Note Title 12/3/2009

Supersymmetry 2

$$\Phi = \phi + \theta\psi + \theta\theta F$$

$$W[\Phi] = L^i \Phi_i + m^{ij}\phi^i\phi^j + g^{ijk}\Phi^i\Phi^j\Phi^k$$

$$V = \frac{\partial W}{\partial \phi_i} F_i + \frac{\partial^2 W}{\partial \phi_i \phi_j}\psi_i\psi_j$$

$$\sum_i \left|\frac{\partial W}{\partial \phi_i}\right|^2$$

Properties $(B \leftrightarrow F)$

1) $\Lambda = 0$

$$\langle 0|\{Q, Q^\dagger\}|0\rangle = \langle 0|\, 2\,\overset{(1,\vec{\sigma})}{\bar{\sigma}^\mu}\, \overset{(H,\vec{p})}{P_\mu}\,|0\rangle = \langle 0|\,2H\,|0\rangle = 2\Lambda$$

if vac is invariant $\bar{Q}|0\rangle = 0 \implies \Lambda = 0$

~~If SUSY~~ $\sim 1\,TeV \implies \Lambda = (1\,TeV)^4$

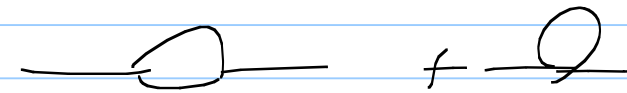
2) Nonrenorm theorems

- flat direction

3) Tight constraints on coupling

Case for weak scale SUSY

1) Stabilize Higgs



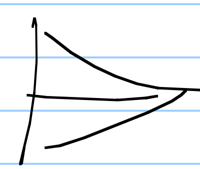
$$\mathcal{L} = -g_F \bar{\Psi}\Psi H - g_S^2 H^2 \phi_S^2$$

$$\Delta m_H^2 = \frac{g_F^2}{4\pi^2}(\Lambda^2 + m_F^2) - \frac{g_S^2}{4\pi^2}(\Lambda^2 + m_S^2) \xrightarrow[g_F = g_S]{} \frac{g_F^2}{4\pi^2}\underbrace{(m_F^2 - m_S^2)}_{\text{not too big}}$$

$\Rightarrow$ weak scale

2) Running couplings

"MSSM + "desert""



3) Dark matter = LSP

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
   - Baryon # - impose - R Parity
   - μ Problem
   - nature of SUSY breaking
   - why weak scale?

Superpotential

dimension of μ

$$W = -\bar{u}_R Y_u Q_L H_u - \bar{d} Y_d Q_L H_d - \text{2 lepton Yukawa} + \mu H_u H_d$$

$$\frac{\partial W}{\partial \phi_i} F^i \to \sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2$$

$$\Rightarrow \mu^2 (H_u^2 + H_d^2)$$

also $\underbrace{L_R^i Q^j \bar{D}^c}_{\text{color singlets}} + \bar{U}\bar{D}\bar{D}$ } violate Baryon #

Discrete Symmetry

$$P_R = (-1)^{3(B-L) + 2S} \quad \text{(spin)} \quad \Longrightarrow \text{conservation of } (B-L)$$

all SM Particles $P_R = +1$
sparticle $P_R = -1$
} $\Longrightarrow$ LSP is stable
$\Longrightarrow$ neutral for Dark Matter

SUSY breaking

Basic Problem $H = \sum_i Q_i^T Q_i > 0$

SUSY $\langle 0|H|0\rangle = 0$

$\Rightarrow$ can't use minimum of any potential

when $\langle 0'|H|0'\rangle > 0$

$\Rightarrow$ need to make $\langle 0|H|0\rangle$ impossible

Example F-term O'Raifeartaigh

$$W = -k\Phi_1 + m\Phi_2\Phi_3 + \frac{y}{2}\Phi_1\Phi_3^2$$

take $\frac{\partial W}{\partial \phi_i} F^i \rightarrow \sum_i \left|\frac{\partial W}{\partial \phi_i}\right|^2$

$$V = \left| -k + \frac{y}{2} \phi_3^2 \right|^2 + |m \phi_3|^2 + |m \phi_2 + y \phi_3 \phi_1|^2$$

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

Other D-term — Fayet Illiopolos $\mathcal{L} = -KD$

Basic result

— after SUSY breaking

$$S\mathrm{Tr}(m^2) = 0 = \sum_j (-1)^j (2j+1) \mathrm{Tr}(m_j^2) = 0$$

$\Longrightarrow$ does not work in SM

$\Longrightarrow$ ~~SUSY~~ beyond MSSM

"Hidden Sector"

- SUSY broken in Hidden sector
- transmitted to MSSM — "flavor blind"
  - gravity mediated
  - anomaly mediated
  - gauge mediated

} not MSSM

"Soft" SUSY breaking

– the extra parameters

all SUSY terms mass dimen of coeff is positive

Hard $\lambda \phi^4$

Soft $m^2_{soft} \phi^2$ no Λ^2

$$\Delta m_H^2 = m_{soft}^2 \ln(\Lambda) + b\, m_{soft}^2$$

$\Rightarrow$ once you have these, no further fine tuning

$$\mathcal{L}_{soft} = M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + M_3 \tilde{g}\tilde{g}$$ gaugino masses

U(1)

$$a_1 \tilde{u} \tilde{Q} H + \cdots$$ squarks

$$- m_u^2 H_u H_u + m_d^2 H_d^2 - \mu B H_u H_d$$ Higgs masses

Higgs Sector – 2 Higgs

Recall SM $\quad \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad + \quad \tilde{\phi} = i\tau_2 \phi^* = \begin{pmatrix} \bar{\phi}^0 \\ -\phi^- \end{pmatrix}$

Yukawa $\quad (\bar{u}, \bar{d})_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}^{\leftarrow \phi} d_R \sim m_d$

$(\bar{u}, \bar{d})_L \, \tilde{\phi} \, u_R \; - \; m_u$

Reasons for 2 doublets

1) $\Phi(\phi, \theta) \longrightarrow \Phi^*(\phi, \bar{\theta}, \theta)$

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

$\quad \nwarrow \bar{\theta}$

Solved by $\Phi_{H_d}(\theta) = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}$, $\Phi_{H_u}(\theta) = \begin{pmatrix} \phi_2^0 \\ \phi_2^- \end{pmatrix}$

2) <u>Anomalies</u>

fermions

gauge anomalies cancel

- extra fermion Higgsino
- 2 Higgs - cancel anomalies

EWSB

- Minimize Higgs Potential
- driven by soft terms

$$V = (\mu^2 + M_u^2) H_u^2 + (\mu^2 + M_d^2) H_d^2 + \mu B H_u H_d$$

$$+ \frac{g_1^2 + g_2^2}{8} \left(|H_u|^2 - |H_d|^2 \right)^2$$

2 doublets 8 DoF 4 charged + 4 neutral

3 DofF into $W^\pm Z^0 \Rightarrow$ 5 particles $h^0, h^{0\prime}, A^0$ h^+ h^-

Scalars Pseudoscalar

Charge conserving vacua $\langle H_u \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v_1 \\ 0 \end{pmatrix}$ $\langle H_d \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}$

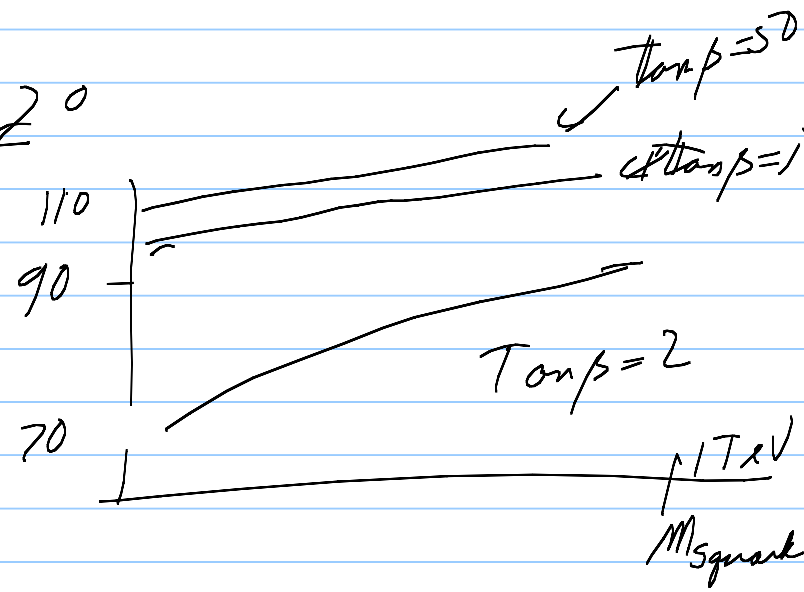
$\tan\beta = v_1/v_2$

$M_Z^2 = \frac{g_1^2+g_2^2}{2}(v_1^2+v_2^2)$

$M_{h^\pm}^2 = M_W^2 + M_A^2$

Tree level 1 Higgs lighter than Z^0

after rad corr $M_H < 125$ GeV



The μ Problem

2 sources of Higgs masses — SUSY conserving: μ

Soft breaking: $m_{H_1}^2, m_{H_2}^2, \mu B$

WHY $\mu \approx m_{soft}$?

<u>Need</u> - EWSB

$(\mu B)^2 > (\mu^2 + m_1^2)(\mu^2 + m_2^2)$

and $\mu^2 + \dfrac{m_1^2 + m_2^2}{2} > \mu B$

$\Big\}$ small portion of parameter space

Flavor physics

$$\tan\beta = v_1/v_2 \gg 1$$

$$\left.\begin{aligned} m_t &= \lambda_t v_1 \\ m_b &\sim \lambda_b v_2 \end{aligned}\right\} \quad \text{large } \tan\beta \Rightarrow \lambda_b \text{ is largest}$$

$\Rightarrow$ b quark become more sensitive flavor test

<u>Suggestions</u>

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Phenomenology

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Formal

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