neutrino Energy Estimation Neural Network Input Variables



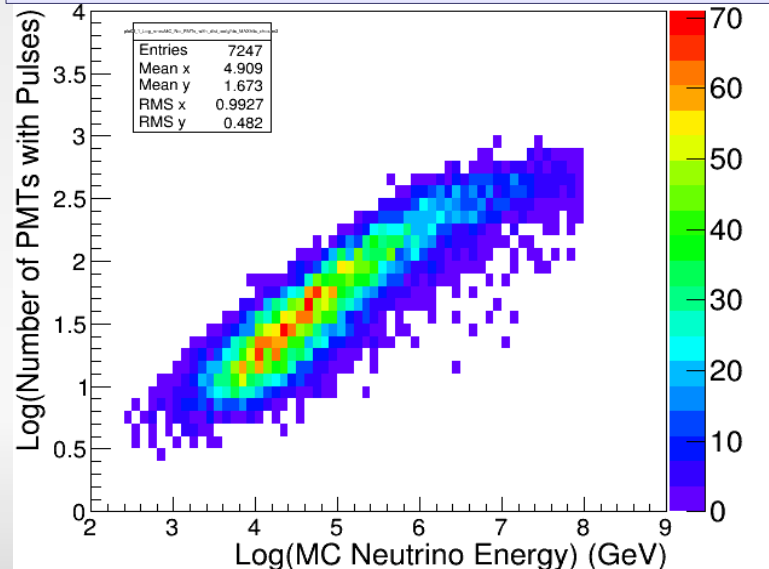
Total Time over Threshold (ToT) in PMTs



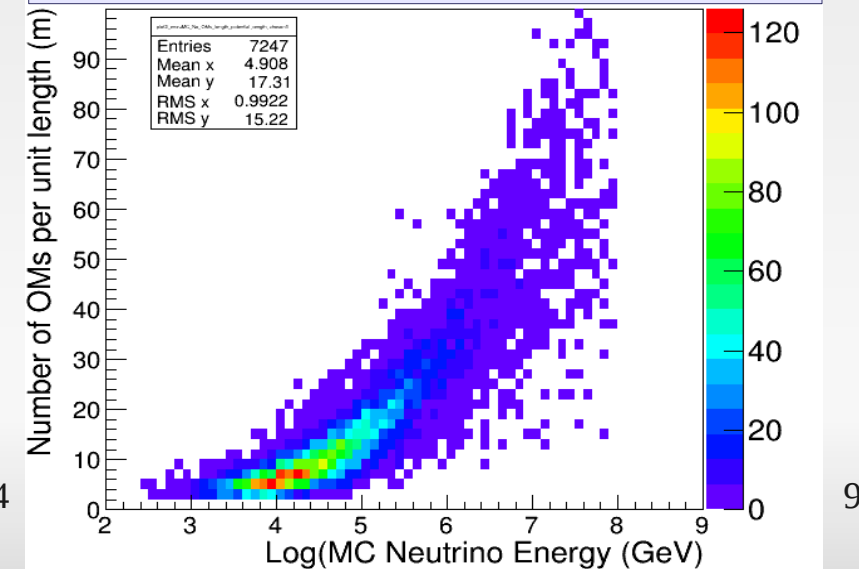
Number of PMTs without signal



Number of PMTs with signal



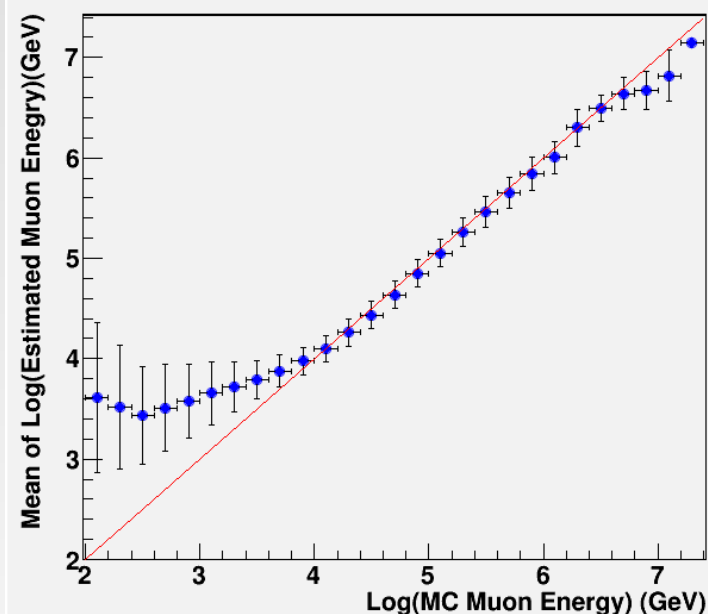
Number of OMs with signal



Results in Muon and Neutrino Energy Estimation

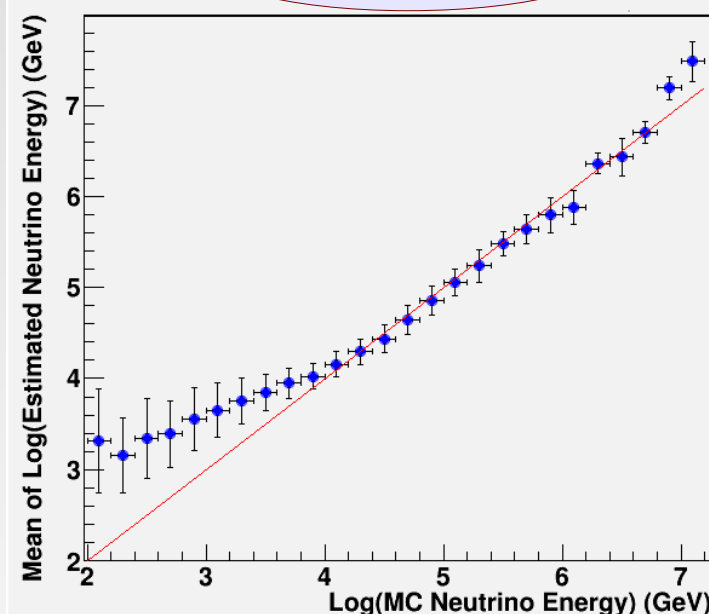
Muons crossing the detector volume

Muon Energy



Events with the neutrino vertex close to the detector volume

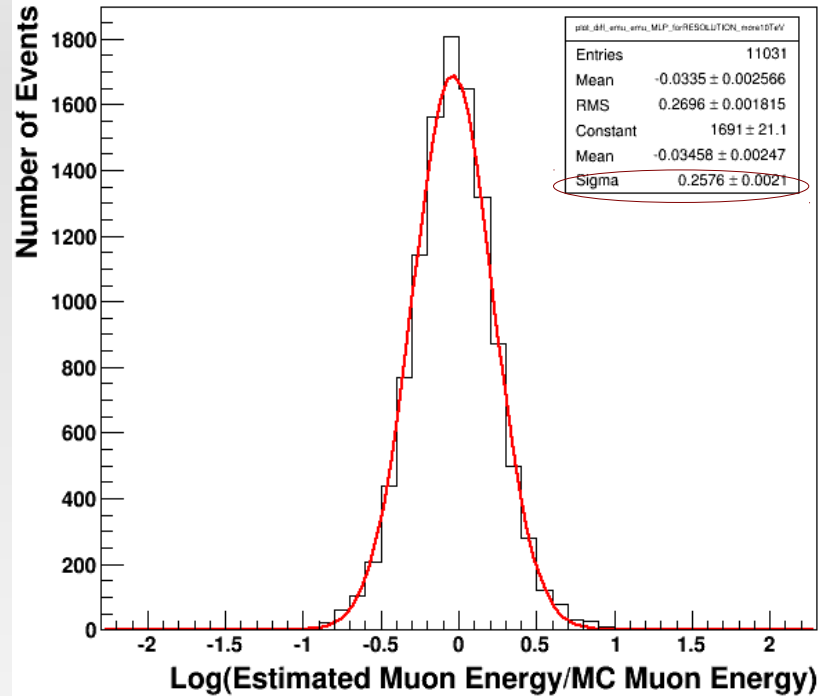
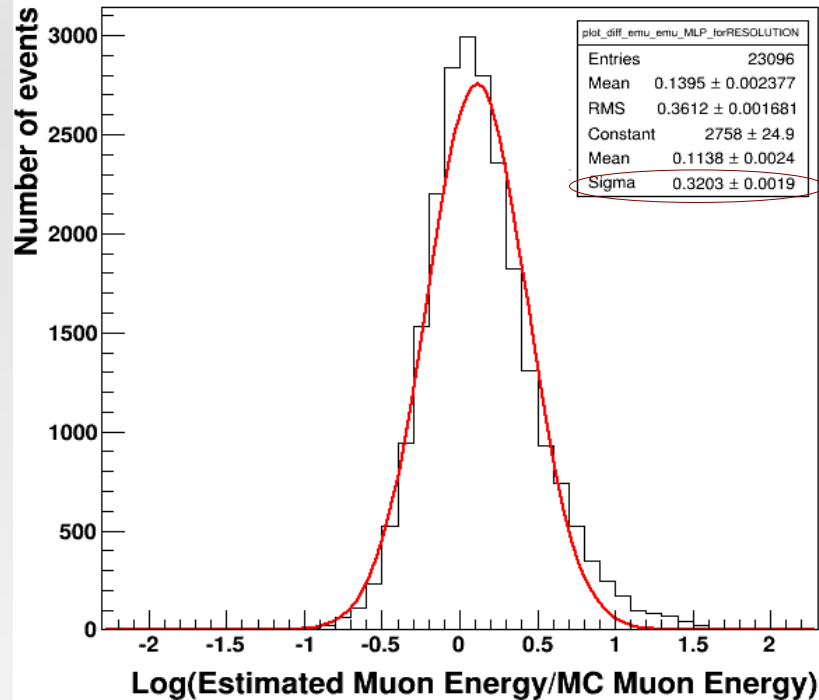
Neutrino Energy



- For muon energies $E_\mu < 1 \text{ TeV}$ we overestimate the energy, while there is a very good linear correlation for $E_\mu \geq 10 \text{ TeV}$.
- 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 $E_\nu \geq 10 \text{ TeV}$.

$$100 \text{ GeV} \leq E_{\mu} \leq 20 \text{ PeV}$$

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



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 $E_{\mu} \geq 10 \text{ TeV}$.



Neutrino Energy Resolution



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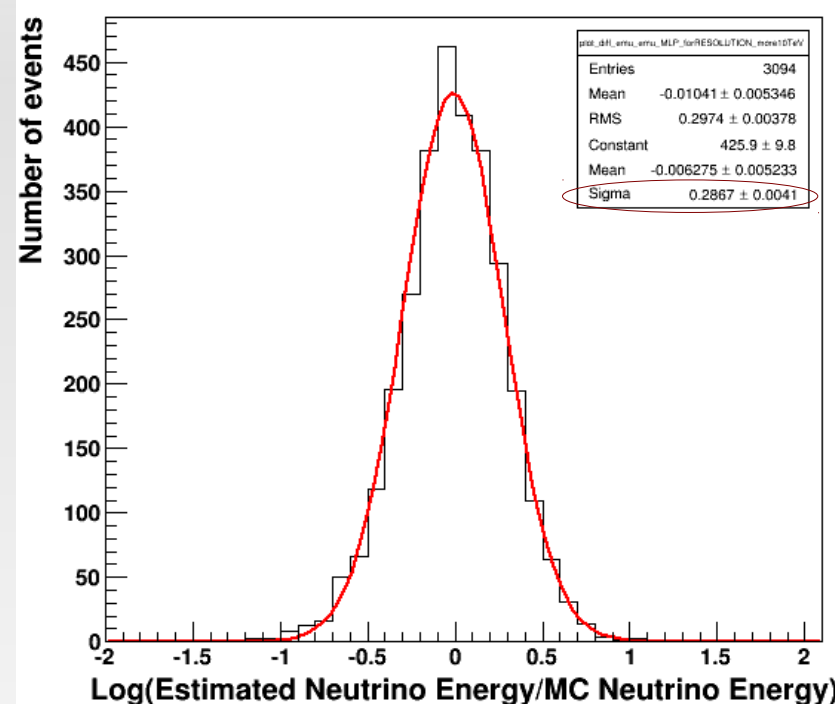
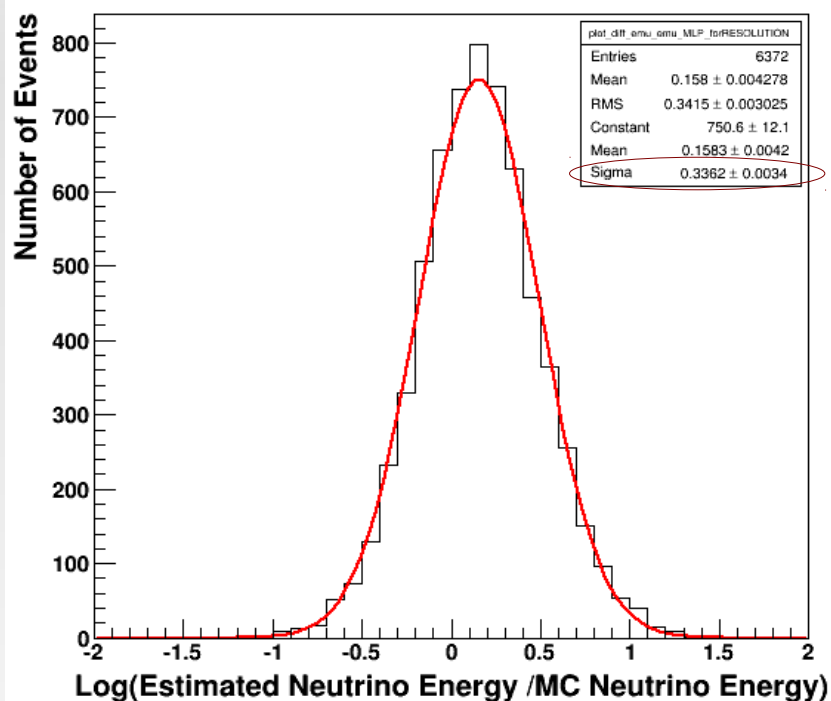
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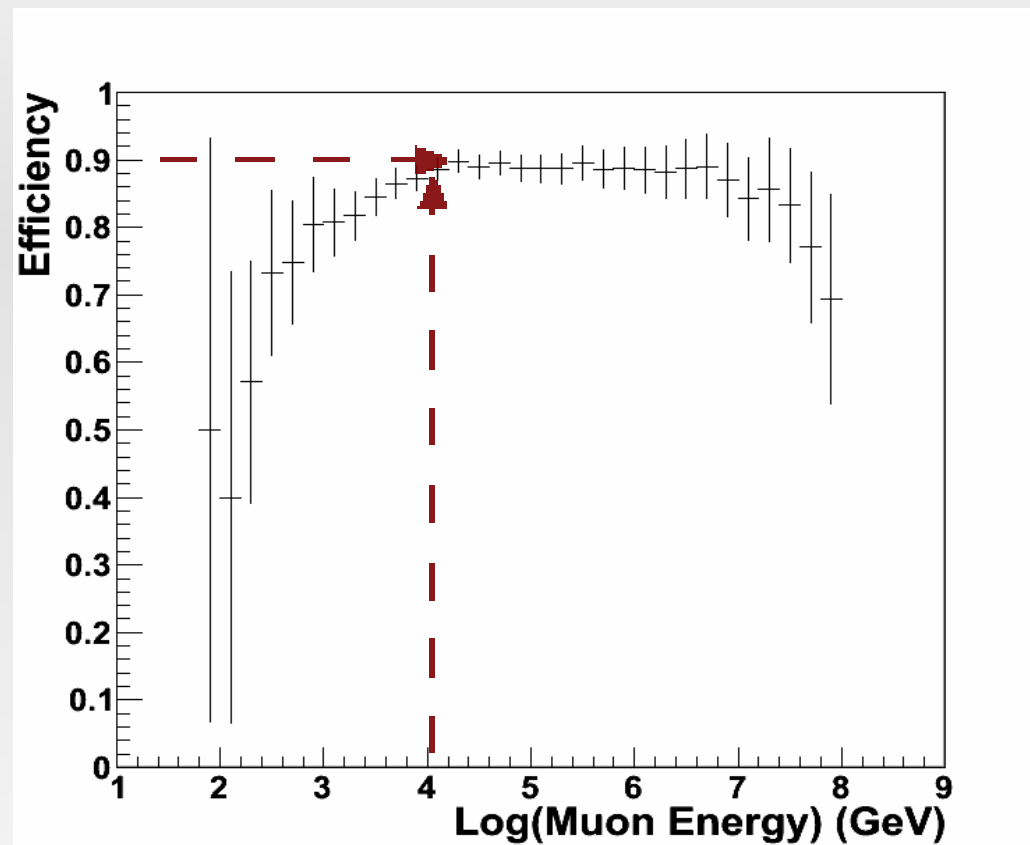
$$100 \text{ GeV} \leq E_\nu \leq 20 \text{ PeV}$$

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



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 $E_\nu \geq 10 \text{ TeV}$.



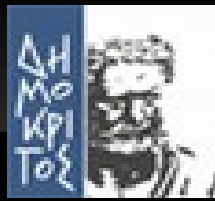
- A very high efficiency for the energy reconstruction is achieved of $\sim 88\%$ for all events crossing the detector volume.
- The efficiency is $\sim 89\%$ for $E_\mu \geq 10 \text{ TeV}$ peaking at $\sim 90\%$ for $E_\mu \simeq 20 \text{ TeV}$.



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 ($E_\mu \geq 10 \text{ TeV}$) 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 $E_\mu \geq 10 \text{ TeV}$.
- The energy resolution is about 0.34 in $\log_{10} E_\nu$ for neutrinos over all energies and becomes **0.29** for $E_\nu \geq 10 \text{ TeV}$.



Backup Slides

Energy Reconstruction Selecting Cuts

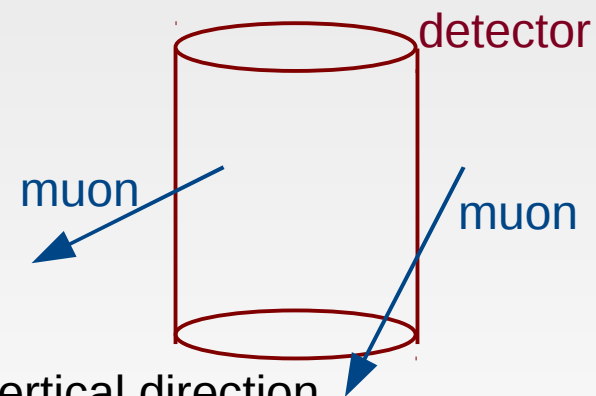
- Minimum Expected Path = $0.5 \cdot h + (R - 0.5 \cdot h) \cdot \sin(\theta_{\text{rec}})$

where: **h**: string's height, **R**: detector radius, **θ_{rec}** : reconstructed muon angle

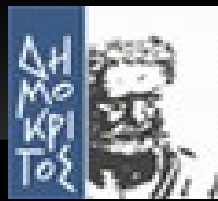
- ➔ For Horizontal Muons Minimum Expected Path is the Detector Radius
- ➔ For Vertical Muons Minimum Expected Path is 0.5*String height

- 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:

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



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



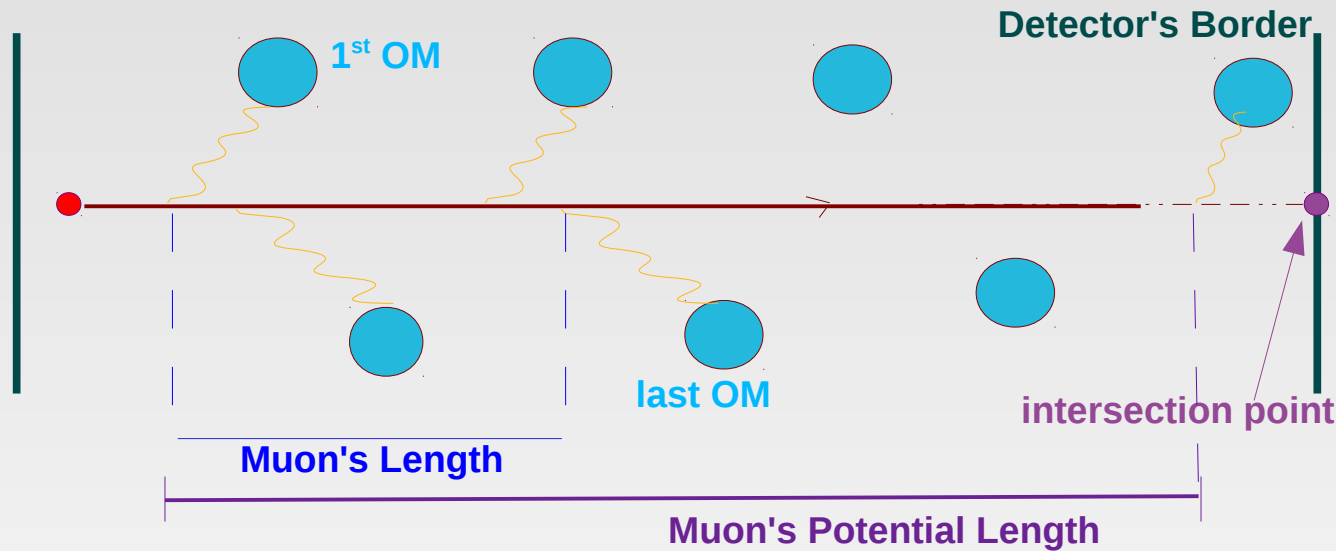
Explaining Selection Cuts



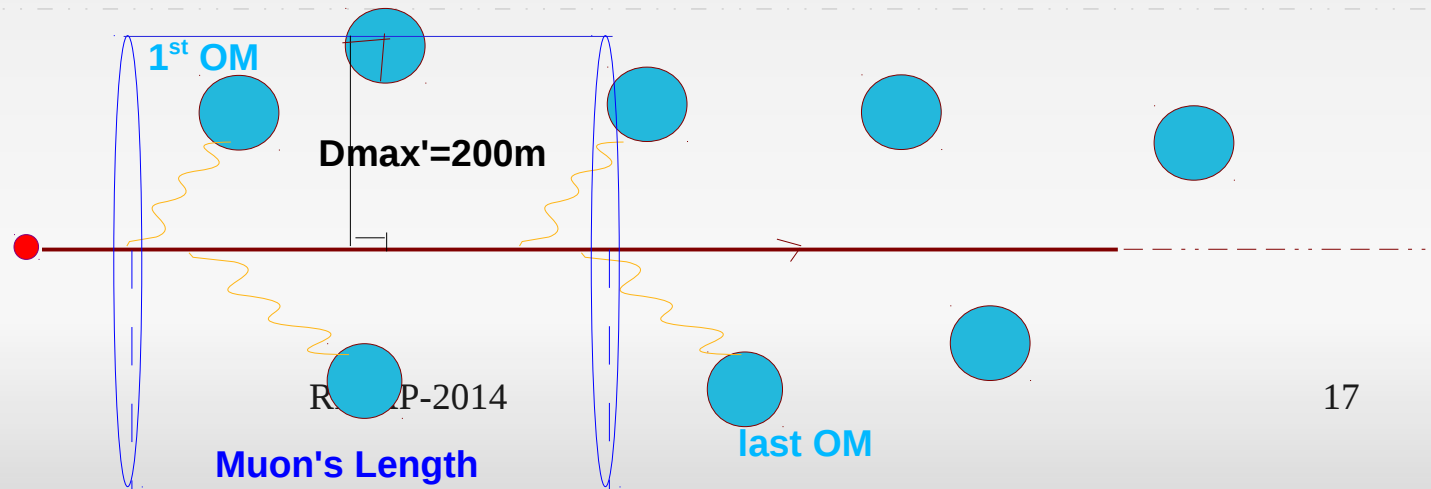
PMTs weight: $\sum \frac{D_i}{D_{max}}$



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

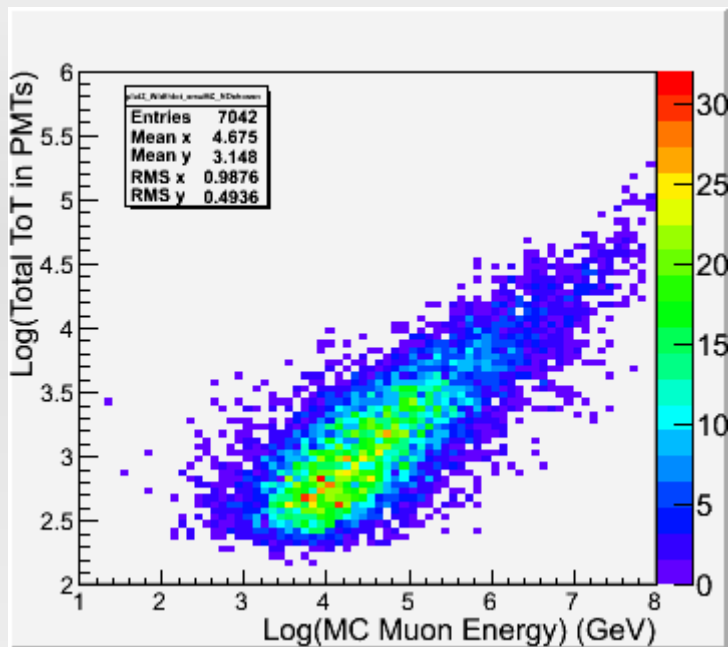


$\frac{\text{PMTs with hits}}{\text{PMTs without hits}}$

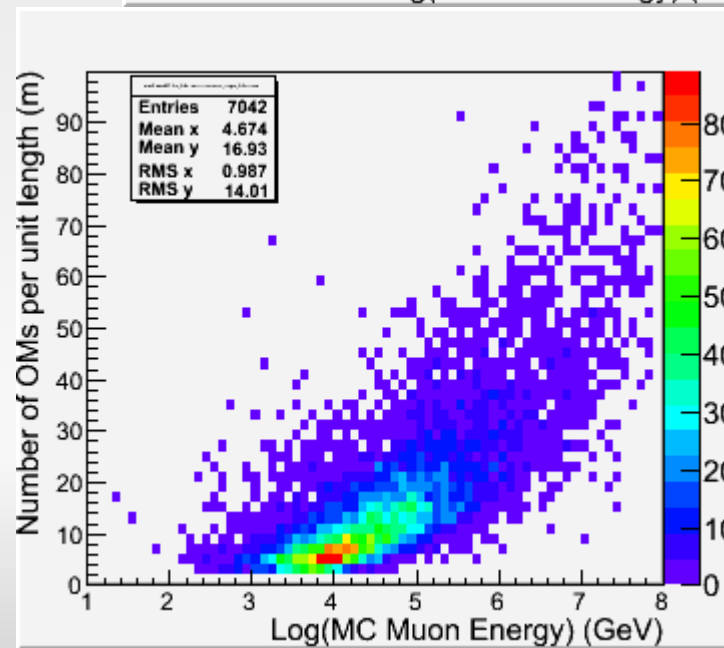
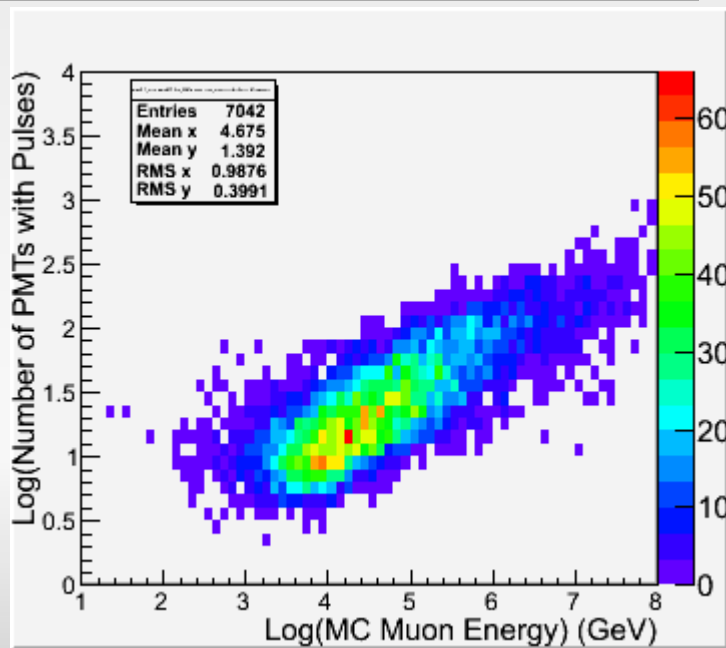
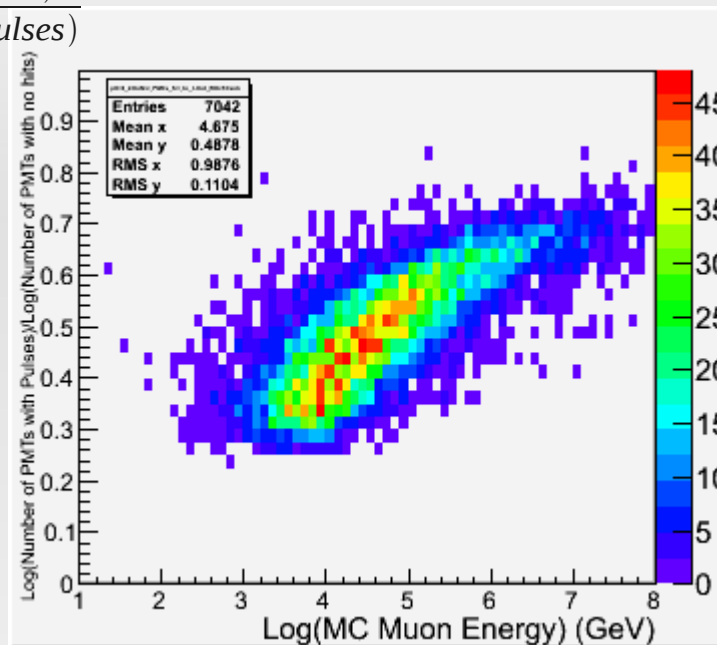




Events that fail to satisfy the selection criteria

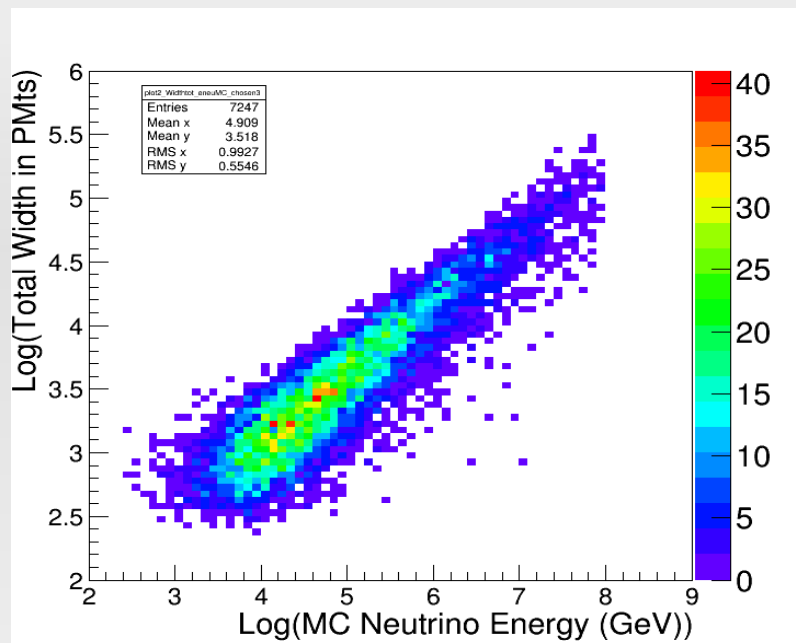


$$\frac{\log(\text{Number of PMTs with Pulses})}{\log(\text{Number of PMTs without Pulses})}$$

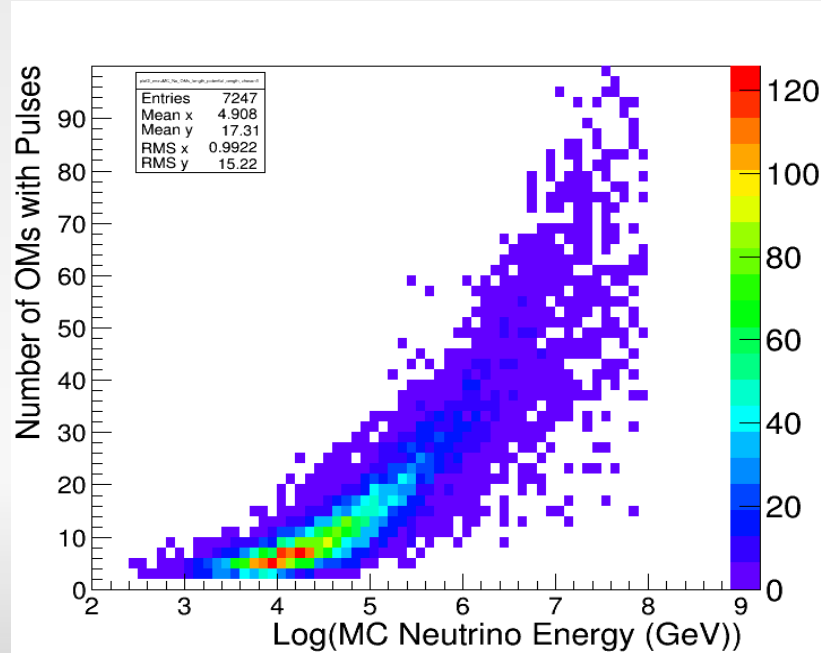
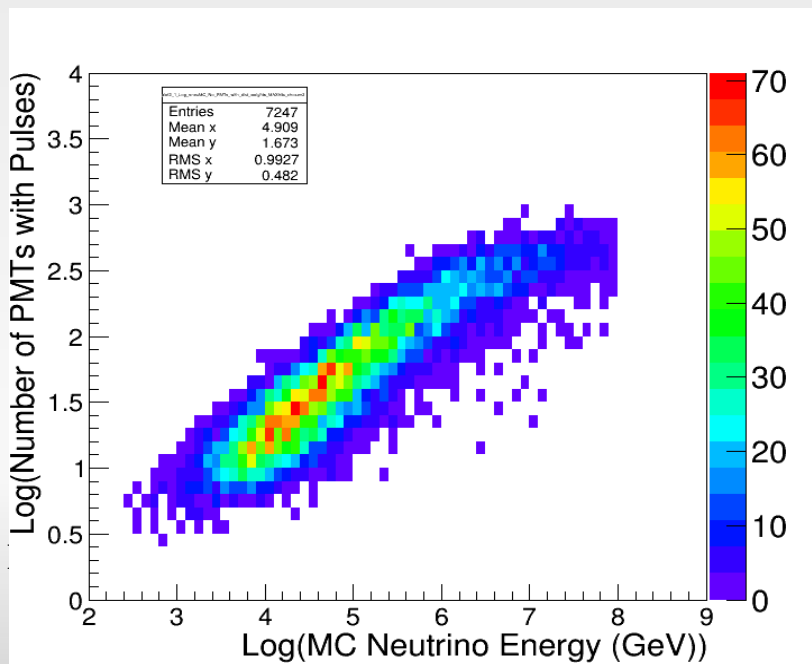
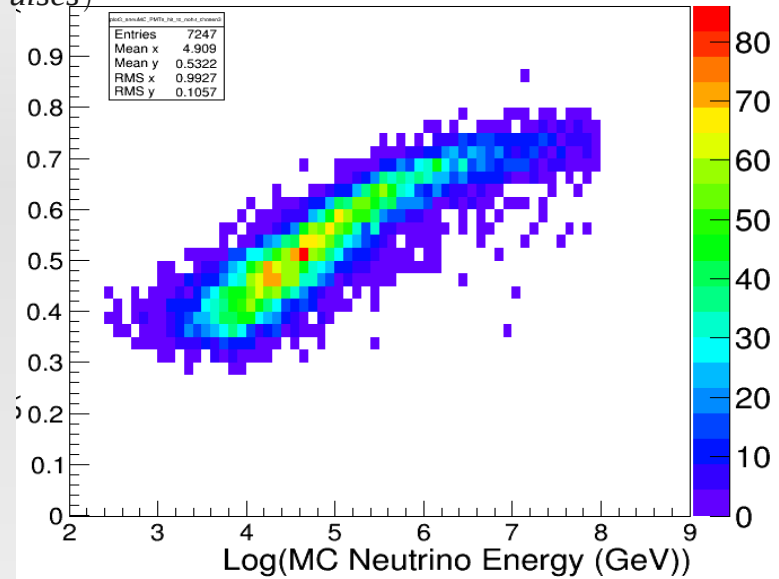




Neutrino Energy Estimation Neural Network Input Variables



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



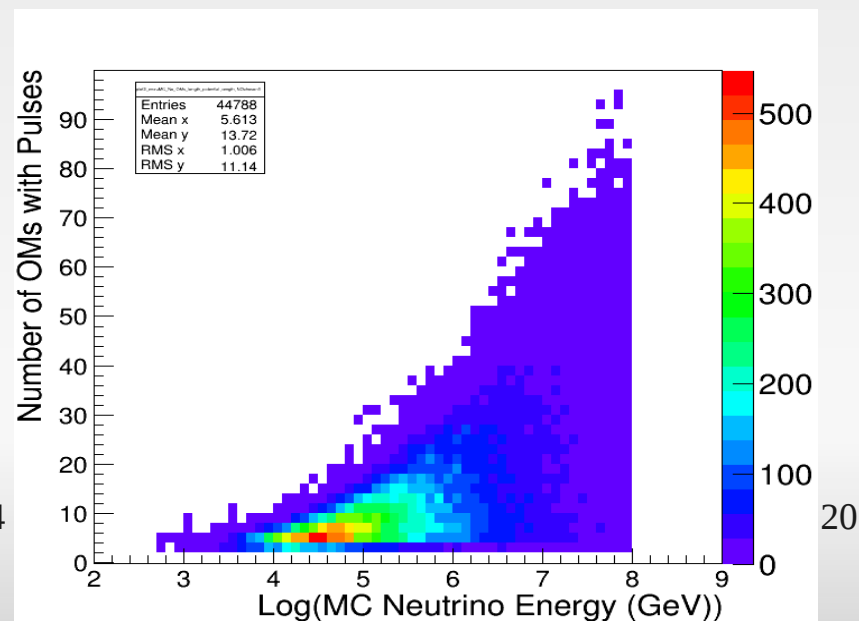
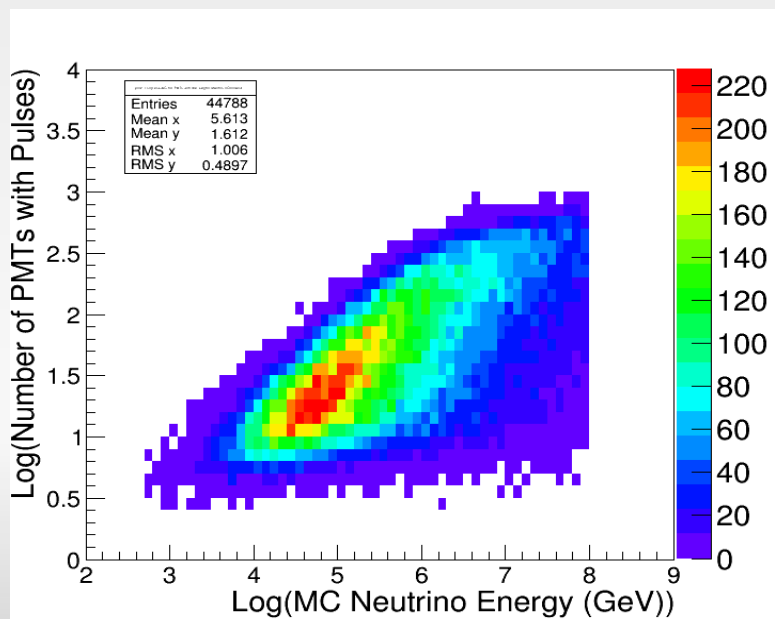
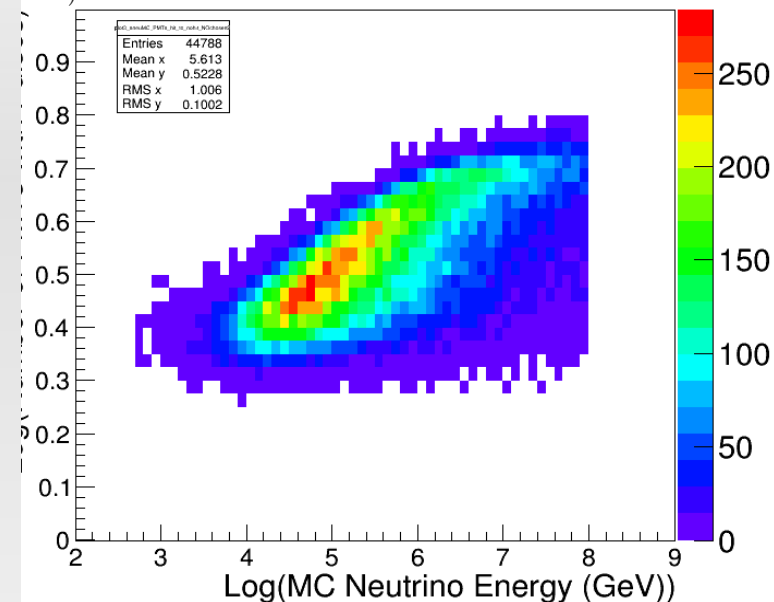
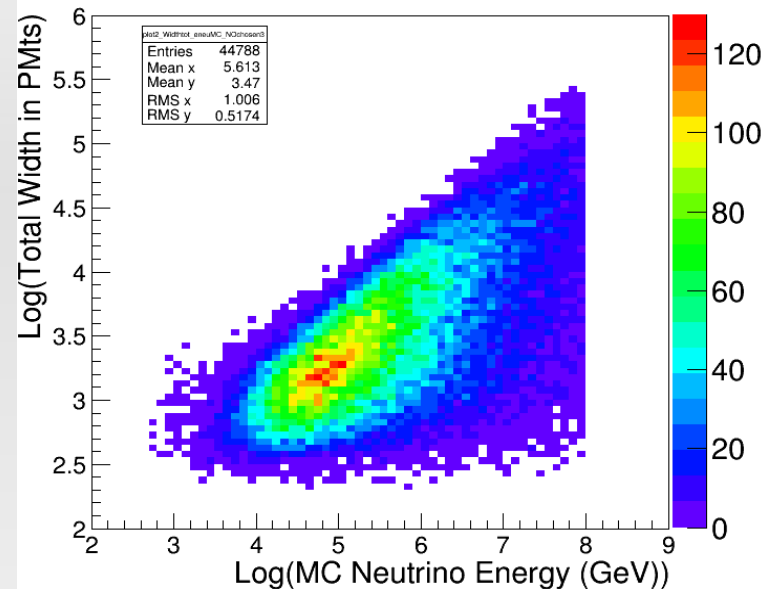
RICAP-2014



Events that fail to satisfy the selection criteria



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



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Neutrino Energy Estimation

MLP Performance



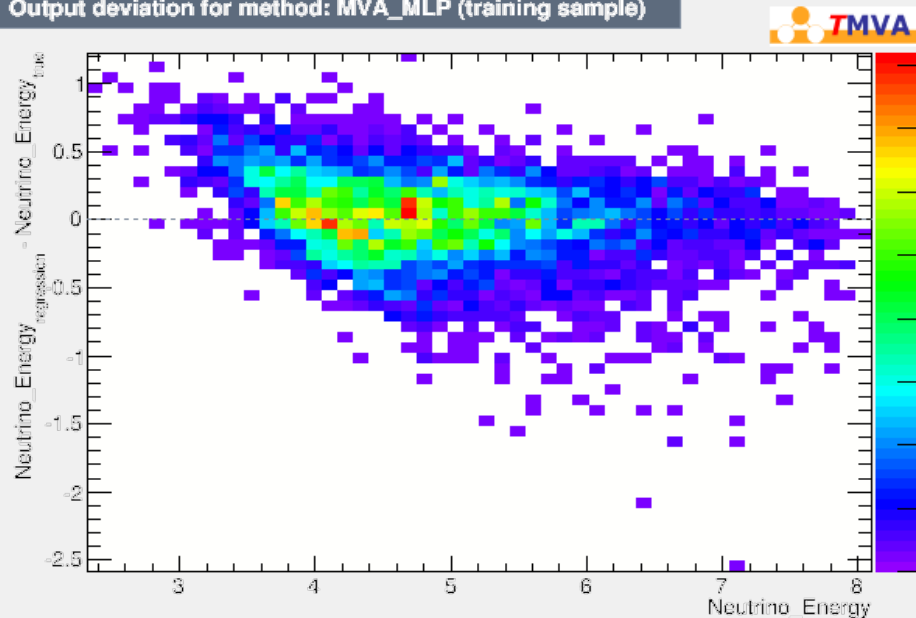
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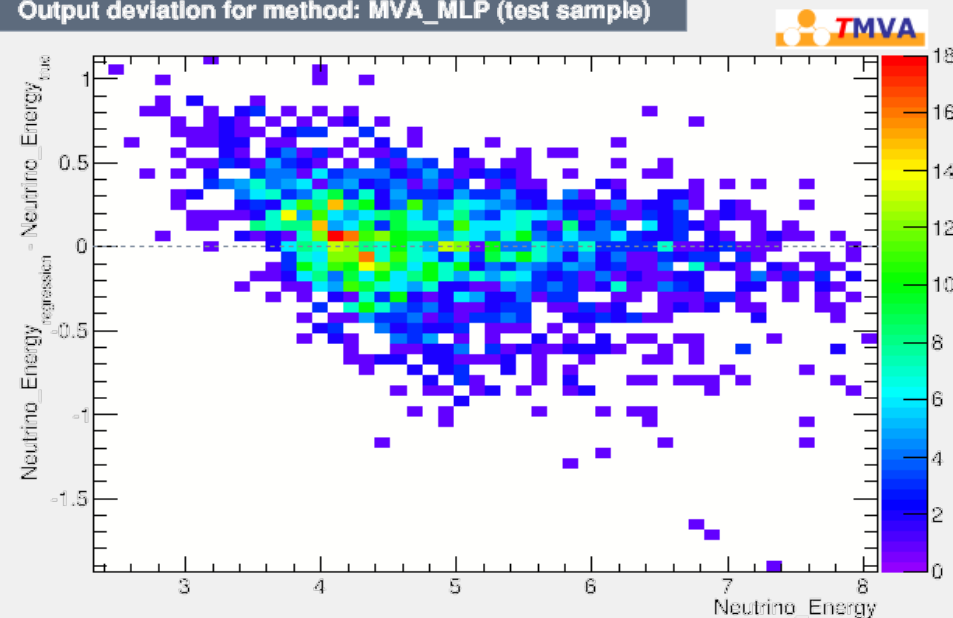


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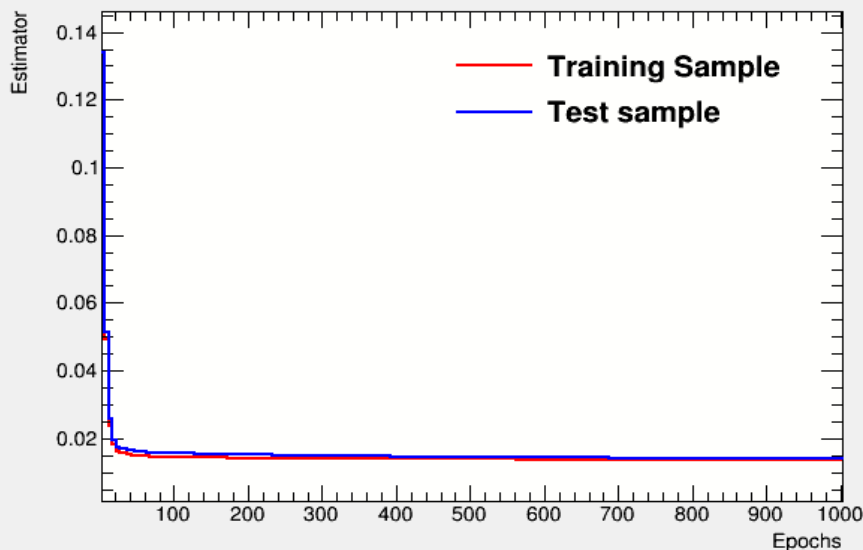
Output deviation for method: MVA_MLP (training sample)



Output deviation for method: MVA_MLP (test sample)

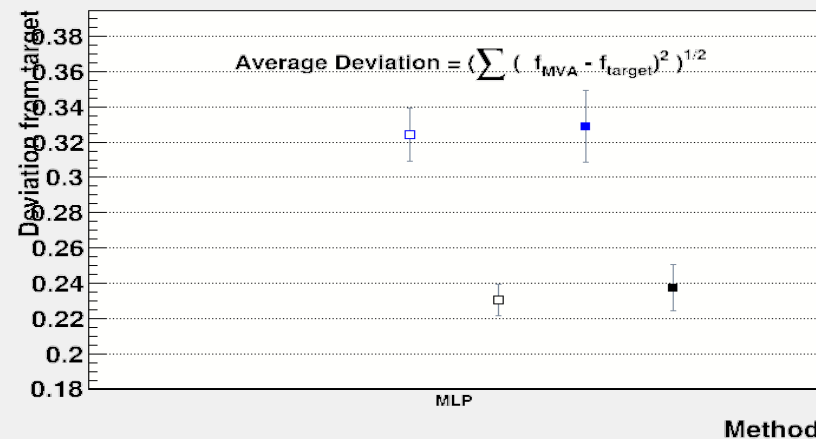


MLP Convergence Test



Average Quadratic Deviation versus Method for target 0

- Training Sample, Average Deviation
- Training Sample, truncated Average Dev. (best 90%)
- Test Sample, Average Deviation
- Test Sample, truncated Average Dev. (best 90%)



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Muon Energy Estimation MLP Performance



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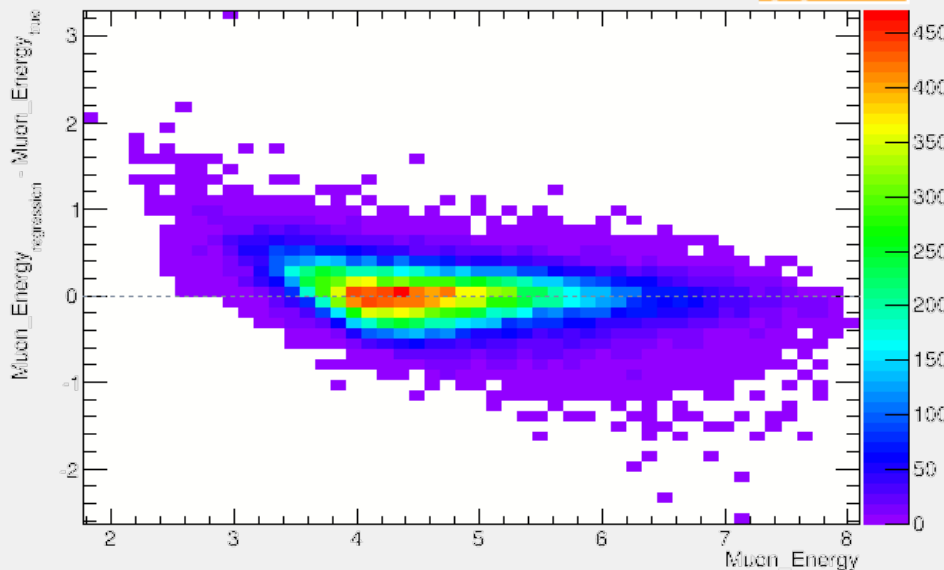
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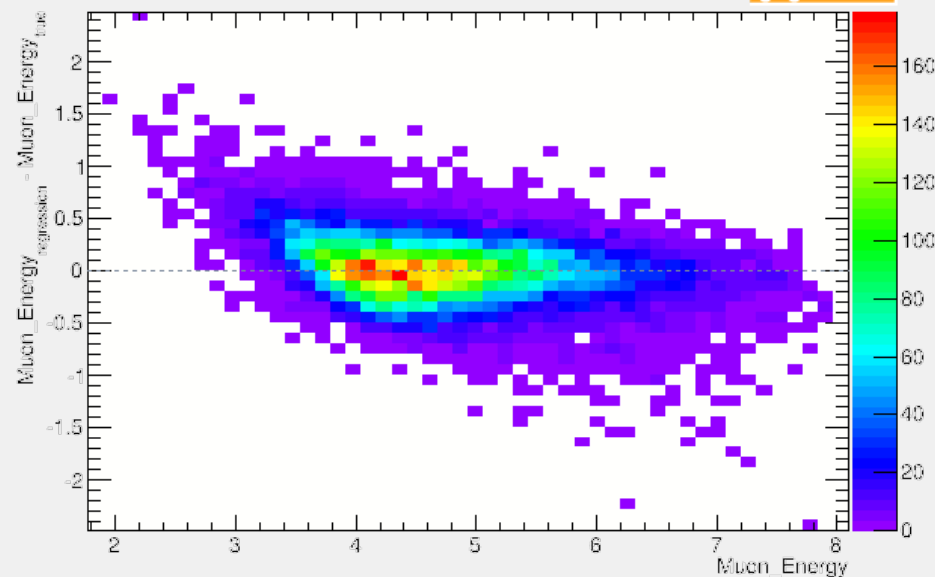


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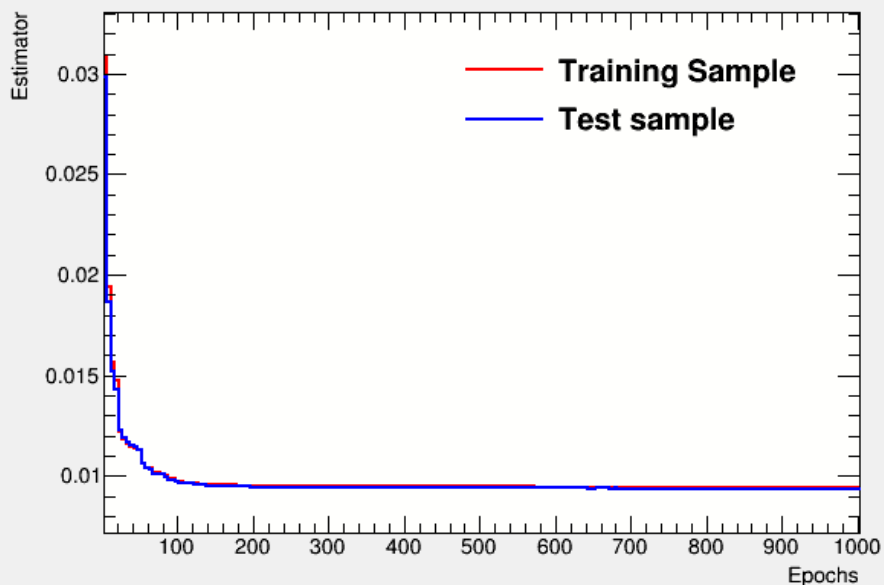
Output deviation for method: MVA_MLP (training sample)



Output deviation for method: MVA_MLP (test sample)



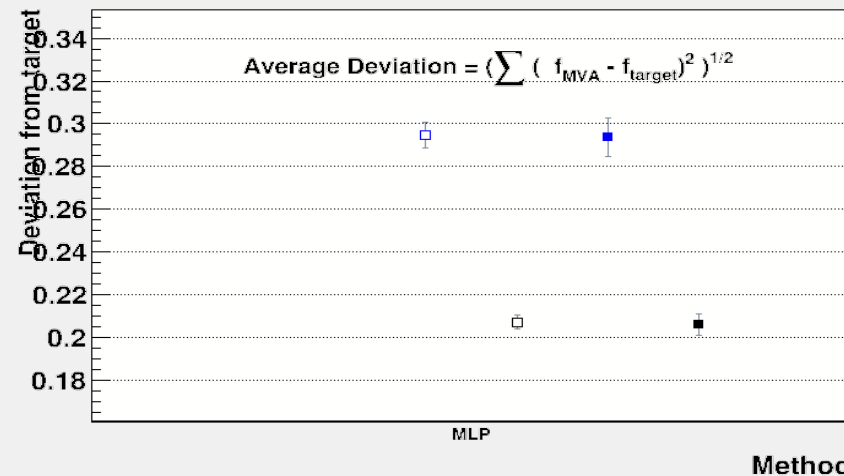
MLP Convergence Test



Average Quadratic Deviation versus Method for target 0



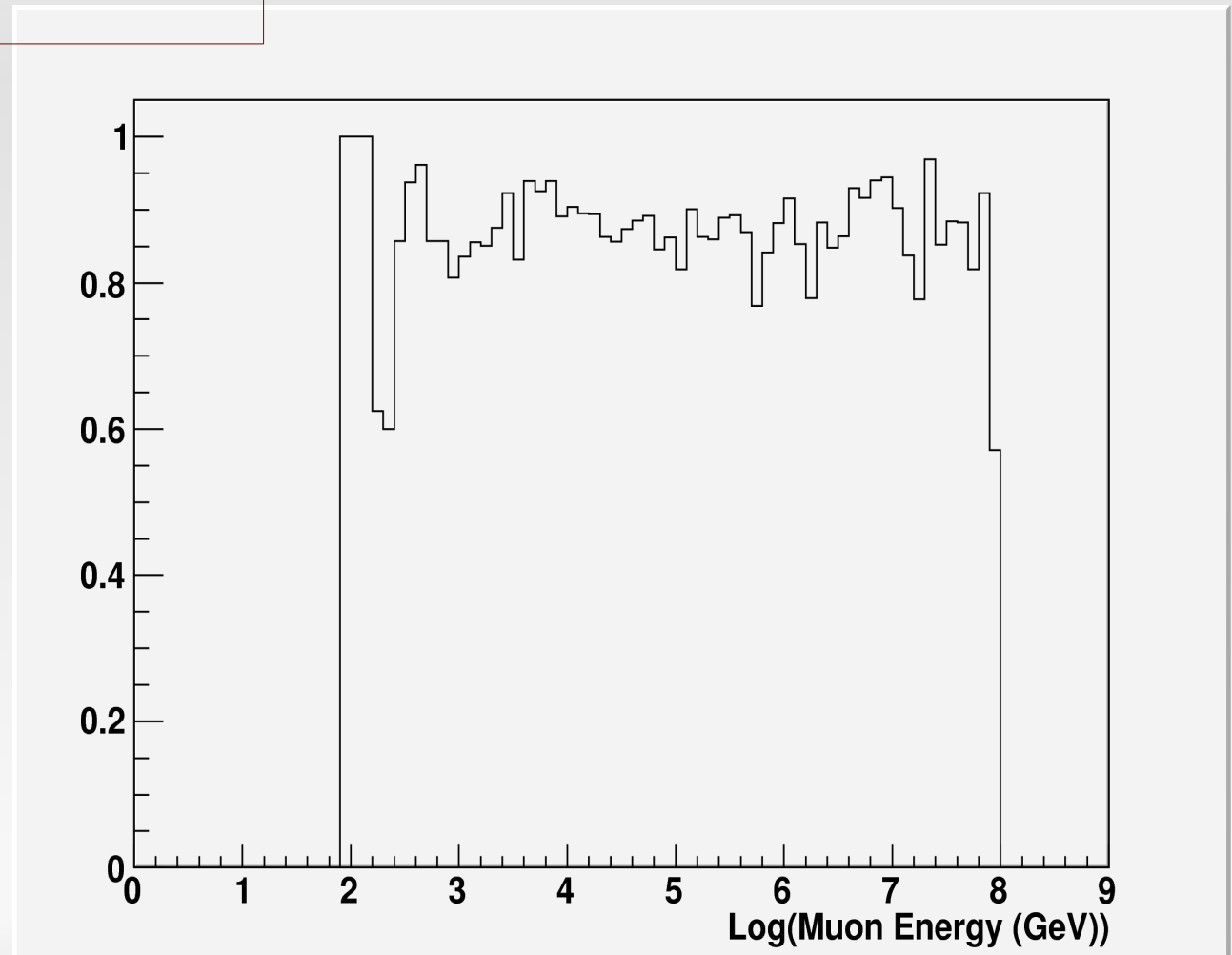
- Training Sample, Average Deviation
- Training Sample, truncated Average Dev. (best 90%)
- Test Sample, Average Deviation
- Test Sample, truncated Average Dev. (best 90%)

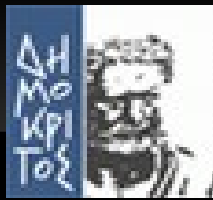


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Selected Well Reconstructed Events for Energy Estimation

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

Muon's Energy Estimation :

- Low Energy Muons

- ➔ muon length

- High Energy Muons

- ➔ light observation in PMTs



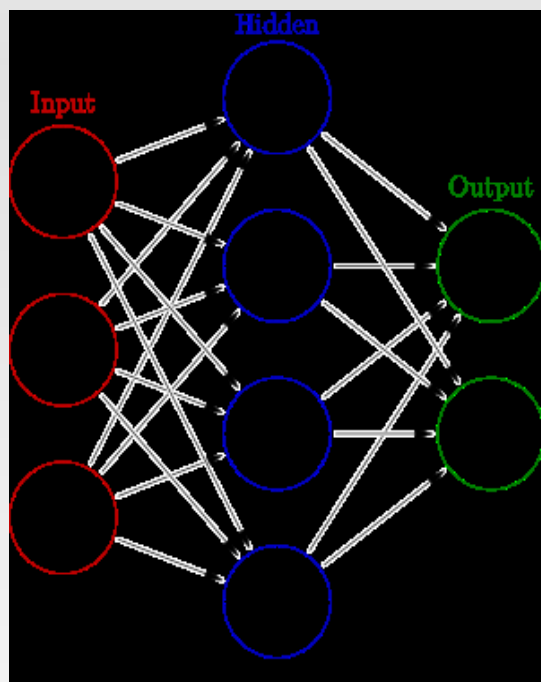
Backup Slides – MVA Methods



```
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');
```

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 $x_a = (x_1, \dots, x_{nvar})_a, a = 1, \dots, N$. 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



Applications Places System 17 °C USA Thu Feb 20, 11:45 lilia

TMVA Options Reference - Mozilla Firefox

File Edit View History Bookmarks Tools Help

ANTARE... Outlook ... TProfile TMVA... x

tmva.sourceforge.net/optic

Configuration options for MVA method :

| Option | Array | Default value | Predefined values | Description |
|----------------------------|-------|---------------|--|---|
| NCycles | No | 300 | - | Number of training cycles |
| HiddenLayers | No | N,N-1 | - | Specification of hidden layer architecture |
| NeuronType | No | sigmoid | - | Neuron activation function type |
| RandomSeed | No | 1 | - | Random seed for initial synapse weights (0 means unique seed for each run; default value '1') |
| EstimatorType | No | MSE | MSE, CE, linear, sigmoid, tanh, radial | MSE (Mean Square Estimator) for Gaussian Likelihood or CE(Cross-Entropy) for Bernoulli Likelihood |
| NeuronInputType | No | sum | sum, sqsum, abssum | Neuron input function type |
| V | No | False | - | Verbose output (short form of VerbosityLevel below - overrides the latter one) |
| VerbosityLevel | No | Default | Default, Debug, Verbose, Info, Warning, Error, Fatal | Verbosity level |
| VarTransform | No | None | - | List of variable transformations performed before training, e.g., D_Background, P_Signal, G_N_AllClasses for: Decorrelation, PCA-transformation, Gaussianisation, Normalisation, each for the given class of events ('AllClasses' denotes all events of all classes, if no class indication is given, 'All' is assumed) |
| H | No | False | - | Print method-specific help message |
| CreateMVAPdfs | No | False | - | Create PDFs for classifier outputs (signal and background) |
| IgnoreNegWeightsInTraining | No | False | - | Events with negative weights are ignored in the training (but are included for testing and performance evaluation) |
| TrainingMethod | No | BP | BP, GA, BFGS | Train with Back-Propagation (BP), BFGS Algorithm (BFGS), or Genetic Algorithm (GA - slower and worse) |
| LearningRate | No | 0.02 | - | ANN learning rate parameter |
| DecayRate | No | 0.01 | - | Decay rate for learning parameter |
| TestRate | No | 10 | - | Test for overtraining performed at each #th epochs |
| EpochMonitoring | No | False | - | Provide epoch-wise monitoring plots according to TestRate (caution: causes big ROOT output file!) |
| Sampling | No | 1 | - | Only 'Sampling' (randomly selected) events are trained each epoch |

TMVA Options Reference - Mozilla Firefox

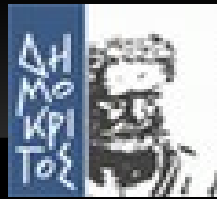
File Edit View History Bookmarks Tools Help

TMVA Options Reference

tmva.sourceforge.net/opti

| | | | | |
|--------------------|----|------------|-------------------|--|
| TrainingMethod | No | BP | BP, GA, BFGS | Train with Back-Propagation (BP), BFGS Algorithm (BFGS), or Genetic Algorithm (GA - slower and worse) |
| LearningRate | No | 0.02 | - | ANN learning rate parameter |
| DecayRate | No | 0.01 | - | Decay rate for learning parameter |
| TestRate | No | 10 | - | Test for overtraining performed at each #th epochs |
| EpochMonitoring | No | False | - | Provide epoch-wise monitoring plots according to TestRate (caution: causes big ROOT output file!) |
| Sampling | No | 1 | - | Only 'Sampling' (randomly selected) events are trained each epoch |
| SamplingEpoch | No | 1 | - | Sampling is used for the first 'SamplingEpoch' epochs, afterwards, all events are taken for training |
| SamplingImportance | No | 1 | - | The sampling weights of events in epochs which successful (worse estimator than before) are multiplied with SamplingImportance, else they are divided. |
| SamplingTraining | No | True | - | The training sample is sampled |
| SamplingTesting | No | False | - | The testing sample is sampled |
| ResetStep | No | 50 | - | How often BFGS should reset history |
| Tau | No | 3 | - | LineSearch size step |
| BPMODE | No | sequential | sequential, batch | Back-propagation learning mode: sequential or batch |
| BatchSize | No | -1 | - | Batch size: number of events/batch, only set if in Batch Mode, -1 for BatchSize=number_of_events |
| ConvergenceImprove | No | 1e-30 | - | Minimum improvement which counts as improvement (<0 means automatic convergence check is turned off) |
| ConvergenceTests | No | -1 | - | Number of steps (without improvement) required for convergence (<0 means automatic convergence check is turned off) |
| UseRegulator | No | False | - | Use regulator to avoid over-training |
| UpdateLimit | No | 10000 | - | Maximum times of regulator update |
| CalculateErrors | No | False | - | Calculates inverse Hessian matrix at the end of the training to be able to calculate the uncertainties of an MVA value |
| WeightRange | No | 1 | - | Take the events for the estimator calculations from small deviations from the desired value to large deviations only over the weight range |

Configuration options for MVA method :



European Union
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MINISTRY OF EDUCATION & RELIGIOUS AFFAIRS
MANAGING AUTHORITY
Co-financed by Greece and the European Union

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

