FERMILAB-POSTER-26-0132-V

Event Reconstruction for Water-based Liquid Scintillator Detectors

Zhenxiong Xie[1], Michael Wilking[1], Guang Yang[2], Cristóvão Vilela[3] for THEIA collaboration

1. School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA

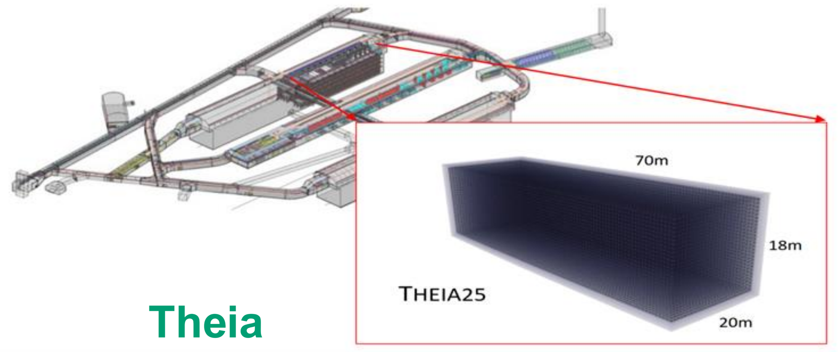
2. Brookhaven National Laboratory, Upton, NY 11980, USA

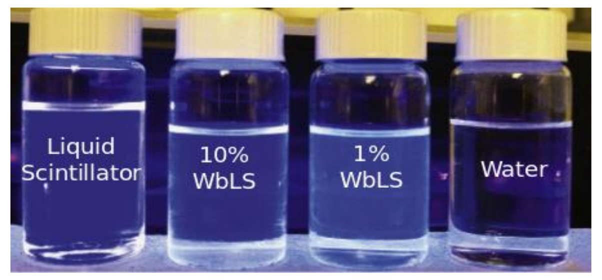
3. Laboratory of Instrumentation and Experimental Particle Physics (LIP), Lisbon, 1649-003, Portugal

Contact: xiez@umn.edu

1. MOTIVATION

- **Cherenkov ring topology** yields track direction and particle ID (PID).
- **Liquid scintillator** offers higher light yield and a lower energy threshold.





WbLS produced at BNL

- **Water-based liquid scintillator (WbLS)** combines advantages from both detectors.
- **Theia**, an R&D WbLS detector[1] (~5% WbLS, 40% photo-coverage) supports a broad multi-purpose physics program spanning long-baseline oscillations, solar and supernova neutrinos, and neutrinoless double beta decay.
- **Challenge:** photosensors record Cherenkov and scintillation light simultaneously, complicating event reconstruction.

2. METHOD: fiTQun

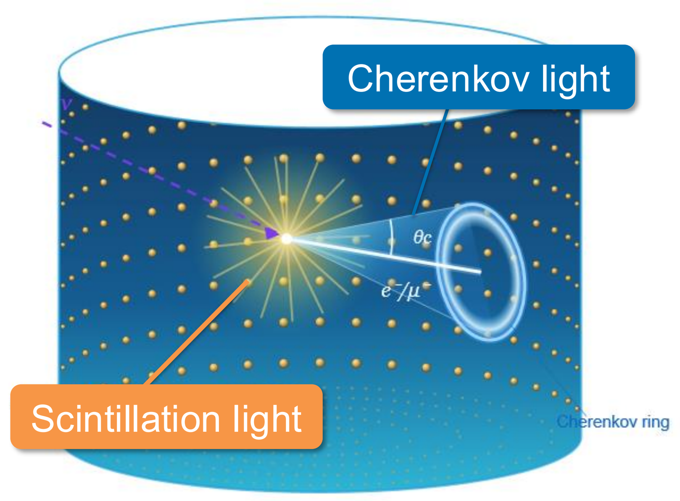
fiTQun is a likelihood-based reconstruction framework proven in **Super-K** for water Cherenkov events in the cylindrical detector.

It maximizes a per-PMT likelihood over the event hypothesis **X**[2]:

$$\mathcal{L}(\mathbf{X}) = \prod_{j}^{n_{\text{unhit}}} P(\text{unhit}|\mu_j) \prod_{i}^{n_{\text{hit}}} (1 - P(\text{unhit}|\mu_i))\, f_q(q_i|\mu_i) f_t(t_i|\mathbf{X})$$

- $\mathbf{X}$ — event hypothesis: vertex, direction, momentum, PID, ring number.
- μ_i — predicted charge for the i-th PMT.
- $P(\text{unhit}\,|\,\mu_i)$ — probability a PMT of predicted charge μ_i records no hit.
- $f_q(q_i\,|\,\mu_i)$ — charge PDF: likelihood of the observed charge q_i given prediction μ_i.
- $f_t(t_i\,|\,X)$ — time PDF: likelihood of the observed hit time t_i under $\mathbf{X}$.

3. EXTENDING fiTQun TO WbLS



Scintillation light is added to the per-PMT likelihood: emitted isotropically along the track and combined with the **Cherenkov** component.

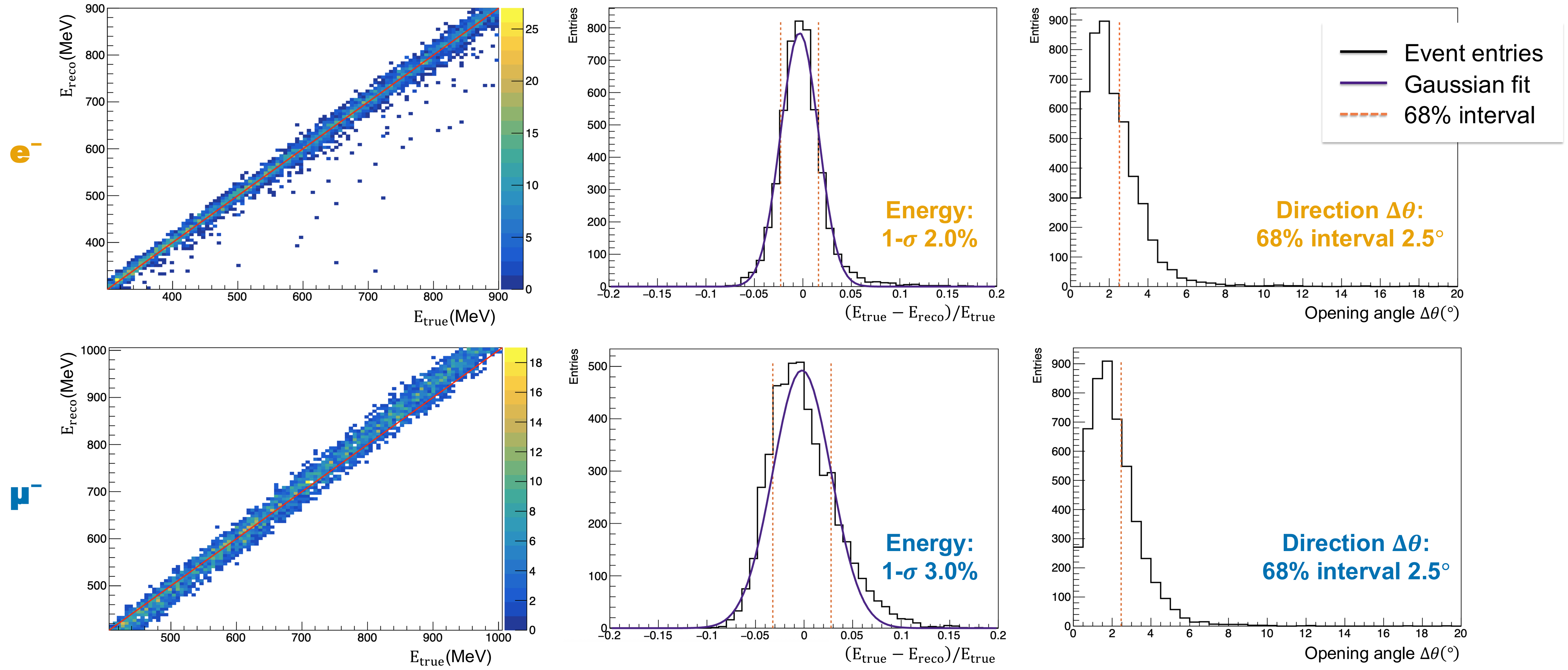
$$\mu_{WbLS} = \mu_{Ch} + \mu_{sci}$$

$$\mu_{Ch} = \Phi_{\text{Ch}} \int_{-\infty}^{\infty} ds\, \rho_{\text{Ch}}(s)\, \Omega(s)\, T_{\text{Ch}}(s)\, \epsilon(s)\, g(\cos\theta(s); s)$$

$$\mu_{sci} = \Phi_{\text{sci}} \int_{-\infty}^{\infty} ds\, \rho_{\text{sci}}(s)\, \Omega(s)\, T_{\text{sci}}(s)\, \epsilon(s)$$

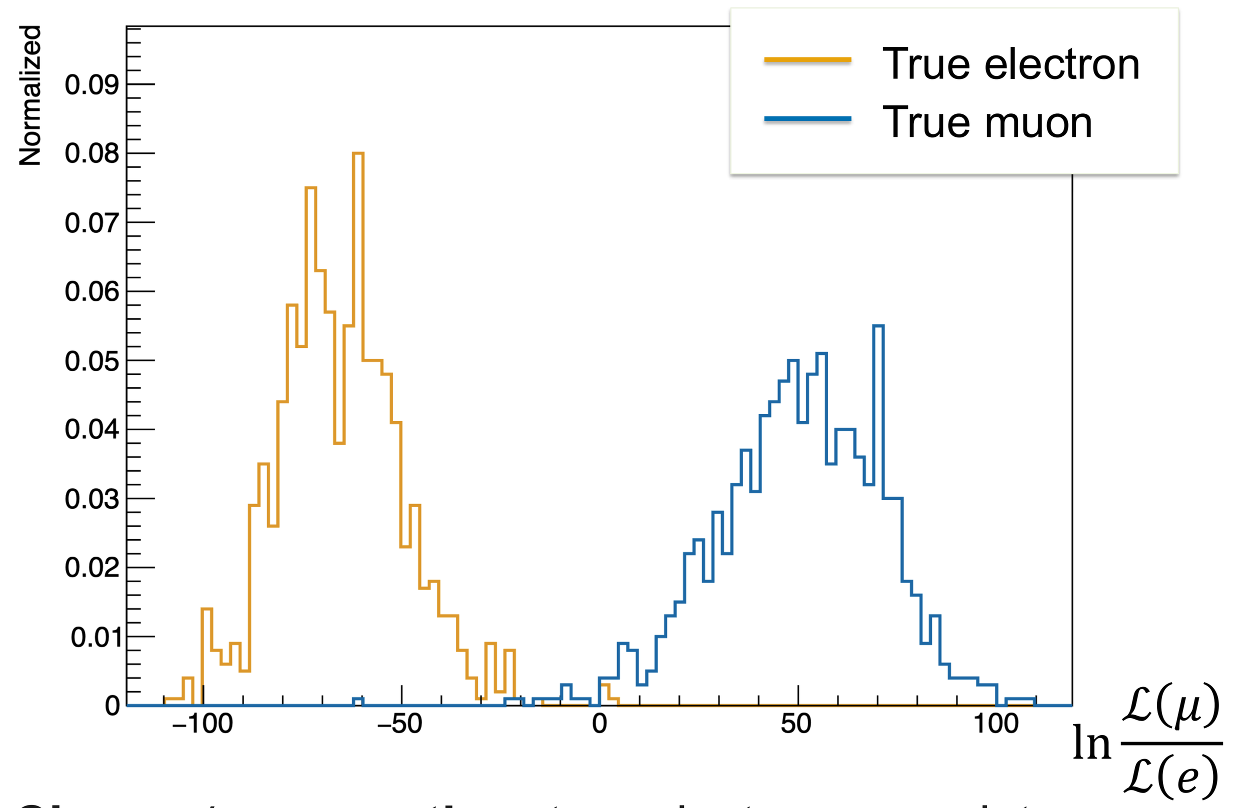
4. WbLS RECONSTRUCTION RESOLUTION

- Demonstrate charge-only reconstruction using direct light only in a ~190-kton fiducial volume, 5% WbLS cylindrical detector.
- Vertex is fixed in the center of the detector.



5. PARTICLE IDENTIFICATION SEPARATION

PID separation for kinetic energy 500 MeV electrons and muons.



Clean e/μ separation: true electrons populate $\ln \mathcal{L}(\mu) - \ln \mathcal{L}(e) < 0$,true muons > 0, with negligible overlap.

6. CONCLUSIONS & OUTLOOK

fiTQun reconstructs energy, PID, vertex position, and direction with competitive resolution in cylindrical WbLS detectors.

- This resolution is comparable to that achieved in water-Cherenkov detectors (fiTQun in Hyper-K[3]: ~4.0% for electrons and ~2.6% for muons).
- The reconstruction performance and clear PID separation demonstrates the feasibility of conducting long-baseline oscillation measurements with WbLS detectors.

Ongoing studies incorporating the time PDF and indirect light are expected to further improve the resolution, particularly for vertex reconstruction and PID separation.

Reference

[1] Theia Collaboration, "Theia: Summary of physics program," Snowmass White Paper Submission, arXiv:2202.12839 (2022).

[2] R.B. Patterson et al., "The extended-track event reconstruction for MiniBooNE," *NIM A* 608 (2009) 206–224.

[3] K. Abe et al., "Physics potential of a long-baseline neutrino oscillation experiment using a J-PARC neutrino beam and Hyper-Kamiokande," PTEP 2015 (2015) 053C02.

This manuscript has been authored by Fermi Forward Discovery Group, LLC under Contract No. 89243024CSC000002 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Poster #141, Session #1,
Neutrino 2026: XXXII International Conference on Neutrino Physics and Astrophysics