Analysis of High Energy Muons at DUNE FD

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Outline:

- Goal
- Muon Energy Measurement Techniques
- Simulation
- Reconstruction
- Future Work
- Earlier simulation based study was done by Kevin Ingles, Tom Junk, Alberto Marchionni and Merrill Jenkins, so more detailed discussion can be found in DUNE-doc-9607-v2 .

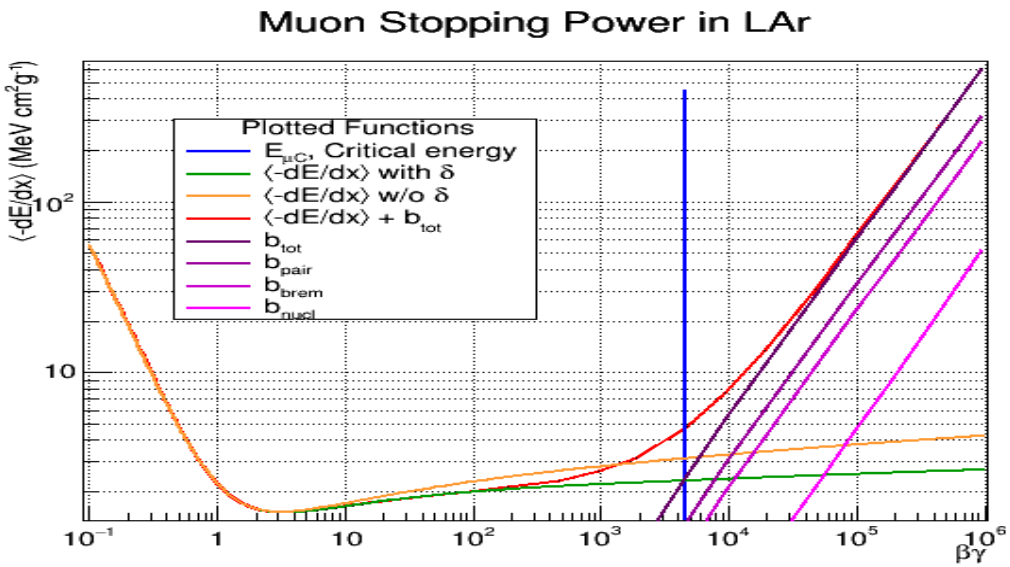
Goal

- Energy reconstruction of very high energy muons originated from Cosmogenic Neutrino(▸ IceCube) and Very High Energy Cosmic Rays.
- Also searches for Weakly Interacting Massive Particles(WIMPs) using neutrino-induced upward through-going muons (▸ S. Desai et al.) .
- This kind of multimessenger astronomy works at the scale of TeV and are being tested at IceCube(▸ R.Abbasi et al.) and Super-Kamiokande(▸ S. Desai et al.) detectors.
- DUNE far detector(FD) may also be used to detect high-energy muons.

Muon Energy Measurement Techniques.

- Muon range : for muons with momentum between MeV to GeV, uses muon track-length that decay into electrons within the detector volume.
- Coulomb Scattering (multiple scattering) : used for muon with momentum between 10's of MeV to few GeV. Muon is deflected by Coulomb interaction with nuclei. RMS of deflections is used as the predictor - notable experiments ICARUS and MicroBooNE(up to around 2 GeV).
- Magnetic Spectroscopy : Magnetic field is used to deflect muon path mainly in the GeV range, radius of curvature used as predictor - notable experiments MINOS and CMS.
- Energy deposition dependent methods : using characteristics of electromagnetic showers as predictors in the 100's of GeV to TeV range - notable experiments Super-Kamiokande and IceCube.

Muons Stopping power in Liquid Argon:



- At very high energies, energy loss is dominated by radiative processes that includes bremsstrahlung, pair production and nuclear interactions.
- Muon stopping power : $< dE_\mu/dx > \approx$ a + bE$_\mu$, where "a" accounts for ionozation and "b" for radiative processes.

Tracks → A showering high-energy muon inside the LArTPC :

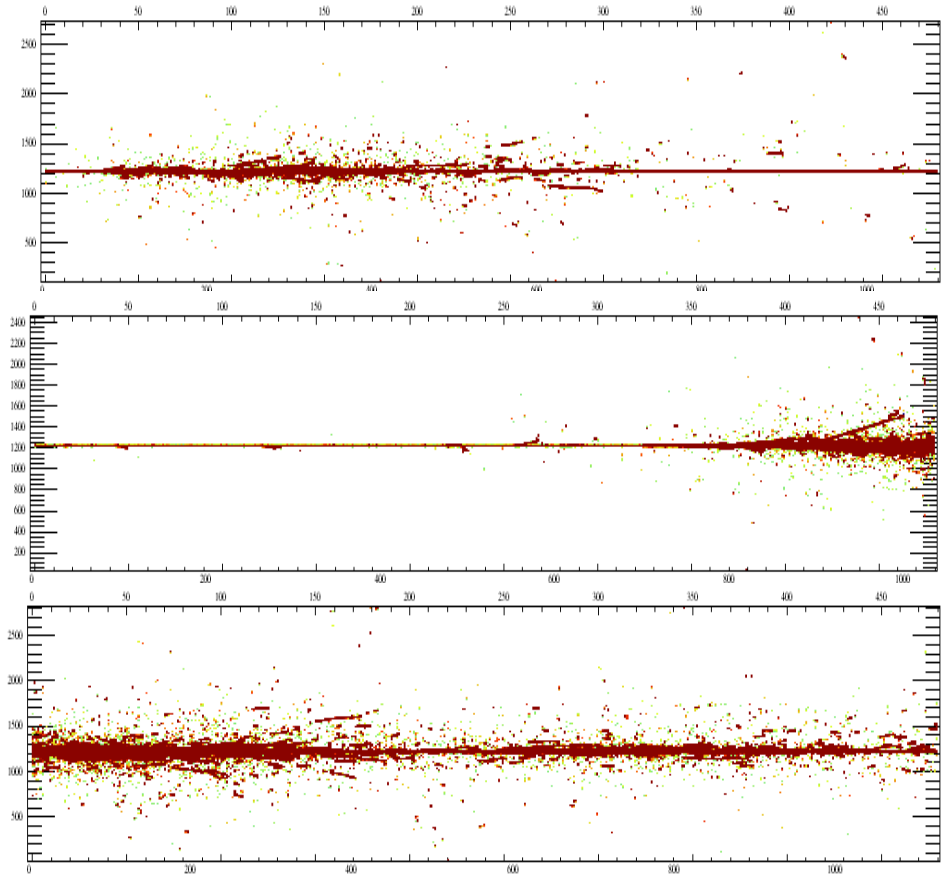
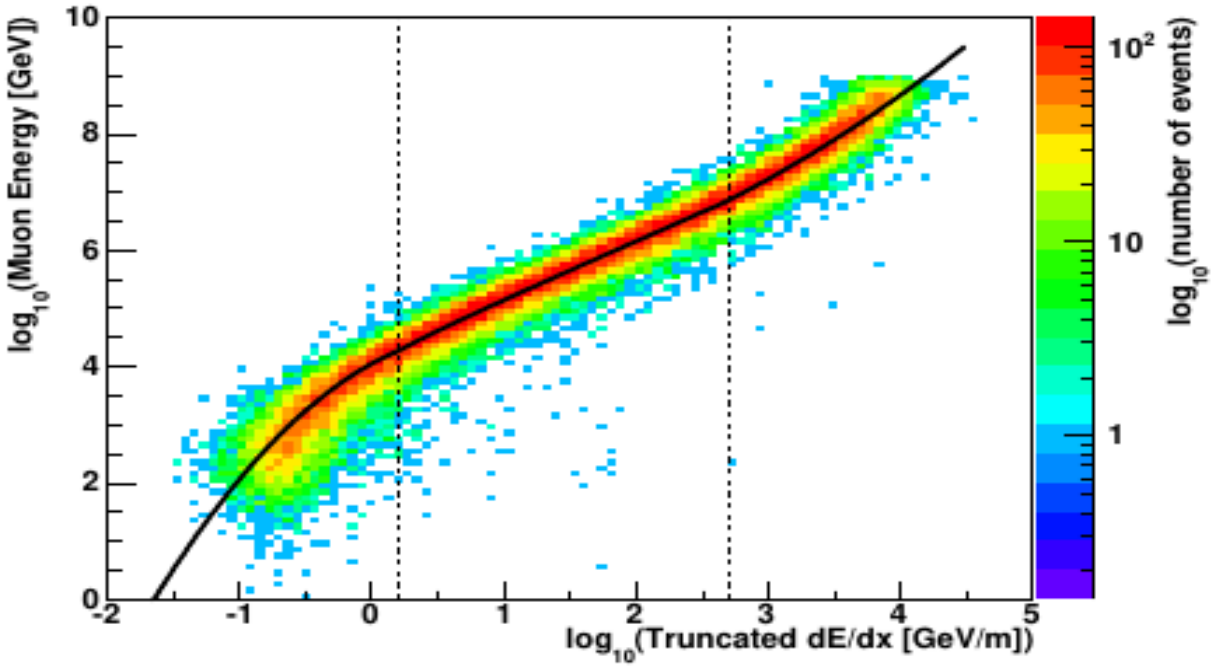


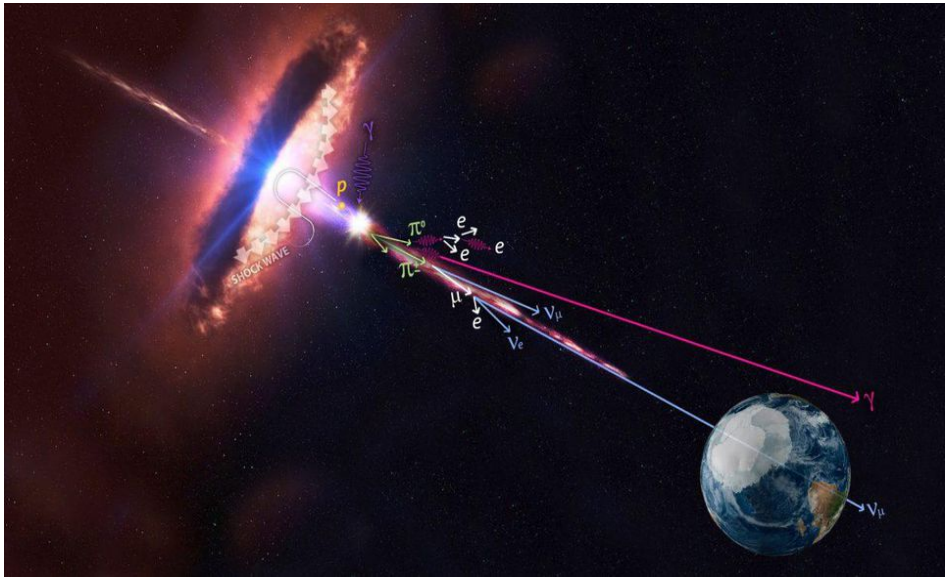
Figure 1 : 10 TeV muon event showing a track and associated showers developments in LArTPC.

IceCube Energy Reconstruction:

- IceCube reconstructed the muon energy by measuring the specific energy loss (dE_μ/dx) along the muon's path and relating the dE_μ/dx to the muon energy (▸ R.Abbasi et al.).
- Simulated E_μ vs truncated dE_μ/dx at the center of the IceCube detector is shown in the Fig.



IceCube detected the source of astrophysical neutrinos:



- Blazar emits both neutrinos and gamma rays that detected by the IceCube Neutrino Observatory(▸ IceCube) as well as by other telescopes on Earth and in space.
- A Neutrino event from the blazar TXS 0506+056 detected by IceCube on 22 September 2017 was coincident in direction and time with a gamma-ray flare.

Simulation :

- For simulation 1000 events are generated with the Particle Gun generator within the Geant4 using LArSoft tool-kit.
- Muons are generated and propagated in the +Z direction of the detector geometry proposed for the DUNE-FD, 10kt single phase.
- 1000 events are generated at each energy values : 100, 500, 1000, 5000, 10000, 20000 and 50000 GeV.
- The energy deposited through the track is estimated by collecting the electron on wires from the Reconstruted Hits/Space-Point.

List of Parameters :

- Here is the list of parameters that will be used to estimate the true muon energy from the observed signals.
- Natural logarithm of quantities used to plot histograms on convenient scale.

Variables	Notation Used
Total Energy deposition per event	$\ln\Delta_{tot}$
Average energy deposited on wires	$\ln\bar{\Delta}$
RMS of energy deposited	$\ln\sigma_{\bar{\Delta}}$
RMS divided by the Average	$\ln(\sigma_{\bar{\Delta}}/\bar{\Delta})$
Average energy deposited excluding MIP wires	$_{noMIP}\ln\bar{\Delta}$
RMS of energy deposited excluding MIP wires	$_{noMIP}\ln\sigma_{\bar{\Delta}}$
RMS divided by the Average excluding MIP wires	$_{noMIP}\ln(\sigma_{\bar{\Delta}}/\bar{\Delta})$
Count of Electromagnetic showers	N_{Shower}

Energy Deposition of Muon :

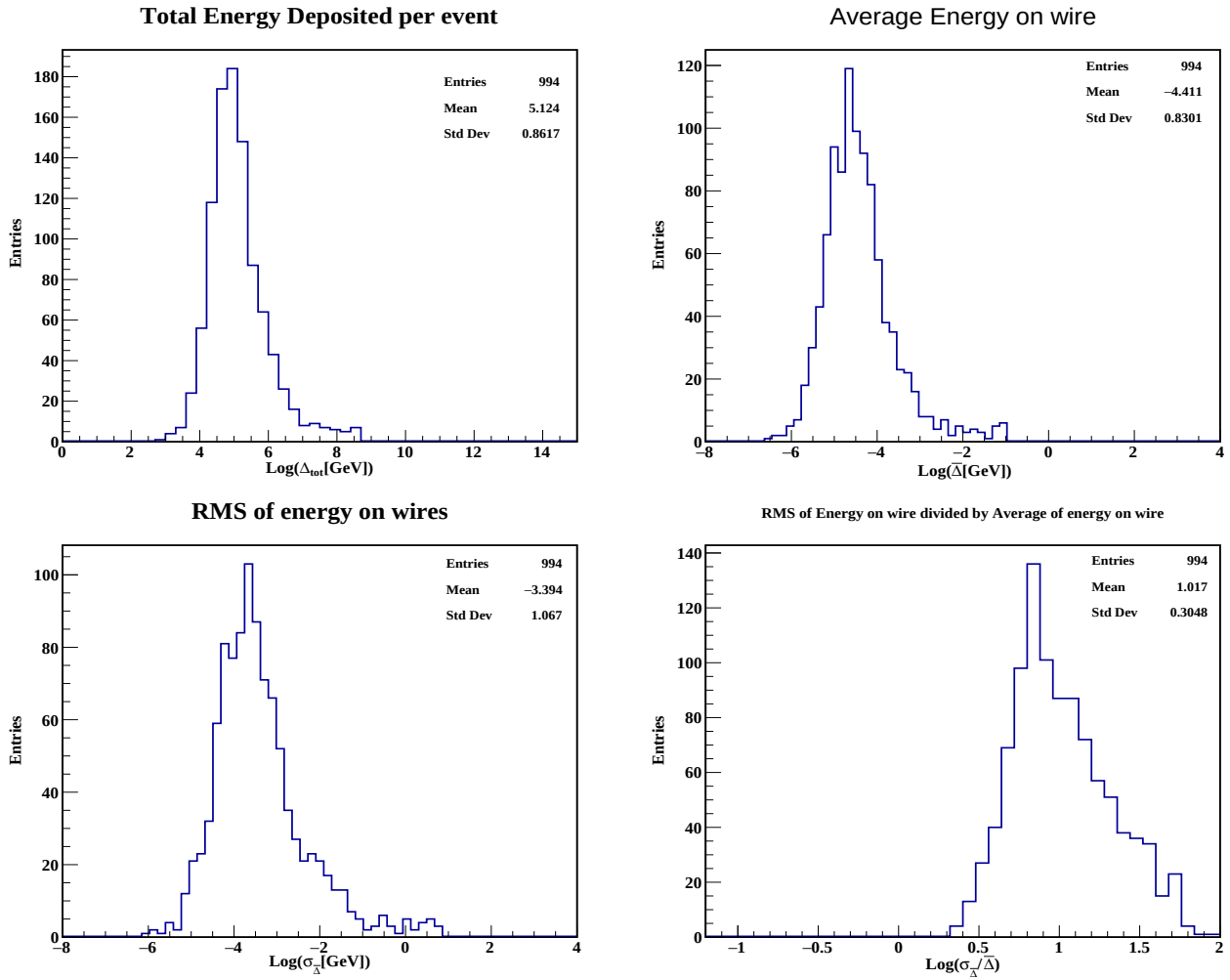


Figure 2 : Histograms for 10 TeV muons events in LArTPC, similar histograms for other energies can be found at : ▸ Histograms

Energy Deposition of Muons:

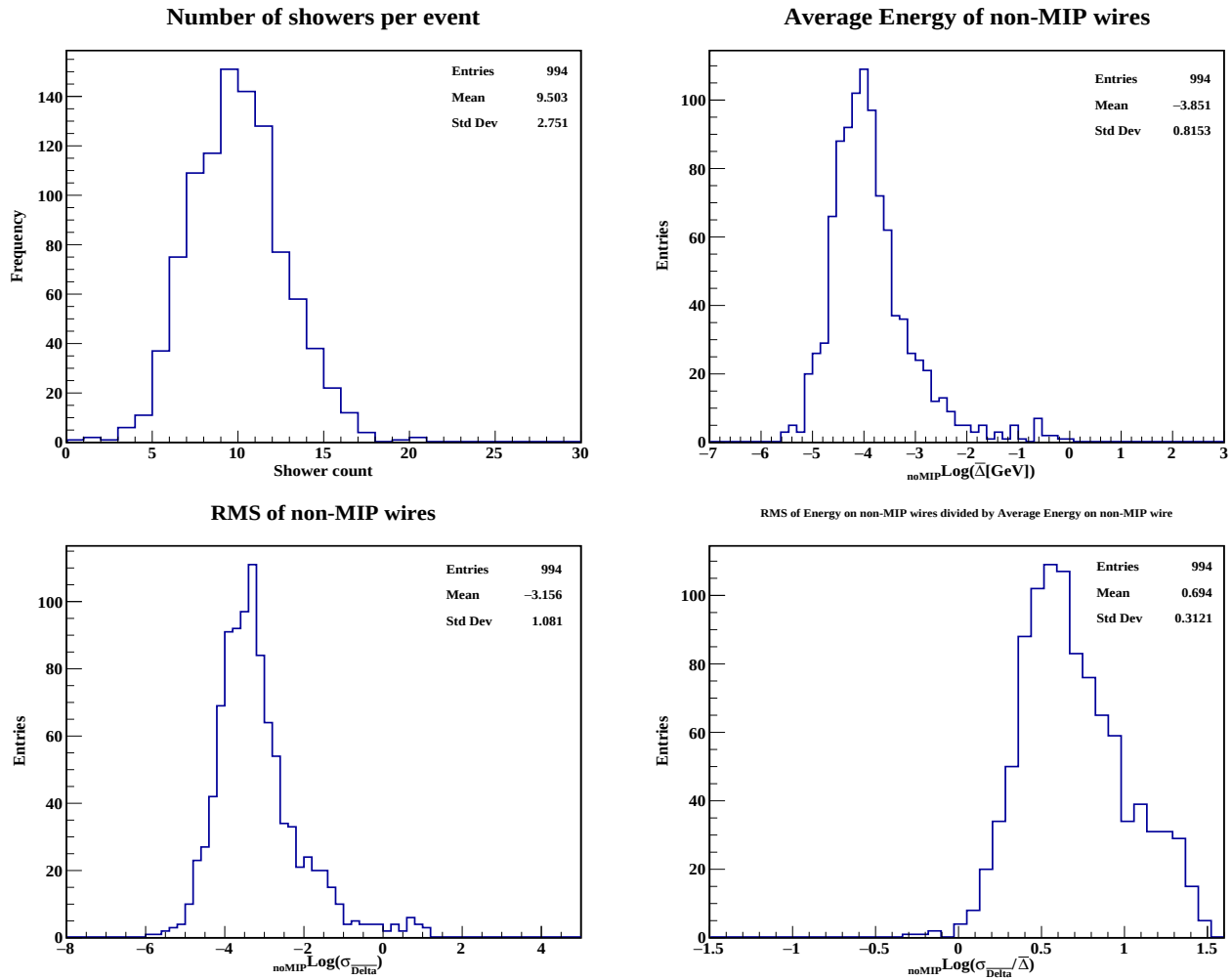


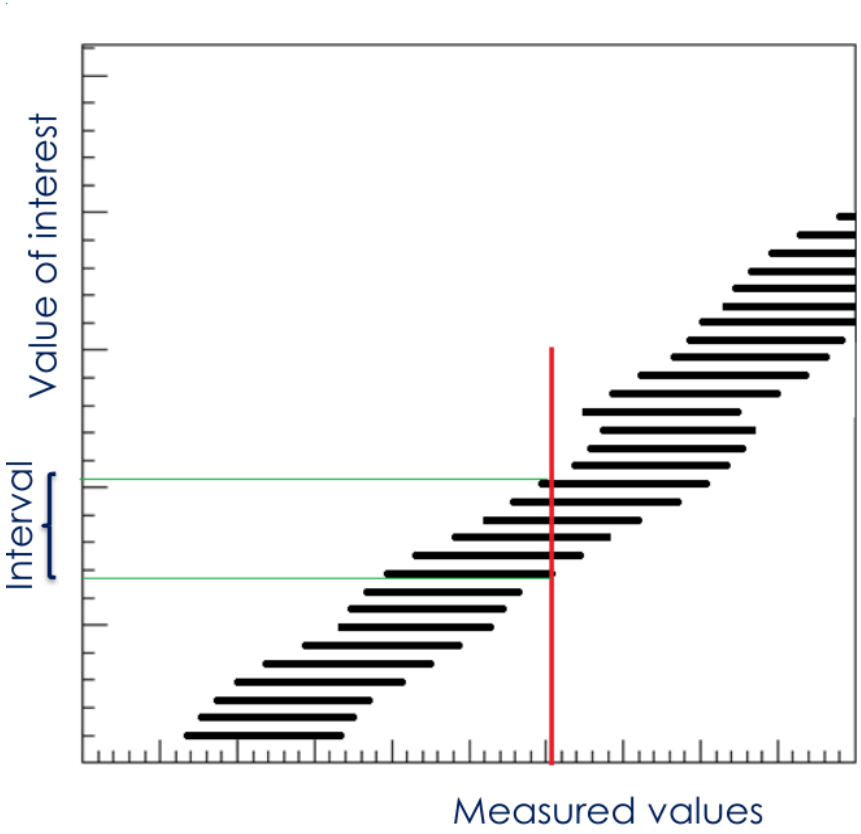
Figure 3 : Histograms for 10 TeV muons events in LArTPC.

Table for estimated values at other energies:

p	ln(p)	Ave $\ln\Delta_{tot}$	Ave $\ln\bar{\Delta}$	Ave $_{noMIP}\ln\bar{\Delta}$	Ave N_{Shower}
(GeV)	(GeV)	(GeV)	(GeV)	(GeV)	
100	4.6052	2.569	-6.812	-6.074	1
500	6.2146	2.888	-6.502	-5.745	1
1000	6.9078	3.156	-6.265	-5.472	3
5000	8.5172	4.506	-4.991	-4.351	7
10000	9.2103	5.124	-4.414	-3.849	10
20000	9.9035	5.760	-3.825	-3.341	13
50000	10.8198	6.637	-3.032	-2.616	17

Neyman Construction :

- Used when a value of interest can not be directly measured.
- Uses variables that can be measured to make an inference about the value of interest.
- Experimental outcomes simulated for each possible value of interest.
- Confidence interval constructed for the measured value for each value of interest.
- The sets of confidence intervals creates a confidence belt.
  - A measurement made represents a vertical line, the intersection with the confidence belt forms an interval for the value of interest.



Confidence Intervals Estimation :

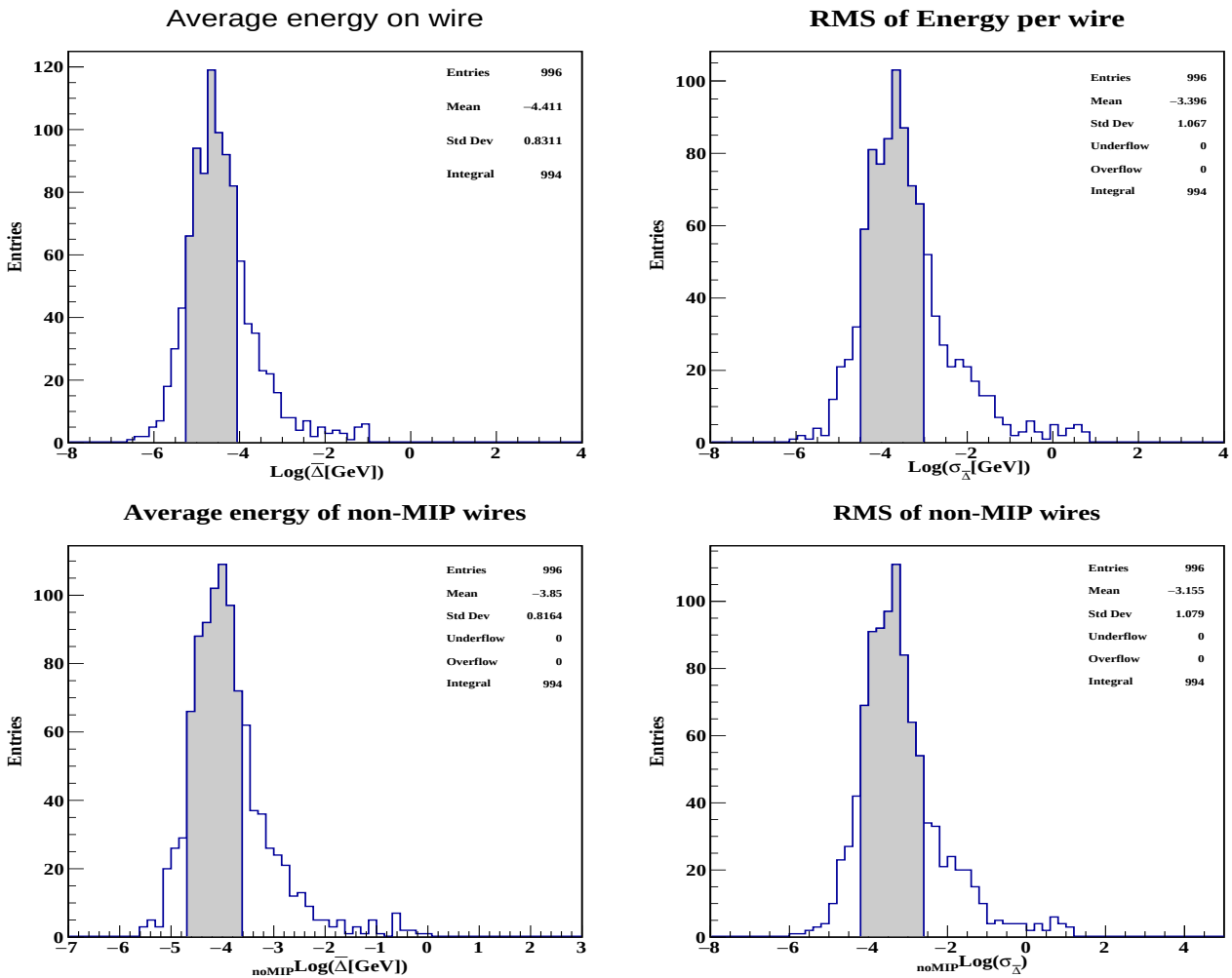


Figure 4 : Calculated confidence intervals(68.3%) corresponding to the variable of interest for 10 TeV muons events, for other energies can be found at : ▸ Histograms

Neyman Construction for the parameters of Interest:

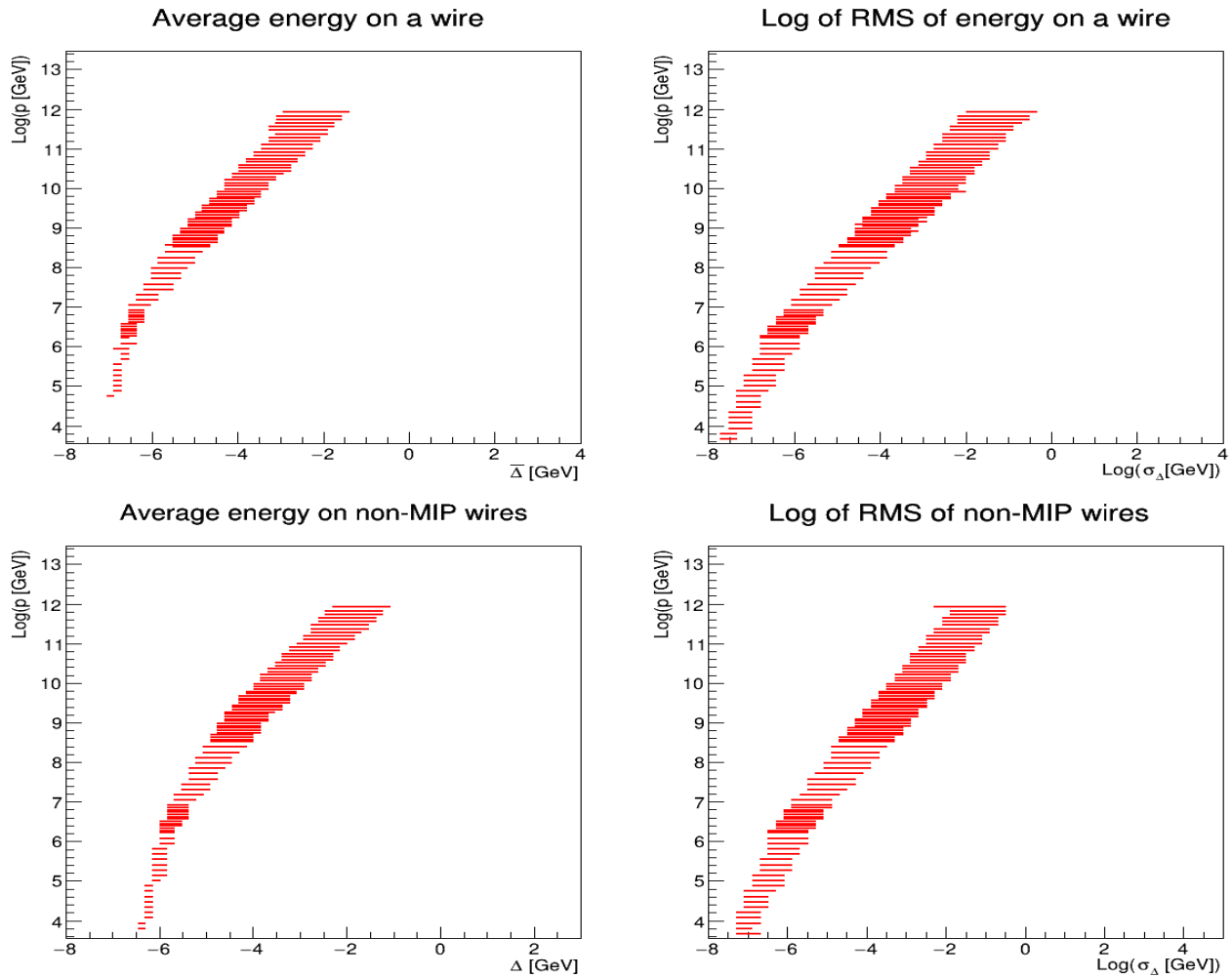


Figure 5 : The confidence belts constructed for the 4 variables of interest for full track length events at all energies.

Density Plot for the parameters of Interest:

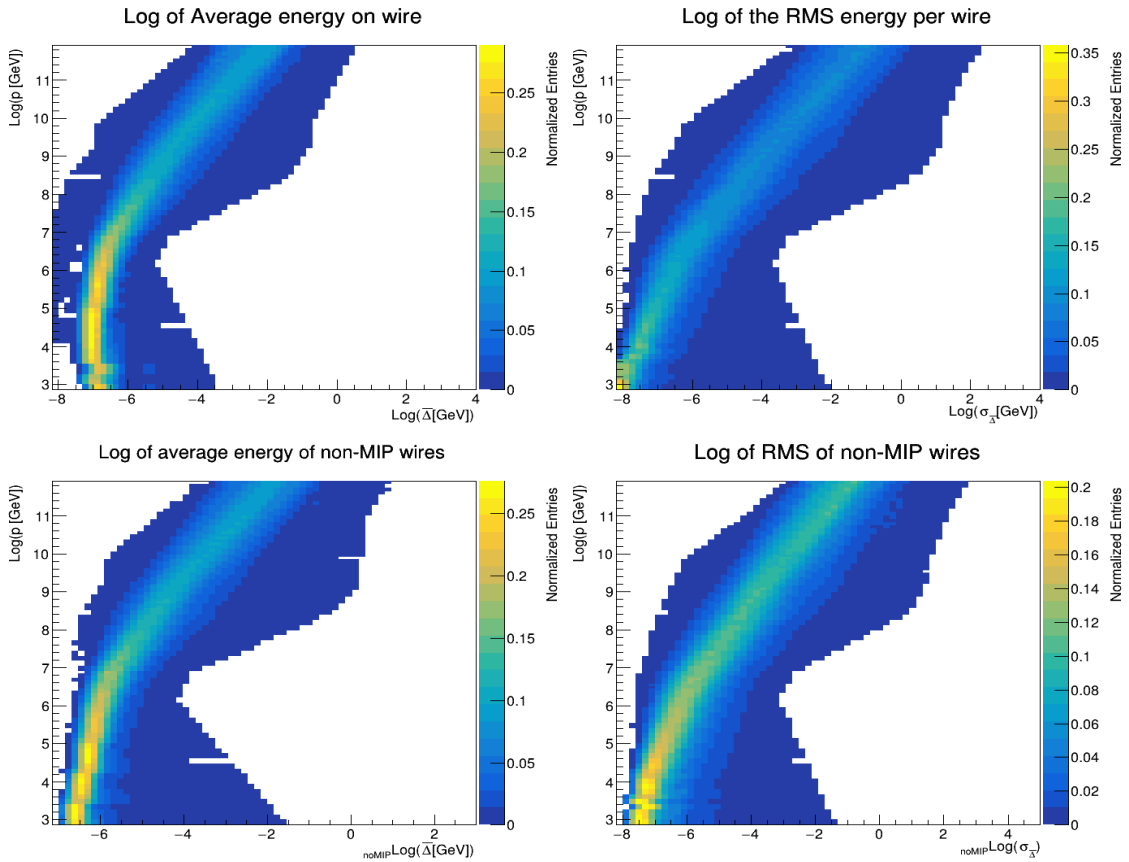


Figure 6 : Histograms for all the energies are plotted together on a 2D histogram. Observe the the bend around 7 on the vertical scale, this corresponds to the critical energy where the showering process begin to dominate the energy loss.

Charge on the Collection Plane:

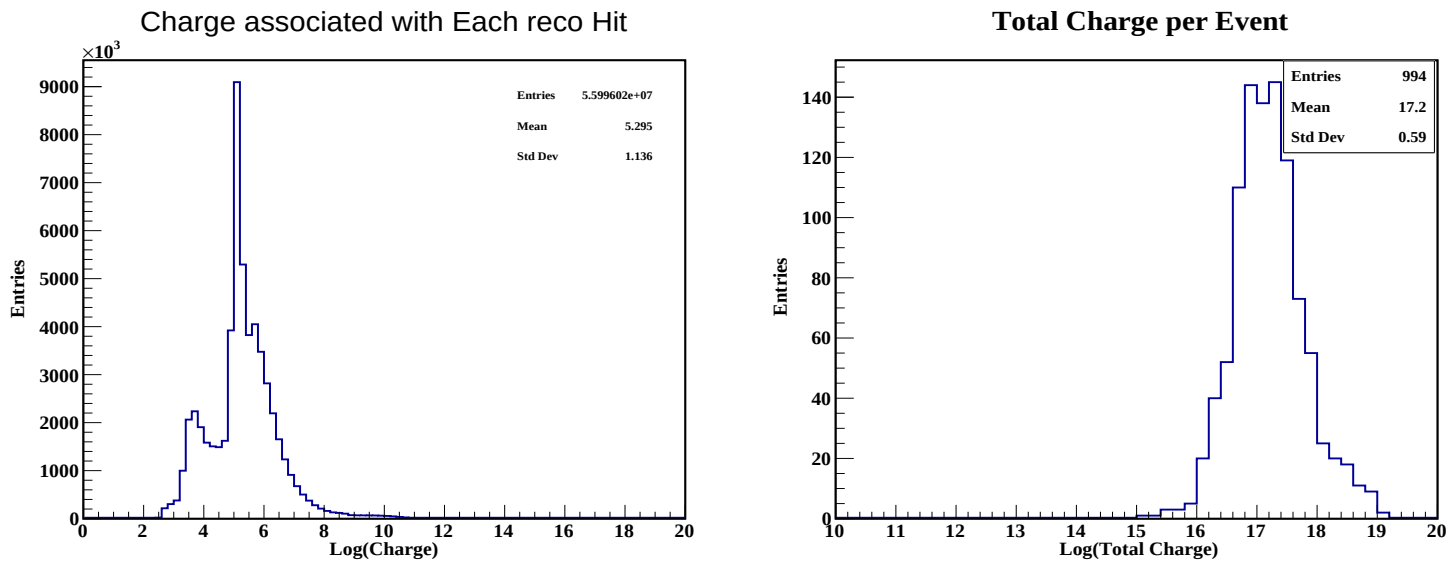


Figure 7 : Left panel shows the Log of Charge at collecting wires planes associated with each reconstructed hit. Right panel show the log of totel charge per event for 10 TeV muons events in LArTPC.

No of Electrons on the Collection Plane:

p (GeV)	ln(p)	exp(Average log of Hit Charge)	Average log of Total Charge)
100	4.6052	182.7282	14.95
500	6.2146	187.1668	15.25
1000	6.9078	190.9478	15.50
5000	8.5172	198.9393	16.69
10000	9.2103	199.3376	17.20
20000	9.9035	197.1569	17.73
50000	10.8198	190.7569	18.40

Future Work

- Track length extrapolation from reconstructed space points.
- Muon Energy estimation from the reconstructed objects(hits, space points, clusters etc.).
- Systematic uncertainty evaluation.
- Energy resolution as a function of muon path length estimation.
- Differentiating upward-going muons from downward-going muons.

Thank you for your attention.

Any Questions ?