$U(1)_R$-Mediated Supersymmetry Breaking

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based on

K.-Y. Choi & HML, JHEP 0903(2009) 132;
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Introduction

- Supersymmetry has been a good candidate for physics beyond the Standard Model, but SUSY must be broken in nature.
- In gravity mediation, hidden-sector SUSY breaking is transmitted by $\int d^4\theta \frac{c_{ij}}{M_P^2} X^\dagger X Q_i^\dagger Q_j$ with $\langle X \rangle = \theta^2 F_X$. Soft masses with generic c_{ij} would lead to FCNC/CP problems.
- In higher dimensions, the hidden sector can be sequestered from the visible sector at a different place in extra dimensions.
- The $U(1)$ flux in extra dimensions stabilizes the moduli. Integrating out the resultant heavy $U(1)$ may generate soft masses by $\int d^4\theta \frac{q_i' g^2}{M_V^2} X^\dagger X Q_i^\dagger Q_i$.
- We consider the SUSY mediation in a $U(1)_R$ model from 6D flux compactifications.

6D chiral gauged supergravity

[Nishino,Sezgin(1984); Salam,Sezgin(1984)]

- 6D chiral gauged supergravity is composed of

$$\begin{aligned} \text{gravity} &: \quad e_M^A, \quad \psi_M, \quad B^+_{MN}, \\ \text{tensor} &: \quad \phi, \quad \chi, \quad B^-_{MN}, \\ \text{vector} &: \quad A_M, \quad \lambda. \end{aligned}$$

- The bosonic part of the 6D bulk supergravity action is

$$\begin{aligned} S &= \int d^6x\sqrt{-g}\Big(R - \frac{1}{4}(\partial_M\phi)^2 - 8g^2 e^{-\frac{1}{2}\phi} \\ &\quad -\frac{1}{4}e^{\frac{1}{2}\phi}F_{MN}F^{MN} - \frac{1}{12}e^{\phi}G_{MNP}G^{MNP}\Big). \end{aligned}$$

- The supersymmetric action for a codimension-two brane with tension was constructed. [Papazoglou,Lee(2007); Lee(2008)]

General warped solutions

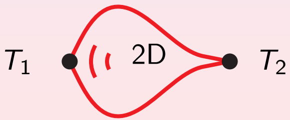
[Gibbons et al(2003); Aghababaie et al(2003); Papazoglou,Lee(2007)]

- The general warped solution with axial symmetry is

$$
\begin{aligned}
ds^2 &= W^2\eta_{\mu\nu}dx^\mu dx^\nu + \frac{W^2}{(1+r^2/r_0^2)^2}\Big(dr^2+\lambda^2\frac{r^2}{W^4}d\theta^2\Big),\\
F_{mn} &= qW^{-6}\epsilon_{mn}, \quad \phi = 4\ln W,
\end{aligned}
$$

where $W^4(r)=\frac{1+r^2/r_1^2}{1+r^2/r_0^2}$ with $r_0^2=\frac{1}{2g^2}$ and $r_1^2=\frac{8}{q^2}$.

- Brane tensions: $T_1 = 2\pi M_*^4(1-\lambda)$, $T_2 = 2\pi M_*^4\Big(1-\lambda\frac{16g^2}{q^2}\Big)$.
- For $q=4g$, we get a unwarped football which preserves 4D $\mathcal{N}=1$ SUSY.



4D effective supergravity

- After KK dimensional reduction for the supersymmetric football, the obtained 4D Kähler potential is

$$\begin{aligned} K &= -\ln\left(\frac{1}{2}(S+S^\dagger)\right) - 4g_R V_R \\ &\quad -\ln\left(\frac{1}{2}(T+T^\dagger-8g_R V_R) - Q_i^\dagger e^{-2r_i g_R V_R} Q_i\right) \\ &\quad +X_m^\dagger e^{-2r_m g_R V_R} X_m \end{aligned}$$

  where $S = s + i\sigma$, $T = t + |Q_i|^2 + ib$ are bulk moduli and $Q_i(X_m)$ are brane(bulk) chiral multiplets.

- The effective superpotential coming from branes and bulk is

$$W = W_{\rm vis}(Q_i) + W_{\rm hid}(Q') + W_{\rm bulk}(S, T, X)$$

- Bulk gauge kinetic function is $f_R = S$ while brane gauge kinetic function is trivial.

$U(1)_R$ anomaly-free MSSM

- $U(1)_R$ is non-linearly realized as

$$V_R \to V_R + \frac{i}{2}(\Phi - \Phi^\dagger), \quad T \to T + 4ig_R\Phi.$$

- SM-$U(1)_R$ mixed anomalies can be cancelled by the variation of a brane-localized Green-Schwarz(GS) term,

$$\mathcal{L}_{GS} = -(\mathrm{Im}\, T)\sum_{a=1}^{3} k_a \frac{1}{2}\mathrm{tr}(F_a\tilde{F}_a)$$

  where $k_a = \frac{C_a}{16\pi^2 g_R}$ with C_a being anomaly coefficients.
- Unified gauge couplings at GUT scale and renormalizable Yukawa couplings fix $C_1 = -15$ and $C_2 = C_3 = -9$.

- One parameter solution for family-universal R-charges of fermions (R-charges of scalar partners: $\tilde{q} = q + 1$,etc):

$$
\begin{aligned}
l &= -3q - \frac{28}{3}, \quad e = -\frac{3}{7}q - \frac{8}{3}, \quad u = \frac{17}{7}q + 4, \\
d &= -\frac{31}{7}q - 12, \quad h_d = \frac{24}{7}q + 11, \quad h_u = -\frac{24}{7}q - 5.
\end{aligned}
$$

- The tree-level μ term is forbidden. We should add $W = \lambda_N N H_u H_d$ for a singlet scalar VEV.
- If neutrino masses are of Majorana type $H_u L H_u L$, $\tilde{q} = -\frac{29}{27} \simeq -1.074$. Otherwise, $\tilde{q}$ is not restricted only by anomaly cancellation.

Moduli stabilization

- For $W=0$, the $U(1)_R$ D-term potential, $V_0=\frac{2g_R^2M_P^2}{s}\left[1-\frac{1}{t}(1-r_i|Q_i|^2)\right]^2$, stabilizes the T modulus while the S modulus remains undetermined.
- In the presence of a bulk gaugino condensate, we take the effective superpotential as

$$W=fQ'+W_0+\left(\frac{\lambda}{X^n}e^{-bS}+\lambda'\varphi^pX^2+\kappa\varphi^q\right).$$

- For $\frac{|W_0|}{2bs}\ll|\kappa|\ll|\lambda'|$, the scalar VEVs are $|X|\ll 1$ and $|\varphi|\ll 1$. Then, the S modulus is stabilized at $s=\mathcal{O}(1)$ for $b=\mathcal{O}(10)$ while the T modulus remains stabilized at $t\simeq 1$.

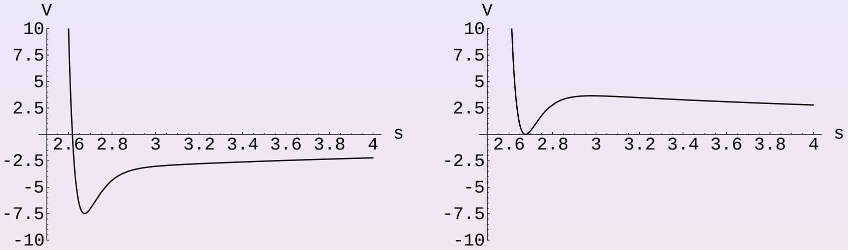


Figure: Plot of the scalar potential for $s = \mathrm{Re}S$ with non-zero W_0 with $f = 0$ (Left) and $f \neq 0$ (Right) to show the uplifting of the potential. Here we used $\lambda = 0.01,\ b = 15,\ \lambda' = 10^{-7},\ p = 3,\ q = 1, n = 1,\ \kappa = -10^{-15}, W_0 = 10^{-16}$, with $f = 0$ (Left) and $f = 1.413 \times 10^{-16}$ (Right). The minimum values are approximately $t_0 \simeq 1.00095, s_0 \simeq 2.673, X_0 \simeq -0.03087, \varphi_0 \simeq -0.00187$.

Soft mass parameters

- Nonzero $F_{Q'}, F_T$ terms are sequestered while only the $U(1)_R$ D-term contributes to scalar soft masses.
- The soft mass parameters at the GUT scale($M_{GUT} = M_A$) are

$$
\begin{aligned}
m_i^2 &\simeq -r_i m_{3/2}^2, \\
M_a &\simeq \frac{C_a g_a^2}{16\pi^2 g_R} F^T \simeq -\frac{9}{16\pi^2 g_R}, \ \text{any } a \\
A_{ijk} &= -F^I \partial_I \ln(\lambda_{ijk}/e^{-K_0} Z_i Z_j Z_k) \simeq -2m_{3/2}, \ \text{any } i,j,k.
\end{aligned}
$$

- At GUT scale, all squarks and leptons soft squared masses are positive for $-\frac{46}{31} < \tilde{q} < -\frac{18}{17}$; Higgs squared soft masses are negative.
- The $U(1)_R$ mediation has 5 free parameters:

$$
m_{3/2}, \quad M_{1/2}, \quad \tilde{q}, \quad \tan\beta, \quad \text{sign}(\mu).
$$

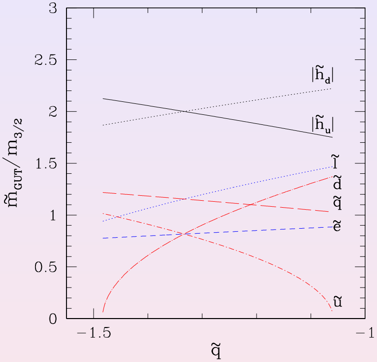
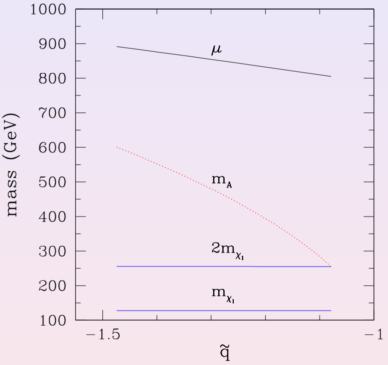


Figure: The soft masses $\tilde{m}_{\rm GUT}$ for sparticles at the GUT scale with a varying $\tilde{q}$. For the Higgs masses, we plot $\tilde{m}_{\rm GUT}=\sqrt{|m^2_{\tilde{h}_{u,d}}|}$.



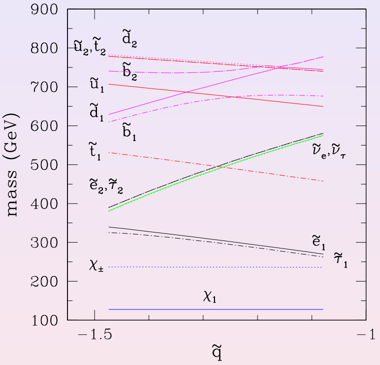


Figure: The particle masses versus $\tilde{q}$ at low energy in the model for $m_{3/2} = 360\,\mathrm{GeV}$, $M = 310\,\mathrm{GeV}$, $\tan\beta = 10$ with $\mu > 0$ and $m_t = 172.7\,\mathrm{GeV}$.

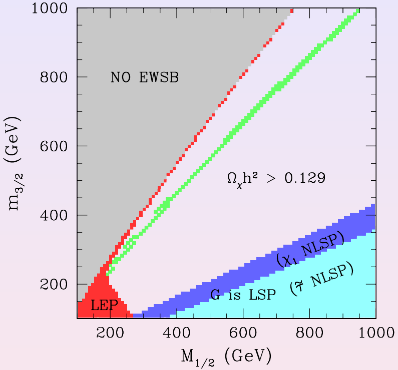


Figure: The scan on the plane of $(M_{1/2}, m_{3/2})$ with $\tilde{q} = -1.1$, $\tan\beta = 10$ and $\mu > 0$. The black region is excluded due to unsuccessful EWSB (upper left corner). The red region is disfavored by the LEP constraints on chargino and Higgs mass $m_{\chi^\pm} > 104\,\mathrm{GeV}$ and $m_{h^0} > 114.4\,\mathrm{GeV}$.

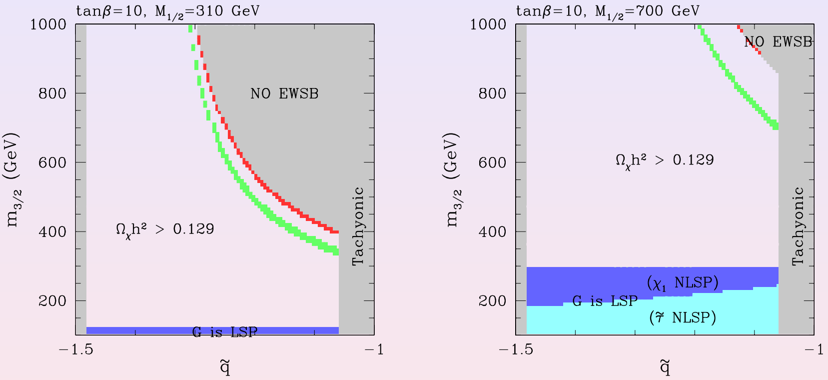


Figure: The gravitino mass vs $\tilde{q}$ with $\tan\beta = 10$ and $\mu > 0$ for $M_{1/2} = 310\,\mathrm{GeV}$ (Left) and $M_{1/2} = 700\,\mathrm{GeV}$ (Right).

	P1	P2	P3	P4
$m_{3/2}$	360	756	175	250
$M_{1/2}$	310	700	500	800
$\tilde{q}$	-1.1	-1.1	-1.1	-1.1
$\tan\beta$	10	10	10	10
μ	810	170	744	111
m_{h^0}	115	120	116	119
m_A	284	626	715	1100
m_{H^0}	284	626	715	1100
$m_{H^\pm}$	295	631	720	1103
m_{χ_1}	127	299	207	339
m_{χ_2}	246	572	393	641
m_{χ_3}	806	1690	747	1117
m_{χ_4}	811	1691	757	1124

$m_{\chi_1^\pm}$	246	572	393	641
$m_{\chi_2^\pm}$	811	1691	757	1124
$m_{\tilde{g}}$	754	1600	1148	1772
$m_{\tilde{u}_1}$	677	1420	1010	1549
$m_{\tilde{t}_1}$	492	1095	781	1228
$m_{\tilde{d}_1}$	768	1612	1027	1568
$m_{\tilde{b}_1}$	710	1495	975	1498
$m_{\tilde{e}_1}$	274	581	224	342
$m_{\tilde{\tau}_1}$	267	570	215	333
Ωh^2	0.1115	0.1099	χ_1 NLSP	$\tilde{\tau}$ NLSP
LSP	χ_1	χ_1	Gravitino	Gravitino

Table: All masses are in GeV. P1, P2: A-annihilation funnel. P3: Gravitino LSP with neutralino NLSP, P4: Gravitino LSP with stau NLSP. (SUSPECT + DarkSusy)

Conclusion

- Flux compactification provides gauged $U(1)_R$ as a new SUSY mediator.
- Scalar soft masses are family-independent but non-universal while gaugino masses are universal.
- Neutralino LSP can be a dark matter in the A-annihilation funnel. In this case, the pseudo-scalar Higgs can be light to be observed at LHC.
- In stau-coannihilation region, neutralino or stau is NLSP and gravitino is LSP. In this case, the BBN constraints require NLSP to be heavier than $1-10$ TeV.