

# New Physics in Astrophysical Neutrino Flavor NuFact 2016

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## Abstract

Astrophysical neutrinos are powerful tools to study fundamental properties of particle physics. We perform a general new physics study on ultra high energy neutrino flavor content by introducing effective operators. We find that at the current limits on these operators, new physics terms cause maximal effects on the flavor content, however, the flavor content at Earth is confined to a region related to the initial flavor content.

## 1 Introduction

In the last decades neutrino experiments have significantly improved our knowledge of these elusive particles. All three angles of the mixing matrix and the two mass differences have been measured. However, there are still a lot of questions to be answered. The absolute value of the neutrino mass is still not known, also the complex CP phase and the sign of one of the mass differences are still unknown.

Most of the popular theoretical models that could naturally explain such light masses propose a new mechanism that happens at higher scales, thus introducing a new physics scale. Some of the models could also account for other unsolved question, such as the origin of the observed baryon asymmetry in the Universe<sup>1,2,3</sup>, propose a Dark Matter candidate<sup>4,5</sup>, or even explain the nature of Dark Energy<sup>6</sup>. In general we expect any new physics scale affect the precision measurements of the oscillation phenomena for highly energetic neutrinos or when observing neutrinos that traveled very long distances<sup>7,8,10</sup>.

The last years the IceCube experiment discovered high energy extraterrestrial neutrinos<sup>11</sup>, probably coming from extra-galactic astrophysical sources, that have energies of order PeV and travel distances of order Mpc-Gpc. The IceCube detector is located in the South Pole and is a kilometer cube of instrumented ice situated more than a kilometer deep in the Antarctic ice. The ice is instrumented with 86 strings of 60 digital optical modules each one has a photo-multiplier for collecting photons. Due to the deep isolation photons are mainly Cerenkov light of charged particles traveling through the ice.

In 4 years 54 neutrinos like events with energies above 20TeV where observe in the IceCube detector at the South Pole<sup>12</sup>. The High Energy Starting Events analysis (HESE), due to the veto region, allows the use of the full sky. There are two main topologies that can be distinguished: the tracks, produced by muons crossing the detector, and the showers, that can be produce by any neutrino flavor via neutral current interaction or by electron/tau neutrino charged current interactions. The track events are mainly produced by the muon neutrinos. The different topologies may give us information about the flavor content of the astrophysical neutrino flux. However, extracting the information is complicated since there are non trivial correlations with the amount of neutrinos and anti-neutrinos, and also with the spectral features of the astrophysical neutrino flux<sup>13,14,15</sup>. More statistics is needed to

$n$	New Physics	Current Bound From SK <sup>21</sup> and IC-atm <sup>22</sup>
0	CPT-odd Lorentz Violation Coupling Space Time Torsion Non Standard Neutrino Interactions	$O_0 < 10^{-23} \text{GeV}$
1	CPT-even Lorentz Violation Violation of the equivalence principle	$O_1/\Lambda_1 < 10^{-27}$

Table 1: Current bounds from Super Kamiokande and IceCube-atmospheric for new physics scales.

extract more precise information about the flavor ratio of the astrophysical neutrinos, which may be achieved in the next generation experiments Icecube-Gen2 <sup>16</sup> and KM3NeT <sup>17</sup>.

Measuring the flavor ratio of these high energetic neutrinos could have implications on neutrino physics <sup>18,9,19</sup>.

## 2 New Physics in Neutrino Oscillations

Neutrino oscillations are quantum effects related to the misalignment between mass and flavor eigenstates. In vacuum the neutrino propagation is well described by a three level quantum system where the Hamiltonian is given by

$$H = \frac{1}{2E}UM^2U^\dagger, \quad (1)$$

with  $U$  being a unitary matrix that relates the propagation and flavor eigenstates space(in vacuum the propagation eigenstates are also called mass eigenstates), and  $M$  is a diagonal matrix that contains the mass eigenvalues. The mixing matrix  $U$  and the mass square differences in  $M^2$  are measured by neutrino oscillation experiments <sup>20</sup>.

In the case of neutrinos propagating very large distances the wave packages of the different mass eigenstates will not overlap and the oscillation phenomena stops, in this case the probability of measuring a flavor  $\alpha$  for a neutrino produced as a flavor  $\beta$  is given by,

$$\bar{P}_{\nu_\alpha \rightarrow \nu_\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2. \quad (2)$$

The decoherence process of neutrinos and the size of the wave packages is still unknown, but for astrophysical distances this is a very good approximation.

In the presence of new physics neutrino oscillations are modified by a new operator in the propagating Hamiltonian,

$$H = \frac{1}{2E}UM^2U^\dagger + \sum_n \left(\frac{E}{\Lambda_n}\right)^n \tilde{U}_n O_n \tilde{U}_n^\dagger = V^\dagger(E)\Delta V(E), \quad (3)$$

where  $O_n$  and  $\Lambda_n$  define the scale of the new physics. The bounds in this operators are well studied in different context. In particular, for the power  $O_0$  and  $O_1$  are shown in Table 1. The matrix that relates the propagation and flavor eigenstates is not  $U$ , but the unitary matrix  $V(E)$  that depends on the neutrino energy. Notice that since the new physics is expected to be relevant at energies of order of the cutoff  $\Lambda_n$  or higher the IceCube neutrinos with the highest energies ever measured, could give relevant information about the new physics.

The oscillation probability formula is the same as eq. (2) just replacing the matrix  $U$  by the matrix  $V(E)$ , notice the energy dependence,

$$\bar{P}_{\nu_\alpha \rightarrow \nu_\beta}(E) = \sum_i |V_{\alpha i}(E)|^2 |V_{\beta i}(E)|^2. \quad (4)$$

### 3 Flavor Ratio at Detection

In order to show the result we plot probabilities densities of measuring a flavor ratio at detection point assuming some flavor ratio at the production. We show the result for different values of the new physics scales using a Bayesian approach in order to have into account the unknown of the flavor structure of the new physics we assume a flat distribution in the Haar measure of  $SU(3)$  for the matrices  $\tilde{U}$ ,

$$d\tilde{U}_n = d\tilde{s}_{12}^2 \wedge d\tilde{c}_{13}^4 \wedge d\tilde{s}_{23}^2 \wedge d\tilde{\delta} , \quad (5)$$

For the uncertainty on the current oscillation parameters we use the results in [www.nu-fit.org](http://www.nu-fit.org) <sup>20</sup>.

In the following we will show the results for the different possible production fluxes:

- Charged Pion Decay (1 : 2 : 0). Pions are produced via a  $\Delta$  resonance and the following decays produce 1 electron and 2 muon neutrinos.
- Pion Decay and Muon Energy Lost (0 : 1 : 0). Like the pion decay scenario but in this case due to synchrotron cooling the secondary Muon loses part of the energy before decaying, making the resulting neutrinos effectively disappear from the high energy IceCube events.
- Neutron Decay (1 : 0 : 0), pure astrophysical neutron source.
- Production of  $\nu_\tau$  (0 : 0 : 1). We add this by completeness, it's not motivated by any known physical scenario but measuring this may very good be a hint of some new physics production mechanism.

In Fig.1 we show the result only with the current uncertainties in the oscillation parameters. Notice that the current precision still give some freedom but independently of the initial flux the allowed parameter region is relatively small.

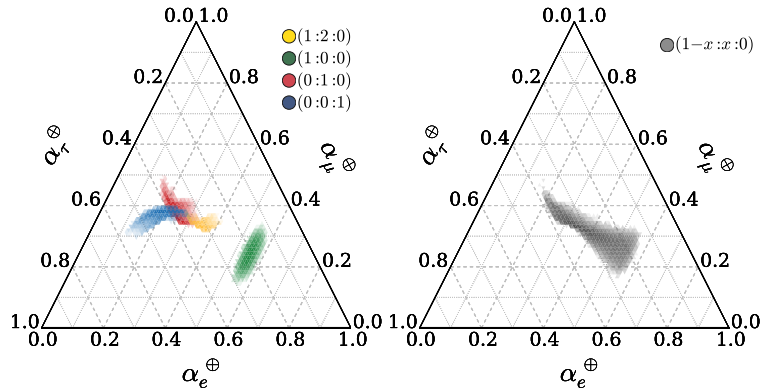


Figure 1 – Non new physics case, here we only show the effect of the current uncertainties in the mixing parameters from neutrino oscillation experiments. In the right we show the case for the 4 benchmark cases described above and in the right the result of a case where both of them are combined with an unknown relative weighting.

In Fig.2 we show the case totally dominated by the new physics scenario, in here the mass term in the Hamiltonian is neglected and we can see the maximum effect for the new physics. In this case, we can see how even in this case the initial information of the flavor at production is still pretty conserve since the overlap of the regions is marginal.

In the following we will see the intermediate case where both terms are relevant for a different value of the the new physics scale, in the case  $n = 0$  and  $n = 1$  this is shown in figures Fig.3 and Fig.4.

Notice that in both cases  $n = 0$  and  $n = 1$  the bottom plot is done with a new physics scale of the same magnitude of the current bounds which directly implies that any measure would put a the strongest bound.

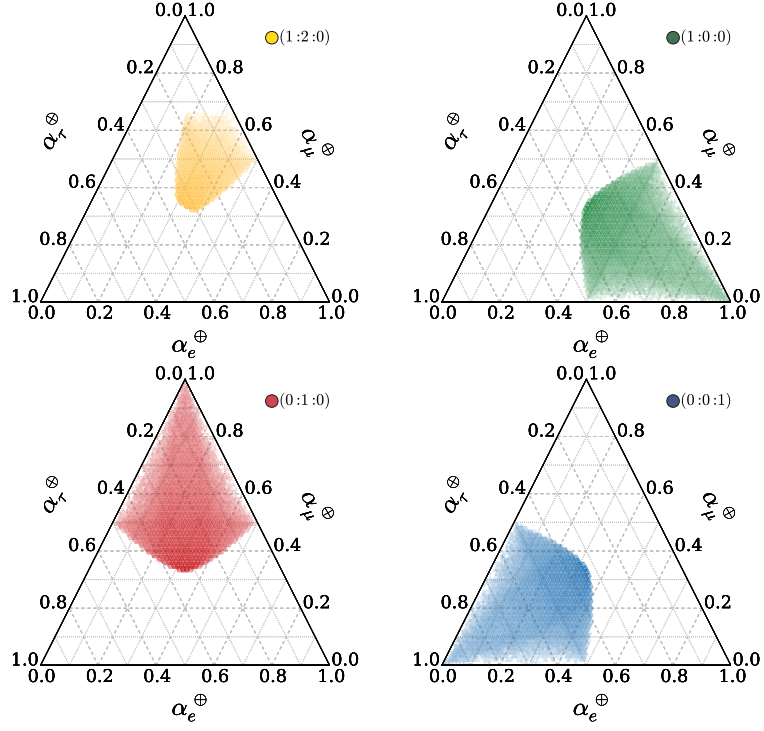


Figure 2 – Only new physics case, here we only show the effect for totally new physics dominated case.

#### 4 Conclusions

Fig.3 and Fig.4 show how sensitive is the astrophysical neutrino flavor ratio to the new physics and how this relatively decouple from the initial productions fluxes. We can reach the following conclusions:

- The measurement of the flavor content at any precision would give the strongest bounds or discovery potential of the new physics scenarios.
- The regions do not overlap significantly, therefore, some flavor information in the production is always preserved. A consequence of this would be that a measurement of tau neutrinos dominated flux outside the standard oscillation regions will imply new physics in the production and propagation.
- Sizable effect in the measure is given by new physics scales that are three orders of magnitude smaller than the current bounds.
- The conclusion is robust for both cases  $n = 0$  and  $n = 1$ , larger  $n$  does not change significantly the result.
- If the production is via pion decay the new physics is confined in a small region.

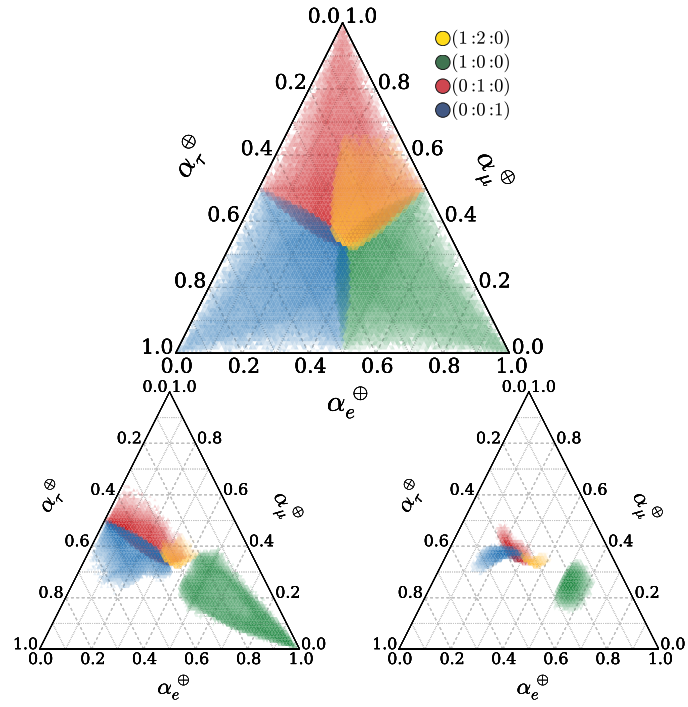


Figure 3 – Case  $n = 0$  with three different values of the new physics scale,  $O_0 = 10^{-23}$  top,  $O_0 = 3.6 \times 10^{-26}$  bottom left, and  $O_0 = 6.3 \times 10^{-28}$  bottom right.

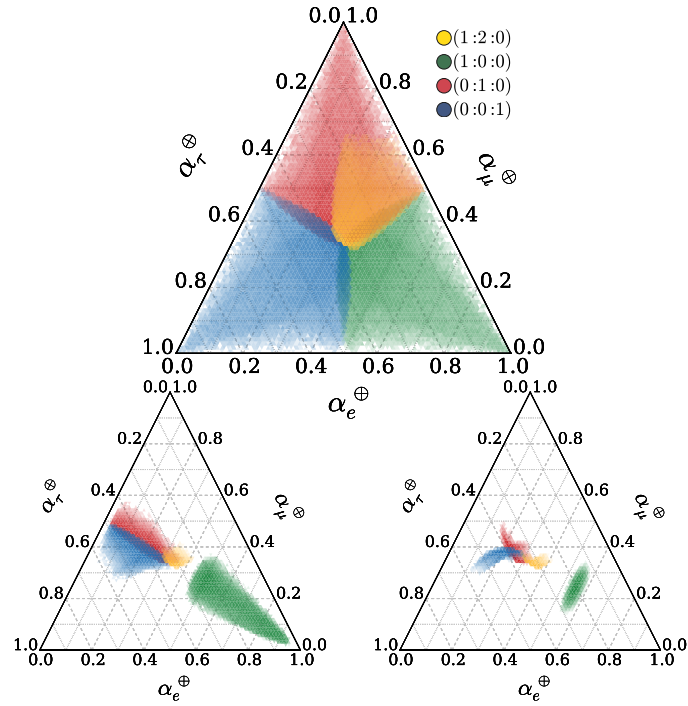


Figure 4 – Case  $n = 1$  with three different values of the new physics scale,  $O_1/\Lambda_1 = 10^{-27}$  top,  $O_1/\Lambda_1 = 1.0 \times 10^{-30}$  bottom left, and  $O_1/\Lambda_1 = 3.2 \times 10^{-34}$  bottom right.

## Acknowledgments

This work was partially supported by grants FPA2014-57816-P, PROMETEOII/2014/050, and the European projects H2020-MSCA-ITN-2015//674896-ELUSIVES and H2020-MSCA-RISE-2015.

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