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A natural scenario for heavy colored and light uncolored superpartners

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ABSTRACT

Influenced by the current trend of experimental data, especially from the LHC, we construct a supersymmetric scenario where a natural dynamics makes the squarks and gluino super-heavy (order 10 TeV) while keeping the sleptons and the weak gauginos light (100–500 GeV). The dynamics relies on the interfusion of two underlying ideas: (i) gauge mediation of supersymmetry breaking with two messenger multiplets, one transforming as a triplet of weak SU(2) and the other as an octet of color SU(3); (ii) perturbative gauge coupling unification at the string scale even with these incomplete SU(5) multiplets. Interestingly, the relative magnitude of the triplet and octet messenger scales that ensures gauge unification at the two-loop level also helps to naturally keep the uncolored superpartners light while making the colored ones heavy.

If the recently discovered scalar particle with a mass of around 125 GeV at the CERN Large Hadron Collider (LHC) [1,2] has to be identified with the lightest supersymmetric (SUSY) Higgs boson then, within the framework of the minimal supersymmetric standard model (MSSM), the stop squarks are expected to be rather heavy (order 10 TeV) having a substantial mixing between their left and right components [3,4]. Side by side, the non-observation of the first two generation squarks and the gluino in the 7 and 8 TeV run of the LHC, with the lower limits on their masses now pushed to around 1.5 TeV [5], sends us an early alert that they might remain elusive even in the 14 TeV run of the LHC. The absence of any statistically significant indirect evidence of new physics in meson oscillation and decays so far, measured with increasingly high precision by the Belle, BaBar and LHCb Collaborations, also endorses the view that colored superparticles might not lie within the periphery of the LHC territory. On the other hand, the uncolored superparticles, namely, the sleptons and the neutralinos/charginos, are (and would remain) relatively less constrained by the LHC [6,7]. Interestingly, the (3.3–3.6)-σ deviation of the measured $(g-2)$ of muon [8] from its standard model (SM) expectation [9,10] might hint towards a light smuon and gaugino/higgsino [11]. Additionally, the reported excess of the diphoton events in Higgs decay by the ATLAS Collaboration [12] can be explained by the presence of light staus [13–15] (though the diphoton decay rate reported by the CMS Collaboration [16] may not be construed as an excess). Even if these apparent discrepancies eventually disappear, the possible existence of light sleptons and weak neutralinos/charginos still merits a careful investigation especially in view of precision measurements at the upcoming International Linear Collider (ILC).

Given the present experimental situation as narrated above, what kind of a broad picture can we draw about plausible supersymmetric models? For example, can we conceive of a scenario that naturally accommodates heavy colored (order 10 TeV) and light uncolored (order 100 GeV) superparticles? This question is very pertinent and timely as in many scenarios, notably the gravity mediated supersymmetry breaking models, the heaviness of squarks also implies a set of heavy sleptons (*modulo* gaugino induced splitting by renormalization group (RG) running). Gauge mediated supersymmetry breaking (GMSB) models [17] offer a way out by introducing messenger particles in the intermediate scale, well below $M_G \simeq 2 \cdot 10^{16}$ GeV, and at that scale the squark masses are generated being proportional to the strong gauge coupling and slepton masses are generated being proportional to the weak gauge coupling. Thus the masses of squarks and sleptons are split right at the time of generation and the relative separation between grows even further when those masses are run down to the weak scale. Note that in the minimal GMSB scenario one employs a Φ_5 and a $\Phi_{\bar{5}}$ messenger multiplets, which transform as a fundamental **5** and a $\bar{\mathbf{5}}$ representation of SU(5), respectively, for the generation of *all* superparticle masses. Still, it is difficult to keep sleptons too light if the squarks become too heavy.

In this Letter, we resurrect an old idea in the GMSB context which introduces an unconventional choice of messenger

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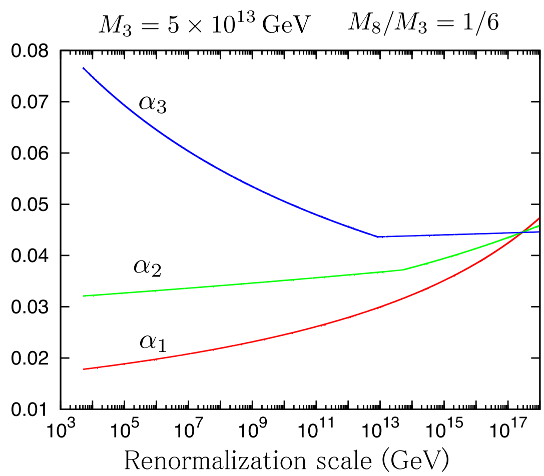

Fig. 1. Unification of the gauge couplings with SU(3) octet and SU(2) triplet messengers with their masses at around 10^{13} GeV. Two-loop RG evolution has been used, and we have used $\alpha_S(M_Z) = 0.1184$ and $m_{\rm SUSY} = 5$ TeV.

particles [18]. One of the key features of this scenario is that the sources for squark/gluino and slepton/weak gaugino mass generation are completely de-linked, which allows us to naturally maintain two orders of mass splitting between them. Instead of taking Φ_5 as $\Phi_{\bar{5}}$, here we employ messenger multiplets transforming as an adjoint octet (Σ_8) of color SU(3) and an adjoint triplet (Σ_3) of weak SU(2) [18]. The choices are not completely arbitrary as the origin of these states can be traced to the non-Goldstone modes of the scalar adjoint **24**-plet of SU(5). The superpotential of the messenger sector reads

$$W_{\rm mess} = (M_8 + \lambda_8 X)\,{\rm Tr}\big(\Sigma_8^2\big) + (M_3 + \lambda_3 X)\,{\rm Tr}\big(\Sigma_3^2\big), \tag{1}$$

where the F-term vacuum expectation value (vev) F_X of the hidden sector superfield X transmits supersymmetry breaking to the observable sector via the messenger multiplets.[1] The following consequences deserve special attention:

(i) Even in the absence of complete SU(5) multiplets, the presence of an identical number of $\Sigma_3(\mathbf{1}, \mathbf{3}, \mathbf{Y} = \mathbf{0})$ and $\Sigma_8(\mathbf{8}, \mathbf{1}, \mathbf{Y} = \mathbf{0})$ messenger multiplets still ensures perturbative gauge coupling unification at a scale somewhat higher than M_G [20]. More specifically, if the masses of these states are around $10^{(13-14)}$ GeV, then unification occurs even with these incomplete multiplets at around the string scale $M_{\rm str} \approx 5 \cdot 10^{17}$ GeV, which is the scale where the gravitational and gauge couplings are perturbatively unified [21]. This can be easily understood using the one-loop beta-functions of the gauge couplings. The gauge couplings at the string scale are given by

$$\begin{aligned}
\alpha_1^{-1}(M_{\rm str}) &= \alpha_1^{-1}(m_{\rm SUSY}) - \frac{b_1}{2\pi}\ln\frac{M_{\rm str}}{m_{\rm SUSY}}, \\
\alpha_2^{-1}(M_{\rm str}) &= \alpha_2^{-1}(m_{\rm SUSY}) - \frac{b_2}{2\pi}\ln\frac{M_{\rm str}}{m_{\rm SUSY}} - \frac{2}{2\pi}\ln\frac{M_{\rm str}}{M_3}, \\
\alpha_3^{-1}(M_{\rm str}) &= \alpha_3^{-1}(m_{\rm SUSY}) - \frac{b_3}{2\pi}\ln\frac{M_{\rm str}}{m_{\rm SUSY}} - \frac{3}{2\pi}\ln\frac{M_{\rm str}}{M_8},
\end{aligned} \tag{2}$$

where $b_i = (33/5, 1, -3)$ are the coefficients of the one-loop beta functions of the gauge couplings with MSSM particle content, and $m_{\rm SUSY}$ is the typical mass scale of the SUSY particles. To provide further intuition into the interplay of the messenger scale and the string scale (where gauge couplings unify), we use Eq. (2) to write (following the spirit of [22])

$$\big(5\alpha_1^{-1} - 3\alpha_2^{-1} - 2\alpha_3^{-1}\big)\big|_{m_{\rm SUSY}} = \frac{6}{\pi}\ln\left(\frac{M_{\rm str}^2 M_{\rm mess}}{m_{\rm SUSY}^3}\right), \tag{3}$$

employing a common messenger scale $M_{\rm mess} \equiv M_3 = M_8$. Putting $\alpha_{1,2,3}^{-1} \simeq (57, 30, 11)$ at $m_{\rm SUSY} = 1$ TeV, we obtain

$$M_{\rm str}^2 M_{\rm mess} = M_G^3. \tag{4}$$

Eq. (4) points to two important things: (i) If the messenger scale lies two orders of magnitude below the GUT scale, then the scale of gauge unification, which is the string scale, hovers at one order higher than the GUT scale. (ii) Even with the same supersymmetric mass of Σ_3 and Σ_8, i.e. $M_3 = M_8$, the unification is always maintained. The splitting ($M_3 > M_8$) is necessarily realized when we require unification at the string scale by considering two-loop RG running of the gauge couplings. For instance, taking $M_{\rm str} = 5 \times 10^{17}$ GeV and $m_{\rm SUSY} = 1$ TeV, one obtains $M_3 = 1.3 \times 10^{13}$ GeV and $M_8 = 3.6 \times 10^{12}$ GeV. In Fig. 1 we demonstrate this unification for $M_8 \simeq M_3/6 \simeq 5 \times 10^{13}$ GeV at the two-loop level.

(ii) The parameters M_8 and $\lambda_8 F_X$ control the squarks and gluino masses, while M_3 and $\lambda_3 F_X$ control the left-slepton and wino masses. Thus the masses of the colored and uncolored sector become completely independent. Moreover, since neither Σ_8 nor Σ_3 has any non-vanishing hypercharge, the bino and the right-sleptons are massless at this stage. A relatively small mass for them can be induced by gravitational interactions. Note that this de-correlation of masses has been achieved by the introduction of separate adjoint messenger multiplets responsible for the mass generation in the colored and uncolored sectors, *without* sacrificing the perturbative gauge unification. Moreover, for the unification to happen at the string scale, one must arrange $M_3 > M_8$, which helps to keep the left-sleptons lighter than the squarks. The elegance of this scenario thus lies in the interlinking of three issues, namely, perturbative string unification, the presence of intermediate scales characterizing gauge mediation, and the relative lightness (more specifically, two orders of magnitude) of uncolored sparticles compared to the colored ones, including the extreme lightness of bino and right-sleptons.

Let us now give a closer look into the superparticle spectrum. In our GMSB setup, the leading contributions to gaugino masses arising from the messenger loops are given by

$$m_{\tilde{B}} \simeq 0, \qquad m_{\tilde{W}} \simeq \frac{g_2^2}{16\pi^2}(2\Lambda_3), \qquad m_{\tilde{g}} \simeq \frac{g_3^2}{16\pi^2}(3\Lambda_8), \tag{5}$$

where $\Lambda_8 \equiv \lambda_8 F_X/M_8$, $\Lambda_3 \equiv \lambda_3 F_X/M_3$. Now, considering that $M_3 > M_8$ (discussed in gauge unification context), we tune λ_8 and λ_3 to ensure $\Lambda_8 \gg \Lambda_3$.[2] The soft mass-squared parameters of the squarks and sleptons are given by

$$\begin{aligned}
m_{\tilde{Q}}^2 &\simeq \frac{2}{(16\pi^2)^2}\left[\frac{4}{3}g_3^4\big(3\Lambda_8^2\big) + \frac{3}{4}g_2^4\big(2\Lambda_3^2\big)\right], \\
m_{\tilde{D}}^2 &= m_{\tilde{U}}^2 \simeq \frac{2}{(16\pi^2)^2}\frac{4}{3}g_3^4\big(3\Lambda_8^2\big), \\
m_{\tilde{L}}^2 &\simeq \frac{2}{(16\pi^2)^2}\frac{3}{4}g_2^4\big(2\Lambda_3^2\big), \qquad m_{\tilde{E}}^2 \simeq 0.
\end{aligned} \tag{6}$$

[1] For a recent discussion with a complete **24**-plet messenger multiplet transforming in the adjoint of SU(5), see [19].

[2] If we impose the universality conditions, $M_3 = M_8$ and $\lambda_8 = \lambda_3$ at $M_{\rm str}$, then $\Lambda_8 \simeq \Lambda_3$ holds even at the weak scale since M_8/λ_8 and M_3/λ_3 are, to a very good approximation, RG invariant. However, we do not impose this universality as it does not lead us to the condition we require for unification, namely, $M_8 \sim M_3/6$.