Collider Physics for String Theorists: #2

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Basics of the MSSM
The SM isn’t perfect

$\mu$
How do we know where to go?

Precision measurements versus direct observation of new particles

“At this point we notice that this equation is beautifully simplified if we assume that space–time has 92 dimensions.”

Much easier if we see new particles
Standard Model isn’t Completely Satisfactory

Quantum corrections drag weak scale to Planck scale

Tevatron/LHC Energies

$\delta M_H^2 \approx M_{Pl}^2$
Quantum Corrections and Supersymmetry

\[ \delta M_H^2 \approx -M_{Pl}^2 \]

Tevatron/LHC Energies

Weak

10^3 GeV

GUT

10^{16}

Planck

10^{19} GeV

Quantum corrections cancel order by order in perturbation theory
What about fermion masses?

- Fermion mass term:
  \[ L = m \overline{\Psi} \Psi = m \left( \overline{\Psi}_L \Psi_R + \overline{\Psi}_R \Psi_L \right) \]

- Left-handed fermions are SU(2) doublets
  \[ q_l = \begin{pmatrix} u \\ d \end{pmatrix}_L \]

- Scalar couplings to fermions:
  \[ L_d = -\lambda_d \overline{Q}_L \Phi d_R + h.c. \]

- Effective Higgs-fermion coupling
  \[ L_d = -\lambda_d \frac{1}{\sqrt{2}} (\overline{u}_L, \overline{d}_L) \begin{pmatrix} 0 \\ v + h \end{pmatrix} d_R + h.c. \]

- Mass term for down quark:
  \[ \lambda_d = -\frac{M_d \sqrt{2}}{v} \]
Fermion Masses, 2

- $M_u$ from $\Phi_c = i\sigma_2 \Phi^*$ (not allowed in SUSY): $L = -\lambda_u \bar{Q}_L \Phi_c u_R + h_c$

\[ \Phi_c = \begin{pmatrix} \phi^0 \\ -\phi^- \end{pmatrix} \quad \lambda_u = -\frac{M_u \sqrt{2}}{v} \]

- Supersymmetric models always have at least two Higgs doublets
  - General 2 Higgs doublet potential has 6 couplings + phase
  - 5 physical Higgs particles: h, H, A, H$^\pm$
  - VEVs described by $\tan \beta = v_2/v_1$
  - $M_W$ gives $v_{SM}^2 = v_1^2 + v_2^2$
  - Supersymmetry restricts form of scalar potential: 2 parameters
    (Usually taken to be $\tan \beta$ and $M_A$)
Particle Content

- Supersymmetric theories constructed from supermultiplets

- Chiral superfield, $\Phi_i$, has:
  - Complex scalar field, $\phi_i$
  - 2-component Weyl fermion field, $\psi_i$
  - Auxiliary Field, $F_i$ (no kinetic energy term)

- Interactions described in terms of chiral superfields

\[ \Phi_i(x) \equiv \phi_i(x) + \sqrt{2}\theta\psi_i(x) + \theta\theta F_i(x) \]

[Taylor series stops at $\theta^2$ since
$\theta$ is anti-commuting Grassman variable, $\theta^3 = \frac{\theta}{2}\{\theta, \theta\}$]

- Components of $\Phi$ have identical quantum numbers (except spin) and masses

- Construct model with supermultiplets corresponding to known particles

- More than doubles spectrum
# Chiral Superfields

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<th>Superfield</th>
<th>SU(3)</th>
<th>SU(2)(_L)</th>
<th>U(1)(_Y)</th>
<th>Particle Content</th>
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<tr>
<td>(\hat{D}^c)</td>
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<td>(\bar{e}_R, \bar{e}^*_R)</td>
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<tr>
<td>(\hat{H}_2)</td>
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<td>2</td>
<td>(\frac{1}{2})</td>
<td>((H_2, \bar{h}_2))</td>
</tr>
</tbody>
</table>
Unification

- Gauge couplings evolve differently in SUSY models
- Running is slower than SM

\[ b_1 = -2 N_g + \frac{3 N_h}{10} \]
\[ b_2 = -6 + 2 N_g + \frac{N_h}{2} \]
\[ b_3 = -9 + 2 N_g \]
The Cynic

- Assume supersymmetric at some scale, $\Lambda_{SUSY}$ (say 1 TeV)
- Input 2 couplings, say $g_1, g_2$, at $M_Z$
- Evolve couplings until they meet at scale $M_{GUT}$
- Assume unification at $M_{GUT}$, $g_i(M_{GUT}) = g_{GUT}$
- Evolve 3rd coupling, say $g_3$, down to $M_Z$
- If $g_3(M_Z)$ disagrees with measured number, change $\Lambda_{SUSY}$
- Keep going until it works!

Amazing fact: consistency occurs for $\Lambda_{SUSY} \sim 1$ TeV

(Actually, $\alpha_s(M_Z)$ typically a little large)
Scalar Interactions

Define superpotential:

\[ W = \frac{1}{2} M^{ij} \phi_i \phi_j + \frac{g^{ijk}}{6} \phi_i \phi_j \phi_k \]

- Most general \( SU(3) \times SU(2)_L \times U(1)_Y \) invariant superpotential:
  (Hats denote scalar component of supermultiplet)

\[
W = -\epsilon_{ij} \mu \hat{H}_1^i \hat{H}_2^j + \epsilon_{ij} \left[ \lambda_L \hat{H}_1^i \hat{L}^c_j \hat{E}^c + \lambda_D \hat{H}_1^i \hat{Q}^j \hat{D}^c + \lambda_U \hat{H}_2^j \hat{Q}^i \hat{U}^c \right]
+ \epsilon_{ij} \left[ \lambda_1 \hat{L}^i \hat{L}^j \hat{E}^c + \lambda_2 \hat{L}^i \hat{Q}^j \hat{D}^c \right] + \lambda_3 \hat{U}^c \hat{D}^c \hat{D}^c
\]

\( i, j \) \( SU(2) \) indices

- Superpotential has Yukawa interactions of fermions with scalars and quartic interactions of potential:

\[
\mathcal{L}_W = -\sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2 - \frac{1}{2} \sum_{ij} \left[ \frac{\partial^2 W}{\partial \phi_i \partial \phi_j} \psi_i \psi_j + \text{c.c.} \right]
\]
Aside on R Parity

Allowed terms in superpotential:

$$W_{RP} = \lambda_1^{ijk} \tilde{L}^i \tilde{L}^j \tilde{E}^c + \lambda_2^{ijk} \tilde{L}^i \tilde{Q}^j \tilde{D}^c + \lambda_3^{ijk} \tilde{U}^c \tilde{D}^c \tilde{D}^c$$

- $W_{RP}$ gives lepton/baryon number violating interactions

$$\mathcal{L} \sim \lambda_2 u_L e_L \tilde{d}_R^s + \lambda_3 \tilde{u}_R \tilde{d}_R \tilde{u}_R^s$$

- Could just make coefficients small

- Limits on proton decay require:

$$| \lambda_2^{11i} \lambda_3^{11i} | < 10^{-27} \left( \frac{M_{d_i}}{100 \text{ GeV}} \right)^2$$

Impose symmetry which forbids $W_{RP}$

- $R$ parity is multiplicative quantum number: Discrete $Z_2$ symmetry

- Imposed by hand

$$R \equiv (-1)^{3(B-L)+2s}$$
Consequences of R Parity

- SM particles have $R = 1$, SUSY partners have $R = -1$
- $\theta \rightarrow -\theta$ does same thing

$$\Phi_i (x) \equiv \phi_i (x) + \sqrt{2}\theta \psi_i (x) + \theta \theta F_i (x)$$

- SM dimension- 4 baryon/lepton number violating interactions forbidden by the gauge symmetries

Consequences of $R$ parity:

- SUSY partners are pair produced
- Lightest SUSY particle (LSP) is stable
Add Gauge Fields

Add:
- Massless gauge boson, $A^a_\mu$
- 2-component Weyl fermion gaugino, $\lambda^a$ (adjoint representation of group)
- Auxilliary Field, $D^a$ (adjoint representation of group; $[mass]^2$)

Gauge invariant interactions are:

$$\mathcal{L}_{gauge} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} - i \lambda^* a_{\mu} \sigma^\mu D_\mu \lambda^a + \frac{1}{2} D^a D^a$$

As usual:

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g f^{abc}_{\mu\nu} A^b_\mu A^c_\nu$$

$$D_\mu \lambda^a = \partial_\mu \lambda^a - g f^{abc}_{\mu\nu} A^b_\mu \lambda^c$$
# Gauge Multiplets of MSSM

<table>
<thead>
<tr>
<th>Superfield</th>
<th>$SU(3)$</th>
<th>$SU(2)_L$</th>
<th>$U(1)_Y$</th>
<th>Particle Content</th>
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</thead>
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<td>$g, \tilde{g}$</td>
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<tr>
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<td>0</td>
<td>$W_i, \tilde{\omega}_i$</td>
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<tr>
<td>$\hat{B}$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>$B, \tilde{b}$</td>
</tr>
</tbody>
</table>
Construct Gauge-Scalar Interactions

\[ \mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{chiral} \]

\[ - \sqrt{2} g \left[ (\phi^* T^a \psi) \lambda^a + \lambda^{\dagger a} \left( \psi^{\dagger T^a \phi} \right) \right] \]

\[ + g (\phi^* T^a \phi) D^a \]

What about terms involving \( D^a \)?

\[ \mathcal{L} \sim \frac{1}{2} D^a D^a + g (\phi^* T^a \phi) D^a \]

Use equation of motion:

\[ D^a = - g (\phi^* T^a \phi) \]

Complete scalar potential:

\[ V (\phi, \phi^*) = F^{*i} F_i + \frac{1}{2} D^a D^a = W_i^* W^i + \frac{1}{2} \Sigma a g_a^2 (\phi^* T^a \phi)^2 \]
Construct Scalar Potential

\[ W \sim -\epsilon_{ij} \mu \hat{H}_1^i \hat{H}_2^j + ... \]

"F-Term": \[
V_F = \sum_i | \frac{\partial W}{\partial \phi_i} |^2
\]
\[ = | \mu |^2 \left( | H_1 |^2 + | H_2 |^2 \right) \]

"D Terms"
\[ V_D = \frac{1}{2} D^a D^a \]
\[ D^a = -g_a \phi_i^* T^a \phi_i \]

\[ H_1 \text{ has } Y = -\frac{1}{2} \]
\[ H_2 \text{ has } Y = +\frac{1}{2} \]

\[ U(1) : \quad D^i = \frac{g}{2} \left( | H_2 |^2 - | H_1 |^2 \right) \]
\[ SU(2) : \quad D^a = \frac{g}{2} \left( H_1^{*j} \sigma_{ij}^a H_1^j + H_2^{*j} \sigma_{ij}^a H_2^j \right) \]

(Normalization \( T^a = \frac{\sigma^a}{2} \))

\[ SU(2) \text{ identity: } \sigma_{ij}^a \sigma_{kl}^a = 2 \delta_{il} \delta_{jk} - \delta_{ij} \delta_{kl} \]

\[ V_D = \frac{g^2}{8} \left( 4 | H_1^* \cdot H_2 |^2 - 2 (H_1^* \cdot H_1)(H_2^* \cdot H_2) + \left( | H_1 |^2 \right)^2 + \left( | H_2 |^2 \right)^2 \right) \]
\[ + \frac{g'^2}{8} \left( | H_2 |^2 - | H_1 |^2 \right)^2 \]
Scalar Potential, #2

\[ V = |\mu|^2 \left( |H_1|^2 + |H_2|^2 \right) + \frac{g^2 + g'^2}{8} \left( |H_2|^2 - |H_1|^2 \right)^2 \]

\[ + \frac{g^2}{2} |H_1^* \cdot H_2|^2 \]

Minimum at \( \langle V \rangle = \langle H_1 \rangle = \langle H_2 \rangle = 0 \)

No EWSB, No SUSY breaking....
SUSY Breaking

- Spontaneous SUSY doesn’t work

Scalar potential:

\[ V(\phi, \phi^*) = F^i F_i + \frac{1}{2} D^a D^a = W^i W_i + \frac{1}{2} \Sigma_a g_a^2 (\phi^* T^a \phi)^2 \]

[\( W \) is superpotential, \( W^i = \frac{\partial W}{\partial \phi_i} = M^{ij} \phi_j + \frac{g^{ijk}}{2} \phi_j \phi_k \)]

SUSY spontaneously broken if either:

\[ \langle 0 | F_i | 0 \rangle \neq 0 \quad \text{O’Raifeartaigh} \]
\[ \langle 0 | D^a | 0 \rangle \neq 0 \quad \text{Fayet-Iliopoulos} \]

- Generates bad mass relations
Spontaneously Broken SUSY = BAD

Define supertrace:

\[ STr \left( M^2 \right) \equiv \sum (-1)^{2s} (2s + 1) Tr \left( M^2 \right) \]
\[ = 3 Tr \left( M_V^2 \right) + Tr \left( M_\phi^2 \right) - 2 Tr M_F^2 \]
\[ = 0 \]

- Holds for arbitrary values of scalar fields
- Holds separately for gauge and matter sector

\[ \tilde{m}_{eL}^2 + \tilde{m}_{eR}^2 = 2 m_e^2 \]
Softly Broken SUSY

Consider low scale SUSY ($\sim 1 \, TeV$) as effective theory

- Break SUSY “softly” (terms of dimension $\leq 3$)
- Add all possible terms which introduce $\log(\Lambda)$ divergences, but not $\Lambda^2$

Allowed terms:
- Scalar Masses ($\phi^*\phi$, $\phi\phi$)
- Gaugino masses ($\lambda^a\lambda^a$)
- Cubic scalar couplings ($\phi_i\phi_j\phi_k$)

Theorem: Introduction of soft terms doesn’t reintroduce $\Lambda^2$ divergences to all orders of PT in SUSY
Parameters of the MSSM

- 5 3 × 3 Hermitian mass matrices for squarks and sleptons:
  \[ M_Q^2 \bar{Q}^* Q + M_u^2 \bar{u}_R^* u_R + M_d^2 \bar{d}_R^* d_R + M_L^2 \bar{L}^* L + M_e^2 \bar{e}_R^* e_R \]
  (45 new parameters)

- 2 (complex) Higgs scalar masses
  \[ m_1^2 H_1^2 + m_2^2 H_2^2 \]
  (4 new parameters)

- 3 gaugino masses (complex)
  \[ \Sigma_{\alpha = 1,2,3} M_{1/2}^a \lambda^a \lambda^a \]
  (6 new parameters)

- 1 complex Higgs mixing parameter
  \[ m_{12}^2 H_1 H_2 \]
  (2 new parameters)

- 27 trilinear couplings for scalar fields (complex)
  \[ H_2 \bar{Q} A_u \bar{u}_R + H_1 \bar{Q} A_d \bar{d}_R + H_1 \bar{L} A_l \bar{e}_R \]
  (54 new parameters)

111 new parameters

SM has 17 parameters → 128 parameters
Soft SUSY Breaking Terms Allow SSB

\[ V = (m_1^2 + |\mu|^2) |H_1|^2 + (m_2^2 + |\mu|^2) |H_2|^2 \]
\[ - m_{12}^2 (\epsilon_{ij} H_i^1 H_j^2 + h.c.) \]
\[ + g^2 + g'^2 \left( |H_2|^2 - |H_1|^2 \right)^2 + \frac{g^2}{2} |H_1^* \cdot H_2|^2 \]

\[ H_1 = \begin{pmatrix} \phi_1^0* \\ -\phi_1^- \end{pmatrix} \quad H_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \]
\[ \langle H_1^1 \rangle = v_1 \quad \langle H_2^2 \rangle = v_2 \]

Potential has 3 parameters. Trade 1 for \( \tan \beta = \frac{v_2}{v_1} \)

Conditions for EWSB:

\[ \rightarrow \text{if } m_{12}^2 = 0 \text{ potential positive definite} \]

“D-flat” direction: \( |H_1^0| = |H_2^0| \)
\[ \rightarrow \text{quartic contributions vanish} \]

Quadratic term in this direction must be positive:

\[ m_1^2 + m_2^2 + 2 |\mu|^2 > 2m_{12}^2 \]

Broken \( SU(2) \times U(1) \):
\[ (m_1^2 + |\mu|^2) (m_2^2 + |\mu|^2) < |m_{12}|^2 \]
Constrained Potential in MSSM

- Tree level scalar potential has 2 free parameters

\[
V = m_{11}^2 H_1 H_1^* + m_{22}^2 H_2 H_2^* - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) + \left( \frac{g^2 + g^2}{8} \right) (H_1 H_1^* - H_2 H_2^*)^2 + \frac{g^2}{2} |H_1 H_2^*|^2
\]

- Typically pick \( M_A, \tan \beta \) as parameters
- Predict \( M_h, M_H, M_{H\pm} \), all couplings (at tree level)
- At tree level, \( M_h < M_Z \)
- Large corrections \( O(G_F m_t^2) \) to predictions
  - Predominantly from stop squark loop

\[
M_h^2 \leq M_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2 \sin^2 \beta} \ln \left[ \frac{\tilde{m}_t^2}{m_t^2} \right] + \ldots
\]
Theoretical Upper bound on $M_h$
Limits on SUSY Higgs from LEP

\( M_t = 169.3, 174.3, 179.3, 183 \text{ GeV} \)
Bound on Charged Higgs

- Fairly model independent
Higgs Masses in MSSM

\[ M_{H^\pm}^2 = M_A^2 + M_W^2 \]
Find Higgs Couplings:

\[ \mathcal{L}_W = \frac{\partial^2 W}{\partial \phi_i \partial \phi_j} \psi_i \psi_j + \text{c.c.} \]

\[ W \sim \epsilon_{ij} \left[ \lambda_L \hat{H}_1^i \hat{L}^c j \hat{E}_c + \lambda_D \hat{H}_1^i \hat{Q}^j \hat{D}_c + \lambda_U \hat{H}_2^j \hat{Q}^i \hat{U}_c \right] \]

Yukawa interactions give mass matrices:

\[ m_d = \lambda_D v_1 \]

\[ \lambda_D = \frac{gm_d}{\sqrt{2} \sin \beta M_W} \]

\[ m_u = \lambda_U v_2 \]

\[ \lambda_U = \frac{gm_u}{\sqrt{2} \cos \beta M_W} \]
MSSM Couplings

Couplings given in terms of $\alpha$, $\beta$

Can be very different from SM

<table>
<thead>
<tr>
<th>$\Phi$</th>
<th>$g_{\Phi uu}$</th>
<th>$g_{\Phi dd}$</th>
<th>$g_{\Phi VV}$</th>
<th>$g_{\Phi ZA}$</th>
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<td>$\sin(\beta - \alpha)$</td>
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<tr>
<td>$H$</td>
<td>$\frac{\sin \alpha}{\sin \beta}$</td>
<td>$\frac{\cos \alpha}{\cos \beta}$</td>
<td>$\cos(\beta - \alpha)$</td>
<td>$\frac{1}{2}\sin(\beta - \alpha)$</td>
</tr>
<tr>
<td>$A$</td>
<td>$i\gamma_5 \cot \beta$</td>
<td>$-i\gamma_5 \cot \beta$</td>
<td>0</td>
<td>0</td>
</tr>
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</table>
Higgs Couplings very different from SM in SUSY Models

Ratio of h coupling to b’s in SUSY model to that of SM
Higgs Couplings different in MSSM

- Couplings to $d$, $s$, $b$ enhanced at large $\tan \beta$
- Couplings to $u$, $c$, $t$ suppressed at large $\tan \beta$

Decoupling limit
Higgs Decays affected at large tan \( \beta \)

- SM: Higgs branching rates to \( bb \) and \( \tau^+\tau^- \) turn off as rate to \( W^+W^- \) turns on (\( M_h > 160 \) GeV)

- MSSM: At large tan \( \beta \), rates to \( bb \) and \( \tau^+\tau^- \) stay large

Heavy \( H^0 \) MSSM BRs

Rate to \( bb \) and \( \tau^+\tau^- \) almost constant in MSSM

A\(^0\) MSSM BRs
New Discovery Channels in SUSY

DØ Run II Preliminary

MSSM Higgs bosons
\( b\bar{b}\phi(\rightarrow b\bar{b}), \phi = h, H, A \)
Gauge Coupling Constants

- $g_{hVV}^2 + g_{HVv}^2 = g_{hVV}^2 (\text{SM})$
- Vector boson fusion and Wh production always suppressed in MSSM
LHC can find $h$ or $H$ in weak boson fusion

Decays to $\tau^+\tau^-$ needed
Production of SUSY Higgs Bosons

- For large tan $\beta$, dominant production mechanism is with b’s
- $b\bar{b}h$ can be 10x’s SM Higgs rate in SUSY for large tan $\beta$

LHC
MSSM discovery

- For large fraction of $M_A \cdot \tan \beta$ space, more than one Higgs boson is observable.
- For $M_A \rightarrow \infty$, MSSM becomes SM-like.
- Plot shows regions where Higgs particles can be observed with $> 5 \sigma$.

Need to observe multiple Higgs bosons and measure their couplings.
Add Scalars to MSSM

- Add Higgs singlet $S$, triplets $T_0, T_{\pm 1}$
- Superpotential,
  $$ W = \lambda_1 H_u H_d S + \lambda_2 H_u T_0 H_d $$
  $$ + \chi_1 H_u T_1 H_u + \chi_2 H_d T_{-1} H_d $$

- At tree level, lightest Higgs mass bound becomes,
  $$ M_H^2 \leq M_Z^2 \cos^2 2\beta + v^2 (\lambda_1^2 + \frac{\lambda_2^2}{2}) \sin^2 2\beta $$
  $$ + 4v^2 (\chi_1^2 \cos^4 \beta + \chi_2^2 \sin^4 \beta) $$

- Higgs mass bound depends on particle content
  - Assume couplings perturbative to $M_{\text{GUT}}$ and SUSY scale
    $\approx 1$ Tev
  - $M_h < 150 – 200$ GeV with singlet and triplet Higgs
Looking For Gluinos

- $gg, q\bar{q} \to \tilde{g}\tilde{g}$ couplings fixed by gauge invariance
- Gluinos are Majorana

\[ \Gamma (\tilde{g} \to l^+ X) = \Gamma (\tilde{g} \to l^- X) \]

- Classic signature is same sign lepton production
Search for Squark/Gluino Production

- Generic squark/gluino production $\rightarrow$ energetic jets & large missing $E_T$
  - Difficult because of large QCD background

\[ HT = \text{scalar sum of } E_T \text{ of jets} \]
M$\text{gluino} < 402$ excluded for M$g \sim Mq$

M$\text{gluino} < 309$ excluded – any M$q$

M$\text{gluino} < 380$ excluded for M$g \sim Mq$

M$\text{gluino} < 230$ excluded -- any M$q$
Charginos

- Fermionic partners of $W^\pm$ mix with charged fermion partners of Higgs
- Mass eigenstates called charginos

$$\tilde{M}_{\chi^\pm} = \begin{pmatrix} M_2 & \sqrt{2}M_W \sin \beta \\ \sqrt{2}M_W \cos \beta & \mu \end{pmatrix}$$
Neutralinos

- Neutral fermions mix:

\[ (\tilde{B}, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0) \]

\[
M_{\chi^0} = \begin{pmatrix}
M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\
0 & M_2 & M_Z c_\beta c_W & M_Z s_\beta c_W \\
-M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\
-M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0
\end{pmatrix}
\]

- Usually assume lightest SUSY particle is lightest \( \chi^0 \)
### SUSY Particles

<table>
<thead>
<tr>
<th>Particles</th>
<th>R=1</th>
<th>R= (-1)^{3B+L+2S}</th>
<th>SParticles</th>
<th>R=-1</th>
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<td>SUSY is a broken symmetry</td>
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**MSSM** has 124 parameters: 
- \(M_1, M_2, M_3\), Gaugino masses, Sfermion masses 
- \(\tan\beta, \mu, m_A\), Higgs(ino) mass/mixing 
- \(A_t, A_b, A_s\) (+45 RPV)
Chargino-Neutralino Production

- Trileptons from chargino-neutralino production: Classic signature

Clear signature – 3 isolated leptons, missing $E_T$
Tevatron Limits on Tri-leptons

\[ \sigma(\tilde{\chi}^\pm_1,\tilde{\chi}^0_2) \times \text{BR}(3l) \text{ (pb)} \]

**DØ Run II Preliminary, 0.9-1.1 fb\(^{-1}\)**

- \( M(\tilde{\chi}^\pm_1) = M(\tilde{\chi}^0_2) = 2M(\tilde{\chi}^0_1) \)
- \( M(\tilde{l}) > M(\tilde{\chi}^0_2) \)
- \( \tan\beta = 3, \mu > 0, \) no slepton mixing

**Legend:**
- **Observed Limit**
- **Expected Limit**

**Graph Parameters:**
- Chargino Mass (GeV)
- LEP
- 3l-max
- heavy-squarks
- large-\(m_0\)
Too Many Unknowns...

Assume soft parameters unify:

Model specified by:

- Common scalar mass, $\tilde{m}_0$
- Common gaugino mass, $M_{1/2}$
- 1 Higgs mass, $m_{12}^2$
- 1 tri-linear coupling, $A_0 \lambda_F$

This model often called mSUGRA, CMSSM

Evolve all masses to $M_Z$ with boundary condition at $M_G$:

\[
\begin{align*}
M_Q^2 (M_G) &= M_u^2 (M_G) = M_d^2 (M_G) = \\
M_L^2 (M_G) &= M_e^2 (M_G) = \tilde{m}_0^2 \\
M_1^2 (M_G) &= M_2 (M_G) = M_3 (M_G) = M_{1/2} \\
m_{12}^2 (M_G) &= m_{12}^2 \\
A_i (M_G) &= A_0 \lambda_i
\end{align*}
\]
LHC/Tevatron will find SUSY

- Discovery of many SUSY particles is straightforward
- Untangling spectrum is difficult
  \( \Rightarrow \) all particles produced together
- SUSY mass differences from complicated decay chains; eg

\[
\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q \rightarrow \tilde{l}^\pm l^{\mp}
\]

\[
\rightarrow \tilde{\chi}_1^0 l^+ l^- q
\]

- \( M_{\chi^0} \) limits extraction of other masses
SM is incomplete

• 23% of universe is cold dark matter:

\[ \Omega_{\text{CDM}h^2} = 0.1126^{+0.0161}_{-0.0181} \]

*No dark matter candidate in SM*

*SUSY has dark matter candidate*
MSSM has dark matter candidate

- LSP: Lightest supersymmetric particle, $\chi_0$ is neutral and stable (in models with R parity)
Supersymmetry (MSSM version)

- Many positive aspects
  - Gauge coupling unification
  - Dark Matter candidate (LSP)
  - Predicts light Higgs boson
    - $M_H < 140$ GeV
  - Agrees with EW measurements