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Phenomenological implications of $D3/D7$ (reversed) μ-split-like supersymmetry scenario

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Abstract. A phenomenological model is presented which can be obtained as a local Swiss-Cheese Calabi–Yau string-theoretic compactification with a mobile $D3$- and fluxed stacks of wrapped $D7$-branes. It provides a natural realization of (reversed) μ-split-like supersymmetry wherein the squarks, sleptons, gauginos, higgsino and one of the Higgs doublets are very heavy while with some fine tuning, it is possible to obtain another light Higgs of mass 125 GeV. We discuss the role of the heavy quarks/sleptons and the light Higgs in (i) obtaining long-lived gluinos (a natural consequence of split SUSY), (ii) verifying that the NLSP decays to the gravitino LSP respects the BBN constraints with the lifetime of the LSP (gravitino) coming out to be of the order or larger than the age of the Universe, (iii) getting gravitino relic abundance of around 0.1 and (iv) obtaining electronic EDM close to the experimental upper bounds.

Keywords. Split supersymmetry; Calabi–Yau; gravitino dark matter; (N)LSP decays; electric dipole moment.

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1. Introduction

One of the greatest challenges in string phenomenology is to relate its parameters to the observables in the low-energy physics world, i.e., to reproduce all the characteristic features of the Standard Model (SM). This fascinating area, due to its fundamental and mathematically structured character, can provide a framework for computing all couplings of the minimal supersymmetric Standard Model (MSSM) dynamically and can give an explanation of the supersymmetry breaking at both low- and high-energy scales. The framework is generally based on two approaches: (i) the top-down approach (global models), which starts from the fundamental theory and tries to deduce from it all the possible low-energy observables, (ii) bottom-up approach (local models), which tries to construct consistent string models that incorporate as many SM features as possible. The 'bottom-up' approach to phenomenological models in the context of D-brane models to realize SM spectrum was initiated in [1] by considering $D3$-branes on the top of orbifold singularities of $\mathbb{C}^3/\mathbb{Z}_3$ with additional intersecting $D7$-branes. Motivated by this approach, different models were constructed in the context of compact Calabi–Yau compactifications by following configurations of intersecting $D7$-branes wrapping different four-cycles (see [2]). With the progress of large volume moduli stabilization [3], realistic constructions reproducing SM spectrum via D-branes were obtained by wrapping of $D7$-branes around blown-up cycle(s) [4] (small divisor in the geometry of Swiss-Cheese Calabi–Yau orientifold), similar to the techniques used in models of branes at singularities. In [5], we have considered a phenomenological model which could be realized locally within the context of type-IIB string theory with a space–time filling $D3$-brane and fluxed stacks of $D7$-branes wrapping a 'big' divisor along with ED3/ED1-instanton generated superpotential and world-sheet instanton-corrected Kähler potential. Interestingly, the spectrum of the particles so obtained indicated the features of (reversed) μ-split-like SUSY scenario. In this scenario, all sfermions, gauginos as well as higgsino mass parameter are considered to be very heavy. However, there is a small split between higgsino mass parameter (heavy) and gaugino mass (light) at a high scale, and thus, a reversed μ-split SUSY. It would be interesting to see the impact on the phenomenological results due to the presence of heavy supersymmetric fermions nearly isospectral with heavy sfermions.

In this contribution, we summarize our study in [5,6] of a phenomenological model that could be locally realized as a large volume $D3/D7$ Swiss-Cheese set-up of [5]. The (s)particles obtained by considering $\mathcal{N}=1$ gauged supergravity limit of this model indicates the signatures of (reversed) μ-split-like SUSY scenario. We further summarize the phenomenological implications of the model that we have explored in refs [5,6].

2. The model

For $\mathcal{N}=1$ compactification, we shall take the phenomenological Kähler potential of our model to be:

$$\begin{aligned} K_{\text{Pheno}} = & -\ln\left[-i(\tau-\bar{\tau})\right] - \ln\left(-i\int_{\text{CY}_3}\Omega\wedge\bar{\Omega}\right) \\ & -2\ln\Bigg[a_B(\sigma_B+\bar{\sigma}_B-\gamma K_{\text{geom}})^{3/2} \\ & \qquad - \left(\sum_i a_{S,i}(\sigma_{S,i}+\bar{\sigma}_{S,i}-\gamma K_{\text{geom}})\right)^{3/2} + \mathcal{O}(1)\mathcal{V}\Bigg], \end{aligned} \tag{1}$$

where τ is the axio-dilaton modulus and Ω corresponds to the complex structure moduli. K_{geom} is the geometric Kähler potential due to the presence of mobile $D3$-branes. The divisor volumes σ_α can be expressed in terms of 'Kähler' coordinates T_α, $\mathcal{M}_{\mathcal{I}}$ as

$$\sigma_\alpha \sim T_\alpha - \left[i\mathcal{K}_{\alpha bc}c^b\mathcal{B}^c + iC_\alpha^{\mathcal{M}_{\mathcal{I}}\bar{\mathcal{M}}_{\bar{\mathcal{J}}}}(\mathcal{V})\text{Tr}\left(\mathcal{M}_{\mathcal{I}}\mathcal{M}^\dagger_{\bar{\mathcal{J}}}\right)\right], \tag{2}$$

$\alpha=(B,S)$ and $\mathcal{M}_{\mathcal{I}}$ being $SU(3_c)\times SU(2)_L$ bifundamental matter field $a_{\mathcal{I}=2}$, $SU(3_c)\times U(1)_R$ bifundamental matter field $a_{\mathcal{I}=4}$, $SU(2)_L\times U(1)_L$ bifundamental matter field $a_{\mathcal{I}=1}$,

$U(1)_L \times U(1)_R$ bifundamental matter field $a_{\mathcal{I}=3}$ along with $SU(2)_L \times U(1)_L$ bifundamental $\tilde{z}_{1,2}$ with the intersection matrix: $C_\alpha^{a_I \bar{a}_{\bar{J}}} \sim \delta_\alpha^B C_\alpha^{I\bar{J}}, C_\alpha^{a_I \bar{\tilde{z}}_{\bar{j}}} = 0$, $\mathcal{G}^a = c^a - \tau b^a$ being complex axionic fields (α, a running over the real dimensionality of a subspace of the internal manifold's cohomology complex). In the context of $\mathcal{N} = 1$ type-IIB orientifolds, in (4), α, a index respectively involutively even, odd sectors of $h^{1,1}(CY_3)$ under a holomorphic, isometric involution. Now, the phenomenological superpotential is given as

$$W_{\text{Pheno}} \sim \left(z_1^{18} + z_2^{18}\right)^{n^s} \mathrm{e}^{-n^s \mathrm{vol}(\Sigma_S) - (\alpha_S z_1^2 + \beta_S z_2^2 + \gamma_S z_1 z_2)}, \tag{3}$$

where $n_s = 2$ and Σ_S is the complexified divisor volume modulus. The bifundamental $\tilde{z}_i$ in K can be considered as equivalent to $z_{1,2} \in \mathbb{C}$ in W. It is expected that $\mathcal{M}_\mathcal{I}, T_{S,B}, \mathcal{G}^a$ will constitute the $\mathcal{N} = 1$ chiral coordinates. The intersection matrix elements $\kappa_{(S/B)ab}$ and the volume-dependent $C_\alpha^{\mathcal{M}_\mathcal{I} \bar{\mathcal{M}}_{\bar{\mathcal{J}}}}(\mathcal{V})$, are chosen in such a way that at a local (metastable) minimum:

$$\begin{aligned} \langle\sigma_S\rangle &\sim \langle(T_S + \bar{T}_S)\rangle \; - iC^{\tilde{z}_i \bar{\tilde{z}}_{\bar{j}}}(\mathcal{V})\mathrm{Tr}(\langle\tilde{z}_i\rangle\langle\bar{\tilde{z}}_{\bar{j}}\rangle) \sim \mathcal{O}(1), \\ \langle\sigma_B\rangle &\sim \langle(T_B + \bar{T}_B)\rangle - iC^{\tilde{z}_i \bar{\tilde{z}}_{\bar{j}}}(\mathcal{V})\mathrm{Tr}(\langle\tilde{z}_i\rangle\langle\bar{\tilde{z}}_{\bar{j}}\rangle) \\ &\quad - iC^{a_I \bar{a}_{\bar{J}}}(\mathcal{V})\mathrm{Tr}\left(\langle a_I\rangle\langle\bar{a}_{\bar{J}}\rangle\right) \sim \mathrm{e}^{f\langle\sigma_S\rangle}, \end{aligned} \tag{4}$$

where f is a fraction not too small as compared to 1, and the stabilized values of T_α around the metastable local minimum is

$$\langle\Re e T_S\rangle, \langle\Re e T_B\rangle \sim \mathcal{O}(1). \tag{5}$$

If the volume $\mathcal{V}$ of the internal manifold is large in string length units, one sees that one obtains a hierarchy between the stabilized values $\langle\Re e \tau_{S,B}\rangle$ but not $\langle\Re e T_{S,B}\rangle$.

2.1 *Local realization of the above model*

Let us briefly review the local $D3$–$D7$-brane framework presented in [5] which realizes the aforementioned phenomenological supergravity model (1)–(5), locally, in string theory. In this, we consider type-IIB compactified on the orientifold of a Swiss-Cheese Calabi–Yau in the large volume scenarios (LVS) limit that includes non-(perturbative) α' corrections and non-perturbative instanton corrections in superpotential [7], in addition to a space–time filling $D3$-brane and multiple fluxed stacks of $D7$-branes wrapping the 'big' divisor. The configuration of $D3$–$D7$-branes as described in [5] was also obtained, locally, in the context of large volume scenarios. However, the set-up of [5] is different from the aforementioned large volume scenario constructs because: (i) it considers four stacks of multiple (magnetized) $D7$-branes in groups of 3 (corresponding to $U(1) \times SU(2)_c$), 2 (corresponding to $U(1) \times SU(2)_L$), 1 (corresponding to a $U(1)$) and 1 (corresponding to another $U(1)$) with the hypercharge corresponding to a linear combination of the four $U(1)$s, wrapping around the 'big' divisor in the rigid limit of the same (given that it was possible to locally stabilize the moduli corresponding to the fluctuations normal to the 'big divisor' Σ_B around which $D7$-branes are wrapped, at null values) but with different choices of two-form fluxes turned on the different two-cycles which are homologously non-trivial from the point of view of four-cycle's homology and not the ambient

Swiss-Cheese Calabi–Yau; (ii) it takes into account the non-perturbative corrections in the Kähler potential [7] in type-IIB Swiss-Cheese Calabi–Yau orientifold compactification, not considered in the 'large volume scenario' proposed in [3].

Further, similar in spirit to [8], we have turned on different but small two-form fluxes on the different two-cycles homologously non-trivial from the point of view of the 'big' divisor's geometry. As a result of this, the initially adjoint-valued matter fields decompose into bifundamental matter fields corresponding to the SM gauge groups. We have provided explicit matrix-valued representations for $SU(3) \times SU(2)_L \times U(1)_L$ bifundamental first-generation quarks, their right-handed EW singlet cousins, $SU(2)_L \times U(1)_L$ bifundamental first-generation leptons and the Higgs, as well as the right-handed EW-singlet leptonic cousins in [5]. All aforementioned matter fields arise from strings stretched between $D7$-branes stacks with different two-form fluxes turned on. The leptons and quarks get identified with the sfermonic superpartners of Wilson line moduli $\mathcal{A}^I$ and the Higgs with the $D3$-brane's position moduli z_i; τ is the axion-dilaton modulus and $\mathcal{G}^a$ are NS–NS and RR two-form axions complexified by the axion-dilaton modulus. In the orientifold-limit of F-theory, one considers an orientifold of the Calabi–Yau involving a holomorphic isometric involution.

Interestingly, we found in [5] that the three-cycle

$$C_3 : |z_1| \equiv \mathcal{V}^{1/36},\ |z_2| \equiv \mathcal{V}^{1/36},\ |z_3| \equiv \mathcal{V}^{1/6}, \tag{6}$$

(the Calabi–Yau can be thought of, locally, as a complex three-fold $\mathcal{M}_3$ which is a T^3 (swept out by $(arg z_1, arg z_2, arg z_3)$-fibration over a large base $(|z_1|, |z_2|, |z_3|)$; precisely apt for application of mirror symmetry as three T-dualities a la Strominger Yau Zaslow (SYZ), C_3 is almost a special Lagrangian submanifold.

The set of $\mathcal{N} = 1$ chiral coordinates (in particular the 'divisor volume') gets modified in the presence of $D3$- and $D7$-branes [9]. To evaluate the Wilson line moduli contribution in one of the $\mathcal{N} = 1$ chiral coordinates T_B, due to inclusion of four Wilson line moduli on the world volume of space–time filling $D7$-branes wrapped around the 'big' divisor restricted to (nearly) a special Lagrangian submanifold, we have constructed four distribution harmonic one-forms ($\mathcal{A}_I$, $I = 1, 2, 3, 4$) localized along the mobile space–time filling $D3$-brane (restricted to the 3-cycle). The construction of involutively odd harmonic distribution one-forms in the large volume limit is given in [5]. (The most non-trivial example of involutions which are meaningful only at large volumes is mirror symmetry implemented as three T-dualities in [10] to a Calabi–Yau which locally can be thought of as a T^3-fibration over a (large) base; all Calabi–Yaus with mirrors (in the conventional sense) are expected to have such a local fibration); $\mathcal{A}_I$s are harmonic only within Σ_B and not at any other generic locus outside Σ_B in the Calabi–Yau manifold.

2.1.1 *Yang–Mills coupling constant.* The Yang–Mills gauge coupling constant squared for the ith gauge group (i: $SU(3)$, $SU(2)$, $U(1)$) is given as

$$g^{-2}_{j=SU(3) \text{ or } SU(2)} = \Re e\big(T_{S/B}\big) + \mathcal{O}(F_j^2)\tau + \cdots, \tag{7}$$

where $\Re e(T_{S/B})$ corresponds to the size of the divisor volume around which $D7$-branes are wrapped and F_j^2 corresponds to non-Abelian two-form fluxes. In dilute flux approximation, $g_{\rm YM}$ is mainly governed by the size of divisor volume around which $D7$-branes are wrapped. In our set-up, $D7$-branes are wrapped around the 'big' divisor. Therefore, gauge coupling will be given by

$$g_{\rm YM}^{-2} \sim \Re e(T_B) \sim {\rm vol}(\Sigma_B) + C_{I\bar{J}}a_I\bar{a}_{\bar{J}} + {\rm h.c.} \sim \mathcal{V}^{1/18} \sim O(1).$$

(justified by the partial cancellation between Σ_B and $C_{I\bar{J}}a_I\bar{a}_{\bar{J}}$ with some fine-tuning).

2.1.2 *Stabilized potential of $\mathcal{N} = 1$ local large volume D3–D7 set-up.* As we do not have a global picture, we content ourselves with a local bulk and open-string moduli stabilization near (6). We showed in [5] that near (6), the moduli can be stabilized as

$$\begin{aligned}
&{\rm vol}(\Sigma_S) \sim \mathcal{V}^{1/18},\ {\rm vol}(\Sigma_B) \sim \mathcal{V}^{2/3};\ \mathcal{G}^a \sim \frac{\pi}{\mathcal{O}(1)k^a(\sim \mathcal{O}(10))}M_P;\\
&|z_{1,2}| \equiv \mathcal{V}^{1/36}M_P, |z_3| \equiv \mathcal{V}^{1/6}M_P;\ |a_1| \equiv \mathcal{V}^{-2/9}M_P, |a_2| \equiv \mathcal{V}^{-1/3}M_P,\\
&|a_3| \equiv \mathcal{V}^{-13/18}M_P, |a_4| \equiv \mathcal{V}^{-11/9}M_P;\\
&\zeta^{A=1,\ldots,h^{0,2}_-(\Sigma_B|_{C_3})} \equiv 0 \text{ (implying rigidity of the non-rigid } \Sigma_B)
\end{aligned} \tag{8}$$

such that $\Re eT_S \sim \Re eT_B \sim \mathcal{V}^{1/18}$ and implying the possibility of obtaining a local metastable de Sitter-like minimum, corresponding to the positive minimum of the potential ${\rm e}^K G^{T_S\bar{T}_S}|D_{T_S}W|^2$ near (8), realizing (5) and thereby the supergravity model described in eqs (1)–(5) for $\mathcal{V} \sim 10^5$ in $l_s = 1$ unit.

The Kähler potential relevant to all the calculations (using the modified $\mathcal{N} = 1$ chiral coordinates; without being careful about $\mathcal{O}(1)$ constant factors) is given as [5]

$$\begin{aligned}
K \sim -2\ln\Bigg(a_B\Bigg[&\frac{T_B+\bar{T}_B}{M_P} - \mu_3(2\pi\alpha')^2\frac{\{|z_1|^2+|z_2|^2+z_1\bar{z}_2+z_2\bar{z}_1\}}{M_P^2}\\
&+\mathcal{V}^{10/9}\frac{|a_1|^2}{M_P^2}+\mathcal{V}^{11/18}\frac{(a_1\bar{a}_2+{\rm h.c.})}{M_P^2}+\mathcal{V}^{1/9}\frac{|a_2|^2}{M_P^2}+\mathcal{V}^{29/18}\frac{(a_1\bar{a}_3+{\rm h.c.})}{M_P^2}\\
&+\mathcal{V}^{10/9}\frac{(a_2\bar{a}_3+{\rm h.c.})}{M_P^2}+\mathcal{V}^{19/9}\frac{|a_3|^2}{M_P^2}+\mathcal{V}^{19/9}\frac{(a_1\bar{a}_4+a_4\bar{a}_1)}{M_P^2}\\
&\times\mathcal{V}^{29/18}\frac{(a_2\bar{a}_4+a_4\bar{a}_2)}{M_P^2}+\mathcal{V}^{47/18}\frac{(a_3\bar{a}_4+a_4\bar{a}_3)}{M_P^2}+\mathcal{V}^{28/9}\frac{|a_4|^2)}{M_P^2}\Bigg]^{3/2}\\
&-a_S\left(\frac{T_S+\bar{T}_S}{M_P}-\mu_3(2\pi\alpha')^2\frac{\{|z_1|^2+|z_2|^2+z_1\bar{z}_2+z_2\bar{z}_1\}}{M_P^2}\right)^{3/2}+\sum n^0_\beta(\cdots)\Bigg)
\end{aligned} \tag{9}$$

and ED3/ED1 generated non-perturbative superpotential used in [5] is given by

$$W \sim \left(\mathcal{P}_{\Sigma_S}|_{D3|_{{\rm near}\ C_3\hookrightarrow\Sigma_B}} \sim z_1^{18}+z_2^{18}\right)^{n^s}\sum\nolimits_{m_a}{\rm e}^{i\tau\frac{m^2}{2}}{\rm e}^{in^sG^am_a}{\rm e}^{in^sT_s}, \tag{10}$$

where a_i, $i = 1$–4 and $z_{1,2}$ correspond to the undiagonalized Wilson line moduli and position moduli, respectively. The evaluation of 'physical'/normalized Yukawa couplings, soft SUSY breaking parameters and various 3-point vertices needs the matrix generated from the mixed double derivative of the Kähler potential to be a diagonalized matrix. After diagonalization, the corresponding eigenvectors as well as eigenvalues ($\mathcal{A}_I\{I = 1-4\}$, $\mathcal{Z}_{1,2}$) are calculated in [5]. Henceforth, we use the diagonalized basis for the calculation of various mass parameters and interaction vertices.

2.1.3 *Mass scales of SM-like particles.* Similar to Standard Model particles, the masses of fermions are calculated from the effective Yukawa couplings ($\hat{Y}^{\rm eff}_{C_i C_j C_k}$) in $\mathcal{N}=1$ gauged supergravity action [11], where C_i is an open string modulus is $\delta\mathcal{Z}_{1,2}/\delta\mathcal{A}_{1,2,3,4}$. By estimating in the large volume limit, all possible Yukawa couplings corresponding to four Wilson line moduli and showing that the RG-flow of the effective physical Yukawa's change almost by $\mathcal{O}(1)$ under an RG flow from the string scale down to the EW scale [5], we see that for $\mathcal{V}\sim 10^5$, $\langle\mathcal{Z}_i\rangle\sim 246$ GeV: $\langle\mathcal{Z}_i\rangle\hat{Y}_{\mathcal{Z}_1\mathcal{A}_1\mathcal{A}_3}\sim$ MeV – about the mass of the electron; $\langle z_i\rangle\hat{Y}_{\mathcal{Z}_i\mathcal{A}_2\mathcal{A}_4}\sim 10$ MeV – close to the mass of the up quark! It shows that fermionic superpartners of $\mathcal{A}_1$ and $\mathcal{A}_3$ correspond respectively to the first generation of left-handed $SU(2)$ and right-handed $U(1)$ leptons, while fermionic superpartners of $\mathcal{A}_2$ and $\mathcal{A}_4$ correspond respectively to left-handed $SU(2)$ and right-handed $U(1)$ quarks.

2.1.4 *Realization of (reversed) μ-split-like SUSY scenario.* After the identification of Wilson line moduli and position moduli with matter superfields and Higgs superfields, we calculated various supersymmetric as well as soft SUSY breaking parameters in [5]. The soft SUSY breaking parameters are calculated by expanding $\mathcal{N}=1$ supergravity potential in the powers of matter fields and Higgs superfield. Then we calculated in [5], the eigenvalues and eigenvectors of the Higgs mass matrix formed by linear combination of two Higgs doublets (using the prescription as given in [12]) by first calculating the masses of the latter and thereafter using RG solution to Higgs mass discussed in [13]. After calculating masses of (s)particles, the gravitino appears to be the lightest supersymmetric particle with mass around 10^8 GeV. The sfermion masses corresponding to the first generation of quarks and leptons (identifiable as Wilson line moduli mass in our framework as mentioned above) are very heavy of the order 10^{10} GeV at string scale. Similarly, the gaugino masses also turn out to be heavy of the order 10^{11} GeV. However, the higgsino masses turn out to be heavier of the order 10^{13} GeV. One of the Higgs doublets was shown to have mass of the order 125 GeV with some fine-tuning, thus showing the possibility of realizing (reversed) μ-split-like SUSY scenario (though there is a 'split' between mass of higgsino, and gaugino and sfermions at very high-energy scale; the SM fermions are light) in the context of our model. The results of the mass scales of the superpartners are summarized in table 1 also. As a benchmark of the split SUSY scenario, we estimated the lifetime of gluino decaying into neutralino and Goldstino upto one loop by evaluating relevant interaction vertices using $\mathcal{N}=1$ gauged supergravity action. The same turned

Table 1. Mass scales of first generation of sparticles.

sparticle(s)	Volume dependence	Mass (GeV)
Gravitino	$m_{3/2}\sim\mathcal{V}^{-2}M_P$	10^8
Gaugino	$M_{\tilde{g}}\sim\mathcal{V}^{2/3}m_{3/2}$	10^{11}
Neutralino	$M_{\chi^0_3}\sim\mathcal{V}^{2/3}m_{3/2}$	10^{11}
$D3$-brane position moduli	$m_{\mathcal{Z}_i}\sim\mathcal{V}^{59/72}m_{3/2}$	10^{12}
Wilson line moduli	$m_{\tilde{\mathcal{A}}_I}\sim\mathcal{V}^{1/2}m_{3/2}$	10^{10}
Physical μ-terms (higgsino)	$\hat{\mu}_{\mathcal{Z}_i\mathcal{Z}_j}\sim\mathcal{V}^{37/36}m_{3/2}$	10^{13}
Physical $\hat{\mu}B$-terms	$\left(\hat{\mu}B\right)_{\mathcal{Z}_1\mathcal{Z}_2}\sim\mathcal{V}^{37/18}m^2_{3/2}$	10^{26} GeV^2

out to be quite high, thus providing another concrete signature of (reversed) μ-split-like SUSY scenario.

3. Phenomenological implications of $D3/D7$ (reversed) μ-split-like SUSY model

In this section, we briefly review some of the important issues addressed in the context of the aforementioned model in refs [5,6].

3.1 *Gravitino as cold dark matter (CDM) candidate*

The typical split SUSY models assume the lightest neutralino to be an appropriate viable cold dark matter (CDM) candidate. However, in our case, gravitino appears to be the lightest supesymmetric particle (LSP). We have demonstrated the possibility of getting gravitino as a viable CDM candidate respecting BBN constraints as well as reproducing a relic abundance of around 0.1 in the context of $\mathcal{N} = 1$ gauged supergravity limit of $D3/D7$ (reversed) μ-split-like SUSY model in [5]. To justify the above, we evaluated:

(1) Lifetime of (N)LSP decay channels – The very important constraint that the hadronic or electromagnetic energy released from decay products of next-to-lightest superparticle (NLSP) must not change the observed abundances of light elements in the Universe essentially fixed by their average lifetime around $\tau \sim 10^2$ s, referred to as the Big Bang nucleosynthesis (BBN) constraint, is met by NLSP candidates, if decay of the same occurs before BBN era. To get an explicit idea, we calculated the decay width of all important two- and three-body decay channels of neutralino as well as sleptons existing as co-NLSPs in our model and found that the lifetime in all (co)-NLSP decay channels was smaller than 10^2 s (onset of BBN era). Therefore, we were justified to argue that NLSP decaying into gravitino did not disturb the cosmological BBN constraint. Thereafter, we also calculated the interaction channels corresponding to R-parity violating neutralino three-body decay to ordinary particles. As the lifetime of this decay mode turned out to very high as compared to decay modes of neutralino into gravitino, we could assume that the neutralino would have preferably decayed into gravitino(LSP)s only. In addition to this, decay lifetime of gravitino turned out to be of the order of the age of the Universe, thus showing the possibility of considering itself as a viable CDM candidate;

(2) Relic abundance of gravitino – For gravitino to be a viable CDM candidate, the contribution of gravitinos to the energy density of the Universe should be less than the the closure limit, i.e. $\Omega_{\tilde{G}} = \rho_{\tilde{G}}/\rho_c < 1$. If the gravitino LSP produced by decay of co-NLSPs is to provide the whole gravitino relic density, the relic abundance of gravitino is given as $\Omega_{\tilde{G}}h^2 = \Omega_{\chi_3^0}h^2 \times (m_{\frac{3}{2}}/m_{\chi_3^0})$, if co-NLSPs freeze out with appropriate thermal relic density ($\Omega_{\chi_3^0}$) before decaying and then eventually decay into the gravitino. As the freeze-out condition depends on thermal cross-section $\langle \sigma v_{\mathrm{M\o l}} \rangle$ of such particles, we have evaluated all important annihilation channels possible in neutralino annihilation and in the case of slepton annihilation by using the partial wave expansion approach. We have basically computed the volume suppression factors corresponding to each interaction vertex by making use of $\mathcal{N} = 1$

gauged supergravity action [5]. By calculating the partial wave coefficient of each channel and utilizing the analytical expression of relic abundance, relic abundance of gravitino $\Omega_{\tilde{G}}h^2$ turned out to be 0.1 by considering neutralino to be the NLSP and 10^{-22} by considering sleptons to be the NLSP [5].

Thus, we can conclude that the gravitino can exist as a potential CDM candidate.

3.2 *Electric dipole moment (EDM) of the electron/neutron (e/n)*

We have also explored the origin of generation of non-zero complex phases in the above-mentioned large volume $D3/D7$ model in ref. [6] and emphasized the possibility of obtaining a sizable contribution of (e/n) EDM even at one-loop level due to the presence of heavy supersymmetric fermions nearly isospectral with heavy sfermions in addition to getting a significant value of (e/n) EDM at two-loop level. Unlike traditional split SUSY models in which one-loop diagrams do not give significant contribution to the EDM of (e/n) because of very heavy sfermions existing as propagators in the loop, we obtained a 'healthy' value of EDM in our model because of the presence of heavy neutralino/chargino and gaugino as fermionic propagators in the loop. The independent CP-violating phases were generated from non-trivial distinct phase factors associated with four Wilson line moduli (identified with first generation leptons and quarks and their $SU(2)_L$-singlet cousins) as well as the $D3$-brane position moduli (identified with two Higgses) and the same were sufficient to produce overall distinct phase factors corresponding to all possible effective Yukawa's as well as effective gauge couplings that we have discussed in the context of $\mathcal{N} = 1$ gauged supergravity action. However, the complex phases responsible to generate non-zero EDM at one-loop level mainly appeared from off-diagonal contribution of sfermion as well as Higgs mass matrices at electroweak scale. In our analysis, we obtained dominant contribution of electron/neutron EDM around $\mathcal{O}(10^{-29})$ ecm from two-loop diagrams involving heavy sfermions and a light Higgs, and electron EDM around $\mathcal{O}(10^{-32})$ ecm from one-loop diagram involving heavy chargino and a light Higgs as propagators in the loop. The neutron EDM got dominant contribution of the order $\mathcal{O}(10^{-33})$ ecm from one-loop diagram involving SM-like quarks and Higgs. Next, by conjecturing that the CP-violating phase could appear from the linear combination of Higgs doublets, we also got an EDM of electron/neutron around $\mathcal{O}(10^{-27})$ ecm in case of two-loop diagram involving $W^{\pm}$ bosons.

4. Conclusions

We have discussed the possibility of realizing '(reversed) μ-split-like SUSY' scenario from a phenomenological model, which we show could be realizable locally as the large volume limit of a type-IIB Swiss-Cheese Calabi–Yau orientifold involving a mobile space–time filling $D3$-brane localized at a nearly special Lagrangian three-cycle embedded in the 'big' divisor (hence the local nature of the model's realization) and multiple fluxed stacks of space–time filling $D7$-branes wrapping the same 'big' divisor. The global embedding is however, not known. Naturally realizing the split-SUSY scenario [12] of N Arkani-Hamed and S Dimopoulos in our model, we showed that the mass of one of the Higgs formed by a linear combination of two Higgs doublets (related to the $D3$-brane position moduli), can be of the order of 125 GeV whereas other Higgs as well as higgsino mass parameter can be very heavy – the '(reversed) μ-split-like SUSY' scenario. The squarks'/sleptons' (the Wilson line moduli on $D7$-branes' world volume) masses also turned out to be very heavy. Motivated by the fact that the gravitino appears as the LSP in our model, we explored the possibility of the gravitino as a viable cold dark matter candidate by showing its lifetime to be of the order of or greater than the age of the Universe whereas lifetimes of decays of the co-NLSPs (the first generation squark/slepton and the lightest neutralino) to the LSP (the gravitino) turned out to be too short to disturb predictions of Big Bang nucleosynthesis (BBN). Assuming non-thermal gravitino production mechanism, we estimated the gravitino relic abundance to be around 0.1 by evaluating the neutralino/slepton annihilation cross-sections and hence showed that the former satisfies the requirement for a dark matter candidate. As another testing ground for split-SUSY scenarios, we estimated EDM of electron/neutron up to two loops in our model and obtained dominant contribution of EDM of electron/neutron to be around 10^{-29} ecm which is roughly of the same order as given by experiments.

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