Combined Cherenkov and Scintillation Event Reconstruction

Zhenxiong Xie
University of Minnesota
xiez@umn.edu

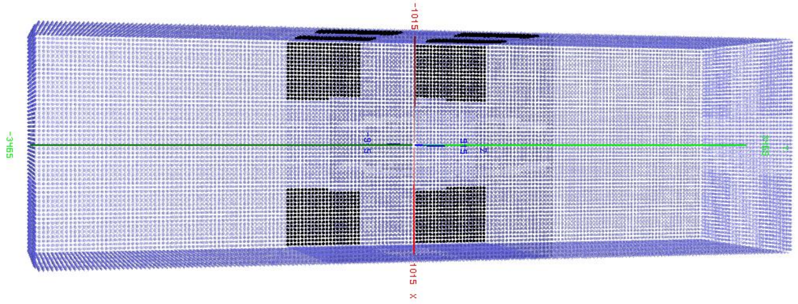
Guang Yang
BNL
gyang1@bnl.gov

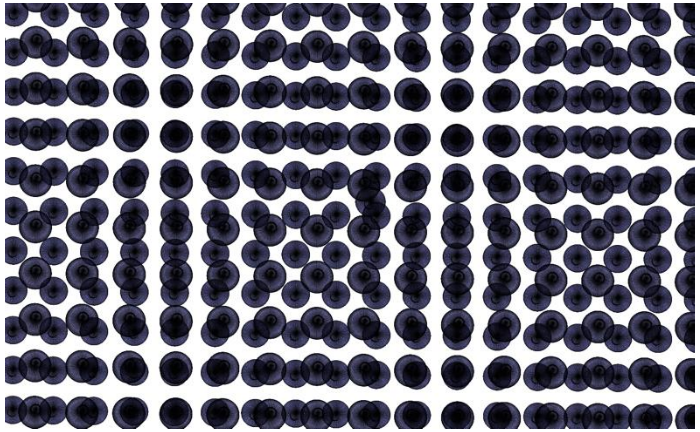
Outline

- Water-based Liquid Scintillator (WbLS) Detector
- Event Reconstruction in Water Cherenkov Detector
- Combined Cherenkov and Scintillation Event Reconstruction

Theia

- Water-based Liquid Scintillator (WbLS) detector provides a different nuclear target based on a combination of water Cherenkov and liquid scintillator technologies.
- Theia is a WbLS detector currently in the R&D stage.
- 40% photo-coverage with ~ 46,000 10-inch PMTs or ~12,000 20-inch PMTs
- 5% Water-based Liquid Scintillator

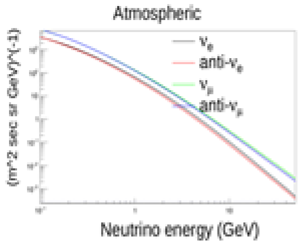


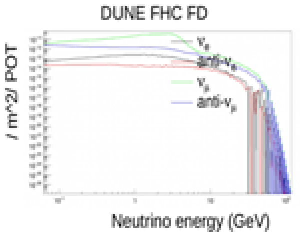


Long-baseline Analysis Workflow

Flux weight

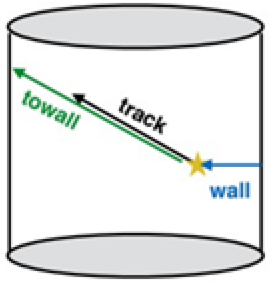
Atmospheric neutrino flux weighted to the DUNE flux





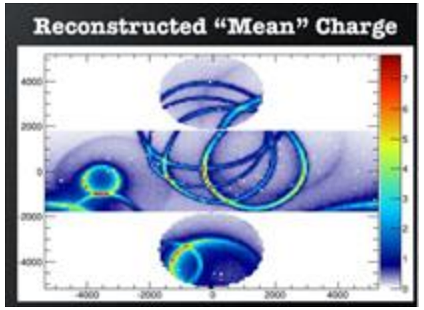
Pre-cut selection

Fully contained Fiducial volume events selected



Ring reconstruction

Estimate each ring's PID and kinematics



Energy reconstruction

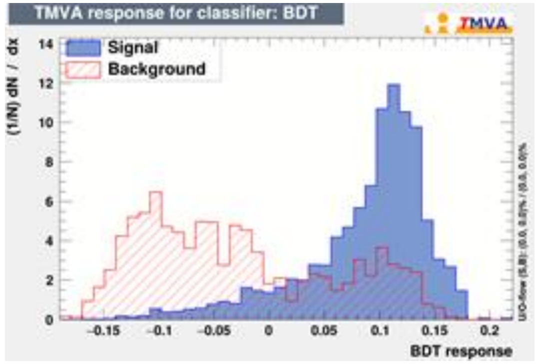
Energy estimated based on the ring number and decay number of the event

$$E_\nu \approx \frac{2M_n E_\ell - m_\ell^2}{2\,(M_n - E_\ell + p_\ell \cos\theta_\ell)}$$

$$(p_\nu + p_n - p_\ell - p_\pi)^2 = m_p^2$$

$\pi 0$ background reduction

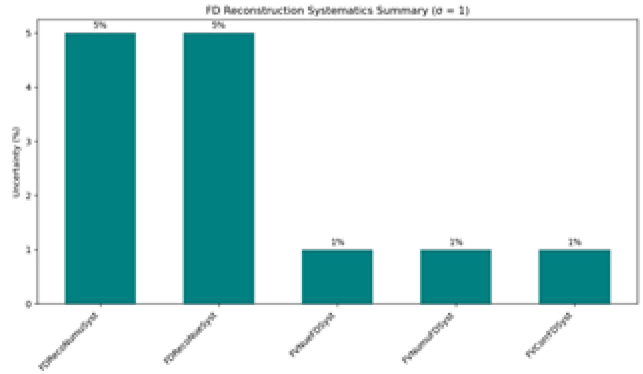
BDT used to reduce the NC background



Systematic Model

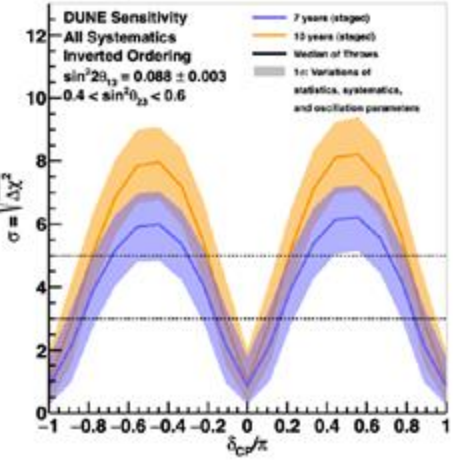
TDR flux systematics applied

TDR LAr detector systematics applied



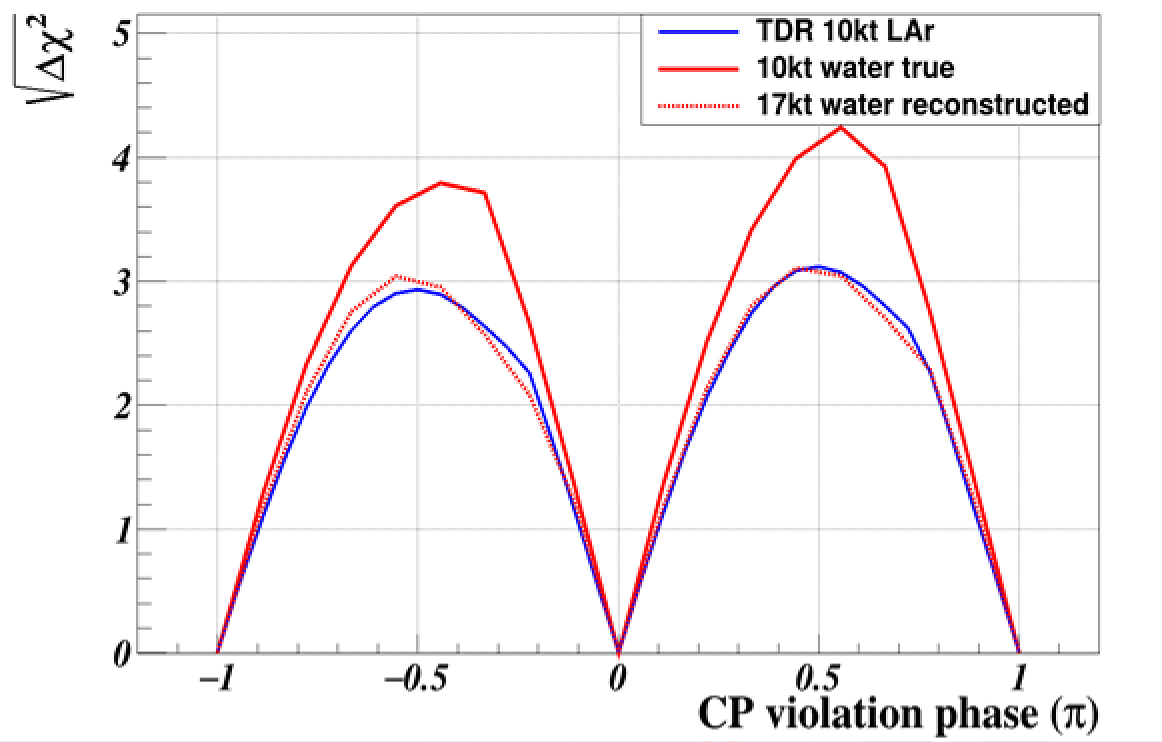
Oscillation Analysis

TDR Cafana is used to estimate the CP violation sensitivity with a pure water detector



Long-baseline Analysis Workflow

Latest CPV Sensitivity



Even without scintillation light, the LBL CP sensitivity for 17kt water detector is similar to 10kt LAr detector.

Flux weight

Atmospheric neutrino flux weighted to the DUNE flux

Pre-cut selection

volume events selected

Ring reconstruction

and kinematics

Energy reconstruction

Energy estimated based on the ring number and decay number of the event

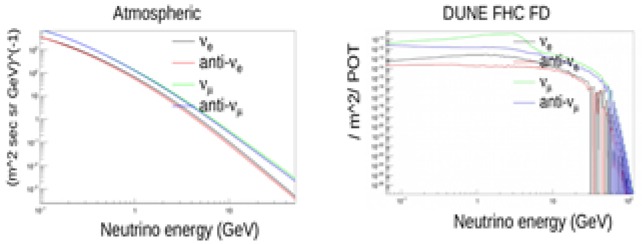
$$E_\nu \approx \frac{2M_n E_\ell - m_\ell^2}{2\left(M_n - E_\ell + p_\ell \cos\theta_\ell\right)}$$

TDR Cafana is used to estimate the CP violation sensitivity with a pure water detector

Long-baseline Analysis Workflow

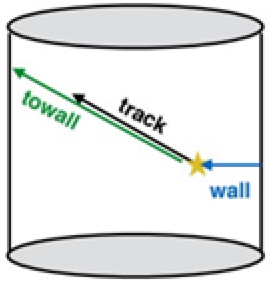
Flux weight

Atmospheric neutrino flux weighted to the DUNE flux



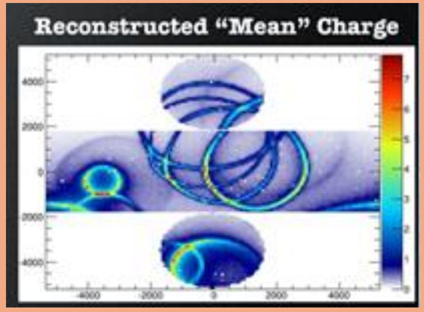
Pre-cut selection

Fully contained Fiducial volume events selected



Ring reconstruction

Estimate each ring's PID and kinematics



Energy reconstruction

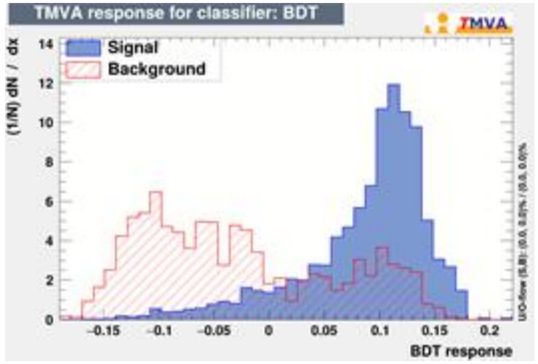
Energy estimated based on the ring number and decay number of the event

$$E_\nu \approx \frac{2M_n E_\ell - m_\ell^2}{2\left(M_n - E_\ell + p_\ell \cos\theta_\ell\right)}$$

$$\left(p_\nu + p_n - p_\ell - p_\pi\right)^2 = m_p^2$$

$\pi0$ background reduction

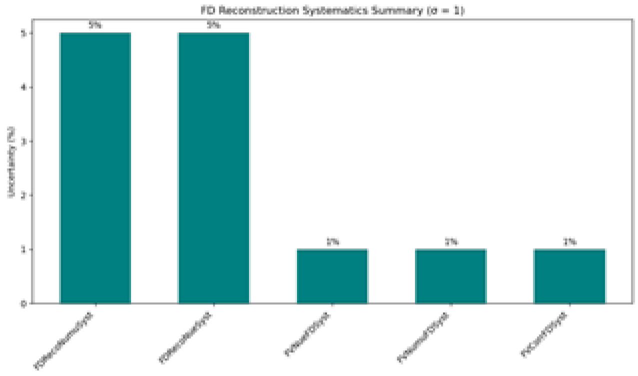
BDT used to reduce the NC background



Systematic Model

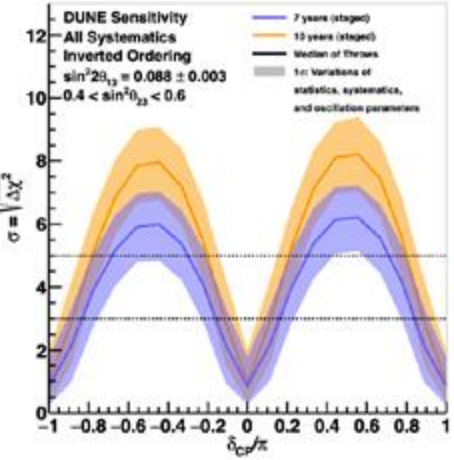
TDR flux systematics applied

TDR LAr detector systematics applied



Oscillation Analysis

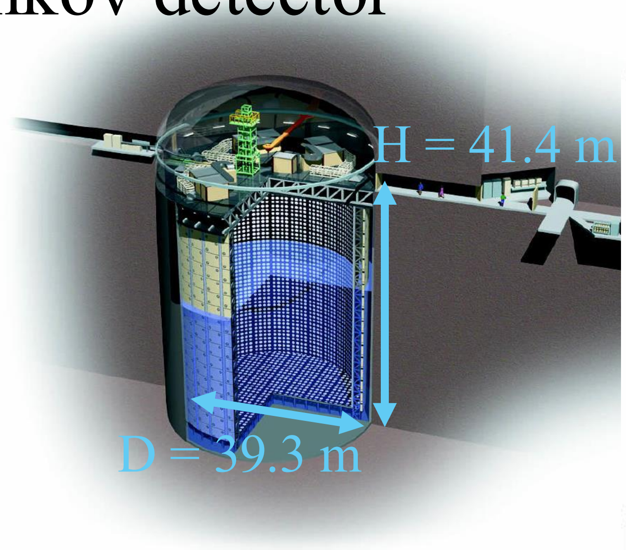
TDR Cafana is used to estimate the CP violation sensitivity with a pure water detector

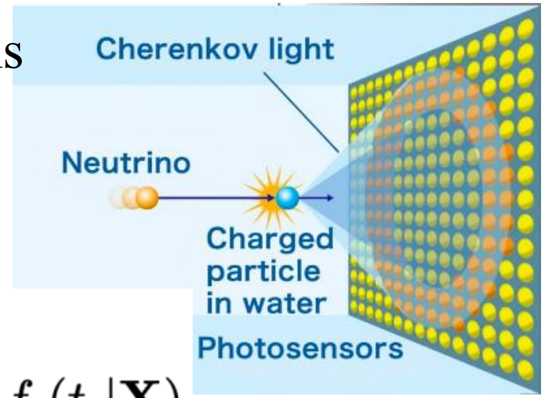


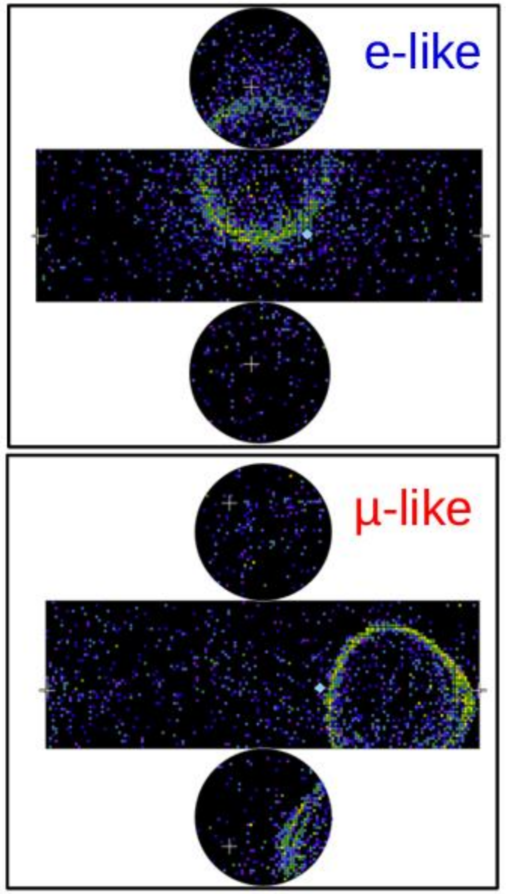
Event Reconstruction in the water Cherenkov detector

- Super-Kamiokande (Super-K)
  - Water Cherenkov neutrino experiment
  - 50 kton of pure water, 22.5 kton of fiducial mass
  - 11,129 inner detector (ID) PMTs (20 inch)
  - 1885 outer detector (OD) PMTs (8 inch)

- Direction/particle ID are reconstructed from the Cherenkov rings
  - A likelihood-based reconstruction software fiTQun is developed and has been used in Super-K
  - The likelihood is profiled w.r.t. momentum, PID, ring number, etc







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

Charge PDF

Time PDF

fiTQun workflow in Super-K

fiTQun is based on the mathematical framework developed by (NIM A608, 206 (2009)) and developed to reconstruct Super-K events.

PMT hits: time, charge

↓ Pre-fit: use time to estimate vertex (t, x)

Pre-fit vertex

↓ Hit clustering: separate subevents by the hit time

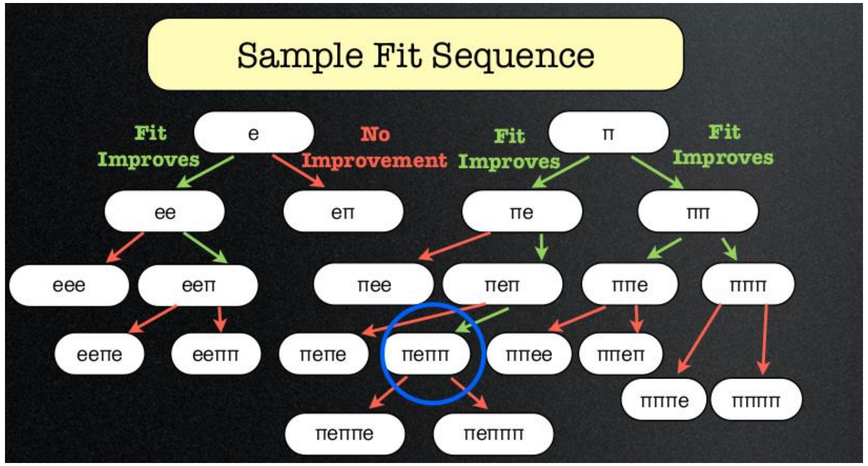
Subevents

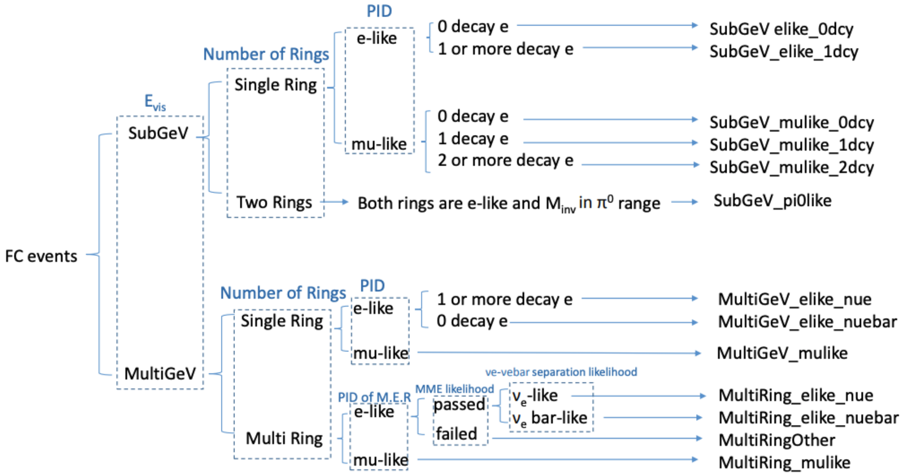
↓ Single-ring fit: optimize the log-likelihood to obtain the best-fit PID, vertex, direction, momentum.

PID, vertex, direction, momentum under 1-ring hypothesis

↓ Multi-ring fit: optimize the log-likelihood by adding one more ring in the hypothesis in one iteration

PID, vertex, direction, momentum, ring number →



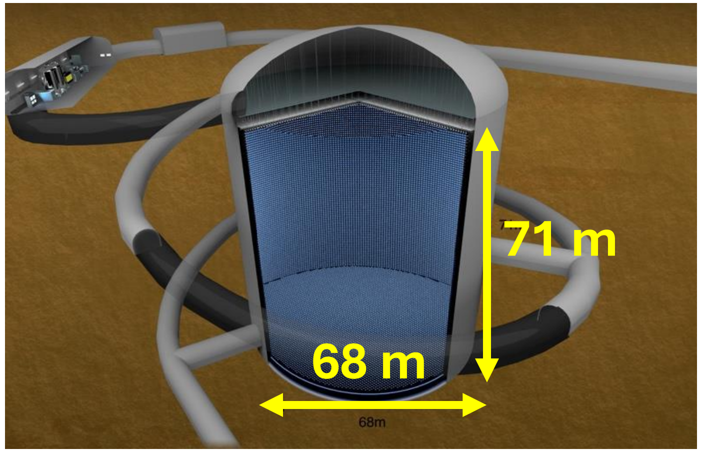


→ OA

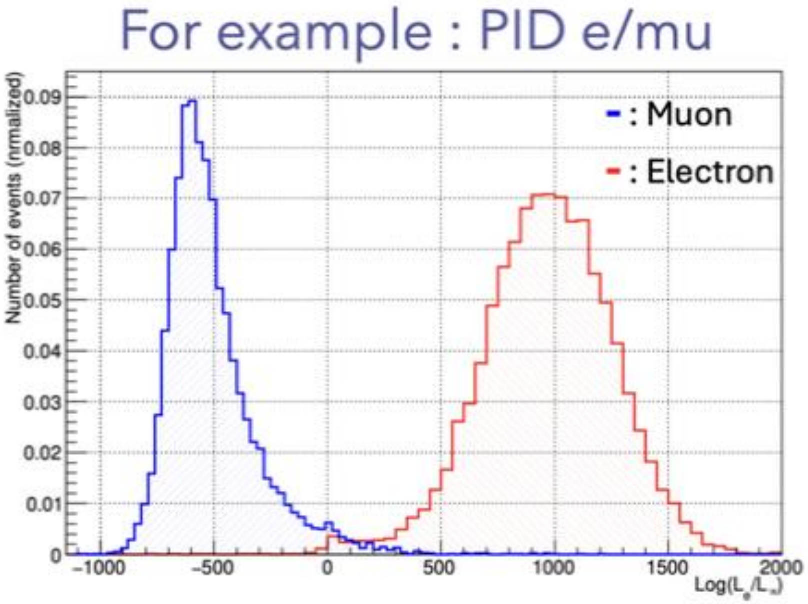
Super-K separate samples by the visible energy, PID and number of decay leptons reconstructed by fiTQun

fiTQun Reconstruction in the Water Cherenkov Detector

- Hyper-K geometry – Cylinder
- Pure water
- ~20k ID 20”PMT (ID mPMTs & 3” OD PMTs are not included in this simulation)
- WCSim (Super-K simulation software) is used to simulate the PMT charge and time.
- Cherenkov light only



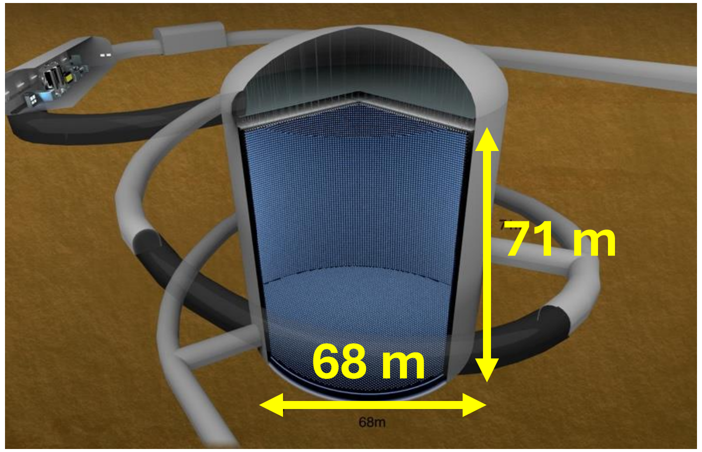
fiTQun reconstructed PID



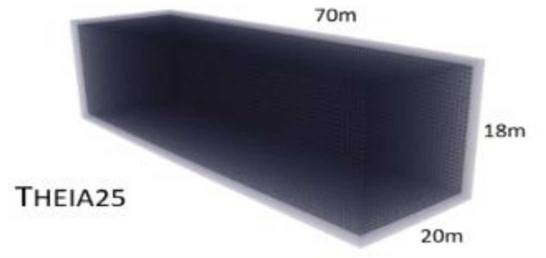
Christine Quach, HK reconstruction, IRN Neutrino Meeting 2024

fiTQun Reconstruction in the WbLS

- Hyper-K geometry – Cylinder
- Pure water
- ~20k ID 20"PMT (ID mPMTs & 3" OD PMTs are not included in this simulation)
- WCSim (Super-K simulation software) is used to simulate the PMT charge and time.
- Cherenkov light only



- Theia25 geometry
- 5% Water-based Liquid Scintillator
- 40% photo-coverage with ~ 46,000 10-inch PMTs or ~12,000 20-inch PMTs
- Ratpac-two is used to simulate the PMT charge and time.
- Cherenkov + scintillation light



Add the Scintillator light to the Cherenkov Reconstruction

ϵ: Angular response
T: transmission of the media and PMT glass
Ω: solid angle factor
Φ: event-energy-dependent light yield

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

Charge PDF — Time PDF

Already exist in Water Cherenkov reconstruction

Predicted charge from Cherenkov light

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

ρ_{Ch}: Cherenkov profile ← g: angular emission profile

Predicted charge from indirect light

$$\mu_{\mathrm{sci}} = \Phi_{\mathrm{sci}} \int_{-\infty}^{\infty} ds \, \rho_{\mathrm{sci}}(s) \, \Omega(s) T_{\mathrm{sci}}(s) \epsilon(s) \left[1 + A_{\mathrm{sci}}\left(R(s), \cos\Theta(s)\right)\right]$$

A_{sci}: Scattering table

What should be added in WbLS reconstruction

Predicted charge from Scintillation light

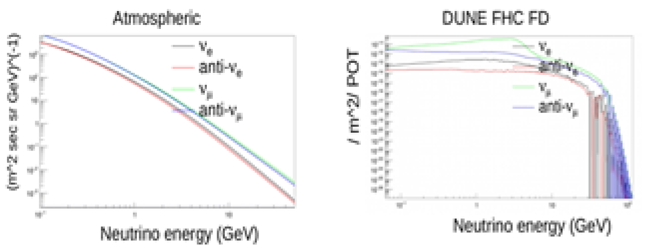
$$\mu_{\mathrm{sci}} = \Phi_{\mathrm{sci}} \int_{-\infty}^{\infty} ds \; \rho_{\mathrm{sci}}(s) \, \Omega(s) \, T_{\mathrm{sci}}(s) \, \epsilon(s) \; .$$

ρ_{sci}: Scintillator profile

Long-baseline Analysis Workflow

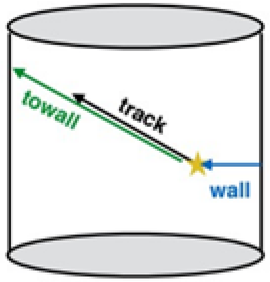
Flux weight

Atmospheric neutrino flux weighted to the DUNE flux



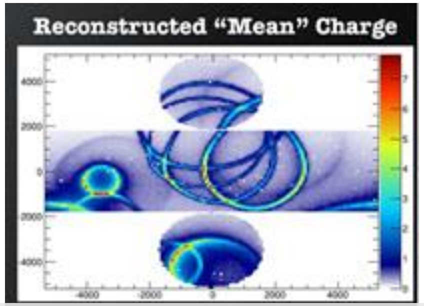
Pre-cut selection

Fully contained Fiducial volume events selected



Ring reconstruction

Estimate each ring's PID and kinematics



Energy reconstruction

Energy estimated based on the ring number and decay number of the event

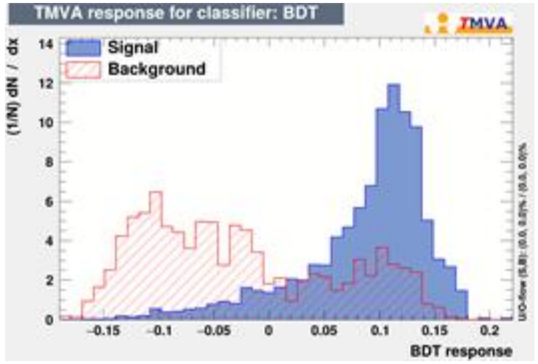
$$E_\nu \approx \frac{2M_nE_\ell - m_\ell^2}{2\left(M_n - E_\ell + p_\ell\cos\theta_\ell\right)}$$

$$\left(p_\nu + p_n - p_\ell - p_\pi\right)^2 = m_p^2$$

When fiTQun is developed to contain the scintillation light, it fits simultaneously for Cherenkov and scintillation light. fiTQun will be able to provide the estimate for the calorimetric energy from particles below Cherenkov threshold.

$\pi 0$ background reduction

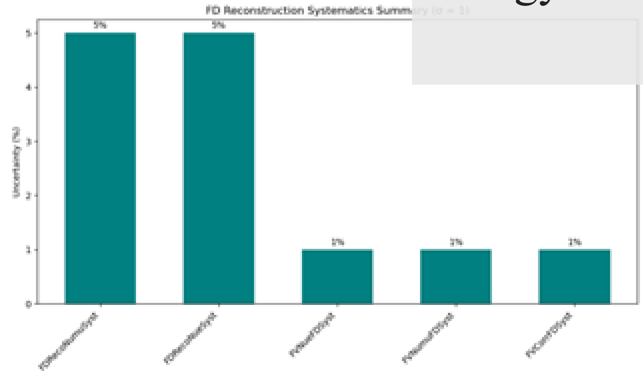
BDT used to reduce the NC background



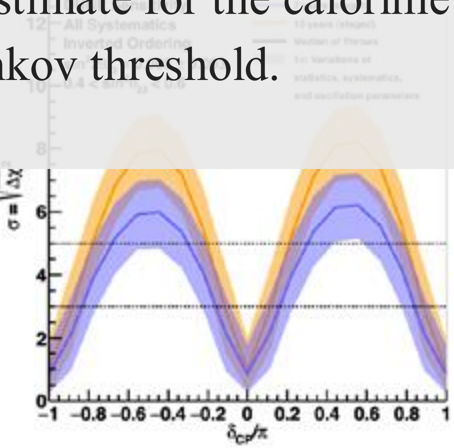
Systematic M

TDR flux systematics applied

TDR LAr detector systematics applied



TDR Cafana is used to estimate the CP violation sensitivity with a pure water detector



Summary

- Water-based liquid scintillator detectors have many advantages
    - Theia is a WbLS detector currently in the R&D stage.
    - Even without scintillation light, the LBL CP sensitivity for 17kt water detector is similar to 10kt LAr detector.
- Reconstruction is ongoing
    - Based on the water Cherenkov reconstruction software fiTQun, the goal is to extend it to add the scintillation light.
    - Future neutrino experiments like DUNE and Hyper-K are exploring some ML-based reconstruction methods, such as WatChMaL, CIDeR-ML. Our future plans also include exploring the use of ML method to reconstruct WbLS events.