Split Supersymmetry from Gauged R-Symmetry

Fei Wang

ZhengZhou University

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内容提要

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Why New Physics Is Needed

- Standard model is very successful in describing physics up to the electroweak scale. Standard Model is the correct low energy effective theory.
- Many free parameters are put in by hand. Origin of flavor structure, three generations, the introduction of yukawa coupling...
- Neutrino mass- trivially accommodated with right handed neutrino and possible large Majorana mass terms.
- Triviality bounds and vacuum stability bounds. Triviality bounds needs light higgs. Triviality bounds

$$\Lambda_\infty \simeq v \times \left(5 \times 10^5\right)^{\frac{246^2}{m_h^2}}.$$

Vacuum stability bounds

$$m_{[H]} \gtrsim 129.5 + 1.4\frac{m_t(\mathrm{GeV}) - 173.1}{0.7} - 0.5\frac{\alpha_s(M_z) - 0.1184}{0.0007}.$$

Why SUSY Is Needed

- The predicted 126 GeV Higgs is relatively light(within the narrow window predicted by weak scale SUSY: $m_h \sim 115 - 135\text{GeV}$).
- Fine tuning problem needs an explanation—naturally solved by weak scale SUSY.
- Dark Matter candidates can naturally be provided by SUSY(with R-parity).
- To understand the origin of the three gauge coupling and matter contents, the Grand Unified Theory(GUT) is proposed. The unification of gauge coupling may indicate the existence of low energy SUSY.
- Radiative electroweak symmetry breaking...

Split SUSY

- Motivation
  - Abandon the naturalness consideration–after all, CC need even worse fine-tuning.
  - Keep the most appealing feature of SUSY: Gauge coupling unification, viable dark matter.
- Setting
  - The scalar superpartner (squarks and sleptons) and $B\mu$ very heavy.
  - Gaugino and higgsino are kept to be light by approximate R-symmetry.
  - Fine tuning a light higgs.
- Advantage
  - Consistent with null search on LHC.
  - Evade the notorious SUSY flavor and CP problems.
  - Relax the Dim-5 operator induced fast proton decay.

Split SUSY

$$\Delta L = M_3\tilde{g}\tilde{g} + M_2\tilde{w}\tilde{w} + M_1\tilde{b}\tilde{b} + \mu\psi_u\psi_d$$
$$+ \sqrt{2}\kappa_u h^\dagger\tilde{w}\psi_u + \sqrt{2}\kappa_d h\tilde{w}\psi_d + \sqrt{2}\frac{1}{2}\kappa'_u h^\dagger\tilde{b}\psi_u - \sqrt{2}\frac{1}{2}\kappa'_d h\tilde{b}\psi_d$$
$$- m^2 h^\dagger h - \frac{\lambda}{2}(h^\dagger h)^2$$

$$\kappa_u(m_S) = g_2(m_S)\sin\beta,\ \kappa_d(m_S) = g_2(m_S)\cos\beta$$
$$\kappa'_u(m_S) = \sqrt{\frac{3}{5}}g_1(m_S)\sin\beta,\ \kappa'_d(m_S) = \sqrt{\frac{3}{5}}g_1(m_S)\cos\beta$$

$$\lambda(m_S) = \frac{\frac{3}{5}g_1^2(m_S) + g_2^2(m_S)}{4}\cos^2 2\beta$$

Split SUSY From GUT Constraints [Fei, Jin Min,Wenyu]

- One-loop RGE disfavor large M_S and will predict small $\alpha_s(M_Z)$ below observed value.
- Two-loop RGE are necessary to push upward the value of $\alpha_s(M_Z)$ by O(0.1).
- So it is necessary to take into account two loop gauge coupling RGE and one loop for yukawa.

$$\frac{d}{d\ln E} g_i = \frac{g_i^3}{(4\pi)^4}\left[\sum_j \Delta B_{ij} g_j^2 - \sum_{a=u,d,e} d_i^a Tr(h^{a\dagger} h^a)\right.$$
$$\left. - d_W(\tilde{g}_u^2 + \tilde{g}_d^2) - d_B(\tilde{g}_u'^2 + \tilde{g}_d'^2)\ \right] + \frac{b_i}{(4\pi)^2} g_i^3,$$

with the $U(1)_Y$ normalization $g_1^2 = \frac{5}{3}(g_Y)^2$

- Two loop RGE with threshold corrections are important.
- Neglect possible GUT scale threshold corrections and higher-dimensional operators.

Scenario IV for Two Loop RGE

E	b_i	ΔB_{ij}	(d_i^u, d_i^d, d_i^e)	(d_i^W, d_i^B)
$[M_Z, M_1]$	$\begin{matrix} \frac{9}{2} \\ -\frac{15}{6} \\ -7 \end{matrix}$	$\begin{matrix} \frac{104}{25} & \frac{18}{5} & \frac{44}{5} \\ \frac{6}{5} & \frac{42}{3} & 12 \\ \frac{11}{10} & \frac{9}{2} & -26 \end{matrix}$	$\begin{matrix} \frac{17}{10} & \frac{1}{2} & \frac{3}{2} \\ \frac{3}{2} & \frac{3}{2} & \frac{1}{2} \\ 2 & 2 & 0 \end{matrix}$	$\begin{matrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{matrix}$
$[M_1, M_2]$	$\begin{matrix} \frac{9}{2} \\ -\frac{15}{6} \\ -7 \end{matrix}$	$\begin{matrix} \frac{104}{25} & \frac{18}{5} & \frac{44}{5} \\ \frac{6}{5} & \frac{42}{3} & 12 \\ \frac{11}{10} & \frac{9}{2} & -26 \end{matrix}$	$\begin{matrix} \frac{17}{10} & \frac{1}{2} & \frac{3}{2} \\ \frac{3}{2} & \frac{3}{2} & \frac{1}{2} \\ 2 & 2 & 0 \end{matrix}$	$\begin{matrix} \frac{9}{20} & \frac{3}{20} \\ 0 & 0 \\ 0 & 0 \end{matrix}$
$[M_2, M_3]$	$\begin{matrix} \frac{9}{2} \\ -\frac{7}{6} \\ -7 \end{matrix}$	$\begin{matrix} \frac{104}{25} & \frac{18}{5} & \frac{44}{5} \\ \frac{6}{5} & \frac{106}{3} & 12 \\ \frac{11}{10} & \frac{9}{2} & -26 \end{matrix}$	$\begin{matrix} \frac{17}{10} & \frac{1}{2} & \frac{3}{2} \\ \frac{3}{2} & \frac{3}{2} & \frac{1}{2} \\ 2 & 2 & 0 \end{matrix}$	$\begin{matrix} \frac{9}{20} & \frac{3}{20} \\ \frac{11}{4} & \frac{1}{4} \\ 0 & 0 \end{matrix}$
$[M_3, M_S]$	$\begin{matrix} \frac{9}{2} \\ -\frac{7}{6} \\ -3 \end{matrix}$	$\begin{matrix} \frac{104}{25} & \frac{18}{5} & \frac{44}{5} \\ \frac{6}{5} & \frac{106}{3} & 12 \\ \frac{11}{10} & \frac{9}{2} & 22 \end{matrix}$	$\begin{matrix} \frac{17}{10} & \frac{1}{2} & \frac{3}{2} \\ \frac{3}{2} & \frac{3}{2} & \frac{1}{2} \\ 2 & 2 & 0 \end{matrix}$	$\begin{matrix} \frac{9}{20} & \frac{3}{20} \\ \frac{11}{4} & \frac{1}{4} \\ 0 & 0 \end{matrix}$
$[M_S, M_U]$	$\begin{matrix} \frac{33}{5} \\ 1 \\ -3 \end{matrix}$	$\begin{matrix} \frac{199}{25} & \frac{27}{5} & \frac{88}{5} \\ \frac{9}{5} & 25 & 24 \\ \frac{11}{5} & 9 & -14 \end{matrix}$	$\begin{matrix} \frac{26}{5} & \frac{14}{5} & \frac{18}{5} \\ 6 & 6 & 2 \\ 4 & 4 & 0 \end{matrix}$	$\begin{matrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{matrix}$

Split SUSY From GUT Constraints

The ratios of gaugino masses and gauge couplings are RGE-invariant (up to one-loop level)

$$\frac{d}{d\ln\mu}\left(\frac{M_i}{g_i^2}\right) = 0 \tag{1.1}$$

This leads to a mass relation given by

$$\frac{M_1}{g_1^2} = \frac{M_2}{g_2^2} = \frac{M_3}{g_3^2} = \frac{M_U}{g_U^2}. \tag{1.2}$$

with universal gaugino mass at the GUT scale.
Gaugino mass unification naturally appear in the ordinary SUSY-SU(5) GUT models (it can be spoiled by the introduction of certain higher dimensional representation Higgs fields, e.g., the **75, 200** dimensional Higgs fields [Tianjun Li, Fei et al]).

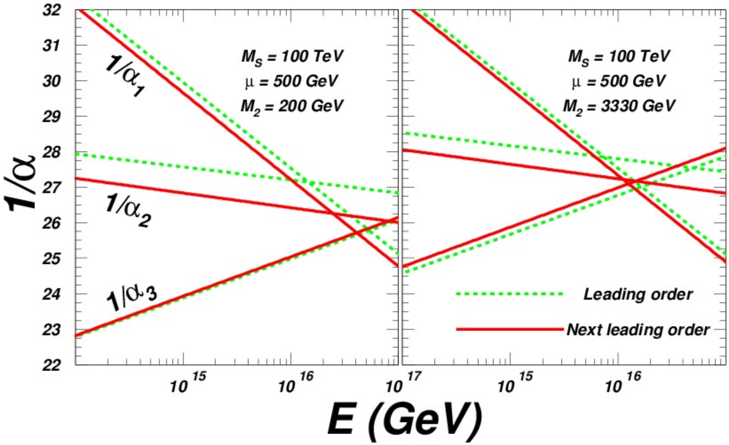


Figure: The RGE running of the three gauge couplings (we only show the region of $E > 10^{14}$ GeV). The dashed lines (green) denote the one-loop results while the solid lines (red) denote the two-loop results.

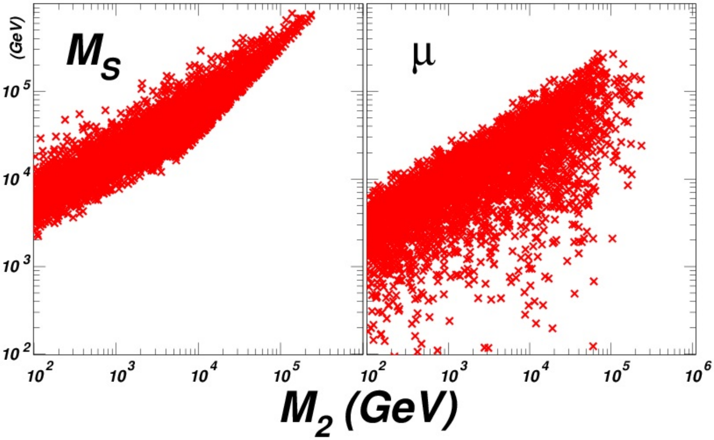
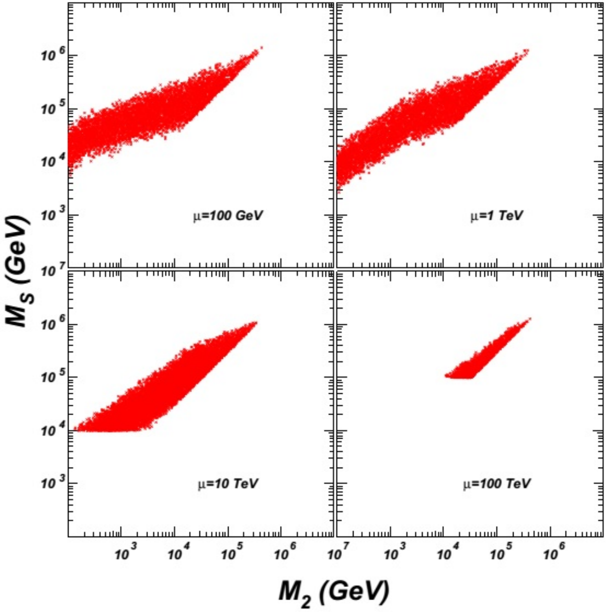


Figure: The scatter plots of the parameter space with the gauge coupling unification requirement.



μ=100 GeV
μ=1 TeV
μ=10 TeV
μ=100 TeV
M_S (GeV)
M_2 (GeV)
10^3
10^4
10^5
10^6
10^7

Split SUSY From Combined GUT and DM Constraints

We scan the parameter space of split-SUSY in the ranges:

$$1 < \tan\beta < 50, \ \ 0 \ < (M_2, \ \mu) < M_S. \tag{1.3}$$

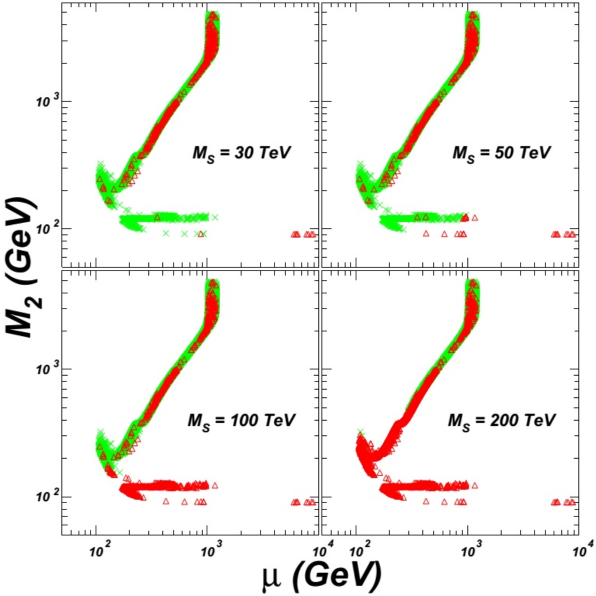
(1) We use the lightest neutralino $\tilde{\chi}_1^0$ to account for the Planck measured dark matter relic density $\Omega_{DM} = 0.1199 \pm 0.0027$ (in combination with the WMAP data);

(2) The LEP lower bounds on neutralino and charginos, including the invisible decay of Z-boson;

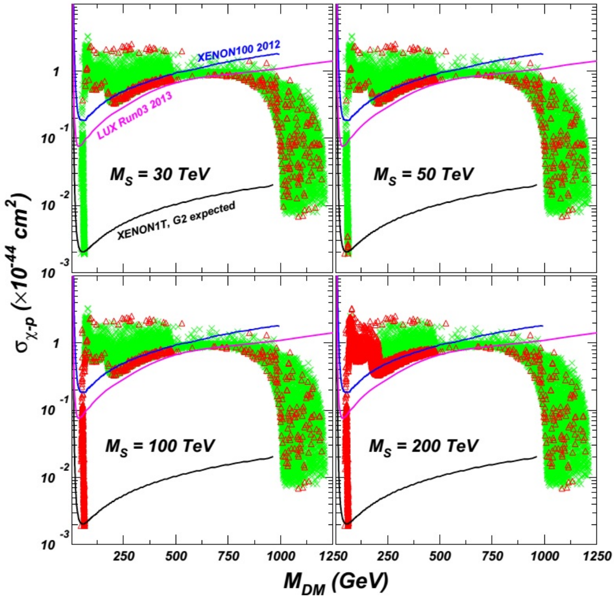
(3) The precision electroweak measurements;

(4) The combined mass range for the Higgs boson: $123\mathrm{GeV} < M_h < 127\mathrm{GeV}$ from ATLAS and CMS collaborations of LHC.

(5) Spin-independent cross section is calculated.



M_S = 30 TeV
M_S = 50 TeV
M_S = 100 TeV
M_S = 200 TeV
M_2 (GeV)
10^3
10^2
10^2
10^3
10^4
μ (GeV)


XENON100 2012
LUX Run03 2013
XENON1T, G2 expected
M_S = 30 TeV
M_S = 50 TeV
M_S = 100 TeV
M_S = 200 TeV
$\sigma_{\chi\text{-}p}$ ($\times 10^{-44}$ cm^2)
M_{DM} (GeV)
1
10^{-1}
10^{-2}
10^{-3}
250 500 750 1000 1250

Split SUSY From Combined GUT and DM Constraints

(1) Upper bound for M_S and possible lower bound for M_2.

(2) DM below 1Tev will be fully covered by LHC.

(3) Mixed higgsino dark matter survives.

Why Use R-symmetry

- Least assumption in supersymmetry–intrinsic in SUSY.
- What is R-symmetry: a symmetry distinguish between different spin components within a multiplet.
  For vector supermultiplet $V(A_\mu, \lambda, \bar{\lambda}, D)$ and chiral supermultiplet $S(z, \psi, F)$

$$
\begin{aligned}
V(x,\theta,\bar{\theta}) &\to V(x, e^{-i\alpha}\theta, e^{i\alpha}\theta), \\
S(x,\theta,\bar{\theta}) &\to e^{-in\alpha} S(x, e^{-i\alpha}\theta, e^{i\alpha}\theta).
\end{aligned} \tag{2.1}
$$

Grassman coordinates transform non-trivially under R-symmetry.

$$
\theta \to e^{-i\alpha}\theta,\ \bar{\theta} \to e^{i\alpha}\bar{\theta}\,, \int d\theta \to e^{i\alpha}\int d\theta\,, \int d\bar{\theta} \to e^{-i\alpha}\int d\theta.
$$

Transformation under R-symmetry

- The transformation on component fields for vector supermultiplet and chiral supermultiplet

$$
\begin{aligned}
&A_\mu \rightarrow A_\mu, \qquad z \rightarrow e^{in\alpha} z \\
&\lambda \rightarrow e^{-i\alpha}\lambda_L\ , \quad \psi \rightarrow e^{i(n-1)\alpha}\psi \\
&\bar{\lambda} \rightarrow e^{i\alpha}\bar{\lambda}\ , \qquad F \rightarrow e^{i(n-2)\alpha}F\ . \\
&D \rightarrow D\ ,
\end{aligned} \tag{2.2}
$$

- Transformation for Kahler potentia and superpotential

$$
\begin{aligned}
K(\phi^\dagger, \phi) &\rightarrow K(\phi^\dagger, \phi)\ , \\
W(\phi) &\rightarrow e^{-2i\alpha}W(\phi)\ , \\
W_\alpha \rightarrow e^{-i\alpha}W_\alpha, \quad \bar{W}_{\dot\alpha} &\rightarrow e^{-i\alpha}W_{\dot\alpha},
\end{aligned} \tag{2.3}
$$

R-symmetry in SUSY

- Widely used with its discrete version–R parity, which is an additional input for SSM. Prohibit dimension four baryon and lepton number violation interactions that lead to fast proton decay.
- Very useful in obtaining some non-perturbation results:
  - non-renormalization theorem in SUSY.
  - Anomaly matching in Seiberg duality.
  - AdS/CFT: $SU(4)_R \sim SO(6)$.
  - SUSY broken criteria:
    Genericaly, spontaneously F-term SUSY broken has a unbroken R-symmetry.
    Metastable SUSY broken has an approximate R-symmetry.
- Anomaly free non-R symmetries(or discrete version) can not forbid the μ-term in MSSM. [by Mu chun Chen]

Gauged R-symmetry

- Global R-symmetry prohibit tree-level gaugino masses which always given too light gaugino.
- Spontaneously broken R-symmetry will lead to light Goldstone boson-R-axion and light gluino.
- Based on quantum gravitational effects, any apparent global symmetries in an effective Lagrangian are accidental consequences of gauge symmetries and are only approximate.
- Gauged R-symmetry is a special case of local superspace transform.
- R-gaugino need the coupling $g_R \bar{\lambda} \gamma^\mu \gamma^5 \lambda V_\mu^R$ which cannot be given in global SUSY. [by Freedman]
- $[Q_\alpha, R] = i(\gamma^5)_\alpha^\beta Q_\beta$ with local R holds only for local SUSY. [by Dreiner]
- Gauged R-symmetry necessarily involve local SUSY. In global SUSY, only global R-symmetry can be constructed.

Gauged R-symmetry and Gravitino

- Graviton multiplet transformation

$$e_\mu^m \to e_\mu^m \,, \; \psi_\mu \to e^{-i\alpha\gamma^5}\psi_\mu . \tag{2.4}$$

- Transformation invlove gravitino with gauged R-symmetry can lead to transformation into the term $g_R\bar{\lambda}\gamma^\mu\gamma^5\lambda V_\mu^R$.
- R-gaugino also transform non-trivially.
- A non-vanishing Fayet-Illiopoulos term is necessarily present in the D-term of the scalar potential.
- Consistency of gauged $U(1)_R$ needs anomaly cancelation.

No-Go Theorem for GUT Model with Gauged R-symmetry

- Impossible to construct a GUT model in four dimensions that leads to the exact MSSM and possesses an unbroken R symmetry.[Maximilian Fallbacher et al,1109.4797]
- Does not apply to GUT models with extra dimensions.
- Orbifold GUT is thus advantageous in getting a GUT model with gauged R-symmetry.
- Automatically realize D-T splitting which is problematic if use various mechanism in 4D.
- Preserving the attractive feature of GUT and R-symmetry.

SU(5) Orbifold GUT Model with Gauged R-symmetry

Consider 5D orbifold $\mathcal{M}_4 \times S^1/(Z_2 \times Z_2)$ with projection

$$P : y \to -y\,, \qquad P' : y' \to -y'\,, \tag{3.1}$$

Here $y' \equiv y + \frac{\pi R}{2}$. We introduce the following orbifold projection choice

$$P = (+\,,+\,,+\,,+\,,+\,)\,, \quad P' = (+\,,+\,,+\,,-\,,-\,)\,. \tag{3.2}$$

We chose the boundary conditions so that the GUT gauge group is broken to $SU(3)_c \times SU(2)_L \times U(1)_Y$ by boundary conditions in the $y = \frac{\pi R}{2}$ brane and preserved in the bulk as well as in the $y = 0$ brane. The superpotential takes the form with $'i, j'$ indicate the family index.

$$\begin{aligned} W \quad &\supseteq \quad \sum_{i,j} \Big[y^a_{ij} \mathbf{10}^A_i \mathbf{10}^B_j \mathbf{5}_H + y^b_{ij} \mathbf{10}^A_i \bar{\mathbf{5}}^A_j \bar{\mathbf{5}}_H + y^c_{ij} \mathbf{10}^C_i \bar{\mathbf{5}}^B_j \bar{\mathbf{5}}_H, \\ &+ \quad y^d_{ij} \bar{\mathbf{5}}^{\mathbf{B}}_{\mathbf{i}} \mathbf{5}_H \mathbf{N} + \lambda \bar{\mathbf{5}}_H \mathbf{5}_H S. \Big] \end{aligned} \tag{3.3}$$

Orbifold GUT Model with Gauged R-symmetry

The orbifold decomposition can be written as

$$
\begin{aligned}
\mathbf{10}^A &= (\mathbf{3},\mathbf{2})^{(+,+)}_{\mathbf{-1/6}} \oplus (\mathbf{\bar{3}},\mathbf{1})^{(+,-)}_{\mathbf{2/3}} \oplus (\mathbf{1},\mathbf{1})^{(+,-)}_{\mathbf{-1}}~, \\
\mathbf{10}^B &= (\mathbf{3},\mathbf{2})^{(+,-)}_{\mathbf{-1/6}} \oplus (\mathbf{\bar{3}},\mathbf{1})^{(+,+)}_{\mathbf{2/3}} \oplus (\mathbf{1},\mathbf{1})^{(+,-)}_{\mathbf{-1}}~, \\
\mathbf{10}^C &= (\mathbf{3},\mathbf{2})^{(+,-)}_{\mathbf{-1/6}} \oplus (\mathbf{\bar{3}},\mathbf{1})^{(+,-)}_{\mathbf{2/3}} \oplus (\mathbf{1},\mathbf{1})^{(+,+)}_{\mathbf{-1}}~, \\
\mathbf{24}_H &= (\mathbf{8},\mathbf{1})^{(+,+)}_{\mathbf{0}} \oplus (\mathbf{3},\mathbf{1})^{(+,-)}_{\mathbf{0}} \oplus (\mathbf{1},\mathbf{1})^{(+,-)}_{\mathbf{0}} \oplus (\mathbf{3},\mathbf{2})^{(+,-)}_{\mathbf{1/6}} \oplus (\mathbf{\bar{3}},\mathbf{2})^{(+,}_{\mathbf{-1}} \\
\mathbf{\bar{5}}^A &= (\mathbf{\bar{3}},\mathbf{1})^{(+,+)} \oplus (\mathbf{1},\mathbf{2})^{(+,-)}~, \\
\mathbf{\bar{5}}^B &= (\mathbf{\bar{3}},\mathbf{1})^{(+,-)} \oplus (\mathbf{1},\mathbf{2})^{(+,+)}~, \\
\mathbf{1}_N &= (\mathbf{1},\mathbf{1})^{(+,+)}_{\mathbf{0}}~,
\end{aligned}
$$

In **10** and **24**, we use the most general boundary conditions so that we can change the Neuman boundary conditions to Dirichlet boundary conditions by adding heavy brane localized mass terms.

Gauged R-symmetry Anomaly Cancelation

- 5D N=1 SUSY corresponds to 4D N=2 SUSY.
- The R-symmetry in this scenario is $SU(2)_R$.
- Boundary conditions preserve only $N = 1$ gauged R-symmetry.
- We adopt the scenario with family independent $U(1)_R$ symmetry.
- There are orbifold correspondence between standard model matter contents and SU(5) representations.
- For bulk fields we can introduce Chern-Simmons term to cancel the gauge anomaly without gauge group broken.
- We need only worry about the anomaly of the zero modes.

Anomaly Cancelation For The Zero Modes

Correspondence between standard model matter contents and SU(5) representations (their fermionic charges)

$$\begin{aligned} Q^R(q) &= Q^R(\mathbf{10}^A)\,, Q^R(d) = Q^R(\bar{\mathbf{5}}^A),\ Q^R(u) = Q^R(\mathbf{10}^B),\ Q^R(l) = Q^R(\bar{\mathbf{5}}^B), \\ Q^R(e) &= Q^R(\mathbf{10}^c)\,, Q^R(h) = Q^R(\mathbf{5}_H)\,, Q^R(\bar{h}) = Q^R(\bar{\mathbf{5}}_H)\,, Q^R(N) = Q^R(\mathbf{1})\,. \end{aligned}$$

The lowest component R-charge R_ϕ is related to R_ψ by the relation

$$R_\phi = R_\psi + 1. \tag{3.4}$$

The consistent yukawa coupling lead to

$$\begin{aligned} q + u + h &= -1\,, \\ q + d + \bar{h} &= -1\,, \\ l + e + \bar{h} &= -1\,, \\ l + n + h &= -1\,, \\ s + h + \bar{h} &= -1\,, \end{aligned} \tag{3.5}$$

Anomaly Cancelation For The Zero Modes

Cancelation for $SU(3)_c, SU(2)_L, U(1)_Y$ anomlay

- $SU(3)_c - SU(3)_c - U(1)_R$

$$3[q + \frac{1}{2}u + \frac{1}{2}d] + 3 + 3o_c = 0 \ ,$$

- $SU(2)_L - SU(2)_L - U(1)_R$

$$3[\frac{1}{2}l + \frac{3}{2}q] + \frac{1}{2}(h + \bar{h}) + 2 = 0 \ ,$$

- $U(1)_Y - U(1)_Y - U(1)_R$

$$3[\frac{1}{2}l + e + \frac{1}{6}q + \frac{4}{3}u + \frac{1}{3}d] + \frac{1}{2}(h + \bar{h}) = 0 \ ,$$

- $U(1)_Y - U(1)_R - U(1)_R$

$$3[-l^2 + e^2 + q^2 - 2u^2 + d^2] + h^2 - \bar{h}^2 = 0 \ ,$$

- $U(1)_R - U(1)_R - U(1)_R$

$$3[2l^3 + e^3 + 6q^3 + 3u^3 + 3d^3] + 2h^3 + 2\bar{h}^3 + 16 + n^3 + s^3 + \sum_m z_m^3 + 8o_c^3 = 0,$$

- $U(1)_R - g_{\mu\nu} - g_{\mu\nu}$

$$3[2l + e + 6q + 3u + 3d] + 2(h + \bar{h}) - 8 + n + s + \sum_m z_m + 8o_c = 0.$$

Possible Solutions with Anomaly Cancelation in Zero Modes

- Possible solution for SSM matter contents:
  A proper family independent anomaly free choice in our scenario have the following fermionic R-charge

$$q=-\frac{1}{3},\ d=\frac{1}{3},\ u=\frac{1}{3},\ l=\frac{1}{3},\ e=-\frac{1}{3},\ n=-\frac{1}{3},\ h=-1,\ \bar{h}=-1$$

- Three additional singlets:

$$z_1=\frac{20}{3},\ z_2=-\frac{68}{3}, z_3=\frac{103}{3}.$$

- Four additional singlets:

$$
\begin{aligned}
(z_1,z_2,z_3,z_4) &= (\frac{64}{3},-\frac{2}{3},-\frac{50}{3},13).\\
(z_1,z_2,z_3,z_4) &= (\frac{61}{3},\frac{11}{3},\frac{16}{3},-11).\\
(z_1,z_2,z_3,z_4) &= (\frac{62}{3},\frac{4}{3},-\frac{41}{3},10).
\end{aligned}
$$

SUSY Broken and Mass Spectrum

The real and gauge-invariant Kahler function are given in unit of Planck scale by the Kahler potential $K(z, z*)$ and superpotential $W(z)$

$$G(z, z^*) = K(z, z^*) + \ln |W(z)|^2 \ , \tag{3.6}$$

The scalar potential is given by

$$V = e^G[G_i G^j (G^{-1})^i_j - 3] + \frac{g_R^2}{2}(G^i Q_i z_i)^2 \ , \tag{3.7}$$

In case of gauged R-symmetry, the R-charge for W is 2, we arrive at

$$D = G^i Q_i z_i = Q_i K^i z_i + W_i Q_i z_i / W = Q_i K^i z_i + 2 \ , \tag{3.8}$$

The first term can be written as

$$e^G[G_i G^j (G^{-1})^i_j - 3] = e^K \left[(G^{-1})^i_j (D_i W)(D^j W^*) - 3|W|^2\right] , \tag{3.9}$$

with $D_i W = W_i + K_i W$.

SUSY Broken and Mass Spectrum

- SUSY broken with non-zero D-term or F-term.
- The broken of R-symmetry caused by GUT singlet z_i (in the hidden sector) .
- Almost vanishing Cosmological constant.
  Cosmological observation requires $<V>=0$. We need negative $<W>$ to cancel the positive $<D>$ contributions.
  Not intend to solve the CC problem.
- Negative charged singlet (with Planck scale VEVs) is helpful in fine-tuning the value of $<D>$ term

$$(2M_{Pl}^2 - |Q_R| <z>^2) \equiv M^2 \sim (10^{10} GeV)^2. \qquad (3.10)$$

- Tune the $<D>$ value to vanish cause even severe fine-tuning.
- Hidden sector involving large exponential of z_i can lead to exponential suppression relative to Planck scale after the singlets are integrated out. [Dreiner]
- Justify the cancelation of $-3|<W>|^2$ with $<D>^2$ contributions

SUSY Broken and Mass Spectrum

- Gravitino mass:

$$m_{3/2} = \kappa^2 < e^{\frac{\kappa^2 K}{2}} |W| > \sim \frac{M^2}{M_{Pl}} \sim 10^2 GeV. \qquad (3.11)$$

- Very high sparticle masses from positive $U(1)_R$ contributions.

$$\bar{y} y g_R^2 < D > \rightarrow m_{\tilde{S}} \sim 10^5 - -10^6 \mathrm{GeV}. \qquad (3.12)$$

  with tiny gauge coupling strength.
- R-gauge bosons obtain masses at order $g_R < z >$–several orders higher than sfermion masses.
- Singlet z_i do not enter the gauge kinetic function $f_{\alpha\beta}$, so gaugino mass can be generated by radiative corrections.
- R-Gauge nonsinglet S can also acquire scalar mass terms from D-term VEVs and gives the μ-term.
- Other terms from gravity mediation by assuming separated hidden and visible sector other than gravity.
- R-symmetry forbid unwanted B,L-violating terms.

Remarks

- An $SU(3)_c$ Octet is necessary to appear in low energy in order for $U(1)_R$ anomaly cancelation. Others choice is possible.
- It is possible to add GUT-preserving brane localized fields for the third generation to obtain anomaly free theory on the $y = 0$ brane.
- By adding proper GUT group singlets with non-trivial R-charge, we can obtain consistent theory with $R[\Psi] = -1$ for the third generations.
- Such input can be used to obtain natural SUSY in the low energy.
- Still in progress.

Thank you!