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Vertex Reconstruction of Shower Muons in Large Liquid Scintillator Detectors using PMT Waveforms

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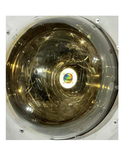
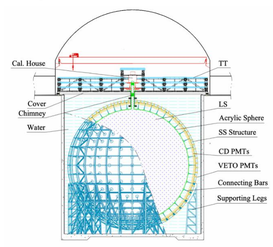
Introduction

- The Jiangmen Underground Neutrino Observatory (JUNO), located in southern China, is a next-generation neutrino experiment[1]. Construction of JUNO is nearing completion, with liquid scintillator filling finished and has started collecting data.





JUNO detector[2]:

- 20k ton LS
- 35k ton water
- 3% energy resolution @1MeV
- 17612 20-inch CD Large PMTs(CD LPMTs)
- 25600 3-in CD Small PMTs
- 2400 20-inch WP Large PMT

JUNO's primary goal is to determine the neutrino mass ordering (NMO) through reactor neutrino oscillation measurements.

IBD

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$+e^-$ (Promated)

+p (2.2MeVdelayed)

β⁻-n Decay Chains of ^{9}Li / ^{8}He

$$^9\mathrm{Li} \rightarrow {}^8Be + n + e^- + \bar{\nu}_e$$

$$^8He \rightarrow {}^7Li + n + e^- + \bar{\nu}_e$$

- Cosmic muons are one of the main background sources in JUNO because they produce isotopes that mimic the inverse beta decay (IBD) signal.
- Cosmogenic isotopes tightly correlated with the muons in time and space, especially abundant in shower regions, posing serious background to signal events.

⟶ Efficient background rejection requires applying tailored reconstruction strategies for shower muon vertex.

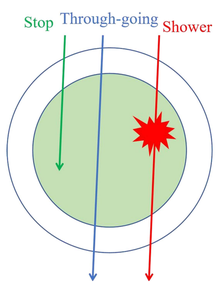
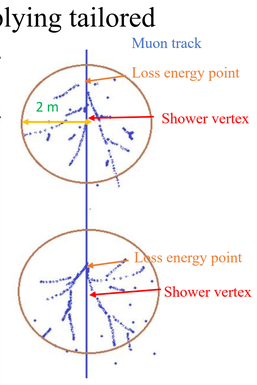
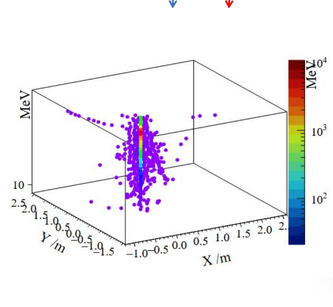


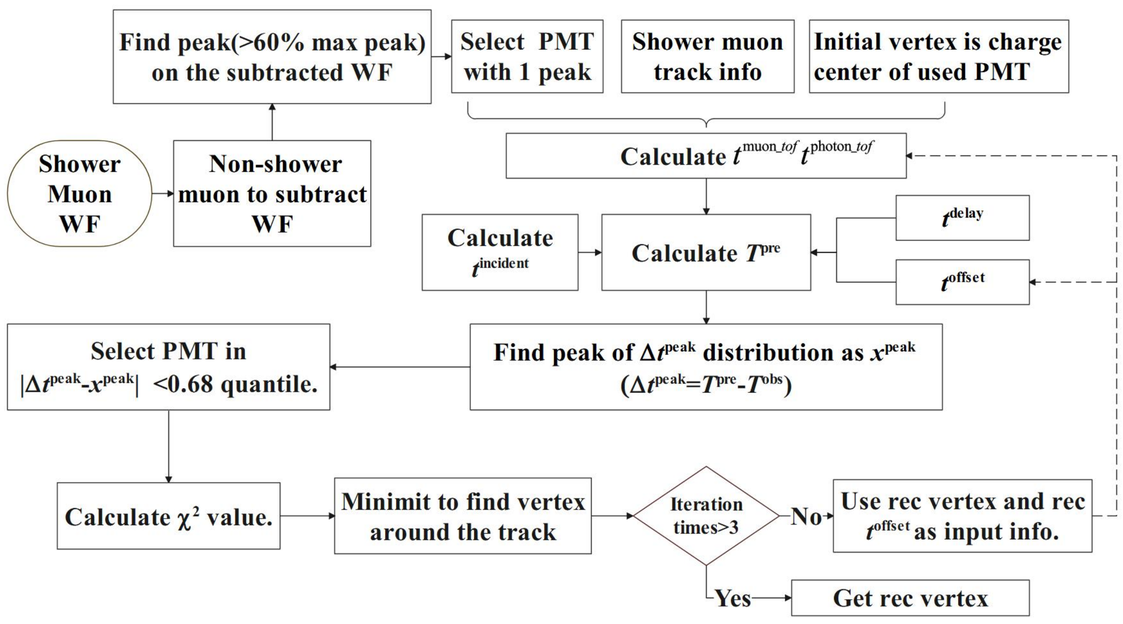
Table 1. The proportion of isotopes produced by different shower energies of single muon and by non-shower muons.

Muon type		Muon ratio	Isotope ratio
Shower muon	All	19.8%	88.2%
	1 - 3 GeV	11.0%	12.2%
	3 - 5 GeV	4.5%	7.0%
	5 - 7 GeV	1.5%	5.1%
	7 - 9 GeV	0.8%	3.6%
	> 9 GeV	2.0%	60.3%
Through-going		76.3%	10.8%
Stop		3.9%	1.0%



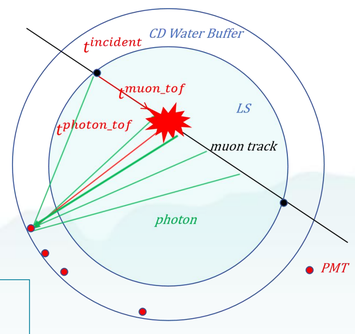


Methods



$$T^{pre} = t^{incident} + t^{muon\_tof} + t^{photon\_tof} + t^{delay} + t^{offset}$$

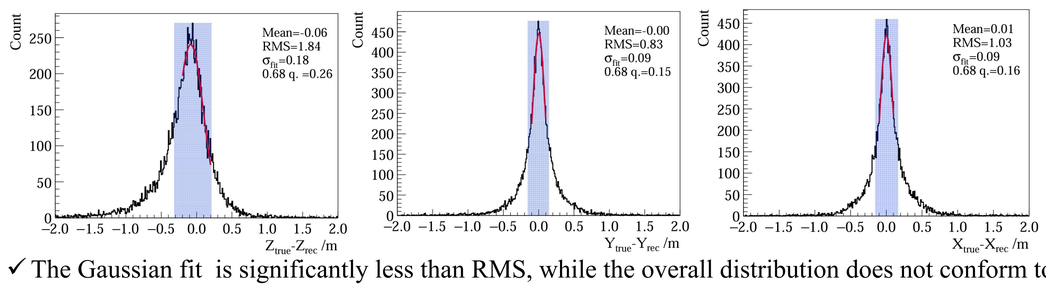
$$\chi^2 = \sum_{i}^{pmt} \frac{(T^{pre} - T^{obs})^2}{{\sigma_{tts}}^2}$$



- $t^{incident}$: The time of muon incident into CD from the earilst PMT
- t^{muon_tof} : Time of flight of muon
- t^{photon_tof} : Time of flight of photons considering effective refractive index
- t^{delay} :The delay time caused by the PMT readout electronics and TT (transit time) of PMT, can be calibrated using laser source
- t^{offset} : Describing the rise time from FHT to peak of waveform
- σ_{tts} : TTS of PMT

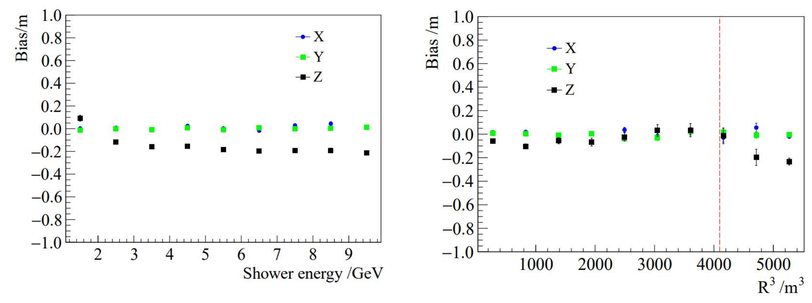
Results

Single shower vertex reconstruction result:



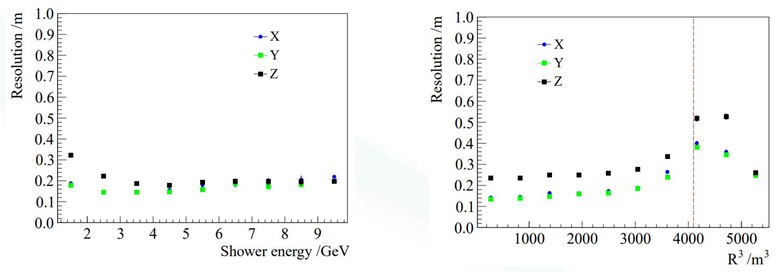
✓ The Gaussian fit is significantly less than RMS, while the overall distribution does not conform to a Gaussian distribution, so we use 0.68 quantile as resolution.

✓ The reconstruction resolution (68 % quantile) of x and y is about 0.16 m and 0.15 m. The reconstruction resolution of z is poor, and about 0.26 m.



✓ The bias of x/y is smaller than that of z. The bias of x/y does not vary significantly with the shower energy and vertex position.

✓ The bias of z becomes worse as the shower energy increases. The reason is that when the shower energy is larger, the shower forward-peaking is more pronounced, which makes recon. more difficult.



✓ The reconstruction resolution (68 % quantile) of x and y is less than 0.4 m. The reconstruction resolution of z is poor, and less than 0.6 m.

✓ The reconstruction performance is relatively poor when the shower energy less than 2 GeV and shower vertex at the edges of the detector.

Conclusions

✓ The muon shower characteristic has been presented and study the isotopes yield contributed from shower.

✓ Shower vertex was reconstructed based on the waveform information.

- Eliminate the muon track impact by subtracting the waveform from track component.

✓ The reconstruction performance:

Single shower vertex within 16 m after considering muon track reconstruction performance:

- Resolution (68% quantile) <0.4 m for z and < 0.3 m for x/y of shower vertex.

Bibliography

1. **JUNO Collaboration. "Potential to Identify the Neutrino Mass Ordering with Reactor Antineutrinos in JUNO". 2025 Chinese Phys. C 49 033104.**
2. **J. Collaboration, Juno physics and detector, Progress in Particle and Nuclear Physics 123,103927 (2022).**