Physics Letters B 760 (2016) 681–688

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Upper bound on the gluino mass in supersymmetric models with extra matters

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ARTICLE INFO

Article history:
Received 20 June 2016
Received in revised form 22 July 2016
Accepted 22 July 2016
Available online 26 July 2016
Editor: J. Hisano

ABSTRACT

We discuss the upper bound on the gluino mass in supersymmetric models with vector-like extra matters. In order to realize the observed Higgs mass of 125 GeV, the gluino mass is bounded from above in supersymmetric models. With the existence of the vector-like extra matters at around TeV, we show that such an upper bound on the gluino mass is significantly reduced compared to the case of minimal supersymmetric standard model. This is due to the fact that radiatively generated stop masses as well the stop trilinear coupling are enhanced in the presence of the vector-like multiplets. In a wide range of parameter space of the model with extra matters, particularly with sizable $\tan\beta$ (which is the ratio of the vacuum expectation values of the two Higgs bosons), the gluino is required to be lighter than ~ 3 TeV, which is likely to be within the reach of forthcoming LHC experiment.

1. Introduction

Although the low-energy supersymmetry (SUSY) is attractive from the points of view of, for example, naturalness, gauge coupling unification, dark matter, and so on, to which the standard model (SM) has no clue, no signal of the SUSY particles has been observed yet. Thus, one of the important questions in the study of models with low-energy SUSY is the scale of SUSY particles.

It is well-known that the observed Higgs mass of ~ 125 GeV [1] gives information about the mass scale of SUSY particles (in particular, stops). The Higgs mass is enhanced by radiative corrections when the stop masses are much larger than the electroweak scale [2–6]. Thus, the stop masses are bounded from above in order not to push up the Higgs mass too much; the stop masses are required to be smaller than 10^4–10^5 GeV as far as $\tan\beta$, which is the ratio of the vacuum expectation value of the up-type Higgs to that of the down-type Higgs, is larger than a few. (For the recent study of such an upper bound, see, for example, [7].) Then, too large gluino masses are also disfavored because, via renormalization group (RG) effects, it results in stops which are too heavy to make the Higgs mass consistent with the observed value. Such an upper bound on the gluino mass is important for the future collider experiments, in particular, for the LHC Run-2, in order to discover and to study models with low energy SUSY. The purpose of this letter is to investigate how such an upper bound on the gluino mass depends on the particle content of the model.

We pay particular attention to SUSY models with extra vector-like chiral multiplets which have SM gauge quantum numbers. In these days, such extra vector-like matters are particularly motivated from the excess of the diphoton events observed by the LHC [8–11]. The most popular idea to explain the diphoton excess is to introduce a scalar boson Φ with which the LHC diphoton excess can be due to the process $gg \to \Phi \to \gamma\gamma$. In such a class of scenarios, vector-like particles which interact with Φ are necessary to make Φ being coupled to the SM gauge bosons. Indeed, it has been shown that the LHC diphoton excess are well explained in SUSY models with vector-like chiral multiplets [12–30]. Assuming a perturbative gauge coupling unification at the GUT scale of $\sim 10^{16}$ GeV,[1] three or four copies of the vector-like multiplets, which transform $\mathbf{5}$ and $\bar{\mathbf{5}}$ in $SU(5)$ gauge group, are suggested, and their masses need to be around or less than 1 TeV. In addition, the vector-like chiral multiplets are also motivated in models with non-anomalous discrete R-symmetry [32,33].

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[1] For the perturbativity bounds on models with extra matters, see [31].

http://dx.doi.org/10.1016/j.physletb.2016.07.061

With extra vector-like chiral multiplets, the RG evolutions of the coupling constants and mass parameters of the SUSY models drastically change compared to those in the minimal SUSY SM (MSSM). Consequently, as we will see, the upper bound on the gluino mass becomes significantly reduced if there exist extra vector-like chiral multiplets. Such an effect has been discussed in gaugino mediation model [34] and in the light of recent diphoton excess at the LHC [25].

In this letter, we study the upper bound on the gluino mass in SUSY models with extra vector-like matters, assuming more general framework of SUSY breaking. We extend the previous analysis and derive the upper bound on the gluino mass. We will show that the bound on the gluino mass is generically reduced with the addition of extra matters. The upper bound becomes lower as the number of extra matters increases, and the bound can be as low as a few TeV which is within the reach of the LHC Run-2 experiment.

2. Enhanced Higgs boson mass and gluino mass

We first explain how the upper bound on the gluino mass is reduced in models with extra vector-like multiplets. To make our discussion concrete, we consider models with extra chiral multiplets which can be embedded into complete $SU(5)$ fundamental or anti-fundamental representation as $\bar{\mathbf{5}}_i = (\bar{D}'_i, L'_i)$ and $\mathbf{5}_i = (D'_i, \bar{L}'_i)$; we introduce N_5 copies of $\mathbf{5}$ and $\bar{\mathbf{5}}$ with $i = 1 \dots N_5$.[2] Then, the superpotential is given by

$$W = W_{\rm MSSM} + M_V(\bar{D}'_i D'_i + \bar{L}'_i L'_i), \tag{1}$$

where $W_{\rm MSSM}$ is a superpotential of the MSSM and M_V is the common masses for vector-like matter fields.[3] Hereafter, M_V (=$M_{D'}$=$M_{L'}$) is taken to be ~ 1 TeV, while $N_5 = 3$ and 4, which are suggested by, for example, the diphoton excess observed by the LHC [12–29].[4]

In order to see how the upper bound on the gluino mass is derived, it is instructive to see the leading one-loop correction to the Higgs mass. Assuming that the left- and right-handed stop masses are almost degenerate, the Higgs boson mass with the leading one-loop corrections in the decoupling limit is estimated as [2–6]

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\ln\frac{M_{\tilde{t}}^2}{m_t^2} + \frac{|X_t|^2}{M_{\tilde{t}}^2}\left(1 - \frac{|X_t|^2}{12M_{\tilde{t}}^2}\right)\right], \tag{2}$$

where m_Z is the Z-boson mass, m_t is the top mass, $M_{\tilde{t}}$ is the stop mass, $v = 174.1$ GeV is the vacuum expectation value of the Higgs boson, and $X_t = A_t - \mu/\tan\beta$ (with A_t being the trilinear coupling of stops normalized by the top Yukawa coupling constant y_t, and μ being the Higgsino mass). Notice that the first term in the square bracket of Eq. (2) is the effect of the RG running of the quartic SM Higgs coupling constant from the mass scale of the SUSY particles to the electroweak scale, while the second one is the threshold correction at the mass scale of the SUSY particles. The Higgs mass becomes larger as $M_{\tilde{t}}$ or X_t increases (as far as $X_t \lesssim \sqrt{6}$). Thus, in order to realize the observed value of the Higgs mass, $m_h \simeq 125$ GeV, there is an upper-bound on $M_{\tilde{t}}$ and X_t. Importantly, the stop masses and the A_t parameter are enhanced with larger value of the gluino mass because of the RG runnings from a high scale to the mass scale of SUSY particles. Consequently, with boundary conditions on the MSSM parameters given at a high scale, we obtain the upper bound on the gluino mass to have $m_h \simeq 125$ GeV. Hereafter, we assume that the MSSM is valid up to the GUT scale $M_{\rm GUT} \sim 10^{16}$ GeV and derive such an upper bound.

Now we consider how the existence of the extra matters affects the upper bound on the gluino mass by using one-loop RG equations (RGEs), although two-loop RGEs are used for our numerical calculation in the next section. With N_5 pairs of the vector-like multiplets, RGEs of gauge coupling constants at the one-loop level are

$$\frac{dg_i}{d\ln\mu_R} = \frac{b_i}{16\pi^2} g_i^3, \tag{3}$$

where μ_R is a renormalization scale; g_1, g_2 and g_3 are gauge coupling constants of $U(1)_Y$ (in $SU(5)$ GUT normalization), $SU(2)_L$ and $SU(3)_C$, respectively. In addition, $(b_1, b_2, b_3) = (33/5 + N_5, 1 + N_5, -3 + N_5)$. For $M_V \lesssim 1$ TeV, $N_5 \lesssim 4$ needs to be satisfied under the condition that the coupling constants remain perturbative up to the GUT scale ($\sim 10^{16}$ GeV). As one can see, for $N_5 \gtrsim 3$, g_3 is not asymptotically free. One-loop RGEs of gaugino masses are

$$\frac{dM_i}{d\ln\mu_R} = \frac{b_i}{8\pi^2} g_i^2 M_i, \tag{4}$$

where M_1, M_2 and M_3 are the Bino, Wino and gluino mass, respectively. (Hereafter, we use the convention in which M_3 is real and positive.) The ratio M_i/g_i^2 is constant at the one-loop level and, with M_i at the mass scale of the SUSY particles being fixed, the gaugino masses at higher scale are more enhanced with larger value of N_5. In particular, for $N_5 \gtrsim 3$, the gluino mass, whose RG effects on A_t and the stop masses are important, become larger as the RG scale increases.[5] In other words, even if $|M_3|$ is large at the GUT scale, the low-energy value of $|M_3|$ is small especially for $N_5 = 4$ [25].

With the enhancement of the gluino mass, the RG effect on the A_t parameter becomes larger. This can be easily understood from the RGE of the A_t parameter; at the one-loop level,

$$\frac{dA_t}{d\ln\mu_R} = \frac{1}{16\pi}\left[\frac{32}{3}g_3^2 M_3 + 6y_t^2 A_t + \cdots\right], \tag{5}$$

where we show only the terms depending on $SU(3)_C$ gauge coupling constant or the top Yukawa coupling constant. One can see that the A_t parameter is generated by the RG effect using the gluino mass as a source, and the low-energy value of $|A_t|$ is likely to become larger as $|M_3|$ increases.

More quantitative discussion about the enhancement of the A_t parameter is also possible. Solving RGEs, the A_t parameter at the mass scale of the SUSY particles, denoted as $m_{\mathcal{S}}$, can be parametrized as

$$A_t(m_{\mathcal{S}}) \simeq \left\{\begin{matrix} -0.77 \\ -1.84 \\ -5.18 \end{matrix}\right\} M_3(m_{\mathcal{S}}) + \left\{\begin{matrix} 0.39 \\ 0.47 \\ 0.36 \end{matrix}\right\} A_0, \tag{6}$$

where the numbers in the curly brackets are the coefficients for the cases of the MSSM (i.e., $N_5 = 0$), $N_5 = 3$, and $N_5 = 4$, from the top to the bottom, which are evaluated by using two-loop RGEs with $m_{\mathcal{S}} = 3.5$ TeV, and $A_0 \equiv A_t(M_{\rm inp})$ with $M_{\rm inp}$ being the scale where the boundary conditions for the SUSY breaking parameters are set. (In our numerical calculations, we take $M_{\rm inp} = 10^{16}$ GeV.)

[2] Our results are qualitatively unchanged even if the vector-like matters are embedded into other representations of $SU(5)$, as far as the parameter N_5 is properly interpreted. For the case with N_{10} copies of $\overline{\mathbf{10}}$ and $\mathbf{10}$ representations, for example, N_5 should be replaced by $3N_{10}$.

[3] Due to the RG runnings, the SUSY invariant masses for D' and L' should differ even if they are unified at the GUT scale. Such an effect is, however, unimportant for our following discussion, and we neglect the mass difference among the extra matters.

[4] The case of $N_5 = 3$ is particularly interesting, since it may be embedded into an E_6 GUT [35].

[5] For $N_5 = 3$, the one-loop beta-function vanishes and M_3 is constant, but $|M_3|$ becomes larger at the high energy scale due to two-loop effects.