VIII SUSY breaking - brief intro.

SUSY:
- desireable features
- need to understand breaking (devil in details??)

Overview of some basic aspects (more lectures needed to do justice) $\longrightarrow$ Luty, TASI

Idea: SSB: $Q_\alpha|0\rangle \neq 0$

Note $\{Q_\alpha, \bar{Q}_{\dot\alpha}\} = 2i\sigma^\mu_{\alpha\dot\alpha}\partial_\mu$

$\times\,\sigma^0$, trace $\rightsquigarrow \cancel{2}\sum_\alpha (Q_\alpha\bar{Q}_{\dot\alpha} + \bar{Q}_{\dot\alpha}Q_\alpha) = \cancel{2}\cdot 4i\partial_0 = 4E$

so $\langle 0|H|0\rangle = \sum_\alpha \|Q_\alpha|0\rangle\|^2 + \|\bar{Q}_{\dot\alpha}|0\rangle\|^2$

thus: $Q_\alpha|0\rangle = 0$

$\Updownarrow$

$H|0\rangle = 0$ (again, no c.c.!)

$\therefore$ E_0 = order param $\cancel{\text{SUSY}}$ (also $E \geq 0$)

alternately $\langle S\rangle \neq 0$ = order param, if $Q_\alpha\langle S\rangle \neq 0$ or $\bar{Q}_{\dot\alpha}\langle S\rangle \neq 0$

Lorentz inv $\Rightarrow$ $\langle\Phi\rangle = \theta^2 F$ F-breaking

or $\langle V\rangle = \theta^2\bar\theta^2 D$ D-breaking

as we've described!

Simple tree models: <u>O'Raifeartaigh</u>

$Q^a = N$ chiral sfields

let $\mathcal{L}_{O'R} = \int d^4\theta \, Q_a^\dagger Q^a + \left(\int d^2\theta \, W(Q) + h.c. \right)$

SUSY vac $\longleftrightarrow$ $0 = \langle F_a^\dagger \rangle = \left\langle \frac{\partial W}{\partial Q^a} \right\rangle$

... N conditions

but not always possible

e.g. $W = \kappa Q$!

but trivial, no mass splittings

better

$$W = \frac{1}{2} \lambda_1 S_1 X^2 + \frac{1}{2} \lambda_2 S_2 (X^2 - v^2)$$

$$\frac{\partial W}{\partial S_1} = \frac{1}{2} \lambda_1 X^2 \qquad \frac{\partial W}{\partial S_2} = \frac{1}{2} \lambda_2 (X^2 - v^2)$$

can't both vanish!

$$\frac{\partial W}{\partial X} = (\lambda_1 S_1 + \lambda_2 S_2) X \rightsquigarrow$$

$$V = \frac{1}{2} |\lambda_1|^2 |X|^4 + \frac{1}{2} |\lambda_2|^2 |X^2 - v^2|^2 + |\lambda_1 S_1 + \lambda_2 S_2|^2 |X|^2$$

$\frac{\partial}{\partial S_1}, \frac{\partial}{\partial S_2} \rightsquigarrow \langle \lambda_1 S_1 + \lambda_2 S_2 \rangle = 0$ or $\langle X \rangle = 0$

$\frac{\partial}{\partial X} \rightsquigarrow \langle X^2 \rangle = \frac{|\lambda_2|^2}{|\lambda_1|^2+|\lambda_2|^2} v^2$ or $\langle X \rangle = 0$

$$\langle V \rangle = \begin{cases} \frac{|\lambda_2|^2}{4}|v|^4 & \langle X \rangle = 0 \\ \frac{|\lambda_1|^2|\lambda_2|^2}{2(|\lambda_1|^2+|\lambda_2|^2)}|v|^4 & \langle X \rangle \neq 0 \end{cases}$$

(note ≥ 0)

$|\lambda_2| > |\lambda_1| \Rightarrow \langle X \rangle \neq 0$ = min.

but flat dir$^{\underline{n}}$: vacua satisfying

$\langle \lambda_1 S_1 + \lambda_2 S_2 \rangle = 0$.

other masses lifted to $\mathcal{O}(\lambda v)$ (ex)

LEFT: X and $\lambda_1 S_1 + \lambda_2 S_2$ fixed

param flat dir$^{\underline{n}}$ by S_2.

$\rightsquigarrow \quad S_1 = -\frac{\lambda_2}{\lambda_1} S_2$

$W_{eff} = -\frac{1}{2}\lambda_2 v^2 S_2$ (ex)

$\Rightarrow$

$$\mathcal{L}_{eff} = \int d^4\theta \left(1 + \frac{|\lambda_2|^2}{|\lambda_1|^2}\right) S_2^\dagger S_2 + \left(\int d^2\theta\, W_{eff} + h.c.\right)$$

note $\frac{\partial W_{eff}}{\partial S_2} \neq 0 \leftrightarrow$ ~~SUSY~~

3/8/07

See in masses in higher-dim terms.

<u>D-breaking</u> $V = \theta^2\bar{\theta}^2 D$

one approach: if $U(1)$, $\mathcal{L}_{FI} = \int d^4\theta \, \xi V$

$\delta_{gauge} \mathcal{L}_{FI} = $ T.D. ex

but not true if ξ = superfield

doesn't arise from SUGRA

alt. ~~SUSY~~ & ~~gauge~~ sym $D = -\sum q_i \phi_i^* \phi_i \neq 0$

(charged fields get vevs).

complicated, not clearly useful, no time...

<u>More General features:</u>

$$V = \underset{\uparrow \atop \frac{\partial W}{\partial Q^a}}{F^a F_a^*} + \frac{1}{2} \underset{\uparrow \atop g_A Q_a^\dagger T_A{}^a{}_b Q^b}{D_A D_A}$$

- goldstino — can find directly from ferm mass matrix

or, current algebra.

$$\text{SUSY} \xrightarrow[\text{Nöther's Thm}]{} \partial_\mu j_\alpha^\mu = 0 \;; \qquad Q_\alpha = \int d^3x \, j_\alpha^0$$

Suppose, e.g., F breaking (w/ D simple generalization.)

Consider $\langle 0| j^\mu_\alpha(q) \psi_\phi |0\rangle = \int \frac{d^4x}{(2\pi)^4} e^{iq\cdot x} \langle T j^\mu_\alpha(x) \psi_\phi(0) \rangle$

partner to $F_\phi \neq 0$

$$q_\mu \cdot (\quad " \quad) = \int \frac{d^4x}{(2\pi)^4} e^{iqx} \underbrace{i \frac{\partial}{\partial x^\mu} \langle T j^\mu_\alpha(x) \psi_\phi(0) \rangle}$$

$$= i \langle [j^0_\alpha(x), \psi_\phi(0)] \rangle \delta(x^0)$$

take $q \to 0$

$$= i \langle [Q_\alpha, \psi_\phi] \rangle = i F$$

$\Rightarrow$ pole in $\langle 0| j^\mu_\alpha(q) \psi_\phi |0\rangle$ @ $q=0$: massless part.

Indeed (ex)
$$j^\mu_\alpha = i\sqrt{2}\,\sigma^\mu_{\alpha\dot\alpha} \psi^{*\dot\alpha} F$$
$$\partial_\mu j^\mu_\alpha = 0 \leftrightarrow \not{\partial}\psi^* = 0.$$

ex find the goldstino in O'Raif.

local SUSY $\Rightarrow$ eaten : super Higgs.

- another general statement about mass matrix w/ tree breaking:

$$0 = \mathrm{tr}\,(-1)^F M^2 \qquad (-1)^F = \begin{matrix} 1 & \text{bosons} \\ -1 & \text{ferms.} \end{matrix}$$

can prove in general; e.g. w/ F breaking/chiral mults.

Recall $\quad \mathcal{M}_{F\,ab} = \partial_a \partial_b W$

Bosos from $\quad V = |\partial_a W|^2$

$$m^2_{a\bar{b}} = \partial_a \partial_{\bar{b}} V = \partial_a \partial_c W \; \partial_{\bar{b}} \partial_{\bar{c}} W^*$$

$$m^2_{ab} = \partial_a \partial_b V = \partial_a \partial_b \partial_c W \; \partial_{\bar{c}} W^*$$

$\uparrow$
off diag (recall cplx basis for scalar field)

$$\Rightarrow \quad \mathrm{Tr}\, \mathcal{M}_B^2 = \sum_{a,c} \partial_a \partial_c W \, \partial_{\bar{a}} \partial_{\bar{c}} W^* = \mathrm{Tr}\, \mathcal{M}_F^2 \quad \checkmark$$

Trouble! light superpartners.

Outs:
- large loop corr$^{\underline{n}}$s
- non-renormalizable terms in K. ($eg \; K_{a\bar{b}} \neq \delta_{ab}$

these $\propto \frac{1}{M^p} \quad \Rightarrow$ typically

SUSY at high scale
$\downarrow$ messenger dynamics
SUSY at low scale.

maybe helps w/ flavor?
(if "blind")

E.g. gravity (or gauge.)

$\rightarrow$ SUGRA

summarize effects in LEFT by higher dim ops. $\propto \frac{1}{M_P^d}$.

Let X = field in "hidden sector", $\langle F_X \rangle \neq 0$, $\langle X \rangle = 0$

$\rightsquigarrow$

$$\Delta \mathcal{L} = \int d^4\theta \left\{ \frac{X X^\dagger Q_i Q_j^\dagger}{M_P^2} Z_{ij} + \frac{b}{M_P} X H \bar{H} + \frac{b'}{M_P^2} X^\dagger X H \bar{H} + h.c. + \cdots \right\}$$

$$+ \int d^2\theta \left(\frac{s_1}{M_P} X W^\alpha W_\alpha + h.c. + \cdots \right)$$

$$+ \int d^2\theta \left(\frac{a_{ij}}{M_P} X Q_i \bar{U}_j H + \cdots \right)$$

$\langle F_X \rangle \rightsquigarrow$ soft <u>SUSY</u> described before!

want $\text{TeV} \sim M_{SUSY} \sim \frac{F_X}{M_P} \Rightarrow F_X \sim (10^{11}\,\text{GeV})^2$

"intermediate scale"

difficulty: Z_{ij}, a_{ij} can violate flavor.

symmetry avoids?

but gravity isn't expected to respect global symmetries, gauge??

Minimal Ansatz: $Z_{Q_{ij}} = Z_{L_{ij}} = \cdots = z_0 \delta_{ij}$

etc. $\longleftrightarrow$ "minimal SUGRA," as described.

feature (ex): H mass runs negative from large λ_t
$\longleftrightarrow$ radiative symm breaking.

Flavor issues suggest: gauge mediation ... another story

Final comment on SUSY breaking & LHC:

$$V_{Higgs} = M_H^2 |H|^2 + M_{\bar{H}}^2 |\bar{H}|^2 - M_{H\bar{H}}^2 (H\bar{H} + h.c.) \quad \leftarrow \mu + \text{soft terms}$$

$$+ \frac{1}{8}(g_1^2 + g_2^2)\left(|H|^2 - |\bar{H}|^2\right)^2 + \frac{1}{2} g_1^2 |H\bar{H}|^4 \quad \leftarrow \text{quart terms } \underline{\text{from D-terms}}.$$

requirements for $SU(2)\times U(1)$ breaking pot (ex)

$$M_H^2 + M_{\bar{H}}^2 - 2|M_{H\bar{H}}|^2 > 0$$

$$|M_{H\bar{H}}|^4 > M_H^2 M_{\bar{H}}^2 .$$

$\rightsquigarrow \quad \langle H \rangle \neq 0, \ \langle \bar{H} \rangle \neq 0. \qquad \tan\beta = \dfrac{\langle H \rangle}{\langle \bar{H} \rangle}$

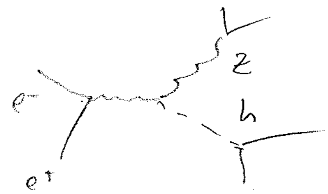
define $\quad m_A^2 = \dfrac{M_{H\bar{H}}^2}{\sin\beta \cos\beta}$

can show:

$$M_{H^0, h^0}^2 = \frac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2) - 4 m_Z^2 m_A^2 \cos(2\beta)}\right)$$

note $\quad m_{h^0} \leq M_Z$!

but LEP bd: $\gtrsim 115$ GeV.



but : • loop corr^{n}s $\Rightarrow$ MSSM not ruled out
• beyond MSSM ?

A very interesting story to be revealed.