Vertex Reconstruction in JUNO

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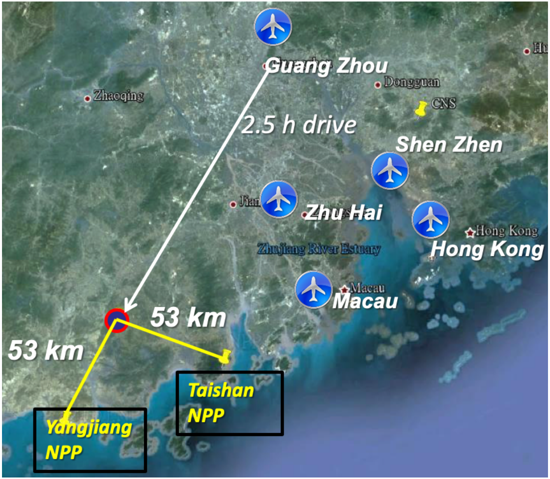
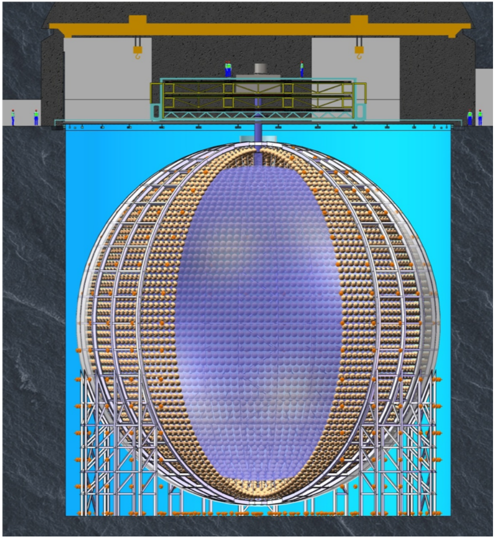
Jiangmen Underground Neutrino Observatory



- Location : Kaiping, Jiangmen city, Guangdong Province, China.
- Baseline optimized for Neutrino Mass Ordering determination : 53 km from Taishan and Yangjiang NPP
- Reactor $\bar{\nu}_e$: ~ 60 / day
- Data taking start : 2021

The JUNO Detector



Top Tracker

- 3 layers of plastic scintillator
- Precise μ tracking

Water Cherenkov Detector

- 25 kton ultra-pure water
- 2.4k 20″ PMTs
- High μ detection efficiency
- Protects CD from external radioactivity

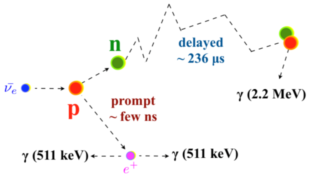
Central Detector

- 35.4 m diameter acrylic sphere
- 20 kton liquid scintillator
- 18k 20″ PMTs + 25k 3″ PMTs, 78% PMT coverage

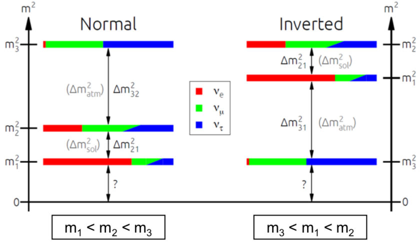
Physics of JUNO

Detection Principle

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

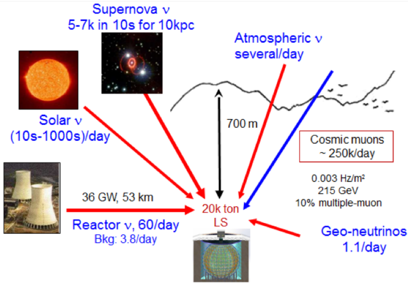


Mass Hierarchy



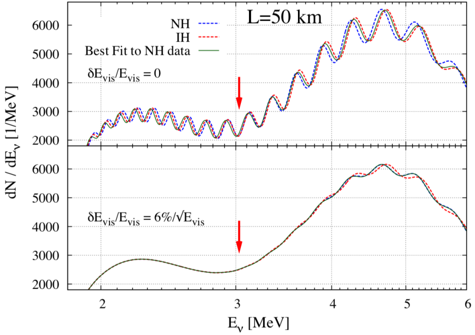
Physics

- Mass Hierarchy (MH)
- Precise measurement of parameter $(\theta_{12}, \Delta m^2_{21}, \Delta m^2_{31})$
- Reduce uncertainty on δ_{CP}
- Understand requirement for $0\nu\beta\beta$ experiment

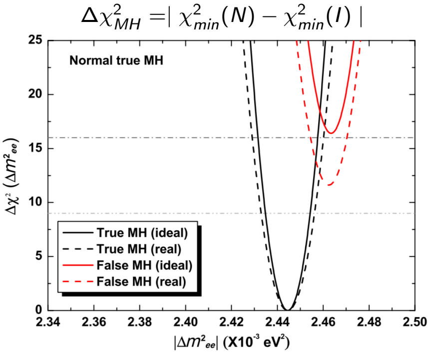


Motivation of Vertex Reconstruction Study

To determine MH, require energy resolution better than $3\%/\sqrt{E}$



Shao-Feng Ge et al., JHEP1305, 131 (2013)

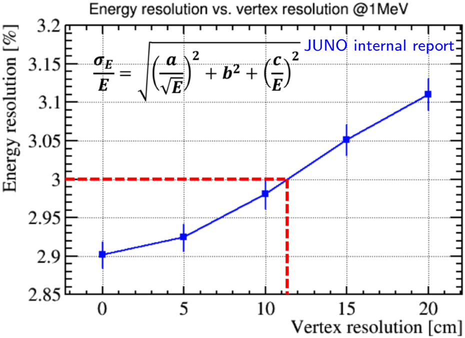


Yu-Feng Li et al., PRD88, 013008 (2013)

Base on the current experiment setup, could reach 3 - 4σ sensitivity in 6 years

Motivation of Vertex Reconstruction Study

Energy resolution vs. Vertex resolution



To achieve 3% energy resolution,
Vertex resolution better than 12cm is needed

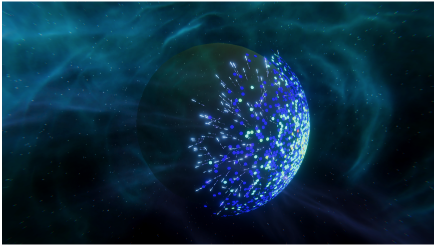
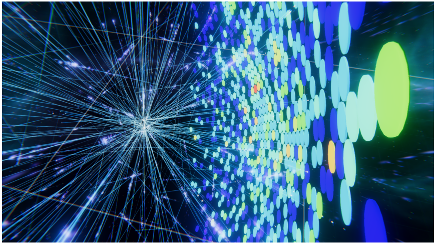


Illustration of Vertex



Vertex Reconstruction

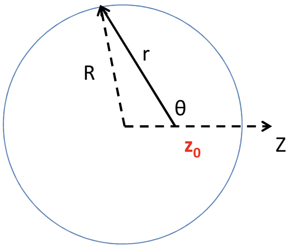
- Charge Center
- Time Likelihood
- Deep Learning

Charge Center Algorithm Principle

Use charge information as weight for each PMT, the vertex position can be estimated by $\vec{r}_{rec}$:

$$\vec{r}_{rec} = \alpha \sum_i q_i \vec{r}_i / \sum_i q_i$$

where :
q_i: i PMT collected charge;
$\vec{r}_i$: i PMT position;
α: 1.2 correction factor



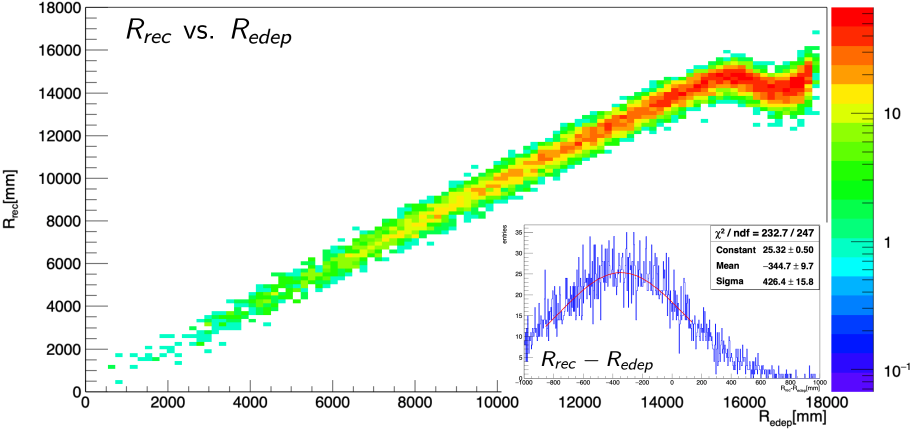
Mathematic calculation :

$$\begin{aligned} z_{rec} &= \frac{1}{4\pi}\int z d\Omega \\ &= \frac{1}{4\pi}\int_0^{2\pi}(z_0 + r \cdot cos\theta) sin\theta d\theta \\ &= \frac{1}{2}\int_0^{2\pi}(z_0 + (\sqrt{R^2 - z_0^2 sin^2\theta} - z_0 cos\theta) \cdot cos\theta) sin\theta d\theta \\ &= \frac{2}{3} z_0 \end{aligned}$$

- Light source deployed at z_0
- Gamma evenly emitted in 4π solid angle of z_0
- Charge center method reconstructs vertex at $2/3\ z_0$

Charge Center Performance

For $R_{edep} > 16$m, due to total refraction, the charge distribution change, charge center method doesn't work well



Vertex Resolution : $\sigma = 400$mm @ 1MeV

- ▷ Charge Center
- ▷ Time Likelihood
- ▷ Deep Learning

Time Likelihood Algorithm Principle

For point-like events like e^+, e^-, γ deposit energy in liquid scintillator and emit photons, define residual hit time :

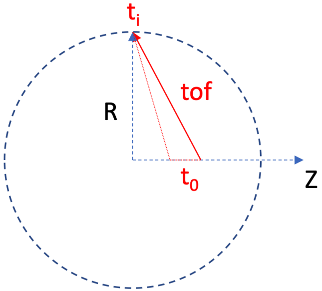
$$t_{i,res} = t_i - tof - t_0$$

where :

t_i : First hit time of i PMT;

tof : Time of flight for scintillating photon;

t_0 : Real time of an event.



Time Likelihood Algorithm Principle

- Charge Center Method to get initial vertex
- For each iteration step with vertex position $\vec{R_0}$, calculate $t_{i,res}$ for each PMT

$$t_{i,res}(\vec{R_0}, t_0) = t_i - \sum_{\alpha} \frac{D_\alpha(\vec{R_0}, \vec{R_i})}{c_\alpha} - t_0$$

  where :
  α : Different material;
  c_α : Light speed in material;
  D_α : Photon travel length in material;
  R_i : Position of i PMT.

- Define Joint Likelihood Function

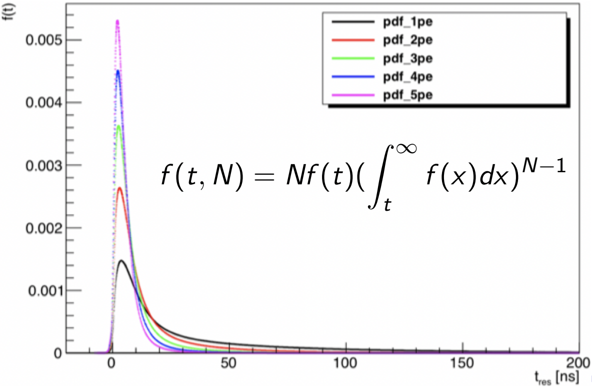
$$\mathcal{L}(\vec{R_0}, t_0) = -\sum_i \ln(f(t_{i,res}))$$

- Minimize likelihood function to get the best vertex position

Possibility Density Function

The quality of vertex reconstruction depends on how well our PDF could describe the physical processes

- Put 4.4MeV γ source at the center, get the t_{res} distribution from simulation for PMT with nPE=1
- In case nPE > 1, use the following equation to calculate the PDF



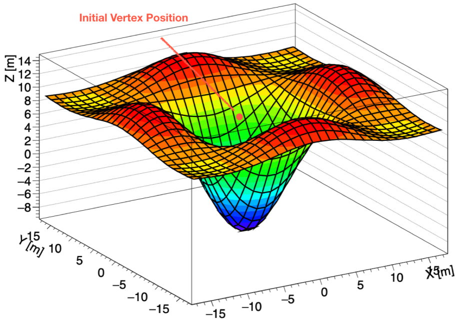
GridSearch Minimization

Step :

* Get initial vertex position from Charge Center Method

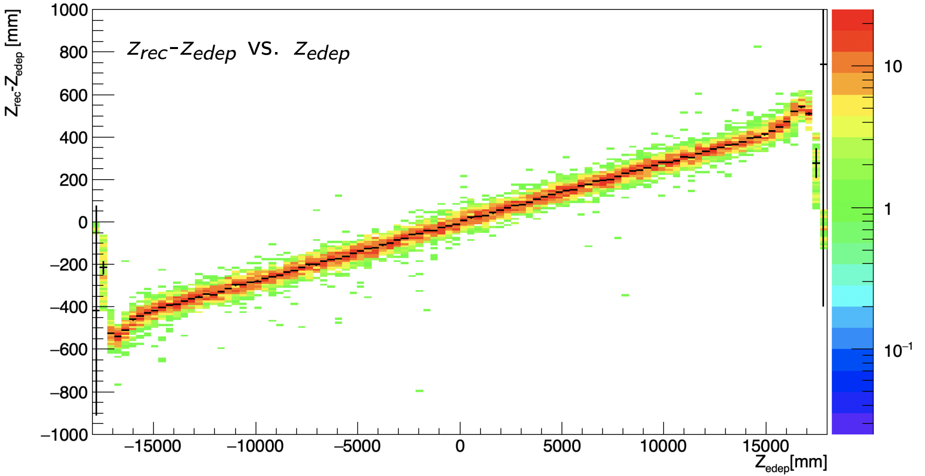
@ For each direction (X,Y,Z) and iteration, ± 1 step to find the minimum grid in the current step_length

& step_length divided by 2 and go to @, stop iterate until step_length $< 0.1mm$



Vertex Reconstruction Bias

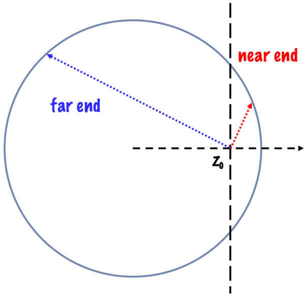
Apparent correlations between z_{rec}-z_{edep} mean bias and z_{edep}



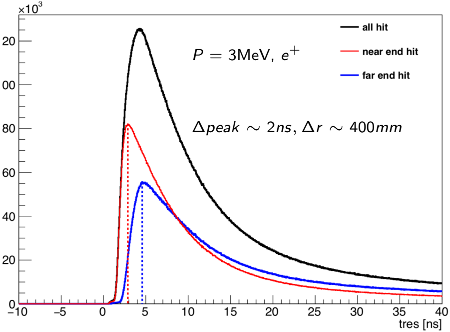
Effective Light Speed

Time of Flight is not correct : $t_{res} = t_i - tof - t_0$

- The actual path length that a photon traveled is longer than the length of straight line between hit and vertex
- Using straight line and c_{LS} $(\frac{c}{n_{LS}})$ makes *tof* smaller than actual, $t_{res} > 0$
- Both near and far ends want to recover its correct path, pushing vertex recostruct to the other end



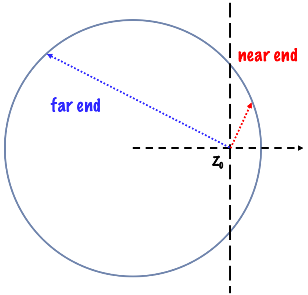
$t_i - tof$ @ $z = 10m$, $n_{LS} = 1.49$



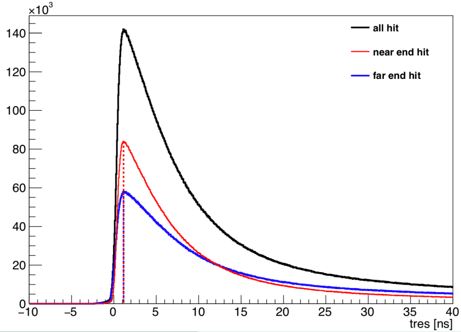
Effective Light Speed

Time of Flight is not correct : $t_{res} = t_i - tof - t_0$

- To correct *tof*, should use true path length (unknown)
- Alternative is to introduce the effective speed of light c_{eff} ($\frac{c}{n_{eff}}$)
- $tof = \frac{distance}{c_{eff}}$, an appropriate c_{eff} can correct *tof* back



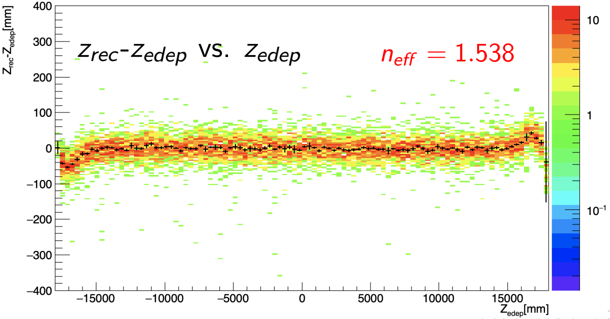
$t_i - tof$ @ $z = 10m$, $n_{eff} = 1.538$



Effective Light Speed

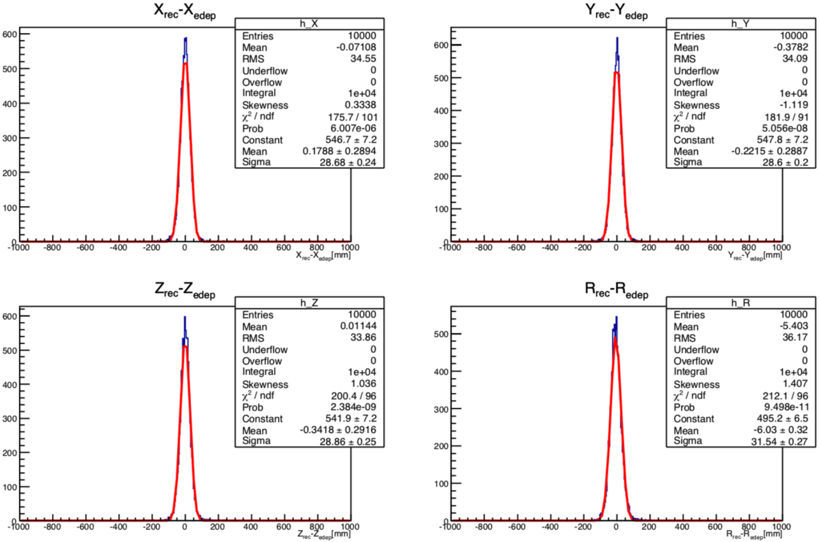
Time of Flight is not correct : $t_{res} = t_i - tof - t_0$

- To correct *tof*, should use true path length (unknown)
- Alternative is to introduce the effective speed of light c_{eff} $(\frac{c}{n_{eff}})$
- $tof = \frac{distance}{c_{eff}}$, an appropriate c_{eff} can correct *tof* back
- c_{eff} is a parameter to simplify the entire optical model, including both geometrical and physical effect



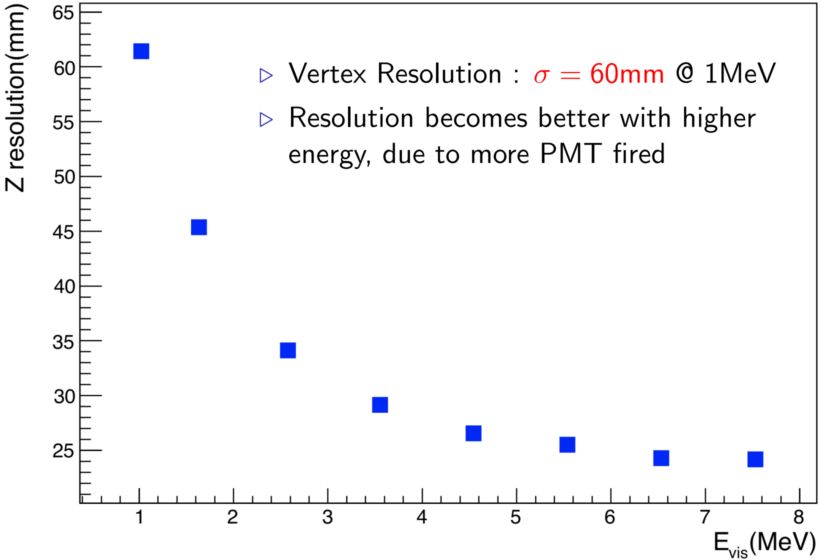
Time Likelihood Performance

Reconstruction in each direction



Time Likelihood Performance

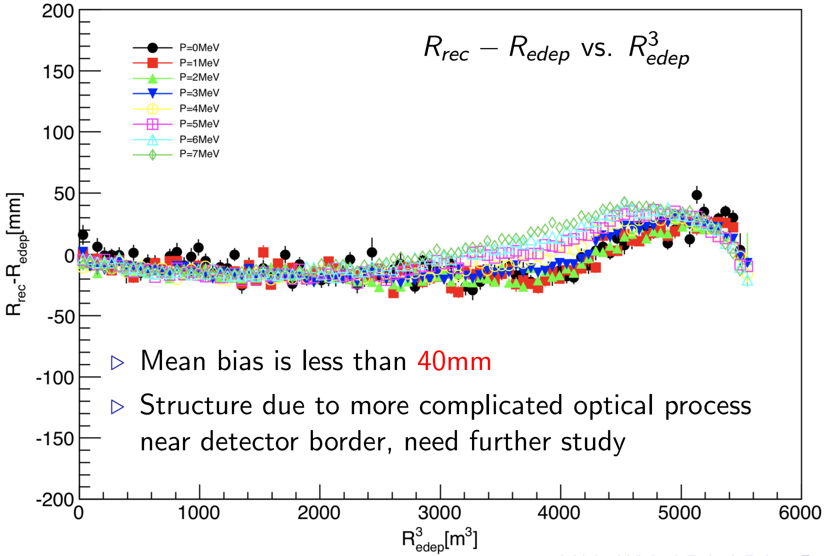
Resolution vs. Energy



- ▷ Vertex Resolution : $\sigma = 60\mathrm{mm}$ @ 1MeV
- ▷ Resolution becomes better with higher energy, due to more PMT fired

Time Likelihood Performance

Vertex Reconstruction Bias



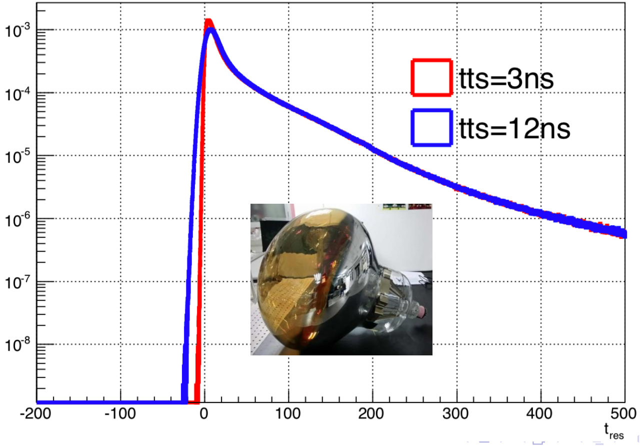
- Mean bias is less than 40mm
- Structure due to more complicated optical process near detector border, need further study

More factors to consider

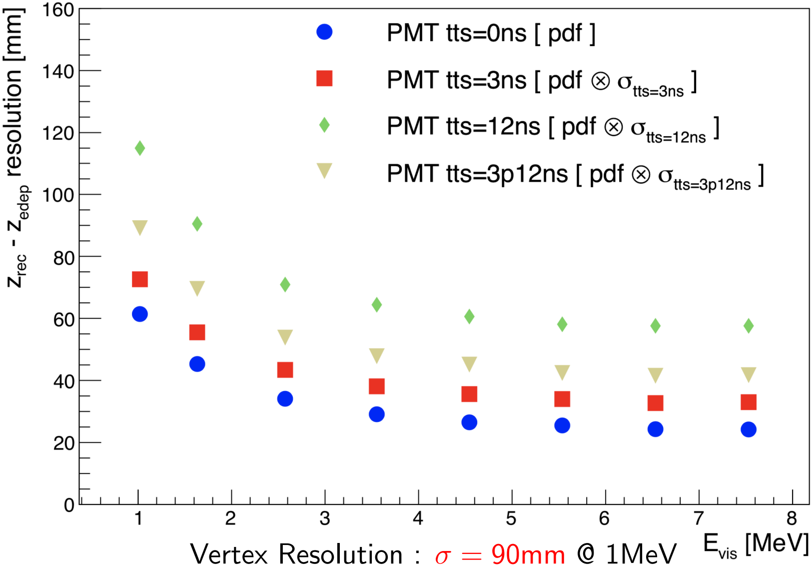
In real experiment, the following effects will worsen resolution

- PMT Time Transit Spread (TTS)
- Waveform Reconstruction
- Dark Noise

t_{res} PDF after consider TTS



Time Likelihood Performance with TTS



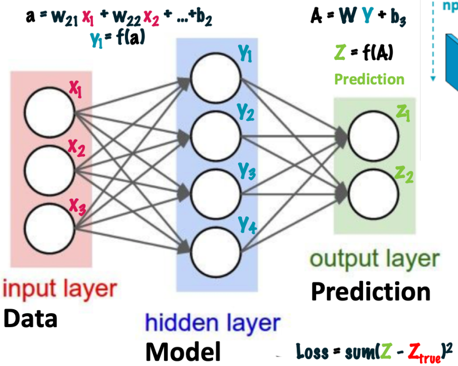
Vertex Resolution : $\sigma = 90$mm @ 1MeV

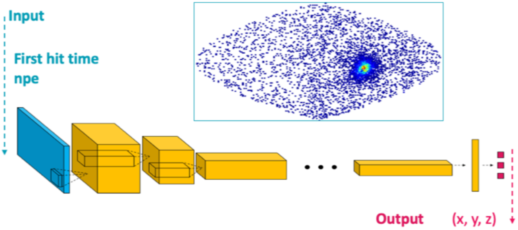
Vertex Reconstruction

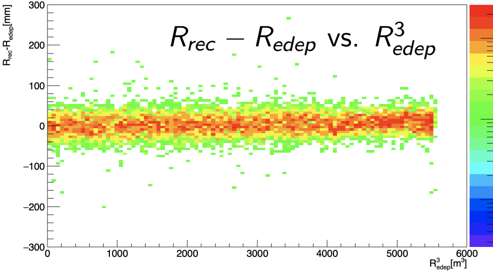
- Charge Center
- Time Likelihood
- Deep Learning

Deep Learning

Basic concept



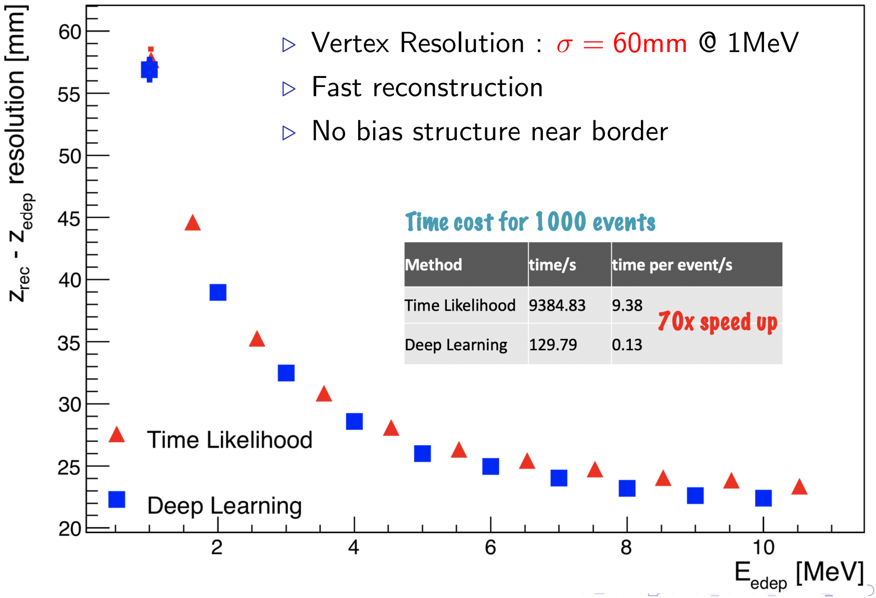




Minimize loss function to get parameters w, b

Deep Learning Performance

- ▷ Vertex Resolution : $\sigma = 60\text{mm}$ @ 1MeV
- ▷ Fast reconstruction
- ▷ No bias structure near border



Time cost for 1000 events

Method	time/s	time per event/s
Time Likelihood	9384.83	9.38
Deep Learning	129.79	0.13

70x speed up

Summary

Conclusion

- Three methods have been developed for vertex reconstruction in JUNO : Charge Center, Time Likelihood, Deep Learning
- Vertex Resolution is 60mm @ 1MeV, and 90mm @ 1MeV with TTS
- Vertex mean bias is less than 40mm

Outlook

- Further investigate the physic behind vertex bias
- Reconstruct with Dark Noise
- Deep Learning with TTS and Dark Noise

The End

Thanks for your attention !