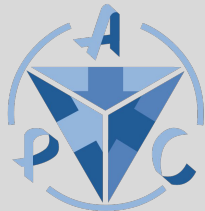


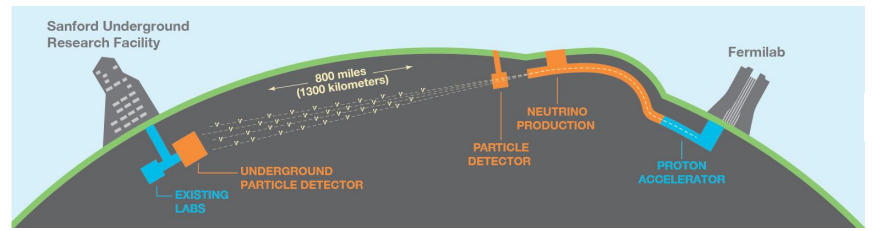


Improving the DUNE MO sensitivity with atmospheric neutrinos with Michel-e tagging

Matteo Galli
04 Nov 2025



IRN Neutrino meeting



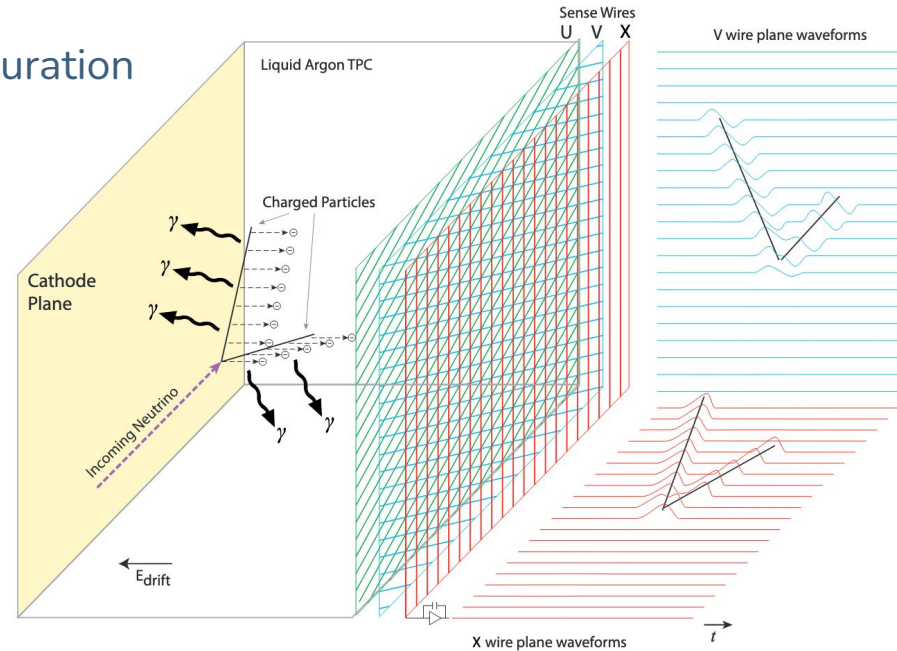
Long-baseline neutrino oscillation experiment:

- Wideband neutrino beam, ($\sim 0.1 - 10$ GeV) generated at Fermilab, Illinois
- **Near Detector** (ND) at Fermilab
- 4 **Far Detector** (FD) modules of 17 kt each using **LArTPC**
 - Underground facility: non beam physics (**atmospheric neutrinos**, supernovae, solar, ...)

Physics goals:

- Neutrino oscillations : measure ν_μ disappearance + ν_e and ν_τ appearance
- Mass Ordering, leptonic CP Violation discovery, θ_{23} octant
- Physics beyond the Standard Model
- Underground detector: Nucleon Decay searches, supernova core collapse

- Ionization **electrons drift** in electric field:
 - **horizontal** (HD) and **vertical** (VD) configuration
- Electrons are detected by a series of **readout planes** (wire planes).
- Kinematic reconstruction of ν events
 - Particle identification (e, μ , proton)
 - Event type classification (ν_μ CC, ν_e CC, NC and potential for ν_τ)



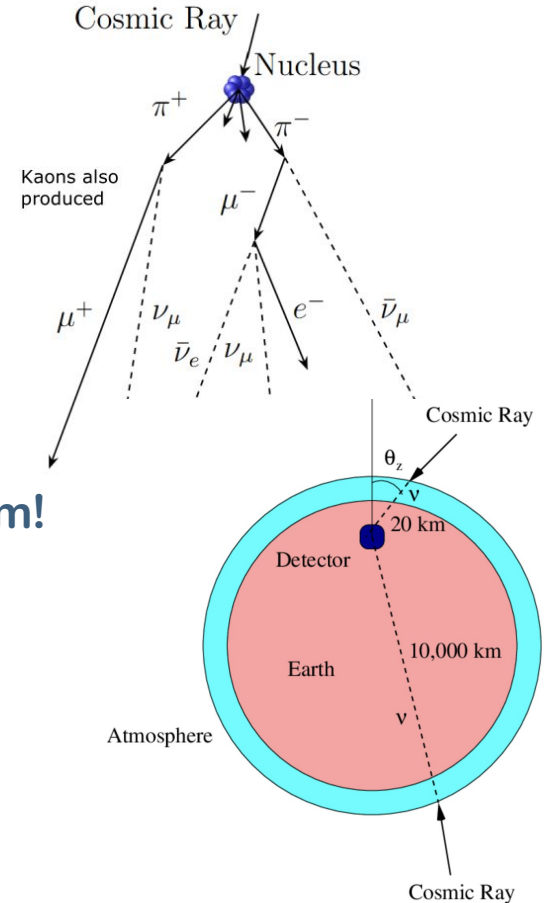
- For this study -> Full simulation of atmospheric neutrinos of the DUNE HD FD
- In this moment reconstruction performances are being improved

Atmospheric neutrinos

- Energy range up to **TeV**
- long distances traveled
- Oscillation probability $P(\nu_\alpha \rightarrow \nu_\beta)$ as a function of E and $\cos(\theta_z)$, related to L
- Complementary to beam measurement
- Atmospheric neutrinos will be there **before the beam!**

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ in matter depends on $(\mp A)$

where $A = 2\sqrt{2}G_F N_e E$, N_e is e^- density in the Earth



Physics case

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

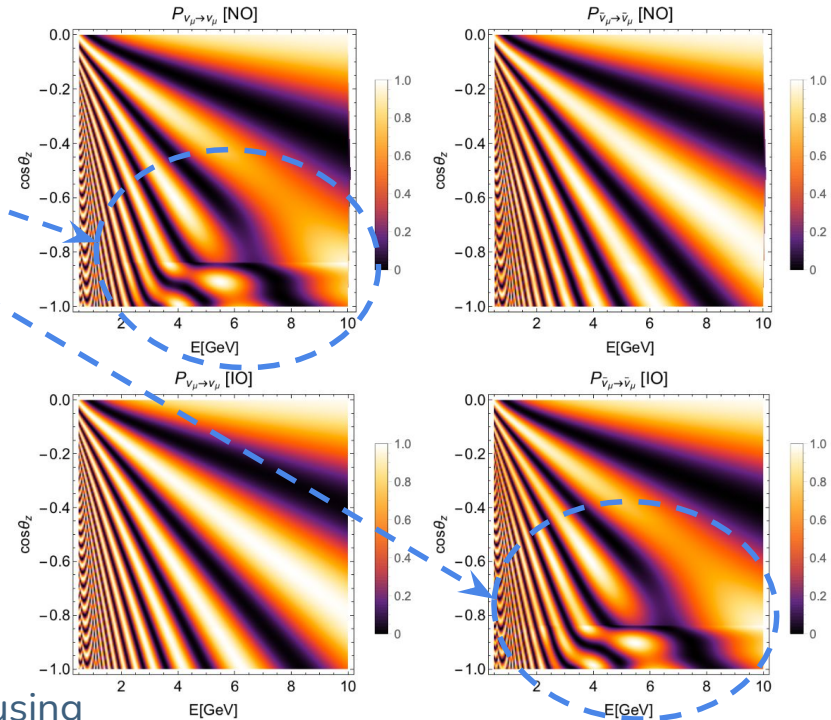
- for **neutrino** in *Normal Ordering*
- for **antineutrino** in *Inverted Ordering*

$\nu/\bar{\nu}$ discrimination allows DUNE improvement in sensitivity to **mass ordering**.

μ -capture method (tagging M-e events) could be use in DUNE to improve sensitivity in mass ordering measurement.

[\[Phys.Rev.D 100 \(2019\) 9, 093004\]](#)

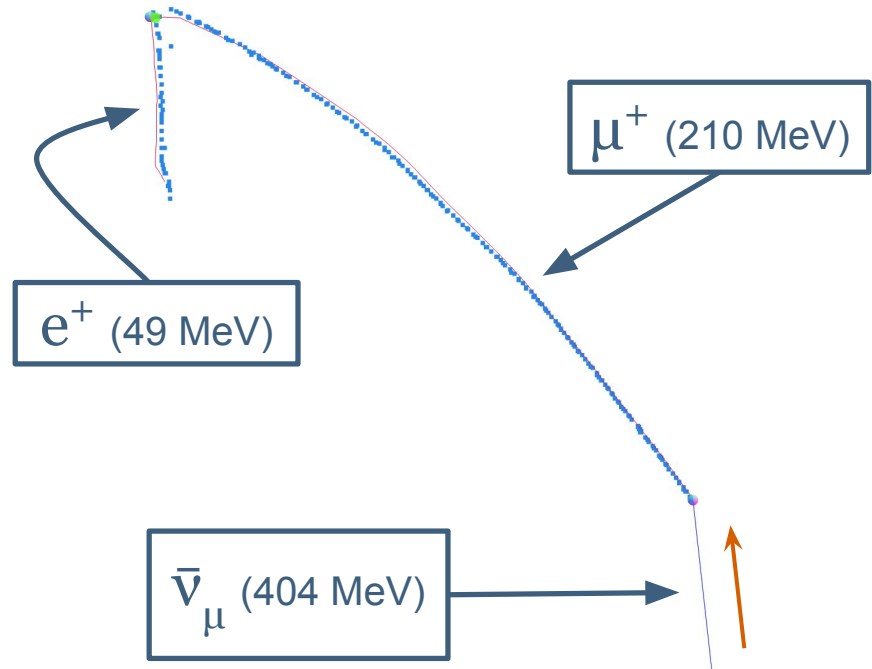
- This method consists of discriminate **muon charge** using **Michel-e** to distinguish **capture events** from **decay events**.
 - μ^+ always decays in e^+
 - μ^- can decay to e^- (~ 28%) or be captured on Argon nuclei (~72%)



- Goal: optimize the **tagging of Michel-e** events in atmospheric neutrino events.
- Strategy: searching Michel-e hits around the endpoint of the reconstructed muon track.

My work in 3 steps:

1. Improve the **muon endpoint** identification related to specific cases.
2. **Selection** of Michel-electron events.
3. Evaluation impact of ν_{μ} separation on **Mass Ordering sensitivity**.

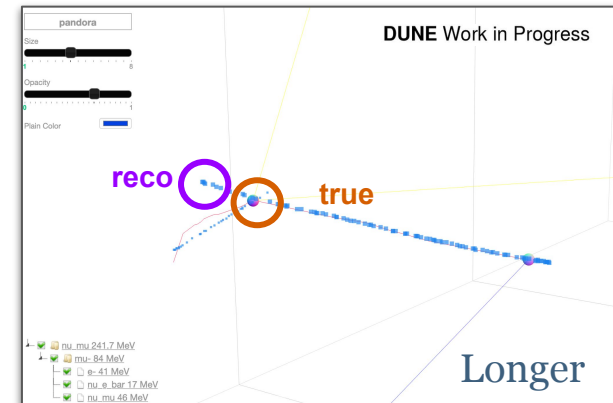
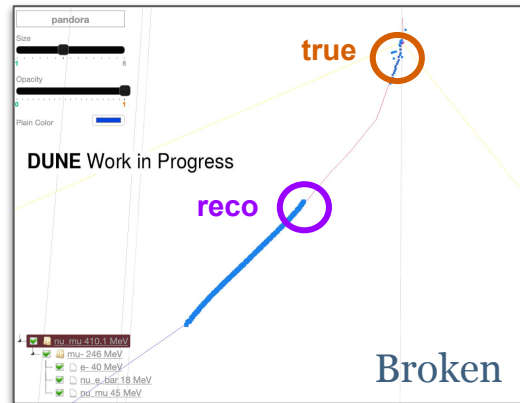
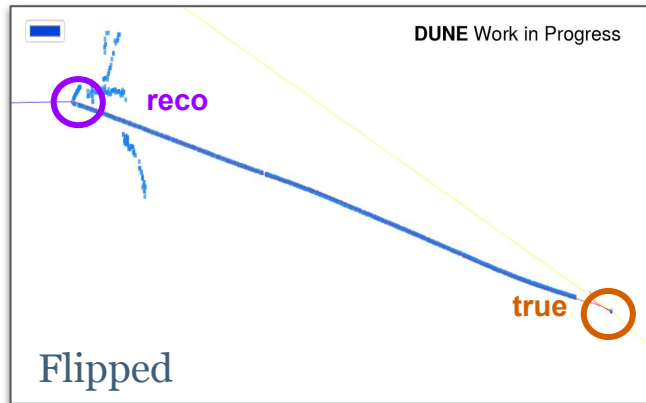


Muon's endpoint identification

Issues in reconstructed muon Tracks

Issues that affect the position of the reconstructed muon endpoint

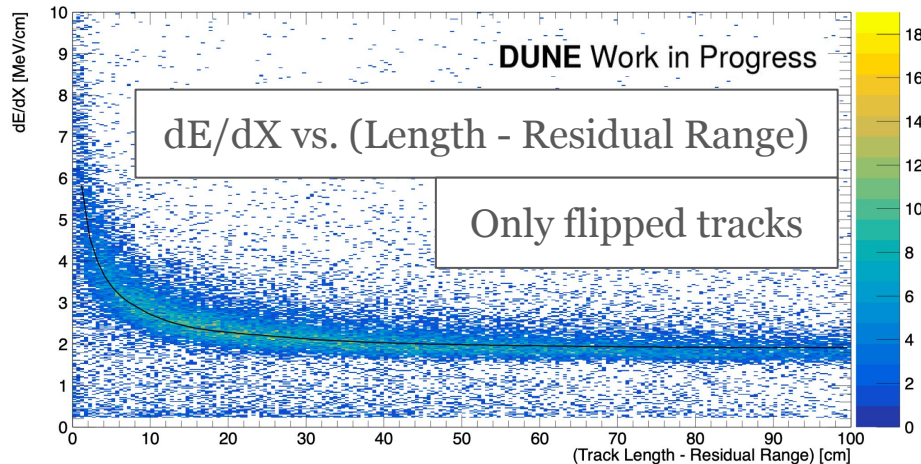
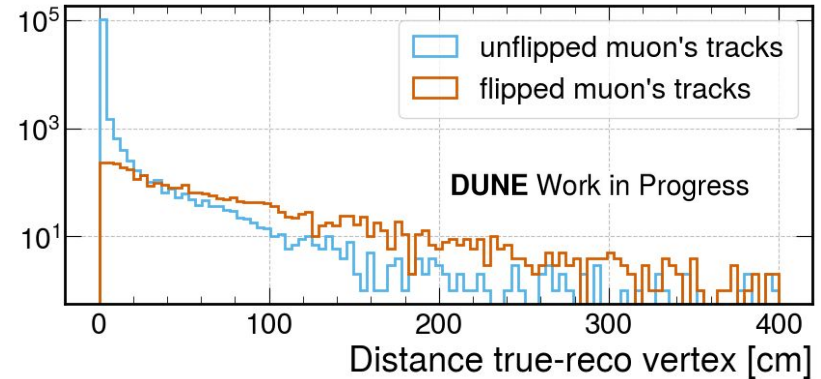
- **Flipped** muon tracks (start/end point) → ~8% of muon tracks
- Tracks with endpoint reconstructed **more than 3 cm away** from true endpoint:
 - **Broken**: more than 3 cm **before** true endpoint → ~9% of not flipped muons
 - **Longer**: more than 3 cm **after** true endpoint → ~11% of not flipped muons



Recovering identification of muon endpoint

Flipped tracks

- Problem: vertex assignment.
- Strategy:
 - Searching **Bragg peak** at beginning of the track.



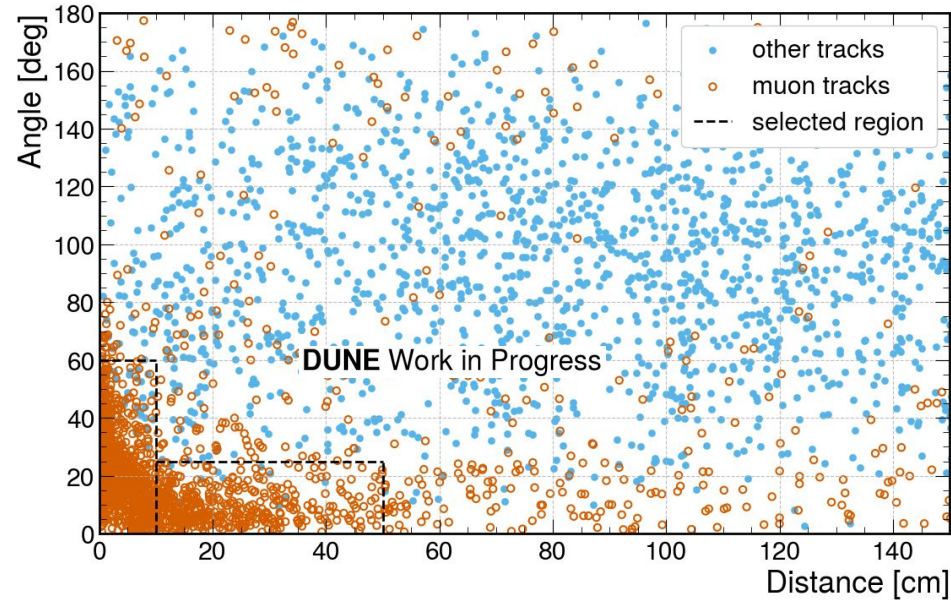
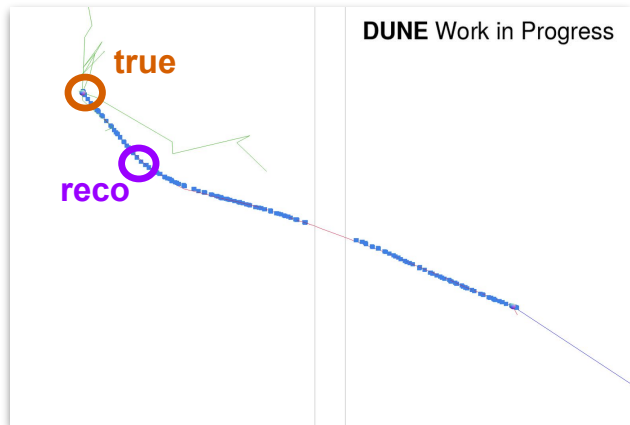
- **Result:**

$$1 - \frac{\# \text{ flipped muons after recovering}}{\# \text{ flipped muons before recovering}} = 14\%$$

Recovering identification of muon endpoint

Broken tracks

- Problem: gap-crossing and no gap crossing
- Strategy: merge the first part of the track looking at
 - **Distance** between the two track segments
 - **Direction angle** between the two broken tracks



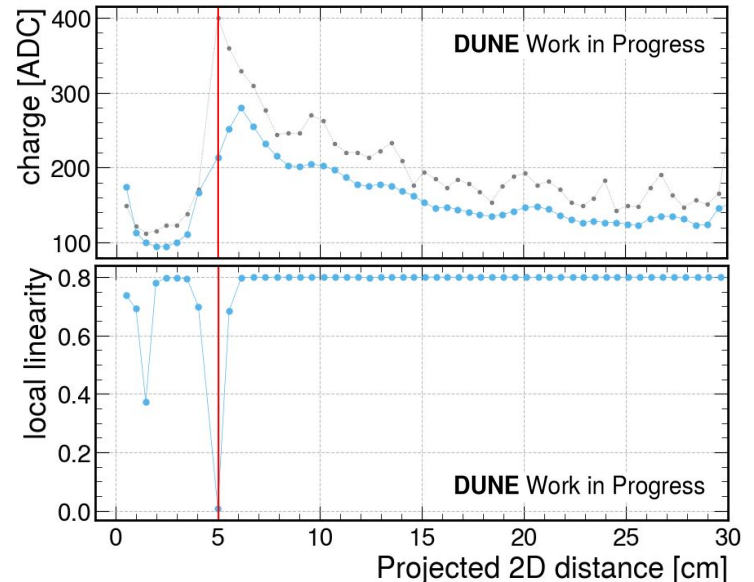
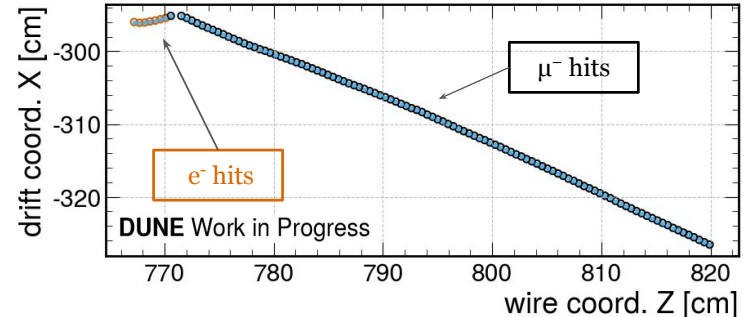
- **Result:** total recovering

$$\frac{\text{events dist endpoint} < 3\text{cm}}{\text{all broken track events}} = 76\%$$

Longer tracks

- Problem: Michel hits part of the muon track
- Strategy:
 - local truncated mean charge → to look for **Bragg peak**
 - local linearity → to look for the **kink** of the electron decay
- **Result:** total recovering

$$\frac{\text{events dist endpoint} < 3\text{cm}}{\text{all longer track events}} = 85\%$$

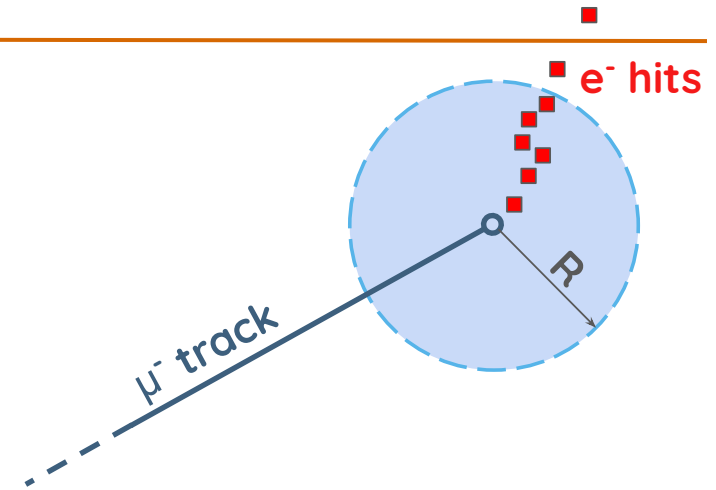


Michel- e^- selection

Michel-e events selection

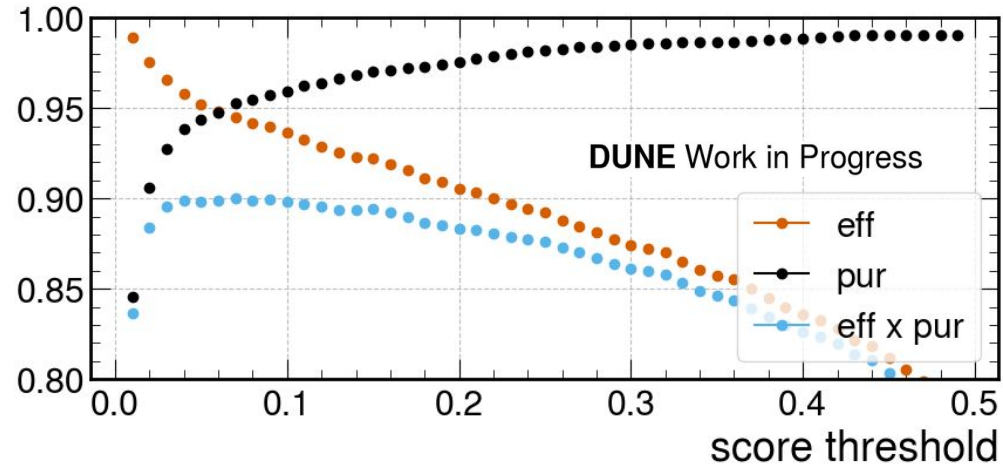
Selection based on hits:

- Requirement: events with **hits** in a region of radius $R = 10$ cm.
- Requirement: at least **5 hits** and a maximum of **40 hits** in the selected region.



Selection based on Convolutional Neural Network score:

- [CNN](#) looks at hits and determines the most likely origin: **shower, track** or **Michel**.
- **Average Michel score** per event relative to selected hits.



Results in Michel-e event tagging using selection of events just shown:

- Tagging **efficiency**:
(number of real M-e selected events)/(number of MC M-e events) = **52%**
- Tagging **purity**:
(number of real M-e selected events)/(number of selected M-e events) = **90%**
- **Limitation**: events w/ MC Michel-e and no hit caused by Michel-e → 14%
 - due to the **low energy** of the M-es -> under investigation

This work contributes to ongoing efforts to **improve atmospheric neutrino reconstruction**

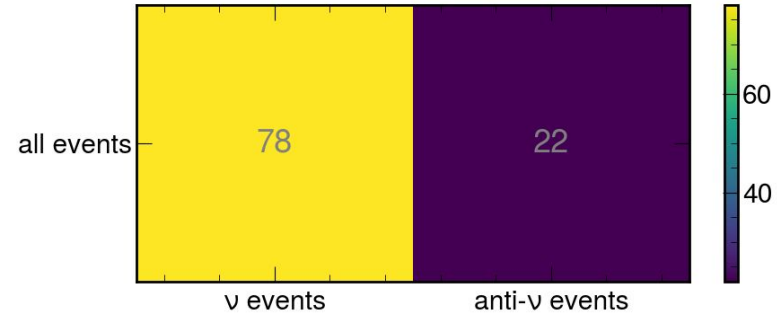
Impact on Sensitivity to Mass Ordering

Number of decay events

For example, considering **flux** and **cross section**:

- Fraction of $\nu_\mu \sim 78\%$
- Fraction of $\bar{\nu}_\mu \sim 22\%$

Evaluation of the number of **M-e** and **non-M-e** events.



Fraction of ν_μ : N_{μ^-}

Fraction of $\bar{\nu}_\mu$: N_{μ^+}

Decay probability for μ^- : $\epsilon^{\text{dec}} = 28\%$

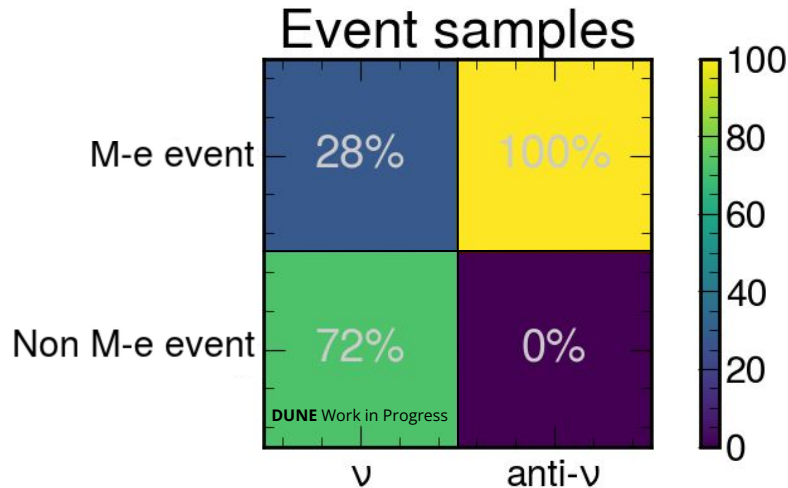
M-e tagging efficiency: ϵ^{t}

M-e event	$N_{\mu^-} \epsilon^{\text{dec}} \epsilon^{\text{t}}$	$N_{\mu^+} \epsilon^{\text{t}}$
Non M-e event	$N_{\mu^-} (1 - \epsilon^{\text{dec}}) + N_{\mu^-} \epsilon^{\text{dec}} (1 - \epsilon^{\text{t}})$	$N_{\mu^+} (1 - \epsilon^{\text{t}})$
	ν events	anti- ν events

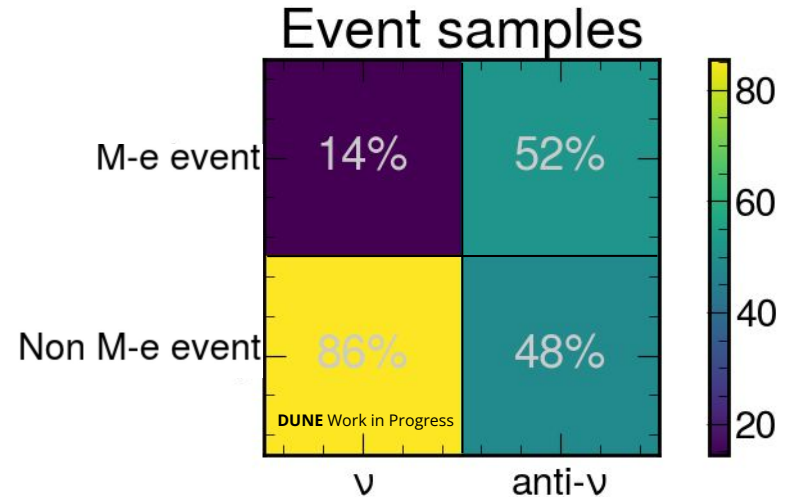
Non-decay and **decay** samples, tagged with Michel-e, using:

- Perfect M-e tagging and purity
- 52% of eff in M-e tagging found and perfect purity (close to ~90% found)

Perfect tagging: $\epsilon^t = 1$, purity=1



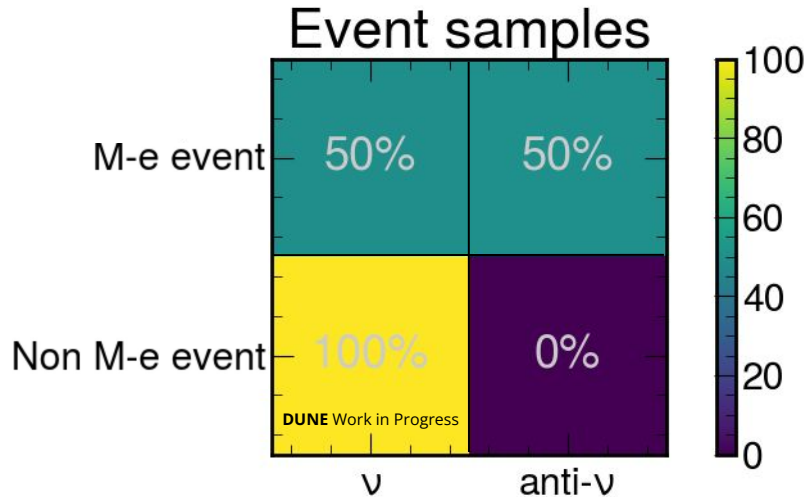
With $\epsilon^t = 0.52$, purity=1



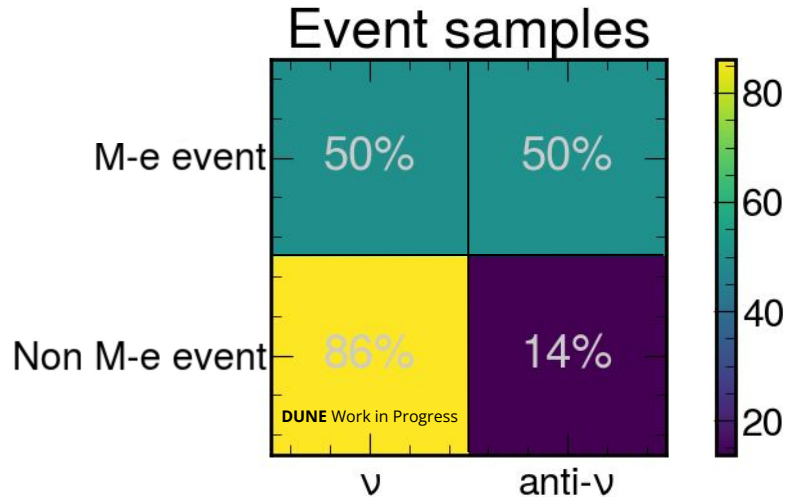
Event samples - 2

Same concept but **normalizing with respect to the rows** of the matrix

Perfect tagging: $\epsilon^t = 1$, purity=1

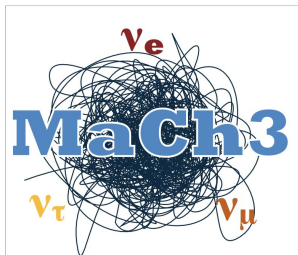


With $\epsilon^t = 0.52$, purity=1



MO sensitivity increases because **non-Michel-e** sample is enriched in **neutrinos**

→ What is the impact of the **M-e** and **Non M-e** sample on Mass ordering sensitivity?

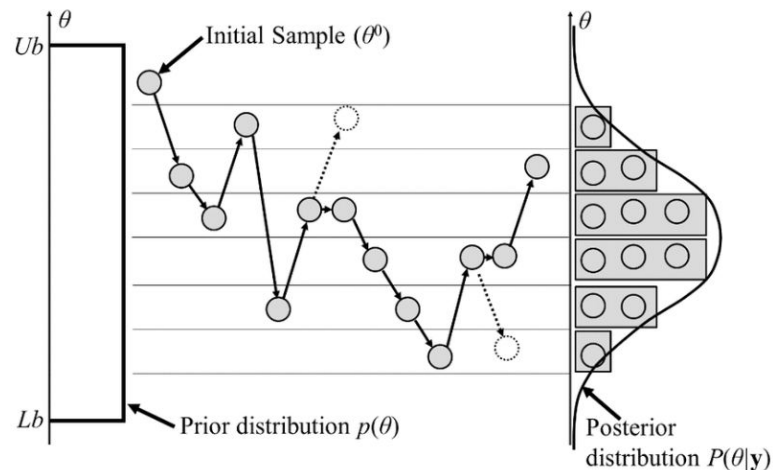


MaCh3 Bayesian analysis framework:

- Oscillation analysis based on Markov Chain Monte-Carlo
- Semi random walk around full parameter space
- Builds up distribution of steps in each parameter
- Get posterior distribution for oscillation parameters

Features of the fit:

- Input files: atmospheric neutrinos
- exposure: 400 kt yrs
- Samples divided by flavor
- Not including systematics nor backgrounds
- Considering $N_{\nu e} + N_{\nu \mu}$ samples, no NC



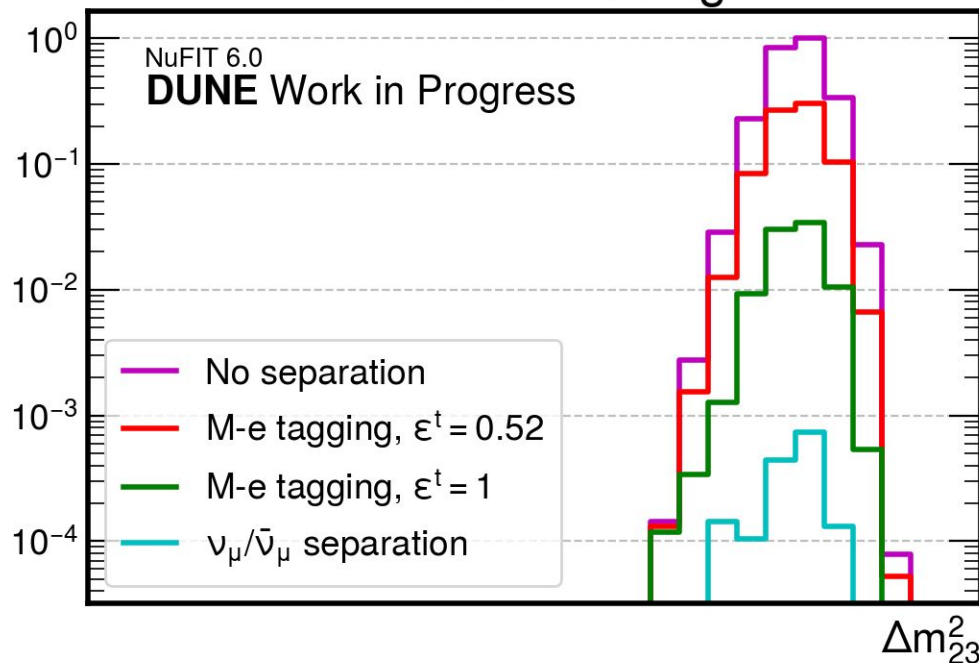
Nue sample + **Numu** sample split in different ways:

1. No $\nu_{\mu}/\bar{\nu}_{\mu}$ separation
2. perfect $\nu_{\mu}/\bar{\nu}_{\mu}$ separation
3. M-e tagging $\epsilon^t = 1$, purity = 1
4. M-e tagging $\epsilon^t = 0.52$

Red histogram refers to a toy study with the $\epsilon^t = 0.52$, $p=1$.

Probability **IO** parameters explain **NO** assumption

Inverted ordering



Bayes factor K measures how much the data **D** supports **hypothesis M1** over **hypothesis M2**.

$$K = \frac{\Pr(D|M_1)}{\Pr(D|M_2)} = \frac{\Pr(M_1|D) \Pr(M_2)}{\Pr(M_2|D) \Pr(M_1)}$$

It gives the ability to reject the hypothesis IO compared to NO.

Taking $\log_{10} B_{10}$ of **No separation** as a reference ($\log_{10} B_{\text{ref}}$):

→ M-e tagging brings a significant improvement even considering $\epsilon^t = 0.52$

DUNE Work in Progress Sample	$\frac{\log_{10}(B_{10})}{\log_{10}(B_{\text{ref}})}$
No separation	1.0
M-e tagging $\epsilon^t=0.52$	1.88
M-e tagging $\epsilon^t=1$	3.43
$\nu_\mu / \bar{\nu}_\mu$ separation	6.18

- One goal of DUNE is the study of Mass Ordering
 - Atmospheric neutrino will provide a complementary measurement to the beam neutrino analysis
 - **M-e tagging** as a way to separate $\nu_\mu / \bar{\nu}_\mu$ and increase sensitivity on MO
 - **Event selection** at Hits level for Michel-e:
 - best efficiency achieved so far \rightarrow 0.52 with purity \sim 0.90
 - Ongoing sensitivity study with **MaCh3** considering **M-e tagging samples**
 - M-e tagging, even with $\epsilon^t = 0.52$, makes a **strong** contribution to discarding the **IO** against the **NO**
- \rightarrow Our current efforts is to improve the reconstruction and complete the sensitivity study to evaluate the impact that atmospheric neutrinos will have in the early years of DUNE

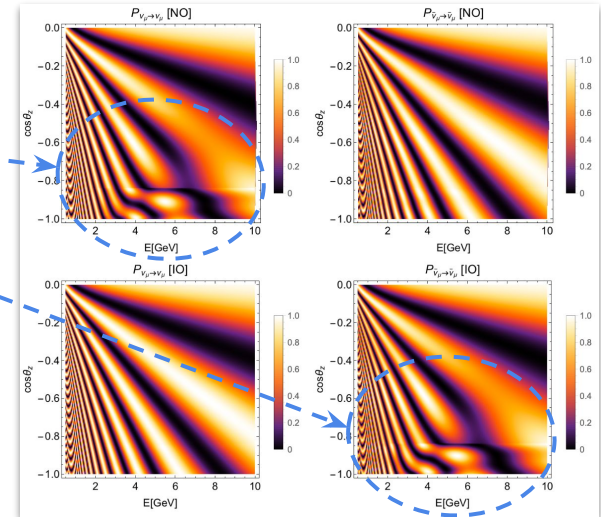
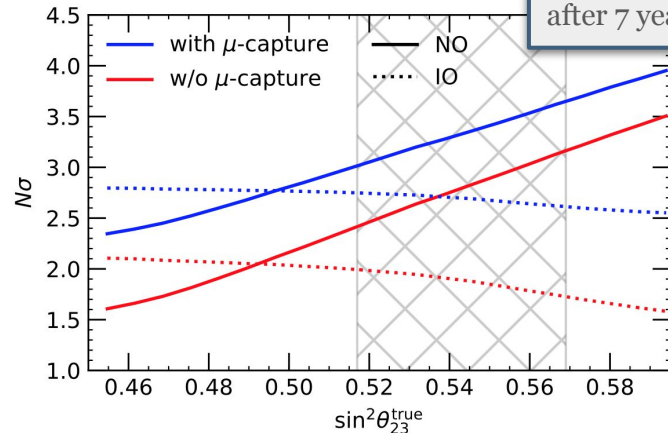
Backup

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

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

$\nu/\bar{\nu}$ discrimination allows DUNE improvement in sensitivity to **mass ordering**.

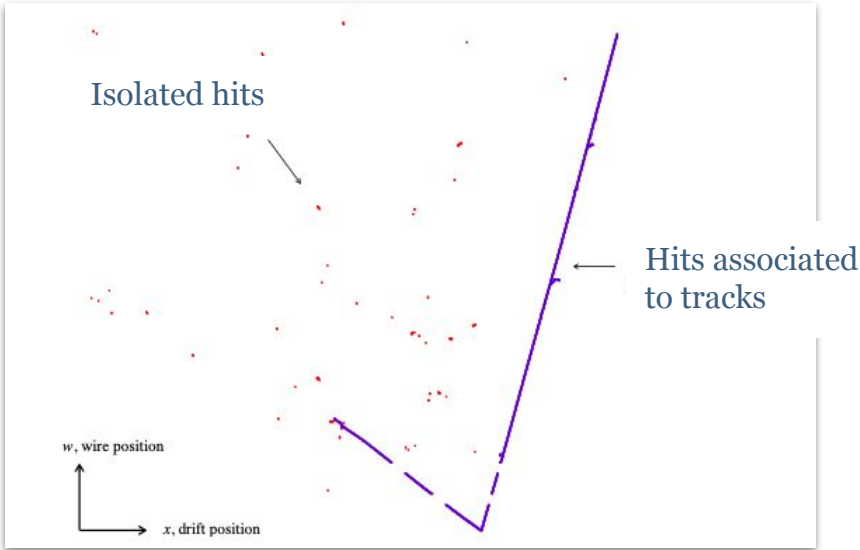
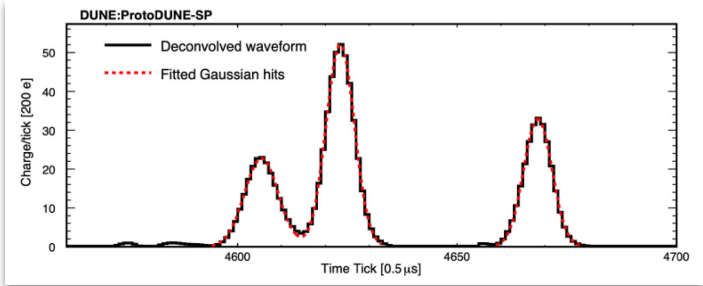
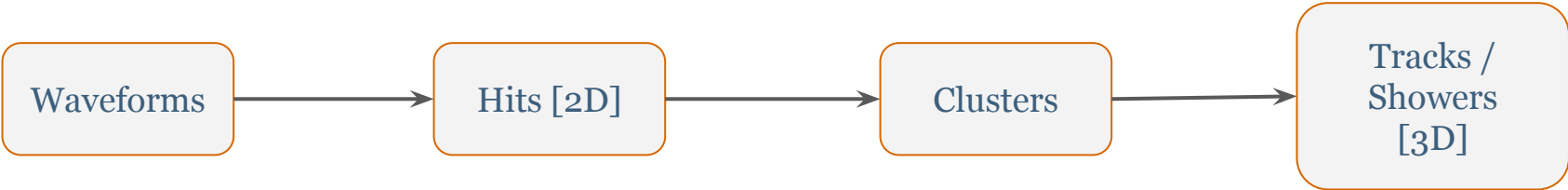
For *NO*, sensitivity of mass ordering $\sim 3.5\sigma$ after 7 years of exposure.



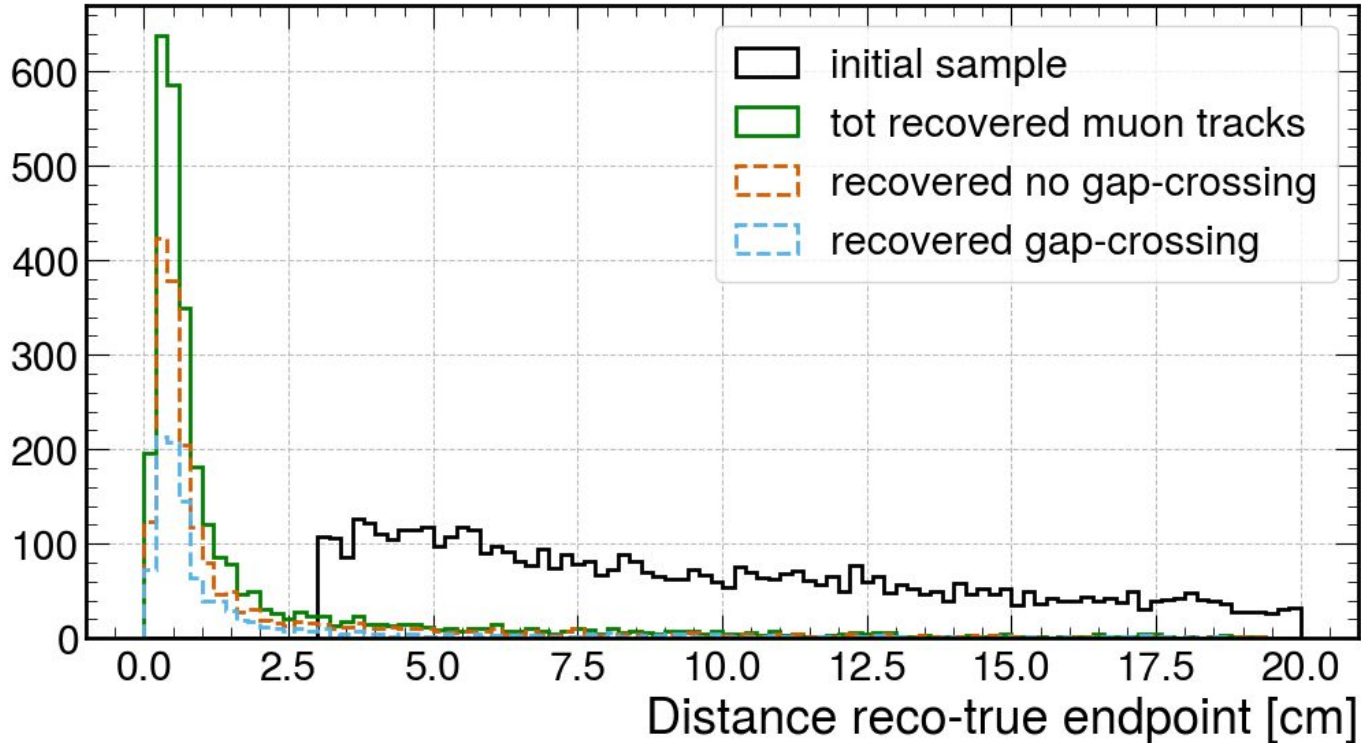
Purpose of the work:

use μ -capture method (**tagging M-e events**) in DUNE to improve sensitivity in mass ordering measurement.

[\[Phys.Rev.D 100 \(2019\) 9, 093004\]](#)



Distance between true and reco endpoint of the muon track:

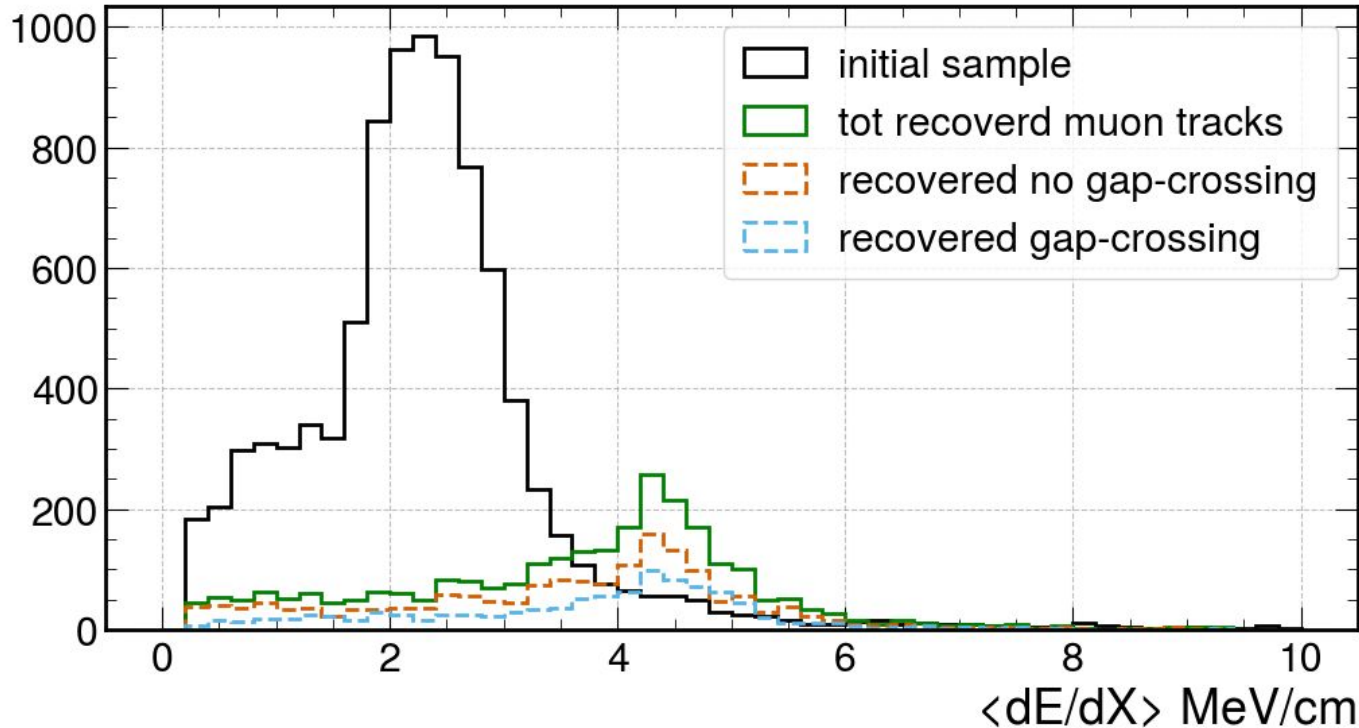


Merging broken track segments leads to improvement in the muon endpoint reconstruction.

- Zone 0-3 cm is populated.
- Higher contribution in case of no gap crossing.

Broken tracks: deposited energy

Average deposited energy in the last 10cm of the track:



MIP value ~ 2 MeV/cm

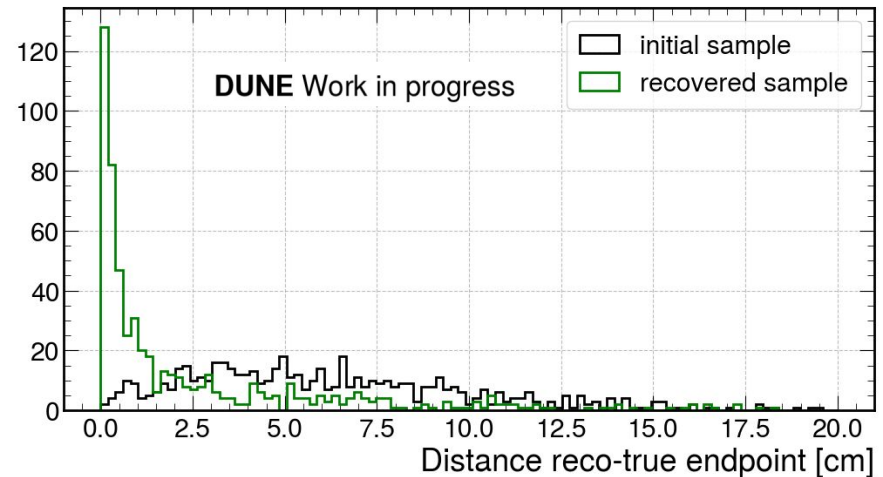
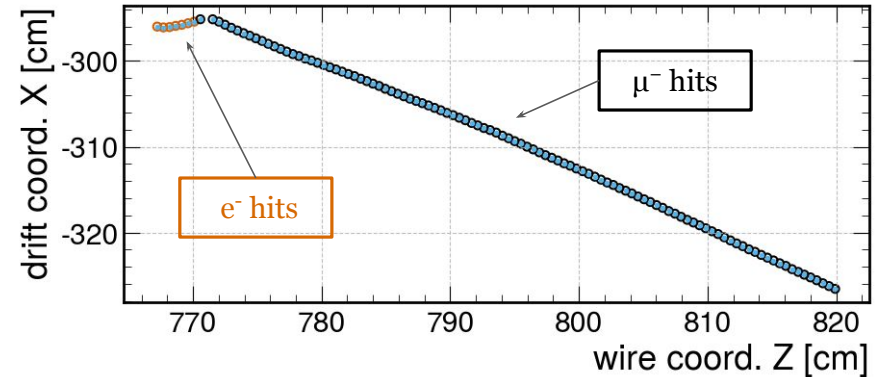
Expect an increase in deposit energy at the end of the muon track:

- The recovered sample shows a second peak consistent with Bragg peak
- Higher contribution in case of no gap crossing.

Idea from a [paper](#) of LArIAT experiment.

2D hit informations to identify endpoint of the muon track:

- local truncated mean charge \rightarrow to look for **bragg peak**
- local linearity \rightarrow to look for the **kink** of the electron decay
- Looking at X and Z hit coordinates from the collection plane.
- Hits in the reconstructed track belong in part to the electron.



Searching endpoint

Looking for an area where observing the Bragg peak of the muon and the kink of the decaying electron.

- grey line represents the **charge** of each individual hit.

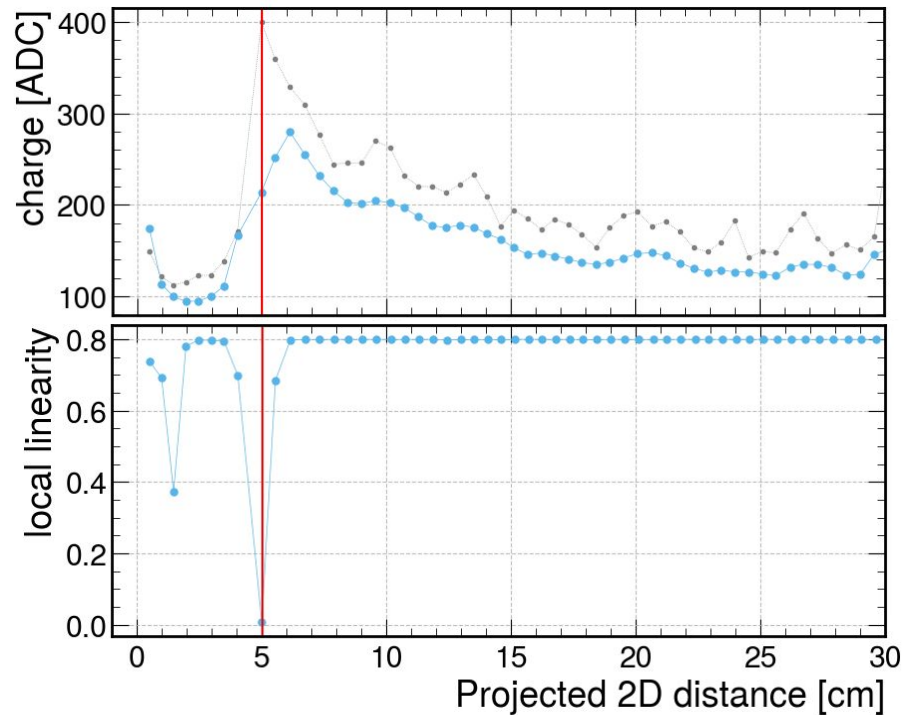
Local linearity:

W is the wire coordinate.

X is the drift coordinate.

b is the number of hits defining the local neighborhood window.

N = 2b+1 is the total number of hits in the neighborhood.



$$\chi_i^2 = \frac{1}{N\sigma_x\sigma_w} \left| \sum_{i-b}^{i+b} [(X_i - \bar{X}) \times (W_i - \bar{W})] \right|$$

Features of the fit:

- **Reco** binning for **Energy** and **$\cos(\theta_z)$**
- fitting different parameters: $\sin^2\theta_{13}$ - $\sin^2\theta_{23}$ - Δm^2_{23} - δ_{cp}

Parameter	Asimov point	Prior	Range
$\sin^2\theta_{23}$	0.546	Flat	[0, 1]
$\sin^2\theta_{13}$	0.0224	Gauss, $\sigma=0.0007$	[0, 1]
Δm^2_{23}	$2.51 \cdot 10^{-3} \text{ eV}^2$	Flat	[-999, 999]
δ_{cp}	-0.96	Flat	[-999, 999]

[NuFIT 6.0](#)

Asimov points related to **Normal Ordering**.

Testing the probability that a **set of parameters related to the IO** could be the true set.