Muon Energy Reconstruction Methods for the IceCube Neutrino Observatory

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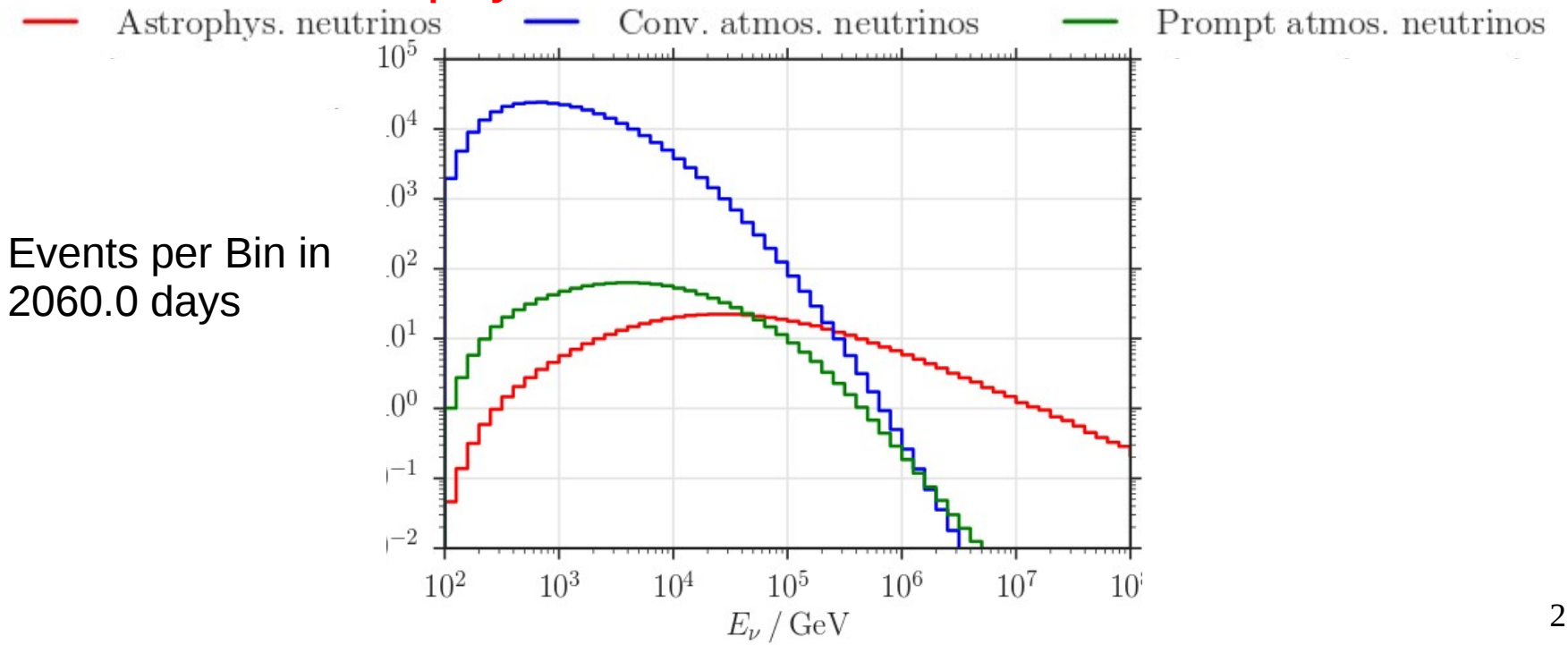
Up-going Muon Diffuse Analysis

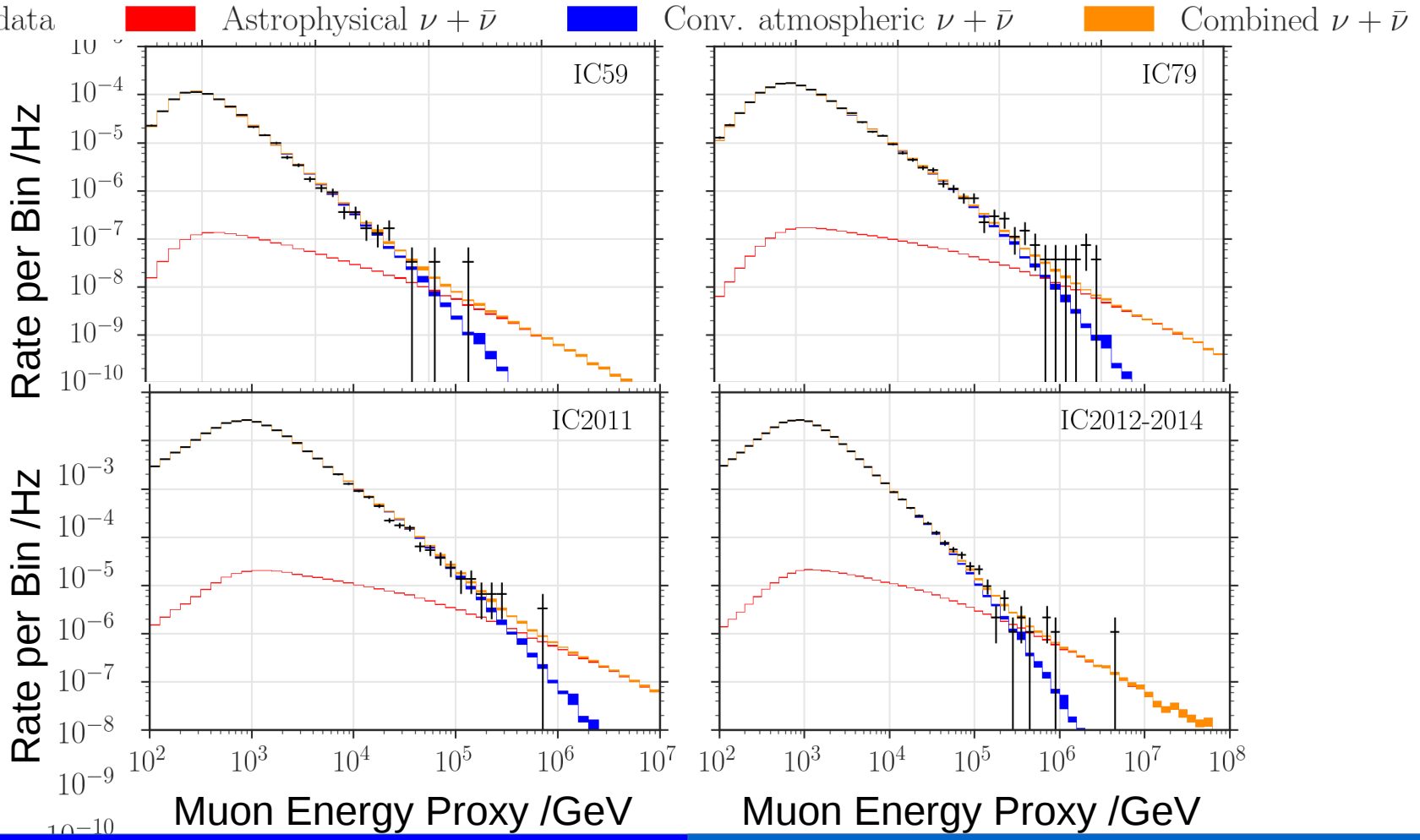
A diffuse analysis involves fitting a data to an expected flux for three components.

- Conventional atmospheric neutrinos; pion and kaon decay
- Prompt atmospheric neutrinos; charmed mesons.
- Astrophysical neutrinos

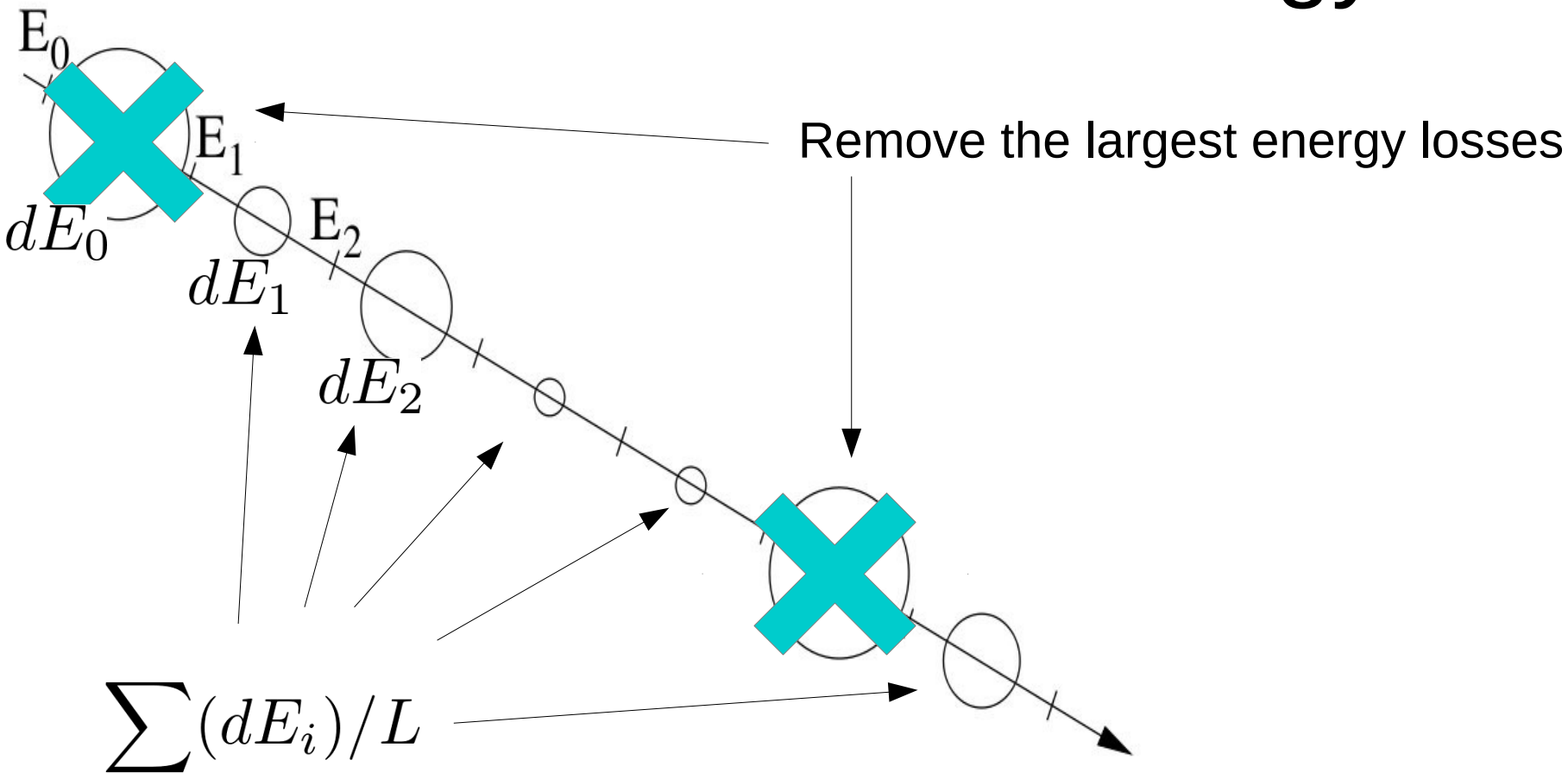


Diffuse Analysis

Most recent published diffuse results with 6 years of IceCube data. With over 350,000 upgoing charge current muon neutrinos shows a astrophysical contribution in the TeV to PeV range.

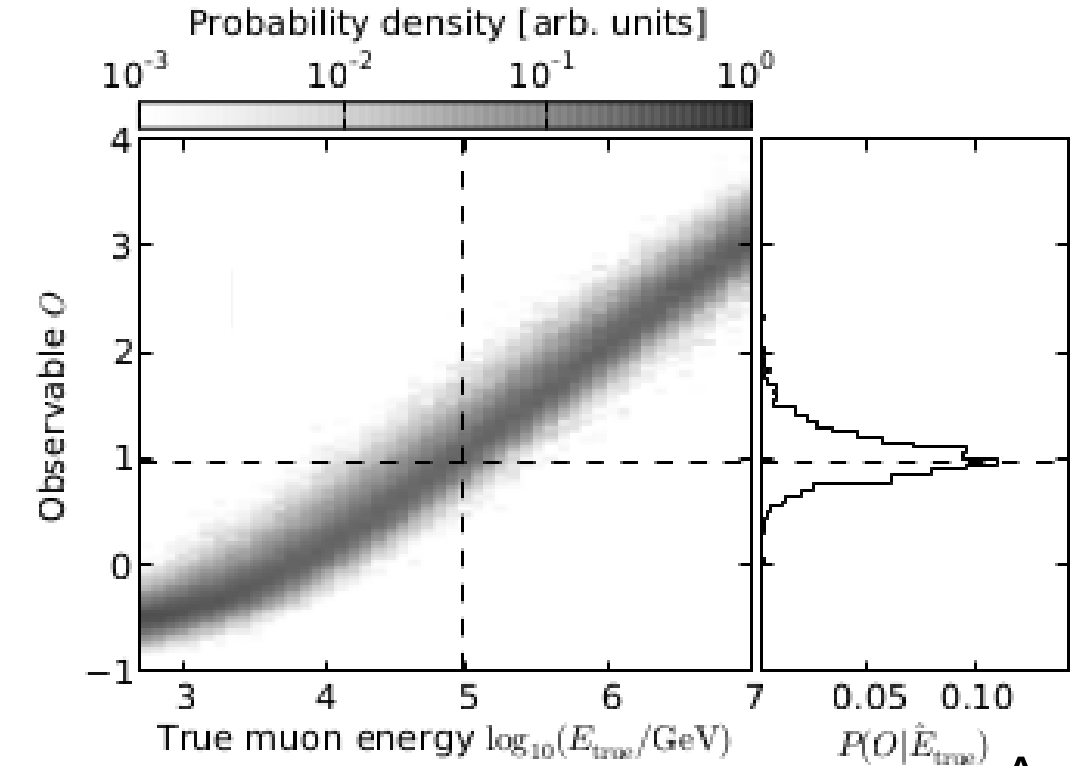


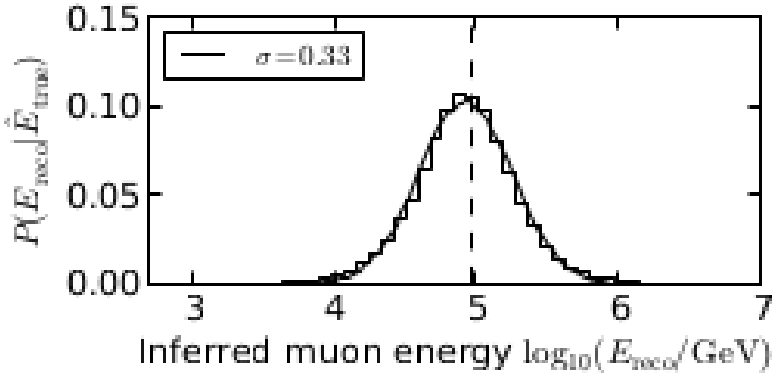
Energy Reconstruction with Truncated Mean Energy



Truncated energy (TE) finds the average energy after removing the largest losses.

Truncated Energy Resolution



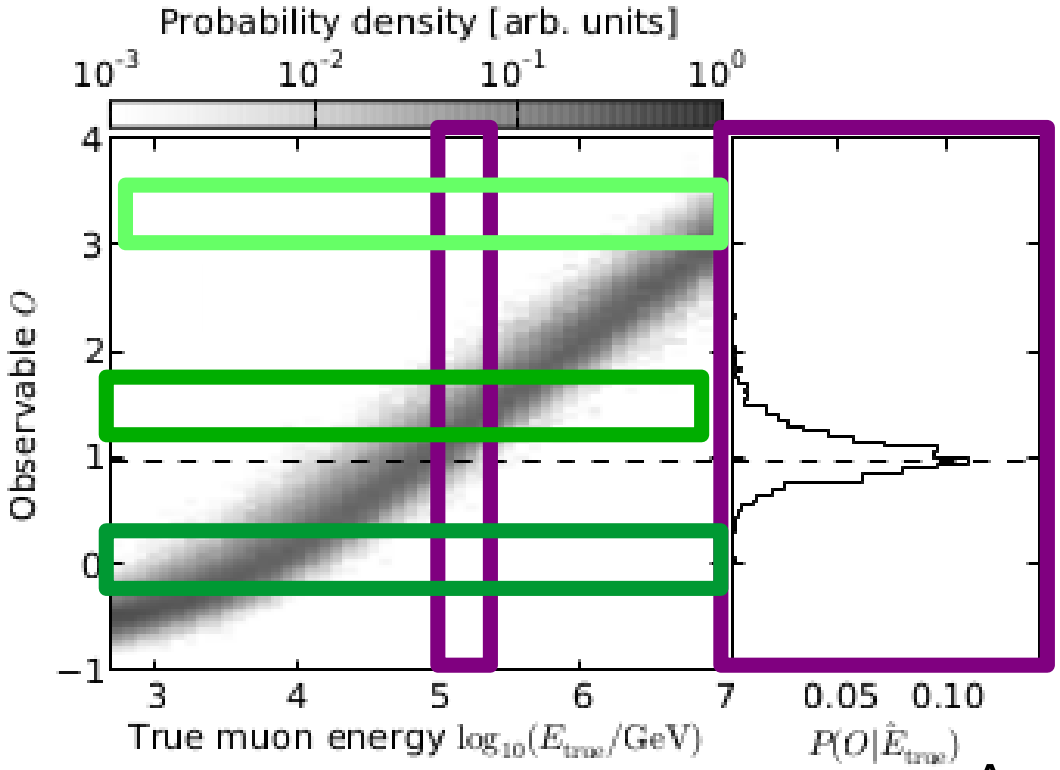


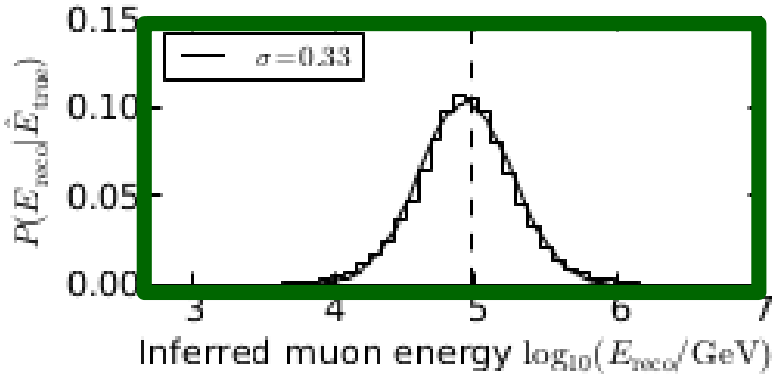
A result matrix is made with the muon energy result as the observable and the true muon energy

Each column of true muon energy is taken as a weight vector.

A slice for each observable is multiplied by the weight, then all slices are combined to give a value for that inferred muon energy.

Truncated Energy Resolution





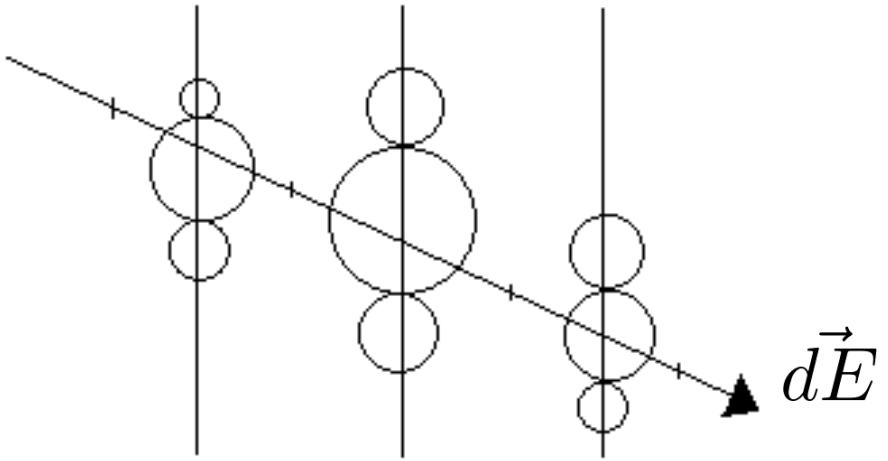
A result matrix is made with the muon energy result as the observable and the true muon energy

Each column of True muon energy is taken as a weight vector.

A slice for each observable is summed and multiplied by the weight to give a value for that inferred muon energy.

Millipede

Reconstructing the detailed light pattern in the modules to an energy loss pattern for the muon track $d\vec{E}$



$$\vec{k} = \Lambda d\vec{E} + \vec{\eta}$$

Data

Noise

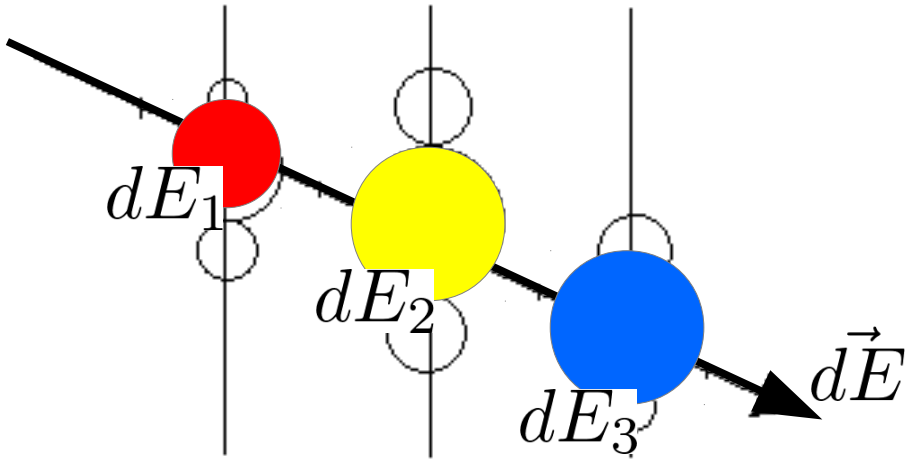
Transmission Matrix

E-loss vector

A Maximum likelihood fit is performed to reconstruct to the best $d\vec{E}$ for data observed.

Millipede

Reconstructing the detailed light pattern in the modules to an energy loss pattern for the muon track $d\vec{E}$



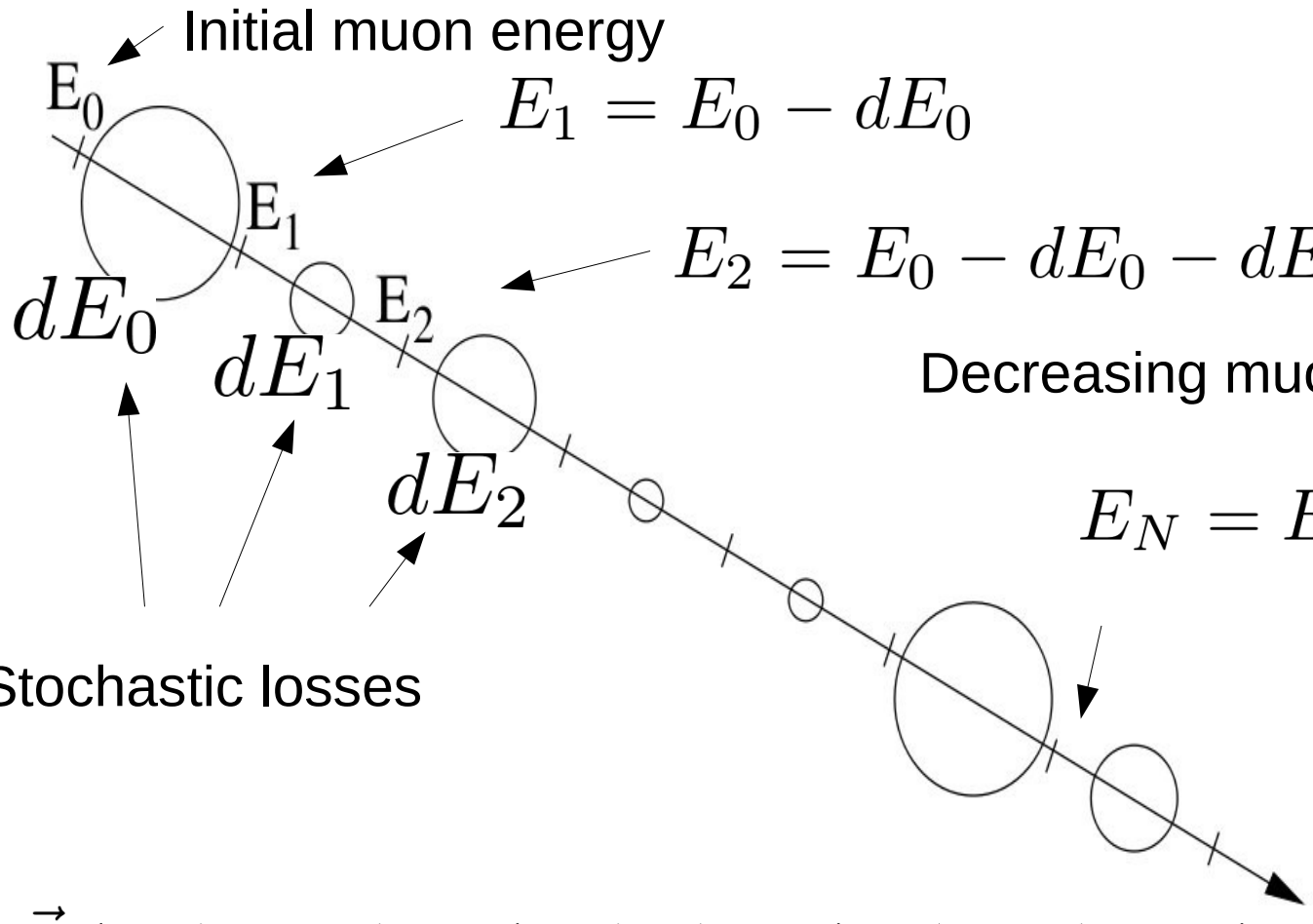
Data → $\vec{k} = \Lambda d\vec{E} + \vec{\eta}$ ← Noise

Transmission Matrix

E-loss vector

A Maximum likelihood fit is performed to reconstruct to the best $d\vec{E}$ for data observed.

Millipede → Edepillim



We refer to E_0 as observable

$$p(d\vec{E}|E_0) = p(dE_0|E_0)p(dE_1|E_1)...p(dE_N|E_N)$$

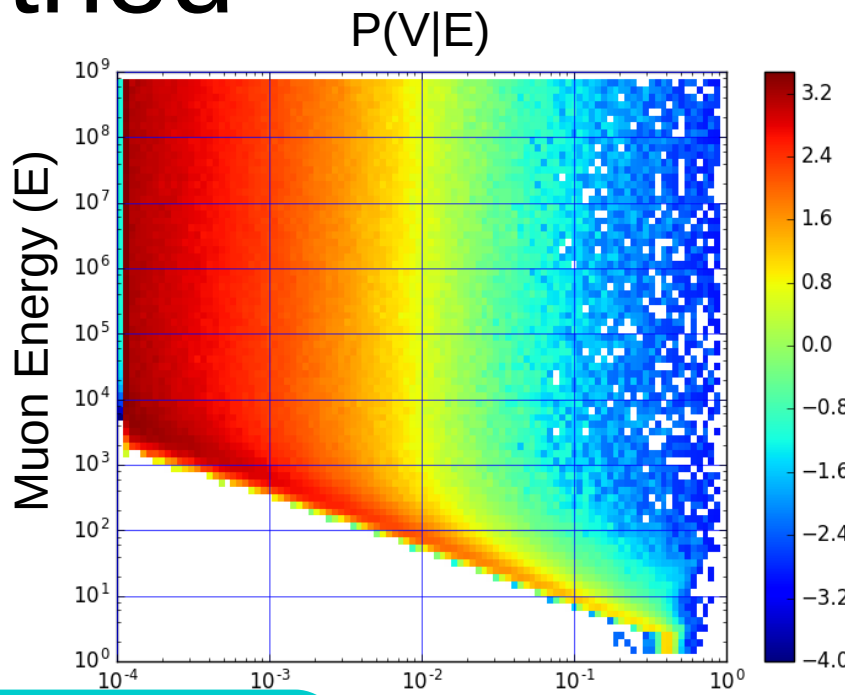
$$p(d\vec{E}|E_0) = p(dE_0|E_0)\prod_{j=1}^{N} p(dE_j|E_0 - \sum_{i=0}^{j-1} dE_i)$$

Probability is the product of the probabilities of the energy loss given muon

Edepillim Method

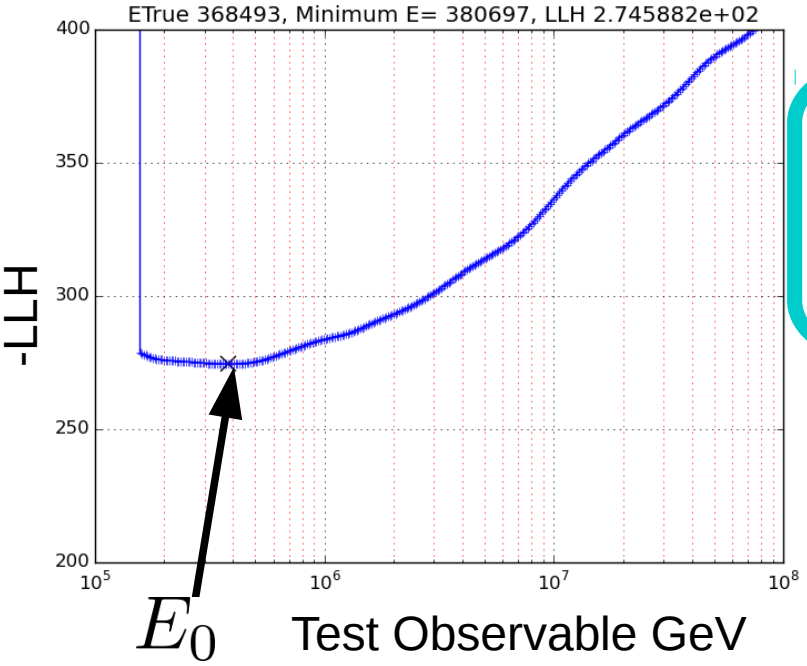
Probability distribution function $P(V|E_N)$ is built from simulation.

Energy Loss Pattern: Millipede/MMC



For a range of initial muon energies

$$LLH = \sum \frac{1}{E} P(\vec{V}|E_0)$$

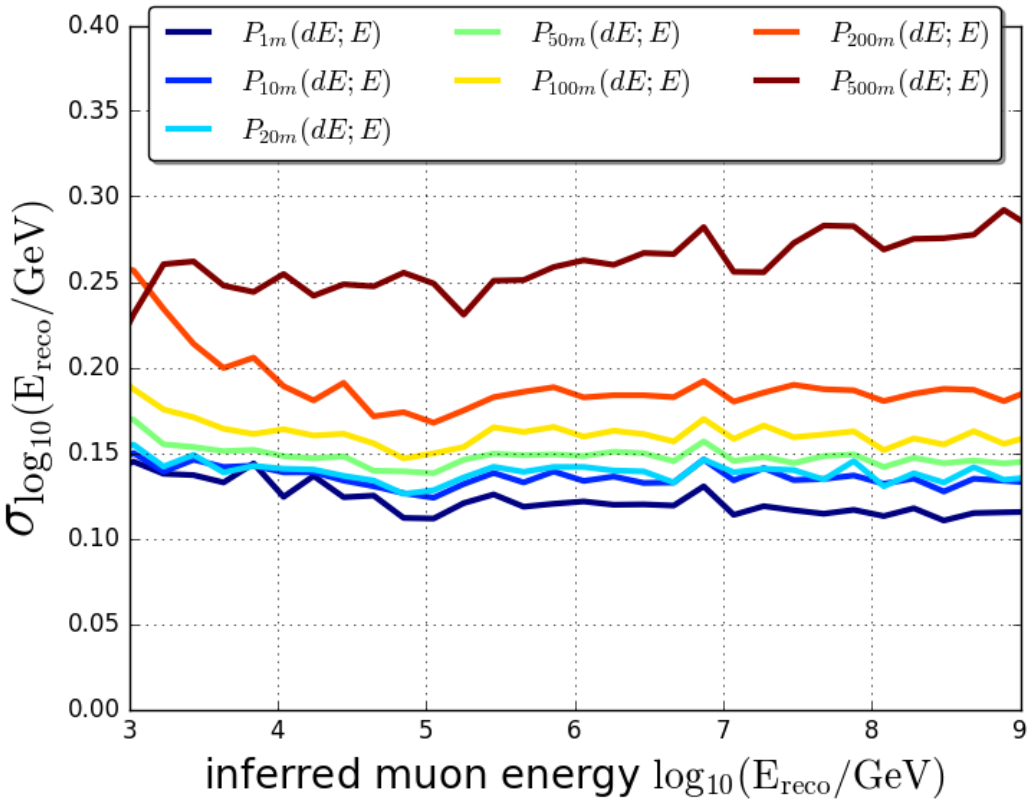


Minimum Log Likelihood of energy range Observable E_0

Edepillim Results

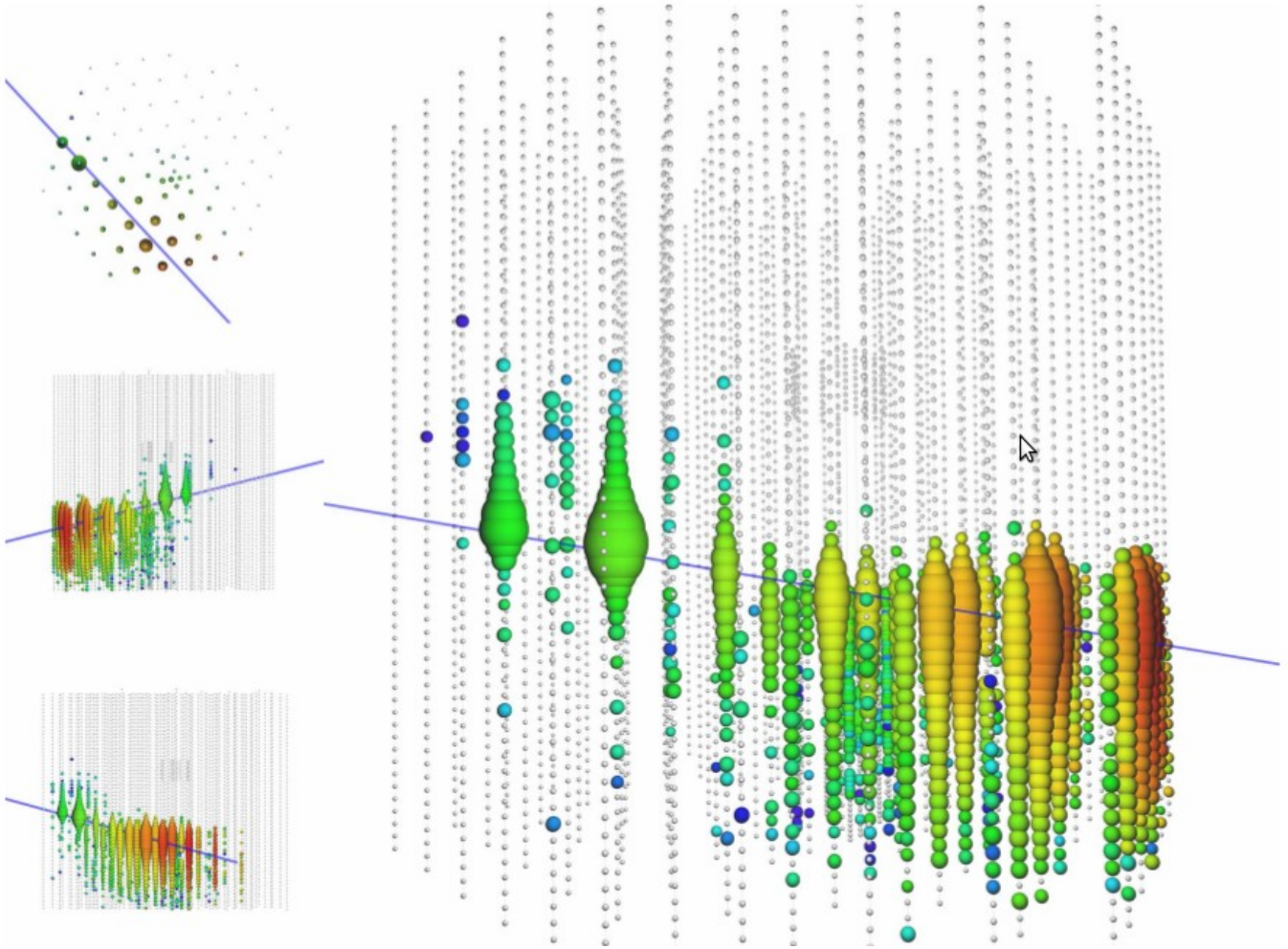
Using a simple simulation of muon energy loss along a 1000m track (no detector information), with varying energy loss bin sizes.

In the true losses larger bin sizes has the effect of worsening the resolution, as detail in the energy loss pattern is lost.

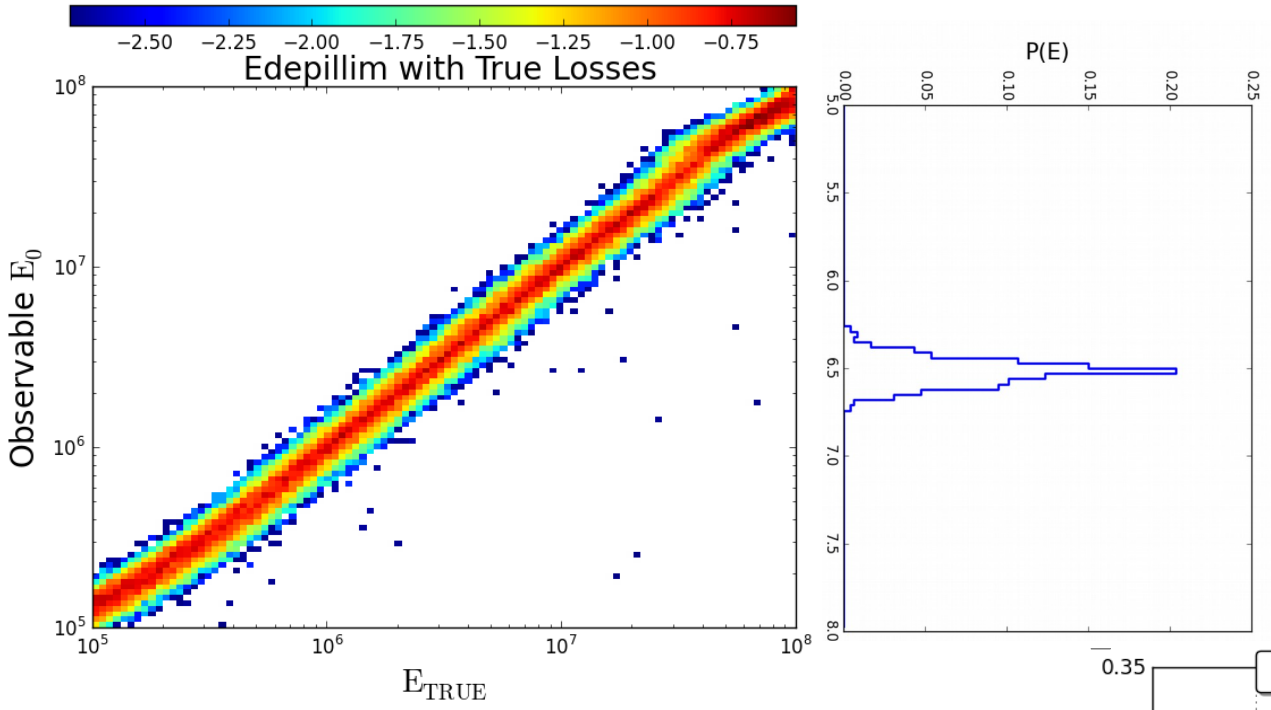


Multi-PeV Track-like Event

In June 2014 there was an event detected in IceCube that had a deposited energy of 2.6 PeV.

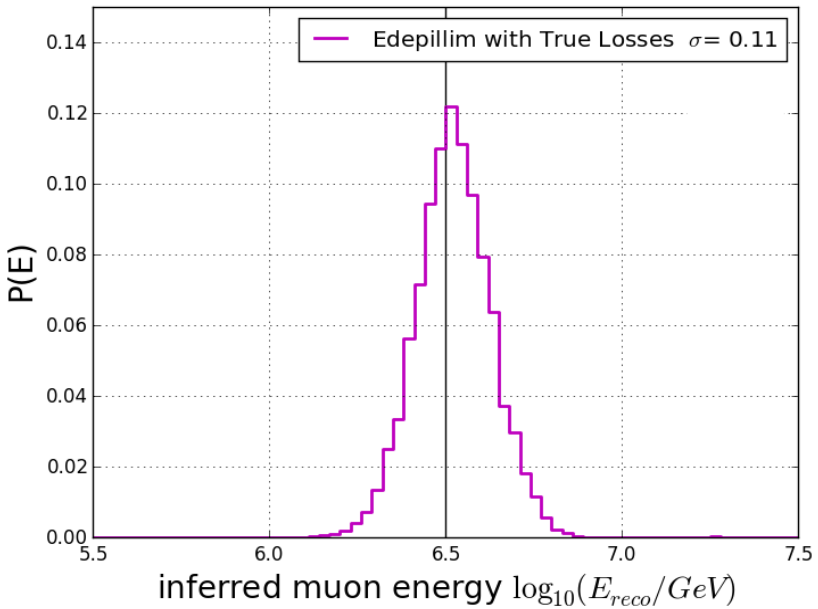


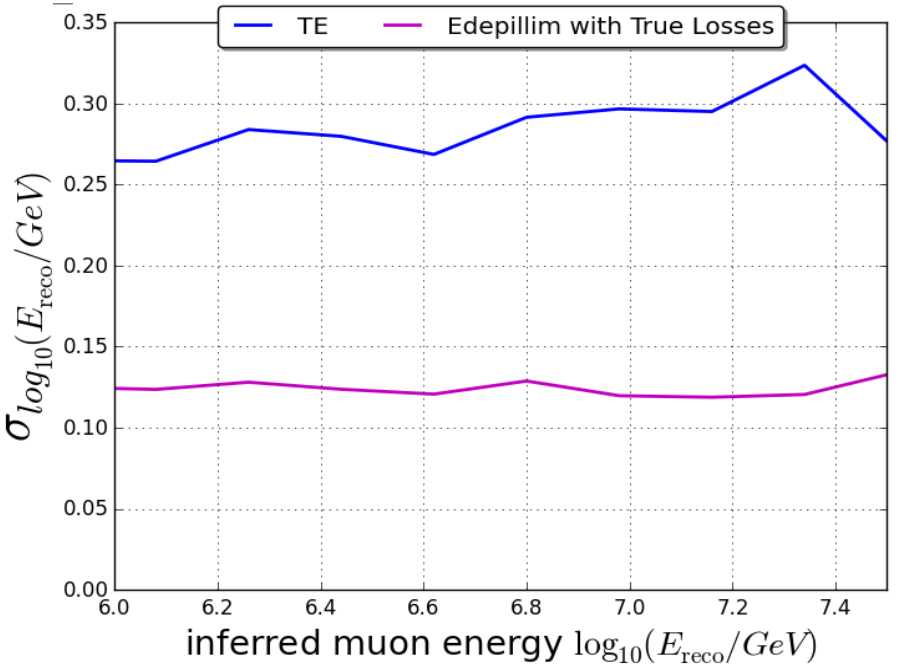
Edepillim with True Losses Resolution



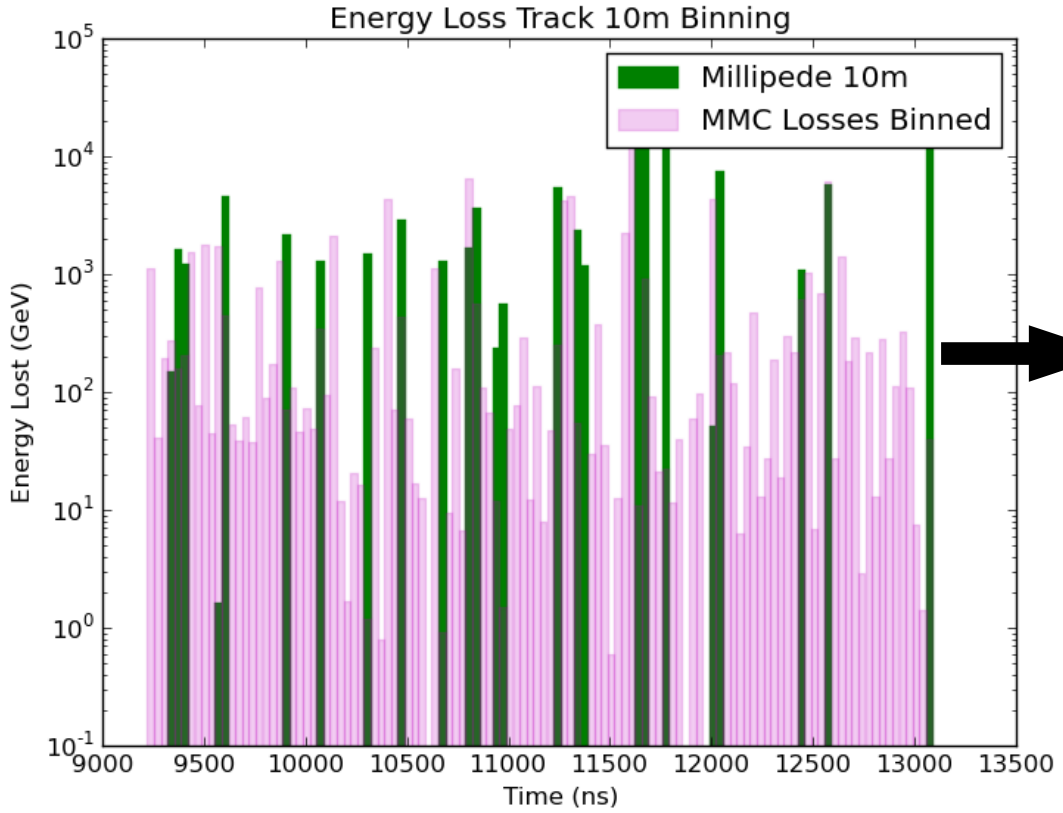
Simulation was of similar events to the Multi-PeV event with fixed direction and high energy.

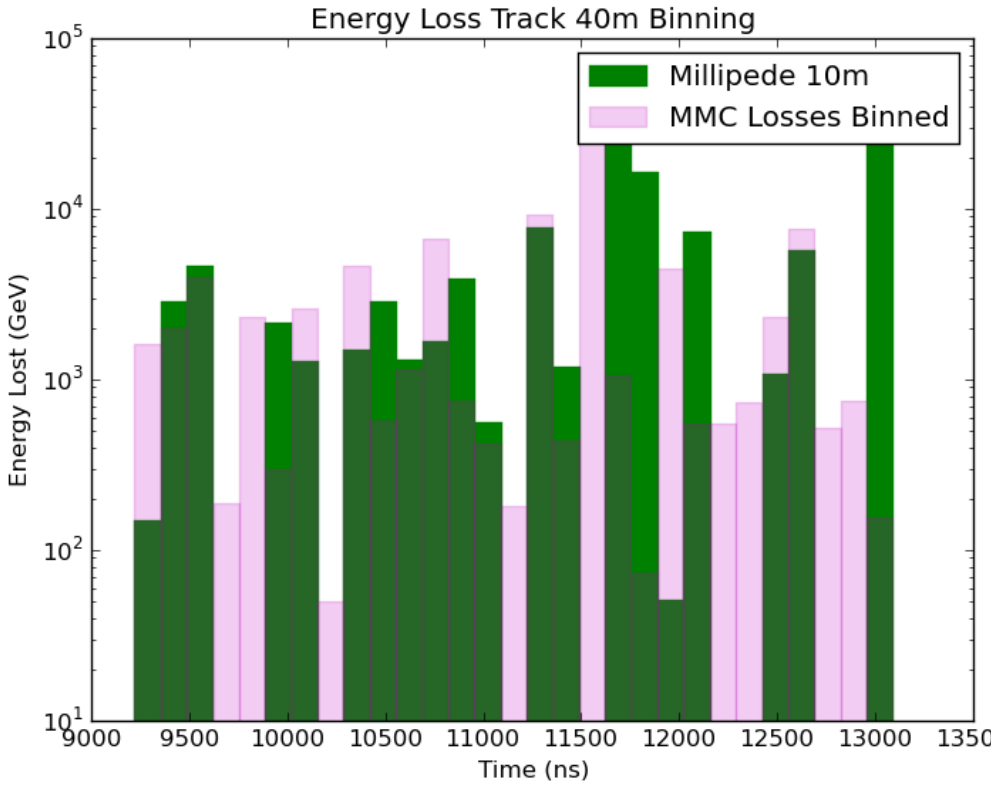
Using the true simulated losses Edepillim has good energy resolution.
This is the optimum of Edepillim's performance





Millipede Rebinning

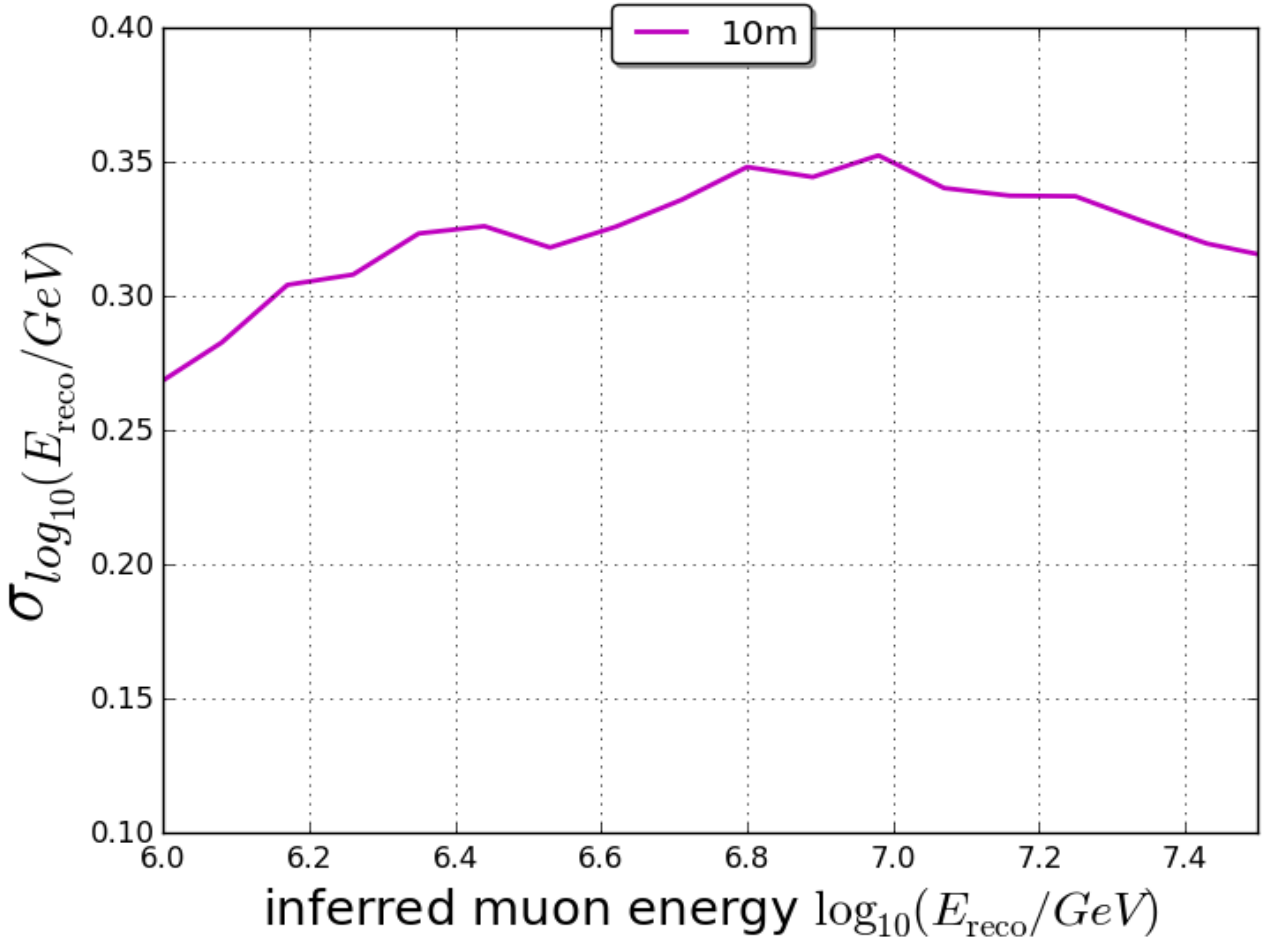




Simple rebinning is performed by adding millipede energy losses to create larger bins. This not only has closer energy estimates but has benefits to Edepillim performance in reducing the number of zero bins.

Edepillim with Rebinning

The rebinning on energy losses has a large improvement on the Edepillim result with the best resolution at 40m.



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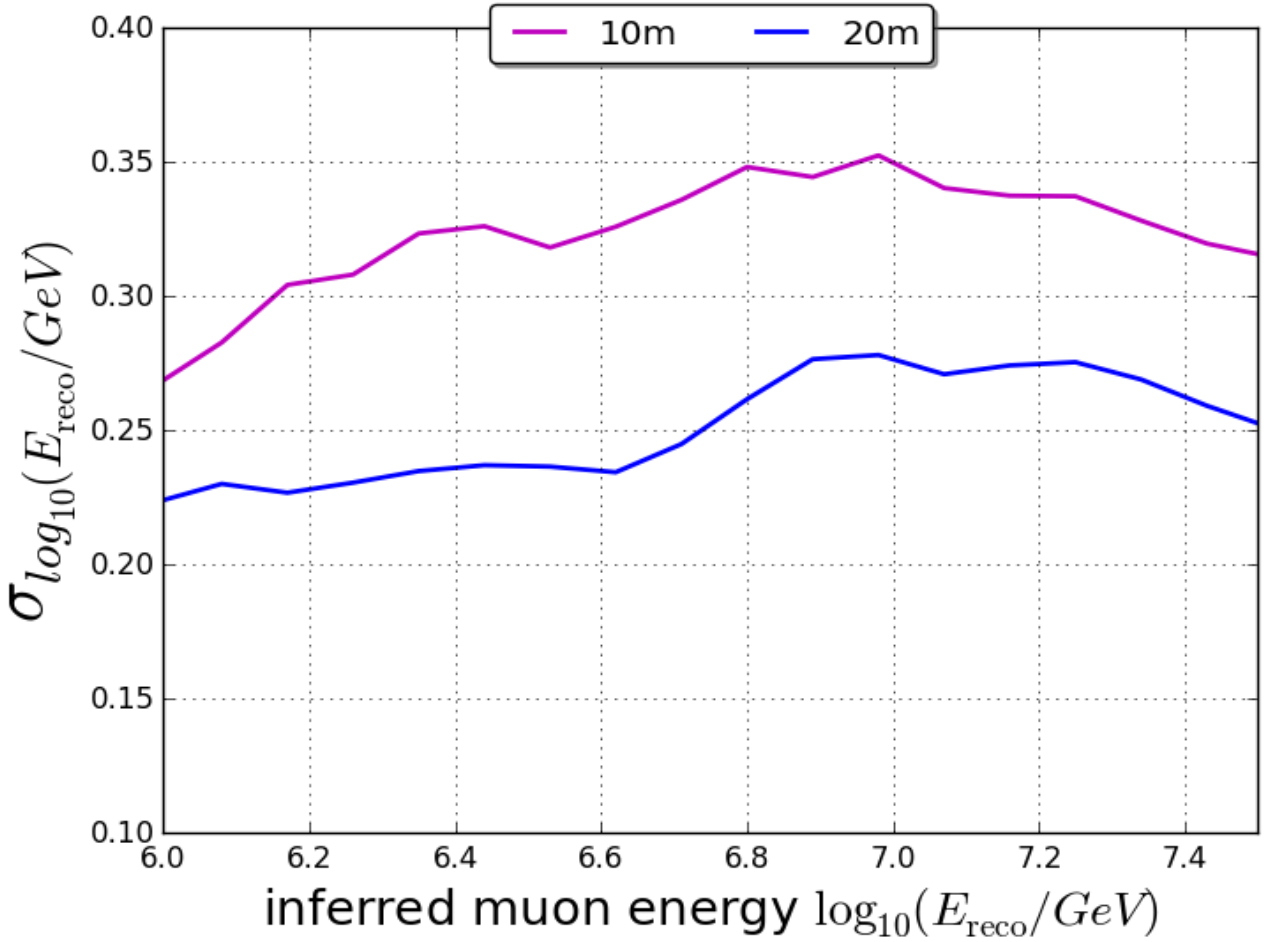

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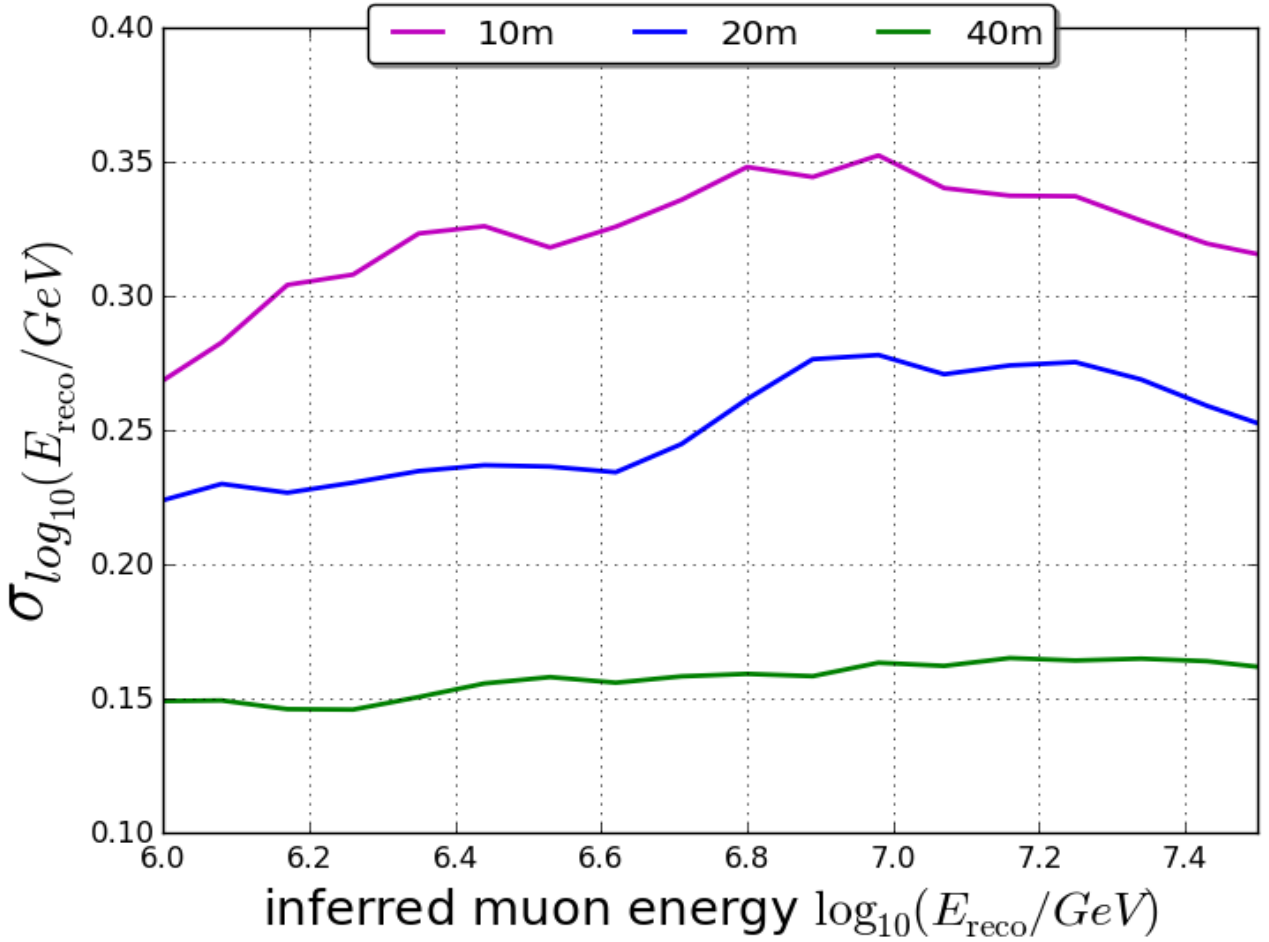

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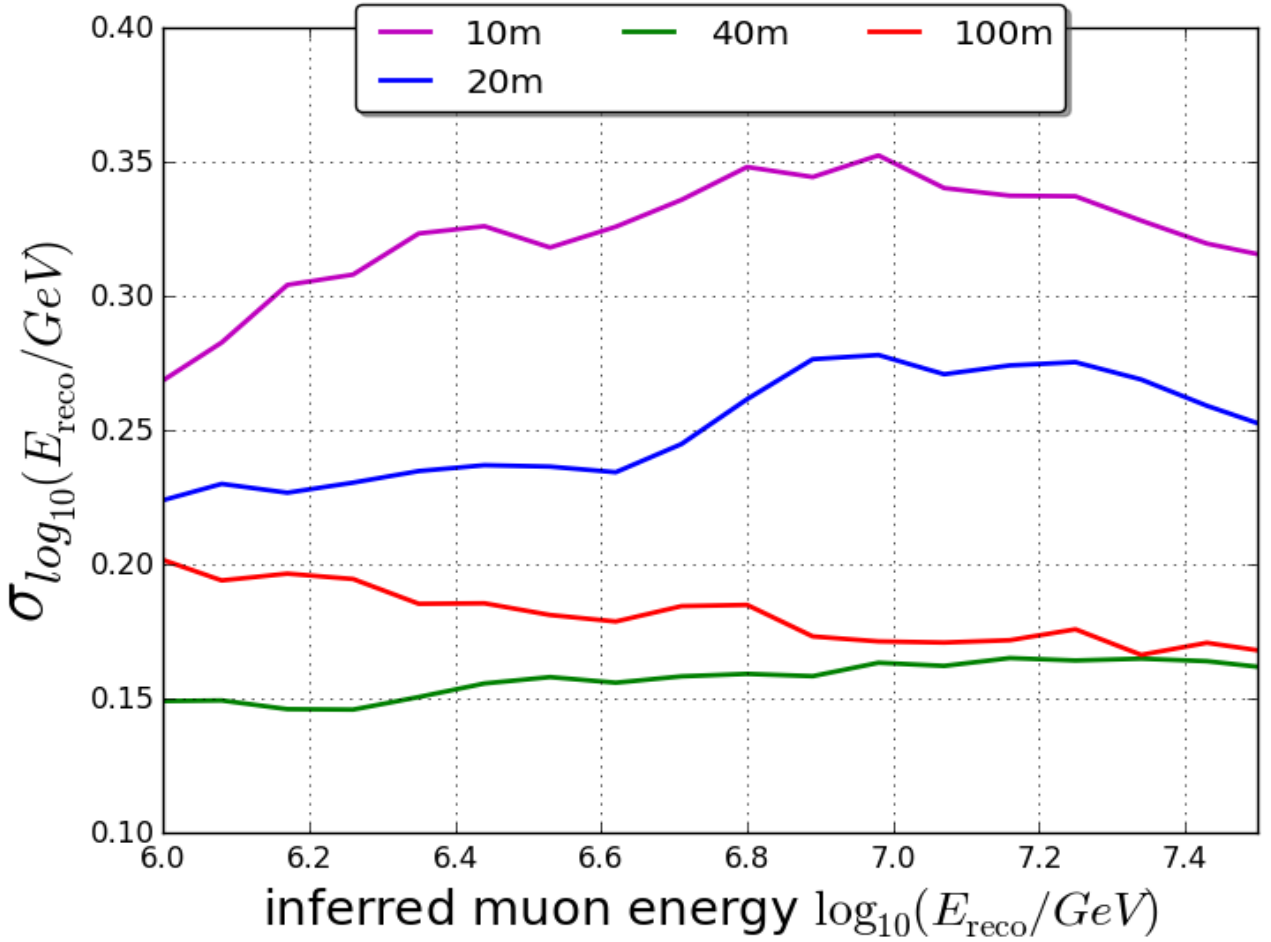

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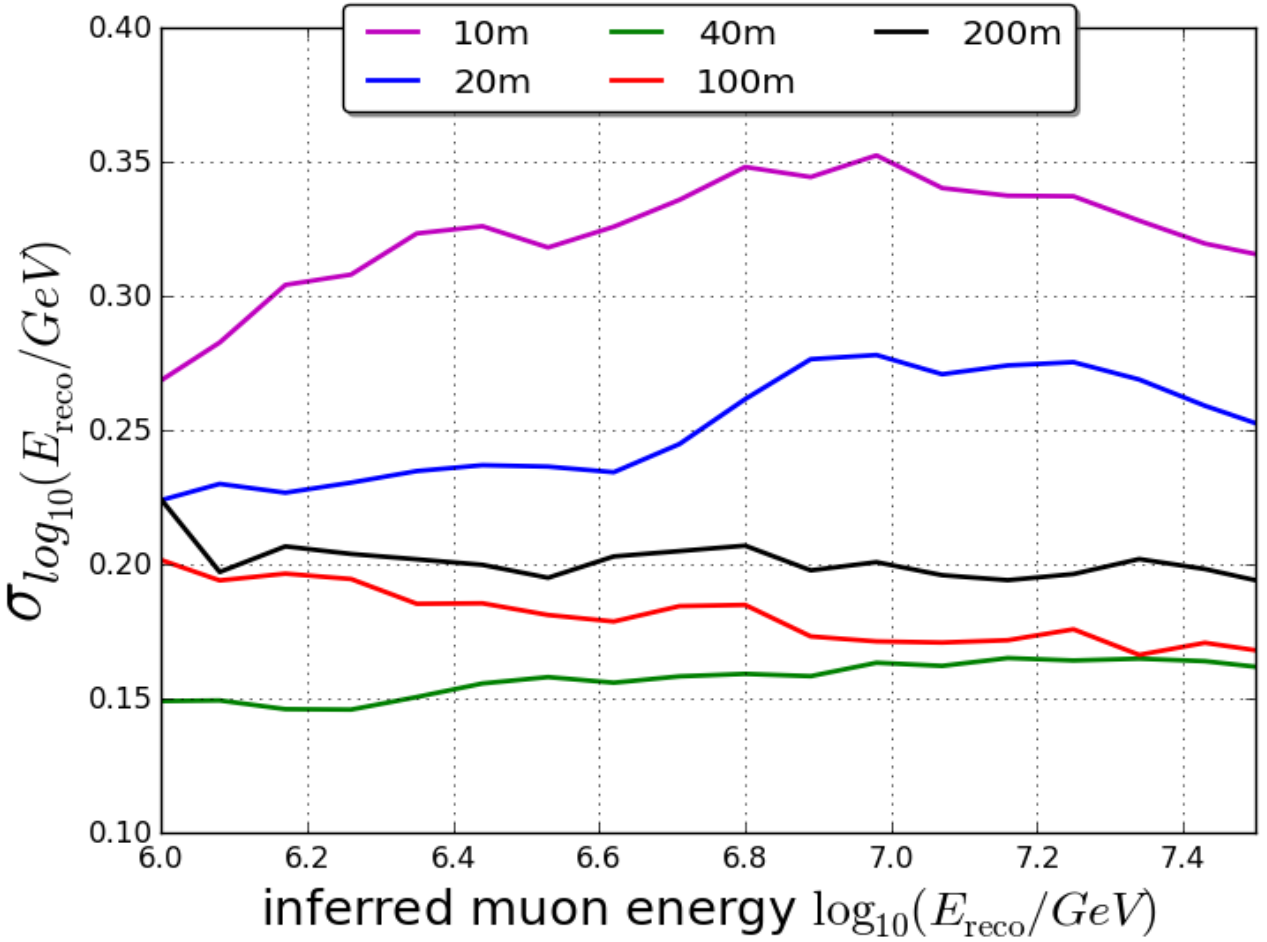

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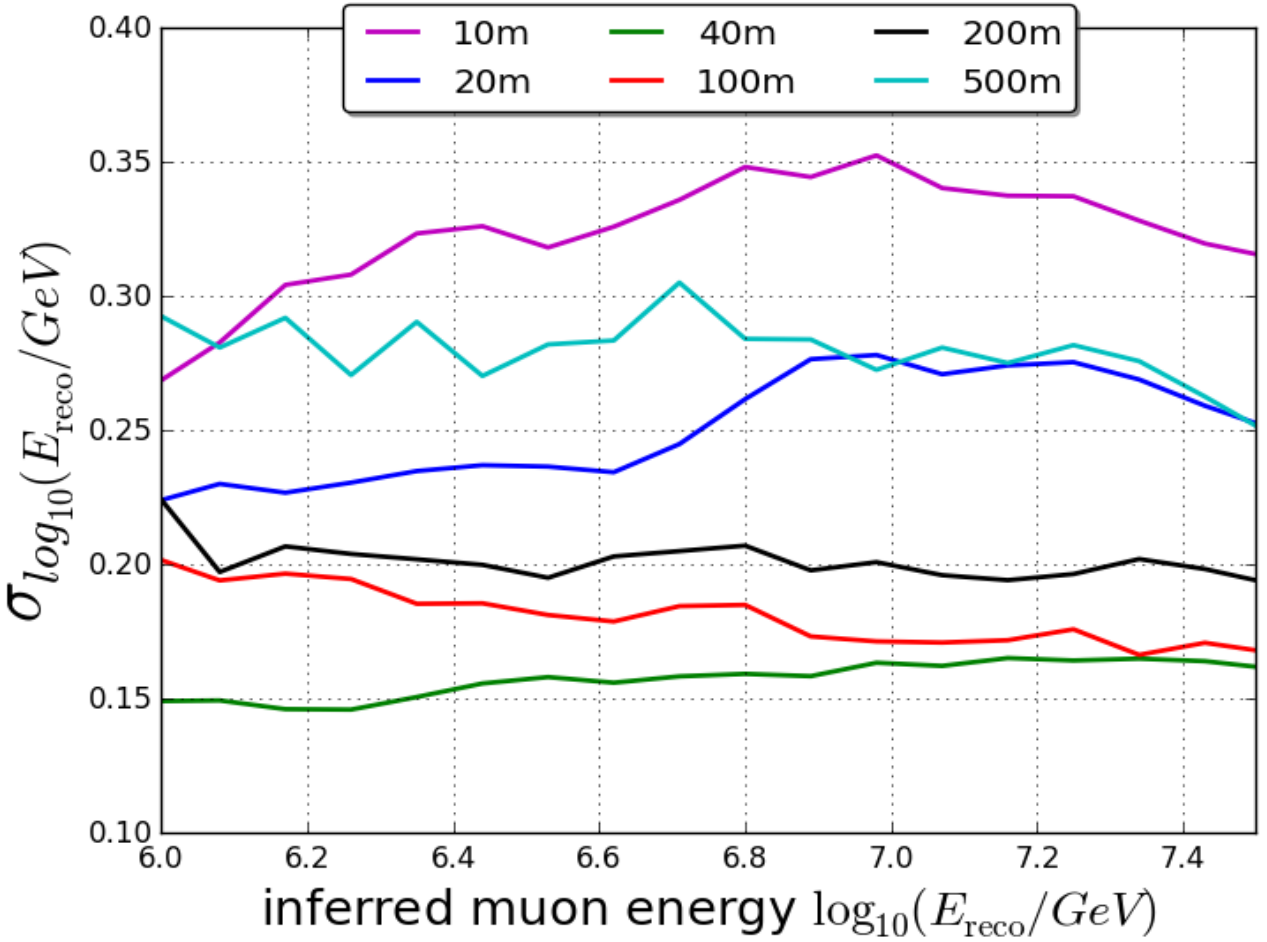
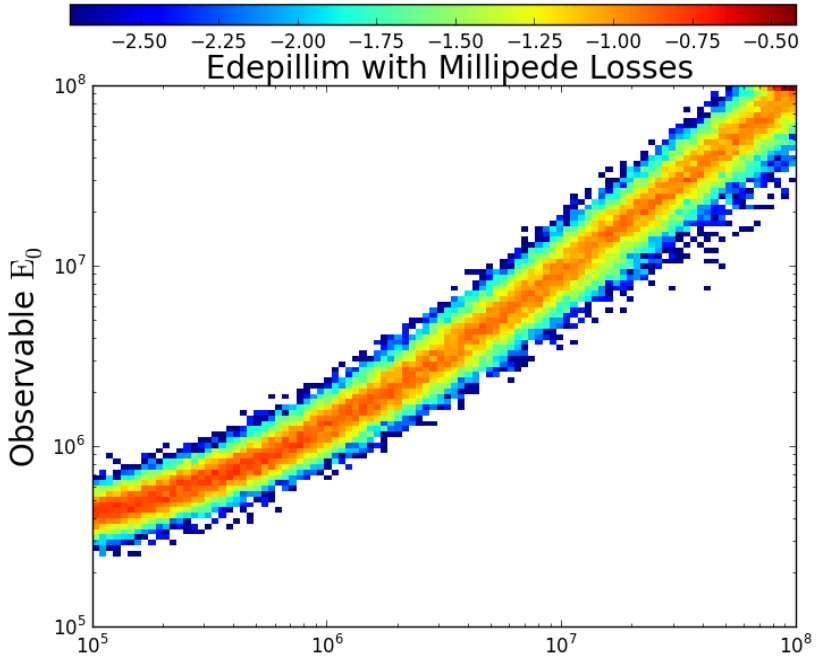
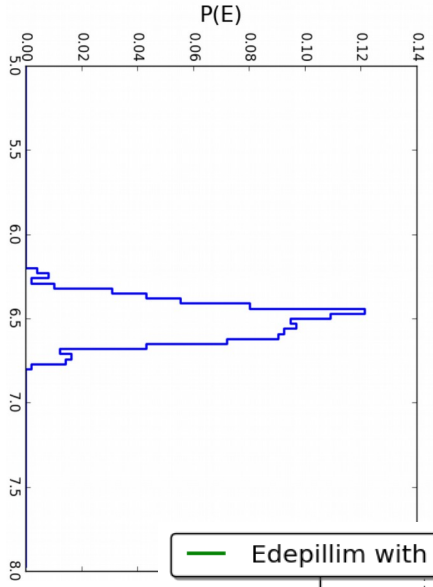
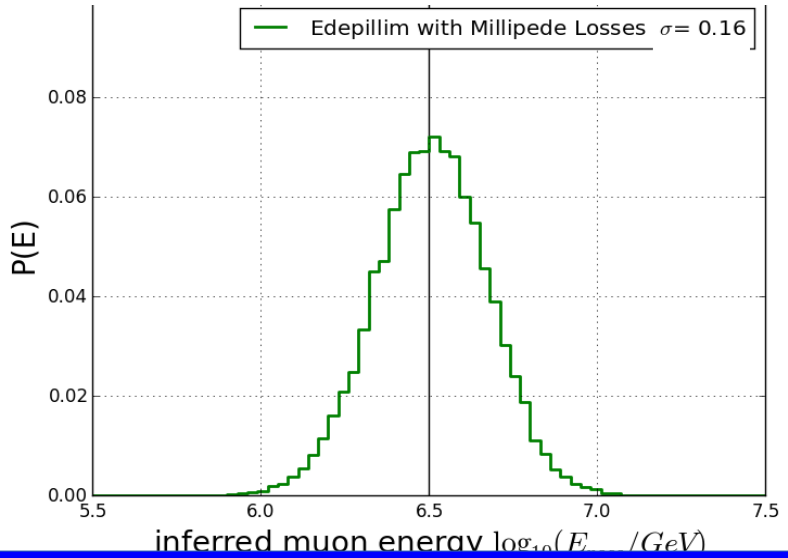


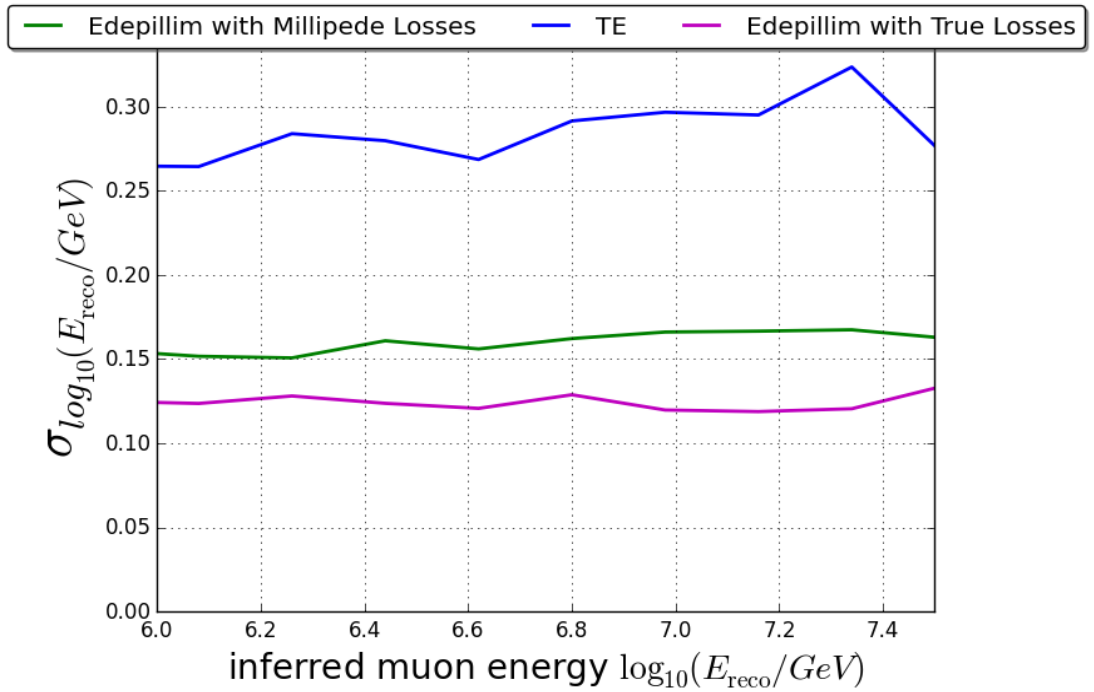
Edepillim with Millipede Losses Resolution





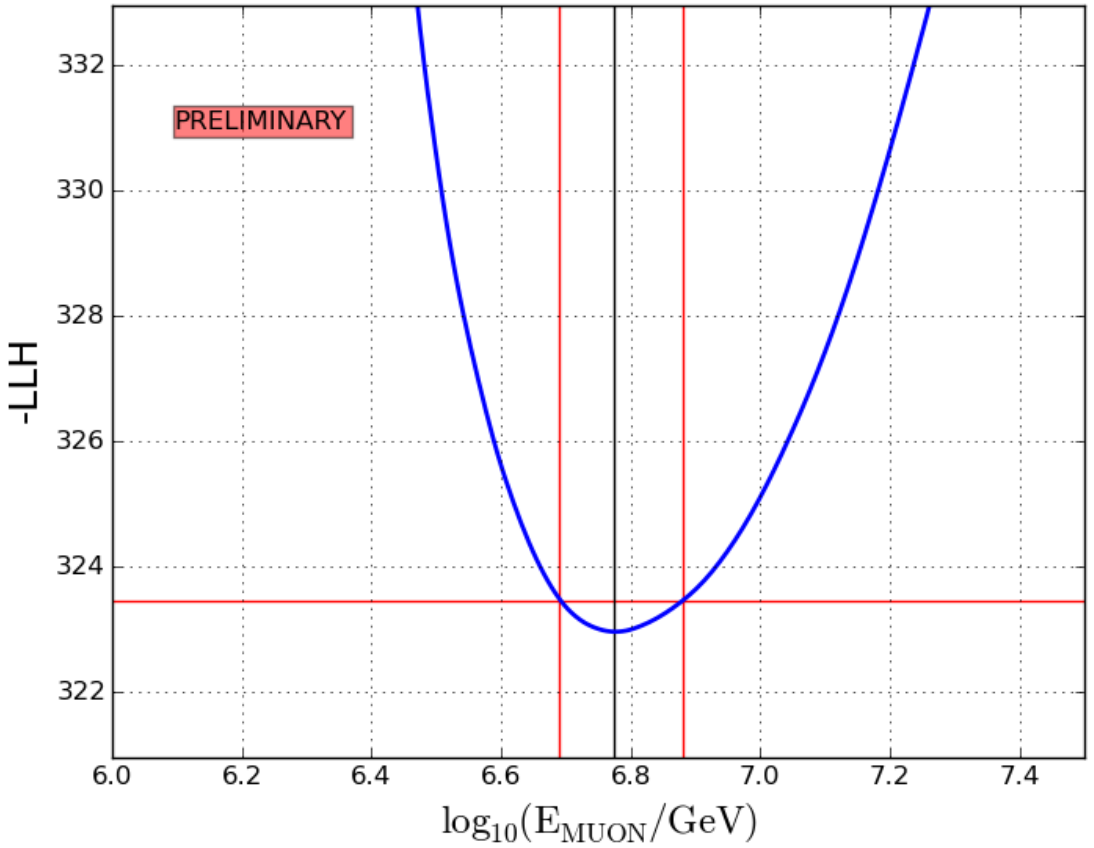
This is an example of Edepillim's performance for a fixed direction simulation. Performance will vary depending on the energy loss pattern reconstruction.

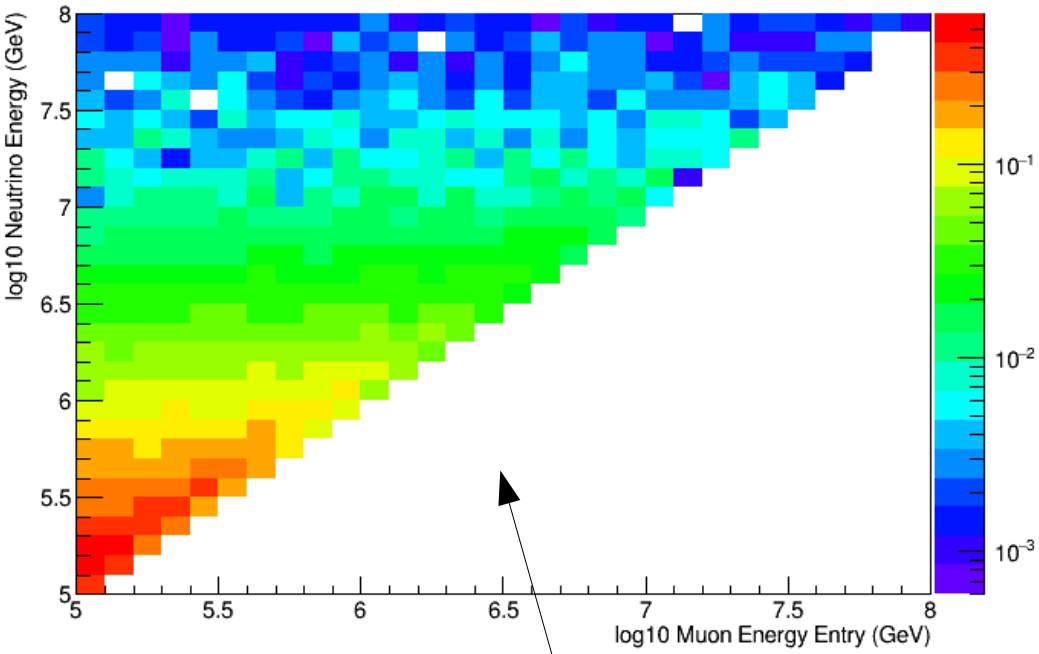




Multi-PeV Track-like Event- Edepillim Reconstruction

Energy reconstruction of Multi-PeV event was done on the best fit Millipede reconstruction using the 40m rebinning technique, that simulation showed to result in the best resolution. $E_0 = 5.95^{+1.65}_{-1.05} .10^6$ GeV

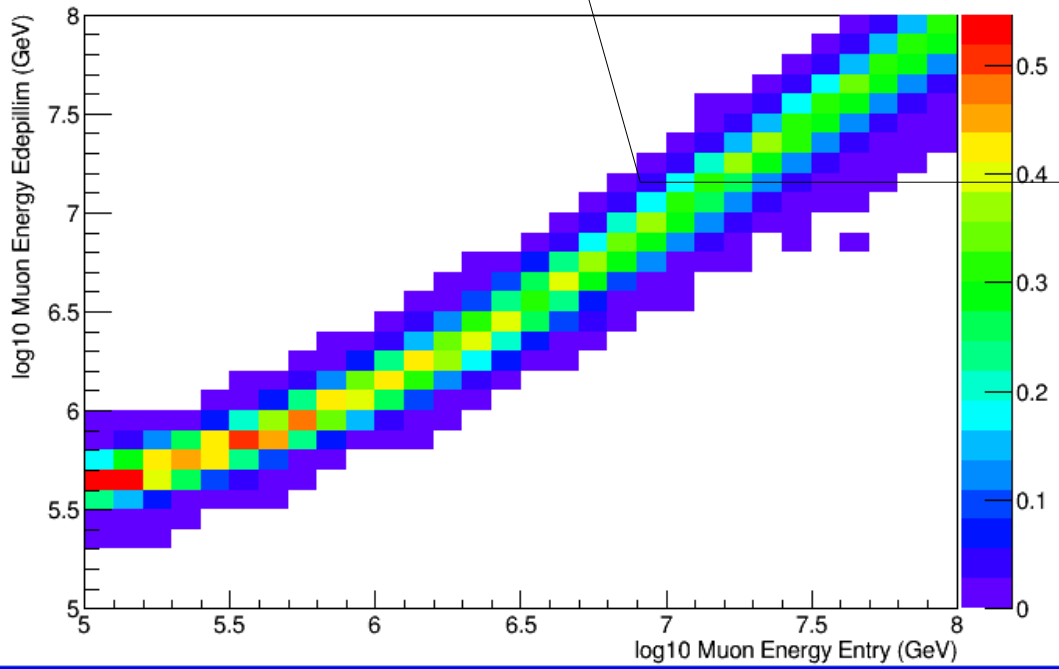


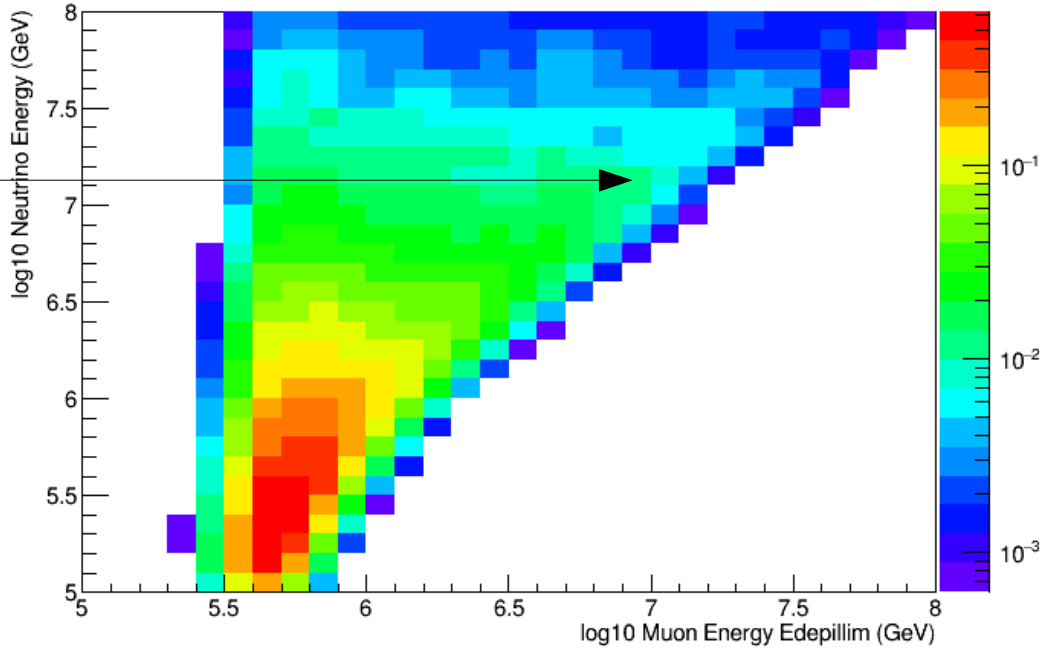


For each simulated event's true muon energy, a spectrum is taken of its neutrino energy.

Each spectrum is put into the corresponding reconstructed energy making a combined spectrum.

For a reconstructed muon energy a corresponding neutrino spectrum can be taken.

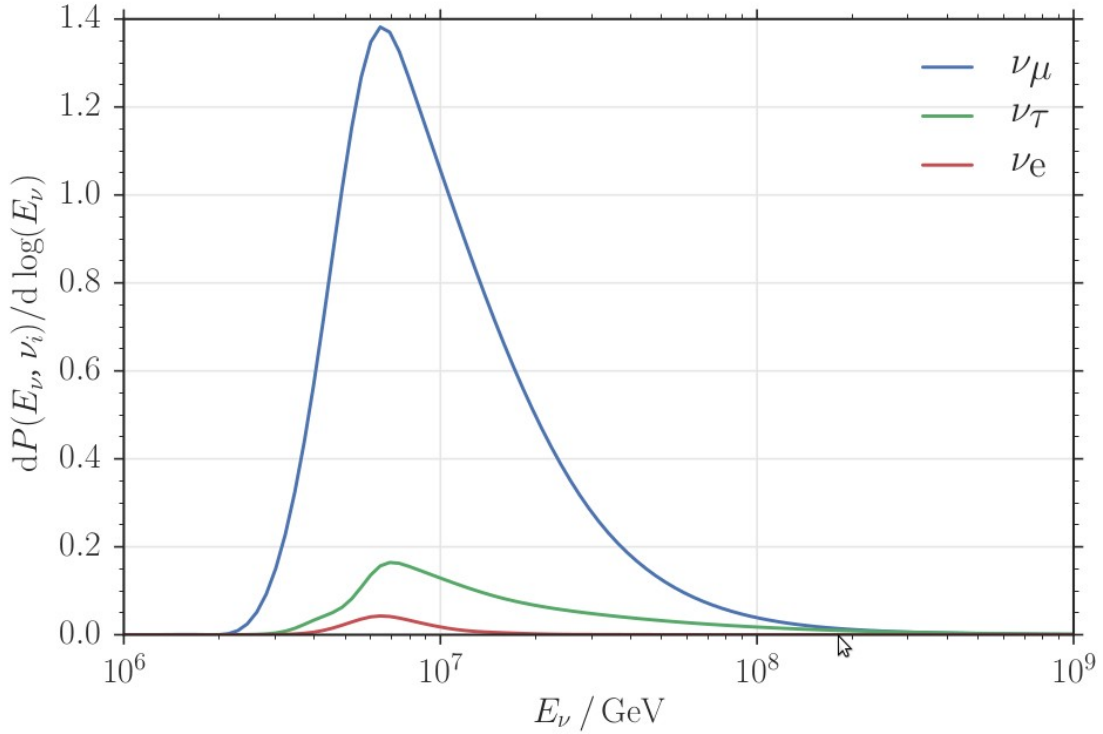




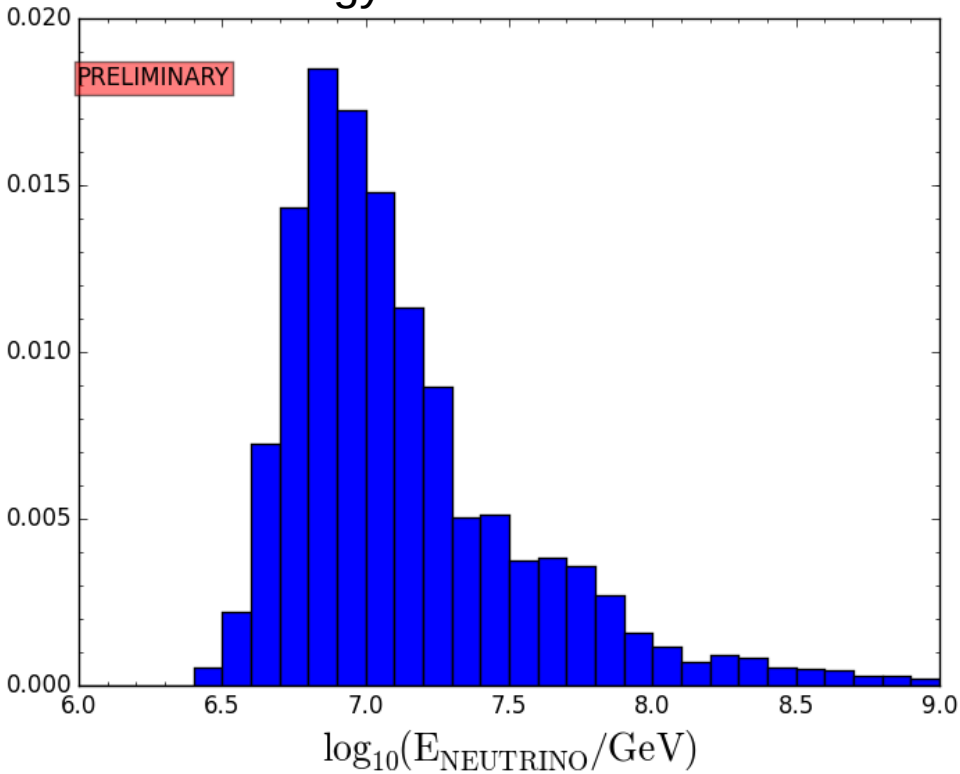
Multi-PeV Track-like Event- Edepillim Reconstruction

Neutrino energy spectrum, assuming the best fit astrophysical flux (since signalness = 0.995) for the Multi-PeV event with Edepillim reconstructed value of 5.95 PeV.

Truncated Energy
Median Energy: 8.7 PeV
Peak Energy: 6.3 PeV



Edepillim
Median Energy: 11 PeV
Peak Energy: 7.1 PeV



Summary/Outlook

- IceCube has detected a high energy astrophysical flux at TeV to PeV.
- For diffuse flux analysis energy resolution is very important for improvement
- IceCube is developing a muon energy reconstruction technique (Edepillim) that uses the energy loss pattern to find initial energy.
- The Edepillim method has great promise as shown by simulation studies.
- Results on the Multi-PeV event shows neutrino energy consistent with previous published result.