Energy reconstruction technique for very high energy muons with DUNE far detector

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Outline:

- Goal
- Muon energy measurement techniques
- Simulation
- Reconstruction
- Future work
- Further detailed discussion can be found here: dune-doc-9607-v2.

Goal

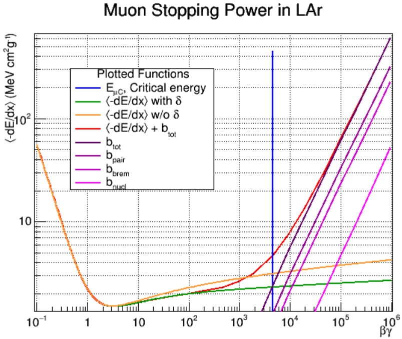
- Energy reconstruction of very high energy muons originating from cosmogenic neutrinos(IceCube) and very high energy cosmic rays.
- Searches for Weakly Interacting Massive Particles(WIMPs) using neutrino-induced upward-going muons, as done by Super-Kamiokande collaboration, (S. Desai et al.) .
- This kind of multimessenger astronomy works at the TeV scale and are being tested at IceCube(R.Abbasi et al.) and SK detectors.
- DUNE far detector(FD) may also be used to detect high-energy muons.

Muon energy measurement techniques.

- Muon range: used 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 the deflections is used as the predictor - notable experiments ICARUS and MicroBooNE(up to around 2 GeV).
- Magnetic Spectroscopy: Magnetic field is used to deflect the muon path mainly in the GeV range, the radius of curvature used as a predictor - notable experiments MINOS and CMS. DUNE FD is not magnetized.
- 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.

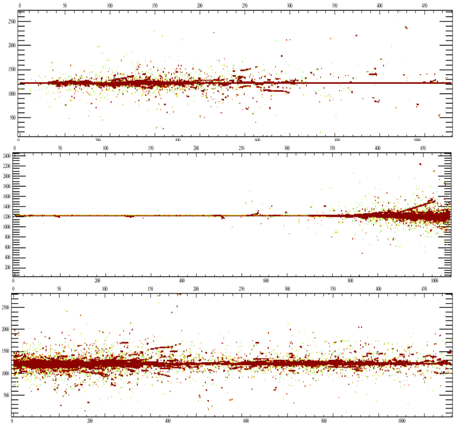
Muons stopping power (dune-doc-9607-v2&9694-v1):

- 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_μ, where a accounts for ionozation and b for radiative processes.



→Critical value for LAr is around 484 GeV or $\beta\gamma \approx 4.2 \times 10^3$.

A showering high-energy muon inside the LArTPC :



- 10 TeV muon event showing a track and associated showers developments in LArTPC(Kevin Ingles, dune-doc-9607-v2).

→

Simulation :

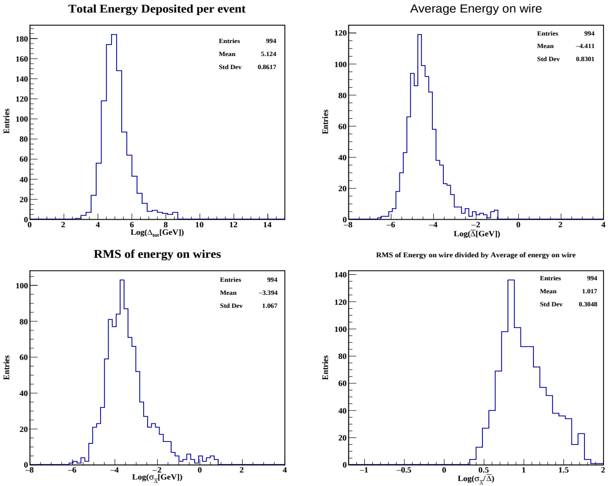
- For simulation events are generated with the particle Gun generator within the Geant4 using the LArSoft toolkit.
- Muons are generated and propagated horizontally and lengthwise of the detector geometry proposed for the DUNE-FD, 10kt single phase.
- 1000 events are generated at each energy values : 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 reconstructed hits and space-point.

List of parameters :

- Here is the list of parameters used in dune-doc-9607-v2, will be used to estimate the true muon energy from the observable.
- Natural logarithm of quantities used to plot histograms on a convenient scale.

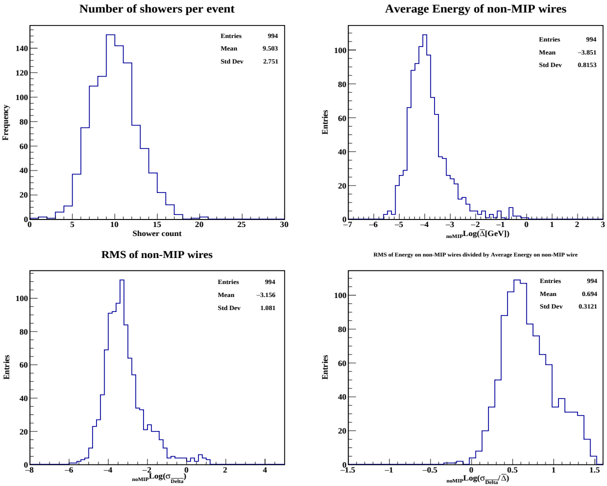
Variables	Notation Used
Total energy deposition per event	$\ln\Delta_{tot}$
Average energy deposited on wires	$\ln\bar{\Delta}$
RMS of energy deposited on wires	$\ln\sigma_{\bar{\Delta}}$
RMS divided by the average	$\ln(\sigma_{\bar{\Delta}}/\bar{\Delta})$
Average energy deposited excluding MIP wires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



- Histograms for 10 TeV muons events in LArTPC, similar histograms for other energies can be found at ▸ Histograms.

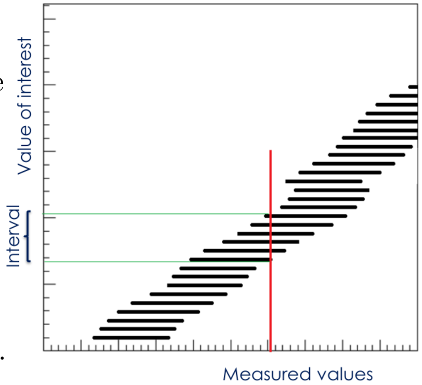
Energy deposition of muons:



- Histograms for 10 TeV muons events in LArTPC.

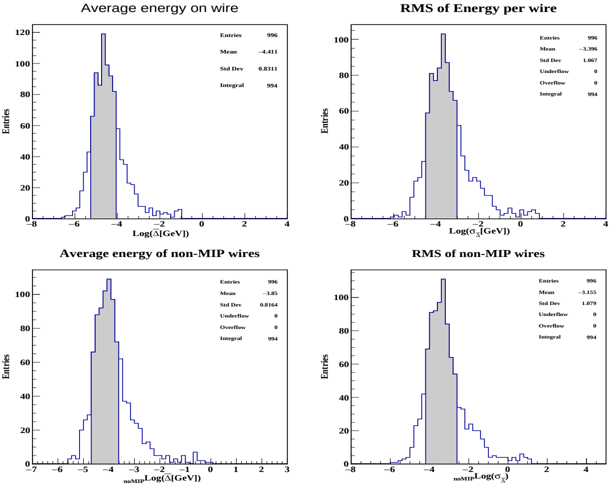
Neyman construction :

- 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.



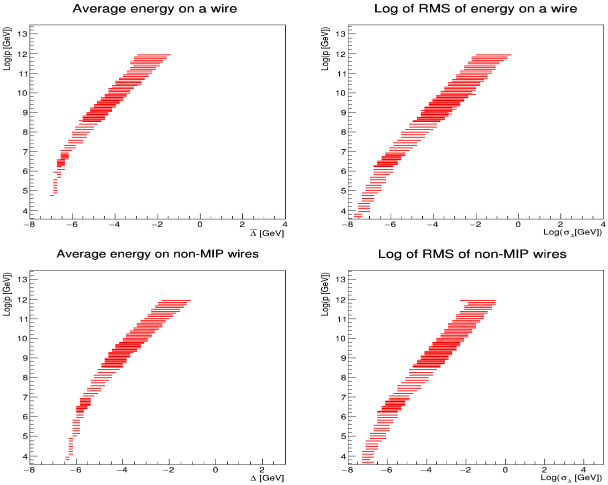
- The sets of confidence intervals creates a confidence belt.
  - A measurement made represents a vertical line, the intersection with the confidence belt forms an interval for the value of interest.

Confidence intervals estimation :



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

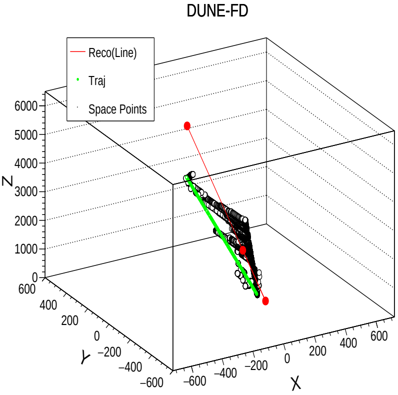
Neyman construction for the parameters of interest:



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

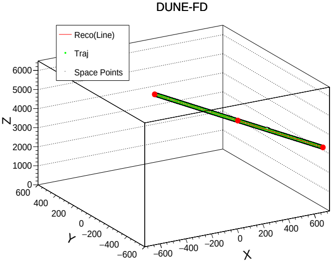
Track length estimation with space points:

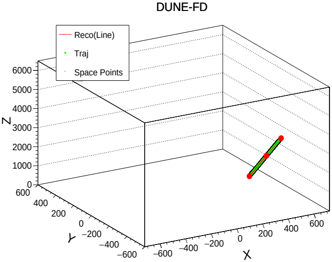
- Reconstruted spacepoint is an object made using hits in the three 2D time vs wire views associated to find 3D points in LArTPC.
- Pandora is used to reconstruct space points (Eur.Phys.J.C75,439(2015)) and (Eur.Phys.J.C78,82(2018).
- PCA is used to estimate the direction vector that is used to calculate the equation of line.
- Estimated average point and line-plane intersection points are represented with red solid circles.

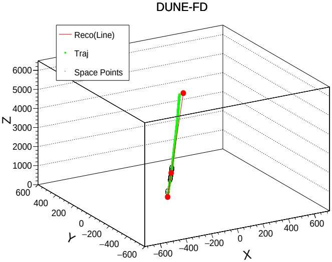


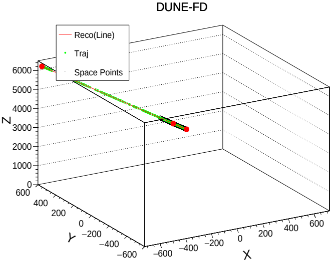
- Intersecting points of the lines with planes is used to estimate the segment of track(track length) available inside the field cage.

Reconstructed track from MUSUN sample:

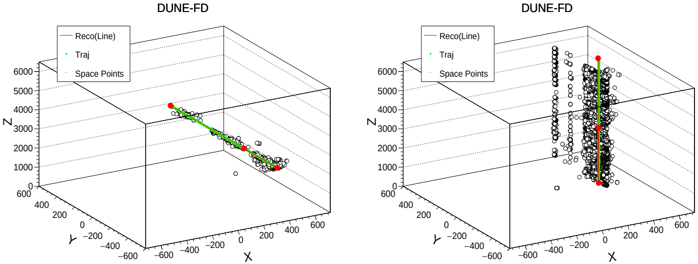






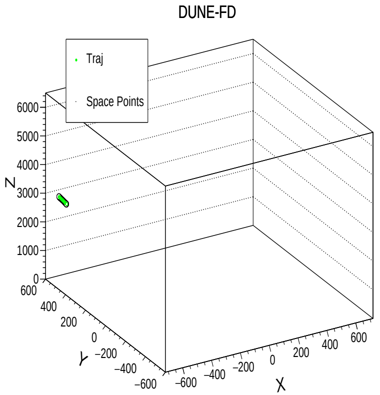


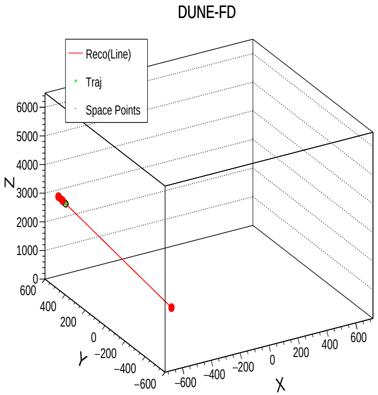
Isochronous tracks :



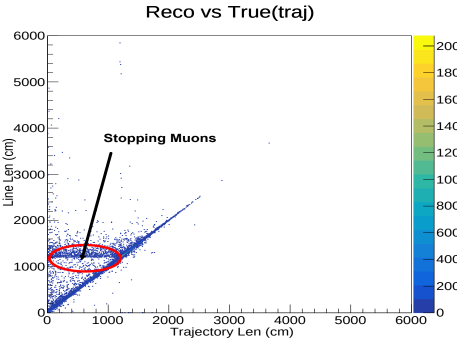
- Reconstructed space point and tracks for 10 TeV muon events propagated perpendicular to the X axis, called isochronous tracks.
- They are all at the same X, which means the drifting electrons arrive at the anode all at the same time, since the association of hits in different views is ambiguous and that gives the wrong space points.
- We must cut out these events from the analyses or treat them specially because they are misreconstructed.

Stopping muons tracks :



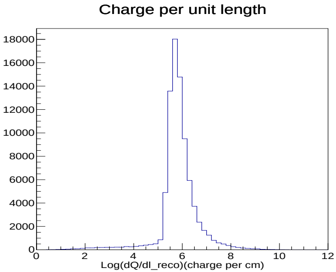


True and reconstructed track length:



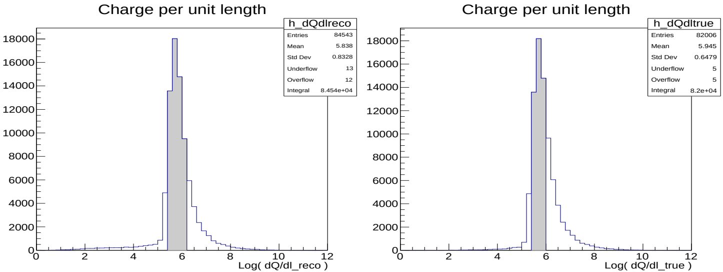
- True track length vs reconstruced track length, here true tracks length are estimated by adding up the trajectory point distances inside the LArTPC.

Charge per unit length(dq/dx):



- Logarithm of charges per unit length, length is estimated (left panel) with reconstructed space-point and adding up the trajectory point distances(right panel).

Charge per unit length(dq/dx):



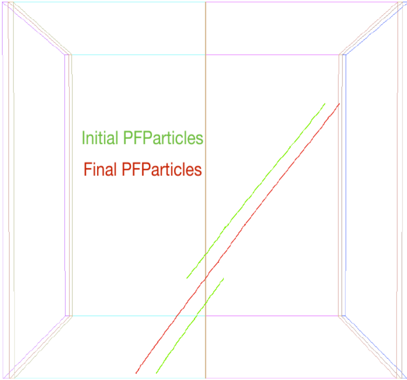
- Logarithm of charges per unit length and its confidence interval that will be used to get the Neyman confidence belt.

Future work

- Characterization of the performance of the track length estimation using space points.
- Remove outlier space points when getting direction.
- Stitch the tracks comes randomly in the time since the space point will be displaced if the time is not known. Or, use the PD system to get time.
- Systematic uncertainty evaluation. (muon radiation modeling, electronics saturation, recombination modeling in dense showers and electron lifetime).
- Energy resolution as a function of muon path length estimation.
- Differentiating upward-going muons from downward-going muons using shower shapes.

Future work : Stitching

- Stitching needs to be done because tracks cross between drift volumes with different directions of the E field.
- They cross anodes and cathodes in the FD.
- If the time is not known but the E field is the same everywhere along a track, then it just appears displaced along the E field.
- If the track crosses an anode or cathode and the time is unknown, then the pieces of the track in different volumes appear displaced in opposite directions and the track appears broken.



Steven Green

Thank you for your attention.

Any questions ?