Neutrino/antineutrino tagging with Michel-electrons in DUNE

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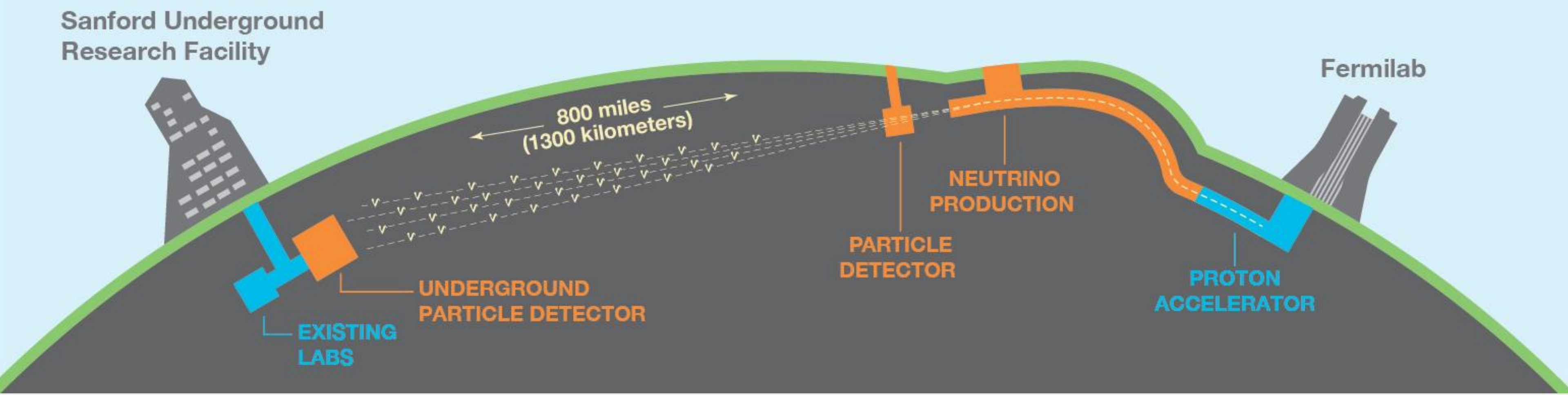
JRJC 2024

Deep Underground Neutrino Experiment



Next-generation, long-baseline neutrino oscillation experiment with:

- Wideband neutrino beam, (~**0.1 – 10 GeV**) generated at Fermilab, Illinois
- **Near Detector** (ND) at Fermilab
- Four **Far Detector** (FD) modules of 17 kt each using **Liquid Argon Time Projection Chambers** (LArTPC)
    - Deep underground detector: non beam physics (atmospheric neutrinos, supernovae, ...)

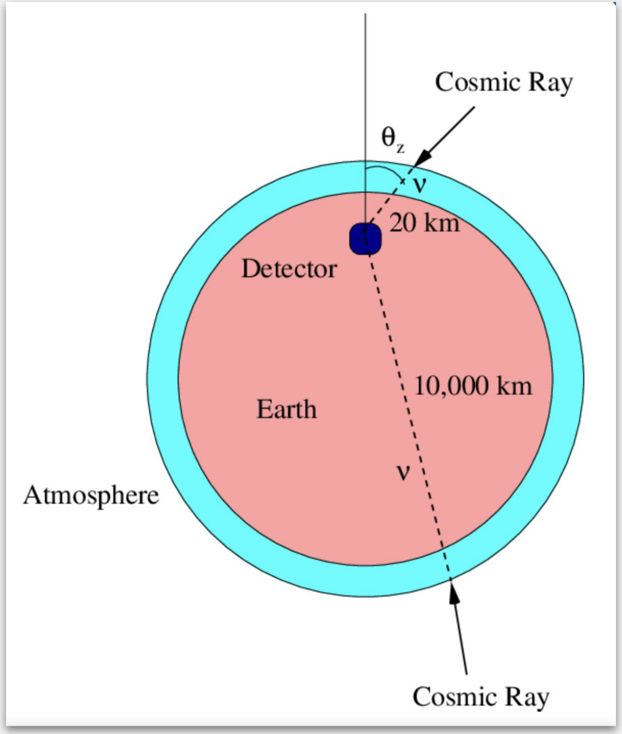
Physics case

For atmospheric neutrinos

- Survival probability **P ($\nu_\mu \rightarrow \nu_\mu$)** as a function of the neutrino energy **E** and zenith angle **θ_z**, related to **L**

$$P_{\alpha\alpha} = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- For **Mass Hierarchy** we measure resonance at **(3-8) GeV** for vertical up-going $\nu_\mu/\bar{\nu}_\mu$ ($-1 < \cos\theta_z < -0.8$)
- Complementary to beam measurement



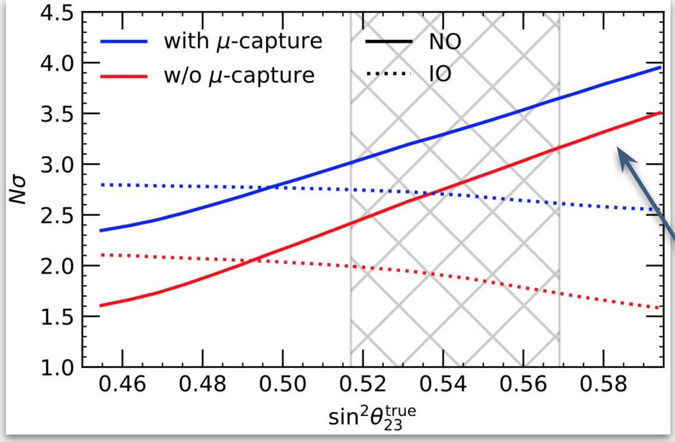
Atmospheric neutrinos will be there before the beam!

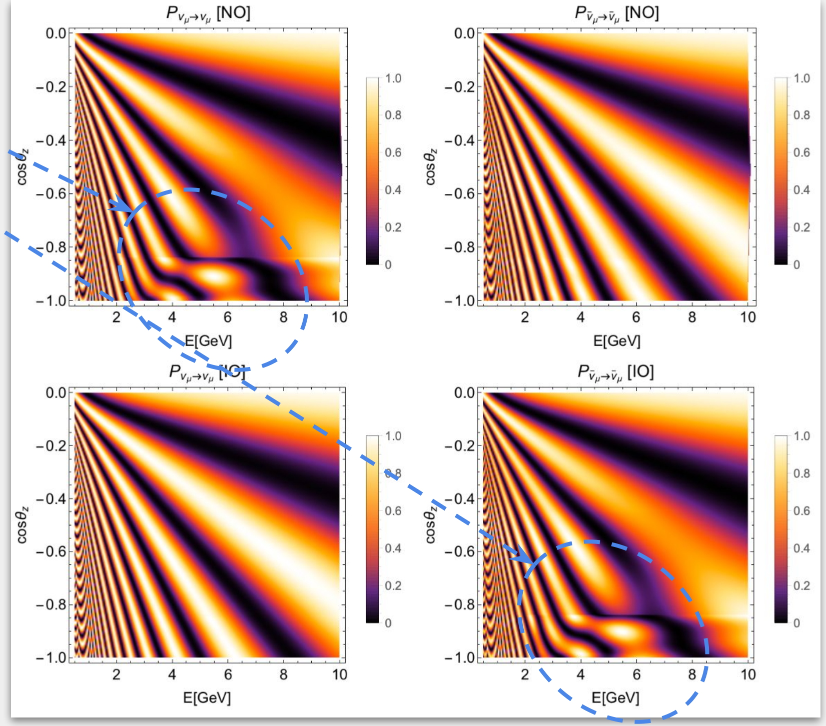
Physics case

Resonance at (3-8) GeV for vertical up-going $\nu_\mu/\bar{\nu}_\mu$ ($-1 < \cos\theta_z < -0.8$)

- for **neutrino** in *Normal Ordering*
- for **antineutrino** in *Inverted Ordering*

Using $\nu/\bar{\nu}$ discrimination, DUNE could significantly improve the sensitivity to **mass ordering** with atmospheric neutrinos. [Phys.Rev.D 100 (2019) 9, 093004]





For *NO*, sensitivity of mass ordering ~ **3.5σ** after 7 years of exposure.

Charge tagging in atmospheric neutrinos

How to distinguish $\nu_\mu/\bar{\nu}_\mu$?

- Charged current (CC) interactions -> μ^-/μ^+
- It's not possible to do **charge discrimination** with LArTPC (no magnetic field)
- A way to find **μ charge** is to distinguish **capture events** from **decay events** with **Michel-e**
  - μ^+ always decays in e^+
  - μ^- can decay to e^- (~ 28%) or be captured on Argon nuclei (~72%)
- We can identify μ decays by tagging of Michel-e

In the paper they assume 100% efficiency for tagging Michel electrons [Phys.Rev.D 100 (2019) 9, 093004]

→ We need to figure out how to maximize the efficiency to approach **at least 70%** (minimum requirement)

Charge tagging in atmospheric neutrinos

How to distinguish $\nu_\mu/\bar{\nu}_\mu$?

- Charged current (CC) intera…
- It's not possib… …d)
- A w… …ith **Michel-e**
    - …
- We…

Wait!

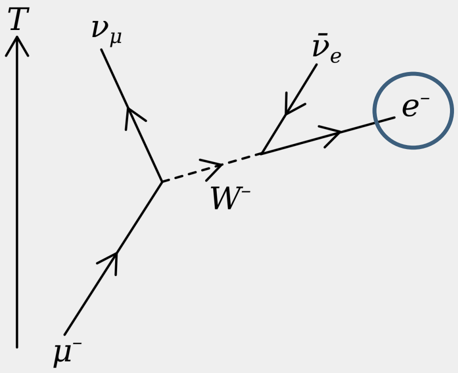
What's a Michel-electron?

In the pape… [Phys.Rev.D 100 (2019) 9, 093004]

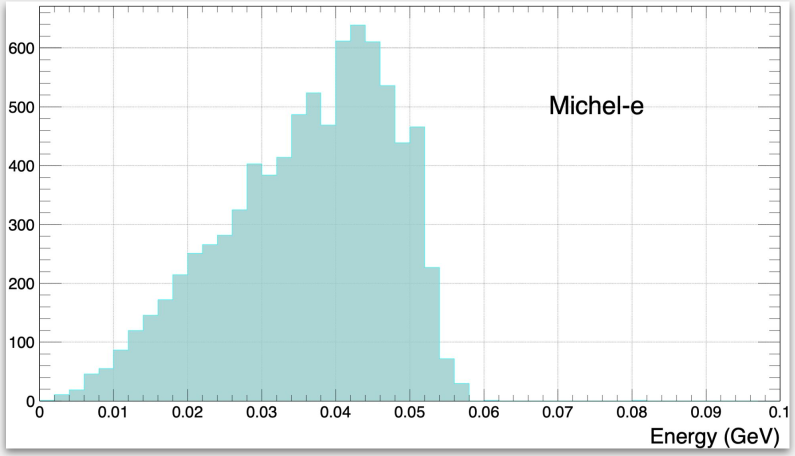
→ We need to… …the efficiency to approach **at least 70%** (minimum requirement)

Michel electron

- A **Michel electron** is an electron produced when a **muon decays at rest**
- M-e has an energy spectrum **0 - ~50 MeV**
- Both $\mathbf{e^+}$ and $\mathbf{e^-}$ are called Michel-electrons, as we cannot distinguish their charge



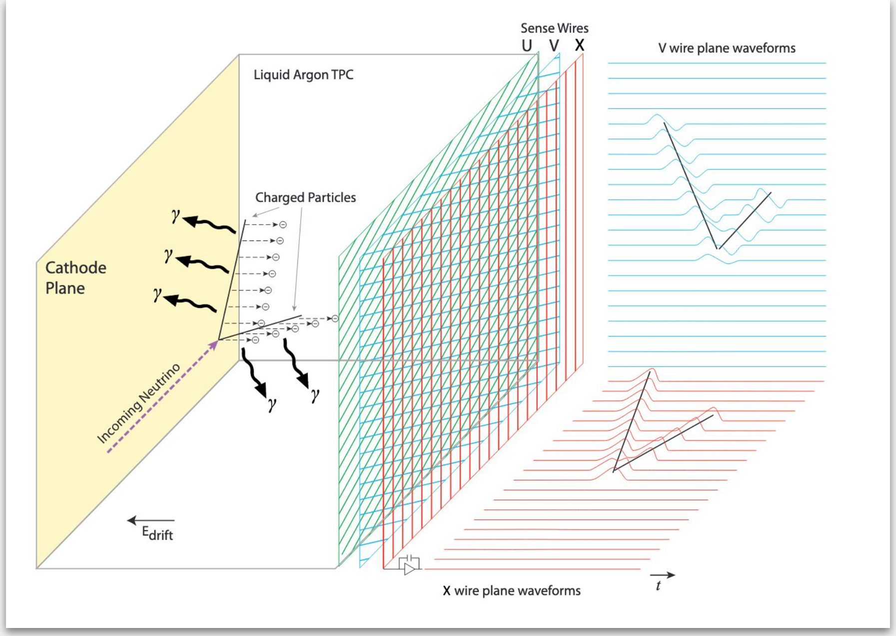
How do we see them in DUNE?



Far Detector - Horizontal Drift

LArTPC technology

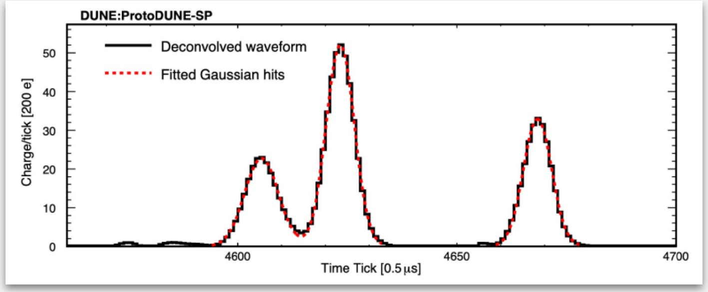
- Time Projection Chamber with a horizontal **electric field**.
- **Charged particles** deposit ionization trails in liquid argon.
- Ionization **electrons drift** in electric field.
- Electrons are detected by a series of **readout planes** (wire planes).

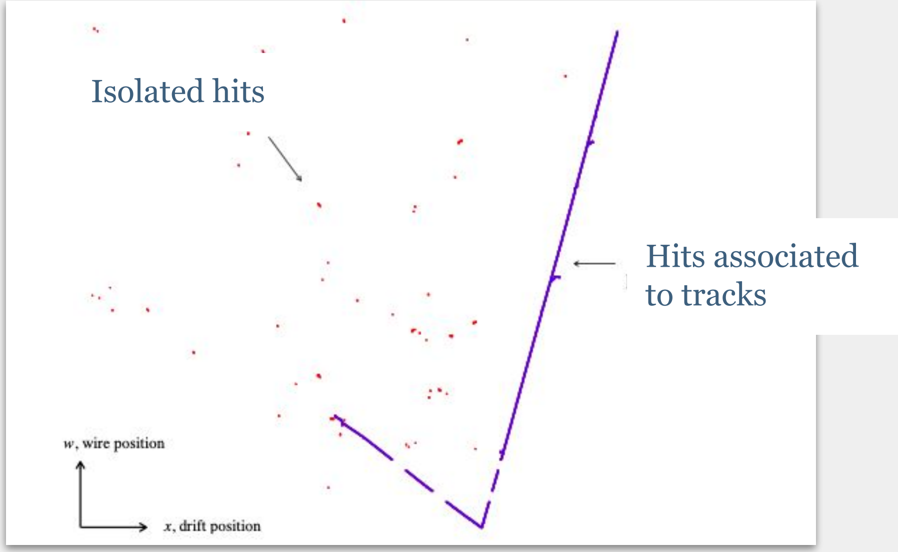


Animation: Neutrino Detection
in Liquid-Argon
Time Projection Chamber

Basics of reconstruction in LArTPCs

Waveforms → Hits [2D] → Clusters → Tracks / Showers [3D]





Michel-electron study in DUNE

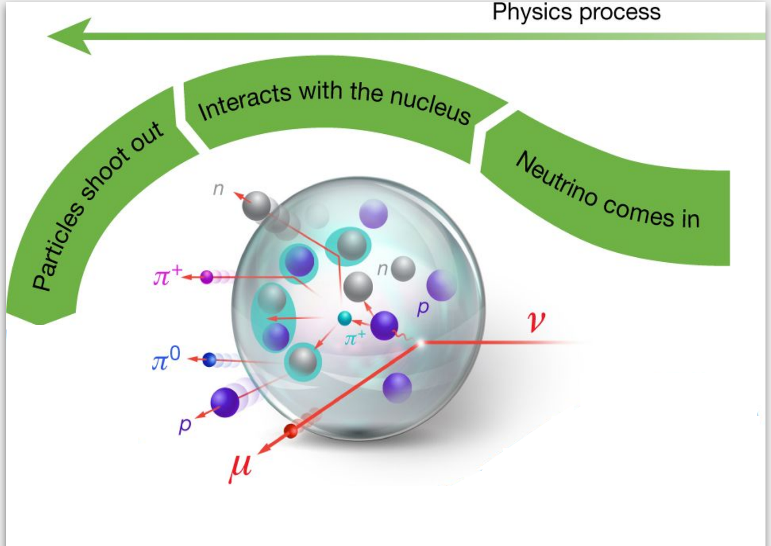
Previous studies on Michel-e in ProtoDUNE-SP paper [Phys.Rev.D 107 (2023) 9, 092012]

Sample of low-energy electrons from **cosmic muons**.

⇒ achieved an **efficiency** tagging electrons of ~ **20%** (95% purity)

My selection is on **Atmospheric neutrinos**:

- simulated samples with full DUNE reconstruction
- without background
- with other particles in the final state

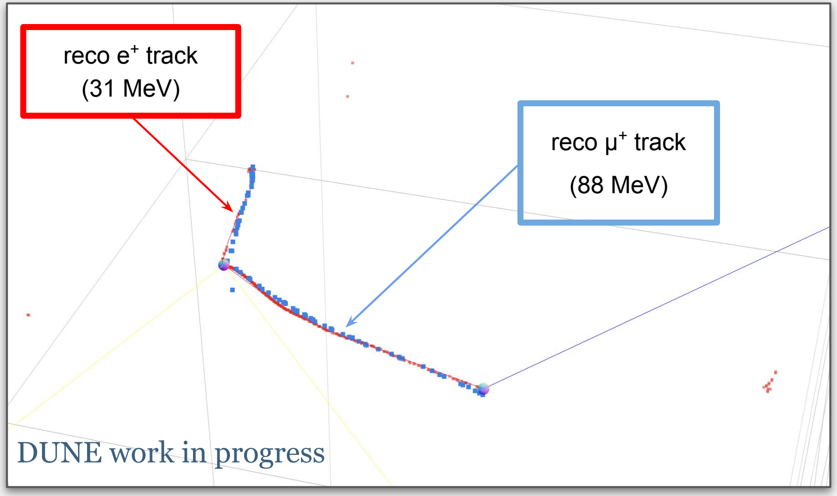


Courtesy of Electrons for Neutrinos Initiative

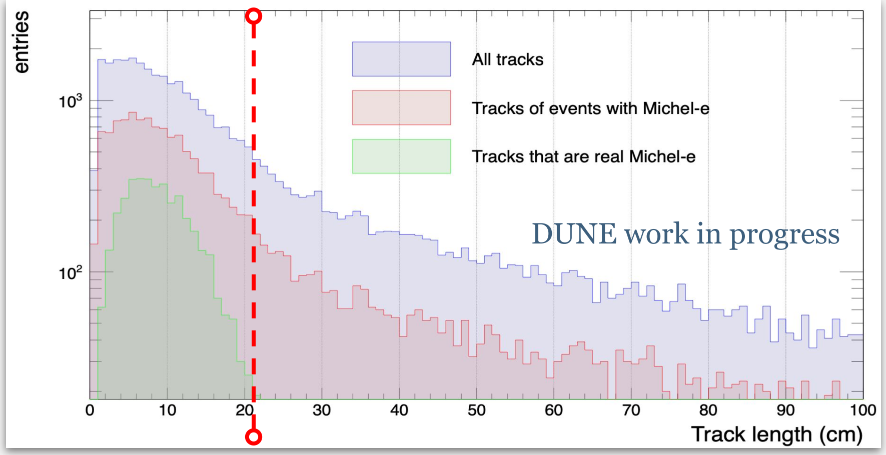
Selection of Michel-electron

First idea for event selection:

- Only use reconstructed Tracks
- Take longest track of event as muon
- For the Michel-e, look at:
  - **length** of the electron track
  - **distance** between the muon track and the electron track



Length and Distance selection



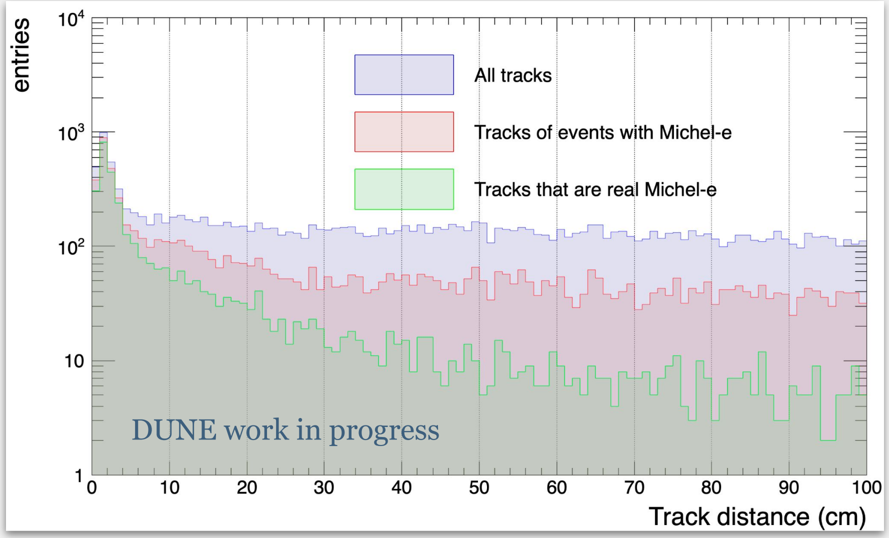
Length of all tracks that are not the longest one (no muon tracks)

Reconstructed tracks that are real electrons have **20 cm** max length.

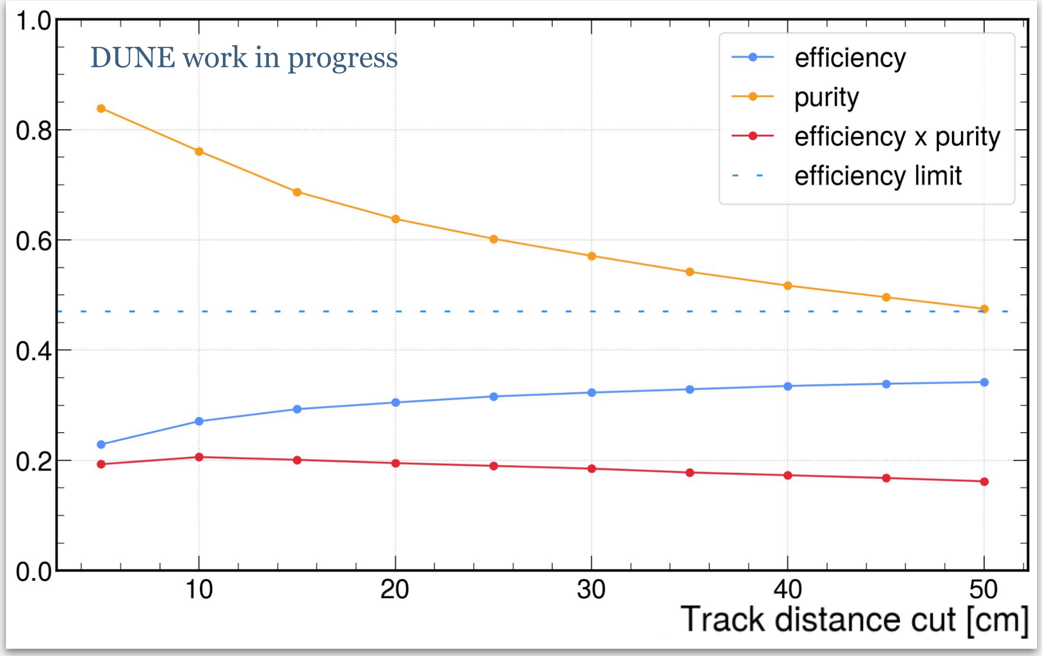
Distance between:

- ➔ Reco track **End Point** of muon
- ➔ Reco track **Start Point** of other tracks

Not easy to select a cut but most of the events below **7 cm**



Efficiency with track selection



efficiency and **purity** as a function of the distance cut.

$$e = \frac{\#\ candidate\ electrons\ that\ are\ actually\ electrons}{\#\ true\ electrons}$$

$$p = \frac{\#\ candidate\ electrons\ that\ are\ actually\ electrons}{\#\ candidate\ electrons}$$

Best results:

e = 27%

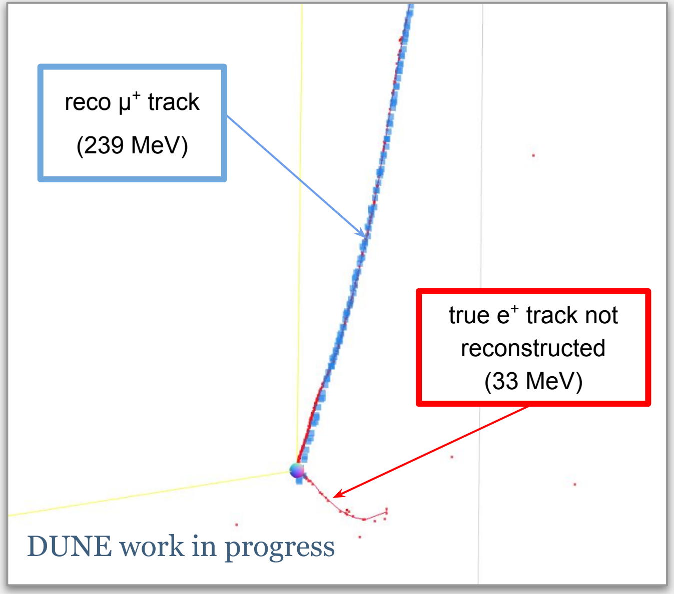
p = 76%

Still far from requirements!

Reco Tracks limitations

Not always works the reconstruction of the electron as a track (or shower).

- Only **47%** of real Michel-electrons are reconstructed as tracks → **efficiency limitation**

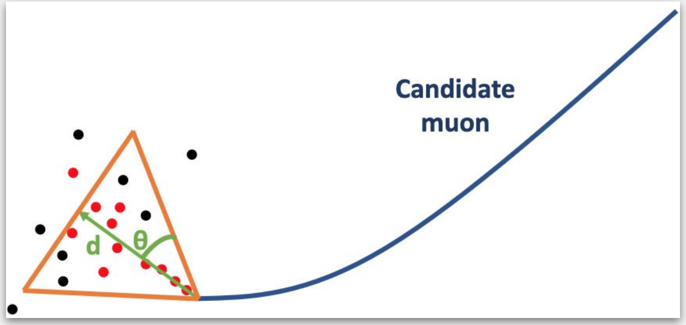


⇒ To improve the selection of Michel-e , we should also look for **unassociated hits** close to the muon track endpoint

Searching Michel-e with Hits information

I consider the information of the hits that do not belong to the muon track:

- Take longest track as muon.
- I look at Hit position in the X-Z plane (**Collection Plane**)



Candidate selection:

- Hits within **15cm** (2D) of the endpoint of the muon track
- Number of hits between **5 and 40**
- Sum of hits charge less than **7000 ADC/0.5 us**

Results of selection:

e = 35%

p = 73%

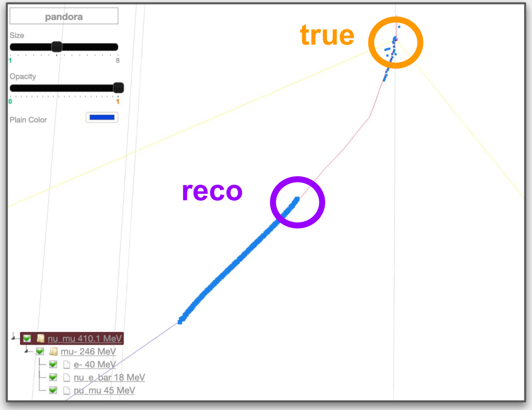
Still far from requirements!

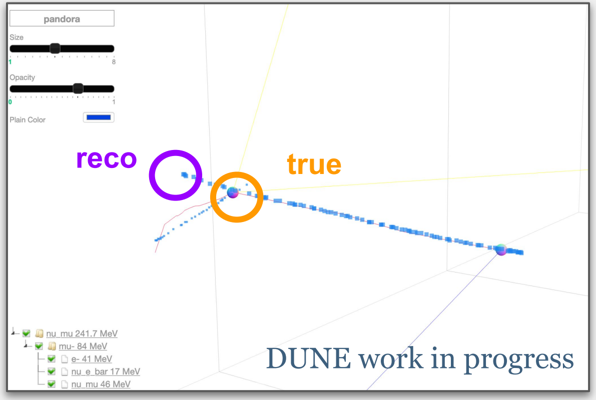
Issues in Reco Tracks

The low efficiency in Michel-e selection is largely due to bad reco and/or selection of the muon track

Of all **longest tracks**:

- Longest Track is **not a muon** → ~13%
- Of all muon tracks:
  - **Flipped** muon tracks (start/end point) → ~8%
  - Of all non-flipped muon tracks:
    - Tracks with end point reconstructed **before/after** true end point → 10% + 10%





⇒ Of all the tracks considered as muons **36%** have problems with the reconstruction.

Track inversion / Muon identification

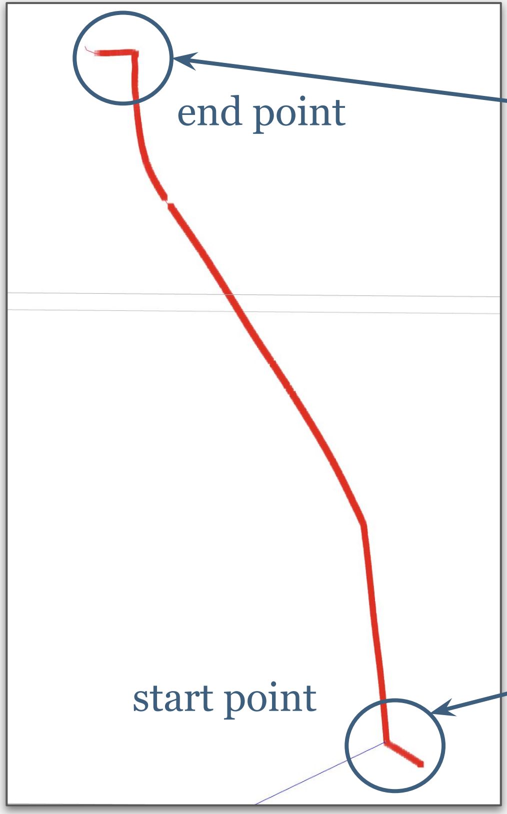
I focused on the muon track reconstruction issues.

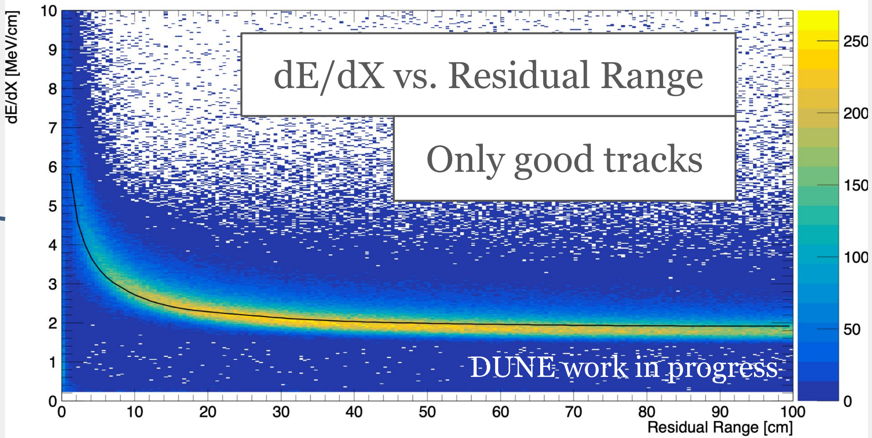
→ necessary to improve the selection:

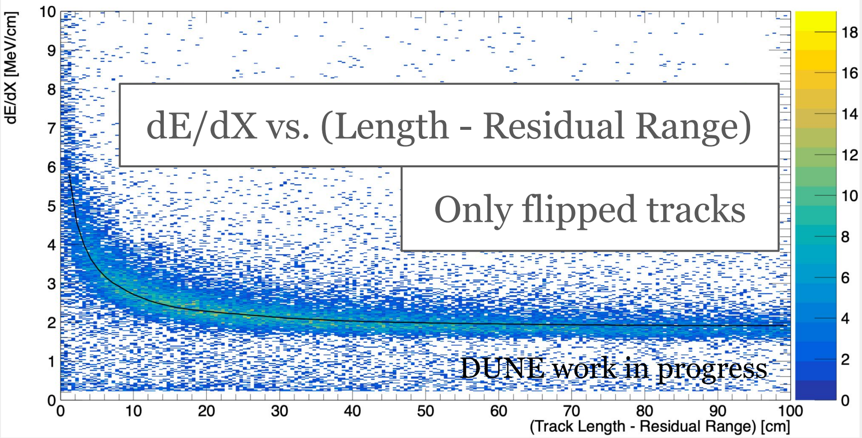
1. Attempt to recover **flipped tracks** using calorimetry information (dE/dx)
   - preliminary results
2. Attempt to recover **broken tracks:**
   - first ideas

Calorimetry Information for track flipping

Look for **Bragg peak** at one end of the track

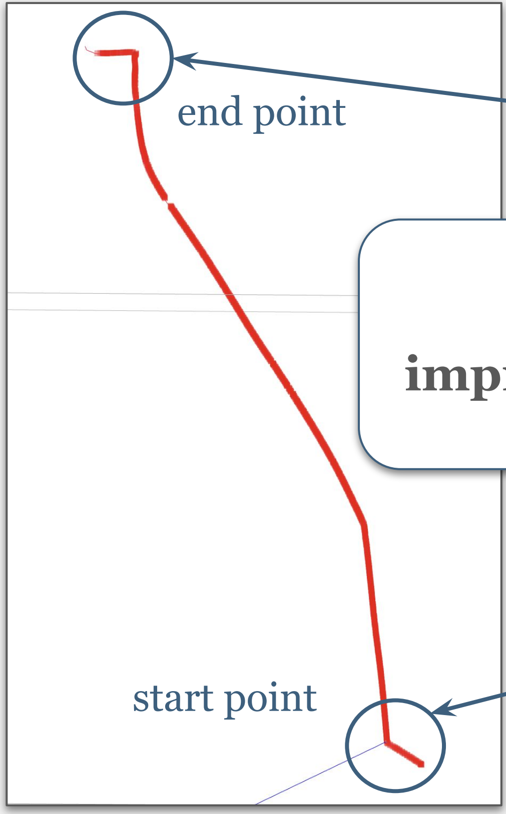




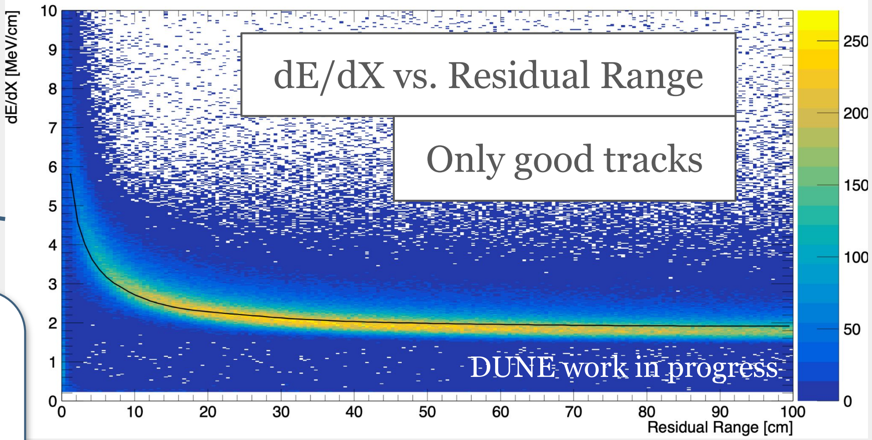


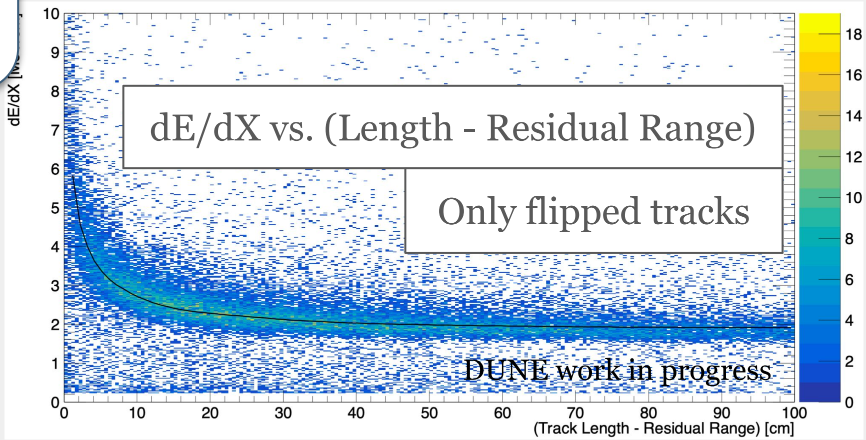
Calorimetry Information for track flipping

Look for **Bragg peak** at one end of the track

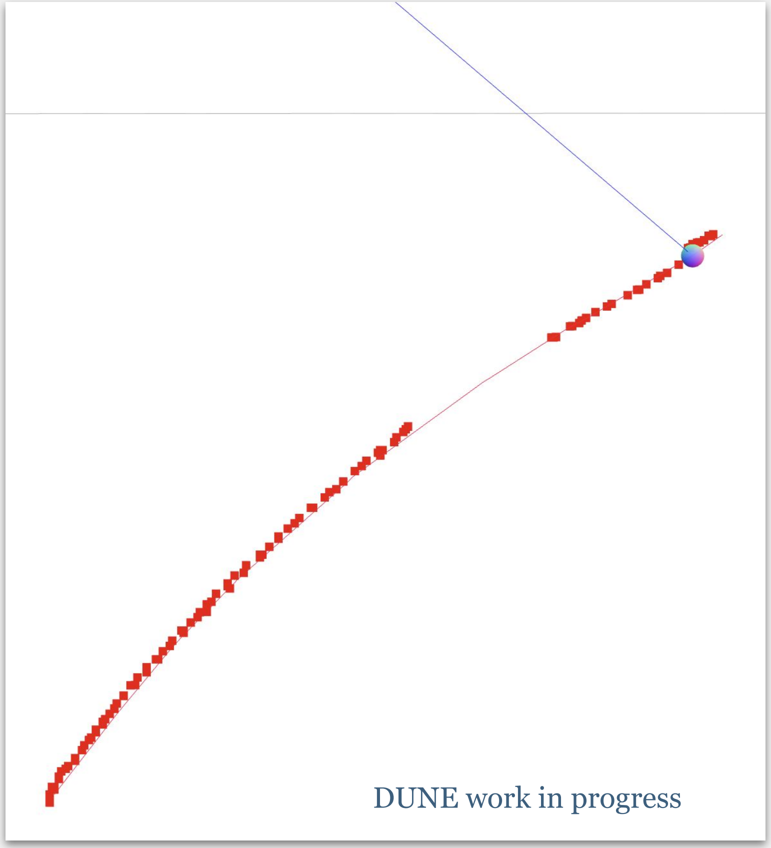


Overall improvement 14%





Broken tracks



Some muon tracks are broken in 2 or more parts

Attempt to merge tracks:

- **distance** between tracks
- **angle** between the track direction

I expect a region of small angles and small/medium distances

Conclusion

Summary:

- One goal of DUNE is the study of **Mass Ordering**. Atmospheric neutrino will provide a complementary measurement to the beam neutrino analysis and will have data first.
- The distinction between neutrino/antineutrino increases the sensitivity of this measurement.
- To do this we should select **M-e** with high efficiency
    - For the moment we haven't achieved a sufficient efficiency

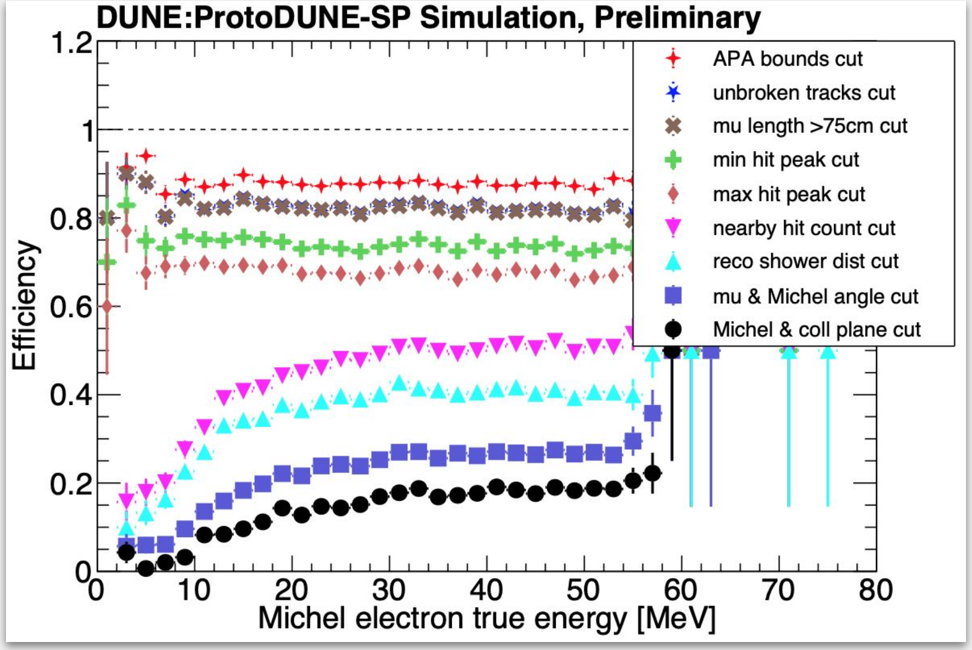
Next steps:

- Improve muon track selection and reconstruction
- Use ML methods to increase the efficiency for Michel electrons

Thank you!

Backup

Selection on ProtoDUNE-SP



Muon track selection in ProtoDUNE:

1. T0-tagged tracks.
2. Tracks starting from point close to or beyond one or more of the detector boundaries.
3. Muon tracks end inside Fiducial Volume. ($-309 < x < +309$, $80 < y < 557$, $80 < z < 610$)
4. Remove tracks that cross the cathode.

Michel-e hits selection:

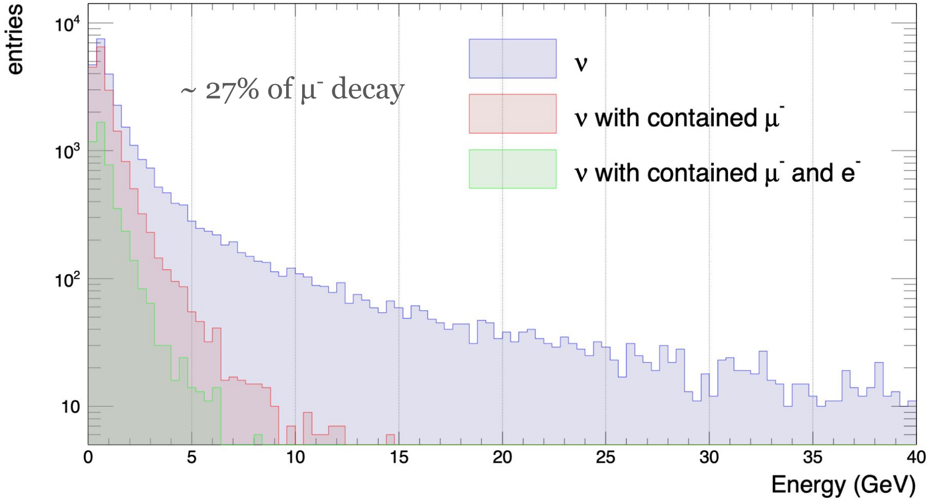
1. Tracks that end around **APA bounds**
2. Unbroken tracks
3. Cosmic muon track **length > 75 cm**
4. Tracks with hit peak **time > 200 ticks** (1 tick = 500 ns)
5. Tracks with hit peak **time < 5800 ticks**
6. Tracks having **5 < nearby hits < 40** around the end point
7. Tracks having closest reconstructed **shower distance < 10 cm**
8. Angle between candidate muon and Michel electron **< 130°**
9. Angle between the detector collection plane and the straight line to Michel candidate **> 10° & < 170°**

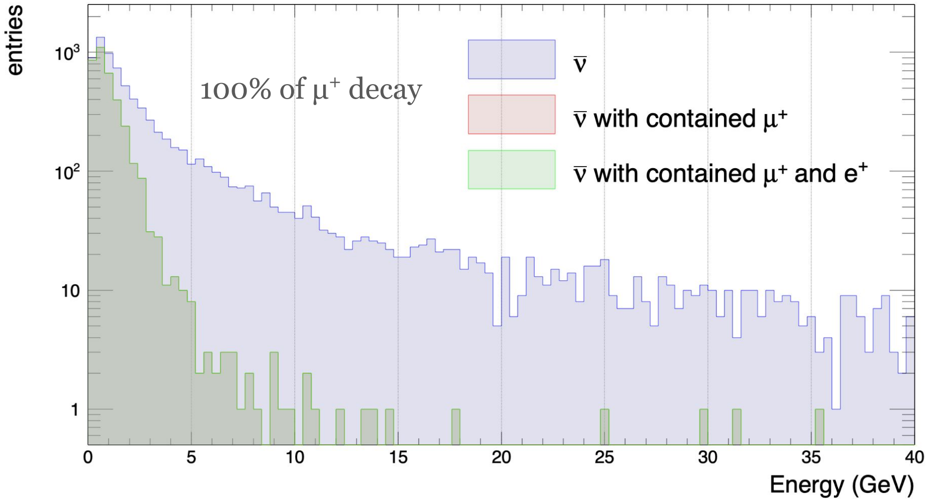
Sanity checks on atmospheric MC samples

True energy distribution of neutrino:

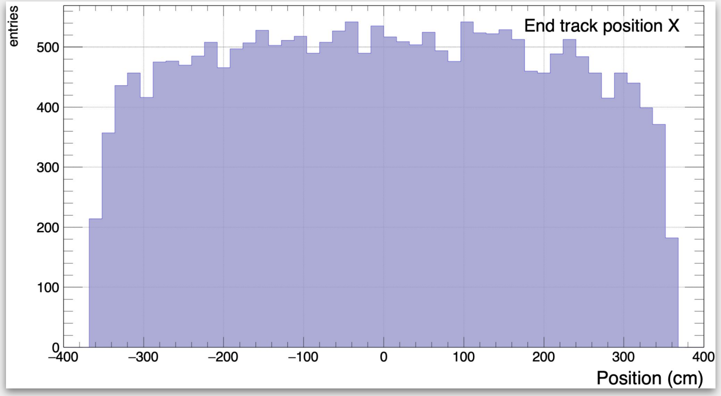
- Two different distribution: $\boldsymbol{\nu_\mu}$ **- cc** events ($\boldsymbol{\mu^-}$) and $\boldsymbol{\bar{\nu}_\mu}$ **- cc** ($\boldsymbol{\mu^+}$) events
- Red: consider only fully contained muons from neutrino interaction
- Green: events where the muons decays to Michel electrons

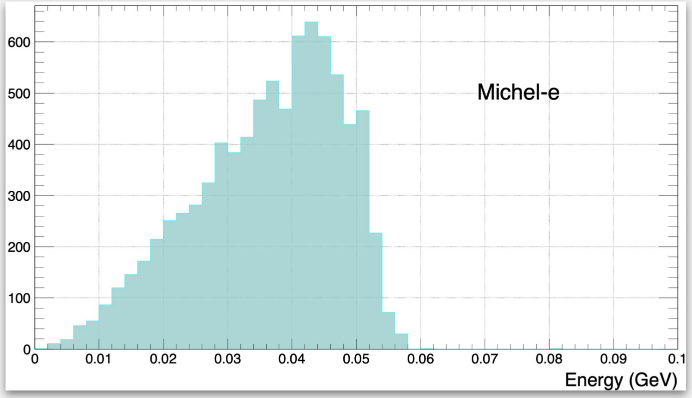
⇒ Event fractions and energy spectra are consistent with expectations

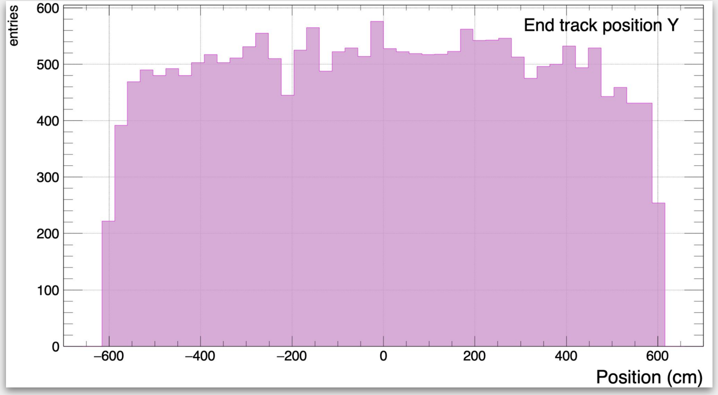


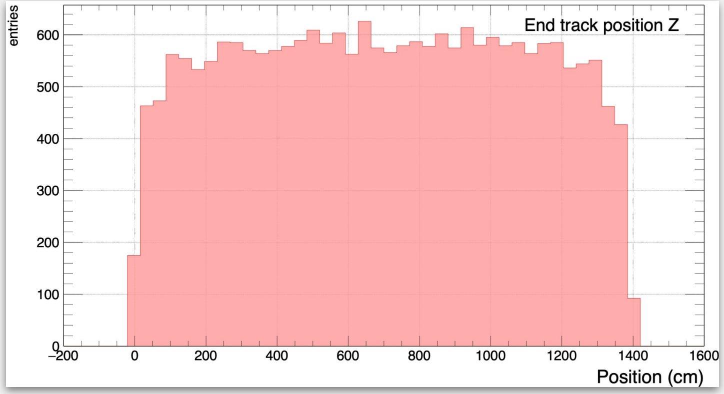


Sanity checks on atmospheric MC samples

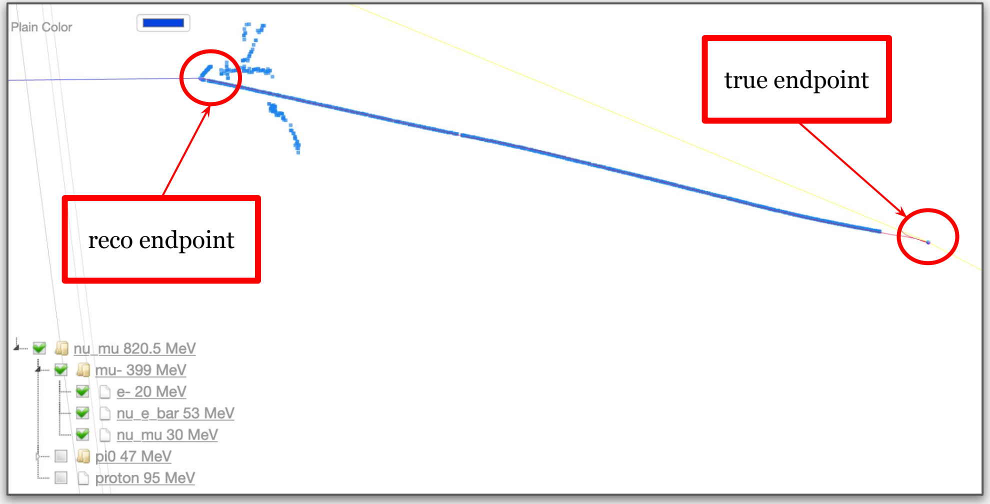


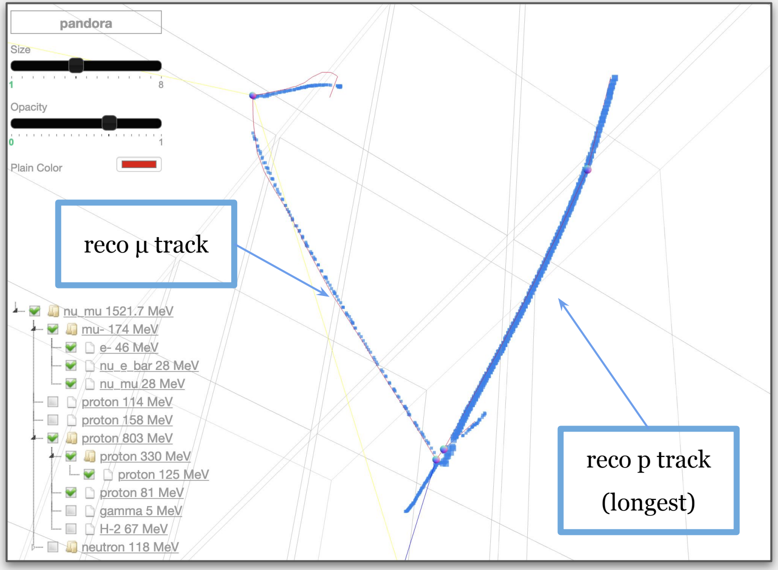




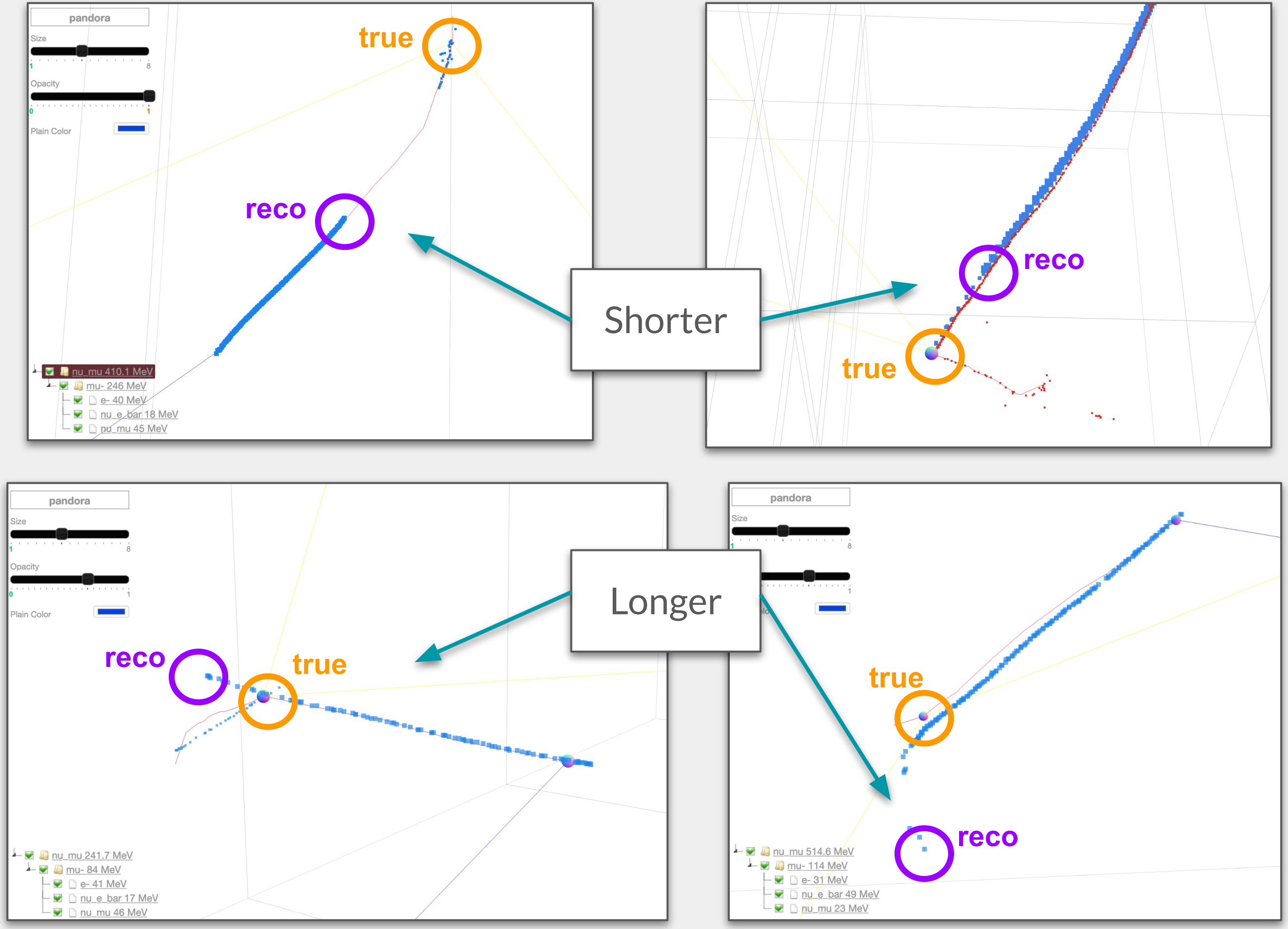


Muon identification / Track inversion





Shorter and Longer tracks



Same analysis using muon tracks end point from the Monte Carlo simulation:

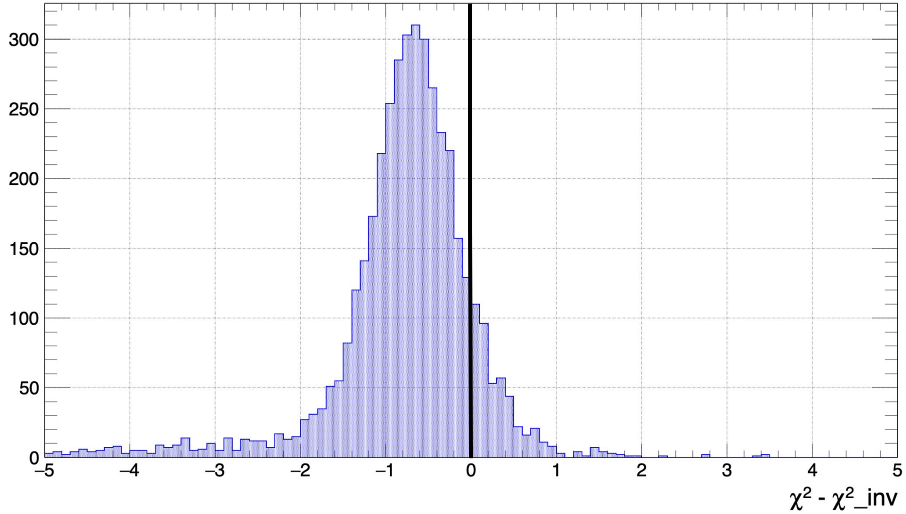
- 5% increase for eff: ~ **40%**
- Same result for purity: ~ **73%**

Calorimetry Results

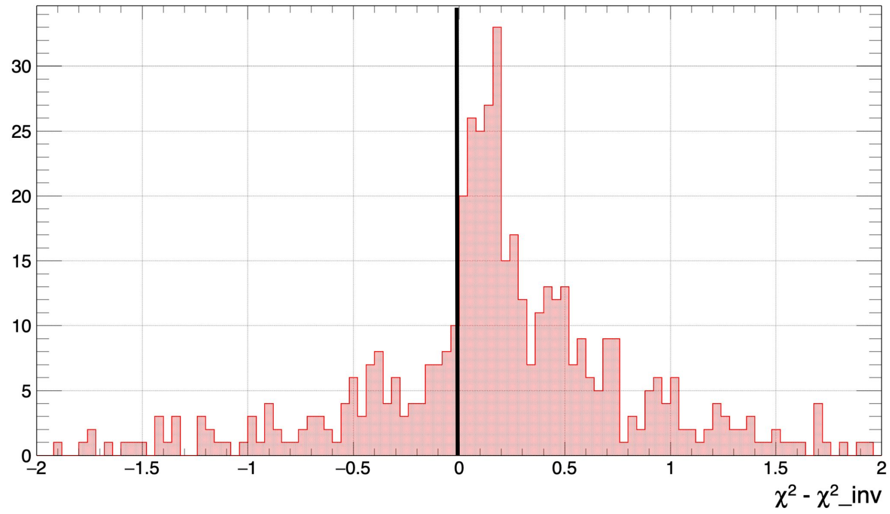
Tracks considered to estimate the improvement on this item:

- The **longest Muon tracks** of the event
- Track **length** > 5 cm
- Reco **endpoint** within 3 cm of the true endpoint

Difference between χ^2 and χ^2**_inv** of the true **non-inverted** tracks

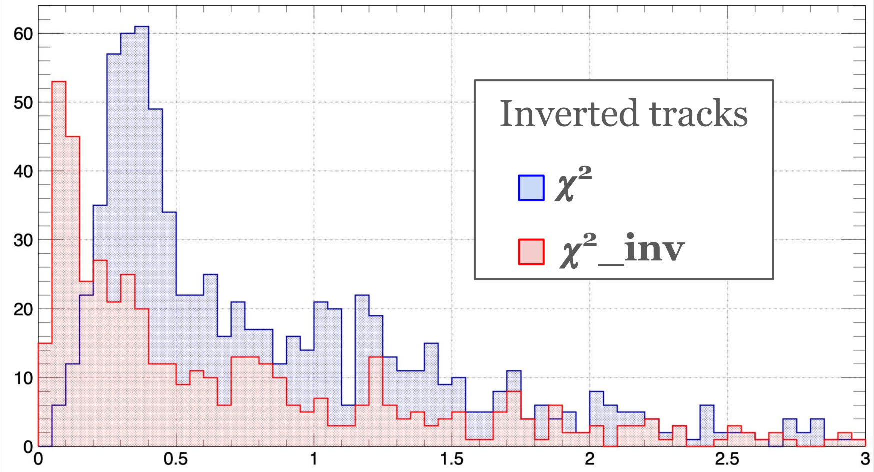


Difference between χ^2 and χ^2**_inv** of the true **inverted** tracks



Calorimetry Results

I selected the inverted tracks by asking: $\chi^2\_inv < \chi^2$ with $\chi^2\_inv < 0.35$



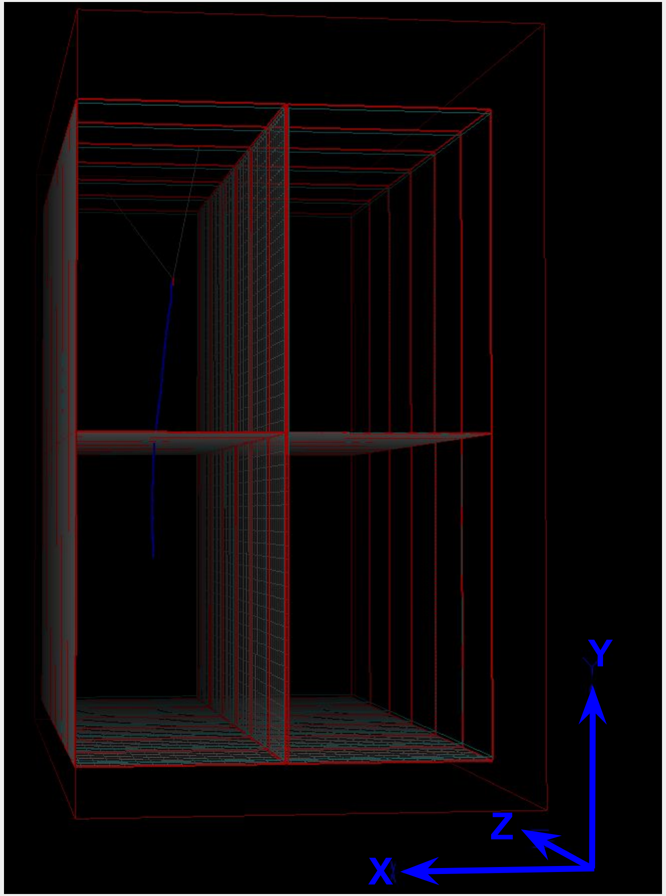
Results:

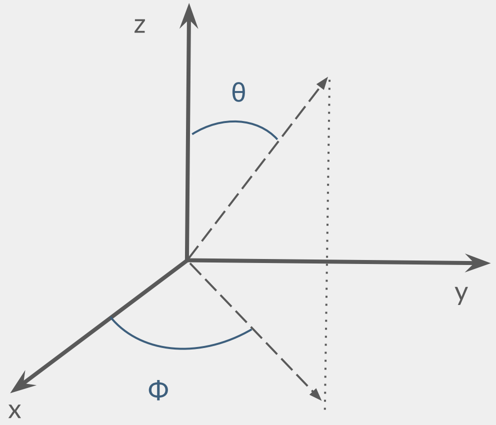
- 24% efficiency in inverted track selection
- 30% of the tracks selected as inverse are good
- Total gain of well-reconstructed tracks in M-e sample : **14%**

Future:

- Looking deposit energy into all three views
- Find out and test already existing tools for better select dE/dX curve

Event display - muon sample





Broken tracks - Very preliminary