Atmospheric Neutrino Trident

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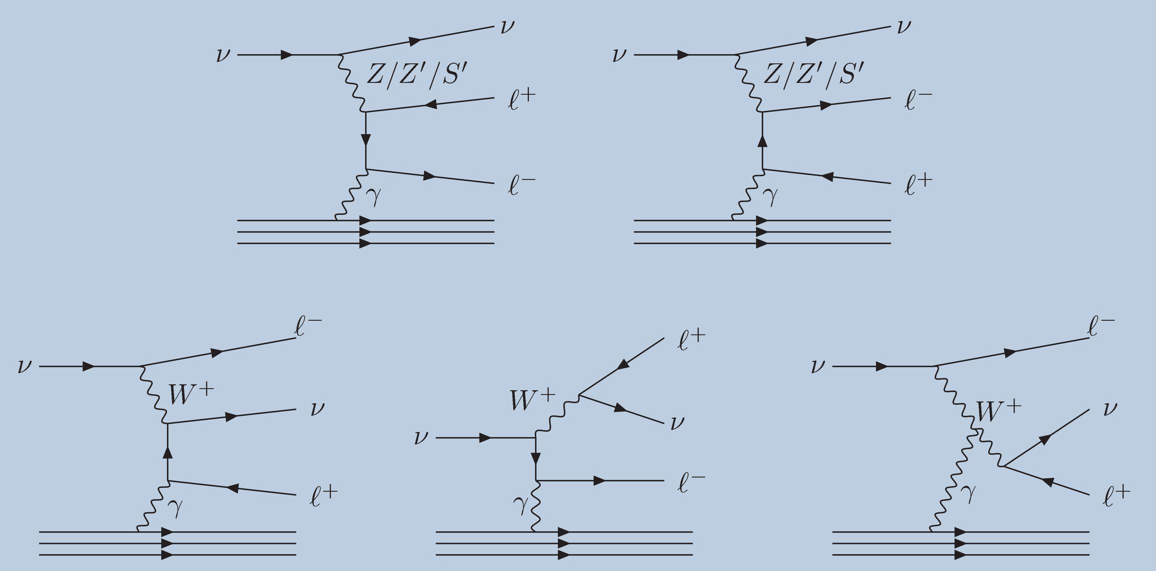
Neutrino Trident Production in the SM

The neutrino oscillation is the first place that new physics beyond the Standard Model (SM) is observed. Nevertheless, current neutrino oscillation experiments cannot directly observe the mechanism behind the neutrino mass, mixing, and interactions. If a neutrino oscillation experiment is turned into an instrument for direct observation of new physics, its physics potential can significantly extend. In this sense, neutrino experiment can also work as collider.

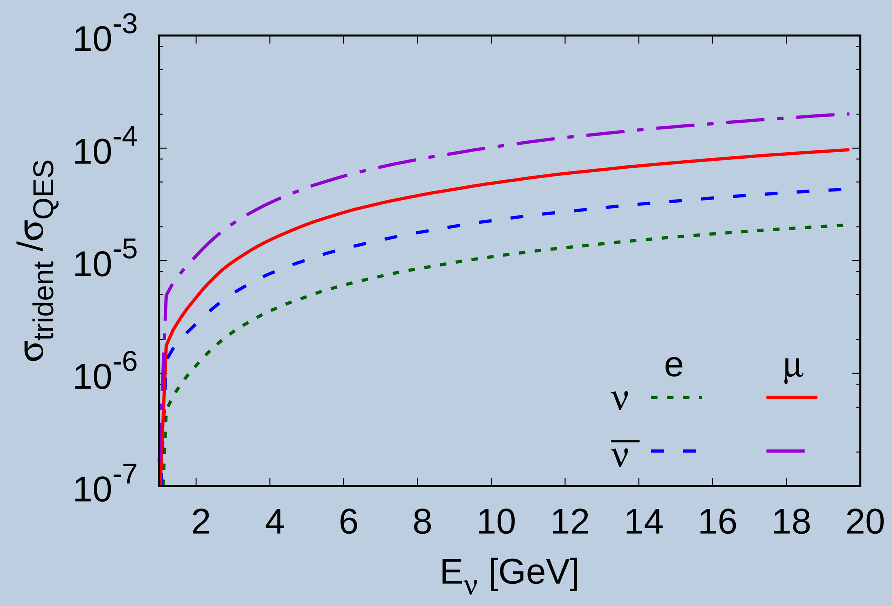
The neutrino trident production,

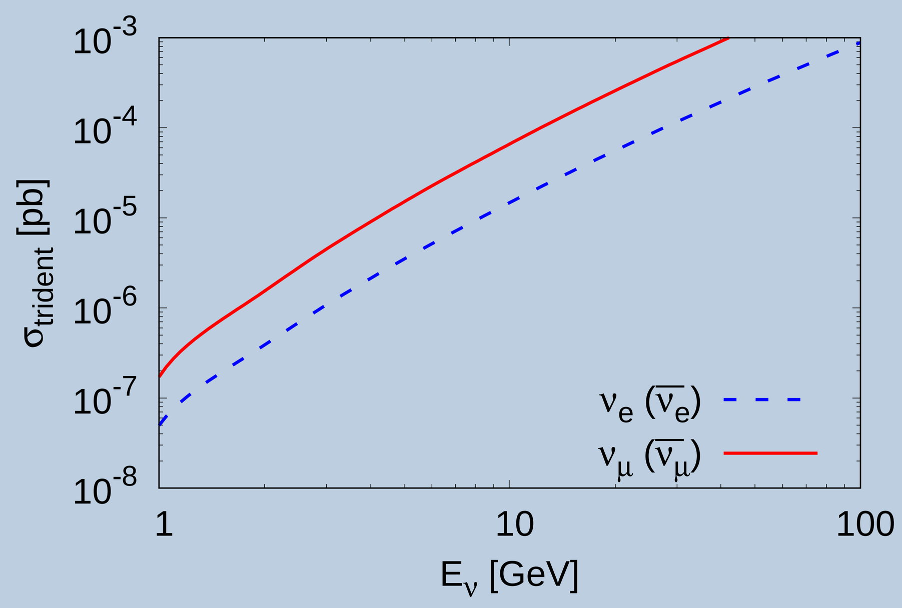
$$\overset{(-)}{\nu_\ell} N \to \overset{(-)}{\nu_\ell} \ell^+ \ell^- X \text{ with } \ell = e, \mu, \tau\,,$$

can serve this purpose. Different from the usual neutral current (NC) scattering of neutrinos, the final state contains 3 leptons, from which the name *trident* production comes.



Since there are more particles in the final state, more propagators are involved. To connect with the incoming neutrino, at least one weak gauge boson, Z or W, is involved. Similarly, connection with nuclei requires another gauge boson. With already one heavy gauge boson involved, sizable contribution can only come from photon. In principle, the Z boson can also connect trident production with nuclei. But its contribution is highly suppressed by the extra Z propagator. The neutrino trident production is essentially driven by nuclei's electromagnetic interaction. Suppression also appears in the last Feynman diagram of the figure shown above, with two W propagators.





The neutrino trident production is typically a factor of $10^{-6} \sim 10^{-4}$ of the usual neutrino scattering cross section. It is much more difficult to be probed than neutrino scattering. Since the mediator is the neutral photon, there is no difference in the total cross section between neutrino and anti-neutrino. However, the cross section depends on neutrino and lepton flavors.

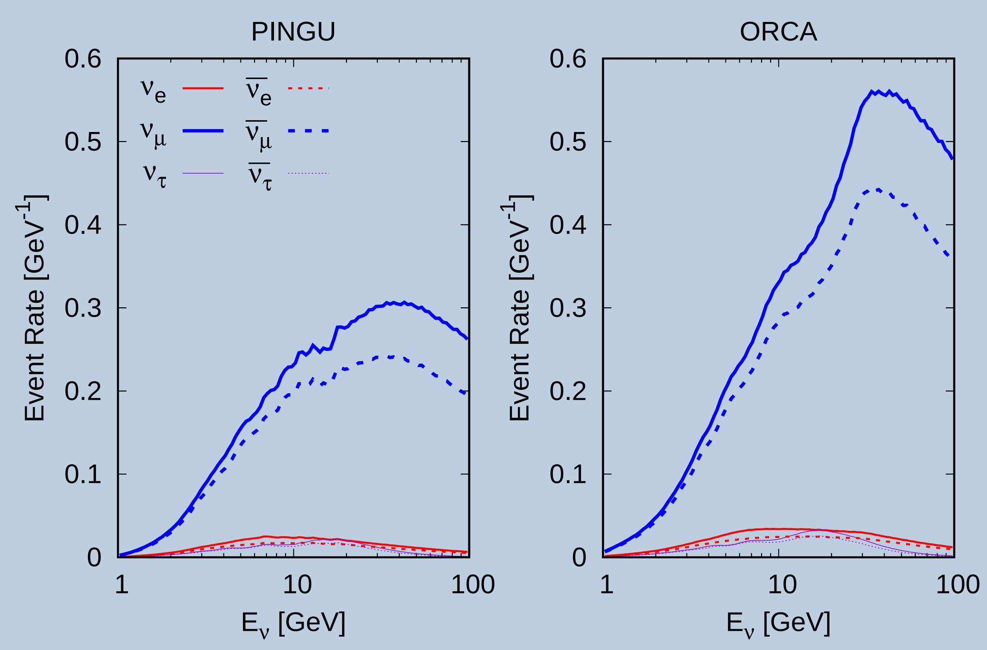
Reference

[1] S. F. Ge, M. Lindner and W. Rodejohann, "*New Physics and Atmospheric Neutrino Trident Production with PINGU and ORCA*," [arXiv:1702.02617 [hep-ph]].

Atmospheric Neutrino Trident Measurement

We propose using the atmospheric neutrinos as a free source to probe neutrino trident production at large Cherenkov detectors such as PINGU and ORCA. With much smaller cross section than the usual neutrino scattering, the trident production requires much larger detector or flux than neutrino oscillation measurement. Since the cross section $\sigma_{\rm trident}$ is typically $4 \sim 6$ orders smaller than $\sigma_{\rm CC}$, the neutrino scattering rate should reach at least 1 million in order to collect a handful of trident production events. Both PINGU and ORCA can reach this criteria.

The PINGU/ORCA detectors are huge ice/water cubes filled with vertical strings of digital optical modules (DOMs). The ice/water is used both as scattering target and measurement medium. Charged particles with speed more than 3/4 of the speed of light in vacuum can emit Cherenkov radiation to be collected by DOMs. The pattern in Cherenkov photons, such as their energy, direction, and arriving time, can be used to identify the final-state particles in the primary interaction. Especially, muon can leave a clear track in PINGU/ORCA, which is a distinctive signal. With 2 muons in the final state, the trident production can be easily recognized by the PINGU/ORCA detector.



For a neutrino telescope that cannot distinguish neutrino from anti-neutrino, such as PINGU and ORCA, large statistics is necessary for the measurement of neutrino mass hierarchy. In total, PINGU can collect roughly 1 million neutrino scattering events and similarly for ORCA. This is roughly what we need to collect more than 10 events of neutrino trident production. And the common systematics can be well constrained by the measurement of neutrino oscillation measurement.

We show the event spectrum at PINGU/ORCA in the figures above. The largest contribution comes from the muon flavor neutrinos since the atmospheric neutrino flux is mainly of muon flavor on one hand and the cross section for muon-pair trident production is much larger for muon neutrino than the other. The difference between neutrino and anti-neutrino is due to the difference in neutrino and anti-neutrino fluxes. The event rate keeps growing with neutrino energy until reaching peak around $E_\nu \sim 30\,$GeV. Since we don't have the information on the fiducial volume above $E_\nu \approx 40\,$GeV, we extrapolate the official fiducial volume up to $E_\nu \sim 100\,$GeV and leave the even high energy range for future study. From the unexplored energy range we expect even much more events to be collected.

The background to muon-pair trident production can come from double muon tracks accidentally produced from two different neutrino scattering processes. It can be significantly reduced by requiring the 2 muons to be produced simultaneously within a time window shorter than roughly 500 seconds, which is definitely achievable at PINGU/ORCA. Requiring the 2 muons to be produced at the place can further reduce this background.

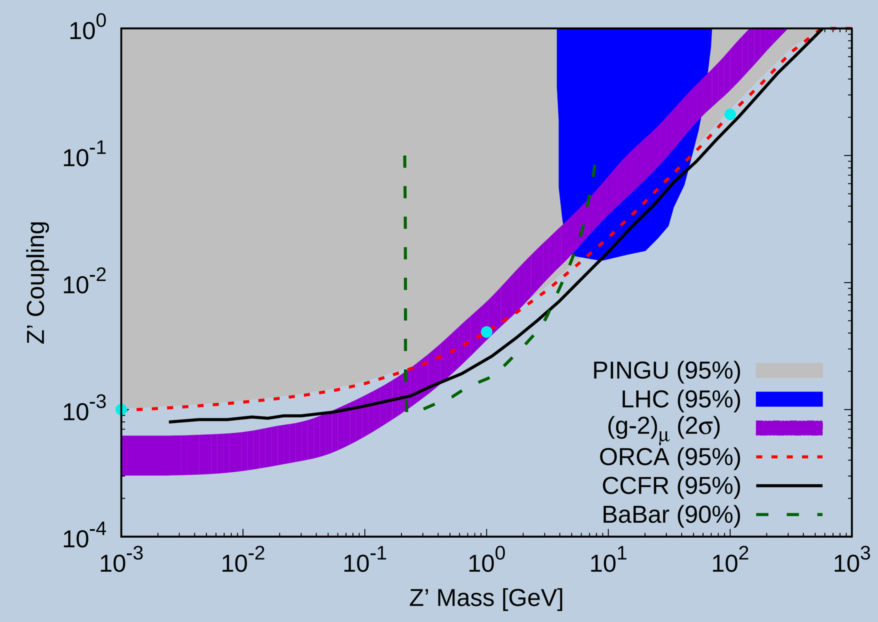
The large Cherenkov detectors such as PINGU and ORCA have several advantages in detecting neutrino trident production. First, the double-track signal is easy to identify without modification of the detector and the search can be carried out simultaneously with the neutrino oscillation measurement. Second, its huge volume guarantees large enough event numbers. Finally, both systematics and background rate are small.

Physics Potential on Probing New Physics

To demonstrate the physics importance of observing atmospheric neutrino trident production at PINGU/ORCA, we consider two example models of new physics. The observation of neutrino oscillations still allow large non-standard interactions (NSI) in the muon and tau flavors. Such contribution can be generated by a vector boson Z' with couplings to the muon- and tau-flavor leptons,

$$\mathcal{L}_{Z'} \equiv g_{Z'} Q_{\alpha\beta} \left[\overline{L}_\alpha \gamma^\mu L_\beta + \overline{\ell}_{R\alpha} \gamma^\mu \ell_{R\beta} \right] Z'_\mu + h.c.\,,$$

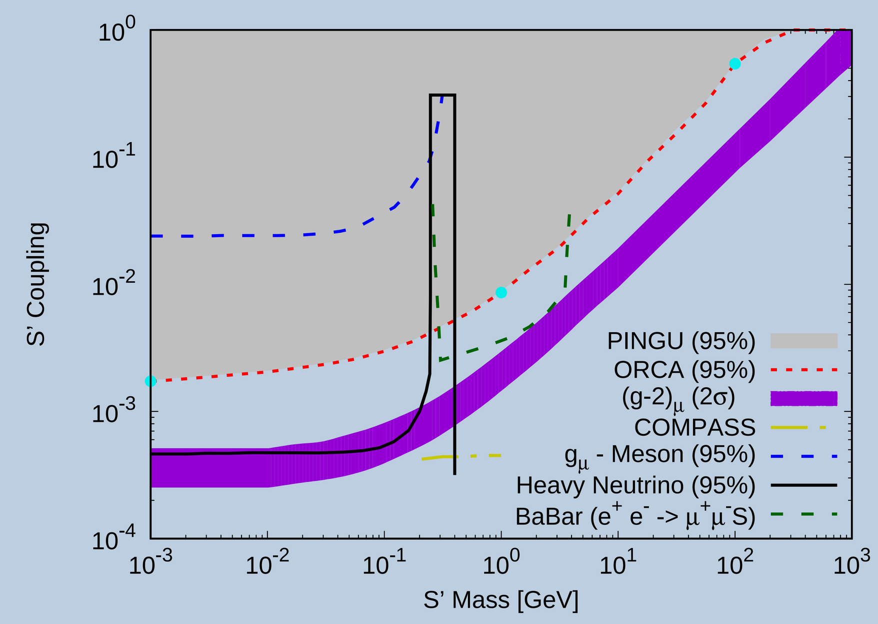
where $Q_{\alpha\beta} = {\rm diag}(0, 1, -1)$. Then Z' can also mediate the neutrino trident production as shown in the Feynman diagram.



The same thing can also happen to scalar S',

$$\mathcal{L}_{S'} \equiv g_{S'} Q_{\alpha\beta} \left[\overline{\ell_{R\alpha}} \ell_{L\beta} + \overline{\nu^c_{L\alpha}} \nu_{L\beta} \right] S' + h.c.\,,$$

where the Yukawa couplings are of the Majorana type.



With 39 (62) events to be collected at PINGU (ORCA), the coupling of Z' (S') can be constrained to the level of 10^{-3} in the low mass region. The neutrino trident production can explore much larger parameter space than colliders. Although the constraint from $(g-2)_\mu$ seems much better, it cannot confront with neutrino trident production directly. If there is other new physics to cancel the contribution of Z' (S'), the $(g-2)_\mu$ constraint on trident production can then be easily avoided.

The results shown above are quite conservative and improvements can come from several aspects. First, we have only considered the event rate up to $E_\nu = 100\,$GeV, due to lack of information on effective volume. The range of higher neutrino energy can contribute several times more events. Second, differential distributions of opening angle and invariant mass as shown below can be used to improve the sensitivity. Third, not just a pair of muons but also other combinations of final-state leptons from trident production can be collected at PINGU/ORCA. Finally, larger version of Cherenkov detectors, such as IceCube and ARCA, can also observe neutrino trident production.