MeV Event Reconstruction in a 500-ton Slow Liquid Scintillator Detector at CJPL

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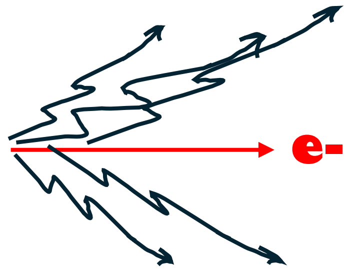
outline

- Motivation
- Detector Setup and Simulation Process
- Readout and Waveform Analysis
- Reconstruction Likelihood
- Reconstruction Results
  - Energy Resolution
  - Vertex Position Resolution
  - Angular Resolution
- Summary

Motivation

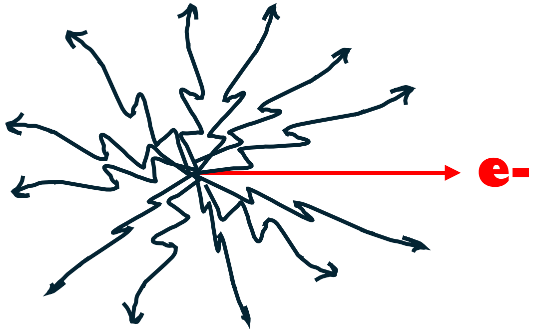
Cherenkov Light



Carry Directional Information

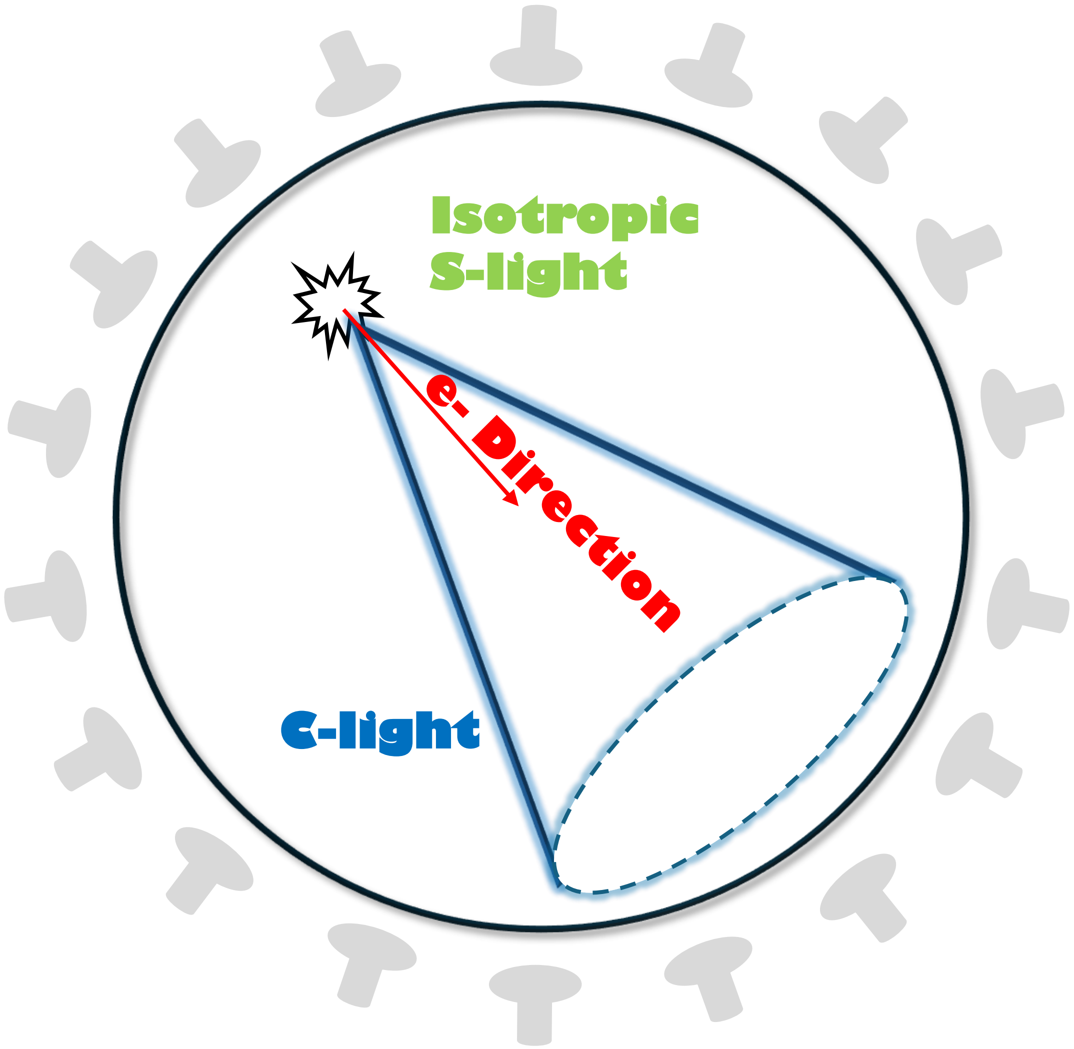
Good Directional Resolution

Scintillator Light



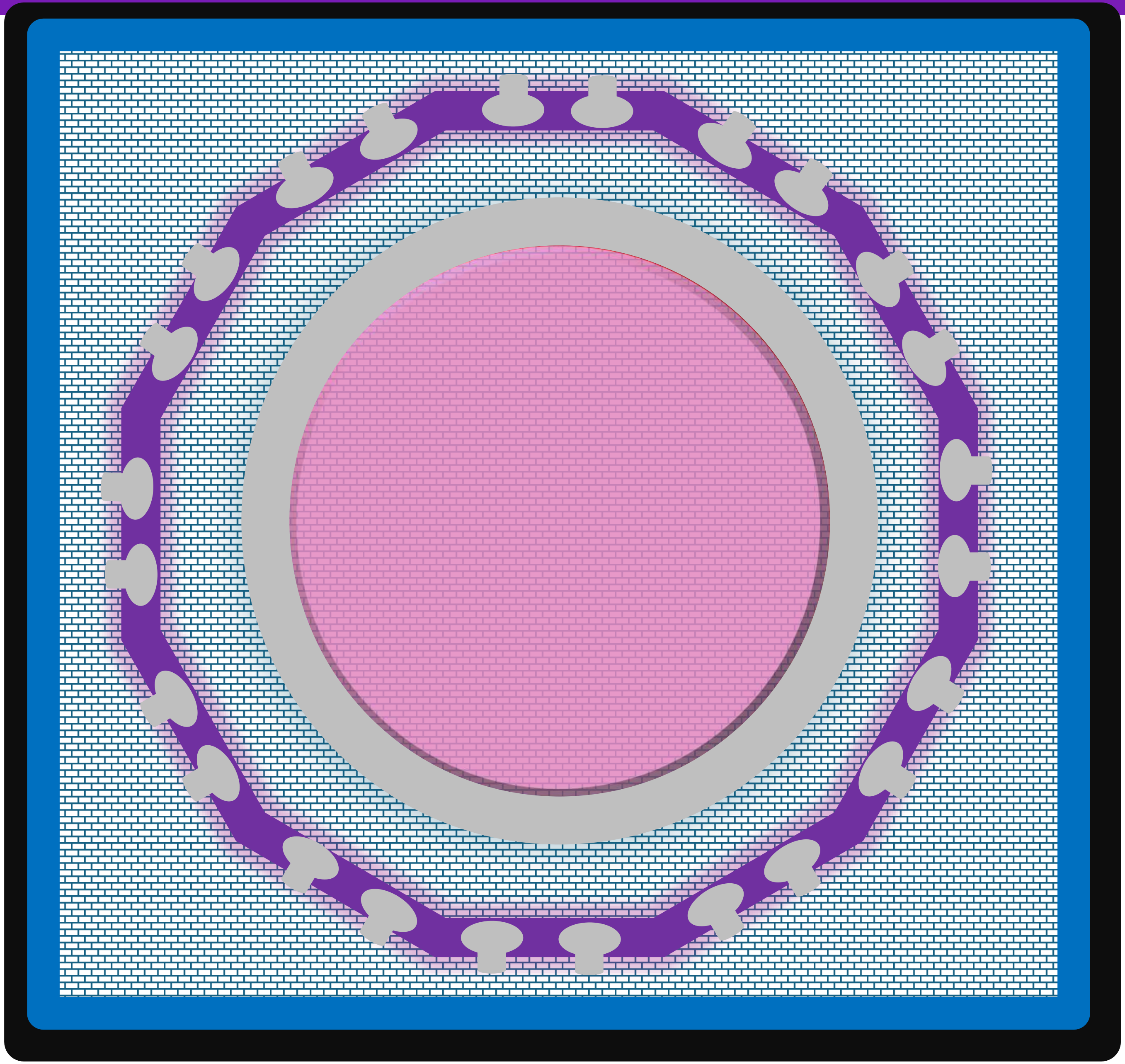
High Light Yield

Good Energy Resolution
Good Vertex Position Resolution



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

Detector Setup



Detector Setup：

Sensitive Volume(LS/Water)： radius 0-4.93m

Acrylic Sphere： radius 4.93-4.98m

Support Steel Plates : radius 5.80-5.90m

Support SteelFrame: radius 5.90-5.937m

2786 MCP-PMTs Position: radius 5.8-5.90m

（fraction of coverage~30%）

Water Box： 14.5m*12.9m*13.2m

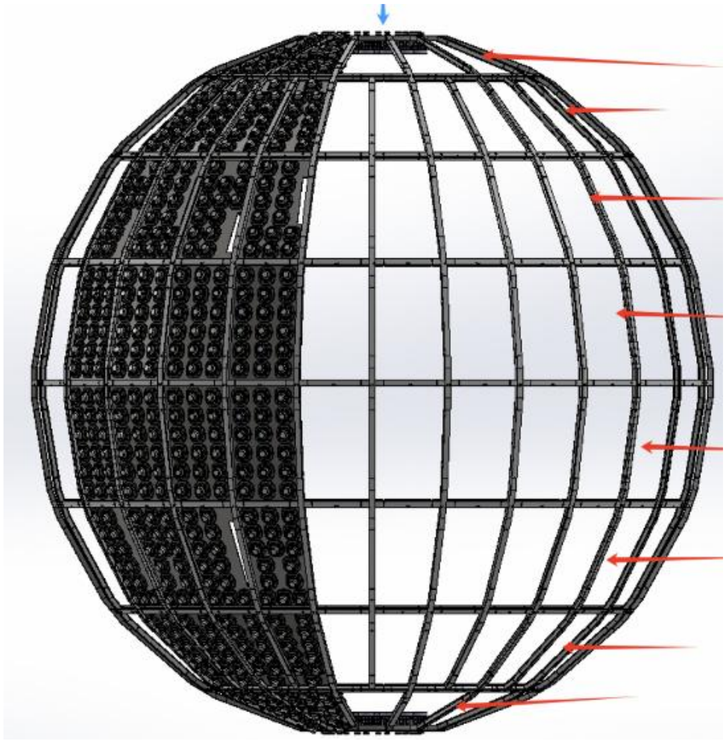
Rock Box: 14.52m*12.92m*13.22m

in

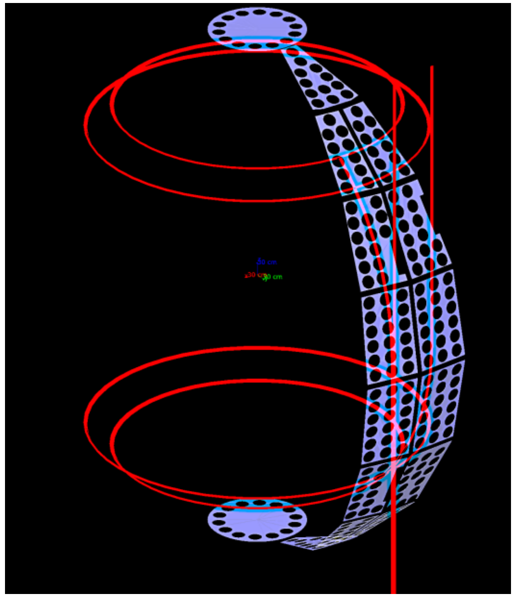
out

Detector Setup

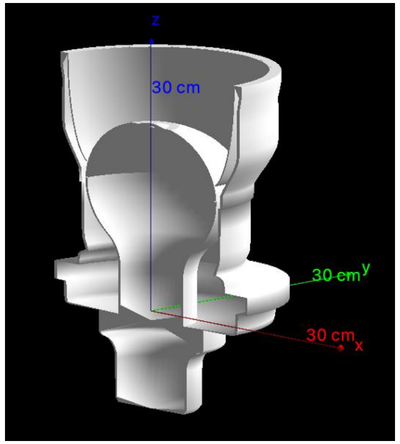
True Geo



MC Geo



TTS ≈ 1.67 ns (FWHM)



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in

out

Derived from the true geometric configuration

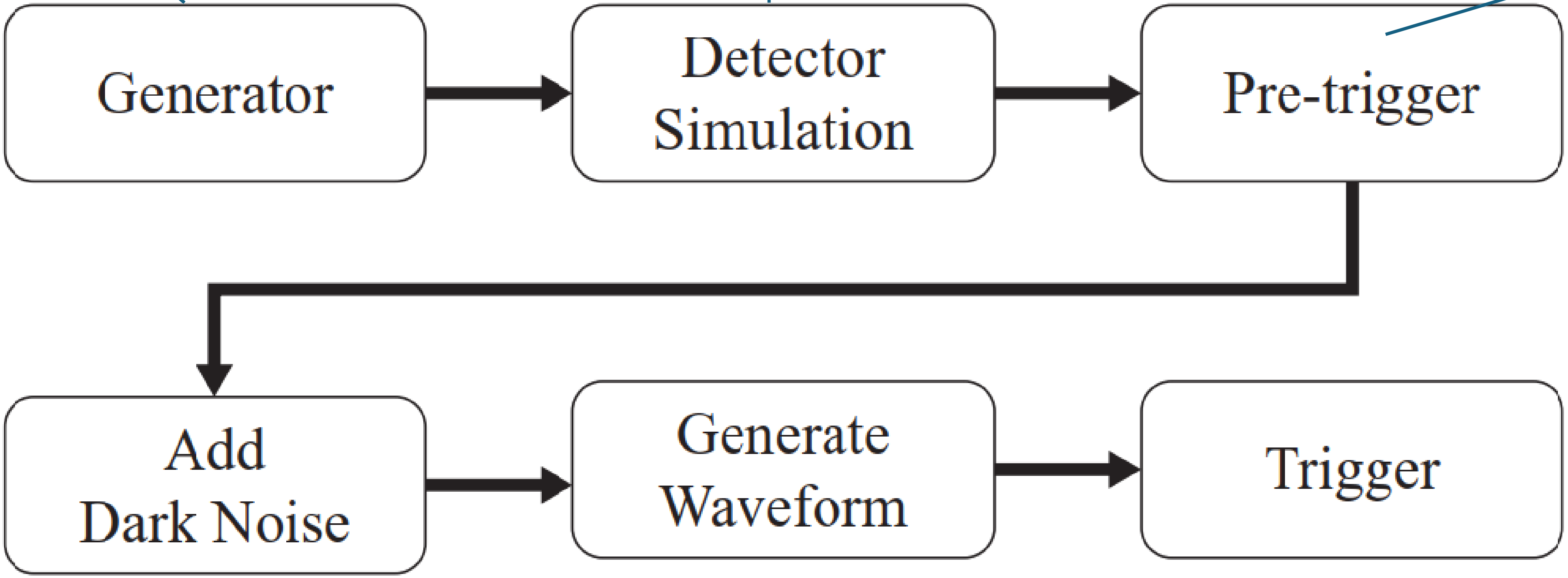
Simulation Process

Software: Jinping Simulation and Analysis Package(JSAP)

Particle Sources: e^-,γ,μ,n,α …
Position/Direction/Energy spectrum

Particle Interactions: Physical and Optical Processes
Hit Information

Preliminary Analysis Hit Info.



Simulation Parameters Setting

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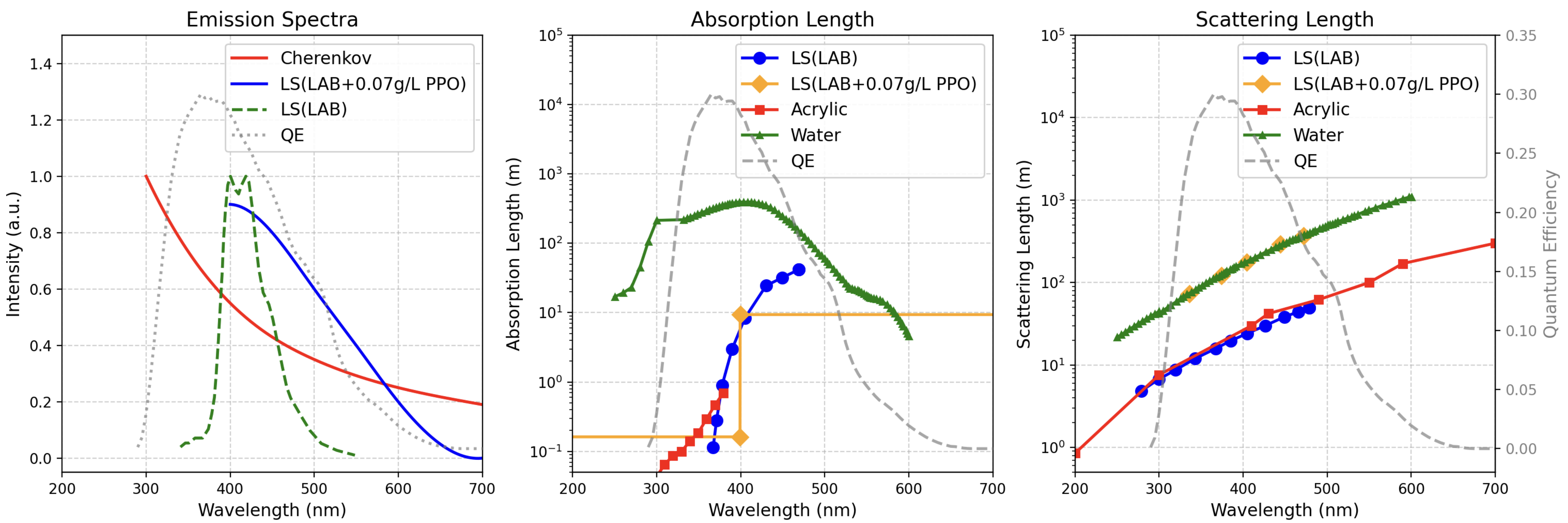


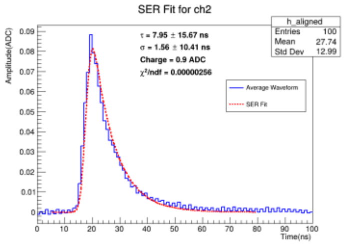
LS Composition	Scintillation light yield (photons/MeV)	Photoelectron number (PE/MeV)	Rise Time Constant (ns)	Decay Time Constant (ns)
Pure LAB	2530	100 Highest RiseTimeConstant	12.2	35.42
LAB+0.07g/LPPO Used in 1-ton prototype	4245	127	1.67	26.59

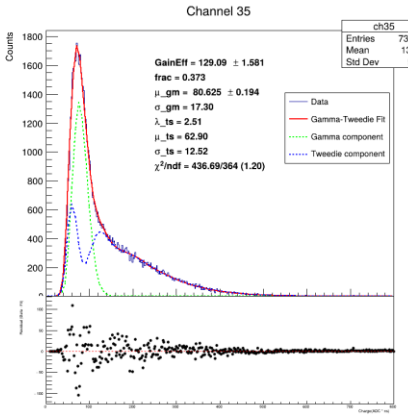
Readout and Waveform Analysis

PMT Gain spectrum

Residual Between True and Fitted Waveforms

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

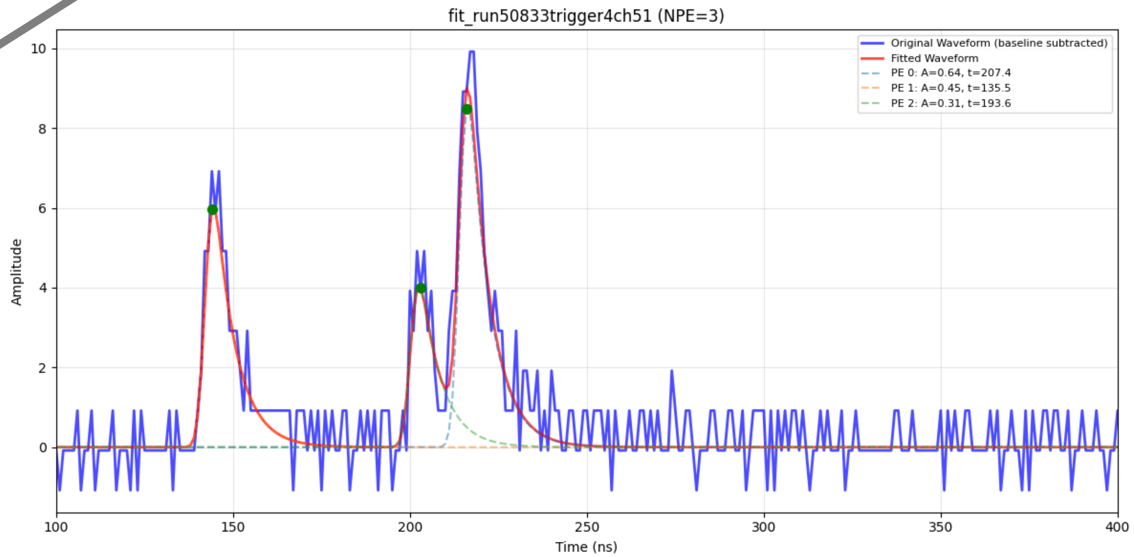




Fit by Minimizing the Negative Log-Likelihood :

- ✓ **PE Number**
- ✓ **PE Time**

Get Single Electron Pulse
Get Gain Spectrum

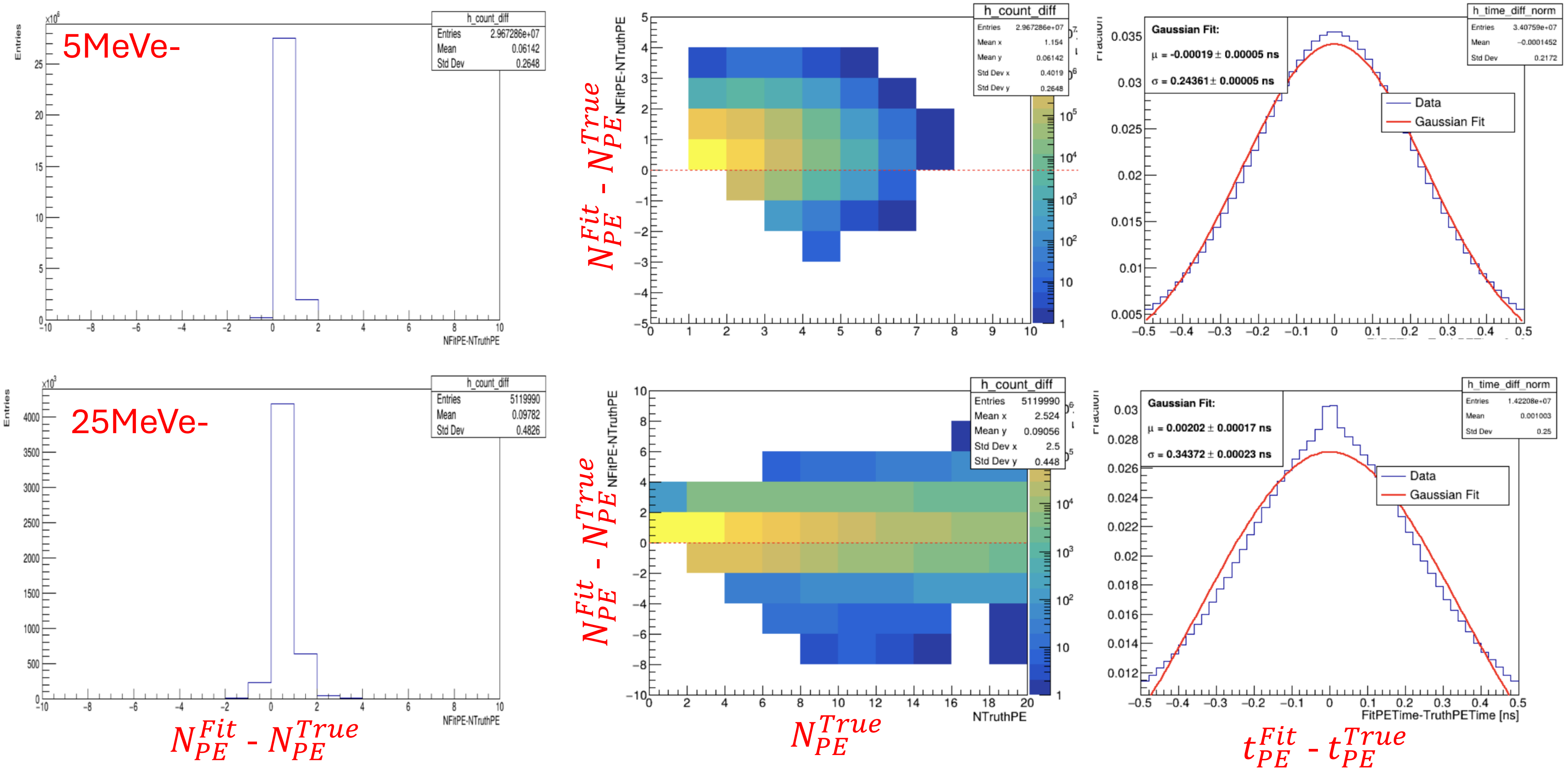


Initialization

•Initial Photoelectron (PE) Count
(estimated from the integrated charge / effective gain)

•Initial PE Time
(estimated by waveform deconvolution)

Waveform Analysis Results



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

Reconstruction Likelihood

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

Construction of the Likelihood Function：

- PE Term
  - ✓ **Photon emission**
  - ✓ **Photon propagation**
  - ✓ **Photon detection**
- PETime Term
  - ✓ Photon path length in different materials
  - ✓ **Group velocity** in different materials

Parameter Initialization

•**Energy:** Estimated from the total PE count.

•**Vertex Position:** Estimated using the center-of-charge (CoC) method.

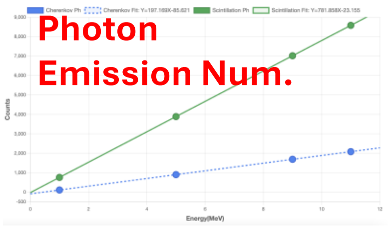
•**Direction:** Uniformly initialized.

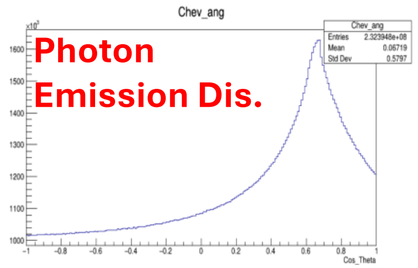
•**Time Constants:** Initialized with trial values.

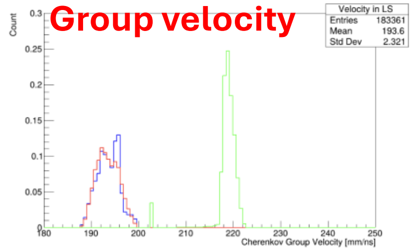
Fit by Minimizing the Negative Log-Likelihood

- ✓ Energy
- ✓ Vertex Position
- ✓ Direction
- ✓ Cherenkov t_0
- ✓ Scintillation t_0

Second Fitting Iteration

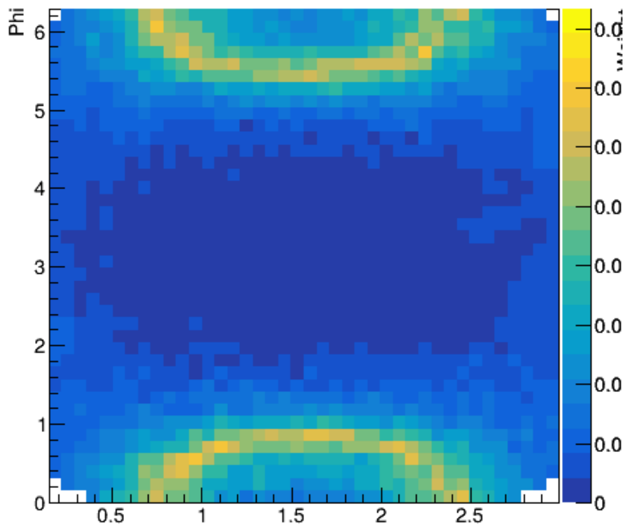




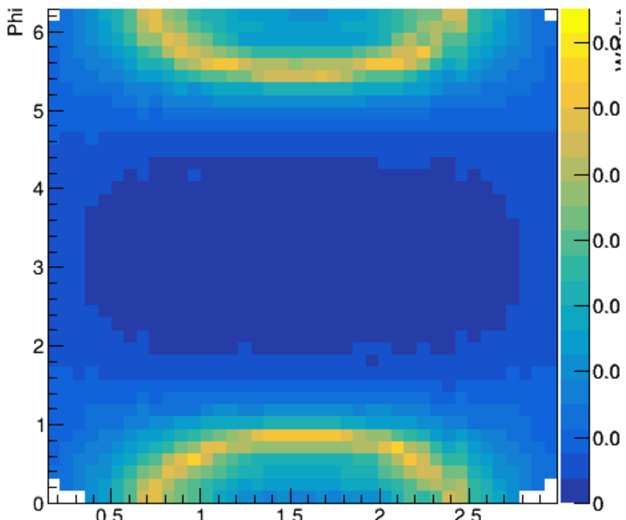


Reconstruction Likelihood: Accuracy of PE distribution

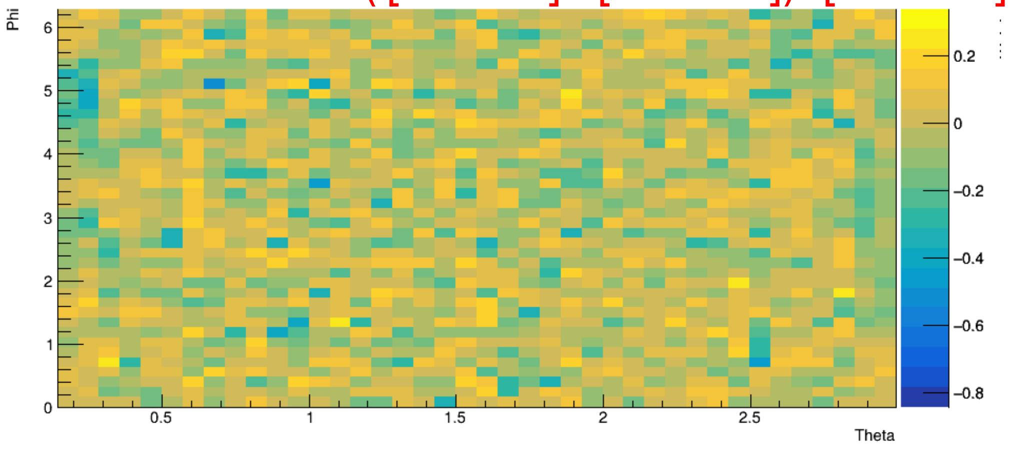
Direct Cherenkov [Full MC]



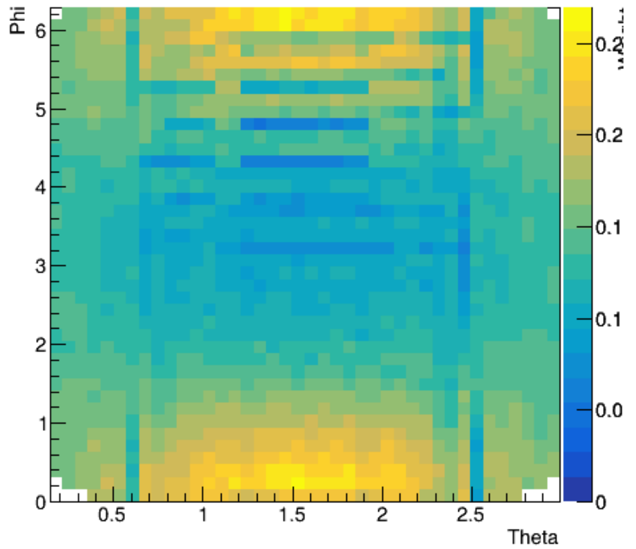
Direct Cherenkov [Predict]



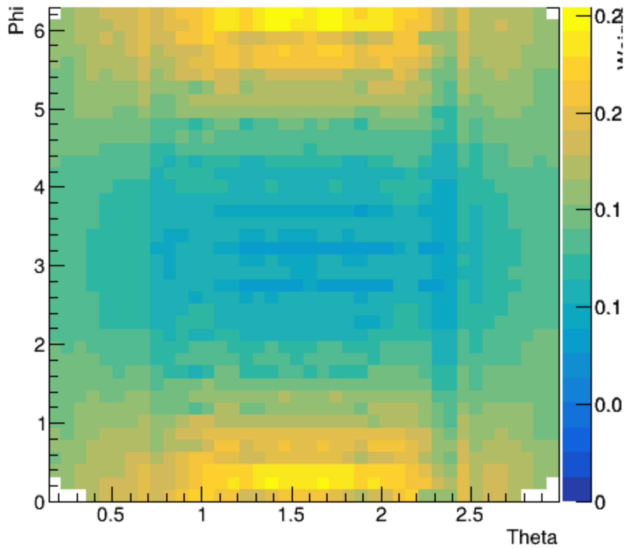
Direct Cherenkov([Predict] - [Full MC])/ [Full MC]



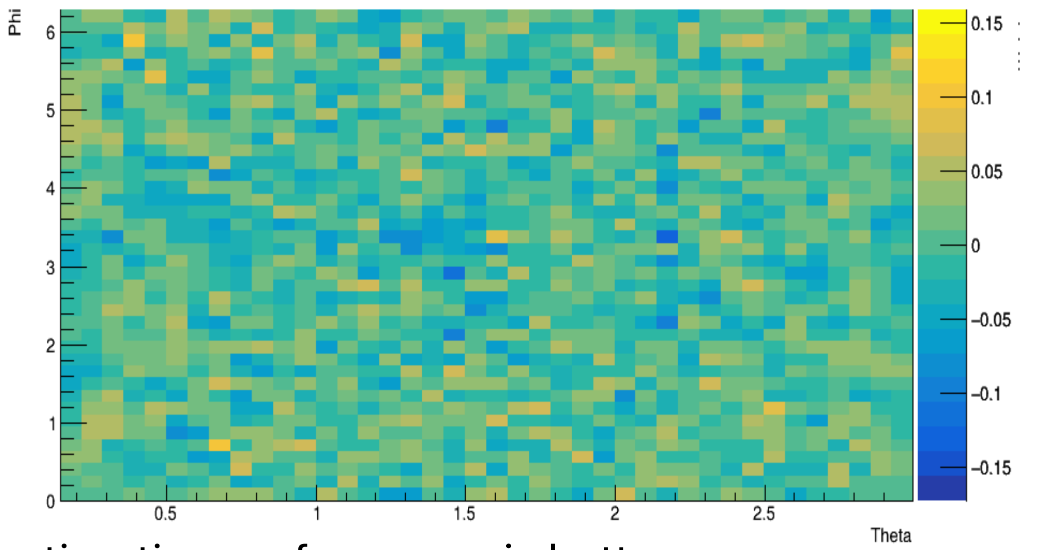
Direct Scintillation [Full MC]



Direct Scintillation [Predict]



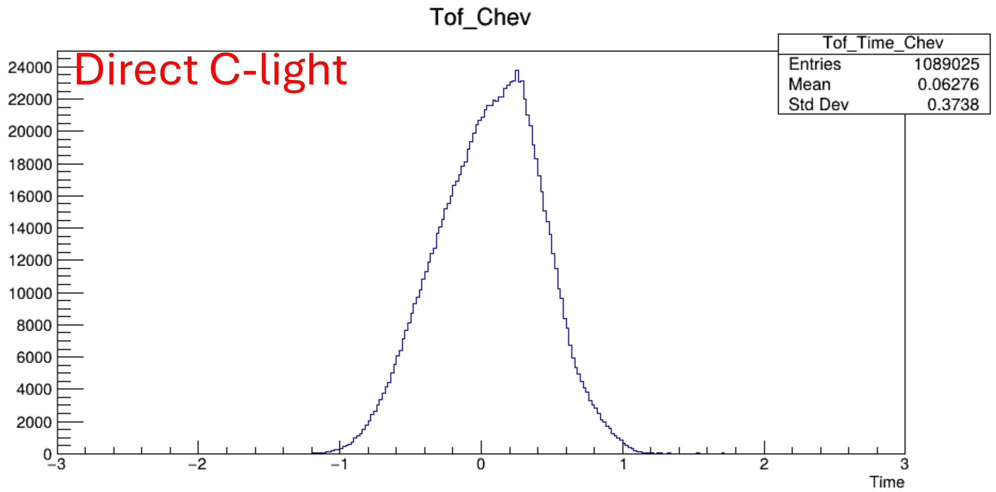
Direct Scintillation([Predict] - [Full MC])/ [Full MC]

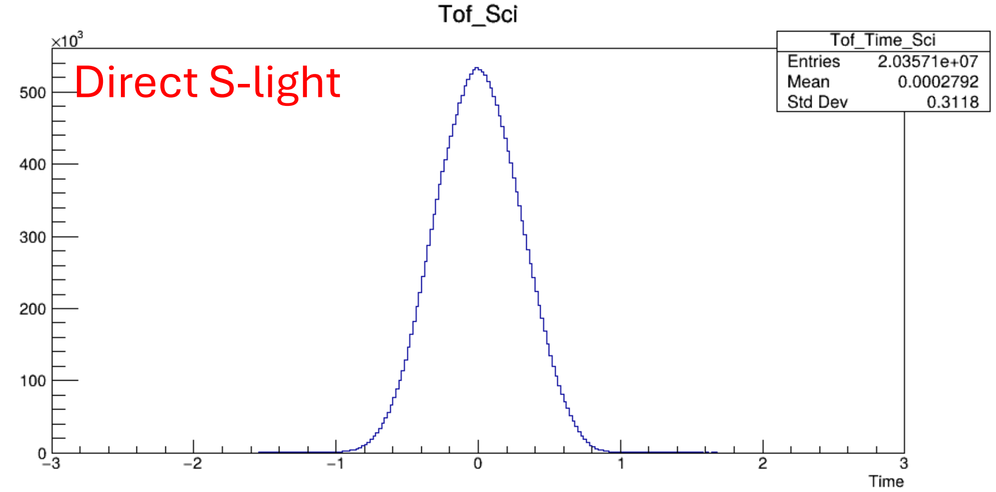


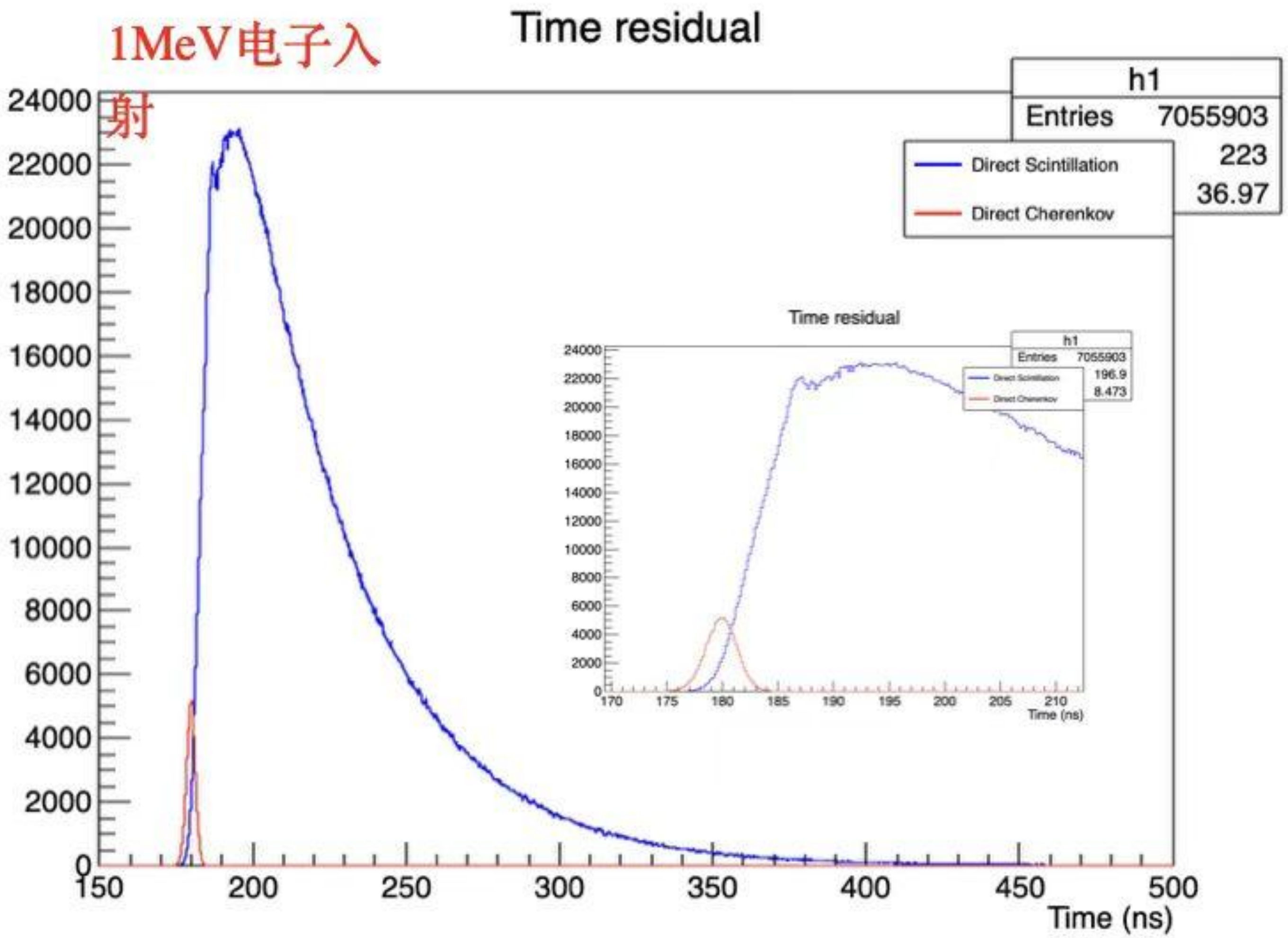
Due to the higher scintillation photon yield under normal incidence, the estimation performance is better than that of Cherenkov light, with an improvement of less than 15%.

Reconstruction Likelihood: Time Residual Distribution

$$t_{ij}^{\mathrm{C,res}} = t_{ij} - t_{\mathrm{event}} - \sum_{\mathrm{m}} \mathrm{TOF}_{i,\mathrm{m}}^{\mathrm{C,pred}}$$

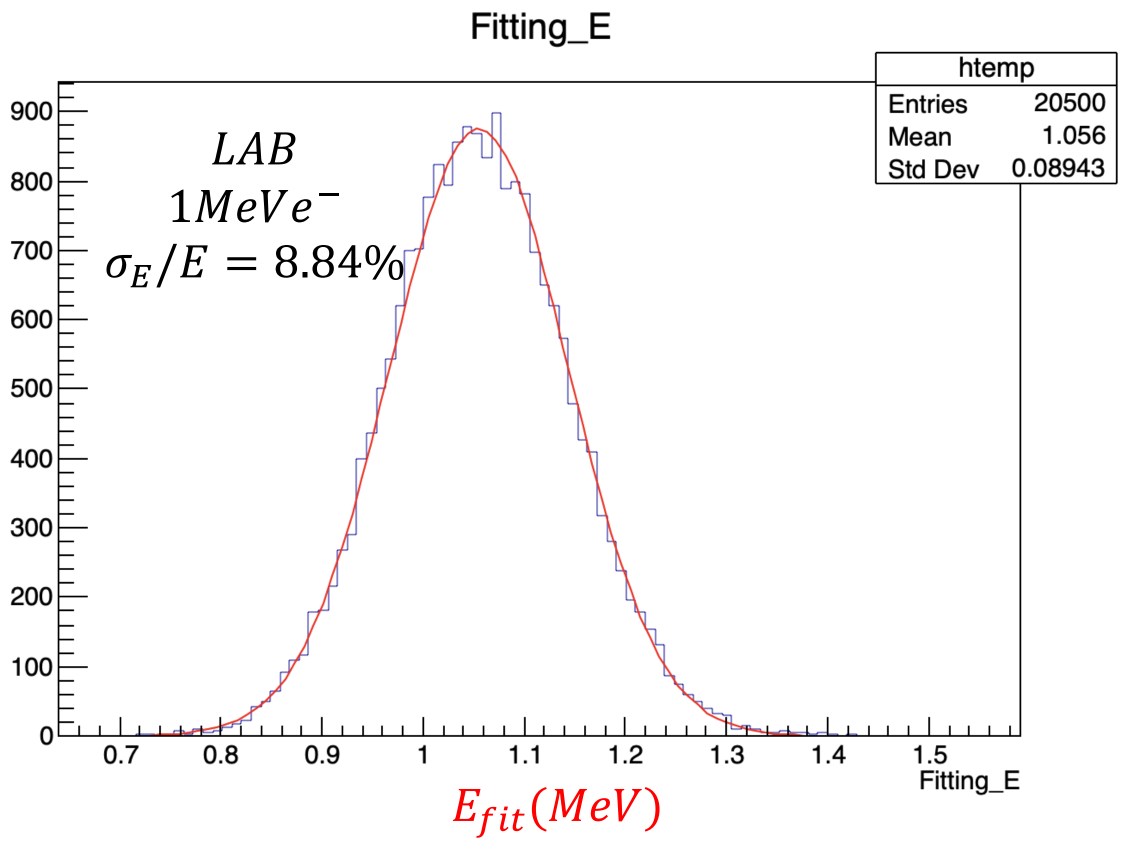


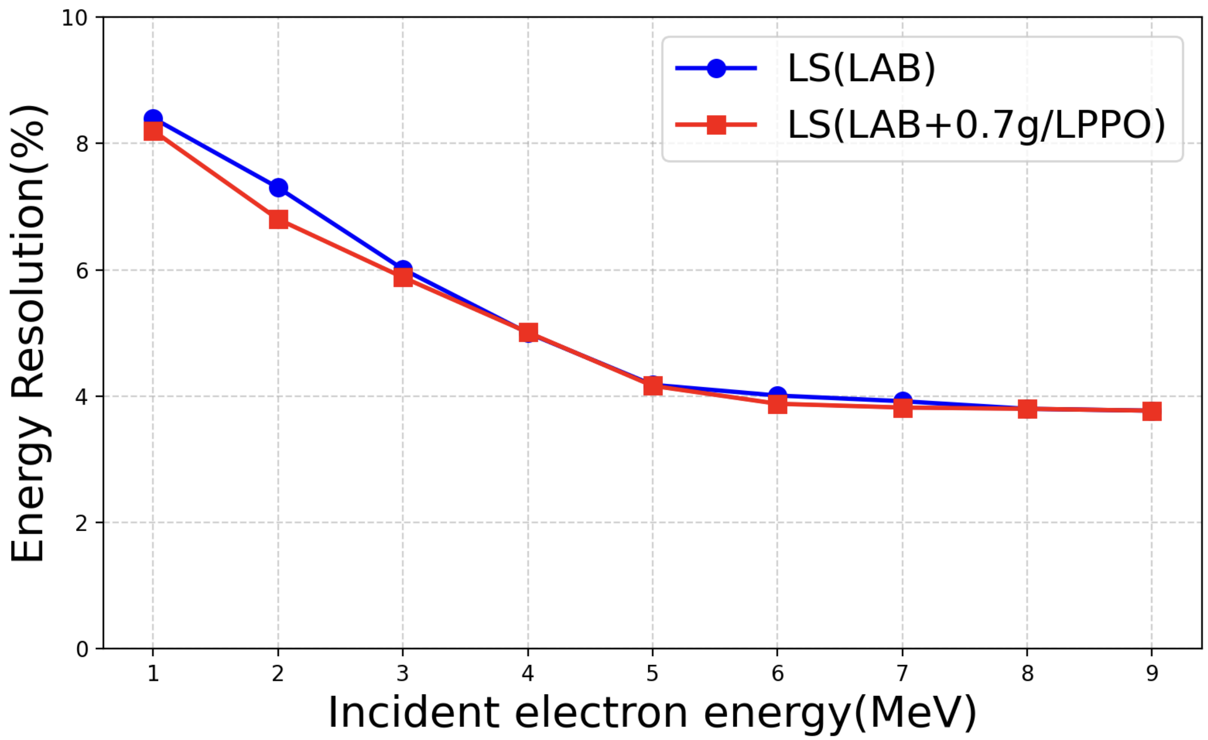




The time of flight (TOF) can be predicted with 1ns accuracy.

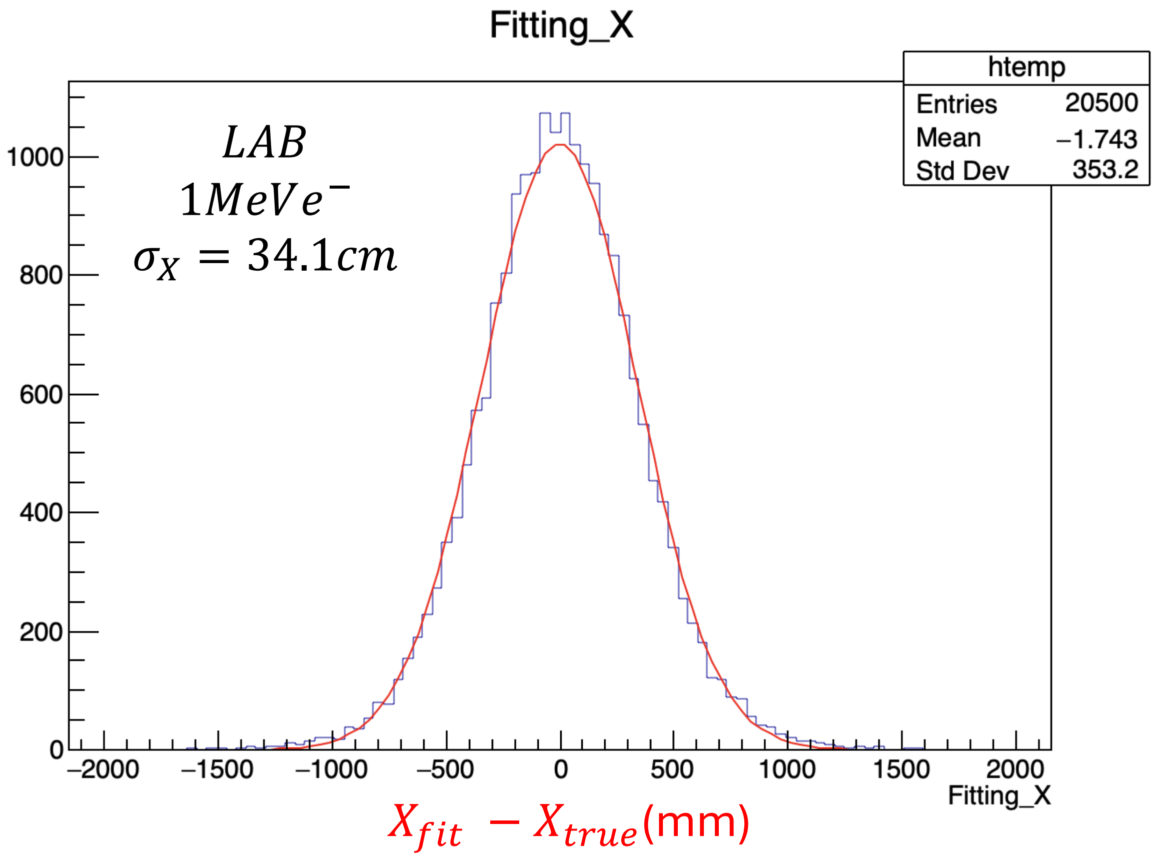
Reconstruction Results: Energy Resolution

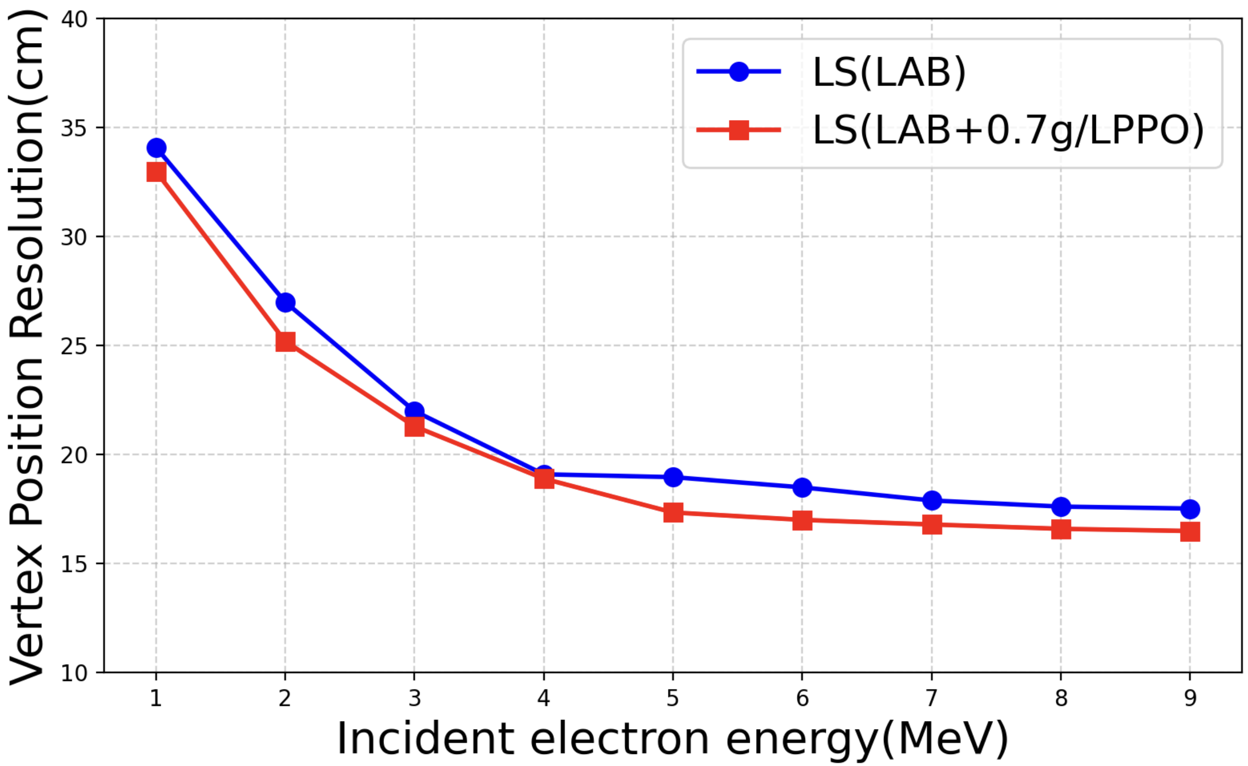




- The two scintillator materials produce comparable photoelectron yields, resulting in similar energy resolution. The LAB + 0.07 g/L PPO mixture exhibits slightly better performance.

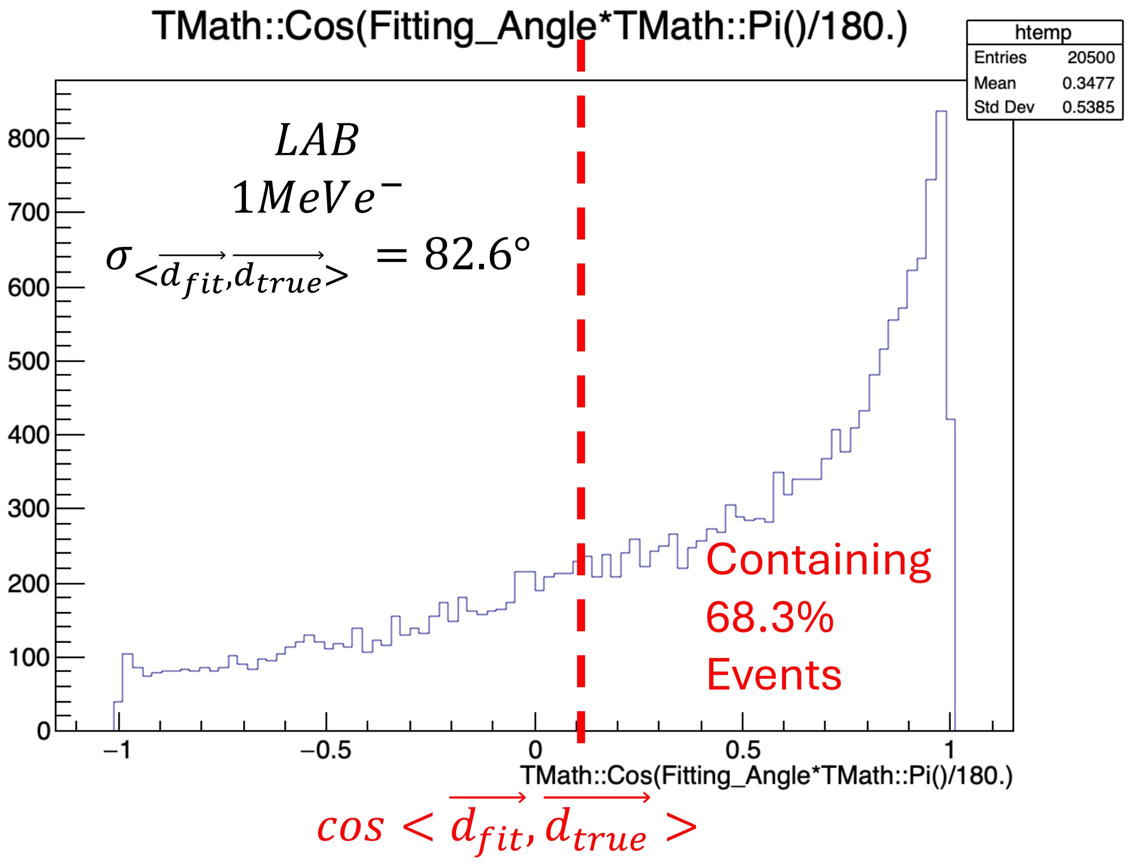
Reconstruction Results: Vertex Position Resolution

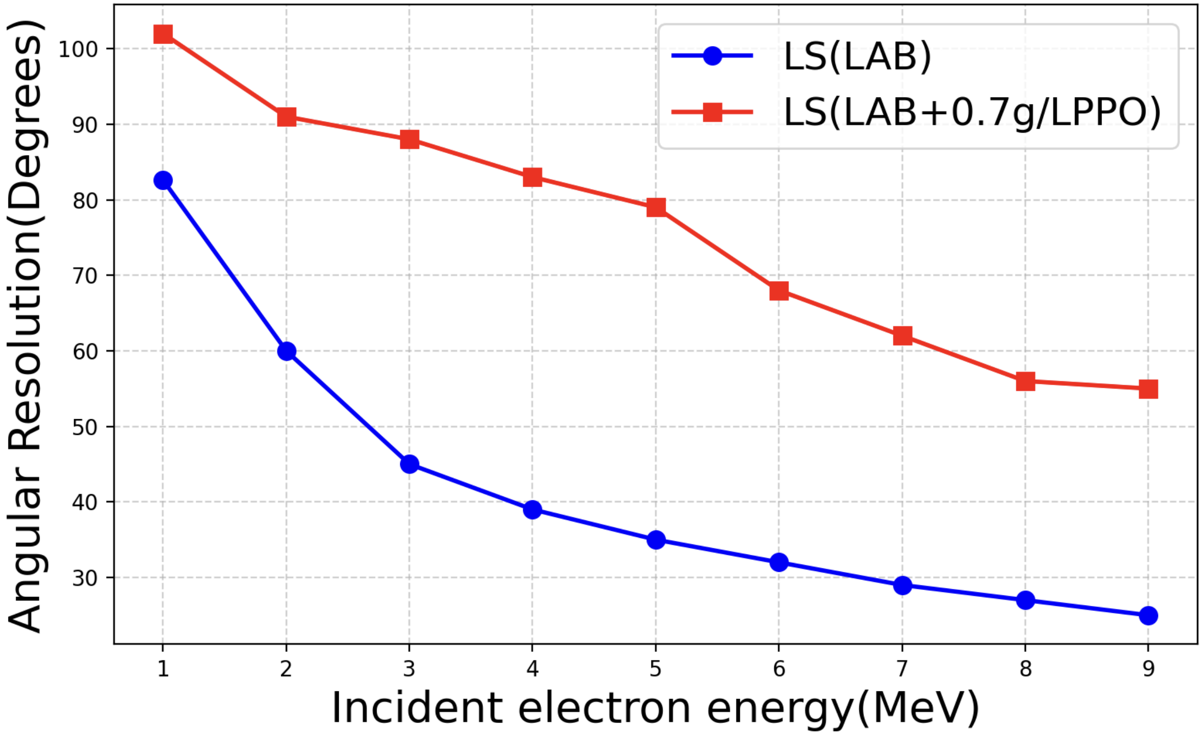




- The LAB + 0.07 g/L PPO mixture exhibits slightly better performance.

Reconstruction Results: Angular Resolution





- **Pure LAB**, with a scintillation rise time of **12.2 ns**, provides better temporal separation between Cherenkov and scintillation photons, resulting in improved directional reconstruction. For **5 MeV electrons**, an angular resolution of approximately **34°** was achieved.
- **LAB + 0.07 g/L PPO**, the scintillator currently used in the **1-ton prototype detector**, has a shorter rise time, leading to less effective Cherenkov/scintillation separation and therefore a lower angular reconstruction accuracy, although the directional signal remains observable.

Summary

- **Cherenkov liquid scintillator (CLS) detectors** enable the separation of Cherenkov and scintillation light by slowing the scintillation emission. This allows the directional information carried by Cherenkov photons to be combined with the high light yield of liquid scintillators, thereby improving the **energy, position, and angular resolutions**.
- A detailed simulation model of the **500-ton Jinping detector** was developed, incorporating the realistic PMT geometry, PMT positions, and the geometrical structures of the supporting steel plates and frames.
- A waveform analysis algorithm was implemented to reconstruct the **photoelectron (PE) count** and **PE hit times** for each waveform, achieving a **PE count resolution of approximately 0.5 PE per waveform** and a **timing resolution of approximately 0.34 ns**.
- Two liquid scintillator formulations were investigated:
  - **Pure LAB**, with a scintillation rise time of **12.2 ns**, provides better temporal separation between Cherenkov and scintillation photons, resulting in improved directional reconstruction. For **5 MeV electrons**, an angular resolution of approximately **34°** was achieved.
  - **LAB + 0.07 g/L PPO**, the scintillator currently used in the **1-ton prototype detector**, has a shorter rise time, leading to less effective Cherenkov/scintillation separation and therefore a lower angular reconstruction accuracy, although the directional signal remains observable. Owing to its higher light yield, this formulation provides better **energy** and **position reconstruction** performance.