Search for Neutrino Trident Events in IceCube

by Sourav Sarkar[1] and Roger Moore

Standard Model (SM) of particle physics has been a great success with the discovery of the fundamental particles and their interactions via strong, weak and electromagnetic forces. However, neutrino oscillation experiment [1] observed that starting with one particular flavour of neutrino from source, it can be detected as a different flavour of neutrino in the detectors. This phenomena, known as neutrino oscillation, requires the neutrinos to have tiny nonzero masses which directly contradicts the prediction of massless neutrinos in SM. Many beyond standard model (BSM) theories (e.g., supersymmetry (SUSY), string theory) have been developed to incorporate such experimental anomalies and require presence of additional fundamental particles that have not been observed yet. One of the processes that can probe into the new physics (NP) is neutrino trident production (NTP) which is our point of interest in this article. NTP is a sub-dominant SM process which can also produce new intermediate particles and we can constrain the properties of these new particles by observing the final state particles. Several collider and neutrino beam experiments are looking for BSM particles, however, their search is limited by upper limits of the beam energy (~ 10TeV) and luminosity (i.e., rate of events). Detection of neutrinos at the IceCube neutrino obeservatory [2] relies on the natural sources of neutrinos (e.g., atmosphere, astrophysical sources) that can produce neutrinos with energy as high as ~ 10PeV. Therefore, search for NTP events in IceCube can have a potential advantage over any collider or beam experiments.

In this article we will briefly discuss the theoretical motivation of searching for NTP events in section 2. Section 3 summarizes the details of IceCube detector and the aspect of detecting NTP events and potential challenges in IceCube. And, finally in section 3, we conclude our discussion by summarizing the article.

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Summary

Neutrino trident production (NTP) is a standard model (SM) sub-dominant process that can be used as a powerful probe for the search of new physics. In this article, we explore the possibility of detecting NTP events at the IceCube neutrino observatory using atmospheric neutrinos.

Theoretical Motivation of Neutrino Trident Production

Neutrino is one of the SM fermions and they do not carry any charge. Therefore, neutrinos can interact only via weak interaction by exchanging charged W boson (charged current (CC) interaction) or neutral Z boson (neutral current (NC) interaction). Cross-section of sub-dominant process like NTP is several order of magnitude less than the cross-section of standard CC or NC neutrino interactions. However, dedicated study of NTP process can be used as powerful probe into the search for BSM physics. In NTP process, an incoming neutrino interacts with the coulomb field of a nucleus and creates three outgoing leptons (an outgoing neutrino and two charged leptons) and a recoiled nucleus as seen in Fig. 1. NTP processes can be both CC and NC depending on the exchange of type of weak bosons. However, weak bosons can also be replaced by additional BSM vector (scalar) bosons Z' (S') from $L_\mu - L_\tau$ model [3]. The presence of such additional BSM bosons can enhance the NTP event rate significantly. CHARM II [5], CCFR [6], and NuTeV [7] have observed NTP events in the past and based on their observed event rate, limits on the mass-coupling constant parametric space have been set which can be seen in Fig. 2 [4]. Among all the NTP processes, we are interested in only the channels that produce two outgoing muons ($\mu^\pm$) as the charged leptons. To investigate the feasibility of detecting NTP events in the higher energy regime, we calculate the SM cross section and simulate events of NTP processes that produce dimuons using equivalent photon approximation (EPA) with CalcHep [8]. From Fig. 3 [left], we notice that the CC contribution of the total cross-section increases with steeper slope at around ~ 4TeV incoming neutrino energy. Right side plot of Fig. 3 shows that W boson becomes on-mass shell (i.e., resonance at ~ 80GeV), which is responsible for increase in the cross-section. Therefore we expect to observe more NTP events as we go higher in energy of the incoming neutrinos and it is only possible with neutrino observatories (like IceCube) as they can detect high energy neutrinos which is beyond the reach of collider experiments.

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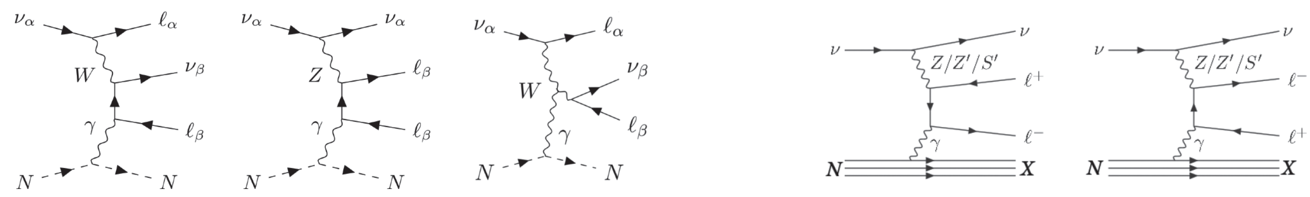

Fig. 1 [Left]: Feynman diagrams for SM NTP processes. *N* is the interacting nucleus and *l* is the charged lepton with flavours $\alpha, \beta = e, \mu, \tau$. [Right]: Feynman diagram replacing *Z* boson with BSM bosons Z' and S'.

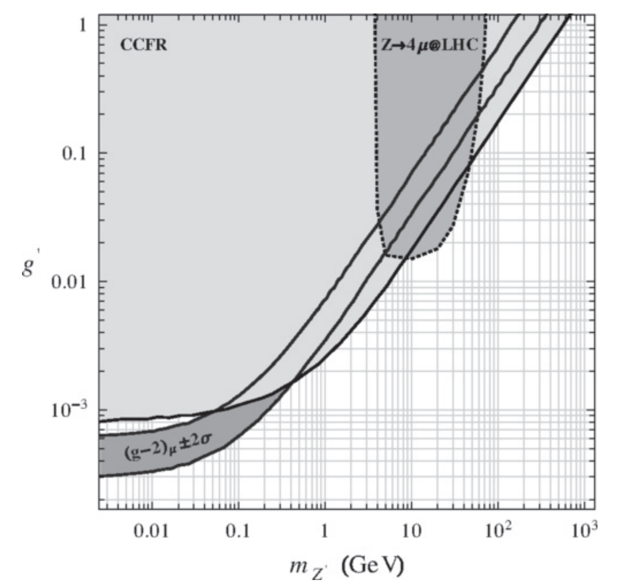

Fig. 2 Parameter space for Z' gauge boson. Shaded region above the lines is the excluded region.

SEARCH FOR NTP EVENTS IN ICECUBE DETECTOR

IceCube neutrino observatory, located at the geographic south pole uses a cubic kilometer of antarctic ice as its detector vol- ume. When a neutrino interacts in the ice, it deposits either a fraction or all of its energy which creates high energy charged particles in the medium. If these charged particles travel faster than the phase velocity of light in ice they emit photons via Cherenkov radiation. IceCube detector aims to detect the Cherenkov photons to get information about the primary inter- action by reconstructing energy, direction and flavour of incoming neutrinos. To detect these Cherenkov photons, 5160 digital optical modules (DOMs) consisting of photomultiplier tubes (PMTs) and related electronics are installed in the ice (shown in Fig. 4 [left]). These DOMs are instrumented on 86 strings at a depth from 1450 m to 2450 m from the surface at the south pole as shown in Fig. 4 [right]. The volume of the full detector is one cubic kilometer and in the middle of the detector, there is a densely spaced infill array of DOMs with higher quantum efficiency (QE) PMTs (i.e., better resolution) to probe into lower energy neutrino interactions. This densely spaced core of the detector is called DeepCore volume which is an order of magnitude smaller compared to the full detector volume. When a muon neutrino interacts in the detector via CC interaction, it produces a high energy muon that can travel a long distance through ice before losing its energy in the surrounding medium and decay. Cherenkov radiation detected from such muons look like elongated tracks in the detector (as shown in Fig. 5 [left]), so they are called 'track-like' event. For all other neutrino interactions (all flavour of NC interactions and electron- and tau-neutrino CC interaction) where secondary particles are other than a muon, they create electromagnetic and hadronic shower in ice where multiple charged particles produce Cherenkov radiation in all direction from the primary interaction vertex allowing the detector to see light isotropically (shown in Fig. 5 [right]) and these events are called 'cascade-like' events.

For the search of NTP events, we are only interested in di-muon production channels, i.e., we will be looking only into track-like events in IceCube. Moreover, there are two muons generated through NTP process simultaneously, so the goal of this research is to look for double-track events in IceCube. We rely on the abundant atmospheric neutrino sample (neutrinos that are created in the earth's atmosphere from the interaction of cosmic rays) for NTP event search. From the well established atmospheric neutrino flux, calculated NTP cross-section and efficiency of detecting track events in IceCube, we can estimate the expected NTP event rate for only SM contributions in both IceCube and DeepCore detector which is given in Table. 1.

Now that we have an expected NTP event rate, our immediate challenge is to build an efficient event reconstruction tool that can distinguish the difference between a single-track event (standard CC) and a double-track event (NTP). The ability of detecting double-track events depend on the detector resolution and separations between two tracks. If the separation is too small, light from those two tracks are not resolvable which can make the double-track and single-track events indistinguishable from each other. We are currently in the process of exploring and exploiting double track signature to develop reconstruction algorithm that can detect such event topology. In order to explore the properties of double track events, we have created toy Monte Carlo (MC) simulations of NTP events in IceCube detector, two sample events are shown in Fig. 6. We are also

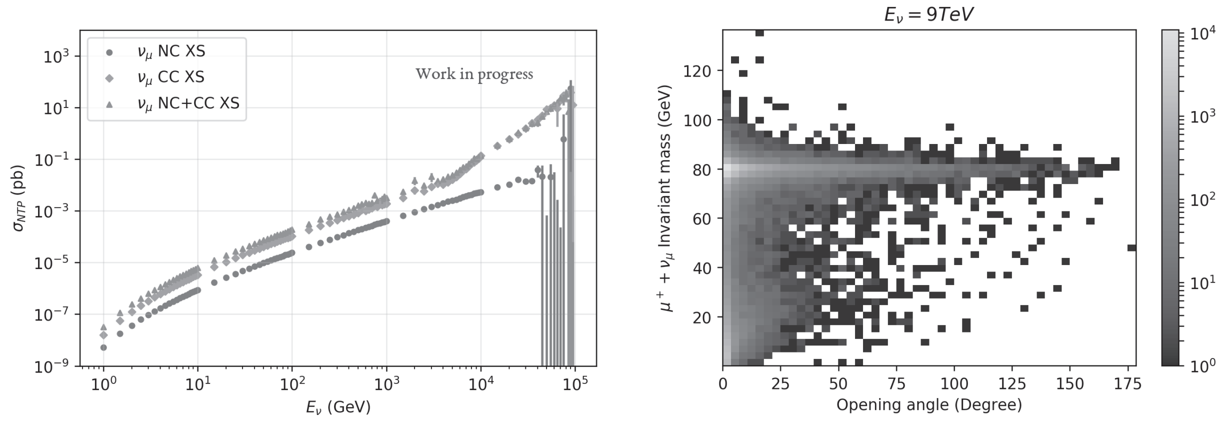

Fig. 3 [Left]: Total Cross-section of NTP channel of di-muon production. [Right]: Distribution of W boson invariant mass and opening angle between two outgoing muons. Peak at 80GeV shows the presence of on-mass shell W boson.

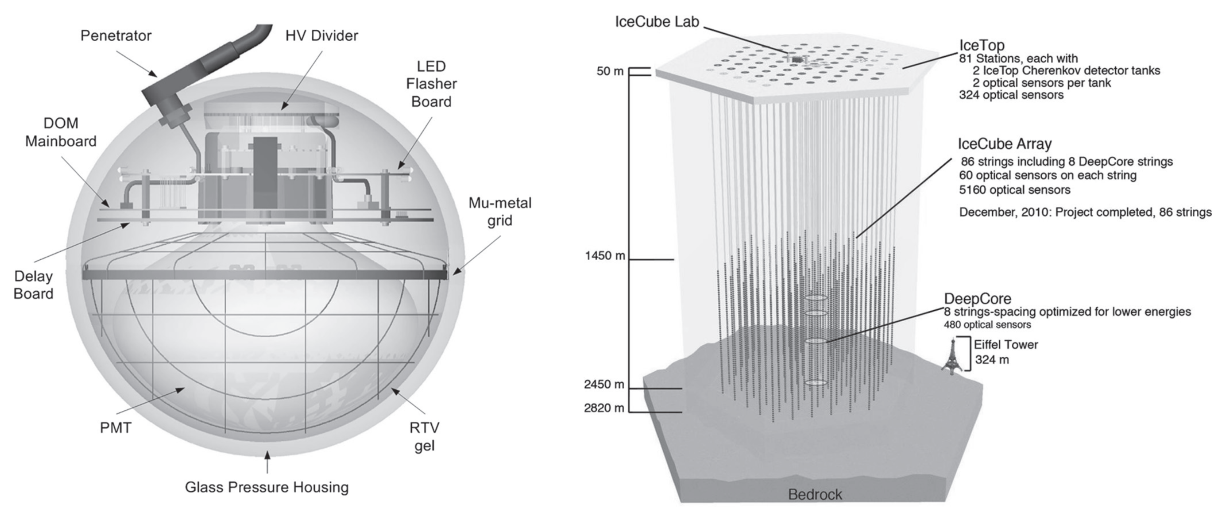

Fig. 4 [Left]: DOM with PMT placed in the bottom half. [Right]: Schematic of IceCube detector configuration.

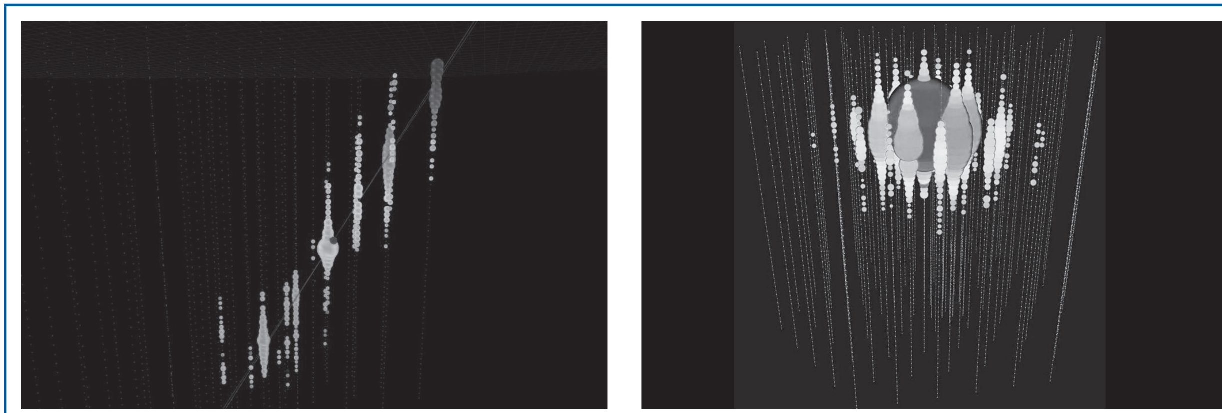

Fig. 5 Track-like (left) and cascade-like (right) event topology in IceCube.

TABLE 1

Estimated NTP and CC event rates from SM in IceCube [left] and DeepCore [right].

IceCube Volume	DeepCore Volume
Emergy range 100GeV – 5TeV	Emergy range 1GeV – 1TeV
~9.35 NTP events/year	~2.17 NTP events/year
~34, 975 standard CC events/year	~192, 060 standard CC events/year

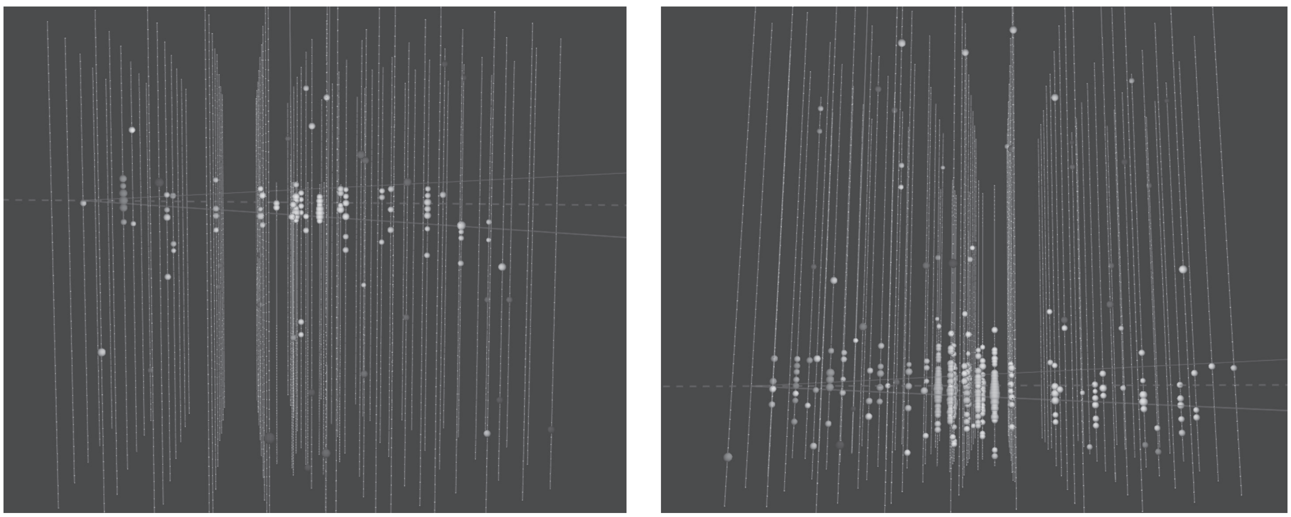

Fig. 6 Double track NTP event simulations in IceCube.

working on determining the limit of the track separation below which it is not possible to detect NTP signal events from standard CC background.

CONCLUSION

In summary, NTP process can be used as a powerful probe into the study of new physics. Collider and neutrino beam experiments are limited by energy of incoming neutrinos to detect significant number of trident events that can set a strong constraint on the BSM bosons search limit. In this work, we explore the possibility of detecting NTP events in IceCube with some advantage over standard collider and beam experiments. However, poor detector resolution and large background events are the challenging hurdles that we need to overcome to get more constraining BSM boson search limit by detecting double track NTP events.

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