Double Neutrino Production and Detection in Neutrino Detectors

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Large, high-energy ($E > 100$ GeV) cosmic neutrino telescopes are now quite mature. IceCube, for example, observes about 50,000 well-reconstructed single atmospheric neutrino events/year, with energies above 100 GeV. Although the neutrino detection probability is small, current detectors are large enough so that it is possible to detect two neutrinos from the same cosmic-ray interaction. In this paper, we calculate the expected rate of double-neutrino interactions from a single cosmic-ray air shower. The rate is small, about 0.07 events/year for a 1 km$^3$ detector like IceCube, with only a small dependence on the assumed cosmic-ray composition and hadronic interaction model. For a larger detector, like the proposed KM3NeT, the rate is about 0.8 events/year, a rate that should be easily observable. These double neutrino interactions are the major irreducible background to searches of pairs of particles produced in supersymmetric neutrino or cosmic-ray air-shower interactions. Other standard-model backgrounds are considered, and found to be small.

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I. INTRODUCTION

High-energy astrophysical neutrinos are being actively studied, with a view to using them to find the acceleration sites for high-energy cosmic rays [1, 2]. Three large detectors, the 1 km$^3$ IceCube [3], the 10$^7$ m$^3$ Baikal detector [4], and the 1.5 $\times$ 10$^7$ m$^3$ ANTARES detector [5] are taking data, and the 5-6 km$^3$ KM3NeT detector [6, 7] has been proposed. These detectors are optimized for neutrinos with energies in the TeV to PeV range, where the atmospheric neutrino flux is substantial; the completed IceCube detector, for example, observes about 50,000 well-reconstructed single atmospheric neutrino events/year [8]. Most of these events are from $\nu_\mu$ (or $\bar{\nu}_\mu$; we do not distinguish between neutrinos and antineutrinos here), which interact and produce muons which travel upward through the detector.

Although these detectors are focused on the detection of single neutrino interactions, they also look for more complex topologies. One signature of great interest consists of two parallel tracks going upward through the detector. This signature could be a sign of some type of `new physics,' such as supersymmetry (SUSY) or Kaluza-Klein models. In supersymmetry, parallel tracks can be created when a neutrino (or cosmic-ray) interacts in the Earth below a detector, producing a pair of SUSY particles [9, 10]. These supersymmetric particles decay, eventually producing a pair of next-to-lightest SUSY particles. If SUSY has a high mass scale, then these particles have a relatively long lifetime, of order $\mu$s. They live long enough to travel long distances ($\approx 1,000$ km) through the Earth. During this trip, they will slowly separate, and will appear in a neutrino detector as a pair of upward-going parallel tracks, with a typical separation of order a few hundred meters [11]. Since these particles are typically quite heavy, they lose energy like nearly minimum ionizing particles. Kaluza-Klein particles are produced via a different mechanism, but have similar observational consequences [12].

Previous studies have considered the standard-model backgrounds to these processes; the major background is from charm production, where both of the charmed particles decay semileptonically [9]. This produces a pair of muons. These muons have a rather short range (even a 1 PeV muon has a range less than 10 km in rock), and a typical transverse momentum of a few GeV/c, so are unlikely to have separated significantly by the time they range out.

Two muons from a pair of neutrino interactions, from the same cosmic-ray air shower, are the only background that is likely to mimic the signatures described above. If the neutrinos are produced in the same cosmic-ray air shower, then they will be nearly parallel, but with a large enough opening angle to separate by a few hundred meters as they pass through the Earth. If the neutrinos have an energy below a few TeV, they may appear to be quasi-minimum-ionizing, and could mimic a pair of supersymmetric or Kaluza-Klein particles.

In this paper, we calculate the rate of double-neutrino events expected to be observable in IceCube and KM3NeT, and discuss the expected characteristics of the events [13]. We do not differentiate between $\nu$ and $\bar{\nu}$ here.

II. AIR SHOWERS, PRODUCTION MODEL AND NEUTRINO INTERACTIONS

The calculation was done in two parts. In the first part, cosmic-ray air showers are generated, and the neu-
trino data retained for analysis in the second part. All
the neutrinos in each event are paired with all of the
other neutrinos in that event, and the separation dis-
tance computed. The neutrino-pair flux is weighted with
the probability of detection. The detection probability
has three components: the energy-dependent probabil-
ities of the two neutrinos interacting with the resulting
muon being observed (assumed independent for each neu-
trino), and the probability (based on their separation) of
both muons passing within the detector active volume.
The lateral separation distance \( D \) is a critical param-
eter. It depends on the distance between the shower and
the detector, and on the opening angle between the two
neutrinos. The opening angle depends on the neutrino
energy and transverse momentum, \( p_T \) (relative to the
shower core). This analysis is sensitive to the particles
with the smallest \( p_T \), unlike studies of high \( p_T \) muons
[14]. \( \nu_\mu \) from pion and kaon decay dominate the atmo-
spheric spectrum [15], and so should constitute most of
the signal; we focus on them. We only consider neutr-
inos with energies above 100 GeV; because of their small
interaction cross-section and large angular spread, lower
energy neutrinos do not contribute significantly. We as-
sume that the neutrinos are produced by the decays of
different pions.

Cosmic-ray air showers were generated using COR-
SIKA version 6.980 [16] to model the cosmic-ray air show-
ers. Two different hadronic interaction models, QGSJET
v01c [17] and DPMJET v2.55 [18] were used. The cosmic-ray spectrum was approximated by the Hörandel
spectrum [19], with the low-energy end of the cosmic-ray
spectrum following an \( E^{-2.7} \) slope, and the high-energy end following \( E^{-3} \):

\[
\Phi(E_p) = \begin{cases} 
1.8 \cdot 10^4 E_p^{-2.7} & \text{for } E_p < 10^6 \text{ GeV} \\
1.1 \cdot 10^6 E_p^{-3.0} & \text{for } E_p > 10^6 \text{ GeV} 
\end{cases}
\]  

(1)

with \( E_p \) the energy of the primary particle in units of
GeV and the flux, \( \Phi(E_p) \) in \( 1/(s \text{ sr } m^2 \text{ GeV}) \).

CORSIKA includes the bending effect of the Earths
magnetic field, and multiple scatterings in the Earths
atmosphere. Multiple scattering is negligible, but the mag-
netic bending of the \( \pi^\pm \) and \( K^\pm \) that decay into \( \nu_\mu \) affects the calculation. For a 5 \( \times 10^{-4} \text{ T field (typi-
cal for the sky above Antarctica) perpendicular to the}
pion direction of motion, a pion is bent by an angle
\( \theta_{\text{B}} = qBc\tau_{\pi}/m_\pi \approx 117 \text{keV}/m_\pi \approx 8.4 \times 10^{-4} \) where \( m_\pi \) and \( \tau_\pi \) are the \( \pi^\pm \) mass and lifetime respectively. The
actual angle between the pion direction and the magnetic
field is usually less than 90°, so the magnetic bending
will be smaller, typically by order 1/\( \sqrt{2} \approx 0.7 \).

In comparison, the bending due to the pion/kaon
transverse momentum, \( p_T \) with respect to the cosmic-ray
direction is \( \theta_{p_T} = p_T/E_\pi \). For a typical scale \( \Lambda_{\text{QCD}} = 300 \)
MeV, the magnetic bending is larger than the \( p_T \) induced
bending for pion energies above 500 GeV. For kaons at
the same energy, the bending is a factor of 8 smaller.
The typical neutrino energy is around 1 TeV, so magnetic
bending is important. Because of the magnetic bending,
the separation requirement preferentially selects like-sign
pion pairs, so that the event sample will prefer neutrino-
neutrino and antineutrino-antineutrino pairs, rather than
mixed pairs.

The probability for two neutrinos to pass through a
finite-sized detector depends on their transverse momen-
tum (\( p_T \)) with respect to each other. The separation \( d \)
depends on the relative \( p_T \), the particle energies, and the
distance travelled. Since these neutrinos travel hundreds
to thousands of kilometers before interacting, the two-
neutrino rate is sensitive to the production of particles
with very low \( p_T \). Both QGSJET and DPMJET generate
low-\( p_T \) particles using phenomenological, Pomeron-based
models. Both of them reproduce accelerator data quite
well, and so have similar \( p_T \) spectra in this region. These
neutrinos mostly come from the decay of pions and kaons,
and the muons that are produced from the pion/kaon de-
cays. In the low \( p_T \) region, both models predict thermal
spectra that are in agreement with experimental data ob-
tained in accelerator experiments. Collider experiments
are not sensitive at very low \( p_T \), so there is some uncer-
tainty here, but we can use data on high-energy cosmic-
ray muon separations to check the models. MACRO [20]
and IceCube [14] have studied muon separation spectra
at small and large separations respectively. The observed
separation spectra and overall rates are in reasonable
agreement with Monte Carlo expectations, although the
zenith angle distributions do not agree well.

CORSIKA generates downward-going showers; for this
analysis, we used the transformation shown in Fig. 1
to convert the downward-going neutrinos into upward-
going. The transformation maps the zenith angle, \( \theta_Z \)
into \( -\theta_Z \). The two neutrinos are propagated through
the Earth, separating as they go. In the relevant energy
range (100 GeV to 10 TeV), neither neutrino oscillation
nor absorption in the Earth is significant.

One weakness of this approach is that it uses both the
magnetic field and ground elevation at the South Pole for
all showers. Most of the relevant showers occur within
1000 km of the detector, and estimates of the inaccuracy
due to the simplification need only consider field varia-
tions over this distance scale. For IceCube, we consider
the region south of latitude \(-75^\circ\). Although the mag-
netic field strength does not vary significantly there, its
direction does. The dip angle (angle between the mag-
netic field lines and vertical) ranges from \(-65^\circ \) to \(-78^\circ \)
there. For a given longitude, the maximum change is \( 6^\circ \)
as the latitude varies from \(-75^\circ \) to \(-90^\circ \) [21]. The
declinations vary more, up to \( 30^\circ \). The field variations can
alter the magnetic bending by up to 50%, but, after aver-
aging over all possible angles of incidence, the net effect
will be much smaller; the overall change in rate should
be less than 25%.

The opening angle is bounded by the geometry, the ob-
served perpendicular separation when the neutrinos are
saved by the simulation and the maximum separation al-
lowed inside the detector. The minimum is set by the
FIG. 1: The geometry used in the calculation for an incident cosmic ray at zenith angle $\theta$. The parameters used are: $R_{\text{obs}}$ for the radius from the center of the Earth to the observation height, at which the particles are saved, $R_{\text{atm}}$ for the radius from the center of the Earth to the top of the atmosphere, $L$ the path length through the Earth and $D$ the final separation after propagation through the Earth.

obscured separation, assuming that the neutrino separation started within the atmosphere. The maximum is determined by the path length through the Earth and the subsequent increase in separation.

The neutrino detection probability depends on both the neutrino interaction probability and the probability of observing the produced muon. We use a simple model which includes both factors \[ \begin{align*}
    \text{P}(\text{detected} | E_{\nu}) &= \begin{cases} 
    1.3 \times 10^{-6} E_{\nu}^{-2.2} & \text{if } E_{\nu} \leq 1 \text{ TeV} \\
    1.3 \times 10^{-6} E_{\nu}^{-0.8} & \text{if } E_{\nu} > 1 \text{ TeV} \\
    0 & \text{if } D > D_{\text{max}}
    \end{cases}
\end{align*} \]

with $E_{\nu}$ the neutrino energy in units of TeV.

These probabilities are based on the model of a detector as a thin plate, sensitive to muons (from $\nu_\mu$ and $\bar{\nu}_\mu$ interactions). Neutrinos are detected if the muons that they produce have a sufficient range to reach the plate.

This calculation neglects the minimum separation for two muons to be detectable as separate particles, $D_{\text{min}}$.

Reconstruction of two parallel tracks is more challenging than for single tracks, with additional degrees of freedom. The IceCube collaboration found that downward-going isolated muons were separable from muon bundles at separations larger than 135 m. For two single muons, the minimum observable separation could be somewhat lower, especially for near-horizontal muon pairs. The rate correction scales as $(D_{\text{min}}/D_{\text{max}})^2$. For $D_{\text{min}} = 135$ m, and $D_{\text{max}} = 1$ km, as in IceCube, this is a small correction; for KM3NeT, it would be even smaller.

Both Icecube and KM3NeT are 3-dimensional, so that neutrinos that interact anywhere in the detector volume may be observed, in addition to neutrinos that interact outside the detector, but whose muons reach the detector volume. Both detectors contain holes, regions where a low-energy (minimum ionizing) muon may pass through undetected. As the neutrino energy rises, the muon range and energy loss both rise, and both effects become less important. Over the relevant neutrino energies, these effects are both less than a factor of two. Fortunately, they work in different directions, and we will assume that they will cancel out. A more accurate calculation would require a detailed dedicated detector Monte Carlo to account for the correlated detection probability, event reconstruction software, and a well defined set of event selection criteria.

III. RESULTS

Figure 2 shows the zenith angle distribution of accepted pairs. As expected, most of the detected pairs are just below the horizon, where the distance between the shower and detector is smallest. For these near-horizontal neutrinos the cosmic-ray air showers have a much longer propagation distance in the atmosphere, so the interaction to detector separation never gets too small. The dominance of the horizontal sensitivity means that the expected rates are somewhat sensitive to the detector shape; detectors with a larger horizontal frontal area should see more neutrino pairs.

Figure 3 shows the primary energies of the cosmic-ray progenitors of the pairs that would be detected. The distribution is peaked for primaries around 30 TeV, well below the knee of the cosmic-ray spectrum, where the cosmic-ray composition is mostly protons. This peak reflects several factors: the cosmic-ray flux decrease with increasing energy, the increasing neutrino production and detection cross-sections, and the narrowing of the average opening angle with increasing neutrino energy. With the rapid fall-off with increasing energy, uncertainties in the cosmic-ray flux at high energies, above the knee, are unimportant.

Figure 4 shows the energy of the observed neutrinos (with 2 entries/pair), with a 1 km maximum separation. This distribution is peaked around 1 TeV, about 3% of the peak of the primary energy distribution. The maximum reflects the competition between the rapid de-
increase in atmospheric neutrino flux with increasing energy, the increasing interaction probability and the decreasing opening angle ($p_T/E_\nu$) with increasing neutrino energy. Events near the minimum energy cutoff, 100 GeV, do not significantly contribute to the rate. In this energy range, prompt neutrinos are not significant.

The correlation between the energies of the two neutrinos is small. This is expected, since the separation distance is determined largely by the $p_T$ and energy of the lowest energy neutrino; as long as one neutrino has an energy substantially above the other one, its energy is largely irrelevant.

Figure 4 shows the predicted detection rate as a function of detector diameter. For small detectors, the naive rate should scale as roughly the square of the surface area of the detector, or as the effective volume to the 4/3 power. For larger detectors, the rate increase is slower, because of the drop in neutrino flux at large transverse momentum.

FIG. 4: The neutrino energies of the pairs that would be detected in the IceCube-model detector (2 entries/pair).

IV. SIGNAL AND BACKGROUND RATES

The overall neutrino rates for a 1 km$^3$ detector are shown in Table I for both QGSJET and DPMJET, for both an all-proton and all-iron assumed cosmic-ray composition. The rates are all in quite good agreement, with the composition making at most a 21% difference. At the relevant energies, a few hundred TeV, cosmic-rays are expected to be mostly protons and lighter nuclei.

For KM3NeT, using a 6 km$^3$ effective volume [7], the rate is about 11 times higher, or about 0.8 events/year. KM3NeT is likely to be wider than it is high, so Fig. 5 may slightly overestimate its rate. These rates do not capture the details of the either detector construction, but the IceCube rate should be accurate within 50%. More detailed calculations would require a complete simulation and an analysis chain.

The flux of double neutrino events is large enough that a signal should be visible in the proposed KM3NeT detector, and an event might be seen in IceCube. Once events are seen, then it is necessary to try to classify them as double neutrinos or as due to new physics. The observed specific energy loss ($dE/dx$) [23] and zenith angle distributions may help in separating the two classes of events. As Fig. 4 shows, about 20% of the mons have energies above 2 TeV, with an average $dE/dx$.
more than 10 times minimum ionizing; this is a larger energy loss than is expected from the considerably heavier supersymmetric or Kaluza-Klein particles. More importantly, most of the neutrino pairs come from near the horizon, whereas neutrino induced supersymmetry interactions are more evenly spread over the upward-going hemisphere. However, the angular distribution is similar to what one would expect from supersymmetric or Kaluza-Klein particles that are produced directly in cosmic-ray air showers. Although these identifying criteria may be inadequate to classify a single event, a small event sample should allow clear conclusions to be drawn.

One potential background to these events (and to searches for supersymmetric and Kaluza-Klein particles) is from muon pairs that are produced in neutrino interactions (or in cosmic-ray air showers), from decays of charmed particles or Drell-Yan pairs. This background has been discussed previously [12]. However, the constraint that the two tracks appear parallel is a powerful constraint to eliminate background. For long muon tracks, IceCube has an angular resolution that is better than 1° [21]; KM3NeT is expected to be a few times better, but we will use a maximum opening angle θ₀ = 1°. Tracks pairs that diverge by more than twice that, or 2° can be eliminated. The 2° parallelism requirement requires that the muons must originate at a vertex at least 2865 m from the detector; if we require that the tracks traverse through most of IceCube, this gives a minimum track length of 3800 m. Muons travelling 3800 m in ice must have a minimum initial muon energy of at least 6 TeV. If the muons path is mostly rock (as in below IceCube or KM3NeT), then the energy threshold would be three times higher. A 6 TeV muon with a 1° opening angle requires pₜ = Eₜ · sin(θₜ) = 105 GeV/c to satisfy the track separation requirement. Such a large pₜ is extremely rare; for comparison the IceCube studies of down-going muons covered the range of a few GeV/c. The large pₜ is required for a range of conditions. For vertices farther from the detector, the opening angle is smaller, but the muon energy rises more quickly, increasing the minimum pₜ. The inclusion of multiple scattering will alter these numbers slightly, but should not change the overall conclusion that the background rate due to neutrino interactions is negligible.

Angular misreconstruction does not affect the conclusions very much. As the allowed actual opening angle rises, the vertex can be closer to the detector and the minimum muon energy drops. However, as the opening angle rises, and pₜ stays large. For example, for θ₀ = 5°, the vertex can be 1100 m from the detector, but the required pₜ is still 87 GeV. If the distance between the two tracks were mis-reconstructed, with, effectively a smaller two-track separation requirement, significant background could be found.

Similar arguments apply for dimuons coming from cosmic-ray air showers. For the muons to be upward-going, the air showers muons must traverse more than 100 km of ice or water (at a depth of 1500 m, the horizontal distance to the surface is 138 km). This is not possible, but there may still be a small background from downward-going dimuons where both muons are mis-reconstructed as upward-going.

A third background is from neutrino pairs where the two neutrinos are produced by different cosmic-ray interactions. The rate for this background depends on the detector angular and temporal resolution; it can be estimated with Poisson statistics. IceCube observes about 50,000 muons from high energy neutrino interactions per year, spread over 2π steradians and 3 × 10⁷ s. For a time difference resolution of 450 ns [14], the number of temporal overlaps is 0.0008 per year. Including the 2° parallelism requirement reduces the rate by another factor of 6,000. This calculation ignores non-uniformities in the acceptance, but these are not large effects. KM3NeT is larger, but its better angular resolution should lead to a similar rate.
V. CONCLUSIONS

In conclusion, the expected rate for a 1 km$^3$ detector like IceCube to observe two upward-going neutrinos from the same cosmic-ray air shower is about one every 14 years. Future, larger detectors, like a 6 km$^3$ KM3NeT will have a substantially larger rate, i.e. 0.8 per year, and so should observe a signal. These double-neutrino events are an irreducible background to searches for pairs of upward-going particles produced by beyond-the-standard-model processes. The other standard-model backgrounds to these processes appear to be very small.

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