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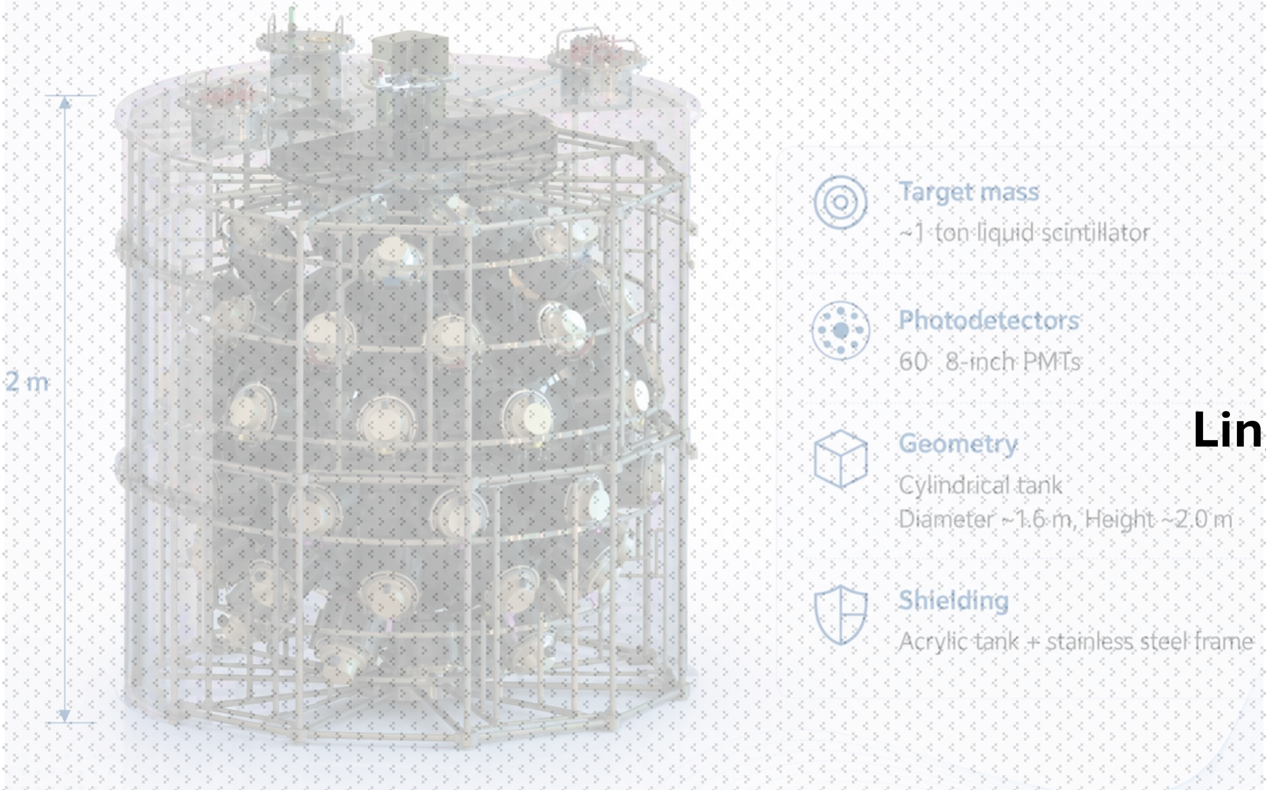
Jinping Neutrino Experiment

MeV Event-by-Event Direction Reconstruction in a Novel Cherenkov Liquid Scintillator Detector



2026.7.16

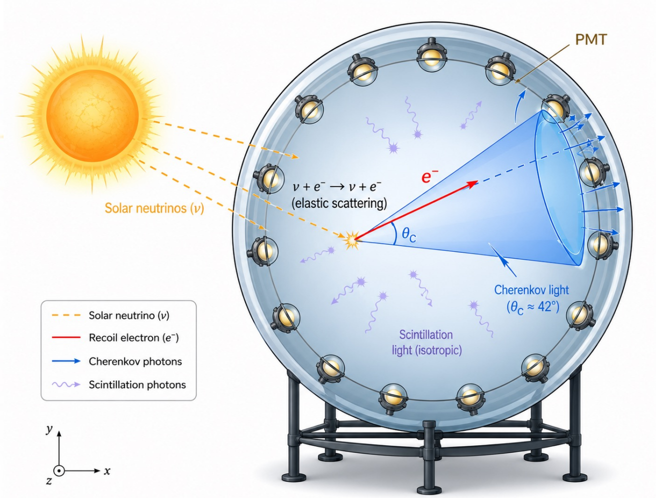
Ling Liu, on behalf of the JNE Collaboration
Center for High Energy Physics
Tsinghua University

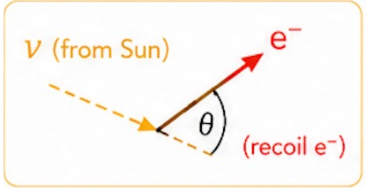
Outline

Motivation

Solar-ν

$\nu + e \rightarrow \nu + e$ (Elastic Scattering)





Recoil electron correlates with the incoming neutrino direction.

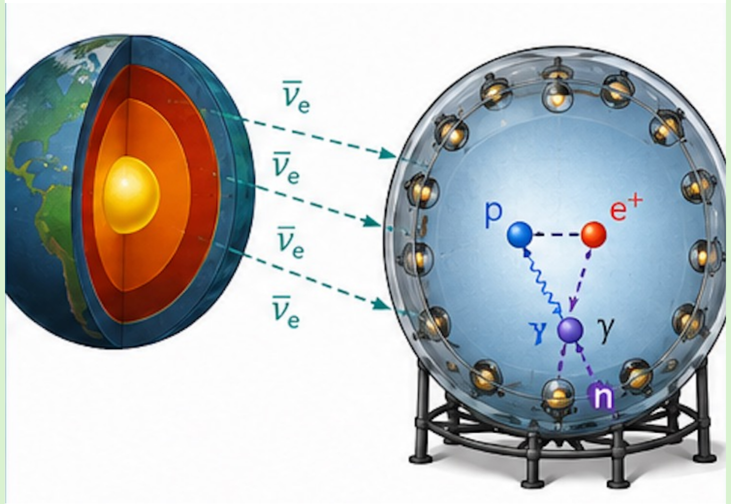
- ✓ Identify the solar direction (known source)
- ✓ Suppress isotopic radioactive background
- ✓ Improve signal significance

Directional information uniquely identifies the solar neutrino signal.

Geo-ν

$\bar{\nu}_e + p \rightarrow e^+ + n$ (Inverse Beta Decay)

$\nu + e \rightarrow \nu + e$ (Elastic Scattering)

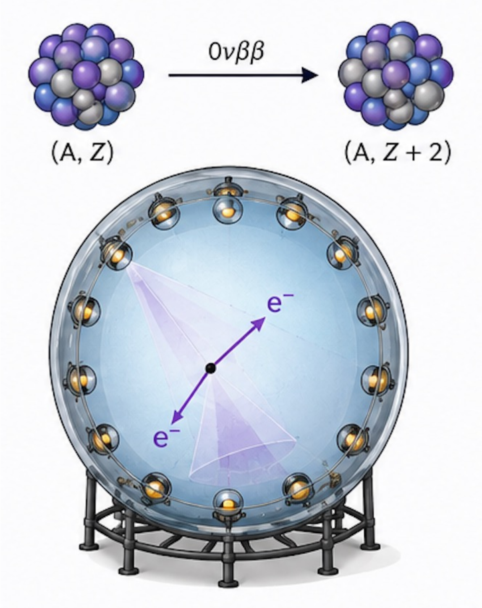


- ✓ Reject solar-neutrino background
- ✓ Separate different neutrino sources (crust / mantle)
- ✓ Improve geoneutrino flux precision

Directional reconstruction helps isolate geo-neutrino candidates.

$0\nu\beta\beta$ Decay

(Neutrinoless Double-Beta Decay)

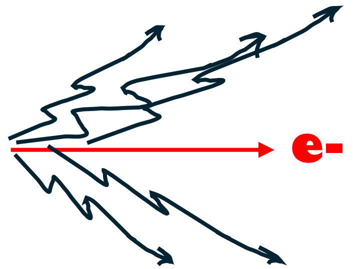


- ✓ Two-electron topology information
- ✓ Powerful background discrimination

Direction and topology enhance signal identification.

Motivation

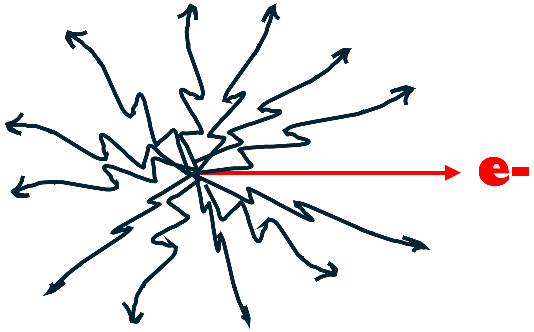
Cherenkov Light



Carry Directional Information

Good Directional Resolution

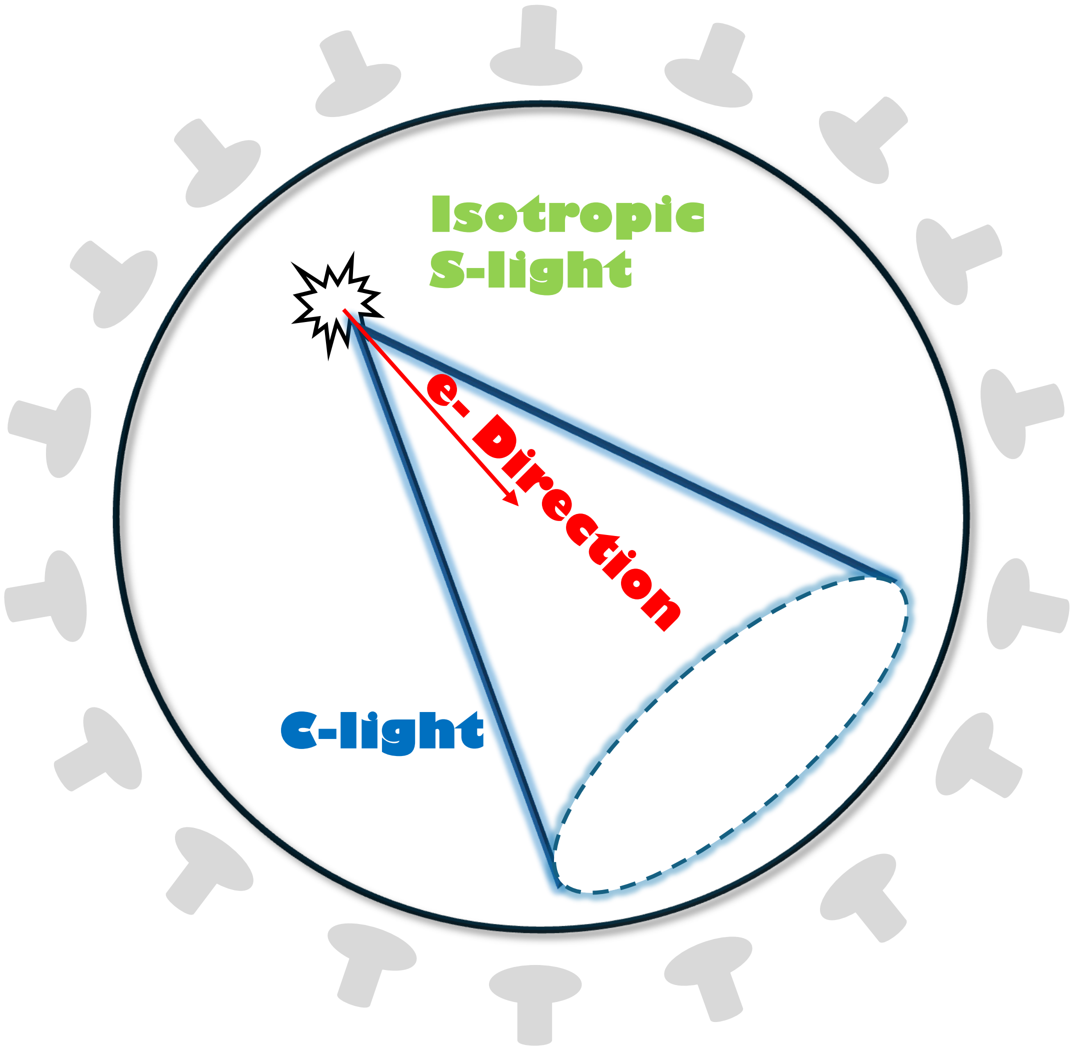
Scintillator Light



High Light Yield

Good Energy Resolution
Good Vertex Position Resolution

Cherenkov Liquid Scintillator Detector：
Slowing down S-light to separate two kinds of light



Experimental Setup: Detector Overview

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1-ton ProtoType

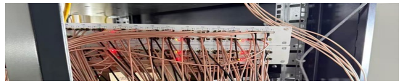
645-650mm

- 60(52) channels
- ~34% coverage

LS Composition	Scintillation light yield(photons/MeV)	Rise Time Constant (ns)	Decay Time Constant(ns)
LAB+0.07g/LPPO	4245	1.67	26.59

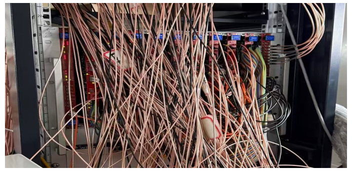
Experimental Setup: Detector Overview

Key Factors for Time Resolution



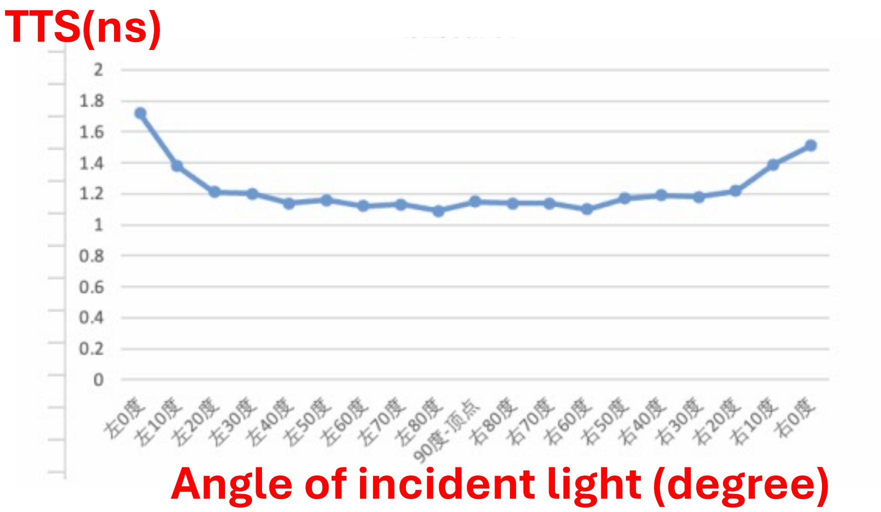
Splitter

CAEN electronics



V1751+V1495

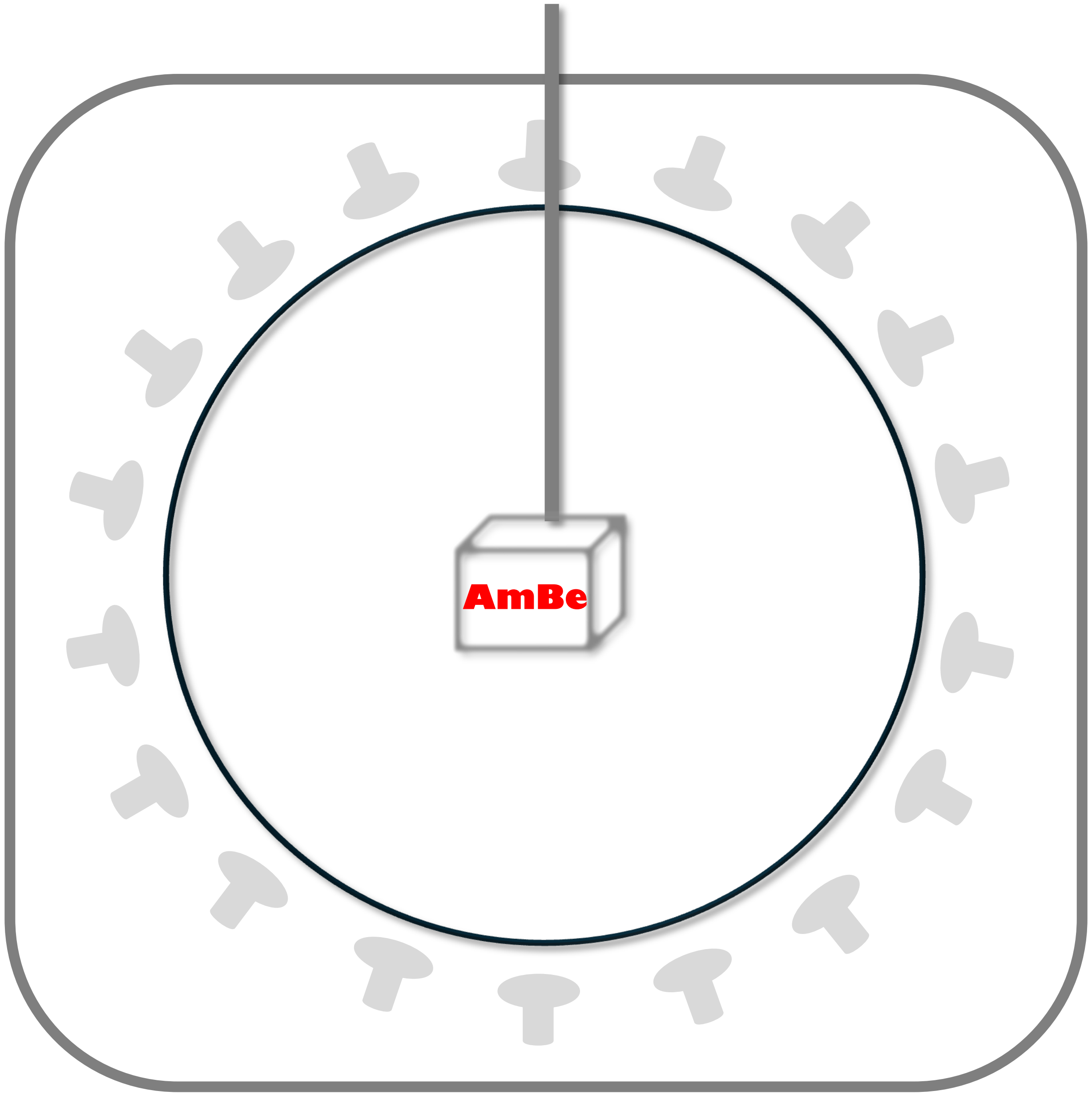
Sampling Rate=1GHz



8-inch **P**hoto**M**ultiplier **T**ubes:

Transit **T**ime **S**pread ≈ **1.67 ns** (full width at half maximum)

Experimental Setup: Americium–Beryllium (*AmBe*) Calibration Source



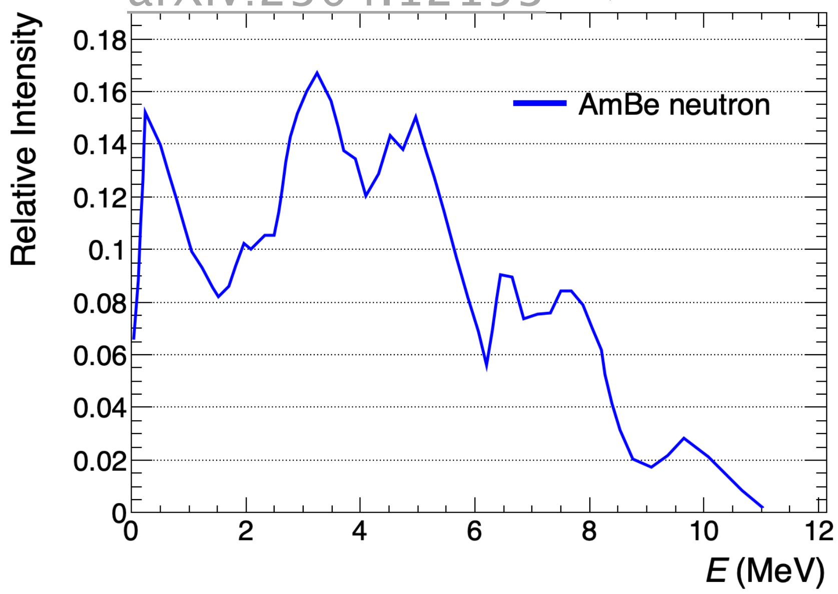
$$^{241}\mathrm{Am} \rightarrow {}^{237}\mathrm{Np} + \alpha$$

$$^{9}\mathrm{Be} + \alpha \rightarrow {}^{12}\mathrm{C}^{*}({}^{12}\mathrm{C}) + n$$

Cascade Decay Signal

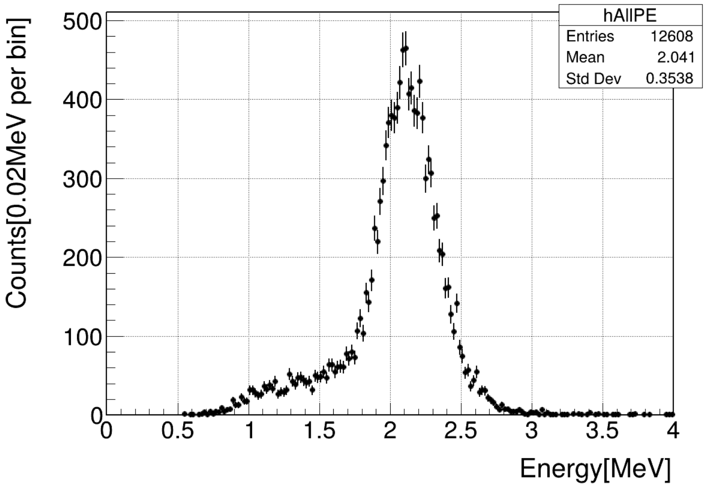
4.438MeV γ

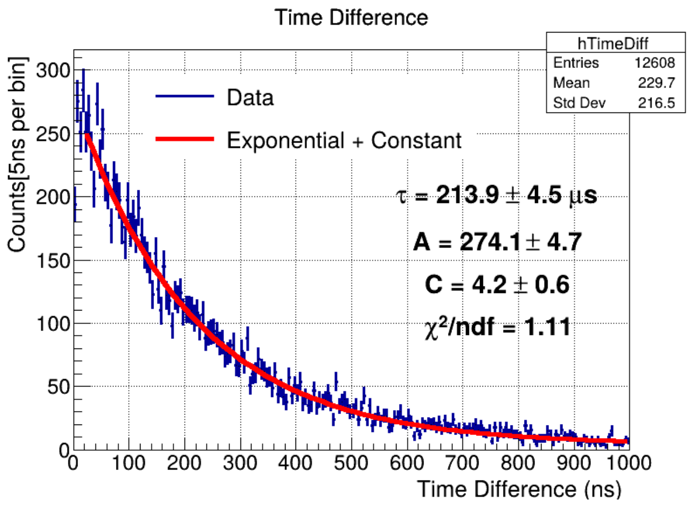
arXiv:2304.12153



Data Analysis： Event Selection

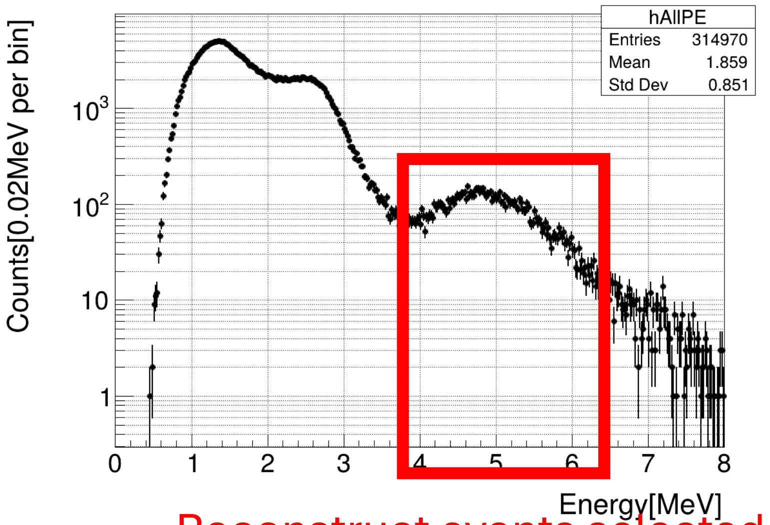
Delayed Energy Spectrum Selection：
- ○ **F**iducial **V**olume Cut: **< 500 mm**
- ○ Double coincidence within **1000 μs**
- ○ **Prompt energy ∈ [3.8, 5.1] MeV**





- **Distinct monoenergetic peak &** characteric **~$200\mu s$** lifetime
- **Low** accidental coincidence background

Prompt Energy Spectrum Selection：
- ○ **F**iducial **V**olume Cut: **< 500 mm**
- ○ Double coincidence within **500 μs**
- ○ **Delayed energy ∈ [1.7, 2.7] MeV**



Reconstruct events selected within the red box

- **Clear 4.438 MeV γ signal**
- **High** accidental coincidence background

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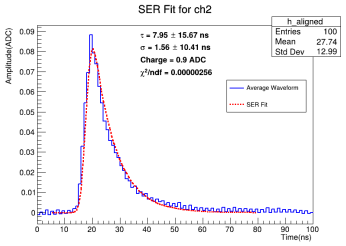
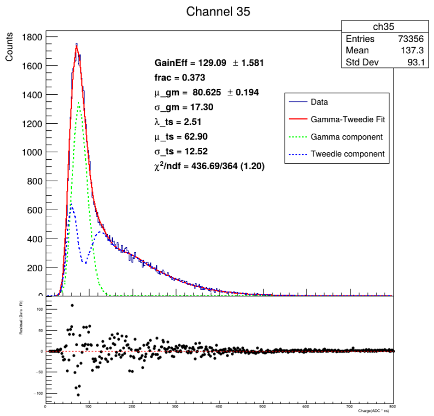
PMT Gain spectrum

Residual Between True and Fitted Waveforms

$$\mathcal{L}(n_i^{\mathrm{Obs}}, t_{ij}, R_{ij}) = \boxed{f_{\mathrm{Poisson}}(n_i^{\mathrm{Obs}}; n_{\mathrm{average}})} \cdot \prod^{\mathrm{windowlength}} \boxed{\mathrm{Gauss}\left(\left[V_{ik} - \sum_{j=1}^{n_i^{\mathrm{Obs}}} R_{ij}\, \mathrm{PE}_{\mathrm{single}}(t - t_{ij})\right], \sigma_{\mathrm{base}}\right)}$$





1

Get Single Electron Pulse

Get Gain Spectrum

2

Initialization

•Initial Photoelectron (PE) Count

(estimated from the integrated charge / effective gain)

•Initial PE Time

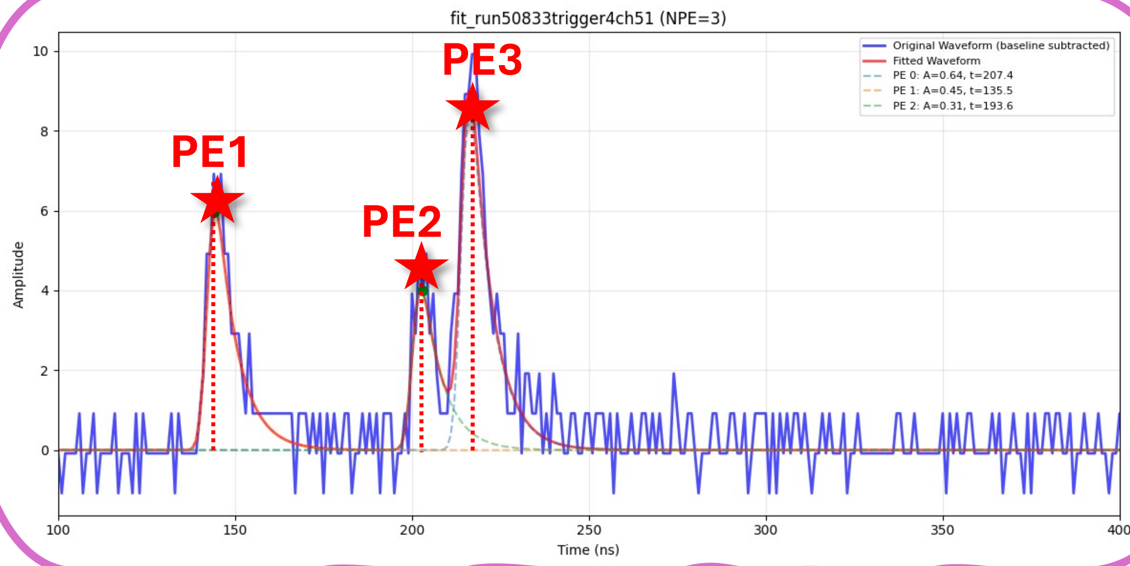
(estimated by waveform deconvolution)

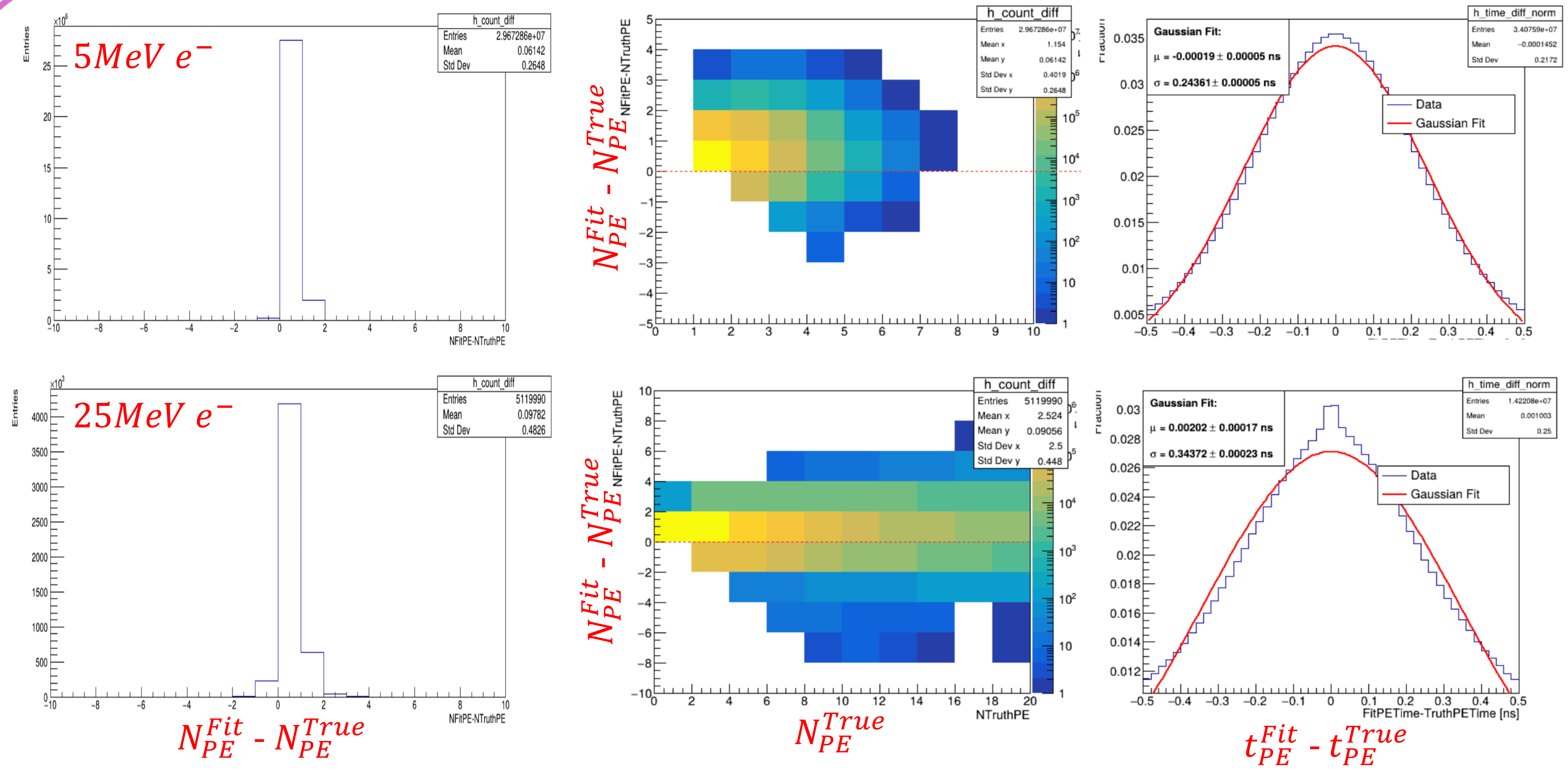
3

Fit by Minimizing the Negative Log-Likelihood：

✓ **PE Number**

✓ **PE Time**





- PE **count** estimation error **< 0.5 PE**, with most events concentrated around zero.
- PE **time** estimation error **< 0.34 ns**.

Data Analysis: Reconstruction Algorithm

PE Term PETime Term

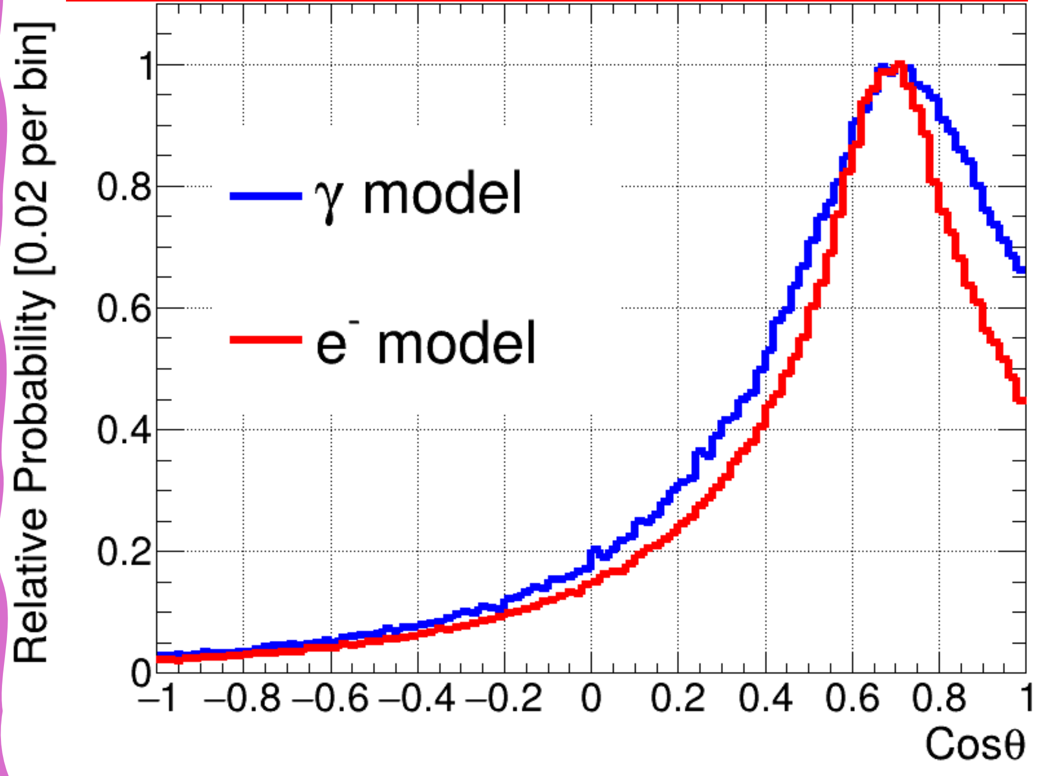
$$\mathcal{L}\left(n_i^{\mathrm{Obs}}, t_{ij} | E, x, y, z, t_{\mathrm{event}}, \vec{d}_{\mathrm{Fit}}\right) = \boxed{\prod_{i}^{N_{\mathrm{PMT}}} P_i^C} \boxed{\prod_{j}^{n_i^{\mathrm{Obs}}} P_{ij}^T}$$

- PE Term
  - ✓ **Photon emission**
  - ✓ **Photon propagation**
  - ✓ **Photon detection**

input

- PETime Term
  - ✓ Photon path length in different materials
  - ✓ **Group velocity** in different materials

MC Cherenkov Angle Distribution



γ model differs from the e^- model

PE Term PETime Term

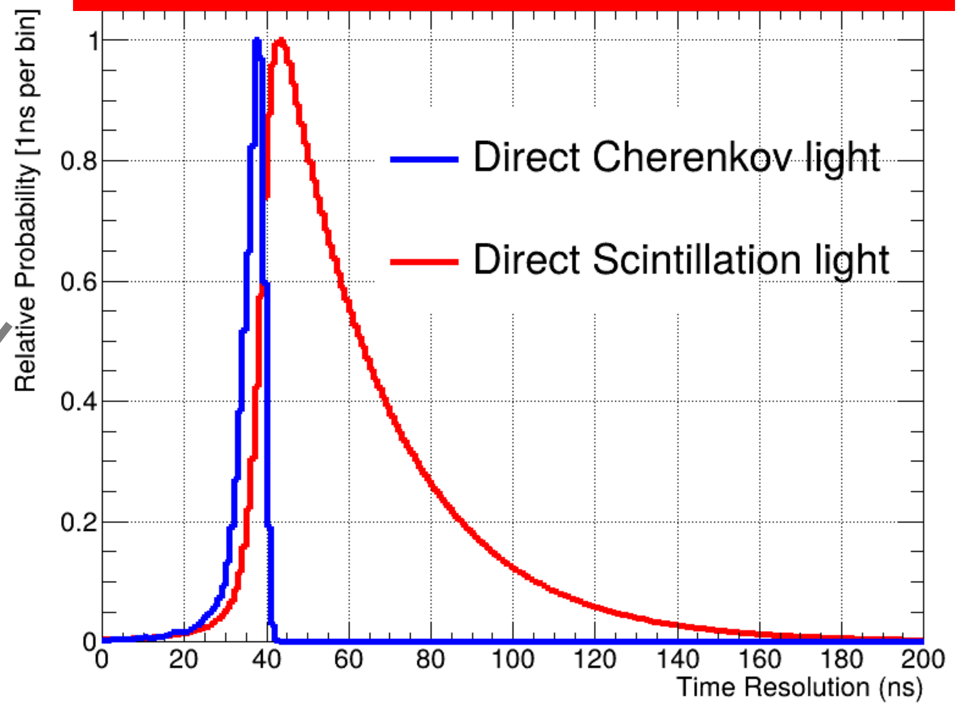
$$\mathcal{L}(n_i^{\mathrm{Obs}}, t_{ij} | E, x, y, z, t_{\mathrm{event}}, \vec{d}_{\mathrm{Fit}}) = \boxed{\prod_{i}^{N_{\mathrm{PMT}}} P_i^C} \boxed{\prod_{j}^{n_i^{\mathrm{Obs}}} P_{ij}^T}$$

- PE Term
  - ✓ **Photon emission**
  - ✓ **Photon propagation**
  - ✓ **Photon detection**

- PETime Term
  - ✓ Photon path length in different materials
  - ✓ **Group velocity** in different materials

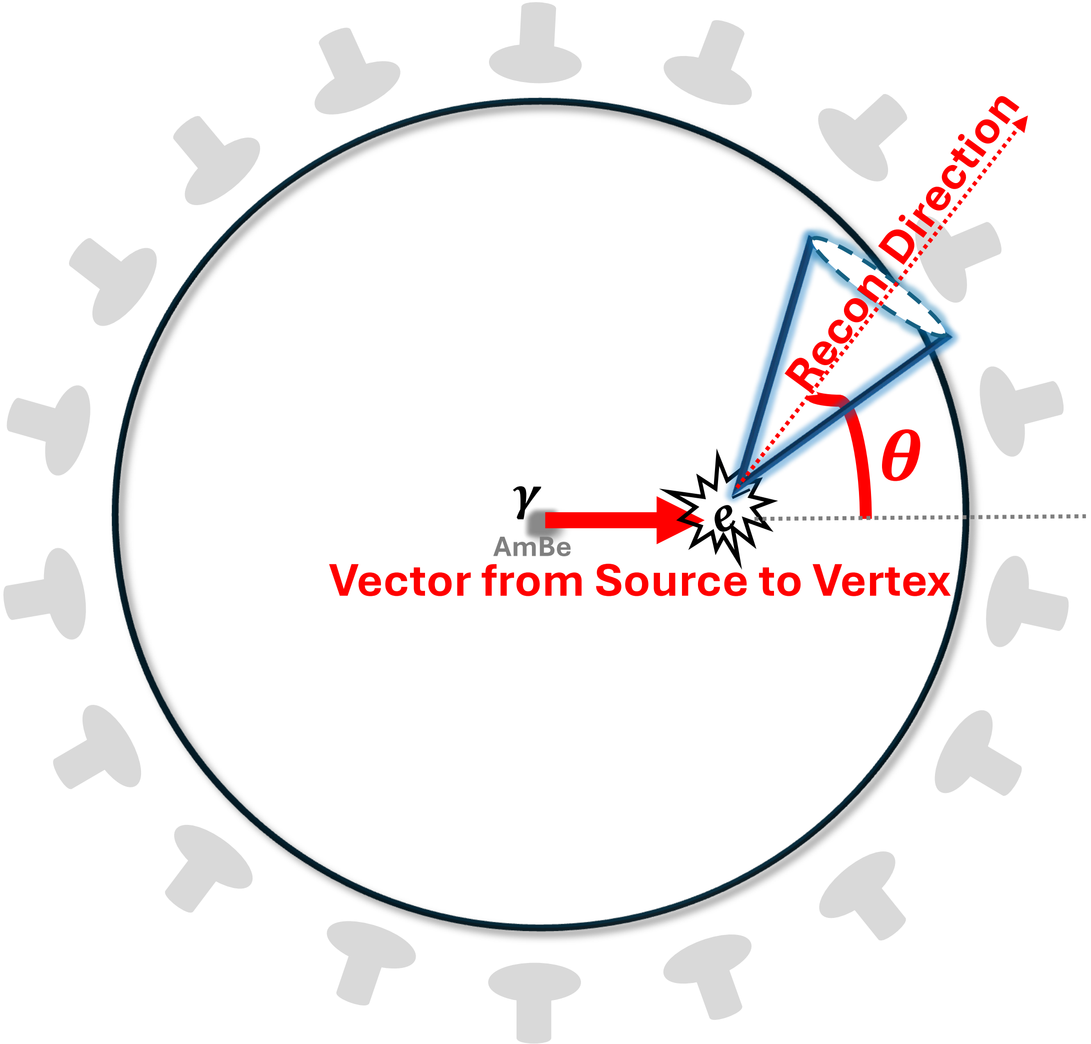
input

MC Time Residual Distribution

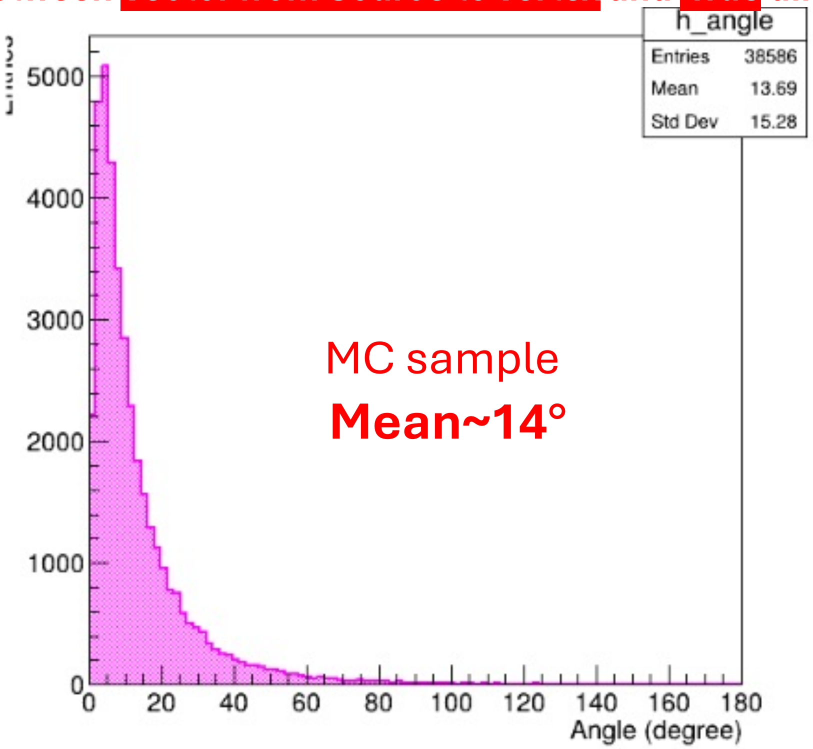


Independent modeling of Cherenkov and Scintillation light time residuals

Data Analysis: Direction Definition

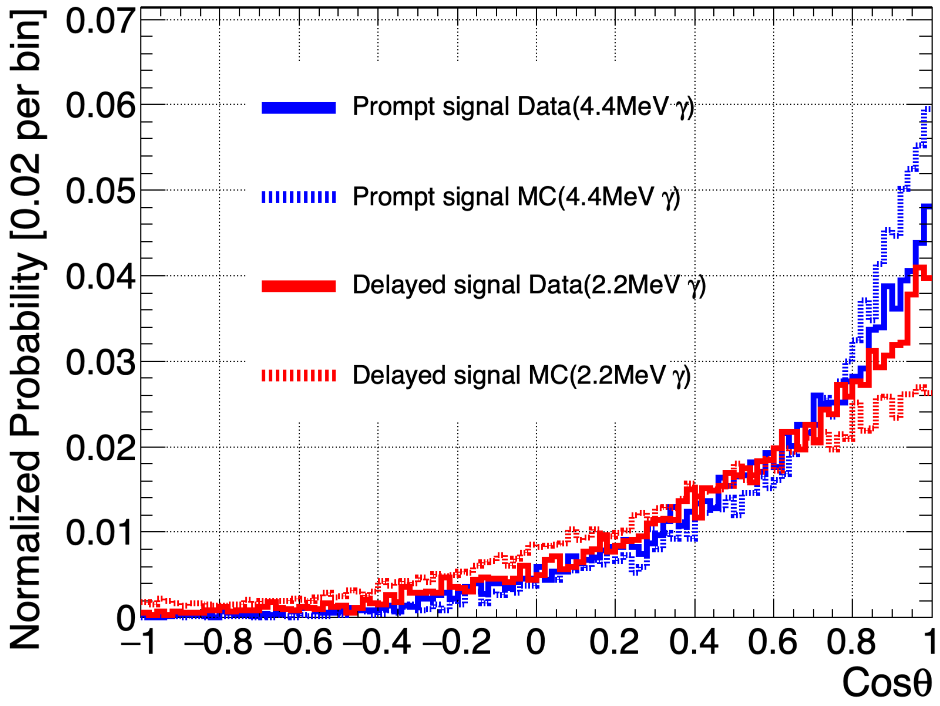


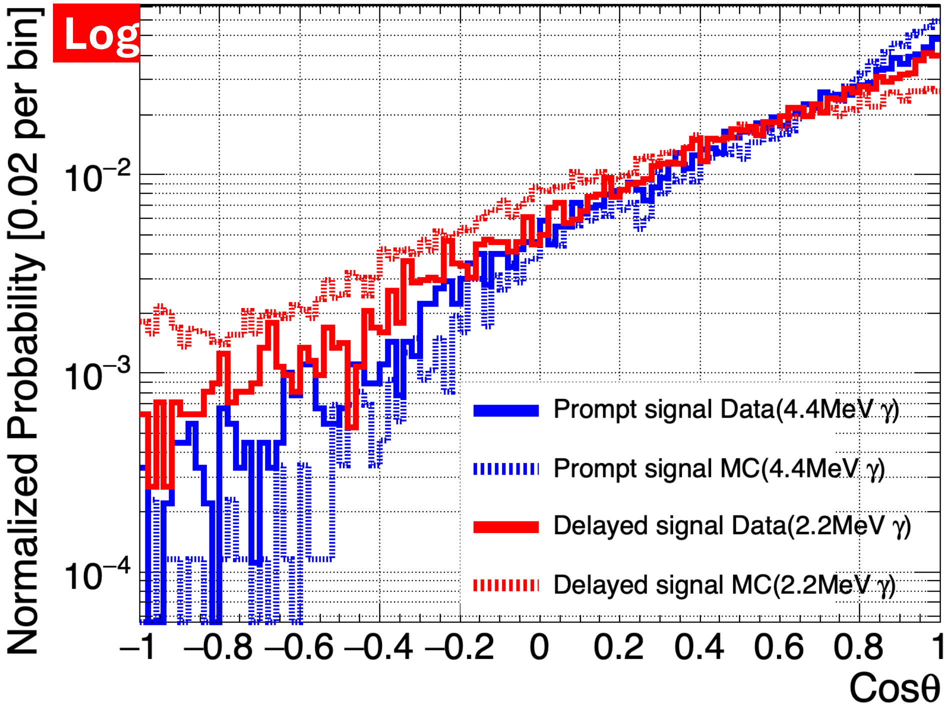
Angle between Vector from Source to vertex and True direction



Direction Definition in DATA**:**
vector from the source position to the event's reconstructed position.
(**SNO+ also used this method**)
arXiv:1812.03355

Data Analysis: Directional Reconstruction Results





θ: angle between **Vector from Source to Vertex** and **Recon** direction

- Clear directional dependence is observed, with good **DATA–MC agreement**.
- **Prompt-signal** region shows **better** directional reconstruction performance than the Delayed-signal region.
- Angular resolution is evaluated using the **Real True** Direction for center-emitted γ events in simulation：

	Delayed-signal（$@2.2MeV\ \gamma$)	Prompt-signal（$@4.4MeV\ \gamma$)
Angular resolution (68.3% containment angle)	67°	43°

Summary

- Novel Cherenkov liquid scintillator detectors enable event direction reconstruction. Requirements:
  - **Long** Scintillation photons **Time Constant**
  - **High Sampling Rate** electronics
  - **Low** PMT **T**ransit **T**ime **S**pread
- Self-developed waveform analysis and event reconstruction algorithms perform well in simulation.
- **First demonstration of MeV event-by-event direction** reconstruction in a liquid scintillator detector.
- Calibration source events are selected from data. Good **DATA–MC agreement** is achieved.

References

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VIII. Kamiokande Collaboration. "Supernova Relic Neutrino Search with Neutron Tagging at Super-Kamiokande-IV." *arXiv preprint arXiv:1311.3738* (2013).

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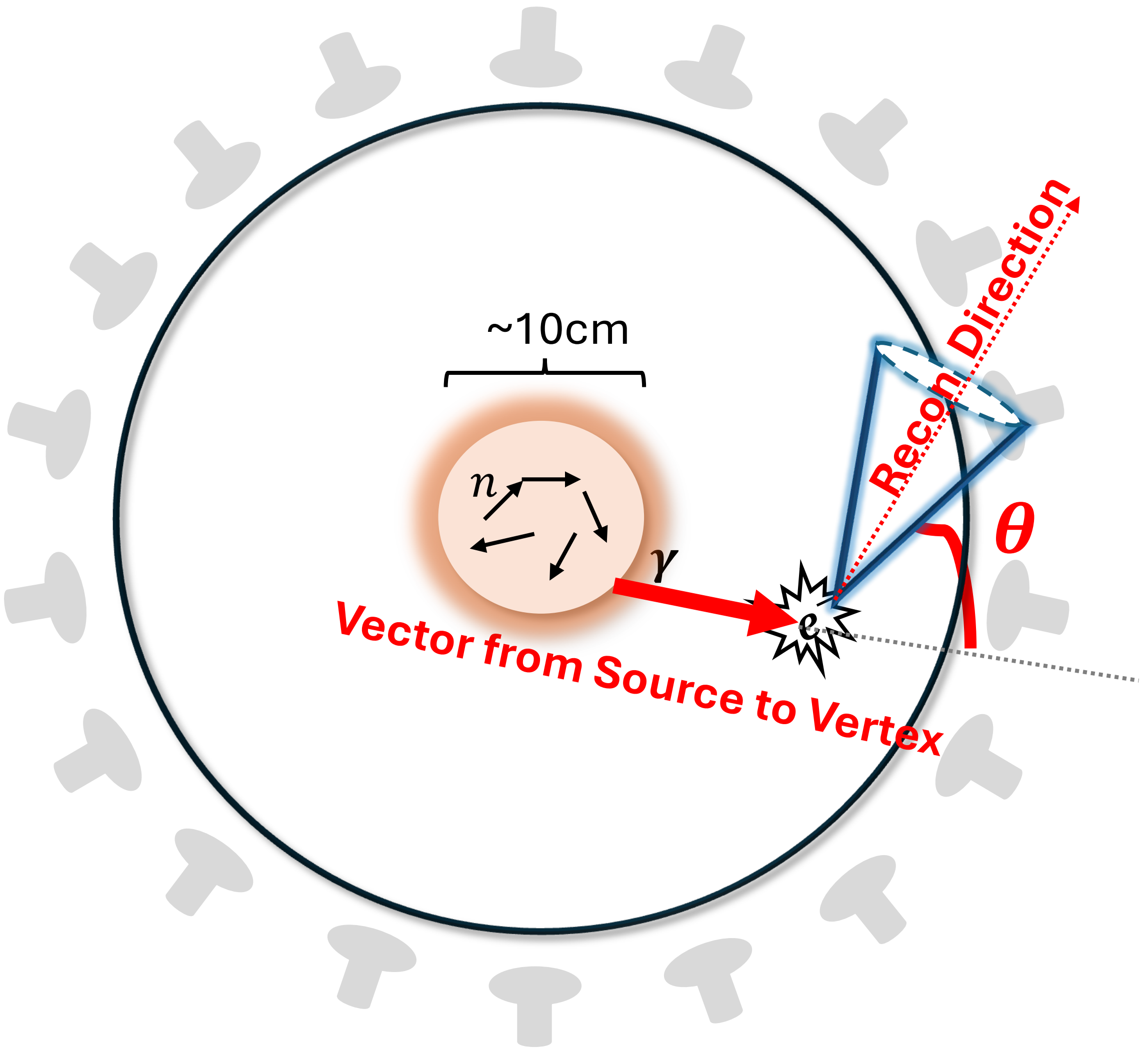
Thanks

Backup



~10cm
n
γ
e
Recon Direction
θ
Vector from Source to Vertex