Intepretations of IceCube high energy neutrinos

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Outline

IceCube 3-year observation

A model

Confronting the data

Summary

Outline

IceCube 3-year observation[IceCube collaboration (2014)]

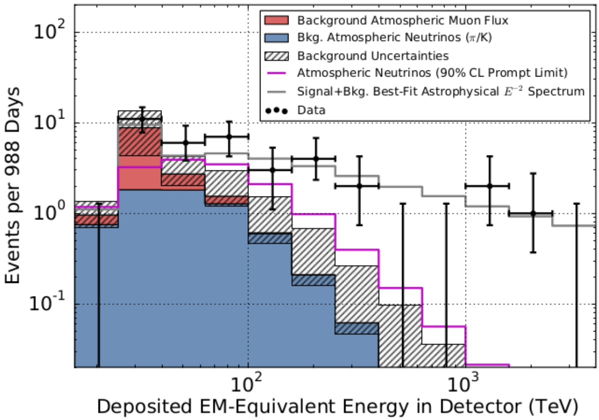

Figure : 37 events (expect 8.4 ± 4.2 cosmic ray muon events and $6.6^{+5.9}_{-1.6}$ atmospheric neutrinos), purely atmospheric explanation rejected at 5.7 σ.

Best fit astrophysical flux $(\nu + \bar{\nu})$/flavor with E^{-2} spectrum:
$0.95 \pm 0.3 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} (expect 3.1 events above 2 PeV)

A model should have the following features

- If the features of the data remain with more statistics, the power law spectrum would be disfavored.
- If the high energy neutrinos result from decays of some particles, the model should have the following features:
  1. A long-lived particle (LLP) Y: $\tau_Y > t_0$ age of the Universe
  2. Peak*: $Y \to \nu X$ with $E_\nu = M_Y/2$
  3. Continuum spectrum: $Y \to ...... \to \nu\nu...$
     e.g. $Y \to \tau\bar{\tau}$, $Y \to t\bar{t}$, $Y \to hh$, $Y \to hhhh$ etc...

  See e.g. [Covi, Grefe, Ibarra, and Tran (2010)], [Esmaili and Serpico (2013)], [Bai, Lu, and Salvado (2013)], [Bhattacharya, Reno, and Sarcevic (2014)]

For simplicity, we consider a scalar LLP Y with mass M.

We found that the channels that can possibly accomodate the data are $\boxed{Y \to \nu X \text{ and } Y \to hhhh}$.

*Peak would be smeared by velocity dispersion of the LLP

Outline

A model

New fields	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
X	1	0	1
Y	1	0	-2
Ψ_L	2	-1/2	2
Ψ_R	2	-1/2	2
N_R	1	0	2

where $\Psi_L = (\psi_L^0, \psi_L^-)^T$ and $\Psi_R = (\psi_R^0, \psi_R^-)^T$.

The idea is to have $\langle X \rangle \equiv w \neq 0$ such that we have $Y \to \nu N_R$ and $Y \to (XX) \to hhhh$ (through off-shell X's).

If $U(1)_X$ is global, we will have one massless Nambu-Goldstone boson (NGB). Taking $w \sim 10^{10}$ GeV, we can have up to 37 NGBs [Chang, Pal and Senjanovic (1985)]. Alternatively $U(1)_X$ can be gauged and w scale is relaxed.

A model: scalar sector

The scalar potential is

$$\begin{aligned} V(X,Y,H) &= \frac{1}{4}\lambda_X \left(X^\dagger X - w^2\right)^2 + \frac{1}{4}\lambda_H \left(H^\dagger H - v^2\right)^2 \\ &+ \frac{1}{4}\lambda_Y \left(Y^\dagger Y\right)^2 + M_Y^2 Y^\dagger Y \\ &+ \lambda_{HX}\left(H^\dagger H - v^2\right)\left(X^\dagger X - w^2\right) + \lambda_{XY}\left(X^\dagger X - w^2\right) Y^\dagger Y \\ &+ \lambda_{HY}\left(H^\dagger H - v^2\right) Y^\dagger Y + \left(\mu_{XY} XXY + \text{h.c.}\right) \end{aligned}$$

We assume $w \gg v = 174$ GeV and $|\mu_{XY}|w^2/M_Y^3 \ll 1$ such that a small vev for Y is induced

$$\langle Y \rangle = u = -|\mu_{XY}|w^2/M_Y^2$$

If $\mu_{XY} \to 0$, there is a Z_2: $\Psi_{L,R} \to -\Psi_{L,R}$ and $Y \to -Y$. Hence μ_{XY} controls the lifetime of our LLP Y_R (real part of Y). Small μ_{XY} technically natural since $\mu_{XY} \to 0$, there is an enhanced symmetry $U(1)_X \times U(1)_Y$.

A model: scalar sector (cont...)

In the scalar sector, we have four new scalars X_R, X_I, Y_R and Y_I and the Higgs h

$$M_R^2 = \begin{pmatrix} \lambda_H v^2 + \lambda_{HY} u^2 & 2\lambda_{HY} uv & 2\lambda_{HX} vw \\ 2\lambda_{HY} uv & M_Y^2 + \frac{3}{2}\lambda_Y u^2 & 2\left(\lambda_{XY} u - \mu_{XY}\right) w \\ 2\lambda_{HX} vw & 2\left(\lambda_{XY} u - \mu_{XY}\right) w & \lambda_X w^2 + \left(\lambda_{XY} u - 2\mu_{XY}\right) u \end{pmatrix}$$

$$M_I^2 = \begin{pmatrix} M_Y^2 + \frac{1}{2}\lambda_Y u^2 & 2\mu_{XY} w \\ 2\mu_{XY} w & \left(\lambda_{XY} u + 2\mu_{XY}\right) u \end{pmatrix}$$

The longevity of Y_R requires a very small $\mu_{XY} \implies$ a small mixing between X and Y and h and Y. The mixing between h and X is controlled by the ratio

$$\delta_{HX} \equiv \frac{4\lambda_{HX}^2}{\lambda_H \lambda_X}$$

With $M_h = 125$ GeV the allowed branching ratio of the invisible higgs decays width is in the ballpark of 20 % [Belanger et al., 2013]

$$\Gamma\left(h \to X_I X_I\right) = \frac{\lambda_{HX}^2 v^2}{32\pi M_h}$$

$\implies \lambda_{HX} \lesssim 0.01$ (for gauged $U(1)_\Psi$, no such decay).

A model: scalar sector (cont...)

The Higgs mass is

$$M_h^2 = \lambda_H \left(1 + \delta_{HX}\right) v^2$$

For simplicity, we assume that $\delta_{HX} < 1$ and all the scalars are approximately mass eigenstates with masses

$$M_{Y_R}^2 = M_Y^2, \quad M_{Y_I}^2 = M_Y^2, \quad M_{X_R}^2 = \lambda_X w^2, \quad M_{X_I}^2 = 0$$

where we use the same symbols to denote the mass eigenstates.

We assume $M_{X_R} \gg M_{Y_R}$ such that Y_R cannot decay to X_R but it can decay to four Higgs through two off-shell X_R. The decay widths for the decays of Y_R to scalars are

$$\begin{aligned}
\Gamma\left(Y_R \to X_I X_I\right) &= \frac{1}{32\pi} \frac{\left(\lambda_{XY} u - |\mu_{XY}|\right)^2}{M_Y} \\
\Gamma\left(Y_R \to hh\right) &= \frac{\lambda_{HY}^2}{32\pi} \frac{u^2}{M_Y} \\
\Gamma\left(Y_R \to hhhh\right) &\approx \frac{\lambda_{HX}^4}{16384\pi^5} \left(\frac{\lambda_{XY} u + |\mu_{XY}|}{\lambda_X}\right)^2 \frac{M_Y^3}{M_{X_R}^4}
\end{aligned}$$

A model: scalar sector (cont...)

Comparing the decay rates

$$\frac{\Gamma\left(Y_R \to X_I X_I\right)}{\Gamma\left(Y_R \to hhhh\right)} = 512\pi^4 \left(\frac{4}{\lambda_H \delta_{HX}}\right)^2 \left(\frac{\lambda_{XY} u - |\mu_{XY}|}{\lambda_{XY} u + |\mu_{XY}|}\right)^2 \left(\frac{M_{X_R}}{M_Y}\right)^4$$

$$\frac{\Gamma\left(Y_R \to hh\right)}{\Gamma\left(Y_R \to hhhh\right)} = 512\pi^4 \left(\frac{4}{\lambda_H \delta_{HX}}\right)^2 \left(\frac{\lambda_{HY} u}{\lambda_{XY} u + |\mu_{XY}|}\right)^2 \left(\frac{M_{X_R}}{M_Y}\right)^4$$

Taking $\lambda_{XY} u \gg |\mu_{XY}|$, $\delta_{HX} = 10^{-1}$, $\lambda_H = M_h^2 / \left[(1+\delta_{HX})v^2\right]$, $M_{X_R} = 5M_Y$, we have

$$\frac{\Gamma\left(Y_R \to X_I X_I\right)}{\Gamma\left(Y_R \to hhhh\right)} \sim 2 \times 10^{11}, \qquad \frac{\Gamma\left(Y_R \to hh\right)}{\Gamma\left(Y_R \to hhhh\right)} \sim 2 \times 10^{11} \left(\frac{\lambda_{HY}}{\lambda_{XY}}\right)^2$$

For $\Gamma(Y_R \to hhhh) > \Gamma(Y_R \to hh)$, we need $\lambda_{HY} \lesssim 2 \times 10^{-6} \lambda_{XY}$.

Longevity of Y_R ($\tau_{Y_R} > t_0 \simeq 4.4 \times 10^{17}\,\mathrm{s}$) implies

$$|\mu_{XY}| \lesssim 6 \times 10^{-18} \frac{\lambda_X}{\lambda_{XY}} \left(\frac{M_Y}{M_{X_R}}\right)^2 \left(\frac{M_Y}{1\,\mathrm{PeV}}\right)^{1/2} \mathrm{GeV}$$

Taking $M_Y = 1$ PeV, $M_{X_R} = 5M_Y$, $\lambda_{XY} = 1$ and $\lambda_X = 10^{-6}$, we have $|\mu_{XY}| \lesssim 2 \times 10^{-25}$ GeV or $u \lesssim 10^{-17}$ GeV.

A model: fermionic sector

The new terms are

$$-\mathcal{L} \supset \left(y_\Psi \overline{\ell_L} \Psi_R Y + y_\nu \overline{\Psi_L} \widetilde{H} N_R + M_\Psi \overline{\Psi_L} \Psi_R + \text{h.c.} \right)$$

We have mixing with the SM leptons

$$\mathcal{L}_m = \begin{pmatrix} \overline{e_L} & \overline{\psi_L^-} \end{pmatrix} m_{e\Psi} \begin{pmatrix} e_R \\ \psi_R^- \end{pmatrix} + \begin{pmatrix} \overline{\nu_L} & \overline{\psi_L^0} \end{pmatrix} m_{\nu\Psi} \begin{pmatrix} N_R \\ \psi_R^0 \end{pmatrix} + \text{h.c.}$$

where

$$m_{e\Psi} = \begin{pmatrix} y_e v & y_\Psi u \\ 0 & M_\Psi \end{pmatrix}$$
$$m_{\nu\Psi} = \begin{pmatrix} 0_{3\times 1} & y_\Psi u \\ y_\nu v & M_\Psi \end{pmatrix}$$

Since we introduce only one N_R, only one massive active neutrino.

A model: fermionic sector (cont.)

Considering $M_\Psi \sim$ PeV, we can easily evade the constraint from flavor violating processes e.g. $\mu \to 3e$ [Ishiwata and Wise (2013)]. In fact for our scenario, the longevity of Y_R makes the constraint irrelevant.

$$\Gamma\left(Y_R \to e_{L_i}\overline{e_{R_j}}\right) = \frac{1}{32\pi}\left|(y_\Psi)_i\right|^2\left|(y_\Psi)_j\right|^2\frac{u^2\left(\hat{m}_e\right)_{jj}^2}{M_\Psi^4}M_Y$$

$$\Gamma\left(Y_R \to \nu_{L_i}\overline{N_R}\right) = \frac{1}{32\pi}\left|(y_\Psi)_i\right|^2\frac{|y_\nu|^2 v^2}{M_\Psi^2}M_Y$$

Taking the ratio of the above, we have

$$\frac{\Gamma\left(Y_R \to e_{L_i}\overline{e_{R_j}}\right)}{\Gamma\left(Y_R \to \nu_{L_i}\overline{N_R}\right)} = \left|\frac{(y_\Psi)_j}{y_\nu}\right|^2\left(\frac{u}{M_\Psi}\right)^2\left(\frac{(\hat{m}_e)_{jj}}{v}\right)^2$$

So the decays to neutrinos always dominate that to the charged leptons.

A model: fermionic sector (cont.)

The mass of light Dirac neutrino is given by

$$m_\nu = \sqrt{\sum_i (y_\Psi)_i^2} u \frac{y_\nu v}{M_\Psi}.$$

while the total decay width of Y_R to neutrinos can be rewritten

$$\sum_i \Gamma\left(Y_R \to \nu_{L_i} \overline{N_R}\right) = \frac{1}{32\pi} \frac{m_\nu^2}{u^2} M_Y$$

Requiring the lifetime of Y_R to be longer than t_0, we have $m_\nu/u \lesssim 10^{-23}$. The longevity of Y_R from the dominant decay channel $Y_R \to X_I X_I$ imposes $u \lesssim 10^{-17}$ GeV. If we gauge $U(1)_\Psi$ to forbid $Y_R \to X_I X_I$, the upper bound on u can increase by an order of 10^{11}.

But the contribution to m_ν is always too small: $m_\nu \lesssim 10^{-20} - 10^{-31}$ eV

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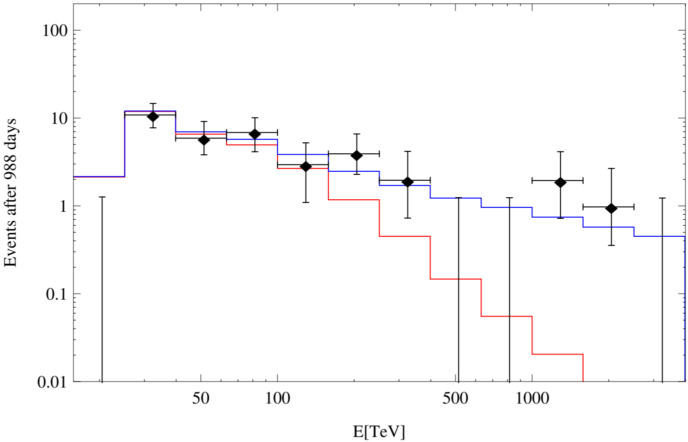
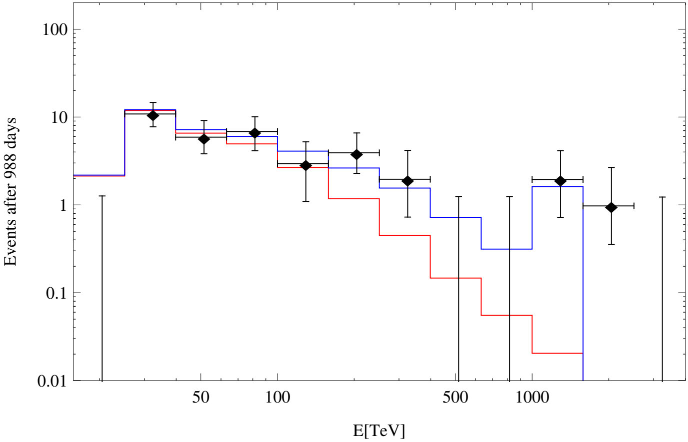
Confronting the data: Power Law $CE^{-\alpha}$



$C = 0.56 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} and $\alpha = 2.02$

p-value: 0.7

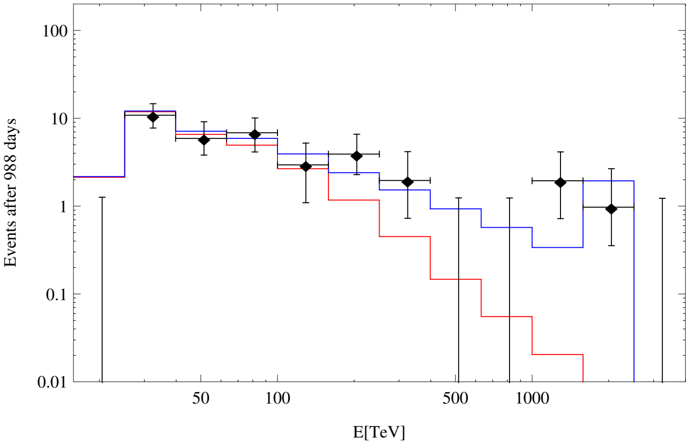
Confronting the data: LLP with $M_Y = 2.2$ PeV



$\tau = 5.9 \times 10^{27}$ s, $\mathrm{BR}(Y_R \to \nu_L \overline{N_R}) = 0.09$ and $\mathrm{BR}(Y_R \to hhhh) = 0.91$

p-value: 3×10^{-3} **Strongly disfavored**

Confronting the data: LLP with $M_Y = 4$ PeV



$\tau = 7.2 \times 10^{27}$ s, BR$(Y_R \to \nu_L \overline{N_R}) = 0.19$ and BR$(Y_R \to hhhh) = 0.81$

p-value: 0.5

Confronting the data: LLP with $M_Y = 4$ PeV

Decay channels	$\mathrm{Br}\,(Y_R \to f)$
$Y_R \to \nu_L \overline{N_R}$	0.19
$Y_R \to hhhh$	0.81
$Y_R \to hh$	0.00

Table : Branching ratios for the decays of Y_R into neutrinos and Higgses with $y_\Psi = y_\nu = 1.6 \times 10^{-10}$, $\delta_{HX} = 0.65$, $\lambda_{XY} = 1$, $\lambda_{HY} = 10^{-7}$, $\mu_{XY} = 3 \times 10^{-24}$ GeV, $w = 10^{10}$ GeV, $M_\Psi = 2.2 \times 10^{11}$ GeV, $M_X = 4$ PeV and $M_{X_R} = 20$ PeV.

In this scenario, the lifetime (including the dominant decay $Y_R \to X_I X_I$) of Y_R is 7.5×10^{17}s. Excluding the decay $Y_R \to X_I X_I$, the lifetime of Y_R is 7.4×10^{27} s.

Outline

Summary

- The neutrino events above 60 TeV cannot be explained by atmospheric neutrinos alone.
- The absence of events in the region 400 TeV - 1 PeV and above 2 PeV would disfavor neutrinos following a continuous power law spectrum (with more statistics).
- A decaying LLP can accomodate the feature of the data if
  1. It has the appropriate lifetime (at least longer than the lifetime of the Universe)
  2. Two-body decay to at least a neutrino to produce peak in energy spectrum
  3. Another long decay chain to neutrino(s) to produce a continuum spectrum
- With the current 3-year data (37 events), the power law spectrum fits as well as the decaying LLP model.
- When can we tell ? (stay tuned to our upcoming paper)

Thank you very much for your attention.

Confronting the data: LLP with $M_Y = 2.2$ PeV

Decay channels	$\mathrm{Br}\,(Y_R \to f)$
$Y_R \to \nu_L \overline{N_R}$	0.09
$Y_R \to hhhh$	0.91
$Y_R \to hh$	0.00

Table : Branching ratios for the decays of Y_R into neutrinos and Higgses with $y_\Psi = y_\nu = 1.6 \times 10^{-10}$, $\delta_{HX} = 0.65$, $\lambda_{XY} = 1$, $\lambda_{HY} = 10^{-7}$, $\mu_{XY} = 8 \times 10^{-25}$ GeV, $w = 10^{10}$ GeV, $M_\Psi = 2.1 \times 10^{11}$ GeV, $M_Y = 2.2$ PeV and $M_{X_R} = 11$ PeV.

In this scenario, the lifetime (including the dominant decay $Y_R \to X_I X_I$) of Y_R is 5.3×10^{17}s. Excluding the decay $Y_R \to X_I X_I$, the lifetime of Y_R is 5.9×10^{27} s.