Gauge-Mediated SUSY breaking

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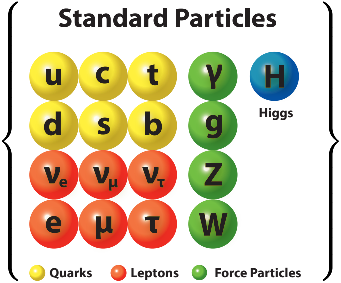
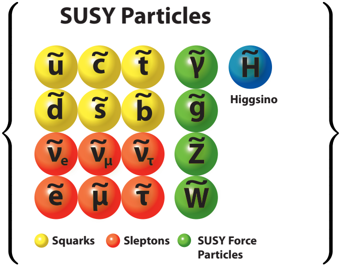
Disclaimer

When I say SUSY, I mean $\mathcal{N} = 1$ SUSY

Evidence

- Degeneracy in (s)particle mass spectrum not observed

P^2


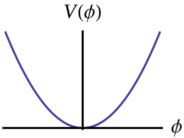
$\neq P^2$


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

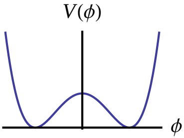
Properties

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

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



GAUGE SUSY



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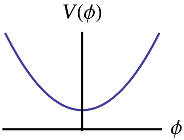
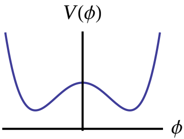


GAUGE ~~SUSY~~



~~GAUGE~~ ~~SUSY~~

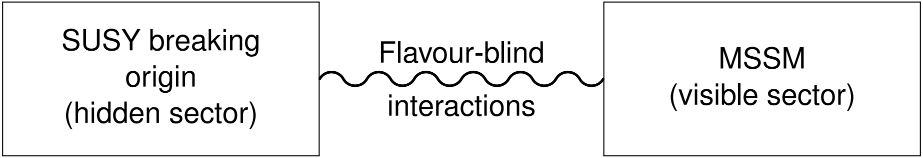
Recipe

- Additional $U(1)$s with associated vector superfields (VSF)
- Gauge-singlet chiral superfields (χSF)

Where are they?

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 $\not{S}\text{USY}$

Tree-level?

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- Non-renormalizable $\implies$ Planck-Scale Mediated $\not{S}\text{USY}$
- Non-tree-level $\implies$ Gauge Mediated $\not{S}\text{USY}$ (GMSB)

Particle Content and Superpotential

Messenger mass spectrum

- SUSY field expansions

$$\Phi \sim \phi + \theta\psi + \dots$$
$$\bar{\Phi} \sim \bar{\phi} + \theta\bar{\psi} + \dots$$

- Messenger mass spectrum

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

Messenger mass spectrum

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- Messenger mass spectrum

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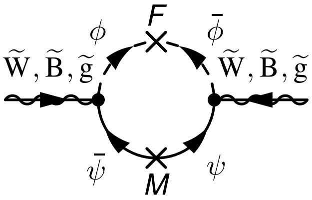
SUSY is broken!

Soft Mass Generation

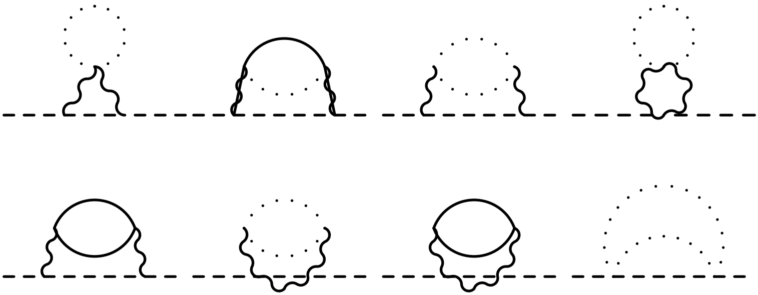
Gaugino masses at one-loop



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

Soft Mass Generation

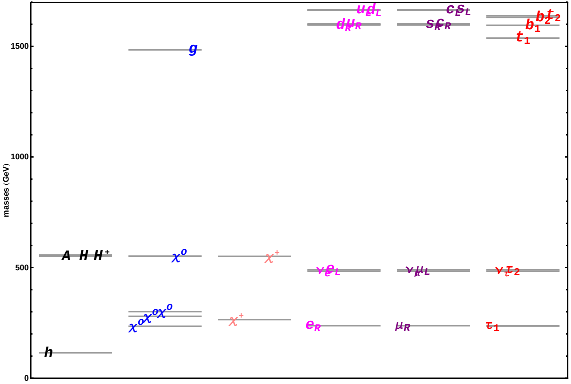
Squark/Slepton masses at two-loop



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

Here's one I made earlier...

$$\Lambda = \frac{F}{M}$$



Blue Peter

Figure: mGMSB spectrum for $\Lambda = 10^5\,\mathrm{GeV}$, $M = 10^4\,\mathrm{GeV}$

Possible research avenues

- Solution to the b and μ problems: NMSSM? Dirac Gauginos?
- Multiple hidden sectors, exotic messengers?
- $\ldots$?

Thanks

Thanks for listening!

More Symmetry, More Natural

- SUSY is a space-time (ST) symmetry

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

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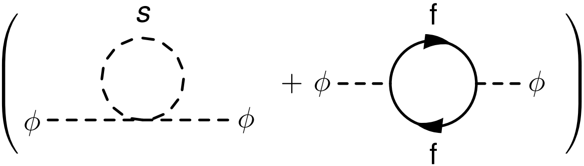
- Scalar masses free from quadratic divergencies

$$\sum_{s,f}$$



$$= 0$$

Gauge Coupling Unification

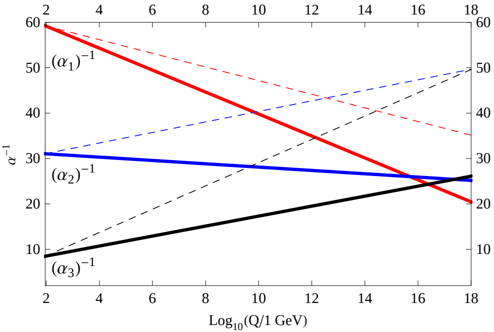
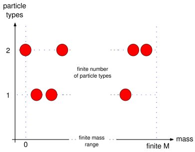


Figure: RGE of α_i^{-1} in SM (dashed) and MSSM (solid)

The Coleman-Mandula Theorem
Assumptions

- 

a finite number of particle types

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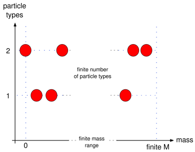
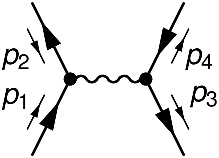
- 

a finite number of particle types
- scattering occurs at almost all energies
  $S = (p_1 + p_2)^2 = (p_3 + p_4)^2$



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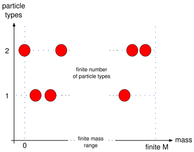
- 

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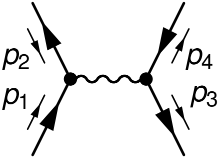
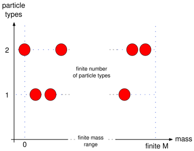


- 

amplitudes for elastic $2 \to 2$ scattering are analytic functions of scattering angles

The Coleman-Mandula Theorem
Conclusions

“ The only possible *Lie algebra* of symmetry generators consist of translations, homogenous Lorentz transformations, together with possible internal symmetry generators (e.g. the generators of gauge groups)”

The Coleman-Mandula Theorem

The only possible Lie algebra

$$\left.\begin{array}{rcl} [J,J'] &=& J'' \\ [J,P] &=& P' \\ [P,P'] &=& 0 \end{array}\right\} \text{Poincaré algera}$$

$$\left.\begin{array}{rcl} [B,B'] &=& B'' \\ [B,J] &=& 0 \\ [B,P] &=& 0 \end{array}\right\} \text{Internal symmetry algebra}$$

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$\Longrightarrow$ No more allowed space-time *symmetries*!

What if...?

Could we have space-time *supersymmetries*?

The Haag-Lopuszanski-Sohnius theorem
Bypassing Coleman-Mandula

A *Lie alebgra*

$$[X, X'] = X''$$

The Haag-Lopuszanski-Sohnius theorem
Bypassing Coleman-Mandula

A *Lie alebgra*

$$[X, X'] = X''$$

is just a special case of a *graded Lie algebra*

$$\{Q, Q'\} = X$$
$$[Q, X] = Q'$$
$$[X, X'] = X''$$

$X =$ commuting element
$Q =$ anti-commuting element

The Haag-Lopuszanski-Sohnius theorem

Bypassing Coleman-Mandula

What generators satisfying a *graded Lie algebra* are consistent with the Coleman-Mandula theorem?

The Haag-Lopuszanski-Sohnius theorem

Commuting elements

We already know the commuting part of the algebra

$$X = \{P, J, B\} \implies [X, X'] = X''$$

Using *graded Jacobi identities*, the rest of the (anti-)commutators of the algebra are fully determined...

The Haag-Lopuszanski-Sohnius theorem

The Super-Poincaré algebra

$$\left.\begin{aligned} \{Q, Q^{\dagger\prime}\} &= P \\ \{Q, Q'\} &= B \\ [P, Q] &= 0 \end{aligned}\right\} \text{Supersymmetry algebra}$$

$$\left.\begin{aligned} [B, B'] &= B'' \\ [B, J] &= 0 \\ [B, P] &= 0 \end{aligned}\right\} \text{Internal symmetry algebra}$$

$$\left.\begin{aligned} [J, J'] &= J'' \\ [J, P] &= P' \\ [P, P'] &= 0 \end{aligned}\right\} \text{Poincaré algera}$$

Unique Extension to Space-time Symmetry

- The generators Q act on particle states

$$Q|\text{Fermion}\rangle = |\text{Boson}\rangle \qquad Q|\text{Boson}\rangle = |\text{Fermion}\rangle$$

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Unique Extension to Space-time Symmetry

- The generators Q act on particle states

$$Q|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle \qquad Q|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle$$

- A particle's spin and hence space-time properties change
- The Qs therefore generate a space-time symmetry!

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

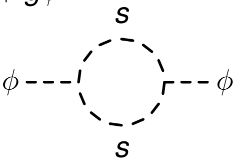
$$m_H^2 = -\mu^2 \sim 100\,\mathrm{GeV}$$

Solving the Higgs Hierarchy Problem

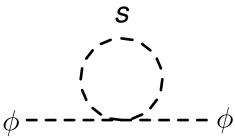
Scalar Field Self-energy at One-loop

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

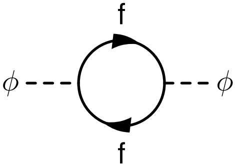
$\phi, s =$ scalars
$f =$ fermions



$\sim \lambda^2 \ln \Lambda$



$\sim \lambda \Lambda^2$



$\sim -g^2 \Lambda^2$

Solving the Higgs Hierarchy Problem

Radiative corrections to Higgs mass

At one-loop

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

Natural Higgs mass

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

Solving the Higgs Hierarchy Problem

Supersymmetric solution

Supersymmetry $\Longrightarrow$ Superpartners

Minimal Supersymmetric Standard Model (MSSM) field content

Standard Model Particle	Supersymmetric Partner
Gauge Boson	Gaugino
Quark	Squark
Leptons	Slepton
Higgs	Higgsino

Solving the Higgs Hierarchy Problem

Supersymmetric solution

For scalar and fermionic superpartners

$$\lambda_s = g_f^2$$

MSSM at one-loop

$$m_H^2 \longrightarrow m_H^2 + \ln\Lambda \sum_{\text{scalars}} \lambda_s^2$$

Natural Higgs mass

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

Problem solved!

Dark Matter, Triggering EWSB

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

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

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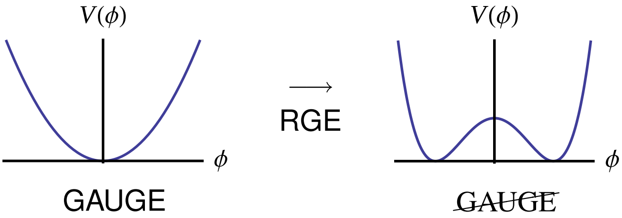
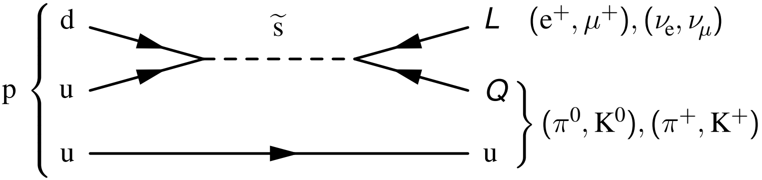
- Renormalization Group Evolution (RGE) triggers EWSB



Dark Matter Candidate
Proton decay

- General MSSM $\implies$ 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 $P_R = (-)1$

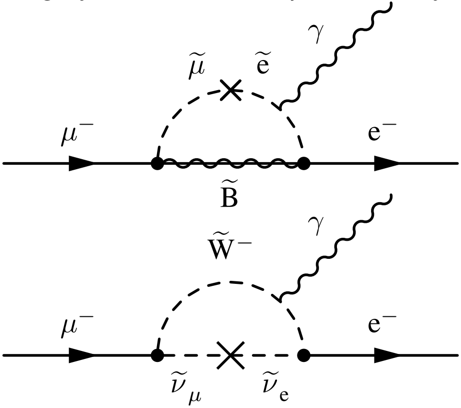
$$\Downarrow$$

- 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

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



- Forbid/suppress the additional loop processes from SUSY

Pros and Cons

Advantages

- Flavour-blind communication automatic
- Theory is renormalizable

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- Theory is renormalizable

Problems

- Higgs ‘b’ term difficult to generate
- LSP is always gravitino

Flavour Universality

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

Easiest way:

- Assume supersymmetry breaking is 'universal'

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

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

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

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 $\not{S}\!\!\!\!\!\;\text{USY}$

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superpartner lighter than SM counterpart

- Non-renormalizable $\Longrightarrow$ Planck-Scale Mediated $\not{S}\!\!\!\!\!\;\text{USY}$
- Non-tree-level $\Longrightarrow$ Gauge Mediated $\not{S}\!\!\!\!\!\;\text{USY}$ (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	**1**	**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	**1**	**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

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

and form the soft supersymmetry breaking Lagrangian density