Vertex and Energy Reconstruction in JUNO

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On behalf of the JUNO collaboration

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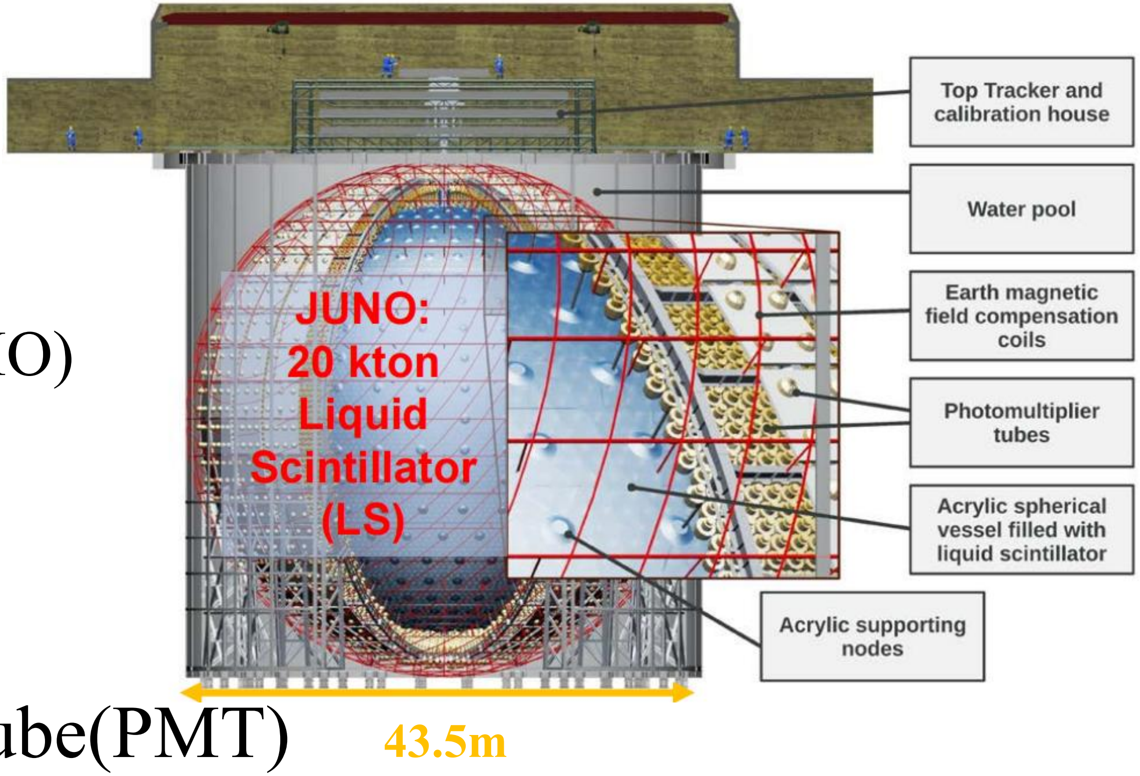
The JUNO experiment

- A multi-purpose observatory
  - Determine the neutrino mass ordering(NMO)
  - Precisely measuring $sin^2\theta_{12}, \Delta m^2_{21}, \Delta m^2_{31}$
  - Supernova, Atmosphere, Solar, etc.
- 20k tons liquid scintillator(LS)
- ~17612 large 20-inch photomultiplier tube(PMT)
- ~25600 small 3-inch PMT
- Unprecedented energy resolution
  - 3% @ 1 MeV



LS detectors

	KamLAND	Borexino	Daya Bay	JUNO
mass	1 kton	0.3 kton	20 ton	20 kton
resolution	6.5%	5%	8%	3%

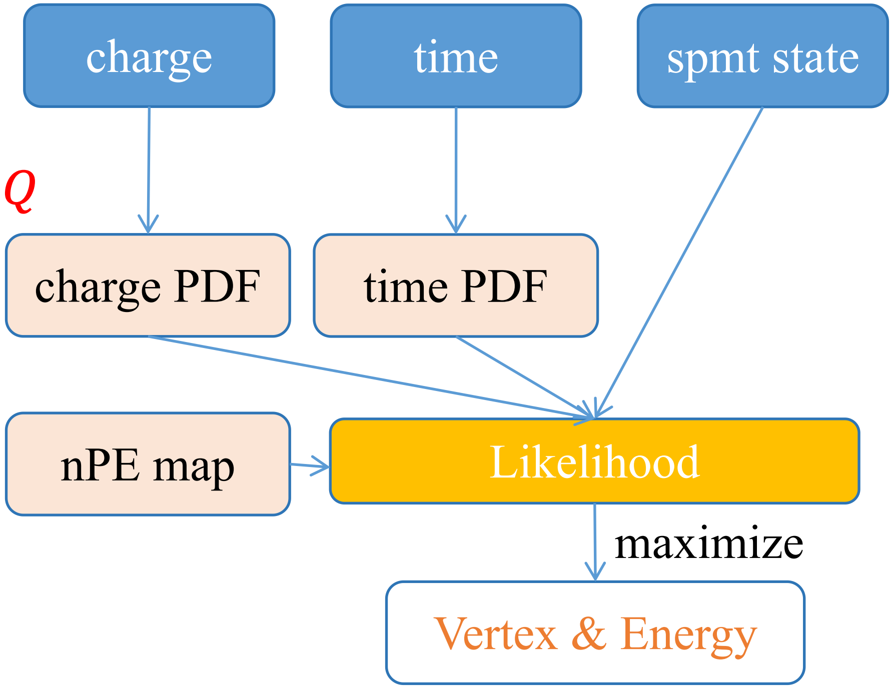
Li, ZY., Zhang, YM., Cao, GF. et al. Event vertex and time reconstruction in large-volume liquid scintillator detectors. NUCL SCI TECH 32, 49 (2021)

Data driven reconstruction

Now the study is based on simulation

- The observables are large PMTs' hit charge $\{q_i\}$, residual hit time $\{t_{i,r}\}$ and small PMTs' hit states

- The nPE map $\hat{\mu}$, time PDF P_T and charge PDF P_Q are constructed from ^{68}Ge calibration data



$r:$ *vertex radial distance*

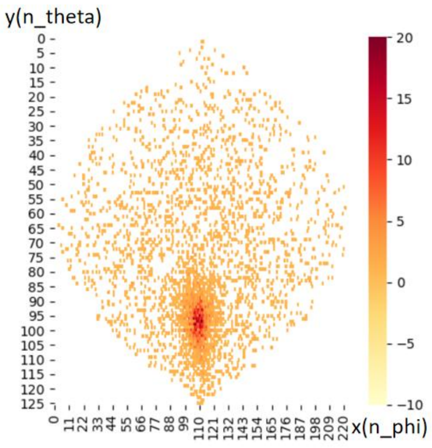
$d:$ *distance to PMT*

$\mu_l:$ *LS PE*

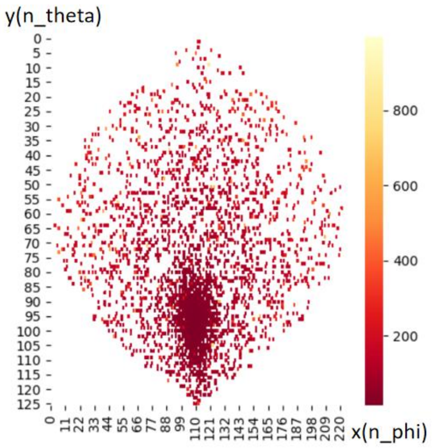
$\mu_d:$ *dark noise PE*

$t_0:$ *event time*

$\mu_j = \hat{\mu}_j E + \mu_j^d$



fired PMTs' charge profile



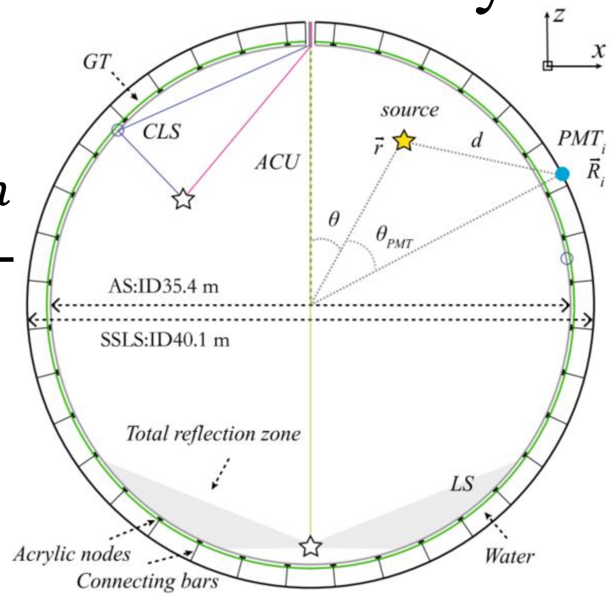
fired PMTs' first hit time profile

$$L(\{q_i\};\{t_{i,r}\}|\vec{r},E,t_0) = \prod_{unhit} e^{-\mu_j} \prod_{LPMT\ hit} \left(\left(\sum_{k=1}^{+\infty} \frac{e^{-\mu_j}\mu_j^k}{k!} P_Q(q_i|k) \right) P'_T(t_{i,r}|r,d_i,\mu_j^l,\mu_j^d) \right) \prod_{SPMT\ hit} (1-e^{-\mu_j})$$

Construction of the nPE map

- nPE map $\hat{\mu}$: The expected number of LS photos per unit visible energy
- Method: Use ^{68}Ge to construct a 3D nPE map: $\hat{\mu}(r, \theta, \theta_{pmt})$, assume the nPE map is φ independent
- Advantage: More precise nPE map than 2D, optimized non-uniformity

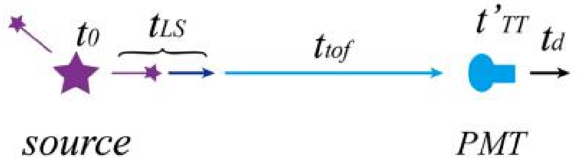
$$\hat{\mu}(r,\theta,\theta_{pmt}) = \frac{1}{E_{vis}}\frac{1}{N_{evt}}\frac{1}{N_{pmt}}\sum_{i=1}^{N_{evt}}\sum_{j=1}^{N_{pmt}}\frac{\frac{q_{i,j}}{\hat{q}_j} - D_{ark}N_{oise}R_{ate}\cdot L_{ength}}{D_{etect}E_{fficency}{}_j}$$



Schematic view of the CD

Huang, GH., Jiang, W., Wen, LJ. et al. Data-driven simultaneous vertex and energy reconstruction for large liquid scintillator detectors. NUCL SCI TECH 34, 83 (2023).

Construction of the time pdfs

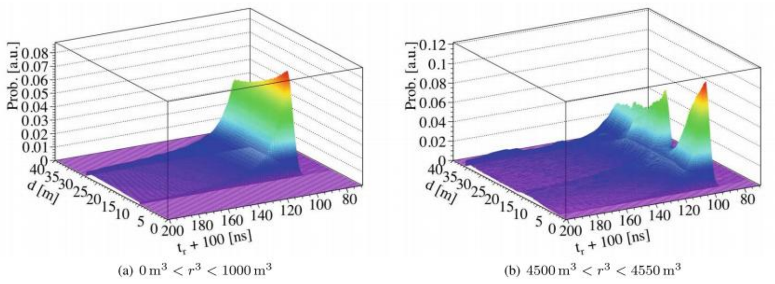


- The pdfs of the probability of the residual time of first hit

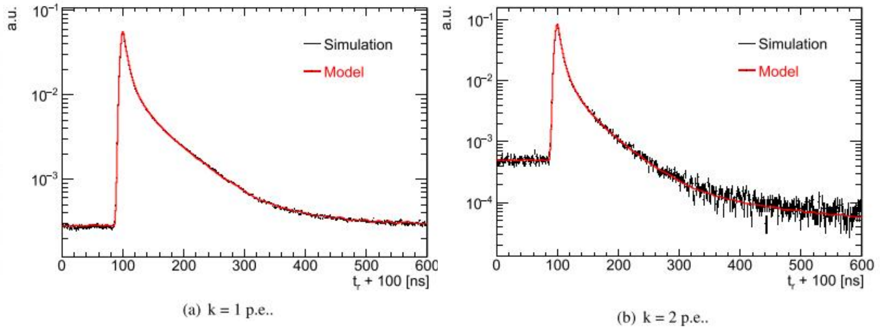
$$t_r = t_{hit} - t_{tof} - t_{delay} - t_0$$

r : vertex radial distance
d : distance to PMT
μ_l : LS PE
μ_d : DN PE

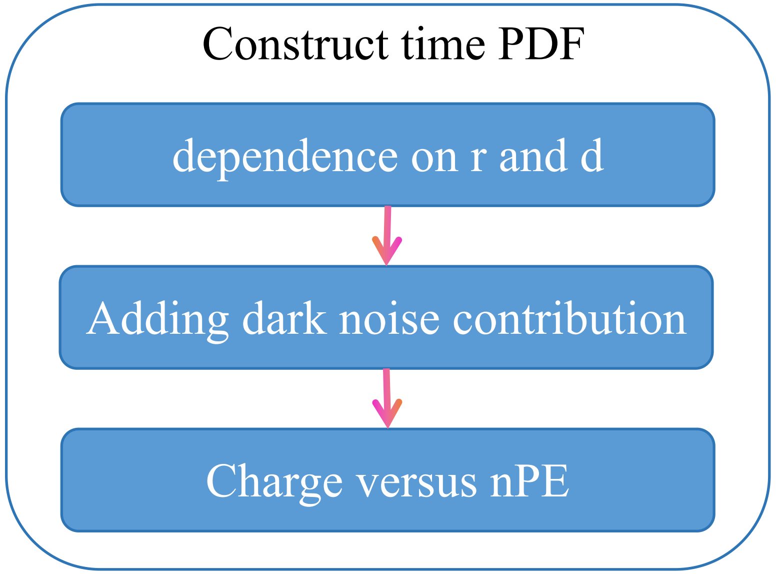
- Challenges: Vertex dependent; Dark noise(DN) contamination
- Method: Use ^{68}Ge calibration data to extract $P'_T(t_r|r, d, \mu_l, \mu_d)$
- Advantage: more precise time pdf, make resolution better near the centre detector edge



Examples of the time PDFs at diferent positions



Time PDF of Dynode-PMT of central ^{68}Ge events considering dark noise



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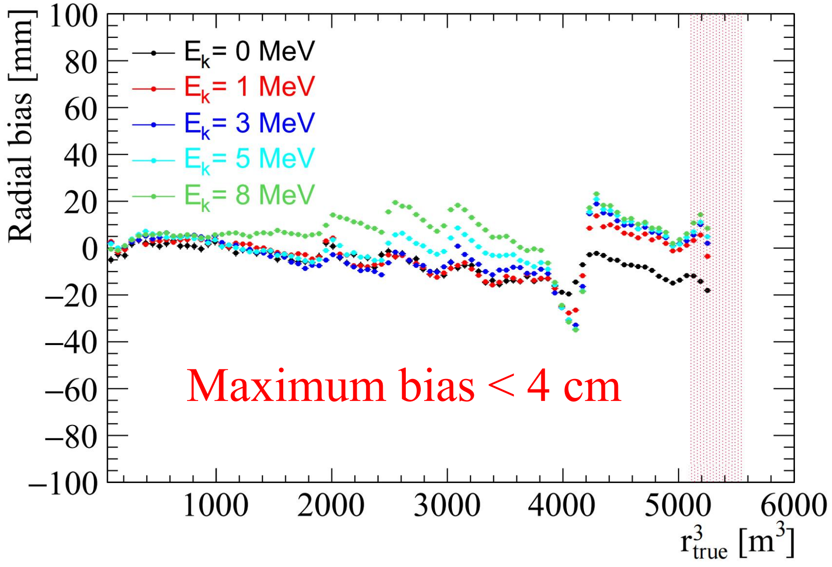
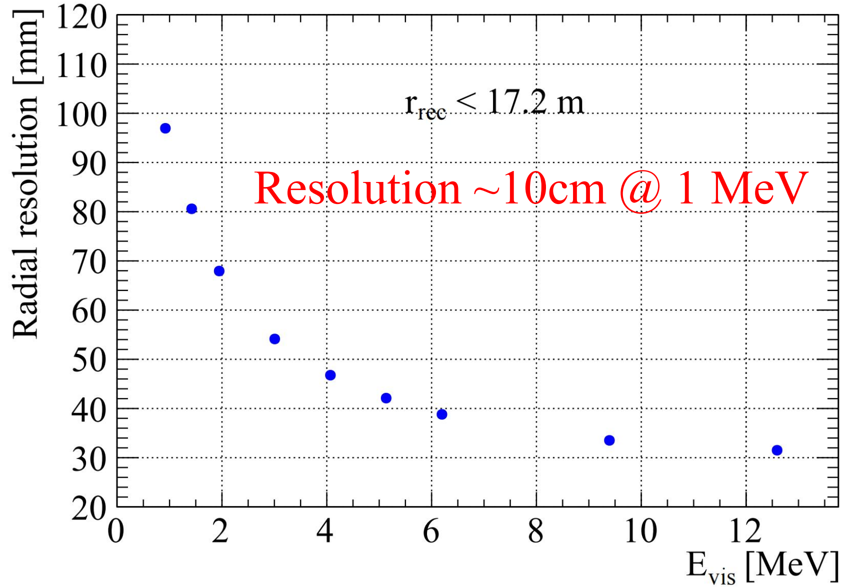
Reconstruction performances

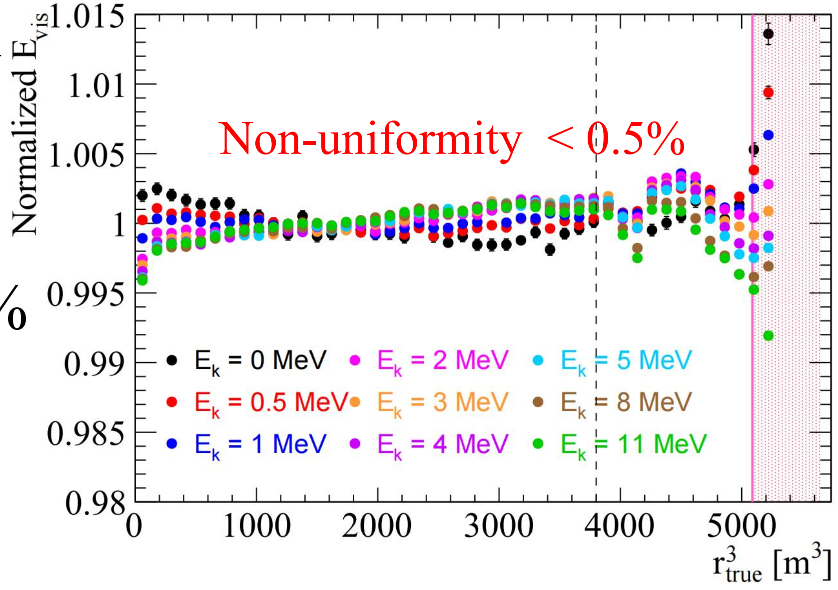
Type	Energy	Statistics	Position
e^+	E_k=(0, 0.5, 1, 2, 3, 4, 5, 8, 11) MeV	500k/set	uniform in CD

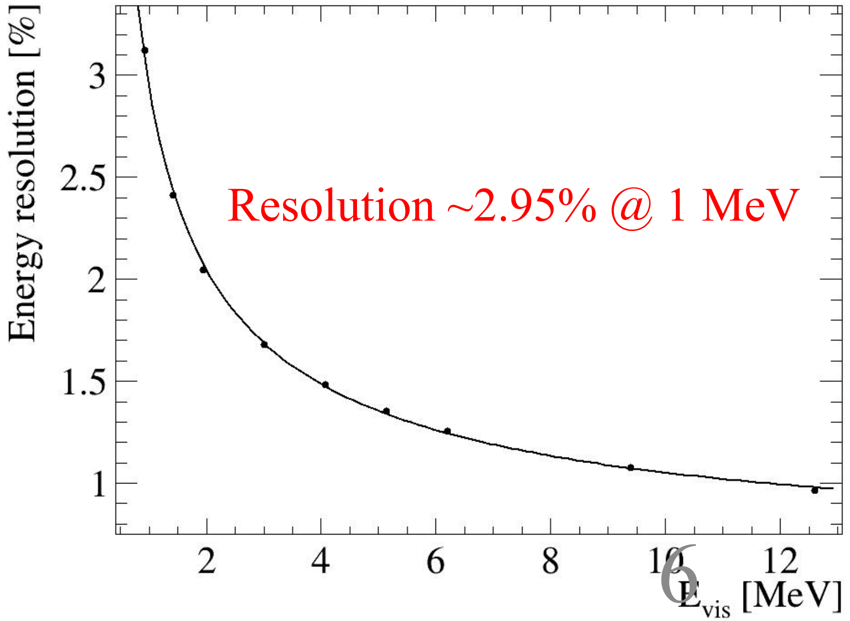
The performances are evaluated with JUNO MC simulation data of uniformly generated positron samples.

- Radial performance
  - Maximum bias < 4 cm
  - Resolution ~10 cm
- Energy performance
  - Non-uniformity < 0.5%
  - Resolution ~2.95%









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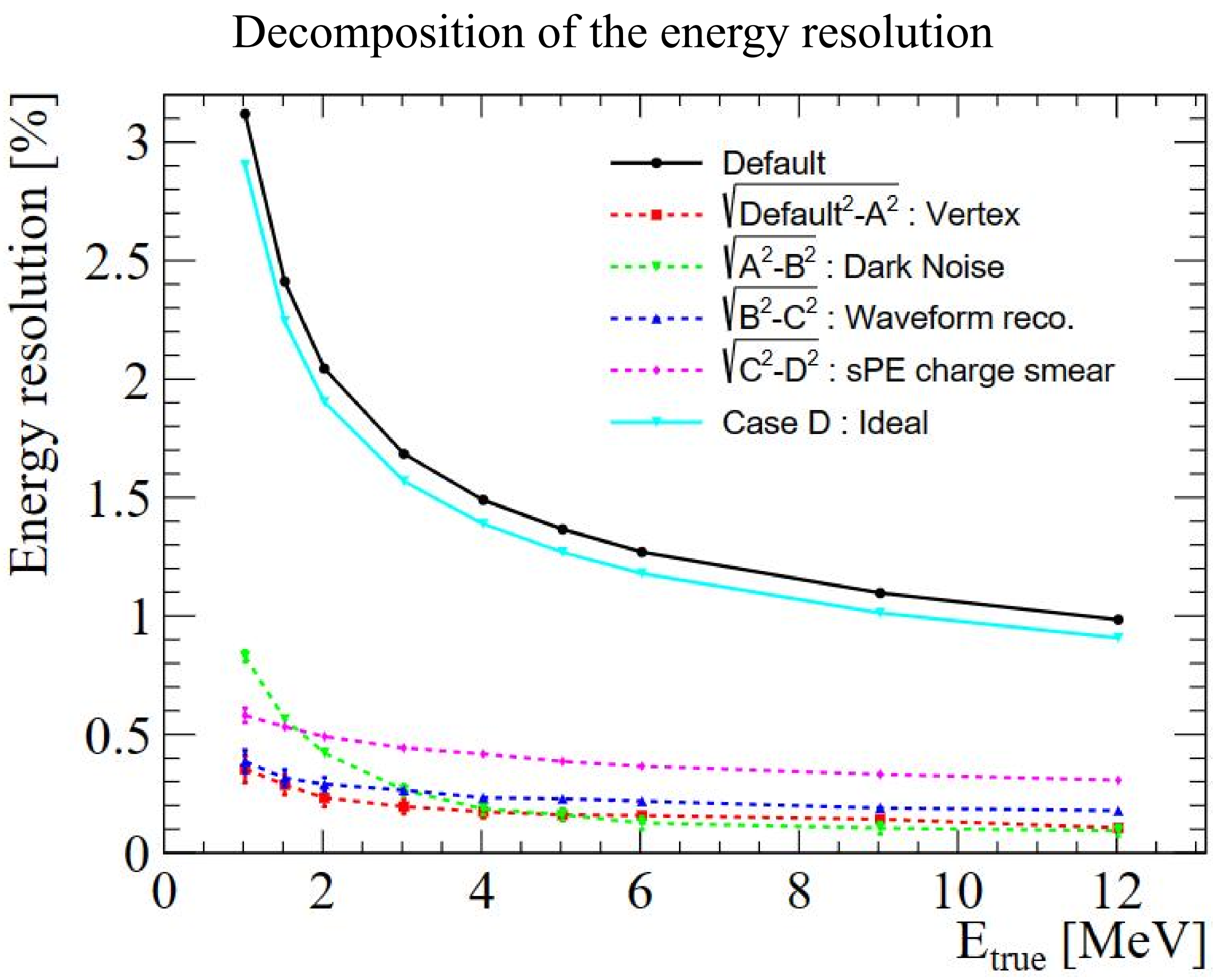
Energy resolution decomposition

- Five components of energy resolution
- Two dominant factors:
  - Below 1.5MeV - Dark Noise
  - Above 1.5MeV - sPE charge smear

PMT convert PE to charge

- Works are ongoing to mitigate the impact of these factors



Summary

- Data driven method makes nPE map, time PDF and charge PDF realistic
- Simultaneous reconstruction of vertex and energy with both charge and time information of PMTs
- Latest performance
  - Vertex : bias < 4 cm, resolution ~ 10 cm @ 1 MeV
  - Energy: non-uniformity < 0.5%, resolution 2.95% @ 1 MeV
- Energy resolution decomposition shows two dominant factors: dark noise and sPE charge smear
- More works are ongoing

Thanks for your attention!