



Split Supersymmetry

A Model Building Approach

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UC Riverside HEP Seminar

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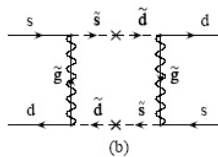
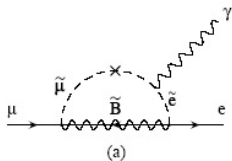
- Gauge Hierarchy Problem

$$\frac{M_{\text{Pl}}}{M_{\text{EW}}} \sim 10^{17}$$

- Naturalness Problem

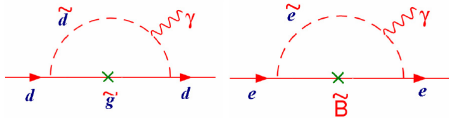
$$\Delta m_H^2 = \frac{3\lambda_t^2}{8\pi^2} \Lambda^2 + \mathcal{O}$$

Low Energy SUSY



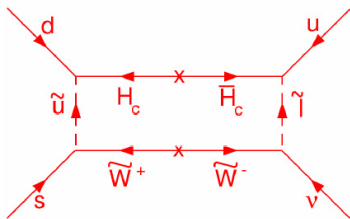
GIM mechanism in SMSoft sector?

Phases in the soft SUSY breaking sector contribute to EDM.



$$\mathcal{L}_{\text{eff}} \sim -\frac{i}{2} d_f \bar{\psi} \sigma_{\mu\nu} \gamma_5 \psi F^{\mu\nu}$$

Proton Decay in SUSY GUTs



$p \rightarrow K^+ \bar{\nu}$

$$\tau_p^{-1} \approx \left(\frac{f^2}{M_{H_c} M_{\text{SUSY}}} \right)^2 \left(\frac{\alpha}{4\pi} \right)^2 m_p^5$$

- Gauge Coupling Unification
 $\sin^2_{\theta} W(M_Z)_{\text{exp}} = 0.23018 \pm 0.00005$
- Evidence of dark matter from WMAP $\Omega_{DM} \simeq 23\%$
- No electric dipole moment $d_e < 2.1 \times 10^{-27} \text{ ecm}$
- No rare lepton decay $\text{Br}(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11}$
- $K_0 - \bar{K}_0$ mixing $\sin^2 \theta_{\tilde{d}} (\Delta m_{\tilde{d}}^2 / \bar{m}_{\tilde{d}}^2)^2 (30 \text{ TeV} / \bar{m}_{\tilde{d}})^2 \lesssim 1$

LOW ENERGY SUSY? SUSY BREAKING?



Gauge Mediated: Universal

Exotic Matter Giudice & Rattazzi, 1998

String Dilaton Mediated: Universal

Stabilization of Dilation Potential Arkani-Hamed et al, 1998

Anomalous $U(1)$ mediated and flavor symmetry: Decoupled

- Gaugino mass (How to suppress SUGRA) Binetruy & Dudas, 1996; Dvali & Pomarol, 1997; Mohapatra & Ritto, 1997
- Negative squark mass (potentially breaks $SU(3)_C$) Arkani-Hamed & Murayama, 1997

$$\frac{1}{g_W^2} \int d^2\theta \sum_a k_a \text{Tr} W_\alpha^a W_{a\alpha} + \text{h.c.}$$
$$\frac{1}{g_W^2} = S - \nu\Theta \text{ or in string : } \frac{1}{g_{\text{st}}^2} = \frac{S + S^\dagger}{2}$$
$$\int d^2\theta \frac{S}{4} \sum_a k_a \text{Tr} W_\alpha^a W_{a\alpha} + \text{h.c.}$$

Chiral field S as a background field and has zero mass dimension

Universal sfermions mass (gauge coupling)

Gaugino Mass

Question: How to Stabilize the Dilaton potential



Anomalous $U(1)_A$ Mediated SUSY Breaking

Dvali & Pomarol, 1996; Mohapatra & Riotto, 1997

Hidden sector and observable sector are both charged under Anomalous $U(1)$.

Only ϕ_- is negatively charged.

$$W = \mu' \phi_+ \phi_- + W_{\text{MSSM}}$$

$$F_{\phi_+} = \mu' \phi_-; \quad F_{\phi_-} = \mu' \phi_+; \quad D = \left(\sum_i q_i |\tilde{Q}_i|^2 + |\phi^+|^2 - |\phi^-|^2 + \xi \right)$$

where

$$\xi = \frac{g^2 \text{Tr} Q_i}{192 \pi^2} M_{\text{Pl}}^2$$



$$\begin{aligned}
 V &= \sum_i |F_i|^2 + \frac{g^2}{2} D^2 \\
 &= -(\mu'^2 - \xi g^2) |\phi_-|^2 + \frac{g^2}{2} |\phi_-|^4 + (\mu'^2 + \xi g^2) |\phi_+|^2 + \frac{g^2}{2} |\phi_+|^4
 \end{aligned}$$

\Rightarrow

$$\begin{aligned}
 \langle |\phi_-| \rangle &= \sqrt{\xi - \mu'^2/g^2} \equiv \epsilon M_{\text{Pl}} \\
 \langle |\phi_+| \rangle &= 0 \\
 \langle |F_{\phi_+}| \rangle &= \mu' \langle |\phi_-| \rangle = \mu' \sqrt{\xi - \mu'^2/g^2} = \mu' \epsilon M_{\text{Pl}} \\
 \langle |F_{\phi_-}| \rangle &= \mu' \langle |\phi_+| \rangle = 0 \\
 \langle D \rangle &= \mu'^2/g^2
 \end{aligned}$$

$$\epsilon \sim 0.2$$



Anomalous $U(1)_A$ vs SUGRA

Soft scalar mass from F_{ϕ_+}

$$\int d^4\theta \frac{\phi_+^\dagger \phi_+ Q^\dagger Q}{M_{\text{Pl}}^2} \Rightarrow \frac{F_{\phi_+}^2}{M_{\text{Pl}}^2} \tilde{Q}^\dagger \tilde{Q}$$

$$m_Q^2 \sim \epsilon^2 \mu'^2$$

Gaugino

$$\int d^2\theta W_\alpha W^\alpha \frac{\phi_+ \phi_-}{M_{\text{Pl}}^2} \sim \epsilon^2 \mu'$$



D-term contribution: \Rightarrow sfermion mass splitting

$$m_{Q_i}^2 = q_i \mu'^2$$

$m_{\tilde{Q}}^2$: $q\mu'^2 \gg \epsilon^2 \mu'^2$ *D*-term Dominate

(*F*-term of the dilaton *S* depends on stabilization of dilaton potential.)

Naturally Split!!

$$\frac{m_\lambda}{m_{\text{SUSY}}} \sim \frac{\epsilon^2}{q} \sim 10^{-3}$$

Babu, et al, 2005



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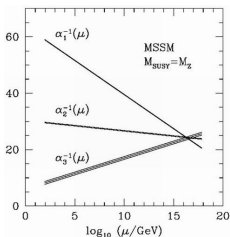
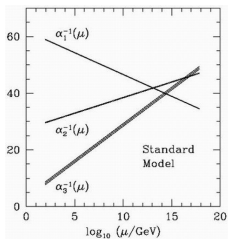
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Gauge Couplings Unification



$$b_3 = -11 + \frac{4}{3} N_g;$$

$$b_3 = -9 + 2N_g$$

$$b_2 = -\frac{22}{3} + \frac{4}{3} N_g + \frac{1}{2} n_H; \quad b_2 = -6 + 2N_g + \frac{1}{2} n_H$$

$$b_1 = \frac{4}{3} N_g + \frac{1}{10} n_H; \quad b_1 = 0 + 2N_g + \frac{3}{10} n_H$$

Matters belong to the GUT multiplets.



- A phenomenological viable theory from bottom-up approach
 - SUSY gauge unification
 - Dark matter candidate
 - Suppressed FCNC
 - Suppressed large CP violation
- Well motivated from string theory
- Fine-tuning may bring in new theoretical interests.

How to realize a split spectrum?

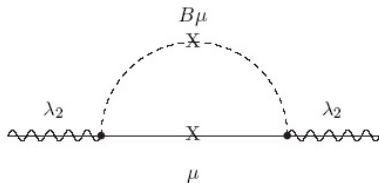
Motivations

Threshold correction in the split SUSY limit

A explicit gauge mediated model $U(1)_{B-L} \times U(1)_R$

- Model
- Other phenomenological feature
- Implications

Threshold Correction at the Split SUSY Limit



$$M_{\lambda_2} = \frac{\alpha_2}{4\pi} \mu \sin 2\beta \left[\frac{m_H^2}{\mu^2 - m_H^2} \log \left(\frac{\mu^2}{m_H^2} \right) - \frac{m_h^2}{\mu^2 - m_h^2} \log \left(\frac{\mu^2}{m_h^2} \right) \right]$$

$$m_H \gg m_\mu \gg m_h$$

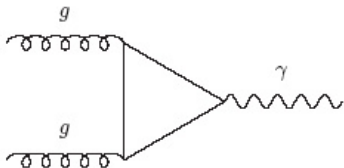
$$M_{\lambda_2} \simeq \frac{\alpha_2}{4\pi} \mu \sin 2\beta \log \left(\frac{m_H^2}{\mu^2} \right)$$

Heavy vectorial matter: heavy fermions as well as heavy scalars



Solutions to the μ -term Problem

μ -term: Another independent fine-tuning in split SUSY?



$$\begin{aligned} A_3 &= 3\alpha + \frac{3}{2}(2(q - \alpha) + (u - \alpha) + (d - \alpha)) \\ &= 3\alpha - \frac{3}{2}(h_u + h_d) \\ q + u + h_u &= 2\alpha, \quad q + d + h_d = 2\alpha \end{aligned}$$

Induce mixed QCD anomaly $A_{[SU(3)_C]^2 \times G}$

The symmetry that ensures the absence of bare μ -term in the superpotential carries mixed QCD anomaly and is broken explicitly by anomaly thus a "Goldstone" induced.

To address the μ -term problem from a gauge symmetry model

- Cancel mixed QCD anomaly by adding exotic quarks?
- Cancel the mixed QCD anomaly via Green-Schwarz Mechanism?



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Threshold Corrections from Heavy Exotic Quarks!!!

Possible Solution

SUSY DSFZ axion+ Anomalous $U(1)_A$
Dynamical Generated M_{PQ}



Under $SU(2)_L \times U(1)_R \times U(1)_{B-L}$ Mohapatra & Nandi, 1997

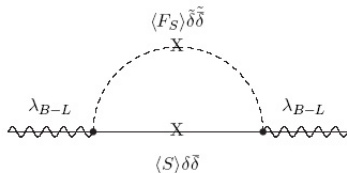
$$\begin{array}{lll} Q(2, 0, 1/3); & L(2, 0, -1); & u^c(1, -1/2, -1/3) \\ d^c(1, 1/2, -1/3); & e^c(1, 1/2, 1); & \nu^c(1, -1/2, 1) \\ H_u(2, 1/2, 0); & H_d(2, -1/2, 0) & \end{array}$$

Higgs fields

$$\delta(1, 1, -2); \bar{\delta}(1, -1, 2); S(1, 0, 0)$$

$$W = Qu^c H_u + Qd^c H_d + Le^c H_d + L\nu^c H_u + \delta\nu^c \nu^c + \mu H_u H_d$$

- $SO(10)$ GUT
- "Seesaw" mechanism for generation of small neutrino mass
- Z_2 subgroup of $U(1)_R$ as an Automatic discrete gauge R -parity



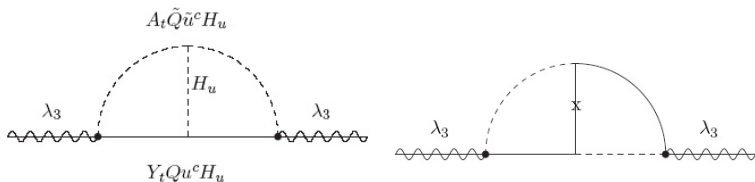
$$W = S \delta \bar{\delta}, \quad \Lambda_S = \frac{\langle F_S \rangle}{\langle S \rangle}$$

$$M_\lambda = \frac{-\alpha_{B-L} - \alpha_R}{4\pi} \Lambda_S$$

$$M_F^2 \simeq 2 \left[x_F^2 \left(\frac{\alpha_{B-L}}{4\pi} \right)^2 \Lambda_S^2 + y_F^2 \left(\frac{\alpha_R}{4\pi} \right)^2 \Lambda_S^2 \right]$$



SM Gaugino Masses



A-term and $B - L$ gaugino induced Gluino Mass

$$A_t = \frac{\alpha}{4\pi} M_\lambda \log\left(\frac{M}{M_\lambda}\right) = \left(\frac{\alpha}{4\pi}\right)^2 \frac{F}{M} \log\left(\frac{M}{M_\lambda}\right)$$

$$M_i = 2C_i \frac{\alpha_i \alpha_t}{(4\pi)^2} A_t \log\left(\frac{M}{M_{\tilde{f}}}\right)$$



$$M \rightarrow M_{\tilde{f}}$$

$$\frac{d}{dt} M_a = \frac{2g_a^2}{(16\pi^2)^2} g_1^2 B_a M_\lambda + \dots$$

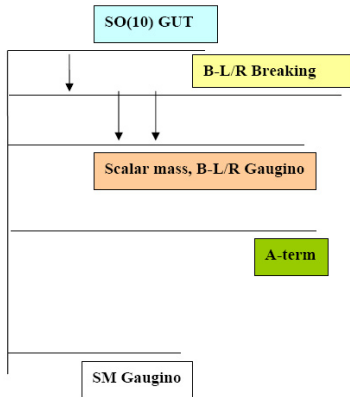
$$B_1 = 4 \left\{ N_G \left[N_c \left(2z_Q^2 Y_Q^2 + z_U^2 Y_U^2 + z_D^2 Y_D^2 \right) + 2z_L^2 Y_L^2 + z_E^2 Y_E^2 \right] + z_{H_u}^2 Y_{H_u}^2 + z_{H_d}^2 Y_{H_d}^2 \right\}$$

$$B_2 = 2 \left[N_G \left(N_c z_Q^2 + z_L^2 \right) + z_{H_u}^2 + z_{H_d}^2 \right]$$

$$B_3 = 2N_G \left(2z_Q^2 + z_U^2 + z_D^2 \right)$$

$$z_F = \frac{g_R}{g_{B-L}} I_{3R} - \frac{g_{B-L}}{g_R} \left(\frac{B-L}{2} \right), \quad Y_F = I_{3R} + \left(\frac{B-L}{2} \right)$$





Most of RGE Runnings locate between $B - L$ breaking scale and $B - L$ gaugino mass scale

Explicit Numeric Example

$$\begin{aligned}\langle F_S \rangle &\simeq 10^{20} \text{ GeV}^2 \\ \langle S \rangle &\simeq 10^{12} \text{ GeV} \\ M_\lambda(B - L/R) &\simeq 10^7 \text{ GeV} \\ M_{\tilde{f}} &\simeq 10^7 \text{ GeV} \\ A_t &\simeq 10^5 \text{ GeV} \\ M_i &\simeq 10^2 \text{ GeV}\end{aligned}$$



$$\int d^2\theta W_\alpha W^\alpha \frac{S}{M_{\text{Pl}}} \sim \frac{\langle F_S \rangle}{M_{\text{Pl}}}$$
$$\int d^4Q^\dagger Q \frac{S^\dagger S}{M_{\text{Pl}}^2} \sim \left(\frac{\langle F_S \rangle}{M_{\text{Pl}}} \right)^2$$

Longer lived Gluino

A. Arvanitaki, C. Davis, P.W. Graham, A. Pierce, J.G. Wacker hep-ph/0504210

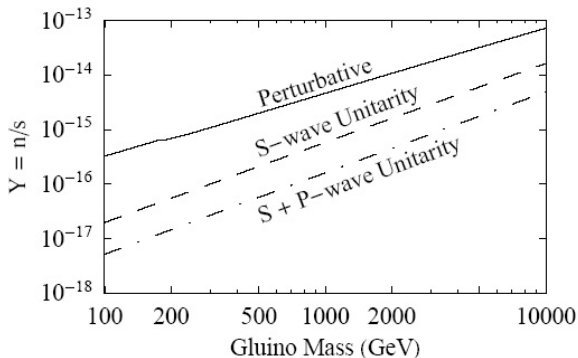


Figure 1: Gluino abundance per co-moving volume as a function of mass. Three curves are shown. In the first (solid), the annihilation cross section is assumed to be simply given by the perturbative cross section of Eqn. 3. The other curves correspond to a cross section that saturates s -wave (dashed) and s -wave plus p -wave unitarity (dot-dashed).



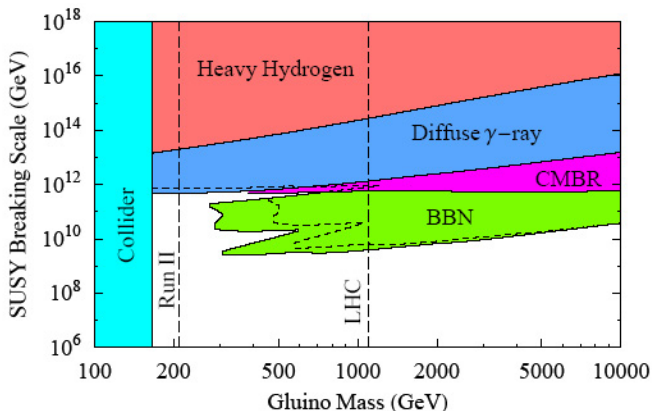
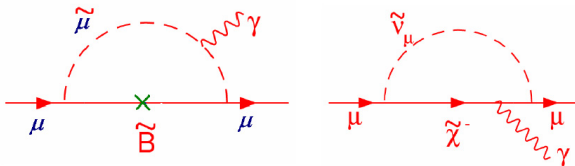


Figure 2: Limits on the supersymmetry breaking scale, m_S , as a function of the gluino mass, $m_{\tilde{g}}$. The bounds are derived assuming a perturbative cross section in Eqn. 3 for temperatures greater than the QCD phase transition, $T > 200$ MeV. For $T < 200$ MeV, we assume that the annihilation cross section saturates s -wave unitarity. Also shown (dashed) are the limits in the case where the annihilation cross section saturated s -wave plus p -wave unitarity. The shaded regions are excluded. The lower edge of the BBN curve arises from the requirement that the D/H ratio remained undisturbed, and corresponds to a lifetime of approximately 100 seconds.

- Predictable SM gaugino masses spectrum: Distinguishable from other split SUSY models
- Bino LSP as dark matter candidate
- Gauge coupling unification by imposing $SO(10)$ normalization
- No FCNC from GMSB (SUGRA contribution suppressed)
- Less CPV phase
- Longer lived gluinos
-

Muon $g - 2$ a_μ



$$\mathcal{L}_{\text{eff}} = \frac{a_\mu}{2m_\mu} \bar{\psi} \sigma_{\mu\nu} \psi F^{\mu\nu}$$

$$\delta a_\mu \simeq \frac{\alpha_2}{8\pi} \frac{m_\mu^2}{M_{\text{SUSY}}^2} \tan \beta$$

Light L ? Unification?