Supersymmetry
Lecture 7.
MSSM Soft breaking and pheno.
6.12.19
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From last time, gaugino masses & phases, scalar mass-squareds & mixing angles, and trilinear scalar couplings (real & imaginary) numbered 105 new parameters in the MSSM that had no counterpart in the SM.

But studying the phenomenology of a 105-dim. parameter space is a practical impossibility. In general, an arbitrary point in this space with random choices for flavor mixings and CP-violating phases will be excluded (for 1-100 TeV-scale sparticle masses) by precision flavor constraints & EDMs.

Fortunately, flavor & EDM constraints are greatly relaxed when the patterns of soft ~~SUSY~~ params. are essentially flavor-blind. This is in fact the case in popular mechanisms for communicating SUSY breaking to the MSSM.

Popular schemes:

Minimal supergravity (mSUGRA)
- universal soft masses for scalars, gauginos, A-terms.

Terning Chap. 16

Gauge mediation (GMSB)
- messengers with nonzero F terms only have gauge int.

Anomaly mediation (AMSB)
- conformal anomaly transmits SUSY breaking via RGEs

Basic MSSM pheno

There is a relatively straightforward way to construct & calculate MSSM interactions & pheno effects. Will assume R-parity cons.

Recall that R-parity governs the B- & L-conserving superpotential terms, and also allows the μ-term. The Yukawa interactions govern the mass generation mechanism for SM chiral fermions after EWSB, but also dictates interactions of the scalar superpartners:

$$W = Y_u\, Q H_u U^c + Y_d\, Q H_d D^c + Y_e\, L H_d E^c$$

All fields here are chiral superfields. Can extract normal fermion Yukawa terms by writing

$Q \sim \sqrt{2}\,\theta^\alpha q_\alpha$, $U^c \sim \sqrt{2}\,\theta^\beta u^c_\beta$, $H_u \sim h_u$

Using $\theta^\alpha \theta^\beta = -\frac{1}{2}\epsilon^{\alpha\beta}\theta^2$,

$$\mathcal{L} \supset Y_u h_u \bar{q} u^c + Y_d h_d \bar{q} d^c + Y_e h_d \bar{L} e^c + h.c.$$

But note we can also swap the fermion & scalar in pairwise manner, governed by the same Yukawa coupling:

$Q \sim \tilde{q}_L + \sqrt{2}\,\theta^\alpha q_\alpha$, $U^c \sim \tilde{u}^c_\beta + \sqrt{2}\,\theta^\beta u^c_\beta$, $H_u \sim h_u + \sqrt{2}\,\theta^\gamma \tilde{h}_{u\gamma}$

Note: tilde denotes SUSY partner of SM field, not necessarily always fermion or scalar.

Note 2: These interactions are all determined in gauge basis, not mass basis. EWSB will generally mix L+R scalar states & Higgsinos with Bino & Winos (both charged "charginos" and neutral "neutralinos").

$$\mathcal{L} \supset Y_u \tilde{h}_u \bar{q} \tilde{u}^c + Y_u \tilde{h}_u \bar{\tilde{q}} u^c + Y_d \tilde{h}_d \bar{q} \tilde{d}^c + Y_d \tilde{h}_d \bar{\tilde{q}} d^c$$
$$+ Y_e \tilde{h}_d \bar{\tilde{L}} e^c + Y_e \tilde{h}_d \bar{L} \tilde{e}^c + h.c.$$

Note 3: Still have to break up SU(2) doublets. Get neutral + charged Higgs ints.

Besides the Yukawa interactions, the Yukawa couplings determine pure scalar interactions from the scalar potential.

$$V = \Sigma |F_i|^2 + \tfrac{1}{2} D^2$$

$$F_i^* = \frac{\partial W}{\partial \Phi_i}\Big|_{\phi_i}$$

$$F_Q^* = \left(Y_u H_u U^c + Y_d H_d D^c\right)\Big|_{\Phi_i = \phi_i}$$

$$= Y_u h_u \tilde{u}^c + Y_d h_d \tilde{d}^c$$

$$F_{u^c}^* = Y_u \tilde{q} h_u$$

$$F_{d^c}^* = Y_d \tilde{q} h_d$$

$$F_{H_u}^* = Y_u \tilde{q} \tilde{u}^c + \mu h_d \qquad \leftarrow W = \mu H_u H_d$$

$$F_{H_d}^* = Y_d \tilde{q} \tilde{d}^c + Y_e \tilde{l}_L \tilde{e}^c + \mu h_u$$

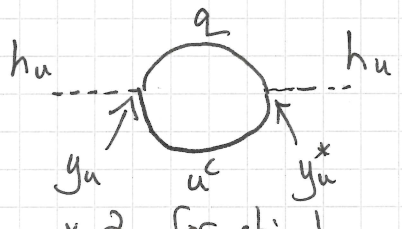
$$F_L^* = Y_e h_d \tilde{e}^c$$

$$F_{E^c}^* = Y_e \tilde{l}_L h_d$$

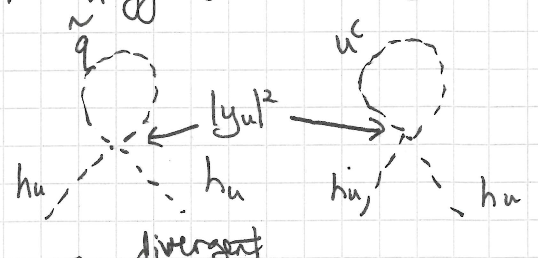
Consider, for example, $|F_Q^*|^2 + |F_{u^c}|^2 + |F_{d^c}|^2$.

$$\mathcal{L} \supset |y_u|^2 |h_u|^2 |\tilde{u}^c|^2 + \left(y_u h_u \tilde{u}^c y_d^* h_d^* \tilde{d}^{c*} + \text{c.c.}\right)$$
$$+ |y_d|^2 |h_d|^2 |\tilde{d}^c|^2$$
$$+ |y_u|^2 |\tilde{q}|^2 |h_u|^2$$
$$+ |y_d|^2 |\tilde{q}|^2 |h_d|^2$$

Will discuss 2-Higgs Doublet Phenomenology more extensively, but we can already ~~demos~~ demonstrate the vanishing of quadratic divergences to the Higgs scalar masses:



x 2 for chiral (easier if written using $y_u h\, t t$ instead of $y_u h \bar{t}_L t_R + \text{h.c.}$)

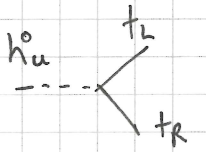


These divergent diagrams are all determined from SUSic superpotential.

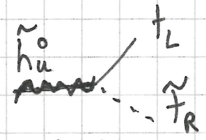
Spin statistics ensures exact cancellation

Easy trick to generate vertices (in gauge basis).
Take SM vertex with 3 legs & replace two by their superpartners.

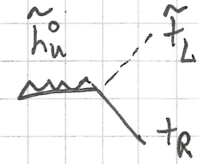
$$\mathcal{L} \supset y_u h_u \bar{q} u^c + y_u \tilde{h}_u \bar{q} \tilde{u}^c + y_u \tilde{h}_u \bar{\tilde{q}} u^c + \ldots$$



Higgs - top_L - top_R



Neutral Higgsino - top_L - RH stop



Neutral Higgsino - LH stop - RH top

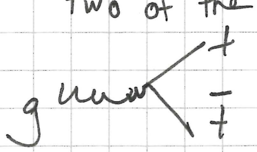
This also works for gauge interactions involving SM fields & their superpartners.

Gauge interactions from
$$\mathcal{L} = \int d^4\theta \; \bar{Q} e^V Q + \bar{U}^c e^V U^c + \ldots$$

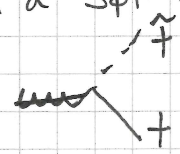
Comment: Trivial to write normal covariant derivatives for all fermions, scalars, gauge bosons [e.g. SM fermions + corresponding sfermions, SM/2HDM Higgs + corresponding Higgsinos, SM gauge bosons + corresponding gauginos.]
Should review scalars in gauge theories (scalar QED + scalar Yang-Mills) if necessary.

Comment: Can apply the same trick as above: supersymmetrize two of the legs in a 3pt. vertex.

Ex.

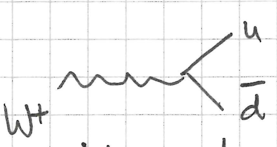


gluon - top - top

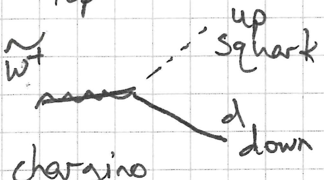


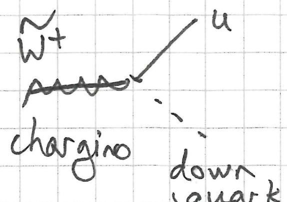
gluino - stop - top

Ex.



W - up - down





Now, main difficulty / complication in MSSM pheno is the effect of tree-level mass mixing from 2HDM structure in squarks, sleptons, charginos, neutralinos. Keep in mind that once EWSB occurs, many new particles have same quantum numbers under remaining $SU(3) \times U(1)_{em}$ → soft breaking params + 2HDM couplings generally mix all flavors.

New MSSM particle content.

Squarks:

3 LH $\tilde{u}_L, \tilde{c}_L, \tilde{t}_L$, 3RH $\tilde{u}_R, \tilde{c}_R, \tilde{t}_R$ ⇒ 6 mass eigenstate up squarks $\tilde{u}_1 \ldots \tilde{u}_6$

3 LH $\tilde{d}_L, \tilde{s}_L, \tilde{b}_L$, 3RH $\tilde{d}_R, \tilde{s}_R, \tilde{b}_R$ ⇒ 6 mass eigenstate down squarks $\tilde{d}_1 \ldots \tilde{d}_6$

Sleptons

3 LH $\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L$, 3RH $\tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R$ ⇒ $\tilde{e}_1 \ldots \tilde{e}_6$

3 LH $\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$ ——— ⇒ $\tilde{\nu}_1 \ldots \tilde{\nu}_3$

Neutralinos:

$\tilde{h}_u^0, \tilde{h}_d^0, \tilde{W}^3, \tilde{B}^0$ ⇒ 4 neutralinos $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$

Charginos:

$\tilde{h}_u^+/\tilde{h}_d^-$, $\tilde{W}^{+/-}$ ⇒ 2 charginos $\tilde{\chi}_1^{+/-}, \tilde{\chi}_2^{+/-}$

Gluino (no mixing)

$\tilde{g}$ ⇒ 1 gluino $\tilde{g}$

+ 2HDM scalars.

To best explain pheno, will digress into a 2HDM discussion.