Phenomenological Implications of D3/D7 μ-split like SUSY

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Plan of the talk

1. Split/μ-split SUSY Scenario
2. Phenomenogical Model: Realization of μ-split SUSY Scenario
3. String Particle Cosmology
4. EDM of Electron/Neutron
5. Concluding Remarks

- The requirement of light Higgs assumes SUSY breaking scale to be LOW !
- In principle, 126 GeV- Good news for SUSY but no hints as yet of SUSY particles at LHC - reason to explore ($>>$ *TeV*)-scale models !

Split Supersymmetry

1. N.A-Hamed, S.Dimopoulos [2004] proposed "split SUSY scenario"; SUSY gets broken at a high energy $m_S \sim 10^{10}$ GeV far above the TeV scale. The scalars of the SSM will then all be at m_S, except for one combination of the two Higgs doublets that must be finely-tuned to be light while fermions like gaugino, higgsino will remain light.
2. Good Features: light Higgs mass, gauge coupling unification, suppresses FCNC problem, stability of proton decay.

μ-split Supersymmetry

1. An alternative scenario named as μ-split SUSY scenario is proposed by (K.Cheung and C.W Chiang [2005]) by further splitting the split SUSY by raising the μ-parameter to a large value (SUSY breaking scale)
2. With this choice, one can consider a model in which all three values $m^2_{H_2}, m^2_{H_1}, \mu^2$ get stabilized at same scale (SUSY breaking scale) naturally. However it should allow cancelation amongst each other to satisfy the radiative EW symmetry breaking condition:

$$\frac{1}{2}M_z^2 = \frac{m^2_{H_2} - m^2_{H_1}\tan^2\beta}{1-\tan^2\beta} - \mu^2.$$

The choice helps to alleviate famous "μ- problem".

- In $\mathcal{N} = 1$ Supergravity, spontaneous SUSY breaking of local SUSY in hidden-sector generates explicit soft SUSY breaking terms.
- In String compactifications, one deals with moduli (gauge neutral massless 4D scalars with gravitational coupling).
  - Visible-sector (open String Moduli)- Matter fields.
  - Hidden-sector (closed string moduli)- Complex dilaton moduli S_i, Complex structure moduli field T_i.

  Auxiliary fields of these hidden-sector moduli super fields are seed of SUSY breaking.

Phenomenological model

- In $\mathcal{N}=1$ supergravity in $\mathbb{R}^{1,3}$ obtained by compactifying type IIB supergravity on a complex three-fold('s orientifold) :

$$K_{\rm Pheno} = -ln\left[-i(\tau-\bar{\tau})\right] - ln\left(-i\int_{CY_3}\Omega\wedge\bar{\Omega}\right)$$

$$-2ln\left[a_B(\sigma_B+\bar{\sigma}_B-\gamma K_{\rm geom})^{\frac{3}{2}} - (\sum_i a_{S,i}(\sigma_{S,i}+\bar{\sigma}_{S,i}-\gamma K_{\rm geom}))^{\frac{3}{2}} + \mathcal{O}(1)\mathcal{V}\right]$$

where the divisor volumes σ_α are expressible in terms of "Kähler" coordinates $T_\alpha, \mathcal{M}_\mathcal{I}$

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

$\alpha=(B,\{S,i\})$ and $\mathcal{M}_\mathcal{I}\equiv SU(3_c)\times SU(2)_L$ 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 $a_{\mathcal{I}=3}$, $SU(2)_L\times U(1)_L$ bifundamental $\tilde{z}_{1,2}$.

Phenomenological model

The phenomenological superpotential is given as under:

$$W_{\rm Pheno} \sim \left(z_1^{18} + z_2^{18}\right)^{n^s} e^{-n^s vol(\Sigma_S) + i n^s \rho_S - n^s(\alpha_S z_1^2 + \beta_S z_2^2 + \gamma_S z_1 z_2)},$$

where the bi-fundamental $\tilde{z}_i$ in K will be equivalent to the $z_{1,2} \in \mathbb{C}$ 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 $\kappa_{S/Bab}$ 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 (meta-stable) minimum:

$$\langle\sigma_S\rangle \sim \langle (T_S + \bar{T}_S)\rangle - iC^{\tilde{z}_i\bar{\tilde{z}}_{\bar{j}}}(\mathcal{V})\, Tr\left(\langle\tilde{z}_i\rangle\langle\bar{\tilde{z}}_{\bar{j}}\rangle\right) \sim \mathcal{O}(1)$$

$$\langle\sigma_B\rangle \sim \langle (T_B + \bar{T}_B)\rangle - iC^{\tilde{z}_i\bar{\tilde{z}}_{\bar{j}}}(\mathcal{V})\, Tr\left(\langle\tilde{z}_i\rangle\langle\bar{\tilde{z}}_{\bar{j}}\rangle\right) - iC^{a_I\bar{a}_{\bar{J}}}(\mathcal{V})\, Tr\left(\langle a_I\rangle\langle\bar{a}_{\bar{J}}\rangle\right)$$
$$\sim e^{f\langle\sigma_S\rangle},$$

$f \stackrel{<}{\sim} 1$, and the stabilized values of T_α around the meta-stable local minimum:

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

Phenomenological model

- To realize the above phenomenological model, *locally*, in string theory consider type IIB compactified on the orientifold (involving a *local large-volume holomorphic isometric involution*) of a Swiss-Cheese Calabi-Yau in the large volume limit that includes perturbative Balasubramanian et al. [2005] and non-perturbative A. Misra, P. Shukla [2007, 2010]; MD, A. Misra [2012] α' corrections and non-perturbative instanton-corrections.

$D3/D7$-Branes A. Misra and P. Shukla [2007, 2010]; MD and A.Misra NPB [2012]

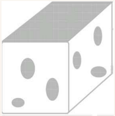
For this purpose, we will consider a space-time filling $D3$-brane and multiple fluxed stacks of space-time filling $D7$-branes wrapping a single four-cycle, the big divisor, with different choice of small two-form fluxes turned on the different two-cycles homologously non-trivial from the point of view of this four-cycle's Homology (for the purpose of decomposing initially adjoint-valued matter fields to bi-fundamental matter fields, for generating the SM gauge groups and to effect gauge-coupling unification at the string scale). Then $z_{1,2}$ get identified with the $D3$-brane's position moduli.

$D3/D7$-Branes

- We will assume that near (but not globally):
$|z_1| \sim \mathcal{V}^{\frac{1}{36}}$, $|z_2| \sim \mathcal{V}^{\frac{1}{36}}$, $|z_3| \sim \mathcal{V}^{\frac{1}{6}}$, the Calabi-Yau is diffeomorphic to the Swiss-Cheese $\mathbb{WCP}^4_{1,1,1,6,9}[18]$. The defining hypersurface for the same is:
$u_1^{18} + u_2^{18} + u_3^{18} + u_4^3 + u_5^2 - 18\psi \prod_{i=1}^5 u_i - 3\phi(u_1 u_2 u_3)^6 = 0$
$(z_1 = \frac{u_1}{u_2}, z_2 = \frac{u_3}{u_2}, z_3 = \frac{u_4}{u_2^6}, z_4 = \frac{u_5}{u_2^9})$
- The Big divisor $\Sigma_B : u_5 = 0$ and the Small divisor $\Sigma_S : u_4 = 0$;

$$\mathcal{V} = \frac{1}{9\sqrt{2}}\left(\tau_B^{\frac{3}{2}} - \tau_S^{\frac{3}{2}}\right)$$

- L(arge) V(olume) S(cenarios) limit: $\tau_S \sim ln\mathcal{V}$ and $\tau_B \sim \mathcal{V}^{\frac{2}{3}}$.



$D3/D7$-Branes A. Misra and P. Shukla [2007, 2010]; MD and A.Misra NPB [2012]

- Near $C_3 : |z_1| \sim \mathcal{V}^{\frac{1}{36}},\ |z_2| \sim \mathcal{V}^{\frac{1}{36}},\ |z_3| \sim \mathcal{V}^{\frac{1}{6}}$ 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 S(trominger) Y(au) Z(aslow); C_3 is almost a s(pecial) Lag(rangian) sub-manifold MD, A. Misra [2012] because it satisfies (using the large volume estimate of $K_{\rm geom}$ using Donaldson's Algorithm A.Misra [2012] guided by GLSM-based estimate A.Misra, P.Shukla [2010]) the requirement that

$$f^*J \approx 0,\ \Re e\left(f^* e^{i\theta}\Omega\right)\Big|_{\theta=\frac{\pi}{2}} \approx \mathrm{vol}(C_3),\ \Im m\left(f^* e^{i\theta}\Omega\right)\Big|_{\theta=\frac{\pi}{2}} \approx 0$$

  where $f : C_3 \rightarrow CY_3$.

- Including a space time filling $D3$-brane and $D7$-brane, $\mathcal{N}=1$ chiral co-ordinates get modified, Jockers and Louis [2004]. In particular,
  $T_\alpha = \frac{3i}{2}(\rho_\alpha - \frac{1}{2}\kappa_{\alpha bc}c^b\mathcal{B}^c) + \frac{3}{4}\kappa_\alpha + \frac{3i}{4(\tau-\bar{\tau})}\kappa_{\alpha bc}\mathcal{G}^b(\mathcal{G}^c - \bar{\mathcal{G}}^c)$
  $+3i\kappa_4^2\mu_7 l^2\delta^B_\alpha C_\alpha^{I\bar{J}}a_I\bar{a}_{\bar{J}} + \frac{3i}{4}\delta^B_\alpha\tau Q_{\tilde{f}} + \frac{3i}{2}\mu_3 l^2(\omega_\alpha)_{i\bar{j}}z^i(\bar{z}^{\bar{j}} - \frac{i}{2}\bar{z}^{\tilde{a}}(\bar{\mathcal{P}}_{\tilde{a}})^{\bar{j}}_l z^l)$.

$D3/D7$-Branes; MD and A.Misra NPB[2012]

- The most non-trivial example of *involutions which are meaningful only at large volumes is mirror symmetry implemented as three T-dualities a la S(trominger) Y(au) Z(aslow) to a Calabi-Yau* which *locally* can be thought of as a T^3-fibration over a (large) base; all Calabi-Yau's with mirrors (in the conventional sense) are expected to have such a local fibration.
- Four local appropriate harmonic distribution one-forms odd under a large-volume involution (analogous to the involutive SYZ mirror symmetry requiring a large base of T^3-fibration) that are in $coker(H^{(0,1)}_{\bar\partial,-}(CY_3) \stackrel{i^*}{\rightarrow} H^{(0,1)}_{\bar\partial,-}(\Sigma^\Lambda))$ localized along C_3 corresponding to the location of the $D3$-brane can be written as: $A_I|_{C_3} \sim \delta(|z_1| - \mathcal{V}^{\frac{1}{36}})\delta(|z_2| - \mathcal{V}^{\frac{1}{36}})\mathbb{A}_I$, where :

$$\mathbb{A}_1 \sim -z_1^{18} z_2^{19} dz_1 + z_1^{19} z_2^{18} dz_2,\ \mathbb{A}_2 \sim -z_1^{18} z_2 dz_1 + z_2^{18} z_1 dz_2,$$
$$\mathbb{A}_3 \sim -z_1^{18} z_2^{37} dz_1 - z_2^{18} z_1^{37} dz_1,\ \mathbb{A}_4 \sim -z_1^{36} z_2^{37} dz_1 + z_2^{36} z_1^{37} dz_2.$$

- $C^B_{I\bar J}$ was estimated in MD and A.Misra NPB [2012].

$D3/D7$-Branes MD and A.Misra NPB[2012]

The Kähler potential relevant to all the calculations is given as.

$$K \sim -2ln\Bigg(\Bigg[T_B + \bar{T}_B - \Bigg(\mu_3 l^2 \left\{|z_1|^2 + |z_2|^2 + z_1\bar{z}_2 + z_2\bar{z}_1\right\} + \mathcal{V}^{\frac{10}{9}}|a_1|^2 + \mathcal{V}^{\frac{11}{18}}(a_1\bar{a}_2 + h.c.) + \mathcal{V}^{\frac{1}{9}}|a_2|^2 + \mathcal{V}^{\frac{29}{18}}(a_1\bar{a}_3 + h.c.) + \mathcal{V}^{\frac{10}{9}}(a_2\bar{a}_3 + h.c.) + \mathcal{V}^{\frac{19}{9}}|a_3|^2 + \mathcal{V}^{\frac{19}{9}}(a_1\bar{a}_4 + a_4\bar{a}_1) + \mathcal{V}^{\frac{29}{18}}(a_2\bar{a}_4 + a_4\bar{a}_2) + \mathcal{V}^{\frac{47}{18}}(a_3\bar{a}_4 + a_4\bar{a}_3) + \mathcal{V}^{\frac{28}{9}}|a_4|^2\Bigg)\Bigg]^{3/2} - \left(T_S + \bar{T}_S - \mu_3 l^2 \left\{|z_1|^2 + |z_2|^2 + z_1\bar{z}_2 + z_2\bar{z}_1\right\}\right)^{3/2} + \sum n^0_\beta(\ldots)\Bigg).$$

$D3/D7$-Branes

MD and A.Misra NPB[2012]

- Stabilized values: $\mathrm{vol}\left(\Sigma_B\right) = \Re e(\sigma_B) \sim \mathcal{V}^{\frac{2}{3}}, \mathrm{vol}\left(\Sigma_S\right) = \Re e\sigma_S \sim \mathcal{V}^{\frac{1}{18}}$ such that $\Re e T_S \sim \mathcal{V}^{\frac{1}{18}}$ and in the dilute flux approximation, gauge couplings corresponding to the gauge theories living on stacks of $D7$ branes wrapping the "big" divisor Σ_B will given by: $g_{YM}^{-2} \sim \Re e(T_B) \sim \mathcal{V}^{\frac{1}{18}} \sim O(1)$ (justified by the partial cancelation between between σ_B and $C_{I\bar{J}} a_I \bar{a}_{\bar{J}}$ i.e $(Vol(\Sigma_B) + C_{I\bar{J}} a_I \bar{a}_{\bar{J}} + h.c. \sim \mathcal{V}^{\frac{1}{18}})$.

$D3/D7$-Branes   MD and A.Misra NPB[2012]

- $1/g^2_{j=SU(3)\ \text{or}\ SU(2)} = Re(T_B) + \mathcal{O}(F_j^2)$.
- One can self-consistently show A.Misra and P. Shukla [2010]; MD and A. Misra [2012] that near $\langle|z_{1,2}|\rangle \sim \mathcal{V}^{\frac{1}{36}} M_p$, $\langle|z_3|\rangle \sim \mathcal{V}^{\frac{1}{6}} M_p$, $\langle|a_1|\rangle \sim \mathcal{V}^{-\frac{2}{9}} M_p$, $\langle|a_2|\rangle \sim \mathcal{V}^{-\frac{1}{3}} M_p$, $\langle|a_3|\rangle \sim \mathcal{V}^{-\frac{13}{18}} M_p$, $\langle|a_4|\rangle \sim \mathcal{V}^{-\frac{11}{9}} M_p$; $\zeta^{A=1,\ldots,h^{0,2}_-(\Sigma_B|c_3)} \equiv 0$ (implying rigidity of the non-rigid Σ_B); $b^a/c^a \sim \frac{\pi}{\mathcal{O}(1)k^a(\sim\mathcal{O}(10))} M_p$, one obtains a local meta-stable dS-like minimum corresponding to the positive semi-definite potential $e^K G^{T_S\bar{T}_S}|D_{T_S}W|^2$.

Mass Scales of Supersymmetric and soft SUSY Parameters; MD and A.Misra NPB[2012]

Gravitino mass Gaugino mass Neutralino mass	$m_{\frac{3}{2}} \sim \mathcal{V}^{-\frac{n^s}{2}-1} M_P, n^s = 2$ $M_{\tilde{g}} \sim V^{\frac{2}{3}} m_{\frac{3}{2}}$ $M_{\chi_3^0} \sim V^{\frac{2}{3}} m_{\frac{3}{2}}$
$D3$-brane position moduli (Higgs) mass Wilson line moduli mass	$m_{\mathcal{Z}_i} \sim \mathcal{V}^{\frac{59}{72}} m_{\frac{3}{2}}$ $m_{\tilde{\mathcal{A}}_I} \sim \mathcal{V}^{\frac{1}{2}} m_{\frac{3}{2}}$ $I = 1, 2, 3, 4$
A-terms	$A_{pqr} \sim n^s \mathcal{V}^{\frac{37}{36}} m_{\frac{3}{2}}$ $\{p, q, r\} \in \{\tilde{\mathcal{A}}_I, \mathcal{Z}_i\}$
Physical μ-terms (Higgsino mass)	$\hat{\mu}_{\mathcal{Z}_i \mathcal{Z}_j} \sim \mathcal{V}^{\frac{37}{36}} m_{\frac{3}{2}}$
Physical $\hat{\mu}B$-terms	$(\hat{\mu}B)_{\mathcal{Z}_1 \mathcal{Z}_2} \sim \mathcal{V}^{\frac{37}{18}} m_{\frac{3}{2}}^2$

Mass scales of Standard Model Particles; MD and A.Misra NPB[2012]

- The Dirac mass term in $\mathcal{N}=1$ gauged supergravity is given by $e^{\frac{K}{2}}\mathcal{D}_i D_j W \bar{\chi}_L \chi_R$ where

$$\mathcal{D}_i D_j W = \partial_i \partial_j W + (\partial_i \partial_j K)\, W + \partial_i K D_J W + \partial_J K D_i W - (\partial_i K \partial_j K)\, W - \Gamma^k_{ij} D_k W.$$

- Considering fluctuations in $\mathcal{Z}_i : \mathcal{Z}_i \to \langle \mathcal{Z}_i \rangle + \delta\mathcal{Z}_i$, $\hat{Y}^{\rm eff}_{\delta\mathcal{Z}_i \delta\tilde{\mathcal{A}}_J \delta\tilde{\mathcal{A}}_K} \equiv \frac{\mathcal{O}(\delta\mathcal{Z}_i)-\text{term in } e^{\frac{K}{2}}\mathcal{D}_J D_K W}{\sqrt{K_{\delta\mathcal{Z}_i \delta\bar{\mathcal{Z}}_i} K_{\delta\mathcal{A}_J \delta\bar{\mathcal{A}}_J} K_{\delta\mathcal{A}_K \delta\bar{\mathcal{A}}_K}}}$; the corresponding Dirac mass will be given by $\langle \delta\mathcal{Z}_i \rangle \hat{Y}^{\rm eff}_{\delta\mathcal{Z}_i \delta\tilde{\mathcal{A}}_J \delta\tilde{\mathcal{A}}_K}$. One can show that under 1-loop RG flow, the Yukawas in our setup change by $\mathcal{O}(1)$ MD, A.Misra [2012] and that its possible that the Higgs VEV flows down to 246 *GeV* A.Misra and P.Shukla [2010].

- $e^{\frac{K}{2}}\mathcal{D}_{\mathcal{A}_1}D_{\mathcal{A}_3}W\Big|_{\mathcal{Z}_i\sim\mathcal{O}(1)\mathcal{V}^{\frac{1}{36}}}(M_s)\sim\mathcal{V}^{-\frac{4}{9}}$ implying that $246\ GeV\times\hat{Y}^{\rm eff}_{\delta\mathcal{Z}_i\delta\tilde{\mathcal{A}}_1\delta\tilde{\mathcal{A}}_3}\Big|_{\mathcal{V}\sim 10^5}\stackrel{\sim}{<}\mathcal{O}(1MeV)$
- $e^{\frac{K}{2}}\mathcal{D}_{\mathcal{A}_2}D_{\mathcal{A}_4}W\Big|_{\mathcal{Z}_i\sim\mathcal{O}(1)\mathcal{V}^{\frac{1}{36}}}(M_s)\sim\mathcal{V}^{-\frac{4}{9}}$ implying that $246\ GeV\times\hat{Y}^{\rm eff}_{\delta\mathcal{Z}_i\delta\tilde{\mathcal{A}}_2\delta\tilde{\mathcal{A}}_4}\Big|_{\mathcal{V}\sim 10^5}\stackrel{\sim}{<}\mathcal{O}(1)\sim\mathcal{O}(10)MeV$
- This suggests that possibly, the fermionic superpartners of $\mathcal{A}_1$ and $\mathcal{A}_3$ correspond respectively to e_L and e_R and the fermionic superpartners of $\mathcal{A}_2$ and $\mathcal{A}_4$ correspond respectively to the first generation u_L and u_R.

Signatures of μ-split SUSY: Light Higgs

- According to *split SUSY scenario* suggested by N.A-Hamed, S.Dimopoulos [2004], one of the finely tuned light Higgs can be produced by considering linear combination of two Higgs doublets.
- Using the similar approach, the diagonalized Higgs mass eigenstates can be represented as:

$$H_1 = D_{h_{11}} H_u + D_{h_{12}} H_d$$
$$H_2 = D_{h_{21}} H_u + D_{h_{22}} H_d.$$

$$D_h = \begin{pmatrix} \cos\frac{\theta_h}{2} & -\sin\frac{\theta_h}{2} e^{-i\phi_h} \\ \sin\frac{\theta_h}{2} e^{i\phi_h} & \cos\frac{\theta_h}{2} \end{pmatrix}, D_h^\dagger M_h^2 D_h = \mathrm{diag}(M^2_{H_1}, M^2_{H_2})$$

and $\tan\theta_h = \frac{2|M^2_{h_{21}}|}{M^2_{h_{11}} - M^2_{h_{22}}}$ for a particular range of $\frac{-\pi}{2} \leq \theta_h \leq \frac{\pi}{2}$.

- The mobile D3-brane position moduli is to be identified with soft Higgs scalar mass parameter. There is lack of universality in moduli masses but universality in trilinear A_{ijk} couplings.

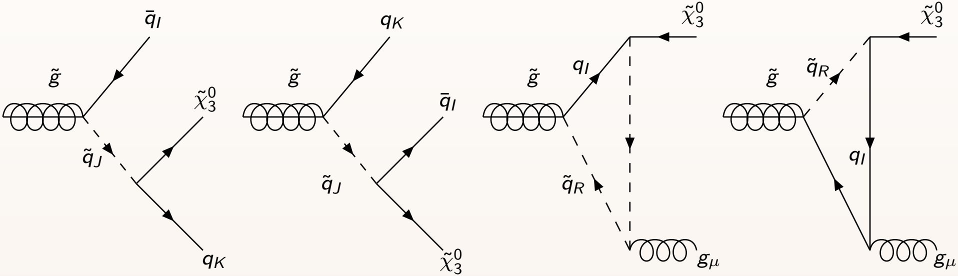
Signatures of μ-split SUSY: Light Higgs

- To get an estimate, using solution of RG flow equation for moduli masses $m^2_{\mathcal{Z}_{1,2}}$ and Higgsino mass $\hat{\mu}_{\mathcal{Z}_1\mathcal{Z}_2}$ as given in Nath, Arnowitt [1998], $A_{\mathcal{Z}_i\mathcal{Z}_i\mathcal{Z}_i} \sim n^s\hat{\mu}_{\mathcal{Z}_1\mathcal{Z}_2}$ A.Misra, P. Shukla [2009]; MD, A.Misra [2012], one-loop ln-running for the $U(1)$ gauge couplings in 2HDM/(MS)SM, assuming $\hat{\mu}B \sim \xi\hat{\mu}^2$ A. Misra,P. Shukla [2009]; MD, A.Misra [2012] (verified at M_s for $\mathcal{O}(1)\xi$) as per EW symmetry breaking, the Higgs mass matrix at the EW-scale can thus be expressed as

$$\begin{pmatrix} m^2_{H_u} & \hat{\mu}B \\ \hat{\mu}B & m^2_{H_d} \end{pmatrix} \sim \begin{pmatrix} m^2_{H_u} & \xi\hat{\mu}^2 \\ \xi\hat{\mu}^2 & m^2_{H_d} \end{pmatrix}.$$

- Assuming non-universality w.r.t. to the $D3$-brane position moduli masses $(m_{Z_{1,2}})$ and the squark/slepton masses, one obtains one light Higgs of the order $125GeV$ mass and one heavy Higgs. However, the higgsino mass parameter to be heavy with a value, at the EW scale of around $\mathcal{V}^{\frac{59}{72}}m_{3/2}$, which is indicative of μ-split SUSY scenario.

Signatures of μ-split SUSY: Long Lived Gluino; MD and A.Misra NPB [2011], MD and A.Misra NPB [2012]



Decay channels of Gluino

$$\mathcal{L}^{\mathcal{N}=1}_{\text{Wess Bagger};\textit{Jockers et al};\text{MD,A.Misra}} =$$

$$g_{YM} g_{T_B \bar{\mathcal{J}}} Tr\left(X^{T_B} \bar{\chi}^{\bar{\mathcal{J}}}_L \lambda_{\tilde{g},\ R}\right) + i g_{\mathcal{I}\bar{\mathcal{J}}} Tr\left(\bar{\chi}^{\bar{\mathcal{I}}}_L \left[\partial\!\!\!/ \chi^{\mathcal{I}}_L + \Gamma^i_{Mj} \partial\!\!\!/ a^M \chi^{\mathcal{J}}_L\right.\right.$$

$$\left.\left. + \frac{1}{4}\left(\partial_{a_M} K \partial\!\!\!/ a_M - \text{c.c.}\right)\chi^{\mathcal{I}}_L\right]\right) + \frac{e^{\frac{K}{2}}}{2}\left(\mathcal{D}_{\bar{\mathcal{I}}} D_{\mathcal{J}} \bar{W}\right) Tr\left(\chi^{\mathcal{I}}_L \chi^{\mathcal{J}}_R\right) - \frac{f_{ab}}{4} F^a_{\mu\nu} F^{b\mu\nu}$$

$$+ \frac{1}{8} f_{ab} \epsilon^{\mu\nu\rho\lambda} F^a_{\mu\nu} F^b_{\rho\lambda} + g_{T_B \bar{T}_B} Tr\left[\left(\partial_\mu T_B - A_\mu X^{T_B}\right)\left(\partial^\mu T_B - A^\mu X^{T_B}\right)^\dagger\right]$$

$$+ g_{T_B \mathcal{J}} Tr\left(X^{T_B} A_\mu \bar{\chi}^{\mathcal{J}}_L \gamma^\nu \gamma^\mu \psi_{\nu,\ R}\right) + \bar{\psi}_{L,\ \mu} \sigma^{\rho\lambda} \gamma^\mu \lambda_{\tilde{g},\ L} F_{\rho\lambda} +$$

$$+ Tr\left[\bar{\lambda}_{\tilde{g},\ L} A\!\!\!/ \left(6\kappa_4^2 \mu_7 (2\pi\alpha') Q_B K + \frac{12\kappa_4^2 \mu_7 (2\pi\alpha') Q_B v^B}{\mathcal{V}}\right)\lambda_{\tilde{g},\ L}\right]$$

$$+ \frac{e^K G^{T_B \bar{T}_B}}{\kappa_4^2} 6i\kappa_4^2 (2\pi\alpha') Tr\left[Q_B A^\mu \partial_\mu \left(\kappa_4^2 \mu_7 (2\pi\alpha')^2 C^{I\bar{J}} a_I \bar{a}_{\bar{J}}\right)\right] + \text{h.c.}$$

$$- \frac{i\sqrt{2}}{4} g \partial_{i/I} f_{ab} Tr\left(\frac{12\kappa_4^2 \mu_7 (2\pi\alpha') Q^a_B v^B}{\mathcal{V}} \bar{\lambda}^b_{\tilde{g},L} \chi^{i/I}_R\right) + \text{h.c.}$$

$$- \frac{\sqrt{2}}{4} \partial_{i/I} f_{ab} Tr\left(\bar{\lambda}^a_{\tilde{g},R} \sigma^{\mu\nu} \chi^{i/I}_L\right) F^b_{\mu\nu} + \bar{\psi}_{L,\ \mu} \sigma^{\rho\lambda} \gamma^\mu \lambda_{\tilde{g},\ L} W^+_\rho W^-_\lambda + \text{h.c.}.$$

Signatures of μ-split SUSY: Long Lived Gluino; MD, A.Misra [2012]

- From the neutralino mass matrix, one obtains the lightest neutralino: $\chi_3^0 \sim -\lambda_g + \tilde{f}\mathcal{V}^{\frac{5}{6}} \frac{v}{M_p}(\tilde{H}_1 + \tilde{H}_2)$ with a mass $\sim V^{\frac{2}{3}} m_{\frac{3}{2}}$
- In case of Gluino decaying into goldstino, $\mathcal{N} = 1$ gauged supergravity lagrangian is given by: J. Wess, J. Bagger [1992]:
  $\mathcal{L} = -g_{I\bar{J}} \left(\partial_\mu \bar{a}^{\bar{J}}\right) \chi^I \sigma^\nu \bar{\sigma}_\mu \psi_\nu - \frac{i}{2} e^{\frac{K}{2}} \left(D_I W\right) \chi^I \sigma^\mu \bar{\psi}_\mu + \text{h.c.}$
- The gravitino field can be decomposed into the spin-$\frac{1}{2}$ Goldstino field $\tilde{G}$ via: S.M. Carroll et al. [1994]
  $\psi_\nu = \rho_\nu + \sigma_\nu \tilde{G}, \; \tilde{G} = -\frac{1}{3}\sigma^\mu \psi_\mu$
- The goldstino-content, is given by:
  $2g_{I\bar{J}} \left(\partial_\mu \bar{a}^{\bar{J}}\right) \chi^I \bar{\sigma}^\mu \tilde{G} + \frac{3i}{2} e^{\frac{K}{2}} \left(D_I W\right) \chi^I \tilde{G} + \text{h.c.}$
- *Life time of various Gluino decay channels:*

Decay Modes	Life Time
$\tilde{g} \to \chi_{\mathrm{n}}^{o} q_I \bar{q}_J$	$10s$
$\tilde{g} \to \tilde{\chi}_3^0 g$	$10^{10}s$
$\tilde{g} \to \psi_\mu q_I \bar{q}_J$	$10^3 s$
$\tilde{g} \to \psi_\mu g$	$10^{-1}s$

Gravitino- Lightest Supersymmetric particle

After calculating the masses of various SM and their superpartners, it appears that gravitino is the Lightest Supersymmetric Particle (LSP) which for $\mathcal{V} \sim 10^5$, NLSP=slepton/squark or neutralino, motivates the query: can we have Gravitino as a viable CDM candidate?

Thermal/non-thermal Production of Gravitino

- Gravitino(M_P-suppressed interactions)- decouple from thermal plasma very early in the universe- might overclose the universe(famous 'cosmological gravitino problem').
- The problem gets resolved because abundance get diluted as universe experiences through inflationary phase.
- Recreate in the reheating phase after inflation by inelastic $2 \rightarrow 2$ scattering and $1 \rightarrow 2$ decay processes of particles from the thermal bath - abundance goes linear in the T_R(reheating temperature).
- In string/M-theory inspired models, this standard way of production of Dark Matter (DM) particles significantly alters because decay of modulus increases the entropy, therefore decrease in relic abundance of gravitino, see Acharya et al. [2010].
- Sizable amount of gravitino's can be produced by (non-thermal) production of gravitinos LSP formed by decays of moduli and can dominate the thermal production of gravitinos in the early plasma, discussed in [Kawasaki et al. [1996], Watson [2009], Dutta et al. [2009], Acharya et al. [2009], Allahverdi et al. [2013]].

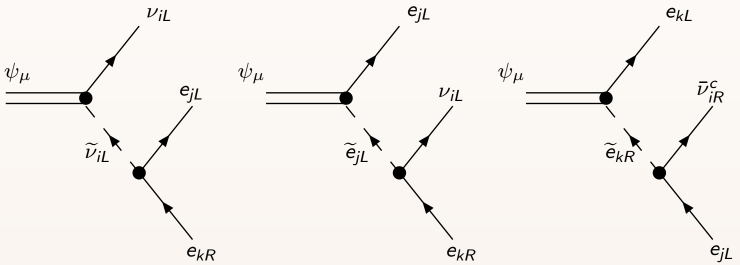
Conditions for Considering Gravitino as a Viable DM Candidate

1. Life time of gravitino should be of the order of age of Universe (around 10^{17} sec).
2. Life time of Co-(NLSP)'s decay into gravitino's should be less than the time period for onset of B(ig)-B(ang) N(ucleosynthesis) era so that energy produced by hadronic/electromagnetic decay does not spoil the bounds given by BBN.
3. Life time for direct decay of Co-(NLSP)'s into ordinary Standard model particles should be more than decay of Co-(NLSP)'s into LSP.
4. Relic abundance of gravitino should always be around 0.1 so that it does not overclose the universe.

Gravitino- Lightest Supersymmetric Particle; MD and A.Misra NPB [2012]

$$W_{\not R_p} = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} U^c_i D^c_j D^c_k + \mu_i H L_i.$$

Decays involving λ_{ijk} coupling

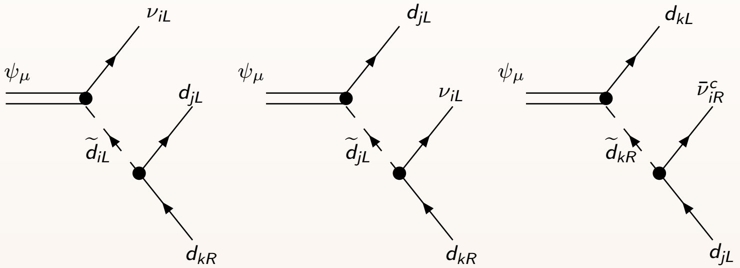


The coefficients of relevant interaction vertices are:

$$C^{\tilde{\nu}_L d_{jL} d_{kR}} = C^{\tilde{d}_{jL} \nu_{iL} d_{kR}} = C^{\tilde{d}_{kR} \bar{\nu}^c_{iR} d_{jL}} \equiv \mathcal{V}^{-\frac{5}{3}}.$$

Gravitino- Lightest Supersymmetric Particle; MD and A.Misra NPB [2012]

Decays involving λ'_{ijk} coupling

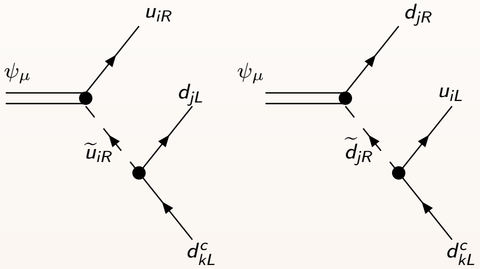


The coefficients of relevant interaction vertices are:

$$C^{\tilde{e}_{jL}\nu_{iL}e_{kR}} = C^{\tilde{\nu}_{iL}e_{jL}e_{kR}} = C^{\tilde{e}_{kR}\bar{\nu}^c_{iL}e_{jL}} \equiv \mathcal{V}^{-\frac{7}{4}}.$$

Gravitino- Lightest Supersymmetric Particle; MD and A.Misra NPB [2012]

Decays involving λ''_{ijk} coupling

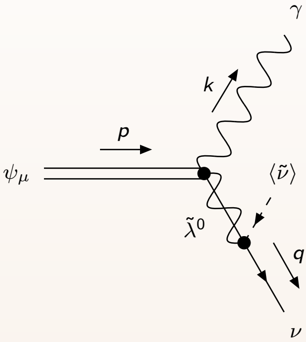


The coefficients of relevant interaction vertices are:

$$C^{\tilde{u}_{iR} d_{jR} d^c_{kL}} = C^{\tilde{d}_{jR} d^c_{kL} u_{iR}} \equiv \mathcal{V}^{-\frac{43}{30}}.$$

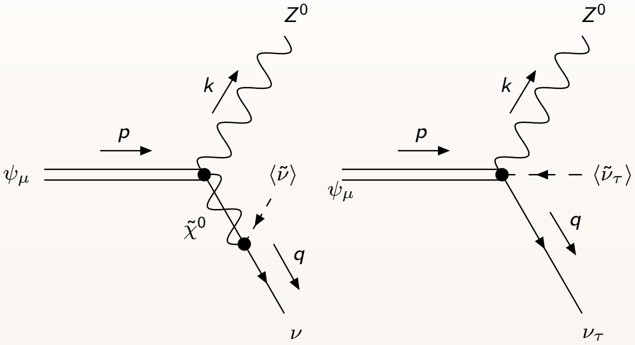
Gravitino- Lightest Supersymmetric Particle; MD and A.Misra NPB [2012]

Gravitino two-body decay



Gravitino- Lightest Supersymmetric Particle; MD and A.Misra NPB [2012]

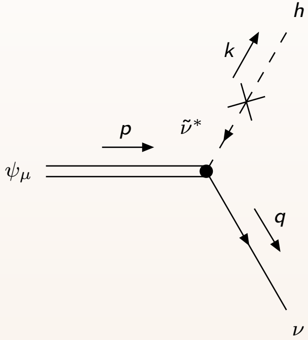
Gravitino two-body decay

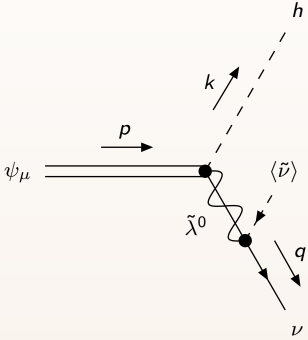


Two-body gravitino decay: $\psi_\mu \to Z^0 + \nu$

Gravitino- Lightest Supersymmetric Particle; MD and A.Misra NPB [2012]

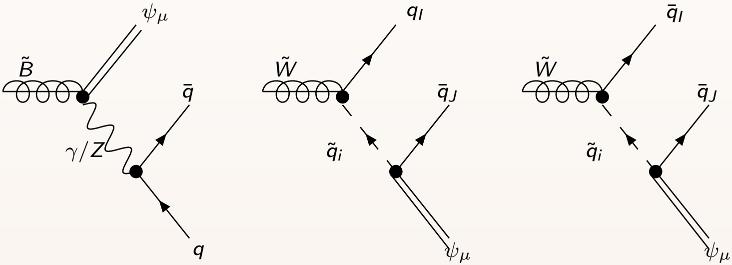
Gravitino two-body decay





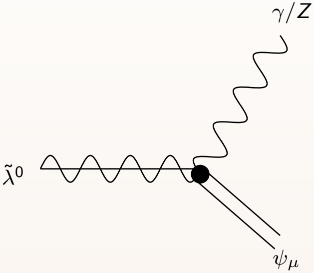
NLSP decay; MD and A.Misra NPB [2012]

Gaugino three-body decay



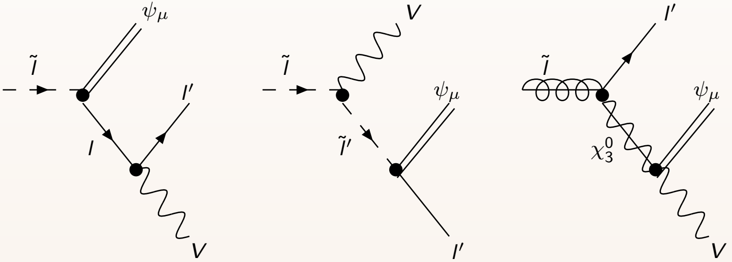
NLSP decay; MD and A.Misra NPB [2012]

Gaugino two-body decay



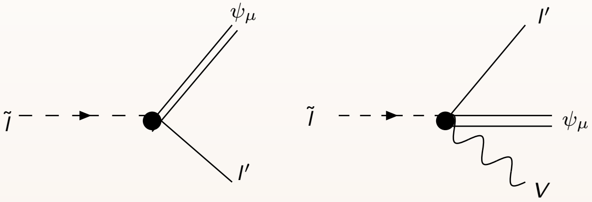
Co-NLSP decay; MD and A.Misra NPB [2012]

Slepton three-body decay



Co-NLSP decay; MD and A.Misra NPB [2012]

Slepton two-body decay



Life time estimates of Various N(LSP) Decay Channels; MD and A.Misra NPB [2012]

Particle decay	Decay Modes	Life Time	Remarks
Neutralino/Gaugino decays	$\tilde{B} \rightarrow \psi_\mu Z/\gamma$	$10^{-30}s$	Obey BBN constarints
	$\tilde{W} \xrightarrow[Z]{\tilde{q}} \psi_\mu u\bar{u}$	$10^{-25}s$	
	$\tilde{B} \xrightarrow{Z} \psi_\mu u\bar{u}$	$10^{-13}s$	
Slepton decays	$\tilde{l} \rightarrow l'\tilde{G}V$	$10^{-28}s$	"
	$\tilde{l}/\tilde{q} \rightarrow l/q\psi_\mu$	$10^{-25.5}s$	
RPV Neutralino decay	$\chi_3^0 \rightarrow u\bar{d}e^-$	$10^{1}s$	does not effect gravitino abundance
Gravitino decays	$\psi_\mu \rightarrow \nu\gamma, \nu Z$	$10^{21}s$	Life time greater than age of Universe
	$\psi_\mu \rightarrow h\nu_e$	$10^{17}s$	
	$\psi_\mu \rightarrow l_i l_j e^c_k$	$10^{21}s$	
	$\psi_\mu \rightarrow l_i q_j d^c_k$	$10^{20}s$	
	$\psi_\mu \rightarrow u^c_i d^c_j d^c_k$	$10^{18}s$	

Relic Abundance of Gravitino; MD and A.Misra NPB [2012]

- If gravitino(LSP) produced by decay of Co-NLSP's is to account for all the gravitinos, the relic abundance of gravitino is given as $\Omega_{\tilde{G}}h^2 = \Omega_{\chi_3^0}h^2 \times \frac{m_{\frac{3}{2}}}{m_{\chi_3^0}}$.
- Evaluation of Relic density depends sensitively on the annihilation cross section ($\sigma v_{\text{Møl}}$) of such particles. To get the idea of same, we have calculated annihilation cross-section of all important channels: $\chi_3^0\chi_3^0 \to hh$, $\chi_3^0\chi_3^0 \to ZZ$, $\chi_3^0\chi_3^0 \to ff$ in case of neutralino annihilation and ($\widetilde{\ell}_a\widetilde{\ell}_b^* \to ZZ$, $\widetilde{\ell}_a\widetilde{\ell}_b^* \to Zh$,$\widetilde{\ell}_a\widetilde{\ell}_b^* \to hh$, $\widetilde{\ell}_a\widetilde{\ell}_b^* \to \gamma\gamma$, $\widetilde{\ell}_a\widetilde{\ell}_b^* \to \gamma h$, $\widetilde{\ell}_a\widetilde{\ell}_b^* \to ll$) in case of slepton annihilation.
- for $m_{\frac{3}{2}} \sim \mathcal{V}^{-2}m_{pl}$, $m_{\chi_3^0} \sim \mathcal{V}^{\frac{2}{3}}m_{\frac{3}{2}}$ and $m_{\tilde{\ell}_a} \sim \mathcal{V}^{\frac{1}{2}}m_{\frac{3}{2}}$, from sleptons (NLSP), $\Omega_{\tilde{G}} = \Omega_{\tilde{\ell}_a} \times \frac{m_{\frac{3}{2}}}{m_{\tilde{\ell}_a}} \sim 10^{-22}$ for $\mathcal{V} \sim 10^5$ and from Neutralino (NLSP), $\Omega_{\tilde{G}} = \Omega_{\chi_3^0} \times \frac{m_{\frac{3}{2}}}{m_{\chi_3^0}} \sim 0.1$ (in accordance with WMAP data and other experimental predictions).

EDM at One-Loop Level

- The e(lectric) d(ipole) m(oment) of a spin-$\frac{1}{2}$ particle is defined by the effective CP-violating dimension-5 operator given as:

$$\mathcal{L}_I = -\frac{i}{2} d_f \bar{\psi} \sigma_{\mu\nu} \gamma_5 \psi F^{\mu\nu}$$

- Negligible one-loop contributions to EDM (super heavy scalar mass in the loop) in typical split-SUSY models. However, the value may be of reasonable order if fermions are also heavy.
- The non-zero CP violating phases appear from complex effective Yukawa coupling and slepton/Higgs mixing mass matrix.
- An overall distinct phase factor for each possible effective Yukawa coupling corresponding to four Wilson line moduli as well as position moduli. We assume the same to be $\mathcal{O}(1)$.

- The Lagrangian involving effective fermion-sfermion-fermion interactions is:

$$\mathcal{L} = C_{f_L \tilde{f}^*_L \lambda^0_i} f_L \tilde{f}_L \tilde{\lambda}^0 + C_{f_L \tilde{f}^*_R \lambda^0_i} f_L \tilde{f}_R \tilde{\lambda}^0 + C_{f^*_R \tilde{f}_L \lambda^0_i} f_R \tilde{f}_L \tilde{\lambda}^0 + C_{f^*_R \tilde{f}_R \lambda^0_i} f_R \tilde{f}_R \tilde{\lambda}^0$$

In terms of diagonalized basis $\tilde{f}_1$ and $\tilde{f}_2$,

$$\mathcal{L}_{int} = \bar{\chi}_f \left((C_{\lambda^0_i f_L \tilde{f}_L} D_{f_{11}} + C_{\lambda^0_i f_L \tilde{f}_R} D_{f_{21}}) \frac{1+\gamma_5}{2} + (C_{\lambda^0_i f_R \tilde{f}_L} D_{f_{11}} + C_{\lambda^0_i f_R \tilde{f}_R} D_{f_{21}}) \frac{1-\gamma_5}{2} \right) \phi_{f_1} \tilde{\lambda}^0 +$$
$$\bar{\chi}_f \left((C_{\lambda^0_i f_L \tilde{f}_L} D_{f_{12}} + C^{\chi^0_i f_L \tilde{f}_R} D_{f_{22}}) \frac{1+\gamma_5}{2} + (C_{\lambda^0_i f_R \tilde{f}_L} D_{f_{12}} + C^{\lambda^0_i f_R \tilde{f}_R} D_{f_{22}}) \frac{1-\gamma_5}{2} \right) \phi_{f_2} \tilde{\lambda}^0 + H.c..$$

- The results of fermion-sfermion-gaugino vertices are:

$$|C_{e_L \tilde{e}^*_L \lambda^0_i}| \equiv \tilde{f} \mathcal{V}^{-1}, |C_{e_R \tilde{e}^*_R \lambda^0_i}| \equiv \tilde{f} \mathcal{V}^{-\frac{3}{5}},$$
$$|C_{e^*_R \tilde{e}_L \lambda^0_i}| \equiv |C_{e^*_L \tilde{e}_R \lambda^0_i}| \equiv \tilde{f} \mathcal{V}^{-\frac{15}{9}}, |C_{u_L \tilde{u}^*_L \lambda^0_i}| \equiv \tilde{f} \mathcal{V}^{-\frac{4}{5}},$$
$$|C_{u_R \tilde{u}^*_R \lambda^0_i}| \equiv \tilde{f} \mathcal{V}^{-\frac{3}{5}}, |C_{u^*_R \tilde{u}_L \lambda^0_i}| \equiv |C_{u^*_L \tilde{u}_R \lambda^0_i}| \equiv \tilde{f} \mathcal{V}^{-\frac{14}{9}}$$

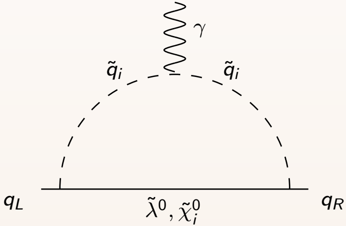


diagram involving gaugino's/neutralino
Ibrahim, Nath [1997]

- The (e/n)EDM expression takes the form:

$$\frac{d_f}{e}|_{\lambda_i^0} = \frac{m_{\tilde{\lambda}_i^0}}{(4\pi)^2}\left[\frac{1}{m^2_{\tilde{f}_1}}\mathrm{Im}\left(C_{\lambda_i^0 f_L \tilde{f}_L} C_{\lambda_i^0 f_R \tilde{f}_R} D_{f_{11}} D^*_{f_{21}} + C_{\lambda_i^0 f_L \tilde{f}_R} C_{\chi_i^0 f_R \tilde{f}_L} D_{f_{21}} D^*_{f_{11}}\right) Q'_{\tilde{f}_1} B\left(\frac{m^2_{\tilde{\lambda}_i^0}}{m_{\tilde{f}_1^2}}\right) + \frac{1}{m^2_{\tilde{f}_2}}\mathrm{Im}\left(C_{\lambda_i^0 f_L \tilde{f}_L} C_{\chi_i^0 f_R \tilde{f}_R} D_{f_{12}} D^*_{f_{22}} + C_{\lambda_i^0 f_L \tilde{f}_R} C_{\lambda_i^0 f_R \tilde{f}_L} D_{f_{22}} D^*_{f_{12}}\right) Q'_{\tilde{f}_2} B\left(\frac{m^2_{\tilde{\lambda}_i^0}}{m_{\tilde{f}_2^2}}\right)\right]$$

- The contribution of neutralino-lepton-slepton vertices are:

$$|C_{\chi_1^0 e_L \tilde{e}_L}| = |C_{\chi_2^0 e_L \tilde{e}_L}| \equiv \mathcal{V}^{-\frac{3}{2}}, |C_{\chi_3^0 e_L \tilde{e}_L}| \equiv \tilde{f}\mathcal{V}^{-1} |C_{\chi_1^0 e_L \tilde{e}_R}| = |C_{\chi_2^0 e_L \tilde{e}_R}| \equiv \mathcal{V}^{-\frac{9}{5}}, |C_{\chi_3^0 e_L \tilde{e}_R}| \equiv \tilde{f}\mathcal{V}^{-\frac{15}{9}},$$
$$|C_{\chi_1^0 e_R \tilde{e}_L}| = |C_{\chi_2^0 e_R \tilde{e}_L}| \equiv \mathcal{V}^{-\frac{9}{5}}, |C_{\chi_3^0 e_R \tilde{e}_L}| \equiv \tilde{f}\mathcal{V}^{-\frac{15}{9}}, |C_{\chi_1^0 e_R \tilde{e}_R}| = |C_{\chi_2^0 e_R \tilde{e}_R}| \equiv \mathcal{V}^{-\frac{10}{9}}, |C_{\chi_3^0 e_R \tilde{e}_R}| \equiv \tilde{f}\mathcal{V}^{-\frac{3}{5}}$$

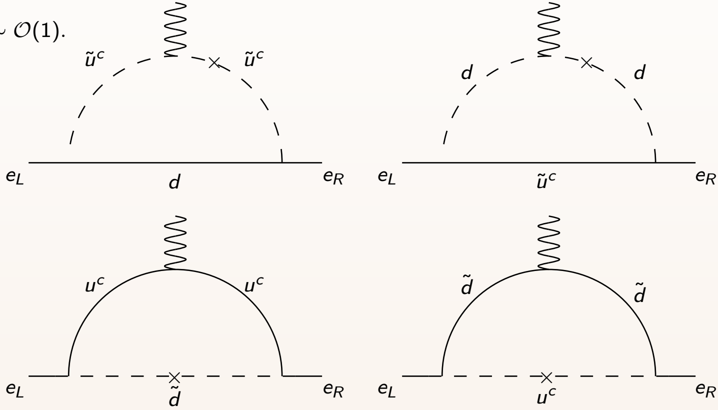
- The contribution of neutralino-quark-squark vertices are:

$$|C_{\chi_1^0 u_L \tilde{u}_L}| = |C_{\chi_2^0 u_L \tilde{u}_L}| \equiv \mathcal{V}^{-\frac{4}{5}}, |C_{\chi_3^0 u_L \tilde{u}_L}| \equiv \tilde{f}\mathcal{V}^{-\frac{4}{5}}, |C_{\chi_1^0 u_L \tilde{u}_R}| = |C_{\chi_2^0 u_L \tilde{u}_R}| \equiv \mathcal{V}^{-\frac{5}{3}}, |C_{\chi_3^0 u_L \tilde{u}_R}| \equiv \tilde{f}\mathcal{V}^{-\frac{14}{9}},$$
$$|C_{\chi_1^0 u_R \tilde{u}_L}| = |C_{\chi_2^0 u_R \tilde{u}_L}| \equiv \mathcal{V}^{-\frac{5}{3}}, |C_{\chi_3^0 u_R \tilde{u}_L}| \equiv \tilde{f}\mathcal{V}^{-\frac{14}{9}}, |C_{\chi_1^0 u_R \tilde{u}_R}| = |C_{\chi_2^0 u_R \tilde{u}_R}| \equiv \mathcal{V}^{-\frac{10}{9}}, |C_{\chi_3^0 u_R \tilde{u}_R}| \equiv \tilde{f}\mathcal{V}^{-\frac{3}{5}}$$

- The coefficient of $R_{\not p}$ interaction vertices are:

$$C_{e_L \tilde{u}^c_R d_L} = C_{e_L \tilde{d} u^c_R} = C_{u_L \tilde{e}^c_R d_L} = C_{u_L \tilde{d}_L e^c_R} \equiv \mathcal{V}^{\frac{5}{3}} e^{i\phi_{y_\alpha}}.$$

- We show $C_{ff^*\gamma}|_{\mathrm{EW}} \sim \mathcal{O}(1)$.



$R\!\!\!/_p$ diagrams- Franck, Hamidian [1997]

One-loop diagram involving Higgs; MD and A.Misra [2013]

- The non-zero complex phases are generated from eigenstates of Higgs mass matrix and effective Yukawa couplings.
- The coefficients of Yukawa interactions are:,

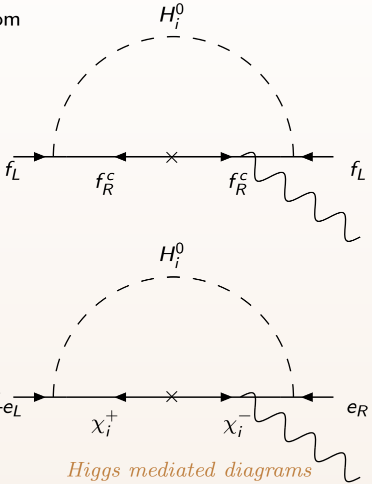
$$\text{for } f = e,\ C_{e_L^* e_R H_u/H_d} = \hat{Y}^{\rm eff}_{\mathcal{Z}_I \mathcal{A}_1 \mathcal{A}_3} \equiv \mathcal{V}^{-\frac{47}{45}} e^{i\phi_{\mathcal{Y}_e}}$$

$$\text{for } f = u,\ C_{u_L^* u_R H_u/H_d} = \hat{Y}^{\rm eff}_{\mathcal{Z}_I \mathcal{A}_2 \mathcal{A}_4} \equiv \mathcal{V}^{-\frac{19}{18}} e^{i\phi_{\mathcal{Y}_u}}.$$

- The coefficients of chargino interactions are:,

$$|C_{e_L^* \chi_1^+ H_u^0/H_d^0}| \equiv \mathcal{V}^{-\frac{1}{10}}, |C_{e_L^* \chi_2^+ H_u^0/H_d^0}| \equiv \mathcal{V}^{\frac{1}{10}};$$

$$|C_{e_R^* \chi_1^- H_u^0/H_d^0}| \equiv \tilde{f}\mathcal{V}^{-\frac{3}{2}}, |C_{e_R^* \chi_2^- H_u^0/H_d^0}| \equiv \tilde{f}\mathcal{V}^{-\frac{15}{9}} \frac{< \mathcal{Z}_i >}{M_p}$$



Higgs mediated diagrams

One-loop diagrams involving gravitino; MD and A.Misra [2013]

- The contribution of relevant gravitino interactions:

$$|C_{e_L\tilde{e}_L\tilde{\gamma}}| \equiv \tilde{f}\mathcal{V}^{-1}, |C_{\tilde{G}e_L\tilde{e}_L\gamma}| \equiv \tilde{f}\mathcal{V}^{-\frac{5}{3}}$$

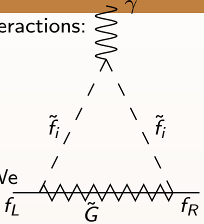
$$|C_{\tilde{G}u_L\tilde{u}_L\gamma}| \equiv \tilde{f}\mathcal{V}^{-\frac{5}{3}}, |C_{u_L\tilde{u}_L\tilde{\gamma}}| \equiv \tilde{f}\mathcal{V}^{-\frac{4}{5}}.$$

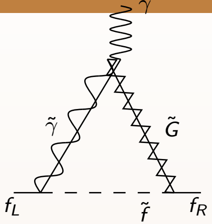
- Diagrams are logarithmically divergent. We use results of Mèndez, Orteu [1985] to calculate magnetic moment of muon in the context of spontaneously broken minimal $\mathcal{N}=1$ gSUGRA.

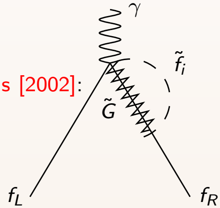
- Using relation between d_f and a_μ, Graesser,Thomas [2002]:

$$a_f = \frac{2|m_f|}{eQ_f}|d_f|\cos\phi$$

m_f, Q_f- mass, charge of fermion; $\phi \equiv \mathrm{Arg}(d_f m_f^*)$. Assuming$\phi_{d_f} \ni (0, \frac{\pi}{2}]$, $\phi_{d_f} \neq \phi_{y_e/y_u}(\phi_{m_f^*})$; we consider $\phi \ni (0, \frac{\pi}{2}] \sim \mathcal{O}(1)$.







One-loop diagrams involving gravitino
Mèndez, Orteu [1985]

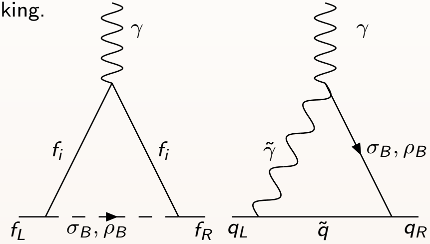
One-loop Diagrams involving Sgoldstino; MD and A.Misra [2013]

- sgoldstino- bosonic component of the superfield corresponding to which there is an F-term (D-term) supersymmetry breaking.
- *Mass of sgoldstino*: At the EW scale,

$$V(n_s=2)|_{EW} \sim e^K K^{\tau_S \bar{\tau}_B} D_{\tau_S} W D_{\bar{\tau}_B} \bar{W} + e^K K^{\tau_B \bar{\tau}_B} |D_{\tau_B} W|^2.$$

Near $\langle \sigma_S \rangle \sim \frac{ln\mathcal{V}}{(\mathcal{O}(1))^4_{\sigma_S}}, \langle \sigma_B \rangle \sim \frac{\mathcal{V}^{\frac{2}{3}}}{(\mathcal{O}(1)_{\sigma_B})^4},$

$$m_{\tau_B} \sim \sqrt{\frac{\left(\frac{\partial^2 V}{\partial \sigma_B^2}\right)_{EW}}{\kappa_4^2 \mu_7 K_{EW}^{\tau_B \bar{\tau}_B}}} \sim \mathcal{O}(1) m_{3/2}.$$



Diagrams involving sgoldstino $\tau_B = \sigma_B + i\rho_B$
Brignole, Perazzi, Zwirner[1999]

- The coefficients of relevant interaction vertices are:

$$|C_{\delta\sigma_B e_L e_R^c}| \equiv \mathcal{V}^{-\frac{92}{15}}, |C_{\delta\sigma_B u_L u_R^c}| \equiv \mathcal{V}^{-\frac{33}{5}}, |C_{\gamma\gamma\delta\sigma_B}| \equiv \frac{\mathcal{V}^{-\frac{2}{3}}}{M_p}, \text{for } \mathcal{V} \sim 10^5.$$

Results of EDM of Electron and Neutron; MD and A.Misra [2013]

Results of all one-loop diagrams contributing to EDM of electron/neutron

One-loop particle exchange	origin of complex phase	d_e(e cm)	d_n(e cm)
$\lambda^0\tilde{f}$	diagonalized sfermion mass eigenstates	10^{-39}	10^{-38}
$\chi_i^0\tilde{f}$	"	10^{-37}	10^{-34}
$f\tilde{f}$	"	10^{-40}	10^{-40}
fh_i^0	digonalized Higgs mass eigenstates	10^{-34}	10^{-33}
$\chi^{\pm}h_i^0$	"	10^{-32}	—
gravitino ($\tilde{G}$)	diagonalized sfermion mass eigenstates	10^{-57}	10^{-57}
sgoldstino (τ_B)	diagonalized sfermion mass eigenstates	10^{-72}	10^{-68}

Barr-Zee Diagrams involving Internal Fermionic Loop; MD and A.Misra [2013]

- CP-violating effects -demonstarted by complex effective Yukawa couplings.
- SM-like Yukawa couplings:

$$\hat{Y}_{h_i^0 e_L e_R^c} \sim \hat{Y}^{\rm eff}_{\mathcal{Z}_i \mathcal{A}_1 \mathcal{A}_3} \equiv \mathcal{V}^{-\frac{47}{45}} e^{i\phi_{y_e}};$$

$$\hat{Y}_{h_i^0 u_L u_R^c} \sim \hat{Y}^{\rm eff}_{\mathcal{Z}_i \mathcal{A}_2 \mathcal{A}_4} \equiv \mathcal{V}^{-\frac{17}{18}} e^{i\phi_{y_u}}.$$

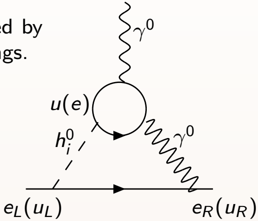
- Chargino interaction vertices:

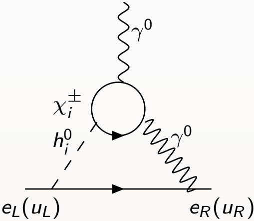
$$C_{\chi_i^+ \chi_1^- h_i^0} \equiv \mathcal{V}^{\frac{1}{4}} e^{i\phi_{\chi_1}}, \; C_{\chi_2^+ \chi_2^- h_i^0} \equiv \mathcal{V}^{\frac{13}{36}} \frac{m_e}{M_p} e^{i\phi_{\lambda_1^0}},$$

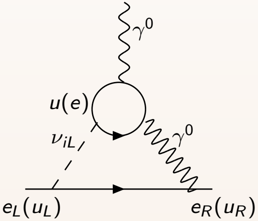
$$|C_{\chi_1^+ \chi_1^- \gamma}| \equiv |\tilde{f}\mathcal{V}^{-\frac{5}{18}}; |C_{\chi_2^+ \chi_2^- \gamma}| \equiv \tilde{f}\mathcal{V}^{-\frac{11}{18}}.$$

- $R\!\!\!/_P$- couplings:

$$\tilde{\lambda}_{\tilde{\nu}_L e_L e_R^c} \equiv \mathcal{V}^{-\frac{5}{3}} e^{i\phi_{\lambda_e}}, \; \tilde{\lambda}_{\tilde{\nu}_L u_L u_R^c} \equiv \mathcal{V}^{-\frac{5}{3}} e^{i\phi_{\lambda_u}}.$$







Pilaftsis [1999], Yamanaka [2012]

Barr-Zee Diagrams involving Internal Sfermion Loop; MD and A.Misra [2013]

- Complex effective trilinear interactions:

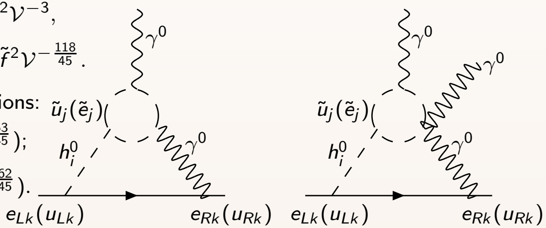
$$C_{\tilde{e}_R\tilde{e}^*_R h^0_i} \equiv (\mathcal{V}^{-2}M_p)e^{i\phi_{\tilde{e}_R}}, C_{\tilde{e}_L\tilde{e}^*_L h^0_i} \equiv (\mathcal{V}^{-\frac{12}{5}}M_p)e^{i\phi_{\tilde{e}_L}},$$
$$C_{\tilde{u}_R\tilde{u}^*_R h^0_i} \equiv (\mathcal{V}^{-2}M_p)e^{i\phi_{\tilde{u}_R}}, C_{\tilde{u}_L\tilde{u}^*_L h^0_i} \equiv (\mathcal{V}^{-\frac{20}{9}}M_p)e^{i\phi_{\tilde{u}_R}}.$$

- Real effective quartic interactions:,

$$C_{\tilde{e}_R\tilde{e}^*_R\gamma\gamma} \equiv \tilde{f}^2\mathcal{V}^{-\frac{13}{5}}, C_{\tilde{e}_L\tilde{e}^*_L\gamma\gamma} \equiv \tilde{f}^2\mathcal{V}^{-3},$$
$$C_{\tilde{u}_L\tilde{u}^*_L\gamma\gamma} \equiv \tilde{f}^2\mathcal{V}^{-\frac{127}{45}}, C_{\tilde{u}_R\tilde{u}^*_R\gamma\gamma} \equiv \tilde{f}^2\mathcal{V}^{-\frac{118}{45}}.$$

- Real effective trilinear interactions:

$$C_{\tilde{e}_L\tilde{e}^*_L\gamma} \equiv (\tilde{f}\mathcal{V}^{\frac{44}{45}}), C_{\tilde{e}_R\tilde{e}^*_R\gamma} \equiv (\tilde{f}\mathcal{V}^{\frac{53}{45}});$$
$$C_{\tilde{u}_L\tilde{u}^*_L\gamma} \equiv (\tilde{f}\mathcal{V}^{\frac{53}{45}}), C_{\tilde{u}_R\tilde{u}^*_R\gamma} \equiv (\tilde{f}\mathcal{V}^{\frac{62}{45}}).$$



Yamanaka [2012]

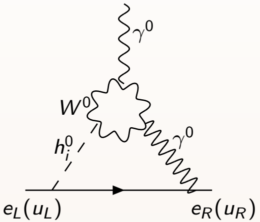
Two-loop Diagram involving W Boson in Internal Loop; MD and A.Misra [2013]

- In the μ split-SUSY model, neutral Higgs are defined as:

$$h_1 = D_{h_{11}} h_u + D_{h_{12}} h_d$$
$$h_2 = D_{h_{21}} h_u + D_{h_{22}} h_d.$$

where

$$D_h = \begin{pmatrix} \cos\frac{\theta_h}{2} & -\sin\frac{\theta_h}{2} e^{-i\phi_h} \\ \sin\frac{\theta_h}{2} e^{i\phi_h} & \cos\frac{\theta_h}{2} \end{pmatrix},$$



Leigh, Paban, Xu [1986]

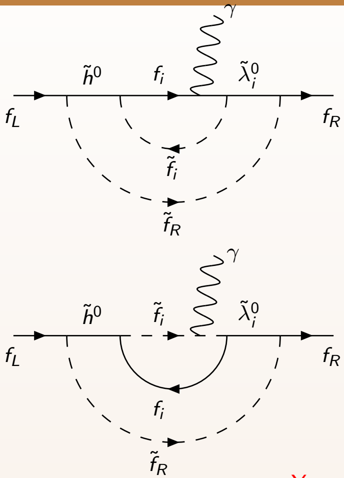
- In the notations of Weinberg, the CP-violating phase appears from the neutral-Higgs-boson exchange and Higgs propagators are represented as:

$$A(q^2) = \sqrt{2} G_f \sum_n \frac{Z_n}{q^2 + m_{H_n}^2}$$

- We show, using gauged supergravity action:

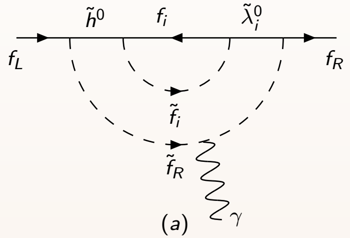
$$C_{W^+W^-\gamma} \equiv \mathcal{V}^{\frac{1}{18}} \equiv \mathcal{O}(1),\, C_{W^+H_i^0W^-} \equiv \frac{M_W^2}{v} e^{i\phi_W}.$$

Two-loop Level Rainbow Type Diagrams; MD and A.Misra [2013]



Yamanaka [2012]

Two-loop Level Rainbow Type Diagrams; MD and A.Misra [2013]



Yamanaka [2012]

Results of EDM of Electron and Neutron; MD and A.Misra [2013]

Results of all two-loop diagrams contributing to EDM of electron/neutron

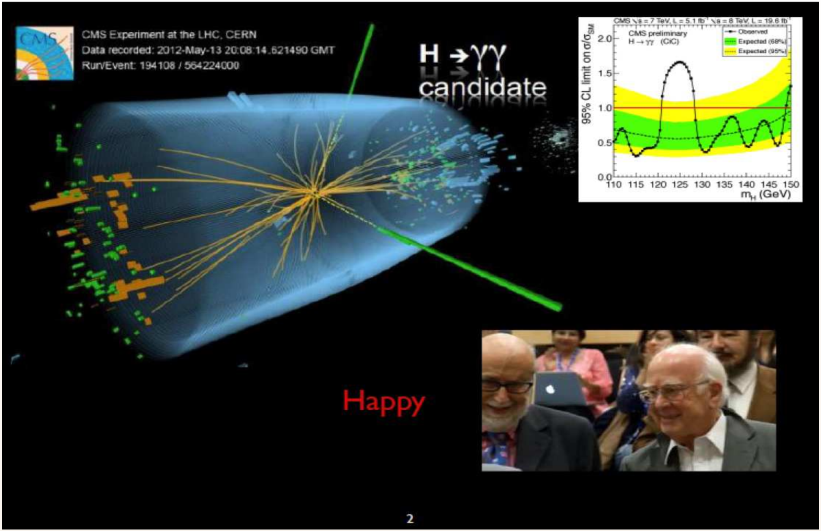
Two-loop particle exchange exchange	origin of complex phase	d_e(e cm)	d_n(e cm)
$h_i^0\gamma f$	Complex effective Yukawa couplings	10^{-36}	10^{-36}
$h_i^0\gamma\chi_i^\pm$	"	10^{-47}	10^{-47}
$\tilde{f} f\gamma$	"	10^{-70}	10^{-70}
$\tilde{f}_i^0 h_i^0\gamma$	"	10^{-29}	10^{-29}
$\gamma W^\pm h_i^0$	Higgs exchange	10^{-27}	10^{-27}
$\tilde{h}^0\tilde{f}\lambda_i^0$(Rainbow type)	diagonalized sfermion mass eigenstates and effective Yukawa's	10^{-55}	10^{-54}
$\nu^0\tilde{f}\lambda_i^0$ (Rainbow type)	"	10^{-52}	10^{-52}

Conclusions and Future Directions:

- Possibility of realizing big-divisor $D3/D7$ μ-Split Supersymmetry (light fermions, heavy sleptons/squarks, one light ($125GeV$) and one heavy Higgs, heavy Higgsino, relatively long-lived gluinos), sleptons/squarks, neutralino/gauginos (with $\mathcal{O}(1)$ mass difference for $\mathcal{V} \sim 10^5$) as the co-NLSPs.
- Gravitino (LSP) as a viable DM candidate.
- Provide a "Healthy" EDM up to two-loop levels (interesting testing ground for split SUSY).

Future Plans:

- Order of magnitude estimate of magnetic moment(a_μ) of muon.
- Estimate of number density of gravitino produced by direct geometric (hidden) moduli decay.
- Explore possibility of baryogenesis by direct decay of geometric (hidden) and visible sector moduli.


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H → γγ
candidate
CMS preliminary
H → γγ (CiC)
Observed
Expected (68%)
Expected (95%)
95% CL limit on σ/σ_SM
m_H (GeV)
110 115 120 125 130 135 140 145 150
0.0 0.5 1.0 1.5 2.0
Happy
2

Thanks for Your Kind Attention !

Back-Up slides

Caveats/Assumptions/limitations

- We have not considered the explicit stabilization of the complex structure moduli - we assume they can be independent of the stabilization of the matter moduli and bulk Kaehler moduli. This is the general assumption in KKLT and LVS models.
- 2. The complete superpotential is the sum of the Gukov-Witten-Vafa complex-structure-moduli-valued contribution and the ED3-instanton/gaugino condensate contribution (generically). Now, we assume the former is cancelled by the ED3-instanton-number-equal-to one ED3-instanton-valued non-perturbative superpotential contribution, and that the requirement of staying within the Kaehler cone for the divisors contributing to the ED3-instanton superpotential would require one not to go beyond ED3-instanton number equal to 2. Restricting the D3-brane to the big divisor automatically nullifies the non-perturbative gaugino-condensate-valued contribution to the superpotential due to arguments of O.Ganor.
- 3. We do not have a global embedding into type IIB string theory of our model.

CCB Minima

- The CCB minima are usually avoided if, in terms of our local setup, the square of the trilinear $\mathcal{A}$ couplings have an upper bound given in terms of a linear combination of squark mass squared and the mass squared of the Higgs doublets (the mass squared of the $D3$-brane position moduli + Higgs mass parameter squared). Writing the above as: $|\mathcal{A}|^2 \leq O(1)m_{\tilde{q}}^2 + \mathcal{O}(1)m_{Z_i}^2 + \mathcal{O}(1)\mu^2$, we have verified that for the Calabi-Yau volume(which is a free parameter in our model) $\mathcal{V} \sim 1/\mathcal{O}(1) \times 10^5$ [in string length units], the inequality is satisfied at the string scale and the inequality is approximately saturated at the EW scale.
- Of course, this inequality is usually obtained by assuming that all sparticles have acquired the same vev at the CCB minimun, which is not true for us. Hence this was only to get an idea about the CCB issue.

CCB Minima

- More relevant to our setup is the fact that the local F-term potential (the D-term is 2-form-flux-suppressed in the dilute flux approximation that we work with) with the mobile space-time filling $D3$-brane restricted to a nearly special Lagrangian 3-cycle, corresponds to the norm-squared of the Kähler vector obtained by the Kähler-covariant derivative of the ED3-instanton superpotential w.r.t. to the complexified big/small divisor modulus at the string/EW scale and is hence positive semi-definite. Thus, there is no 'UFB' problem.
- Further, at the string and EW scale, the CCB minimum corresponding to non-zero vevs for the $D3$-brane position moduli identified with two Higgses and Wilson line moduli, identified with the sleptons and squarks, is approximately degenerate with SM-like vacua with non-zero vevs only for the Higgs. Further, the $SU(3)_c$-violating vertices in our model relevant to, e.g., gluino decays, (N)LSP decays, etc., despite the non-zero vevs for sleptons and squarks, are highly volume-suppressed as compared to the $SU(3)_c$-preserving vertices.

To calculate the decay widths of all important 2- and 3-body channels involving gauge particles, we will be utilizing/generalizing results of H. Jockers [2005] in the $\mathcal{N} = 1$ gauged supergravity action of Wess and Bagger with the understanding that

- For multiple $D7$-branes, the non-abelian gauged isometry group [corresponding to gauging of a Pecci-Quinn/shift symmetry along the RR two-form axions c^a and the zero-form axion ρ_B due to the dualization of the Green-Schwarz term $Tr\left(Q_B \int_{\mathbf{R}^{1,3}} dD_B^{(2)} \wedge A\right)$ - $D_B^{(2)}$ being an RR two-form axion modifies the covariant derivative of T_B by an additive shift given by $6i\kappa_4^2\mu_7\,(2\pi\alpha')\,Tr(Q_B A_\mu)$] can be identified with the SM group (i.e. A_μ is the SM-like adjoint-valued gauge field Wess+Bagger); $Q_B = 2\pi\alpha' \int_{\Sigma_B} i^*\omega_\alpha \wedge P_-\tilde{f}$.

The Kähler potential

$$K\left(\left\{\sigma^b,\bar{\sigma}^B;\sigma^S,\bar{\sigma}^S;\mathcal{G}^a,\bar{\mathcal{G}}^a;\tau,\bar{\tau}\right\};\left\{z_{1,2},\bar{z}_{1,2};\mathcal{A}_1,\bar{\mathcal{A}}_1\right\}\right) =$$

$$-ln\left(-i(\tau-\bar{\tau})\right) - ln\left(i\int_{CY_3}\Omega\wedge\bar{\Omega}\right) - 2ln\Bigg[a\left(T_B+\bar{T}_B-\gamma K_{\rm geom}\right)^{\frac{3}{2}} -$$

$$a\left(T_S+\bar{T}_S-\gamma K_{\rm geom}\right)^{\frac{3}{2}} + \frac{\chi}{2}\sum_{m,n\in\mathbf{Z}^2/(0,0)}\frac{(\bar{\tau}-\tau)^{\frac{3}{2}}}{(2i)^{\frac{3}{2}}|m+n\tau|^3}$$

$$-4\sum_{\beta\in H_2^-(CY_3,\mathbf{Z})} n^0_\beta \sum_{m,n\in\mathbf{Z}^2/(0,0)}\frac{(\bar{\tau}-\tau)^{\frac{3}{2}}}{(2i)^{\frac{3}{2}}|m+n\tau|^3} cos\left(mk.\mathcal{B}+nk.c\right)\Bigg]$$

$$+\frac{C_s^{KK\ (1)}(z^{\tilde{a}},\bar{z}^{\tilde{a}})\sqrt{\tau_s}}{\mathcal{V}\left(\sum_{(m,n)\in\mathbf{Z}^2/(0,0)}\frac{\frac{(\tau-\bar{\tau})}{2i}}{|m+n\tau|^2}\right)} + \frac{C_b^{KK\ (1)}(z^{\tilde{a}},\bar{z}^{\tilde{a}})\sqrt{\tau_b}}{\mathcal{V}\left(\sum_{(m,n)\in\mathbf{Z}^2/(0,0)}\frac{\frac{(\tau-\bar{\tau})}{2i}}{|m+n\tau|^2}\right)}$$

$$-2ln\left(\sum_{\beta\in H_2^-(CY_3,\mathbf{Z})} n^0_\beta(\ldots)\right) + \left(|\delta z_1|^2+|\delta z_2|^2+\delta z_1\bar{\delta}z_2+\delta z_2\bar{\delta}z_1\right)\hat{K}_{z_i\bar{z}_j} +$$

$$\left((\delta z_1)^2+(\delta z_2)^2\right)\hat{Z}_{z_iz_j} + c.c....$$ (A. Misra and P. Shukla(2009))