NEUTRINO PROPERTIES PROBED BY LEPTON NUMBER VIOLATING PROCESSES AT LOW AND HIGH ENERGIES*

S. STOICA

Horia Hulubei Fondation, P.O.Box MG-12, RO-077125 Bucharest-Magurele, Romania,
E-mail: sabin.stoica@unescochair-hhf.ro

Received February 21, 2013

Fundamental properties of the neutrinos like their absolute mass, their character (are they Dirac or Majorana particles?), their mass hierarchy, the number of neutrino flavors, etc., are still unknown. Lepton Number Violating (LNV) processes are capable to decide on these issues. Since recently, the neutrinoless double beta decay was considered the only process able to distinguish between Dirac or Majorana neutrinos and to provide information about the mass scale of the electron neutrino. Now, the increase of the integrated luminosity at the LHC experiments makes feasible the study of LNV processes at high energy, as well. In this lecture I shall give a short review on these processes at low and high energies highlighting the motivation for their search.

Key words: lepton number violating processes, neutrinos, neutrinoless double beta decay, LHC, LHCb.

1. INTRODUCTION

Results of the neutrino oscillation experiments have convincingly showed that neutrinos have mass and oscillate. These lepton flavor violating processes are at present the only confirmed evidences that extend our understanding on the Standard Model (SM), and that strongly encourage us for searching of beyond SM (BSM) physics.

However, fundamental properties of the neutrinos as their absolute mass scale, their character (if they are Dirac or Majorana particles), the number of neutrino flavors, the mechanism of their mass generation and their mass hierarchy, are still unknown. The knowledge of these properties is of fundamental importance for understanding the formation, composition and evolution of the universe, as well as all the processes that the neutrinos take part in.

* Paper presented at the 8th Workshop on Quantum Field Theory and Hamiltonian Systems, September 19–22, 2012, Craiova, Romania.

In this context there is an increased interest in the study of LNV processes, since they are capable to provide information on the above mentioned neutrino properties.

Since recently, the neutrinoless double beta decay $(0\nu\beta\beta)$ was considered the only process capable to distinguish between Dirac or Majorana neutrinos and to give a hint on the absolute mass scale of the electron neutrino. At present, the increased luminosity of the LHC experiments at CERN makes feasible the searching of LNV processes at LHC, as well. They can bring complementary information to that which can be extracted from low-energy neutrino studies. Also important, these investigations can use information from low-energy studies. In this paper, I make a short presentation of these processes at low and high energies highlighting the motivation for their search. Besides the low-energy process, the $0\nu\beta\beta$ decay mode, I present the first attempts of analyzing LNV processes in hadron collider experiments, particularly in the LHCb experiment from CERN-Geneva. The paper is organized as follows: in the Section 2 I shortly show the present status of our knowledge about the neutrino properties. In the section 3 I refer to the $0\nu\beta\beta$ process and to how one can extract the relevant neutrino parameters from the information provided by the study of this decay mode and by neutrino oscillation experiments. Section 4 is dedicated to the presentation of the LNV processes at high energies and to the first attempts for their search in the LHC, especially in the LHCb experiment at CERN. The paper ends up with Section Conclusions where I sum up the importance of the study of these LNV processes and I sketch some future prospects.

2. NEUTRINO PROPERTIES

The neutrino has half-integer spin $(1/2)$ and is therefore a fermion. It is an electrically neutral lepton, interacting only through the weak force and gravity.

Because the cross section in weak nuclear interactions is very small, neutrinos can pass through matter almost unhindered. Detection of neutrinos is therefore challenging, requiring large detection volumes or high intensity artificial neutrino beams. All neutrinos observed to date have left-handed helicity.

From neutrino oscillation experiments we know that neutrinos have a non-zero mass, and that they can oscillate and mix, properties that are in contradiction with the genuine formulation of the SM. The squared mass differences between mass eigenstates and the mixing angles $(\theta_{12,}\ \theta_{23,}\ \theta_{13})$ are measured within a few percentage accuracy by various experiments running in both terrestrial and underground laboratories, and measuring neutrinos coming from sun or atmosphere, or produced in accelerators and reactors [1-8].

The actual values of these parameters are: 1) $\Delta m^2_{12} = \Delta m^2_{sol} \sim$ $\sim 7.58 \times 10^{-5}\, eV^2$; $\tan^2 \theta_{12} \sim 0.484 \rightarrow \theta_{12} \sim 35^0$ - measured in solar ν (underground) + KamLAND (reactor) experiments; 2) $|\Delta m^2_{13}| = |\Delta m^2_{32}| =$ $= \Delta m^2_{atm} \sim 2.40 \times 10^{-3}\, eV^2$; $\sin^2 \theta_{23} \sim 1.02 \rightarrow \theta_{23} \sim 45^0$ – measured in atmospheric ν (underground) + $K2K$ (reactor) + MINOS (accelerator) experiments; 3) $\sin^2 2\theta_{13} \sim 0.092$; $\theta_{13} \sim 9^0$ - Daya Bay (reactor) experiment. This last measurement (with 5.2σ statistical significance) allows an unambiguous differentiation between oscillation $1-3$ and the anomalous disappearance of anti-electron neutrinos from the reactor ν flux at RENO and Double-Chooz experiments, strengthening the argument for existence of a sterile neutrino. Measurements of the imbalance matter-antimatter are expected to start in the next future at T2K, RENO, MINOS, etc. experiments. An important remark is the following: while the sign of Δm^2_{12} can be measured due to matter effects of the neutrino propagation from sun, the sign of Δm^2_{13} cannot be measured. In a three flavor neutrino analysis this leads to two possible scenarios for the neutrino mass hierarchy, the so-called i) "normal" $(m_1 < m_2 << m_3)$ and ii) the "inverted" $(m_3 << m_1 < m_2)$ hierarchies, which are shown in Fig. 1.

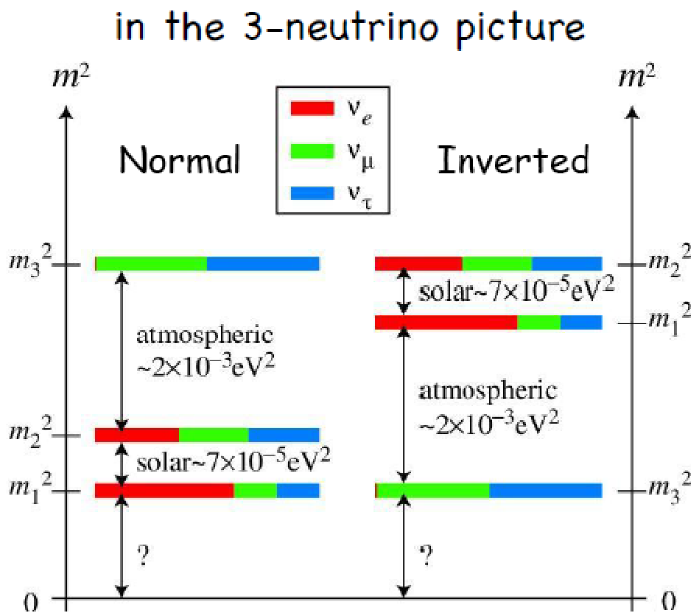

Fig. 1 – Hierarchical neutrino mass scheme: a) normal hierarchy; b) inverted hierachy.

As we mentioned above, there remain still unknown: i) the absolute mass of the neutrinos; ii) their mass hierarchy; iii) the mechanism of the mass generation; iv) their character (are they Majorana or Dirac particles?); v) are there also other species of neutrinos than the three (active) ones that we know?; vi) is the CP symmetry violated in the lepton sector, and if yes, how much? Information on all these issues can be provided by the study of LNV processes.

3. LEPTON NUMBER VIOLATING PROCESSES AT LOW-ENERGY: NEUTRINOLESS DOUBLE BETA DECAY

Lepton number (LN) conservation is a symmetry that is experimentally verified to a very high precision, and it is assumed within the SM. However, it is not a consequence of a known gauge symmetry, and other theories more general than the SM allow the non-conservation of this quantum number. Lepton number violation was first invoked to argue the possible existence of the $0\nu\beta\beta$ decay mode, a process which could probe the Dirac or Majorana character of neutrinos. More detailed information about its study can be found in some recent publications [9–12].

Double beta decay (DBD) is a nuclear natural decay by which an even-even nucleus transforms into another even-even nucleus with the same mass but the nuclear charge changed by two units. It occurs whatever single β decay cannot occur due to energetic reasons, or if it is highly forbidden by angular momentum selection rules. Figure 2 illustrates such a situation. Within the SM this process occurs with the emission of two electrons and two anti-neutrinos, and this decay mode ($2\nu\beta\beta$) was already measured for eleven isotopes. Theoretically, the expression of its half life can be factorized as follows:

$$[T^{2\nu}{}_{1/2}]^{-1} = G^{2\nu}(Q_{\beta\beta}, Z)\,|M^{2\nu}|^2, \tag{1}$$

where $G^{2\nu}$ is a phase space factor depending on the energy $Q_{\beta\beta}$ released in the decay and on the nuclear charge Z, and $M^{2\nu}$ are the nuclear matrix elements (NMEs) which depend on the nuclear structure of the isotope that decays. The values of the half-lives measured until present vary between $10^{18} - 10^{24}$ years. However, within theories that go BSM, in which LNV is permitted, the DBD process may occur without emission of neutrinos. This implies that neutrino is a Majorana particle with mass different from zero.

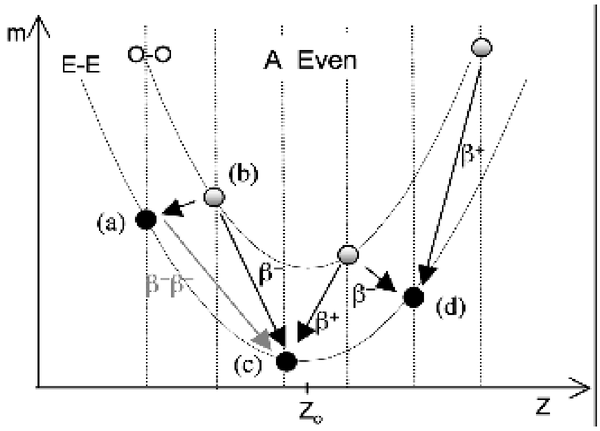

Fig. 2 – Ilustration of a DBD process: nuclei (a) and (d) are stable against β decay, but unstable against $\beta\beta$ decay: $\beta^-\beta^-$ for (a) and $\beta^+\beta^+$ for (d).

Considering the most common mechanism of occurrence, *i.e.* exchange of light Majorana neutrinos between two nucleons inside the nucleus and in the presence of only LH weak interactions, the half-life of this decay mode can be expressed as:

$$[T^{0\nu}{}_{1/2}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\,|\,M^{0\nu}\,|^2 < m_\nu{}^2 > / \, m_e, \qquad (2)$$

where $G^{0\nu}$ and $M^{0\nu}$ are quantities with similar significance as those from Eq. (1). The additional parameter $< m_\nu >$ appearing in Eq. (2) is a BSM parameter, that can be expressed in terms of neutrino mass eigenstates and mixing parameters:

$$< m_\nu >^2 = |\sum_i U_{ei}{}^2 m_i\,|^2 = |\sum_i |U_{ei}|^2\, e^{i\alpha} m_i\,|^2 \qquad (3)$$

Experimentally one can distinguish the two DBD modes by measuring the sum of the electron energies: i) for the $2\nu\beta\beta$ mode the number of DBD events *versus* the sum of the electron energies is a Gaussian-like function (the electrons share their energy with the two neutrinos), while ii) in the case of $0\nu\beta\beta$ mode this function is a vertical line at the energy $Q_{\beta\beta}$ (all the energy released in the decay is taken by the two electrons).

The extraction of the ν parameters is a very important issue. As one can see from Eqs. (2) and (3) it depends on the measured half-life and on the precise calculation of the NMEs. Their accurate calculation is a challenge for the theoretical study of $0\nu\beta\beta$. A measurement of the $0\nu\beta\beta$ decay rate combined with neutrino oscillation data and a reliable calculation of the NMEs, would yield insight into all three neutrino mass eigenstates. In the following we show how the neutrino mass parameter can be extracted in the case of one dominant mechanism of occurrence for $0\nu\beta\beta$. Based on the present measured values of the neutrino mixing parameters, one can extract limits for the neutrino mass scale. This is done separately for the two mass hierarchy scenarios.

Normal hierarchy:

$$|< m_\nu >| = c^2_{13} s^2_{12} (\Delta m^2_{sun})^{1/2} + s^2_{13} (\Delta m^2_{atm})^{1/2} e^{2i\alpha} \leq 4 \times 10^{-3} eV \quad (4)$$

Inverted hierarchy:

$$\begin{aligned} &|< m_\nu >| = | c^2_{13} s^2_{12} (\Delta m^2_{sun})^{1/2} + (\Delta m^2_{atm})^{1/2} s^2_{13} (1 - \sin^2 2\theta_{12} \sin \alpha_{12})^{1/2} \rightarrow \\ &\rightarrow 1.5 \cdot 10^{-2} eV \leq |< m_\nu >| \leq 5.0 \times 10^{-2} eV \end{aligned} \quad (5)$$

It is worth to mention that in the case of normal hierarchy there is no lower limit for the electron neutrino mass, so an exact cancellation between the terms in Eq. (4) may occur. By contrary, in the case of inverted hierarchy such a lower limit exists, and it can be checked by the next generation of the DBD experiments. This is an important experimental challenge in the study of this process. Theoretically, the main challenge is the accurate calculation of the NMEs involved in DBD. If the $0\nu\beta\beta$ will be discovered, an important issue will be to establish the (dominant) mechanism of its occurrence. In case when more mechanisms contribute to the $0\nu\beta\beta$ occurrence, the expression of the half-life is modified accordingly. An interesting case is that when two mechanisms dominate: exchange of light (active) plus heavy (sterile) Majorana neutrinos. Recently, it has shown that in spite of the naive expectation that the light neutrinos give the dominant contribution, heavy sterile neutrinos can saturate the present experimental bound of $0\nu\beta\beta$ decay process. In this case, under the assumption that only one flavor (N) of heavy neutrino exists, the expression of the half-life reads:

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu} (M_\nu \eta_\nu + M_N \eta_N)^2, \eta_\nu = \sum_i U_{ei}^2 m_i \,|\, m_e;\ \eta_N = U_{eN}^2 m_p / M_N \quad (6)$$

$$< m_\nu >_{3+1} = | c^2_{12} c^2_{13} c^2_{14} e^{2i\alpha 1} m_1 + c^2_{13} c^2_{14} s^2_{12} e^{2i\alpha 2} m_2 + s^2_{13} c^2_{14} e^{2i\alpha 3} m_3 + s^2_{14} M_N \quad (7)$$

In this scenario it is demonstrated that there is no interference between the terms contributing to the half-life, and thus one can get bounds on the mixing parameters between the active flavors and the sterile one.

4. LEPTON NUMBER VIOLATING PROCESS AT HIGH ENERGIES

In the extensions of the SM where a Majorana mass term is introduced, the LN is violated by two units. Thus, any such LNV process can probe the Majorana character of the neutrino. At present the increase of the integrated luminosity at the

LHC and superB experiments makes feasible the study of LNV processes at high energy, as well. There are many possible decay channels that violate the LN by two units. The common experimental signature of these channels is the presence of same sign di-leptons in the decay products. Below we give a list of such possible decays. There are baryon decays, meson decays, tau decays, top quark decays, or double Higgs decays, with 3-body or 4-body products in the final states.

- Baryon decays: $B \to B l_1^{\pm} l_2^{\pm}$

  $\sum^{-} \to \sum^{+} e^{-} e^{-}$; $\Xi^{-} \to q \mu^{-} \mu^{-}$ Hyperons

  $\Xi^{+}{}_{c} \to \Xi^{-} \mu^{+} \mu^{+}$, *etc.*

- Meson decays: $M^{\pm} \to M^{-/+} l_1^{\pm} l_2^{\pm}$ (3-body decays)

  $M^{o} \to l_1^{-} l_2^{-} M_1^{+} M_2^{+}$ (4-body decays)

- Tau decays: $\tau^{-} \to \mu^{+} \mu^{-} \mu^{-}$; $\tau_{-} \to q \mu^{-} \mu^{-}$

  $\tau^{-} \to \nu_{\tau} l^{-} l^{-} X^{+}$

- same sign dileptonic production: $pp \to l_1^{+} l_2^{+} X$

- top-quark decay: $t \to b l_1^{+} l_2^{+} W^{-} W^{-}$

- double-charged Higgs decays: $H^{\pm\pm} \to l_1 l_2^{\pm} X$

The decay sensitivity of different heavy flavor LNV processes is determined by comparing the scale of the neutrino mass with the energies of the decay process [13]. We have three different cases: 1) light neutrinos $(m_{\nu}{}^{2} << q^{2})$ are involved. In this case the decay rate $R \sim < m_{ll'} > = \sum_{i} U_{li} U_{l'i} m_{i}$ (U_{li} – mixing parameters of the active neutrinos); 2) heavy neutrinos $(m_{\nu}{}^{2} >> q^{2})$ are involved, and in this case the decay rate →(V_{lN} – mixing parameters between light (active) and heavy (sterile) neutrinos); and 3) the mass of the involved neutrinos is of the order of the energy decay process $(m_{N}{}^{2} \sim q^{2})$. In this case they can be produced on their mass shell and the decay rates are enhanced due to the resonant effect associated to their decay widths $\Gamma_{N} \to R \sim \sum_{N} V_{lN} V_{l'N} / \Gamma_{N}$. For the first two cases the decay rates are quite small: in the first case due to the smallness of both the mixing parameters between the active neutrinos and of the neutrino mass (of $\sim 1\,eV$), and in the second case due to the smallness of the mixing parameters between the light (active) and heavy (sterile) neutrinos divided by the large mass of the heavy neutrino. The branching fractions (Br) in these cases are of the order of

$10^{-20}-10^{-31}$ and, at the present luminosities, they cannot be detected. The third case is quite interesting since the theoretical predictions for the Br for these resonant decay processes become at reach of the present and next future high energy experiments.

Until now several LNV processes at high energy were already investigated. Their non-observation has set bounds on the Br, and further to the neutrino mixing parameters. In the following we shortly present the most important such investigations performed at LHC experiments at CERN.

ATLAS [14]: an inclusive search of events with two isolated leptons (e or μ) having the same electric charge. The data are selected from events collected from pp collisions at $sqrt(s)=7$ TeV by the ATLAS detector and correspond to an integrated luminosity of $34\,pb^{-1}$. The spectra in dilepton invariant mass are compared to SM predictions. No evidence is found for contributions beyond those of the SM. Limits are set on the cross-section in a fiducial region for new sources of same-sign high-mass dilepton events in the ee, $e\mu$ and $\mu\mu$ channels. Four models predicting same-sign dilepton signals are constrained: two descriptions of Majorana neutrinos, a cascade topology similar to supersymmetry or universal extra dimensions, and fourth generation down-type quarks. Assuming a new physics scale of 1 TeV, Majorana neutrinos produced by an effective operator V with masses below $460\,GeV$ are excluded at 95% CL. A lower limit of $290\,GeV$ is set at 95% CL on the mass of fourth generation down type quarks.

CMS [15]: searched for events with same-sign isolated dileptons $(ee, e\mu, \mu\mu, \mu\tau, \tau\tau)$. The searches used an integrated luminosity of $35\,pb^{-1}$ of pp collision data at a ECM of $7\,TeV$ collected by the CMS experiment at the LHC. The observed numbers of events agree with the SM predictions, and no evidence for new physics was found. To facilitate the interpretation of the data in a broader range of new physics scenarios, information on the event selection, detector response, and efficiencies is provided.

LHCb has investigated several LNV processes from meson and tau decays. A first search of same sign dileptons was performed in the decays of $B+\to K^-(\pi^-)\mu^+\mu^+$ at an integrated luminosity of $36\,pb^{-1}$ [16]. No signal was observed in either channel. They set limits of the Br for the two channels as follows: $Br(B^+\to K^-\mu^+\mu^+, 5.4\times10^{-8}$ and $Br(B^+\to\pi^-\mu^+\mu^+), 5.8\times10^{-8}$ at 95% CL, which improves the previous existed limits by factors of 40 , 30, respectively. Another analysis was performed for the B^- decays into same sign di-muon channels at an integrated luminosity of $380\,pb^{-1}$ [17]. Also, no signal was observed beyond the SM and limits were set for the channels $Br(B^-\to D^+\mu^-\mu^-), 5.6\times10^{-7}$ and $B(B^-\to D^{*+}\mu^-\mu^-), 4.1\times10^{-6}$ at 90% CL.

Besides these B meson channels a first search for tau decays was also performed [18]. Particularly, such an investigated process was $\tau^- \to \mu^+\mu^-\mu^-$, which is in the same time a Lepton Flavor Violating process. The analysis was done using $1.0\, fb^{-1}$ of data collected in 2011 at $(s)^{1/2} = 7\, TeV$. The upper limit for the Br was $Br < 7.8 \times 10^{-8}$ at 95% CL.

These studies performed at LHC experiments will certainly be improved in the next future with new data sets at increased luminosities. Besides these already investigated channels there are many others that merit to be investigated, according to the theoretical estimations for the Br. For example, the hyperon decay channels are weakly constrained at present $(Br \sim 10^{-3} - 10^{-4})$. In addition, there are very recent theoretical estimations which show that 4-body decay channels of neutral mesons (B, D), or the tau decay channel $\tau^- \to \nu_\tau \mu^-\mu^-\pi^+$ can provide us with even more stringent bounds on the Br and neutrino mixing parameters between muon and sterile (N) flavors [19]. Thus, the study LNV channels at high energies opens an interesting direction of investigation at LHC and super B factories in the next future.

5. CONCLUSIONS

Recent neutrino oscillation experiments have convincingly shown that neutrinos are massive particles and they mix. This is the first evidence that extends our understanding on the SM and encourages us to search for BSM physics. The large majority of BSM theories involve massive Majorana neutrinos which imply LN non-conservation. Concerning the neutrino properties we still do not know important issues as: the absolute scale of the neutrino masses and the mass hierarchy, the mechanism of mass generation, the nature of neutrinos (are they Dirac or Majorana particles?), the number of neutrino flavors, etc. LNV processes can shed light on these issues, and that is why there is a strong interest to search for such processes. At low energy the $0\nu\beta\beta$ process is intensively studied both theoretically and experimentally. Theoretically, a key challenge is to develop nuclear structure methods for a precise calculation of the NMEs involved in DBD. Experimentally, there are many running experiments, and others are planned to start in the next future. The expectation is to explore the entire region of neutrino masses associated with the inverted mass hierarchy scenario. If the $0\nu\beta\beta$ will be discovered, the next challenge will be to find the dominant mechanism(s) which contributes to its occurrence. At present, a new opportunity appears: the search of LNV processes at high energies. The very large "effective luminosity" of $0\nu\beta\beta$ becomes now to be compensated by the increased luminosity at LHC and super B

factories. Thus, the search of the LNV processes at high energies opens a new and interesting direction of research. Also, the combined information extracted from low- and high-energy experiments will help the study of LNV processes and will be in the benefit of both avenues of investigation.

Acknowledgments. This work was supported by a grant of the Romanian Ministry of Education, CNCS – UEFISCDI, project no. PN-II-ID-PCE-2011-3-0318, contract no. 58/28.10.2011.

REFERENCES

1. Y. Ashie *et al.* [SK collaboration], Phys. Rev. D **71**, 112005 (2005).
2. T. Araki *et al*. [KamLAND collaboration], Phys. Rev. Lett. **94**, 081801 (2005).
3. M. H. Ahn *et al*. [K2K collaboration], Phys. Rev. D **74**, 072003 (2006).
4. P. Adamson *et al.* [MINOS collaboration], Phys. Rev. Lett. **106**, 181801 (2011).
5. F. An *et al.* [Daya Bay collaboration], Phys. Rev. Lett. **108**, 171803 (2012).
6. J. Ahn *et al.* [RENO collaboration], Phys. Rev. Lett. **108**, 191802 (2012).
7. Y. Abe *et al*. [Double Chooz collaboration], Phys.Rev.Lett. **108**, 131801 (2012).
8. K. Abe *et al*. [T2K Collaboration], Phys. Rev. D **85**, 031103 (2012).
9. J. D. Vergados, H. Ejiri, F. Simkovic, *Theory of neutrinoless double beta decay*, arXiv:1205.0649 [nucl-th] (2012).
10. A. Faessler, *The Neutrinoless Double Beta Decay, Physics beyond the Standard Model and the Neutrino Mass*, arXiv:1203.3648 [nucl-th] (2012).
11. W. Rodejohann, J. Mod. Phys. E **20**, 1833 (2011).
12. M. Horoi, S. Stoica, Phys. Rev. C **81**,024321 (2010).
13. A. Atre, T. Han, S. Pascoli, B. Zhang, JHEP **0905**, 030 (2009).
15. CMS collaboration, JHEP **1106**, 077 (2011).
16. LHCb collaboration, Phys. Rev. Lett. **108**, 101601 (2012).
17. LHCb collaboration, Phys. Rev. **85**, 112004 (2012).
18. LHCb collaboration, *Search for the lepton flavour violating decay* $\tau^- \to \mu^+\mu^-\mu^-$ *Hadronic B decays*, talk given at *Flavour Physics and CP Violating* 2012, 21-25 May, Hefei, Anhui, China (2012);
    P.Seyfert, *Searches for Lepton Flavour Violation and Lepton. Number Violation in Hadron Decays* talk given at *Flavour Physics and CP Violating* 2012, 21-25 May, Hefei, Anhui, China (2012).
19. G. Lopez-Castro, N. Quinteros, *Lepton number violation in tau lepton decays*, arXiv:1212.0037 [hep-ph] (2012).