NON-STANDARD SUSY SPECTRA IN GAUGE MEDIATION [a]

E. DUDAS,[⋆,#] S. LAVIGNAC[†] and J. PARMENTIER[⋆,†]

[⋆] *Centre de Physique Théorique, Ecole Polytechnique, F-91128 Palaiseau, France*

[#] *Laboratoire de Physique Théorique, Université de Paris-Sud, F-91405 Orsay, France*

[†] *Institut de Physique Théorique, CEA-Saclay, F-91191 Gif-sur-Yvette Cedex, France*

If the messenger fields of gauge mediation couple to the Higgs fields of an underlying Grand Unified Theory, the resulting messenger mass splitting leads to a non-minimal gauge-mediated superpartner spectrum with well-defined gaugino mass ratios. Some of these spectra exhibiting striking features, such as a light neutralino LSP, or a wino/gluino NLSP with a gravitino LSP.

1 Introduction

Most phenomenological studies of supersymmetry assume gaugino mass unification, namely: [b]

$$\frac{M_1}{\alpha_1} = \frac{M_2}{\alpha_2} = \frac{M_3}{\alpha_3} , \tag{1}$$

where M_1, M_2 and M_3 are the bino, wino and gluino masses, and $\alpha_a = g_a^2/4\pi$, $a = 1, 2, 3$, are the $U(1)_Y$ (in the $SU(5)$ normalization), $SU(2)_L$ and $SU(3)_C$ gauge couplings. This relation is satisfied both in minimal supergravity (mSUGRA) and in minimal gauge mediation. It does not necessarily hold in more general schemes of supersymmetry breaking and mediation, though, and it is useful to study alternative theory-motivated gaugino mass relations. Indeed, a departure from Eq. (1) can lead to non-standard collider signatures of supersymmetry, as well as to new possibilities for dark matter (which is very constrained in mSUGRA). Also, some gaugino mass patterns are known to reduce the degree of fine-tuning in the Higgs sector of the Minimal Supersymmetric Standard Model (MSSM).

Non-minimal gaugino mass relations have been considered both in the context of supergravity mediation (see e.g. Ref. [1]) and of general gauge mediation. [2] In this talk we point out that if the messenger fields of gauge mediation couple to the Higgs fields of an underlying Grand Unified Theory (GUT), the resulting messenger mass splitting leads to a non-minimal gauge-mediated superpartner spectrum with well-defined gaugino mass ratios. [3] We discuss sample spectra exhibiting striking features, such as a light neutralino LSP, [3] or a wino/gluino NLSP with a gravitino LSP. [4]

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[b] Strictly speaking, gaugino mass unification means $M_1 = M_2 = M_3$ at the unification scale, where $\alpha_1 = \alpha_2 = \alpha_3$. However, at the one-loop level, this is equivalent to saying that Eq. (1) holds at any scale.

2 Quick review of gauge mediation

Let us begin with a quick review of gauge-mediated supersymmetry breaking (GMSB). [5] Supersymmetry is assumed to be broken in a hidden sector, and its breaking is transmitted to the observable sector (i.e. to the MSSM) by gauge interactions. The key ingredient is a set of chiral superfields (Φ, $\tilde{\Phi}$) in vector-like representations of the SM gauge group, called messenger superfields, which couple to a chiral superfield X parametrizing the breaking of supersymmetry:

$$W_{\rm mess} \; = \; X\Phi\tilde{\Phi}\,, \qquad\qquad \langle X \rangle \; = \; M + F\theta^2, \tag{2}$$

where F is the order parameter of supersymmetry breaking. This yields a supersymmetric mass M for the messenger superfields, as well as a supersymmetry-breaking mass splitting $F\varphi\tilde{\varphi}+\text{h.c.}$ for their scalar components. This mass splitting in turn induces soft terms in the observable sector via gauge interactions. Gaugino and scalar masses arise at the one-loop and two-loop levels, respectively. At the lowest order in F/M^2, and at the messenger scale M:

$$M_a \; = \; \frac{\alpha_a}{4\pi} \sum_i 2T_a(R_i)\, \frac{F}{M}\ , \tag{3}$$

$$m^2_\chi \; = \; 2 \sum_a C^a_\chi \left(\frac{\alpha_a}{4\pi}\right)^2 \sum_i 2T_a(R_i) \left|\frac{F}{M}\right|^2\ , \tag{4}$$

where the index a refers to the gauge group factor, and the index i to the component ϕ_i of Φ belonging to the irreducible representation R_i of the SM gauge group. In Eqs. (3) and (4), $T_a(R_i)$ is the Dynkin index of the representation R_i , and C^a_χ is the quadratic Casimir coefficient for the MSSM chiral superfield χ, both with respect to the gauge group G_a.

The main advantage of GMSB is that the induced soft terms are automatically flavour blind, since gauge interactions are the same for all fermion generations. Hence, there are no large supersymmetric contributions to flavour-violating processes. Another characteristic feature of gauge mediation is that the lightest supersymmetric particle (LSP) is the gravitino: unless $M > (\alpha/4\pi)M_P$, where M_P is the Planck scale, its mass $m_{3/2} = F/\sqrt{3}M_P$ is suppressed relative to a typical GMSB soft mass $M_{\rm GM} = (\alpha/4\pi)F/M$. For $m_{3/2} > 100$ keV, the gravitino behaves as a cold relic and can constitute the dark matter of the universe; however its relic abundance depends on an a priori unmeasurable parameter, the reheating temperature after inflation. Furthermore, in order for the late decays of the next-to-lightest supersymmetric particle (NLSP) not to spoil the successful predictions of Big Bang Nucleosynthesis (BBN), strong constraints must be imposed on the gravitino mass and/or on the NLSP nature and mass.

Eqs. (3) and (4) correspond to the case of a single messenger mass and F-term, known as minimal gauge mediation. It is characterized by a fixed superpartner spectrum at the messenger scale, up to M_a/m_χ and to an overall scale. [c] In particular, Eq. (1) holds. One can consider a more general situation in which different M_i and F_i are associated with each ϕ_i; in this case, often referred to as general gauge mediation, [2] the superpartner spectrum depends on 3 complex and 3 real parameters.

3 Combining gauge mediation with unification

Let us now assume an underlying unified gauge group G ($G = SU(5), SO(10), \cdots$), with messenger superfields (Φ, $\tilde{\Phi}$) in a real representation $\mathbf{R} \oplus \bar{\mathbf{R}}$ of G. Since $\mathbf{R} \otimes \bar{\mathbf{R}} = \mathbf{1} \oplus \text{Adj.} \oplus \cdots$, they can couple to the adjoint Higgs field Σ involved in the GUT symmetry breaking:

$$W_{\rm mess} \; = \; \lambda_X X\Phi\tilde{\Phi} \, + \, \lambda_\Sigma \Sigma\Phi\tilde{\Phi}\ . \tag{5}$$

[c] This statement assumes that the messengers form complete representations of a unified group, e.g. $\mathbf{5} \oplus \bar{\mathbf{5}}$ of $SU(5)$. This is actually required in order to maintain gauge coupling unification.

More generally, the G-breaking field Σ may be in a representation included in the tensor product $R \otimes \bar{R}$. Assuming $\lambda_X X_0 \ll \lambda_\Sigma \langle \Sigma \rangle$, where $\langle X \rangle = X_0 + F\theta^2$, Eq. (5) leads to a GUT-induced mass splitting inside the messenger multiplets, with a different mass M_i for each messenger component ϕ_i. Since the M_i are determined by group theory, one obtains a predictive non-minimal GMSB scenario. In the following, we present three examples of such scenarios, based on different GUT group and messenger representations.

3.1 *Light neutralino LSP scenario: $G = SU(5)$, $\Sigma = \mathbf{24}$*

Let us start with an underlying $SU(5)$ gauge group, broken down to $SU(3)_C \times SU(2)_L \times U(1)_Y$ by an adjoint Higgs field Σ. The vev of Σ is uniquely determined by the requirement that it is an SM gauge singlet: $\langle \Sigma \rangle = V \,\mathrm{Diag}(2,2,2,-3,-3) = 6VY$, where $V \approx 10^{16}\,\mathrm{GeV}$ and Y is the hypercharge generator in the defining representation, normalized as $Y = Q - T_3$. Assuming that $\lambda_\Sigma \langle \Sigma \rangle$ gives the dominant contribution to the messenger mass M, this induces the following mass splitting inside the messenger multiplets:

$$\Phi(\bar{5}) \;=\; \left\{ \phi_{\bar{3},1,+1/3}\,,\ \phi_{1,2,-1/2} \right\}, \qquad M_\Phi \;=\; \{ 2\lambda_\Sigma V\,,\ -3\lambda_\Sigma V \}\,, \tag{6}$$

$$\Phi(10) \;=\; \left\{ \phi_{3,2,+1/6}\,,\ \phi_{\bar{3},1,-2/3}\,,\ \phi_{1,1,+1} \right\}, \qquad M_\Phi \;=\; \{ \lambda_\Sigma V\,,\ -4\lambda_\Sigma V\,,\ 6\lambda_\Sigma V \}\,, \tag{7}$$

for messengers in $(\mathbf{5},\, \bar{\mathbf{5}})$ and $(\mathbf{10},\, \overline{\mathbf{10}})$ representations, respectively, and more generally:

$$M_i \;\propto\; \lambda_\Sigma V Y_i \;. \tag{8}$$

Plugging Eq. (8) into Eqs. (3) and (4), one obtains for the bino mass:

$$M_1 \;=\; \frac{\alpha_1}{4\pi} \sum_i 2\, \frac{3}{5}\, Y_i^2\, \frac{\lambda_X F_X}{6\lambda_\Sigma V Y_i} \;\propto\; \sum_i Y_i \;, \tag{9}$$

where we have used $T_1(R_i) = 3Y_i^2/5$. Since Y is an $SU(5)$ generator, its trace over a complete $SU(5)$ representation vanishes, yielding a massless bino (up to corrections due to $X_0 \neq 0$ and to other possible subleading contributions to the messenger masses):

$$M_1|_{\mathrm{GM}} \;=\; 0 \;. \tag{10}$$

However, since the messenger fields are heavy, with masses of order $\lambda_\Sigma \times 10^{16}\,\mathrm{GeV}$, supergravity corrections to the soft terms can no longer be neglected: the ratio of a typical supergravity over GMSB contribution is $m_{3/2}/M_{\mathrm{GM}} \sim \lambda_\Sigma V/(\alpha_{\mathrm{GUT}} \lambda_X M_P/4\pi) \sim \lambda_\Sigma/\lambda_X$. Assuming a moderate hierarchy of couplings $\lambda_\Sigma \ll \lambda_X$, one ends up with:

$$M_1 \sim m_{3/2} \;\ll\; (M_2, \mu) \sim M_{\mathrm{GM}} \;, \tag{11}$$

implying that the LSP is a light, mostly-bino neutralino (the renormalization group running gives $M_1 \sim 0.5\, m_{3/2}$ at the weak scale), a rather unconventional feature in gauge mediation. While the prediction $M_1|_{\mathrm{GM}} = 0$ is independent of the messenger representation $\mathbf{R}$, this is not the case for the other superpartner masses. In particular, one has:

$$(\mathbf{5}, \bar{\mathbf{5}}) \;:\; \frac{M_2/\alpha_2}{M_3/\alpha_3} \;=\; \frac{3}{2}\,, \qquad (\mathbf{10}, \overline{\mathbf{10}}) \;:\; \frac{M_2/\alpha_2}{M_3/\alpha_3} \;=\; \frac{7}{12}\;. \tag{12}$$

The ratio of the gluino to the wino masses can therefore be used, in principle, to determine the messenger representation in this scenario. The Higgs and superparticle spectrum corresponding to messengers in $(\mathbf{10},\, \overline{\mathbf{10}})$ representations is displayed in the upper left panel of Fig. 1, for a messenger scale $M_{\rm mess} \equiv \lambda_\Sigma V = 10^{13}$ GeV, $M_{\rm GM} \equiv \frac{\alpha_3(M_{\rm mess})}{4\pi} \frac{\lambda_X F}{\lambda_\Sigma V} = 215$ GeV, $m_{3/2} = 85$ GeV and $\tan\beta = 15$. A universal supergravity contribution of $m_{3/2}$ has been added to all soft masses.

The main distinctive features of this scenario, besides a light neutralino LSP, are non-universal gaugino masses and light singlet sleptons. A neutralino lighter than 50 GeV as in Fig. 1 does not contradict the LEP bound, since the latter assumes gaugino mass unification. The WMAP constraint[6] $\Omega_{DM} h^2 = 0.1109 \pm 0.0056$ is satisfied thanks to the efficient annihilations $\tilde\chi^0_1 \tilde\chi^0_1 \to \tau^+\tau^-$ mediated by the light $\tilde\tau_1$. The requirement that the late decays of the gravitino (which is the NLSP) into $\tilde\chi^0_1\gamma$ and $\tilde\chi^0_1 q\bar q$ do not spoil the successful BBN predictions put an upper bound on the reheating temperature, $T_R \lesssim 10^{5-6}$ GeV.[7] Finally, the hadron collider signatures of the light neutralino scenario are not very different from the ones of a standard mSUGRA scenario like SPS1a (in which $M_{\tilde\chi^0_1} = 97$ GeV), in spite of slightly increased cross sections for processes such as $p\bar p / pp \to \tilde\chi^0_1 \tilde\chi^0_1 +$ jet.[8]

A complete model with an explicit supersymmetry breaking sector coupled to the messenger fields has been provided in Ref.[3]

3.2 Wino NLSP scenario: $G = SO(10)$, $\Sigma = \mathbf{45}$, messengers in $(\mathbf{10}, \mathbf{10}')$

Let us now consider an uderlying GUT group $SO(10)$, with messenger fields in the vector representation $\mathbf{10}$. Since $\mathbf{10} \otimes \mathbf{10} = \mathbf{1}_s \oplus \mathbf{45}_a \oplus \mathbf{54}_s$, the messengers can couple to an $SO(10)$ adjoint $\mathbf{45}$ or to a $\mathbf{54}$ Higgs multiplet, both of which can be used in the first stage of $SO(10)$ breaking down to $SU(3)_C \times SU(2)_L \times U(1)_Y$ (often in combination). The $\mathbf{54}$ case leads to the same spectrum as the $SU(5)$ scenario with a pair of $(\mathbf{5}, \bar{\mathbf{5}})$ messengers. The $\mathbf{45}$ case requires two distinct messenger fields $\mathbf{10}_M$ and $\mathbf{10}'_M$, since the adjoint appear in the antisymmetric product of two vector representations. The $\mathbf{45}$ has two SM singlet vevs, in the $B-L$ and T_{3R} directions respectively. Viable spectra are difficult to obtain with the former possibility, so we consider only the latter, with the following messenger superpotential:

$$W_{\rm mess} \;=\; \lambda_X X \mathbf{10}_M \mathbf{10}'_M \,+\, \lambda_{45} \mathbf{10}_M \mathbf{45}\, \mathbf{10}'_M \,. \tag{13}$$

The vev $\langle \mathbf{45} \rangle = V_R T_{3R}$ does not contribute to the masses of the colour triplets/antitriplets in $\mathbf{10}_M$ and $\mathbf{10}'_M$, thus suppressing the wino mass with respect to the bino and gluino masses. Assuming $M_T \ll \lambda_{45} V_R$ (where M_T is the mass of the colour (anti-)triplet messengers, originating e.g. from $X_0 \neq 0$ or from a direct mass term $M_T \mathbf{10}_M \mathbf{10}'_M$), one obtains:

$$M_2 \;\propto\; \frac{\lambda_X F}{M_T} \left(\frac{M_T}{\lambda_{45} V_R} \right)^2 , \qquad M_1,\, M_3 \;\propto\; \frac{\lambda_X F_X}{M_T} \,. \tag{14}$$

The NLSP is therefore likely to be a wino, the LSP being the gravitino. The wino relic density is strongly suppressed relative to a bino relic density due to efficient gauge annihilations; however, its late decays can still be problematic for BBN[9], requiring $m_{3/2} \lesssim$ few GeV. The mass splitting $M_{\tilde\chi^+_1} - M_{\tilde\chi^0_1}$, induced by one-loop corrections, is always positive and slightly greater than the charged pion mass. The dominant lighter chargino decay mode, $\tilde\chi^+_1 \to \tilde\chi^0_1 \pi^+$, is therefore very slow and will lead to displaced vertices at colliders. This is reminiscent of anomaly-mediated scenarios where the wino is the LSP,[10] except that here the wino is a long-lived NLSP.

The Higgs and superparticle spectrum is displayed in the upper right panel of Fig. 1, for a messenger scale $M_{\rm mess} \equiv \lambda_{45} V_R = 10^{11}$ GeV, $M_{\rm GM} = 550$ GeV, $M_T = M_{\rm mess}/6$ and $\tan\beta = 15$. The characteristic signature at the LHC is $\tilde\chi^+_1 \tilde\chi^-_1$ production in association with a jet, leaving two displaced vertices plus missing transverse energy.

3.3 Gluino NLSP scenario: $G = SO(10)$, $\Sigma = \mathbf{45}$, messengers in $(\overline{\mathbf{16}}, \mathbf{16})$

The last example we consider has a GUT group $SO(10)$ and a pair of $(\mathbf{16}, \overline{\mathbf{16}})$ messengers coupling to an adjoint Higgs field with a vev in the $B-L$ direction, $\langle \mathbf{45} \rangle = V_{B-L} T_{B-L}$. The mass of each messenger component ϕ_i is therefore determined by its $B-L$ charge, $M_i = (B-L)_i \lambda_{45} V_{B-L}$. This leads to a cancellation in the gluino mass formula:

$$M_3|_{\rm GM} \;=\; \frac{\alpha_3}{4\pi}\, \frac{\lambda_X F_X}{\lambda_{45} V_{B-L}} \left(2 \times \frac{1}{1/3} + \frac{1}{-1/3} + \frac{1}{-1/3} \right) =\; 0\ . \tag{15}$$

A nonzero gluino mass can arise e.g. from supergravity corrections, as in the light neutralino scenario. Since the renormalization group equations increase the gluino mass when going to lower energies, starting from $M_3(M_{\rm mess}) \sim m_{3/2} \ll M_{\rm GM}$ yields a long-lived gluino NLSP with a gravitino LSP. The Higgs and superparticle spectrum is displayed in the lower panel of Fig. 1, for a messenger scale $M_{\rm mess} \equiv \lambda_{45} V_{B-L} = 10^{13}\,{\rm GeV}$, $M_{\rm GM} = 150\,{\rm GeV}$, $m_{3/2} = 70\,{\rm GeV}$ and $\tan\beta = 15$. A universal supergravity contribution of $m_{3/2}$ has been added to all soft masses. The lightest neutralino and gluino masses are $M_{\tilde\chi^0_1} = 228.9\,{\rm GeV}$ and $M_{\tilde g} = 218.4\,{\rm GeV}$.

This scenario shares some features with split supersymmetry, in which the gluino is also long-lived, but the LSP is the lightest neutralino. In particular, the gluino will hadronize and form R-hadrons after having been produced at colliders. If the lightest R-hadron is neutral, it will escape the detector leaving only a small fraction of the event energy. The corresponding signature, monojet + missing energy (from gluino pair production in association with a high p_T jet), allows to set a lower bound $M_{\tilde g} > 210\,{\rm GeV}$ from Tevatron data. [11] The LHC should probe masses up to 1.1 TeV. There is also the possibility that some neutral R-hadrons are converted into charged ones and stop in the detector after having lost their energy. [12] The stopped gluinos will ultimately decay not synchronized with a bunch crossing. The D0 collaboration has looked for such events and set a bound $M_{\tilde g} < 270\,{\rm GeV}$ for $\tau_{\tilde g} < 3$ hours; [13] this bound does not apply to our scenario, in which $\tau_{\tilde g} \sim 10^7$ s. Such a long lifetime has been claimed to be inconsistent with BBN constraints once bound state effects during nucleosynthesis are taken into account. [14] This would favour a scenario in which the gluino mass originate from subdominant contributions to messenger masses rather than from supergravity corrections, with $m_{3/2} < 1\,{\rm GeV}$.

4 Conclusions

If supersymmetry breaking is mediated by gauge interactions and there is an underlying GUT at the unification scale, the dominant contributions to messenger masses may come from a coupling between the GUT and messenger sectors. This leads to a non-minimal GMSB superpartner spectrum which is mainly determined by the unified gauge group and by the messenger representations. We presented examples of spectra showing non-standard features such as a light neutralino LSP, or a wino/gluino NLSP with a gravitino LSP. BBN constraints favour the neutralino LSP scenario.

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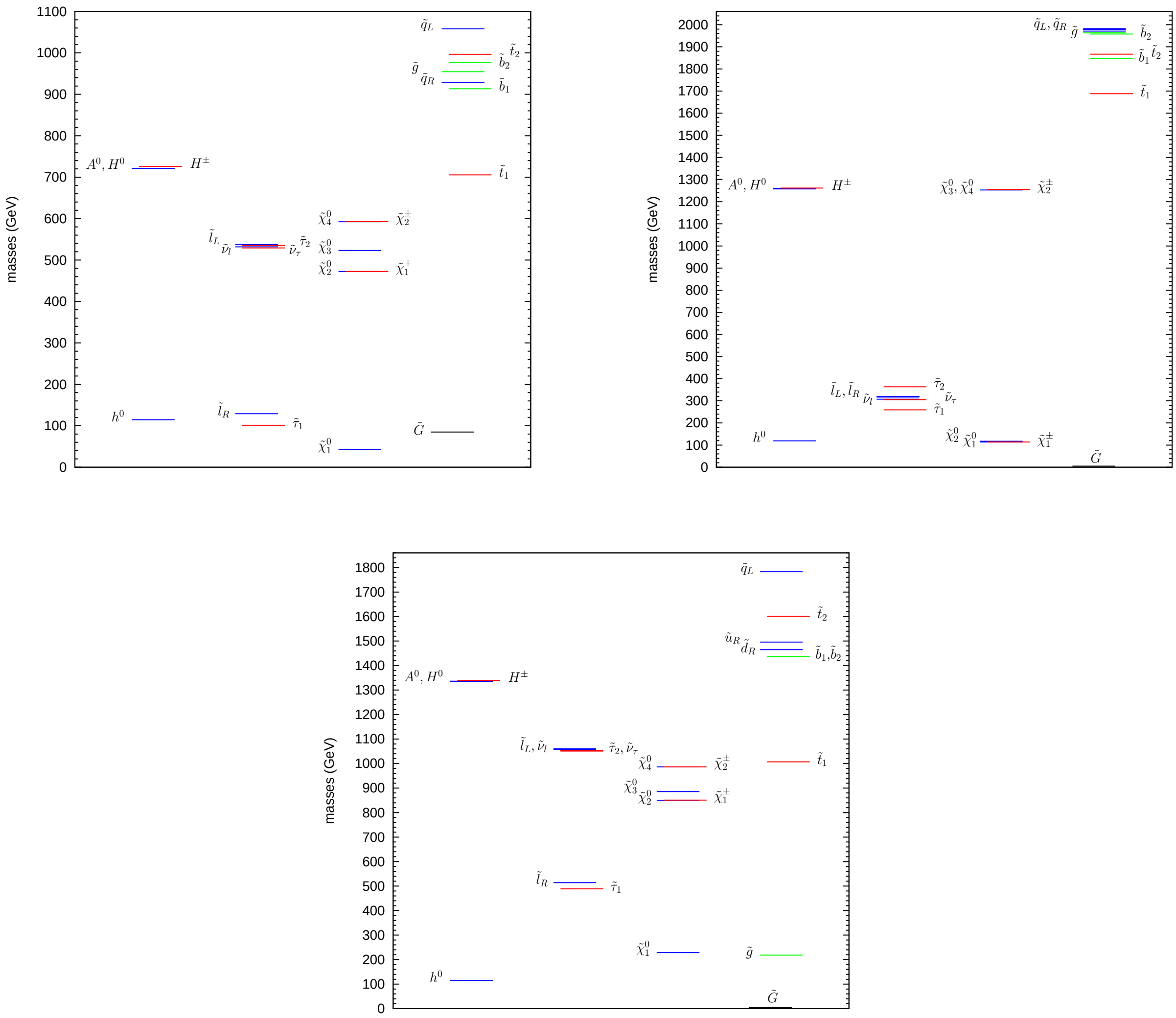

Figure 1: Sample Higgs and superparticle spectra. (a) Upper left panel: unified gauge group $G = SU(5)$, messengers in $(\mathbf{10}, \overline{\mathbf{10}})$, coupling $\overline{\mathbf{10}}_M \mathbf{24}\, \mathbf{10}_M$, $M_{\rm mess} = 10^{13}\,$GeV, $M_1(M_{\rm mess}) = m_{3/2} = 85\,$GeV, $\tan\beta = 15$. (b) Upper right panel: $G = SO(10)$, messengers in $(\mathbf{10}, \mathbf{10}')$, coupling $\mathbf{10}_M \mathbf{45}\, \mathbf{10}'_M$ with $\langle \mathbf{45} \rangle \propto T_{3R}$, $M_{\rm mess} = 10^{11}\,$GeV, $\epsilon = 1/6$, $\tan\beta = 15$. (c) Lower panel: $G = SO(10)$, messengers in $(\mathbf{16}, \overline{\mathbf{16}})$, coupling $\overline{\mathbf{16}}_M \mathbf{45}\, \mathbf{16}_M$ with $\langle \mathbf{45} \rangle \propto T_{B-L}$, $M_{\rm mess} = 10^{13}\,$GeV, $M_3(M_{\rm mess}) = m_{3/2} = 70\,$GeV, $\tan\beta = 15$.

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