\[ \Phi = \phi + \theta \psi + \bar{\theta} \bar{\psi} \]

\[ W[\Phi] = \int \bar{\phi} \gamma_\alpha \phi \, d\phi^\alpha + \text{min} \, \phi \bar{\phi} + \sum_{i=1}^N \phi^i \bar{\phi}^i \]

\[ V = \frac{\partial W}{\partial \phi^\alpha} F_{\alpha} + \frac{\partial W}{\partial \bar{\phi}^i} \bar{\psi}^i \psi_i \]

\[ \sum_{i=1}^N |\phi_i|^2 \]
Properties ($B \rightarrow F$)

1) $\Lambda = 0$

$$\langle 0| \not \Sigma Q, \not \Sigma^+ 3| 0 \rangle = \langle 0| 2 \not \Sigma^+ P_{\mu} | 0 \rangle = \langle 0| 2 H 10 \rangle = 2 \Lambda$$

if rac is invariant $\not \Sigma| 10 \rangle = 0 \Rightarrow \Lambda = 0$

$$\text{left SUSY } \sim 1 T_e U \Rightarrow \Lambda = (1 T_e U)^Y$$

2) Nonrenormal theorem

- flat direction

3) Tight constraint on coupling
Case for weak scale SUSY

1) Statically Higgs

\[ L = - \frac{g_1}{4} \bar{\Phi} \gamma^\mu \Phi H - \frac{g_2}{2} \bar{\Phi} W^\mu \Phi_s \]

\[ \Delta M_H^2 = \frac{g_1^2}{4} \left( m_H^2 + M_F^2 \right) - \frac{g_2^2}{4} \left( m_H^2 + m_S^2 \right) \rightarrow \frac{g_1^2}{4} \left( M_F^2 - m_S^2 \right) \]

not too big

\[ \Rightarrow \text{weak scale} \]

2) Running couplings

MSSM + desert

3) Dark matter = LSB
MSSM

1) No simplification
   - a superfield for every known particle

2) Extra Higgs

3) 105 extra parameters

4) Flavor physics needs to be fine tuned

5) Remaining issues
   - Babym(O – impose R Parity
   - μ Problem
   - nature of SUSY breaking
   - why weak scale?
Superpotential

\[ W = -U_R Y_u Q_L H_u - d Y_d Q_L H_u - 2 \text{lepton Yukawa} + \mu H_u H_d \]

also \[ L^c \bar{L}^c + u \bar{u} d \bar{d} \] \[ Q^c \bar{Q}^c \] \[ \text{violate} \]

conjugate

\[ \frac{\partial W}{\partial \phi_i} \geq \frac{1}{2} |\frac{\partial W}{\partial \phi_i} |^2 \]

\[ \Rightarrow m^2 (H_u^2 + H_d^2) \]

Discrete Symmetry \[ \chi^\text{spin} \]

\[ P = (-1)^{2(B-L)+2S} \]

\[ \Rightarrow \text{conservation of } (B-L) \]

all SM Particle \[ P_R = +1 \]

Sparticle \[ P_R = -1 \]

\[ \Rightarrow \text{LSP is stable} \]

\[ \Rightarrow \text{neutral for Dark Matter} \]
\textbf{SUSY breaking}

Basic Problem \[ H = \sum_i Q_i^\dagger Q_i > 0 \]

SUSY \(\langle 0 | H | 0 \rangle = 0\)

\[ \implies \text{can't use minimum of any potential} \]

Even \(\langle 0 | H | 0 \rangle > 0\)

\[ \implies \text{need to make } \langle 0 | H | 0 \rangle \text{ impossible} \]

\underline{Example F-term \text{ O'Raifeartaigh}}

\[ W = -k \phi_1 + m \frac{\phi_2 \phi_3}{\sqrt{2}} + \frac{\lambda}{2} \phi_1^2 \phi_2^2 \]

take \[ \frac{\partial W}{\partial \phi_i} F_i' \implies \frac{\partial W}{\partial \phi_i} \]
\[ V = \left| -h + \frac{e}{2} \phi_3^2 \right|^2 + \left| m \phi_3 \right|^2 + \left| m \phi_2 + y \phi_2 \phi_1 \right|^2 \]

minimum \( \phi_2 = \phi_3 = 0 \), \( V = k^2 \neq 0 \), \( \phi_1 = \) anything (flat direction)

Other D-term - Fayet Illipoulos \( \mathcal{I} = -k D \)

Basic result - after SUSY breaking
\[ S \mathcal{D}_i (m^2) = 0 = \sum_{j} (-1)^{i-j} (2j+1) \tan (m_j^2) = 0 \]

\( \Rightarrow \) does not work in SM

\( \Rightarrow \) SUSY beyond MSSM
"Hidden Sector"

- SUSY broken in Hidden Sector
- transmitted to MSSM - "flavor blind"
- gravity mediated
- anomaly mediated
- gang mediated
"Soft" SUSY breaking
- the extra parameter
- all SUSY terms mass dimension of \( \alpha' \) is positive

\[ H \text{ and } \lambda \phi^4 \]

\[ \text{Soft } \frac{\lambda^2 \phi^2}{\Lambda_{\text{soft}}} \leq m_0 \lambda^2 \]

\[ \Delta M_H^2 = M_{\text{soft}}^2 \ln(n) + b M_{\text{soft}}^2 \]

\[ \Rightarrow \text{ once you have these, no further fine tuning} \]
\[ L_{\text{soft}} = M_1 \tilde{B} \tilde{B} + M_2 \tilde{W} \tilde{W} + M_3 \tilde{g} \tilde{g} + \text{gaugino masses} \]

\[ \alpha_1 \tilde{u} \tilde{Q} \tilde{H} + \text{- - -} \]

\[ -m_u^2 H_u H_u + m_d^2 H_d^2 - m_B H_u H_d + \text{Higgs masses} \]
Higgs Sector - 2 Higgs

Recall: SM \( \Phi = (\phi^0) + \tilde{\phi} = i \tilde{\tau}_2 \phi^* = (\tilde{\phi}^0) \)

Yukawa \((\bar{u}, d)(\phi^0) d_R \sim M_d \)

\((\bar{u}, d) \Phi u_R \sim M_u \)

---

Reason for 2 doublets

1) \( \Phi(\psi, \theta) \rightarrow \Phi^*(\psi, \bar{\theta}, \bar{\theta}) \)

\( W = W[\bar{G}] \Rightarrow \text{can't include } \Phi^*(\bar{G}) \)

\( \Phi^*(\bar{G}) \)

Solved by \( \Phi^*_H(\theta) = (\phi_1^0) \)

\( \Phi^*_H(\theta) = (\phi_2^0) \)

\( \Phi^*_H(\theta) = (\phi_1^-) \)

\( \Phi^*_H(\theta) = (\phi_2^-) \)
2) Anomalies

- extra fermion Higgsino
- 2 Higgs - cancel anomalies

\( \sum \) fermion

gauge anomalies cancel
\[ V = (\mu^2 + M^2) |H_u|^2 + (M^2 + M_d^2) |H_d|^2 + \mu_B H_u H_d \]

\[ + \frac{\mu_t}{2} (|H_u|^2 - |H_d|^2)^2 \]

2 doublets \& DoF \quad 4 \text{ charged} + 4 \text{ neutral} \quad \sqrt{2} \text{ scalars} \quad \sqrt{2} \text{ Higgs scalars}

3 DoF \text{ into } W^\pm \Rightarrow 5 \text{ particles } h^0, h^0', A^0, h^+, h^-
Charge conserving Lasso
\[ \langle H_a \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} N_1 \\ 0 \end{pmatrix} \quad \langle H_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ N_2 \end{pmatrix} \]

\[ \tan \beta = \frac{N_1}{N_2} \]

\[ M_Z^2 = \frac{1}{2} \left( N_1^2 + N_2^2 \right) \]

\[ M_{h^2} = M_W^2 + M_A^2 \]

Truth level 1 Higgs lighter than 200 GeV

After had corr, \( M_H < 125 \text{ GeV} \)

\[ \tan \beta = 1 \]

\[ \tan \beta = 3 \]

\[ \tan \beta = 2 \]

\[ M^2 \text{squark} \]

\[ M^2 \text{Higgs} \]
The $\mu$ Problem

2 sources of Higgs mass

SUSY conserving $\mu$

Soft breaking $M_{1/2}, M_{1/2}, M_{1/2}$

Why $\mu \approx M_{SUSY}$?

Need - EWSB

$(m_B)^2 > (m_{\tilde{\chi}^0_1}^2 + m_{\tilde{\tau}^0_1}^2) (\mu^2 + m_{\tilde{\chi}^0_1}^2)$

and $m^2 + \frac{m_{\tilde{\chi}^0_1}^2 + m_{\tilde{\tau}^0_1}^2}{2} > m_B$

\text{small portion of parameter space}
Flavor physics

\[ \tan \beta = \frac{M_1}{M_2} \gg 1 \]

\[ M_t = \frac{\lambda_t}{\lambda_b} N_1 \]

\[ M_b \sim \frac{\lambda_b}{\lambda_t} N_2 \]

\[ \Rightarrow b \text{ quark becomes more sensitive flavor test} \]
Suggestion

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M. Brees

Phenomenology

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X. Tata

Formal

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J. Beger