SUSY breaking, hybrid $\mathcal{N} = 1/2$ theories, and the nature of *.inos

Daniel Busbridge
Supervised by: Valya Khoze and Steve Abel

Institute for Particle Physics Phenomenology
Durham University

Young Theorists' Forum 2011, Durham

Outline

1. Concepts
   - What is SUSY?
   - Irreducible representations of $\mathcal{N} = 1$ SUSY
2. Spontaneous ~~SUSY~~
   - The Sad Truth
   - Generic Features
3. Dirac *.inos
   - Dirac vs. Majorana Fermions
   - Parameter space limitations
   - $R-$symmetry
4. MRSSM
   - Higgs Sector
5. Optional extras

SUSY is a space-time (ST) symmetry

$$\left.\begin{array}{rcl} Q|\text{Fermion}\rangle & = & |\text{Boson}\rangle \\ Q|\text{Boson}\rangle & = & |\text{Fermion}\rangle \end{array}\right\} Q\text{s generate a ST symmetry}$$

$$\{Q, Q^\dagger\} = P \Longleftrightarrow [\theta Q, \theta^\dagger Q^\dagger] = \theta\theta^\dagger P$$

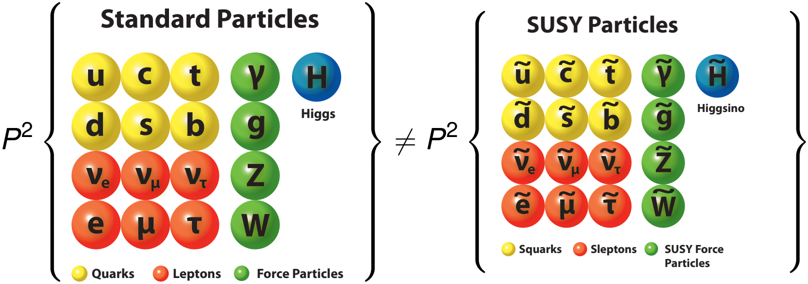
An Introduction to Superspace

$$x \longrightarrow (x, \theta, \theta^\dagger)$$
$$s(x) \longrightarrow S(x, \theta, \theta^\dagger)$$

$$\Phi = \phi + \theta\psi + \theta^2 F + \ldots$$
$$\mathbf{V} = \theta\theta^\dagger A + \theta^{\dagger 2}\theta\lambda + \theta^2\theta^{\dagger 2} D + \ldots$$
$$\mathbf{W}_\alpha = \lambda_\alpha + \theta_\alpha D + \ldots$$

Evidence

- Degeneracy in (s)particle mass spectrum not observed

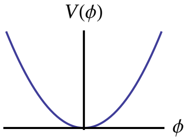


- If SUSY is realized, it is broken at low energies

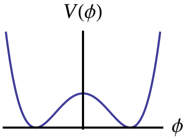
Properties

- Theory is SUSY but scalar potential V admits ~~SUSY~~ vacua

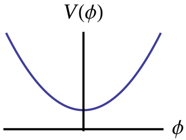
$$Q|\text{vacuum}\rangle \neq 0 \Longleftrightarrow V(\text{vacuum}) > 0$$



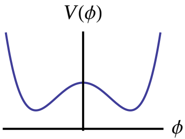
GAUGE SUSY



~~GAUGE~~ SUSY



GAUGE ~~SUSY~~



~~GAUGE~~ ~~SUSY~~

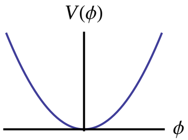
Recipe

- $U(1)$ VSF spurion $\langle \mathbf{W}_\alpha \rangle = \theta_\alpha D$
- Gauge-singlet χSF spurion $\langle \mathbf{X} \rangle = \theta^2 F$

How does this work?

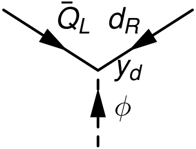
The Standard Model Higgs Mechanism

$$\Lambda > \Lambda_{\rm EWSB}$$



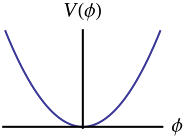
GAUGE

$$-\mathcal{L} \supset y_d \bar{Q}_L \phi d_R$$



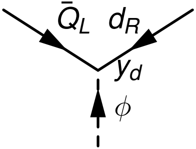
The Standard Model Higgs Mechanism

$$\Lambda > \Lambda_{\text{EWSB}}$$



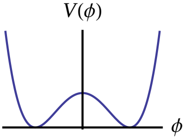
GAUGE

$$-\mathcal{L} \supset y_d \bar{Q}_L \phi d_R$$



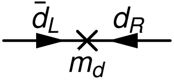
$$\Lambda < \Lambda_{\text{EWSB}}$$

$$\phi \longrightarrow (0, \nu + H)$$



~~GAUGE~~

$$-\mathcal{L} \supset \underbrace{y_d \nu}_{m_d} \bar{d}_L d_R$$

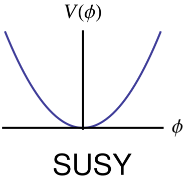


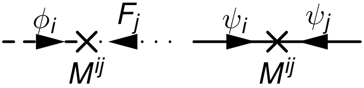
SUSY Breaking in Wess-Zumino Model

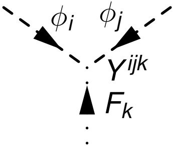
$$\Lambda > \Lambda_{\not{SUSY}}$$

$$\mathcal{L} = \int d^2\theta \underbrace{M^{ij}\Phi_i\Phi_j + Y^{ijk}\Phi_i\Phi_j\Phi_k}_{W(\Phi_i)} + \text{h.c.} + \int d^2\theta d^2\theta^\dagger \underbrace{\Phi^{*i}\Phi_i}_{K(\Phi^{*i},\Phi_i)}$$

$$\supset -M^{ij}\left(\phi_i F_j + \psi_i\psi_j\right) - Y^{ijk}\phi_i\phi_j F_k + \text{h.c.} + F^{*i}F_i$$





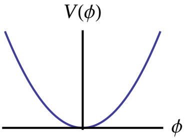


SUSY Breaking in Wess-Zumino Model

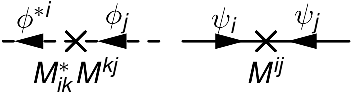
$$\Lambda > \Lambda_{\not{\text{SUSY}}}$$

$$\mathcal{L} = \int d^2\theta \underbrace{M^{ij}\Phi_i\Phi_j + Y^{ijk}\Phi_i\Phi_j\Phi_k}_{W(\Phi_i)} + \text{h.c.} + \int d^2\theta d^2\theta^\dagger \underbrace{\Phi^{*i}\Phi_i}_{K(\Phi^{*i},\Phi_i)}$$

$$\supset -M^*_{ik}M^{kj}\phi^{*i}\phi_j - M^{ij}\psi_i\psi_j$$



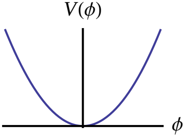
SUSY



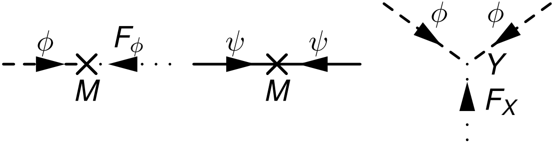
SUSY Breaking in Wess-Zumino Model

$$\Lambda > \Lambda_{\not{\text{SUSY}}}$$

$$\mathcal{L} = \int d^2\theta \left(M\Phi^2 + Y\Phi^2 X \right) + \text{h.c.} + \int d^2\theta d^2\theta^\dagger \Phi^* \Phi$$
$$\supset -M\,(\phi F_\phi + \psi\psi) - Y\phi\phi F_X + \text{h.c.} + |F_\phi|^2 + |F_X|^2$$



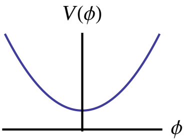
SUSY



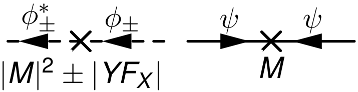
SUSY Breaking in Wess-Zumino Model

$$\Lambda < \Lambda_{\not{\text{SUSY}}} \quad \langle X \rangle = \theta^2 F$$

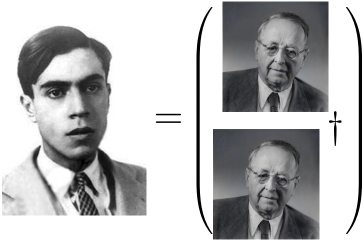
$$\mathcal{L} = \int d^2\theta \left(M\Phi^2 + Y\Phi^2 X \right) + \text{h.c.} + \int d^2\theta d^2\theta^\dagger \Phi^* \Phi$$
$$\supset -M\psi\psi - (|M|^2 \pm |YF_X|)|\phi_\pm|^2$$



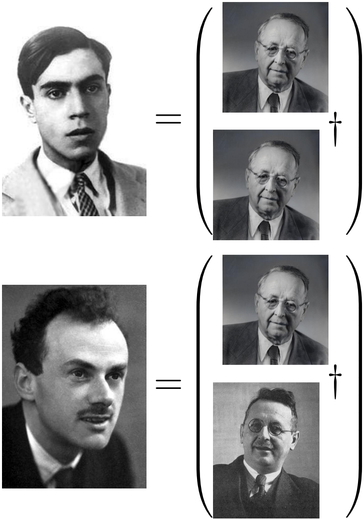
$\not{\text{SUSY}}$



Dirac and Majorana particles



Dirac and Majorana particles



Mass terms

Majorana mass

$$-\mathcal{L}_{\text{Majorana}} \supset M_M \bar{\Psi}_M \Psi_M = M_M(\xi\xi + \xi^\dagger \xi^\dagger) \qquad \Psi_M = \begin{pmatrix} \xi \\ \xi^\dagger \end{pmatrix}$$

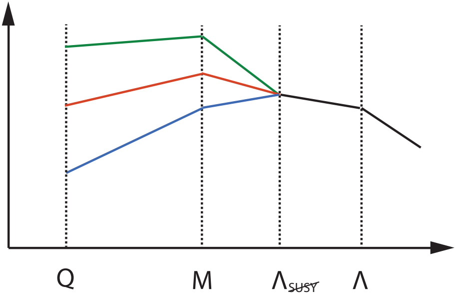
Dirac mass

$$-\mathcal{L}_{\text{Dirac}} \supset M_D \bar{\Psi}_D \Psi_D = M_D(\xi\chi + \xi^\dagger \chi^\dagger) \qquad \Psi_D = \begin{pmatrix} \xi \\ \chi^\dagger \end{pmatrix}$$

$$-\mathcal{L}^{\text{MSSM}}_{\text{soft}} \supset M_3\, \widetilde{\text{g}}\widetilde{\text{g}} + M_2\, \widetilde{\text{W}}\widetilde{\text{W}} + M_1\, \widetilde{\text{B}}\widetilde{\text{B}}$$

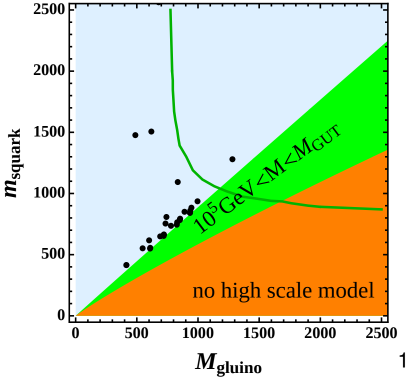
Approximate SQCD β Functions

$$\frac{d}{dt} m_{\tilde{q}}^2 \sim m_{\tilde{q}}^2 + M_{\tilde{g}}^2$$
$$\frac{d}{dt} M_{\tilde{g}} \sim M_{\tilde{g}}$$



$$m_{\tilde{q}}^2(Q) \sim m_{\tilde{q}}^2(M) + a\, m_{\tilde{q}}^2(M) + b\, M_{\tilde{g}}^2(Q)$$

The Forbidden Zone



[1]

[1] Jaeckel, J., Khoze, V. V., Plehn, T., & Richardson, P. (2011). Travels on the squark-gluino mass plane. http://arxiv.org/abs/1109.2072

What is $R-$symmetry?

$$\{Q, Q^\dagger\} = P$$

Invariant under

$$Q \rightarrow e^{iR_Q\theta} Q, \quad Q^\dagger \rightarrow Q^\dagger e^{-iR_Q\theta}, \quad P \rightarrow P$$

Choose $R_Q = -1$

$$[Q, R] = Q \qquad [\theta, R] = -\theta$$
$$[Q^\dagger, R] = -Q^\dagger \qquad [\theta^\dagger, R] = \theta^\dagger$$

R-charge of Gauginos

$$V = V^\dagger \implies R_V = 0$$

$$V \supset \theta^{\dagger 2}\theta\lambda$$

$$R_\theta = -R_{\theta^\dagger} = 1 \implies R_\lambda = 1$$

Majorana Gaugino Masses

$$-\mathcal{L}^{\text{gaugino}}_{\text{Majorana}} \supset M_M(\lambda\lambda + \lambda^\dagger\lambda^\dagger)$$

$$\lambda\lambda \xrightarrow{U(1)_R} e^{2i\theta}\lambda\lambda$$

Majorana gaugino masses violate $U(1)_R$ symmetry

Dirac Gaugino Masses

$$-\mathcal{L}_{\text{Dirac}} \supset M_D(\lambda\chi + \lambda^\dagger\chi^\dagger)$$

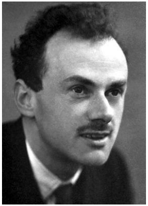
$$\lambda\chi \xrightarrow{U(1)_R} e^{i(1+R_\chi)\theta}\lambda\chi$$

Dirac gaugino masses can preserve $U(1)_R$ symmetry

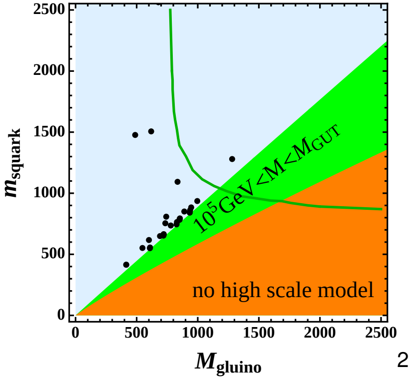
The idea

$U(1)_R$ $\longleftrightarrow$ $\not{U(1)}_R$

$M_M \to 0$ $\quad M_M \sim M_D \quad$ $\frac{M_M}{M_D} \gg 1$



The Forbidden Zone



[2]

[2] Jaeckel, J., Khoze, V. V., Plehn, T., & Richardson, P. (2011). Travels on the squark-gluino mass plane. http://arxiv.org/abs/1109.2072

Minimal Dirac Gauginos

$$R_{\chi_g} = -1, \quad \mathbf{O}_g \supset \theta \chi_g, \quad \langle \mathbf{W}'_\alpha \rangle = \theta_\alpha D$$

Names	Superfield	$SU(3)_C$	$U(1)_R$
RHGs	$\mathbf{O}_g$	**Ad**	0
GFs	$\mathbf{W}_{3\alpha}$	**Ad**	1

$$\mathcal{L}^{\rm Dirac}_{\rm gluino} = \int d^2\theta \frac{\mathbf{W}'^\alpha}{\Lambda} \mathrm{Tr}\left[\mathbf{W}_{3\alpha} \mathbf{O}_g\right] \supset -m_D \lambda_3 \chi_g$$

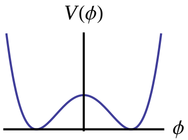
$$m_D = \frac{D}{\Lambda} \tag{1}$$

$\mathcal{N} = 2$ vector multiplet $(\mathbf{O}_g, \mathbf{V}_3)$

MSSM Higgs

$$W_{\text{MSSM}} = y_u \bar{\mathbf{u}}\mathbf{Q}\cdot\mathbf{H}_u + y_d \bar{\mathbf{d}}\mathbf{Q}\cdot\mathbf{H}_d + \mu \mathbf{H}_u\cdot\mathbf{H}_d + \cdots$$

$$\Lambda < \Lambda_{\text{EWSB}}$$



~~GAUGE~~

$$H_u^0 \longrightarrow v_u + \cdots$$
$$H_d^0 \longrightarrow v_d + \cdots$$

$$\mathcal{L} \supset \int d^2\theta W(\Phi_i) \supset -\mu \tilde{\mathbf{H}}_u \cdot \tilde{\mathbf{H}}_d$$

Dirac Higgsinos

Superfield	$SU(2)_L$	$U(1)_Y$	$U(1)_R$
$\mathbf{H}_u$	$\square$	$\frac{1}{2}$	0
$\mathbf{R}_d$	$\square$	$\frac{1}{2}$	2
$\mathbf{H}_d$	$\square$	$-\frac{1}{2}$	0
$\mathbf{R}_u$	$\square$	$-\frac{1}{2}$	2

$$W_{\text{Higgs}} = \left(\mu_u + \lambda_u^S \mathbf{S}\right) \mathbf{H}_u \cdot \mathbf{R}_u + \lambda_u^T \mathbf{H}_u \cdot \mathbf{T}\mathbf{R}_u + (u \leftrightarrow d)$$

$\mathcal{N} = 2$ Hypermultiplet $(\mathbf{H}_u, \mathbf{R}_d)$

Is $R-$symmetry useful?

- Dangerous $\Delta L = \Delta B = 1$ operators forbidden
- Proton decay through $Q_L Q_L Q_L L_L$, $U_R U_R D_R E_R$ forbidden
- Majorana Neutrino mass $H_u H_u L_L L_L$ allowed[3]

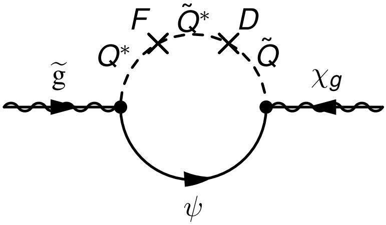
[3] Kribs, G., Poppitz, E., & Weiner, N. (2008). Flavor in supersymmetry with an extended R symmetry. Physical Review D, 78(5) 055010

Summary of MRSSM

- All *.inos are Dirac
- Higgs and Gauge sector form $\mathcal{N} = 2$ representations
- Gauginos much heavier than squarks possible

Outlook

- High-scale completion? Gauge mediation?[4]



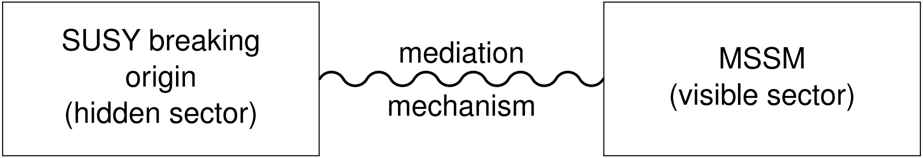
- Create a consistent effective theory at the high scale
- Identify important phenomenology using simplified models

[4] Benakli, K., & Goodsell, M. D. (2008). Dirac Gauginos in GGM. arXiv:0811.4409

Thanks

Thanks for listening!

Where to Break Supersymmetry
Hidden sectors



How to Communicate ~~SUSY~~

Tree-level?

How to Communicate ~~SUSY~~

Tree-level?

- Supertrace Theorem:

$$\left.\begin{array}{c}\text{tree level communication}\\ +\\ \text{renormalizable couplings}\end{array}\right\} \begin{array}{c}\text{SUSY partner lighter}\\ \text{than SM counterpart}\end{array}$$

How to Communicate ~~SUSY~~

Tree-level?

- Supertrace Theorem:

$$\left.\begin{array}{c}\text{tree level communication}\\ +\\ \text{renormalizable couplings}\end{array}\right\} \begin{array}{c}\text{SUSY partner lighter}\\ \text{than SM counterpart}\end{array}$$

- Non-renormalizable $\implies$ Planck-Scale Mediated ~~SUSY~~
- Non-tree-level $\implies$ Gauge Mediated ~~SUSY~~ (GMSB)

Particle Content and Superpotential

blank

Messenger mass spectrum

Messenger mass spectrum

	m^2
$\phi, \bar{\phi}$	$M^2 \pm F^2$
$\psi, \bar{\psi}$	M^2

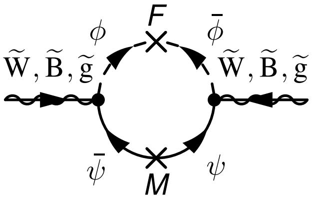
Messenger mass spectrum

Messenger mass spectrum

	m^2
$\phi, \bar{\phi}$	$M^2 \pm F^2$
$\psi, \bar{\psi}$	M^2

SUSY is broken!

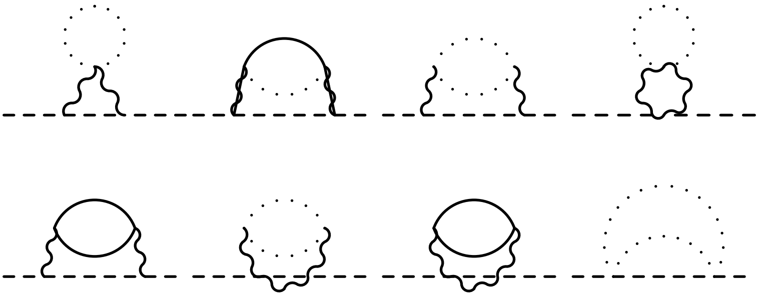
Soft Mass Generation
Majorana Gaugino masses at one-loop



$$M_a \propto \alpha_a \Lambda \qquad \Lambda = \frac{F}{M}$$

Soft Mass Generation

Squark/Slepton masses at two-loop



$$m^2_{\text{sq, sl}} \propto \Lambda^2 \sum_a \alpha_a^2 \qquad \Lambda = \frac{F}{M}$$

Solving the Higgs Hierarchy Problem

Quick Higgs revision

Standard Model Higgs potential

$$V(H) \sim \mu^2|H|^2 + \lambda|H|^4$$

Higgs vacuum expectation value (VEV)

$$\langle H \rangle = \sqrt{-\mu^2/2\lambda} \sim 174\,\mathrm{GeV}$$

Implies a Higgs mass

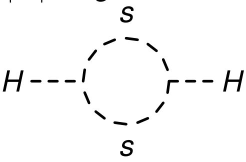
$$m_H^2 = -\mu^2 \sim 100\,\mathrm{GeV}$$

Solving the Higgs Hierarchy Problem

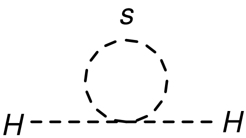
Higgs self-energy at one-loop

$$-\mathcal{L} \subset \lambda |s|^2 |H|^2 + g H \bar{f} f$$

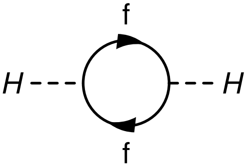
s = scalars
f = fermions



$$\sim -\lambda_s m_S^2 \ln\left(\frac{\Lambda}{m_S}\right)$$



$$\sim \lambda_s \Lambda^2$$



$$\sim -\lambda_f^2 \Lambda^2$$

Solving the Higgs Hierarchy Problem

UV cut-off at one-loop

At one-loop

$$m_H^2 \longrightarrow m_H^2 + \Lambda^2 \left(\sum_{\text{scalars}} \lambda_s - \sum_{\text{fermions}} g_f^2 \right) - \sum_{\text{scalars}} \lambda_s m_s^2 \ln \left(\frac{\Lambda}{m_s} \right)$$

Natural Higgs mass

$$\Lambda \sim m_{\text{Pl}} \implies m_{\text{nat}} \sim m_{\text{Pl}}$$

Solving the Higgs Hierarchy Problem

Dim-reg at one-loop

At one-loop

$$m_H^2 \longrightarrow m_H^2 - \sum_{\text{scalars}} \lambda_s m_s^2 \ln\left(\frac{\mu}{m_s}\right)$$

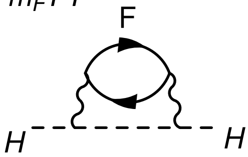
- m_H sensitive to *heaviest* particles Higgs couples to!
- Why is m_H so small?

Solving the Higgs Hierarchy Problem

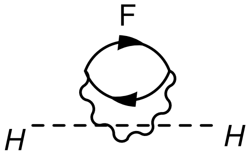
Some two loop Higgs self-energy processes

$-\mathcal{L} \subset m_F \bar{F} F$

$F =$ fermions



$$\sim g^4 \left(\Lambda^2 + m_F^2 \ln \left(\frac{\Lambda}{m_F} \right) \right)$$



Solving the Higgs Hierarchy Problem

You saved us... thanks supersymmetry!

$$
\begin{array}{ll}
 & \psi/\phi/A \text{ pairings} \\
+ & \lambda_f = \lambda_s^2 \text{ etc.} \\
\hline
 & V(\phi) \text{ well behaved} \\
\hline
\end{array}
$$

Unavoidable with supersymmetry

Gauge Coupling Unification

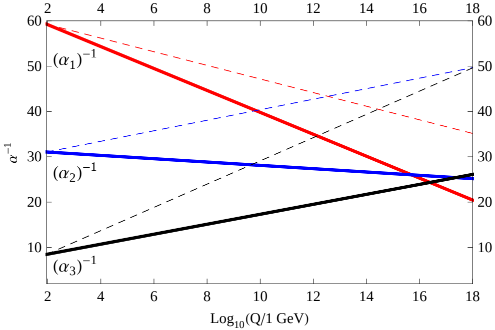


Figure: RGE of α_i^{-1} in SM (dashed) and MSSM (solid)

Dark Matter, Triggering EWSB

- In *R*-parity conserving SUSY, LSP is DM candidate

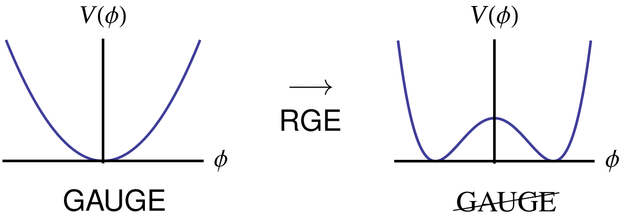
$$\begin{aligned} \text{Gauge Mediated } \not{\text{SUSY}} &\rightarrow \widetilde{G} \\ \text{Gravity Mediated } \not{\text{SUSY}} &\rightarrow \widetilde{\chi}_1^0 \end{aligned}$$

Dark Matter, Triggering EWSB

- In R-parity conserving SUSY, LSP is DM candidate

$$\begin{array}{rcl} \text{Gauge Mediated } \not{\text{SUSY}} & \to & \widetilde{G} \\ \text{Gravity Mediated } \not{\text{SUSY}} & \to & \widetilde{\chi}_1^0 \end{array}$$

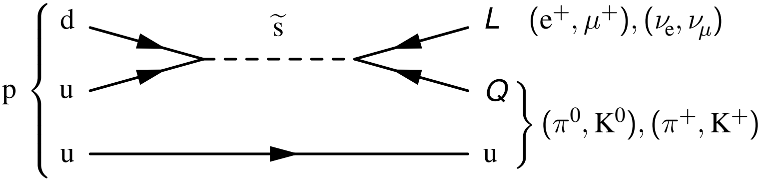
- Renormalization Group Evolution (RGE) triggers EWSB



Dark Matter Candidate

Proton decay

- General MSSM $\Longrightarrow$ rapid proton decay



- Forbid these interactions by imposing symmetries

Dark Matter Candidate
$R-$parity

- Define a multiplicatively conserved quantum number P_R
- Let all (supersymmetric) particles have $P_R = (-)1$

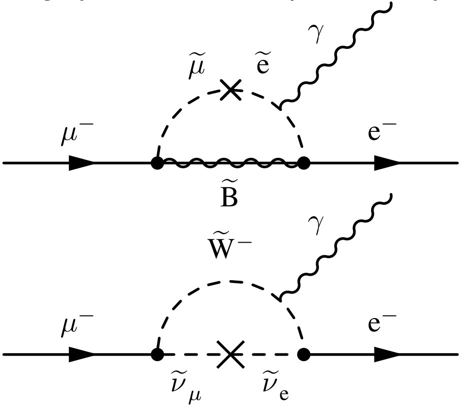
$$\Downarrow$$

- Interaction vertices contain even numbers of superpartners
- Forbids process mediating rapid proton decay
- The lightest supersymmetric particle (LSP) is stable

Dark matter candidate!

Flavour Changing Neutral Currents

- $\mu^- \to e^-\gamma$ is highly constrained experimentally



- Forbid/suppress the additional loop processes from SUSY

Pros and Cons

Advantages

- Flavour-blind communication automatic
- Theory is renormalizable

Pros and Cons

Advantages

- Flavour-blind communication automatic
- Theory is renormalizable

Problems

- Higgs '*b*' term difficult to generate
- LSP is always gravitino

Flavour Universality

$$-\mathcal{L}_{\text{soft}}^{\text{MSSM}} \subset \sum_{\phi=Q,L,\bar{u},\bar{d},e} \tilde{\phi}^\dagger m_\phi^2 \tilde{\phi} + \left(\tilde{\bar{u}} a_u \tilde{Q} H_u - \tilde{\bar{d}} a_d \tilde{Q} H_d - \tilde{\bar{e}} a_e \tilde{L} H_d + \text{h.c.}\right)$$

Easiest way:

- Assume supersymmetry breaking is ‘universal’

$$(m_i)_{jk} = m_i \delta_{jk}, \quad i = (Q, L, u, d, e)$$

- Assume that the $(\text{scalar})^3$ couplings are $\propto$ the corresponding Yukawa couplings

$$a_i \propto y_i, \quad i = (u, d, e)$$

Consequences

We find...

At any RG scale, the squark and slepton mass matrices appear

$$\left(m^2_\phi\right)_{ij} \approx \begin{pmatrix} m^2_{\phi_1} & 0 & 0 \\ 0 & m^2_{\phi_1} & 0 \\ 0 & 0 & m^2_{\phi_3} \end{pmatrix}_{ij} \qquad \phi = (Q, L, \mathrm{u}, \mathrm{d}, \mathrm{e})$$

How to Communicate ~~SUSY~~

Tree-level?

- For tree-level renormalizable couplings

$$\mathrm{STr}\mathcal{M}^2 = \sum_J (-1)^{2J}(2J+1)\mathcal{M}_J^2 = 0,$$

$$\Downarrow$$

superpartner lighter than SM counterpart

How to Communicate ~~SUSY~~

Tree-level?

- For tree-level renormalizable couplings

$$\mathrm{STr}\mathcal{M}^2 = \sum_J (-1)^{2J}(2J+1)\mathcal{M}_J^2 = 0,$$

$$\Downarrow$$

superpartner lighter than SM counterpart

- Non-renormalizable $\Longrightarrow$ Planck-Scale Mediated ~~SUSY~~
- Non-tree-level $\Longrightarrow$ Gauge Mediated ~~SUSY~~ (GMSB)

Minimal Model
Content

- Extra field content

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Φ	$\square$	$\square$	$-\frac{1}{3}$
$\bar{\Phi}$	$\bar{\square}$	$\bar{\square}$	$+\frac{1}{3}$
S	$\mathbf{1}$	$\mathbf{1}$	0

Minimal Model
Content

- Extra field content

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Φ	$\square$	$\square$	$-\frac{1}{3}$
$\bar{\Phi}$	$\bar{\square}$	$\bar{\square}$	$+\frac{1}{3}$
S	$\mathbf{1}$	$\mathbf{1}$	0

- Superpotential

$$W = \lambda \bar{\Phi} X \Phi$$

- X is goldstino superfield

$$\langle X \rangle = M + \theta^2 F$$

MSSM Soft Lagrangian

The most general set of positive mass dimension terms who obey SM symmetries but break SUSY are

$$
\begin{aligned}
\mathcal{L}_{\mathrm{soft}}^{\mathrm{MSSM}} = &-\frac{1}{2}\left(M_3\,\widetilde{\mathrm{g}}\widetilde{\mathrm{g}} + M_2\,\widetilde{\mathrm{W}}\widetilde{\mathrm{W}} + M_1\,\widetilde{\mathrm{B}}\widetilde{\mathrm{B}} + \mathrm{c.c.}\right) \\
&-\left(\widetilde{\mathrm{u}}\mathbf{a}_{\mathrm{u}}\widetilde{Q}\mathrm{H}_{\mathrm{u}} - \widetilde{\mathrm{d}}\mathbf{a}_{\mathrm{d}}\widetilde{Q}\mathrm{H}_{\mathrm{d}} - \widetilde{\mathrm{e}}\mathbf{a}_{\mathrm{e}}\widetilde{L}\mathrm{H}_{\mathrm{d}} + \mathrm{c.c.}\right) \\
&-\widetilde{Q}^{\dagger}\mathbf{m}_{Q}^{2}\widetilde{Q} - \widetilde{L}^{\dagger}\mathbf{m}_{L}^{2}\widetilde{L} - \widetilde{\mathrm{u}}\mathbf{m}_{\mathrm{u}}^{2}\widetilde{\mathrm{u}}^{\dagger} - \widetilde{\mathrm{d}}\mathbf{m}_{\mathrm{d}}^{2}\widetilde{\mathrm{d}}^{\dagger} - \widetilde{\mathrm{e}}\mathbf{m}_{\mathrm{e}}^{2}\widetilde{\mathrm{e}}^{\dagger} \\
&- m_{\mathrm{H_u}}^{2}\mathrm{H}_{\mathrm{u}}^{*}\mathrm{H}_{\mathrm{u}} - m_{\mathrm{H_d}}^{2}\mathrm{H}_{\mathrm{d}}^{*}\mathrm{H}_{\mathrm{d}} - (b\,\mathrm{H}_{\mathrm{u}}\mathrm{H}_{\mathrm{d}} + \mathrm{c.c}),
\end{aligned}
$$

and form the soft supersymmetry breaking Lagrangian density