Sub-GeV events energy reconstruction with 3-inch PMTs in JUNO

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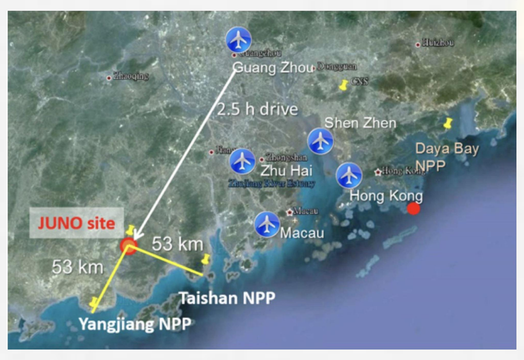
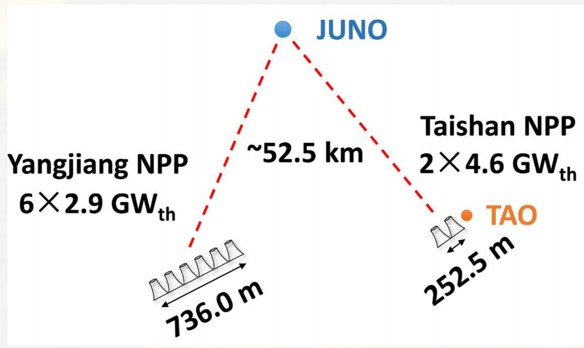
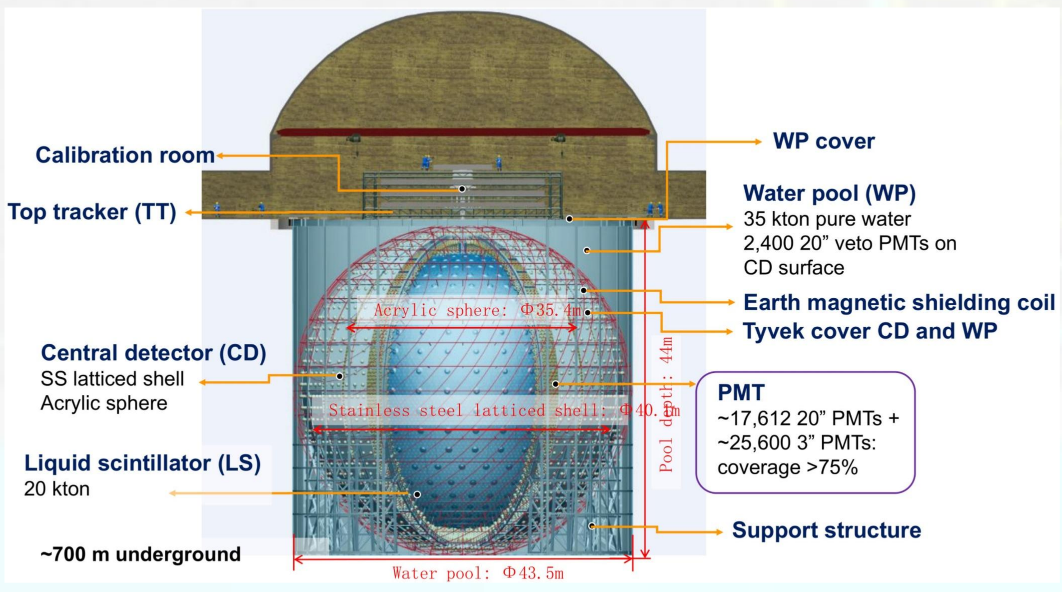
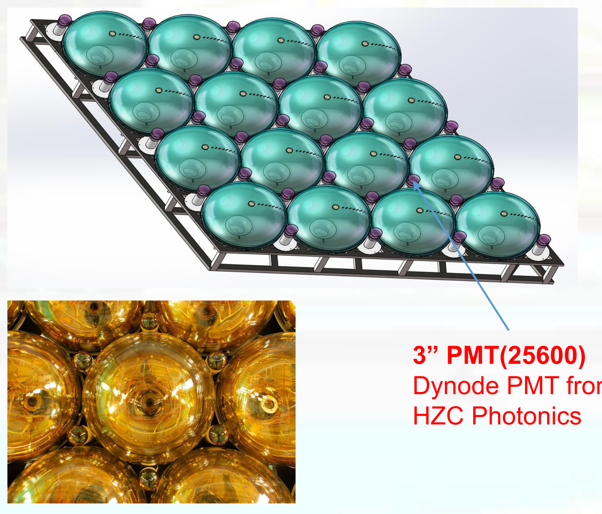
JUNO Experiment and Detector



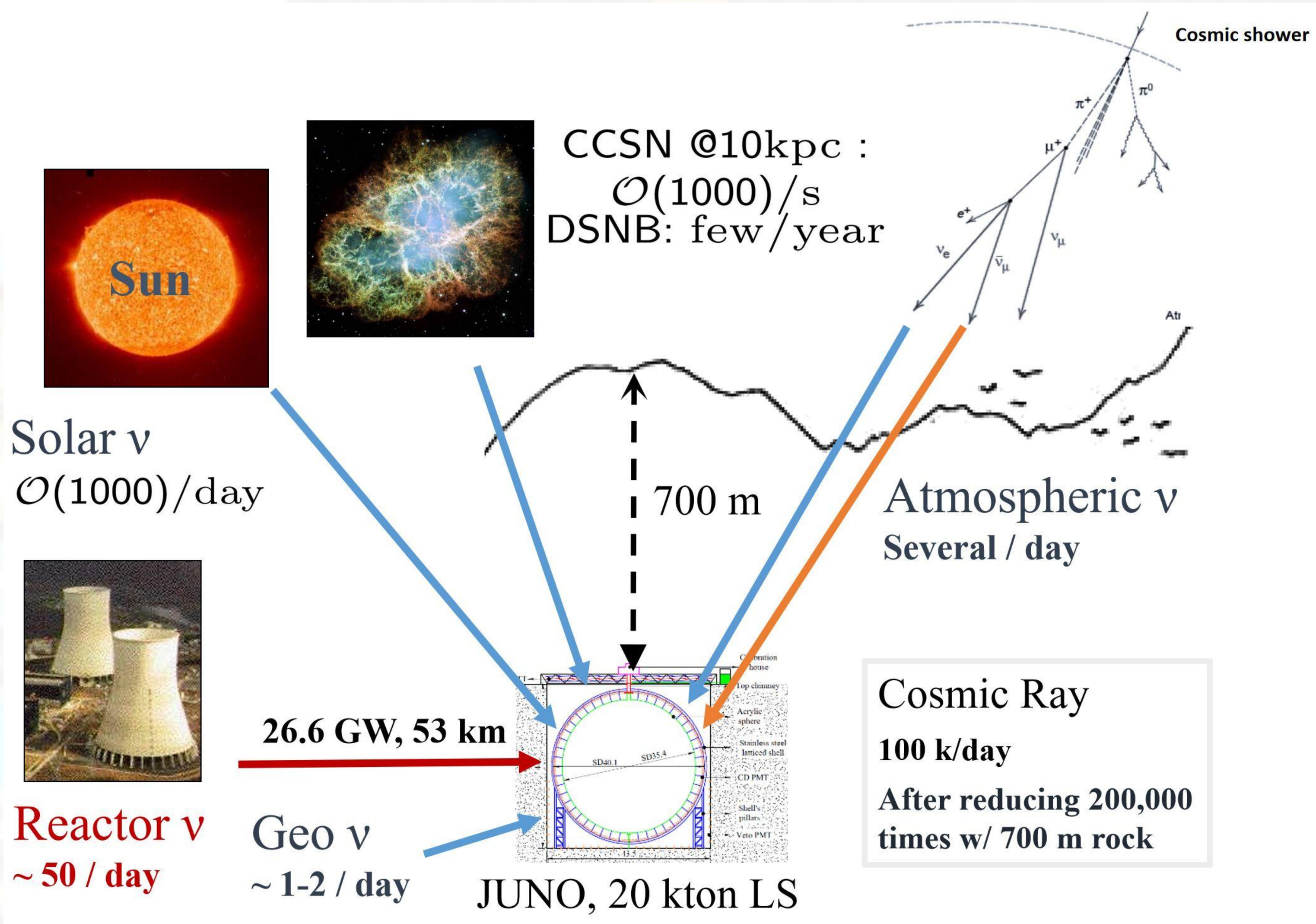






- 25,600 3-inch "small" and 17,612 20-inch "large" photomultiplier tubes (SPMTs and LPMTs, respectively) detect the light produced by neutrino interactions in the CD.

Multiple Physics Purpose in JUNO



- It is imperative to develop reconstruction algorithms tailored to the energy ranges of diverse physical detection objects.

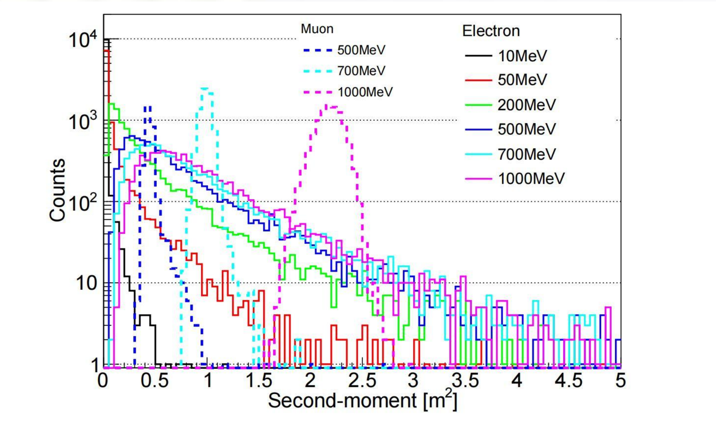
Detection Characteristics of Sub-GeV Events in JUNO

Energy deposition

- It is cluster-like rather than point-like.
- Introduce the second moment S to describe the shape of events

$$S = \frac{\sum_{\alpha=1}^{N_E} E_\alpha \times [\vec{r_\alpha}(x_\alpha, y_\alpha, z_\alpha) - \vec{r}(x,y,z)]^2}{\sum_{\alpha=1}^{N_E} E_\alpha}$$

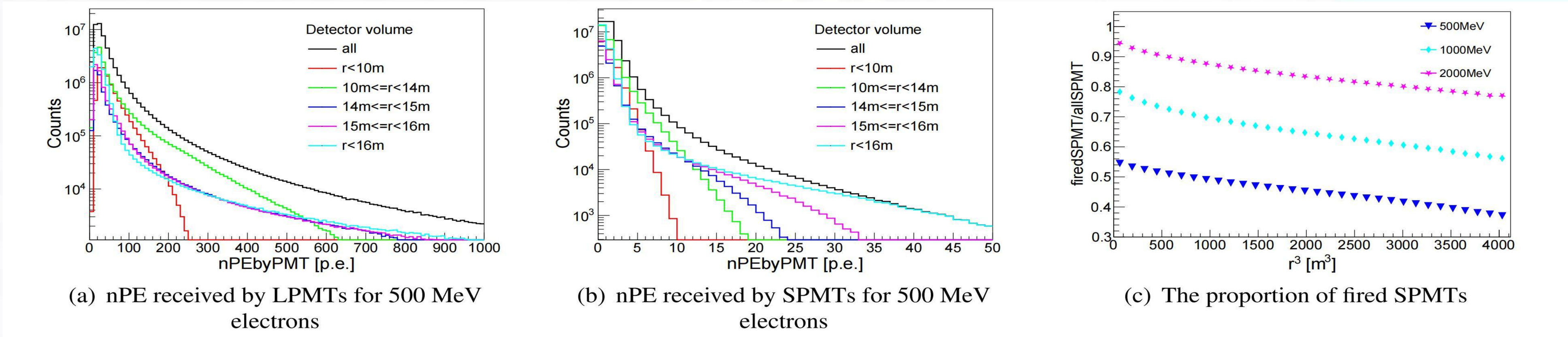
where N_E is the number of secondary energy depositions for the event. E_α and $\vec{r_\alpha}(x_\alpha, y_\alpha, z_\alpha)$ are the energy deposition and position in the α^{th} secondary energy deposition, respectively. $\vec{r}(x,y,z)$ is the energy-deposit center for the event, which is the weighted average of secondary energy deposition



Distributions of the second-moment for electrons with different kinetic energies.

Charge dynamic range of PMTs

- LPMT (20 inch):
  - Most LPMTs will receive tens or even hundreds of PEs.
  - Accurate charge reconstruction is a challenge
- SPMT (3 inch):
  - About half of the SPMTs are unfired



(a) nPE received by LPMTs for 500 MeV electrons (b) nPE received by SPMTs for 500 MeV electrons (c) The proportion of fired SPMTs

The distribution of nPE received by LPMTs (a) and SPMTs (b) for 500 MeV electrons deposited their kinetic energies in the LS. (c) The proportion of fired SPMTs for electrons deposited their kinetic energies at different locations.

Method of Energy Reconstruction

Basic idea: Only use the firing information (fired or unfired) of 25600 SPMTs

$$P_{\text{unfired}}(\mu_i^{\text{true}}) = P(q_i < q_i^{\text{threshold}} | \mu_i^{\text{true}}) = \text{Poisson}(k_i = 0 | \mu_i^{\text{true}}) + P_{\text{threLoss}}(\mu_i^{\text{true}}),$$

$$P_{\text{fired}}(\mu_i^{\text{true}}) = P(q_i \geq q_i^{\text{threshold}} | \mu_i^{\text{true}}) = 1 - P_{\text{unfired}}(\mu_i^{\text{true}})$$

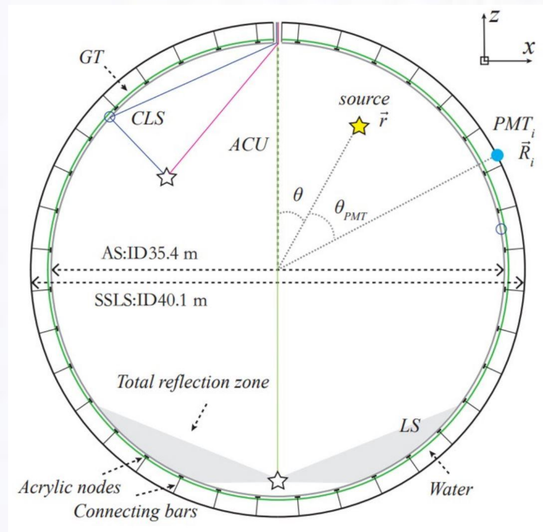
where q_i is the reconstructed charge of the i^{th} SPMT, μ_i^{true} ($\mu_i^{\text{true}} = \mu_i^{\text{phy}} + \mu_i^{\text{dn}}$) is the mean value of the Poisson distribution, which consists of two components:

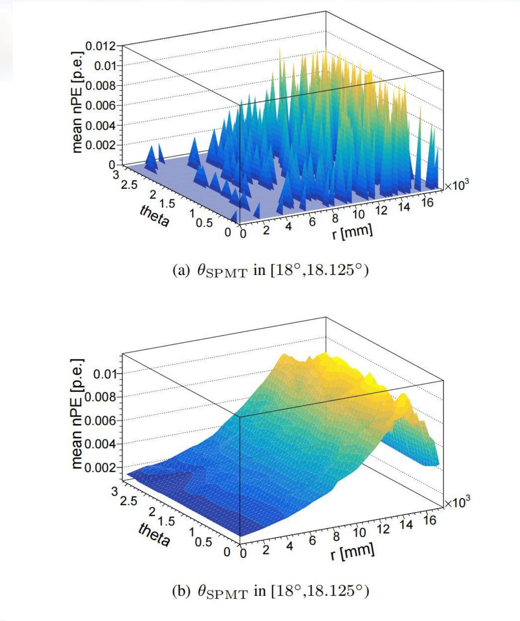
(1) μ_i^{phy} caused by the visible energy of physics events;
(2) μ_i^{dn} introduced by the dark count (DR$_i$) of the i^{th} SPMT, and it can be calculated by $\mu_i^{\text{dn}} = \text{DR}_i \times t$ in a time window of t;

$P_{\text{threLoss}}(\mu_i^{\text{true}})$ is the probability of $q_i < q_i^{\text{threshold}}$ (0.3 PEs in this study) in the case of $k_i > 0$, calculated as following:

$$P_{\text{threLoss}}(\mu_i^{\text{true}}) = \sum_{k_i=1}^{n} [\text{Poisson}(k_i|\mu_i^{\text{true}}) \times \int_0^{q_i^{\text{threshold}}} \text{Gaus}(q_i | g_i, \sigma(g_i))\, dq_i]$$

where $g_i = S_i^{\text{gain}} \times k_i$ and $\sigma(g_i) = \sqrt{g_i} \times \sigma_i^{\text{spe}}$, with n indicates the case of multiple PEs, S_i^{gain} corresponds to the ratio between the real SPMT gain and the normal SPMT gain (3×10^6) in JUNO, σ_i^{spe} denotes spe resolution of the i^{th} SPMT. In real detection, S_i^{gain}, σ_i^{spe} and DR$_i$ can be obtained from PMT calibration.





Example of calibration map for one θ_{SPMT} group whose θ_{SPMT} values from 18° to 18.125°.

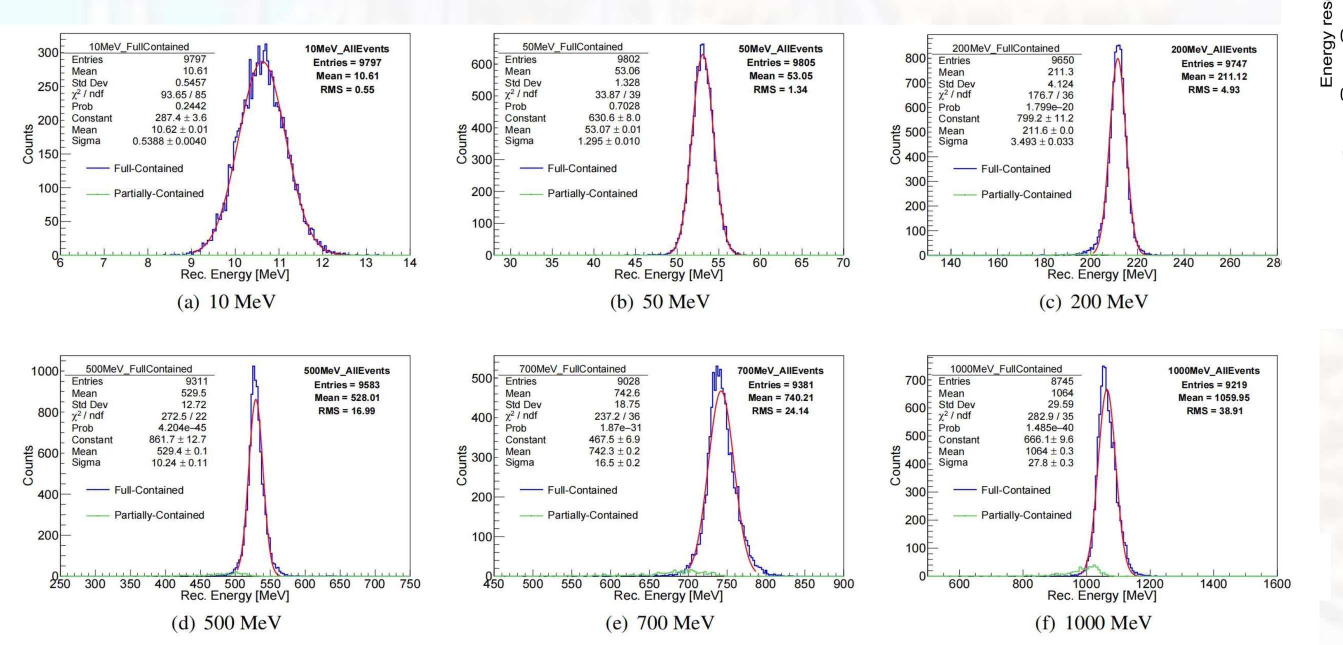
- The relationship between $\mu_i^{\text{phy}}(\mu_i^{\text{phy\_source}})$ and the relative position can be determined using the calibration data.
- The relationship between the event's visible energy E_{vis} and μ_i^{phy} for the i^{th} SPMT can be described as:

$$\mu_i^{\text{phy}} = \frac{E_{\text{vis}}}{E^{\text{source}}} \times \mu_i^{\text{phy\_source}}$$

$$\mathcal{L} = \prod_1^{N_{\text{unfired}}} P_{\text{unfired}}(\mu_i^{\text{phy}}) \prod_1^{N_{\text{fired}}} P_{\text{fired}}(\mu_i^{\text{phy}})$$

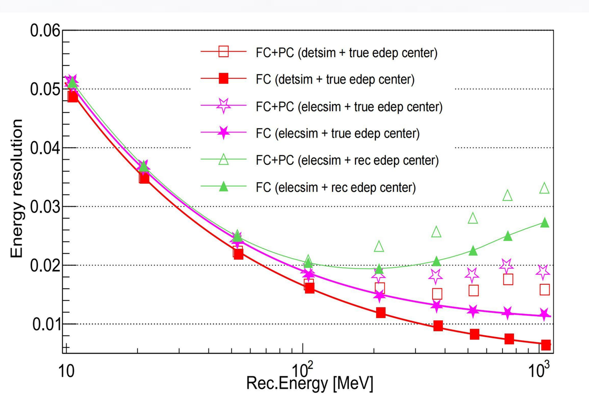
- Finally, $-\ln\mathcal{L}$ will be minimized so as to acquire the reconstructed E_{vis}

Energy Reconstruction Performance

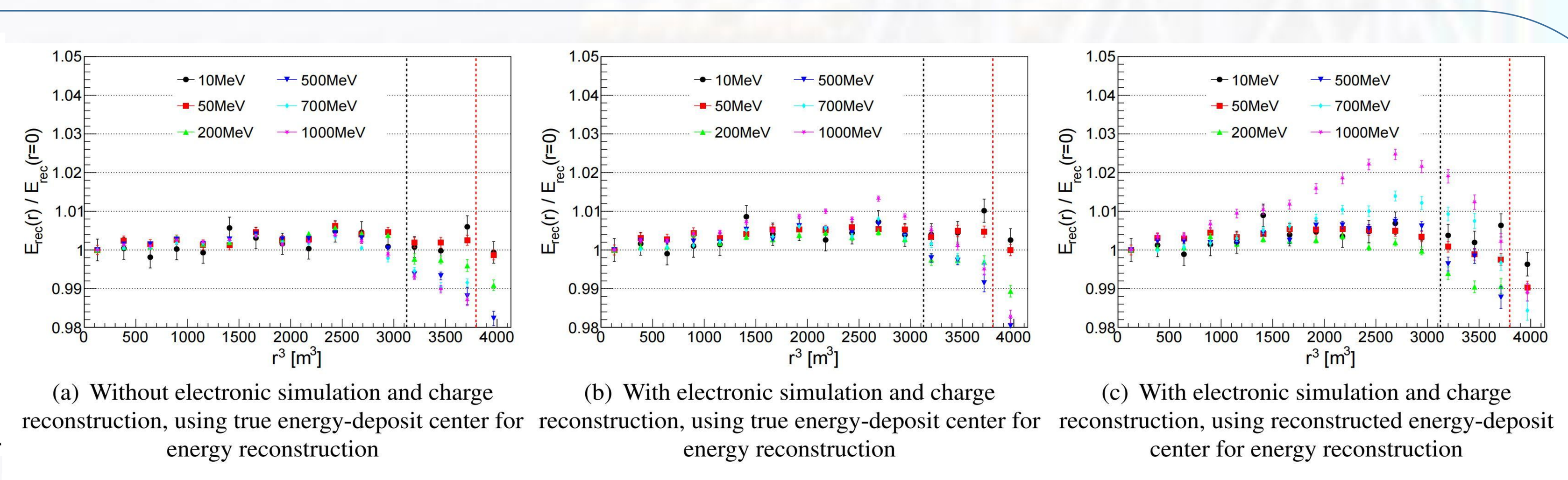


(a) 10 MeV (b) 50 MeV (c) 200 MeV (d) 500 MeV (e) 700 MeV (f) 1000 MeV

Discrete energy reconstruction with reconstructed edep vertex after electronic simulation and charge reconstruction. The blue line is the FC events and the green line is the PC events. According to the fitting results (red line) of FC spectra, it can be observed that the reconstructed visible energy is about 6% larger than the deposited energy of the electron. More specifically, for electrons with kinetic energies of 10 MeV, 50 MeV, 200 MeV, 500 MeV, 700 MeV and 1 GeV, the ratio of reconstructed visible energy to deposited energy is found to be 1.062, 1.061, 1.058, 1.059, 1.060 and 1.064, respectively. The corresponding explanation is provided in the text.



Resolution in several discrete energy in simulation phase.



(a) Without electronic simulation and charge reconstruction, using true energy-deposit center for energy reconstruction (b) With electronic simulation and charge reconstruction, using true energy-deposit center for energy reconstruction (c) With electronic simulation and charge reconstruction, using reconstructed energy-deposit center for energy reconstruction

Uniformity of discrete energy reconstruction for all (FC+PC) events. On each plot, black vertical dotted lines correspond to $r = 14.6$ m, and red vertical dotted lines ($r = 15.6$ m) correspond to the boundary of the total reflection region, which is caused by larger refractive index of the LS (which has a similar refractive index to the Acrylic) than water.

Summary

- This study proposes a unique way to reconstruct event energy with PMT counting technology, i.e. the OCCUPANCY method, which does not rely on precise charge measurement in a single PMT channel.
- Our algorithm can be applied to detect various physics events (no track-like) across a wide energy range from MeV to GeV in JUNO.

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