Effects of Majorana physics on UHE ν_τ flux traversing the Earth

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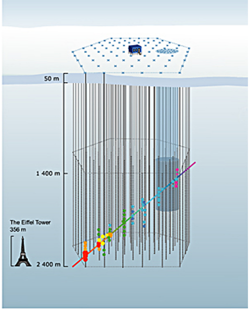
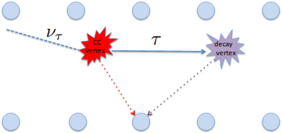
Based on Eur. Phys. J. C 77 68 (2017), arXiv:1609.07661

Motivation: Ultra High Energy ν in IceCube

- Observed UHE Φ_ν $(TeV - EeV)$ [1]
  - yet unknown
    - origin
    - spectral shape
    - flavor composition
- Still unobserved ν_τ [2]

- Effective Majorana neutrino interactions beyond Type I seesaw
- Sterile Majorana neutrinos: Searches and bounds on $\nu_\mu - \nu_s$ mixings [3]
- Study new effects on ν_τ-flux





[1] IceCube Coll., Phys. Rev. Lett. 113 101101 (2014) 1405.5303
[2] IceCube Coll., Phys. Rev. D 93 022001 (2016) 1509.06212
[3] IceCube Coll., Phys.Rev.Lett. 117, 7, 071801 (2016), 1605.01990

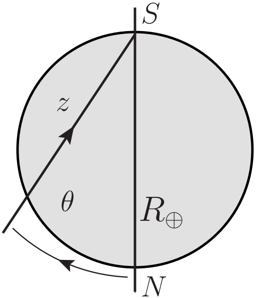
What is measured

- Neutrino telescopes
  number of detected events (IceCube)

$$N = n_T \int dt \int d\Omega \int dE\, \Phi_{\nu_\tau}(E,\theta)\, \sigma^{CC}_{\nu_\tau}(E)$$

- Change of Φ_{ν_τ} while they traverse the Earth:

$$\frac{\partial \Phi_{\nu_\tau}(E,\theta)}{\partial \chi} \qquad \chi(z) = \int_0^z dz' \rho_n(z')$$



- See if Φ_{ν_τ} is affected by possible Majorana neutrino effective interactions

Effective lagrangian approach

- Minimal Type-I seesaw scenarios left-right neutrino mixing $U_{lN}^2 \sim \frac{m_\nu}{M_N} \leq 10^{-10}$ → we neglect the mixing and model the heavy Majorana neutrinos interactions with standard particles with an effective lagrangian [6]
- Only *one* right-handed neutrino N as an observable degree of freedom

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \sum_{\mathcal{J}} \alpha_{\mathcal{J}} \mathcal{O}_{\mathcal{J}}^{(n)}$$

- Dim 5 operators : $\mathcal{O}_W \sim (\bar{L}\tilde{\phi})(\phi^\dagger L^c)$
  $\mathcal{O}_{N\phi} \sim (\bar{N}N^c)(\phi^\dagger \phi)$ (A. Caputo talk)
  $\mathcal{O}_{NB}^{(5)} \sim (\bar{N}\sigma_{\mu\nu}N^c)B^{\mu\nu}$ [7] Vanishes for one N

[6] F. del Aguila, S. Bar Shalom, A. Soni y J. Wudka. Phys. Lett. B 670, 399 (2009), 0806.0876

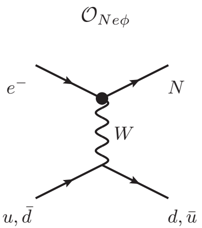
[7] A. Aparici, K. Kim, A. Santamaria, J. Wudka, Phys. Rev. D 80, 013010 (2009), 0904.3244

Effective operators

The (dim $= 6$) operators are [1] (tree-level-generated):

Scalar and vector bosons (SVB)

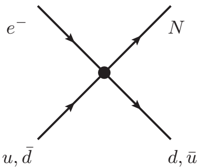
$$\mathcal{O}^i_{LN\Phi} = (\Phi^\dagger \Phi)(\overline{L}_i N \tilde{\Phi})$$
$$\mathcal{O}^i_{NN\Phi} = i(\Phi^\dagger D_\mu \Phi)(\overline{N}\gamma^\mu N)$$
$$\mathcal{O}^i_{Ne\Phi} = i(\Phi^T \epsilon D_\mu \Phi)(\overline{N}\gamma^\mu e_i)$$



B-number conserving four-fermion (4-f) contact terms:

$$\mathcal{O}_{duNe} = (\bar{d}\gamma^\mu u)(\bar{N}\gamma_\mu l), \quad \mathcal{O}_{fNN} = (\bar{f}\gamma^\mu f)(\bar{N}\gamma_\mu N),$$
$$\mathcal{O}_{LNLe} = (\bar{L}N)\epsilon(\bar{L}l), \quad \mathcal{O}_{LNQd} = (\bar{L}N)\epsilon(\bar{Q}d),$$
$$\mathcal{O}_{QuNL} = (\bar{Q}u)(\bar{N}L), \quad \mathcal{O}_{QNLd} = (\bar{Q}N)\epsilon(\bar{L}d),$$
$$\mathcal{O}_{LN} = |\bar{N}L|^2, \quad \mathcal{O}_{QN} = |\bar{Q}N|^2$$

Allow for family changes!



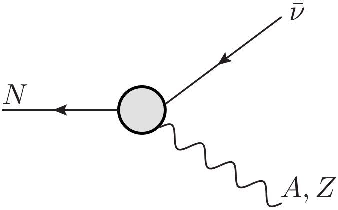
[1] F. del Aguila, S. Bar Shalom, A. Soni y J. Wudka. Phys. Lett. B 670, 399 (2009), 0806.0876

Effective operators

- One loop generated one-loop (1-loop) suppressed by a factor $1/16\pi^2$ [1]

$$\mathcal{O}_{NB} = (\bar{L}\sigma^{\mu\nu} N)\tilde{\phi} B_{\mu\nu}$$
$$\mathcal{O}_{NW} = (\bar{L}\sigma^{\mu\nu}\tau^I N)\tilde{\phi} W^I_{\mu\nu}$$

neutrino magnetic moment



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Bounds on the couplings $\alpha_{\mathcal{J}}^{(i)}$

- Contributions to experimental measures of the different operators by sets corresponding to $\mathcal{O}_{SVB}$, $\mathcal{O}_{4-f}$, $\mathcal{O}_{1-loop}$ taking into account the dimensionless combination:

$$\zeta_{\mathcal{O}} = \left(\frac{\alpha_{\mathcal{O}} v^2}{2\Lambda^2}\right)^2 \qquad \Lambda = 1 \ TeV$$

$$m_N > m_\tau$$

Process / Coupling	ζ_{SVB}	ζ_{4-f}	ζ_{1-loop}
$Z \to NN$ †	$< 7.56 \times 10^{-4}$	-	-
$e^+e^- \to \nu N$ †	-	$< 2.85 \times 10^{-1}$	-
$e^+e^- \to NN$ †	-	$< 2.63 \times 10^{-1}$	-
$Z \to \nu N$ †	-	-	$< 6.75 \times 10^{-4}$

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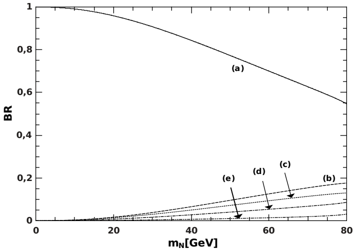
N decay channels:



(a) $N \to \sum_{i=1,3} \nu_i\,\gamma$, **(b)** $N \to \sum_{i=1,3} d\bar{d}\nu_i(\bar{\nu}_i)$, **(c)** $N \to \sum_{i=1,3} u\bar{u}\nu_i(\bar{\nu}_i)$, **(d)** $N \to$ *leptons* **(e)** $N \to \sum_{i=1,3} u\bar{d}l_i$.

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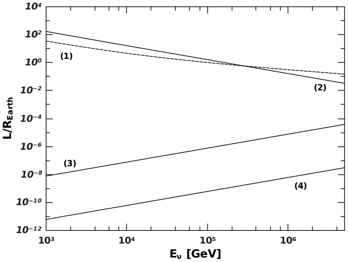
Surviving Φ_{ν_τ}

- absorption / regeneration : processes take out / add ν_τ with energy E to the flux
- Standard interactions with nucleons $\mathcal{N}$
  - $\nu_\tau \mathcal{N} \to \nu_\tau X$ NC
  - $\nu_\tau \mathcal{N} \to l^\pm X$ CC (1)
- N production: $\nu_\tau \mathcal{N} \to NX$ (2)
- $\tau \to \nu_\tau X$ (3)
- $N \to \nu_\tau \gamma$ (4)
- N-nucleon interactions

$m_N > m_\tau$



- $L_{\rm int}(E) = \frac{1}{\langle \rho_n \rangle \sigma(E)}$
- $L_{\rm dec}(E) = \frac{E}{m} \Gamma^{\rm tot}_{\rm rest}$

Coupled evolution equations for Φ_{ν_τ}, Φ_τ and Φ_N

Surviving Φ_{ν_τ}

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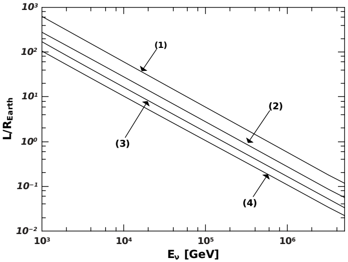
Coupled evolution equations for Φ_{ν_τ}, Φ_τ and Φ_N

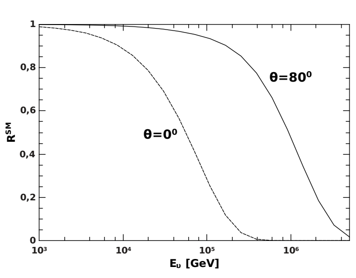


- $L_{\rm int} \; N$
  - $N\mathcal{N} \to lX$ (1)
  - $N\mathcal{N} \to \nu_\tau \, X$ (2)
  - $\nu_\tau \, \mathcal{N} \to NX$ (3)
  - $N\mathcal{N} \to NX$ (4)

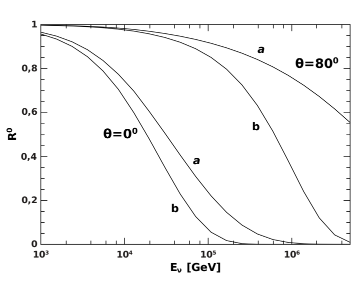
Results

N effects: a reduction in ν_τ flux

$$R^{SM}(\theta, E_{\nu_\tau}) = \frac{\Phi_{\nu_\tau}}{\Phi^{SM}_{\nu_\tau}}$$



$$R^{0}(\theta, E_{\nu_\tau}) = \frac{\Phi_{\nu_\tau}}{\Phi^{0}_{\nu_\tau}}$$



$\Phi^0_{\nu_\tau} = 2.3 \times 10^{-18} (E/100\ TeV)^{-2.6} GeV^{-1} cm^{-2} s^{-1} sr^{-1}$

(a) SM Earth attenuation

(b) Majorana effective interactions effect

Results

$$N = n_T \int dt \int d\Omega \int dE\ \Phi_{\nu_\tau}(E,\theta)\ \sigma^{CC}_{\nu_\tau}(E)$$

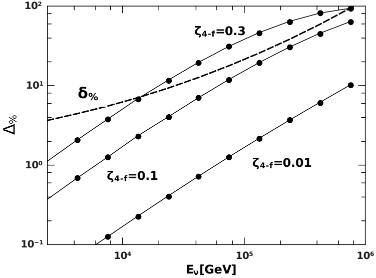
Nadir angle $0^\circ < \theta < 60^\circ$, $t = 10$ years.
Energy interval binning: $\Delta log_{10} E = 0.25$.

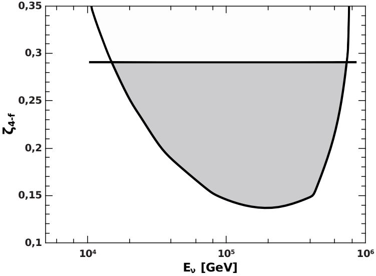
- Testable parameter space
  Relevant operators: $4-f$

Compare:

- Percentage deviation
  $\Delta_\% = 100 \times (N_{\mathrm{SM}} - N_{\mathrm{Maj}})/N_{\mathrm{SM}}$
- Percentage relative error
  $\delta_\% = 100/\sqrt{N_{\mathrm{SM}}}$

- Region (E_ν, ζ_{4-f})
  $\Delta_\% = \delta_\%$





Final remarks

- Complementary tool to explore sterile Majorana neutrino physics
- Effective Majorana neutrino interactions could be detected / ruled out by IceCube

Thank you and the Invisibles 17 Workshop organizers!