



# $\nu_{\mu}/\bar{\nu}_{\mu}$ separation tagging Michel-electrons in atmospheric neutrino events at DUNE

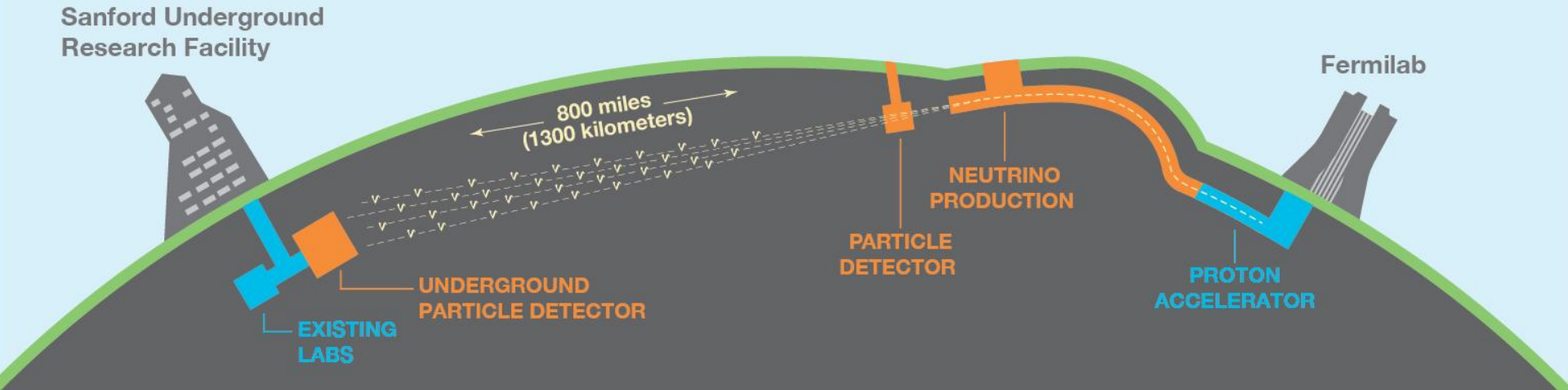
Matteo Galli  
30 March 2026



Congrès des Doctorant·es  
2026

# Deep Underground Neutrino Experiment

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

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

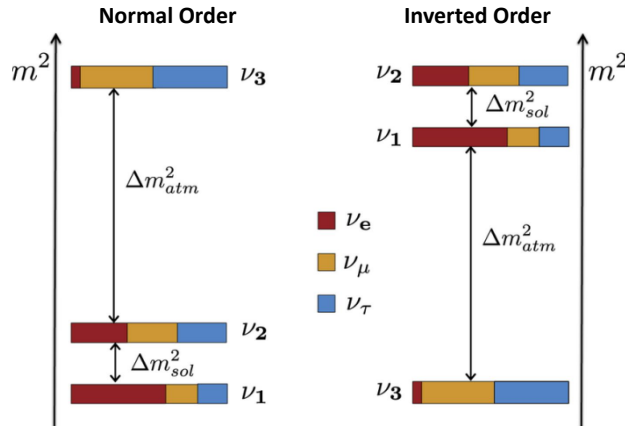
One of the physics goals:

- **Mass Ordering**: measuring  $\nu_\mu$  disappearance +  $\nu_e$  and  $\nu_\tau$  appearance

## Neutrino Mass Ordering

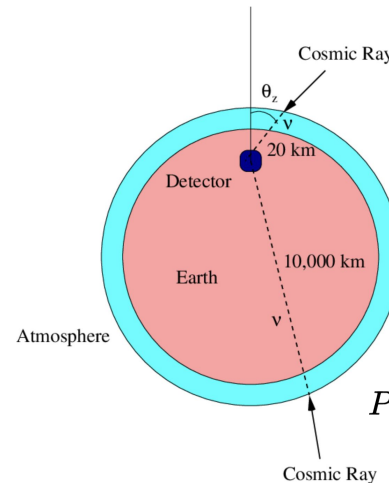
Two non-equivalent orderings for the spectrum of neutrino masses:

- Normal Ordering (NO) with  $m_1 < m_2 < m_3$ .
- Inverted ordering (IO) with  $m_3 < m_1 < m_2$ .



## Atmospheric neutrinos

- Energy range up to **TeV**
- long distances traveled
- Survival probability  $P(\nu_\mu \rightarrow \nu_\mu)$  as a function of **E** and  **$\cos(\theta_z)$** , related to **L**

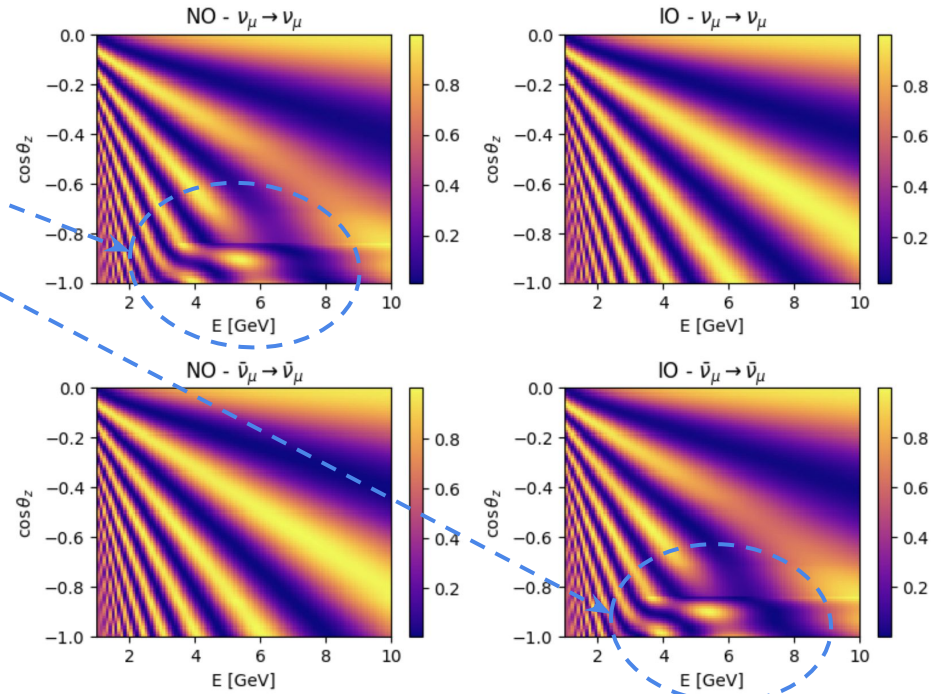


$$P_{\alpha\alpha} = 1 - \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

# Physics case

Resonance (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**.



**$\mu$ -capture** method (tagging M-e events) could be use in DUNE to make this separation

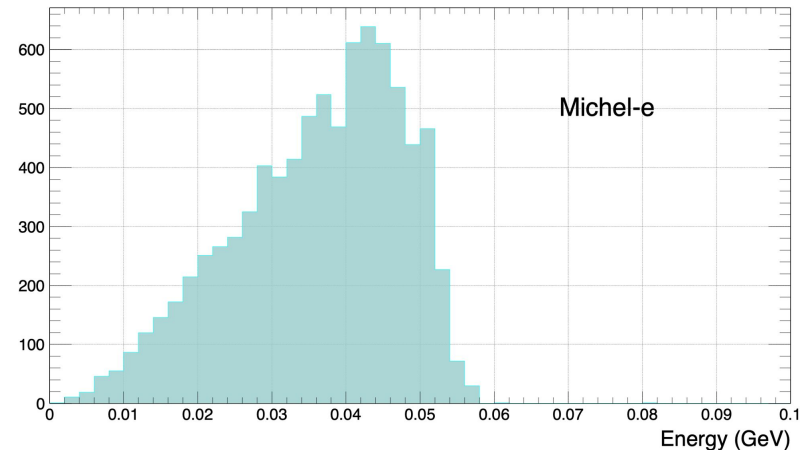
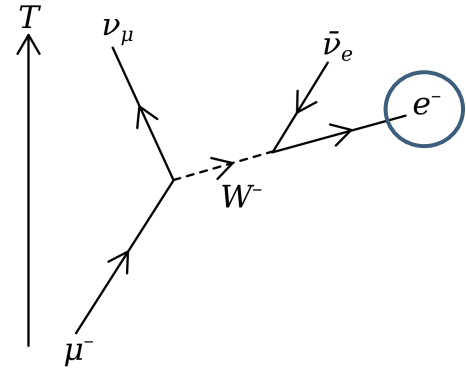
[[Phys.Rev.D 100 \(2019\) 9, 093004](#)]

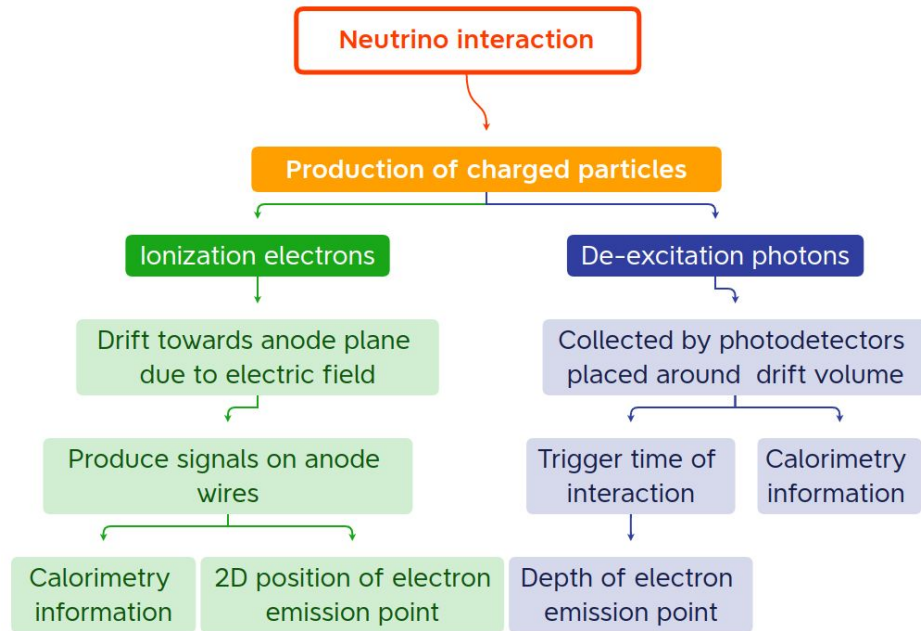
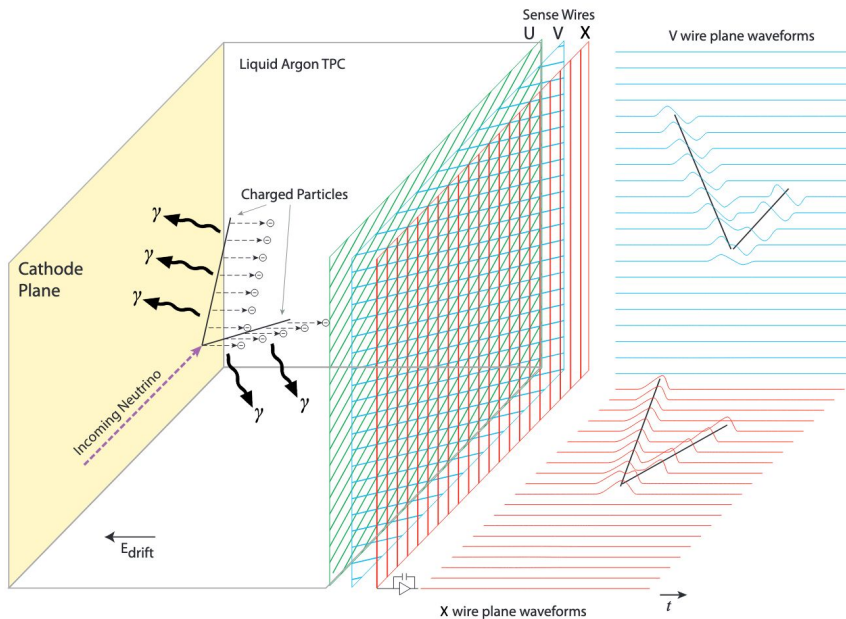
## Distinguishing $\nu_\mu$ from $\bar{\nu}_\mu$ without a Magnetic Field

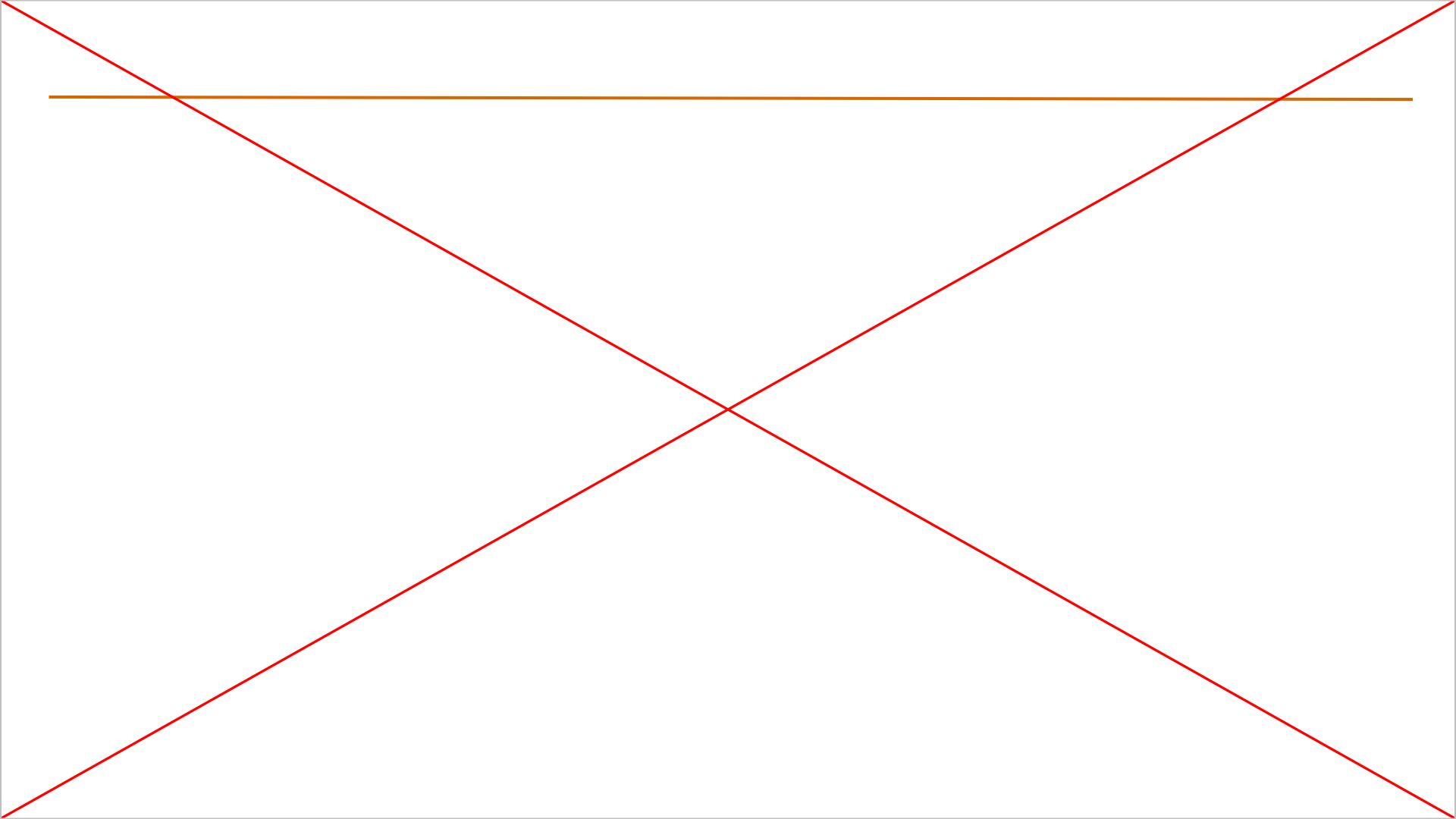
- The Challenge: LArTPC detectors lack a magnetic field, making direct charge discrimination of  $\mu^\pm$  impossible.
- The Workaround: Distinguish  $\mu^-$  from  $\mu^+$  by analyzing their behavior at the end of their track.
- Decay vs. Capture:
  - **$\mu^+$  (from  $\bar{\nu}_\mu$ ): 100% decay into a Michel electron ( $e^+$ ).**
  - **$\mu^-$  (from  $\nu_\mu$ ): Only ~28% decay; ~72% undergo Nuclear Capture on Argon nuclei**
- Method: Identify  $\mu^+$  events by tagging the presence of a Michel electron

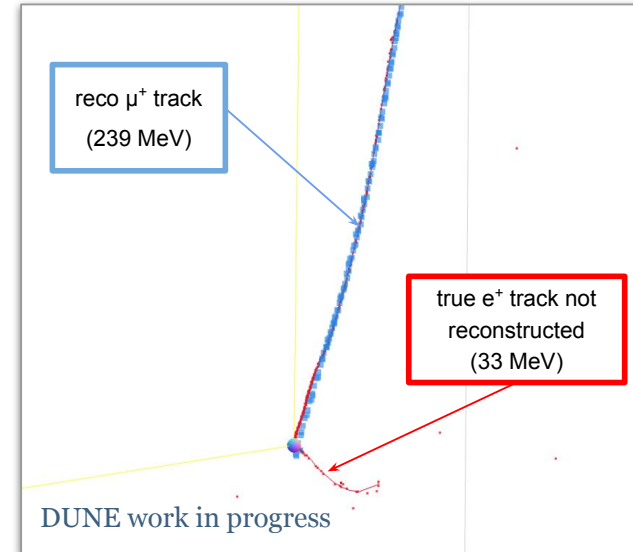
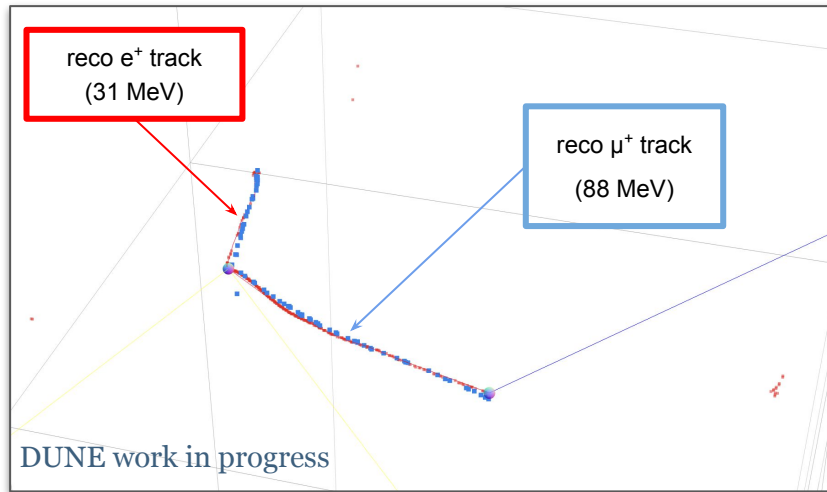
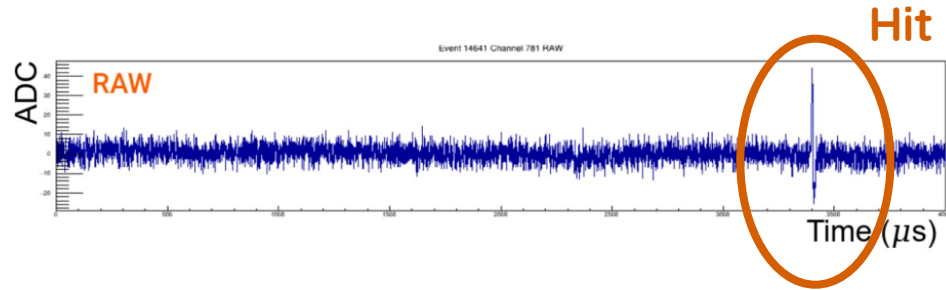
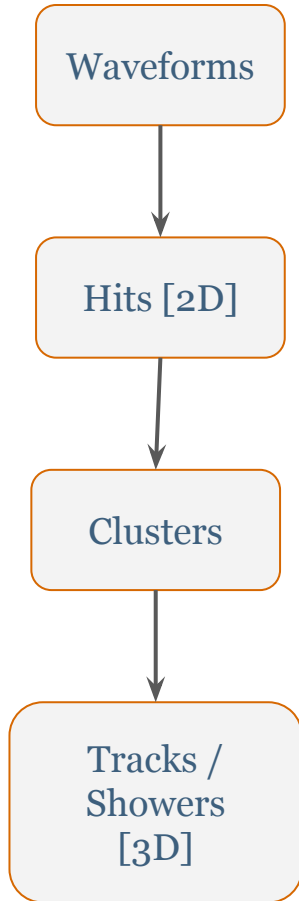
- A **Michel electron** is an electron produced when a **muon decays at rest**
- M-e has an energy spectrum **0 - ~50 MeV**
- Both  **$e^+$**  and  **$e^-$**  are called Michel-electrons, as we cannot distinguish their charge

How do we see them in DUNE?

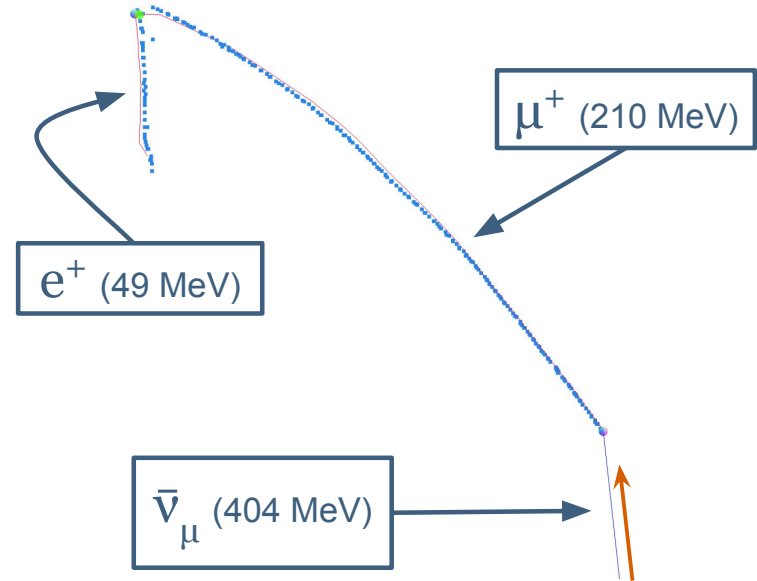




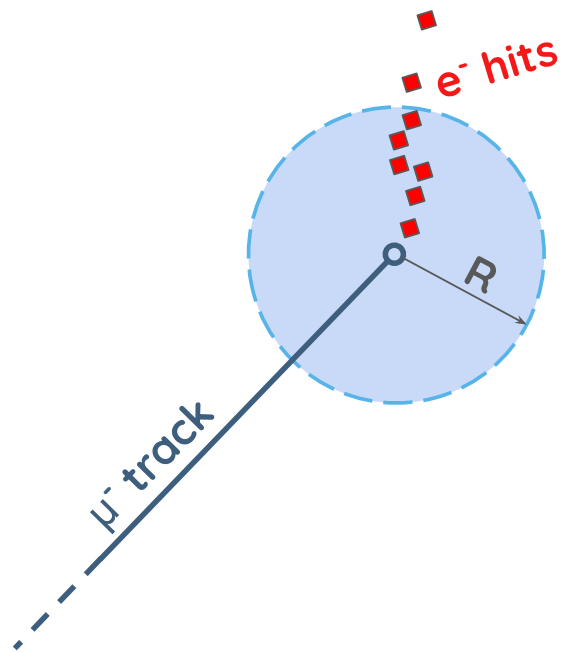




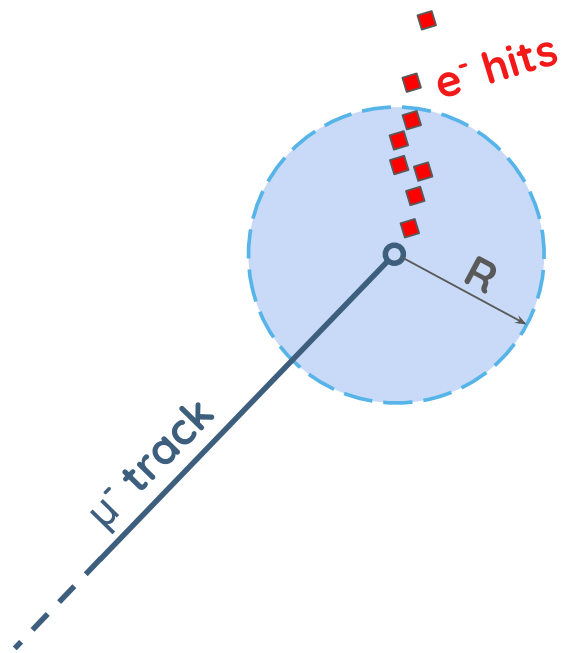
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- Strategy:
  - Hits inside a **circular region**
  - **Number of hits** inside the region
  - Average [CNN](#) **Michel score** of the hits inside the selected region

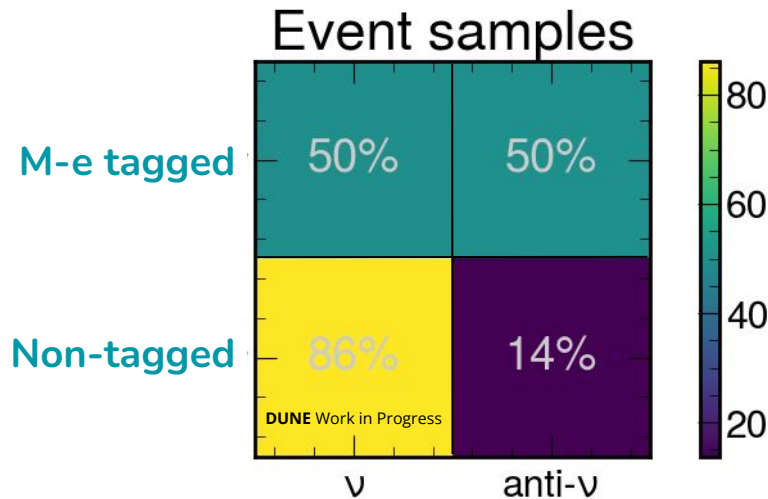


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  - Hits inside a **circular region**
  - **Number of hits** inside the region
  - Average [CNN Michel score](#) of the hits inside the selected region
- Result of the selection:
  - Efficiency **52%**    Purity **90%**

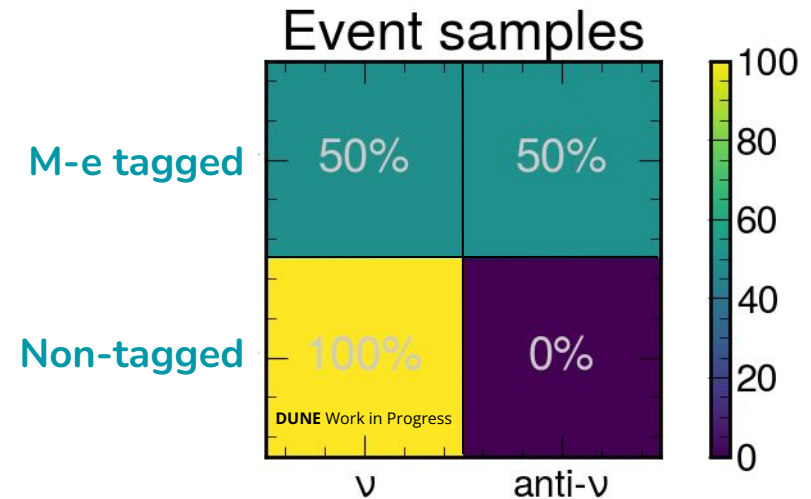


**M-e** and **non-M-e** samples, tagged with Michel-e, using:

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



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



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

## Summary:

- DUNE's unique capabilities with a wide range of off-beam programmes
  - great contribution from **atmospheric neutrinos**
- One goal of DUNE is the study of **Mass Ordering**. Atmospheric neutrino will provide a complementary measurement to the beam neutrino analysis
- **$\nu / \bar{\nu}$  separation** in atmospheric neutrinos improves MO sensitivity
- So far,  $\nu / \bar{\nu}$  separation using **Michel-e tagging** has been studied and its impact on the oscillation analysis evaluated
- The analysis is currently being finalised and will be included in the thesis defence next **September**

**Stay tuned for the exciting upcoming results of the DUNE collaboration**

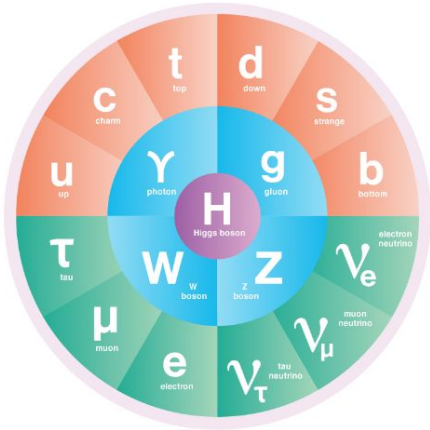
**Thank you!**

**Backup**

Chadwick & Geiger observe  $\beta$ -decays of radioactive nuclei in a bubble chamber



- **Elementary Particle:** A member of the lepton family with no electric charge.
- **Nearly Massless:** So light that for decades they were thought to have zero mass.
- **Weak Interactions:** They only interact via gravity and the weak nuclear force, allowing them to pass through a light-year of lead without stopping.



● QUARKS ● LEPTONS ● BOSONS ● HIGGS BOSON

- Electron Neutrino ( $\nu_e$ )
- Muon Neutrino ( $\nu_\mu$ )
- Tau Neutrino ( $\nu_\tau$ )

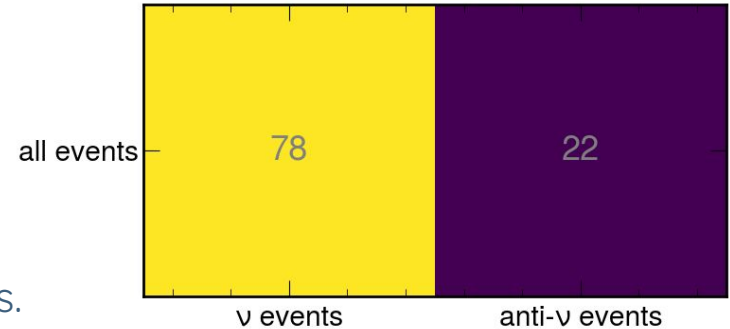


# Number of decay events

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  $\nu_\mu$ :  $N_{\mu^-}$

Fraction of  $\bar{\nu}_\mu$ :  $N_{\mu^+}$

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

M-e tagging efficiency:  $\epsilon^t$

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