Event vertex reconstruction in JUNO

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The JUNO detector [1]

Central detector (CD): 20 kton of **liquid scintillator** (LAB)
~43000 PMTs (**~78% photocoverage**)

Main goal: **Neutrino Mass Ordering determination** with reactor $\overline{\nu}_e$

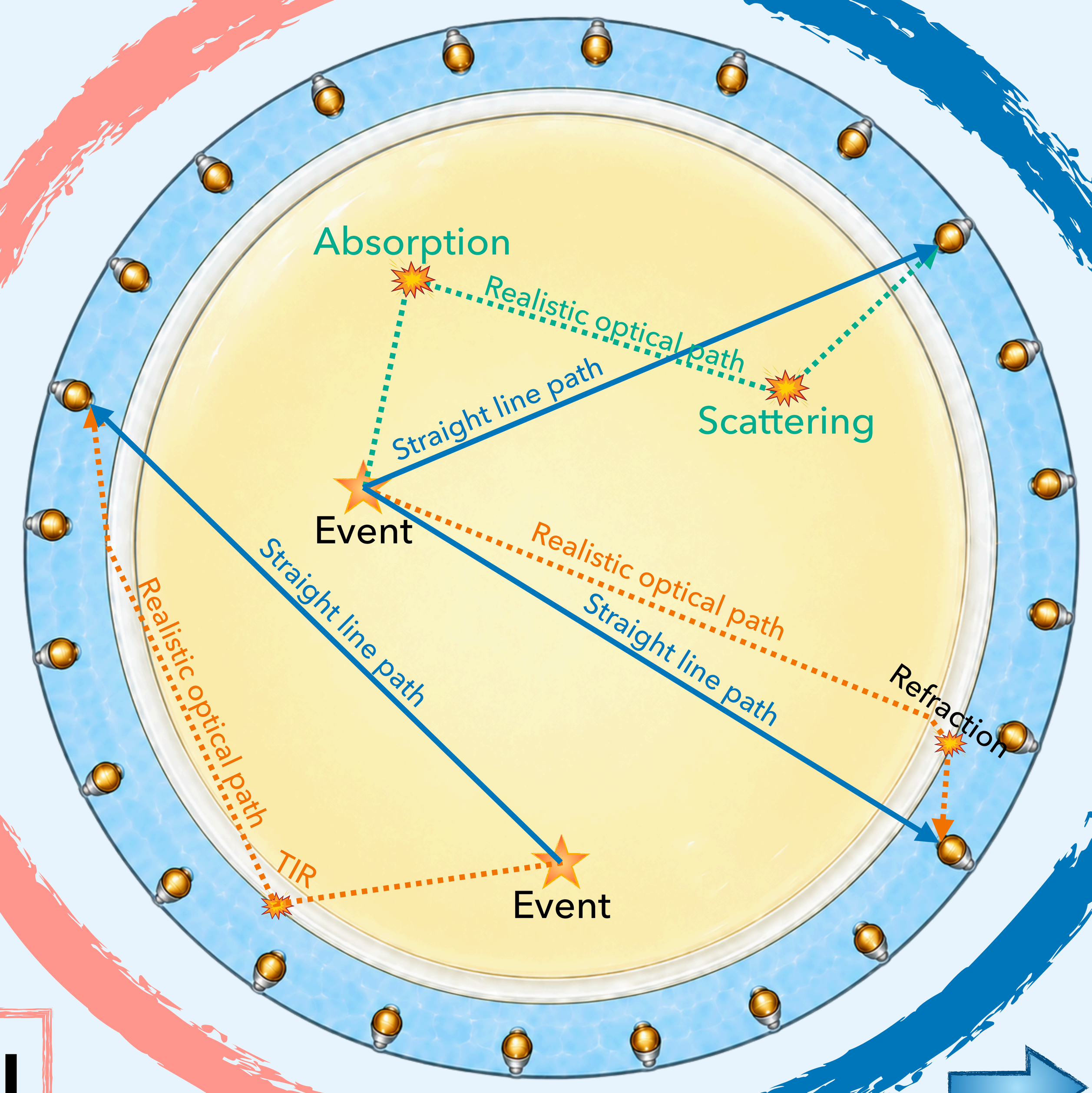
Main requirement: **Excellent energy resolution** (~3% @ 1 MeV)

Large detector volume (R = 17.7 m)

→ position dependent energy response

→ influence on energy resolution

→ **Precise vertex reconstruction is crucial**



Methods and challenges

Proxies for event reconstruction in liquid scintillator detector:

- Collected **charge** distribution (Q_i) (Q)
- **Hit time** after time-of-flight correction (residual time t_{res}) (T)

$$t_{res}(\vec{r}_{event}, \vec{r}_{PMT}) = t_i - \mathrm{ToF}_i - t_0 \qquad \mathrm{ToF}_i = \frac{|\vec{r}_{event} - \vec{r}_{PMT}|}{v_g(n(\lambda))}$$

arrival time at PMT — time-of-flight — trigger time

Photons don't travel following a simple straight line because of the following effects:

- Absorption and reemission, and Rayleigh scattering
- Reflection, refraction, and Total Internal Reflection (TIR) (due to interface between media with different refractive indeces)

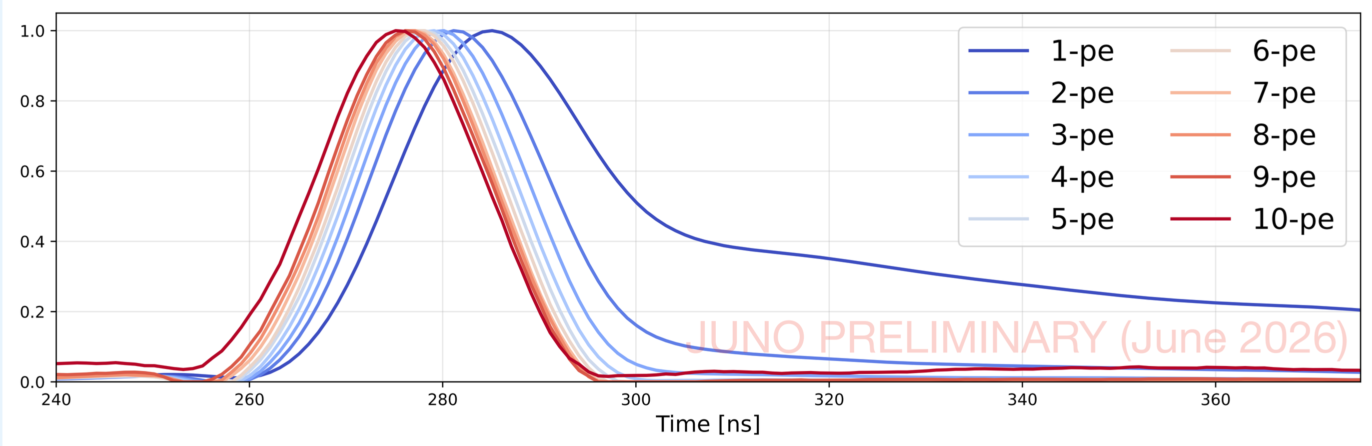
→ **This must be taken into account with effective parameters**

Reconstruction approaches

(T) ☑ **VTREP:** look for $\vec{r}_{event}$ where t_{res} distribution is sharpest (by exponential weighting in the time domain) within ±30 ns around the peak (mitigate dark noise and light propagation effects) [2]

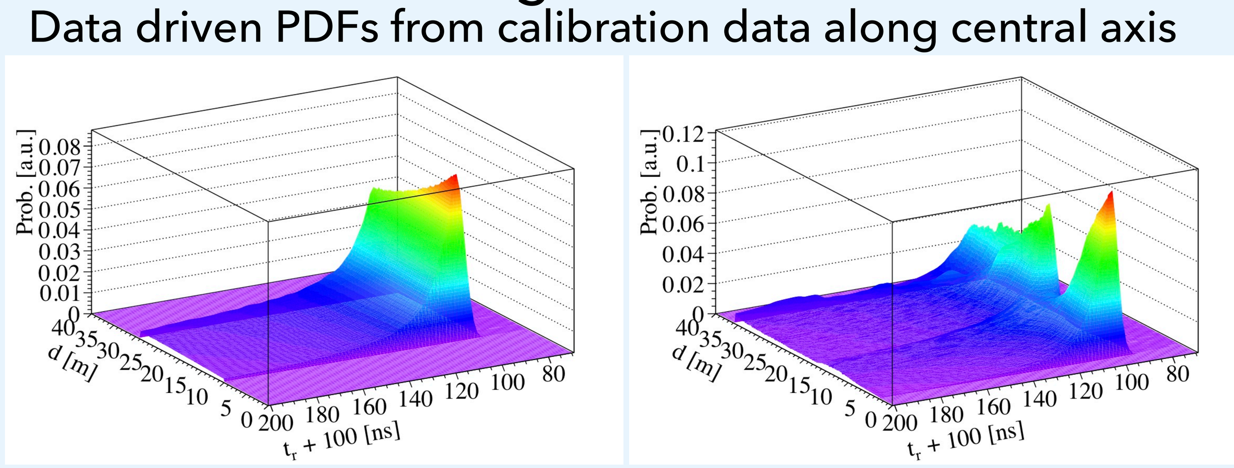
(T) ☑ **JVertex:** maximum-likelihood estimation with first hit times (Dynode PMTs only) [3]

Data driven PDFs from calibration data according to detected photon multiplicity



(T)(Q) ☑ **OMILREC:** combined time and charge maximum-likelihood estimation [4]

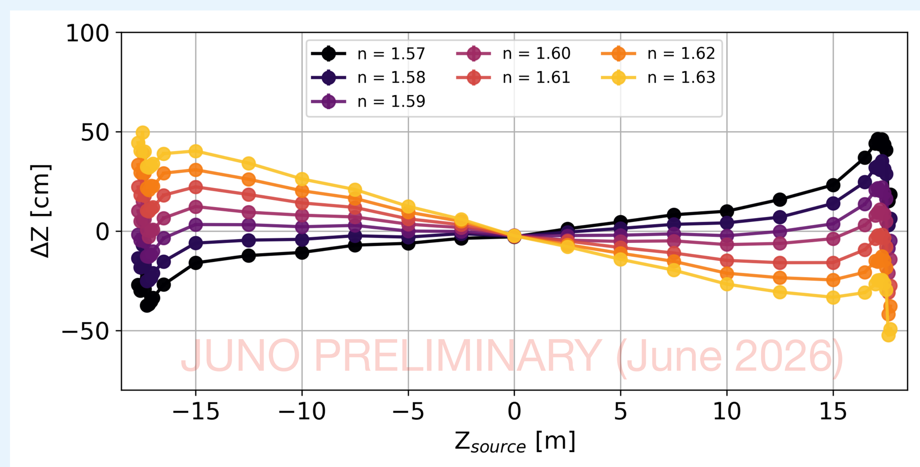
Data driven PDFs from calibration data along central axis



Detector center — TIR region (R > 15 m)

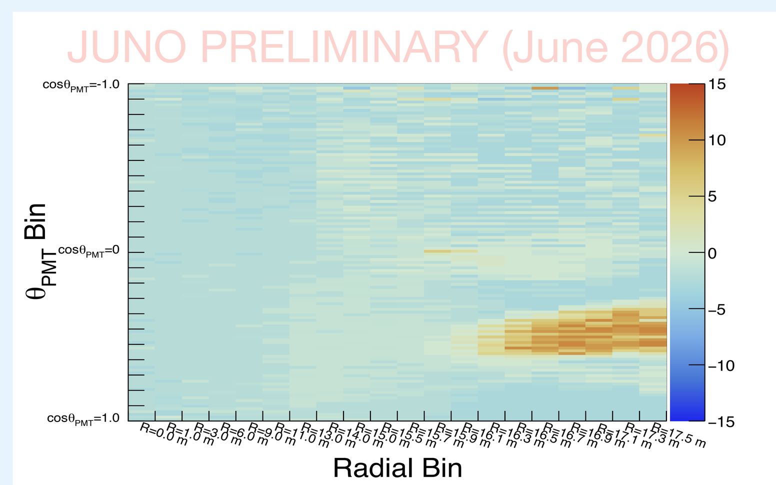
Effective parameters

☑ **Effective refractive index (n_{Eff})**



n_{Eff} tuned to minimize light propagation outward bias

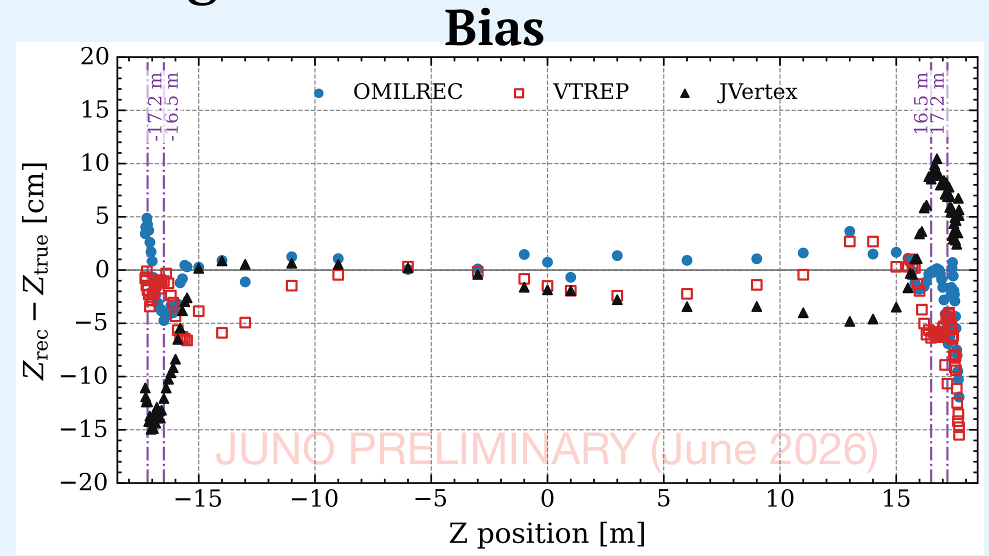
☑ **ToF data-driven correction**

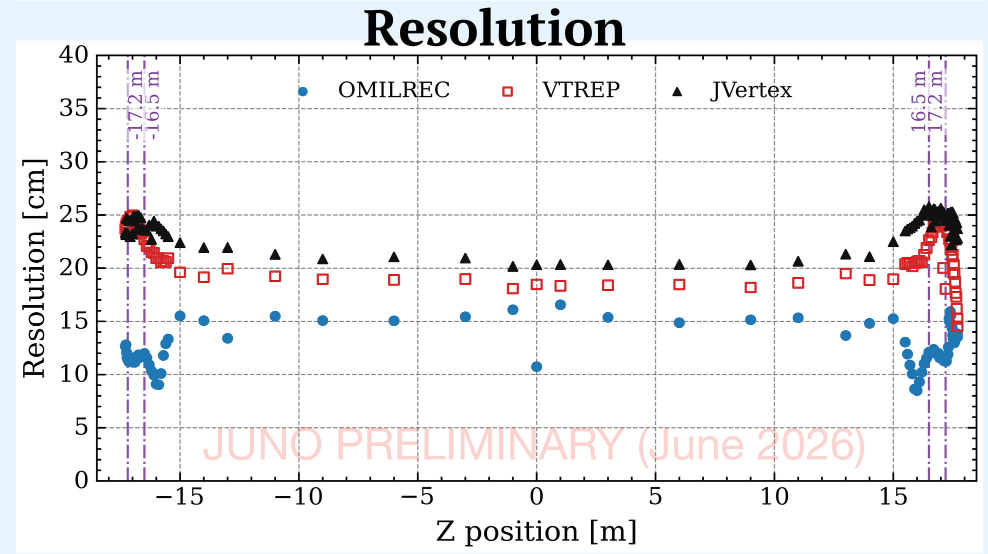


Addittional correction for light propagation effects in VTREP

Performance

Validation with dedicated calibration campaigns along the detector central axis





Conclusions

Vertex reconstruction in JUNO is validated by three independent methods, showing stable performance with a maximum of ~15 cm bias and 15/20 cm spatial resolution across the full 35.4 m detector volume.

[1] A. Abusleme et al. JUNO physics and detector. Prog. Part. Nucl. Phys., 123:103927, 2022
[2] A. Takenaka et al. Neutron source-based event reconstruction algorithm in large liquid scintillator detectors. Eur. Phys. J. C, 85(10):1097, 2025
[3] JUNO Collaboration, Initial performance results of the JUNO detector, Chin. Phys. C
[4] G. Huang, W. Jiang, L. Wen, Y. Wang, and W. Luo. Data-driven simultaneous vertex and energy reconstruction for large liquid scintillator detectors. Nucl. Sci. Tech., 34(6):83, 2023.