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MeV-scale Cherenkov Event Reconstruction and Directional Indication of Solar Neutrinos in the JUNO Water Phase

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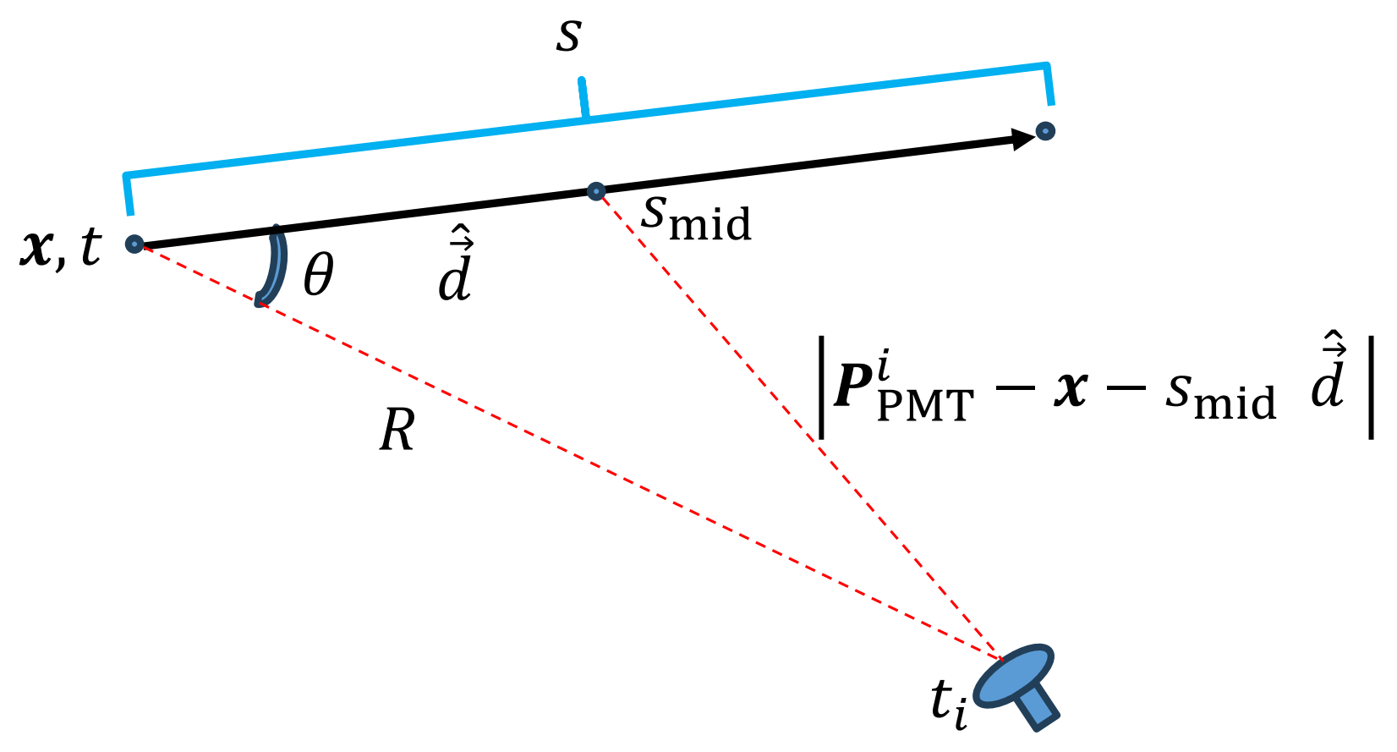
Likelihood Reconstruction and Optical Model

A maximum-likelihood method is developed to reconstruct the **vertex**, **direction**, and **energy-related observables** of MeV-scale events in the JUNO water phase. The fit parameters are the event time t_0, the interaction vertex (x, y, z), and the particle direction (p_x, p_y, p_z). PMT first-hit timing and photoelectron (PE) expectations are combined in a unified likelihood[1]:

$$\mathcal{L}(\boldsymbol{x}; q, t) = \prod_{i\in\{q>0\}} \left[P_{\pi,i}\left(0 \mid \mu_{i,\underline{t}}^{t_i}\right) f_t(t_i)\, P_{\pi,i}\left(N_i - 1 \mid \mu_{i,t_i}^{\overline{t}}\right)\right] \times \prod_{j\in\{q=0\}} P_{\pi,j}\left(0 \mid \mu_j\right).$$

Here, N_i is the detected number of PEs at the i-th PMT, μ_j is the expected number of PEs at the j-th PMT, and $\mu_{i,\underline{t}}^{t_i}$ and $\mu_{i,t_i}^{\overline{t}}$ are the expected PE counts in the time windows $[\underline{t}, t_i]$ and $[t_i, \overline{t}]$, respectively.



Time Residual

Direct and indirect light contributions are included in the optical model. The time residual is defined as

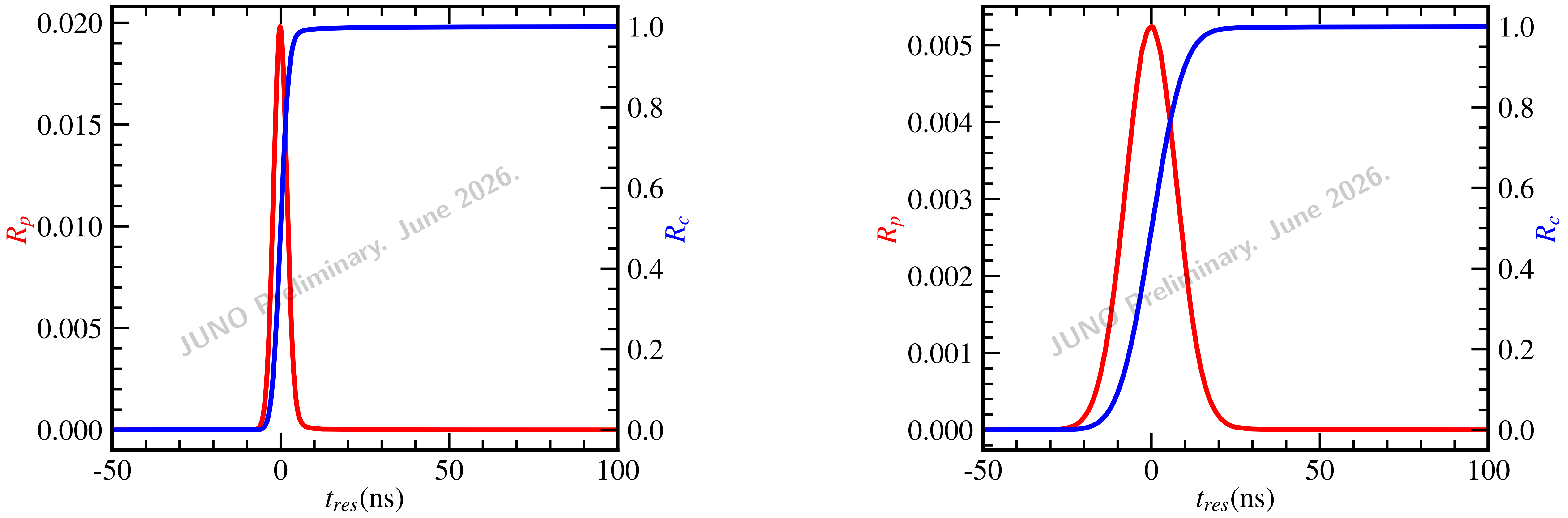
$$t_{\text{res},i} = t_i - t_0 - s_{\text{mid}}/c - \frac{\left|\boldsymbol{P}_{\text{PMT}}^{i} - \boldsymbol{x} - s_{\text{mid}}\hat{\boldsymbol{d}}\right|}{c_w},$$

where c is the speed of light in vacuum and c_w is the assumed speed of light in water. Dark noise is modeled as a **homogeneous Poisson process**. The detector operated as a large water Cherenkov detector during the commissioning water phase of JUNO[2, 3]:

$$f_t(t_i) = \mu_c R_p(t_{\text{res},i}) + b.$$

Time Response Modeling

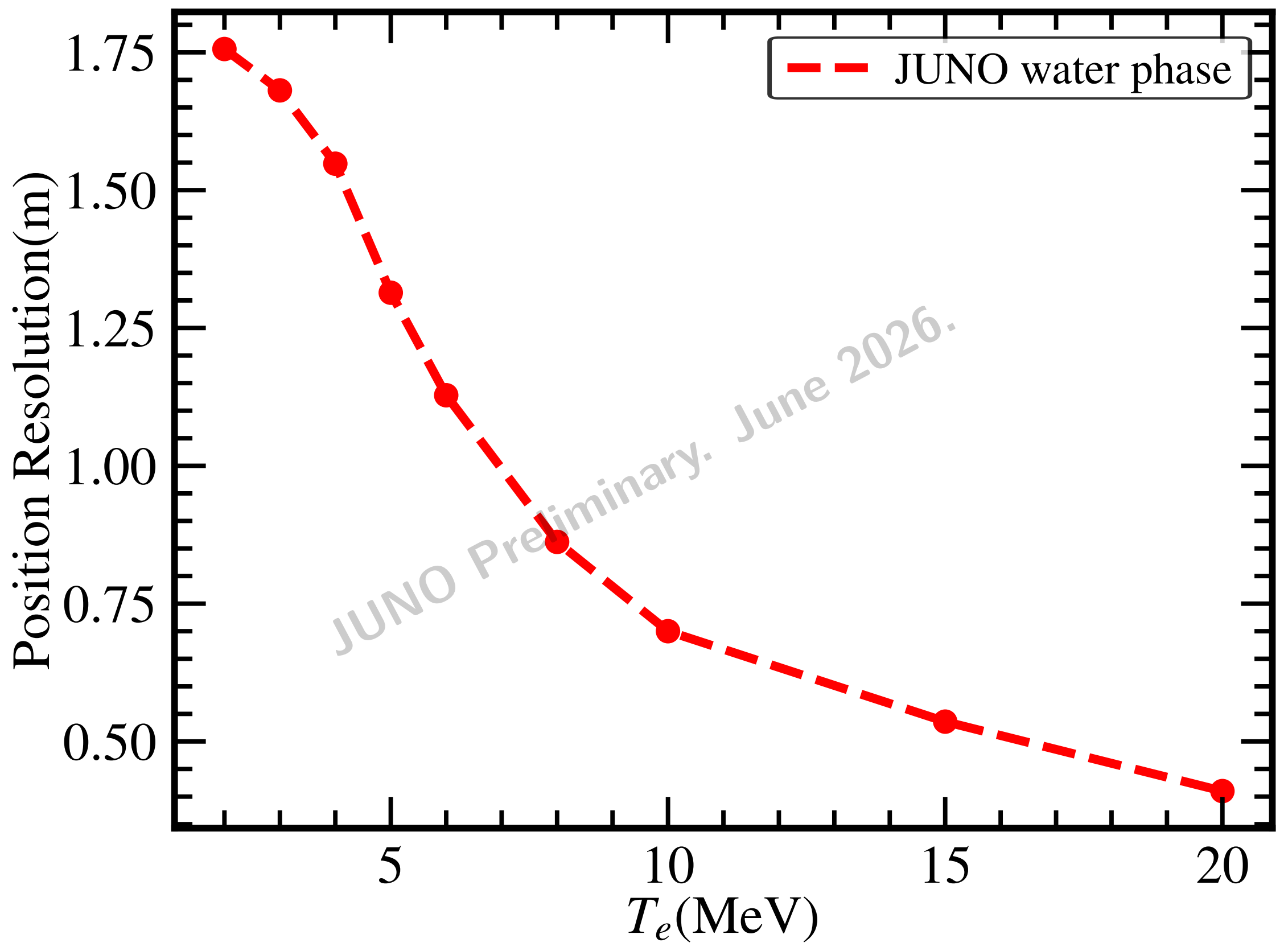
The residual-time intensity function is constructed from simulation and folded with PMT transit-time spread to describe the first-hit timing response in the likelihood. The broad timing response of MCP PMTs significantly worsens the time residual distribution and must be modeled carefully in reconstruction.

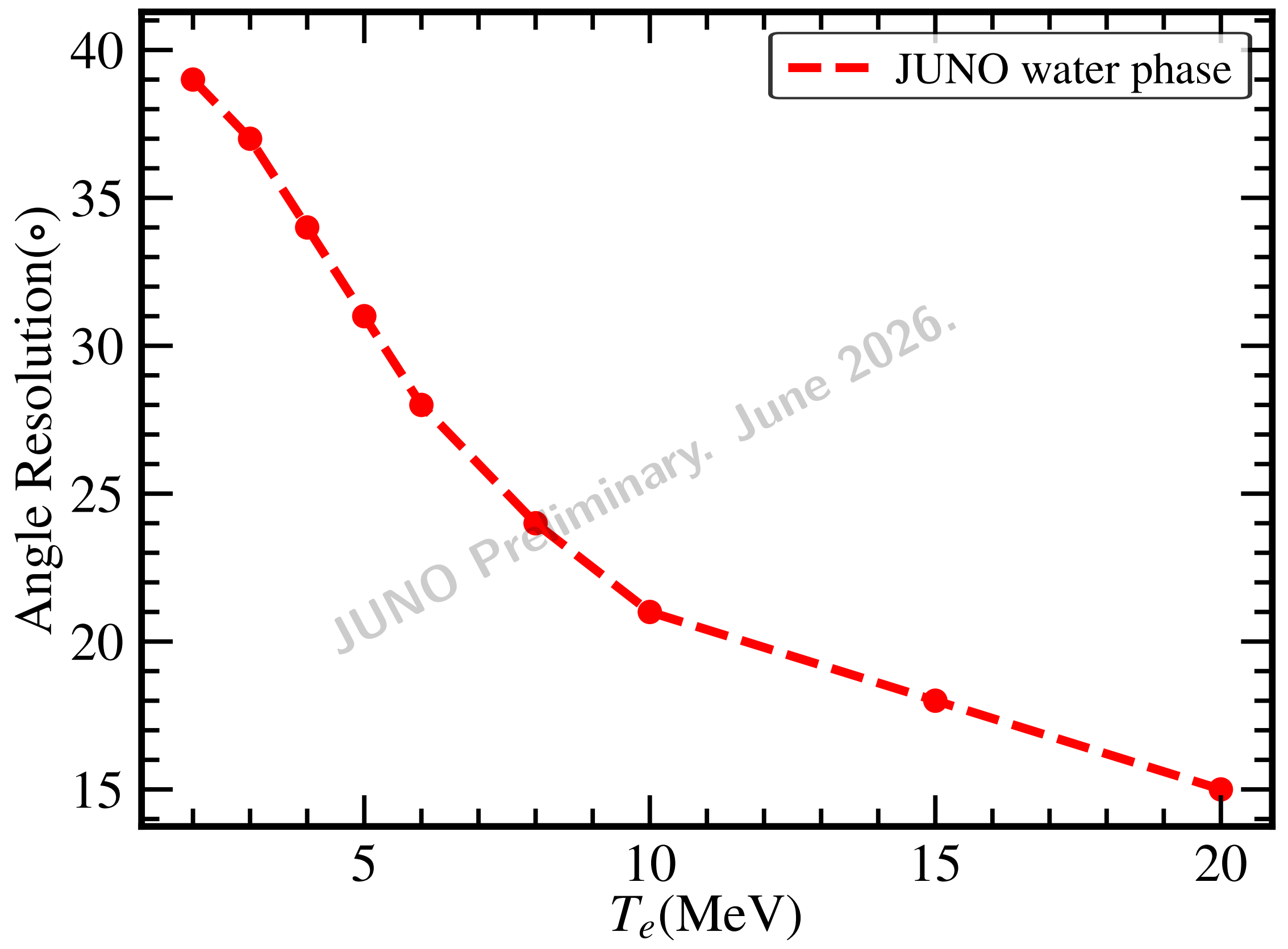


Residual-time intensity function and CDF after TTS smearing for Dynode PMTs (left) and MCP PMTs (right).

Simulation Performance

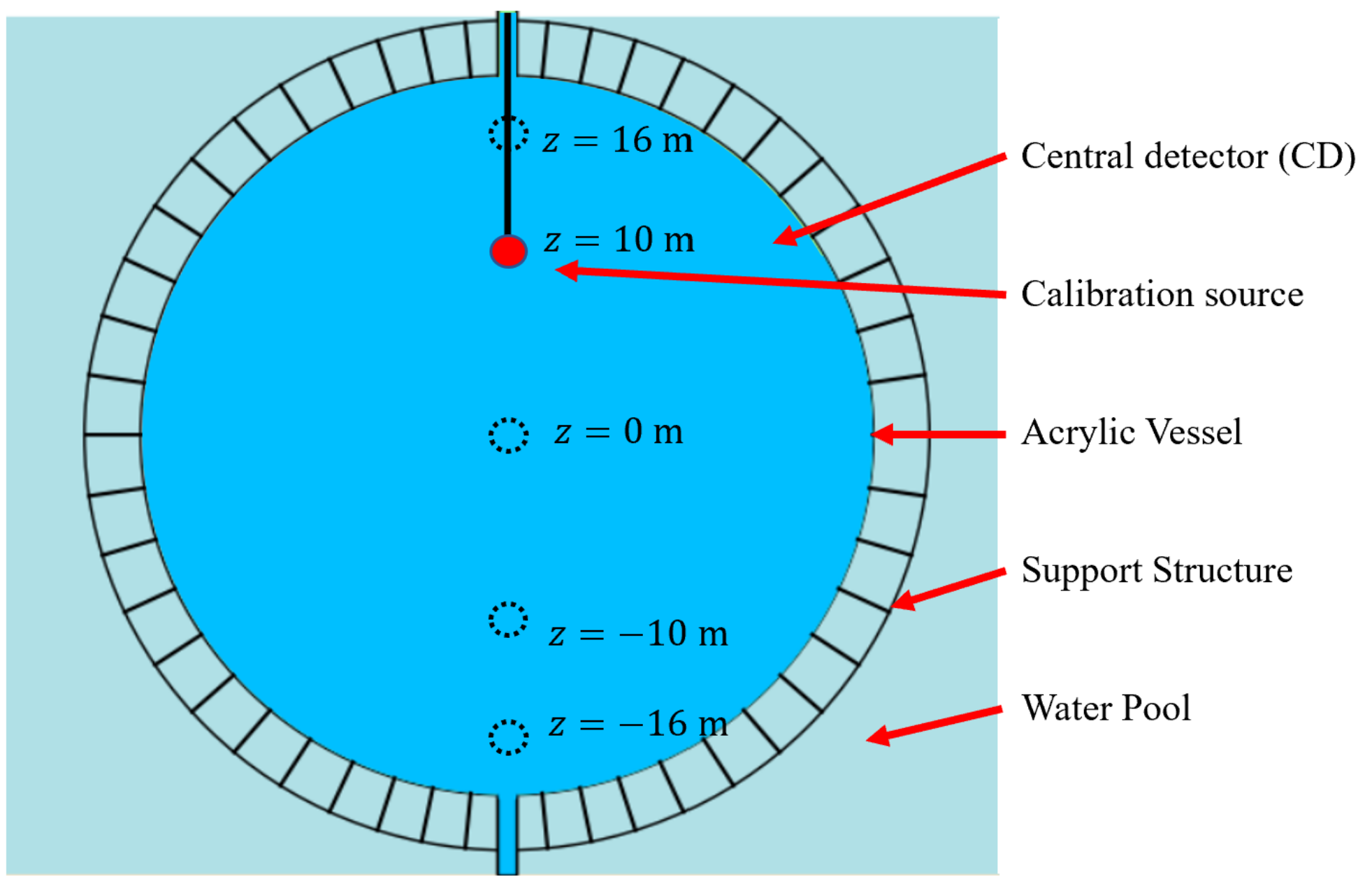
Electrons from 2 to 20 MeV are simulated uniformly in the detector. Despite the low Cherenkov photon yield and strong noise contamination, the reconstruction achieves **meter-level vertex resolution** and effective **direction reconstruction** at MeV scale.



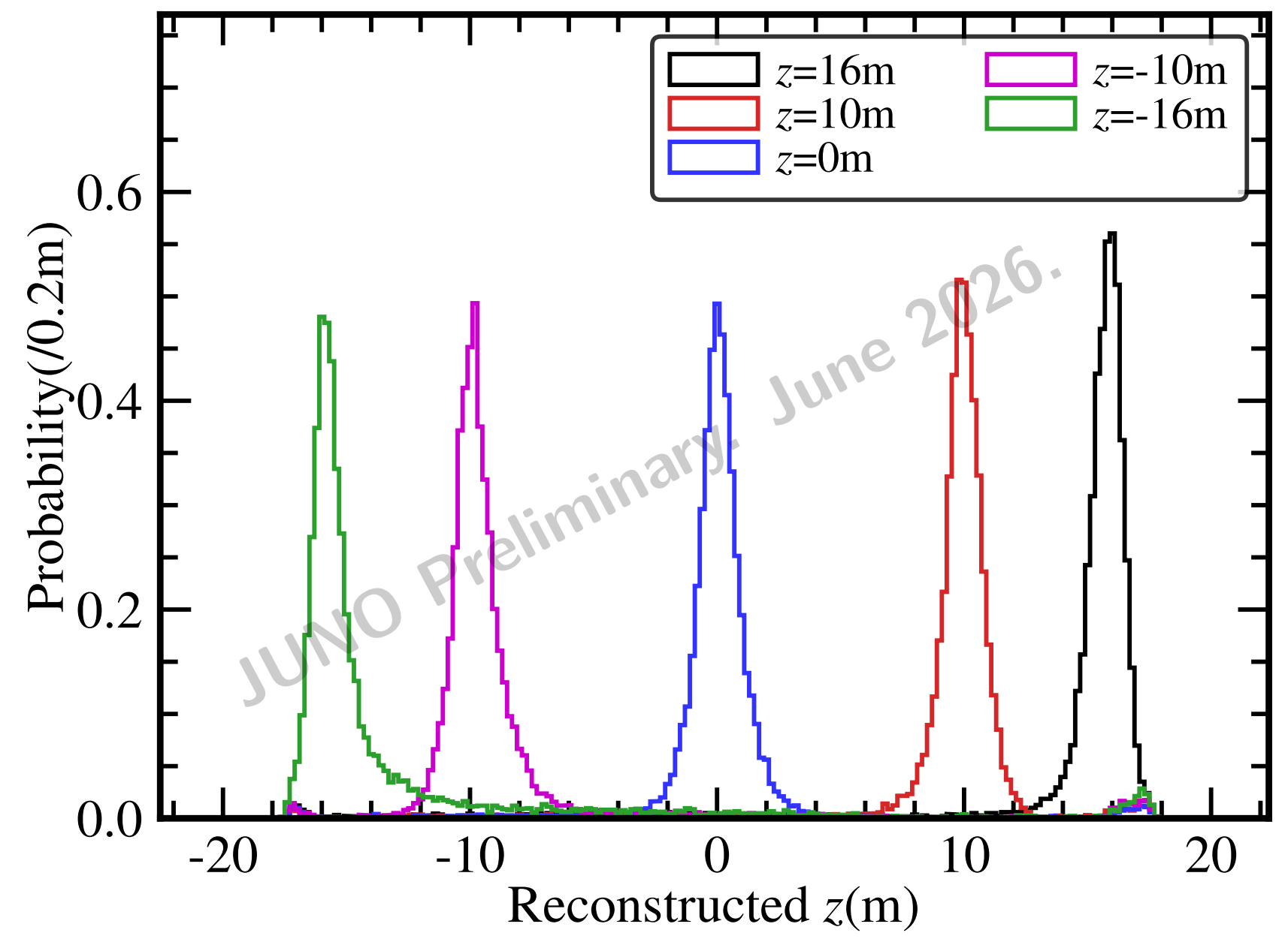


Calibration Validation

AmBe and AmC neutron source data are used to validate reconstruction in real data. Prompt γ events are selected through neutron coincidence tagging, providing clean low-energy samples for detector-response studies.

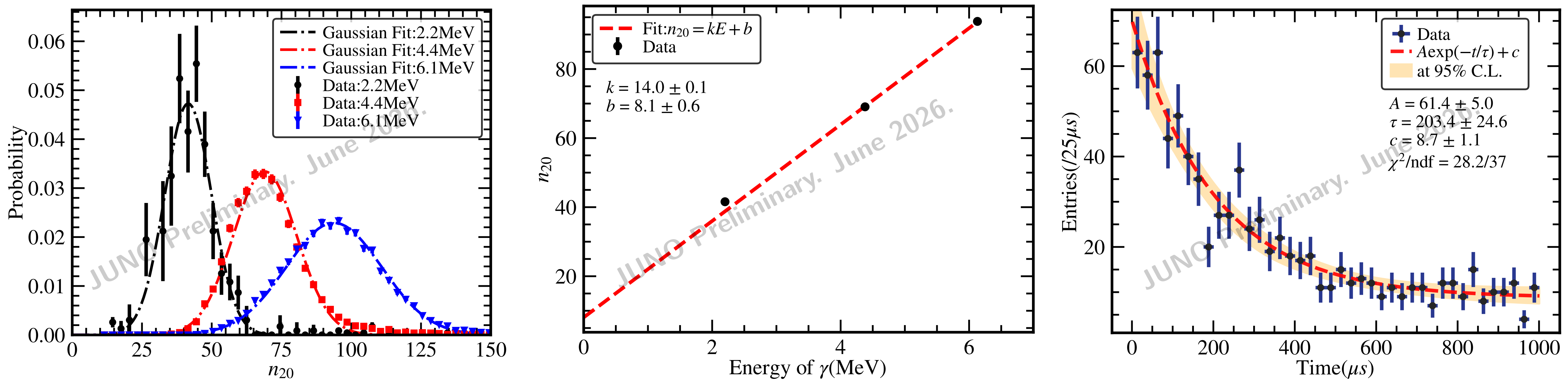


The reconstructed z-position distributions of prompt AmBe events show clear peaks at the expected source locations, demonstrating stable low-energy vertex reconstruction.



Distinct peaks from AmBe, AmC, and neutron-capture γ events establish the energy scale.

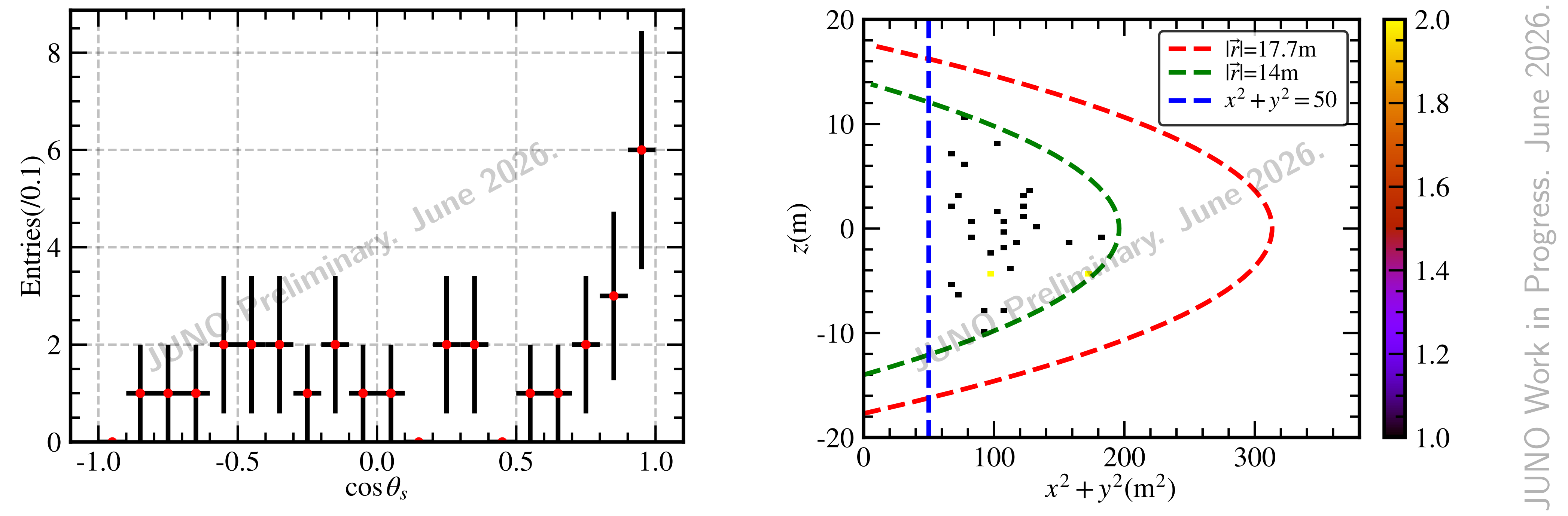
n_{20} represents the count of residual time distribution within the range of $[-20, 20]$ ns, which serves as the primary metric for energy.



In-situ Validation with Solar Neutrino Candidates

After event reconstruction and selection, the angular distribution relative to the Sun shows a **clear excess at small solar angle**. This provides the key **in-situ validation** of the reconstruction algorithm and demonstrates that JUNO can recover MeV-scale directional information during its water-phase prior to detector filling.

6.50 ± 2.54 events **2.42σ**



solar-angle distribution, and candidate position distribution.

Conclusion

A complete **likelihood-based reconstruction chain** was developed for MeV-scale Cherenkov events in the JUNO water phase. The method explicitly handles **low light yield**, **high dark noise**, and **broad PMT timing response**. Source calibration validates the reconstructed vertex, energy-related observables, and directional information, while the observed directional excess correlated with the Sun position provides a direct **in-situ** demonstration of the method's effectiveness.

References

[1] Xuewei Liu, Wei Dou, Benda Xu, et al. First-principle event reconstruction by time-charge readouts for TAO. *Eur. Phys. J. C*, 85(4):438, 2025.

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[3] Angel Abusleme et al. Initial performance results of the JUNO detector. 11 2025.