Mind the Gap on IceCube: Cosmic neutrino spectrum and muon anomalous magnetic moment

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Abstract. The high energy cosmic neutrino spectrum reported by the IceCube collaboration shows a gap in the energy range between 500 TeV and 1 PeV. In this presentation, we illustrate that the IceCube gap is reproduced by the neutrino interaction mediated by the new gauge boson associated with a certain combination of the lepton flavour number. The gauge interaction also explains the other long-standing gap in the lepton phenomenology: the gap between theory and experiment in the muon anomalous magnetic moment.

1. Introduction

After the first discovery of the high-energy cosmic neutrino events [1, 2], the IceCube collaboration has been successfully collecting the data, and today we know the spectrum of cosmic neutrino at the energy range between \( \mathcal{O}(10) \) TeV and \( \mathcal{O}(1) \) PeV [3,4]. The shape of the spectrum already starts telling us interesting features; First, no event is observed in the energy range above 3 PeV, i.e., there seems to be a sharp edge at 3 PeV. Second, the best-fit spectral index (index of the power law) is quite high, which seems to be higher than 2.5. Finally, there is a gap at the energy region between 500 TeV and 1 PeV. In this presentation, we are motivated by the gap in the spectrum and propose a new physics framework to explain it.

There is also a long-standing gap in the lepton sector of the standard model of particle physics, which is the disagreement between theory and experiment in the muon anomalous magnetic moment. We try to address both the gaps — make a gap in the cosmic neutrino spectrum and fill the gap in the muon anomalous magnetic moment, introducing one new physics.

2. Model and muon anomalous magnetic moment

In order to reproduce the gap, we introduce a new abelian gauge symmetry associated the muon number minus tau number \( U(1)_{L_\mu - L_\tau} \). The new gauge boson \( Z' \) interacts with muon neutrino and tau neutrino, which explains the gap in the spectrum, and also with muon and tau inevitably. The symmetry was originally proposed by the authors of Refs. [5, 6] as a gauge-anomaly-free extension of the standard model. The new gauge interaction is described as

\[
\mathcal{L}_{Z'} = g_{Z'} \overline{L_\mu} \gamma^\mu L_\mu Z'_1 + g_{Z'} \overline{L_\tau} \gamma^\mu R_\tau Z'_3 - g_{Z'} \overline{L_\mu} \gamma^\mu L_\mu Z'_1 - g_{Z'} \overline{L_\tau} \gamma^\mu R_\tau Z'_3, \quad (1)
\]

in the Lagrangian. The interaction with muon gives us a chance to solve the gap between theory and experiment in the muon anomalous magnetic moment. The parameter region favored by the
measurement of the muon anomalous magnetic moment is indicated with the red band in the left plot of Fig. 1. Although the Z' interaction is supported by the muon observable, it is constrained by various laboratory experiments. In the plot, two relevant constraints are indicated. The hatched region is excluded by the neutrino trident process: $\nu_\mu N \to \nu_\mu \mu^+ X$ [7, 8], and the gray-shaded region is disfavoured by the observation of the solar neutrino-electron elastic scattering [9], which is induced through the $\gamma$-Z' mixing. In conclusion, the sweet spot is narrowed down to the region where $g_{Z'} \sim O(10^{-4})$ and 10 MeV $\lesssim M_{Z'} \lesssim 100$ MeV. In this presentation, we use $g_{Z'} = 5.0 \cdot 10^{-4}$, $M_{Z'} = 11$ MeV (2)

as a reference choice of the parameters, with which the Z' contribution to the muon anomalous magnetic moment is calculated to be $a_\mu^{Z'} = 24.2 \cdot 10^{-10}$.

3. Cosmic neutrino spectrum

In the framework described in the previous section, cosmic neutrinos with a particular energy are resonantly scattered by the cosmic neutrino background (CνB) with the new gauge interaction [10–18] and lose their energy. The cross section of the scattering process can be approximately written as

$$\sigma = \frac{2\pi g_{Z'}^2}{M_{Z'}^2} \delta \left(1 - \frac{M_{Z'}^2}{s}\right),$$

where $s$ is the center of mass energy, which is estimated as $s = 2(1 + z)m_\nu E_\nu$ at redshift $z$. From this expression, one can see that the mass of Z' must be set at $O(1)$ MeV to make the resonance at the energy $E_\nu$ corresponding to the IceCube gap ($\sim 1$ PeV) with neutrino mass $m_\nu$ of $O(0.1)$ eV. In addition, to make the gap deep enough, we must also require the condition that the size of the cross section is so large that cosmic neutrinos with the energy corresponding to the IceCube gap cannot travel the distance between their sources and the Earth. The averaged
travelling distance of cosmic neutrino can be estimated with the mean free path $\lambda$ which is roughly given as $1/(n_{C\nu B} \sigma)$ where $n_{C\nu B}$ is the number density of C$\nu$B in the Universe. The requirement, $\lambda \lesssim O(1)$ Gpc, leads the condition that the coupling $g_{Z'}$ must be larger than $O(10^{-4})$. Interestingly, the conditions to reproduce the IceCube gap suggest the parameter region favored by the measurement of the muon anomalous magnetic moment (cf. left plot in Fig. 1).

Taking account of the redshift distribution of the neutrino sources, we numerically solve the partial differential equations of the cosmic neutrino evolution and calculate the flux $\Phi(E_\nu)$ at the Earth, which are shown in the right panel of Fig. 1. Here, we examine power-law spectra with the spectrum indices $s_\nu = \{2.1, 2.3, 2.5\}$ as the initial cosmic neutrino flux at the source. The sources of the cosmic neutrino are assumed to be distributed following the star formation rate. For neutrino mass spectrum, we take the normal hierarchy and set the lightest neutrino mass to $8\times 10^{-2}$ eV. The curves fit nicely to the observed flux which is indicated with crosses in the right panel of Fig. 1. The details of our setup and numerical calculations are found in Ref. [10].

4. Summary
Introducing a new $U(1)_{L_\mu - L_\tau}$ gauge symmetry, we have successfully reproduce the gap in the cosmic neutrino spectrum reported by the IceCube collaboration, and at the same time, we have made an additional contribution to the muon anomalous magnetic moment, which fills the gap between the standard model prediction and the experimental observation.

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