MO sensitivity with Michel-e tagging on atmospheric neutrinos

Matteo Galli
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DUNE France Meeting

Physics case

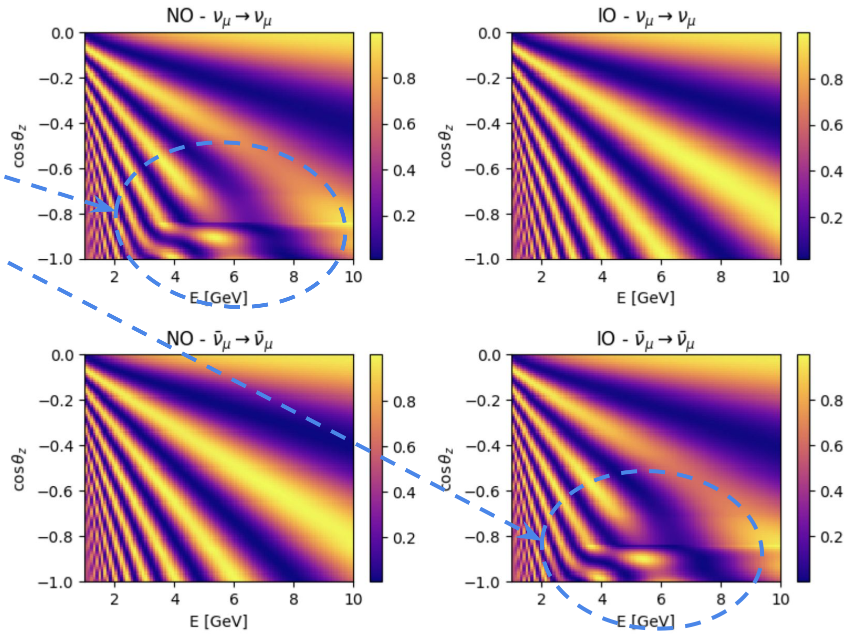
Resonance (3-8) GeV for vertical up-going $\nu_\mu/\bar{\nu}_\mu$

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

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

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

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

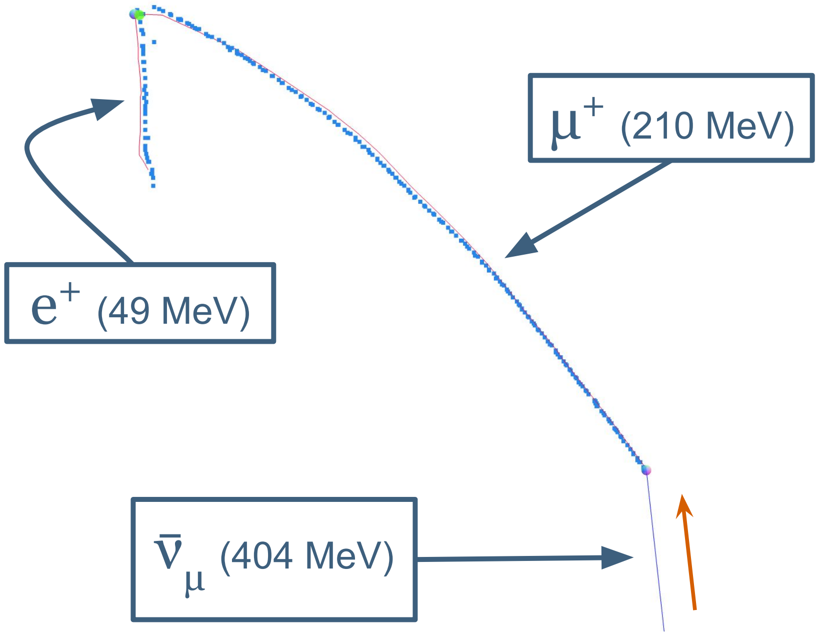


- This method consists of discriminate **muon charge** using **Michel-e** to distinguish decay events from non-decay events
  - μ^+ always decays in e^+
  - μ^- can decay to e^- (~ 28%) or be captured on Argon nuclei (~72%)

Strategy

- Goal:
  - Optimize the **tagging of Michel-e** events in atmospheric neutrino events
  - Evaluate impact of ν_μ separation on **Mass Ordering sensitivity**

- Strategy:
  - Selection of **ν_μCC events**
  - Selection of the μ **endpoint**
  - Search for **Michel-e hits** around the endpoint of the muon track
  - Evaluate the **Michel-e tagged** event sample



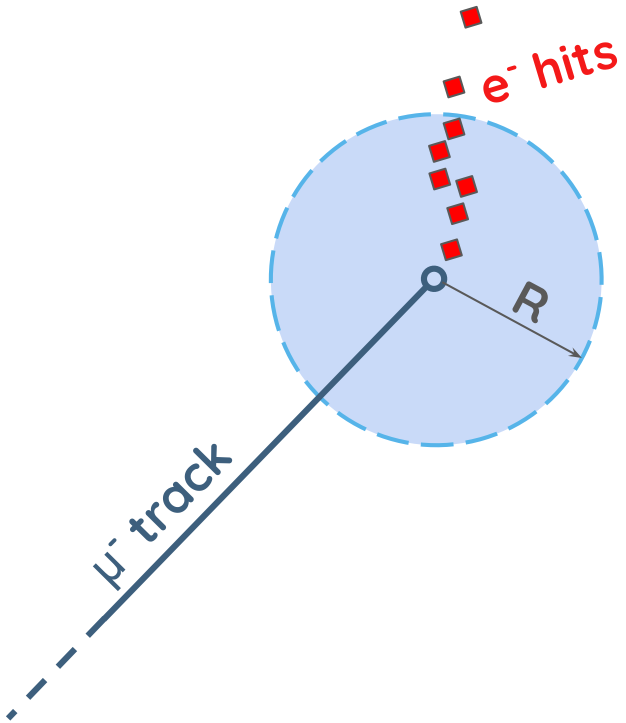
Michel-e tagging

Michel-e tagging

Michel-e tagging based on:

[Phys. Rev. D 107, 092012]

- Hits inside a **circular region** around the muon endpoint
- **Number of hits** inside the selected region
- Average CNN **Michel score** of the hits inside the selected region



Study efficiency on:

1. **Selected sample**
   - **True ν_μCC** events
   - Muon track with a **reconstructed endpoint** within 3 cm of the **true endpoint**
2. **Overall atm production**

Selection of ν_μ CC events

- Applying realistic event selection (using only **Reco** info)
  → Allows studying **backgrounds** of the selected neutrino event sample
- STEP 1 : ν_μ CC events selected with a CVN
  - For each event, the reconstructed flavor is selected as the flavor with the highest output score from the CVN
  - Fraction of **true flavor** in selected ν_μ CC events:

True flavor	Fraction
ν_μ CC	80.8 %
ν_e CC	4.9 %
ν_τ CC	2.3 %
NC	11.9 %

- STEP 2: Muon track
  - Selected as the longest track of the event
  - Applied recovery when the endpoint is not reconstructed correctly:
    - Broken tracks → endpoint reconstructed before the true one
    - Longer tracks → endpoint reconstructed after the true one

Selection results with Reco informations

- STEP 3: Michel-e tagging.
  - Considering Hits inside a circular region of radius **R = 10 cm**
    - Number of hits: between **5** and **40** in the selected region
    - CNN Average Michel score > **0.2**

	Efficiency (# selected ν_μCC / # true ν_μCC)	Purity (# selected ν_μCC / # sel. evts.)
after STEP 1	87%	81%
after STEP 2	82%	81%

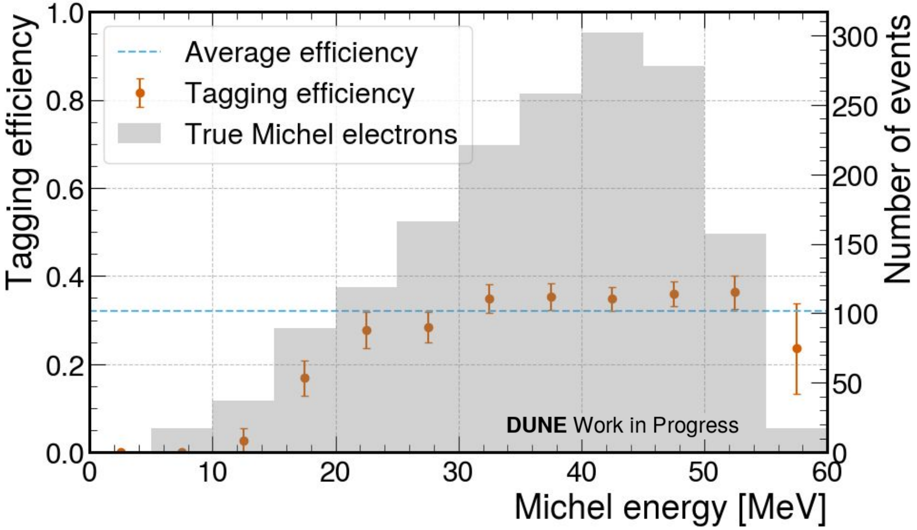
	Efficiency (# selected M-e / # true M-e)	Purity (# selected M-e / # sel. evts.)
after STEP 3	32%	90%

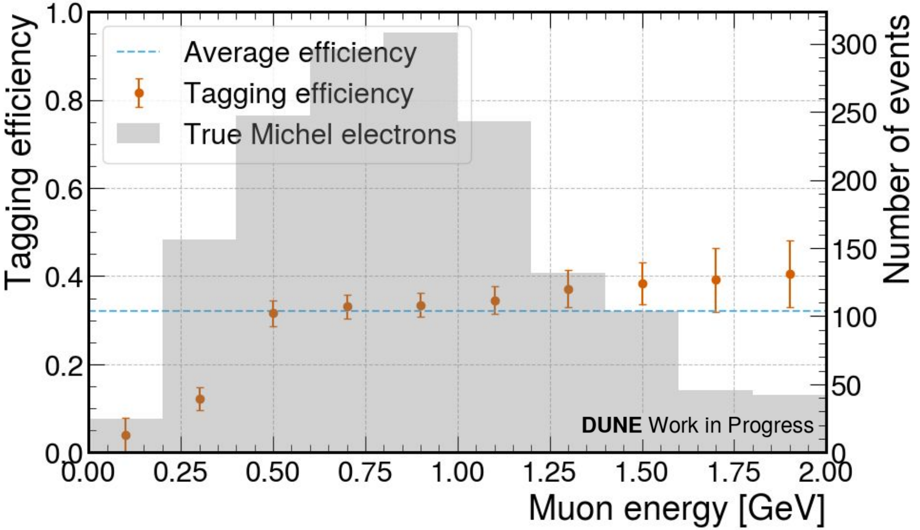
Michel-e tagging stability

Results in Michel-e event tagging using selection based on **reco events**:

- Tagging **efficiency**: = **32%**

Dependence on the **energy** of the **Michel-e** and of the **muon**



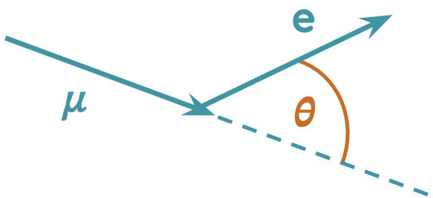


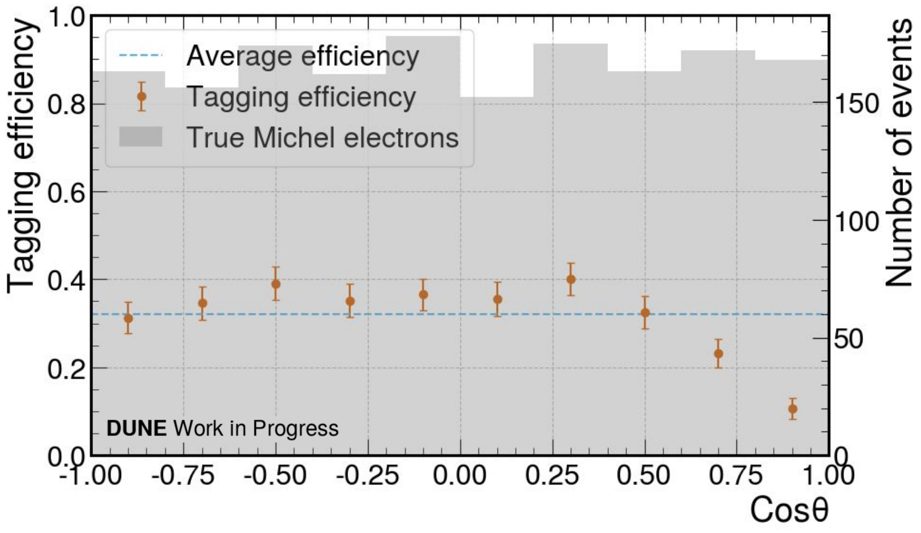
Michel-e tagging stability

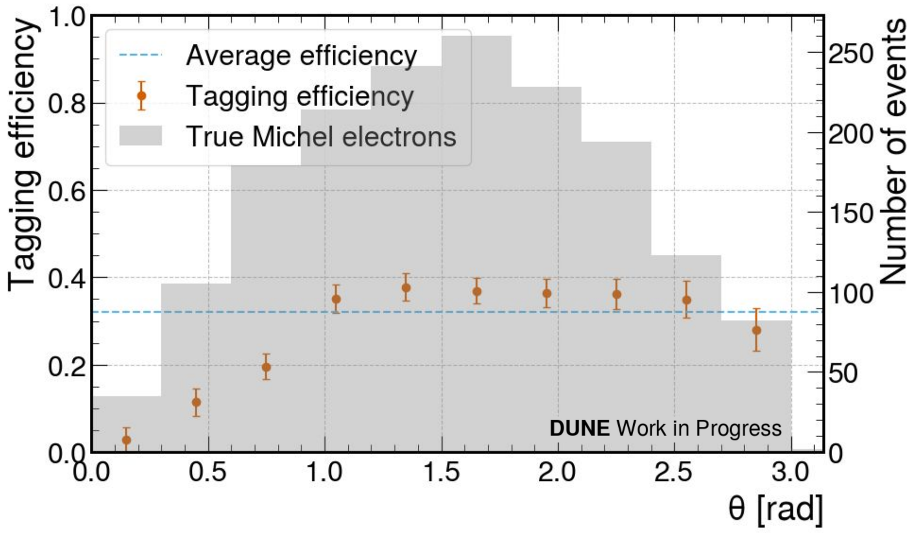
Results in Michel-e event tagging using selection based on **true ν_μCC** events:

- Tagging **efficiency**: = **32%**

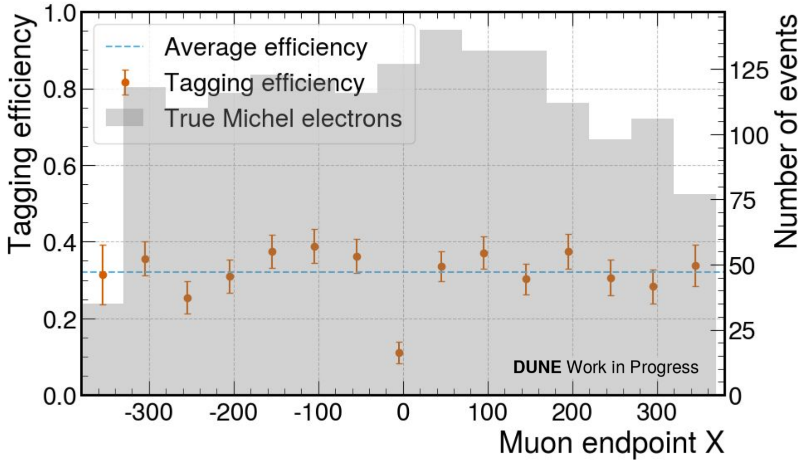
Depending on the **angle** between **muon** and **Michel-e**

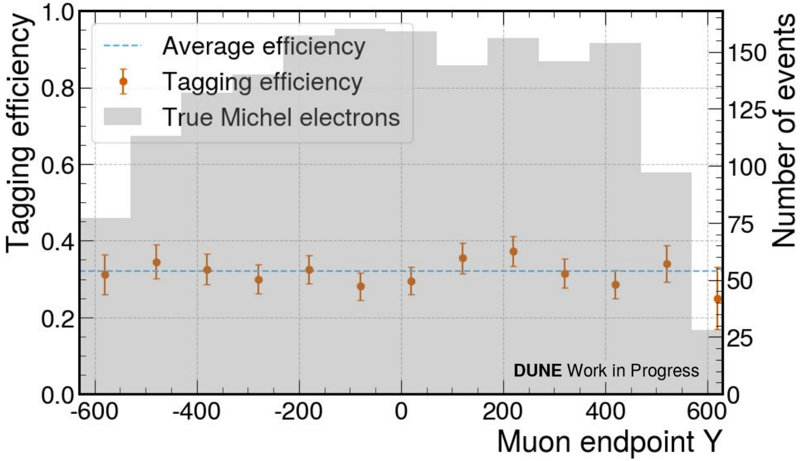


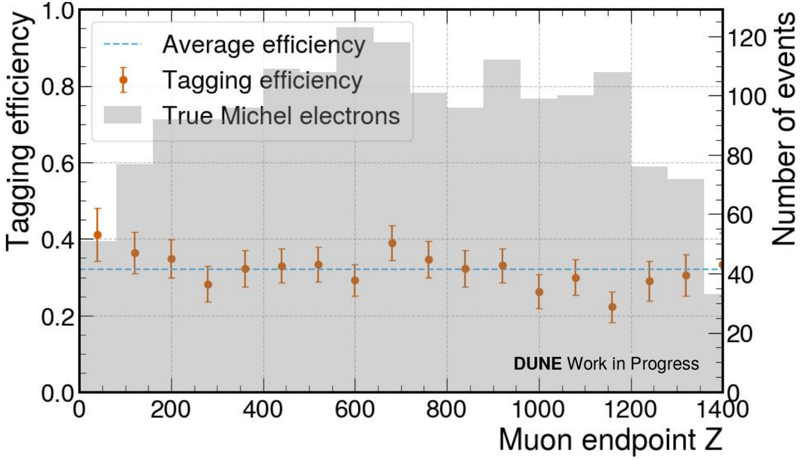




Michel-e tagging stability







Results in Michel-e event tagging using selection based on **true ν_μ CC** events:

- Tagging **efficiency**: = **32%**

Dependence on the **muon endpoint position**

M-e's background events

From the final Michel-e events sample → **event backgrounds**

- Fraction of **true flavor** in:
  - Michel-e tagged events
  - Non-tagged events

	ν_μCC	$\bar{\nu}_\mu$CC	ν_eCC	$\bar{\nu}_e$CC	ν_τCC	$\bar{\nu}_\tau$CC	NC
M-e tagged	50.5	37.3	2.7	0.1	0.1	0.2	9.2
Non-tagged	64.2	16.9	3.8	0.7	1.8	0.7	11.8
All ν_μCC	63.3	18.3	3.8	0.7	1.7	0.7	11.6

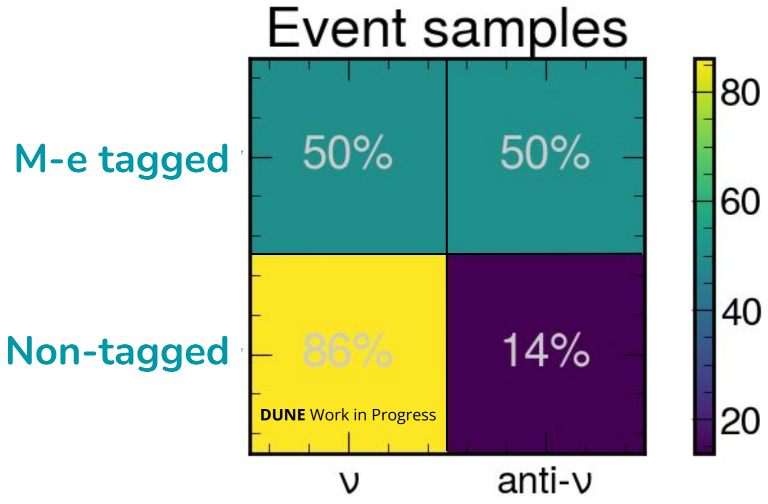
DUNE Work in Progress

Impact on sensitivity to Mass Ordering

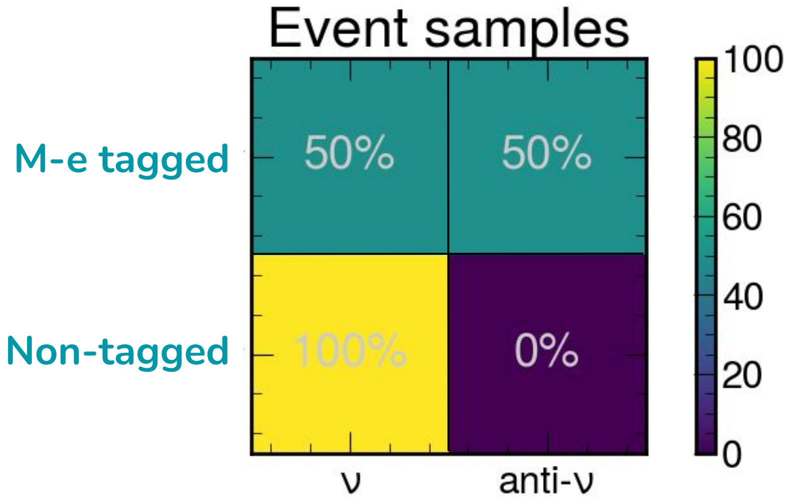
Building event samples

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

With $\boldsymbol{\varepsilon^t}$ **=0.52**, purity=1



Perfect tagging: $\boldsymbol{\varepsilon^t}$ **= 1**, purity=1



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

Atmospheric parameters fit

MaCh3 analysis framework:

- Oscillation analysis based on Markov Chain Monte-Carlo
- Get posterior distribution for oscillation parameters

Features of the fit:

- Input files: atmospheric neutrinos
- exposure: 400 kt yrs
- Not including systematics

Taking in account **$(\nu_e + \bar{\nu}_e)$** sample + **$(\nu_\mu + \bar{\nu}_\mu)$** splitted in **5 ways**:

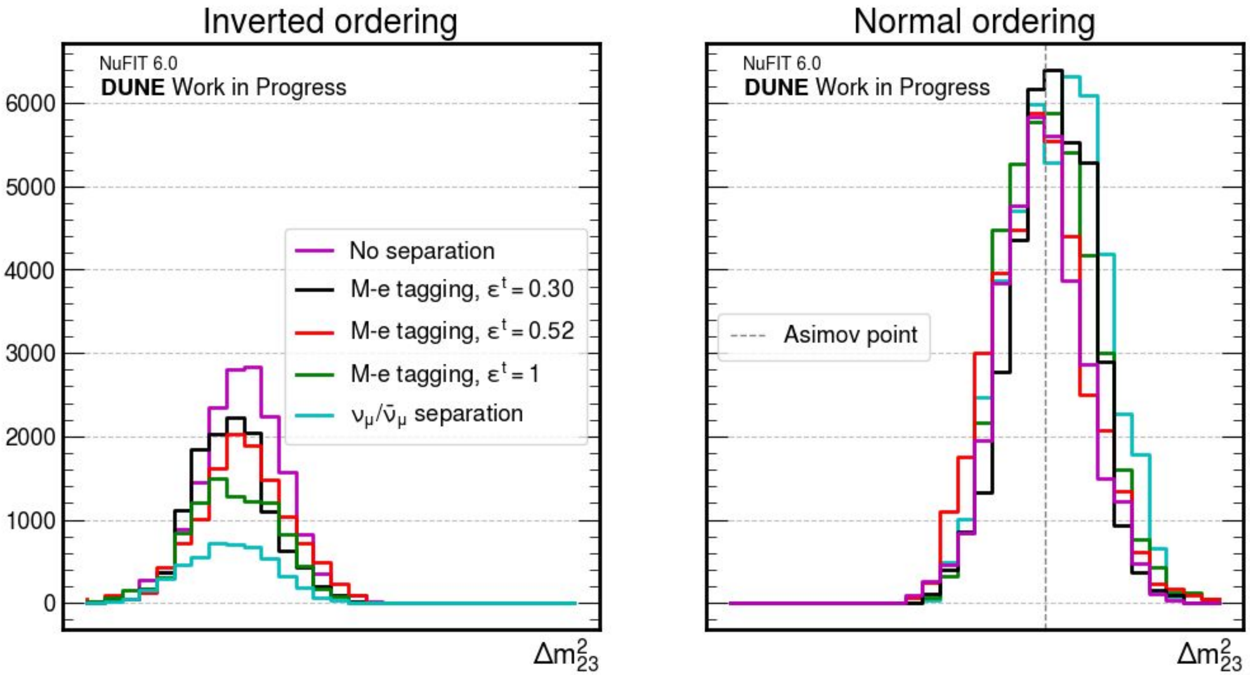
1. **No** $\nu_\mu/\bar{\nu}_\mu$ separation
2. **Perfect** $\nu_\mu/\bar{\nu}_\mu$ separation
3. Perfect M-e tagging **$\varepsilon^t = 1$**, no backgrounds
4. M-e tagging **$\varepsilon^t = 0.52$** + backgrounds
5. M-e tagging + realistic event selection **$\varepsilon = 0.32$** + backgrounds

Posterior probabilities

Normal Ordering oscillation parameters

→ testing the ability to discard IO

1. **No $\nu_\mu/\bar{\nu}_\mu$ separation**
2. **Perfect $\nu_\mu/\bar{\nu}_\mu$ separation**
3. **M-e tagging $\varepsilon^t = 1.0$**
4. **M-e tagging $\varepsilon^t = 0.52$**
5. **M-e event sel. $\varepsilon = 0.30$**

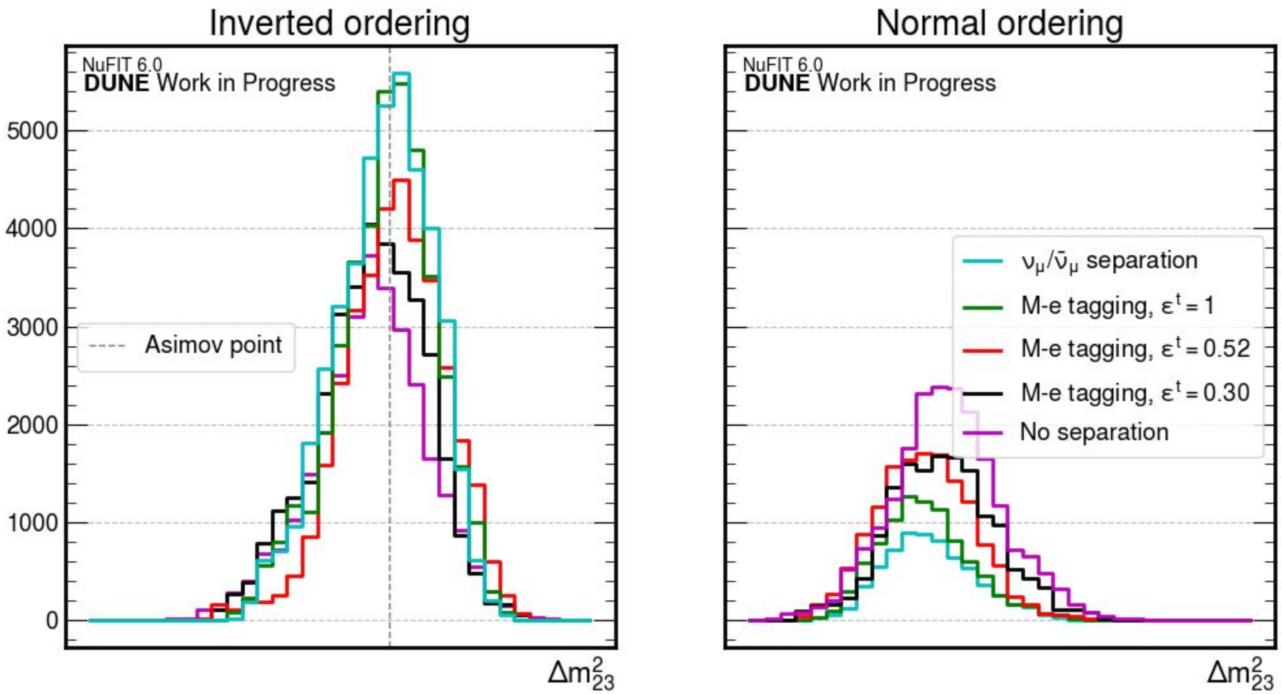


Posterior probabilities

Inverted Ordering oscillation parameters

→ testing the ability to discard NO

1. **No $\nu_\mu/\bar{\nu}_\mu$ separation**
2. **Perfect $\nu_\mu/\bar{\nu}_\mu$ separation**
3. **M-e tagging $\varepsilon^t = 1.0$**
4. **M-e tagging $\varepsilon^t = 0.52$**
5. **M-e event sel. $\varepsilon = 0.30$**

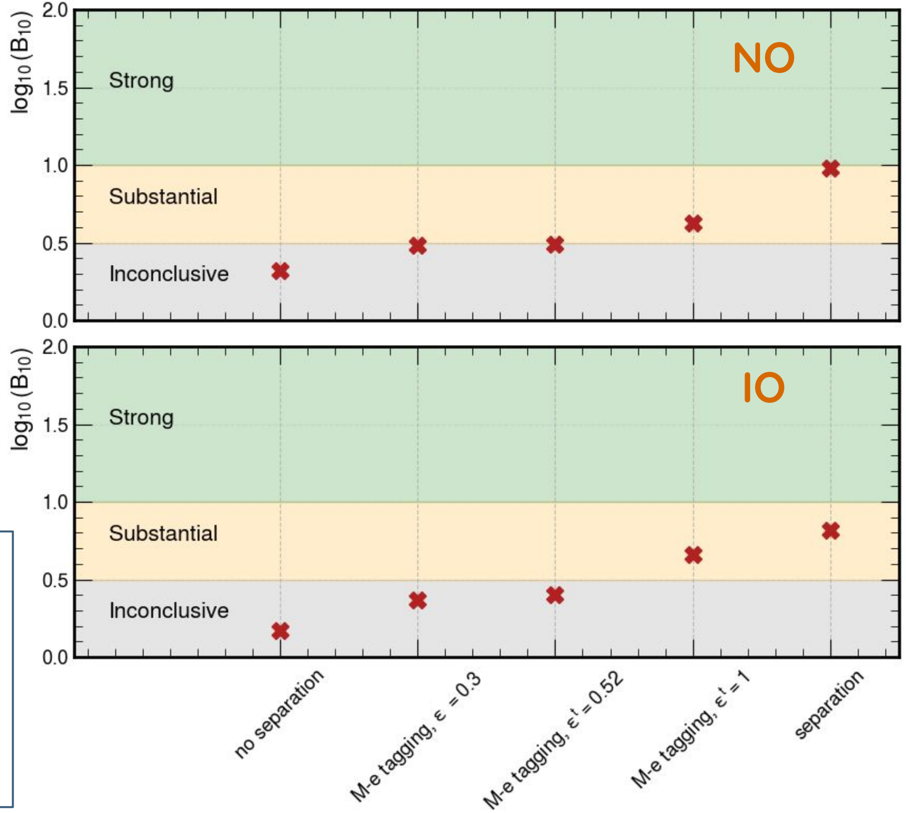


Impact on MO

- Bayes factor (B_{10}) → how much data favors H_1 over H_0

$$B_{10} = \frac{P(D|H_1)}{P(D|H_0)}$$

- M-e tagging method less sensitive to perfect separation but can make a decisive contribution
- There is still room for improvement in reconstruction and selection.



As a complementary study:

- **Krittika** is evaluating M-e tagging's impact on MO using [fast-osc-feedback]()

ProtoDUNE HD data/MC comparison

Plans

- Goal: estimate uncertainty on efficiency
  - can be used as a systematic in the study of oscillation parameters
- Sample:
  - ProtoDUNE HD cosmic **data** from this list
  - Stopping muons from **Beam + Cosmics simulation**

ProtoDUNE-HD Good Cosmic Runs [edit]

Contact: Jake Calcutt

TPC & DAPHNE @ 176kV & 7.8mV/fc [edit]

118 Runs:

Run Number	Raw File Count	Trigger Primitive File Count
27979	5992	730
27980	16344	1996
27997	4440	590
28009	488	80
28011	552	90
28014	96	14
28016	7032	873
28024	1505	224

Generators: Beam + Cosmics

This includes the updated APA1 collection plane field response. However, due to an oversight, this includes on SCE-off simulation.

2025 MC Production Datasets

Beam Momentum	Metacat scope:dataset
-5 GeV	hd-protodune:hd-protodune__pdhd_mc_2025a__full-reconstructed__10_10_04d01__standard_reco_protodunehd_MC__pdhd_5GeV_h4input_cosmics__out1__-5GeV__v1_official
-1 GeV	hd-protodune:hd-protodune__pdhd_mc_2025a__full-reconstructed__10_10_04d01__standard_reco_protodunehd_MC__pdhd_1GeV_h4input_cosmics__out1__-1GeV__v1_official
5 GeV	hd-protodune:hd-protodune__pdhd_mc_2025a__full-reconstructed__10_10_04d01__standard_reco_protodunehd_MC__pdhd_5GeV_h4input_cosmics__out1__5GeV__v1_official
1 GeV	hd-protodune:hd-protodune__pdhd_mc_2025a__full-reconstructed__10_10_04d01__standard_reco_protodunehd_MC__pdhd_1GeV_h4input_cosmics__out1__1GeV__v1_official

Plans - Analysis

- Sample of stopping muons
  - **Jérémy** has already done a great job on ProtoDUNE for this purpose
  - Two analyzers as a starting point (seems not many changes are needed)
- Selection on charge information
  - Apply my selection to tag Me events
  - Compare results respect the two samples
- Selection on light information
  - **Shu** is developing a study on Me light response
  - Idea is to combine my **charge selection** with his **light selection**

Cut	Efficiency (MC)	Efficiency (DATA)
$t_{1st} \in [120, 130]$	69574/74930 (92.9%)	7009/8284 (84.6%)
$\frac{I_{2nd}}{I_{1st}} \in [0.13, 0.4]$	37334/69574 (53.7%)	2334/7009 (33.3%)
$1.0 < I_{2nd}$	26085/37334 (69.9%)	1042/2334 (44.6%)
(I_{2nd}, X)	25658/26085 (98.4%)	955/1042 (91.7%)
$0.07 < r_{2nd}$	20691/25658 (80.6%)	660/955 (69.1%)
$\frac{I_{3rd}}{I_{2nd}} < 0.6$	17169/20691 (83.0%)	594/660 (90.0%)
$0.7 < (I_{2nd} - I_{3rd})$	15907/17169 (92.6%)	550/594 (92.6%)
$X > 30 \cup X < -100$	15004/15907 (94.3%)	502/550 (91.3%)
Total Efficiency	15004/71520 (21.0%)	502/7987 (6.3%)

Conclusion

Summary:

- Michel-e tagging
  - Performed only on well-reconstructed ν_μ CC events (e=0.52)
  - With realistic selection on atm production, incl. backgrounds (e=0.32)
- Performed first study with **MaCh3** considering **M-e event selection and tagging**
  - M-e tagging significantly **improves the rejection** of the wrong mass ordering

Ongoing:

- Test the Michel-e selection on **ProtoDUNE HD cosmic data vs MC**
  - In this moment -> testing modules on data
  - Combined different studies

Thank you!