Sparticle spectrum and EWSB of mixed modulus-anomaly mediation in fluxed string compactification models

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Abstract. We examine low energy sparticle mass-spectrum and electroweak symmetry breaking (EWSB) in the mixed modulus-anomaly mediation which is naturally realized in KKLT flux compactification. We find that the anomaly-mediation effect lowers messenger scale in the moduli-mediation and leads to ‘squeezed’ mass-spectrum distinct from any known mediation mechanisms. The lightest neutralino typically becomes a mixed state of bino and higgsino or pure higgsino, which has a considerable impact on the cold dark matter physics.

INTRODUCTION

In string theory, the moduli-mediation \[2\] has been known for some time as a natural mechanism of supersymmetry (SUSY) breaking in low energy 4D effective theory. However, any reliable predictions can not be derived before all the moduli are stabilized and cosmological constant is fine-tuned to the observed vanishing value \[3\].

Recently, KKLT have proposed an interesting set-up in which all the moduli are stabilized by flux and non-perturbative dynamics on branes \[4\]. Resultant SUSY AdS vacuum is uplifted to dS vacuum by introducing additional source of SUSY breaking. Soft SUSY breaking of visible sector in KKLT set-up has been examined carefully under the assumption that the visible sector is sequestered from the SUSY-breaking uplifting sector.\[5, 6\]. It is noticed that in this class of models the moduli-mediated SUSY breaking is typically \[O\left(m_3^{3/2}/4\pi^2\right)\] and the loop-suppressed anomaly-mediation \[7\] can play equally important roll.

In this paper, we discuss that this mixed modulus-anomaly mediation is equivalent to reducing the mediation scale in the moduli-mediation up to non-negligible Yukawa interactions and realizes distinct pattern of SUSY breaking at low energy scale, which leads to its characteristic phenomenology.

KKLT SET-UP

Let us first define the KKLT set-up following \[4, 5, 6\]. Throughout this paper, we assume \[M_{Pl} = 1\] otherwise explicitly specified. We consider type IIB string theory compactified on Calabi-Yau (CY) orientifold. Dilaton, S and complex structure moduli, \[Z^\alpha\] are stabilized by introducing NS and RR three form fluxes, while Kähler moduli \[T^i\] remain light at this stage. Integrating out \[S, Z^\alpha\] and assuming a single Kähler modulus \[T\] remain light at this stage. Integrating out \[S, Z^\alpha\] and assuming a single Kähler modulus \[T\] low energy 4D effective action in superconformal formulation of \(N=1\) supergravity is given by,

\[
S_{N=1} = \int d^4x \sqrt{g^C} \left[ \int d^4\theta \langle e^{K_{eff}/3} \rangle \left( -3 \exp \left( \frac{K_{eff}}{3} \right) \right) \right. \\
\left. + \left\{ \int d^2\theta \left( \frac{1}{4} f_a W_a^{\alpha} W_a^\alpha + C^3 W_{eff} \right) + h.c. \right\} \right], \tag{1}
\]

where \(C = C_0 + \theta^2 F^C\) denotes the chiral compensator superfield. 4D metric in superconformal frame, \(g^{\mu\nu}_{\mu\nu}\) is related to metric in the Einstein frame, \(g^{\mu\nu}_{\mu\nu} = (C^c)^{-1} e^{K_{eff}/3} g^{E}_{\mu\nu}\). Kähler potential and superpotential are given by,

\[
\begin{align*}
K_{eff} &= K_0 + Z_i (T + T^*) Q_i^\dagger Q_i, \\
W_{eff} &= W_0 + \frac{1}{6} \lambda_{ij\alpha} Q_i Q_j Q_\alpha,
\end{align*}
\tag{2}
\]

where \(Q_i\) are chiral matter superfields while \(W^{\alpha i}\) denote chiral field strengths of gauge supermultiplet. They can live on D3 brane or D7 brane wrapping on the 4-cycle of the CY orientifold. Their kinetic functions are given by,

\[
Z_i = \frac{1}{(T + T^*)^{n_i}}, \quad f_\alpha = T^i_{\alpha i},
\tag{3}
\]

1 This talk is based on the work presented in [1].
where \( n_i = 1, l_i = 0 \) for D3 and \( n_i = 0, l_i = 1 \) for D7. Matter fields also originate in an intersection of two (three) D7 branes with \( n_i = 1/2 \) \((n_i = 1\) [8].

In the minimal KKLT setup, we introduce a gaugino condensation on D7 brane to stabilize the Kähler modulus \( T \). The nonperturbative dynamics generates exponential \( T \) dependence in the superpotential and it breaks the no-scale structure of the model:

\[
K_0 = -3 \ln(T + T^*), \quad W_0 = w_0 - A e^{-a T},
\]

where \( w_0 \) is original constant superpotential induced by the fluxes. The lower solid curve in Fig. 1 shows potential for \( T \) obtained by integrating out \( C \) in the Einstein frame:

\[
V_0 = e^{K_0} \left( K_0^{TT} D_T W_0(D_T W_0^* - 3 |W_0|^2) \right). \quad (5)
\]

The potential minimum is given by SUSY AdS vacuum, \( D_T W_0 = 0 \) with \( V_0 = -3 |m_{3/2}|^2 \) and the Kähler modulus is stabilized at \( \langle a T \rangle \approx \ln(A/w_0) \approx \ln(M_{Pl}/m_{3/2}) \).

KKLT propose to uplift this AdS vacuum to dS vacuum by introducing an explicit source of SUSY breaking. This is done by \( D3 \) brane trapped in a warped throat with a red-shift factor \( e^{\Delta \min} \sim \sqrt{m_{3/2}/M_{Pl}} \) [10]. In low-energy action, its effect is described by a spurion operator up to corrections further suppressed by \( e^{\Delta \min} \) [3]:

\[
S_{\text{lift}} = -\int d^4x \sqrt{-g} \int d^4\theta |C|^4 \theta^2 \bar{\theta}^2 \mathcal{P}_{\text{lift}}, \quad (6)
\]

where \( \mathcal{P}_{\text{lift}} = D(T + T^*)^{np} \) with \( D \sim e^{4\Delta \min} M_{Pl}^{-2} \). Integrating out \( C \) in the Einstein frame, we obtain the following uplifting potential:

\[
V_{\text{lift}} = e^{2K_0/3} \mathcal{P}_{\text{lift}}(T, T^*) \equiv D/(T + T^*)^{2-np}. \quad (7)
\]

Strictly speaking, uplifting by \( D3 \) brane predicts constant \( \mathcal{P}_{\text{lift}}(n_P = 0) \), however we leave \( np \) free to cover potential extensions. Desired dS vacuum can be achieved by fine-tuning \( D \) as shown by the upper solid curve in Fig. 1.

This uplifting process slightly shifts the position of the minimum from the original SUSY preserving vacuum and induces non-zero \( F^T = -e^{K_0/2} K^{TT} (D_T W)^* \). While \( m_{3/2} = e^{K_0/2} W_0 \) is almost constant and \( V_0/3 = -|m_{3/2}|^2 \) is canceled by the uplifting. This leads to a hierarchy:

\[
\left| \frac{F^T}{(T + T^*)} \right|^2 = \frac{K_{TT}^{TT}}{3} |F^T|^2 \approx |\delta m_{3/2}^2| < |m_{3/2}|^2. \quad (8)
\]

Actual minimization of the uplifted potential gives,

\[
\frac{F^C}{C_0} \approx \frac{m_{3/2}^2}{M_{Pl}^2 (T + T^*)^{3/2}},
\]

\[
\frac{F^T}{(T + T^*)} \approx \frac{2 - np}{a(T + T^*)} m_{3/2}^2, \approx \mathcal{O} \left( m_{3/2}/4\pi^2 \right),
\]

suggesting that the loop-suppressed anomaly mediation is comparable to the moduli-mediation [3][4]. Here, we define \( \alpha \) which parameterizes their relative significance:

\[
\alpha = \frac{m_{3/2}^2/\ln(M_{Pl}/m_{3/2})}{M_0} \approx \frac{F^C/C_0}{a Re(T)} \left( \frac{F^T}{(T + T^*)} \right)^{-1}. \quad (10)
\]

**MIRAGE MESSENGER SCALE**

We calculate low energy mass-spectrum of visible fields in KKLT set-up. Their soft SUSY breaking is written as \ref{Gauginos},

\[
\mathcal{L}_{\text{soft}} = -m_{\tilde{l}}^2 |\tilde{Q}|^2 - \left( \frac{1}{2} M_a \lambda^a \lambda^a + \frac{1}{2} \delta_{ijk} \tilde{Q}_i \tilde{Q}_j \tilde{Q}_k + \text{h.c.} \right),
\]

where \( \lambda^a \) denote gauginos, \( \tilde{Q}_i \) represent sfermions and \( y_{ijk} \) are canonically normalized Yukawa couplings. Just below the cut-off, the standard calculation [3][7] gives,

\[
M_a = \frac{l_a M_0 + h_a}{8\pi^2 S_{\text{GUT}}} \frac{F^C}{C_0},
\]

that the coefficient \( X \) is further suppressed by the small warp factor, so its contribution to the sfermion mass can be ignored compared to the soft masses induced by \( F^T \) and \( F^C \).

\footnote{Gaugino vertex is given by, \( \mathcal{L} = i \bar{\tilde{Q}}_i T^a \lambda^a + \text{h.c.} \) where \( \lambda^a \) denote fermions and \( T^a \) is a generator of gauge group.}
\[ A_{ijk} = a_{ijk} M_0 - \frac{1}{16\pi^2} (\gamma_i + \gamma_j + \gamma_k) \frac{F^C}{C_0} , \]

\[ m_i^2 = c_i |M_0|^2 - \frac{1}{32\pi^2} \frac{d\gamma_i}{d\ln \mu} \left( \frac{F^C}{C_0} \right)^2 \]

\[ + \frac{1}{8\pi^2} \left\{ \sum_{jk} a_{ijk} \frac{|Y_{ij}|^2}{2} - \sum_A |\mathcal{A}_{\alpha} C_A(Q_i)| \right\} \times \left( M_0 \left( \frac{F^C}{C_0} \right)^* + M_0^* \left( \frac{F^C}{C_0} \right) \right) , \]

where \( M_0 \equiv F^T / (T + T^*) \), \( a_{ijk} = 3 - n_i - n_j - n_k \) and \( c_i = 1 - n_i \) for the moduli-mediated contribution and,

\[ \frac{dg_a}{d\ln \mu} = \frac{b_a}{8\pi^2 S_a'^3} , \quad \frac{d\ln Z_i}{d\ln \mu} = \frac{1}{8\pi^2} \gamma_i , \]

for the anomaly-mediated contribution. Note that interference terms appear due to non-zero \( \partial_i \gamma \). If visible gauge fields originate in D3 and no Yukawa coupling with D7 singlets, the above formulas reduce to the pure anomaly-mediation. Because it has been examined extensively by the literature and is plagued with tachyonic slepton, we assume D7 visible gauge fields \((l_a = 1)\) which naturally lead to gauge coupling unification.

Surprising new feature of this mixed modulus-anomaly mediation arises from correspondence between renormalization group (RG) running in the moduli-mediation and the anomaly-mediation itself. They have precisely same form at one-loop if \( a_{ijk} = 1 \) and Yukawa couplings are vanishing except for fields satisfying \( c_i + c_j + c_k = 1 \). Thus we can obtain analytic solutions for the soft terms in the mixed modulus-anomaly mediation up to corrections coming from Yukawa couplings with \( n_1 + n_j + n_k \neq 2 \):

\[ M_a(\mu) = M_0 - M_0 \frac{b_a}{4\pi^2} s_a^2(\mu) \ln \left( \frac{M_{\text{MMS}}}{\mu} \right) , \]

\[ A_{ijk}(\mu) = a_{ijk} M_0 + M_0 \frac{1}{8\pi^2} (\gamma_i(\mu) + \gamma_j(\mu) + \gamma_k(\mu)) \]

\[ \times \ln \left( \frac{M_{\text{MMS}}}{\mu} \right) , \]

\[ m_i^2(\mu) = c_i |M_0|^2 \]

\[ + \frac{|M_0|^2}{4\pi^2} \left\{ \gamma_i(\mu) - \frac{1}{2} \frac{d\gamma_i(\mu)}{d\ln \mu} \ln \left( \frac{M_{\text{MMS}}}{\mu} \right) \right\} \]

\[ \times \ln \left( \frac{M_{\text{MMS}}}{\mu} \right) , \]

where \( M_{\text{MMS}} \equiv (m_{3/2}/M_{\text{GUT}})^{\alpha/2} M_{\text{GUT}} \) and we used \( F^C/C_0 \approx m_{3/2} \) and \[10] 4. These solutions show that net effect of the anomaly mediation is shifting messenger scale in the modulii-mediation from \( M_{\text{GUT}} \) to the mirage messenger scale, \( M_{\text{MMS}} \). It is noted that this scale is not associated with any physical threshold and cut-off of the theory still stays at \( M_{\text{GUT}} \). This new feature of the anomaly-mediation does not depend on detail of the co-existing mediation scheme as far as the above conditions are satisfied.

\[ \text{FIGURE 2. Gaugino mass squares in KKLT set-up (D7 visible gauge fields).} \]

\[ \text{FIGURE 3. Scalar mass squares in KKLT set-up (D7 visible gauge/matter fields).} \]

\[ ^4 \text{If } Q_i \text{ have } U(1) \text{ charges } Y_i \text{ and } Tr(cY) \text{ is non-zero, } Y_i \text{ components in } c_i |M_0|^2 \text{ behave as an effective D-term. Thus further corrections appear for these components due to running of the } U(1) \text{ coupling.} \]
Fig. 2, 3 show the results of numerical calculation for the gaugino and sfermion mass squares at $M_{SUSY} = 1 \text{ TeV}$. Gauge and Yukawa couplings at $M_{SUSY}$ are estimated using 2-loop RG equations in the SM and subsequently evolved to $M_{GUT} = 2 \times 10^{16} \text{ GeV}$ by 1-loop RG equations in the MSSM. The soft SUSY breaking terms are calculated by solving 1-loop RG equations imposing the boundary conditions at $M_{GUT}$. We choose all the visible fields originating in D7 ($n_i = 0$). Shaded regions at $\alpha = 2/3$, 1.2 correspond to the cases, $n_p = -1,0,1$ assuming $10\%$ ambiguity. The minimal KKLT predicts $\alpha_{KKLT} \approx 1$ and $M_{MMS} \approx 10^{10} \text{ GeV}$. Reduced mediation scale generally leads to squeezed (compressed) mass spectrum, which is distinct from any known mediation mechanisms. In particular, we have unified gaugino and the 1st and 2nd generation sfermion masses at $\alpha = 2$ because of $M_{MMS} \approx M_{SUSY}$. Higgs and the third generation masses (dashed curves) are disturbed by Yukawa couplings. Note that these predictions are different from those of lower cut-off models because here gauge couplings still unify at $M_{GUT}$. These distinct pattern of the spectrum can be tested by coming LHC and future ILC.

Let us examine the electroweak (EW) symmetry breaking in the mixed modulus-anomaly mediation. Here we assume the minimal model with $\mu$ and $B$ terms:

$$W_H = \mu H H, \quad \mathcal{L}_{soft} = B \mu H H.$$  

They can be solved by minimizing the tree-level Higgs potential for fixed $\tan \beta = (H_2) / (H_1)$,

$$\mu^2 = \frac{M_Z^2}{2} + m_{H_1}^2 - m_{H_2}^2 \tan^2 \beta, \quad |B \mu| = \sin(2\beta)(m_{H_1}^2 + m_{H_2}^2 + 2\mu^2)/2.$$  

Figure 4. shows $\mu$ and $B$ in the unit of $M_0$. Here all the visible matters live in the intersection ($n_i = 1/2$) and we fix $\tan \beta = 10$. The dashed (thin solid) curves indicate the case, $M_Z = 0.3 M_0$ ($M_Z \ll M_0$). $M_2^2 > 0$ in (18) ensures that there’s no EW symmetry breaking above the thin solid $|\mu/M_0|$ curve. Increasing $\alpha$, lowered messenger scale weakens the radiative EW symmetry breaking [11] and reduces $|\mu|$. Eventually $|\mu|^2$ is driven into negative and EW symmetry is restored. While the bino mass increases with $\alpha$, again because of the reduced messenger scale. These effects drive the lightest neutralino into a mixed state of bino and Higgsino ($\alpha \approx 1$) or pure Higgsino ($\alpha \approx 2$). This qualitative feature is robust for different choices of matter fields although precise position of the mixed region and nature of the lightest supersymmetric particle (LSP) depend on the models. Generally, heavier initial Higgs mass or lower $M_0/M_Z$ tends to introduce stop LSP and D3 slepton or large $\tan \beta$ likely leads to stau LSP. If they are stable, they will pose severe constraints on the models. If the mixed or pure Higgsino neutralino is LSP, faster annihilation rate and stronger interaction with nuclei will dramatically change the cold dark matter physics based on the conventional bino LSP scenario [12]. Thus the mixed modulus-anomaly mediation can have a considerable impact on cosmology as well as with hierarchically heavy gravitino and moduli fields [13, 14].

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