Bayesian Reconstruction for Point-like Events

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^{9}Li/^{8}He Background in JUNO

IBD reaction:

$$\bar{\nu}_e + p \rightarrow e^+ + n \tag{1}$$

High energy μ will produce ^{9}Li/^{8}He in LS, which will produce $\beta^- - n$ decay:

$$^7\mathrm{Li} \rightarrow 2\alpha + e^- + \bar{\nu}_e + n \tag{2}$$

$$^8\mathrm{He} \rightarrow {}^7\mathrm{Li} + e^- + \bar{\nu}_e + n \tag{3}$$

They are confusing compared with IBD, because they could only be distinguished if e^+/e^- could be identified.

e^+ Energy Deposition

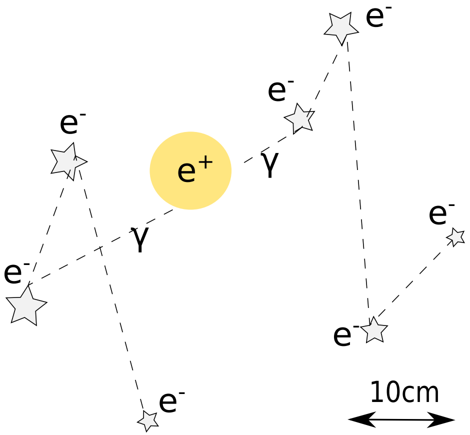


图: Schematics of e^+ energy deposition, which could be described as "clear sky, stars and a full moon". e^- energy deposition is simpler, which only contains a "full moon".

More Precision

To identify e^+/e^-, we need a reconstruction method for multiple point-like events.

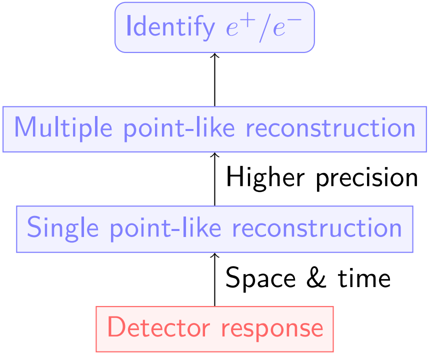
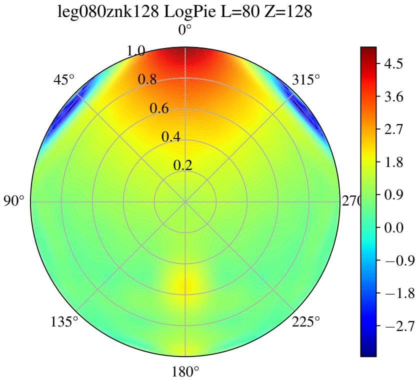


图: The algorithm development logic

Probe for Jinping I



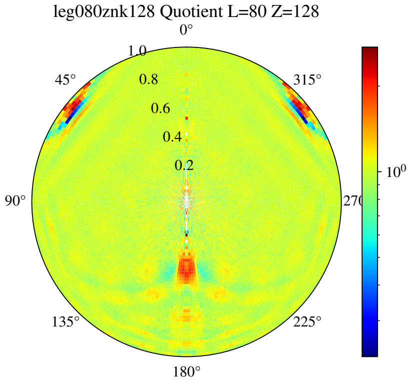


图: Probe function integrated by t. Note the total reflection area and the focus area.

图: Real charge divided by Probe function. There's still some area where the fit Probe is not ideal.

For the structure of Jinping 1t detector, see Lin Zhao's report.

Probe for Jinping II

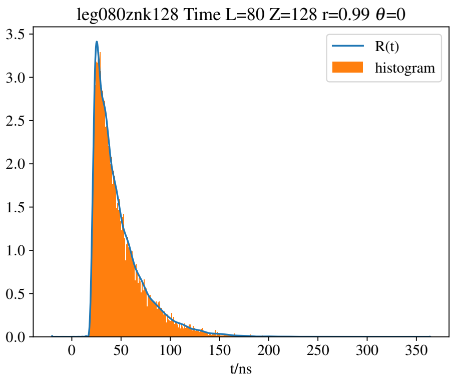


图: The PE time histogram and the fit Probe, the intensity of the inhomogeneous Poisson process.

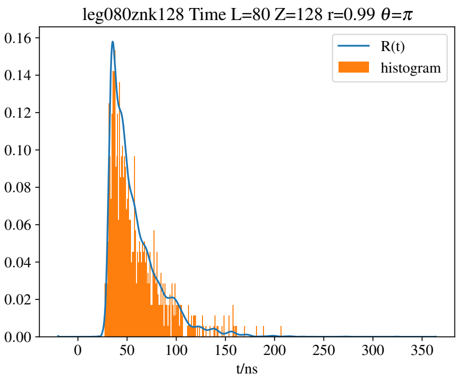


图: Note that the intensity is differ from the vertex position.

Fit the Detector Response

Consider a point-like event $\delta(\mathbf{r}, t_0)$, we hope to obtain the response on PMT j, which is an inhomogeneous Poisson process:

$$G_j[\delta(\mathbf{r}, t_0)] = R_j^\delta(t; r, \theta_j; E) \tag{4}$$

while R_j^δ is called Probe function.

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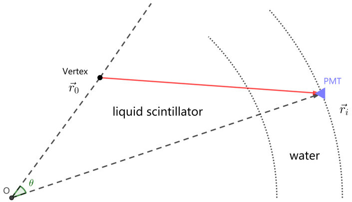
R_j can be obtained by

- Photon propagation
- Regression, neural networks, and others...

e.g.

$$R_j(t; r, \theta_j; E) \to \sum_{m,n} a_j^{mn}(E) P_m(t) Z_n(r, \theta_j) \quad (5)$$



Fast Bayesian Matching Persuit

FBMP is a waveform analysis algorithm, which does not give a certain hit sequence, but a series of hit sequence $\{\mathbf{s}\}$, with their own probability $p(\mathbf{w}|\mathbf{s})$.

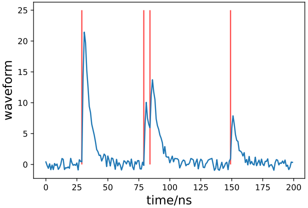


图: Perfect PE matching waveform, $p(\mathbf{w}|\mathbf{s})$ hits maximum

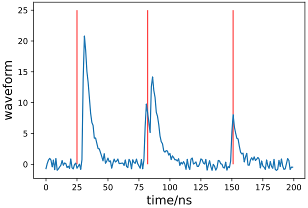


图: Not so perfect, $p(\mathbf{w}|\mathbf{s})$ is smaller but still > 0

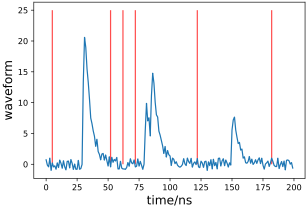


图: Completely mismatch, $p(\mathbf{w}|\mathbf{s}) \to 0$

For more information of FBMP, see Dacheng Xu's poster.

Take Use of More Information

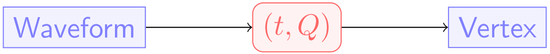


图: Traditional method uses the most likely PE t & Q from waveform for vertex reconstruction.

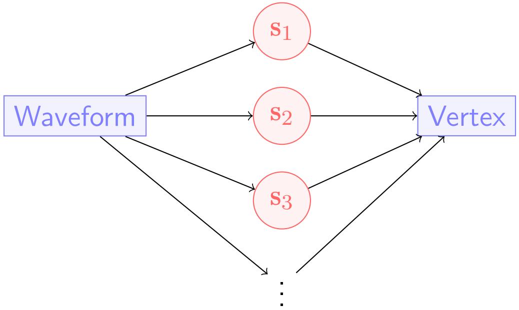


图: BAPPE uses a series of hit sequence $\{\mathbf{s}\}$ and directly reconstruct to vertex.

Bayesian Probe for Point-like Events

The final problem is reconstruction, that is, to maximize $p(t, \mathbf{r}, E|\mathbf{w})$, while

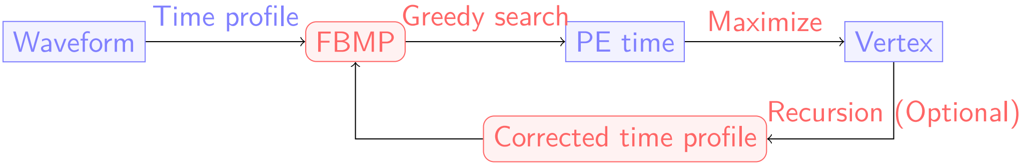
$$p(t, \mathbf{r}_j, E|\mathbf{w}_j)p(\mathbf{w}_j) = \sum_{\mathbf{s}} \left(p(\mathbf{w}_j|\mathbf{s})p(\mathbf{s}|t, \mathbf{r}_j, E)\right) p(t, \mathbf{r}, E) \tag{6}$$

which $p(\mathbf{w}_j|\mathbf{s})$ is obtained from FBMP, and $p(\mathbf{s}|t, \mathbf{r}_j, E)$ is calculated with Probe function. Consider that $p(\mathbf{w_j})$ and $p(t, \mathbf{r}, E)$ is constant, we could only focus on maximizing

$$\mathcal{L}(t, \mathbf{r}_j, E) = \sum_{\mathbf{s}} \left(p(\mathbf{w}_j|\mathbf{s})p(\mathbf{s}|t, \mathbf{r}_j, E)\right) \tag{7}$$

BAPPE Workflow

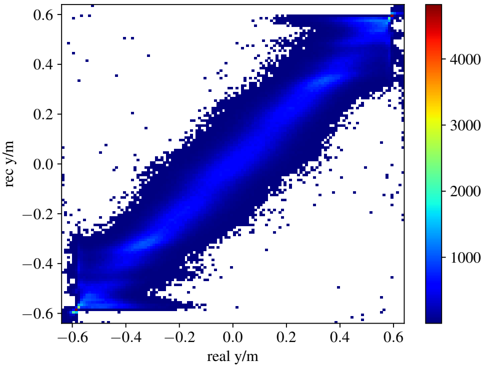
We could also consider correct the time profile with reconstructed vertex from previous calculation, and apply BAPPE recursively.



With BAPPE, we could reconstruct vertex and energy directly from waveforms. It unifies the traditional method, which splits the steps by time-charge and vertex-energy reconstruction.

BAPPE Sample

- Jinping-like detector
- Radius: $0.645\,\mathrm{m}$
- Energy: $2\,\mathrm{MeV}$
- Vertices are all on the y axis.
- PMT number: 30
- Coverage: $\sim 13\%$



This is the first successful reconstruction result directly from waveforms to vertices.

Summary

- We developed a new reconstruction method combining waveform analysis, vertex reconstruction and energy reconstruction.
- Reconstruct vertex directly by waveform is feasible.
- There's still some challenges in calibration of Probe.

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Outlook

- BAPPE is suitable of a lot LS detectors, e.g., Jinping, JUNO, etc.
- Welcome to Wei Dou's report on BAPPE2.

Probe for TAO-like I

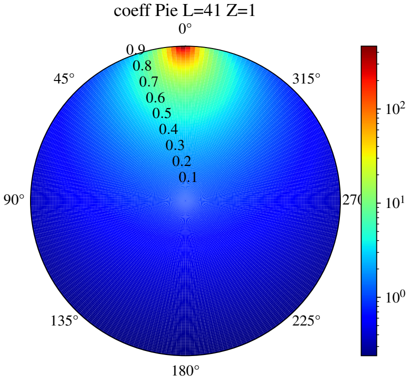


图: Probe function integrated by t

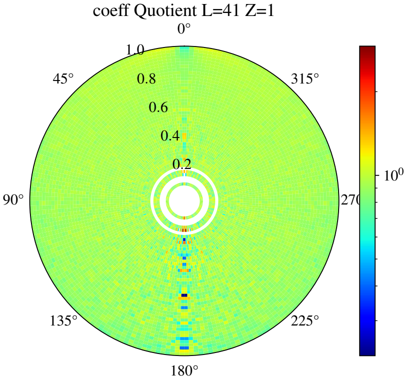
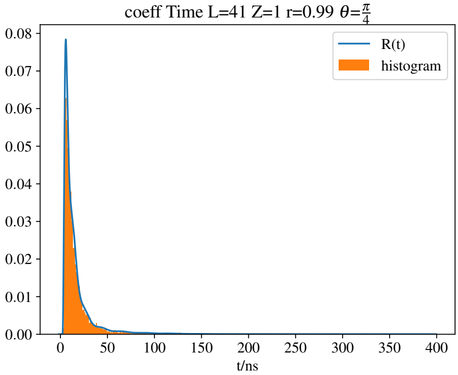
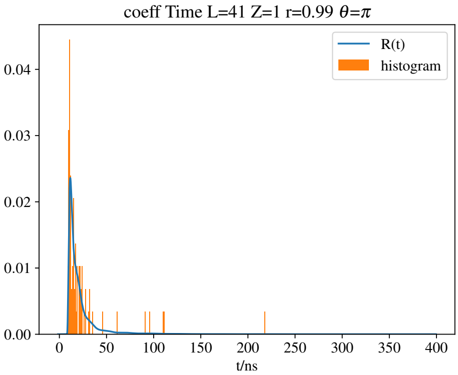


图: Real charge divided by Probe function

Probe for TAO-like II





Fit the Probe Function

For each PE i and event k, the likelihood is

$$\log \mathcal{L} = \log \prod_i R_{j_i}(t_i; r_i, \theta_{j_i}) - \sum_{j,k} \int R_j(t; r^k, \theta_j^k) \mathrm{d}t \tag{8}$$

Probe function is the expectation of charge, which should be nonnegative. To satisfy this constraint, we could decompose the square root of Probe:

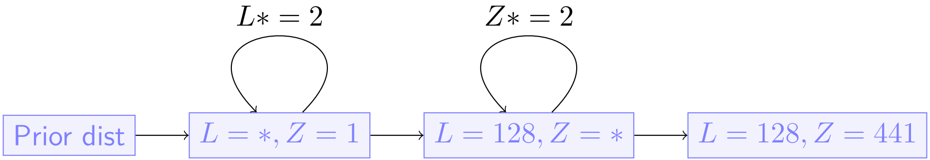
$$\sqrt{R_j(t; r, \theta_j; E)} = \sqrt{\frac{E}{\tilde{E}}} \sum_{m,n} a_j^{mn}(\tilde{E}) P_m(t) Z_n(r, \theta_j) \tag{9}$$

This decomposition gives convenience for integration:

$$\int_{-1}^{1} R_j(t; r, \theta_j; E) \mathrm{d}t = \frac{E}{\tilde{E}} \sum_{m,n,p} a_j^{mn} a_j^{pn} Z_n(r, \theta_j) Z_p(r, \theta_j) \tag{10}$$

Fit the Probe Function

In practice, we could use MCMC to maximize $\mathcal{L}$.
As it usually causes a lot of time, we could approach step by step to the order we would like.
For example, we could start by 1-order Legendre and 1-order Zernike.



We could also approach it by giving a good prior, obtained from the fitting of marginal distribution of PE.