Discrete R symmetries for the MSSM and beyond

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based on work with

Raby, Ratz, Ross, Schieren, Schmidt-Hoberg & Vaudrevange,
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Outline

Motivation

- Supersymmetry, when being broken at TeV scale, is a technical solution to the hierarchy problem in SM.
- There are strong constraints on the soft SUSY breaking parameters by FCNC and CP violating processes.
- We focus on the constraints in the SUSY-preserving sector of MSSM.
- The most general effective superpotential being compatible with SM gauge symmetry in MSSM is

$$\begin{aligned} W &= \lambda_u H_u Q U^c + \lambda_d H_d Q D^c + \lambda_l H_d L E^c + \mu H_u H_d \\ &\quad + \mu' H_u L + \lambda L L E^c + \lambda' L Q D^c + \lambda'' U^c D^c D^c \\ &\quad + \frac{1}{M_P}(\lambda_1 QQQL + \lambda_2 U^c U^c D^c E^c + \lambda_3 QQQH_d + \cdots) \end{aligned}$$

- Phenomenological constraints are

$$\begin{aligned} \text{EWSB} &: \quad \mu \sim 10^{-16} M_P, \\ \text{Neutrino mass} &: \quad \mu' \leq 10^{-21} M_P, \\ \text{Proton stability} &: \quad \lambda'\lambda'' \leq 10^{-26}, \quad \lambda'\lambda_3 \leq 10^{-10}, \\ & \quad \lambda_1 \leq 10^{-8}, \quad \lambda_2 \leq 10^{-8}. \end{aligned}$$

- Global discrete symmetries are violated by gravity effects. So, discrete symmetries should be of gauge symmetry origin.
- Z_2 Matter-parity: allows the dim-5 proton decay operators.
- Z_3 Baryon-triality: forbids both dim-4 B violating operators and dimension-5 proton decay operators but allows dim-4 L violating operators. [Ibanez, Ross (1992)]
- Z_6 Proton-hexality ($= Z_2 \otimes Z_3$): forbids all dim-4 B/L violating operators and dim-5 proton decay operators.

  [Dreiner, Luhn, Thormeier (2005)]
- However, all these symmetries allow the problematic μ term.

Outline

Discrete R symmetries

- N=1 SUSY algebra contains a global $U(1)_R$ symmetry, e.g. for a chiral superfield $\Phi = \phi + \theta\psi + \theta^2 F_\phi$:

$$\Phi(\theta) \to e^{iq\alpha}\Phi(e^{-i\alpha}\theta);\ \phi \to e^{iq\alpha}\phi,\ \psi \to e^{i(q-1)\alpha}\psi.$$

- Discrete subgroups of the continuous $U(1)_R$ symmetry can arise as the discrete remnants of Lorentz group in compact dimensions in string compactifications. [Blaszczyk et al (2009)]
- Discrete Z_N^R symmetries can be anomaly-free with extra matters. [Kurosawa, Maru, Yanagida (2001); Hamaguchi, Maru (2003)]
- We consider the Green-Schwarz mechanism to cancel Z_N^R anomalies. The Z_4^R symmetry is the unique one satisfying the anomaly cancellation, $SO(10)$-compatibility, no tree-level μ term and all the known fermion masses.

- Suppose that the dilaton transforms as $\delta S = \frac{i}{2}\delta_{GS}$ under an anomalous $U(1)_A$. Then, the $U(1)_A$ anomalies appear from the variation of the following Green-Schwarz term,

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

where k_a are the Kac-Moody levels with $k_a = \frac{C_a}{2\pi^2\delta_{GS}}$ for the quantum $U(1)_A$ anomalies C_a. [Green, Schwarz (1984)]

- For level-1 gauge groups, we are led to the universal anomaly conditions,

$$2\pi^2\delta_{GS} = \frac{1}{24}\mathrm{tr}q = \frac{1}{3}\mathrm{tr}q^3 = \mathrm{tr}(l_G(r)q)$$

where $\mathrm{tr}(l_G(r)q)$ is the G-G-$U(1)_A$ mixed anomaly.

- For a non-R discrete Z_N, the universal anomaly conditions are

$$2\pi^2\delta_{GS} = \frac{1}{24}\mathrm{tr}q = \mathrm{tr}(l_G(r)q) \mod \eta$$

where $\eta = N(N/2)$ for odd(even) N and q is the Z_N charge.

- For a discrete Z_N^R, we have G-G-Z_N^R anomalies containing the gaugino contribution with R-charge α,

$$A_{G-G-Z_N^R} = \mathrm{tr}(l_G(r)q) + l(\mathrm{adj})\cdot\alpha \mod \eta.$$

So, the anomaly universality becomes different than the case of non-R discrete symmetries.

[Chamseddine, Dreiner (1996); K.-Y.Choi, HML (2009)]

Unique Z_4^R for the MSSM

[Babu, Gogoladze, Wang (2003); Lee et al (2010)]

- In MSSM with R-charges, q_{10_i} for 10_i and $q_{\bar{5}_i}$ for $\bar{5}_i$, the mixing $SU(3)_C$ and $SU(2)_L$ anomalies are

$$A_{3-3-Z_N^R} = \frac{1}{2}\sum(3q_{10_i} + q_{\bar{5}_i} - 4\alpha) + 3\alpha,$$
$$A_{2-2-Z_N^R} = \frac{1}{2}\sum(3q_{10_i} + q_{\bar{5}_i} - 4\alpha) + 2\alpha + \frac{1}{2}(q_H + q_{\bar{H}} - 2\alpha).$$

- The anomaly cancellation with $A_{3-3-Z_N^R} = A_{2-2-Z_N^R}$ mod η leads to the condition for the R-charges of Higgs doublets,

$$q_H + q_{\bar{H}} = 4\alpha \mod 2\eta.$$

$\Rightarrow$ The μ term is forbidden because $H\bar{H}$ has R-charge 2α.
[cf. A non-R Z_N with $\alpha = 0$ does not forbid the μ term.]

- For Z_N^R commuting with $SO(10)$, $q_{10_i} = q_{\bar{5}_i} = q$: the quark and charged lepton masses and the Weinberg operator $(LH_u)^2$ for neutrino masses yields

$$\begin{aligned} 2q + q_H &= 2\alpha \mod N, \\ 2q + q_{\bar{H}} &= 2\alpha \mod N, \\ 2q + 2q_H &= 2\alpha \mod N. \end{aligned}$$

- The solution is $q_H = q_{\bar{H}} = 0 \mod N$ and $2q = 2\alpha \mod N$. Then, with $\alpha = 1$, the Z_4^R symmetry is the unique one forbidding the μ term.
- The Z_4^R symmetry also forbids all the dangerous B/L violating terms in MSSM.
- The Z_4^R symmetry is embeddable in string compactifications.

[Blaszczyk et al (2009)]

$U(1)_Y$-mixed and pure Z_N^R anomalies

- When hypercharge Y is normalized by the underlying GUT, the $U(1)_Y - U(1)_Y - Z_N^R$ anomaly is

$$A_{1-1-Z_N^R} = \frac{3}{5}\Big\{2\Big(\frac{1}{2}\Big)^2[q_H + q_{\bar{H}} - 2] +3(q_{\bar{5}} - 1)\Big[2\Big(\frac{1}{2}\Big)^2 + 3\Big(\frac{1}{3}\Big)^2\Big] +3(q_{10} - 1)\Big[6\Big(\frac{1}{6}\Big)^2 + 3\Big(\frac{2}{3}\Big)^2 + (1)^2\Big]\Big\}.$$

- The $U(1)_Y$ anomaly coefficient is not invariant under shifting charges by multiples of N so the there must be a charge assignment satisfying the anomaly universality.
- For the case of Z_4^R, $A_{3-3-Z_4^R} = A_{2-2-Z_4^R} = 1 \bmod 2$. Thus, the anomaly universality is satisfied for $q_H = q_{\bar{H}} = -4$.

- The $(Z_N^R)^3$ anomaly does not yield model independent constraints as it depends on the charge normalization non-linearly. [Banks, Dine(1992); Araki et al(2008)]
- On the other hand, the grav-grav-Z_N^R anomaly is of potential interest for phenomenology, because additional light singlets may be necessary:

$$\begin{aligned} A_{g-g-Z_N^R} &= -21+8+3+1+3[10(q_{10}-1)+5(q_{\bar{5}}-1)] \\ &\quad +2(q_H+q_{\bar{H}}-2) = 24A_{G-G-Z_N^R} \mod \eta. \end{aligned}$$

- For the case of Z_4^R, this becomes $-9-4=24$ mod 2, which is not satisfied. So, there must be additional SM singlet fermions with R-charges such that the sum is odd. In the presence of GS mechanism, the dilatino cancels the grav-grav-Z_4^R anomaly.

Outline

R symmetry breakdown and the μ term

- The μ term is generated by

$$\int d^4\theta X^\dagger H\bar{H} + \text{h.c.} \quad \text{or} \quad \int d^2\theta Y H\bar{H} + \text{h.c.}$$

  where X, Y are singlets having R-charges, 0 and 2, respectively. A nonzero F-term of X or a scalar vev of Y breaks Z_4^R, leaving the unbroken Z_2, which corresponds to R-parity in MSSM.
- In our case, the Z_4^R symmetry breaks down through a nonzero superpotential vev coming from non-perturbative effects. Identifying Y with $\langle W\rangle$, the μ term is of order $\frac{\langle W\rangle}{M^2}$ with M being the messenger scale by Giudice-Masiero mechanism.

[Giudice, Masiero (1988)]

- When the Higgs doublets come from the Wilson lines of extra dimensions, the higher dimensional gauge invariance leads to Kähler potential,

$$K = K_0 + |H|^2 + |\bar{H}|^2 + (H\bar{H} + \mathrm{h.c.}) + \cdots$$

  In supergravity, the holomorphic coupling $H\bar{H}$ in Kähler potential, leads to the μ term, $\langle W \rangle H\bar{H}$.
- When the gaugino condensate in hidden sector exists, it can couple to the Higgs bilinear in the R-covariant form,

$$W_{np} = e^{-bS}(AH\bar{H} + \kappa QQQL)$$

  where b is constant and A, κ are constants built of some field VEVs.
- For $\frac{\langle W \rangle}{M_P^2} \sim Ae^{-bS}$, the μ term is of order the gravitino mass while the coefficients of the dimension-5 proton decay operators are as small as $10^{-15}/M_P$.

Outline

1. Discrete R symmetries
2. R symmetry breakdown and the μ term
3. $SU(5)$-compatible extensions

$SU(5)$-compatible extensions

- For the Z_N^R being compatible with $SU(5)$, the anomaly universality, leads to more Z_N^R's with N being the divisor of 24.
- Allowing Yukawa couplings and Weinberg operators and no R-parity violating couplings leads to $N = 4, 6, 8, 12, 24$. All but Z_6^R are anomalous, requiring a Green-Schwarz mechanism.
- For Z_8^R, the NMSSM is possible by including a singlet N:

$$W = \lambda N H \bar{H} + \kappa N^3.$$

- For higher order Z_N^R's than Z_8^R, the μ term is generated by an intermediate-scale vev of an singlet S:

$$W = \frac{1}{M_P}(\lambda S^2 H \bar{H} + \kappa S^4).$$

- In the case of Z_{12}^R, the axion coming from the singlet S solves the strong CP problem too.

Conclusion

- We have obtained the unique Z_4^R symmetry being compatible with $SO(10)$ in MSSM, solving the problems of the μ term and the dimension-5 proton decay operators.
- In the case of Z_4^R, the μ term of order the gravitino mass is generated by Giudice-Masiero mechanism.
- The Z_4^R symmetry is of possible origin from the isometry of internal dimensions in string compactifications and the supergravity coupling for the μ term is due to the higher dimensional gauge invariance of the Higgs doublets.
- There are more interesting Z_N^R models, which are compatible with $SU(5)$ and are beyond the MSSM by having light singlets or the axion.