JUNO Detector Energy Resolution in Physics Data-Taking Phase

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Introduction

Antineutrino Detection

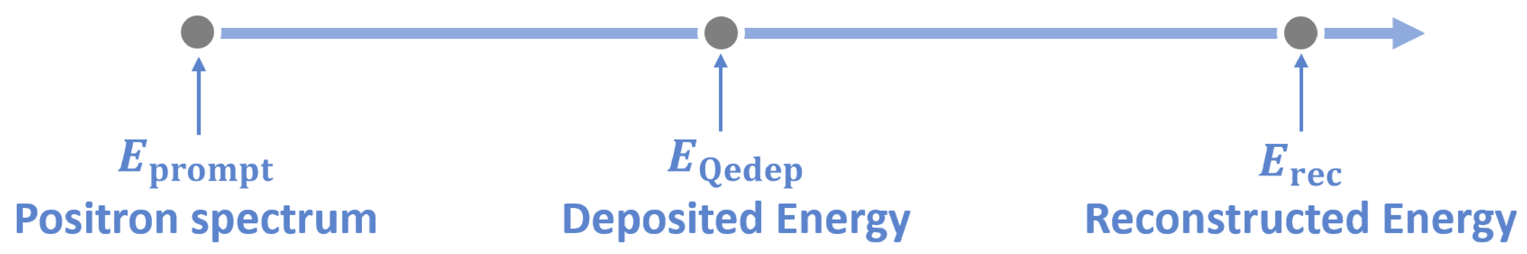
Prompt signal

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

Delay signal

Distinct coincident event pair correlated in time and space

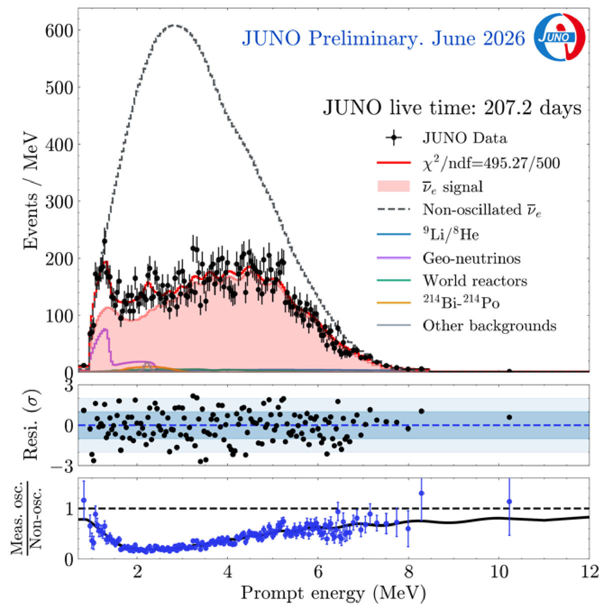
What is the detector response function in JUNO?



- $E_{\bar{\nu}_e} \approx E_{e^+} + 0.78$ MeV
- Predicted with the reactor power and neutrino flux models.
- $P_{sur}(E_{\bar{\nu}_e})$ from oscillation theory

- Liquid scintillator nonlinearity: Scintillation quenching (Birks law) + Cherenkov light
- Instrumental linearity

- Energy resolution
  - Photoelectron stats.,
  - PMT charge smear
- Energy scale
  - Residual non-uniformity
  - Energy scale stability



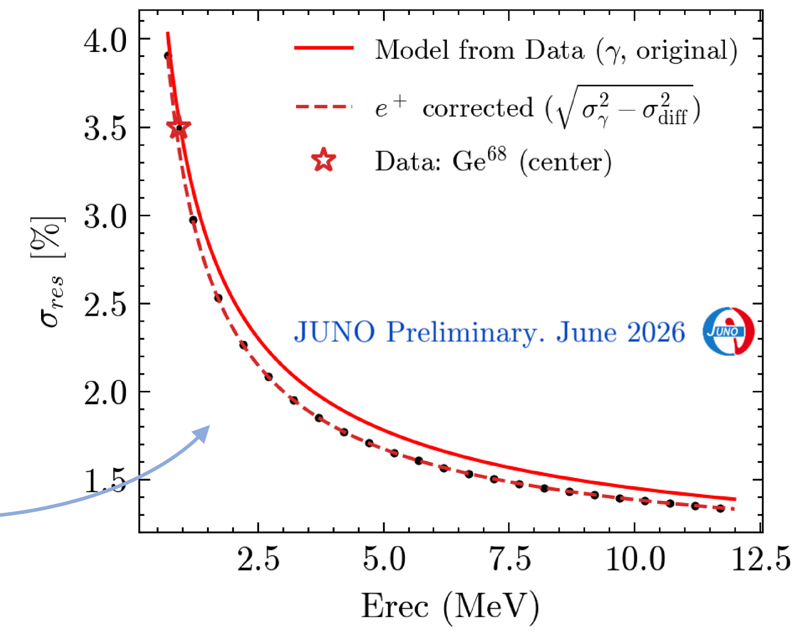
From Resolution to Oscillation Analysis

Step 1: $\gamma \dashrightarrow e^+$ at Detector Center

- Particle-dependent energy resolution has been studied previously through simulation and is now well understood among γ, e^- and e^+.
- Geant4 predicted correction was applied on γ curve by

$$\sigma^2_{diff} = \sigma^2_{\gamma,MC} - \sigma^2_{e^+,MC}$$

$$\sigma_{e^+} = \sqrt{\sigma^2_{\gamma} - \sigma^2_{diff}}$$



Step 2: Energy Response Matrix (Edep → Erec) Construction

◆ radius-dependent prediction

- Energy response matrix for each equal r^3volumes per shell

$$R_{ji} = \int_{E^{rec}_{j,low}}^{E^{rec}_{j,high}} \mathcal{N}\left(E_{rec};\, E_{vis,0}(E_{dep,i}),\, \sigma(E_{vis,0})\right) dE_{rec}$$

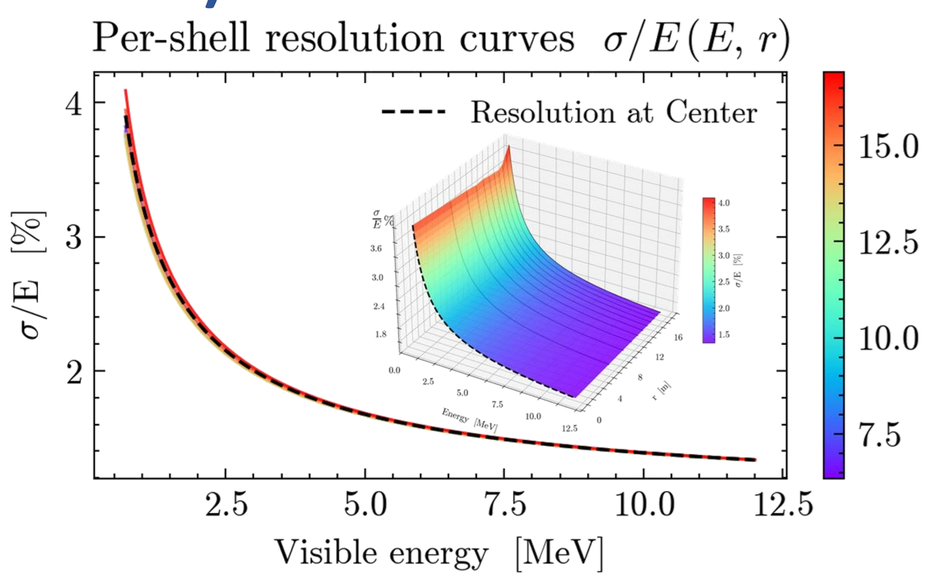
$$E_{vis,0} = E_{dep} \cdot f_{NL}(E_{dep}) \cdot (1 + \alpha_{escale})$$

(i: Edep, j: Erec)

Use Po214 and energy curve at center to extrapolate the 3D energy resolution map

- Add all shell by volume-weights

For uniform IBD distribution, this gives a volume-averaged detector response



◆ model the ^{14}C pile-up

R^{np}: convolve the energy response matrix inherited from last step with the ^{14}C pile-up spectrum

$$R^{C14} = (1 - \varepsilon - \varepsilon^2 - \varepsilon^3)R + \varepsilon R^{1p} + \varepsilon^2 R^{2p} + \varepsilon^3 R^{3p}$$

Fold the with ^{14}C pile-up ($\varepsilon \approx 4.7$ % see poster #323)
Measured from JUNO periodic data and calibration data
Consider the effect until 3 pile-up

Energy Reconstruction

- ➢ A comprehensive calibration system monitors energy nonlinearity and the energy response (see poster #248)
- ➢ Likelihood-based reconstruction **OMILREC**: A data-driven likelihood-based algorithm to fit vertex R and E_{vis} jointly from large PMT charge, and the time. (see Energy Reco. Poster #272)

Combined charge + time likelihood

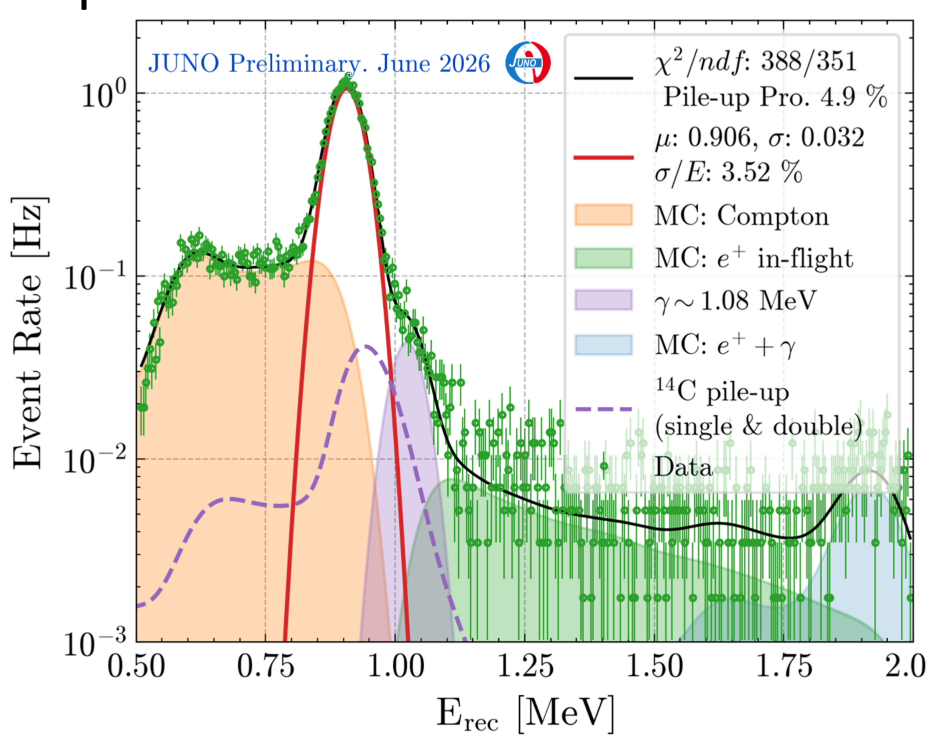
$$\mathcal{L} = \prod_{j\in\mathcal{U}} e^{-\mu_j} \prod_{i\in\mathcal{F}} \left(\sum_{k\geq1} P_Q(q_i|k) P(k|\mu_i) \right) \prod_{i\in\mathcal{T}} P_T(t_{i,r}|\mathbf{r}, d_i, \mu_i)$$

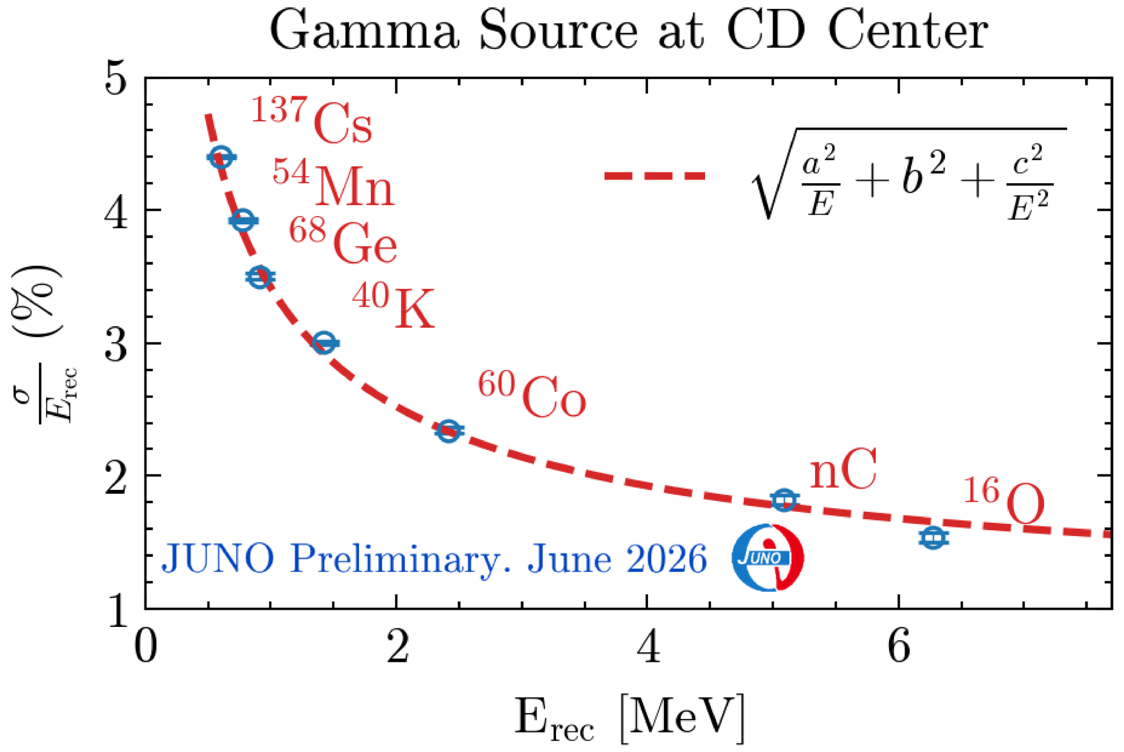
Expected light at PMT$_i$

$$\mu_i(\mathbf{r}, E_{vis}) = E_{vis}\hat{\mu}_i^L(\mathbf{r})c_i + \mu_i^D$$

- **OMILREC Constructs nPE map from ACU ^{68}Ge (along Z axis) source and full-detector sample ^{214}Po**

- Energy spectra from γ sources at CD center are fit with the energy loss in the source enclosure, and ^{14}C pile-up taken into account

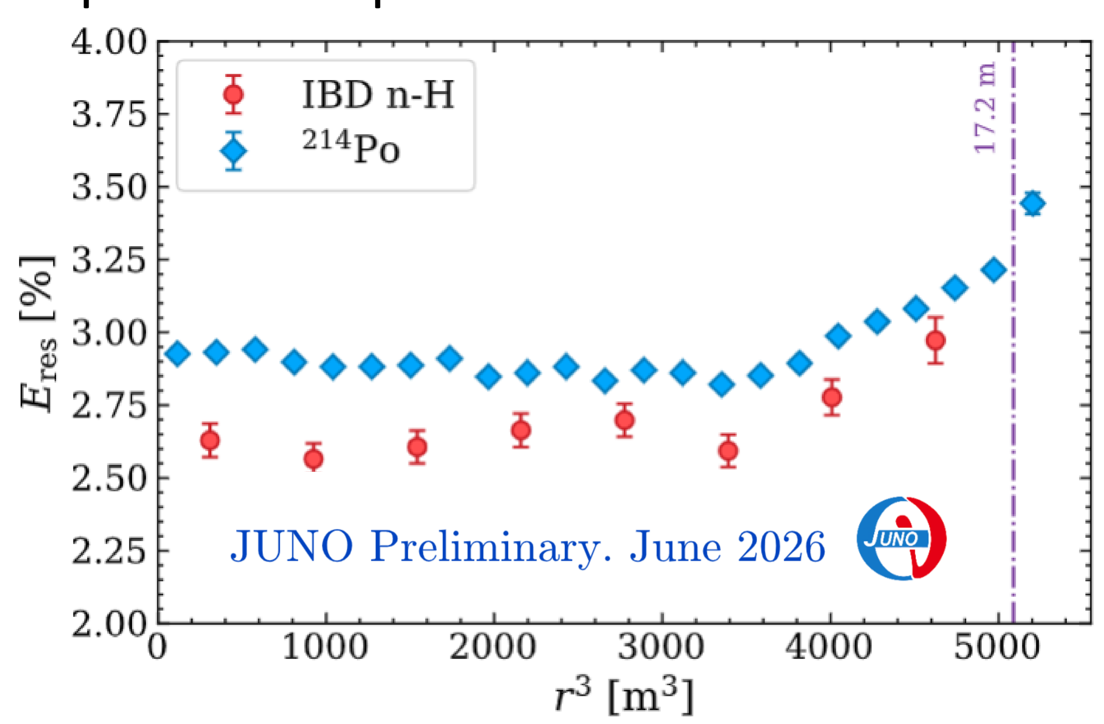


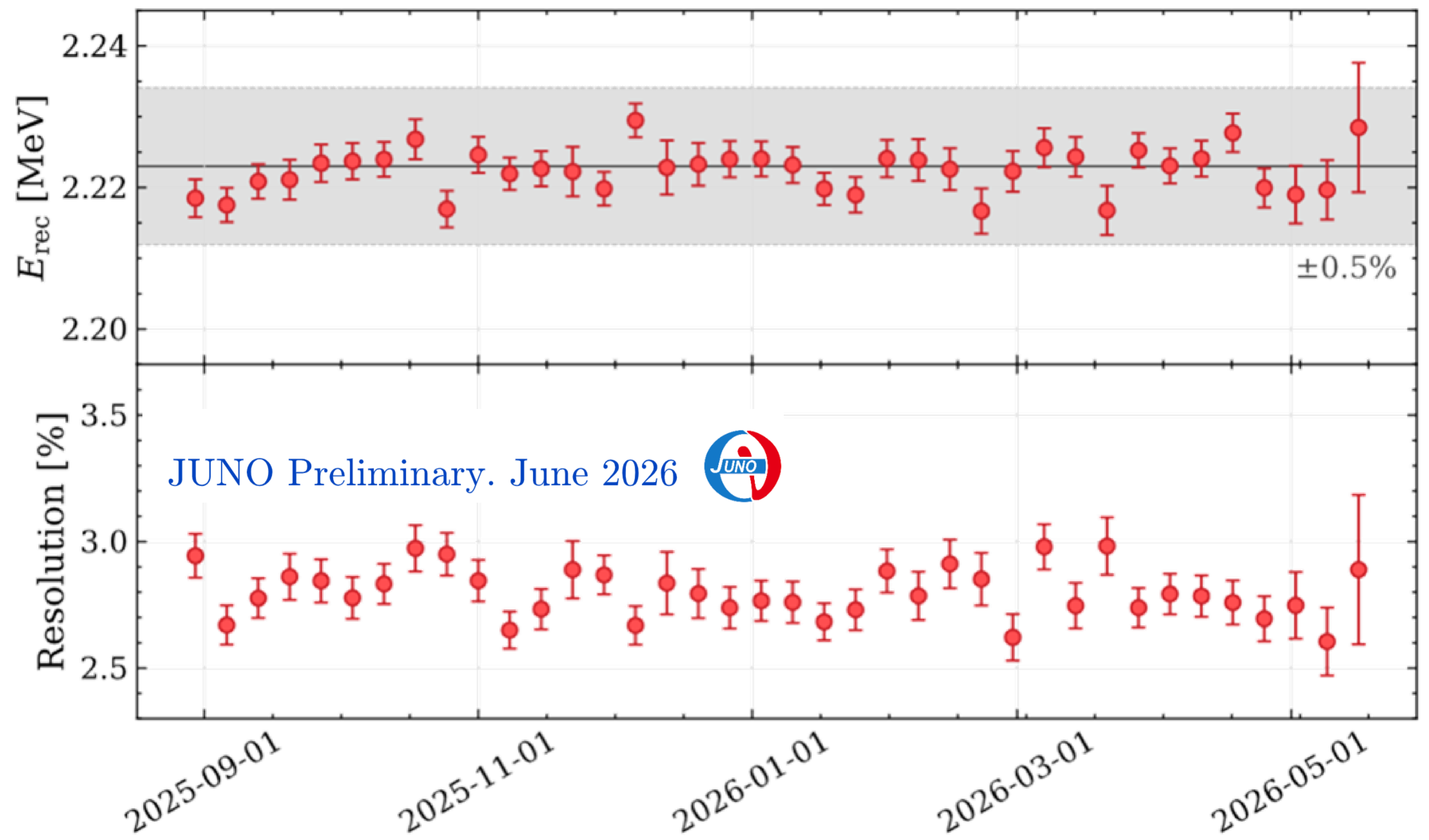


The energy resolution parameters (abc model) is evaluated with gamma calibration sources

- RMS of stability ≈ 0.35% ← nH capture from $\bar{\nu}_e$ and cosmogenic ^{9}Li

- Energy resolution features particle-dependence and position-dependence in JUNO's data





Systematic and Fit strategy

- The uncertainty of response-related parameters are introduced by covariance matrix obtained by toy MC

$$V^{resp}_{ij} = \frac{1}{M-1}\sum_{m=1}^{M}\left(N_i^{(m)} - \bar{N}_i\right)\left(N_j^{(m)} - \bar{N}_j\right)$$

$$\boldsymbol{\theta} = \{a, b, c, \varepsilon, \alpha_{escale}, \alpha^{(0)}_{NL}, \alpha^{(1)}_{NL}, \alpha^{(2)}_{NL}, \alpha^{(3)}_{NL}\} \quad \chi^2_{CNP} = \Delta\mathbf{N}^T\left(V^{stat} + V^{resp}\right)^{-1}\Delta\mathbf{N}$$

This method is adopted by JUNO's latest results