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# A Pure Probabilistic Approach to Event Recosnstruction at JUNO

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## Background

### Neutrino mass hierarchy

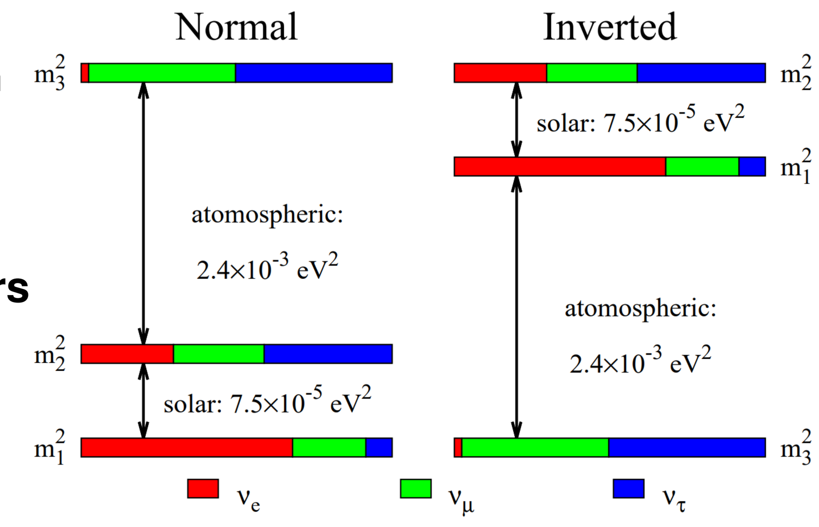
relies on $\Delta m_{31}^2$ $\Delta m_{32}^2$

- Normal hierarchy(NH) or inverted hierarchy(IH) for mass eigenstate
- (For JUNO) Medium baseline (~50 km) reactor antineutrino oscillation
- The determination of mass hierarchy is helpful for: $\bar{\nu}_e \to \bar{\nu}_e$
  - defining the goal of neutrinoless double beta decay
  - measuring lepton CP-violating phase

### Precision messurement of neutrino oscillation parameters

- Model-independent way to probe new physics
  - test the standard three-flavor neutrino model
    e.g., test the unitarity of the MNSP matrix
  - narrow down the parameter space of the effective mass of the neutrino double beta decay

Two possible mass hierarchies:




### Jiangmen Underground Neutrino Observatory(JUNO)

Determine neutrino mass hierarchy at 3-4σ significance
Measure neutrino oscillation parameters(better than 1%)
$\sin^2\theta_{12}$ $\Delta m_{21}^2$ $|\Delta m_{ee}^2|$

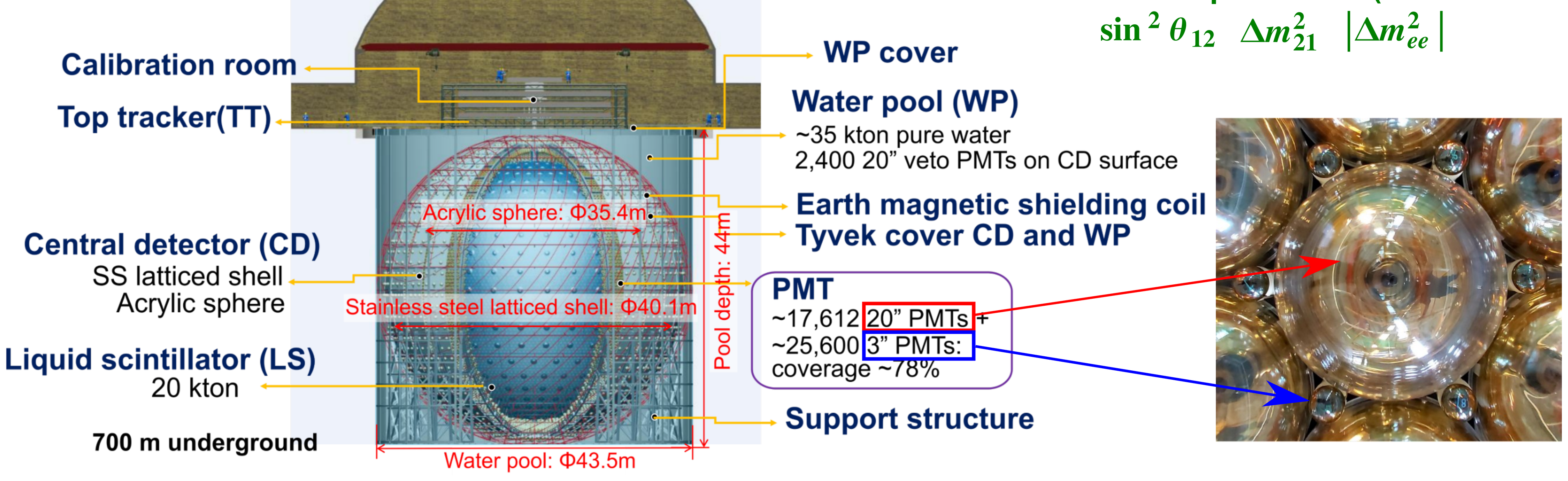



Figure 1: A scheme view of the JUNO detector(left) [1] and JUNO PMT(right)

### Reconstruction methodology of point-source events

- considers dependence of scintillation light time response curve on PE(photoelectron) number
- **pure probabilistic**, deduced from first principles
- follows naturally from the time response curve and is **unbiased**

**Application:**
JUNO 3-inch PMT with **first PE time** and **charge** readouts

## Problem Model

**Rotationally symmetrical about the $O$-$\vec{r}_j$ axis**

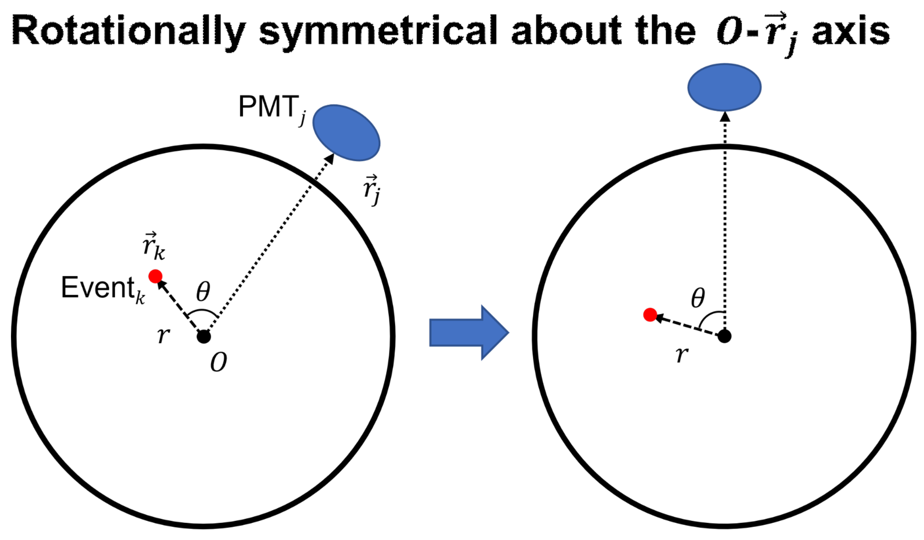



Figure 2: Intuitively, we can rotate the detector so that PMT $j$ is above.

**PE number on PMT $j$ follows nonhomogeneous Poisson process**

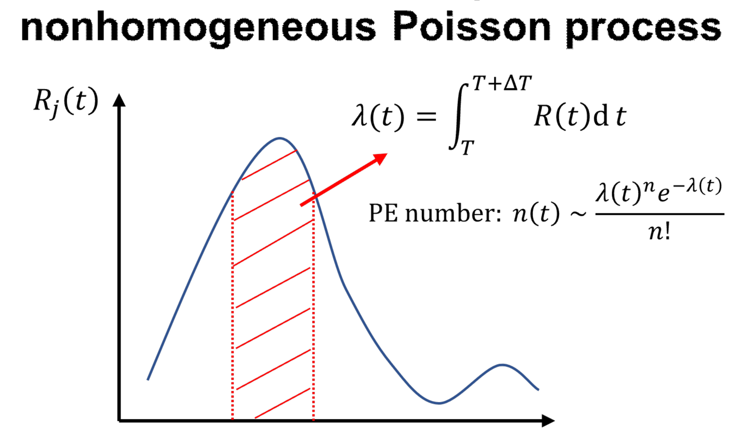



Figure 3: PE number at $T$ follows Poisson distribution $\Pr(\lambda(T))$, where $\lambda(T) = \int_T^{T+\Delta T} R(t)\,\mathrm{d}t$.

**All PMTs are identical**

- Ignore the difference of PMTs, such as geometry, quantum efficiency and so on.
- Consider the difference in more elaborate fitting.

## PMT Expected Response Function

- Defined as Poisson intensity $R_j(t;\vec{r},E)$, for point source event $\delta(\vec{r},E)$
- Energy linearity: $R_j(t;r,\theta_j,E) = ER_j(t;r,\theta_j)$

ensure nonnegativity

$$R_j(t;r,\theta_j) = \frac{1}{l_j^2(r,\theta_j)}\left[\sum_{m,n} a^{mn} P_m\left(t - s_j(r,\theta_j)\right) Z_n(r,\theta_j)\right]^{\boxed{2}} \quad (1)$$

- $t$: PE time, mapped to $(-1,1)$
- $r,\theta$: position of initial vertex relative of PMT $j$. $r$ is mapped to $(0,1)$
- $P_m(t)$: $m$ order Legendre polynomial
- $Z_n(r,\theta)$: $n$ order Zernike polynomial
- $a^{mn}$: fitting coefficient
- $l_j(r,\theta_j)$: distance between initial vertex and image of PMT $j$
- $s_j(r,\theta_j)$: flight time from initial vertex to image of PMT $j$

Reduce the difficulty of fitting and improve fitting accuracy

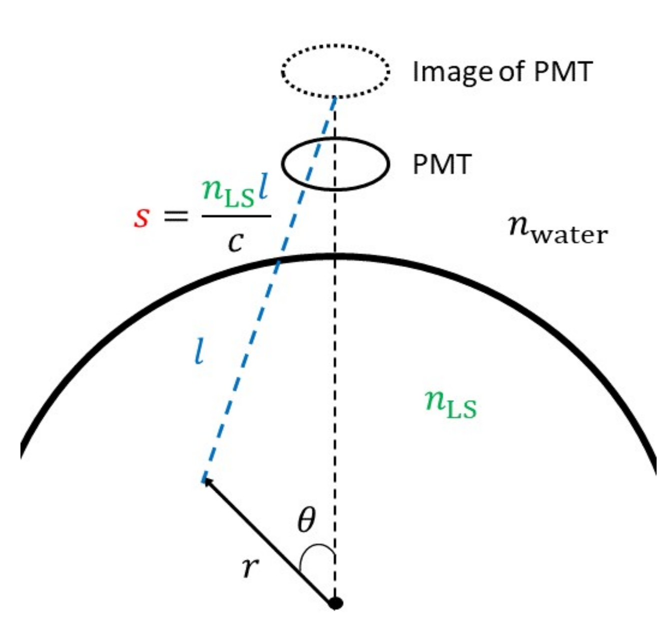



Figure 4: Physical meanings of $l_j(r,\theta_j)$ and $s_j(r,\theta_j)$

## Response Function Examples

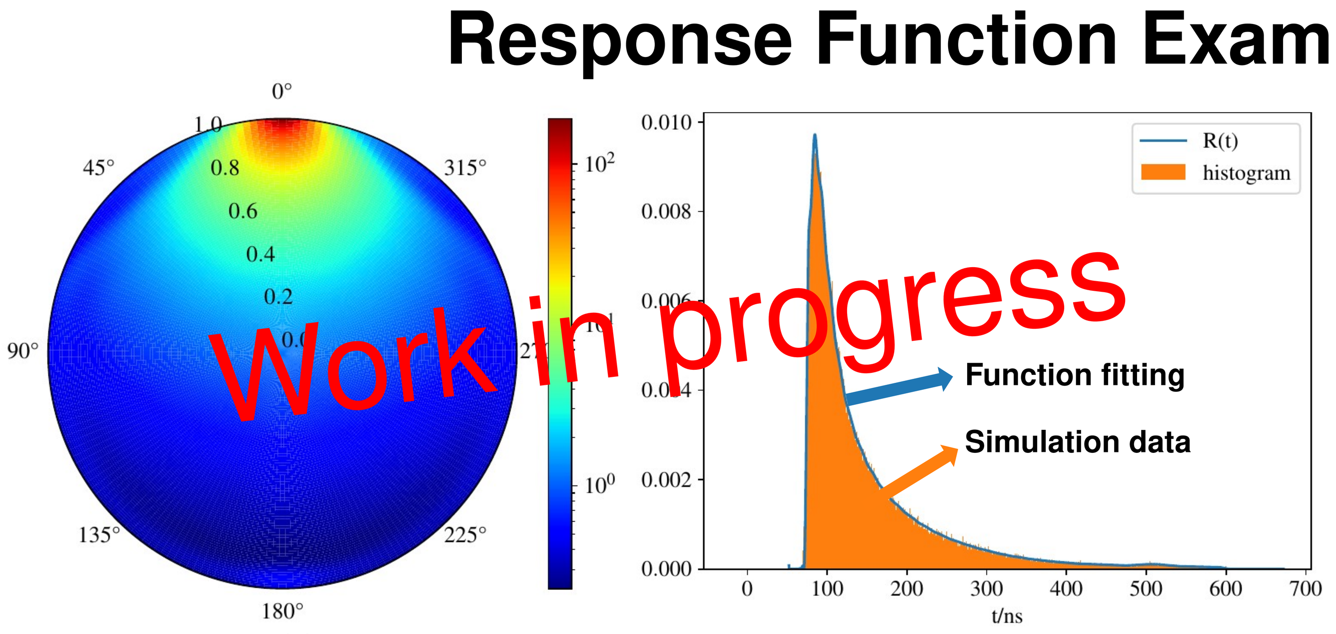



Figure 5: Use 96 order Legendre and121 order Zernike polynomials to express $R_j(t;r,\theta_j)$.
(a) shows the position response (time integration);
(b) shows the time response$R_j(t;1,\pi/4)$.

## Calibrate $a^{mn}$ of Response Function

**Calibration Likelihood:**

$$\log\mathcal{L} = \log\left\{\prod_{i} R_{j_i}(t_i;r_i,\theta_{j_i}) \prod_{k,j} \exp\left[-\int R_j(t;r^k,\theta_j^k)\,\mathrm{d}t\right]\right\}$$

$i$: PE index, $k$: Event, $j$: PMT

$$= \underbrace{\sum_i \log R_{j_i}(t_i;r_i,\theta_{j_i})}_{\text{hit}} - \underbrace{\sum_{k,j}\int R_j(t;r^k,\theta_j^k)\mathrm{d}t}_{\text{nonhit}} \quad (2)$$

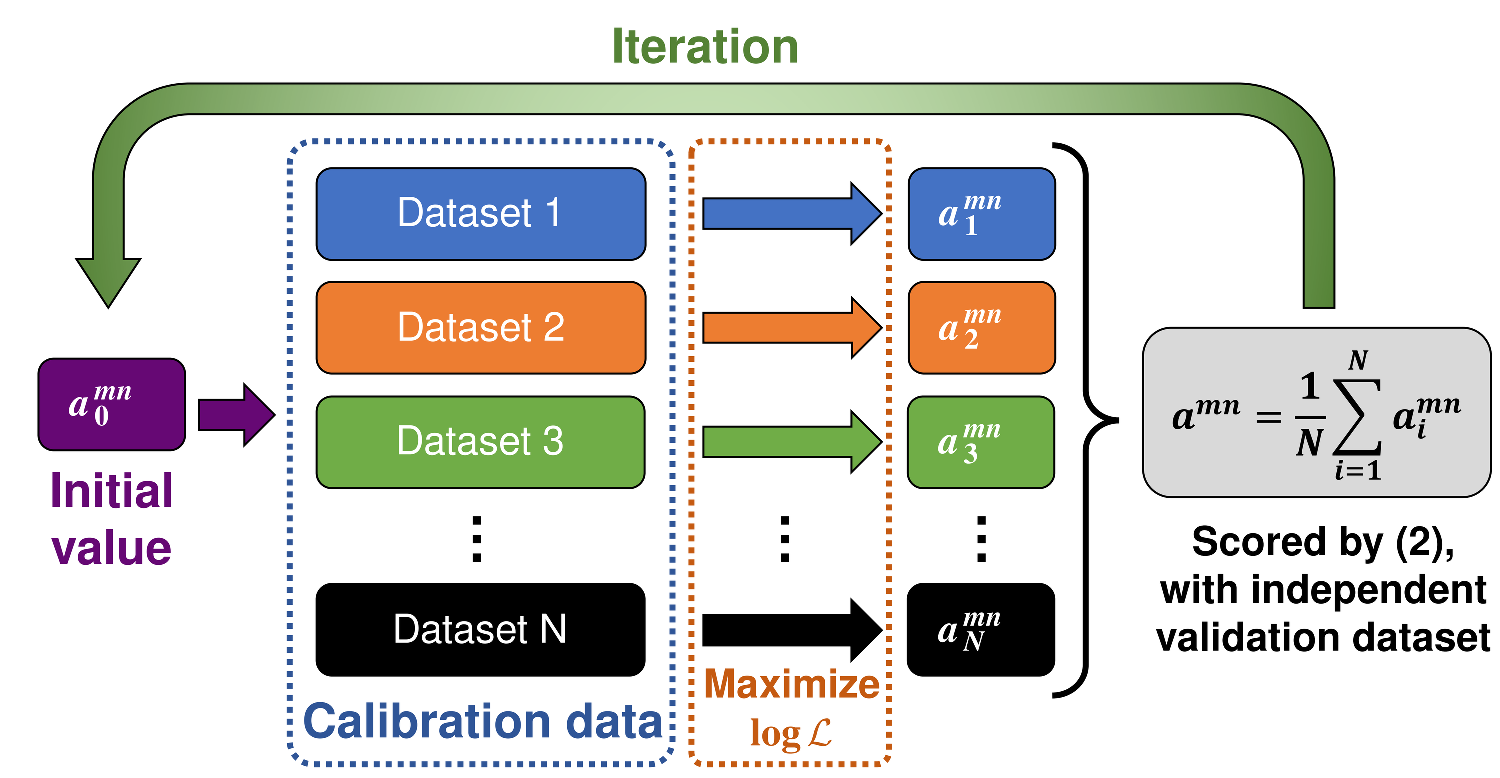



Figure 6: Calibration workflow. Datasets are (currently) from JUNO Monte Carlo simulation.

## Reconstruction Methodology

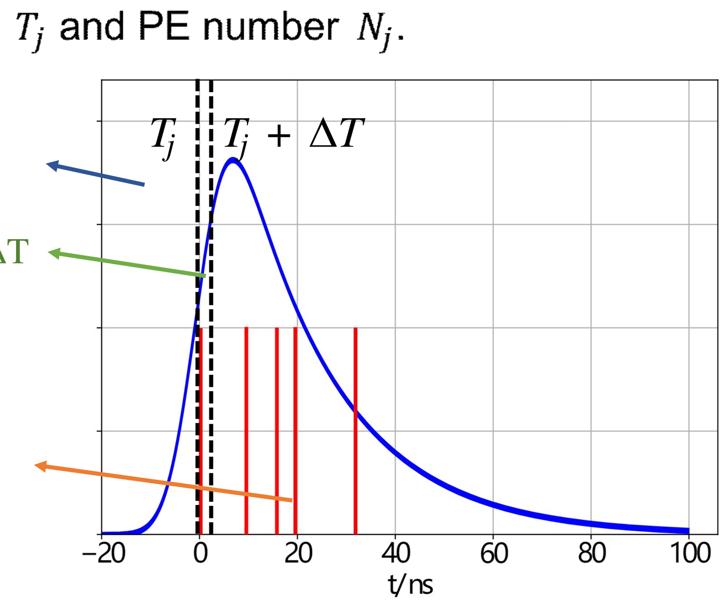
Consider the joint distribution of first PE time $T_j$ and PE number $N_j$.

**No PE in** $(-\infty, T_j)$: $\exp\left(\int_{-\infty}^{T_j} R_j(t)\mathrm{d}t\right)$

**One PE in** $(T_j, T_j+\Delta T)$: $\exp\left(-R_j(T_j)\Delta T\right) R_j(T_j)\Delta T$

**$N_j - 1$ PEs in** $(T_j+\Delta T, +\infty)$:

$$\frac{\exp\left(-\int_{T_j+\Delta T}^{+\infty} R_j(t)\mathrm{d}t\right)\left[\int_{T_j+\Delta T}^{+\infty} R_j(t)\mathrm{d}t\right]^{N_j-1}}{(N_j-1)!}$$




**Multiply**

$$P(T_j,N_j) = \frac{\exp\left(\int_{-\infty}^{+\infty} R_j(t)\mathrm{d}t\right) R_j(T_j) \left[\int_{T_j+\Delta T}^{+\infty} R_j(t)\mathrm{d}t\right]^{N_j-1}}{(N_j-1)!}$$

**Normalization:**

$$\sum_{N_j=0}^{+\infty} \int P(N_j,T_j)\mathrm{d}T_j = 1$$

**Reconstruction Likelihood**

$$\mathcal{L}_{T,N}(\vec{r}) = \prod_j^{\text{hit}} P(N_j,T_j;\vec{r}) \times \prod_j^{\text{nonhit}} P(N_j=0;\vec{r})$$

$$= \prod_j^{\text{hit}} \frac{\exp\left(\int_{-\infty}^{+\infty} R_j(t;\vec{r})\mathrm{d}t\right) R_j(T_j;\vec{r}) \left[\int_{T_j+\Delta T}^{+\infty} R_j(t;\vec{r})\mathrm{d}t\right]^{N_j-1}}{(N_j-1)!} \times \prod_j^{\text{nonhit}} \exp\left(-\int_{-\infty}^{+\infty} R_j(t;\vec{r})\mathrm{d}t\right)$$

## Results

1000 events, 1MeV $e^-$, distributed uniformly in center detector

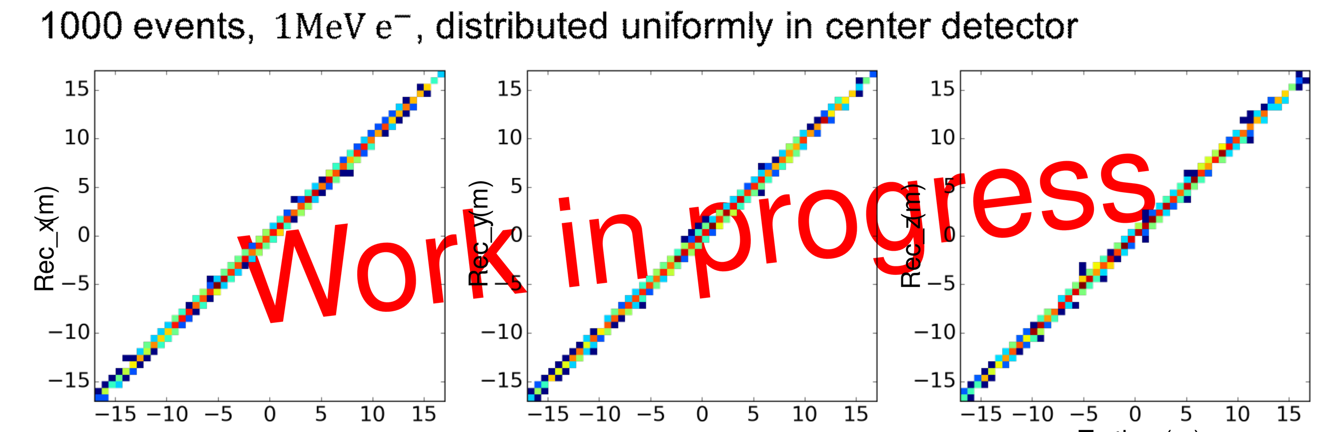



Figure 7: Reconstruction results on x, y and z axes.

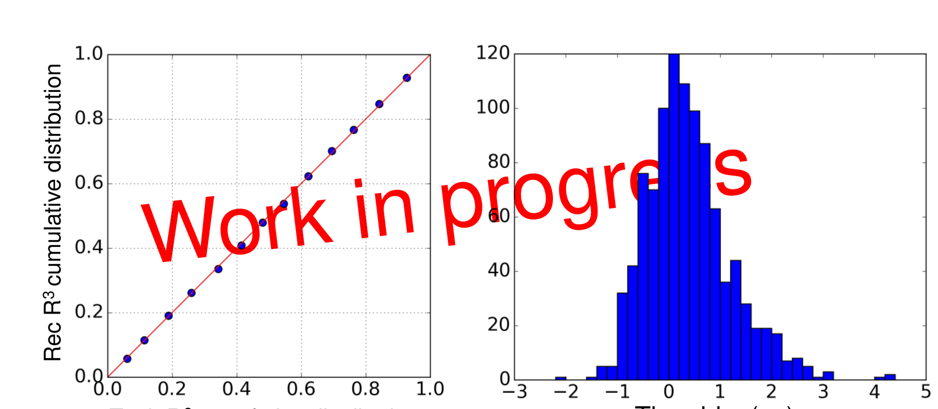



Figure 8: P-P plot of $R^3$(left)and time bias histogram(right).

**JUNO small PMT reconstruction is verified.**

## Summary

- PMT response function is effective to describe the response of point-source event.
- The approach is pure probabilistic and is verified to be unbiased on radius

## Prospect

- PE number will be replaced with charge, based on charge model of small PMT.
- The approach can be applied to other system with time and charge readouts.

### References

1. Yang, Cheng-Feng, et al. "Reconstruction of Muon Bundle in the JUNO Central Detector." *arXiv preprint arXiv:2201.11321* (2022).
2. An, Fengpeng, et al. "Neutrino physics with JUNO". *Journal of Physics G: Nuclear and Particle Physics* 43.3 (2016): 030401.