# Muon Veto Optimization for the Reactor Neutrino Oscillation Measurements in JUNO

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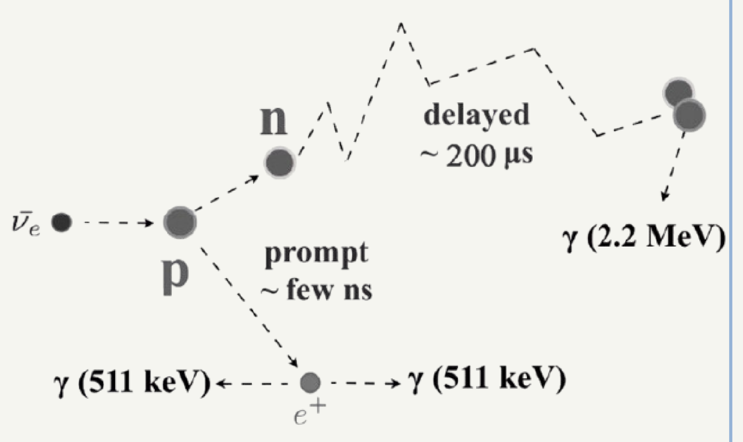
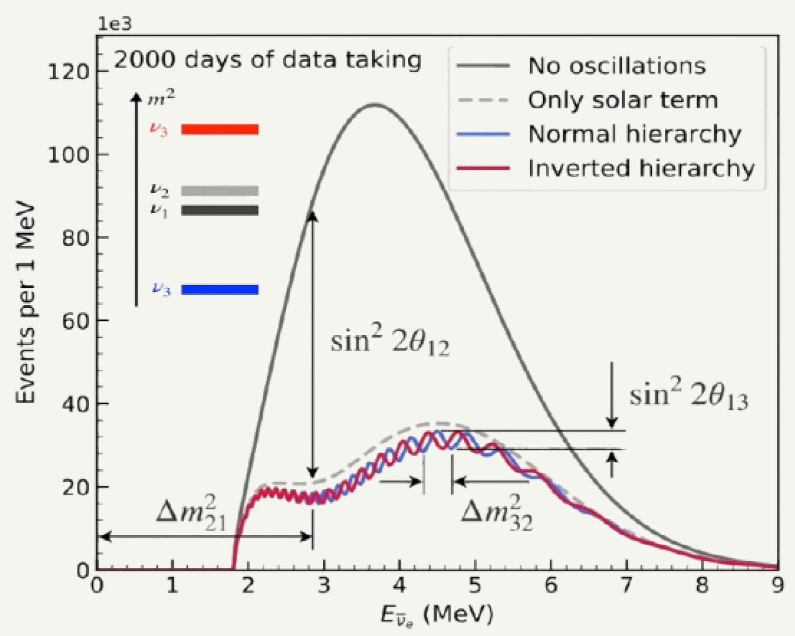
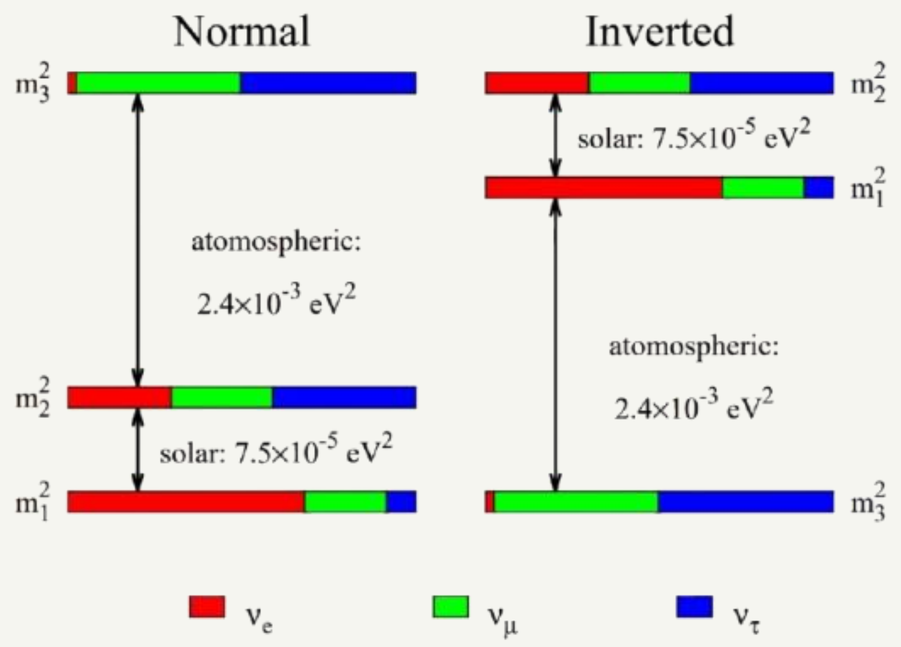
**Statement: Results correspond to one of three methods used to perform oscillation analysis**

## 1.Physics goals in JUNO

- Reactor neutrino[1][2], produce inverse beta decay (IBD) signal, with different energy spectrum based on different mass ordering
- Main physics goals
  - Neutrino mass ordering
  - Precision measurement of $\theta_{12}$, $\Delta m^2_{21}$, $|\Delta m^2_{31}|$



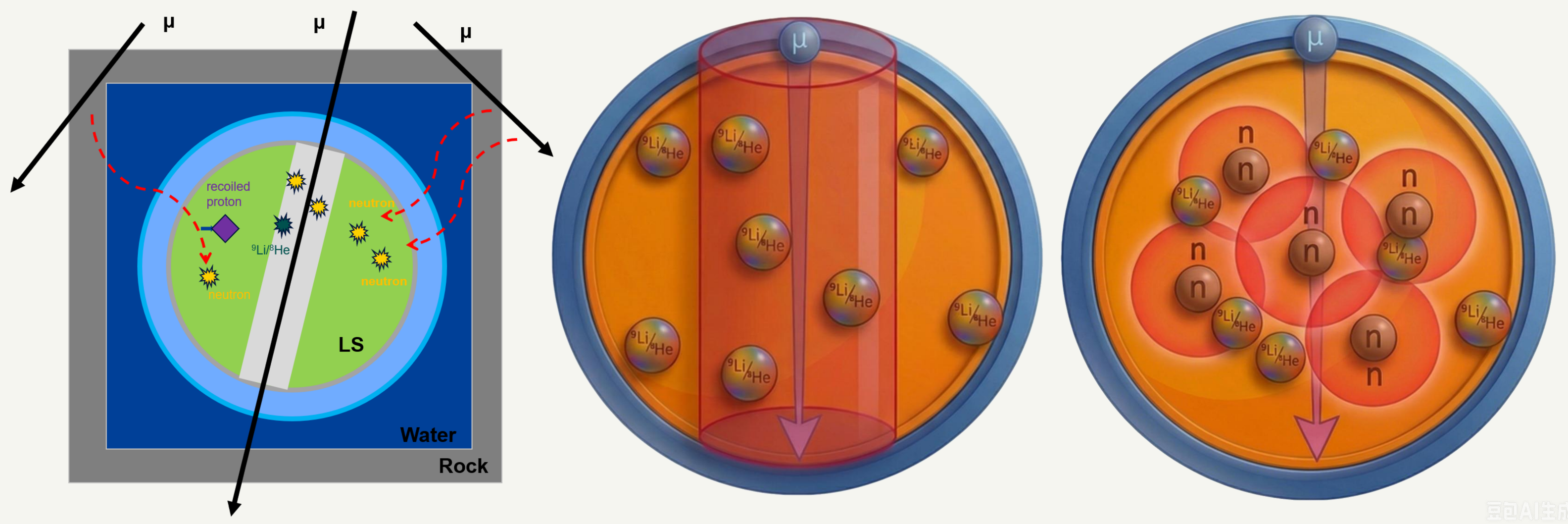

## 2.Muon veto in JUNO

- ~5Hz muon rate in JUNO, produce lots of secondary particles when go through the detector.
- ~51% $^9$Li and ~16% $^8$He go through β-n decay branch, which is one of the main background in JUNO:

$$^9\text{Li} \xrightarrow{\beta-} e^- + {}^9\text{Be}^* \rightarrow e^- + \alpha + \alpha + n$$

$$^8\text{He} \xrightarrow{\beta-} e^- + {}^8\text{Li}^* \rightarrow {}^7\text{Li} + e^- + n$$

- ~95% of $^9$Li/$^8$He are produced in association with an accompanying neutron.
- Muon veto cuts:
  - Spherical veto cut using accompanying neutrons
  - Cylindrical veto cut along muon tracks
- Time cuts (based on $^9$Li/$^8$He lifetime) and distance cuts
- Muon also produce few double-neutron and fast neutron background, ~0.1/day.

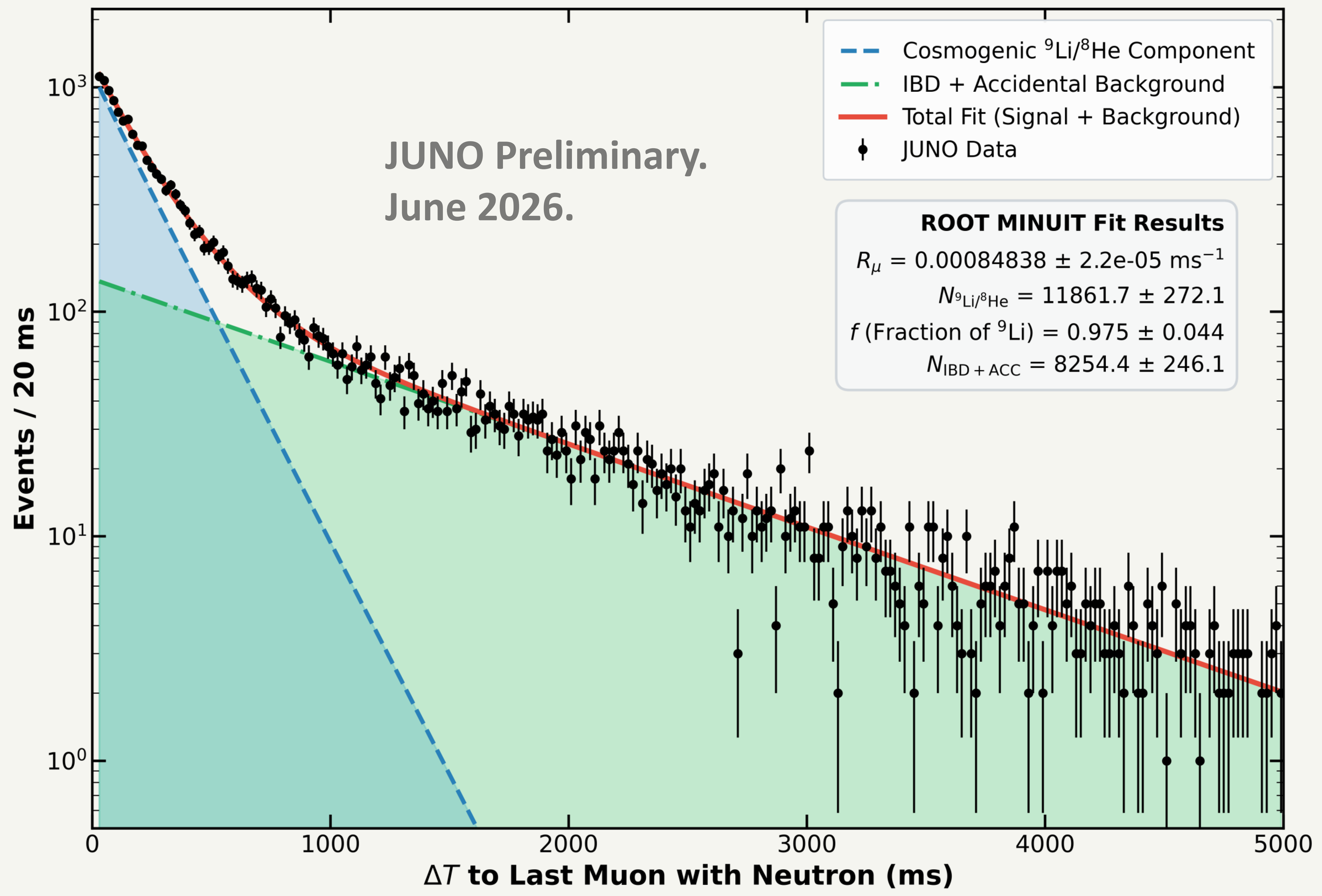



## 3.Estimation method

$$N^{\text{after muon veto}}_{^9\text{Li}/^8\text{He}} = N^{\text{after muon veto}}_{\text{IBD candidate}} - (N^{\text{before muon veto}}_{\text{IBD candidate}} - N^{\text{before muon veto}}_{^9Li/^8He})\,.\,\text{IBD efficiency}$$

To estimate the residual $^9$Li/$^8$He background after muon veto:

- **Number of IBD candidates**: directly from event selection, ~95/day before muon veto.
- $N^{\text{after muon veto}}_{^9\text{Li}/^8\text{He}}$:
  - Fitting the time spectrum of IBD candidates to last muon with neutron.
  - **Neutron accompanying efficiency**(the ratio of $^9$Li/$^8$He produced with neutron) estimation: ~95%.
  - Rate of $^9$Li/$^8$He before muon veto: ~59/day.
- **IBD efficiency**(the ratio of survival IBDs after muon veto):
  - Uniformly distributed prompt signals.
  - Sampling ΔR and ΔT from calibration data.
  - Measure data-driven virtual IBD events' survival rate after muon veto.




## 4.Muon veto optimization

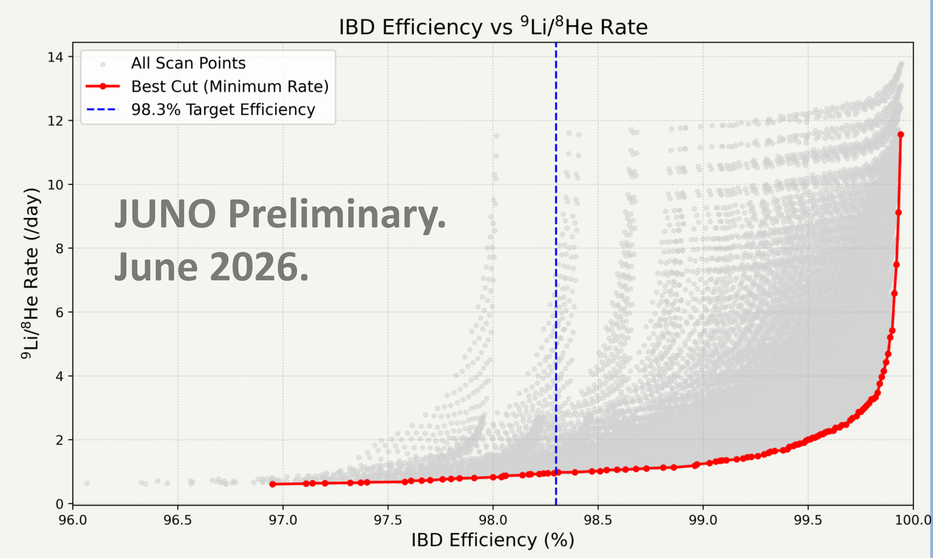
- For muon produced neutron, **neutron veto** applied:

distance to spallation neutron < Cut1 − A × time to muon

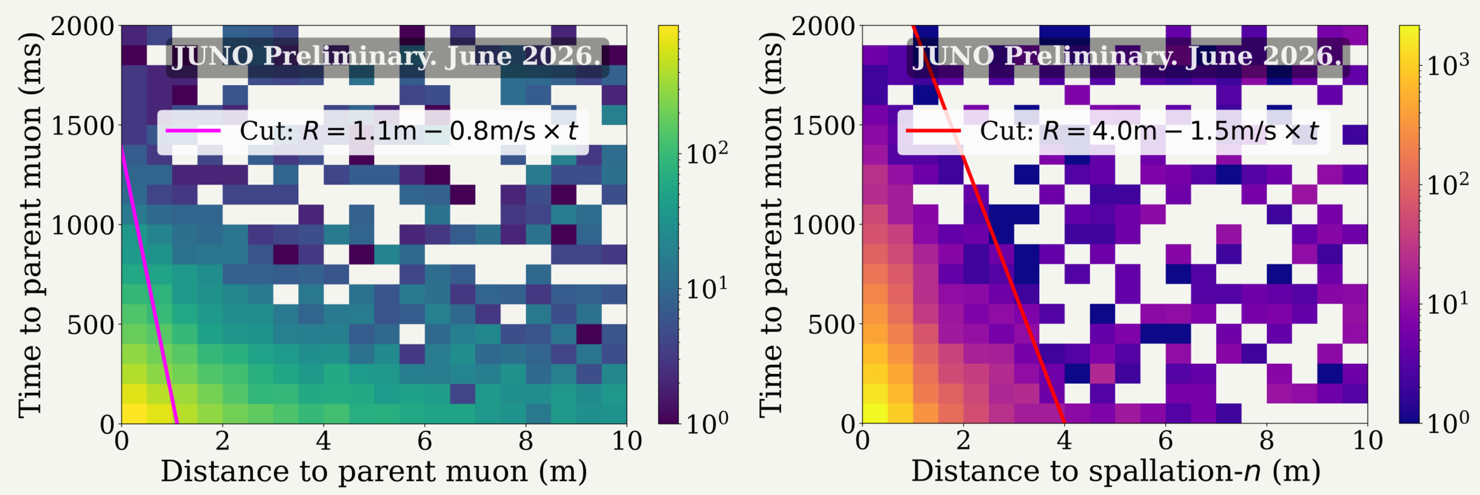
- For muon without neutron, **muon track veto** applied[3]:

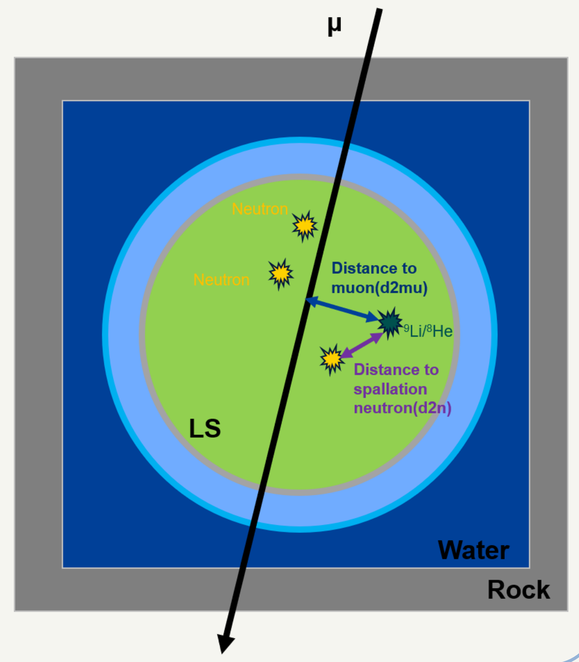
distance to muon track < Cut2 − B × time to muon

- Scan A, B, Cut1, Cut2 to optimize muon veto.




- Final cuts used:
  - Neutron veto: distance to spallation neutron (d2n) < 4m – 1.5m.s$^{-1}$ time to muon.
  - Muon track veto: distance to muon track (d2mu) < 1.1m – 0.8m.s$^{-1}$ time to muon.




## 5.Result

- Rate of $^9$Li/$^8$He before muon veto: 59 ± 1/day
- Rate of $^9$Li/$^8$He after muon veto: **2.0 ± 1.6 /day**
- IBD efficiency of muon veto: **98.33% ± 0.06%**

| Data(Release) | Nov 2025[4] | Current(neutrino 2026) |
|---|---|---|
| $^9$Li/$^8$He rate before muon veto/day | 58.3±2.1 | 58.5±1.5 |
| Neutron veto | • D2n< 4m<br>• Time to muon < 1.2s | D2n < 4m – 1.5m.s-1 time to muon |
| Muon track veto | • D2mu< 1m<br>• Time to muon < 0.5s | D2mu < 1.1m – 0.8m.s-1 time to muon |
| IBD efficiency | 98.20% ± 0.05% | 98.33% ± 0.06% |
| $^9$Li/$^8$He rate after muon veto/day | 4.7±2.6 | 2.0±1.6 |

**Note:**

- **The improvement in the final $^9$Li/$^8$He rate is primarily driven by the optimized spatiotemporal veto. It should be noted that other updates (e.g., reconstruction, hardware) also affect the final value.**
- **Results obtained by different methods is compatible**

**References:** [1] Fengpeng An et al."Neutrino Physics with JUNO" J. Phys. G (2016). [2] Angel Abusleme et al."Sub-percent Precision Measurement of Neutrino Oscillation Parameters with JUNO". 2022 Chinese Phys. C 46 123001. [3]. Xiaoying Lu, Junya Wei. "[Neutrino 2026] Cosmic Muon Track Reconstruction in JUNO". JUNO Document 16532-v7. [4] The JUNO Collaboration. "Measurement of reactor neutrino oscillation with the first JUNO data". Nature 654, 343-348 (2026).