Rare Processes as a Window Into Extra Dimensions

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Abstract.
We have studied manifestation of extra dimensions in rare processes. The study of flavour changing processes (rare processes) offer by far the most sensitive and uncontroversial test for extra-dimensional extensions of the standard model(SM). Before their direct detection on collider beyond SM effects may manifest themselves in rare processes. Our attention was devoted to lepton flavour violation processes and neutral B-meson double radiative decays in frame of extra dimensional models. Numerical estimates show that in case of B-meson double radiative decays we can get a difference from SM-result as much as ~40%. We thus hope that not too much time will pass until this difference will be accessible for experimental analysis.

We have detailed investigated the role of extra dimensions and mini black holes in the lepton flavour violation processes. We have estimated lepton flavour violation processes rates and concluded that three body decays seem more favourable then radiative one. On the other hand the search for l→3l decays could be more favourable by some experimental reasons even if Br(l→3l) is less than Br(l→lγ).

Introduction

With the wealth of new and upgraded experimental facilities able to cover the precision tests of the Standard Model (SM) is ever promising. The new facilities like BaBar at SLAC and Belle at KEK generate asymmetric e^+e^- collisions to trace the B-physics more accurately than before. On the other hand, the symmetric e^+e^- collision facility of CLEO-III at Cornel University has also upgraded its luminosity by a factor of ~10 better. Furthermore, the hadron-hadron collision facilities such as LHCB at CERN and BTEV at FERMILAB as well as lepton-hadron machine HERA-B at DESY emerge as the powerful tools for detailed investigation of a lot of B-decays. Finally, possible realization of the plans on SuperB – a highest luminosity Flavor Factory at Frascaty or (and) KEK seems to be the most powerful battlement towards B-physics exploration.

The recent successes of the Standard Model do not weaken the arguments in favour of New Physics at the TeV scale. Finding and identifying it represents the prime challenge for a generation of high energy physicists. To differentiate between different scenarios of New Physics we need to analyze their impact on flavour dynamics. A continuing comprehensive program of heavy flavour studies instrumentalizing the high sensitivity of analyses is intrinsically connected to core mission of the above mentioned facilities. The article is organized as follows: in the section 1 we presented full ACD contributions into $B_{s,d} \to \gamma\gamma$ amplitudes and CP asymmetry parameter in these processes; section 2 is devoted to the lepton flavour violation in frame of extra dimension models.

1. $B_{s,d} \to \gamma\gamma$ in the ACD model with one extra dimension

The exploration of B-physics, including rare decays of B-mesons, are one of the central issues of the physics programs at running and forthcoming accelerator facilities. The process $B_{s,d} \to \gamma\gamma$, which is subject of this paper, has a clean experimental signature: the final photons will be easily detected in the experiments. It would be noted that the two final photons produced in this process may be both in a CP-even state and in a CP-odd one. This circumstance provides a nontraditional source for CP-violation in B-physics. This latter issue of CP study is one of the burning questions not only of the Flavor Dynamics study in B-physics, but has much more fundamental importance with its diverse real and potential manifestations in general both in frames of SM and New Physics [1].

The process $B_{s,d} \to \gamma\gamma$ is sensitive to effects beyond the Standard Model (BSM). The experimental interest to this decay caused by its clean signature stimulates efforts of theoretical groups as well [2-19]. In particular $B_{s,d} \to \gamma\gamma$ was calculated in the framework of the SM with and without QCD corrections, in multi-Higgs doublet models, and in supersymmetric models.

It is known, that in the SM the double radiative decays of the $B_{s,d}$ mesons, $B_{s,d} \to \gamma\gamma$, first arise at the one loop level with the exchange in the loops by up-quarks and W-bosons. Branching ratios for above decays are of the order of ~ $10^{-7}(10^{-9})$ in frame of the SM.

On the other hand there is possibility to modify above mentioned decays in extended versions of the SM. It was shown that in extended versions of the SM (multi-Higgs doublet models, supersymmetric models) one could reach a branching ratio as large as $Br(B_s \to \gamma\gamma) \sim 10^{-6}$ depending on the parameters of the models. This enhancement was achieved mainly due to exchange of charged scalar Higgs particles within the loop. There exists an analogous possibility in other exotic models as well for the scalar particle exchange in the loop, which could potentially change this process. For example, the Appelquist, Cheng and Dobrescu (ACD) model with only one universal extra dimension [20] presents us with such an opportunity. One should note that in the above approach towers of charged Higgs particles arise as real objects with certain masses, not as fictitious (ghost) fields. The modern models [20, 23-26] with extra space-time dimensions have received a great deal of attention because the scale at which extra dimensional effects can be relevant could be around a few TeV. The first proposal for using large (TeV) extra dimensions in the SM with gauge fields in the bulk and matter localized on the orbifold fixed points was developed in Ref. [27]. Models with extra space-time dimensions can be constructed in several ways. Among them the following major approaches are most remarkable: i) the ADD model of Arkani-Hamed, Dimopoulos and Dvali [23]; in this approach all elementary particles except the graviton are localized on the brane, while the graviton propagates in the whole bulk; ii) the RS model of Randal and Sundrum with a warped 5-dimensional space-time and nonfactorized geometry [25,26]; iii) the ACD model of Appelquist, Cheng and Dobrecu (so called Universal Extra Dimensional model), where all the particles move in the whole bulk [20]. It is this latter type of model, that we will consider in the following.

In the papers [21,22] we have calculated the contributions of real scalars $a_{(n)}$ (which exists as a towers of charged scalar particles in the framework of ACD model of Universal Extra Dimension [20]) to the $B_{s,d} \to \gamma\gamma$ decays. This time we aim to investigate full ACD contributions into above mentioned processes. These contributions are due to exchange of $a_{(n)}$ and $G_{(n)}$ scalar towers and towers of W-bosons $W_{(n)}$ in the appropriate loops. The Feynman graphs describing the contributions of the particles $a_{(n)}$, $G_{(n)}$ and $W_{(n)}$ to the processes under consideration are shown schematically in Fig.1.

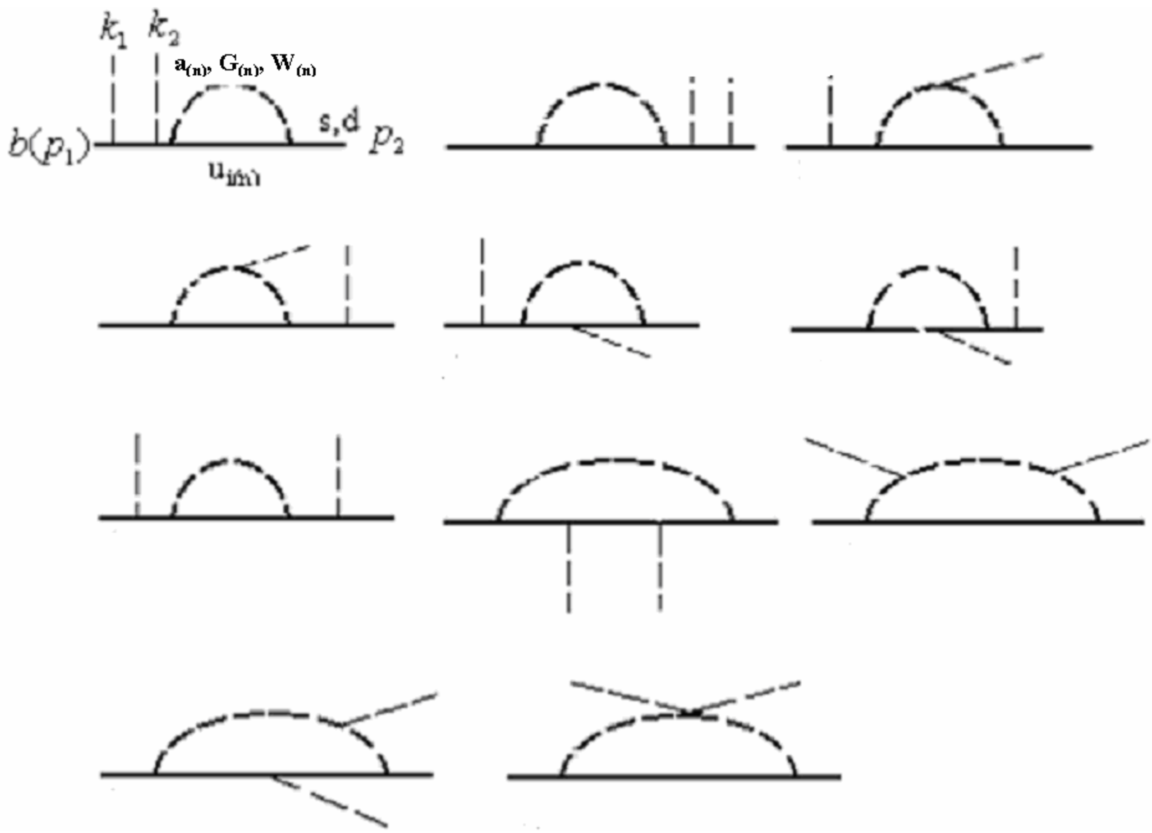

Fig.1. Double radiative B-meson decay $B_{s,d} \to \gamma\gamma$ in frames of ACD model.

The dashed lines in the loops correspond to the charged KK towers of $a_{(n)}$, $G_{(n)}$ and $W_{(n)}$, while the solid lines in the loops are for the up-quark KK towers.

The amplitude for the decay $B_{s,d} \to \gamma\gamma$ has the form

$$T(B \to \gamma\gamma) = \varepsilon_1^{\mu}(k_1)\varepsilon_2^{\nu}(k_2)[Ag_{\mu\nu} + iB\varepsilon_{\mu\nu\alpha\beta}k_1^{\alpha}k_2^{\beta}]. \tag{6}$$

This equation is correct after gauge fixing for final photons which have chosen as [2,5,8,9]

$$\varepsilon_1 \cdot k_1 = \varepsilon_1 \cdot k_2 = \varepsilon_2 \cdot k_2 = \varepsilon_2 \cdot k_1 = 0, \tag{7}$$

where ε_1 and ε_2 are photon polarization vectors, respectively [2,5,8,9]. The condition Eq.(7) together with energy-momentum conservation leads to

$$\varepsilon_i \cdot P = \varepsilon_i \cdot p_1 = \varepsilon_i \cdot p_2 = 0, \tag{8}$$

where

$$P = k_1 + k_2 \text{ and } p_1 = p_2 + k_1 + k_2. \tag{9}$$

The total contributions into CP-even (A) and CP-odd (B) amplitudes from Eq.(6) are calculated as sums of the appropriate contributions of the diagrams in Fig.1, corresponding to the contributions of the particles $a_{(n)}$, $G_{(n)}$ and $W_{(n)}$ in the ACD model with only one extra dimension. Let us note that we used following formula for the hadronic matrix elements:

$$\left\langle 0 \middle| \bar{s}(\bar{d})\gamma_{\mu}\gamma_5 b \middle| B(P) \right\rangle = -if_B P_{\mu} \ . \tag{11}$$

Apart from one particle reducible (1PR) diagrams, one particle irreducible (1PI) ones contribute to the amplitudes, and hence, to their CP-even (A) and CP-odd (B) parts. We should note that each of the 1PI contributions is finite. Let us discuss these contributions in more details. In the SM only one 1PI diagram (one with the W-boson exchange in the loop, when both photons are emitted by virtual up-quarks) gives the contribution of the order of $\sim 1/M_W^2$. In Ref. [29] it was observed that diagrams with light quark exchange contribute as $\sim 1/M_W^2$, while diagrams containing the heavy quarks are of order of $\sim 1/M_W^4$. In the ACD model the contributions of such diagrams are of the order of $\sim 1/M_W^4$ because the estimate for all KK-tower masses , including the ones exchanged in the loops, in our case are $M \geq 250\,\text{GeV}$ [28, 30]. Likewise discussions show that all the 1PI diagrams existing in the ACD model also are of order $\sim 1/M_W^4$. Thus, the leading 1PI diagrams are negligible and we do not consider them.

The total contributions to the $B \to \gamma\gamma$ decay amplitudes are:

$$A_{ACD} = i\frac{\sqrt{2}}{32\pi^2}(eQ_d)^2 f_B G_F \frac{m_b^3}{m_{s(d)}} \frac{M_W^2}{M_{W(n)}^2} V_{ib} V_{is(d)}^* \left\{ C(x_{i(n)}) - 12\frac{m_i m_{i(n)}}{M_W^2} c_{i(n)} s_{i(n)} f_1(x_{i(n)}) - \right.$$
$$\left. \frac{3}{2} f_2(x_{i(n)}) \left(1 + \frac{m_i^2}{M_W^2} - 2\frac{m_b m_{s(d)}}{M_{W(n)}^2} \frac{n^2}{R^2 M_W^2} \right) \right\},$$
$$B_{ACD} = \frac{2}{m_b^2} A, \tag{12}$$

where

$$C(x) = \frac{22x^3 - 153x^2 + 159x - 46}{6(1-x)^3} + \frac{3(2-3x)x^2 \ln x}{(1-x)^4},$$
$$f_1(x) = \frac{5x-3}{6(1-x)^2} + \frac{3x-2}{3(1-x)^3}\ln x, \quad f_2(x) = \frac{2x^2+5x-1}{6(1-x)^3} + \frac{x^2}{(1-x)^4}\ln x,$$
$$x_{i(n)} = \frac{m_{i(n)}^2}{M_{W(n)}^2}. \tag{13}$$

As it is obvious from Fig.1 the correct calculation assumes the inclusion of the crossed diagrams (not shown on Fig.1). In the kinematics we use, cf. Eqs.(7)-(10) this leads to a factor 2 for all amplitudes for the one given by diagram 11. However, diagram 11 belongs to the class of 1PI diagrams. As it was stated above, one particle irreducible diagrams does not give leading contributions into process and therefore their contributions ($\sim 1/M_W^4$) are negligible comparing with that of the 1PR diagrams.

On the other hand, using the unitarity feature of the CKM matrix, the amplitude for double radiative B-meson decay can be rewritten as:

$$T = \sum_{i=u,c,t} \lambda_i T_i = \lambda_t \left\{ T_t - T_c + \frac{\lambda_u}{\lambda_t}\left(T_u - T_c\right) \right\}, \tag{14}$$

where $\lambda_i = V_{ib} V_{is(d)}^*$.

Let us note that we restricted ourselves by calculating the leading order terms of $\sim 1/M_W^2$ from the up-quark KK-towers. In this approximation it turns out that the $u_{(n)}$ and $c_{(n)}$ towers have equal contributions. Therefore, the expressions for the amplitudes have a simpler form than before:

$$A = \lambda_t\left(A_{t(n)} - A_{c(n)}\right), \quad B = \lambda_t\left(B_{t(n)} - B_{c(n)}\right). \tag{15}$$

Furthermore, it is easy to obtain from Eq.(6) the expression for the $B \to \gamma\gamma$ decay partial width and CP-asymmetry parameter:

$$\Gamma(B\to\gamma\gamma)=\frac{1}{32\pi M_B}\left[4|A|^2+\frac{1}{2}M_B^4|B|^2\right]$$
$$\delta=\frac{4|A|^2}{4|A|^2+\frac{1}{2}M_B^4|B|^2} \tag{16}$$

Now we are in the position to compare the ACD contribution to the decay $B\to\gamma\gamma$ with that of the SM. For the completeness let us write down the expressions for the CP-even and CP-odd parts of the $B_{s,d}\to\gamma\gamma$ decays which was calculated in frames of SM earlier [2-19]:

$$A_{SM}=i\frac{\sqrt{2}m_b^3}{32\pi^2 m_{s(d)}}G_F f_B(eQ_d)^2\lambda_t(C(x_t)+\frac{23}{3})$$
$$B_{SM}=i\frac{2\sqrt{2}m_b}{32\pi^2 m_{s(d)}}G_F f_B(eQ_d)^2\lambda_t(C(x_t)+\frac{23}{3}+16\frac{m_{s(d)}}{m_b}) \tag{17}$$

where C(x) is defined inEq.(13) and $x_t=m_t^2/M_W^2$.

As our calculation shows :

$$\frac{\Gamma_{SM+ACD}(B\to\gamma\gamma)}{\Gamma_{SM}(B\to\gamma\gamma)}=\left\{2\left[C(x_t)+\frac{23}{3}+\frac{M_W^2}{M_{W(n)}^2}\left(C(x_{t(n)})-C(x_{c(n)})-\right.\right.\right.$$
$$\left.\left.6\frac{m_t m_{t(n)}}{M_W^2}\sin 2\alpha_{t(n)}f_1(x_{t(n)})-\frac{3}{2}f_2(x_{t(n)})(1+\frac{m_t^2}{M_W^2})+\frac{3}{2}f_2(x_{c(n)})\right)\right]^2+$$
$$\frac{M_B^4}{m_b^4}\left[C(x_t)+\frac{23}{3}+16\frac{m_{s(d)}}{m_b}+\frac{M_W^2}{M_{W(n)}^2}\left(C(x_{t(n)})-C(x_{c(n)})-6\frac{m_t m_{t(n)}}{M_W^2}\sin 2\alpha_{t(n)}f_1(x_{t(n)})-\right.\right.$$
$$\left.\left.\left.-\frac{3}{2}f_2(x_{t(n)})(1+\frac{m_t^2}{M_W^2})+\frac{3}{2}f_2(x_{c(n)})\right)\right]^2\right\}/$$
$$\left\{2\left[C(x_t)+\frac{23}{3}\right]^2+\frac{M_B^4}{m_b^4}\left[C(x_t)+\frac{23}{3}+16\frac{m_{s(d)}}{m_b}\right]^2\right\} \tag{18}$$

Numerical estimate of Eq.(18) leads that $\Gamma_{SM+ACD}(B\to\gamma\gamma)/\Gamma_{SM}(B\to\gamma\gamma)\approx 0.59$ in case when $1/R\approx 250\,\text{GeV}$. With decreasing of the compactification radius the above mentioned ratio becomes close to unity (the results are shown on Fig.2).

What about CP-asymmetry parameter δ [4,5] in frame of ACD model

$$\frac{\delta_{SM+ACD}}{\delta_{SM}}=\left[C(x_t)+\frac{23}{3}+\frac{M_W^2}{M_{W(n)}^2}\left(C(x_{t(n)})-C(x_{c(n)})-6\frac{m_t m_{t(n)}}{M_W^2}\sin 2\alpha_{t(n)}f_1(x_{t(n)})-\right.\right.$$
$$\left.\left.-\frac{3}{2}f_2(x_{t(n)})(1+\frac{m_t^2}{M_W^2})+\frac{3}{2}f_2(x_{c(n)})\right)\right]^2\left[C(x_t)+\frac{23}{3}\right]^{-2}$$
$$\left\{2\left[C(x_t)+\frac{23}{3}\right]^2+\frac{M_B^4}{m_b^4}\left[C(x_t)+\frac{23}{3}+16\frac{m_{s(d)}}{m_b}\right]^2\right\}$$

$$\left\{2\left[C(x_t)+\frac{23}{3}+\frac{M_W^2}{M_{W(n)}^2}\Big(C(x_{t(n)})-C(x_{c(n)})-\right.\right.$$

$$\left.\left.6\frac{m_t m_{t(n)}}{M_W^2}\sin 2\alpha_{t(n)} f_1(x_{t(n)})-\frac{3}{2}f_2(x_{t(n)})(1+\frac{m_t^2}{M_W^2})+\frac{3}{2}f_2(x_{c(n)})\Big)\right]^2+$$

$$\frac{M_B^4}{m_b^4}\left[C(x_t)+\frac{23}{3}+16\frac{m_{s(d)}}{m_b}+\frac{M_W^2}{M_{W(n)}^2}\Big(C(x_{t(n)})-C(x_{c(n)})-6\frac{m_t m_{t(n)}}{M_W^2}\sin 2\alpha_{t(n)} f_1(x_{t(n)})-\right.$$

$$\left.\left.-\frac{3}{2}f_2(x_{t(n)})(1+\frac{m_t^2}{M_W^2})+\frac{3}{2}f_2(x_{c(n)})\Big)\right]^2\right\}^{-1} . \qquad (19)$$

numerical estimate of the expression (19) shows that in case of $1/R \approx 250$ GeV we have $\delta_{SM+ACD}/\delta_{SM} \approx 0.8$ and the above mentioned ratio becomes close to unity with decreasing of the compactification radius (Fig.3).

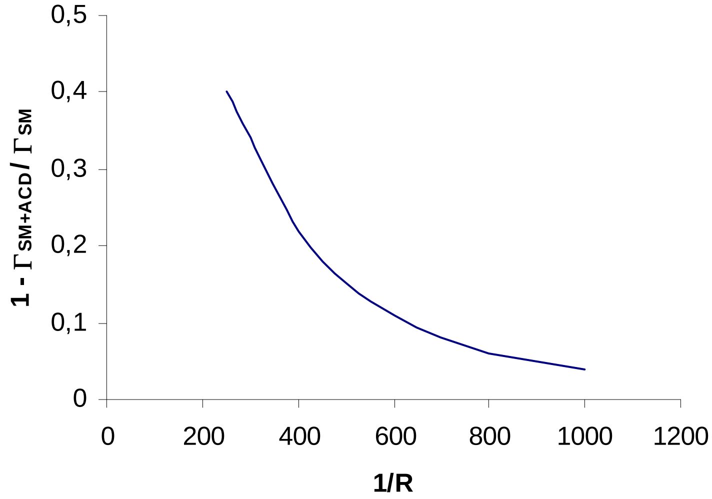

Fig.2. B-meson double radiative decays width in frames of ACD model.

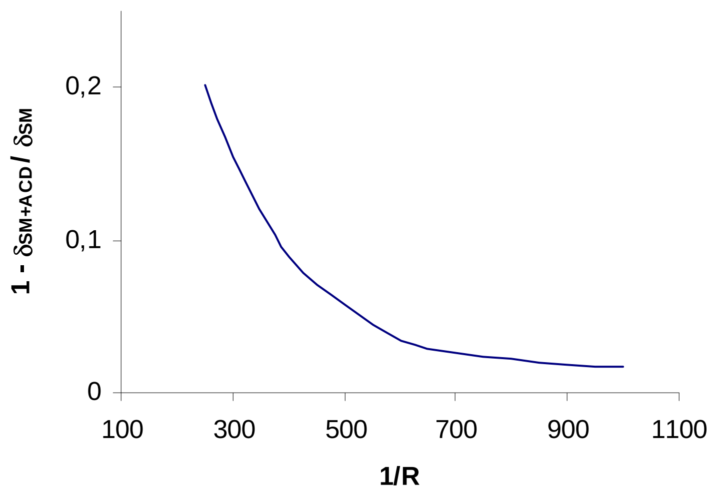

Fig.3. CP-asymmetry parameter δ for B meson double radiative decay in frame of ACD model.

2. Lepton flavour violation in the extra dimensional models

Lepton flafour violation (LFV) processes first arise in the Standard Model (SM) with neutrino mixing as the one loop level. Hence they have typical suppression factor m^2/M^2 (where m are masses of leptons running in the loop). Because of such a strong suppression factor those processes stay out experimental limitations. On the other hand just those processes would be very sensitive to the New Physics (NP) beyond the SM (BSM), because of some possible mechanism which enhance them.

In some extensions of the SM the rates of LFV processes enhance and become close to the modern experimental limitations. Important goal of forthcoming experiments is the search for such LFV phenomena. This latter inspires theoretical investigations in this direction as well.

The goal of this note is just the analysis of LFV processes via intermediate black hole in the large extra dimension scenario. Namely, our attention will be devoted to $l\to 3l$ and $l\to l\gamma$ decays. This interest is caused by forthcoming PSI experiment (on μ–decays on the planed level of branching ratio $\sim 10^{-14}$) and the interest of the hep society to τ/charm factories.

It is interesting that usual hierarchy of $l\to l\gamma$ and $l\to 3l$ decays seems like $Br(l\to l\gamma)>Br(l\to 3l)$. It is not excluded vice-versa situation in some BSM approaches, which could be interesting from the point of view NP. On the other hand, the search for $l\to 3l$ decays could be more favourable by some experimental reasons even if $Br(l\to 3l)$ is less than $Br(l\to l\gamma)$. In this aspect even more intriguing would be situation with the hierarchy $Br(l\to 3l)>Br(l\to l\gamma)$. This case is just the situation which could be predicted by the case of LFV via intermediate black hole processes in the large extra dimension scenario.

Black holes of the effective Planck range $M_{Pl}\sim 1$ Tev naturally arisen in extra dimension theories [20, 23-26]. LHC is considered as a factory for TeV scale black holes ($M_{bh}\sim 1$TeV). We can accept the conjecture that black holes violate global symmetries including lepton number. So, black holes could manifest themselves in LFV processes as intermediate states and enhance $l\to 3l$, $l\to l\gamma$, which are suppressed in frame of SM with massive neutrinos. We assume that black holes with mass lighter than effective Planck mass have a zero charges (electric, color) and zero angular moment in the classical case and this future is adopted by quantum gravity too.

LFV processes are intensively investigated in large extra dimension scenarios [32, 33]. As these studied show in case when theoretical approaches are not enriched other way than simply adding extra dimension to the SM, there is hard to get theoretical predictions close to experimental bounds. From common theoretical sense it is expected that LFV processes would possible enhance in case when particles running in the appropriate loops have close masses. This situation was expected in UED scenario. In this case quadratic GIM suppression factor changed by linear one in terms of particles towers masses. This situation is realized in the ACD model, but when we go from the tower mass parameters to the SM mass parameters, this enhancement seems to be false and we have no considerable enhancement of LFV processes [33].

Loop amplitudes with comparable mass of intermediate fermions and scalar bosons running in the loop seem to be quite large because the generic quadratic suppression factor is changed to a linear one. Such a situation with comparable masses in principle is realizable in the models with universal extra dimensions. On the other hand it is not obvious without specific calculations how would be changed the SM estimate of the above processes in the models with universal extra dimensions. Some details of the models can enhance suitable amplitudes and others can cause suppression. It is impossible to estimate summary effects of this interplay without specific calculations. We have calculated the relevant Kaluza-Klein contributions to $l\to l\gamma$. On general grounds, one expects an enhancement of this amplitude. We show that this expectation is not fulfilled because of the almost degeneracy of the massive neutrino towers modes from different generations [33].

In the paper [34] detailed investigation of the role of black holes in the LFV processes is considered. It were estimated $l\to 3l$, $l\to l\gamma$ rates and mentioned that three body decays seem more

favorable then radiative ones. It was noted that predictions for the cross section for LFV processes $e^+ e^- \rightarrow \mu e$ and $Br(\mu \rightarrow 3e)$ are surprisingly close to experimental limits.
The same predictions for the black hole intermediate state contributions in frame of [35] estimated by us shows that enhance $l \rightarrow 3l$ is more favorable than enhance $l \rightarrow l\gamma$.

Conclusion.

We have discussed one of the windows towards the theoretical avenue of New Physics manifestation. The experimental success of SM is very impressive during decades after its establishment as a Bible of HEP: at least yet we know only experimental derivation from “standard thinking” due to discovery of finite neutrino masses in various neutrino oscillation experiments. That is why there is important to know, how massive and at which extent of confidence level would be an experimental interventions of New Physics beyond SM in all sectors of HEP knowledge, including the modern models [20,23-26] with large extra space-time dimensions. Large Extra Dimensions are well motivated theoretically; Large Extra Dimensions and low scale quantum gravity effects are at reach at present (Tevatron) and future colliders (LHC); Large Extra Dimensions have unambiguous experimental signatures; Large Extra Dimensions can also help to solve theoretical Particle Physics problems; If Large Extra Dimensions will found at LHC or somewhere else it would possibly constitute the most important revolution in the History of Particle Physics and not only in physics.

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