Reconstruction for pile-up events based on Markov chain Monte Carlo method in liquid scintillator detectors

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Liquid Scintillator Detectors

- Liquid scintillator detectors have become crucial in neutrino physics due to their cost-effectiveness and high precision.
- Close successive events (^{14}C coincidence, ^{212}Bi^{212}Po) will pile up within the 1 μs time window.
- We explore multi-site reconstruction algorithm to address it.

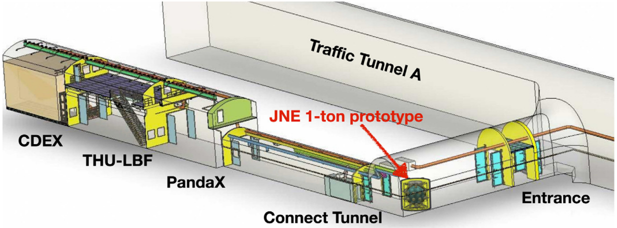

Figure: Schematic layout of hall A at CJPL-I

Pile up within the same time window

- The PEs from different vertices overlap in the same time window.
- The waveform analysis method FSMP (arxiv: 2403.03156) is developed to reconstruct the t_{PE}. (TAUP2025: oral 191)
- PE timings makes the separation of different vertices more possible.

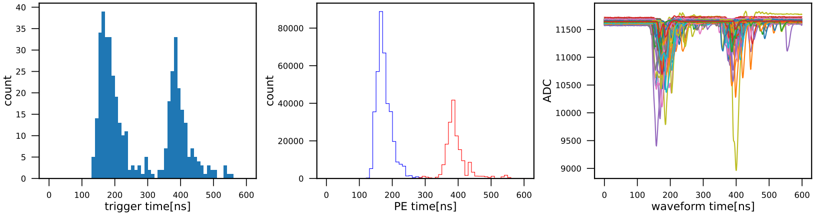

Figure: Pile up event example

BAyesian **P**robe for **P**oint-like **E**vents

BAyesian Probe for Point-like Events

Based on the waveforms observed from PMTs, predict $(\vec{r}, E, t_0)$ of the vertex.

- FSMP outputs posterior ensemble of **PE timings sequence**.
- $\{z_j\}$ contains richer temporal information than first hit time and charge, for enhanced resolution.

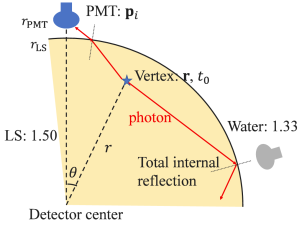

Figure: Vertex lighting schematic

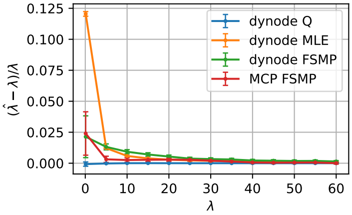

Figure: performance of FSMP with toy MC

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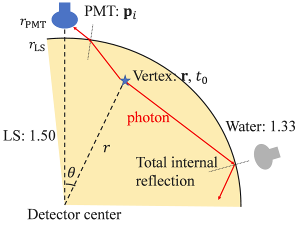


Figure: Vertex lighting schematic

- Probe(doi: 10.1016/j.nima.2023.168692): The Poisson intensity of $\{\boldsymbol{z}_j\}$ is determined by *probe* $R_j(t; \vec{r}, E, t_0)$ and the darknoise count rate b_j of each PMT. (TAUP 2025: poster 96)
- BAPPE is accomplished by integrating FSMP and *probe* through the total probability formula

Likelihood

Likelihood for the given true value $\boldsymbol{z}$

$$p(\boldsymbol{z}_j|\vec{r}, E, t_0) = \prod_{k=1}^{n_j}[R_j(t_{jk}; \vec{r}, E, t_0) + b_j] \exp\left\{-\int_{\underline{t}}^{\overline{t}}[R_j(t - t_0; \vec{r}, E, t_0) + b_j]\mathrm{d}t\right\}$$

- $\{\boldsymbol{z}_j\}$: PE timings sequence of the jth PMT
- $R_j(t_{jk}; \vec{r}, E, t_0)$: The probe is suitable for deployment across multiple detectors: JNE, OSIRIS, TAO, JUNO
- b_j: Dark noise naturally incorporates into the Poisson intensity

Likelihood

Likelihood function

Likelihood for the given true value $\boldsymbol{z}$

$$p(\boldsymbol{z}_j|\vec{r}, E, t_0) = \prod_j \prod_{k=1}^{n_j} [R_j(t_{jk}; \vec{r}, E, t_0) + b_j] \exp\left\{ -\int_{\underline{t}}^{\overline{t}} [R_j(t - t_0; \vec{r}, E, t_0) + b_j] \mathrm{d}t \right\}$$

Full likelihood

$$\mathcal{L}(\vec{r}, E, t_0|\{\boldsymbol{w}_j\}) = \prod_j p(\boldsymbol{w}_j|\vec{r}, E, t_0) = \prod_j \widetilde{\sum_{\boldsymbol{z}}} p(\boldsymbol{w}_j|\boldsymbol{z}_j) p(\boldsymbol{z}_j|\vec{r}, E, t_0)$$

$\widetilde{\sum}_{\boldsymbol{z}}$ is implemented within FSMP. $\{\boldsymbol{z}_j\}$ leads to a more concise and direct likelihood.

BAPPEn: BAPPE for multi-site events

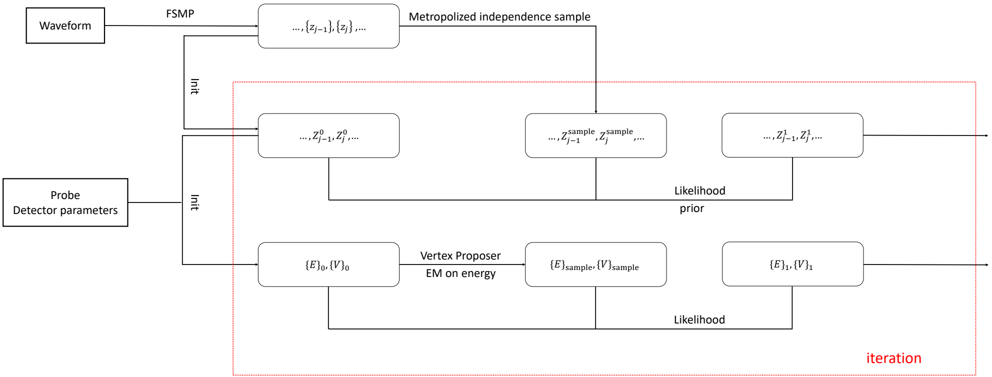
- Denote $(\vec{r}, t_0)$ as $\mathcal{V}$
- The additivity of Poisson processes naturally extends to multi-site reconstruction.

Likelihood function of BAPPEn for multi-point events

$$p(\boldsymbol{z_j}|\{E_m\},\{\mathcal{V}_m\}) = \prod_{k=1}^{n_j}\left[\sum_{m=1}^{N} R_j(t_{jk};E_m,\mathcal{V}_m)+b_j\right]\exp\left\{-\int\sum_{m=1}^{N}[R_j(t;E_m,\mathcal{V}_m)+b_j]\mathrm{d}t\right\}$$

Gibbs sampling

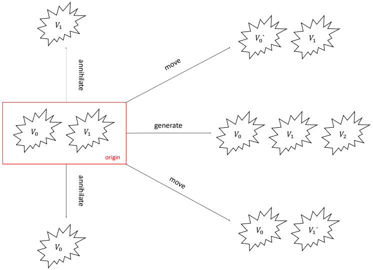
Using Gibbs group sampling to sample from the posterior distribution of parameters.



Reversible Jump MCMC on the group of $(\{E_m\}, \{\mathcal{V}_m\})$

Perturbation of $\{\mathcal{V}_m\}$: Reversible Jump MCMC

- Generate: a vertex is randomly generated $(\{\mathcal{V}_m\}_i \to \{\mathcal{V}_m\}_i \cup \mathcal{V}_+)$
- Annihilate: one of the vertices is randomly chosen to be removed $(\{\mathcal{V}_m\}_i \to \{\mathcal{V}_m\}_i \setminus \mathcal{V}_-)$
- Move: one of the vertices is randomly selected to move its position $(\{\mathcal{V}_m\}_i \setminus \{\mathcal{V}_-\} \cup \{\mathcal{V}_+\})$



Too many parameters make it difficult to converge. Using the EM algorithm on $\{E_m\}$ with the profile likelihood to speed up

$$p(\{\mathbf{z}\}|\{\mathcal{V}_m\}) = \arg\max_{\{E_m\}} \; p(\{\mathbf{z}\}|\{E_m\}, \{\mathcal{V}_m\})$$

Performance of BAPPE on Simulated Data

JNE 1-ton prototype

Figure: JNE 1-ton prototype

- Location: The China Jinping Underground Laboratory (CJPL)
- Scintillator: 0.07 g/L PPO, 13 mg/L bisMSB in LAB
- Radius of scintillator: 0.645 m
- PMTs: 60 8-inch NNVT MCP-PMTs
- Data acquisition: 1 GHz FADC, 1000 ns readout
- Simulation Trigger threshold: 25 PMTs hit
- Simulation Dataset: 4000 ^{212}Bi decay events uniformly distributed in the detector.

Performance of Energy on Delayed Vertex in ^{212}Bi^{212}Po

- The delayed vertex is 8.95MeV α.
- E_{truth} is defined as the number of photons emitted by 1 MeV electron.
- The energy resolution is $11.08 \pm 0.27\%$ @ 0.87 MeV.

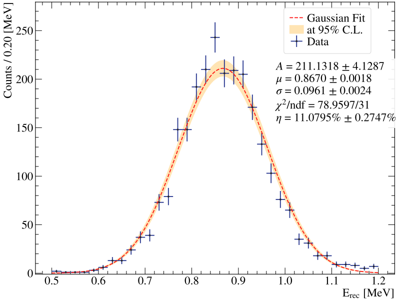


Figure: Energy reconstruction

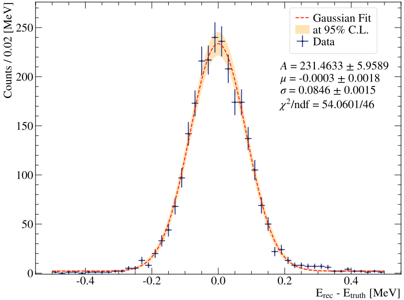


Figure: Energy bias distribution

Performance of Position and Timing on Delayed Vertex in BiPo212

- The spatial resolution $\sigma(\mathrm{x}_{\text{rec}} - \mathrm{x}_{\text{truth}})$ is 3.71 ± 0.80 cm @ 0.87 MeV.
- The timing resolution $\sigma(\mathrm{DeltaT}_{\text{rec}} - \mathrm{DeltaT}_{\text{truth}})$: 1.482 ± 0.024ns.

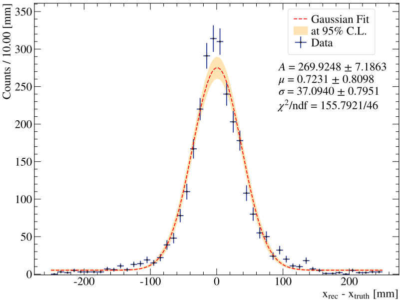


Figure: Position reconstruction

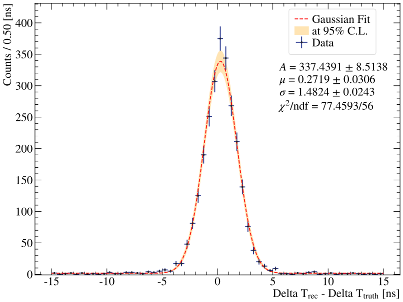
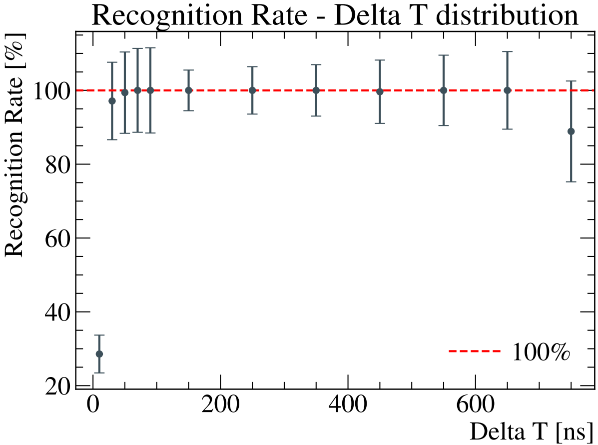


Figure: Energy reconstruction

Performance of BiPo212 discrimination

- Events separated by more than 100 ns are resolvable within the time window.



Affect of Afterpulse

Affect of Afterpulse

Affect of Afterpulse

- The after-pulses from MCP-PMTs are not accounted for in the simulation, which affects the event reconstruction when the BAPPEn algorithm is applied to the raw data.
- In the time window of 1000ns, the after-pulse can be observed in the MCP-PMT of JNE 1-ton prototype.(doi: 10.1016/j.nima.2023.168506)

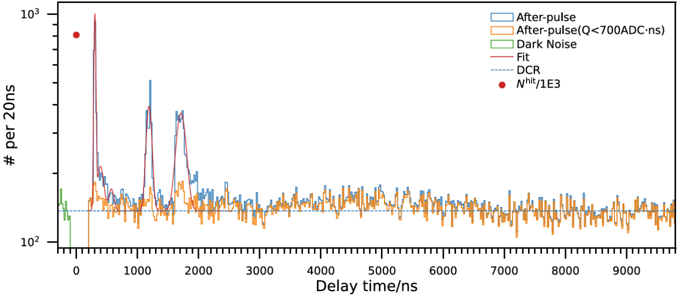


Figure: time distributions of darknoises, after-pulses for an MCP-PMT

After-pulse parameters of MCP-PMTs

- The after-pulse from H^+, H_2^+, He^+ will affect the reconstruction of BAPPEn.
- The after-pulse needs to be modeled in the likelihood function of BAPPEn.

	H^+	H_2^+	He^+
t / ns	300 ± 4	414 ± 25	596 ± 53
A / N^{hit} / 10^{-3}	1.6 ± 1.1	0.5 ± 0.3	0.2 ± 0.2
σ / ns	16 ± 6	46 ± 9	33 ± 10

Table: After-pulse parameters of MCP-PMTs(doi: 10.1016/j.nima.2023.168506)

Summary

- BAPPE is a joint reconstruction method based on likelihood from waveform to vertex.
- BAPPEn is an extension of BAPPE for multi-site events.
- The performance of BAPPEn is verified on the simulated ^{212}Bi^{212}Po dataset in the JNE 1-ton prototype.

Prospects

- Consider the after-pulse in the likelihood function of BAPPEn.
- Apply BAPPEn to the ^{212}Bi^{212}Po candidates and ^{14}C pile up events in the liquid scintillator detectors. Such as JNE, JUNO.

Thank you for listening!

Gibbs sampling on the group of $\boldsymbol{z}$

FSMP provides accurate posterior distribution of **PE timings sequence** $\{\boldsymbol{z}\}$
Perturbation of $\boldsymbol{z_j}$: Using $\boldsymbol{z}'_j$ frequency weighted random selection (Metropolized independence sampler)

$$\boldsymbol{z}_j \to \boldsymbol{z}'_j$$

The acceptance of $\boldsymbol{z_j}$ is

$$\min\left\{1, \frac{p(\boldsymbol{z}'_j|\{E_m\},\{\mathcal{V}_m\})q_j(\boldsymbol{z}_j)}{p(\boldsymbol{z}_j|\{E_m\},\{\mathcal{V}_m\})q_j(\boldsymbol{z}'_j)}\right\}$$

- $q_j(\boldsymbol{z}_j)$ is the pre-determined prior distribution when FSMP sampling on $\boldsymbol{z}$

Energy Calibration with n-H Capture Gammas

- n-H capture gammas: 2.223 MeV delayed vertex from AmBe source
- Reconstruted energy of n-H capture gammas: 2.737 ± 0.001 MeV
- Energy resolution: 6.661 ± 0.011% @ 2.223 MeV

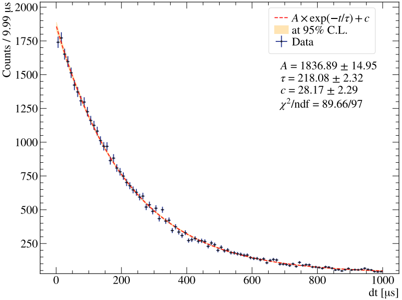


Figure: dt of n-H capture gammas

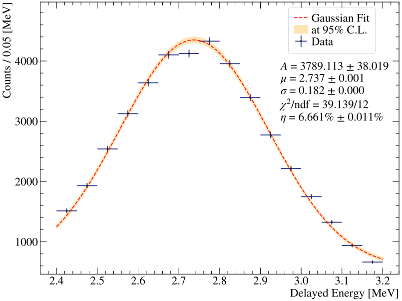
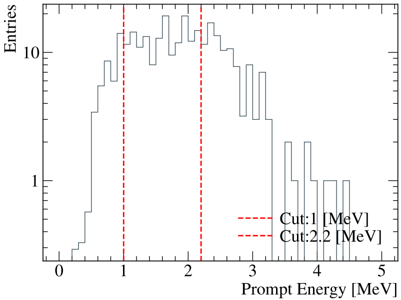


Figure: Energy spectrum of n-H

BiPo212 Cascades Selection

- Effective PMTs: 48. Trigger threshold: 32 PMTs hit
- Readout time window: 1000 ns
- Dataset: 27.3 h continuous data acquistion on 20250329-20250330

- Prompt energy $\in$ [1, 2.2] MeV
- Delayed energy $\in$ [0.7, 1.1] MeV
- Distance $<$ 15 cm
- Delat T $\in$ [50, 800] ns
- Prompt Timing $\in$ [100, 200] ns
- Delayed Timing $\in$ [150, 800] ns



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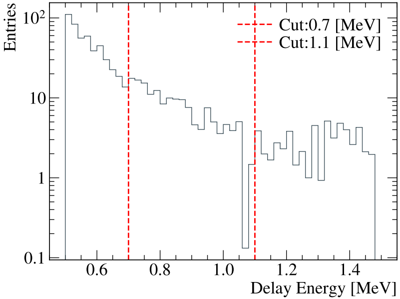

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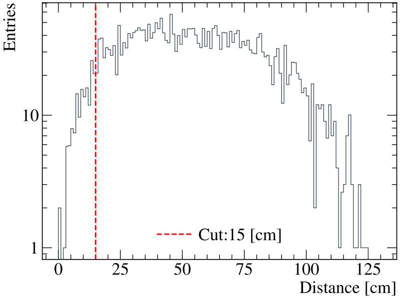

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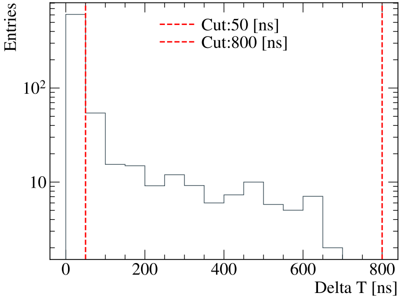

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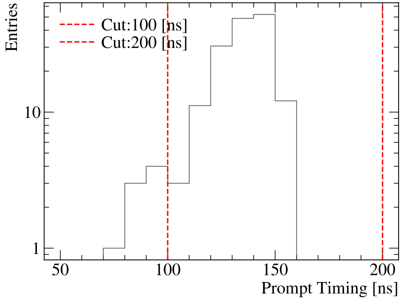

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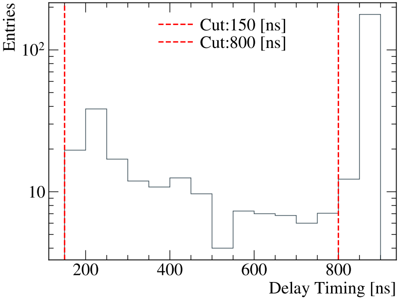

Half-life fitting

- The reference value is $\tau = 431$ ns
- Fitted: $\tau = 446.62 \pm 107.35$ ns