Lecture 6. (p.1)

Supersymmetry.

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Soft SUSY breaking terms + MSSM pheno

From last time, we saw that the spectrum of states in the spontaneously broken SUSY model,

$$W = \lambda A (X^2 - \mu^2) + m B X,$$

had fermion + boson masses split ⇒ sure sign of SUSY breaking. (Note the splitting still preserved a supertrace condition) On the other hand, couplings + interactions remained the same. So if the masses were degenerate, SUSY would be restored, while if the interactions were different, SUSY would be broken. This is essentially the distinction between soft and hard SUSY breaking.

If we write down mass terms in $\mathcal{L}$ that split bosons + fermions (caveat: only exception is an explicit mass for chiral fermion component of a superfield, which is a hard SUSY breaking term - Shifman, p. 540), then these mass terms are order parameters for SUSY breaking. As we go to higher energies, the mass spectra look more SUSic.

Shifman, sec. 66

In fact, we can always bootstrap these terms as spurions of some superfields with non-zero F or D terms + calculate as if the $\mathcal{L}$ were SUSic. This also requires that UV divergences can only be logarithmic with scale (related to supertrace protection).

We then define three types of SUSY soft breaking terms:

Dine Sec. 10.4

$$\mathcal{L} = \int d^2\theta \; \eta_1 \mathrm{Tr} W^2 + h.c.$$
$$\eta_1 = F_1 \theta^2, \quad F_1 \neq 0$$

This is a gaugino mass term [recall that the lowest component of W^α is λ^α, gaugino = fermion partner to gauge boson.]

$$\mathcal{L}_2 = \int d^4\theta \; Z \bar{Q} e^V Q$$
$$\mathcal{L}_3 = \int d^2\theta \; \eta_2 Q^2 + h.c.$$

These are soft scalar mass terms, $m\bar{q}q$ and $mq^2 + h.c.$, respectively.

$$\mathcal{L}_4 = \int d^2\theta \; \eta_3 Q^3$$

These are trilinear scalar couplings (mass dim. 1)

Soft SUSY Breaking + MSSM

For SUSY to be realistic, it must be broken in Nature. We can treat this in 2 ways:

1.) Construct a UV model of SUSY breaking incorporating the Standard Model field content

2.) Consider SUSY breaking dynamics separate from SUSY breaking soft parameters.

Analogy: DM EFT: most important phenomenology characterized by possible mediators. Similarly, different mediation mechanisms dictate different patterns of the soft breaking terms.

We will adopt the second approach.

Minimal Supersymmetric Standard Model

MSSM

Field content:

$Q \sim (3, 2, 1/6)$ Charges under $SU(3) \times SU(2) \times U(1)$

$U^c \sim (\bar{3}, 1, -2/3)$ Since natural language of the chiral superfield is LH, use charge conjugation to define all fields as LH superfields.

$D^c \sim (\bar{3}, 1, +1/3)$

$L \sim (1, 2, -1/2)$

$E^c \sim (1, 1, +1)$

$H_u \sim (1, 2, 1/2)$ IOW, regard RH particles as charge conjugates of LH ~~fields~~ antiparticle fields.

$H_d \sim (1, 2, -1/2)$

Note: ① Anomalies from fermionic components of Higgs fields necessitate a vector-like set of reps: $H_u + H_d$. Would have both chiral (Adler-Bell-Jackiw) anomalies + Witten anomaly if one (H_u or H_d) were absent.

② Interesting ~~cont~~ corollary:
The SM is a QFT (and model content) that cannot be supersymmetrized consistently, unless additional fields are added.

Gauge interactions from

$$\mathcal{L} = \int d^4\theta \; \bar{Q} e^V Q + \ldots \quad \text{for } V = \text{gauge superfields of } SU(3),\ SU(2),\ U(1)_Y.$$

Will result in scalar-scalar-gauge boson interactions, fermion-fermion-gauge boson interactions, and gaugino-scalar-fermion interactions (+ gaugino-gaugino-gauge boson + usual non-Abelian gauge interactions.)

Superpotential interactions

As in the SM, we write down all renormalizeable interactions (up to dim. 3 in W) allowed by gauge invariance.

First, we have the usual Yukawa interactions, except that $\tilde{H} \to H_u$, since we are forbidden from writing conjugate superfields in W.

$$\mathcal{L} = \int d^2\theta \, \left(Y_u^{ij} H_u Q_{ui} U_j^c + Y_d^{ij} H_d Q^i D^{cj} + Y_e^{ij} H_d L^i E^{cj} \right) + h.c.$$

We will study how MSSM particles inherit the Yukawa interactions later, when we discuss MSSM pheno.

Second, we have a new term

$$\mathcal{L} = \left(\int d^2\theta \; \mu H_u H_d \right) + h.c.$$

Martin Sec. 5.1.

This "μ-term" is SUSic. It's equivalent to a supersymmetric vector-like mass, since H_u and H_d form a vector-like rep. under the gauge symmetries. Lots of literature about fine-tuning this term to avoid a large hierarchy between the SUSY scale (since μ is a SUSic mass scale parameter in W) and the soft SUSY breaking terms.

Additional "problematic" terms:

$$\mathcal{L} = \left(\int d^2\theta \, \lambda^{ijk} L_i L_j E^c_k + K^{ijk} Q^i L^j D^{ck} + \eta^i L_i H_u + \rho^{ijk} U^c_i D^c_j D^c_k \right) + h.c.$$

Each of these SUSic terms violates lepton or baryon #.

Proton decay limits ~ 10^{32-33} years force these couplings to be tiny ~~and~~ if the mass scale of the sparticles is TeV. (Even so, if we make the mass scale of proton decay operators @ dim. 6 to be 10^{16} GeV, we must have a very suppressed Wilson coefficient.)

Thus, phenomenologically, we must forbid these terms by a new symmetry.

① Choose to impose B + L as global symmetries. This is unappealing because they are accidental in SM and anomalous.

② Impose R-parity. $R = (-1)^{3(B-L)+2s}$

Superfields QUDLE ~ $R = -1$

$H_u H_d$ ~ $R = +1$

So these B + L violating terms are turned off.

Phenomenologically, can turn on one set of R-parity violating couplings + be consistent with proton decay (which requires both B + L violation.) Useful for studying LSP (lightest SUSic particle) decay.

For conserved R-parity, ~~[illegible]~~ LSP is stable.

Soft ~~SUSY~~ in MSSM

Recall we had 3 categories of soft ~~SUSY~~ terms:

① Gaugino masses

$$\mathcal{L} = -\frac{1}{2}\left(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B} + c.c. \right)$$

$\tilde{g}$ = gluino, fermionic partner of gluon
$\tilde{W}$ = wino, " " " W boson (gauge basis)
$\tilde{B}$ = bino, " " " hypercharge boson (gauge basis)

② Soft scalar masses.

Suppress gauge + flavor indices

$$\mathcal{L} = -m_Q^2 |\tilde{q}_L|^2 - m_L^2 |\tilde{\ell}|^2 - m_u^2 |\tilde{u}^c|^2 - m_D^2 |\tilde{d}^c|^2 - m_E^2 |\tilde{e}^c|^2 - m_{H_u}^2 |h_u|^2 - m_{H_d}^2 |h_d|^2 - (b\mu \, h_u h_d + c.c.)$$

$\tilde{q}_L, \tilde{u}, \tilde{d}$ = squarks = "scalar quarks"
$\tilde{\ell}, \tilde{e}$ = sleptons = "scalar leptons"

$m_Q^2, m_L^2, m_u^2, m_D^2, m_E^2$ are all 3x3 Hermitian matrices
$m_{H_u}^2, m_{H_d}^2$ real
$b\mu$ complex

③ Trilinear scalars

$$\mathcal{L} = \left(a_u \, \tilde{q}_L H_u \tilde{u}^c + a_d \, \tilde{q}_L H_d \tilde{d}^c + a_e \, \tilde{\ell} H_d \tilde{e}^c \right) + c.c.$$

a_u, a_d, a_e are 3x3, complex matrices.

Martin, Sec. 5.3.

In total ~~general~~, MSSM has 105 <u>new</u> masses, phases + mixing angles that have no counterpart in SM.
⇒ UV models will dictate patterns in soft params.