An Introduction to Supersymmetry and the MSSM

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First of a series of seminars on BSM at the LHC

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Outline of Talk One

1. Supersymmetry Basics

2. How to Read Superpotentials

3. Fields of the MSSM

4. Supersymmetry Breaking

5. Connecting Scales via RGEs

6. Some SUSY Breaking Paradigms

The Building Blocks

⇒ What is meant by a "supermultiplet"?

- Irreducible multiplet of the supersymmetry algebra
- Fields of the same quantum number(s), but different spin
  - ⋆ Chiral supermultiplet: $F = \left\{ \widetilde{f},\ f,\ F_f \right\}$

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- NOT dynamical – no kinetic terms in the component Lagrangian
- Required for SUSY algebra to close "*off-shell*"
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- But important: vevs trigger SUSY breaking (more later)!

More on Auxiliary Fields

$\Rightarrow$ Potential part of the Lagrangian determined by auxiliary fields

$$V = \sum_I |F_i|^2 + \frac{1}{2}\sum_a |D_a|^2 - \frac{|M|^2}{3M_{\rm PL}^2}$$

- Consider *global SUSY limit* $M_{\rm PL} \to \infty$
  - ⋆ $\langle V \rangle = 0$ if SUSY intact
  - ⋆ $\langle V \rangle > 0$ when SUSY broken

$\Rightarrow$ Auxiliary field equations of motion

$$\begin{aligned} \overline{F}_i &= \left.\frac{\partial W}{\partial \Phi_i}\right|_{\Phi\to\phi} \\ D_a &= g_a \sum_i \phi_i^\dagger (T_a) \phi_i \\ \langle M \rangle &= -3 m_{3/2} \end{aligned}$$

From "Superspace" to *Real* Space

$\Rightarrow$ A supersymmetric Lagrangian is defined by a *superpotential* W

- A superpotential W must itself be a chiral (holomorphic) object
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$$u_R^c = \tilde{u}_R^c + \theta u_R^c + \theta^2 F_u \qquad H_u = \begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix} + \theta \begin{pmatrix} \chi_u^+ \\ \chi_u^0 \end{pmatrix} + \theta^2 \begin{pmatrix} F_{H_u}^+ \\ F_{H_u}^0 \end{pmatrix}$$

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- Tensor calculus made simple: every term must have two thetas

$$W \ni \lambda_u Q u_R^c H_u \rightarrow \lambda_u \tilde{u}_L u_R^\dagger \chi_u^0 + \lambda_u u_L \tilde{u}_R^c \chi_u^0 + \lambda_u u_L u_R^\dagger h_0 + \lambda_u \tilde{d}_L u_R^\dagger \chi_u^+ + \cdots$$

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$$W \ni \lambda_u Q u_R^c H_u \to \lambda_u \tilde{u}_L u_R^\dagger \chi_u^0 + \lambda_u u_L \tilde{u}_R^c \chi_u^0 + \lambda_u u_L u_R^\dagger h_0 + \lambda_u \tilde{d}_L u_R^\dagger \chi_u^+ + \cdots$$

- Terms involving auxiliary fields: the scalar potential $V \sim \sum_i |F_i|^2$

$$W = \lambda_u Q u_R^c H_u \to \tilde{u}_L \tilde{u}_R^c F_{H_u}^0 + \cdots \to |\tilde{u}_L \tilde{u}_R^c|^2 + \cdots$$

The MSSM I: Field Content

⇒ Fields of the MSSM

Names		spin 0	spin 1/2	$SU(3)_C$, $SU(2)_L$, $U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \;\; \widetilde{d}_L)$	$(u_L \;\; d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
($\times 3$ families)	$\bar{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
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sleptons, leptons	L	$(\widetilde{\nu}\;\; \widetilde{e}_L)$	$(\nu \;\; e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
($\times 3$ families)	$\bar{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H_u^+ \;\; H_u^0)$	$(\chi_u^+ \;\; \chi_u^0)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
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- New fermions create triangle anomalies, e.g. $\mathrm{Tr}\left[Y^3\right] \neq 0$
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- New fermions create triangle anomalies, e.g. $\mathrm{Tr}\left[Y^3\right] \neq 0$
- Need opposite hypercharge fermion
- Yukawa (mass) interactions: superpotential cannot involve $Qu_R^c(H_d)^\dagger$, etc.

The MSSM II: Superpotential

⇒ Most general gauge-invariant, renormalizable superpotential

$$W = W_{\mathrm{MSSM}} + W_R$$

$$\begin{aligned} W_{\mathrm{MSSM}} &= \lambda_u Q u_R^c H_u + \lambda_d Q d_R^c H_d + \lambda_e L e_R^c H_d + \lambda_\nu L \nu_R^c H_u + \mu H_u H_d \\ W_R &= \lambda' Q d_R^c L + \lambda'' d_R^c d_R^c u_R^c + \lambda''' L L e_R^c + \mu' L H_u \end{aligned}$$

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- Higgs states can mix with leptons
- New contributions to FCNC's at loop level $\rightarrow \lambda \sim 0.05$
- Products of operators can allow rapid proton decay ($\tau_p \simeq \tau_n$)

$$\text{e.g. } p \rightarrow \ell^+ \pi^0 \quad \text{via} \quad \widetilde{s}_R, \widetilde{b}_R \quad \text{exchange} \rightarrow \lambda' \lambda'' \sim 10^{-30}$$

The MSSM III: R-Parity

⇒ So we introduce *R-parity* : $R_p = (-1)^{3(B-L)+2s}$

- Without $2s$ we have "matter parity"

$$P_M(Q,u,d,L,e) = -1 \quad P_M(H_u,H_d) = +1$$

- With spin it instead separates SM from superpartners

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- Immediately forbids all of W_R
- The "two superpartner" rule
- All superpartners must decay into *Lightest Supersymmetric Particle* (LSP)
  - ⋆ Stable
  - ⋆ Neutral and weakly-interacting $\rightarrow$ cold dark matter?
  - ⋆ Signature implication: missing energy

Interlude on the "Hierarchy Problem"

$\Rightarrow$ Quadratic vs. Logarithmic divergences

- Scalar masses (and $\langle V \rangle$ itself) get power-law divergences at one loop

$$m_S^2\big|_{\rm one-loop} = m_S^2\big|_{\rm bare} + \delta m^2 \sim m_S^2\big|_{\rm bare} + \frac{\lambda^2}{16\pi^2}\Lambda_{\rm UV}^2$$

- Fermion mass terms protected by chiral symmetry

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⇒ Consider corrections to SM m_H^2 via $\Delta V = -\lambda_S |H|^2 |s|^2$

$$\delta m_H^2\big|_{\text{f}} = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{\text{UV}}^2 + 6m_f^2\ln(\lambda_{\text{UV}}/m_f)\right]$$

$$\delta m_H^2\big|_{\text{s}} = \frac{\lambda_s}{16\pi^2}\left[\Lambda_{\text{UV}}^2 - 2m_s^2\ln(\lambda_{\text{UV}}/m_s)\right]$$

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  - ⋆ The scalar and fermion masses are similar

$$\delta m_H^2\big|_{\rm f+s} \sim \frac{\alpha}{16\pi^2}(m_f^2 - m_s^2)\ln\left(\Lambda_{\rm UV}/m\right)$$

- Hence the desire that $(m_f^2 - m_s^2) \lesssim 1\ {\rm TeV}$

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$\Rightarrow$ Breaking should be “soft”

- Super-renormalizable terms (positive mass-dimension)
- No new non-supersymmetric contributions to chiral symm. breaking
- No interference in the dimensionless relations such as $\lambda_S = |\lambda_F|^2$

$\Rightarrow$ Breaking parameterized by spurion field vevs...*spontaneous*

Gaugino Masses I

$$\mathcal{L}_{\text{soft}} \ni -\frac{1}{2} M_a \lambda_a \lambda_a$$

⇒ Gluinos (M_3)

- Only $s = 1/2$, $SU(3)$ adjoint-valued fields $\rightarrow$ no mixing
- Adjoint irrep.'s $\rightarrow$ self-conjugate $\rightarrow$ "LH" and "RH" components identical

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⇒ Charginos (M_2 and μ)

- Four 2-component spinors: Higgsinos (χ_u^+, χ_d^-) and W-inos ($\widetilde{\lambda}_1$, $\widetilde{\lambda}_2$)

$$\psi^{\pm} = \left(\widetilde{W}^+, \chi_u^+, \widetilde{W}^-, \chi_d^- \right)$$

- Charged → can be grouped into two Dirac spinors ($\widetilde{C}_1$, $\widetilde{C}_2$)
- Mass terms in 4×4 notation: $\mathcal{L} \ni -\frac{1}{2} \left(\psi^{\pm}\right)^T M_{\widetilde{C}} \left(\psi^{\pm}\right) \;\; + \text{c.c.}$

$$M_{\widetilde{C}} = \begin{pmatrix} 0 & X^T \\ X & 0 \end{pmatrix} \qquad X = \begin{pmatrix} M_2 e^{i\varphi_2} & g_2 v_u \\ g_2 v_d & \mu e^{i\varphi_\mu} \end{pmatrix}$$

Gaugino Masses II – EM Neutral Sector

$\Rightarrow$ Neutralinos (M_1, M_2 and μ)

- Four 2-comp. spinors: Higgsinos (χ_u^0, χ_d^0), W-ino $\widetilde{\lambda}_3 = \widetilde{W}^0$ and B-ino $\widetilde{B}$

$$\psi^0 = \left(\widetilde{B}, \widetilde{W}^0, \chi_d^0, \chi_u^0\right)$$

- Neutral $\rightarrow$ can be organized into four Majorana spinors $\widetilde{N}_i$

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- Mass terms in 4×4 notation: $\mathcal{L} \ni -\frac{1}{2}\left(\psi^0\right)^T M_{\widetilde{N}} \left(\psi^0\right) \quad +\text{c.c.}$

$$M_{\widetilde{N}} = \begin{pmatrix} M_1 e^{i\varphi_1} & 0 & -g' v_d/\sqrt{2} & g' v_u/\sqrt{2} \\ 0 & M_2 e^{i\varphi_2} & g' v_d/\sqrt{2} & -g' v_u/\sqrt{2} \\ -g' v_d/\sqrt{2} & g' v_d/\sqrt{2} & 0 & -\mu e^{i\varphi_\mu} \\ g' v_u/\sqrt{2} & -g' v_u/\sqrt{2} & -\mu e^{i\varphi_\mu} & 0 \end{pmatrix}$$

⇒ Typical eigenstates if $M_1 \lesssim M_2 \ll \mu$

$$m_{\widetilde{N}_1} \simeq M_1; \quad m_{\widetilde{N}_2} \simeq m_{\widetilde{C}_1} \simeq M_2; \quad m_{\widetilde{N}_3} \simeq m_{\widetilde{N}_4} \simeq m_{\widetilde{C}_1} \simeq \mu$$

$$\widetilde{N}_1 \sim \widetilde{B}; \quad \widetilde{N}_2 \sim \widetilde{W}^0; \quad \widetilde{N}_3, \widetilde{N}_4 \sim \widetilde{H}$$

$$\widetilde{C}_1 \sim \widetilde{W}^\pm; \widetilde{C}_2 \sim \widetilde{H}^\pm$$

SUSY Breaking in the Scalar Sector

⇒ Scalar masses and analytic, super-renormalizable scalar potential terms

$$\mathcal{L}_{\text{soft}} \ni -\sum_f \widetilde{f}^i (m_f^2)_i^j \widetilde{f}_j^* - \left(\frac{1}{2} b_{ij} \tilde{f}^i \tilde{f}^j + \text{ c.c.}\right) - \left(\frac{1}{6} a_{ijk} \tilde{f}^i \tilde{f}^j \tilde{f}^k + \text{ c.c.}\right)$$

- Scalar masses will generally **not** be diagonal in same basis where fermion masses are diagonal

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$$\mathcal{L}_{\rm soft} \ni -\sum_f \widetilde{f}^i (m_f^2)_i^j \widetilde{f}_j^* - \left(\frac{1}{2} b_{ij} \tilde{f}^i \tilde{f}^j + \text{ c.c.}\right) - \left(\frac{1}{6} a_{ijk} \tilde{f}^i \tilde{f}^j \tilde{f}^k + \text{ c.c.}\right)$$

- Scalar masses will generally **not** be diagonal in same basis where fermion masses are diagonal
- *A-terms* a_{ijk} and *B-terms* b_{ij} need **not** be proportional to λ_{ijk} and μ_{ij}

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⇒ Many contributions to physical scalar quark (lepton) masses

$$m_{\tilde{t}}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + D_u & v_u a_t - \lambda_t \mu v_d \\ v_u a_t - \lambda_t \mu v_d & m_{u_3}^2 + m_t^2 + D_{\bar{u}} \end{pmatrix}$$

with $D_u,\ D_{\bar{u}} \sim m_Z^2$

The μ parameter

$\Rightarrow$ A *supersymmetric* mass term

$$
\begin{aligned}
W &\ni \mu H_u H_d = \mu (H_u)_\alpha (H_d)_\beta \epsilon^{\alpha\beta} \\
&\to \mu(\chi_u^+ \chi_d^- - \chi_u^0 \chi_d^0) + |\mu|^2 \left(|h_u^0|^2 + |h_d^0|^2 + |h_u^+|^2 + |h_d^-|^2 \right)
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- Non-vanishing μ needed to give Higgsinos mass
- But if $V_H \sim m_H^2 |h|^2 + \lambda |h|^4$, need $m_H^2 < 0$ if we want $\langle h \rangle \neq 0$
- So we need $|\mu|^2 \lesssim m_{\tilde{f}}^2 \sim (1 \text{ TeV})^2$

$\Rightarrow$ But not tied to SUSY breaking, so no need to be EW scale!

- Example: consider a singlet of SM gauge group S

$$\Delta W = \lambda_S S H_u H_d$$

- If S has other Yukawa interactions, may have DSB $\langle S \rangle \neq 0$ and $\mu_{\text{eff}} = \lambda_S \langle S \rangle$

Higgs Sector I: EWSB scalar potential

$\Rightarrow$ Assume that only Higgs fields obtain vevs at minimum

- Minimum can always be found such that $\langle h_u^+ \rangle = \langle h_d^- \rangle = 0$
- Phase rotations on remaining two Higgs states can make potential real and $\langle h_u^0 \rangle = v_u$, $\langle h_d^0 \rangle = v_d$ real and positive

$$\begin{aligned} V &= \left(|\mu|^2 + m_{H_u}^2\right) |h_u^0|^2 + \left(|\mu|^2 + m_{H_d}^2\right) |h_d^0|^2 \\ & \quad -(b h_u^0 h_d^0 + \text{ c.c.}) + \frac{1}{8}(g^2 + g'^2)(|h_u^0|^2 - |h_d^0|^2)^2 \end{aligned}$$

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$\Rightarrow$ Two minimization conditions $\langle \partial V / \partial h_u^0, h_d^0 \rangle = 0$

$$\mu^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2}M_z^2; \quad 2b = (m_{H_d}^2 + m_{H_u}^2 + 2\mu^2)\sin 2\beta$$

- Here we have introduced the parameter $\tan\beta = v_u / v_d$
- Note that $v^2 = v_u^2 + v_d^2 \simeq (174 \text{ GeV})^2$ and $M_z^2 = \frac{v^2}{2}(\frac{5}{3}(g')^2 + g_2^2)$

Higgs Sector II: Mass Eigenstates

$\Rightarrow$ Two doublets $\rightarrow$ 8 d.o.f. - 3 d.o.f. (eaten) = 5 Higgs eigenstates

$$
\begin{aligned}
A &\sim \sin\beta\,\mathrm{Im}(h_d^0) + \cos\beta\,\mathrm{Im}(h_u^0) \\
H^+ &\sim \cos\beta\, h_u^+ + \sin\beta\,(h_d^-)^* \\
\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} &\sim \sqrt{2}\begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} \mathrm{Re}[h_u^0] - v_u \\ \mathrm{Re}[h_d^0] - v_d \end{pmatrix}
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⇒ Masses of these are given by

$$m_A^2 = 2b/\sin 2\beta; \quad m_{H^\pm}^2 = m_A^2 + m_W^2$$

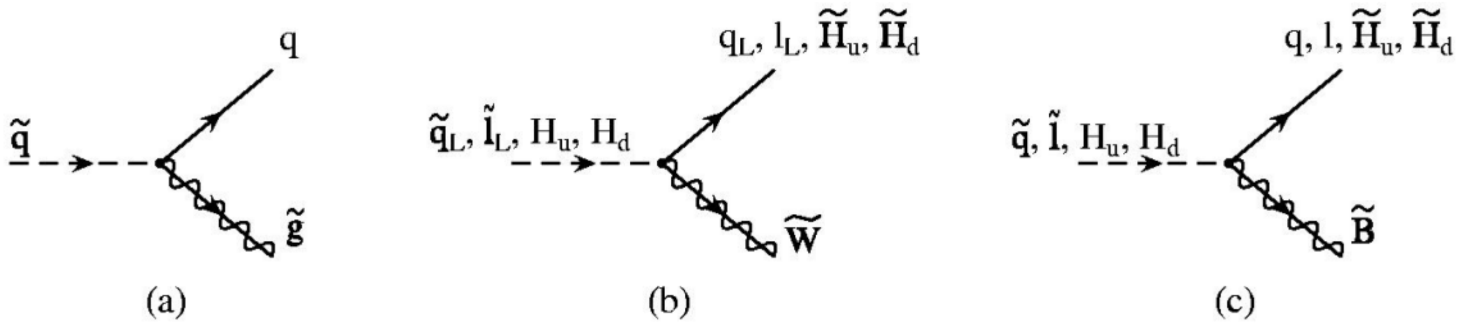
$$m_{h^0,H^0}^2 = \frac{1}{2}\left(m_A^2 + M_z^2 \mp \sqrt{(m_A^2 + M_z^2)^2 - 4M_z^2 m_A^2 \cos^2 2\beta}\right)$$

⇒ Parameterizing the Higgs sector

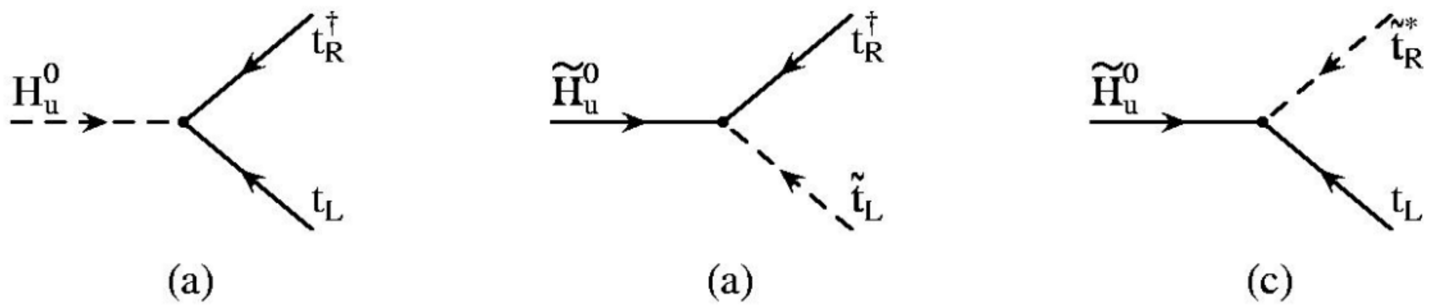
- Minimization conditions allow swap: M_z, $\tan\beta$ for μ, b
- A useful low-energy parameterization: m_A, μ and $\tan\beta$

Feynman Diagrams with Superpartners

⇒ Example: scalar field decays

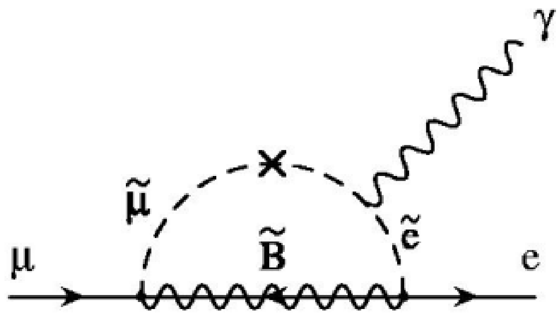


⇒ Example: Top Yukawa (superpotential) interactions

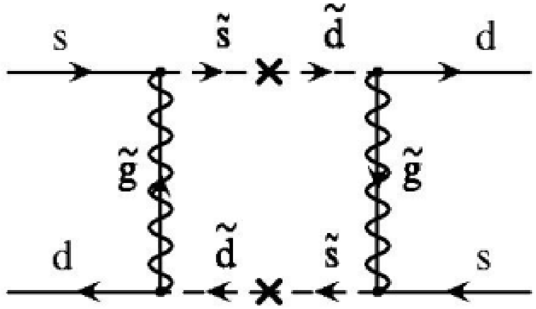


Scalar Field Woes

$\Rightarrow$ FCNCs: $\mu \to e\gamma$, $K^0 - \bar{K}^0$ mixing, ...



(a)



(b)

$\Rightarrow$ CP violation: lepton EDMs, ...

Connecting Scales – RGEs I

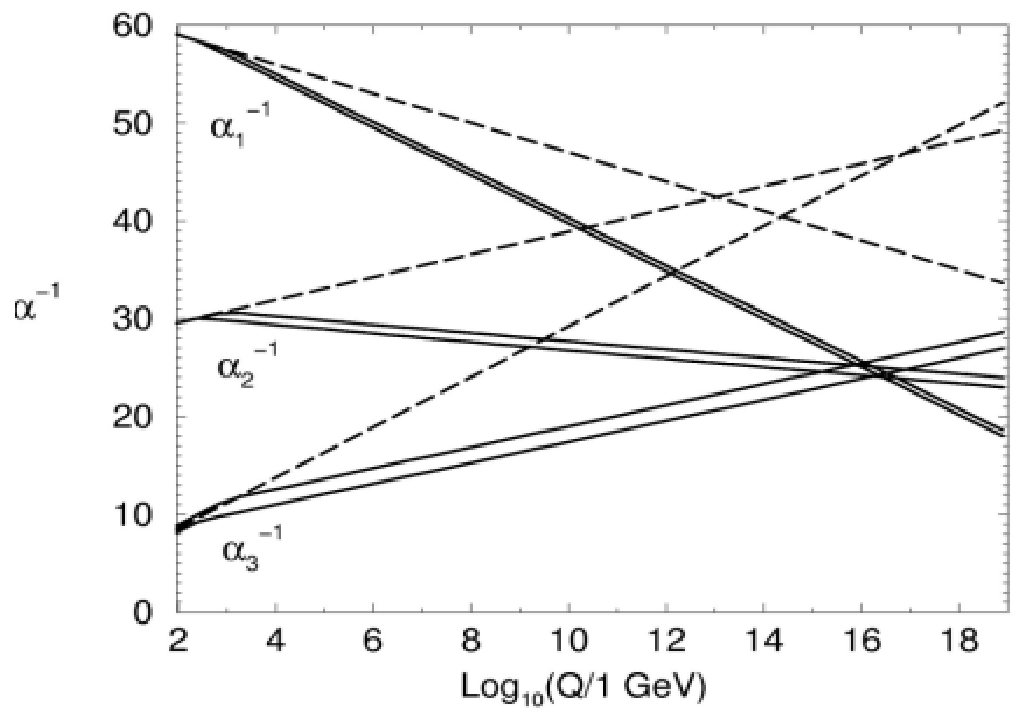
⇒ Gauge couplings run independently at one loop

$$\frac{d}{dt} g_a = \frac{b_a}{16\pi^2} g_a^3 \qquad t \equiv \ln(\mu/M_z)$$

- *Beta-function coefficient* b_a defined by

$$b_a = \tfrac{1}{3}\sum_s C_2(R_s) + \tfrac{2}{3}\sum_f C_2(R_f) - \tfrac{11}{3} C_2(G)$$

- For SUSY multiplets, this simplifies to $b_a = \sum_R C_2(R) - 3C_2(G)$



Connecting Scales – RGEs II

$\Rightarrow$ Dimensionless couplings run as a group $\{\lambda,\ g^2\}$

- That is $\frac{d}{dt}(g_a, \lambda_i) = f(g_a, \lambda_i)$

- Allows Yukawas to be run *upwards* from known low-scale quantities

$$m_t = \lambda_t(m_t)v_u = \lambda_t(m_t)(174\ \text{GeV})\sin\beta,$$
$$m_b = \lambda_b(m_b)v_d = \lambda_b(m_b)(174\ \text{GeV})\cos\beta\ \alpha_s(M_z), \text{ etc.}$$

$\Rightarrow$ Gaugino masses run independently at one loop

- Beta-functions coefficients for M_a proportional to g_a^2

$$\frac{M_1}{g_1^2} \simeq \frac{M_2}{g_2^2} \simeq \frac{M_3}{g_3^2} \rightarrow M_3 : M_2 : M_1 \simeq 7 : 2 : 1$$

- To all orders mass-dimension 1 operators run as a group $\{M_a,\ a_{ijk}\}$

Connecting Scales – RGEs III

⇒ Scalar masses depend on *everything*:

$$16\pi^2 \frac{d}{dt} m_{H_u}^2 = 3X_t - 6g_2^2|M_2|^2 - \frac{6}{5}g_1^2|M_1|^2$$

$$16\pi^2 \frac{d}{dt} m_{Q_3}^2 = X_t + X_b - \frac{32}{3}g_3^2|M_3|^2 - 6g_2^2|M_2|^2 - \frac{2}{15}g_1^2|M_1|^2$$

$$X_t = 2|\lambda_t|^2(m_{H_u}^2 + m_{Q_3}^2 + m_{u_3}^2) + 2|a_t|^2$$
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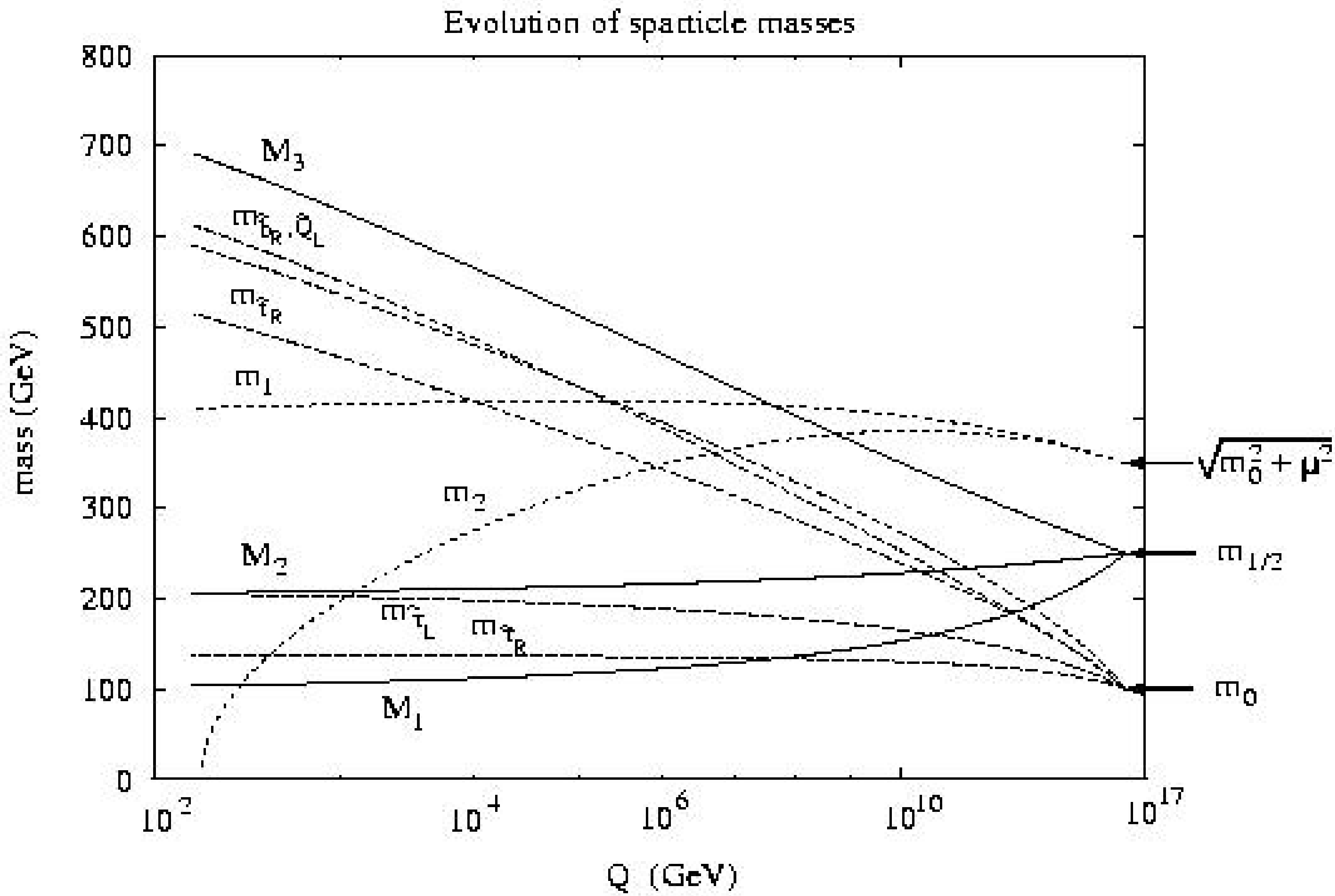
⇒ b and μ run as a system

- That is $\frac{d}{dt}(b, \mu) = f(b, \mu, g_a, \lambda_i)$
- This means M_z and $\tan\beta$ can be used to determine b and μ *at the high (input) scale too*

Variation of Parameters with Scale



Breaking SUSY, Generally

$\Rightarrow$ What is a *hidden sector* ?

- No tree-level (renormalizable) interaction of MSSM fields to SUSY breaking order parameters $\langle F \rangle$, $\langle D \rangle$, $\langle M \rangle$
- Thus $\langle D_Y \rangle \neq 0$ and $\left\langle F_{H_u,H_d} \right\rangle \neq 0$ can't be dominant source of SUSY breaking

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- Instead, expect terms like $\langle F_X / M_X \rangle \, \lambda_a \lambda_a$ or $\left\langle |F_X|^2 / M_X^2 \right\rangle k_{ij} (\phi^i)^* \phi^j$
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⇒ Why must we break SUSY in one?

- If no hidden sector, then at least some scalars lighter than fermions!
- Spontaneous breaking in our sector can only be through $\langle D_Y, D_3 \rangle \neq 0$ and $\left\langle F_{H_u,H_d} \right\rangle \neq 0$

$$m_{\tilde{t}}^2 \sim m_t^2 \pm (a D_Y + b D_3)$$

Gravity Mediation

As a result of putting SUSY breaking in a hidden sector that models are classifed more by how SUSY breaking is transmitted to our sector than how it was actually broken in the first place.

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- Imagine soft Lagrangian given by

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$\Rightarrow$ Resulting soft terms

$$m_{1/2} = \frac{F_G}{M_G},\ m_0^2 = |\frac{F_S}{M_S}|^2,\ a^\alpha_{ijk} = \lambda^\alpha_{ijk}\frac{F_A}{M_A},\ b = \mu\frac{F_B}{M_B}$$

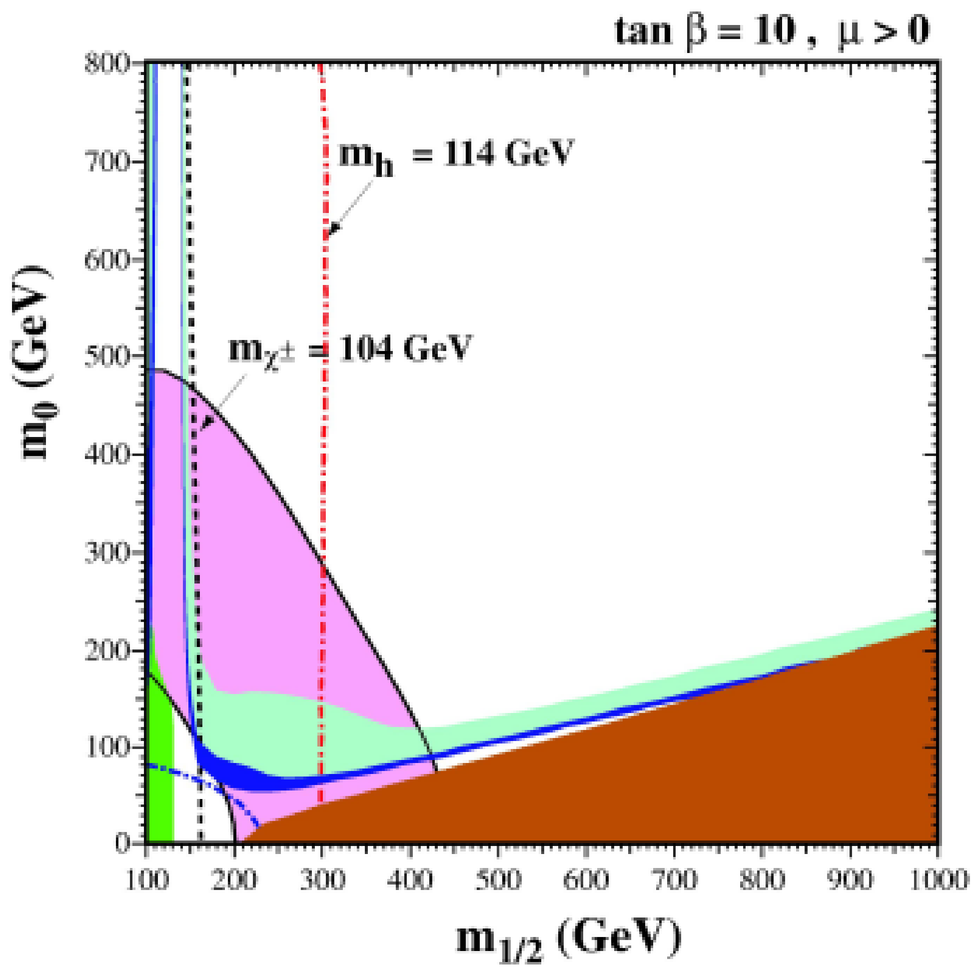
Minimal Supergravity (mSUGRA)

- Defined by parameter set:
  $\{m_{1/2},\ m_0,\ A_0,\ \tan\beta,\ \mathrm{sgn}(\mu)\}$

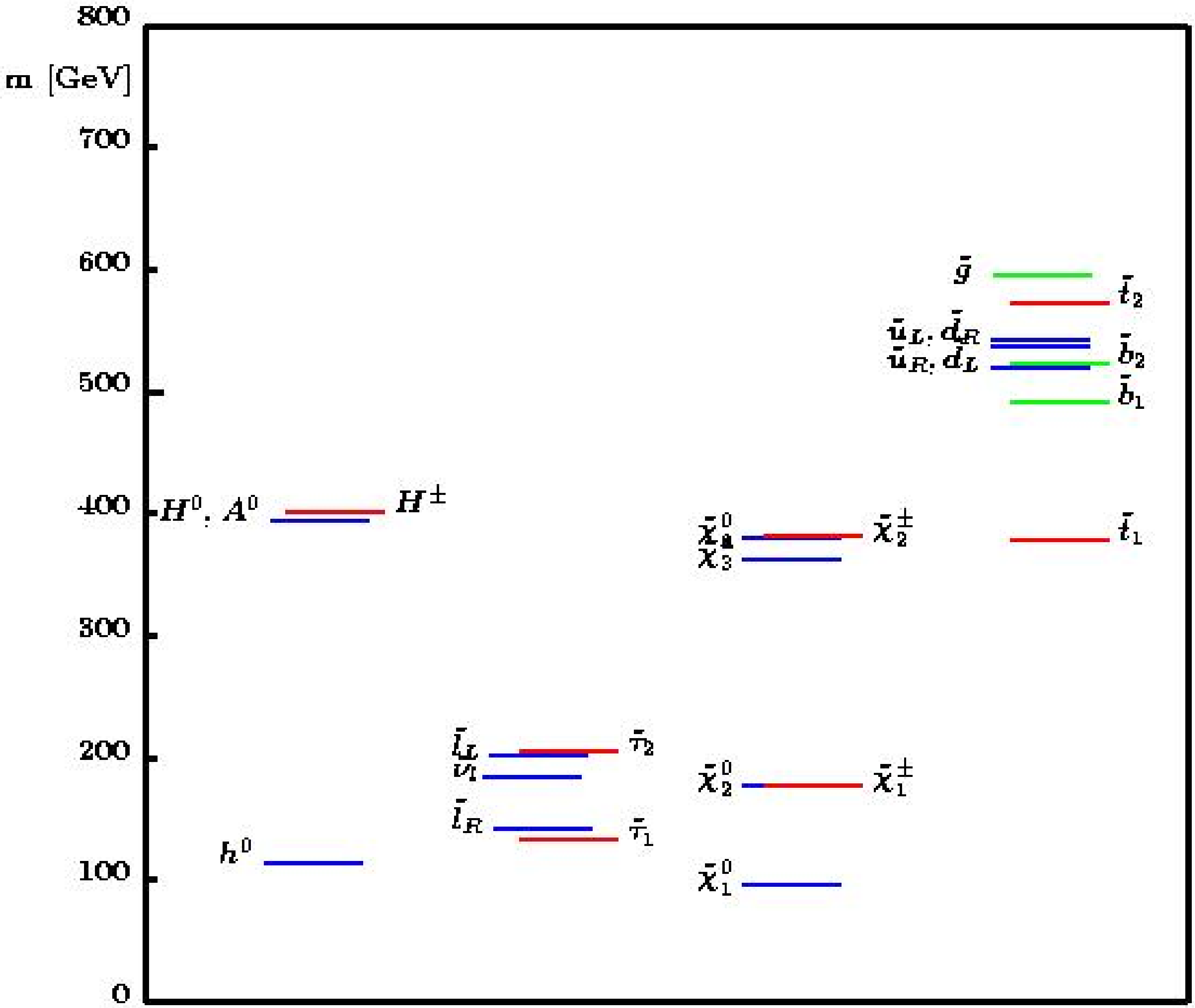
- Many special cases
  - ⋆ No-scale models
  - ⋆ Dilaton-dominated models
  - ⋆ Focus-point models....

- Generally have B-ino LSP (or stau LSP)

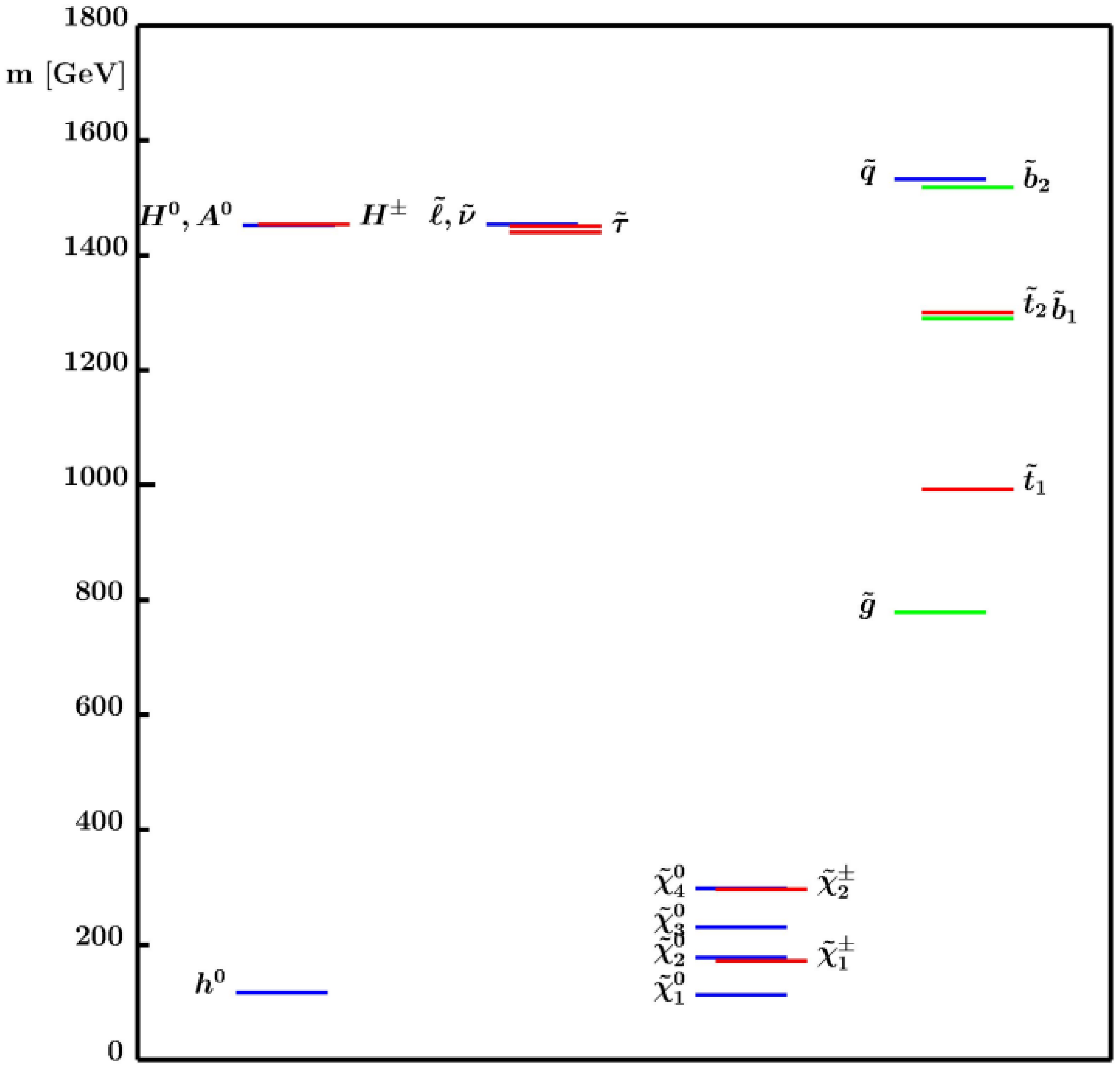
- This case:
  $A = -100\ \mathrm{GeV}$
  $\tan\beta = 10$
  sgn(μ) = +



mSUGRA Sample Spectrum A



mSUGRA Sample Spectrum B



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$$\delta M_a(\Lambda_{\rm UV}) = \frac{g_a^2(\Lambda_{\rm UV})}{16\pi^2} N_a \frac{F^X}{M_X}; \quad \delta m_A^2(\Lambda_{\rm UV}) = 2 \sum_a N_a C_a^A \left(\frac{g_a^2(\Lambda_{\rm UV})}{16\pi^2}\right)^2 \left(\frac{F^X}{M_X}\right)^2$$

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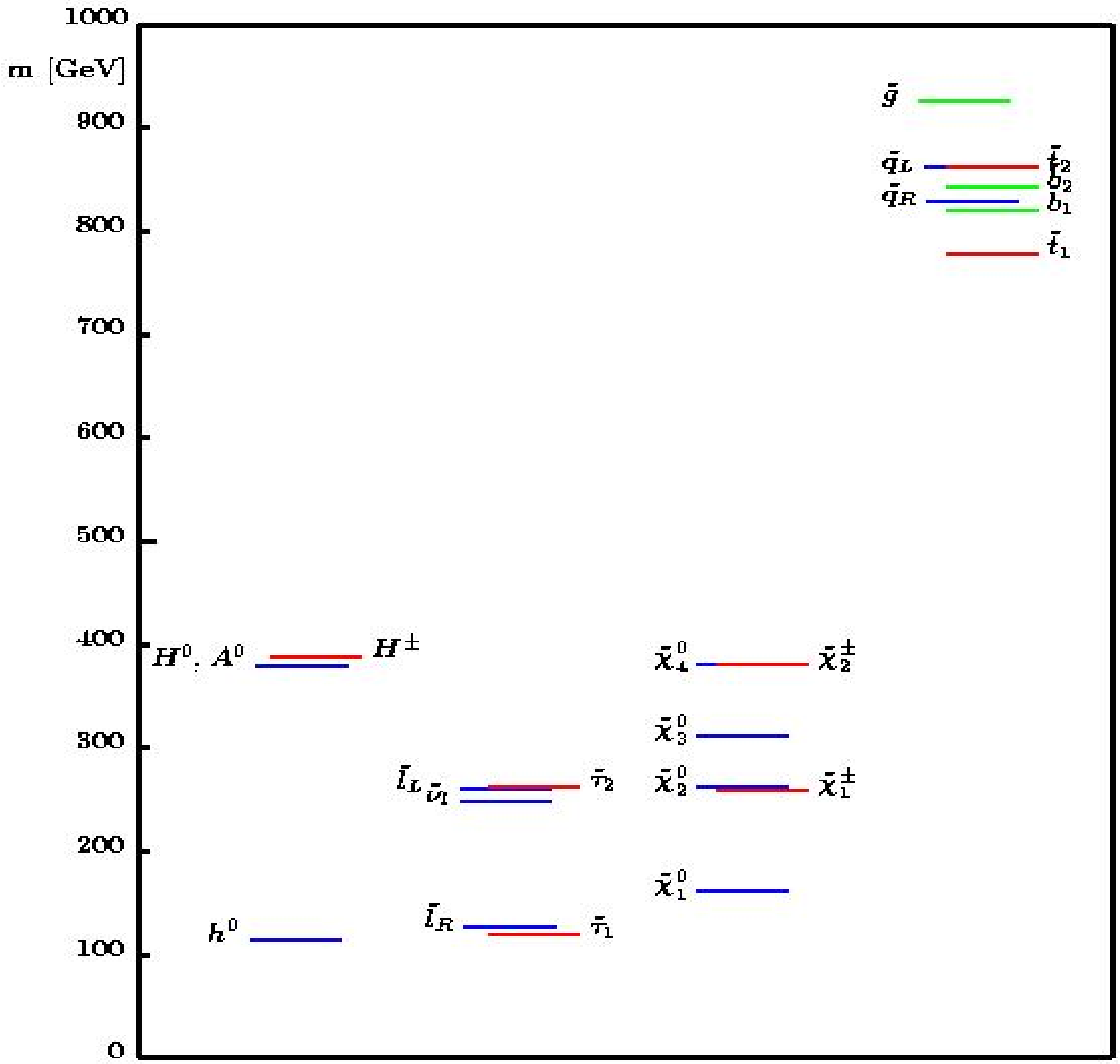
- One must reduce the impact of gravity $\rightarrow m_{3/2} \sim \mathcal{O}({\rm eV} - {\rm keV})$

GMSB Phenomenology

- Parameter set: $\Lambda = F_X/M_X$, N_{mes}, $\tan\beta$
- LSP is gravitino; NLSP is slepton or neutralino
- No missing energy signal!
- This case: $\Lambda = 2$, $N = 3$, $\tan\beta = 15$



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4. A set of projects for future study