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Improving the T2K Oscillation Analysis With fiTQun: A New Maximum-Likelihood Event Reconstruction for Super-Kamiokande

Andrew D. Missert on behalf of the T2K Collaboration

University of Colorado Boulder, Boulder, CO, USA

E-mail: andrew.missert@colorado.edu

Abstract.

A new event reconstruction algorithm, fiTQun, has been developed for the Super-Kamiokande detector. Super-Kamiokande is a ring-imaging water Cherenkov detector with a 22.5-kton fiducial volume located 1000 m underground in the Kamioka Mine in Japan. Neutrino events in the detector's central volume produce charged particles whose Cherenkov rings are imaged by more than 11,000 photomultiplier tubes (PMTs) that line the walls of the detector. This new reconstruction software is able to reconstruct the detailed kinematics of the neutrino interaction from the charge and timing information of each PMT. In contrast to previous reconstruction algorithms that use image processing and pattern recognition techniques, fiTQun uses a maximum-likelihood approach that takes advantage of the known Cherenkov emission profiles and the detector response to evaluate the likelihood of a given reconstruction hypothesis. This approach provides a unifying framework for all aspects of the event reconstruction, including kinematics, ring counting, and particle identification. Using fiTQun to reconstruct neutrino events for the Tokai-to-Kamioka (T2K) experiment can greatly improve the current event selection by reducing pion backgrounds, improving separation of electrons and muons, and reconstructing the neutrino energy with greater precision. These improvements should significantly increase T2K's sensitivity to the oscillation parameters.

1. Introduction

The T2K Experiment [1] is an accelerator-based long-baseline neutrino oscillation experiment in Japan. The experiment works by producing a beam of predominantly muon-flavored neutrinos with a peak energy of 600 MeV. By observing the changes in the neutrino flux after the beam has propagated 295 km to the far detector, T2K can measure the oscillation parameters θ_{13} , θ_{23} , Δm_{23}^2 , and, less strongly, δ_{CP} .

The far detector used in the T2K experiment is Super-Kamiokande (SK), a water Cherenkov detector with a 22.5-kton fiducial volume located 1000 meters underground in the Kamioka mine. The SK water volume is partitioned into an outer detector (OD) and an inner detector (ID). The OD functions as a veto for entering events, while the ID is lined with over 11,000 photomultiplier tubes (PMTs) for imaging the distinctive light patterns produced by charged particles in the detector moving faster than the speed of light in water. Super-Kamiokande is capable of distinguishing between charged-current (CC) ν_e and ν_μ events by discriminating between the Cherenkov emission characteristics of electrons and muons. The task of event



reconstruction at SK is to take the individual charge and timing information for each PMT and identify each particle in the event as well as its position and momentum.

2. A Maximum-Likelihood Approach to Event Reconstruction

A new software package for event reconstruction at Super-Kamiokande: fitQun, tackles the reconstruction problem using a maximum-likelihood approach. In this approach, a likelihood function is evaluated as a function of the particle track parameters such as particle ID, momentum, and vertex.

$$L(\mathbf{x}) = \prod_j^{unhit} P_j(unhit|\mathbf{x}) \prod_i^{hit} \{P_i(hit|\mathbf{x})\} f_q(q_i|\mathbf{x}) f_t(t_i|\mathbf{x}) \quad (1)$$

The likelihood function is expressed as a product over all PMTs in equation 1. The symbol \mathbf{x} denotes the vector of track parameters. The functions $P_j(unhit|\mathbf{x})$ and $P_i(hit|\mathbf{x})$ denote the probability that the PMT records a hit given the track parameters \mathbf{x} . If the PMT is hit, the functions $f_q(q_i|\mathbf{x})$ and $f_t(t_i|\mathbf{x})$ denote the probability of recording charge q_i at time t_i , depending on the specifics of the particle track \mathbf{x} . This function is maximized using MINUIT to obtain the optimal track parameters for each event.

A key part of the likelihood evaluation is building up the predicted charge distribution for a given set of track parameters. The optimal track parameters generally have the best agreement between the predicted and observed charge distributions. To build the predicted charge distribution, an integral is performed over the Cherenkov emission profile for each PMT. Since the Cherenkov emission profile is different for electrons and muons, there will be a likelihood difference between the two hypotheses that can be used as a parameter for particle identification.

3. Performance of Maximum-Likelihood Reconstruction

The fitQun algorithm generally improves on the already good performance of previous reconstruction algorithms, which use image processing and pattern recognition techniques. The fitQun reconstruction features an improved muon-electron mis-identification (mis-ID) rate across a broad spectrum of energies (figure 1). It also greatly enhances the rejection of neutral-current π^0 events, which are a significant background in the ν_e appearance analysis [3]. This new reconstruction can also distinguish between muons and charged pions due to the hard hadronic scattering of the charged pions.

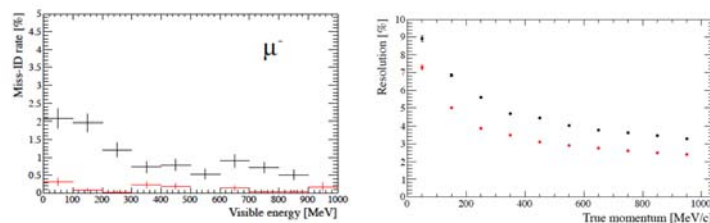


Figure 1: Comparisons between the fitQun algorithm (red) and previous reconstruction techniques (black) for particle identification (left) and momentum resolution (right).

4. Fiducial Volume Optimization for fitQun Reconstruction

The current SK fiducial volume cut requires the reconstructed vertex to be greater than 2 meters from the ID wall. Due to the increased precision of the vertex and direction reconstruction with the new algorithm, the fiducial volume cuts should be re-optimized. Initial Monte Carlo studies show that the algorithm can perform quite well near the ID wall as long as the particle track is allowed sufficient space to properly image the Cherenkov ring. If we define a variable "wall" to be the minimum distance from the vertex to the ID wall, and a variable "towall" to be the distance along the particle track to the ID wall, then a 2-dimensional cut in the space of $(towall, wall)$ could potentially increase the effective fiducial volume while preserving good reconstruction performance.

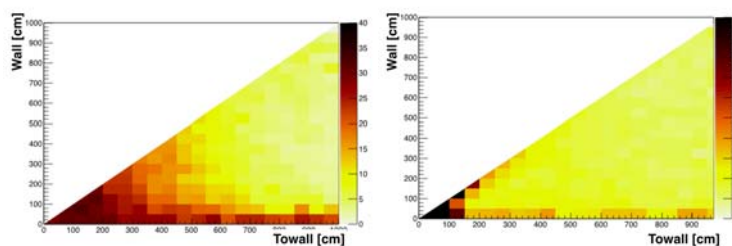


Figure 2: Momentum resolution in % (left) and direction resolution in degrees (right) for reconstructed muons in various fiducial volume regions. Darker regions denote poorer reconstruction performance.

5. Systematic Error Estimation

Optimizing the fitQun fiducial volume for SK requires a precise understanding of how the reconstruction performs on actual data in different fiducial volume regions. The best data sample to study fitQun reconstruction performance in these areas is the atmospheric neutrino sample. When looking at distributions of reconstructed quantities it becomes apparent that these distributions exhibit significant shifts in different fiducial volume regions. A framework has been developed that parameterizes these shifts in the Monte Carlo distributions in a way that can be fit to data. A Markov Chain Monte Carlo (MCMC) approach is used to probe the allowed shift parameters in various fiducial volume regions. By applying these shift parameters to the T2K Monte Carlo, the systematic error in each fiducial volume bin can be estimated.

6. Conclusions

The fitQun algorithm uses a new maximum-likelihood approach for reconstructing neutrino events in the SK detector. This event reconstruction offers considerable performance improvements over the previous techniques. The fitQun reconstruction has already substantially contributed to the T2K oscillation analysis by improving the rejection of neutral pion events from the ν_e appearance sample. Once the systematic errors for the fitQun reconstruction can be estimated in all fiducial volume regions, a new fitQun fiducial volume cut can be optimized, which could potentially increase the statistics for all of T2K oscillation analyses [3] [4].

References

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