Higgs mass and muon anomalous magnetic moment in the MSSM with gauge-gravity hybrid mediation

Bin Zhu,[1,*] Ran Ding,[2] and Tianjun Li[3,4,5]

[1]*Department of Physics, Yantai University, Yantai 264005, People's Republic of China*
[2]*Center for High-Energy Physics, Peking University, Beijing, 100871, People's Republic of China*
[3]*Key Laboratory of Theoretical Physics and Kavli Institute for Theoretical Physics China (KITPC),*
Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, People's Republic of China
[4]*School of Physical Sciences, University of Chinese Academy of Sciences,*
Beijing 100049, People's Republic of China
[5]*School of Physical Electronics, University of Electronic Science and Technology of China,*
Chengdu 610054, People's Republic of China

In general, we can propose the hybrid supersymmetry breakings and hybrid mediations in the supersymmetric standard models. In this paper, we study the hybrid mediation for supersymmetry (SUSY) breaking. In particular, we study how to keep the good properties of gravity mediation, gauge mediation, and anomaly mediation, while solving their problems simultaneously. As an example, we consider the gauge-gravity mediation, where all the supersymmetric particles (sparticles) obtain the SUSY breaking soft terms from the traditional gravity mediation while gauge mediation gives dominant contributions to the soft terms in the colored sector due to the splitted messengers. Thus, we can realize the electroweak supersymmetry naturally where the sleptons, sneutrinos, and electroweakinos are light within one TeV while the squarks and gluino are heavy around a few TeVs. Then we can explain 125 GeV Higgs mass, satisfy the LHC SUSY search bounds, and explain the anomalous magnetic moment of muon, etc. Moreover, the gluino and squarks are well beyond the current LHC run II searches.

I. INTRODUCTION

It is well known that supersymmetry (SUSY) provides a natural solution to the gauge hierarchy problem in the standard model (SM). For the supersymmetric SMs (SSMs) with R-parity, gauge coupling unification can be realized, the lightest supersymmetric particle (LSP) serves as a viable dark matter (DM) candidate, and electroweak (EW) gauge symmetry can be broken radiatively due to the large top quark Yukawa coupling, etc. Moreover, gauge coupling unification strongly suggests grand unified theories (GUTs), and SUSY GUTs can be elegantly constructed from superstring theory. Therefore, supersymmetry is an important bridge between the most promising new physics beyond the SM and the high-energy fundamental physics.

The great success at the LHC so far is the discovery of a SM-like Higgs boson (h) with mass $m_h = 125.09 \pm 0.24$ GeV [1,2]. However, to achieve such a SM-like Higgs boson mass in the minimal SSM (MSSM), we need either the multi-TeV top squarks with small mixing or TeV-scale top squarks with large mixing [3]. Also, the LHC SUSY searches give stringent constraints on the viable parameter space of the SSMs. For example, the latest SUSY search bounds show that the gluino ($\tilde{g}$) mass is heavier than about 1.9 TeV, whereas the light stop ($\tilde{t}_1$) mass is heavier than about

900 GeV [4]. Thus, there exists the electroweak fine-tuning problem in the SSM. Then how to construct the natural SSMs, which can realize the correct Higgs boson mass and satisfy the LHC SUSY search constraints, is a big challenge.

In addition to the gauge hierarchy problem in the SM, the anomalous magnetic moment of the muon $a_\mu = (g_\mu - 2)/2$ remains one of the strong hints for physics beyond the SM (BSM) since it is deviated from the SM prediction more than the 3σ level. The discrepancy compared to its SM theoretical value is given as [5–7]

$$\Delta a_\mu = (a_\mu)_{\mathrm{exp}} - (a_\mu)_{\mathrm{SM}} = (28.6 \pm 8.0) \times 10^{-10}. \quad (1.1)$$

In the SSMs, the light smuon, muon-sneutrino, Bino, Winos, and Higgsinos would contribute to Δa_μ [8–12]. The contributions to Δa_μ from the neutralino-smuon and chargino-sneutrino loops can approximately be expressed as

$$\Delta a_\mu^{\tilde{\chi}^0 \tilde{\mu}} \simeq \frac{1}{192\pi^2} \frac{m_\mu^2}{M_{\mathrm{SUSY}}^2} (\mathrm{sgn}(\mu M_1) g_1^2 - \mathrm{sgn}(\mu M_2) g_2^2) \tan\beta,$$
$$(1.2)$$

$$\Delta a_\mu^{\tilde{\chi}^\pm \tilde{\nu}} \simeq \mathrm{sgn}(\mu M_2) \frac{1}{32\pi^2} \frac{m_\mu^2}{M_{\mathrm{SUSY}}^2} g_2^2 \tan\beta, \quad (1.3)$$

where M_{SUSY} denotes the typical mass scale of the relevant sparticles. It is obvious that if all the relevant sparticles have masses around the same scale, the chargino-sneutrino loop

*zhubin@mail.nankai.edu.cn

contributions would be dominant. Thus, we have $\Delta a_\mu \sim 10^{-9}(\frac{100\ \text{GeV}}{M_{\text{SUSY}}})^2 \tan\beta$ for $\text{sgn}(\mu M_2) > 0$. From Ref. [10], we know that the 2σ bound on Δa_μ can be achieved for $\tan\beta = 10$ if four relevant sparticles are lighter than 600–700 GeV, while for smaller $\tan\beta$ (~ 3), the lighter sparticles ($\lesssim 500$ GeV) are needed. Therefore, to explain the muon anomalous magnetic moment, we need the light smuon, muon-sneutrino, Bino, Winos, and Higgsinos.

Inspired by the above LHC Higgs [13] and SUSY [14] searches, the experimental results/constraints on B physics [15,16], flavor changing neutral current (FCNC) [17–19], dark matter relic density from WMAP experiment [20], and direct dark matter search from the XENON100 experiment [21], one of us with his collaborators proposed the electroweak supersymmetry (EWSUSY): the squarks and/or gluino are heavy around a few TeVs while the sleptons, sneutrinos, Bino, Winos, and/or Higgsinos are light within one TeV [22]. To realize the EWSUSY in the MSSM, we considered the generalized minimal supergravity (GmSUGRA) [23,24] with the nonuniversal gaugino masses, universal/nonuniversal scalar masses, and universal/nonuniversal trilinear soft terms. For the later and relevant studies, see Refs. [25–40]. Especially, the heavy squarks are preferred by the SUSY FCNC and CP violation problems. The light electroweak SUSY sector is very promising on both model building and phenomenological study.

In short, for the SUSY model building and phenomenology, we still need to explore the natural SSMs which are consistent with all the latest experimental results. As we know, supersymmetry can be broken via F-term and D-term, and there are three main mediation mechanisms for the supersymmetry breaking: gravity mediation, gauge mediation, and anomaly mediation. Because each mediation mechanism has its merits and drawbacks, we shall propose the generic hybrid F-term and D-term supersymmetry breaking and hybrid mediations, where all the merits can be preserved while the problems can be solved. The examples for the hybrid supersymmetry breakings are the SSMs with pseudo-Dirac gluino [41] and the UV insensitive anomaly mediation [42]; and the examples for the hybrid mediations are the deflected anomaly mediation [43], mirage mediation [44], deflected mirage mediation [45], and gravity-gauge mediation [46]. In this paper, we study the hybrid mediation for supersymmetry breaking in general, and set up the solid foundation for our future research program. In particular, we discuss how to keep the good properties of gravity mediation, gauge mediation, and anomaly mediation, while solving their problems simultaneously. As a concrete example, we consider the gravity-gauge mediation, which is comparable. Once the messenger scale is taken to be around 10^{16} GeV, we obtain $m_{3/2} \sim M_{\text{GMSB}}$, and then gravity mediation can be comparable with gauge mediation. This proposal is different from the previous gravity-gauge mediation in Ref. [46], where the gauge mediation is dominant. Moreover, as we know, to obtain the 125 GeV Higgs boson mass in the

minimal content of the gauge mediated supersymmetry breaking (GMSB) which employ a pair of $(5, \bar{5})$ of $SU(5)$ GUT as messengers, the soft masses of sleptons and electroweakinos are pushed up to a few TeVs and then we cannot explain the anomalous magnetic momentum of the muon. In other words, the splitting between the gluino/squarks and the electroweakinos/sleptons/sneutrinos is not large enough. This inspired the GMSB proposal with adjoint messengers [35,36,38–40], which can naturally generate such large splitting. However, a critical problem is that the desired large splitting causes the tachyonic slepton problem. To solve this problem, people have considered one extra pair of $SU(5)$ $(5, \bar{5})$ messenger fields [35], or additional universal scalar mass and Bino mass from gravity mediation [38], or $U(1)_{B-L}$ D-term contributions [39,40], etc. In this paper, we assume that the squarks and gluino obtain the large and dominant SUSY breaking soft terms from gauge mediation, while the sleptons, sneutrinos, Bino, Winos, and/or Higgsinos obtain the dominant SUSY breaking soft terms from gravity mediation. Our proposal is different from the above scenarios: (1) The messenger fields need not be $SU(3)$ adjoint field; (2) we do not have the $SU(2)$ adjoint messenger; (3) we have the universal gaugino mass, scalar mass, and trilinear term from gravity mediation. Interestingly, such kind of hybrid model inherits the merits of both gravity and gauge mediations. In particular, the $\mu - B_\mu$ problem in the GMSB is solved due to the Giudice-Masiero mechanism for gravity mediation, and the LSP neutralino can still be the DM candidate.

This paper is organized as follows. In Sec. II, we study the hybrid supersymmetry breakings and hybrid mediations in general. In Sec. III we lay out our model contents with taking into account some soft spectra in GMSB. The phenomenology aspects especially on muon $g - 2$ anomaly and current LHC constraints is investigated in Sec. IV.

II. HYBRID SUPERSYMMETRY BREAKINGS AND HYBRID MEDIATIONS

In a supersymmetric theory, the scalar potential has F-terms and D-terms. Thus, there are two kinds of supersymmetry breakings: F-term and D-term supersymmetry breakings. Usually, we consider the F-term supersymmetry breaking. As an example, to propose the SSMs with the pseudo-Dirac gluino and Majorana Wino/Bino, we have studied the hybrid F-term and D-term supersymmetry breaking before [41].

As we know, there are three major supersymmetry breaking mediation mechanisms.

Gravity mediated supersymmetry breaking.—Gravity mediation has been studied systematically and extensively, especially, the minimal supergravity (mSUGRA) and constrained MSSM (CMSSM) with universal supersymmetry breaking soft terms: gaugino mass, scalar mass, and trilinear term. Also, the generalized mSUGRA (GmSUGRA) can have nonuniversal soft terms. Usually, the LSP is the lightest

neutralino, and can have correct density via coannihilation, well-tempered neutralino, and resonance annihilation, etc., or we can have multicomponent dark matter and then the Higgsino can be the LSP. In the string models, gravity mediation has been considered as the dominant mediation mechanism as well. In short, gravity mediation has enough degrees of freedom and can be consistent with all the current experimental results. However, in principle, the big challenge is the flavor changing neutral current (FCNC) problem and CP violation problem for the general gravity mediation.

Gauge mediated supersymmetry breaking (GMSB).— Gauge mediation solves the FCNC and CP violation problems since the gauge interaction is flavor blind. Unlike gravity mediation, the LSP is gravitino, whose mass can be constrained from cosmology. For the minimal gauge mediation, we have two problems: (1) The supersymmetry breaking trilinear A term is very small. Thus, to have the correct Higgs boson mass, we need heavy stop quarks with mass above 5 TeV. This problem can be solved via the Yukawa deflected gauge mediation with additional Yukawa mediation; (2) $\mu - B_\mu$ problem.

Anomaly mediated supersymmetry breaking (AMSB).— Anomaly mediation can solve the FCNC and CP violation problems as well. Anomaly mediation requires a mechanism to suppress gravity mediation since it is generated at loop level, for example, the sequestering mechanism between the observable and hidden sectors. The gaugino mass is proportional to the corresponding one-loop gauge beta function, while scalar masses and trilinear A-terms depend on the anomalous dimensions of the corresponding scalar fields. Thus, it predicts that Wino will be the LSP. However, the big problem is that sleptons are tachyonic. There are two kinds of solutions: (1) The UV insensitive anomaly mediation with addition D-term contributions to scalar masses [42]; (2) the deflected anomaly mediation with extra gauge mediation [43]. In this scenario, the gravitino is heavier than 25 TeV and will decay before the big-bang nucleosynthesis (BBN), so we can solve the cosmological moduli problem.

As we know, the hybrid mediations for supersymmetry breaking have been studied previously, and let us give two kinds of examples: (1) The deflected anomaly mediation [43], mirage mediation [44], deflected mirage mediation [45] can be considered as the hybrid gauge and anomaly mediations. (2) The gravity-gauge mediation was proposed previously [46–48]. But to evade the FCNC and CP violation problems, the gravity mediation is suppressed compared to the gauge mediation.

As we pointed out in the Introduction, there exists the electroweak fine-tuning problem in the SSMs and the LHC supersymmetry searches give strong constraints on the SSMs. Therefore, with the hybrid supersymmetry breakings and hybrid mediations, we may construct the natural SSMs which can evade the LHC supersymmetry search constraints and solve the problem in the SSMs with single

mediation. Let us give a few examples: (1) In the next to MSSM (NMSSM) with gauge mediation, there is a problem for the singlet (S) soft mass and its trilinear term $A_\kappa \kappa S^3$. This problem can be solved by considering the hybrid gravity-gauge mediation. (2) In the anomaly mediation, we can introduce another superfield or modulus whose F-term is nonzero, and its supersymmetry breaking effect is mediated to the observable sector via gravity interaction. Thus, the tachyonic slepton problem in anomaly mediation and the moduli problem in gravity mediation can be solved simultaneously. (3) In the natural SSMs with small fine-tuning measures, we generically have the nonuniversal boundary conditions, and sometimes there exists a little bit of hierarchy between the soft mass terms. For example, we need the following approximate gaugino mass relation [49]:

$$\left(\frac{M_1}{15M_3}\right)^2 + \left(\frac{M_2}{2.6M_3}\right)^2 = 1, \tag{2.1}$$

which can be realized naturally via hybrid mediation. (4) In the supernatural supersymmetry [50–53], the electroweak fine-tuning measure is automatically at the order 1, and then we can solve the supersymmetry electroweak fine-tuning problem naturally. To generalize it to the effective supernatural supersymmetry [54], we need additional supersymmetry breaking soft terms, which are subdominant and will not affect the electroweak fine-tuning measure. Thus, we can combine the no-scale supergravity or M-theory inspired supergravity with the other mediations.

III. MODEL

The most general SUSY breaking soft terms in the MSSM are [55]

$$\begin{aligned}
\mathcal{L}_{\text{soft}} = &-\frac{1}{2}(M_3\tilde{g}\,\tilde{g} + M_2\tilde{W}\,\tilde{W} + M_1\tilde{B}\,\tilde{B} + \text{H.c.}) \\
&- (\tilde{q}T_u\tilde{u}H_u - \tilde{q}T_d\tilde{d}H_d - \tilde{l}T_e\tilde{e}H_d + \text{H.c.}) \\
&- m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (B_\mu H_u H_d + \text{H.c.}) \\
&- \tilde{f}^+ m_{\tilde{f}}^2 \tilde{f}. \tag{3.1}
\end{aligned}$$

In the GMSB, SUSY breaking [56] is parametrized by a spurion field X with

$$\langle X \rangle = M + \theta^2 F. \tag{3.2}$$

In our model, clearly different from the minimal GMSB, X directly couples to colored messenger multiplet Φ_G which takes adjoint representation under the $SU(3)$ gauge group. The corresponding superpotential can be written as

$$W_{\text{mess}} = \lambda X \Phi_G \Phi_G. \tag{3.3}$$

This gives a supersymmetric mass M as well as a nonsupersymmetric mass term $F\phi\tilde{\phi} + \text{H.c.}$ for its scalar component, which leads to a splitted squared-mass

$M^2 \pm F$ for the complex scalar messengers. Such mass splitting in the messenger sector is then communicated to the soft terms in the MSSM through radiative corrections with messenger loops. The gaugino masses are generated at one loop order with

$$M_i = \frac{g_i^2}{16\pi^2} n_G \Lambda a_i, \qquad (3.4)$$

where the n_G is the Dykin index of Φ_G. Indices $i = 1, 2, 3$ denote bino, wino and gluino. For the Φ_G messenger, the corresponding Dynkin indices are $a_{1,2} = 0$, $a_3 = 3$. As a consequence, bino and wino do not receive any contribution from messenger loops while the gluino obtains large masses from nonzero a_3. Meanwhile, scalar masses come from the two-loop order with

$$m_l^2 = m_e^2 = m_{H_u}^2 = m_{H_d}^2 = 0,$$
$$m_u^2 = m_d^2 = \frac{g_3^4}{32\pi^4} n_G \Lambda^2 f\left(\frac{\Lambda}{M_{\text{mess}}}\right),$$
$$m_q^2 = \frac{3g_3^4}{16\pi^4} n_G \Lambda^2 f\left(\frac{\Lambda}{M_{\text{mess}}}\right). \qquad (3.5)$$

In the above equations, M_{mess} is the messenger scale, $\Lambda \equiv F/M_{\text{mess}}$, and f as well as the following g in Eq. (3.8) are the loop functions which can be found in Ref. [56]. In the absence of additional messenger interactions, the soft bilinear term B_μ and trilinear terms $A_{u,d,e}$ are zero at the messenger scale and are generated by running of renormalization group equations (RGEs). From Eq. (3.5), one found that the soft masses of slepton and color sectors are obtained with distinct contributions at the messenger threshold. This feature naturally guarantees large mass splitting which is favored by muon a_μ anomaly. Nevertheless, if slepton masses do not get an additional contribution, it will suffer from a dangerous tachyonic problem. For this reason, we incorporate the gravity mediation to avoid tachyonic sleptons. As we know, gravity is usually ignored when considering gauge mediation, while the situation changes if the messenger scale is around 10^{15} GeV where the gravity mediation is comparable with gauge mediation. Thus, in such a case, gauge mediation is naturally associated with additional gravity mediation. In supergravity mediation, the flavor structure of the soft terms is strongly constrained by flavor changing neutral current processes (FCNCs) which strongly suggests flavor-universal soft terms,

$$\tilde{m}_{ij}^2 = m_0^2 \delta_{ij}, \quad T_{u,d,e} = A_0 Y_{u,d,e}, \quad M_{1,2,3} = m_{1/2}. \quad (3.6)$$

For simplicity, we denote it as the type-I model. The basic property of such type mode is that only the color sector obtained soft masses at the messenger scale. Thus, Higgs mass will be sensitive to the general relation between m_0 and Λ. In addition, relatively large m_0 is favored in order to

stabilize the slepton masses. As another example, we further consider the messenger sector is Φ_D and Φ_D^c whose quantum numbers under $SU(3)_C \times SU(2)_L \times U(1)_Y$ are $(\mathbf{3}, \mathbf{1}, -\mathbf{1/3})$ and $(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1/3})$, respectively. The corresponding superpotential is

$$W_{\text{mess}} = \lambda X \Phi_D \Phi_D^c. \qquad (3.7)$$

Here, we denote it as the type-II model. The corresponding nonzero soft terms at the messenger scale are given by

$$M_1 = \frac{g_1^2}{40\pi^2} n_d \Lambda g\left(\frac{\Lambda}{M_{\text{mess}}}\right),$$
$$M_3 = \frac{g_3^2}{40\pi^2} n_d \Lambda g\left(\frac{\Lambda}{M_{\text{mess}}}\right),$$
$$m_q^2 = \frac{1}{128\pi^4}\left(\frac{1}{150} g_1^4 + \frac{4}{3} g_3^4\right) n_d \Lambda^2 f\left(\frac{\Lambda}{M_{\text{mess}}}\right),$$
$$m_u^2 = \frac{1}{128\pi^4}\left(\frac{8}{75} g_1^4 + \frac{4}{3} g_3^4\right) n_d \Lambda^2 f\left(\frac{\Lambda}{M_{\text{mess}}}\right),$$
$$m_d^2 = \frac{1}{128\pi^4}\left(\frac{2}{75} g_1^4 + \frac{4}{3} g_3^4\right) n_d \Lambda^2 f\left(\frac{\Lambda}{M_{\text{mess}}}\right),$$
$$m_l^2 = m_{H_u}^2 = m_{H_d}^2 = \frac{3g_1^4}{128\pi^4} n_d \Lambda^2 f\left(\frac{\Lambda}{M_{\text{mess}}}\right),$$
$$m_e^2 = \frac{g_1^4}{3200\pi^4} n_d \Lambda^2 f\left(\frac{\Lambda}{M_{\text{mess}}}\right). \qquad (3.8)$$

One can see that compared with the type-I model, this model has extra contributions from the $U(1)_Y$ sector. This scenario leads to bino, slepton and Higgs sectors also receiving nonzero soft mass at the messenger scale. As we will discuss in the next section, which notably improves the slepton tachyonic problem and changes the particle spectra. based on the above discussion, the particle spectra in our model are governed by the following parameters:

$$\{m_0, m_{1/2}, A_0, \text{sign}(\mu), \tan\beta, \Lambda, M_{\text{mess}}, n_{G/d}\}. \quad (3.9)$$

Among them, $n_{G/d}$ is the Dynkin index of the messengers, and thus is not a variable. Also, $\text{sign}(\mu)$ is obviously not a variable as well. Therefore, our models only have two more parameters Λ and M_{mess} compared to the mSUGRA/CMSSM. In other words, we do not have a larger number of parameters. Then an interesting question is what is the minimal version of these scenarios that can work. To our knowledge, the minimal scenario is that we consider (Φ_D, Φ_D^c) as messengers and no-scale supergravity. In the no-scale supergravity, $m_0 = A_0 = B_\mu = 0$. Then the parameters are

$$\{M_{1/2}, \tan\beta, \Lambda, M_{\text{mess}}\}. \qquad (3.10)$$
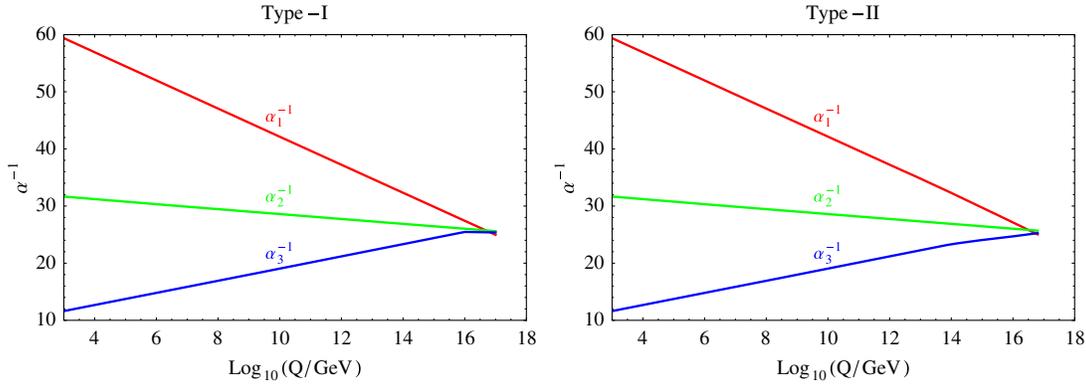
FIG. 1. Gauge coupling unification in type-I (left) and type-II (right) models. For both models, GUT can be realized at scale $M_U \simeq 10^{16-17}$ GeV.

There are only four parameters, just like the mSUGRA/CMSSM.

Next, we would like to emphasize that the generic vectorlike particles, which do not form complete $SU(5)$ or $SO(10)$ representations in GUTs, can be obtained from the orbifold constructions [57–59], intersecting D-brane model building on type II orientifolds [60–62], M-theory on S^1/Z_2 with Calabi-Yau compactifications [63,64], and F-theory with $U(1)$ fluxes [65–68]. In particular, the generic vectorlike particles from orbifold GUTs and F-theory GUTs have been studied previously in detail in Refs. [69–71]. To be concrete, the vectorlike particles (Φ_D, Φ_D^c) in the type-II model can be realized in all the above model buildings, while the messenger Φ_G in the type-I model can only be obtained in the intersecting D-brane model building on type-II orientifolds. Furthermore, in a full supergravity framework, if one would like to consider the gauge mediation with GUT scale mediation, such a combination might have the messengers in the incomplete GUT representations. For example, in Ref. [72], by Poppitx and Trivedi, the global symmetry is $SP(N-3)$, whose subgroup can be identified as the SM gauge symmetry. The minimal $SP(2k)$ group, which contains the SM gauge group, is $SP(8)$. The messenger fields in the fundamental representation 8 can be considered in the incomplete $SU(5)$ representations. Moreover, the next to the minimal group $SP(10)$ has $SU(5)$ as a subgroup, and then the messengers can be in the complete $SU(5)$ representations. However, how to obtain the SM chiral fermions in the $SP(8)$ and $SP(10)$ models is a subtle question.

Finally, we briefly comment on realization of the gauge coupling unification (GUT) in both models. As is well known, the modification of messenger representation plays a crucial role on GUT. Unlike the minimal gauge mediation supersymmetry breaking (mGMSB) where the messengers form complete $SU(5)$ representations, g_3 coupling has big contributions from the messenger threshold in type-I model, which in general violate the conventional GUT condition unless the messenger scale is close to the GUT scale, while for the type-II model, the situation is improved

due to the relatively small contributions to $b_{1,3}$. As a consequence, the messengers can be at a slightly lower scale. The gauge coupling unifications in type-I and type-II models are given in Fig. 1.

IV. NUMERICAL RESULTS

In this section, we present the numerical studies for both type-I and II models with focus on sparticle spectra and muon anomalous magnetic moment. In our numerical calculations, the universal soft terms in Eq. (3.6) are first generated at the GUT scale in terms of gravity mediation for both type-I and type-II models. The behaviors of soft terms then controlled by RGE effects running from GUT scale to messenger scale. Below messenger scale, the messenger fields are integrated out to generate threshold soft terms which are given in Eqs. (3.4) and (3.5) for the type-I model and in Eq. (3.8) for the type-II model. For this purpose, we implemented boundary conditions in Eqs. (3.6), (3.4), (3.5), and (3.8) in the *Mathematica* package SARAH [73–77]. Then SARAH is used to create a SPheno [78,79] version for the MSSM to calculate particle spectrum. The tasks of parameter scans are implemented by package SSP [80].

Based on the discussion in Sec. III, the two most important parameters in our model are m_0 and Λ. We thus investigate their effects in first. The contour distributions of m_h, Δa_μ, $m_{\tilde{t}_1}$ and $m_{\tilde{g}}$ in the $\Lambda - m_0$ are presented in Figs. 2–4, for all of the figures, the left (right) panel corresponding to the type-I (type-II) model. Here, the other parameters are fixed as $M_{\text{mess}} = 10^{16}$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 20$, and $\text{sign}(\mu) = 1$.

One finds that the two types of models have distinct behaviors. For the type-I model, there exists a boundary which can be fitted by $m_0 \geq 0.08\Lambda$–95 GeV. Below this line, parameter space is filled with tachyonic sleptons. On the other hand, the type-II model does not suffer from the tachyonic problem in most of the parameter regions.

Such behaviors can be understood by a simple analysis of RGE effects. Although we use complete two-loop RGEs
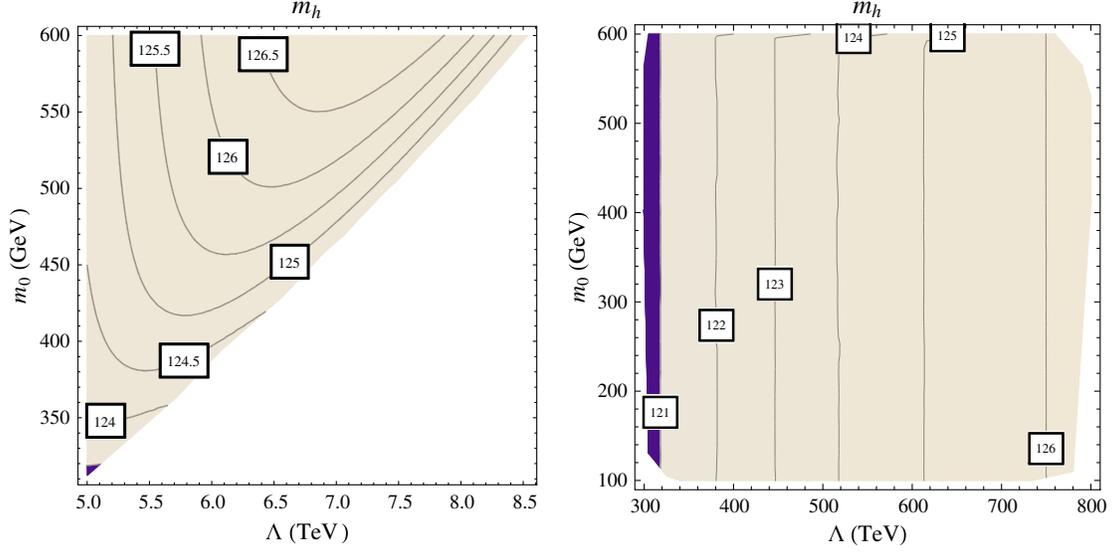
FIG. 2. Contour distributions of Higgs mass on the Λ-m_0 plane, left (right) panel for the type-I (type-II) model.
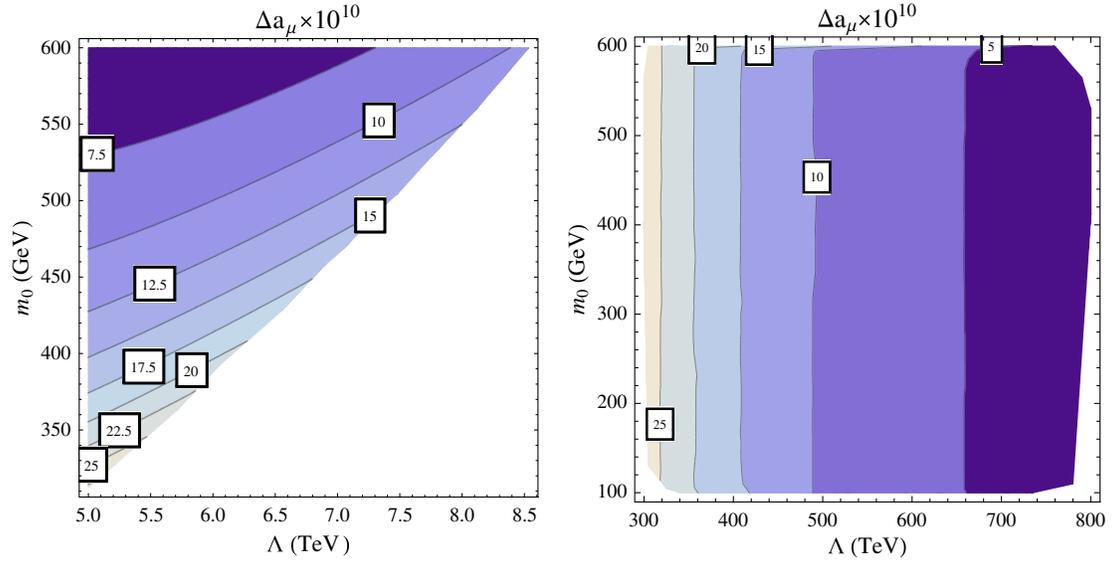
FIG. 3. Contour distributions of $\Delta a_\mu \times 10^{10}$ on the Λ-m_0 plane, left (right) panel for the type-I (type-II) model.

in numerical calculation, the one-loop RGEs are sufficient to illustrate here. The one-loop RGEs are sufficient to illustrate here. The relevant RGEs are collected in Ref. [81]. Those for slepton masses are given as

$$\beta_{m_{\tilde{l}}^2} = (m_{\tilde{l}}^2 + 2m_{H_d}^2)y_e^\dagger y_e + 2y_e^\dagger m_{\tilde{e}}^2 y_e + y_e^\dagger y_e m_{\tilde{l}}^2 + 2T_e^\dagger T_e$$
$$- 6g_2^2|M_2|^2 - \frac{6}{5}g_1^2|M_1|^2 - \frac{3}{5}g_1^2\Sigma, \quad (4.1)$$

$$\beta_{m_{\tilde{e}}^2} = 2m_{\tilde{e}}^2 + 4m_{H_d}^2)y_e y_e^\dagger + 4y_e m_{\tilde{l}}^2 y_e^\dagger + 2y_e y_e^\dagger m_{\tilde{e}}^2 + 4T_e T_e^\dagger$$
$$- \frac{24}{5}g_1^2|M_1|^2 + \frac{6}{5}g_1^2\Sigma. \quad (4.2)$$

In the above equation, quantity Σ is defined as

$$\Sigma = m_{H_u}^2 - m_{H_d}^2 + \text{Tr}[m_{\tilde{q}}^2 + m_{\tilde{l}}^2 - m_{\tilde{u}}^2 + m_{\tilde{d}}^2 + m_{\tilde{e}}^2]. \quad (4.3)$$

There are four types of contributions on the right-hand sides, i.e. the terms respectively proportional to Yukawa coupling matrix y_e, soft trilinear couplings T_e, gaugino masses M_i and quantity Σ. Among them, the first term is only important for third generation, the second and third terms are suppressed in the type-I model due to $M_{1,2} = A_0 = 0$ at messenger scale. In this case, evolution of slepton masses are dominated by Σ terms (for third generation sleptons are dominated by both Σ and y_e terms). Once Σ has
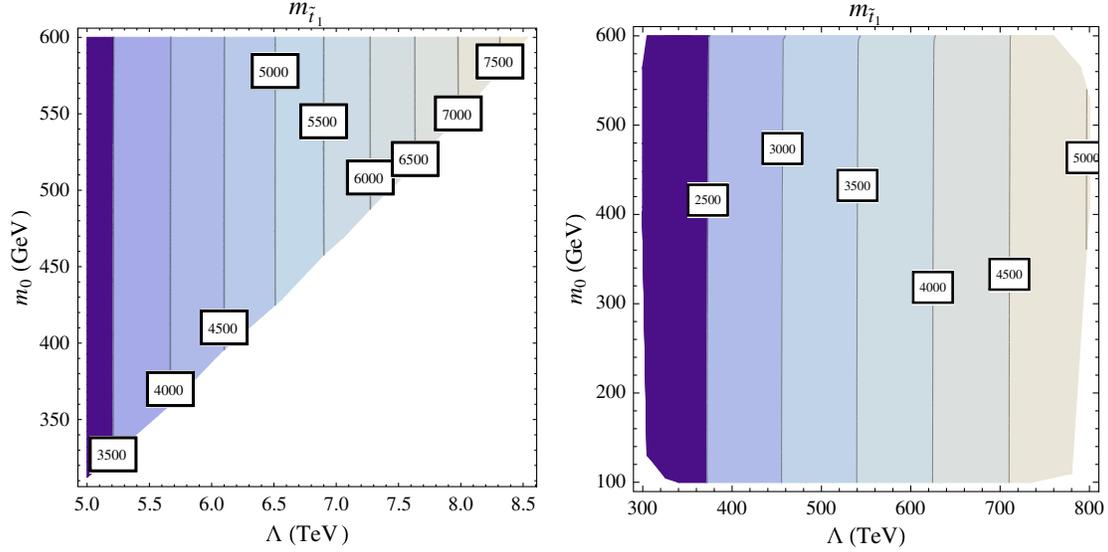
FIG. 4.   Contour distributions of light stop mass on the Λ-m_0 plane, left (right) panel for the type-I (type-II) model.

a large positive value, the right-handed sleptons especially for third generation are most easy to become tachyons as RGEs running down from the input scale to the low-energy scale. Since quantity Σ depends on all the scalar and Higgs squared-mass parameters, we present their relevant RGEs as follows:

$$\beta_{m_{\tilde{q}}^2} = (m_{\tilde{q}}^2 + 2m_{H_u}^2)y_u^\dagger y_u + (m_{\tilde{q}}^2 + 2m_{H_d}^2)y_d^\dagger y_d$$
$$+ [y_u^\dagger y_u + y_d^\dagger y_d]m_{\tilde{q}}^2 + 2y_u^\dagger m_{\tilde{u}}^2 y_u$$
$$+ 2y_d^\dagger m_{\tilde{d}}^2 y_d + 2T_u^\dagger T_u + 2T_d^\dagger T_d - \frac{32}{3}g_3^2|M_3|^2$$
$$- 6g_2^2|M_2|^2 - \frac{2}{15}g_1^2|M_1|^2 + \frac{1}{5}g_1^2\Sigma, \qquad (4.4)$$

$$\beta_{m_{\tilde{u}}^2} = 2m_{\tilde{u}}^2 + 4m_{H_u}^2)y_u y_u^\dagger + 4y_u m_{\tilde{q}}^2 y_u^\dagger + 2y_u y_u^\dagger m_{\tilde{u}}^2 + 4T_u T_u^\dagger$$
$$- \frac{32}{3}g_3^2|M_3|^2 - \frac{32}{15}g_1^2|M_1|^2 - \frac{4}{5}g_1^2\Sigma, \qquad (4.5)$$

$$\beta_{m_{\tilde{d}}^2} = 2m_{\tilde{d}}^2 + 4m_{H_d}^2)y_d y_d^\dagger + 4y_d m_{\tilde{q}}^2 y_d^\dagger + 2y_d y_d^\dagger m_{\tilde{d}}^2 + 4T_d T_d^\dagger$$
$$- \frac{32}{3}g_3^2|M_3|^2 - \frac{8}{15}g_1^2|M_1|^2 + \frac{2}{5}g_1^2\Sigma, \qquad (4.6)$$

$$\beta_{m_{H_u}^2} = 6\text{Tr}[(m_{H_u}^2 + m_{\tilde{q}}^2)y_u^\dagger y_u + y_u^\dagger m_{\tilde{u}}^2 y_u + T_u^\dagger T_u]$$
$$- 6g_2^2|M_2|^2 - \frac{6}{5}g_1^2|M_1|^2 + \frac{3}{5}g_1^2\Sigma, \qquad (4.7)$$

$$\beta_{m_{H_d}^2} = \text{Tr}[6(m_{H_d}^2 + m_{\tilde{q}}^2)y_d^\dagger y_d + 6y_d^\dagger m_{\tilde{d}}^2 y_d + 2(m_{H_d}^2 + m_{\tilde{l}}^2)y_e^\dagger y_e$$
$$+ 2y_e^\dagger m_{\tilde{e}}^2 y_e + 6T_d^\dagger T_d + 2T_e^\dagger T_e]$$
$$- 6g_2^2|M_2|^2 - \frac{6}{5}g_1^2|M_1|^2 - \frac{3}{5}g_1^2\Sigma. \qquad (4.8)$$

One finds that $m_{H_u}^2$ and $m_{H_d}^2$ are generally decrease as RGEs running down, which is also the necessary condition

to trigger electroweak symmetry breaking (EWSB). On the other hand, squark masses receive a significant contribution from the term proportional to $|M_3|^2$, thus increasing with RGE evolution from the input scale to the low-energy scale. Moreover, in the type-I model, only gluino and squarks obtain soft masses at messenger scale which are respectively proportional to Λ and Λ^2. Therefore, contributions of squark masses are much larger than other terms in Eq. (4.3) ($m_{H_u}^2 - m_{H_d}^2$ and $m_{\tilde{l}}^2 + m_{\tilde{e}}^2$) and dominate the RGE running of slepton masses. As a consequence, whether sleptons become tachyonic is determined by the competition between input m_0 at GUT scale and Λ at messenger scale, which obviously imposes a lower bound on m_0 for a given Λ and indicates such boundary roughly satisfies a linear relation. On the other hand, for the type-II model, the bino, slepton and Higgs sectors obtain nonzero soft mass at messenger scale [see Eq. (3.8)], which then relaxes the slepton tachyonic problem through two ways: First, it enhances the initial slepton masses at messenger scale; second, it improves RGE running behavior through the term proportional to $|M_1|^2$.

There are some other important features to be learned from these figures. We summarize them below.

First, one expects Higgs mass should be simply growth with increases of Λ since the Higgs mass is mainly lifted by stop mass at one-loop. It is indeed true for the type-II model as is shown on the right of Fig. 2, while the parameter dependence on Higgs mass for the type-I model is a little bit more complicated. At the low Λ region, Higgs mass follows the expected behavior. However, with the increasing of Λ, allowed parameter space is forced to shift to the large m_0 region in order to obtain the correct Higgs mass and avoid tachyonic sleptons at the same time. As a consequence, a turning point appears for each contour of Higg mass. In addition, due to different input soft masses at messenger scale, the type-II model is asked for much larger Λ
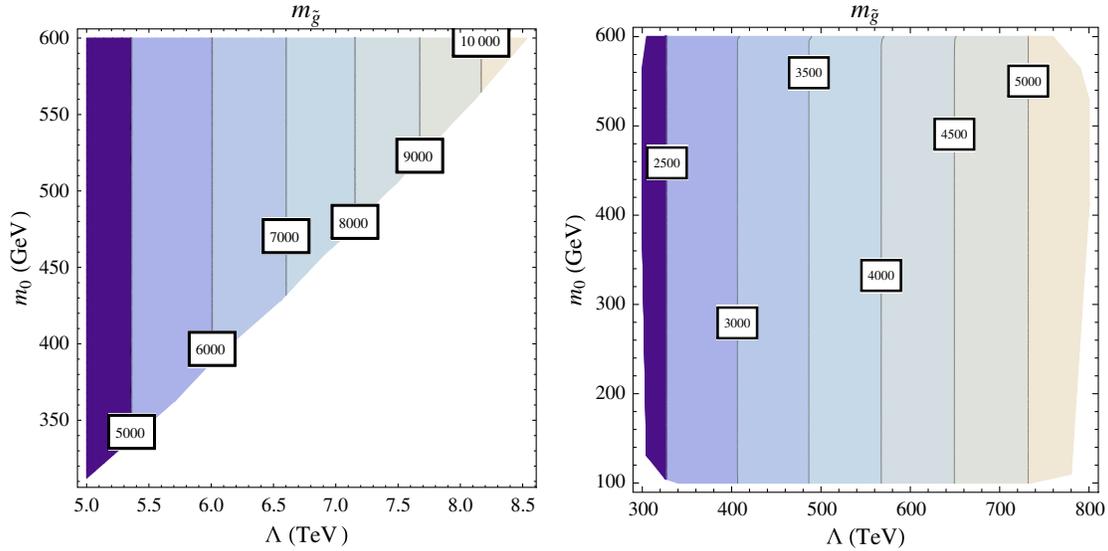
FIG. 5.   Contour distributions of gluino mass on the Λ-m_0 plane, left (right) panel for the type-I (type-II) model.

compared with the type-I model to reach acceptable Higgs mass. Therefore, only large Λ regions in the figure can satisfy such a requirement.

Second, muon $g - 2$ anomaly requires that slepton and electroweakino masses fall into $\mathcal{O}(100)$ GeV, Δa_μ is more dependent on m_0 than Λ for the type-I model. Moreover, the slope of the Δa_μ contour reflects RGE effects which are discussed previously, i.e., required m_0 increases with increasing of Λ. Especially, Δa_μ is able to approach its observed central value at small m_0 and Λ regions. On the other hand, it is difficult to realize for the type-II model. The reason is that Δa_μ favors the low Λ region, while Higgs mass requires the large Λ region. Therefore, the type-I model is more favored from the point view of explanation of the muon anomalous magnetic moment.

Third, the spectra of colored sparticles fall into the multi-TeV mass range in our model which can be found in Fig. 4,5, which certainly exceeds current and upcoming LHC SUSY limits [82,83]. In addition, their parameter dependence is simply for both types of models, i.e., monotonically increasing with Λ as one expects.

In order to examine the full parameter space in Eq. (3.9), we further performed random scans within the following regions:

$$\Lambda \in [5 \times 10^3, 10^4] \text{ GeV},$$

$$m_0 \in [10, 600] \text{ GeV} \quad \text{for the type-I model},$$

$$\Lambda \in [10^4, 10^6] \text{ GeV},$$

$$m_0 \in [100, 1000] \text{ GeV} \quad \text{for the type-II model},$$

$$m_{1/2} \in [100, 700] \text{ GeV},$$

$$\tan\beta \in [5, 30] \quad \text{for both type-I and II models}.$$

During the scan, we applied various constraints from collider and low-energy experiments, which are given below:

(1) The Higgs mass: $m_h \in [123, 127]$ GeV.
(2) LEP bounds and B physics constraints [84,85]:

$$1.6 \times 10^{-9} \leq \text{BR}(B_s \to \mu^+\mu^-) \leq 4.2 \times 10^{-9}(2\sigma),$$

$$2.99 \times 10^{-4} \leq \text{BR}(b \to s\gamma) \leq 3.87 \times 10^{-4}(2\sigma),$$

$$7.0 \times 10^{-5} \leq \text{BR}(B_u \to \tau\nu_\tau) \leq 1.5 \times 10^{-4}(2\sigma).$$

$$(4.9)$$

(3) The muon $g - 2$ anomaly [7]:

$$4.7 \times 10^{-10} \leq \Delta a_\mu \leq 52.7 \times 10^{-10}(3\sigma). \quad (4.10)$$

(4) LHC constraints:
    (a) Gluino mass $m_{\tilde{g}} > 1800$ GeV [86,87],
    (b) Light stop mass $m_{\tilde{t}_1} > 850$ GeV [86,88],
    (c) Light sbottom mass $m_{\tilde{b}_1} > 840$–1000 GeV [89,90],
    (d) Degenerated first two generation squarks (both left-handed and right-handed) $m_{\tilde{q}} > 1000$–1400 GeV [90].

The corresponding results are displayed in Figs. 6–12. In all of these figures, blue points denote total valid samples; green points denote samples which fulfill Higgs mass, LEP bounds and B physics constraints; red points denote samples which further satisfy muon $g - 2$ anomaly and LHC constraints. As one expects, the viable parameter distributions in the full parameter space basically agree with our previous discussion, i.e., their behaviors are mainly determined by Λ and m_0, while the choice of $m_{1/2}$ and $\tan\beta$ have relatively less effects. There only one feature is worth being emphasized: comparing with the type-I model, the type-II model has heavier slepton and electroweakino spectra, which then require a larger $\tan\beta$ to enhance their contributions in the loop in order
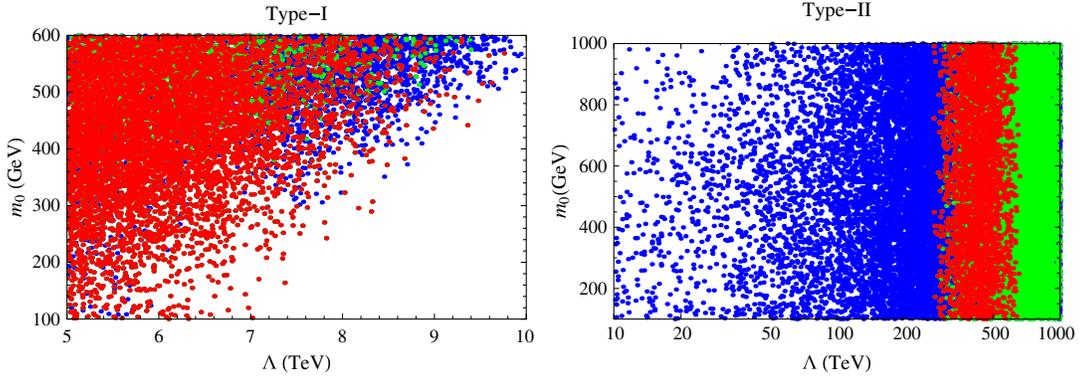
FIG. 6.   Distributions of samples in the Λ-m_0 plane, left (right) panel for type-I (type-II) model.
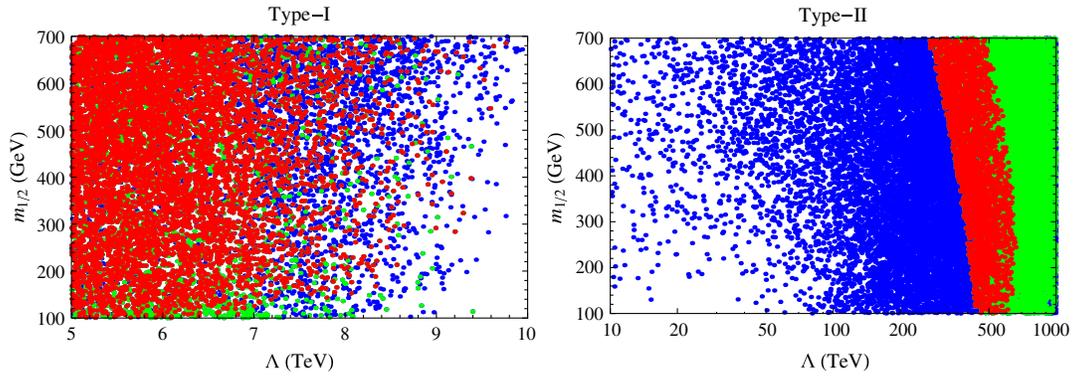
FIG. 7.   Distributions of samples in the Λ-$m_{1/2}$ plane, left (right) panel for the type-I (type-II) model.
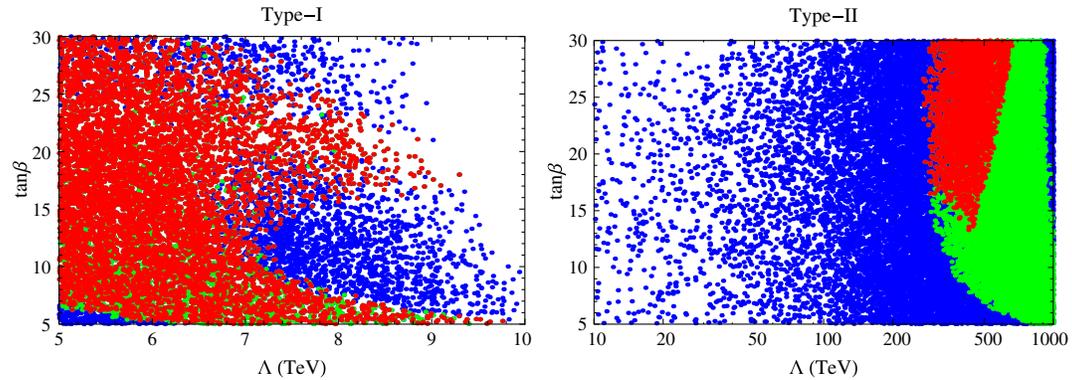
FIG. 8.   Distributions of samples in the Λ-$\tan\beta$ plane, left (right) panel for the type-I (type-II) model.
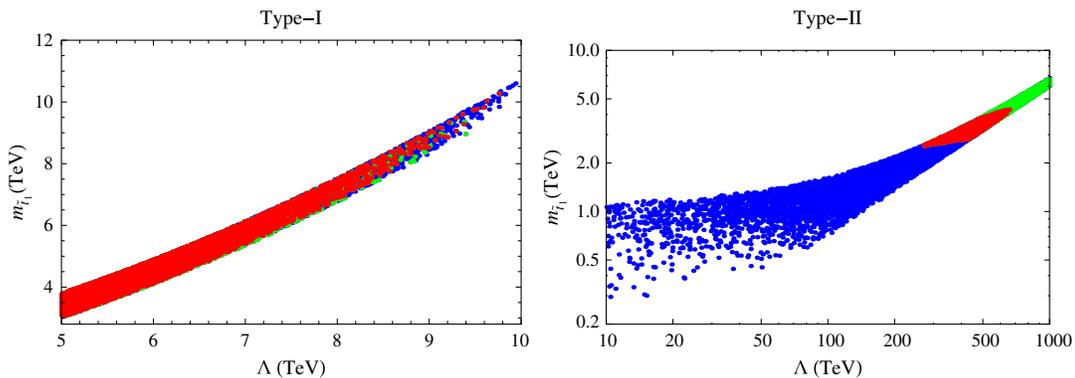
FIG. 9.   Distributions of stop masses versus Λ, left (right) panel for the type-I (type-II) model.
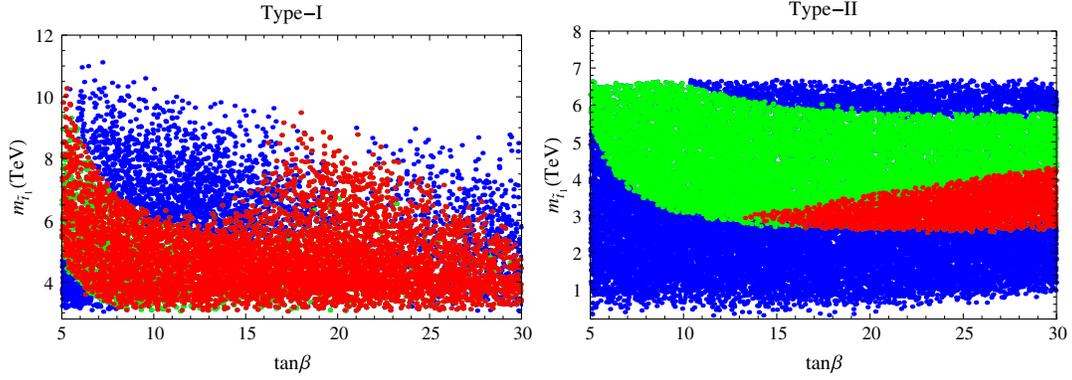
FIG. 10.   Distributions of stop masses versus $\tan\beta$, left (right) panel for the type-I (type-II) model.
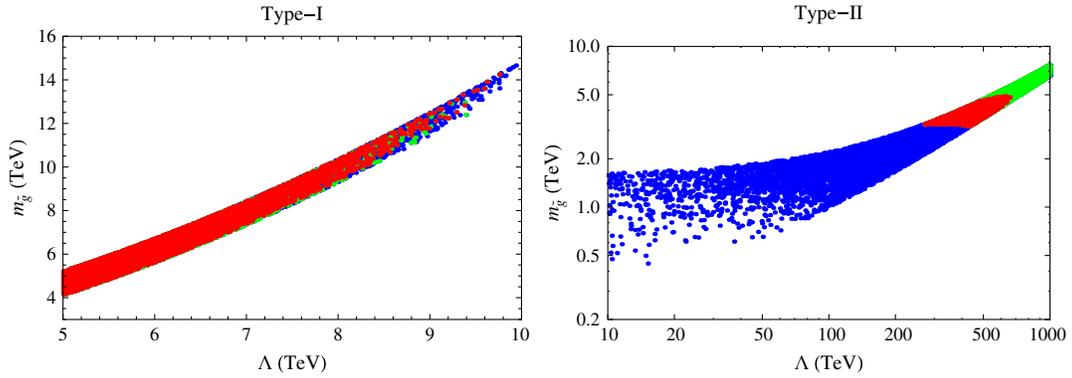
FIG. 11.   Distributions of gluino masses versus Λ, left (right) panel for the type-I (type-II) model.

to provide sufficient Δa_μ. To be specific, for samples passing the muon $g - 2$ anomaly, $\tan\beta$ cannot be lower than 13.

Moreover, we show benchmark points for two type models. The input parameters, important particle spectra and Δa_μ are shown in Table I, and the corresponding complete spectra are displayed in Fig. 13. Finally, we would like to comment on the supersymmetry breaking soft term relations between gauge mediation and gravity mediation for these two benchmark points. For simplicity,

we assume that gravitino mass is equal to scalar mass in gravity mediation. In the type-I model, the supersymmetry breaking F-term for gauge mediation is $F_{\text{Gauge}} = \Lambda M_{\text{mess}} = 5 \times 10^{19}$ GeV, while the supersymmetry breaking F-term for gravity mediation is $F_{\text{Gravity}} = \sqrt{3} m_0 M_{\text{Pl}} = 1.45627 \times 10^{21}$ GeV. Because there is a factor 29.1254 difference between these two F-terms, we need some fine-tuning around 3.4% to obtain the proper supersymmetry breaking soft terms. In the type-II model, the
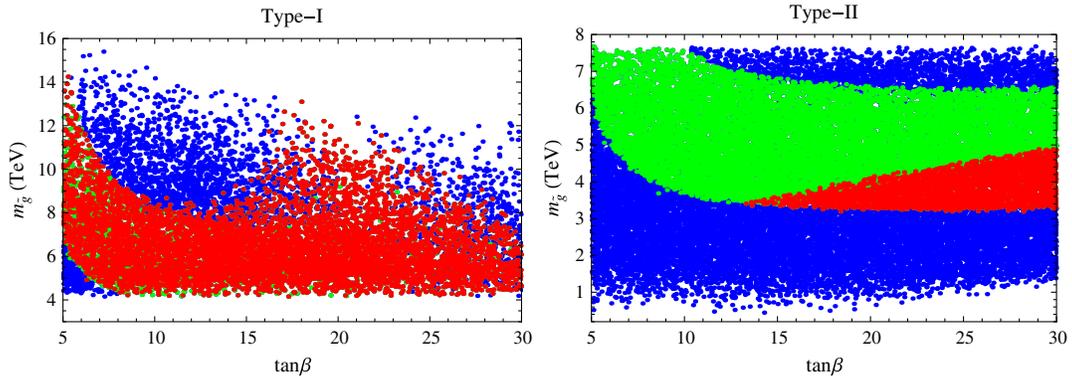
FIG. 12.   Distributions of gluino masses versus $\tan\beta$, left (right) panel for the type-I (type-II) model.
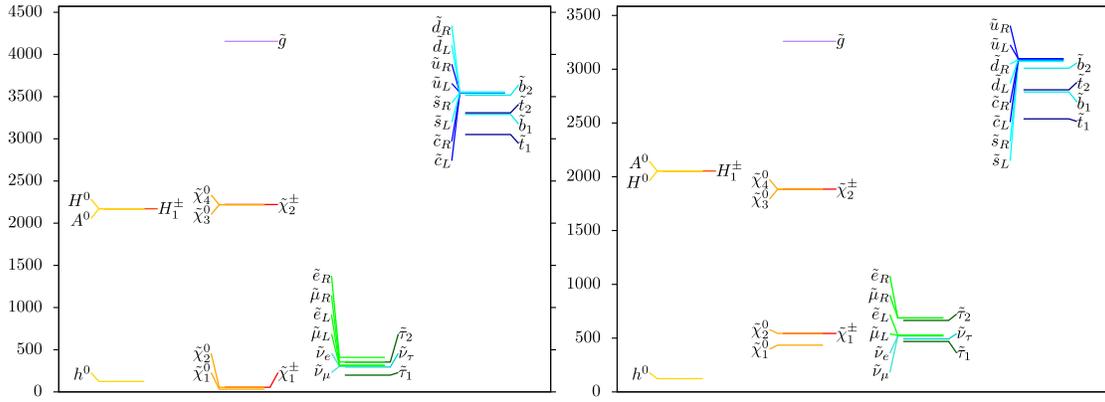
FIG. 13.   The complete particle spectra for two benchmark points: left (right) panel for the type-I (type-II) model.

TABLE I.   The input parameters, important particle spectra and Δa_μ for two benchmark points.

Model	Λ	m_0	$m_{1/2}$	$\tan\beta$	m_h	$m_{\tilde{t}_1}$	$m_{\tilde{g}}$	Δa_μ
Type-I	5×10^3	346	116	17.3	124	3051	4155	1.37×10^{-9}
Type-II	2.7×10^5	992	678	23.1	123	2538	3259	6.83×10^{-10}

supersymmetry breaking F-term for gauge mediation is $F_{\text{Gauge}} = \Lambda M_{\text{mess}} = 2.7 \times 10^{21}$ GeV, while the supersymmetry breaking F-term for gravity mediation is $F_{\text{Gravity}} = \sqrt{3} m_0 M_{\text{Pl}} = 4.17521 \times 10^{21}$ GeV. So F_{Gauge} and F_{Gravity} are at the same order, and can be considered as the same F-term. Therefore, we can explain why the supersymmetry breaking soft terms from gauge and gravity mediations are comparable. In other words, the type-II model on supersymmetry breaking is indeed natural.

V. CONCLUSION

The muon anomalous magnetic moment has been treated as a new physics guideline for a long time. If considering it as a tantalizing hint for new physics beyond the SM, we proposed a modified version of the MSSM in the framework of hybrid gauge-gravity mediation SUSY breaking, avoiding the tachyonic slepton problem in usual GMSB. We study the particle spectra with emphasize on the parameter space which can simultaneously explain the Higgs mass of 125 GeV and the observed muon $g-2$

anomaly. We found that the slepton and squarks sector can be easily split for both type-I and type-II models. In particular, the type-I model is more suitable to interpret the muon anomalous magnetic moment although it more relies on soft slepton masses provided by gravity mediation. In the entirety of allowed parameter space, the masses of the light squarks and gluino fall into the multi-TeV mass range. It is expected to be exceeded by abilities of the current and upcoming LHC SUSY direct searches and could be reached at future HE-LHC, FCC-hh and SPPC. Finally, the dark matter candidate is still the lightest neutralino and thus all of the advantages in the WIMP scenario can be preserved in our model.

[1] G. Aad *et al.* (ATLAS Collaboration), Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B **716**, 1 (2012).

[2] S. Chatrchyan *et al.* (CMS Collaboration), Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B **716**, 30 (2012).

[3] M. Carena, S. Gori, N. R. Shah, and C. E. M. Wagner, A 125 GeV SM-like Higgs in the MSSM and the $\gamma\gamma$ rate, J. High Energy Phys. 03 (2012) 014.

[4] W. Adam, Searches for SUSY, at the 38th International Conference on High Energy Physics.

[5] G. W. Bennett *et al.* (Muon $g-2$ Collaboration), Final report of the muon E821 anomalous magnetic moment measurement at BNL, Phys. Rev. D **73**, 072003 (2006).

[6] G. W. Bennett *et al.* (Muon $g-2$ Collaboration), An improved limit on the muon electric dipole moment, Phys. Rev. D **80**, 052008 (2009).

[7] M. Davier, A. Hoecker, B. Malaescu, and Z. Zhang, Reevaluation of the hadronic contributions to the muon $g-2$ and to alpha(MZ), Eur. Phys. J. C **71**, 1 (2011); **72**, 1874 (E) (2012).

[8] T. Moroi, The muon anomalous magnetic dipole moment in the minimal supersymmetric standard model, Phys. Rev. D **53**, 6565 (1996); **56**, 4424(E) (1997).

[9] S. P. Martin and J. D. Wells, Muon anomalous magnetic dipole moment in supersymmetric theories, Phys. Rev. D **64**, 035003 (2001).

[10] M. Byrne, C. Kolda, and J. E. Lennon, Updated implications of the muon anomalous magnetic moment for supersymmetry, Phys. Rev. D **67**, 075004 (2003).

[11] D. Stockinger, The muon magnetic moment and supersymmetry, J. Phys. G **34**, R45 (2007).

[12] F. Domingo and U. Ellwanger, Constraints from the muon $g-2$ on the parameter space of the NMSSM, J. High Energy Phys. 07 (2008) 079.

[13] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ HiggsPublicResults; https://twiki.cern.ch/twiki/bin/view/ CMSPublic/PhysicsResultsHIG.

[14] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ SupersymmetryPublicResults; https://twiki.cern.ch/twiki/ bin/view/CMSPublic/PhysicsResultsSUS.

[15] R. Aaij *et al.* (LHCb Collaboration), First Evidence for the Decay $Bs \to mu + mu-$, Phys. Rev. Lett. **110**, 021801 (2013).

[16] O. Buchmueller, R. Cavanaugh, A. De Roeck, J. R. Ellis, H. Flacher, S. Heinemeyer, G. Isidori, K. A. Olive, F. J. Ronga, and G. Weiglein, Likelihood functions for supersymmetric observables in frequentist analyses of the CMSSM and NUHM1, Eur. Phys. J. C **64**, 391 (2009).

[17] E. Barberio *et al.* (Heavy Flavor Averaging Group (HFAG) Collaboration), Averages of b-hadron properties at the end of 2006, arXiv:0704.3575.

[18] D. Asner *et al.* (Heavy Flavor Averaging Group Collaboration), Averages of b-hadron, c-hadron, and tau-lepton properties, arXiv:1010.1589.

[19] Y. Amhis *et al.* (Heavy Flavor Averaging Group Collaboration), Averages of B-hadron, C-hadron, and tau-lepton properties as of early 2012, arXiv:1207.1158.

[20] G. Hinshaw *et al.* (WMAP Collaboration), Nine-year Wilkinson microwave anisotropy probe (WMAP) observations: Cosmological parameter results, Astrophys. J. Suppl. Ser. **208**, 19 (2013).

[21] E. Aprile *et al.* (XENON100 Collaboration), Dark Matter Results from 225 Live Days of XENON100 Data, Phys. Rev. Lett. **109**, 181301 (2012).

[22] T. Cheng, J. Li, T. Li, D. V. Nanopoulos, and C. Tong, Electroweak supersymmetry around the electroweak scale, Eur. Phys. J. C **73**, 2322 (2013).

[23] T. Li and D. V. Nanopoulos, Generalizing minimal supergravity, Phys. Lett. B **692**, 121 (2010).

[24] C. Balazs, T. Li, D. V. Nanopoulos, and F. Wang, Supersymmetry breaking scalar masses and trilinear soft terms in generalized minimal supergravity, J. High Energy Phys. 09 (2010) 003.

[25] G. F. Giudice, P. Paradisi, A. Strumia, and A. Strumia, Correlation between the Higgs decay rate to two photons and the muon $g-2$, J. High Energy Phys. 10 (2012) 186.

[26] M. Ibe, S. Matsumoto, T. T. Yanagida, and N. Yokozaki, Heavy squarks and light sleptons in gauge mediation— From the viewpoint of 125 GeV Higgs boson and muon $g-2$, J. High Energy Phys. 03 (2013) 078.

[27] P. Grajek, A. Mariotti, and D. Redigolo, Phenomenology of general gauge mediation in light of a 125 GeV Higgs, J. High Energy Phys. 07 (2013) 109.

[28] M. Endo, K. Hamaguchi, S. Iwamoto, and T. Yoshinaga, Muon $g-2$ vs LHC in supersymmetric models, J. High Energy Phys. 01 (2014) 123.

[29] S. Mohanty, S. Rao, and D. P. Roy, Reconciling the muon $g-2$ and dark matter relic density with the LHC results in nonuniversal gaugino mass models, J. High Energy Phys. 09 (2013) 027.

[30] G. Bhattacharyya, B. Bhattacherjee, T. T. Yanagida, and N. Yokozaki, A natural scenario for heavy colored and light uncolored superpartners, Phys. Lett. B **725**, 339 (2013).

[31] S. Akula and P. Nath, Gluino-driven radiative breaking, Higgs boson mass, muon $g-2$, and the Higgs diphoton decay in supergravity unification, Phys. Rev. D **87**, 115022 (2013).

[32] S. Iwamoto, LHC SUSY searches after the Higgs discovery: Respecting the muon $g-2$, arXiv:1304.5171.

[33] A. Choudhury and A. Datta, Neutralino dark matter confronted by the LHC constraints on electroweak SUSY signals, J. High Energy Phys. 09 (2013) 119.

[34] T. Cheng and T. Li, Electroweak supersymmetry (EWSUSY) in the NMSSM, Phys. Rev. D **88**, 015031 (2013).

[35] G. Bhattacharyya, B. Bhattacherjee, T. T. Yanagida, and N. Yokozaki, A practical GMSB model for explaining the muon $(g-2)$ with gauge coupling unification, Phys. Lett. B **730**, 231 (2014).

[36] V. S. Mummidi and S. K. Vempati, A little more gauge mediation and the light Higgs mass, Nucl. Phys. **B881**, 181 (2014).

[37] T. Li and S. Raza, Electroweak supersymmetry from the generalized minimal supergravity model in the MSSM, Phys. Rev. D **91**, 055016 (2015).

[38] G. Bhattacharyya, T. T. Yanagida, and N. Yokozaki, Focus point gauge mediation with incomplete adjoint messengers and gauge coupling unification, Phys. Lett. B **749**, 82 (2015).

[39] I. Gogoladze, Q. Shafi, and C. S. Un, Reconciling muon $g-2$, 125 GeV Higgs and dark matter in gauge mediation models, Phys. Rev. D **92**, 115014 (2015).

[40] I. Gogoladze, A. Mustafayev, Q. Shafi, and C. S. Un, Gauge mediation models with adjoint messengers, Phys. Rev. D **94**, 075012 (2016).

[41] R. Ding, T. Li, F. Staub, C. Tian, and B. Zhu, Super-symmetric standard models with a pseudo-Dirac gluino from hybrid F- and D-term supersymmetry breaking, Phys. Rev. D **92,** 015008 (2015).

[42] I. Jack and D. R. T. Jones, Fayet-Iliopoulos D-terms and anomaly mediated supersymmetry breaking, Phys. Lett. B **482,** 167 (2000); N. Arkani-Hamed, D. E. Kaplan, H. Murayama, and Y. Nomura, Viable ultraviolet-insensitive supersymmetry breaking, J. High Energy Phys. 02 (2001) 041; R. Kitano, G. D. Kribs, and H. Murayama, Electroweak symmetry breaking via UV insensitive anomaly mediation, Phys. Rev. D **70,** 035001 (2004).

[43] A. Pomarol and R. Rattazzi, Sparticle masses from the superconformal anomaly, J. High Energy Phys. 05 (1999) 013; R. Rattazzi, A. Strumia, and J. D. Wells, Phenomenology of deflected anomaly mediation, Nucl. Phys. **B576,** 3 (2000); N. Okada, Positively deflected anomaly mediation, Phys. Rev. D **65,** 115009 (2002).

[44] K. Choi, A. Falkowski, H. P. Nilles, and M. Olechowski, Soft supersymmetry breaking in KKLT flux compactification, Nucl. Phys. **B718,** 113 (2005); M. Endo, M. Yamaguchi, and K. Yoshioka, A bottom-up approach to moduli dynamics in heavy gravitino scenario: Superpotential, soft terms and sparticle mass spectrum, Phys. Rev. D **72,** 015004 (2005); K. Choi, K. S. Jeong, and K. i. Okumura, Phenomenology of mixed modulus-anomaly mediation in fluxed string compactifications and brane models, J. High Energy Phys. 09 (2005) 039.

[45] L. L. Everett, I. W. Kim, P. Ouyang, and K. M. Zurek, Deflected Mirage Mediation: A Framework for Generalized Supersymmetry Breaking, Phys. Rev. Lett. **101,** 101803 (2008); Moduli stabilization and supersymmetry breaking in deflected mirage mediation, J. High Energy Phys. 08 (2008) 102.

[46] Z. Kang and T. Li, Asymmetric origin for gravitino relic density in the hybrid gravity-gauge mediated supersymmetry breaking, J. High Energy Phys. 10 (2012) 150.

[47] E. Dudas, S. Lavignac, and J. Parmentier, A light neutralino in hybrid models of supersymmetry breaking, Nucl. Phys. **B808,** 237 (2009).

[48] A. M. Iyer, V. S. Mummidi, and S. K. Vempati, Gravitational rescue of minimal gauge mediation, Int. J. Mod. Phys. A **31,** 1650045 (2016).

[49] S. Antusch, L. Calibbi, V. Maurer, M. Monaco, and M. Spinrath, Naturalness of the nonuniversal MSSM in the light of the recent Higgs results, J. High Energy Phys. 01 (2013) 187.

[50] T. Leggett, T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, No naturalness or fine-tuning problems from no-scale supergravity, arXiv:1403.3099.

[51] T. Leggett, T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, Confronting electroweak fine-tuning with no-scale supergravity, Phys. Lett. B **740,** 66 (2015).

[52] G. Du, T. Li, D. V. Nanopoulos, and S. Raza, Super-natural MSSM, Phys. Rev. D **92,** 025038 (2015).

[53] T. Li, S. Raza, and X. C. Wang, Supernatural supersymmetry and its classic example: M-theory inspired NMSSM, Phys. Rev. D **93,** 115014 (2016).

[54] R. Ding, T. Li, F. Staub, and B. Zhu, Supersoft super-symmetry, conformal sequestering, and single scale super-symmetry breaking, Phys. Rev. D **93,** 095028 (2016).

[55] D. J. H. Chung, L. L. Everett, G. L. Kane, S. F. King, J. D. Lykken, and L. T. Wang, The soft supersymmetry breaking Lagrangian: Theory and applications, Phys. Rep. **407,** 1 (2005).

[56] G. F. Giudice and R. Rattazzi, Theories with gauge mediated supersymmetry breaking, Phys. Rep. **322,** 419 (1999).

[57] Y. Kawamura, Gauge symmetry reduction from the extra space S^1/Z_2, Prog. Theor. Phys. **103,** 613 (2000); Triplet-doublet splitting, proton stability and an extra dimension, Prog. Theor. Phys. **105,** 999 (2001); Split multiplets, coupling unification and extra dimension, Prog. Theor. Phys. **105,** 691 (2001).

[58] G. Altarelli and F. Feruglio, SU(5) grand unification in extra dimensions and proton decay, Phys. Lett. B **511,** 257 (2001).

[59] L. Hall and Y. Nomura, Gauge unification in higher dimensions, Phys. Rev. D **64,** 055003 (2001).

[60] R. Blumenhagen, M. Cvetic, P. Langacker, and G. Shiu, Toward realistic intersecting D-brane models, Annu. Rev. Nucl. Part. Sci. **55,** 71 (2005), and references therein.

[61] M. Cvetic, I. Papadimitriou, and G. Shiu, Supersymmetric three family SU(5) grand unified models from type IIA orientifolds with intersecting D6-branes, Nucl. Phys. **B659,** 193 (2003); **696,** 298(E) (2004).

[62] C. M. Chen, T. Li, and D. V. Nanopoulos, Flipped and unflipped SU(5) as type IIA flux vacua, Nucl. Phys. **B751,** 260 (2006).

[63] V. Braun, Y. H. He, B. A. Ovrut, and T. Pantev, A heterotic standard model, Phys. Lett. B **618,** 252 (2005); The exact MSSM spectrum from string theory, J. High Energy Phys. 05 (2006) 043, and references therein.

[64] V. Bouchard and R. Donagi, An SU(5) heterotic standard model, Phys. Lett. B **633,** 783 (2006), and references therein.

[65] R. Donagi and M. Wijnholt, Model building with F-theory, Adv. Theor. Math. Phys. **15,** 1237 (2011).

[66] C. Beasley, J. J. Heckman, and C. Vafa, GUTs and exceptional branes in F-theory—I, J. High Energy Phys. 01 (2009) 058.

[67] C. Beasley, J. J. Heckman, and C. Vafa, GUTs and exceptional branes in F-theory—II: Experimental predictions, J. High Energy Phys. 01 (2009) 059.

[68] R. Donagi and M. Wijnholt, Breaking GUT groups in F-theory, Adv. Theor. Math. Phys. **15,** 1523 (2011).

[69] T. Li and D. V. Nanopoulos, General gauge and anomaly mediated supersymmetry breaking in grand unified theories with vectorlike particles, J. High Energy Phys. 10 (2011) 090.

[70] J. Jiang, T. Li, D. V. Nanopoulos, and D. Xie, Flipped $SU(5) \times U(1)_X$ models from F-theory, Nucl. Phys. **B830,** 195 (2010).

[71] T. Li, SU(5) and SO(10) models from F-theory with natural Yukawa couplings, Phys. Rev. D **81,** 065018 (2010).

[72] E. Poppitz and S. P. Trivedi, New models of gauge and gravity mediated supersymmetry breaking, Phys. Rev. D **55,** 5508 (1997).

[73] F. Staub, SARAH, arXiv:0806.0538.

[74] F. Staub, From superpotential to model files for FeynArts and CalcHep/CompHep, Comput. Phys. Commun. **181,** 1077 (2010).

[75] F. Staub, Automatic calculation of supersymmetric renormalization group equations and self-energies, Comput. Phys. Commun. **182,** 808 (2011).

[76] F. Staub, SARAH 3.2: Dirac gauginos, UFO output, and more, Comput. Phys. Commun. **184,** 1792 (2013).

[77] F. Staub, SARAH 4: A tool for (not only SUSY) model builders, Comput. Phys. Commun. **185,** 1773 (2014).

[78] W. Porod, SPheno, a program for calculating supersymmetric spectra, SUSY particle decays and SUSY particle production at $e+e-$ colliders, Comput. Phys. Commun. **153,** 275 (2003).

[79] W. Porod and F. Staub, SPheno 3.1: Extensions including flavor, *CP* phases and models beyond the MSSM, Comput. Phys. Commun. **183,** 2458 (2012).

[80] F. Staub, T. Ohl, W. Porod, and C. Speckner, A tool box for implementing supersymmetric models, Comput. Phys. Commun. **183,** 2165 (2012).

[81] S. P. Martin and M. T. Vaughn, Two loop renormalization group equations for soft supersymmetry breaking couplings, Phys. Rev. D **50,** 2282 (1994); **78,** 039903(E) (2008).

[82] G. Aad *et al.* (ATLAS Collaboration), ATLAS run 1 searches for direct pair production of third-generation squarks at the Large Hadron Collider, Eur. Phys. J. C **75,** 510 (2015); **76,** 153(E) (2016).

[83] T. Golling *et al.*, Physics at a 100 TeV pp collider: Beyond the standard model phenomena, arXiv:1606.00947.

[84] V. Khachatryan *et al.* (CMS and LHCb Collaborations), Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data, Nature (London) **522,** 68 (2015).

[85] Y. Amhis *et al.* (Heavy Flavor Averaging Group (HFAG) Collaboration), Averages of *b*-hadron, *c*-hadron, and τ-lepton properties as of summer 2014, arXiv:1412.7515.

[86] CMS Collaboration, Report No. CMS-PAS-SUS-16-030.

[87] The ATLAS Collaboration, Report No. ATLAS-CONF-2016-078.

[88] The ATLAS Collaboration, Report No. ATLAS-CONF-2016-077.

[89] M. Aaboud *et al.* (ATLAS Collaboration), Search for bottom squark pair production in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Eur. Phys. J. C **76,** 547 (2016).

[90] CMS Collaboration, Report No. CMS-PAS-SUS-16-015.