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Dark Sector searches at Neutrino Experiments

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Chapter 1

Introduction

Despite considerable progress in the understanding of fundamental particles and interactions thanks to the Standard Model of particle physics, some key open questions remain. What is the origin of neutrino masses? What is dark matter made of? Why is there an imbalance between baryons and anti-baryons in the Universe? These questions call for new physics beyond the Standard Model. While the focus has been on new physics at the TeV scale for decades, recent theoretical and experimental developments have brought new attention to the dark sectors, i.e. extensions of the Standard Model at scales below the electroweak scale and which are weakly coupled to the visible sector. New fermions, called heavy neutral leptons (HNL), are common features in these models feature in these models feature. They are highly motivated theoretically and have distinct phenomenological consequences. The project will focus on a specific signature called double bangs in neutrino observatories. New physics models allow neutrinos to up-scatter into heavier states (HNL) when interacting with matter. If the incident neutrino is energetic enough, the heavy neutrino may be highly boosted and travel some distance before decaying. High-energy neutrinos would lead to an initial signature in the first scattering and a subsequent one when the HNL decays into visible particles. For this reason, these events are called "double-bang" (DB). They would be a unique signature of dark sectors of this kind. The DB event topology has an extremely low background rate from coincident atmospheric cascades, making this a distinctive signature of new physics. The aim of this project is to consider "double-bang" event topology at neutrino observatories (IceCube, KM3Net).

1.1 Dark sectors

Searches for new particles beyond the Standard Model have always focused on the assumption that they would be at least charged under one of the SM gauge groups. The lack of experimental results has however shifted the attention towards different paradigms to explain new physics. In particular, the interest in **Dark Sectors** has been growing. The name comes from the fact that they are not charged under any of the SM gauge groups - the reason why we are not able to see them is simply that they do not interact through the Standard Model interactions.
These dark sectors are thought to be a sort of world parallel to our own. In order to allow interactions between the visible sectors and dark sectors other than the gravitational one, we assume that the interaction happens through a *portal* - in this way this paradigm becomes experimentally accessible. The portal may take various forms that can be classified by the type and dimension of its operators. The best motivated and most studied cases contain relevant operators taking different forms depending on the spin of the mediator: Vector (spin 1), Neutrino (spin 1/2), Higgs (scalar) and Axion (pseudo-scalar).

1.1.1 Neutrino portal

Neutrinos in the standard model are predicted to be massless. However, observation of lepton flavour number violation in neutrino oscillations shows that these particles have, though small, a mass. This fact is the only established piece of evidence showing that the standard model is incomplete and that new physics is required to account for this.

Chapter 2

HNLs three-body decay

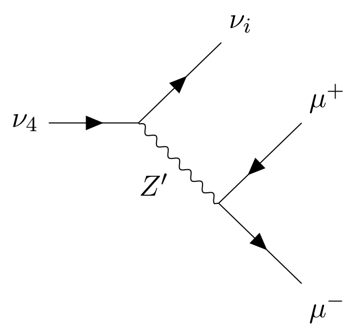
2.1 Computations

2.1.1 $\nu_4 \to \nu_i \mu^+ \mu^-$

We consider the following process:

$$\nu_4(\mathrm{p}) \to \nu_i(k1) + \mu^+(k2) + \mu^-(k3)$$

Where ν_4 is the HNL in the theory under consideration, ν_i is a massless neutrino flavour state and μ^+ and mu^- are the Standard Model muons. We want to compute the total width for this decay. We neglect the mass of the neutrinos in the final states while we keep the masses of the muons.



We consider only processes mediated by the dark photon Z'. The full amplitude reads:

$$i\mathcal{M} = \overline{u}(k_1)U^*_{D4}U^*_{Di}g_X\gamma^\mu\frac{(1-\gamma_5)}{2}u(p)\frac{\overline{u}(k_3)e\chi c_W\gamma_\mu v(k_2)}{(p-k_1)^2 - m^2_{Z'}} \tag{2.1}$$

Squaring the amplitude and summing over final states gives (we can approximate the denominator):

$$\begin{aligned}\sum|\mathcal{M}|^2 = \sum\frac{(g_X\chi e c_W)^2}{m^2_{Z'}}|U_{D4}U_{Di}|^2[\overline{u}(k_1)\gamma^\mu\frac{1-\gamma_5}{2}u(p)]\\ [\overline{u}(k_3)\gamma_\mu v(k_2)][\overline{u}(p)\gamma^\nu\frac{1-\gamma_5}{2}u(k_1)][\overline{v}(k_2)\gamma_\nu u(k_3)]\end{aligned} \tag{2.2}$$

Performing the sum over spin, averaging over initial states and using the identities for the traces of gamma matrices we find:

$$
\begin{aligned}
\frac{1}{2}\sum|\mathcal{M}|^2 =& \frac{1}{2}\frac{(g_X\chi ec_W)^2}{m_{Z'}^2}|U_{D4}U_{Di}|^2 Tr[\not{k}_1\gamma^\mu\frac{1-\gamma_5}{2}(\not{p}-m4)\gamma^\nu\frac{1-\gamma_5}{2}] \\
& Tr[(\not{k}_3-m_\mu)\gamma_\mu(\not{k}_2+m_\mu)\gamma_\nu] \\
=& \frac{1}{2}\frac{(g_X\chi ec_W)^2}{m_{Z'}^2}|U_{D4}U_{Di}|^2\frac{1}{2}Tr[\not{k}_1\gamma^\mu\not{p}\gamma^\nu(1-\gamma^5)] \\
& (Tr[\not{k}_3\gamma_\mu\not{k}_2\gamma_\nu]-m_\mu^2 Tr[\gamma_\mu\gamma_\nu]) \\
=& \frac{1}{2}\frac{(g_X\chi ec_W)^2}{m_{Z'}^2}|U_{D4}U_{Di}|^2 8(p^\mu k_1^\nu - p.k_1 g^{\mu\nu} + p^\nu k_1^\mu) \\
& (k_{2\mu}k_{3\nu} - k_2.k_3 g_{\mu\nu} + k_{2\nu}k_{3\mu} - m_\mu^2 g_{\mu\nu}) \\
=& 8\frac{(g_X\chi ec_W)^2}{m_{Z'}^2}|U_{D4}U_{Di}|^2(p.k_2 k_1.k_3 + p.k_3 k_1.k_2 - p.k_1 m_\mu^2)
\end{aligned} \tag{2.3}
$$

To compute the total width of the process:

$$
d\Gamma = \frac{1}{2m_4}\frac{1}{2}\sum|\mathcal{M}|^2 dP \tag{2.4}
$$

where the phase space is given by (following 'Quark and Leptons .. ' by Halzen & Martin:

$$
\begin{aligned}
dP =& \frac{d^3k_1}{(2\pi)^3 2E_1}\frac{d^3k_2}{(2\pi)^3 2E_2}\frac{d^3k_3}{(2\pi)^3 2E_3}(2\pi)^4\delta^{(4)}(p-k_1-k_2-k_3) \\
=& \frac{1}{(2\pi)^5}\frac{d^3k_1}{2E_1}\frac{d^3k_3}{2E_3}\theta(E-E1-E3)\delta^{(4)}((p-k_1-k_3)^2) \\
=& \frac{1}{(2\pi)^5}\frac{4\pi E_1^2 dE_1}{2E_1}\frac{2\pi E_3|k_3|dE_3 dcos\theta}{2E_3}\theta(E-E1-E3)\delta^{(4)}((p-k_1-k_3)^2)
\end{aligned} \tag{2.5}
$$

We choose the reference frame in the rest frame of the decaying particle, fixing the z-axis along the direction of motion of ν_i. We will therefore have:

$$
\begin{aligned}
p &= (m_4, 0, 0, 0) \\
k_1 &= (E_1, 0, 0, E_1) \\
k_2 &= (E_2, \vec{k_2}) \\
k_3 &= (E_3, \vec{k_3})
\end{aligned} \tag{2.6}
$$

The argument inside the delta can be rewritten as:

$$
\begin{aligned}
& \delta^{(4)}(m_4^2 + m_\mu^2 - 2m_m u E_1 - 2m_4 E_3 - 2E_1E_3 + 2E_1|k_3|cos\theta) \\
=& \frac{1}{2E_1|k_3|}\delta^{(4)}(m_4^2 + m_\mu^2 - 2m_m u E_1 - 2m_4 E_3 - cos\theta)
\end{aligned} \tag{2.7}
$$

with θ being the angle between the direction of the momentum of k_3 and k_1. Between the first and the second line the properties of the dirac delta have been used in order to perform the integration over Also the amplitude squared can be rewritten by performing the scalar products and using the conservation of 4-momenta ($p - k_1 - k_2 - k_3 = 0$), allowing to rewrite $k_2 = p - k_1 - k_3$:

$$\begin{aligned}\frac{1}{2}\sum|\mathcal{M}|^2 =& \frac{1}{2}\frac{(g_X\chi e c_W)^2}{m_{Z'}^4}|U_{D4}U_{Di}|^2[(m_4^2 - m_4E_1 - m_4E_3)(E_1E_3 - E_1|k_3|cos\theta)+ \\ & m_4E_3(m_4E_1 - E_1E_3 + E_1|k_3|cos\theta) - m\mu^2 m_4E_1]\end{aligned} \tag{2.8}$$

Putting everything together and performing the integral over $cos\theta$ using the dirac delta we find:

$$\begin{aligned}d\Gamma =& \frac{1}{16\pi^3}\frac{(g_X\chi e c_W)^2}{m_{Z'}^4}|U_{D4}U_{Di}|^2[(m_4 - E_1 - E_3)(E_1E_3 - E_1|k_3|)+ \\ & E_3(m_4E_1 - E_1E_3 + E_1|k_3|) - m\mu^2 E_1]dE_1dE_3\end{aligned} \tag{2.9}$$

We can expand $|k_3| = \sqrt{E_3^2 - m_\mu^2} = E_3(1 - \frac{m_\mu^2}{2E_3^2}) + O(m_\mu^4)$:

$$\begin{aligned}d\Gamma =& \frac{1}{16\pi^3}\frac{(g_X\chi e c_W)^2}{m_{Z'}^4}|U_{D4}U_{Di}|^2 \\ & \left[\frac{m_4m_\mu^2E_1}{2E_3} - \frac{m_\mu^2E_1^2}{2E_3} - 2E_1m_\mu^2 + m_4E_3E_1\right]dE_1dE_3\end{aligned} \tag{2.10}$$

At this point what is left to do is to find the interval of integration by considering the kinematics of the process. Following "Quark and Leptons" by Halzen and Martin, we can see that the δ-function integration introduces the following restrictions on the energies E_1 and E_3, stemming from the fact that -1$\leq cos\theta \leq$1:

$$\begin{aligned}\frac{E_3(m_4^2 + m_\mu^2 - 2m_4E_3)}{2m_\mu E_3 + m_\mu^2} \leq & E_1 \leq \frac{E_3(m_4^2 + m_\mu^2 - 2m_4E_3)}{2m_\mu E_3 + 4E_3^2 - m_\mu^2} \\ m_\mu \leq & E_3 \leq \frac{m_4^2 + m_\mu^2}{2m_\mu}\end{aligned} \tag{2.11}$$

where for E_3 we have used the fact that the lower limit on E_1 must be positive and that E_3 cannot be smaller than the mass of the muon. We can now integrate and find the total width for the decay of ν_4.

Chapter 3

Chapter 4

Chapter 5

Conclusions

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