NEUTRAL CURRENT π^0 BACKGROUNDS AT T2K

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T2K is a long-baseline neutrino beam experiment designed to measure θ_{13} by observing ν_e appearance through oscillation in the ν_μ beam. The most challenging reducible background for this is neutral current π^0 production. This is a common interaction which can be mis-reconstructed as the ν_e appearance signal in the far detector, Super-Kamiokande. A specialized algorithm is used to help identify these π^0 events as background.

1 Introduction

T2K (Tokai to Kamioka) is a long-baseline neutrino beam experiment now running between the Japan Proton Accelerator Research Complex (J-PARC) facility in Tokai and Super-Kamiokande. The experiment has three main parts: A neutrino beam production facility using the 30 GeV proton synchrotron at J-PARC, a near detector complex (about 280m from the beam source) to measure the beam before oscillation, and the Super-Kamiokande (SK) water Cherenkov detector near Kamioka (295km from the beam source), used as the far detector.

The primary goal of the experiment is to measure θ_{13}, one of the three neutrino mixing angles. It is not presently known whether this parameter is non-zero. If it is non-zero, the CP-violating phase for neutrinos may be measurable through oscillation experiments. The signal for non-zero θ_{13} for T2K will be ν_e appearance in the ν_μ beam. The near detectors will measure the intrinsic ν_e contamination in the neutrino beam, so an excess beyond that ($\sim 3\%$) observed at Super-Kamiokande will indicate $\nu_\mu \to \nu_e$ oscillation.

SK is actually located 2.5° off from the beam center. This was done because the neutrino energy distribution is much more sharply peaked off-axis than in the direct beam, even if the intensity is lower. The T2K distance and energy (295km, and $\sim$ 600 MeV, respectively), were chosen so that expected $\nu_\mu \to \nu_e$ oscillation due to θ_{13} is optimized in L/E (distance over neutrino energy, the quantity that determines neutrino oscillation probabilities).[1]

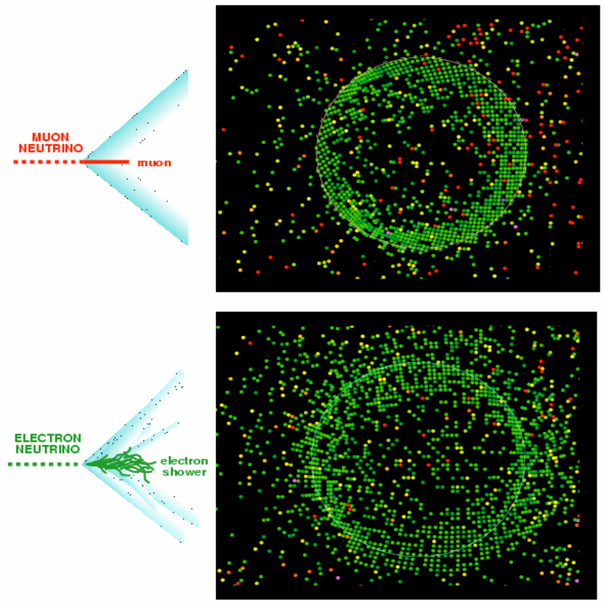

Figure 1: Examples of e-like and μ-like rings. Each colored dot represents a PMT hit by Cherenkov light.

2 Neutrino Detection at SK

SK, as a water Cherenkov detector, can only detect charged particles moving through it. Cherenkov radiation is the radiation emitted when particles travel faster than the speed of light in their medium ($0.75c$ in water). The cones of Cherenkov light project on to the detector walls as rings. This light is detected by the 11,146 photomultiplier tubes (PMTs) lining the inner wall of SK's tank. The shape, position, and timing of rings are used to reconstruct interaction vertices, and particle momenta and directions.[2]

The type of particle producing the ring can also be inferred from ring patterns. Heavy particles, such as muons or charged pions, will tend to produce rings with well-defined sharp outer boundaries. These particles lose energy primarily through ionization and atomic excitation. Those mechanisms (along with Cherenkov radiation) do not tend to alter the particle's straight track, allowing the ring to be sharply defined.

On the other hand, the low mass electrons will lose energy primarily through bremsstrahlung. The high energy photons (gammas) emitted as bremsstrahlung will themselves pair-produce and make electrons to bremsstrahlung further. The result is that a single electron (or positron) quickly multiplies to many e^+e^- pairs, all traveling roughly in the same direction. Additionally, the electrons multiple scatter off water molecules as they travel, so even a single electron will not travel in a straight line. The sum of Cherenkov light from all these particles is a ring with a diffuse outer boundary.

All rings identified in SK events are classified as either showering (e-like) or non-showering (μ-like). Examples of each of these are shown in Figure 1.

High energy photons, by themselves, do not produce Cherenkov light, as they are uncharged. However, they will pair produce while traveling through the water, and those electrons and positrons will bremsstrahlung radiate and produce a shower. In this way, both high energy gammas and electrons of similar energy will appear as showering rings. There is effectively no difference in the ring pattern between electron rings and gamma rings of comparable energies, although there may be a small offset from the interaction vertex in the case of the gamma, due to the finite pair-production length.

3 Identifying T2K Signal at SK

A clear sign of electron neutrino interaction must be observed at SK to give evidence for $\nu_\mu \rightarrow \nu_e$ oscillation. A charged current (CC) interaction mode is necessary because neutral current (NC) interactions are flavor independent. Of the CC interactions, the optimal signal is a charged current quasi-elastic (CCQE) interaction, given by:

$$\nu_e + n \rightarrow e^- + p \tag{1}$$

The proton does not usually acquire sufficient momentum to reach Cherenkov threshold. Thus, all that is measured is a single e-like ring.

There are a few advantages to the CCQE interaction mode, making it easier to distinguish oscillation signal from backgrounds. The single electron (with no other particles above Cherenkov threshold) is impossible to produce from any ν_μ interaction. The simplicity of the interaction also allows for the energy of the incident neutrino to be reconstructed. Using conservation of energy and momentum, the known incident neutrino direction, and the lepton energy and direction, the energy is reconstructed, despite no knowledge of the proton's momentum. Ignoring small corrections:

$$E_\nu^{\text{rec}} = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l \cos\theta_{\nu-l}} \tag{2}$$

where m_N is the nucleon mass, E_l and p_l are the product lepton's energy and momentum, respectively, and $\cos\theta_{\nu-l}$ is the angle between the lepton direction and the incident neutrino beam direction.

Being able to reconstruct the neutrino energy is very useful because the ν_μ beam is sharply peaked about a particular energy. Intrinsic beam ν_e, due to kaon or muon decay at beam production, tend to be higher energy than ν_μ, providing a valuable cut against a background that is very difficult to identify otherwise. Additionally, events with reconstructed energies below the ν_μ beam peak are likely to have been mis-reconstructed.

Thus, the basic identifiers for a ν_e CCQE event are: only one e-like ring, no other rings, no decay-electron. Further cuts can be made on reconstructed neutrino energy, or other kinematic parameters, to further reduce backgrounds such as the intrinsic beam ν_e.

4 The NC π^0 Background

Unfortunately, there is a very common ν_μ interaction which has a small chance of being mis-reconstructed as single-ring e-like. This is NC π^0 production:

$$\begin{aligned} \nu_\mu + N \rightarrow N + \pi^0 \\ \pi^0 \rightarrow \gamma + \gamma \end{aligned} \tag{3}$$

where N represents a proton or neutron.

Depending on the kinematics of the decay, it is possible for one of the product gammas to have a much higher energy than the other. In this case, one of the gammas may be missed by the normal ring-finding algorithms, "washed out" by scattered light from the higher energy gamma. This problem cannot be fixed by lowering the threshold for 2nd ring detection, as that would cause more false-positive second rings to be identified in the noise for true 1-ring events. The detection threshold is already well optimized.

Using only the single-ring, e-like, no decay-electron selection cuts, NC π^0 is the dominant background mode, with approximately 60% of background events coming through this mechanism.

5 NC π^0 Rejection

The primary tool we use to reject these events where the 2nd gamma ring is not found is an algorithm called Pattern Of Light Fitter (POLfit). This is a specialized algorithm for finding a second e-like ring in an event with a single found e-like ring. It begins with the vertex, momentum, and direction from the first found ring. A three-dimensional space of angles (θ, ϕ) and the fraction of energy in the second gamma (γ-frac) is set up. A light pattern generating algorithm then produces the expected PMT charge distribution for the first gamma in the previously reconstructed direction, and the second gamma in the (θ, ϕ) direction with γ-frac of the total energy detected in the event. A likelihood function is then used to see how good a fit this pattern is to the original detected event.

From this starting grid, an optimization algorithm (MINUIT) is used to search different values of (θ, ϕ, γ-frac) to find where the optimal likelihood match is. Additional patterns are generated and likelihoods calculated until the optimal fit for the 2nd gamma is found. Note that the likelihood calculation does not need to see the 2-ring pattern as more likely than the 1-ring pattern. This means that the algorithm will always find a second ring candidate, whether or not it is favored over the 1-ring hypothesis.

Now, the momenta and directions of the two rings can be used to compute an invariant mass. If the two rings are actually the two gammas from a π^0 decay, the reconstructed invariant mass should be close to the true π^0 mass, 135 MeV/c^2. If some random noise were picked up as the second ring, it is likely to be fitted with a very low energy, which will lead to a low invariant mass. Thus, by making a cut requiring the POLfit invariant mass to be significantly smaller than the π^0 mass (for example, $m < 100$MeV/c^2), approximately 74% of the remaining NC π^0 events can be rejected, with minimal reduction of signal efficiency. This cut can bring the remaining NC π^0 background count down below the number of remaining intrinsic beam ν_e, even with a cut on reconstructed neutrino beam energy.

6 Conclusion

Neutral current π^0 events in which only one of the decay gammas is reconstructed are a major source of background for the T2K ν_e appearance search. Using a special algorithm to search for a lower energy second gamma ring and then checking the 2-ring invariant mass provides a powerful cut to reject this background.

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References

1. Y. Itow *et al.*, arXiv:hep-ex/0106019v1
2. Y. Fukuda *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A *501*, 418 (2003).