The Supersymmetric Standard Models with a Pseudo-Dirac Gluino from Hybrid $F$– and $D$–Term Supersymmetry Breakings

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We propose the Supersymmetric Standard Models (SSMs) with a pseudo-Dirac gluino from hybrid $F$– and $D$–term supersymmetry (SUSY) breakings. Similar to the SSMs before the LHC, all the supersymmetric particles in the Minimal SSM (MSSM) obtain the SUSY breaking soft terms from the traditional gravity mediation and have masses within about 1 TeV except gluino. To evade the LHC SUSY search constraints, the gluino also has a heavy Dirac mass above 3 TeV from $D$–term SUSY breaking. Interestingly, such a heavy Dirac gluino mass will not induce the electroweak fine-tuning problem. We realize such SUSY breakings via an anomalous $U(1)_X$ gauge symmetry inspired from string models. To maintain the gauge coupling unification and increase the Higgs boson mass, we introduce extra vector-like particles. We study the viable parameter space which satisfies all the current experimental constraints, and present a concrete benchmark point. This kind of models not only preserves the merits of pre-LHC SSMs such as naturalness, dark matter, etc, but also solves the possible problems in the SSMs with Dirac gauginos due to the $F$-term gravity mediation.

Introduction—It is well-known that the weak scale supersymmetry (SUSY) is the most promising extension for physics beyond the Standard Model (SM) [1]. It provides a well-motivated and complete framework to understand the basic questions of TeV-scale physics: the gauge hierarchy problem is solved naturally, the lightest supersymmetric particle (LSP) such as neutralino can be a dark matter candidate, and gauge coupling unification can be realized, etc. The gauge coupling unification strongly suggests the Grand Unified Theories (GUTs), and only the superstring theory may describe the real world. Thus, the supersymmetric SM (SSM) is also a bridge between the low energy phenomenology and high-energy fundamental physics.

However, the discovered SM-like Higgs boson with a mass around 125 GeV [2,3] is a little bit too heavy in the Minimal SSM (MSSM) since it requires the multi-TeV top squarks with small mixing or TeV-scale top squarks with large mixing [4]. Also, there exist strong constraints on the SSMs from the LHC SUSY searches. For example, the gluino mass $m_{\tilde{g}}$ and first two-generation squark mass $m_{\tilde{q}}$ should be heavier than about 1.7 TeV if they are roughly degenerate $m_{\tilde{q}} \sim m_{\tilde{g}}$, and the squark mass $m_{\tilde{q}}$ is heavier than about 850 GeV for $m_{\tilde{g}} \gg m_{\tilde{q}}$ [5]. Therefore, the naturalness of the SSMs is challenged.

The basic idea to lift Higgs mass without threatening the hierarchy problem is the introduction of additional tree-level contributions [6–12]. To escape the LHC SUSY search constraints, there are quite a few proposals: natural SUSY [13–14], compressed SUSY [15–17], stealth SUSY [18], heavy LSP SUSY [19], $R$-parity violation [20–21], supersoft SUSY [22–31], etc. Here, we would like to point out that all the sparticles in the SSMs can be within about 1 TeV as long as the gluino is heavier than 3 TeV, which is obviously a simple modification to the SSMs before the LHC. Also, such a heavy gluino will not induce the electroweak fine-tuning problem if it is (pseudo-)Dirac like the supersoft SUSY. However, there exists some problems for supersoft SUSY with Dirac gauginos: $\mu$ problem can not be solved via the Giudice-Masiero (GM) mechanism [32], the $D$-term contribution to the Higgs quartic coupling vanishes, the right-handed slepton may be the LSP, and the scalar components of the adjoint chiral superfields might be tachyonic and then break the SM gauge symmetry, etc [22]. The first three problems can be solved in the $F$-term gravity mediation, while the last problem was solved recently [31]. Therefore, we will propose the SSMs with a pseudo-Dirac gluino from hybrid $F$– and $D$–term SUSY breakings. To be concrete, all the sparticles in the MSSM obtain SUSY breaking soft terms from the traditional gravity mediation, and only gluino receives extra Dirac mass from the $D$–term SUSY breaking. Especially, all the MSSM sparticles except gluino can be within about 1 TeV as the pre-LHC SSMs. The merits of this proposal are: keeping the good properties of pre-LHC SSMs (naturalness, as well as explanations for the dark matter and muon anomalous magnetic moment, etc), evading the LHC SUSY search constraints, and solving the problems in supersoft SUSY via $F$-term gravity mediation. We show that such SUSY breakings can be realized by an anomalous $U(1)_X$ gauge symmetry inspired from string models. To achieve the gauge coupling unification and increase the Higgs boson mass, we will introduce vector-like particles. We shall discuss the low energy phenomenology, and the detailed studies will be given elsewhere [33].
Model Building—In order to generate the Dirac gluino mass, a chiral superfield \( \Phi \) in the adjoint representation of \( SU(3)_C \) is needed. To maintain the gauge coupling unification and lift the Higgs boson mass, we need to introduce some extra vector-like particles. To avoid the Landau pole for the SM gauge couplings below the GUT scale, we only have two kinds of models: \( \Delta b = 3 \) and \( \Delta b = 4 \) where \( \Delta b \) is the one-loop beta functions of the SM gauge couplings from all the new particles. We will study the model with \( \Delta b = 3 \) elsewhere (For Dirac gaugino case, see Ref. [29]). Here, we consider the model with \( \Delta b = 4 \), where the additional particles and their quantum numbers under \( SU(3)_C \times SU(2)_L \times U(1)_Y \) are: \( \Phi(8,1,0), \ XD(3,1,-1/3), \ XD^c(\bar{3},1,1/3), \ T_+ (1,3,1), \ \)and \( T_- (1,3,-1) \). In this model, the \( SU(2)_L \times U(1)_Y \) Dirac gaugino masses are forbidden, and the neutralino masses and mixings can be generated via Type II seesaw mechanism [34].

Comparing to the MSSM, the new superpotential terms with universal vector-like particle mass are

\[
W = M_V (T_+ T_- + XD^c XD) + \lambda H_u T_- H_u + \lambda^\prime H_d T_+ H_d ,
\]

where \( H_d \) and \( H_u \) are the MSSM Higgs fields, and to simplify the discussions we shall neglect \( \lambda^\prime \) in the following. The corresponding SUSY breaking soft terms are

\[
-L_{soft} = B_T T_+ T_- + B_D XD^c XD + T_+ H_u T_- H_u + M_D G\Phi + h.c. + \tilde{m}_D^2 \tilde{\phi},
\]

where \( B_{a,T,D} \) are bilinear soft terms, \( m_D^2 \) are soft scalar masses, and \( M_D \) is the Dirac gluino mass.

SUSY Breaking—To realize the hybrid \( F^- \) and \( D^- \) term SUSY breakings, we shall consider the anomalous \( U(1)_X \) gauge symmetry inspired from string models. Unlike Ref. [35], we introduce two SM singlet fields \( S \) and \( S' \) with \( U(1)_X \) charges 0 and \( -1 \), and assume that all the SM particles and vector-like particles are neutral under \( U(1)_X \). In general, there could exist other exotic particles \( Q_X^S \) with \( U(1)_X \) charges \( q_X^S \) from any real string compactification. Thus, the \( U(1)_X \) \( D^- \) term potential is

\[
V_D = \frac{g_Y^2}{2} D^2 = \frac{g_X^2}{2} \left( \sum_X q_X^S |Q_X^S|^2 - |S'|^2 + \xi \right)^2 ,
\]

where for example, in the heterotic string compactification [36], the Fayet-Iliopoulos term is given by

\[
\xi = \frac{g_X^2 \text{Tr} X}{384 \pi^2} M_{P1}^2 ,
\]

where \( M_{P1} \) is the reduced Planck scale.

To achieve gravity mediation, we consider the following superpotential from the instanton effect which breaks \( U(1)_X \)

\[
W_{\text{Instanton}} = M_I S S' .
\]

This is the key difference between our scenario and that in Ref. [35] where the superpotential is \( U(1)_X \) invariant and then one can not realize the traditional gravity mediation. Minimizing the potential, we obtain

\[
\langle S \rangle = 0 , \quad \langle S' \rangle^2 = \xi - M_I^2 / g_X^2 , \quad \langle F_S \rangle = 0 , \quad (5)
\]

\[
\langle F_S \rangle = M_I \sqrt{\xi - M_I^2 / g_X^2} , \quad \langle D \rangle = M_I^2 / g_X^2 . \quad (6)
\]

Because \( S \) is neutral under \( U(1)_X \), the traditional gravity mediation can be realized via the non-zero \( F_S \). The Dirac mass for gluino/\( \Phi \) and soft scalar masses for \( \Phi \) and \( T_{+/-} \) can be generated respectively via the following operators

\[
\int d^4 \theta \frac{D^2}{M^*} W_{3,\alpha} \Phi + \frac{D^2 (D^a V^a D_0 X')}{M^*} X'' , \quad (7)
\]

where we neglect the coefficients for simplicity, \( X' \) and \( X'' \) can both be \( \Phi \) as well as respectively be \( T_{+/-} \) and \( T_{-/+} \), and \( M_c \) can be the Planck scale for gravity mediation or the effective messenger scale. Similar to the above second kind of operators, we can have the operators for \( H_d / H_u \) and \( XD^c / XD \), which will be assumed to be suppressed due to the localizations of the particles in the extra space dimensions in Type IIA/B string constructions, or the suppressed couplings with messengers.

Let us consider two cases for \( M_* \): (i) We choose \( M_* = M_{P1}, M_I = 10^8 \) GeV, \( Tr q^X = 2 \), and \( g_X = 10^{-3} / a \) with \( a \) a real number. So we get \( D = 10^{22} / a^2 \) GeV\(^2\) and \( F_S = 5.5 a \times 10^{23} \) GeV\(^2\). For \( a = 2^{-1/2} \), we have \( D/F_S = 5.1 \), i.e., the Dirac gluino mass and the soft scalar masses of \( T_{+/-} \) and \( \Phi \) are about 5.1 times larger than the gravity mediation via \( F_S \). This case may be realized in Type IIA/B compactifications with the D-branes wrapping the large cycles but not in the heterotic string compactifications since \( g_X \) is small. (ii) We choose \( M_I = 1.25 \times 10^9 \) GeV, \( Tr q^X = 2 \), and \( g_X = 0.8 \), which may be realized in heterotic string as well. So we have \( D = 2.44 \times 10^{10} \) GeV\(^2\) and \( F_S = 5.5 \times 10^{21} \) GeV\(^2\). Thus, we need the effective messenger scale \( M_* \) around \( 10^9 \) GeV to realize the relatively heavy masses for Dirac gluino and scalar components of \( T_{+/-} \) and \( \Phi \). In our model, the vector-like particles like \( XD^c / XD \) can be messengers.

Phenomenology Study—First, with two-loop renormalization group equations (RGEs) for gauge couplings and two-loop RGEs for Yukawa couplings [37, 38], we present gauge coupling unification in Fig. 1 for \( M_V = M_D = 5 \) TeV, and the GUT scale is around \( 10^{17} \) GeV. To avoid the Landau pole problem for gauge couplings, we need \( M_V \geq 3 \) TeV and \( M_D \geq 3 \) TeV. Thus, the contribution to Higgs boson mass from \( MH_u T_- H_u \) will be suppressed. In our model, we can have \( m_{T_+} \gg M_V \) and then there exists non-decoupling effect as the Dirac NMSSM [39, 40]. The Higgs boson mass is increased by

\[
\Delta m_h^2 = \lambda_{\text{eff}}^2 \sin^4 \beta v^2 ,
\]

where \( \tan \beta \equiv (H_u) / (H_d) \), and

\[
\lambda_{\text{eff}}^2 \equiv \lambda^2 (m_{T_+}^2 / (M_{P1}^2 + m_{T_+}^2)) .
\]
Unlike the Dirac NMSSM, this contribution does not vanish at large $\tan \beta$ limit, which is properly accommodated with some interesting low energy constraints such as the following $\Delta a_\mu$.

**Numerical Results**—For the numerical studies, we are going to study the effective theory at the SUSY scale after integrating out the vector-like particles. We implement our model in the Mathematica package **SARAH** [41–47]. **SARAH** is used in a second step to generate the various relevant outputs necessary for our analysis: we use the Fortran modules for **SPheno** [48, 49] to calculate the mass spectra and precision observables, and the model files for **CalcHEP** [50] which are used together with **micrOMEGAs** [51, 52] to calculate the dark matter relic density and direct detection rates.

We consider all the current experimental constraints from the LEP, LHC, and B physics experiments, etc. The Higgs mass range is taken from 123 GeV to 127 GeV. Also, the SM prediction for the anomalous magnetic moment of the muon [53, 54] has a discrepancy with the experimental results [55, 56] as follows

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

In our scans, the input parameter ranges or values are given in Table I. In Fig. 1 we present the Higgs mass versus $\lambda_{\text{eff}}$ to show the large impact of the non-decoupling effect, in addition to the other constraints, especially the allowed range of $\Delta a_\mu$. We see that for moderate values of $\lambda_{\text{eff}}$ around 0.2 – 0.3, the Higgs mass falls into the desirable range, unlike the DiracNMSSM. Another interesting property is that the electroweak symmetry breaking (EWSB) can be realized even in the range of small $\mu$, which alleviates the following fine-tuning problem.

**Fine-Tuning**—Because we discuss the simple low energy phenomenology here, we consider the low energy fine-tuning measure defined in Ref. [57] as follows

$$\Delta_{\text{EW}} = \frac{2}{M_Z^2} \max(C_{H_d}, C_{H_u}, C_\mu, C_{B_\mu}, C_{\delta m^2_{\tilde{H}_u}}). \quad (11)$$

where

$$C_{H_d} = \left| \frac{m_{H_d}^2}{\tan^2 \beta - 1} \right|, \quad C_{H_u} = \left| \frac{m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} \right|, \quad (12)$$

$$C_\mu = |\mu|^2, \quad C_{B_\mu} = |B_\mu|, \quad (13)$$

$$C_{\delta m^2_{\tilde{H}_u}} = \frac{(\lambda M_Y)^2}{16 \pi^2} \log \left( \frac{M_{\tilde{g}}^2 + m_{\tilde{H}_u}^2}{M_Y^2} \right). \quad (14)$$

Compared to Ref. [57] we have additional $C_{\delta m^2_{\tilde{H}_u}}$ from the triplet threshold corrections to $m_{H_d}$. We find that the entire fine-tuning measure is given by $C_\mu$ while the other terms $C_{H_d,u}$, $C_{B_\mu}$ and $C_{\delta m^2_{\tilde{H}_u}}$ are negligible. In particular, the fine-tuning measure can be as low as 50 for the viable parameter space, even if the threshold effects at large $M_V$ and $M_D$ are considered. Since our MSSM sparticles except the gluino can be within about 1 TeV while gluino is Dirac, it seems that the fine-tuning

| $\tan \beta$ | $\lambda_{\text{eff}}$ | $\mu$ | $B_\mu$ | $M_1$ | $M_2$ | $M_D$ | $m_{\tilde{Q}_{1&2}}$ | $m_{\tilde{Q}_{3}}$ | $m_{\tilde{l}_{1&2}}$ | $m_{\tilde{L}_{3}}$ | $m_\phi$ |
|---------|---------|-------|---------|-------|-------|-------|----------------|----------------|----------------|----------------|-------|
| 5, 60   | 0.1, 0.7| 0.3, 1| $10^{-3}$, 1| 0.01, 0.1| 0.5, 1| 3, 5 | 0.8, 0.9 | 0.4, 0.7 | 0.1, 0.5 | 0.07, 0.16 | $\sqrt{3}, \sqrt{5}$ |

**TABLE I.** The input parameter ranges or values used in our scans. All the mass parameters are given in appropriate power of TeV. Here, $M_1$ are gaugino masses, $\mu$ is the bilinear Higgs mass in the superpotential and $B_\mu$ is the corresponding soft mass. We consider the universal scalar mass for the left- and right-handed squarks (sleptons) $\tilde{Q} \in \{ \tilde{q}, \tilde{d}, \tilde{u} \}$ and the degenerated first and second generations. We choose $M_3 = 0.6$ TeV and the vanishing trilinear soft terms for three generations.

![FIG. 1. Gauge coupling unification for $M_V = M_D = 5$ TeV.](image1)

![FIG. 2. The Higgs mass versus $\lambda_{\text{eff}}$. The blue points provide the spectra without tachyons. In addition to satisfy the Higgs mass requirement, the green and red points have $\Delta a_\mu$ within $3\sigma$ and $1\sigma$ ranges, respectively.](image2)
The fine-tuning problem, the gluino also has a heavy Dirac mass, we introduced extra vector-like particles. We realize the gauge coupling unification and lift the Higgs boson mass, we introduced extra vector-like particles. We have studied the viable parameter space which satisfies all the current experimental constraints, and given a concrete benchmark point. This kind of models keeps the MSSM particles obtain the SUSY breaking soft terms from the traditional gravity mediation and can have masses within about 1 TeV. To escape the LHC SUSY search constraints and avoid the electroweak fine-tuning problem, the gluino also has a heavy Dirac mass above 3 TeV from D-term SUSY breaking. To realize the gauge coupling unification and lift the Higgs boson mass, we introduced extra vector-like particles. We have studied the viable parameter space which satisfies all the current experimental constraints, and given a concrete benchmark point. This kind of models keeps the merits of pre-LHC SSMs and solve the possible problems in the supersoft SUSY.

**Conclusion**—We have proposed the SSMs with a pseudo-Dirac gluino from hybrid F- and D-term SUSY breakings, which can be achieved via an anomalous $U(1)_X$ gauge symmetry inspired from string models. All the MSSM particles obtain the SUSY breaking soft terms from the traditional gravity mediation and can have masses within about 1 TeV except gluino. To escape the LHC SUSY search constraints and avoid the electroweak fine-tuning problem, the gluino also has a heavy Dirac mass above 3 TeV from D-term SUSY breaking. To realize the gauge coupling unification and lift the Higgs boson mass, we introduced extra vector-like particles. We have studied the viable parameter space which satisfies all the current experimental constraints, and given a concrete benchmark point. This kind of models keeps the merits of pre-LHC SSMs and solve the possible problems in the supersoft SUSY.

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![Table II. The particle spectrum (in GeV) for a benchmark point with pseudo-Dirac gluino masses 2927 GeV and 3470 GeV for $\tan \beta = 29$, $M_1 = 0.21$ TeV, $\mu = 0.5$ TeV, $B_{\mu} = 0.02$ TeV$^2$, $M_2 = 0.5$ TeV, $M_3 = 0.6$ TeV, $M_D = 3$ TeV, $\lambda_{\text{eff}} = 0.22$, $m_\Phi = 2$ TeV, $m_{\tilde{Q},1k2} = m_{\tilde{L},1k2} = 1$ TeV, $m_{\tilde{Q},3} = 0.404$ TeV, $5 < \tan \beta < 30$, $10$ GeV < $M_1 < 300$ GeV, $90$ GeV < $m_{\tilde{L},3} < 300$ GeV. All the other parameters are taken as in Table I. We use the relatively large values for $\mu$ and $M_2$ of 500 GeV to suppress the Higgsino and wino components of the LSP neutralino. This reduces the direct detection rates since the coupling to the Z boson is highly reduced. Moreover, we need not only a small mass splitting between the light stau and LSP neutralino to get an efficient coannihilation but also to soften the LEP bounds on SUSY searches: for $m_{\tilde{\tau}} - m_{\tilde{\chi}} > 7$ GeV a limit of $m_{\tilde{\tau}} > 87$ GeV is present while for nearly degenerated staus and neutralinos this limit becomes much weaker [60]. Finally, the fine-tuning measure is still small, $\Delta_{\text{FT}} \simeq 60$.

As the preferred range for the LSP neutralino relic density, we consider the 2σ interval combined range from Planck+WP+highL+BAO [61],

$$0.1153 < \Omega_{\text{CDM}}h^2 < 0.1221 \quad (15)$$

In Fig. 3 we show the results for spin-independent LSP neutralino-nucleon cross section. Because the masses of the first two generations of squarks have been fixed at 1 TeV and the Higgsino component in the LSP is heavily suppressed, the constraints from direct detection searches are easily evaded for all the considered points. The spin-independent cross sections are about one or two orders of magnitude below the current best limit provided by the LUX experiment [62]. Especially, the points with the LSP masses above 20 (15) GeV are within the reach of the projected XENON1T (XENON10T) sensitivity [63]. Also, we find that the current constraints on spin-dependent cross sections are much weaker at the moment. To be concrete, in Table II we present a viable benchmark point whose MSSM particles except gluino are within 1 TeV.

**Dark Matter**—For simplicity, we concentrate on the LSP neutralino-stau coannihilation scenario here. To achieve this goal, we choose the following input parameter values or ranges: $\mu = 0.5$ TeV, $B_{\mu} = 0.15$ TeV$^2$, $M_2 = 0.5$ TeV, $M_3 = 0.6$ TeV, $M_D = 3$ TeV, $\lambda_{\text{eff}} = 0.22$, $m_\Phi = 2$ TeV, $m_{\tilde{Q},1k2} = m_{\tilde{L},1k2} = 1$ TeV, $m_{\tilde{Q},3} = 0.404$ TeV, $5 < \tan \beta < 30$, $10$ GeV < $M_1 < 300$ GeV, $90$ GeV < $m_{\tilde{L},3} < 300$ GeV. All the other parameters are taken as in Table I. We use the relatively large values for $\mu$ and $M_2$ of 500 GeV to suppress the Higgsino and wino components of the LSP neutralino. This reduces the direct detection rates since the coupling to the Z boson is highly reduced. Moreover, we need not only a small mass splitting between the light stau and LSP neutralino to get an efficient coannihilation but also to soften the LEP bounds on SUSY searches: for $m_{\tilde{\tau}} - m_{\tilde{\chi}} > 7$ GeV a limit of $m_{\tilde{\tau}} > 87$ GeV is present while for nearly degenerated staus and neutralinos this limit becomes much weaker [60]. Finally, the fine-tuning measure is still small, $\Delta_{\text{FT}} \simeq 60$.

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![Figure 3. The spin-independent LSP neutralino-nucleon cross section versus the LSP mass. The blue points have the particle spectra without tachyons. The yellow points satisfy the Higgs mass requirement and have $\Delta M_{h}$ within $3\sigma$ range. The green points have the correct relic density given in Eq. (15). And the red points satisfy all the current constraints.](image-url)
