The Fast Stochastic Matching Pursuit for Neutrino Experiments

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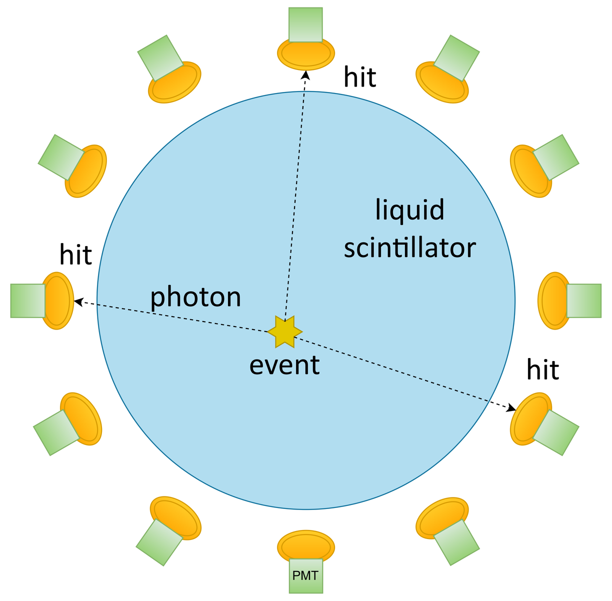
I. Motivation

To improve **energy and timing resolution** with waveform analysis in a liquid scintillator detector,

waveform $\boldsymbol{w}$ from PMTs in LS detector	analysis →	PE count expectation μ, event time t_0, *high resolution needed*

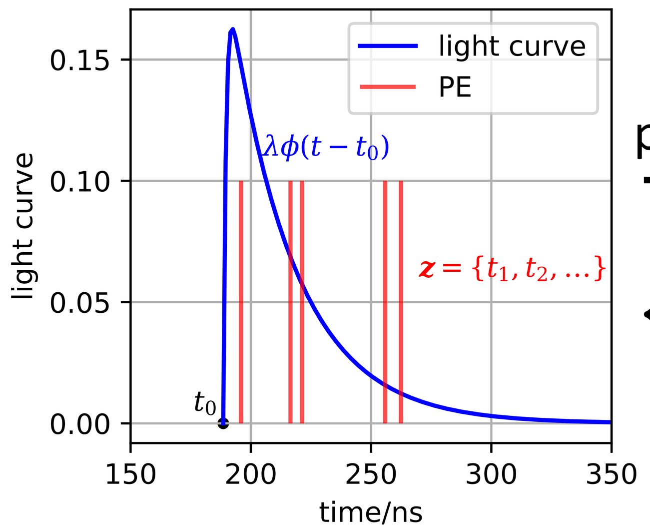
FSMP is a *reliable* analysis method in **Bayesian** sense. It deals with *pile-ups*, and gives better resolution of μ and t_0.



$$p(\boldsymbol{z}, t_0|\boldsymbol{w}) = \frac{p(\boldsymbol{w}|\boldsymbol{z}, t_0)p(\boldsymbol{z}, t_0)}{p(\boldsymbol{w})}$$

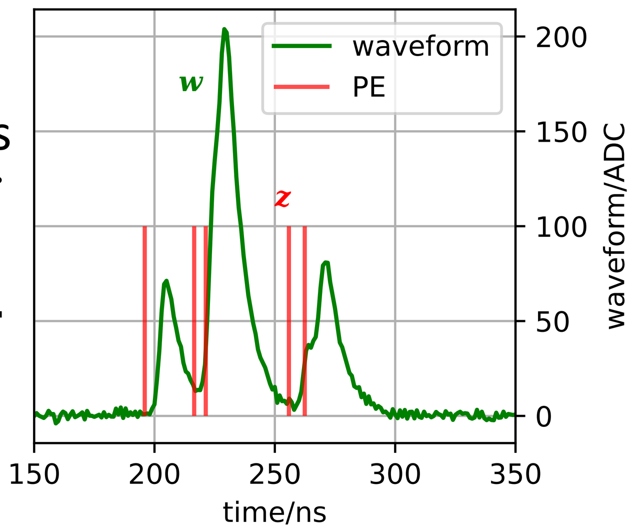
The event energy E and position $\boldsymbol{r}$ may be estimated by MLE:

$$(\hat{E}, \hat{\boldsymbol{r}}) = \arg\max_{E,\boldsymbol{r}} p(E, \boldsymbol{r}|\mu, t_0, \boldsymbol{w}) = \arg\max_{E,\boldsymbol{r}} \frac{p(\mu, t_0|E, \boldsymbol{r})p(E, \boldsymbol{r})}{p(\mu, t_0|\boldsymbol{w})}$$

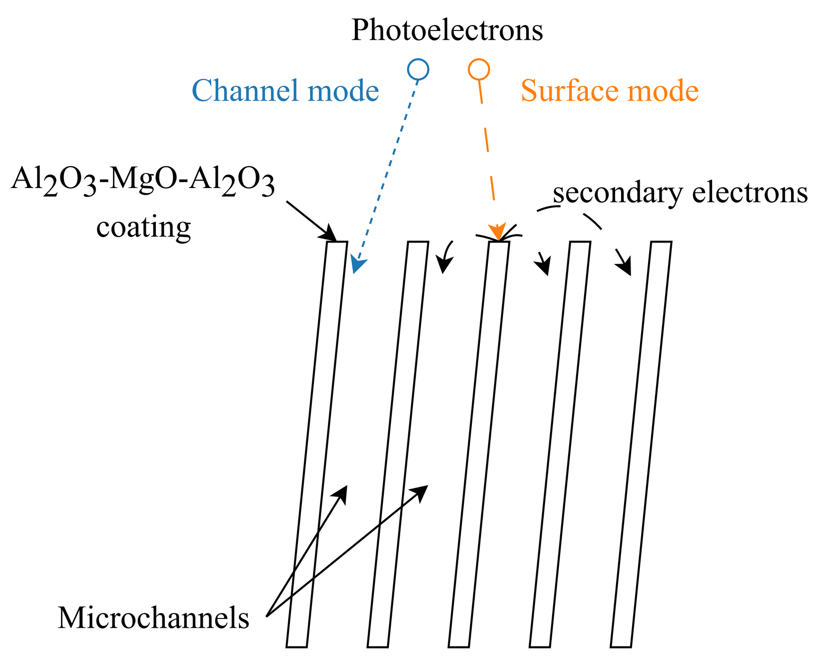


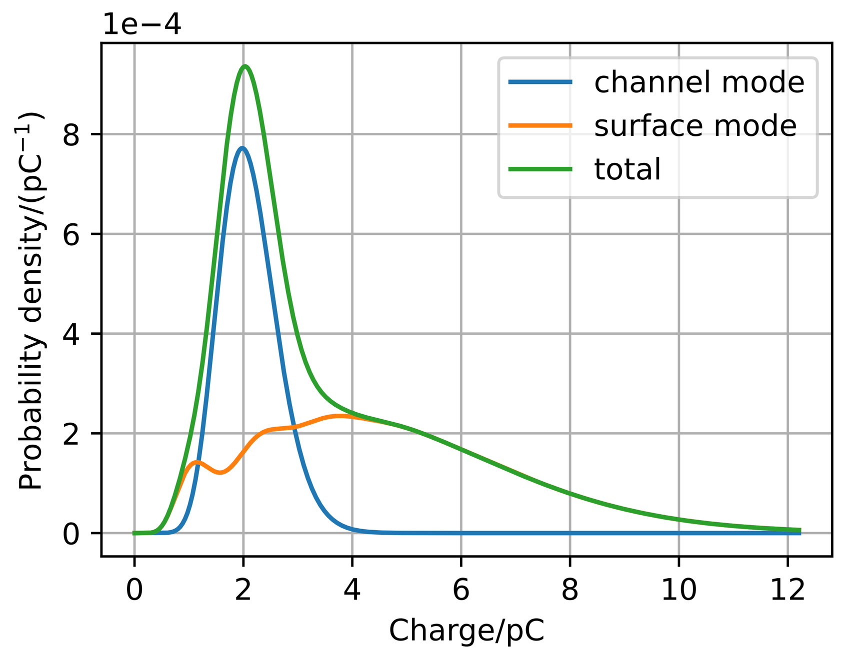
PMT physical process →

← analysis with FSMP



II. Charge model for MCP-PMTs



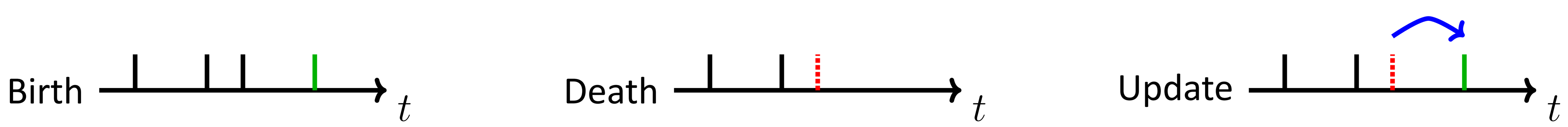


There are channel mode and surface mode of PE in MCP-PMTs (arXiv 2402.13266).

We use a mixture of multiple normal distributions to represent the charge model.

III. The RJMCMC sampling in FSMP

Fast stochastic matching pursuit (FSMP, arXiv 2403.03156) supports any charge model constructed with mixed Gaussian model, including MCP-PMTs' charge model.



Choose jumps with acceptance probability, and samples PE sequence $\boldsymbol{z}$.

IV. Bias and resolution

The relative resolution of μ, and the resolution of t_0 are defined as

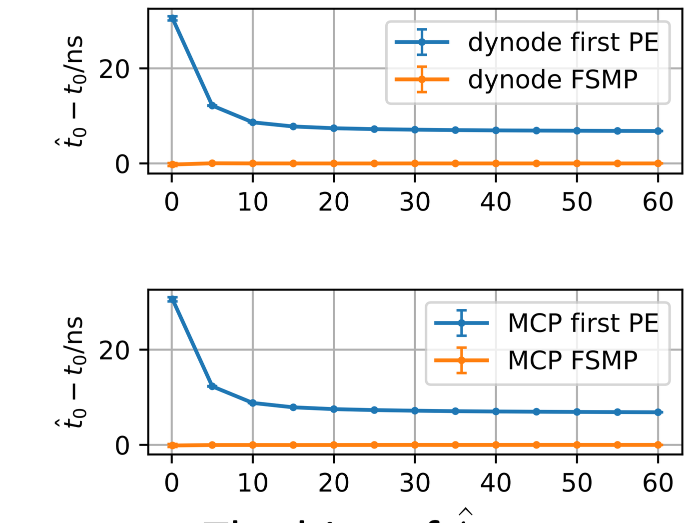
$$\eta' = \frac{\sqrt{\mathrm{Var}[\hat{\mu}]}/\mathrm{E}[\hat{\mu}]}{\sqrt{\mathrm{Var}[N_{\mathrm{PE}}]}/\mathrm{E}[N_{\mathrm{PE}}]}, \eta_t = \frac{\sqrt{\mathrm{Var}[\hat{t}_0 - t_0]}}{\mathrm{E}[\hat{t}_0]}$$

where N_{PE} is number of PEs.

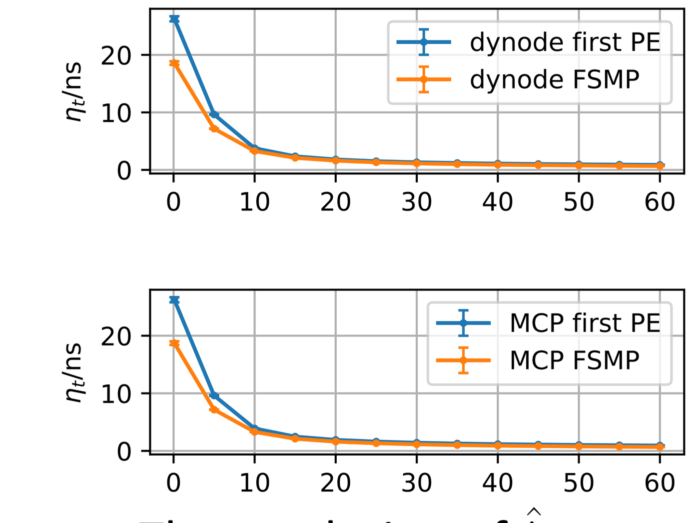
The first PE method uses the first PE time as event time, which is biased.

Q is the integration of waveforms. MLE is the MLE without timing information. The FSMP is MLE with FSMP analysis.

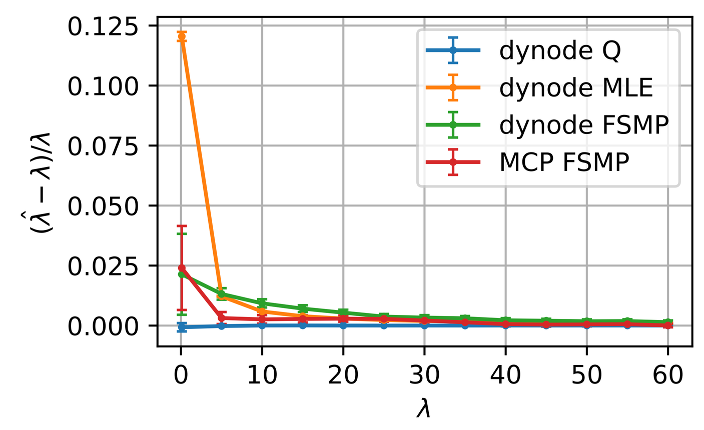
In the most optimistic case, the resolution improvement of μ could be seen as the improvement of energy resolution.



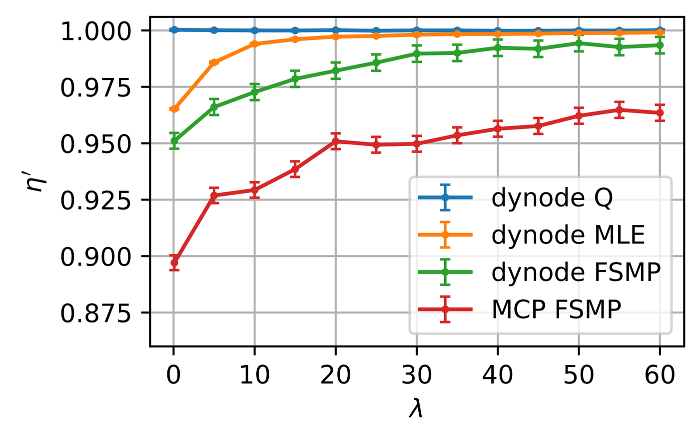
The bias of $\hat{t}_0$.



The resolution of $\hat{t}_0$.



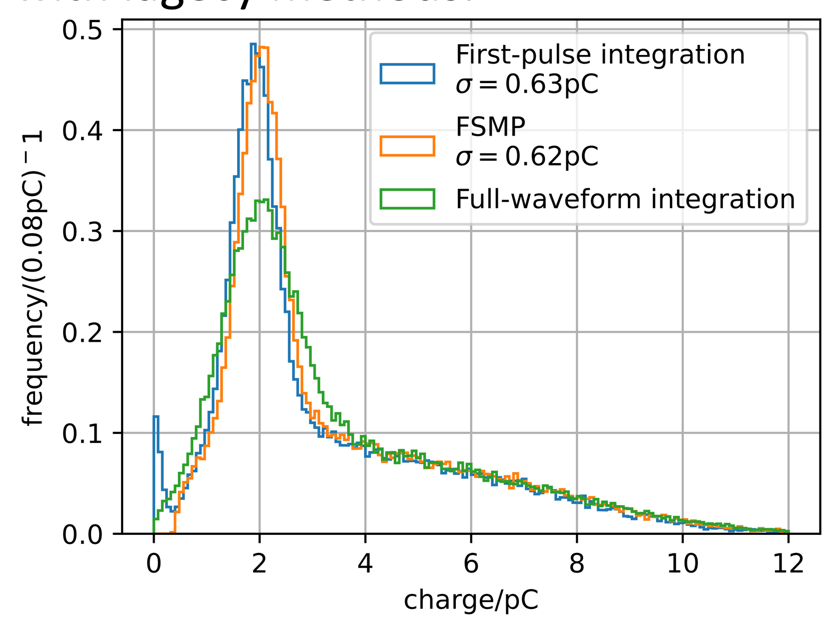
The relative bias of $\hat{\mu}$.

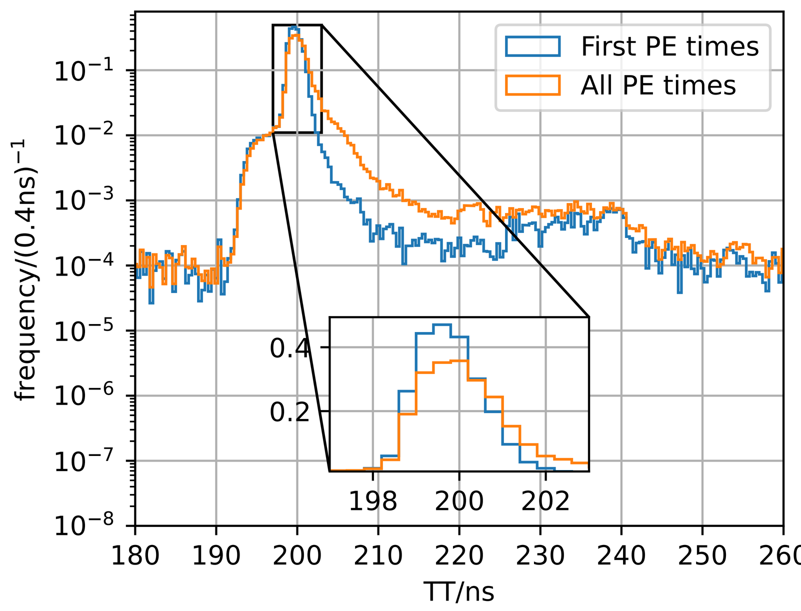


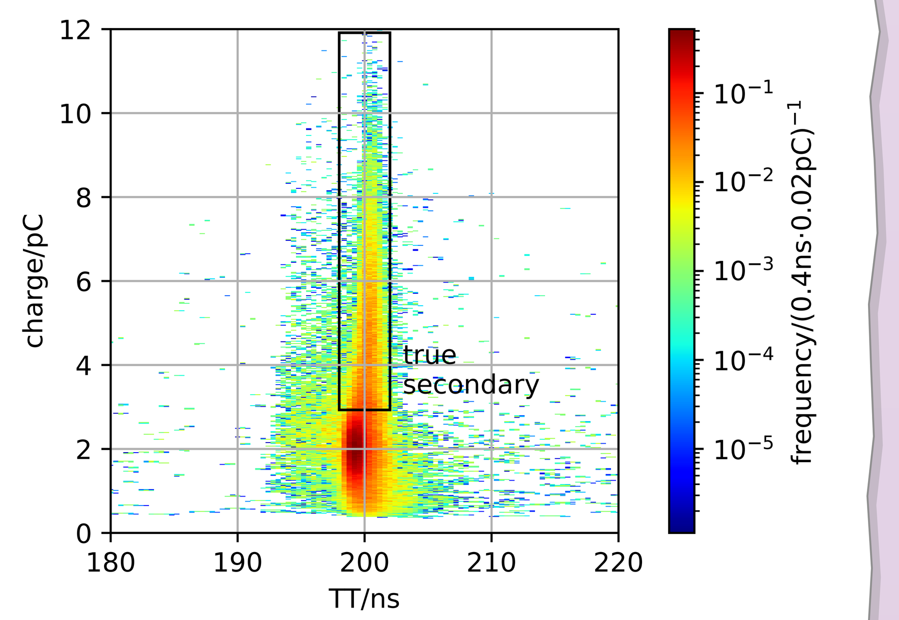
The relative resolution of $\hat{\mu}$.

V. Laboratory test

We tested FSMP with the 8-inch MCP-PMT used in JNE, comparing the charge distribution and PE time distribution with lagecy methods.







The charge distribution utilizes more information than first-pulse integration and gives better resolution than full-waveform integration. The PE time distribution gives full timing information, and gives better estimation of the TTS than first PE times. It distinguishes the *true-secondary* PEs when comparing with the charges.

VI. Summary

- **Better energy:** the resolution is up to $10\,\%$ better ($\mu = 1$).
- **Better timing:** unbiased estimator, and the resolution is $30\,\%$ better ($\mu = 1$).
- **High performance:** ~ 100 waveforms per second, ~ 100 times faster on consumer GPUs than CPUs.
- We have applied FSMP to the **JNE**, and are actively working on applying it to the **JUNO**.