Lectures on Supersymmetry

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Epiphany term 2005

<u>Part 2:</u>

SUSY breaking:

- Spontaneous breaking of global SUSY

- Gravity- and Gauge-mediated SUSY breaking

Models for SUSY breaking

Phenomenological constraints on soft-breaking terms:

E.g.: $(m^2)_{ij}\varphi_j^*\varphi_i = \tilde{e}_R m^2_{ee}\tilde{e}^\dagger_R + \tilde{e}_R m^2_{e\mu}\tilde{\mu}^\dagger_R + \ldots$

$(m^2)_{ij}$: 3×3 matrix in family (flavor) space

no a priori reason why off-diagonal terms $m^2_{e\mu}$ should be much smaller than diagonal terms m^2_{ee} , $m^2_{ij} \sim 1$ TeV^2

but: if off-diagonal terms are large

$\Rightarrow$ observable lepton number violation (e.g. $\mu \to e\gamma$)

Strong experimental constraints:

if $m^2_{e\mu} \approx m^2_{ee}$
$\Rightarrow$ SUSY contribution 5–6 orders of magnitude above experimental limit

$\Rightarrow$ need $m^2_{e\mu} \ll m^2_{ee}$

Similarly for squark mass matrices; also strong constraints on $\mathcal{CP}$-violating complex phases

$\Rightarrow$ experimental constraints satisfied if SUSY breaking is suitably 'universal', $\approx$ diagonal in flavour space

$\Rightarrow$ small flavour-changing neutral currents (FCNC)
no new complex phases in this limit

$\Rightarrow$ hints of an "organizing principle" for soft breaking terms?

Simplest ansatz:

Assume universality at high energy scale (GUT scale, M_{Pl}, . . .)

- All scalar masses are the same: $\tilde{m}^2 = m_0^2$ (assumption of "universality")
- The gaugino masses are the same: $M_i = m_{1/2}$ ("GUT relation")
- Soft-breaking trilinear terms are universal:
  $\mathcal{L}_{\mathrm{tri}} = A_0(H_U Q y_u \bar{u} + H_D Q y_d \bar{d} + H_D L y_l \bar{e})$, y_u, y_d, . . . are the same matrices which appear in Yukawa couplings (assumption of "proportionality")

Results in five parameters, if possible phases are ignored:

$$m_0^2,\ m_{1/2},\ A_0,\ b,\ \mu$$

Require correct value of M_Z

$\Rightarrow$ $|\mu|$, b given in terms of $\tan\beta$, $\mathrm{sign}\,\mu$

$\Rightarrow$ Scenario characterized by

$$m_0^2,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}\,\mu$$

Usually called ‘CMSSM’ (constrained MSSM) or ‘mSUGRA’ (see below)

In agreement with all phenomenological constraints (see below)

Spontaneous breaking of global SUSY

If global SUSY is spontaneously broken $\Rightarrow$ $\langle 0|H|0\rangle = E_{\text{vac}} > 0$

$\Rightarrow$ $V > 0$ required

$$V(\varphi_i, \varphi_j^*) = \underbrace{\sum_i \left|\frac{\partial \mathcal{V}}{\partial \varphi_i}\right|^2}_{F\text{-term}} + \underbrace{\frac{1}{2} g^2 \sum_a (\varphi_i^* T_{ij}^a \varphi_j + \xi^a)^2}_{D\text{-term}}$$

$\Rightarrow$ either $\langle F\rangle > 0$ (F-term breaking) or $\langle D\rangle > 0$ (D-term breaking)

$\Rightarrow$ requires that $F_i = 0$, $D^a = 0$ cannot be simultaneously satisfied for any values of the fields

F-term breaking:

need linear term in superpotential $\mathcal{V}(\phi_i) = a_i\phi_i + \frac{1}{2}m_{ij}\phi_i\phi_j + \frac{1}{3}\lambda_{ijk}\phi_i\phi_j\phi_k$

$\Rightarrow$ requires a chiral superfield that is a singlet under all gauge groups

$\Rightarrow$ not possible within the MSSM

D-term breaking:

If $\langle\varphi_i\rangle = 0 \Rightarrow \xi^a$-term (Fayet-Iliopoulos term) leads to spontaneous SUSY breaking

Does not work in the MSSM (leads to charge and color-breaking minima)

Further problems of spontaneous breaking of global SUSY:

- Mass sum rules for SM particles and superpartners (at tree level), e.g.

  $$\sum_i (-1)^f m_i^2 = 0$$

  $(-1)^f = 1$ for bosons, $(-1)^f = -1$ for fermions

  $\Rightarrow$ not all superpartners can be heavier than SM particles

  $\Rightarrow$ spectra not realistic

- difficult to give masses to gauginos (SUSY doesn't allow scalar–gaugino–gaugino couplings)

- hierarchy problem, if characteristic SUSY-breaking scale enters as parameter in the Lagrangian

- cosmological constant problem

$\Rightarrow$ Very difficult to build realistic model

Problems can be overcome if SUSY breaking happens in a ‘hidden sector’, i.e. by fields which have only very small couplings to ordinary matter

SUSY breaking in the hidden sector: tree-level (like F- and D-term breaking) or dynamical breaking (similar to chiral symmetry breaking in QCD), . . .

SUSY-breaking terms in the MSSM arise radiatively via interaction that communicates SUSY breaking rather than through tree-level couplings to SUSY breaking v.e.v.s

$\Rightarrow$ phenomenology depends mainly on mechanism for communicating SUSY breaking rather than on SUSY-breaking mechanism itself

If mediating interactions are $\approx$ flavor-diagonal
$\Rightarrow$ universal soft-breaking terms

“Hidden sector” : $\longrightarrow$ Visible sector:

SUSY breaking MSSM

“Gravity-mediated” : mSUGRA

“Gauge-mediated” : GMSB

“Anomaly-mediated” : AMSB

“Gaugino-mediated”

...

SUGRA: mediating interactions are gravitational

GMSB: mediating interactions are ordinary electroweak and QCD gauge interactions

AMSB, Gaugino-mediation: SUSY breaking happens on a different brane in a higher-dimensional theory

Gravity-mediated SUSY breaking

Local SUSY $\Leftrightarrow$ supergravity:

Spontaneous breaking of global SUSY $\longrightarrow$ massless neutral Weyl fermion: "goldstino"

Spontaneous breaking of local SUSY $\longrightarrow$ goldstino absorbed ("eaten") by gravitino

$\Rightarrow$ gives longitudinal components to gravitino

$\Rightarrow$ gravitino acquires a mass, graviton stays massless

"Super-Higgs mechanism"

only known consistent way of breaking local SUSY

It is possible to have spontaneous breaking of local SUSY and also $\langle V \rangle = 0$

Quantum field theory of supergravity:

QFT with spin 2 (and spin $\frac{3}{2}$) field is not renormalizable

$\Rightarrow$ cannot be extended to arbitrarily high energies

$\Rightarrow$ QFT of supergravity has to be interpreted as effective theory

contains non-renormalizable terms prop. to inverse powers of M_{Pl}

Best candidate for fundamental theory: string theory

SUSY breaking in hidden sector:

$\Rightarrow$ supergravity Lagrangian contains non-renormalizable terms that communicate between hidden and visible sector $\sim 1/M_{\mathsf{Pl}}^n$

Dimensional analysis:

SUSY breaking in hidden sector by v.e.v. $\langle F \rangle$, coupling $\sim 1/M_{\mathsf{Pl}}$

require $m_{\mathsf{soft}} \to 0$ for $\langle F \rangle \to 0$ (no SUSY breaking) and for $M_{\mathsf{Pl}} \to \infty$ (vanishing gravitational interaction)

$$\Rightarrow \quad m_{\mathsf{soft}} \approx \frac{\langle F \rangle}{M_{\mathsf{Pl}}}$$

For $m_{\mathsf{soft}} \lesssim 1$ TeV (hierarchy problem)

$\Rightarrow$ $\sqrt{\langle F \rangle} \approx 10^{11}$ GeV: scale of SUSY breaking in hidden sector

In general: $m_{\frac{3}{2}} \approx \frac{\langle F \rangle}{M_{\mathsf{Pl}}}$

$\Rightarrow$ $m_{\frac{3}{2}} \approx m_{\mathsf{soft}}$, gravitational interactions

$\Rightarrow$ gravitino not important for collider phenomenology

Non-renormalizable terms in supergravity Lagrangian:

$$\mathcal{L}_{\mathrm{NR}} = -\frac{1}{M_{\mathrm{Pl}}} F_X \sum_a \frac{1}{2} f_a \lambda^a \lambda^a + \text{h.c.} - \frac{1}{M_{\mathrm{Pl}}^2} F_X F_X^* \, k_j^i \varphi_i \varphi^{*j}$$
$$- \frac{1}{M_{\mathrm{Pl}}} F_X \left(\frac{1}{6} y'^{ijk} \varphi_i \varphi_j \varphi_k + \frac{1}{2} \mu'^{ij} \varphi_i \varphi_j\right) + \text{h.c.}$$

F_X: auxiliary field for a chiral supermultiplet X in the hidden sector

φ_i, λ^a: scalar and gaugino fields in the MSSM

If $\sqrt{\langle F_X \rangle} \sim 10^{10}$–$10^{11}$ GeV

$\Rightarrow$ yields soft SUSY-breaking terms of MSSM with $m_{\mathrm{soft}} \approx 10^2$–$10^3$ GeV

Assumption of a "minimal" form of the supergravity Lagrangian (theoretically difficult to justify; supergravity doesn't require flavor-universal terms)

$\Rightarrow$ soft-breaking terms which obey "universality" and "proportionality"

$\Rightarrow$ "supergravity inspired scenario", "mSUGRA", characterized by five parameters

$$m_0^2,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}\,\mu$$

m_0: universal scalar mass parameter

$m_{1/2}$: universal gaugino mass parameter

A_0: universal trilinear coupling

$\tan\beta$: ratio of Higgs vacuum expectation values

sign(μ): sign of supersymmetric Higgs parameter

m_0, $m_{1/2}$, A_0: GUT scale parameters

$\Rightarrow$ particle spectra from renormalization group running to weak scale

Lightest SUSY particle (LSP) is usually lightest neutralino

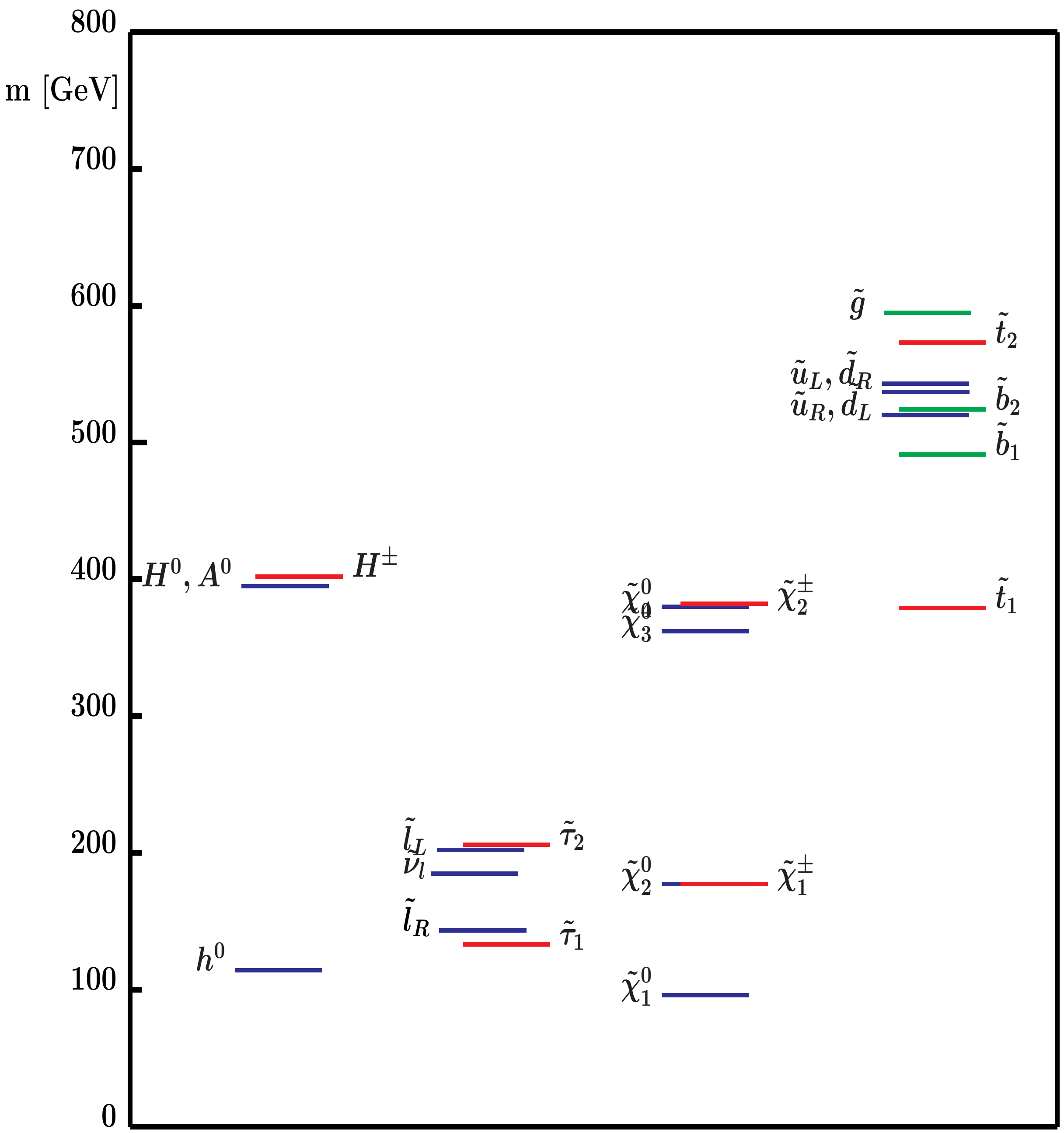
gaugino masses run in same way as gauge couplings

$\Rightarrow$ gluino heavier than charginos, neutralinos

“Typical” mSUGRA scenario

(SPS 1a benchmark scenario):

www.ippp.dur.ac.uk/∼georg/sps



Gauge-mediated SUSY breaking (GMSB)

New chiral supermultiplets, "messengers", couple to SUSY breaking in hidden sector

Couple indirectly to MSSM fields via gauge interactions

$\Rightarrow$ mediation of SUSY breaking via electroweak and QCD gauge interactions

$\Rightarrow$ $\approx$ flavour-diagonal

SUSY breaking in messenger spectrum

$\Rightarrow$ masses of SUSY particles from loop diagrams with messenger particles, gauge-interaction strength

$$\Rightarrow \quad m_{\text{soft}} \approx \frac{\alpha_i}{4\pi} \frac{\langle F \rangle}{M_{\text{mes}}}, \quad M_{\text{mes}} \sim \sqrt{\langle F \rangle}$$

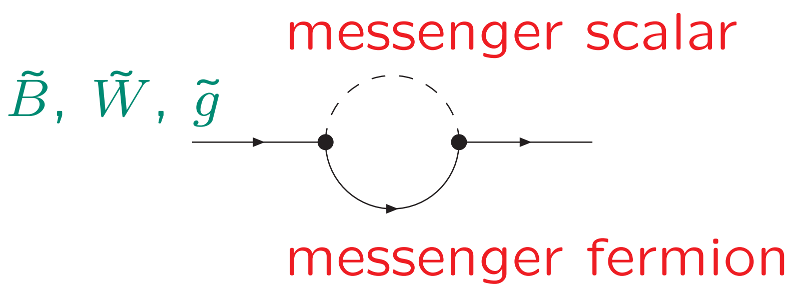
For $m_{\text{soft}} \lesssim 1$ TeV $\Rightarrow \sqrt{\langle F \rangle} \approx 10^4$–$10^5$ GeV

$\Rightarrow$ scale of SUSY breaking in hidden sector much lower than in SUGRA

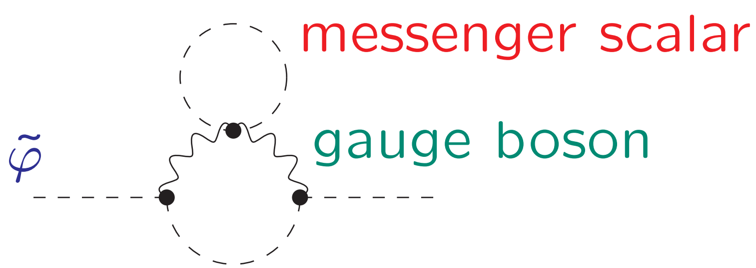
Gravitino mass: $m_{\frac{3}{2}} \approx \frac{\langle F \rangle}{M_{\text{Pl}}} \approx 10^{-9}$ GeV

$\Rightarrow$ Gravitino is always the lightest SUSY particle (LSP)

Gaugino masses generated at one-loop order, $m_\lambda \approx \frac{\alpha_i}{4\pi}$



Scalar masses generated at two-loop order, $m_\varphi^2 \approx \left(\frac{\alpha_i}{4\pi}\right)^2$



$\Rightarrow$ Typical mass hierarchy in GMSB scenario between strongly interacting and weakly interacting particles $\sim \alpha_3/\alpha_2/\alpha_1$

GMSB scenario characterized by

$$M_{\text{mes}}, N_{\text{mes}}, \Lambda, \tan\beta, \text{sign}(\mu)$$

M_{mes}: messenger mass scale

N_{mes}: messenger index (number of messenger multiplets)

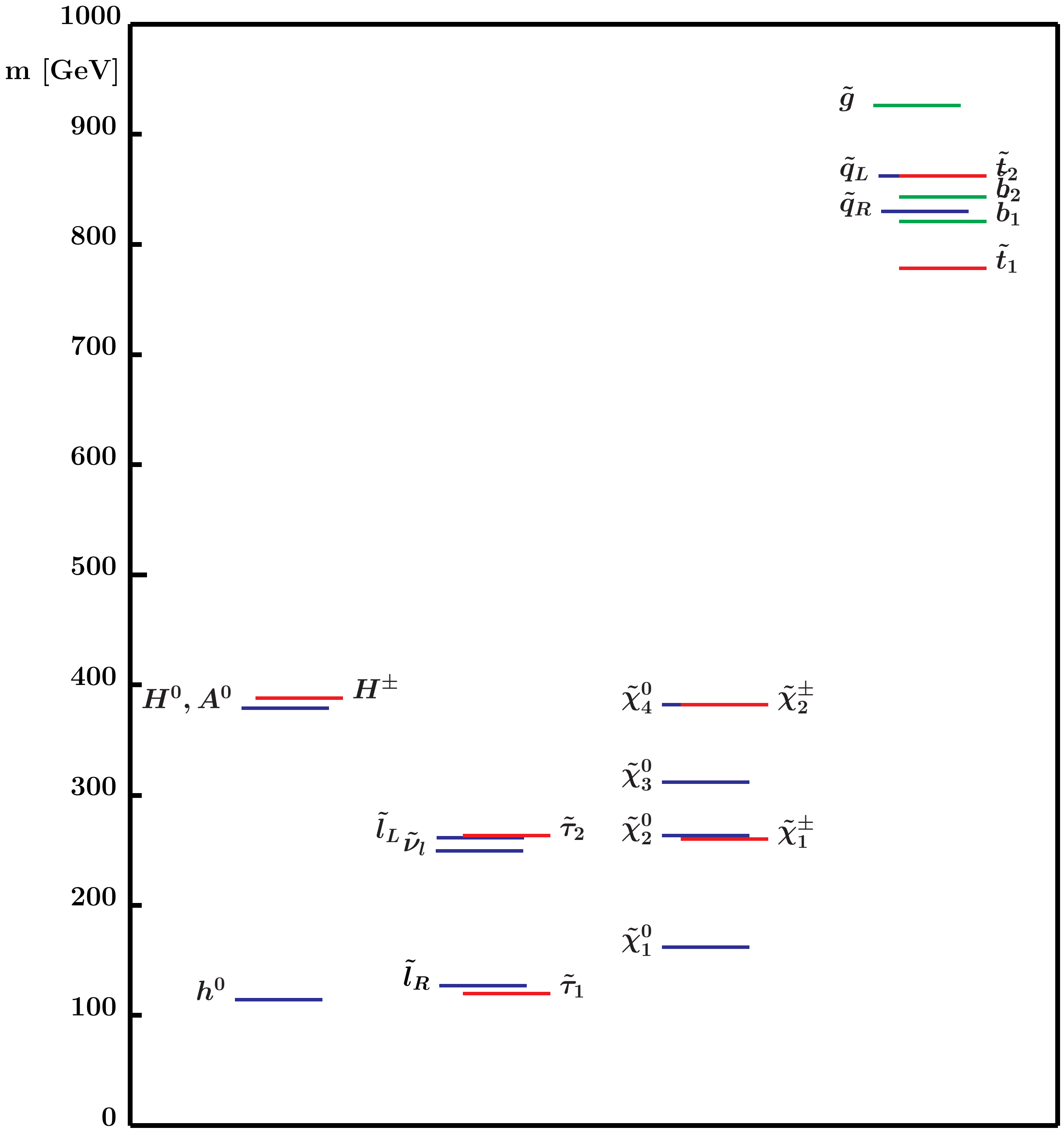
Λ: universal soft SUSY breaking mass scale felt by low-energy sector

LSP is always the gravitino, next-to-lightest SUSY particle (NLSP):
$\tilde{\chi}_1^0$ or $\tilde{\tau}_1$

can decay into LSP inside or outside the detector

GMSB scenario with $\tilde{\tau}$ NLSP

(SPS 7 benchmark scenario):



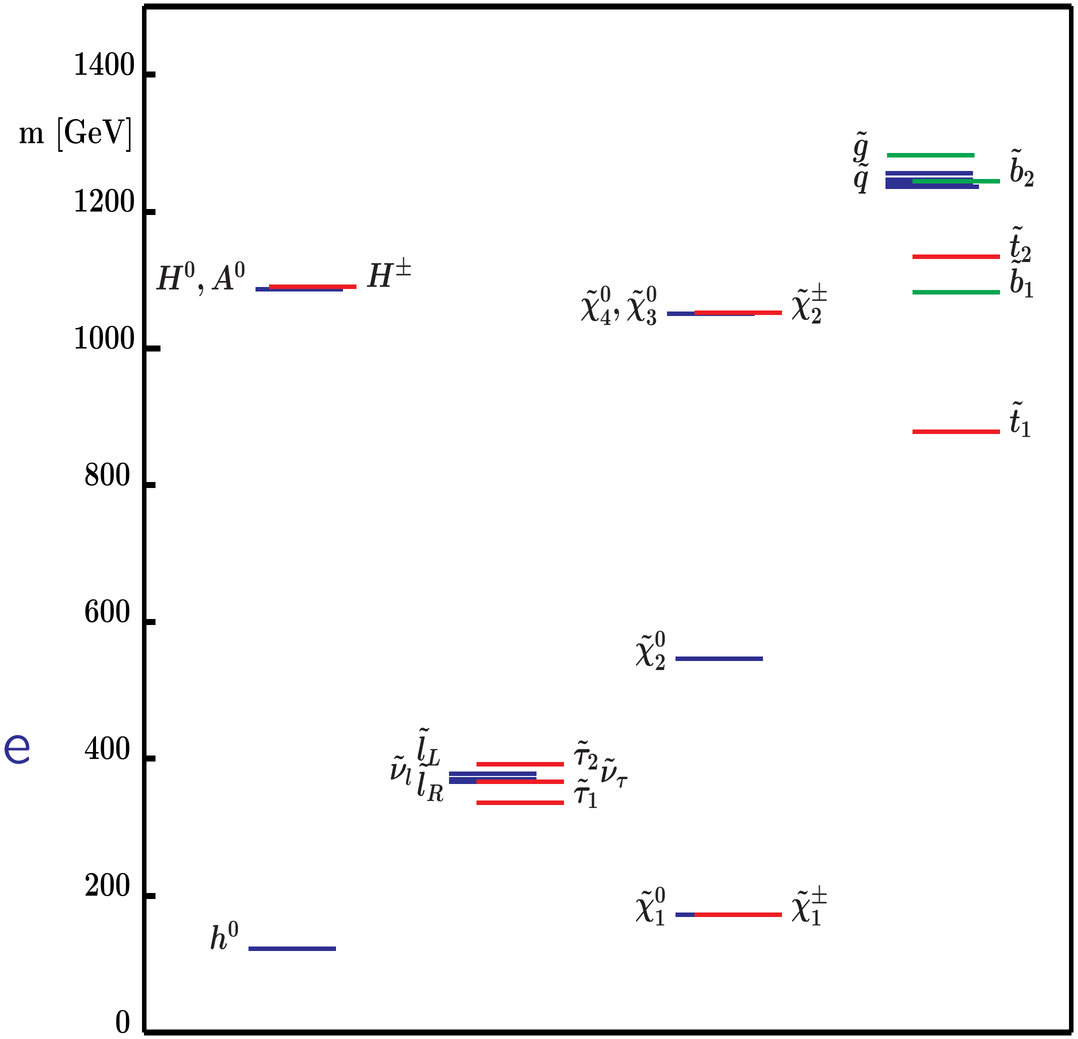
AMSB scenario characterized by

$$m_{\mathsf{aux}}, m_0, \tan\beta, \mathrm{sign}(\mu)$$

m_{aux}: overall scale of SUSY particle masses

m_0: phenomenological parameter: universal scalar mass term

AMSB spectrum (SPS 9):



typical feature: very small neutralino–chargino mass difference