R-Parity Violating Supersymmetry LSP Decays and the Neutrino Mass Hierarchy

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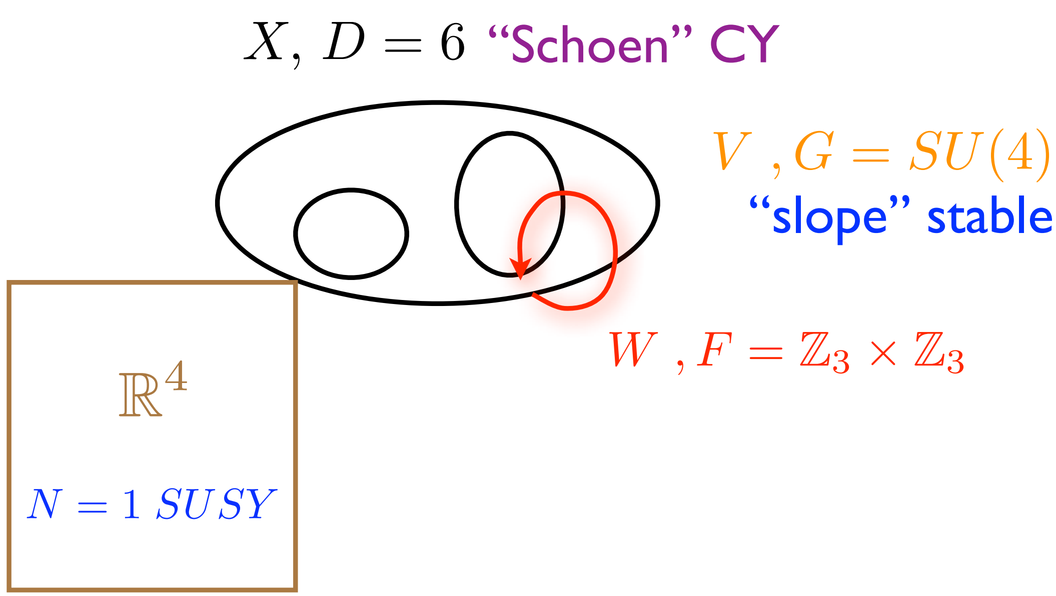
SU(4) Heterotic Compactification:



$\mathbb{R}^4$ Theory Gauge Group:

$G=SU(4)\Rightarrow\quad E_8\longrightarrow\ Spin(10)$

Choose the $\mathbb{Z}_3\times\mathbb{Z}_3$ Wilson lines to be

$$\chi_{T_{3R}}=e^{iY_{T_{3R}}\frac{2\pi}{3}}\ ,\quad \chi_{B-L}=e^{iY_{B-L}\frac{2\pi}{3}}$$

where

$$Y_{B-L} = 2(H_1 + H_2 + H_3) = 3(B-L)$$
$$Y_{T_{3R}} = H_4 + H_5 = 2(Y - \frac{1}{2}(B-L)) = 2T_{3R}$$

arise "naturally" and is called the "canonical basis". $\Rightarrow$

$$Spin(10) \rightarrow SU(3)_C \times SU(2)_L \times U(1)_{T_{3R}} \times U(1)_{B-L}$$

$\mathbb{R}^4$ Theory Spectrum:

$n_r = (h^1(X, U_R(V)) \otimes \mathbf{R})^{\mathbb{Z}_3 \times \mathbb{Z}_3} \Longrightarrow$ 3 families of quarks/leptons

$$Q = (U,D)^T = (\mathbf{3}, \mathbf{2}, 0, \frac{1}{3}), \quad u = (\bar{\mathbf{3}}, \mathbf{1}, -\frac{1}{2}, -\frac{1}{3}), \quad d = (\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{2}, -\frac{1}{3})$$
$$L = (N,E)^T = (\mathbf{1}, \mathbf{2}, 0, -1), \quad \nu = (\mathbf{1}, \mathbf{1}, -\frac{1}{2}, 1), \quad e = (\mathbf{1}, \mathbf{1}, \frac{1}{2}, 1)$$

and 1 pair of Higgs-Higgs conjugate fields

$$H = (\mathbf{1}, \mathbf{2}, \frac{1}{2}, 0), \quad \bar{H} = (\mathbf{1}, \mathbf{2}, -\frac{1}{2}, 0)$$

under $SU(3)_C \times SU(2)_L \times U(1)_{T_{3R}} \times U(1)_{B-L}$.

That is

- *When the two Wilson lines corresponding to the canonical basis are turned on simultaneously, the resulting low energy spectrum is precisely that of the MSSM–that is, three families of quark/lepton chiral superfields, each family with a right-handed neutrino supermultiplet, and one pair of Higgs-Higgs conjugate chiral multiplets. There are no vector-like pairs or exotic particles.*

- *Since each quark/lepton and Higgs superfield of the low energy Lagrangian arises from a different* **16** *and* **10** *representation of $Spin(10)$ respectively, the parameters of the effective theory, and specifically the Yukawa couplings and the soft supersymmetry breaking parameters, are uncorrelated by the $Spin(10)$ unification. For example, the soft mass squared parameters of the right-handed sneutrinos need not be universal with the remaining slepton supersymmetry breaking parameters.*

There are many pairs of U(1)XU(1) generators with these two properties--such as Y_Y, Y_{B-L} . So why have we chosen the canonical basis? Answer--kinetic mixing.

Canonical Kinetic Mixing:

For arbitrary $U(1)_1 \times U(1)_2$

$$\mathcal{L}_{kinetic} = -\frac{1}{4}((F^1_{\mu\nu})^2 + 2\alpha F^1_{\mu\nu} F^{2\mu\nu} + (F^2_{\mu\nu})^2 + \dots)$$

For $U(1)_{T_{3R}} \times U(1)_{B-L}$, $(H_i|H_j) = \delta_{ij} \Longrightarrow$ the "Killing" bracket

$(Y_{T_{3R}}|Y_{B-L}) = 0 \quad \Rightarrow \quad Tr(Y_{T_{3R}} Y_{B-L})_{\mathfrak{so}(10)} = 0 \quad \Rightarrow$ no initial mixing

- *Since the generators of the canonical basis are Killing orthogonal in* $\mathfrak{so}(10)$*, the value of the kinetic field strength mixing parameter* α *must vanish at the unification scale. That is,* $\alpha(M_u) = 0$.

Furthermore, for the canonical basis

$$Tr(Y_{T_{3R}} Y_{B-L})_{16} = 0 \ , \ Tr(Y_{Y_{3R}} Y_{B-L})_{H\bar{H}} = 0$$

This is not true for any other pair of generators--such as Y_Y, Y_{B-L} .

- *The generators of the canonical basis are such that $Tr(T^1T^2)=0$ when the trace is performed over the matter and Higgs spectrum of the MSSM. This guarantees that if the original kinetic mixing parameter vanishes, then α will remain zero under the RG at any scale. This property of not having kinetic mixing greatly simplifies the renormalization group analysis of the $SU(3)_C \times SU(2)_L \times U(1)_{T_{3R}} \times U(1)_{B-L}$ low energy theory.*

What about non-canonical bases? We can prove a theorem that

- *The only basis of $\mathfrak{h}_{3\oplus 2} \subset \mathfrak{h}$ for which $U(1)_{Y_1} \times U(1)_{Y_2}$ kinetic mixing vanishes at all values of energy-momentum is the canonical basis $Y_{T_{3R}}, Y_{B-L}$ and appropriate multiples of this basis.*

Sequential Wilson Line Breaking:

$\pi_1(X/(\mathbb{Z}_3 \times \mathbb{Z}_3)) = \mathbb{Z}_3 \times \mathbb{Z}_3$ $\Rightarrow$ 2 independent classes of non-contractible curves. $\Rightarrow$ each Wilson line has a mass scale $M_{\chi_{T_{3R}}}, M_{\chi_{B-L}}$ .Three possibilities

$$M_{\chi_{T_{3R}}} \simeq M_{\chi_{B-L}} \quad , \quad M_{\chi_{B-L}} > M_{\chi_{T_{3R}}} \quad , \quad M_{\chi_{T_{3R}}} > M_{\chi_{B-L}}$$

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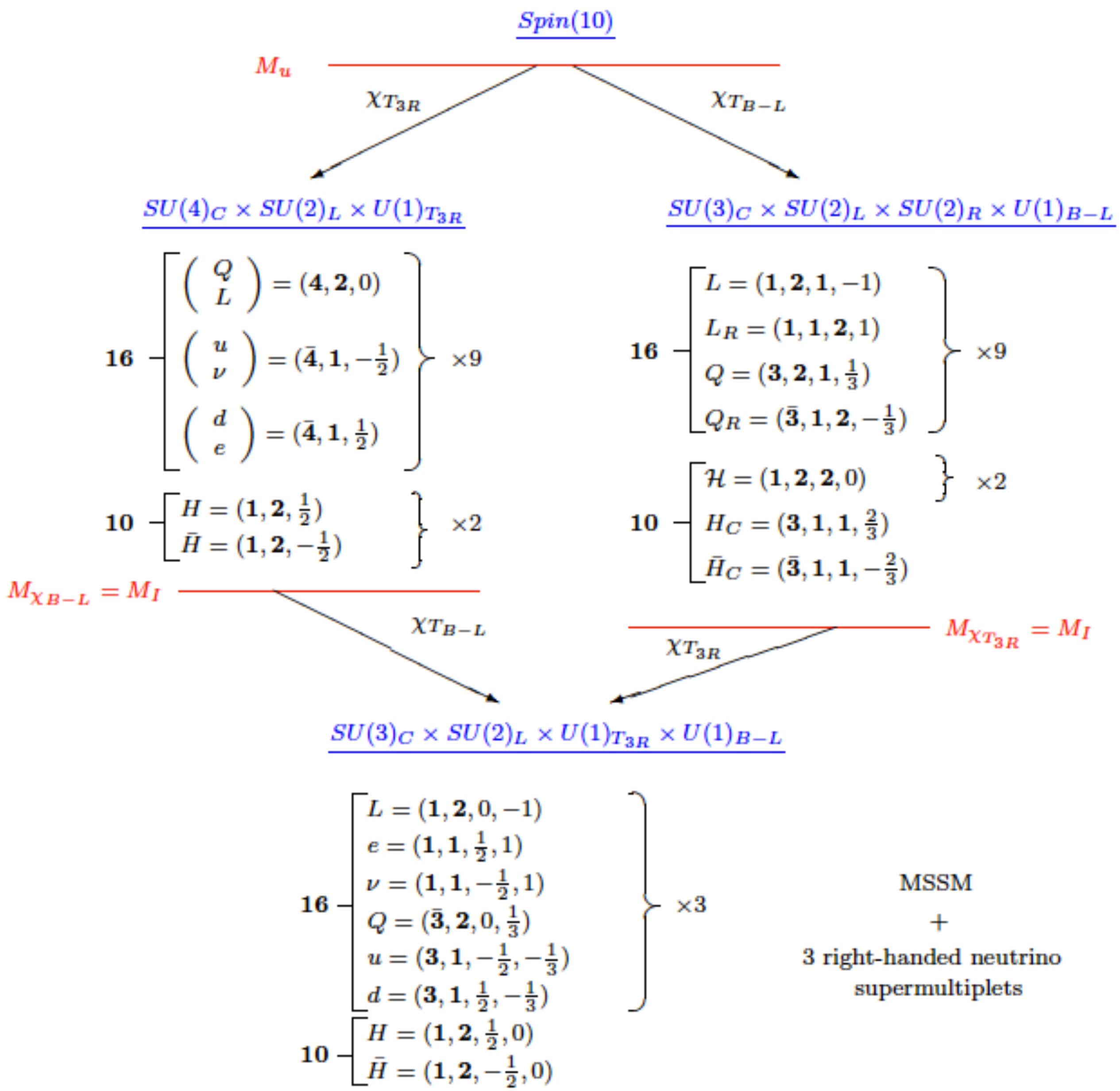


- The two sequential Wilson line breaking patterns of $Spin(10)$.

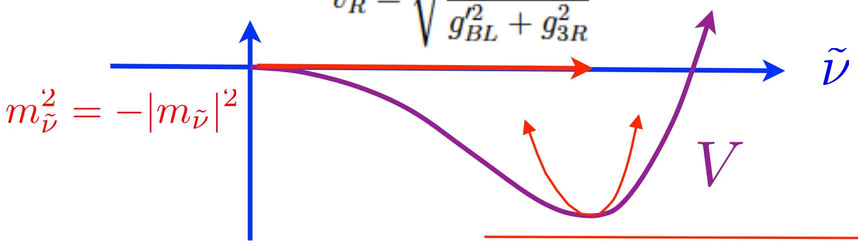
$$M_I$$

$$W = Y_u Q H_u u^c - Y_d Q H_d d^c - Y_e L H_d e^c + Y_\nu L H_u \nu^c + \mu H_u H_d$$

$$-\mathcal{L}_{\text{soft}} = m^2_{\tilde{\nu}^c} |\tilde{\nu}^c|^2 + m^2_{\tilde{L}} |\tilde{L}|^2 + m^2_{H_u} |H_u|^2 + m^2_{H_d} |H_d|^2$$
$$+ \left(M_R \tilde{W}_R^2 + M_2 \tilde{W}^2 + M_{BL} \tilde{B}'^2 + M_3 \tilde{g}^2 + a_\nu \tilde{L} H_u \tilde{\nu}^c + b H_u H_d + \text{h.c.} \right) + \cdots$$

Third family sneutrino:

$$v_R = \sqrt{\frac{-8 m^2_{\tilde{\nu}}}{g'^2_{BL} + g^2_{3R}}}$$



$$\Rightarrow \; U(1)_{T_{3R}} \times U(1)_{B-L} \to U(1)_Y$$

$$M_{B-L} \; (= M_{Z'} = \sqrt{2}\, |m_{\tilde{\nu}}|)$$

$$R = (-1)^{3(B-L)+2s} \Rightarrow R|_{\tilde{\nu}} = -1 \Rightarrow \langle \tilde{\nu} \rangle \; \textit{spontaneously breaks } R-\textit{parity}$$

$$\Rightarrow \; SU(3)_C \times SU(2)_L \times U(1)_Y \text{ MSSM } \textit{with}$$

$$W \supset \epsilon_i L_i H_u \;\; , \quad \mathcal{L} \supset \; -\frac{1}{2} v_R \left[-g_R \nu_3^c \tilde{W}_R + g_{BL} \nu_3^c \tilde{B}' \right] + \text{h.c.} \;\; , \quad \epsilon_i \equiv \frac{1}{\sqrt{2}} Y_{\nu i3} v_R$$

$M_{B-L} > 2.3\ TeV$

$M_{SUSY} \equiv \sqrt{\tilde{t}_1 \tilde{t}_2}$

leading log improved version of

$$m_{h^0}^2 = M_Z^2 \cos^2 2\beta + \frac{3}{8\pi^2} y_t^2 m_t^2 \left[\ln \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}} F\left(\frac{m_{\tilde{t}_1}}{m_{\tilde{t}_2}}\right) - \frac{1}{12} \frac{X_t^4}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} G\left(\frac{m_{\tilde{t}_1}}{m_{\tilde{t}_2}}\right) \right]$$

$$X_t = A_t - \mu \cot \beta$$

$m_{h^0} = 125.36 \pm 0.82\ GeV$

$M_{EW} \equiv M_Z = 91.2 GeV$

$$|\mu|^2 = \frac{m_{H_u}^2 \tan^2 \beta - m_{H_d}^2}{1 - \tan^2 \beta} - \frac{1}{2} M_Z^2$$

$$\frac{2b}{\sin 2\beta} = 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2$$

$$\Rightarrow \quad v_{Li} = \frac{\frac{v_R}{\sqrt{2}} (Y^*_{\nu_{i3}} \mu v_d - a^*_{\nu_{i3}} v_u)}{m_{\tilde{L}_i}^2 - \frac{g_2^2}{8}(v_u^2 - v_d^2) - \frac{g_{BL}^2}{8} v_R^2}$$

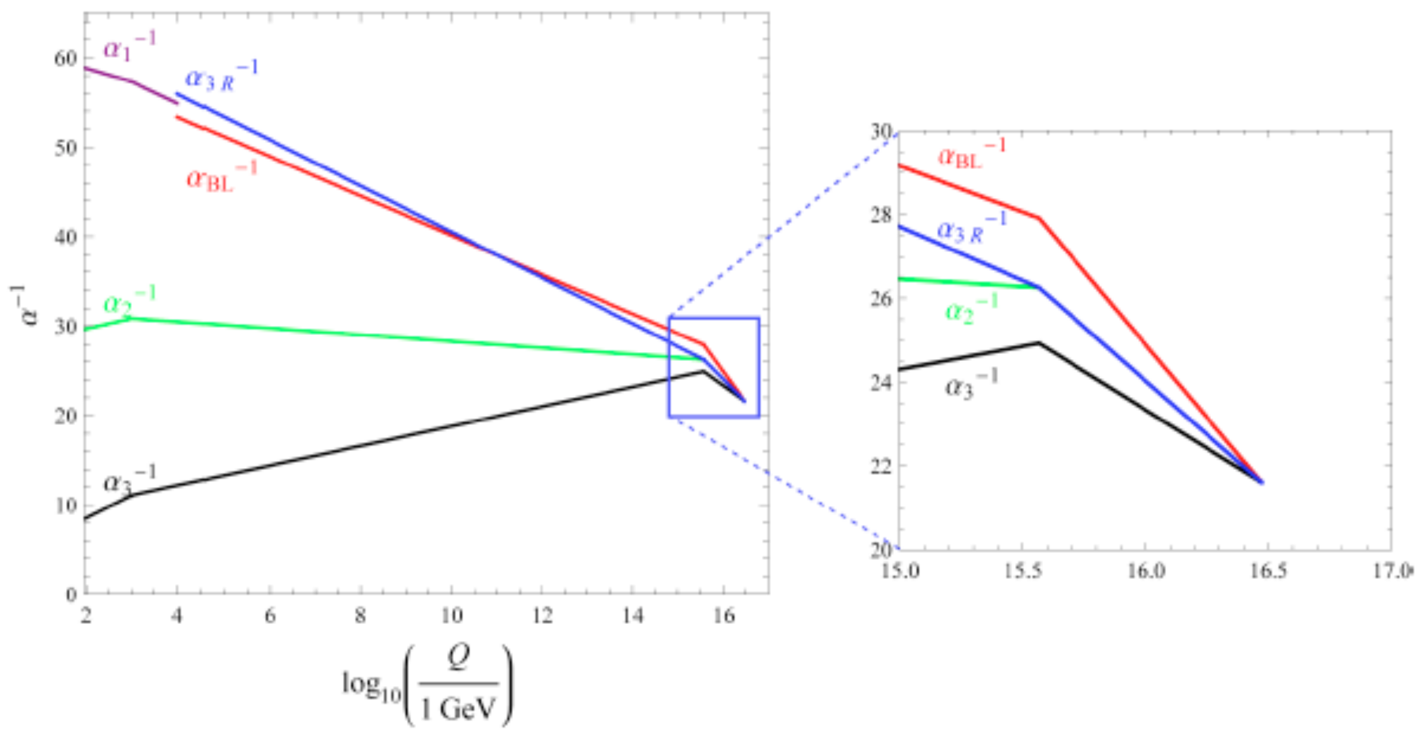
We will enforce gauge coupling unification using the experimental values $\alpha_1 = 0.017$, $\alpha_2 = 0.034$, $\alpha_3 = 0.118$ at M_{EW}. This allows us to determine both M_u, α_u and M_I in terms of M_{SUSY} and M_{B-L}.

For example, in the left-right case taking

$$M_{SUSY} = 1\ TeV, \quad M_{B-L} = 10\ TeV$$

$\Rightarrow$

$$M_u = 3.0 \times 10^{16}\ GeV, \quad \alpha_u = 0.046, \quad M_I = 3.7 \times 10^{15}\ GeV$$



Also demand gaugino mass unification at M_u .

We will enforce that all sparticle masses exceed their present experimental bounds. For example, LSP independent bounds are

$$\begin{aligned} m_{\tilde{e}_{L,R}} &> 107\ \mathrm{GeV} \\ m_{\tilde{\mu}_{L,R}} &> 94\ \mathrm{GeV} \\ m_{\tilde{\tau}_{L,R}} &> 82\ \mathrm{GeV} \\ m_{\tilde{\nu}_L} &> 94\ \mathrm{GeV} \\ m_{\tilde{g}} &> 1200\ \mathrm{GeV} \end{aligned}$$

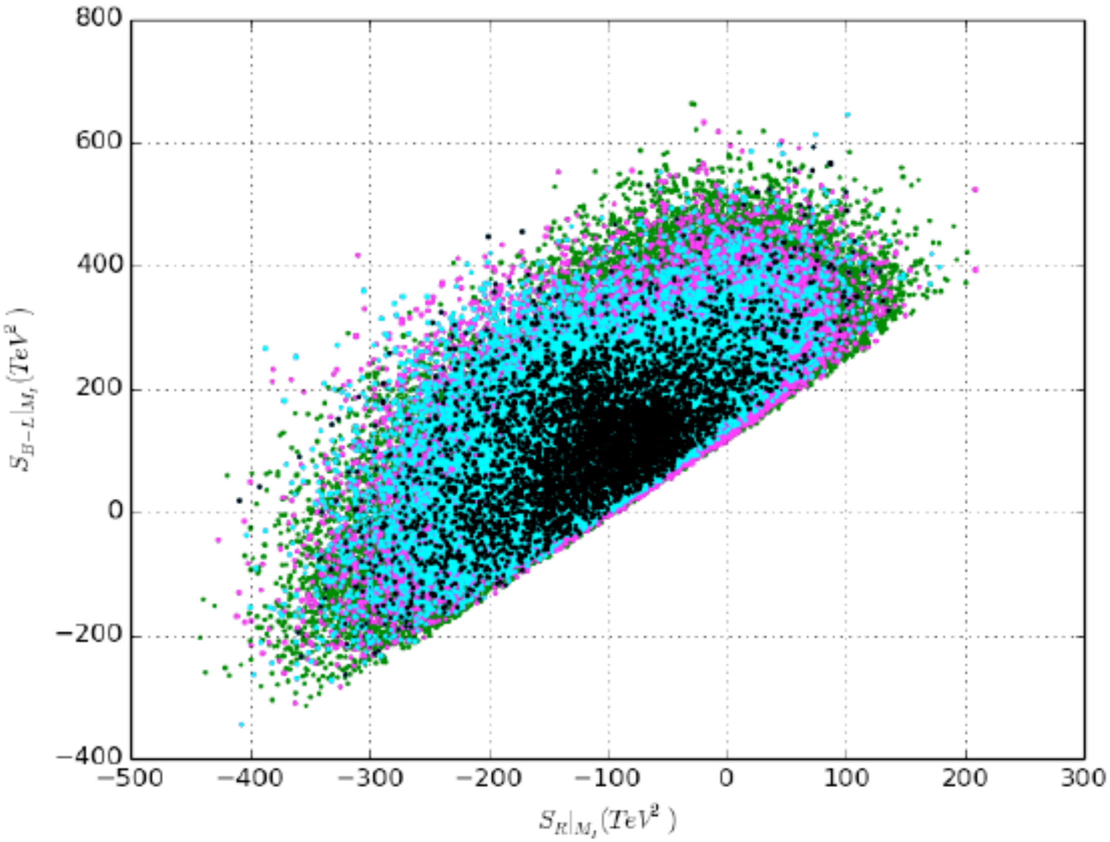
For, let us say, a stop LSP some bounds are

$$\begin{aligned} m_{\tilde{u}_{L,R}} &> 1200\ \mathrm{GeV} \\ m_{\tilde{c}_{L,R}} &> 1200\ \mathrm{GeV} \\ m_{\tilde{d}_{L,R}} &> 1200\ \mathrm{GeV} \\ m_{\tilde{s}_{L,R}} &> 1200\ \mathrm{GeV} \\ m_{\tilde{t}_1} &> 420\ \mathrm{GeV} \\ m_{\tilde{b}_1} &> 1200\ \mathrm{GeV} \end{aligned}$$

Finally, we will statistically scatter all initial massive parameters at M_I around a chosen "average" mass M. That is,

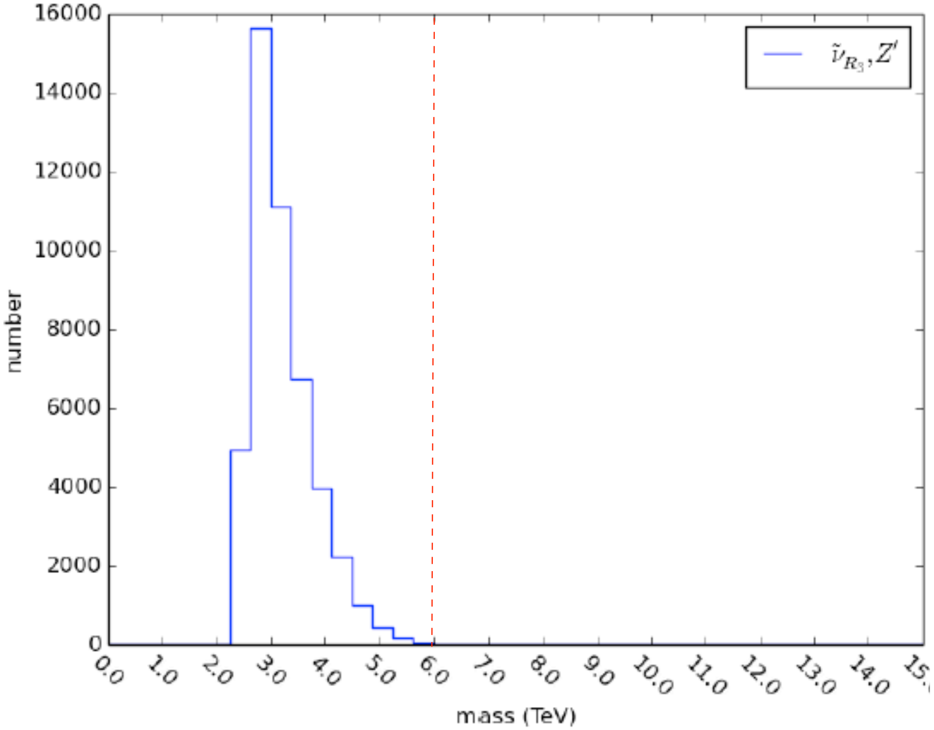
$$\frac{M}{f} < m < Mf \quad \text{for} \quad m = m_{soft},\ M_{gaugino},\ A_{cubic}$$

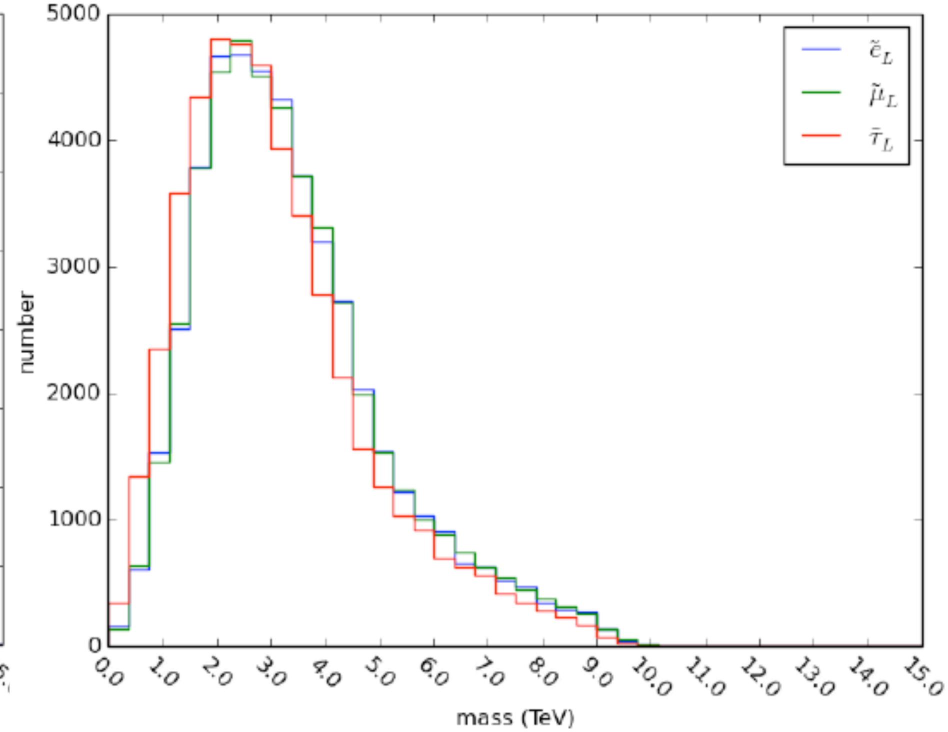
Typical "run": Choose $M = 2280\ GeV$, $f = 4$ and scan 10,000,000 points $\Rightarrow$



- break $U(1)_{3R} \times U(1)_{B-L} \to U(1)_Y$ with $M_{Z'} > 2.3\ TeV$
- break $SU(2)_L \times U(1)_Y \to U(1)_{EM}$ with $M_Z = 91.2\ GeV$
- $m_{h^0} = 125.36 \pm 0.82\ GeV$
- satisfy all sparticle experimental lower bounds ⟵ 45,000 points

One can analyze the mass spectrum over the 45,000 acceptable (black) points. For example

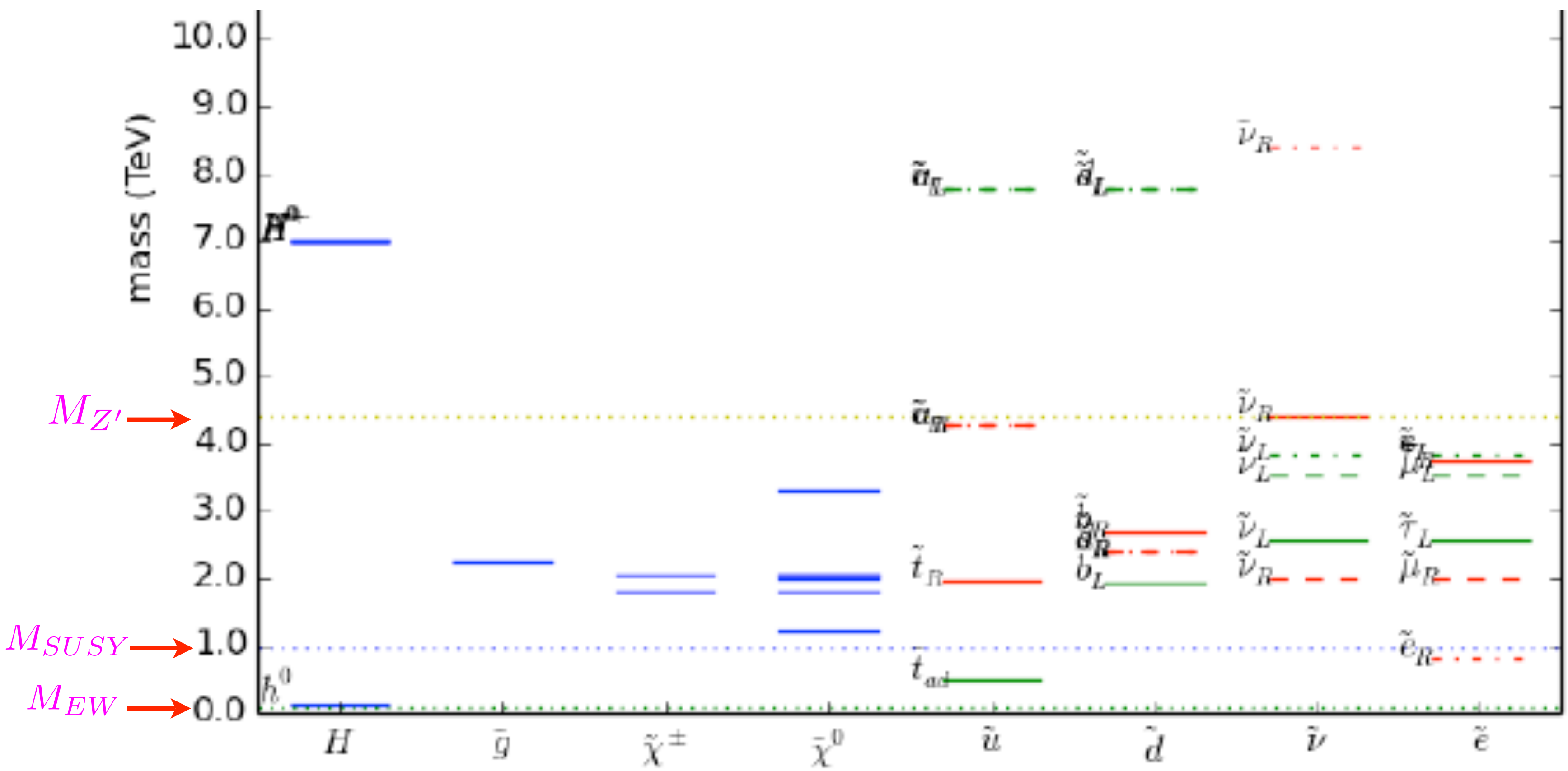




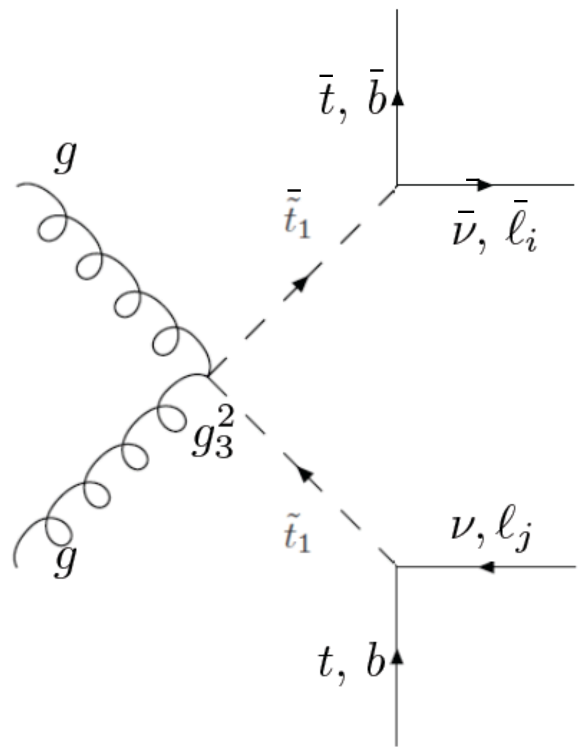
Note that $2.3\ TeV < M_{Z'} < 6\ TeV \Rightarrow Z'$ is potentially observable at the LHC. Although statistically the largest number of left-handed sleptons have mass of order 2.5 TeV, they can be < 500GeV.

The phenomenologically acceptable vacua can have different LSP's.

These include $\tilde{B},\ \tilde{\nu},\ \tilde{\tau},\ \tilde{t},\ldots$. Note that they now can be charged and colored since they decay sufficiently quickly due to RPV interactions. Here we will consider third family stop LSP's since they are exotic and are directly and copiously produced at the LHC. For example, at one acceptable point the sparticle spectrum is



The left and right stops diagonalize to mass eigenstates $m_{\tilde{t}_1} < m_{\tilde{t}_2}$ with mixing angle $0 < \theta_t < 90^\circ$. Generically, $\tilde{t}_1$ decays via RPV interactions as a "leptoquark" $\Rightarrow$ $\tilde{t}_1 \to t\,\nu_i,$ or $\tilde{t}_1 \to b\,\ell_i^+$



For an “admixture” LSP $(\theta_t \lesssim 80^\circ)$, the dominant channel is

$$\tilde{t}_1 \to b\,\ell_i^+$$

with partial widths

$$\Gamma(\tilde{t}_1 \to b\,\ell_i^+) = \frac{1}{16\pi}(|G^L_{\tilde{t}_1 b\ell_i}|^2 + |G^R_{\tilde{t}_1 b\ell_i}|^2)m_{\tilde{t}_1}$$

where

$$\begin{aligned} G^L_{\tilde{t}_1 b\ell_i} &= -Y_b c_{\theta_t}\frac{1}{\mu}\epsilon_i \\ G^R_{\tilde{t}_1 b\ell_i} &= -g_2^2 c_{\theta_t}\frac{\tan\beta m_{\ell_i}}{\sqrt{2}M_2\mu}v_{Li}^* - Y_t s_{\theta_t}\frac{m_{\ell_i}}{\sqrt{2}v_d\mu}v_{Li}^* \end{aligned}$$

Furthermore, demanding that these decays be “prompt”,

that is, the decay length be less than 1mm in the chamber $\Rightarrow$

$$10^{-4}\ GeV < \epsilon_i (= \frac{1}{\sqrt{2}}Y_{\nu i3}v_R) < 1\ GeV$$

Inserting these (and other constraints) into the neutralino mass matrix $\Rightarrow$

- One order TeV and two light "sterile" right-handed neutrinos.
- Three left-handed neutrinos with Majorana mass matrix

$$m_{\nu ij} = A v_{L_i}^* v_{L_j}^* + B \left(v_{L_i}^* \epsilon_j + \epsilon_i v_{L_j}^* \right) + C \epsilon_i \epsilon_j$$

A,B,C are complicated flavor independent functions of all parameters.

Independently of A,B,C we find $det\ m_{\nu ij} = 0$ with only one massless eigenstate. ⇒ The left-handed neutrino masses must either be in a "normal hierarchy" (NH) with

$$m_1 = 0 < m_2 \sim 8.7 \text{ meV} < m_3 \sim 50 \text{ meV}$$

or in an "inverted hierarchy" (IH) with

$$m_1 \sim m_2 \sim 50 \text{ meV} > m_3 = 0$$

We inserted the zero mass and used the atmospheric/solar data.

Additionally, when diagonalizing the mass matrix one must fix many parameters so that the experimental results for the mixing angles

$$\sin^2\theta_{12} = 0.306^{+0.012}_{-0.012}, \quad \sin^2\theta_{23} = 0.446^{+0.007}_{-0.007} \text{ or } 0.587^{+0.032}_{-0.037}, \quad \sin^2\theta_{13} = 0.0229^{+0.0020}_{-0.0019}$$

are satisfied. This gives two sets of fixed parameters, one for the NH and one for the IH, each of which has two subsets due to the ambiguity in θ_{23}. This leaves all parameters discussed above to be scanned over as well as statistically scattering $10^{-4}\,\text{GeV} < |\epsilon_i| < 1\,\text{GeV}$

Conclusion: The VEV of the right-handed third-family sneutrino $\Rightarrow$

a) The partial widths of the stop LSP decays via RPV interactions.

b) Majorana masses for the neutrinos via a "see-saw" mechanism.

$\Rightarrow$ Relationship between stop LSP decays and the neutrino mass hierarchy!

Defining $\mathrm{Br}(\tilde{t}_1 \to b\ell_i^+) \equiv \frac{\Gamma(\tilde{t}_1 \to b\ell_i^+)}{\sum_{i=1}^{3} \Gamma(\tilde{t}_1 \to b\ell_i^+)}$ and using $\mathrm{Br}(\tilde{t}_1 \to b\, e^+) + \mathrm{Br}(\tilde{t}_1 \to b\, \mu^+) + \mathrm{Br}(\tilde{t}_1 \to b\, \tau^+) = 1$

$\Rightarrow$

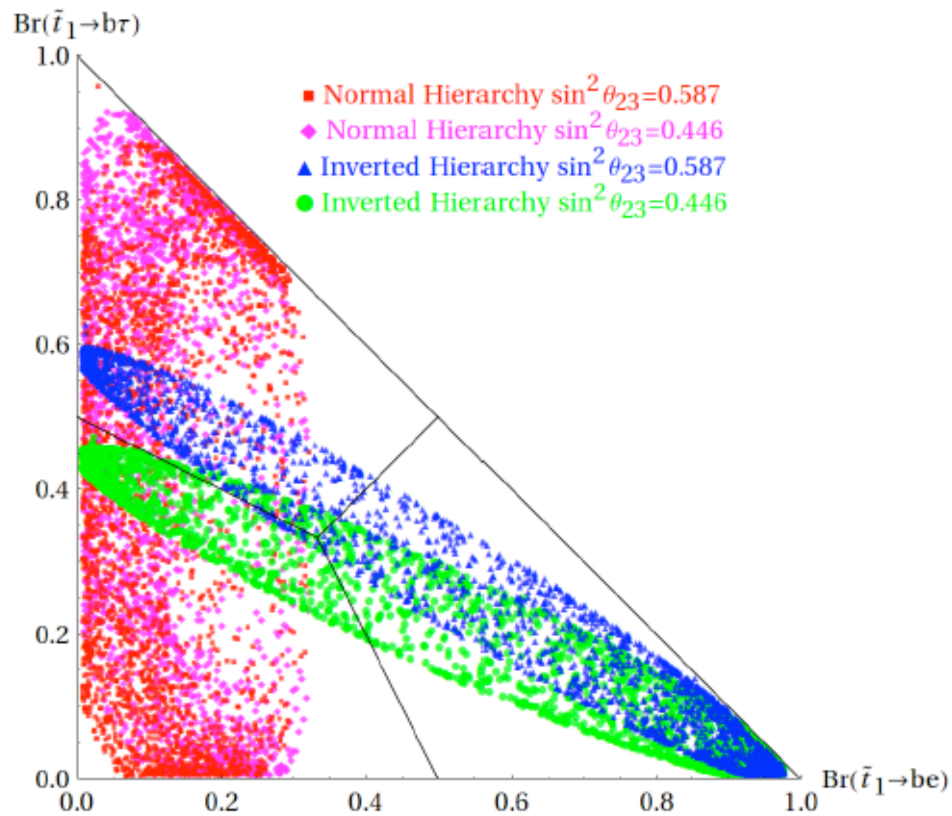


Figure 1: The results of the scan specified in Table 1 using the central values for the measured neutrino parameters in the $\mathrm{Br}(\tilde{t}_1 \to b\,\tau^+)$ - $\mathrm{Br}(\tilde{t}_1 \to b\,e^+)$ plane. Due to the relationship between the branching ratios, the $(0,0)$ point on this plot corresponds to $\mathrm{Br}(\tilde{t}_1 \to b\,\mu^+) = 1$. The plot is divided into three quadrangles, each corresponding to an area where one of the branching ratios is larger than the other two. In the top left quadrangle, the bottom–tau branching ratio is the largest; in the bottom left quadrangle the bottom–muon branching ratio is the largest; and in the bottom right quadrangle the bottom–electron branching ratio is the largest. The two different possible values of θ_{23} are shown in blue and green in the IH (where the difference is most notable) and in red and magenta in the NH.

Using previous leptoquark searches at the LHC, one can put lower bounds on the LSP stop. We find that

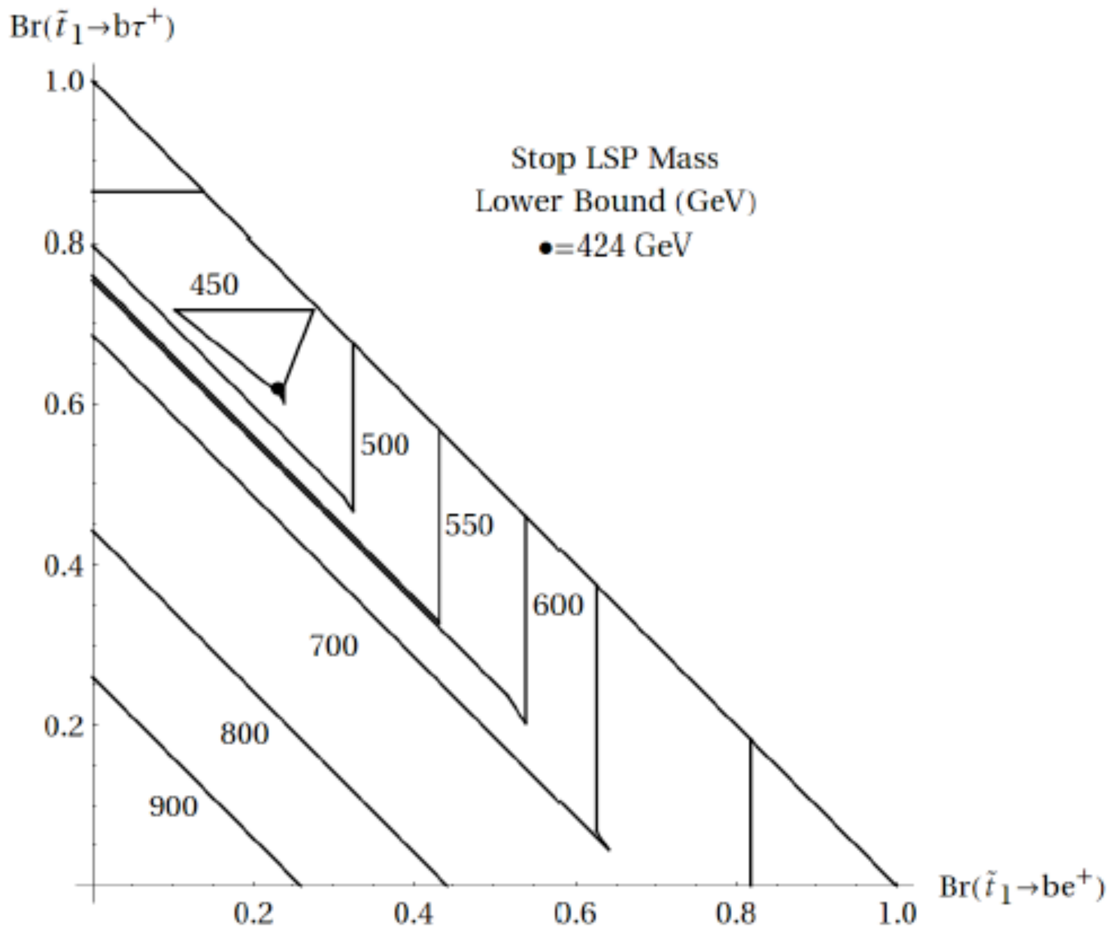


Figure 2: Lines of constant stop lower bound in GeV in the $\text{Br}(\tilde{t}_1 \to b\tau^+)$ - $\text{Br}(\tilde{t}_1 \to be^+)$ plane. The strongest bounds arise when the bottom–muon branching ratio is largest, while the weakest arise when the bottom–tau branching ratio is largest. The dot marks the absolute weakest lower bound at 424 GeV.