Dirac-ness of massive neutrinos composed of Majorana states

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Majorana neutrinos lead naturally to Lepton Flavour Violation (LFV). Representative LFV processes both at low energy physics and high energy hadron and lepton collisions are discussed. It is shown when a superposition of Majorana states mimic Dirac type of neutrinos, leading to recovery of the Lepton Flavour Conservation (LFC). A strength of LFV is a measurable quantity, which in turn gives correlations among Majorana neutrino parameters at the level of mixing or mass matrices, thus revealing possible details of neutrino mass generation mechanism. As far as TeV massive neutrinos are concerned, which are searched presently at the LHC, an example of possible neutrino parametrization is discussed which is in agreement with low energy stringent LFV processes. This parametrization goes beyound simplified ATLAS and CMS analysis done so far and is proposed as a next step in direction of more complete future LHC searching analysis.

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INTRODUCTION

Neutrino physics is full of surprises with many experimental measurements which not always survived but which in a meantime, quite often, led to bold, interesting or even weird theoretical interpretations.

Presently, due to neutrino oscillation phenomenon, it is already established that two out of three known neutrinos are massive, though their masses are very tiny, at the electronovolt level. Commonly we call them all the light (active) neutrinos. It was a long story which led to this result, started around a half century ago with a Homestake experiment and the so-called solar neutrino problem, leading finally to the discovery of the first type of neutrino oscillations [1]. About three decades ago, evidence for a 17-keV neutrino mass state (also called a Simpson's neutrino) coupled to the electron neutrino in nuclear decay spectra measurements made another huge controversy. The unclear situation lasted more or less during the period 1985-1993. Finally, this neutrino anomaly has been resolved and the Simpson's neutrino disappeared (in some experiments even 8 σ C.L. have been announced). For a review on this issue, see e.g. [2, 3]. On the way there were yet another controversies connected with neutrinoless doubly beta decay signals (see comments in [4]), or more recently, in the OPERA experiment. Especially the last result excited not only physics society but also media through the world. Finally we are again in a trivial world where neutrinos are not faster than light [5].

Certainly, we can expect more such situations in the future, as neutrino experiments explore very tiny and by definition *weak* effects and belong to one of the most challenging experiments in physics, ever.

A year ago another puzzle has been reported by the CMS Collaboration which deals with products of proton-proton collisions at Large Hadron Collider (LHC) [6]. This time a concern is about production and subsequent decay of hypothetical heavy neutrinos N, associated with right-handed currents and a new charged gauge boson W_2. CMS report triggered a lot of theoretical activity and was a fruitful seed for new ideas in quest of New Physics at the LHC [7–17] [1]. CMS reported 13 electron-positron-jet-jet (e^+e^-jj) events which are beyound the Standard Model analysis. Second, one additional event which breaks the lepton number was identified (e^-e^-jj). Finally, no excess connected with muon pair production ($\mu\mu jj$) has been found.

Why these, should be said honestly, still statistically dim events are so spectacular and excited many theoreticians so much? The shortest answer is: 13 LFC e^+e^-jj events over a single LFV e^-e^-jj event indicates that heavy neutrinos are of pseudo-Dirac nature. Meaning: they brake lepton number only slightly, and this calls for proper theoretical interpretations[2].

A hunt for LFV low and high energy processes in particle physics is a decades long story. Fact is that even single LFV event detection would be a signal for New Physics. Present bounds for low energy LFV signals, such as $\mu \to e\gamma$ are already impressive, and they should increase very much in the future, at the so-called intensity frontier experiments where New Physics can be probed up to unimaginable 10 000 TeV scale [**?** **?**], which is four orders of magnitudes higher than capabilities of present or doubtless future high energy colliders energies cite

If heavy neutrinos have to do anything with the CMS anomaly, their masses are presumable about trillion times larger than masses of known light neutrinos (i.e. $M_N \sim$

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[1] Interesting before CMS era works are [18, 19]...gdzie indziej For interpretations of the CMS signals not connected with neutrino physics, see [20–22]. Interestingly, there are also other channels where TeV resonances are discussed, e.g. diboson channels cite...

[2] If e^-e^-jj event is misidentified, then excesses are only due to LFC events, which can be explained by Dirac neutrinos, as discussed in dobrescu.

TeV). There is a good theoretical reason for such heavy states. Popular see-saw mechanism has been constructed to explain smallness of the known light neutrino mass states cite(). Here neutrinos are naturally of Majorana nature, they are self-conjugate and can lead to the Lepton Flavour Violation processes cite. Alternatively, there is also another interesting mechanism, inverse seesaw, in which also pseudo-Dirac neutrinos can appear cite. Here LFV can vary more naturally and can be large or small.

Our main focus is to show how starting with Majorana neutrinos and an effective right-handed charged current, a strength of LFV can change in physical processes. First reason for LFV can be a mixing of flavour Majorana states, however, other factors can affect signals either: decay widths, CP phases, and Majorana heavy neutrino mass splittings. Settling down these issues, our final goal is to convience a reader that such fine details are important for experimental analysis, e.g. just mentioned CMS data cite or ATLAS analysis to which we will come.

In what follows, we will consider not only some hadron or lepton colliders collisions, which may lead to LFV, but also prominent low energy processes of this kind.

RIGHT-HANDED CURRENTS AND LFV AT THE LHC AND AT THE INTENSITY FRONTIER

Our discussion will be based on the following lagrangian

$$\mathcal{L} \supset \frac{g}{\sqrt{2}} \sum_{a=1}^{3} \overline{\nu}_a \gamma^\mu P_L (U_{PMNS})_{aj} l_j W_{1\mu}^+ + \text{h.c.} \quad (1)$$

$$+ \frac{\tilde{g}}{\sqrt{2}} \sum_{a=1}^{3} \overline{N}_a \gamma^\mu P_R (K_R)_{aj} l_j W_{2\mu}^+ + \text{h.c.} \quad (2)$$

Eq.1 describes the SM physics of charged currents. It includes the neutrino mixing matrix U_{PMNS}, responsible for neutrino oscillations phenomena. Eq.2 is responsible for non-standard effects connected with new heavy neutrino massive states N_a and right-handed currents mediated by additional heavy charged gauge boson W_2.

In further discussion we assume that N_a are heavy flavour neutrino states which are composed of Majorana massive states N_i, $N_a = \sum_{i=1}^{3} (K_R)_{ai} N_i$. K_R is with a good approximation a unitary mixing matrix which diagonalizes heavy neutrino sector leading to the N_i massive states. $\tilde{g}$ is a gauge coupling equal to the SM gauge coupling g, or smaller, if we wish strict gauge coupling unification cite...

The CMS excess in dilepton data mentioned in the Introduction can be explained by the process schematicaly sketched in Fig. 1 This is a prominent process which has

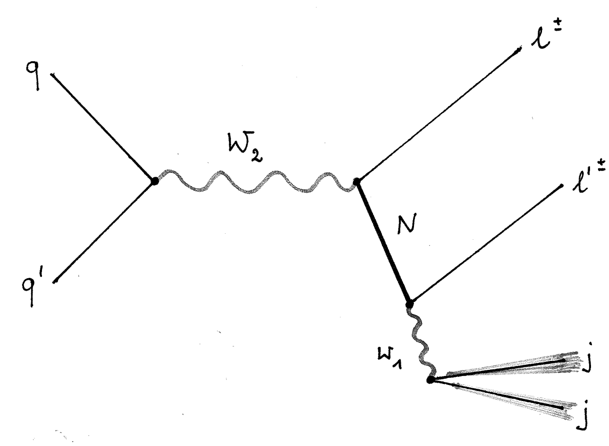

FIG. 1: Production signal of a heavy gauge bosons W_2 decaying to charged leptons l_i $(i = 1, 2, 3)$ and an on-shell heavy neutrinos N_a $(a = 1, 2, 3)$. Heavy neutrinos further decays mainly via 3-body process $N_a \to l_j jj$ leading to two jets and two charged leptons in the final state: $pp \to W_2^\pm \to l_i^\pm N_a \to l_i^\pm l_j^\mp jj$ (OS) and $pp \to W_2^\pm \to l_i^\pm N_a \to l_i^\pm l_j^\pm jj$ (SS). For Majorana neutrinos, in the SS case the leptonic crossed diagram exists.

been discussed long before LHC[3] and even Tevatron era [23]. In this process same-sign (SS) leptons indicates lepton number violation, which indirectly reveals Majorana neutrino nature. If only excess is seen with opposite-sign leptons, this would indicate that Dirac neutrinos are there. In between, kinds of mixed states are possible. It is known from Feynman rules [24, 25] that a charged lepton determines lepton number flow in a vertex, so a neutrino is uniquely a particle or an antiparticle, depending on a sign of the charged lepton. That is why charged currents driven by charged gauge bosons or scalars can not lead to determination of neutrinos nature [24]. Neutral currents change situation but Z bosons are explicitly absent in Fig. 1 (for a specific contribution of Higgs bosons, see Appendix). What remains is the Majorana propagator, which is self-conjugate. Then on the way from one vertex to the another, lepton number can change, resulting in the same two final charged leptons.

For further discussion, we introduce three parameters which should be fitted to the experimental data. The first

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[3] Apart from this often called "smoking gun" process where heavy neutrino states can be discovered and LFV can be investigated, there are also other interesting LHC process like... considered in ....

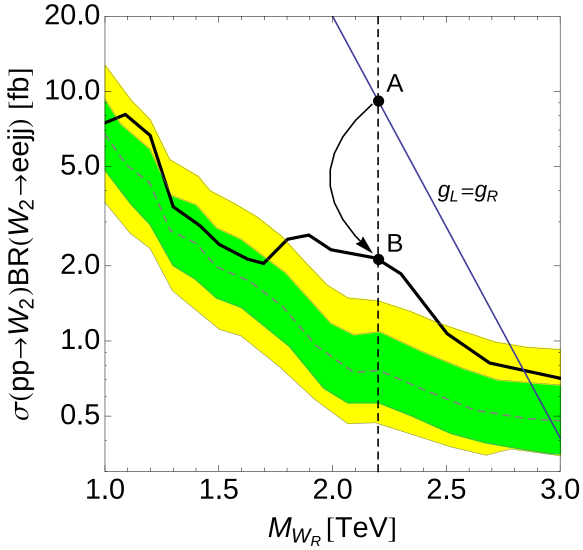

FIG. 2: Brazil band and Tomek, opisz A,B,C,D i odpowiednio wprowadz litery w eq.5

parametrizes the number of SS events to the number of OS events[4]

$$r = \frac{N_{SS}}{N_{OS}},\ r_{\rm CMS} = \frac{1}{13}, \tag{3}$$

the second gives the ratio of different flavour dileptons

$$r' = \frac{N_{\mu\mu jj}}{N_{eejj}},\ r'_{\rm CMS} = 0, \tag{4}$$

finally, the third parameter cares about the excees in the total cross section

$$\gamma = \frac{\sigma(pp\to eejj)_{CMS} - \sigma(pp\to eejj)_{SM}}{\sigma(pp\to eejj)_0},\ \gamma_{\rm CMS} \simeq 0.54. \tag{5}$$

Index A in Eq. 5 refers to the MLRSM cross section prediction (with $g_L = g_R$ and trivial heavy neutrino mixings and mass degeneracy, as analyzed in by the CMS collaboration) while B refers to the cross section derived assuming W_2 hypothesis, see Fig.1 for details. Such a prametrization is better for small statistics, especially in a limit of no excess, $\gamma = 0$?

Eqs. 3-5 can be reconciled with Eq.2 for the following neutrino mass parameters (and $M_{W_2} = 2.2$ TeV)

$$M_{N_{1,3}} = 0.925\,\text{TeV}, \quad M_{N_2} = 10\,\text{TeV} \tag{6}$$

[4] In [16] mistakenly $r_{\rm CMS} = \frac{1}{14}$ was assumed. However, CMS estimated 13 OS events. Fortunately, $r_{\rm CMS} << 1$, so this change practically does not influence motivation, discussion and results given in [16].

and mixing matrix of the form:

$$K_R = \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\phi_3}\sin\theta_{13} & 0 & e^{i\phi_3}\cos\theta_{13} \end{pmatrix}, \tag{7}$$

choosing $\theta_{13} = ...$ and $\phi = /pi/2$, for details, see [16].

Using parametrization Eq. 7, Eq. 2 explicitly reads

$$\mathcal{L}_{\mathcal{RHC}} = \left(\cos\theta_{13}\overline{N}_1 - e^{i\phi_3}\sin\theta_{13}\overline{N}_3\right)\Omega \tag{8}$$

where $\Omega = \frac{\tilde{g}}{\sqrt{2}}\gamma^\mu P_R(K_R)_{aj} l_j W^+_{2\mu}$.

As we can see, neutrinos N_1,N_2 contributes with different weights into vertices in Fig. 1, if neutrinos are non-degenerate, additional weigth factors appears. Both neutrinos interfere leading to different values of r and γ parameters, as shown in Fig. 3. Present CMS r and γ values prefer pseudo-Dirac neutrinos (for Dirac case, bottom star, mixing between two Majorana neutrino states should be maximal $\theta = \pi/4$, so the CP phase $\phi = \pi/2$). For two top stars, there is no mixing among neutrino states and neutrino is purely of Majorana neuture. In Fig. 3 it is also shown what happend if masses of Majorana neutrinos are not the same, here however also Majorana decay widths are important.

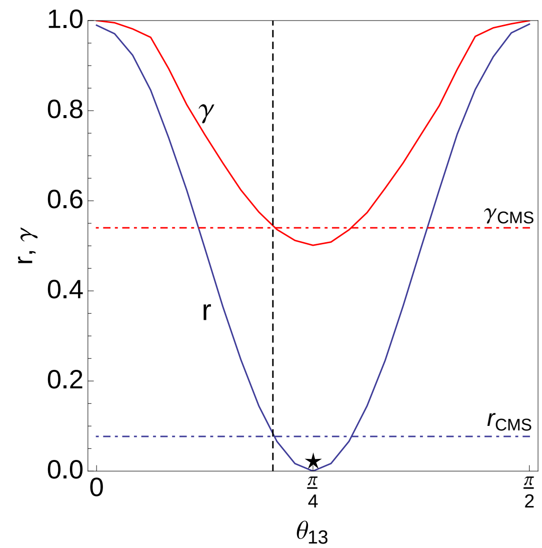

FIG. 3: TOMEK: inny rysunek, wszystko ma byc na jednym. Dependence of r (blue) and γ (red) on θ_{13} for $M_{N_1} = M_{N_3} = 925$ GeV and $M_{N_2} = 10$ TeV. Horizontal dot-dashed lines show values of $r_{\rm CMS} = 0.07$ and $\gamma_{\rm CMS} = 0.54$ observed in the CMS experiment. Vertical dashed line corresponds to the value of θ_{13} for which both $r = r_{\rm CMS}$ and $\gamma = \gamma_{\rm CMS}$. A star represents a scenario in which $\theta_{13} = \pi/4$ and $\phi_3 = \pi/2$ what gives Dirac-type heavy neutrino.

In the diagrams we consider the kinematics and masses of particles allows for the exchange of a neutrino close to its mass shell. Then the total cross section is dominated by the exchange of the neutrino in the s-channel.

Close to the mass pole its energy dependence can be described by the Breit-Wigner type distribution. If more than one neutrinos are presented, amplitudes corresponding to different mass eigenstates have to be added coherently. When cross section is calculated, the interference term between different amplitudes can be negative and suppress SS lepton production. The size of the interference term can compete with the Breit-Wigner contribution only if the neutrino mass difference is of the order of the neutrinos widths (lines.... in Fig). Otherwise the interference term contributes only to the continuum background and is irrelevant for processes where the dominant contributions comes for the resonant s channel (line ...). Therefore the possible suppresion of the SS signal can occur only if the heavy Majorana neutrinos are almost degenerated.

Based on results shown in Fig. 3, different scenarios are summarized in Table

$\epsilon = \frac{\Delta M}{max(\Gamma_i)}$	r, Eq.3	ΔL violation	Nature
0	0	0	Dirac
$<< 1$	small	moderate	pseudo-Dirac
~ 1	large	substantial	Majorana
$>> 1$	1	maximal	Majorana

TABLE I: Dirac-ness of neutrino states composed of Majorana massive states measured by r parameter (Eq.3) in $pp \to lljj$, see Fig. 3.

We may ask how to describe a situation in a case of stable neutrinos, in this case neutrino decay width is zero. We can think here about light active SM neutrinos. In this case Dirac nature of neutrinos is restored as ..... Robert....

Robert: moze lepiej?: To make the picture complete, we can think about a situation is where a process is t-channel dominated and, as discussed above, neutrino decay widths are irrelavant. Here interferences can be substantial even for very large Majorana neutrino mass splittings, leading effectively to restoration of the lepton flavour (destructive interference may kill the cross section totally). This can happen for another variant of the diagram shown in Fig.3 in which quark and jet lines are removed: $e^-e^- \to W^-W^-$. This situation has been discussed in cite , we update it here in a different context. moze appendix nie jest potrzebny, jedynie wykres

PONIZEJ JESZCZE NIE ZROBIONE:

mu e gamma, tau e gamma bezneutrinowy

This is a simplified

mamy tylko L_CC lagrangian z mieszaniem stanu N. to wszystko. katy mieszania i masy sa input parametrami, to be fixed in experiments. Our aim is to show that taking such subtle details of the right handed sector gives a deeper insight into results, otherwise many things can be missed. One example. In the ATLAS experiment .... SS ...-¿ Dirac missed

Common reasoning for that is the following:
For Majorana neutrinos the same number of SS and OS events is expected,
and as CMS indicates strongly that $r << 1$, then Dirac-type of neutrinos must be involved.

In principle, that no lepton number violation is observed does not necesserarily mean that Dirac neutrinos are there. Imagine for instance the process where only charged currents are involved. Such a situation was discussed in the introduction. On the other hand, if lepton number is violated then Majorana neutrinos are there [26].

Second remark is more important. There are many theoretical arguments for heavy Majorana massive neutrinos: they are more economic as only two degrees of freedom are needed, they may lead altogether with small Dirac mass terms to the see-saw mechanism. So, if experimentalists would trust intuition of theoreticians and we assume that heavy Majorana neutrinos exist then to check it experimentally, enough is to find lepton number violating events, in our process these are SS dileptons. However, if no SS signals are found, then possibility that neutrinos are of Dirac type is missed. And this seems to be exactly the ATLAS collaboration case.

Let us note that in the original paper [23] which is usually invoke in this situation it was really shown that for Majorana neutrinos $r = 1$. However, in this paper the mixing between generations of heavy neutrinos was ignored and a simple factorization of the process into W_R production times branching ratios is possible. Then, of course, number of same sign eejj events is equal to opposite sign eejj events, even for non-degenerate Majorana neutrino masses. Further rule of thumb arguments for that are given in the Appendix.

This is a mass matrix for three types of massive Majorana neutrinos with general CP phases. We know elements of this matrix quite well in the light sector, it has almost tri-maximal form , meaning that mixings among $\nu_1 - \nu_2$, $\nu_1 - \nu_3$ and $\nu_2 - \nu_3$ flavours are large. Now, what can we say about right-handed sector? It is a kind of a *tabula rasa*, but not completely as limits on signals driven by such heavy neutrino states exist. Presently the stringest constraint comes from the lepton flavour violating $\mu \to e\gamma$ process.

Process	Current Limit	Planned Limit
$\tau \to \mu\gamma$	6.8E-8	1.0E-9
$\tau \to \mu\mu\mu$	3.2E-8	1.0E-9
$\tau \to eee$	3.6E-8	1.0E-9
$\mu \to e\gamma$	5.7E-13	1.0E-14
$\mu N \to eN$	7.0E-13	1.0E-17
$\mu \to eee$	1.0E-12	1.0E-16

TABLE II: Current and planned limits on Lepton CFLV

For unitary K_R, ($\left(K_R^\dagger K_R\right)_{e\mu} = 0$) and for $\left(\frac{m_i}{m_{W_R}}\right) \ll 1$, assuming mixing only between two generations we get simplified equation

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left(\frac{m_W}{m_{W_R}}\right)^4 \left(\sin\theta\cos\theta\frac{\Delta m_{12}^2}{m_{W_R}^2}\right)^2 . \quad (9)$$

For maximal mixing between two generations, $M_{W_R} = 2200$ GeV and neutrinos masses at the scale of TeV, we need the splitting to be of the order of about 100GeV to get an agreement with the current bounds, see Fig. 4. In other words, the splitting must be smaller than about 200 GeV. The splitting depends also on the mass of the neutrino itself, as shown in Fig. .

Robert, dokladnie jakie parametry? opisz caption figs

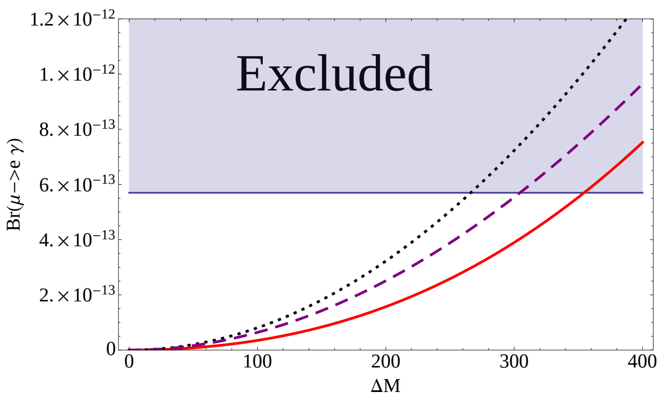

FIG. 4: Estimation of the maximal splitting between heavy neutrino masses allowed for large LFV $\mu \to e\gamma$ process. Solid line coresponds to mass $m_{N_1} = 500$GeV, dotted line $m_{N_1} = 1500$GeV and dashed line $m_{N_1} = 2500$GeV. We assumed maximal mixing between the first and the second generation and no mixing between third generation.

Based on Figs.3,5 let us try to summarize

pozniej... We can also look at this diagram different way: rotating the diagram by 90 degrees and directing the jets oppositely, we get simple the main diagram which is responsible for the neutrinoless doubly beta decay. This is why investigating process in Fig. 1, LFV low energy processes should be also considered ...ref...

SUMMARY

We have considered potential effects of the dileptons signals coming purely from the heavy neutrino sector, neglecting large light-heavy neutrino mixings, for which see-saw I type is not enough, and we need other modelling, for instance through inverse see-saw mechanisms []. In this case future lepton colliders would be a good place to diseantangle the models.

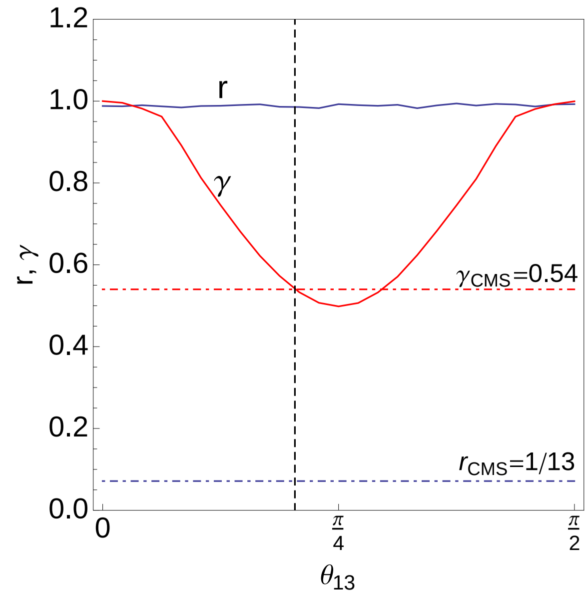

FIG. 5: Dependence of r (blue) and γ (red) on θ_{13} for $M_{N_1} = 924.5$, $M_{N_3} = 925.5$ GeV and $M_{N_2} = 10$ TeV. Horizontal dot-dashed lines show values of $r_{\rm CMS} = 0.07$ and $\gamma_{\rm CMS} = 0.54$ observed in the CMS experiment. Vertical dashed line corresponds to the value of θ_{13} for which $\gamma = \gamma_{\rm CMS}$.

we discussed typical hadron, lepton and low energy processes which in fact intersect each other....

even if CMS not servive, our discussion shows possible way how....

Acknowledgements

We would like to thank Marek Zrałek and Dobrescu? for interesting discussions. Work is supported by the Polish National Science Centre (NCN) under the Grant Agreement No. DEC-2013/11/B/ST2/04023 and under postdoctoral grant No. DEC-2012/04/S/ST2/00003.

APPENDIX 1. MAJORANA NEUTRINOS AND THE $r = 1$ DILEPTONS PROCESS

TOMEK

If we look in the basic diagram in Fig.1, we can see that the amplitude for the signal is a sum of terms from intermediate neutrino states, weighting by the neutrino mixing matrix KR and kinematical factors.

In the SS case we have two K_R mixing elements with the same complex conjugacy while in the OS case they are opposite, which matters for CP effects.

Tomek, jak to najlatwiej pisac prostymi wzorami?

...

In the case non-degenerate case such simple arguments are absent and we have to make numerical estimations.

APPENDIX 2. MLRSM HIGGS BOSONS CONTRIBUTIONS TO THE DILEPTONS-PLUS-TWO-JETS PROCESS

MAGDA

APPENDIX 3. OFF-SHELL INTERFERENCES OF MAJORANA NEUTRINOS WITH LARGE MASS SPLITTINGS IN THE $e^-e^- \to W^-W^-$ PROCESS

MAGDA/TOMEK

moze niepotrzebny, tylko rysunek w glownym

APPENDIX 4. LFV LOW ENERGY PROCESSES.

ROBERT: UPORZADKUJ, potem cos sie wrzuci do glownego, zobacz co z tau-¿ e gamma, czy nasze KR jest ok, no i rysunek do neutrinoless

Neglecting light-heavy neutrinos mixing, Eq.19, branching ratio for $\mu \to e\gamma$ is [27]

$$Br(\mu \to e\gamma) \;=\; 3\frac{\alpha}{8\pi}\left(\frac{m_{W_1}}{m_{W_2}}\right)^4 \left|\sum_i (K_R)_{ei}\,(K_R)_{i\mu}\,F\left(\frac{m_i^2}{m_{W_2}^2}\right)\right|^2 \tag{10}$$

where m_i is the mass of the heavy neutrino and

$$F(x) \;=\; \frac{1}{6\,(1-x)^4} \times \left[10 - 43x + 78x^2 - 49x^3 + 4x^4 + 18x^3\ln(x)\right] \tag{11}$$

Sum over i runs over all six neutrinos. Light neutrino contribution is negligible, unless there is a large contribution due to the non unitarity of K_L.

For unitary K_R, ($\left(K_R^\dagger K_R\right)_{e\mu} = 0$) and for $\left(\frac{m_i}{m_{W_R}}\right) \ll 1$, assuming mixing only between two generations we get simplified equation

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left(\frac{m_W}{m_{W_R}}\right)^4 \left(\sin\theta\cos\theta\frac{\Delta m_{12}^2}{m_{W_R}^2}\right)^2. \tag{12}$$

Notice that the same equation holds also in the case of light neutrinos, if we put $m_{W_R} = m_W$. This contribution is negligible since

$$\frac{\Delta m_{12}^2}{m_W^2} \approx \frac{10^{-3}\mathrm{eV}^2}{80\mathrm{GeV}^2} \sim 10^{-25}.$$

For $M_{W_R} = 2200$GeV the branching ratio is suppressed by $\frac{3\alpha}{8\pi}\left(\frac{m_W}{m_{W_R}}\right)^4 \sim 10^{-9}$, which gives good estimation of the order of magnitude. To get an agreement with experimental bounds we need to adjust masses and mixing, such that $\left|\left[K_R^\dagger F\left(\frac{m_i^2}{m_{W_R}^2}\right)K_R\right]_{e\mu}\right|^2 \ll 1$. For unitary K_R the important suppression comes, not directly from the masses of neutrinos, but rather from the splitting of the masses. For maximal mixing between two generations, $M_{W_R} = 2200$ GeV and neutrinos masses at the scale of TeV, we need the splitting to be of the order of about 100GeV to get an agreement with the current bounds, see Fig. 4. In other words, the splitting must be smaller than about 100 GeV. The splitting depends also on the mass of the neutrino itself, as shown in Fig. .

Robert, dokladnie jakie parametry? opisz caption figs

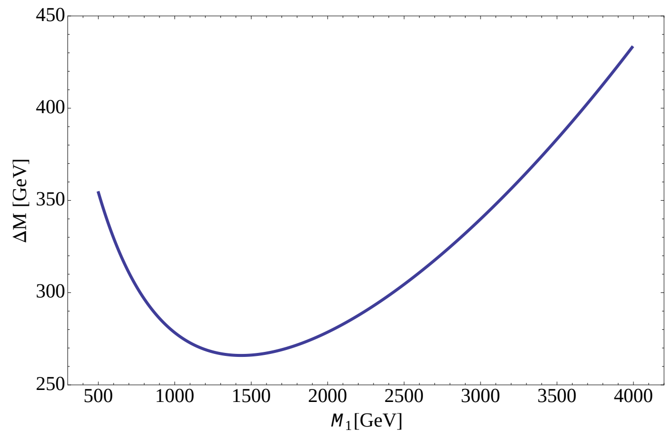

FIG. 6: Estimation of the maximal splitting between heavy neutrino masses allowed for large LFV $\mu \to e\gamma$ process as a function of the mass of first heavy neutrino. We assumed maximal mixing between the first and the second generation and no mixing with the third generation. We also take $m_{W_R} = 2200$GeV and $g_R = g_L$.

jaki wklad bezneutrinowy daje w tym przypadku? jaki wklad od lekkich?

APPENDIX 5. IN THE BEGINNING WAS THE WORD: SHORT HISTORY OF NEUTRINOS NAMING

MOJE

Neutrinos: Dirac, pseudo-Dirac, quasi Dirac, schizophrenic, ...

OGOLNIE:

$$N_\alpha \;=\; \Omega(\cos\theta N_1 + e^{i\phi}\sin\theta N_2) \tag{13}$$

where Ω is a normalization factor. In our case where there is no light-heavy neutrino mixings it is just 1.

For $\theta = \Pi/4$ there is a maximal mixing between two Majorana states, if in addition $\phi = \pm\Pi/2$, Dirac neutrino state is constructed [28]. Classically pseudo-Dirac neutrino has been introduced for light neutrinos demanding $m_D >> m_R$ in Eq. 17. In such a case neutrinos can mix maximally leading to the almost degenerate mass states with opposite CP phases ... Of course, for a typical see-saw this is not a case, and another constructions are necessary, for instance, inverse or linear see-saw mechanisms...

Explicitly it means that

$$N_e = \cos\theta_{13} N_1 + \sin\theta_{13} N_3 \quad (14)$$
$$N_\mu = N_2 \quad (15)$$
$$N_\tau = -e^{i\phi_3}\sin\theta_{13} N_1 + e^{i\phi_3}\cos\theta_{13} N_3 \quad (16)$$

and for electrons produced in the process as shown in Fig. 1 two neutrino states N_1 and N_3 interfere. Chosing properly two parameters θ_{13} and ϕ_3, r and γ values in Eqs. 3 and 5 can be fixed. The result is shown in Fig. **??**.

In such models pseudo-Dirac nature of the RH neutrinos, the ??smoking gun?? signal for type I seesaw, namely the lepton number violating same-sign di-lepton signal [8] is absent in this case

pseudo-dirac inverse [29] [30] [31] [32] nowy atlas [33]

As we will discuss this situation more carefully in the paper, it is useful to see basic Feynman diagram for this reaction.

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It might well be that here a situation can be similar to some cases just described and the signal will disappear. However, the situation as it is makes a good reason and give an opportunity to look at the neutrino physics yet from another angle.

APPENDIX

TEGO NIE BEDZIE

Having in mind the previous work [16] and some further interesting discussions especially given in [12–15], we would like to answer in the present work to some questions concerning detection of heavy neutrinos through the dilepton signals at the LHC, namely

(i) What is an effective composition of the degenerate Majorana states which may lead to some nonzero but small r, negligible r' and substantial γ parameters?

(ii) What can be the largest mass splitting among heavy neutrino states?

(iii) How heavy Majorana neutrino decay width modulates the signal?

(iv) How lepton flavour violating processes restrict right-handed neutrino mass and mixing matrices?

(v) How does departure from the $g_L = g_R$ case influence heavy neutrino sector parametrization?

(vi) Do Higgs bosons effects can be substantial?

Trying to answer to these general questions, we will use values of parameters connected with the CMS dilepton anomaly, Eqs. 3-5.

Neutrino masses and mixings depends on the structure of the neutrino mass matrix [28]. As in [16], we assume a typical see-saw typy I mass matrix

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}. \quad (17)$$

We assume $M_D[\mathcal{O}(MeV)] \ll M_R[\mathcal{O}(TeV)]$ and no light-heavy neutrino mixings

FOOTNOTE In our typical see-saw mechanism with natural scales assumed, these mixings must be anyway small [29, 34].... Large light-heavy neutrino mixings can be obtained through so-called modified or inverse see-saw mechanisms [32, 35, 36]. Here typical mass matrix

$$M_N = \begin{pmatrix} 0 & m_D & m_L \\ m_D^T & 0 & M \\ m_L^T & M^T & \mu_S \end{pmatrix} (18)$$

leads to the pseudo-Dirac neutrino states.

In this way most of possible connections between heavy and light neutrino sectors are cut away, and we can explore heavy sector effects exclusively. The neutrino mixing matrix takes then the following form [16]

$$U \approx \begin{pmatrix} 1 & 0 \\ 0 & K_R^\dagger \end{pmatrix}, (19)$$

where, K_R is an unitary 3×3 matrix defined by $M_R = K_R^T \mathrm{diag}(M_{N_1}, M_{N_2}, M_{N_3}) K_R$, $M_{N_a} > 0$.

In general, K_R can be parametrized [37] in the following way

$$K_R = U_1 U U_2, (20)$$

where $U_1 = \mathrm{diag}(1, e^{i(\alpha_{23}-\alpha_{13})}, e^{i(\alpha_{33}-\alpha_{13})})$ and $U_2 = \mathrm{diag}(e^{i\alpha_{11}}, e^{i\alpha_{12}}, e^{i\alpha_{13}})$ while

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \quad (21)$$

and c_{rs}, s_{rs} stand for $\cos\theta_{rs}$ and $\sin\theta_{rs}$ respectively.

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