First-principle event reconstruction by time-charge readouts for the Taishan Antineutrino Observatory

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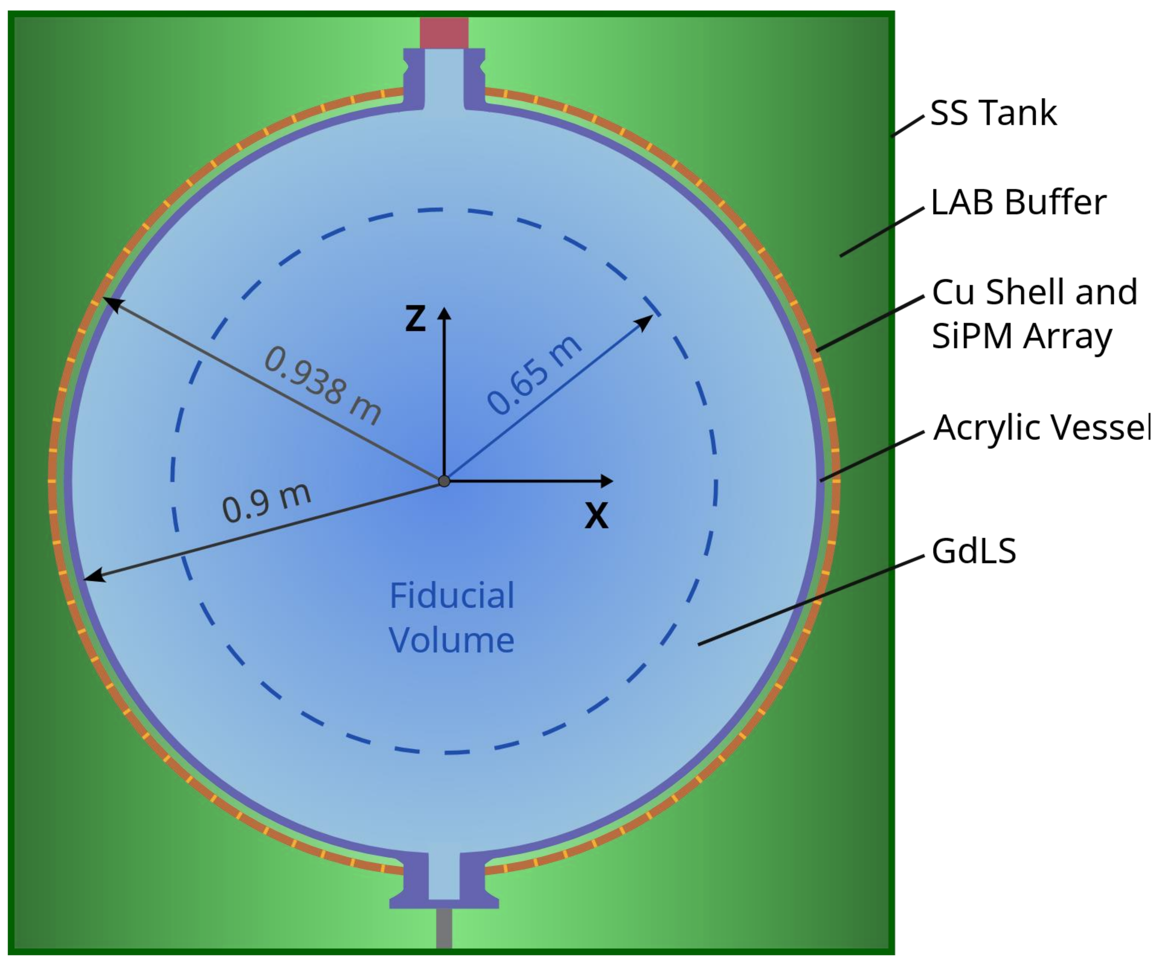
ID: 319

I. Introduction

Taishan Antineutrino Observatory (TAO)

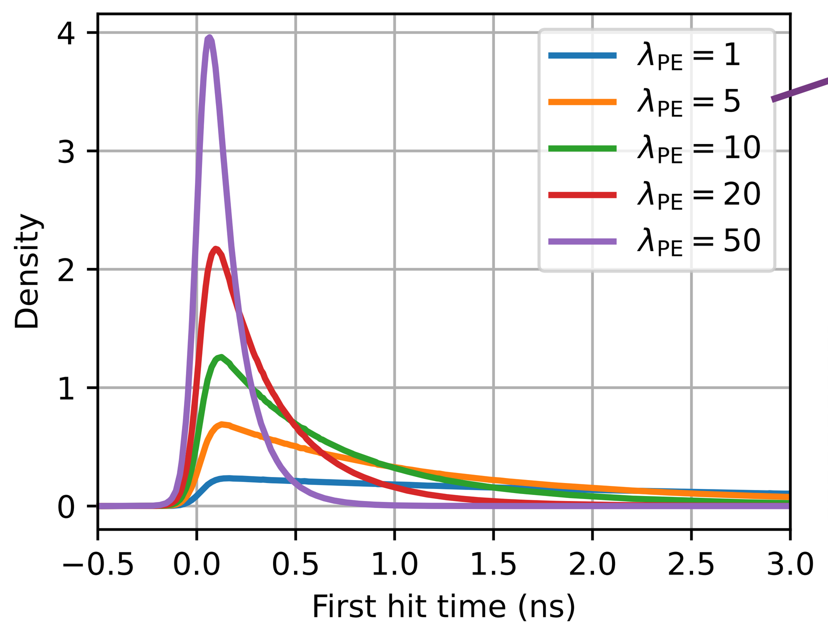
Physics Goals:
- ❑ **Model-independent reference spectrum** for JUNO.
- ❑ Benchmark the nuclear database.



Schematic of the TAO central detector

- 44m away from Taishan NPP
- **~2.8 tons** GdLS (~4000 PE / MeV)
- 4024 50 × 50 mm^2 SiPM tiles
- Coverage ~ **94%**
- Photon detection efficiency > **50%**
- Energy resolution **2% @ 1MeV**

Reconstruction using first hit time T and charge Q



λ_{PE}: Expected PE count on a SiPM

Dependence between **first hit time T** and ~~PE count~~ **charge Q** needs to be considered.

Strategies:
1. Get **T-Q map** from **calibration** data.
2. Derive **T-Q joint distribution** in theory.

II. Detector response

Vertex pos $\vec{r}$ and energy E → (Optical model) → Expected PE count $\lambda_{PE}(t)$ on SiPM → (Tweedie GLM) → Charge distribution on SiPM

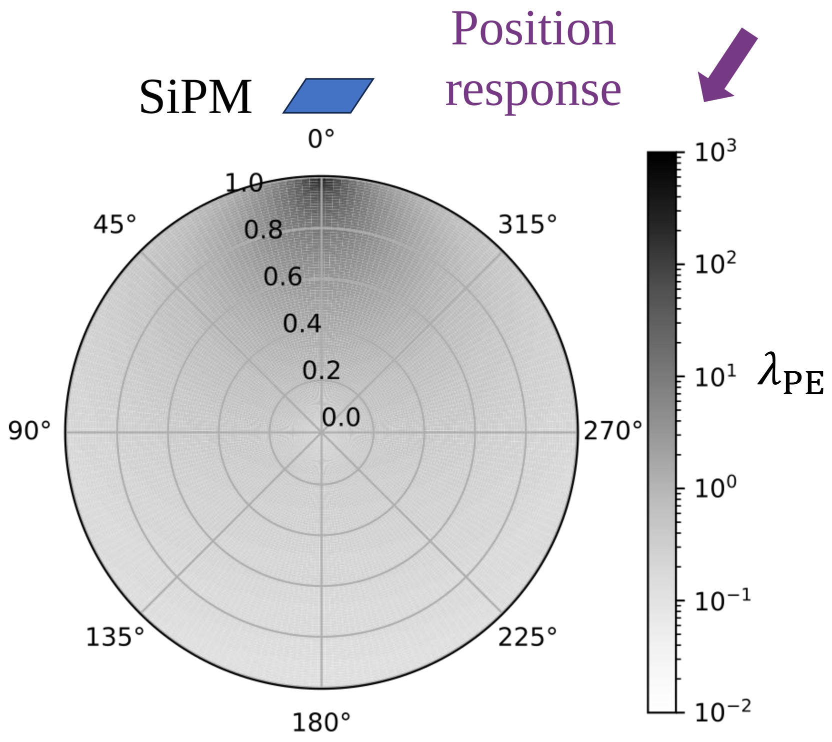
Optical detector model

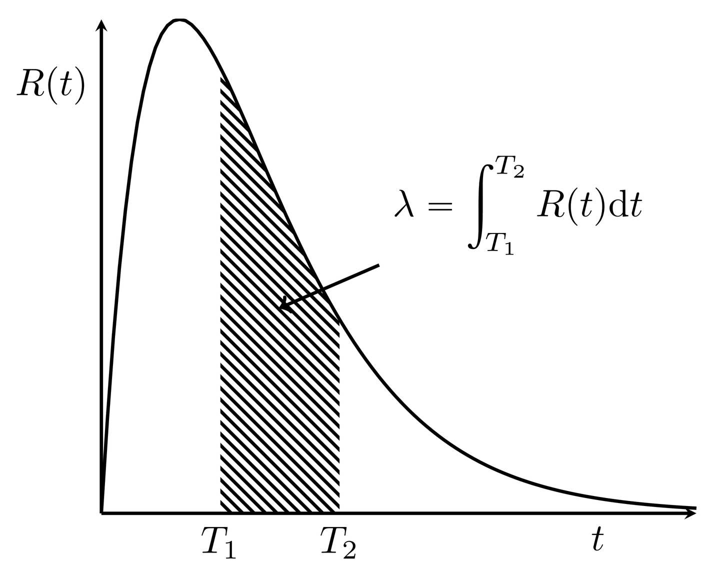
Occurrence of PE on SiPM follows an **inhomogeous Poisson process**.

$$R(t;\vec{r},E) = E \cdot R(t;\vec{r})$$

$$R(t;r,\theta) = \boxed{I(r,\theta)} \cdot \boxed{P(t;r,\theta)}$$

Position response — Time response





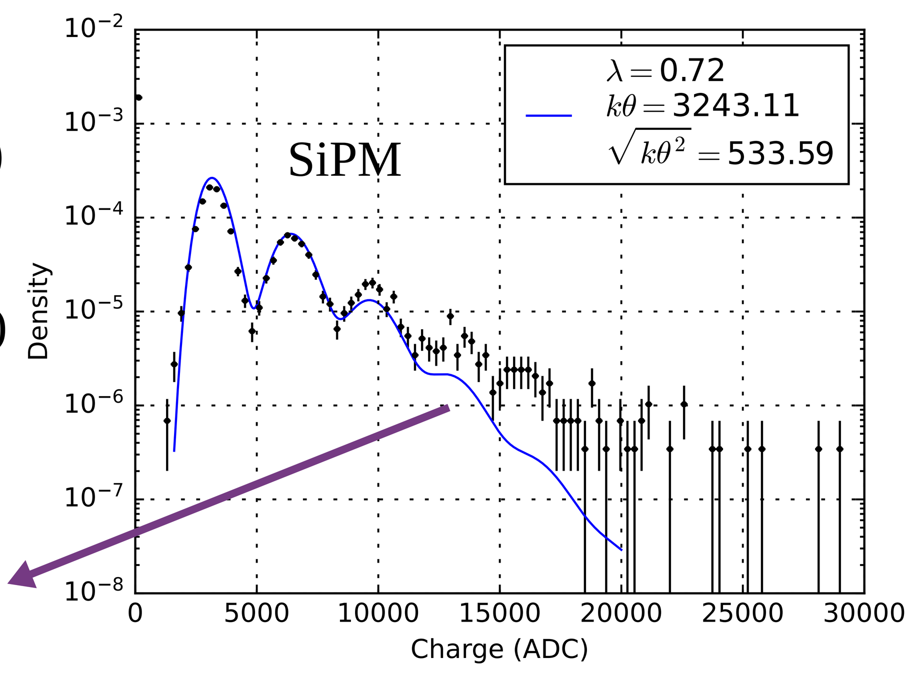
Tweedie generalized linear model (GLM)

$$f_{Tw}(Q;\lambda_{PE},k,\theta) = \sum_{N_{PE}=0}^{\infty} f_{Ga}(Q;N_{PE}k,\theta) p_\pi(N_{PE};\lambda_{PE})$$

$f_{Ga}(Q;k,\theta)$: Gamma distribution (SER)

$p_\pi(N_{PE};\lambda_{PE})$: Poisson distribution

Due to the influence of **crosstalk**, the assumption of **Poisson** in Tweedie distribution **no longer holds true**.

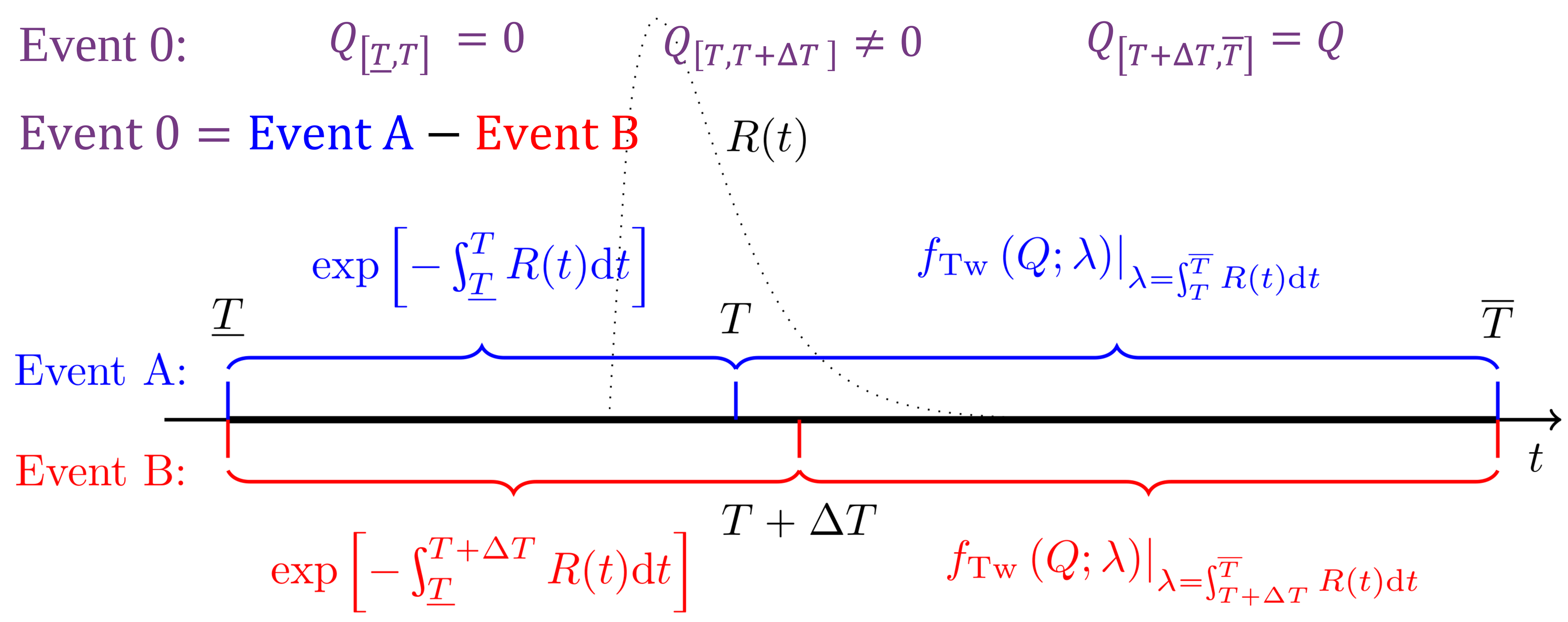


III. Reconstruction likelihood

Likelihood using charge Q:

$$\prod_j^{N_{SiPM}} f_{Tw}\left[Q_j; b\lambda_{j,[\underline{T},\overline{T}]}(\vec{r},E),\phi,\xi\right]$$

Joint distribution of first hit time T and charge Q



$$f_{TQ}[T,Q;R(t)]\Delta T = \underbrace{\exp\left[-\int_{\underline{T}}^{T} R(t)\mathrm{d}t\right] f_{Tw}(Q;\lambda)|_{\lambda=\int_T^{\overline{T}} R(t)\mathrm{d}t}}_{\text{Event A}} - \underbrace{\exp\left[-\int_{\underline{T}}^{T+\Delta T} R(t)\mathrm{d}t\right] f_{Tw}(Q;\lambda)|_{\lambda=\int_{T+\Delta T}^{\overline{T}} R(t)\mathrm{d}t}}_{\text{Event B}}$$

$\Delta T \to 0$

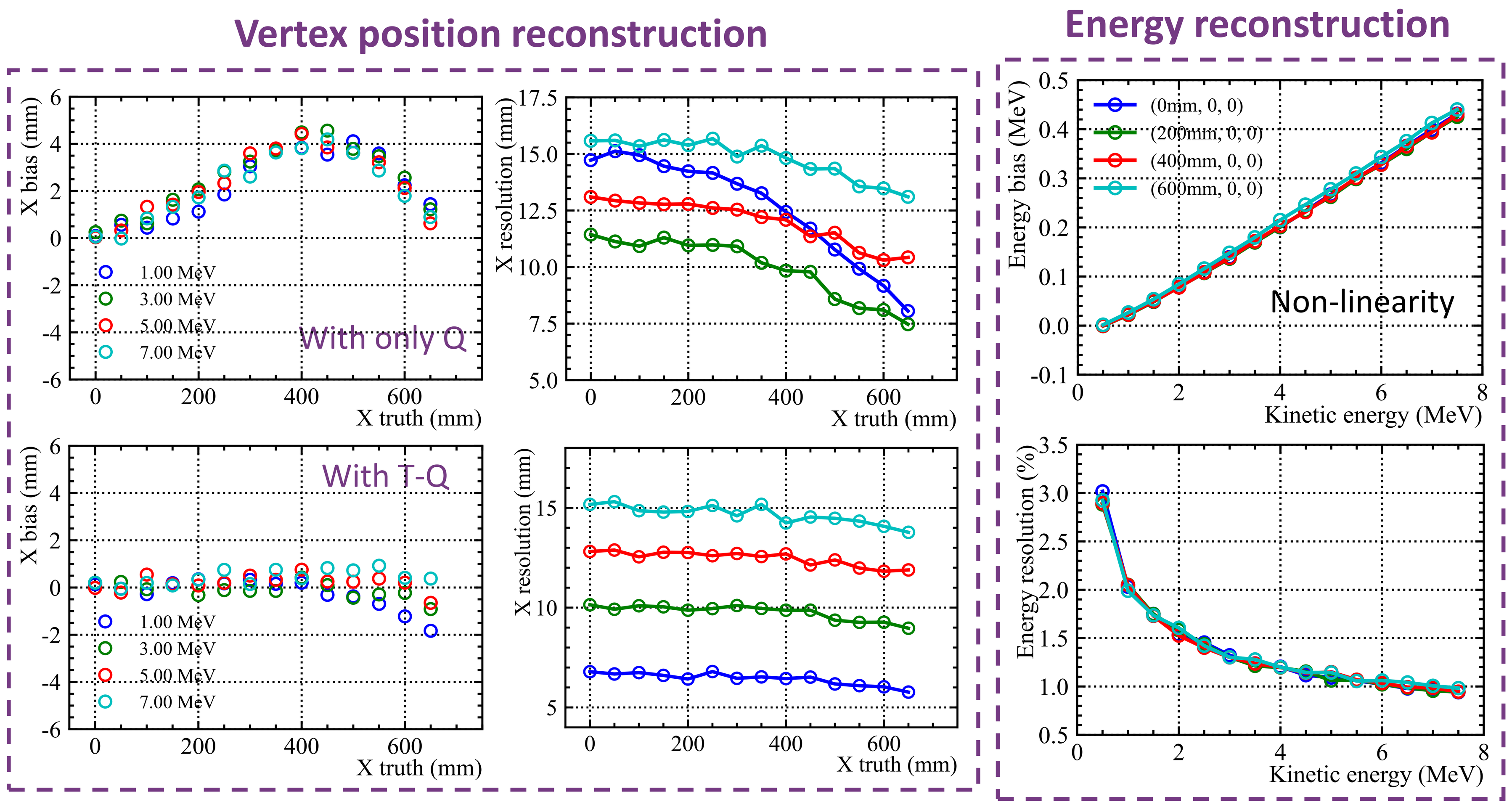
$$f_{TQ}[T,Q;R(t)] = \exp\left[-\int_{\underline{T}}^{T} R(t)\mathrm{d}t\right] R(T)\left(1+\frac{\partial}{\partial\lambda}\right) f_{Tw}(Q;\lambda)\Big|_{\lambda=\int_T^{\overline{T}} R(t)\mathrm{d}t}$$

Likelihood using T and Q

$$\underbrace{\prod_{Q_j>0}}_{\text{hit}} f_{TQ}[T_j,Q_j;ER_j(t-t_0);\vec{r}] \underbrace{\prod_{Q_j=0}}_{\text{nonhit}} p_\pi\left[0;\lambda_{j,[\underline{T}-t_0,\overline{T}-t_0]}(\vec{r},E)\right]$$

IV. Results

Use e^- simulated by TAO offline software to evaluate algorithm.



- Time is important to **reduce bias** and **get better resolution** in pos rec.
- For TAO detector, time information has a negligible impact on energy rec.

V. Conclusion

- ✓ To handle dependence of first hit time T and charge Q, we derive **the joint distribution of T-Q from first principles**.
- ✓ For point events (e^-) in TAO detector, the algorithm shows good vertex position resolution **(< 16 mm)** and energy resolution **2% @ 1 MeV**.
- ✓ The method is applicable to other experiments that utilize PMTs for **T-Q readouts**.

Reference

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[5] L.N. Kalousis et al. Journal of Instrumentation. 15, 2020