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Decoupled SUSY-SU(5) and Proton Decay: The role of flavor violation

Priyanka Lamba[a,*]

[a] *Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, ul. Pasteura 5, PL-02-093 Warsaw, Poland,*

E-mail: priyanka.lamba@fuw.edu.pl

We show that assuming flavor violation in the first two generations of sfermions in the decoupling limit leads to interesting consequences for proton decay in minimal SUSY-SU(5). We assume that decoupling sfermions lie within 30 TeV. The decay mode $p \to e^+\pi^0$, which usually has sensitivity beyond that of DUNE and Hyper K is brought within the reach of these experiments due to the flavor mixing. The most dominant decay mode in minimal SUSY-SU(5) is $p \to K^+\bar{\nu}_e$ which essentially rules this model out for this range of masses, is now able to survive due to cancellation from flavor mixing and further interestingly can be explored at DUNE and HyperK. Finally, partial decoupling has interesting consequences for the mode $p \to K^+\bar{\nu}_\tau$ and becomes the most constrained mode.

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1. Indroduction

Proton decay is one of the most important signatures of baryon number violation. Baryon number violation is the most impressive prediction of GUT models. As we know the GUT scale energy is not attainable by accelerators. However it can be indirectly probed through proton decay measurements. The discovery of proton decay would indicate physics beyond Standard Model and perhaps towards a Grand Unified Theory (GUT). A typical grand unified theory is based on simple groups like SU(5) or SO(10). SU(5) is a minimal simple gauge group which unifies all SM gauge couplings and has additional gauge bosons which are typically called X and Y bosons which carry both color and weak indices. Thus they can lead to transitions between quarks and leptons at the same vertex, leading to baryon number violation. These typically lead to six dimensional baryon number violating operators in effective field theory, after integrating out the GUT gauge bosons. Supersymmetric SU(5) on the other hand, also allows for dimension five operators which leads to fast proton decay. The main decay mode of proton decay $p \rightarrow K^+\bar{\nu}$ in SUSY-SU(5) GUT has been searched for and continues to be searched for in various underground neutrino experiments. In fact, for supersymmetric particles of about a few TeV, the proton decay bounds coming from Kamioka and IMB experiments have ruled out the minimal SUSY-SU(5) model. However, these models can be rescued if one concentrates on regions where there are peculiar cancellations taking place in the proton decay matrix elements or there are high threshold corrections which modify the GUT scale. There are a lot of detailed analyses on the proton decay in the minimal SUSY-GUT models[1–5]. One of the famous statements during that time was that "Not even decoupling can save SUSY SU(5)". This was by Murayama and Pierce who pointed out that even if you decouple the first two generations of squarks the stability of the proton is not going to increase[6]. Further Murayama and Arkani-Hamed have shown that in the presence of decoupling, some of the masses could become tachyonic (especially the third generation) due to renormalization group running[7]. Thus decoupling does not fit in naturally within the framework of Grand Unified theories. The proton decay computations have been refined over the years with both LLLL and RRRR operators being taken into consideration by Goto *et. al* [4] and also by Shirai *et. al* [8]. A review can be found by Pran Nath *et. al*[9]. A recent computation on heavy supersymmetry in SUSY SU(5) can be found by Lavignac and Bajc[10]. In the mean time, there have several developments in the field: 1) Higgs has been discovered with a mass of 125 GeV, 2) LHC has not found supersymmetric particles and in fact all the evidence including flavor and dark matter seems to be pointing towards a decoupling scenario 3) Super-K limits on proton decay have become stronger 4) The constraints on WIMP dark matter have become particularly strong. All these aspects seem to point towards supersymmetry parameter space which is either partially or fully split [11] (Dimopoulos *et. al*) or a generational split in the supersymmetric parameter space [12]. The other reason to look back into these results is more phenomenological. There are at least three new experiments which will be looking for proton decay in this decade. These experiments are sensitive to at least two important modes of proton decay leading to an improvement of factor of 5 to an order of magnitude in the limits. The present and upcoming limits on two main decay modes are shown in Table. 1.

DUNE and Hyper-K are complementary experiments for neutrino physics. DUNE is more sensitive to the mass hierarchy, due to large effects of matter because of long baseline as compared to Hyper-K, which has shorter baseline that has less matter effect, but will have increased sensitivity

p Decay Modes	Partial mean life (10^{33} years)		
	Current (90% CL)	**Future (3σ discovery)**	**Future (90% CL)**
$p \to \pi^0 e^+$	16 [13]	DUNE: 15 (25) [14]	DUNE: 20 (40) [14]
		Hyper-K: 63 (100) [14]	Hyper-K: 78 (130) [14]
$p \to \pi^0 \mu^+$	7.7 [13]	Hyper-K: 69 [14]	Hyper-K: 77 [14]
$p \to K^+ \bar{\nu}$	5.9[15]	JUNO: 12 (20)[14]	JUNO: 19 (40)[16]
		DUNE: 30 (50)[14]	DUNE: 33 (65)[17, 18]
		Hyper-K: 20 (30)[14]	Hyper-K: 32 (50)[14]

Table 1: For future prospects, the detector operations are assumed for 10 (20) years [19].

to the measurements of the CP-violation phase. Hyper-K is more sensitive to proton decay channel $p \to \pi^0 e^+$ and $p \to K^+\bar{\nu}$. Hyper-K will have highest sensitivity to $p \to \pi^0 e^+$ till order of 10^{35} years but it will be challenging to detect the K^+ from nucleon decays in a water Cherenkov detector since its momentum is below the Cherenkov light threshold, thus only the decay products of K^+ can be used for the identification of K^+, so the expected limit on this channel is an order of magnitude lesser than $p \to \pi^0 e^+$ channel. The complementary experiment DUNE is also a sensitive to nucleon decay. Due to its smaller mass compared to Hyper-K, it is competitive mainly in modes with distinctive final state tracks such as those involving kaons. The improvement in lifetime limits expected for 10(20) years of Hyper-Kamiokande and DUNE exposure given in Table. 1. In this work, we revisited the minimal SUSY-SU(5) GUT model for generational spilt SUSY spectrum. We did full analysis including all LHC, Higgs mass, flavor, and dark matter experimental constraints on SUSY spectrum. We also studied proton decay with and without flavor violation.

2. The set up: SU(5) with sliding decoupling scale

Weak scale supersymmetry is highly constrained due to various experimental observations. Especially flavor changing processes, like ΔM_K, $b \to s\gamma$, $\mu \to e\gamma$, $\mu \to eee$ etc., either need highly degenerate first two generations of squarks, or some symmetry to suppress off-diagonal entries of squark masses matrices or very heavy first two generations of sfermions with masses around 50-100 TeV. From phenomenological point of view, we assume first two generations between a few TeV to 30 TeV and all other SUSY particles to be near weak scale. The schematic energy scale diagrams of split generation and effects of flavor mixing on splitting are presented in fig. (1). We cannot take first two generation sfermion masses arbitrarily large within this framework as it could lead to color and charge breaking minima (see section 3). We used the term “split-generation" for this case. In this section, we describe our notation for “split-generation" scenario. We define splitting parameters and mass matrices of sfermions at GUT scale where we define boundary values, and at TeV scale where we calculate the SUSY spectrum.

At M_{GUT}, we specify the boundary values for the soft masses (defined in the so-called super-CKM basis, in which the up-type quark mass matrices are diagonal and squarks are rotated parallel

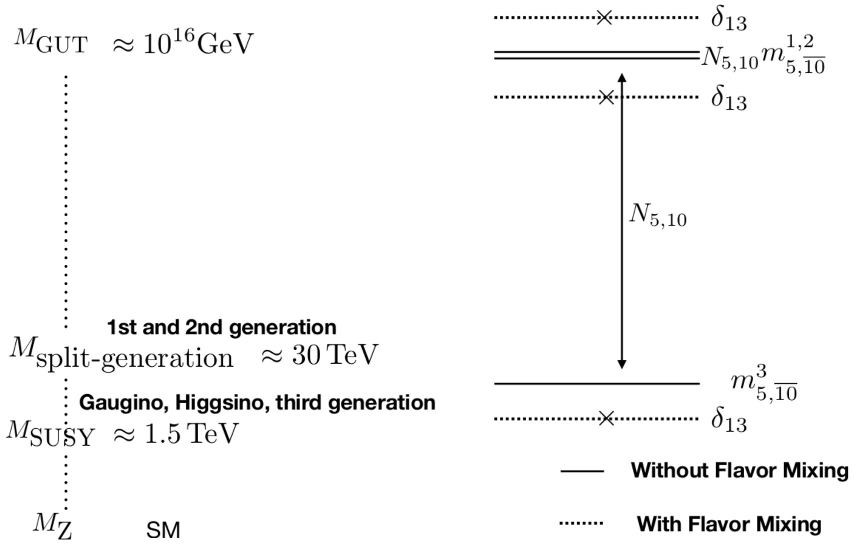


Figure 1: Illustration of scales and scalars generation separation.

to their superpartners) as follows:

$$m^2_{\tilde{Q}} = m^2_{10}\begin{pmatrix} 1 & 0 & \delta^{10}_{13}/N_{10} \\ 0 & 1 & 0 \\ \delta^{10}_{13}/N_{10} & 0 & 1/(N_{10})^2 \end{pmatrix} \tag{1}$$

$$m^2_{\tilde{d}} = m^2_{\bar{5}}\begin{pmatrix} 1 & 0 & \delta^{\bar{5}}_{13}/N_{\bar{5}} \\ 0 & 1 & 0 \\ \delta^{\bar{5}}_{13}/N_{\bar{5}} & 0 & 1/(N_{\bar{5}})^2 \end{pmatrix} \tag{2}$$

(Q, u, e) superfields are elements of same 10-plet supermultiplet of SU(5). Similarly (d, L) superfields are also elements of same 5-plet supermultiplet of SU(5). In SUSY SU(5), mass matrices at the GUT scale have following relations:

$$m^2_{\tilde{Q}} = m^2_{\tilde{u}} = m^2_{\tilde{e}} \quad ; \quad m^2_{\tilde{d}} = m^2_{\tilde{L}} \tag{3}$$

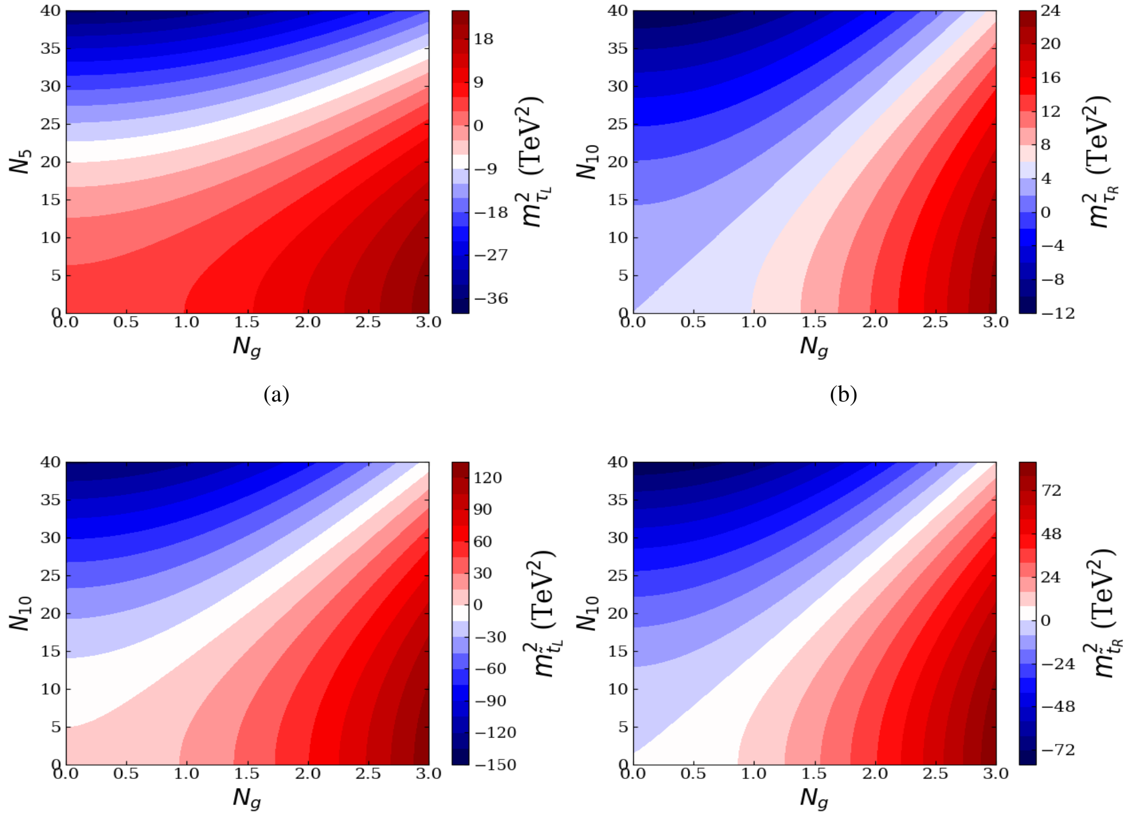
where,

$$\delta_{13} = \frac{m^2_{13}}{\sqrt{m^2_1 m^2_3}} = \frac{m^2_{13}N}{\sqrt{m^2_0 m^2_0}} = \frac{m^2_{13}N}{m^2_0} \quad\implies m^2_{13} = \frac{\delta_{13}m^2_0}{N} \tag{4}$$

where N is splitting between first generation to third generation masses at GUT scale.

3. How decoupled should the first two generation scalars be?

Here, we analytically study the allowed splitting between the generations. The soft square masses at the weak scale in terms of GUT scale parameters are determined by the RGEs, including



(a) (b) (c) (d)

Figure 2: Soft mass square parameters for $\tilde{\tau}_{L/R}$ and $\tilde{t}_{L/R}$ at low scale as a function of N_g and $N_{5,10}$.

the heavy scalar contribution at the two-loop level ref. [7, 20]. We take $m_{\tilde{t}}(GUT) = m_{H_u}(GUT) = A_t(GUT)/\sqrt{3}$. Soft mass squares of stop and stau at the weak scale are:

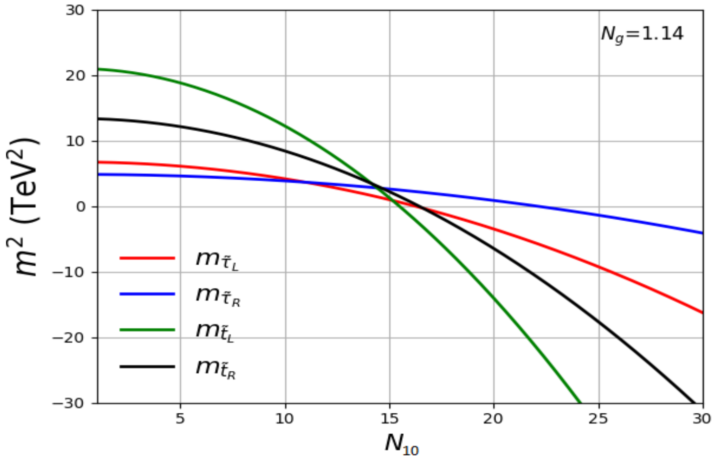
$$m^2_{\tau_L}(N_g, N_5) = 4(1 + 0.519N_g^2 - 0.006382N_5^2) \tag{5}$$

$$m^2_{\tau_R}(N_g, N_{10}) = 4(1 + 0.159N_g^2 - 0.002488N_{10}^2). \tag{6}$$

$$m^2_{\tilde{t}_L}(N_g, N_{10}) = 4(0.511 + 0.1177N_g + 3.52N_g^2 - 0.021884N_{10}^2) \tag{7}$$

$$m^2_{\tilde{t}_R}(N_g, N_{10}) = 4(0.024 + 0.2372N_g + 2.33N_g^2 - 0.01239N_{10}^2) \tag{8}$$

These masses are plotted in terms of GUT scale splitting parameter in fig. 2. In these plots, x-axis is ratio of gluino mass to stop mass at GUT scale ($N_g = M_3/m_{\tilde{t}}$) and y-axis is ratio of first two generation sfermion masses which are degenerate at GUT scale to stop mass at GUT scale ($N_{10} = m_{1,2}/m_{\tilde{t}}$). Red contours have positive mass square values and blue contours have tachyonic spectrum. From fig. (2), we can see that with very large gluino mass, maximum splitting can be 40. In fig. (3) we choose $n_g = 1.1428$ which is approximate value for our case. In this plot x-axis in N_{10} and y-axis is square masses of third generation. From this plot we can say that max N_{10} value is in between 15-20, for which the spectrum is not tachyonic.



(a)

Figure 3: Soft mass square parameters for $\tilde{\tau}_{L/R}$ and $\tilde{t}_{L/R}$ at low scale as a function $N_{5,10}$ with fixed N_g.

Paramter	Range
m_{hu}, m_{hd}	$[-30, 30]$ TeV
$m_{10}, m_{\bar{5}}$	$[1, 30]$ TeV
$M_{1/2}$	$[0.7, 3]$ TeV
A_0	$[-8, 8]$ TeV
$N_{10}^1, N_{\bar{5}}^1$	$[1, 20]$
$\delta_{13}^{10}, \delta_{13}^{\bar{5}}$	$[-1, 1]$
$\tan\beta$	5

Table 2: Range of parameters values.

4. Results

We implement split-generation scenario in SuSeFlav code [21] which is a supersymmetric spectrum calculator. We interface the proton decay calculation routines with the adapted SuSeFlav version, where we implement modified two-loop beta functions in RGE and SUSY threshold, at two different scales (SUSY scale and first two generations sfermion scale).
We study the two scenarios, without flavor mixing ($\delta_{ij} = 0$) and with flavor mixing in first and third generation of 10-plet sfermion. We consider $m_{10} = m_{\bar{5}}, N_{10}^1 = N_{\bar{5}}^1$ and define sfermion matrix as given in eqs. (1-4) and consider only diagonal LR mixing in sfermion mass matrices. We consider generational splitting up to a factor of 20 but it could be even higher ~ 30 to 40 (with large gluino mass see fig. (2,3)). The splitting factor being larger than 40 leads to negative third generation sfermion masses because of two loop RGE effect of heavy first two generations. In all the figures, projected scanned points have Higgs mass (m_h) in 123-128 GeV range, gluino mass ($m_{\tilde{g}}$) > 2.2 TeV and stop mass ($m_{\tilde{t}}$) > 1.2 TeV. We study three important modes $p \to \pi^0 e^+$, $p \to K^+ \bar{\nu_\tau}$ and $p \to K^+ \bar{\nu_e}$ of proton decay in detail with and without flavor mixing, in split-generation scenario.

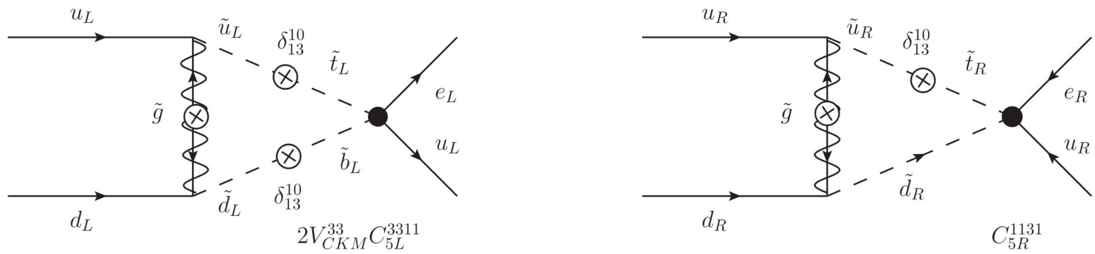


Figure 4: Gluino dressing diagram with δ^{10}_{13} insertion for $p \to \pi^0 e^+$.

For $p \to \pi^0 e^+$, future experiment providing highest sensitivity is Hyper-K [14] and for $p \to K^+\bar{\nu}$, DUNE experiment will be providing the highest sensitivity. In all figures, red line is for the highest future sensitivity and the black line is for current experimental bound.

In fig. (5(a)), we show the proton life time for $p \to \pi^0 e^+$ channel. The shaded yellow region is the contribution coming from dimension six baryon violating operators. The dominant contribution in the case of no flavor mixing comes from these dimension 6 operators and will be probed in future experiments. We can see that all the data points are much above the current and future experimental limits. In this process without flavor mixing, only the chargino dressing diagram is most relevant, which gives the highest contribution in LL and LR type of four fermion operators. With the GUT scale splitting, partial lifetime is not changing much, except in the very low N_{10} region; that is because of heavy degenerate spectrum which decreases the partial decay width (as also noticed by Shirai et. al). After including flavor mixing in fig. (5(b)), gluino dressing diagram (see fig. (4)) starts contributing in LL and RR four fermion operators and becomes the most dominating contribution that increases the partial decay width. This rules out a lot of parameter space from current and future experimental limits. In fig. (5(b)) we can see the overall partial decay width is increasing with increasing N_{10} but for very low value of N_{10} the allowed partial lifetime varies from 10^{24} upto 10^{40} years. This comes from the variation of δ^{10}_{13} value, see figs. (5(c) and 5(d)). Large value of δ^{10}_{13} for low value of N_{10} will destroy the degeneracy in the spectrum. Because of that, as shown in fig. (5(d)), partial life time is decreasing as $|\delta^{10}_{13}|$ is increasing. If we look at figs. (5(c), 5(d) and 5(e)), above the experimental limits there are both low and high δ^{10}_{13} value points. Large $\delta^{10}_{13} > 0.1$ have large N_{10} and low m_{10}. These points have a highly degenerate low energy spectrum (around 5 TeV) at weak scale (large LR and flavor mixing causes degenerate low energy spectrum even with large GUT scale splitting). For a low δ^{10}_{13}, large m_{10} with low N_{10} will again have a heavy, almost degenerate, spectrum that will increase partial lifetime. We also checked Br($\tau \to e\gamma$) w.r.t δ^{10}_{13} and found that there is no bound on our parameter space from the current experiments.

Without flavor mixing, the decay channel $p \to K^+\bar{\nu}_e$ is the most constrained channel in SUSY-SU(5) model and is well known in the literature. As we can see in fig. (6(a)), almost all points are ruled out by the current experimental bound, except for the low N_{10} regions (which leads to the heavy, almost degenerate, spectrum). Furthermore, the allowed points will be completely covered in future DUNE experiment. So this channel will either be seen in the near future experiments or null results will rule out flavor diagonal SUSY SU(5) scenario. In this process without flavor mixing, dominant contribution comes from chargino dressing diagram in both LL type four fermion operators $((ud)_L(s\nu)_L)$ and $((us)_L(d\nu)_L)$. In figs. (6(b)-6(e)), when we add δ^{10}_{13}, gluino and

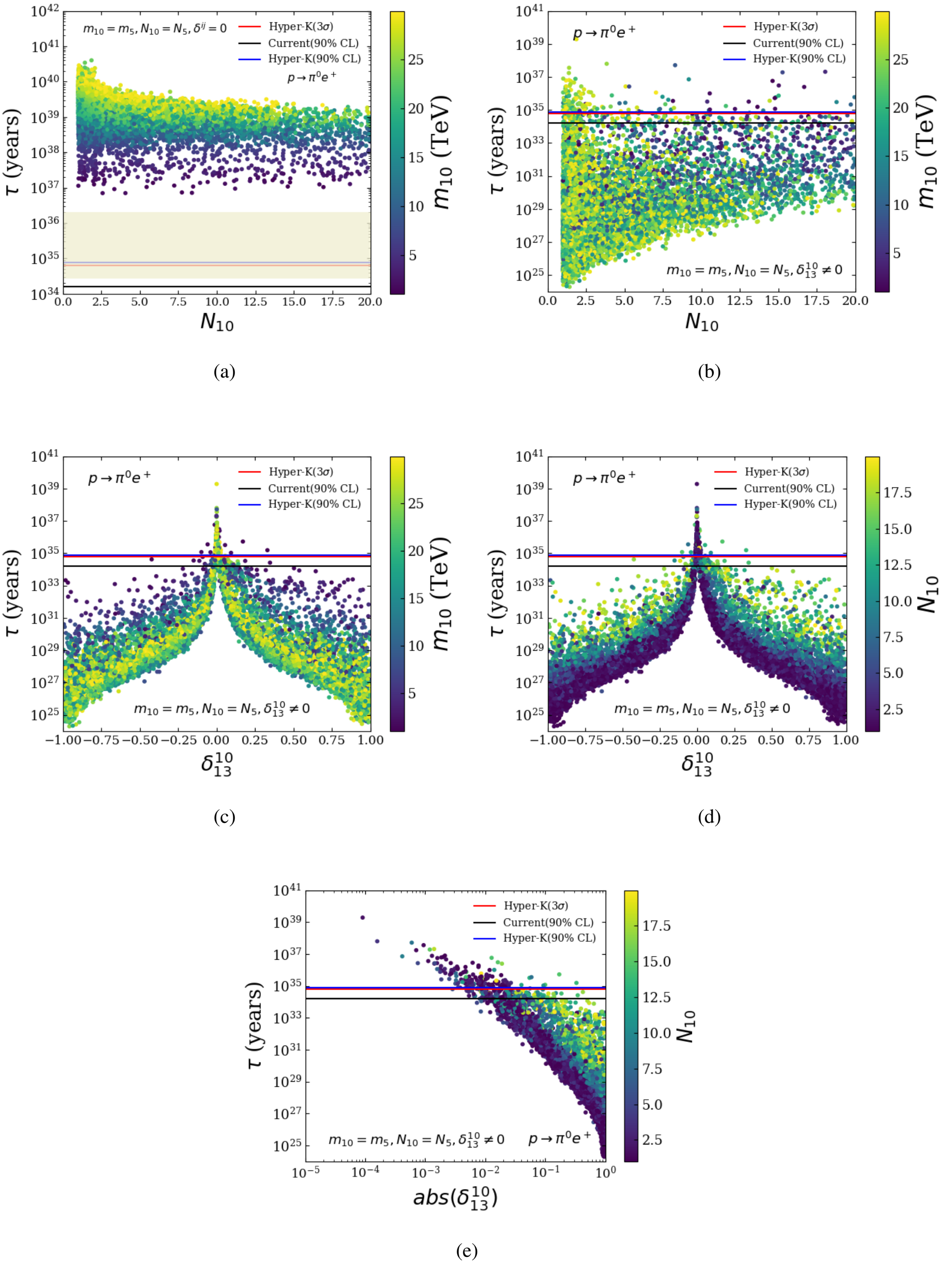


Figure 5: In these plots, we analyse proton decay mode $p \to e^+\pi^0$ with and without flavor mixing.

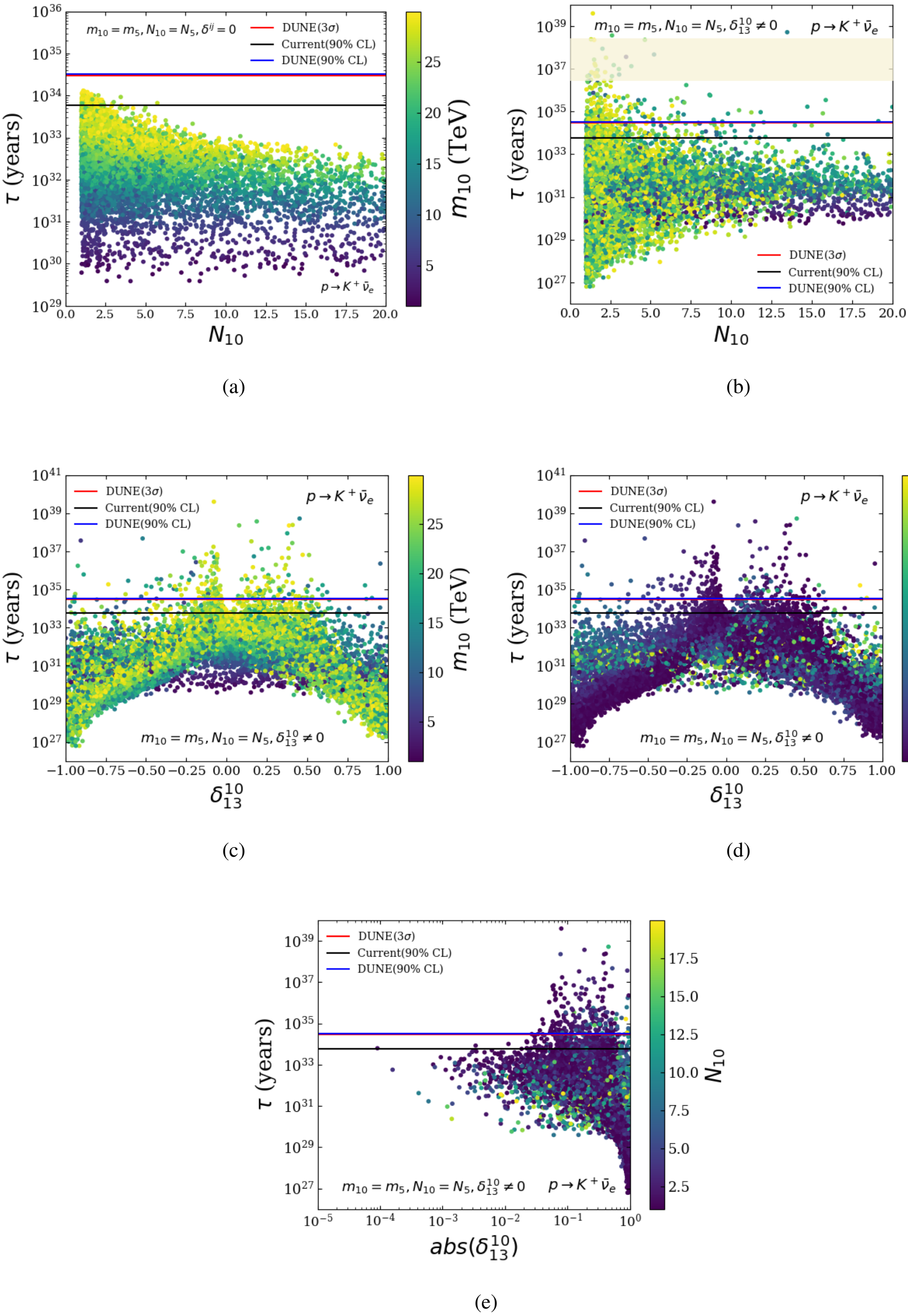


Figure 6: In these plots, we analyse proton decay mode $p \to K^+ \bar{\nu}_e$ with and without flavor mixing.

neutralino dressing contributions become relevant in addition to chargino contribution in both the above mentioned operators. These new contributions have opposite signs (depending on the sign of δ^{10}_{13} see in figs. (6(c) and 6(d)) w.r.t the chargino contribution which lead to both enhancement as well as cancellation in the decay rate see fig. (6(e)). Because of these peculiar cancellations, even order one low δ^{10}_{13} values are allowed by future sensitivity. In $p \to K^+\nu_\tau$ channel, because of relatively larger τ Yukawa coupling, chargino dressed diagram also contributes in RL fermion operators in addition to LL operator (present in the previous case). In fig. (7(a)), even without including flavor mixing, gluino and neutralino have relevant contribution in LL operators because tau have larger C_{5L}, C_{5R} contributions as compared to the electron case. So there is already a cancellation region in fig. (7(a)) even without adding flavor. Adding flavor will only increase overall magnitude of partial decay width, reducing the life time of proton, see fig. (7(b)).

5. Conclusion

In this work, we considered a novel decoupling scenario named 'split-generation'. We assumed the first and second generation sfermions to be heavy (order of 10s of TeV) and the remaining SUSY spectrum to lie around a few TeV. We studied proton decay rates (including contributions from both D=5 and D=6 operators) for two dominant channels ($p \to e^+\pi^0$ and $p \to K^+\bar{\nu}$) in minimal 'split-generation' SUSY-SU(5), both with and without flavor mixing in heavy and light (third) generation. The contribution of D=5 baryon number violating operators to the decay mode $p \to e^+\pi^0$ is usually beyond the reach of future experiments, but here it is brought within the reach of Hyper-K, DUNE and JUNO due to the flavor mixing that opens up the gluino contribution to the amplitudes. The most dominating decay mode $p \to K^+\bar{\nu}_e$ which essentially rules this model out for the range of masses we consider, is now able to survive and further interestingly can be explored at DUNE and Hyper-K due to peculiar cancellations in different dressing diagrams by introduction of flavor mixing. The split-generation in scalars has interesting consequences for the mode $p \to K^+\bar{\nu}_\tau$.

While we find parameter space points that satisfy the constraints from $p \to K^+\bar{\nu}_\tau$ and $p \to K^+\bar{\nu}_e$ separately, when taken together do not leave any allowed parameter space. But we find points near but below the boundary of these combined current limits which points towards a need to increase the SUSY scale or a more refined scan to look at the cancellation region with more statistics. We are studying this currently. We are also working on accounting for all other decay modes and with other flavor mixings (δ's).

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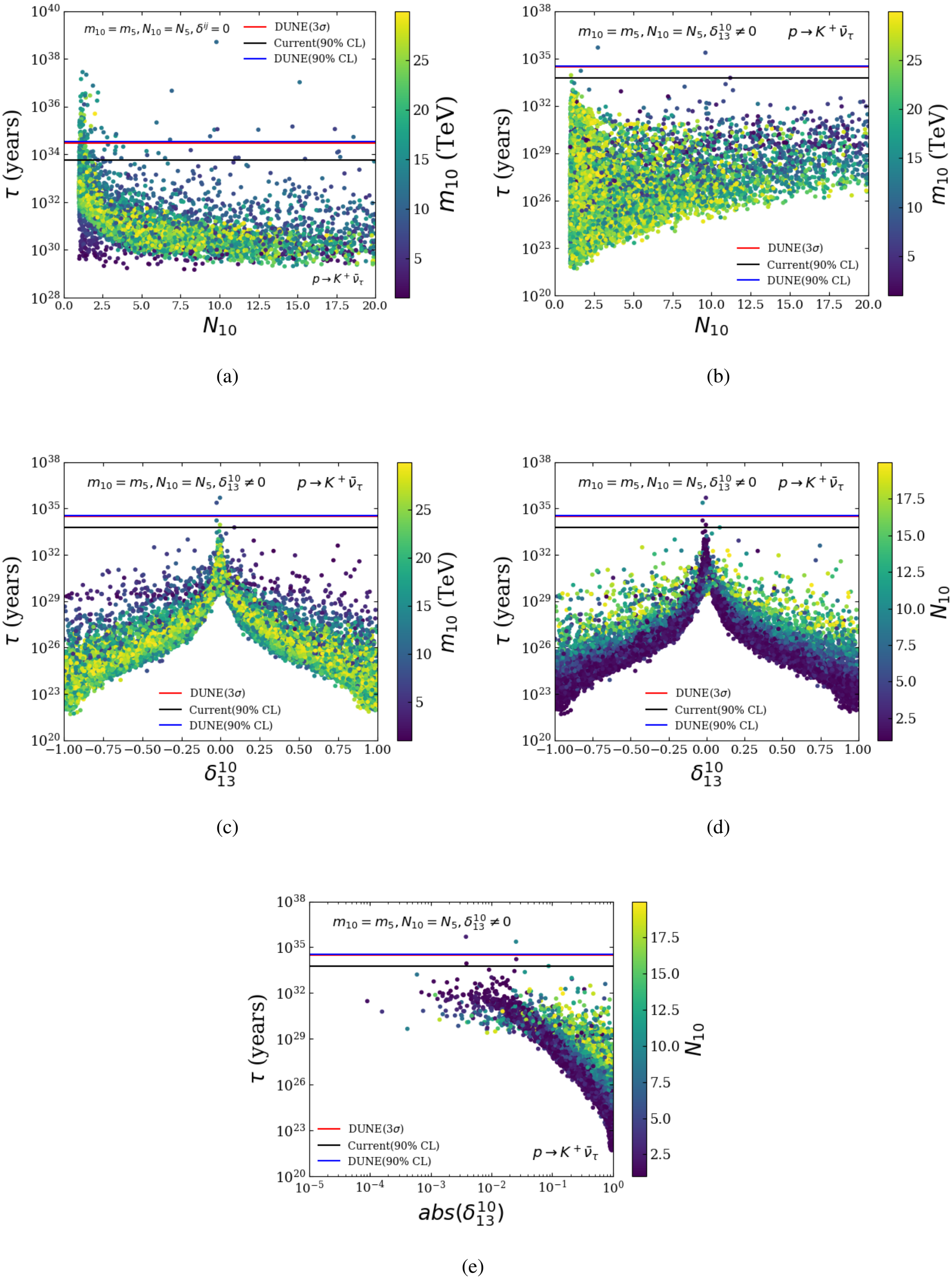

Figure 7: In these plots, we analyse proton decay mode $p \to K^+\bar{\nu}_\tau$ with and without flavor mixing.

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