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Simultaneous analysis of neutrinoless double beta decay and LHC pp-cross sections: limits on the left-right mixing angle

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Abstract. The extension of the Standard Model of electroweak interactions, to accommodate massive neutrinos and/or right-handed currents, is one of the fundamental questions to answer in the cross-field of particle and nuclear physics. The consequences of such extensions would reflect upon nuclear decays, like the very exotic nuclear double-beta-decay, as well as upon high-energy proton-proton reactions of the type performed at the LHC accelerator. In this talk we shall address this question by looking at the results reported by the ATLAS and CMS collaborations, where the excitation and decay of a heavy-mass boson may be mediated by a heavy-mass neutrino in proton-proton reactions leading to two jets and two leptons, and by extracting limits on the left-right mixing, from the latest measurements of nuclear-double-beta decays reported by the GERDA and EXO collaborations.

1. Introduction

The search for experimental signals of nuclear double-beta-decay transitions, particularly the still undetected neutrinoless double-beta-decay mode, has been accompanied by an intense theoretical activity aimed at the calculation of the relevant nuclear matrix elements [1]. Basically, the theoretical aspects of the problem include the formulation of nuclear structure models, to describe the wave functions of the nuclear states which participate in the decay, and the use of a given model of the neutrino and of the electroweak currents, to calculate the expectation values of the lepton sector of the theory [2]. At the end, the half-life of the decay is expressed in terms of products of nuclear structure factors and lepton factors, like the average neutrino mass and the left-right and right-right couplings. These two couplings are, of course, depending on the extension of the Standard Model adopted in the calculations, particularly they depend on the left-right mixing angle and on the mass of the right-handed boson [5]. The conditions in which the $0\nu\beta\beta$ decay can take place have been studied in the last decades, and a systematics of the involved nuclear matrix elements has become available recently [6].

From the experimental side an intensive search, for the signals of the transitions which may demonstrate the existence of the neutrinoless double-beta-decay, is currently going on [7]. Very recently, world-record limits for the non-observation of the $0\nu\beta\beta$ have been reached by the GERDA [8], KamLAND-Zen [9], and EXO-200 [10] experiments.

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By the other side, that is referring to high energy pp collisions, limits on the left-right (LR) symmetry and the mass of heavy neutrinos may be established from data taken at the LHC [11]. In this respect, the data taken by the ATLAS [12] and CMS detectors [13] on the two-jets two-leptons final states may be analyzed in terms of the decay of a right-handed boson, assuming that the mass of the right-handed neutrino is lighter than the mass of the right-handed boson [11].

In this work we shall discuss on the possibility of setting limits for LR couplings from $0\nu\beta\beta$ and compare them with the values extracted from the pp cross section measurements.

2. Formalism

The minimal extension of the SM includes left-right and right-right electroweak interactions [2, 3, 4]. The left- and right-handed bosons W_L and W_R, of this minimal extension, are expressed in terms of the $\mathrm{SU}(2)_L$ and $\mathrm{SU}(2)_R$ gauge bosons W_1 and W_2 as

$$\begin{aligned} W_L &= W_1 \cos\zeta - W_2 \sin\zeta \\ W_R &= W_1 \sin\zeta + W_2 \cos\zeta \end{aligned} \tag{1}$$

where ζ is the mixing angle, the mass of the left-handed boson is of the order of 80 MeV, and the mass of the right-handed boson is still unknown. Upper limits on the mixing angle ζ are of the order of 10^{-2}[14].

The $0\nu\beta\beta$ decay is a second order process, mediated by the electroweak hamiltonian [2], and the half-life of it is readily evaluated by folding the currents on the lepton (electron-neutrino) and nuclear (neutron-proton) components of the initial, intermediate and final wave functions[1]. The corresponding expression is written

$$\begin{aligned} \left[T_{1/2}^{(0\nu)}\right]^{-1} &= C_{mm}^{(0\nu)}\left(\frac{\langle m_\nu\rangle}{m_\mathrm{e}}\right)^2 + C_{m\lambda}^{(0\nu)}\langle\lambda\rangle\left(\frac{\langle m_\nu\rangle}{m_\mathrm{e}}\right) \\ &+ C_{m\eta}^{(0\nu)}\langle\eta\rangle\left(\frac{\langle m_\nu\rangle}{m_\mathrm{e}}\right) + C_{\lambda\lambda}^{(0\nu)}\langle\lambda\rangle^2 \\ &+ C_{\eta\eta}^{(0\nu)}\langle\eta\rangle^2 + C_{\lambda\eta}^{(0\nu)}\langle\eta\rangle\langle\lambda\rangle \ . \end{aligned} \tag{2}$$

In this expression, the factors $C_{ij}^{(0\nu)}$ of Eq.(2) are functions of nuclear matrix elements [1] and leptonic phase-space factors [1]. These nuclear structure factors are calculated by taking expectation values, on the nuclear wave functions, of the hadronic currents, and by replacing the neutrino propagator by energy denominators with energies determined by the energy of the intermediate nuclear states and the energy of the neutrino. The quantities $\langle m_\nu\rangle$, $\langle\lambda\rangle$, and $\langle\eta\rangle$ are the neutrino mass, the RR, and the LR couplings [15], averaged over the elements of the neutrino mixing matrix.

The systematics on the nuclear matrix elements which are relevant for the known double-beta decay emitters can be found in [6]. Although, in the past, different models yield very different values for these nuclear matrix elements, large scale QRPA and shell model calculations do agree in the main features of them and the search to fix the remaining uncertainties now focus on the renormalization effects which may affect the axial-vector coupling constant, g_A, whose value may be indeed different for single and double-beta decay transitions, as pointed out recently [15].

For the sake of brevity we shall present here the adopted values for the nuclear structure factors and referred the reader to the published sources for further details [1, 6, 15].

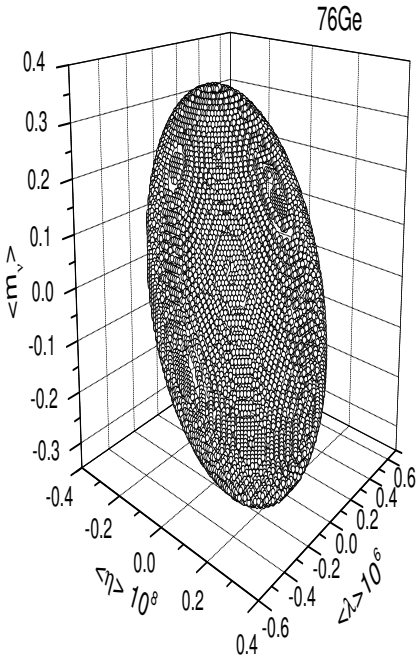

Figure 1. Limits of the variables $\langle m_\nu \rangle$ (in units of eV), $\langle \lambda \rangle$, and $\langle \eta \rangle$ based on the lower limit for the half-life of ^{76}Ge.

3. Results and Discussions

With these nuclear structure factors and with the assumption that the neutrino participant in double beta decays is indeed a linear combination of neutrino mass eigenstates, we will set allowed lower limits on the mass of the right-handed boson W_R, independently of the mechanism which may be responsible for the decay and/or of the texture or mass hierarchy of the neutrino mass eigenstates. For a given value of the half-life, $T_{1/2}^{(0\nu)}$, the allowed value of the effective neutrino mass and LR and RR couplings are constrained by Eq. (2). The upper value for the effective neutrino mass is extracted by projecting the ellipsoid on the mass axis, and the same procedure is repeated to determine the upper values of the LR and RR couplings. Figures 1 and 2 show the ellipsoids constructed from the half-life limits obtained by GERDA [8], for the case of A=76, and KamLAND-Zen [9] and EXO-200 [10], for A=136, respectively. As it can be seen both ellipsoids are tilted with respect to the mass axis, hence the neutrino mass bound is relaxed with respect to the normally claimed value setting the right-handed parameters to be zero. By keeping the value of the half-life fixed at the experimental lower limit, we vary the neutrino mass and the mixing angle ζ, and turn on the left-right and right-right couplings. In the space of all these variables, we search for the sections which are consistent with the half-life constraint.

The ratio between the determined values of $\langle \lambda \rangle$ and $\langle \eta \rangle$ will then be proportional to the ratio between the masses of the right and left handed bosons, as shown in [16].

As said before, we have taken the nuclear-structure factors $C_{ij}^{(0\nu)}$ for the ground-state-to-ground-state decays of ^{76}Ge and ^{136}Xe, from the systematics of [6] and they can be considered as reference values, the validity of which has been extensively discussed in our previous works [1, 6]. The extracted values of the couplings are of the order of 0.477×10^{-6} and 0.286×10^{-8},

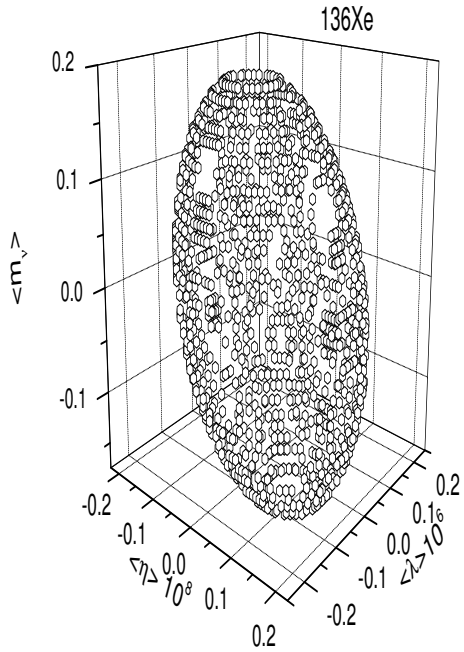

Figure 2. The same as Fig. 1 for the nuclide ^{136}Xe.

for λ and η, respectively.

Direct limits on the masses of W_R and heavy Majorana neutrinos have been obtained by the ATLAS and CMS experiments at the LHC [13]. The search was performed in the two-muons - two jet channel. The limits obtained by the ATLAS experiment are based on a luminosity of 2.1 fb^{-1} but include electrons in addition to muons in the two-lepton channels [12].

Fig. 3 shows the results of the calculations. In the figure the extracted mass of the right-handed boson is given as a function of the logarithm of the mixing angle ζ.

The analysis of the results displayed in Fig.3 is consistent with a lower limit of the order of 0.5 TeV, for the mass of W_R, if the largest allowed value of the mixing angle ζ is of the order of 10^{-2} [14]. This result are not in tension with the scale expected from the ATLAS and CMS constraints, but to be consistent with the limits extracted from the $0\nu\beta\beta$ data, the mixing angle should be, at least, one order of magnitude smaller than the limit determined by TWIST, if one takes both the ATLAS/CMS and double-beta-decay data simultaneously.

In summary, we have taken the latest results of the GERDA, Exo-200 and KamLAND-Zen double beta decay experiments, and extracted from them the average neutrino mass, LR and RR couplings, and discussed the implications of these results on the mass of the right-handed boson, which may be of order of ≥ 3.0 TeV if the LR mixing angle is of the order of 10^{-3}. More details on the calculations will be published [16]

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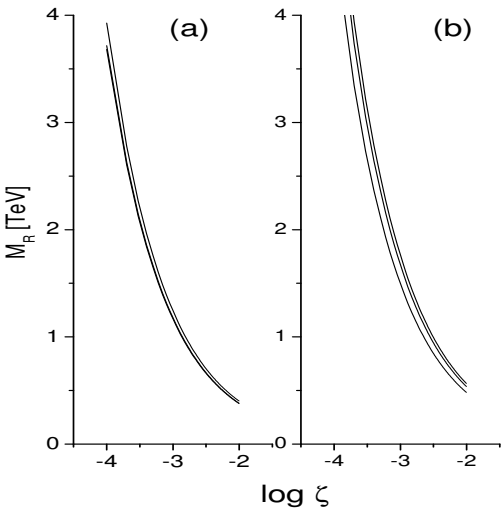

Figure 3. Mass of the right handed boson, M_{W_R} as a function of the mixing angle ζ, from the decay of ^{76}Ge (inset (a)) and ^{136}Xe (inset (b)). The curves, from top to bottom, correspond to $\langle m_\nu \rangle = 0.016$, 0.12, and 0.25 eV (inset (a)), and 0.013, 0.065, and 0.122 eV (inset(b))

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