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

Goal

- Energy reconstruction of very high energy muons originating from cosmogenic neutrinos[1] and very high energy cosmic rays.
- Searches for Weakly Interacting Massive Particles (WIMPs) using neutrino-induced upward-going muons, as done by Super-Kamiokande[2].
- This kind of multimessenger astronomy works at the TeV scale and are being tested with IceCube[3] and SK.
- DUNE far detector (FD) may also be used to detect high-energy muons.

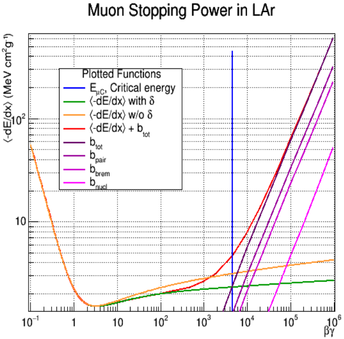
[1] Science 13 Jul 2018: Vol. 361, Issue 6398, pp. 147-151.
[2] S. Desai et al. Phys. Rev. D 70, 083523
[3] R.Abbasi et al. NIM A703:190,2013, arXiv:1208.3430

Muon energy measurement techniques

- Muon range: used for momenta between MeV and GeV.
- Coulomb Scattering : used for momentum between 10's of MeV to few GeV, example experiments ICARUS and MicroBooNE.
- Magnetic Spectroscopy: used for momentum in GeV range, example experiments MINOS and CMS. DUNE FD is not magnetized.
- Energy deposition dependent methods: used for momentum between 100's of GeV to TeV range, example experiments Super-Kamiokande and IceCube.

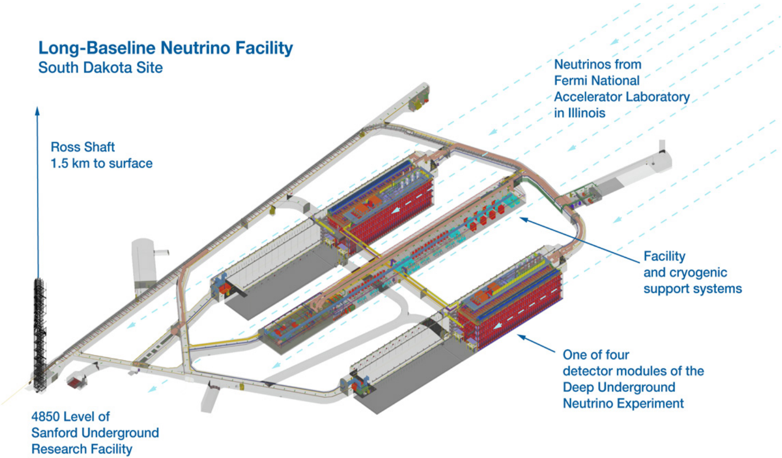
Muons stopping power

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



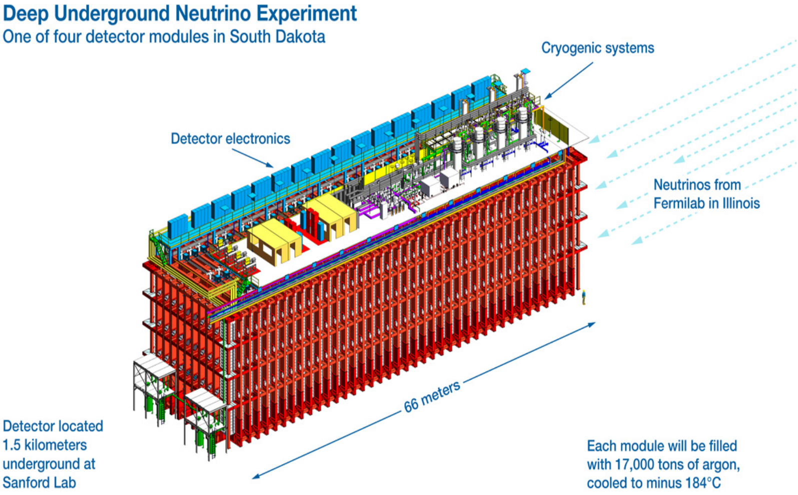
- Critical energy for LAr is around 484 GeV.

The DUNE Far Detector



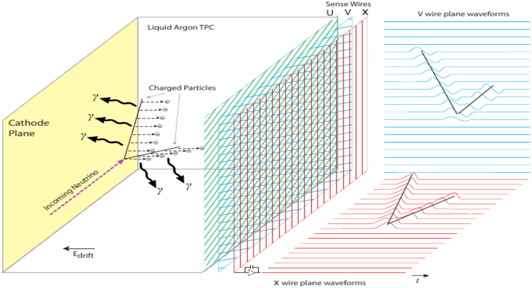
- A next-generation experiment for neutrino science, nucleon decay, and supernova physics.

A Single-Phase DUNE FD Module[4]



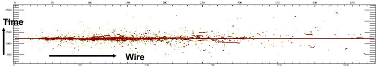
[4] arXiv:2002.03010

Three-Plane Readout

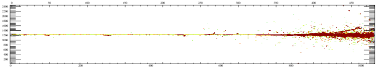


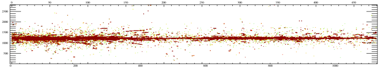
- Detector fully submerged in liquid argon.
- Ionization electrons drift in the electric field.
- Drifting electrons induce signals on U and V wires and are collected by the X wires.
- Hits in separate planes associated together to reconstruct 3D space points.

A high-energy muon in a LArTPC



X plane





10 TeV muon event showing a track and associated showers[5].

[5] Kevin Ingles, senior thesis at the University of South Alabama, April - 2018.

Simulation and Reconstruction

- Events are generated with a particle gun and simulated using GEANT4 and the LArSoft toolkit.
- Muons are generated and propagated horizontally and lengthwise of the detector geometry proposed for the DUNE-FD.
- 1000 events are generated at each energy value : 100 GeV to 50 TeV.
- The energy deposited by the track is estimated from drifting ionization charge that is collected by anode wires.
- Charge on wires are reconstructed as hits. Hits associated between planes allow reconstruction of three-dimensional space points.

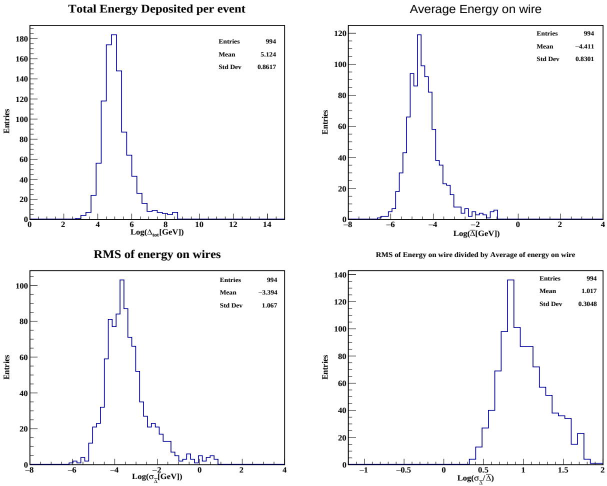
List of parameters

- Here is the list of parameters used in[6], which will be used to estimate the true muon energy from the observable.
- Natural logarithm of quantities used to plot histograms on a convenient scale.

Inclusive Energy Measures	Shower-only Energy Measures
Average energy deposition ($\text{Log}(\bar{\Delta})$)	Average energy deposition ($_{noMIP}\text{Log}\bar{\Delta}$)
RMS of energy deposition ($\text{Log}(\sigma_{\bar{\Delta}})$)	RMS of energy deposition ($_{noMIP}\text{Log}\sigma_{\bar{\Delta}}$)
RMS divided by the average ($\text{Log}(\sigma_{\bar{\Delta}}/\bar{\Delta})$)	RMS divided by the average $_{noMIP}\text{Log}(\sigma_{\bar{\Delta}}/\bar{\Delta})$
Total energy deposition ($\text{Log}(\Delta_{tot})$)	Count of electromagnetic showers N_{Shower}

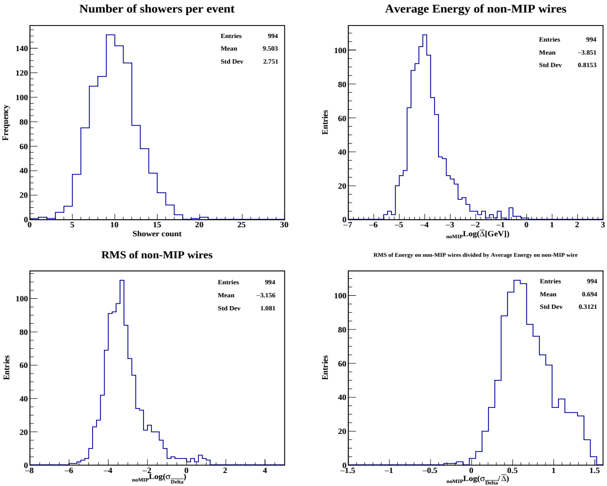
[6] Kevin Ingles, senior thesis at the University of South Alabama, April - 2018.

Energy deposition of muon



- Histograms for 10 TeV muons events in LArTPC.

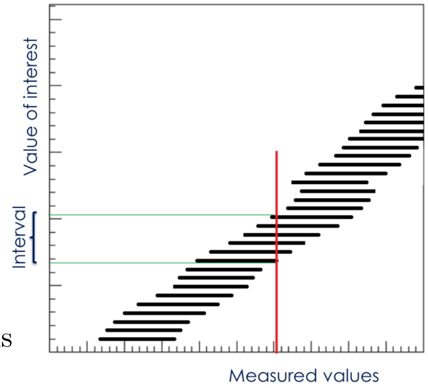
Energy deposition of muons



- Histograms for 10 TeV muons events in LArTPC.

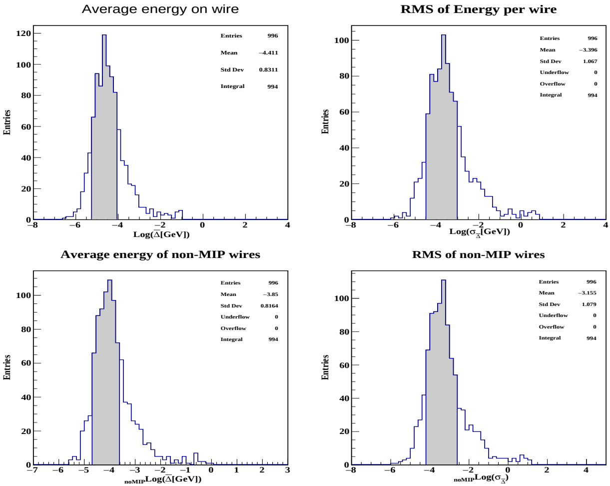
Neyman construction

- Used when a value of interest can not be directly measured.
- Experimental outcomes simulated for each possible value of interest.
- Confidence interval constructed for the measured value.
- 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.

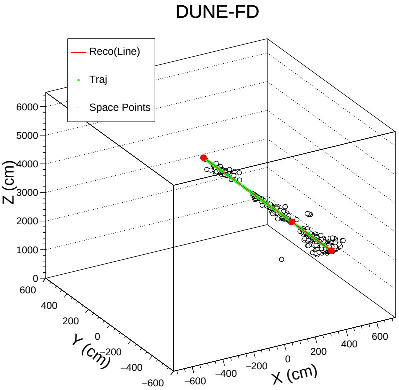
Confidence intervals calculation



- Feldman-Cousins ordering is used to shade the histograms (68.3%) and make the belts.

Track length estimation with space points

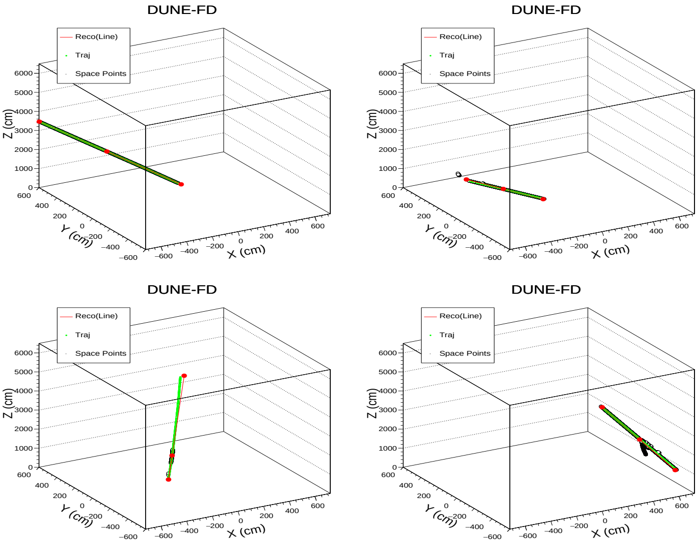
- Reconstructed spacepoint is an object made using hits in the three 2D time vs wire views associated to find 3D points in LArTPC.
- Pandora is used to reconstruct space points[7].
- PCA is used to estimate the direction vector that is used to calculate the equation of line.
- Estimated average point and line-plane intersection points are represented with red solid circles.

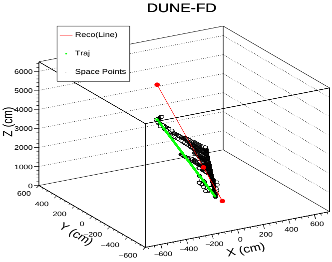


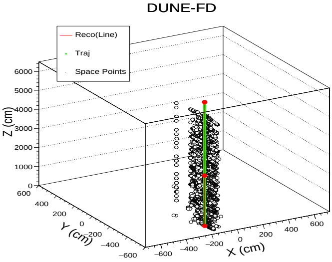
  - Intersecting points of the lines with planes is used to estimate the segment of track (track length) available inside the field cage.

[7] Eur. Phys. J. C 75, 439 (2015) and Eur. Phys. J. C 78, 82 (2018)

Reconstructed track from MUSUN sample

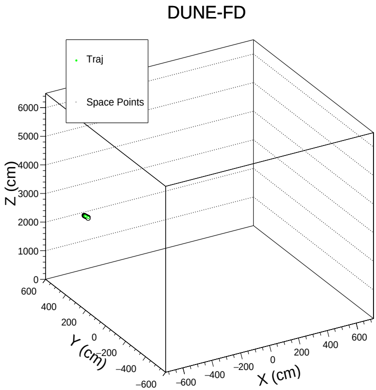


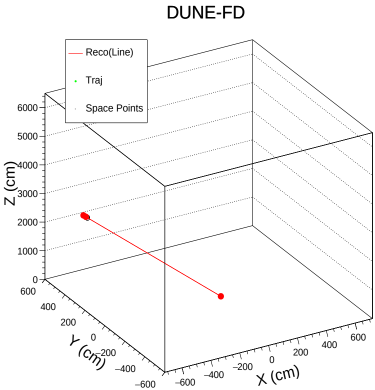




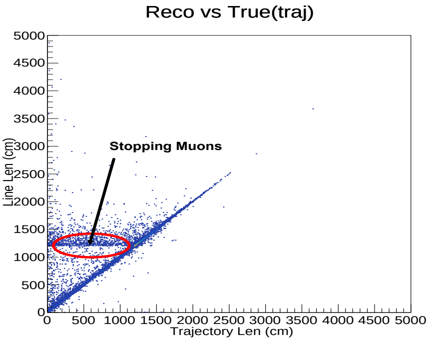
- Space points for tracks traveling perpendicular to the X axis (E field).
- Charge arrives simultaneously on all anode wires.
- Association of hits between planes is ambiguous.
- Wrong 3D locations found for space points.
- Events must be removed from analysis or treated specially.

Stopping muon tracks



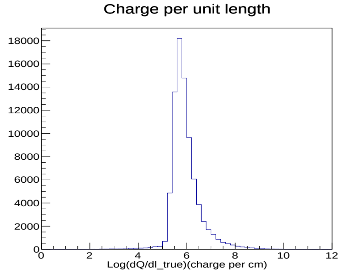


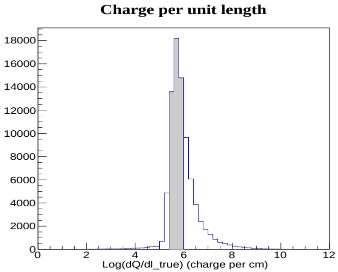
True and reconstructed track length



- Here true tracks length are estimated by adding up the trajectory point distances inside the LArTPC.

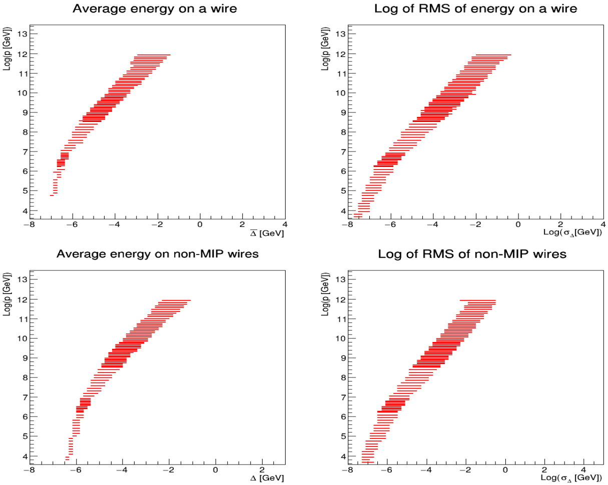
Charge per unit length (dq/dx)





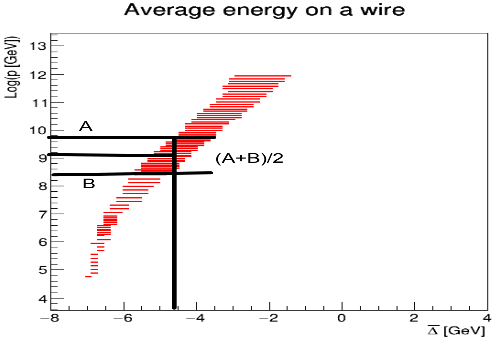
- Logarithm of charges per unit length and its confidence belt.

Neyman construction for the parameters of interest



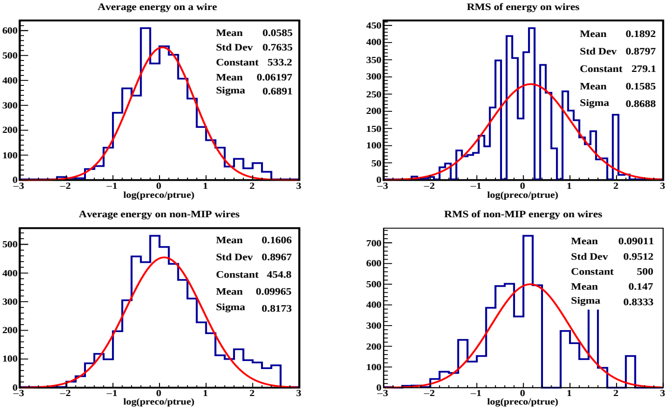
- The confidence belts constructed for the 4 variables of interest for full track length events at all energies.

Preco from the Confidence Interval



- preco = exp((A+B)/2).
- Where A is the top of the confidence region in log(p) for a particular muon, and B is the bottom of the confidence region in log(p) for the same muon.
- The suggested value is in the center of the interval.

Muon momentum resolution



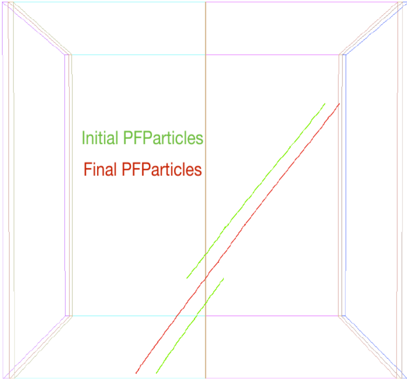
- Muon momentum resolution for the 4 variables of interest for full track length and 10 TeV energy.

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.
- Energy resolution as a function of muon path length estimation.
- Differentiating upward-going muons from downward-going muons using shower shapes.
- Identify and remove stopping muons from the high-energy sample but that can be use for calibration.
- Systematic uncertainty evaluation. (muon radiation modeling, electronics saturation, recombination modeling in dense showers and electron lifetime).

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 ?