Energy and timing resolution boost with waveform analysis

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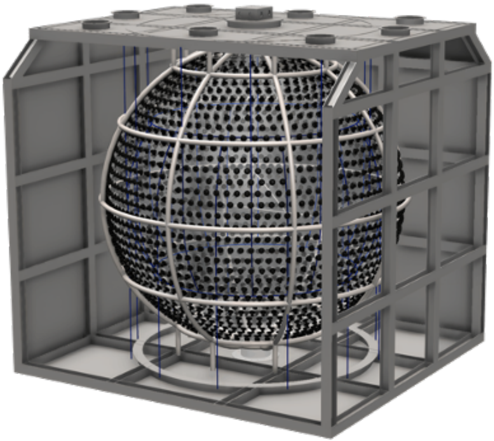
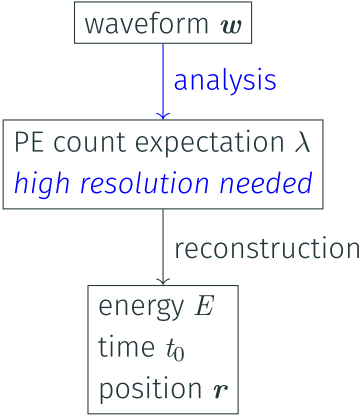
Motivation: high time resolution

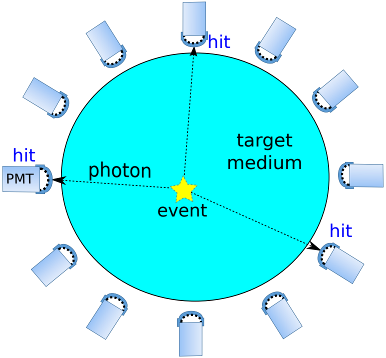
- Jinping Neutrino Experiment (JNE) is a 500-ton liquid scintillator detector under construction.
- Aims to detect neutrinoless double beta decays, geo-neutrinos, and solar neutrinos.
- Slow liquid scintillator:
  - Provides potential to distinguish Cherenkov & scintillation lights.
  - Needs sub-nanosecond time resolution when time difference <10 ns.



Motivation: high energy resolution

JUNO needs high energy resolution for neutrino mass ordering (NMO).





JNE and JUNO are spherical, liquid scintillator detectors.

A first-principle bottom-up approach on photon counting from waveforms

Photoelectrons (PEs) detected by PMT i follow an inhomogeneous Poisson process $R_i(t; E, t_0, \boldsymbol{r})$, incorporating scintillation time profile, photon time-of-flight, scattering, and re-emission effects.

$$
\begin{aligned}
\mathcal{L}(\{\boldsymbol{w}_i\}|E, t_0, \boldsymbol{r}) &= \prod_i p[\boldsymbol{w}_i|R_i(t; E, t_0, \boldsymbol{r}) + b_i] \\
&= \prod_i \sum_j p(\boldsymbol{w}_i|\boldsymbol{z}_j)p[\boldsymbol{z}_j|R_i(t; E, t_0, \boldsymbol{r}) + b_i]
\end{aligned}
$$

dark noise

waveform

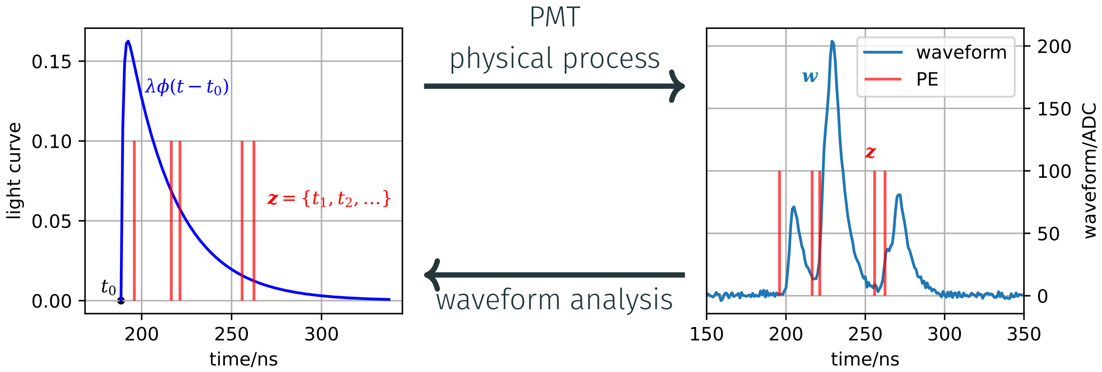
total probability

all PE times (sampled)

SPE charge spectrum embedded

PE arrival as random processes

PEs follow an inhomogeneous Poisson process with intensity $\lambda\phi(t - t_0)$.



Sample PEs from Poisson process

Convolve PEs into a waveform

Waveform analysis: a trans-dimensional integration

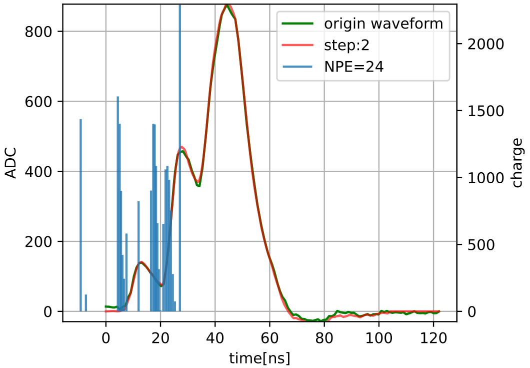
FSMP[1] (arXiv 2403.03156) samples PE times $\boldsymbol{z}$ from each waveform.

$$p(\boldsymbol{w}|R) = \underbrace{p(\boldsymbol{w}|\emptyset)p(\emptyset|R)}_{\text{no integral}}$$

$$+ \underbrace{\int_{\boldsymbol{z}\in T} p(\boldsymbol{w}|\boldsymbol{z})p(\boldsymbol{z}|R)\mathrm{d}\boldsymbol{z}}_{\text{single integral}}$$

$$+ \underbrace{\iint_{\boldsymbol{z}\in T^2} p(\boldsymbol{w}|\boldsymbol{z})p(\boldsymbol{z}|R)\mathrm{d}\boldsymbol{z}}_{\text{double integral}}$$

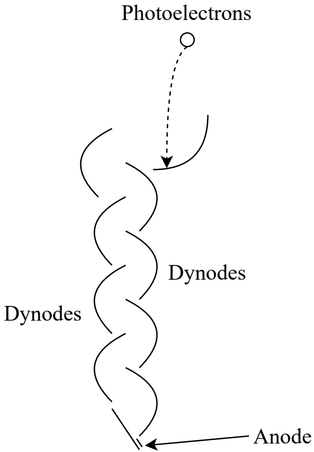
$$+ \underbrace{\iiint_{\boldsymbol{z}\in T^3} p(\boldsymbol{w}|\boldsymbol{z})p(\boldsymbol{z}|R)\mathrm{d}\boldsymbol{z}}_{\text{triple integral}} \cdots .$$

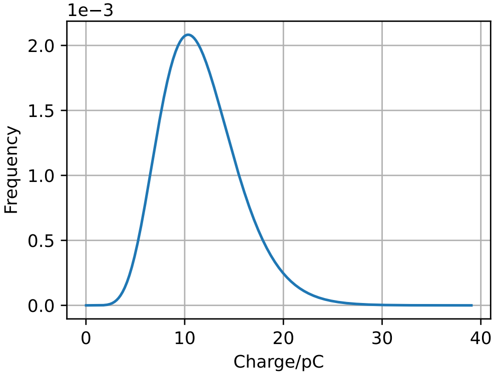


[1] Fast Stochastic Matching Pursuit

Charge model: single-PE spectra matters

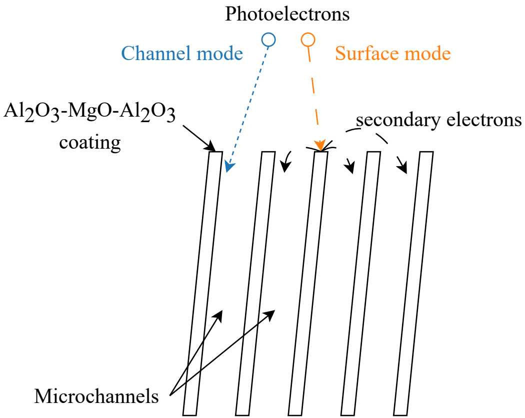
For dynode PMTs, the deposited charge follows a Gamma distribution.

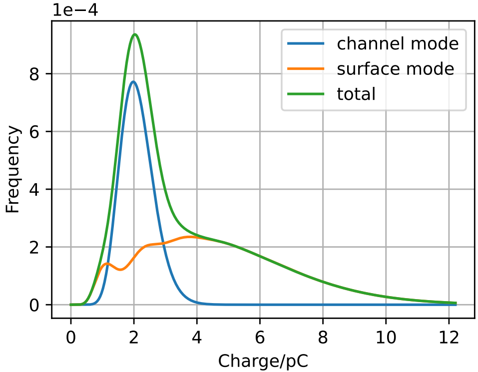




Charge Model: Microchannel Plate PMTs

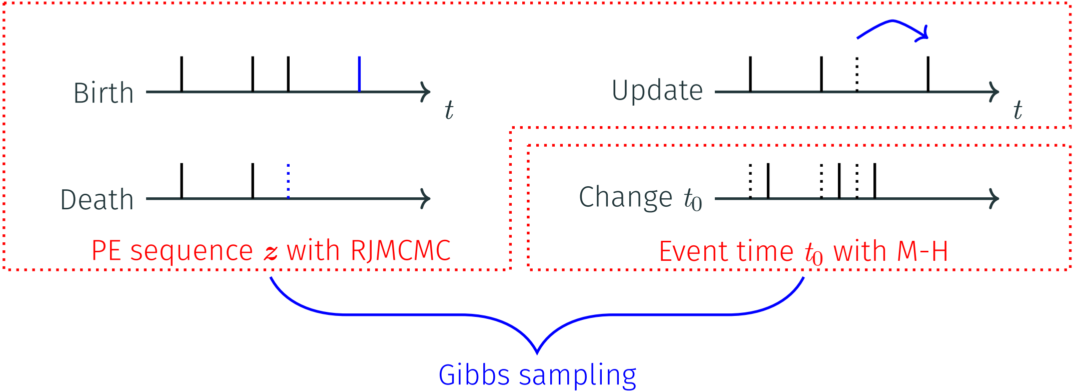
MCP-PMT charge distributions are more complex: a mixture of a Gamma distribution and a Poisson–Gamma compound, reflecting different modes of PEs.



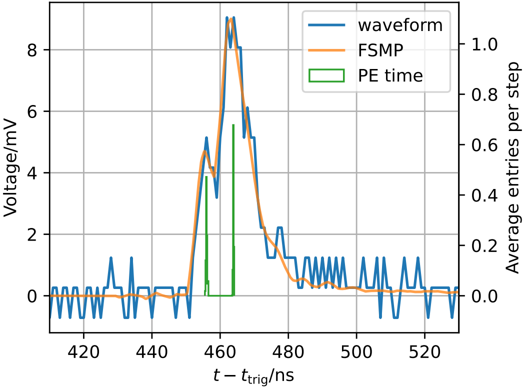


The MCMC jumps in FSMP

FSMP employs Metropolis–Hastings and reversible-jump MCMC to jointly sample event time t_0 and PE sequence $\boldsymbol{z}$.



Laboratory test: time resolution

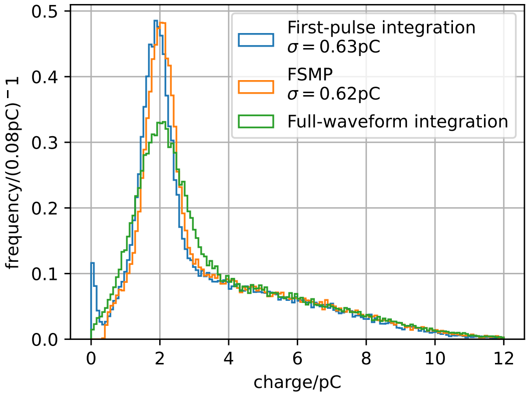


- Investigated the performance of a novel 8-inch MCP-PMT for JNE (arXiv 2303.05373).
- Laser light source in the laboratory.
- FSMP achieved sub-nanosecond resolution for individual PEs.

- The standard deviation of PE time <1 ns when the time difference <10 ns.
- It meets the requirements of JNE.

Laboratory test: charge distribution

- First-pulse method: reduces electronic noise, but introduces bias.
- Full waveform integration: unbiased, but worsens peak resolution.
- FSMP: models both noise and charge response, achieving higher resolution without bias.

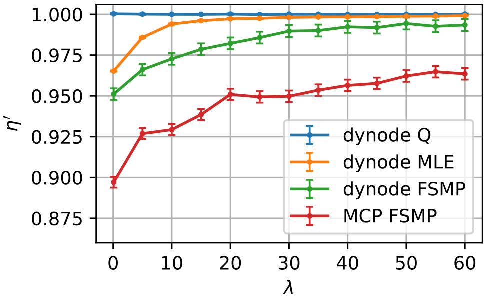


Numerical experiment: energy resolution

- Estimate PE count expectation λ and compute resolution:

$$\eta = \frac{\sqrt{\mathrm{Var}[\hat{\lambda}]}}{\mathrm{E}[\hat{\lambda}]}, \eta' = \eta/\eta_Q$$

- Benchmark against charge integration method.
- At $\lambda = 1$: FSMP improves resolution by ∼5% for dynode PMTs, and ∼10% for MCP-PMTs.



Compare to JUNO:

- $\lambda = 1$: $E = 13\,\mathrm{MeV}$
- $\lambda = 60$: $E = 783\,\mathrm{MeV}$

Summary

- FSMP rigorously models Poisson process and charge model, providing a unified probabilistic description of reconstruction.
- Studies show improvements in energy and time resolutions.
- FSMP is a promising waveform analysis for liquid scintillator neutrino experiments.
  - JNE: possible to distinguish Cherenkov and scintillation photons.
  - JUNO and other scintillator detectors: preliminary studies suggest a potential $5\,\%$ to $10\,\%$ improvement for the energy resolution under optimistic scenarios.
- We will combine FSMP with a more precise detector response (Chuanhui Hao, poster #96) and an MCMC-based reconstruction method (Chuang Xu, oral #260).