Introduction to supersymmetry, the MSSM, and (a little bit) beyond

Jean-Loïc Kneur

LPTA, Montpellier

Atelier ATLAS-france,
Seignosse, 11 septembre 2007

Plan

1. Short review of motivations for supersymmetry (and unexpected bonus)

2. Ingredients and construction of supersymmetric Lagrangians

3. Essential of Minimal Supersymmetric Standard Model (MSSM)

4. Breaking supersymmetry: spontaneous, explicit, etc

5. Different popular SUSY-breaking models (minimal SUGRA, GMSB, AMSB, ...)

6. Some existing constraints on MSSM

1. Supersymmetry: Motivations

Supersymmetry: Poincaré + Fermions $\leftrightarrow$ Bosons symmetry:

$$Q|F\rangle = |B\rangle, \quad Q|B\rangle = |F\rangle$$

numerous *independent* motivations +unexpected bonus

•Super-Poincaré: the largest possible symmetry (in 4-dim):

basic algebra (schematically):

$$\{Q, Q^\dagger\} \propto P_\mu; \quad [Q, P_\mu] = 0$$

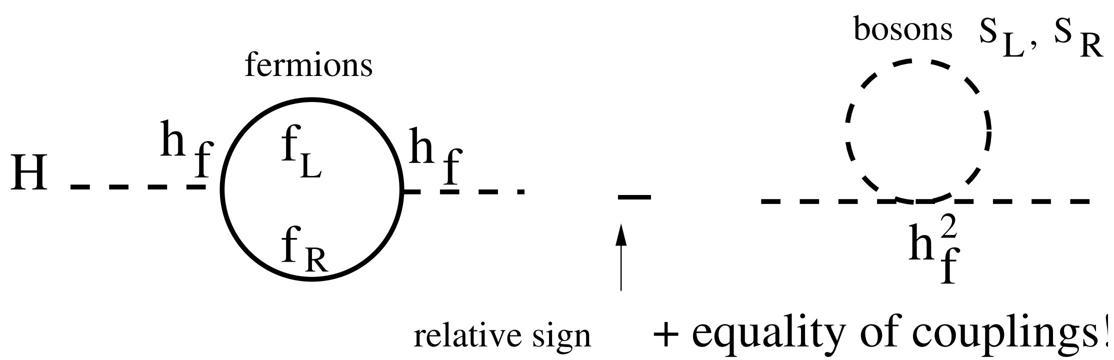
“square-root" of translation: escape of 60’s no-go theorems (Coleman-Mandula) for enlarged space-time+internal symmetries $[space - time\ sym] \otimes internal\ sym]$

-if made a local symmetry, necessary ingredient of a quantum gravity $\rightarrow$ Supergravity etc

The "hierarchy" or naturalness problem

radiative corrections to Higgs mass: $\delta m^2_{Higgs} \propto M^2_{GUT,Planck}$??

Stabilized!



$$\delta m_H^2 = \frac{N_c h_f^2}{16\pi^2}\left[-2M_{Pl}^2 + 3m_f^2 \ln\frac{M_{Pl}^2}{m_f^2} + 2M_{Pl}^2 - 2m_s^2 \ln\frac{M_{Pl}^2}{m_s^2}\right]$$

Moreover even the $\ln$ terms cancel if m_f, m_s arise from sym. breaking ($m_f \sim h_f v = m_s$) (another graph then)

exact SUSY $\rightarrow$ equality of masses AND couplings.

Broken SUSY: $m_f \neq m_s \rightarrow \ln$ terms survive: "fine-tuning" pb

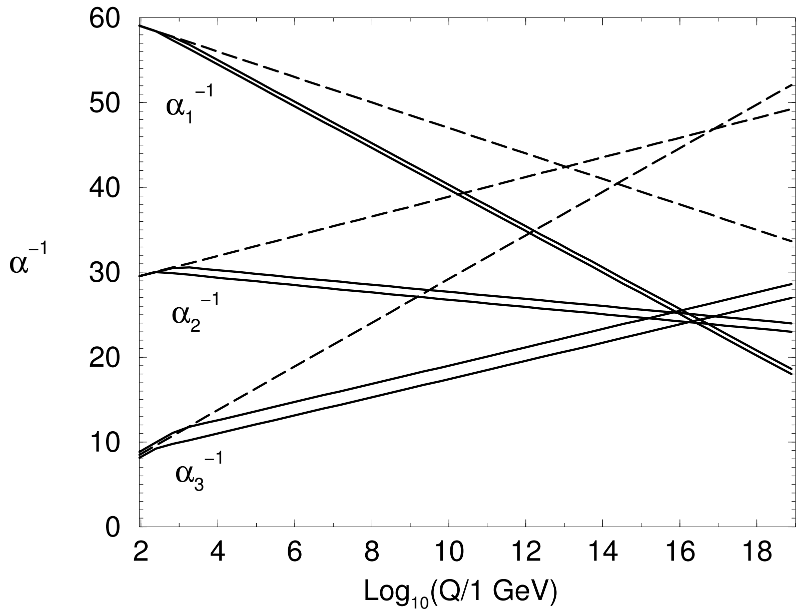
$\rightarrow$ acceptable IF $m_{sparticles} \lesssim \mathcal{O}$ (1 TeV)

NB origin of the large rad. corr. $\propto mt^4 \ln[..]$ to MSSM H mass

+Unexpected bonus (not original motivations but welcome)

•Grand Unification *consistent* with Proton lifetime limits

-Due to SUSY particle threshold
+ SUSY Renor Group Evol.
(totally excluded in SM)



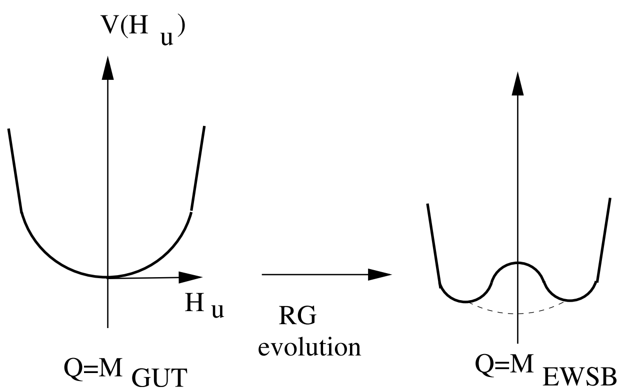
-Unification scale $M_{GUT} > 10^{16}$: large enough to escape Proton decay limits (Superkamiokande) $\sim 1.9\ 10^{33}$ years

-However, $1 - 2\%$ mismatch $1 - \alpha_S(M_{GUT})/\alpha_1(M_{GUT})$: hoped to be explained by GUT scale threshold corrections...

(but dim 5 operators can disturb this “conventional wisdom"!)

Another unexpected bonus..

• *Radiative* electro-weak sym. breaking: “mexican hat" scalar potential induced by Renormalization Group (RG) evolution: GUT $\rightarrow$ low energy



$m^2_{H_u}(E) < 0$ by RG evolution $E_{GUT} \rightarrow E_{EWSB}$ ($\propto m_t^2$)
made possible thanks to the large value of m_{top}!

(does not explain why m_{top} is large, though)

Yet another unexpected bonus...

• Very plausible candidate to Dark Matter (neutralino LSP)
present strong indication that $\sim$ 10% of mass in universe is neutral, weakly interacting cold DM

But, problem: SUSY has to be broken: what's the right model? :<...
To date: NO consistent model of spontaneous (or dynamical) SUSY-breaking! (breaking has to be in a “hidden" sector)

$\rightarrow$ proliferation of SUSY-breaking (arbitrary) parameters:
All possible gauge-invariant interactions between quite many (s)particles.. IF no more theoretical prejudices applied

2. Basics of supersymmetric gauge theories

•Supersymmetric extensions of SM follow the rules of (super)gauge theories:

based on two set of fields with specific gauge+susy transformations:

-Chiral fields: left-handed fermions + scalar partners
-Vector fields: vector gauge bosons + fermion (majorana) partners

-Right handed fermions: from charge conjugate representation of chiral fields: $(\psi_R)^c = (\psi^c)_L$
-Higgs field: described by chiral fields: $\Leftrightarrow$ fermion partners

A bit of supersymmetric formalism

Basic ingredients: 2-components spinors χ_α, $\bar{\psi}^{\dot{\alpha}}$ $\quad \alpha, \dot{\alpha} = 1, 2$

makes supersymmetric properties more manifest

may be contracted to form Lorentz-invariants:

$(\psi\chi) \equiv \psi^\alpha \chi_\alpha \equiv \psi^\alpha \epsilon_{\alpha\beta} \chi^\beta$, $\epsilon_{\alpha\beta}$ antisymmetric: $\epsilon_{12} = -\epsilon_{21} = 1$

Standard Dirac spinor (4-component object):

$$\Psi_D = \begin{pmatrix} \chi_\alpha \\ \bar{\psi}^{\dot{\alpha}} \end{pmatrix}, \quad \bar{\Psi}_D \equiv \Psi^\dagger \gamma_0 = (\psi^\alpha, \ \bar{\chi}_{\dot{\alpha}}), \quad \gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \bar{\sigma}_\mu & 0 \end{pmatrix}$$

$\rightarrow$ standard (Dirac) contraction e.g. $\bar{\Psi}_D \Psi_D = \psi\chi + h.c.$ etc

Majorana: $\quad \Psi_M = \begin{pmatrix} \chi_\alpha \\ \bar{\chi}^{\dot{\alpha}} \end{pmatrix}$ $\quad$ i.e. such that $\Psi^c_M = \Psi_M$

Note $(\Psi_D)_L = \frac{1}{2}(1 - \gamma_5)\Psi_D = \chi_\alpha$, $\quad (\Psi_D)_R = \frac{1}{2}(1 + \gamma_5)\Psi_D = \bar{\psi}^{\dot{\alpha}}$

Superspace formalism

Convenient: describe boson+ fermion by same “superfield":
in addition to usual space coordinate x_μ, introduce new anticommuting spinor variables θ_α, $\theta_{\dot\alpha}$
$\theta_\alpha\theta_\beta = -\theta_\beta\theta_\alpha \to (\theta_\alpha)^2 = 0$ but $\theta\theta \equiv \theta^\alpha\epsilon_{\alpha\beta}\theta^\beta \neq 0$!

e.g chiral superfield (irreducible SUSY representation):
$\Phi(x,\theta,\bar\theta = 0) = \phi(x) + \sqrt{2}\theta\psi(x) + \theta^2 F(x)$
where ϕ scalar, ψ fermion, F scalar (auxiliary) fields
-Expansion stops at θ^2 due to anticommuting properties of θ

-F “scalar" has dim $[m]^2$ and NO kinetic term
($\Leftrightarrow$ function of other fields from its eq. of motion):
F assures (off-shell) matching of boson vs fermion d^0 freedom

Supersymmetric transformation of fields

Supersymmetry transformation = translation in superspace parameterized in terms of infinitesimal (Grassman) ζ

-SUSY generators expressed as derivative operators

$Q_\alpha = -i\partial_\theta + \sigma^\mu \bar{\theta}\partial_\mu$ (analog of $P_\mu \to i\partial_\mu$)

where extra terms originates from $\{Q, Q^\dagger\} \propto P_\mu$

Components of chiral field transform as

$$\delta\phi = \sqrt{2}\zeta\psi, \qquad \delta F = -i\sqrt{2}\zeta\sigma^\mu\partial_\mu\psi$$

$$\delta\psi = -i\sqrt{2}\sigma^\mu\bar{\zeta}\partial_\mu\phi + \sqrt{2}\zeta F$$

Note F transforms as total derivative:

a basic ingredient for SUSY-invariant Lagrangians

Vector Superfield (are hermitian)

Similarly the vector superfield reads in the simplest gauge choice (so called Wess-Zumino):

$$V(x,\theta,\bar\theta) = -(\theta\sigma^\mu\bar\theta)V_\mu + i\theta^2\bar\theta\bar\lambda - i\bar\theta^2\theta\lambda + \tfrac{1}{2}\theta^2\bar\theta^2 D$$

where V_μ usual vector field, λ its Majorana fermion partner, D auxiliary (scalar), with appropriate SUSY-transformations.

Again, auxiliary field D transforms as total derivative

There is also a chiral superfield, derived from V, generalizing "gauge field strength":

$$W_\alpha(x,\theta,\bar\theta) = -i\lambda_\alpha + (\theta\sigma_{\mu\nu})^\alpha F^{\mu\nu} + \theta^\alpha D - \theta^2(\bar\sigma^\mu\mathcal{D}_\mu\bar\lambda)^\alpha$$

tranforms like usual $V_{\mu\nu}$ under gauge symmetry

$\rightarrow$ building blocks to construct SUSY-invariant Lagrangian.

Supersymmetric Lagrangian

Armed with this formalism, “straightforward" to construct SUSY- and gauge-invariant Lagrangians

$\mathcal{L}_{SUSY} = \frac{1}{4g^2}(Tr[W^\alpha W_\alpha]_F + h.c) + \sum_i [\bar{\Phi} e^{(gV)} \Phi]_D + [W(\Phi)]_F$

where $[\cdots]_{F,D}$ means appropriate “projection" (θ^2, $\theta^2\bar{\theta}^2$ coefficients resp.) that transform as total derivative.

$W(\Phi)$ superpotential = dim-3 gauge-invariant polynomial function of chiral field Φ:

$$W(\Phi) = c_i \Phi_i + \frac{m_{ij}}{2}\Phi_i\Phi_j + + \frac{\lambda_{ijk}}{3!}\Phi_i\Phi_j\Phi_k$$

Scalar potential:

$$V(F_i, F_i^*, D^a) = \sum_i F_i^* F_i + \frac{1}{2}\sum_a (D^a)^2$$

$$F_i^* = \frac{\partial W(\Phi)}{\partial \Phi_i}, \qquad D^a = -g\sum_i(\phi_i^* T^a \phi_i)$$

3. Minimal Supersymmetric Standard Model (MSSM) in short

Table 1: Chiral Supermultiplet of MSSM

(s)particles		spin 0	spin 1/2	$SU(3)_c, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	$(3, 2, 1/6)$
(x 3 families)	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$(\bar{3}, 1, -2/3)$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	$(\bar{3}, 1, 1/3)$
sleptons, leptons	L	$(\tilde{\nu}, \tilde{e}_L)$	(ν, e_L)	$(1, 2, -1/2)$
(x 3 families)	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	$(1, 1, 1)$
Higgs, Higgsinos	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	$(1, 2, 1/2)$
	H_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	$(1, 2, -1/2)$

Table 2: Vector Supermultiplet of MSSM

(s)particles	spin 1/2	spin 1	$SU(3)_c, SU(2)_L, U(1)_Y$
gluino, gluon	$\tilde{g}$	g	$(8, 1, 0)$
Winos, W boson	$\tilde{W}^\pm, \tilde{W}^0$	$W^\pm W^0$	$(1, 3, 0)$
Binos, B boson	$\tilde{B}$	B	$(1, 1, 0)$

MSSM Superpotential (R-parity conserving!)

$$W = \sum_{i,j=gen} -Y^u_{ij}\,\hat{u}_{Ri}\hat{H}_u.\hat{Q}_j + Y^d_{ij}\,\hat{d}_{Ri}\hat{H}_d.\hat{Q}_j + Y^l_{ij}\,\hat{l}_{Ri}\hat{H}_d.\hat{L}_j + \mu\hat{H}_u.\hat{H}_d\,,$$

$\mathcal{L}_{SUSY}$ = kin. terms (SUSY +gauge) $+F^2, D^2$ terms $\propto \partial_{\phi_i}W$, etc

Note at this (exact supersymmetric SM) stage:

-$m_{fermions} = m_{bosons}$? Yes, before EWSB, but all masses zero!

some amount of F/B mass diff. due to EWSB! (see later)

-quartic couplings determined by gauge couplings

-equality of fermion and boson couplings:

essential for cancellation of all quadratic UV div.

$\Rightarrow$ only logarithmic div (wave fction and gauge cpling renormalization, superpotential $W(\Phi)$ NOT renormalized)

-Only new parameter: μ

Clearly unrealistic! must introduce supersymmetry breaking...

Digression: R-parity and its violation business

In MSSM, Higgs superfields H_u, H_d have same quantum numbers as leptons: $\rightarrow$ SUSY+gauge-inv allow mixing: $\mu^i L_i H_u, \lambda^{ijk} L_i L_j \bar{e}_k$ etc $\rightarrow$ L-violation *+ ν-mass contributions !!*
similarly trilinear quark terms allowed: $\bar{u}\bar{d}\bar{d} \rightarrow B$-violation

Some couplings very constrained by rare decays, P decay, etc, but not all

$\rightarrow$ introduce discrete symmetry: R-parity (Fayet 1976)
$R = (-1)^{2s+3B+L}$
$\rightarrow R_P$(matter fermions) $= +1$, R_P(all spartners) $= -1$
ensure that superpartners produced by pairs
lightest R_P-odd partner (LSP) stable (DM candidate)

Rk: R_P is discrete version of $U(1)$ R-sym in extended models

General (arbitrary) parameters of “soft" SUSY-breaking:

soft SUSY-breaking = that do not reintroduce quadratic UV divergences

- Mass Terms for Gluinos, Winos and Binos:

$$-\mathcal{L}_{\text{gaugino}} = \frac{1}{2}\left[M_1\tilde{B}\tilde{B} + M_2\sum_{a=1}^{3}\tilde{W}^a\tilde{W}_a + M_3\sum_{a=1}^{8}\tilde{G}^a\tilde{G}_a \ + \ \text{h.c.}\right]$$

minimal SUGRA universality: $M_1(E_{GUT}) = M_2(E_{GUT}) = M_3(E_{GUT}) \equiv m_{1/2}$

- Mass terms for sfermions:

$$-\mathcal{L}_{\text{sfermions}} = \sum_{i=gen} m^2_{\tilde{Q}i}\tilde{Q}^\dagger_i\tilde{Q}_i + m^2_{\tilde{L}i}\tilde{L}^\dagger_i\tilde{L}_i + m^2_{\tilde{u}i}|\tilde{u}_{R_i}|^2 + m^2_{\tilde{d}i}|\tilde{d}_{R_i}|^2 + m^2_{\tilde{l}i}|\tilde{l}_{R_i}|^2$$

mSUGRA universality: $m_{\tilde{Q}i}(E_{GUT}) = \cdots = m_{\tilde{l}i}(E_{GUT}) \equiv m_0$

Mass and bilinear terms for Higgs scalars:

$$-\mathcal{L}_{\text{Higgs}} = m^2_{H_u} H_u^\dagger H_u + m^2_{H_d} H_d^\dagger H_d + B\mu(H_u.H_d + \text{h.c.})$$

mSUGRA universality: $m^2_{H_u}(E_{GUT}) = m^2_{H_d}(E_{GUT}) \equiv m_0^2$

•Finally, some trilinear interactions between scalars (sfermions and Higgs bosons):

$$-\mathcal{L}_{\text{tril.}} = \sum_{i,j=gen} \left[-A^u_{ij} Y^u_{ij} \tilde{u}_{R_i} H_u.\tilde{Q}_j + A^d_{ij} Y^d_{ij} \tilde{d}_{R_i} H_d.\tilde{Q}_j + A^l_{ij} Y^l_{ij} \tilde{l}_{R_i} H_d.\tilde{L}_j \; + \; \text{h.c.} \right]$$

mSUGRA universality: $A^u_{ij}(E_{GUT}) = A^d_{ij}(E_{GUT}) = A^l_{ij}(E_{GUT}) \equiv A_0 \delta_{ij}$

Sparticle spectrum: • 5 Higgs scalars: $h, H, H^\pm, A$

•2 Charginos: $\tilde{\chi}^\pm_{1,2}$; 4 neutralinos $\tilde{\chi}^0_{1-4}$, 1 gluino $\tilde{g}$

•Numerous sfermions: sleptons $(\tilde{e}, \tilde{\mu}, \tilde{\nu}_e$,.. $\tilde{\tau}_{1,2})$,

squarks: $(\tilde{u}, \tilde{d}, ..\tilde{b}_{1,2}, \tilde{t}_{1,2})$

An Extension of MSSM: N(ext)MSSM

• μ-parameter problem in MSSM:

$$\mu \overset{?}{\sim} M_{\rm susy} \sim M_{\rm weak}$$

- $\mu = 0$? (could be if “R-symmetry")
  But experimentally excluded
- $\mu = M_{\rm Pl} \longrightarrow$ "hierarchy" problem

• Solution: add a singlet S coupled to H_u, H_d

$$W_{\rm NMSSM} = \cancel{\mu H_u H_d} + \lambda S H_u H_d + \frac{1}{3}\kappa S^3 \text{ (+ Yukawas)}$$

After potential minimization: $\mu_{\rm eff} \equiv \lambda \langle S \rangle \sim M_{\rm susy}$

• $\lambda, \kappa \to 0, \mu_{\rm eff} \neq 0$: MSSM + decoupled singlet sector

The NMSSM in short

- particle content:
  - $\widetilde{S}$: one more neutralino $\longrightarrow \widetilde{\chi}^0_{i=1..5}$
  - S_R: one more neutral (CP even) scalar $\longrightarrow h_{i=1,2,3}$
  - S_I: one more (CP odd) scalar $\longrightarrow A_{i=1,2}$

  $\Rightarrow$ New physics beyond MSSM

- Parameters: $V_{\rm Higgs} = V_F + V_D + V_{\rm soft}$

$$V_{\rm soft} = \left(\lambda A_\lambda H_u H_d S + \frac{1}{3}\kappa A_\kappa S^3 + {\rm hc} \right) + m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + m^2_S|$$

+ 3 minimization conditions:

$$\mu_{\rm eff} = \lambda\langle S\rangle, \quad \tan\beta = \frac{\langle H_u\rangle}{\langle H_d\rangle}, \quad M_Z^2 = \bar{g}^2\left(\langle H_u\rangle^2 + \langle H_d\rangle^2\right)$$

$\Longrightarrow$ 6 free parameters: $\lambda, \ \kappa, \ A_\lambda, \ A_\kappa, \ \mu_{\rm eff}, \ \tan\beta$

compared to MSSM: 2 free parameters $(m_A, \tan\beta)$

4. How to break supersymmetry?

Why is it so difficult to break SUSY *spontaneously*?

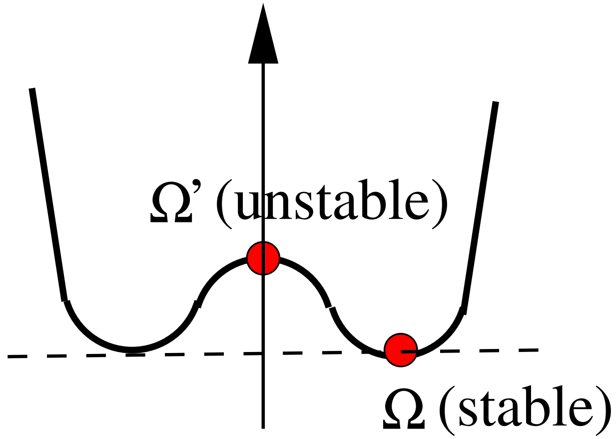
SUSY algebra involves the Hamiltonian: $H = P_0 = \sum Q_\alpha^2 \geq 0$

$\rightarrow$ expect (in global SUSY)

$\langle H \rangle_{\Omega\ supersymmetric} = 0;$

$\langle H \rangle_{\Omega'\ non-supersymmetric} > 0$

$V \sim \frac{1}{2} \sum (F^2 + D^2) > 0$



from SUSY-transformation (schematically):

$\delta\psi \sim (\sigma^\mu \partial_\mu \phi + F)\zeta,$ $\qquad \delta\lambda \sim (\sigma^\mu \sigma^\nu V_{\mu\nu} + D)\zeta$

$\langle F \rangle$and/or$\langle D \rangle \neq 0 \leftrightarrow \langle \delta\psi \rangle$and/or$\langle \delta\lambda \rangle \neq 0$ spont. breaking with sfermion ψ or gaugino λ Goldstone fermion resp.

(Analogy with usual SSB: $\delta\phi_2 = \theta\phi_1$, so $\langle \phi_1 \rangle \neq 0 \rightarrow \langle \delta\phi_2 \rangle \neq 0$)

Only way to get spontaneous SUSY-breaking:

look for models where $F_i = 0$ and/or $D^a = 0$ cannot be *simultaneously* satisfied for *any* field values.

Toy models do exist, but turn to be both

-contrived and exceptional situations

-phenomenologically unrealistic
(can't match SM gauge etc structure and/or strongly already excluded e.g due to sparticle mass limits)

Toy models of spontaneous SUSY-breaking

-O'Raifeartaigh: (F-term breaking) superpotential W such that
$V = |m\phi_1|^2 + |\lambda(\phi_1^2 - a^2)|^2 + |m\phi_2 + 2\lambda\phi_3\phi_1|^2$
(ϕ_i are chiral superfields)

immediate that the first two terms can't be *both* zero $\rightarrow$ SSSB.

More precisely if $|m|^2 > 2|\lambda^2 a^2|$ global min at $\phi_1 = \phi_2 = 0$;
$\rightarrow \langle F_3 \rangle \neq 0$: *flat* direction along ϕ_3 (so-called “moduli" field)

SUSY-breaking manifests as fermion ψ_1 mass m
while ϕ_1^+, ϕ_1^- mass $m^2 \pm 2\lambda^2 a^2$.
However note the sum rule (a generic feature):
$m^2_{\phi_1^-} + m^2_{\phi_1^+} = 2m^2_{\psi_1}$ just like exact SUSY...

Clearly excluded in MSSM!

D-term spontaneous SUSY-breaking

Fayet-Iliopoulos model: for $U(1)$ gauge symmetry

$V = |mQ|^2 + |m\bar{Q}|^2 + \frac{1}{8}|Q^\dagger Q - \bar{Q}^\dagger \bar{Q} + 2\kappa_{FI}|^2$, $Q, \bar{Q}$ chiral Sfields.

Linear term in κ_{FI} allows SSSB (for $m^2 > \kappa_{FI}/2$):

only OK for $U(1)$ (non-abelian sym: no invariant linear term!).

-maybe possible for extra $U(1)$ beyond SM: Z' models

(Still, not sufficient for realistic MSSM spectrum)

-Note D-term and F-term present in MSSM:

some $m_F \neq m_B$ amount triggered by EWSB...

(e.g. in sfermions mass terms) but not consistent alone

(tachyonic and/or obviously excluded) sfermion masses

typically $\rightarrow$ MSSM really needs soft terms!

$\rightarrow$ SUSY-breaking in hidden sector, communicated to SM

5. Generic features of hidden sector SUSY-breaking

Analogy with EWSB in SM: parameterized by $\langle v \rangle$

EWSB sector	Mediating interactions (= Yukawa couplings)	Observable sector
$h \to \langle v \rangle$	h, q, l	q, l

“Hidden" SUSY-breaking sector	Mediating interactions	Observable sector
$Z \to \langle F \rangle$	Z, Q, L	Q, L

SUSY-breaking parameterized by $\langle F \rangle$ of dim $[m]^2$

3 popular patterns: gravity-, gauge-, and anomaly-mediated

Actually all appear in a complete Supergravity picture!

Distinction arise from assumption on dominant mechanisms

Gravity-mediated susy breaking (minimal SUperGRAvity)

Start from Supergravity with “Kähler potential" $K(\phi, \phi^*)$

(Non-renormalizable terms)$\rightarrow$ suppressed by $1/M_{Planck}$

$\rightarrow$ soft terms of order $\sim \langle F \rangle / M_{Planck}$ when $Z \rightarrow \langle F \rangle$:

$$c_{ij} \ \frac{Z^\dagger Z}{M^2_{Planck}} \ \phi^*_i \phi_j \rightarrow m^2_0 \text{ scalar masses}$$

$$c_a \ \frac{Z}{M_{Planck}} \ \lambda_a \lambda_a \rightarrow m_{1/2} \text{ gaugino masses}$$

$$c_{ijk} \ \frac{Z}{M_{Planck}} \ \phi_i \phi_j \phi_k \rightarrow A_0 \text{ trilinear terms}$$

$F \sim M_{weak} M_{Planck} \sim [10^{10} GeV]^2$: high scale SUSY-breaking

(but $\langle F \rangle$ may also be triggered by gaugino condensation)

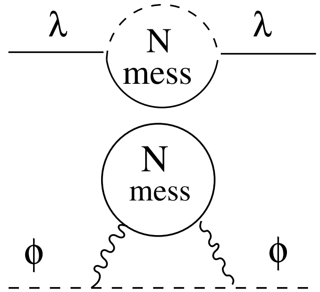
-Caution: famous universality in mSUGRA comes from minimal assumptions on Kähler and Super potential (i.e *separable* hidden/visible $K(\phi, \phi^*)$, $W(\phi)$ contributions)

Non-universal terms are there in more general scenario...

Gauge-mediated SUSY-breaking (GMSB)

Add N “messenger" Q, L heavy fields with mass M_{mess} and SUSY-breaking vev $\langle F \rangle$ that couple to SM gauge fields

$$M_\lambda \sim N \frac{g^2}{16\pi^2} \frac{\langle F \rangle}{M_{mess}}$$



$$m_\phi^2 \sim N [\frac{g^2}{16\pi^2}]^2 \; [\frac{\langle F \rangle}{M_{mess}}]^2$$

Trilinear terms $A_i(M_{mess}) \sim 0$ (2-loop; but much suppressed)

choose $M_{mess} \ll M_{Planck}$:

$\frac{F}{M_{mess}} \gg \frac{F}{M_{Planck}} \rightarrow$ gravity-mediated contributions negligible

Scalar masses determined by gauge quantum nbs:

solve SUSY flavor pb

Low scale SUSY breaking $F \sim M_{mess}^2$, $\sqrt{F} \sim 10^4$ GeV

but 10^4GeV $\lesssim M_{mess} \lesssim 10^{14}$ GeV possible

NB LSP can be (very light) gravitino: $M_{3/2} \sim \langle F \rangle / M_{Planck}$

Anomaly-mediated SUSY-breaking (AMSB)

The anomaly (symmetry breaking at quantum level) of the (super)conformal symmetry induces soft SUSY breaking!
NB was always present; but assumed sub-dominant (loop-suppressed) in standard "mSUGRA"

gauginos: $M_i \sim b_i \frac{g_i^2}{16\pi^2} M_{3/2}$ $\quad$ b_i(RGE) $= (33/5, 1, -3)$

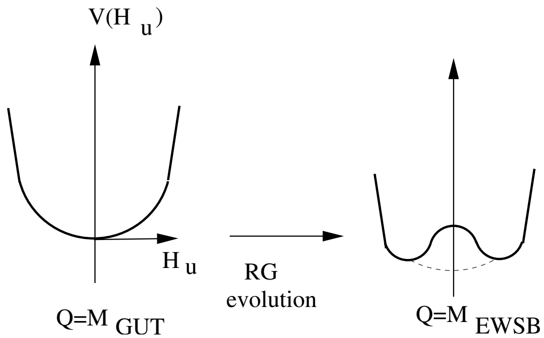
squarks, sleptons: $(m^2)^i_j \sim (\dot{\gamma})^i_j [\frac{M_{3/2}}{16\pi^2}]^2$; also $A_i \sim \frac{M_{3/2}}{16\pi^2}$
γ^i_j standard RGE anomalous mass dimensions
e.g. $\gamma_Q = -Y_u^\dagger Y_u - Y_d^\dagger Y_d + \sum_i c_i g_i^2$
Almost flavor blind!
But generally tachyonic $\tilde{l}_L, \tilde{l}_R \rightarrow$ add a m_0 term by hand...
however some recent criticisms (e.g. Dine+Seiberg '07)
perhaps more consistent "m_0" terms will soon emerge??..

6. Some constraints on MSSM

Unescapable constraint: *consistent* electro-weak symmetry breaking (EWSB) $SU(2)_L \times U(1)_Y \to U(1)_{em}$

In MSSM: *produced* by RG evolution of $m^2_{H_u}(E)$, $m^2_{H_d}(E)$:

$\sim$ OK if $m^2_{H_u}(E) < 0$ by RG evolution $E_{GUT} \to E_{EWSB}$ ($\propto m_t^2$)



AND $|\mu|$ *determined* by minimization of the scalar potential:

$2\mu^2 = \tan(2\beta)(\hat{m}^2_{H_u} \tan\beta - \hat{m}^2_{H_d} cot\beta - M_Z^2)$

$2B\,\mu = \sin 2\beta\,(\hat{m}^2_{H_u} + \hat{m}^2_{H_d} + 2\mu^2)$

$\tan\beta \equiv \frac{v_u}{v_d}$, $\qquad \hat{m}^2_{H_i} = m^2_{H_i} + \partial_{v_i} V^{eff}_{loop}(m_{sparticles}, \mu)$

$\to$ not always consistent solution for μ $\to$ excluded domains

μ very sensitive to rad. corr., m_t,.. via Renorm. Group Evolution (RGE):

$$\frac{d\,(m^2_{H_u})}{d\,\ln E} \propto m_t^2(m^2_{H_u} + ...)$$

and $\mu^2 \sim -m^2_{H_u} - m^2_Z/2$ (for $\tan\beta \gg 1$),

•μ enters everywhere in MSSM spectrum:
Higgses, $\tilde{\chi}^{\pm}, \tilde{\chi}^0$ (via Higgsinos $\tilde{H}_u, \tilde{H}_d$), $\tilde{q}, \tilde{l}$ (via mixing)

Also: “CCB" minima (Charge and/or Color breaking) deeper than electroweak min. can appear

(CCB domains to exclude e.g if trilin. cpling A_i too large)

Ingredients of spectrum calculation in MSSM

–for example SuSpect 2.35 (A. Djouadi, JLK, G. Moultaka)

•Low energy input $\alpha(M_Z), \alpha_S(M_Z)$, $M_t^{\text{pôle}}$, $M_\tau^{\text{pôle}}$, $m_b^{\overline{\text{MS}}}(m_b)$; $\tan\beta(M_Z)$

via radiative corrections $\Rightarrow g_{1,2,3}^{\overline{\text{DR}}}(M_Z), Y_\tau^{\overline{\text{DR}}}(M_Z), Y_b^{\overline{\text{DR}}}(M_Z), Y_t^{\overline{\text{DR}}}(M_Z)$

•Choice of SUSY-breaking model (mSUGRA, GMSB, AMSB,..)

Fixes initial condition at high energy (mSUGRA: $m_0, m_{1/2}, A_0$, sign(μ), etc...).

•Evolution of parameters by RGE down to $M_{\text{EWSB}} \sim \mathcal{O}(100GeV - -1TeV)$

•Control of EWSB consistency (convergence of μ, no CCB minima, etc...)

•Diagonalisation of mass mixing matrices and pole mass calculation (Including Rad. Corrections for Higgses, sfermions, gauginos)

Experimental Constraints on MSSM

- previous LEP limits on sparticle masses:

$m_{\chi_1^+} \gtrsim 104$ GeV

$m_{\tilde{\tau}^\pm} \gtrsim 100$ GeV

$m_{\tilde{t}_1, \tilde{b}_1} \gtrsim 100$ GeV

(Latest TeVatron limits: see Laurent Duflot presentation!!)

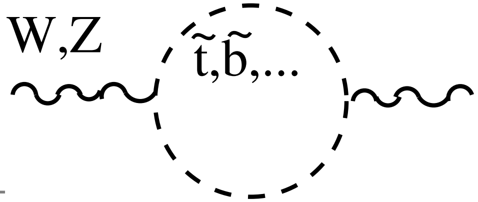
Direct (LEP) limits on Higgs mass:

$M_h \gtrsim 114$ GeV

(but th. uncertainty on M_h: ~ 3 GeV)

-not valid if A light: $\rightarrow M_{h,A} \gtrsim 90$ GeV (limits from $e^+e^- \rightarrow hA$)

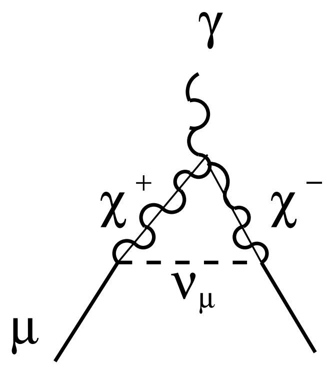
Indirect constraints: from virtual SUSY contributions:



constraining IF e.g large $\tilde{t}, \tilde{b}$ mass splittings

• $g_\mu - 2$ constraints: SUSY loop contributions

Charginos+ sneutrino (leading); (Also Neutralinos + smuon)



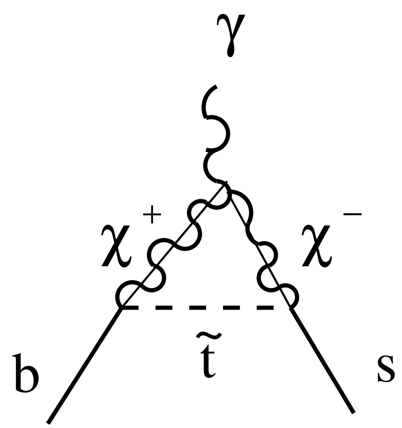
Standard Model (SM) contributions: hadron vacuum polarization (from dispersion relation: $\sigma(e^+e^-)$, τ decays)

Recent re-emergence of a 2-3σ-discrepancy
if taking only $\sigma(e^+e^-)$ data (see Fabio Zwirner's talk)
approx.: $10.6 \cdot 10^{-10} < \Delta a_\mu^{SUSY} < 43.6 \cdot 10^{-10}$
$\rightarrow$ Rather constraining: ($\mu < 0$ not favored)

• $b \to s\gamma$ constraints:

SM contributions: $W^{\pm}$ and t essentially

SUSY contributions: Charginos + stops; H^{+} + top



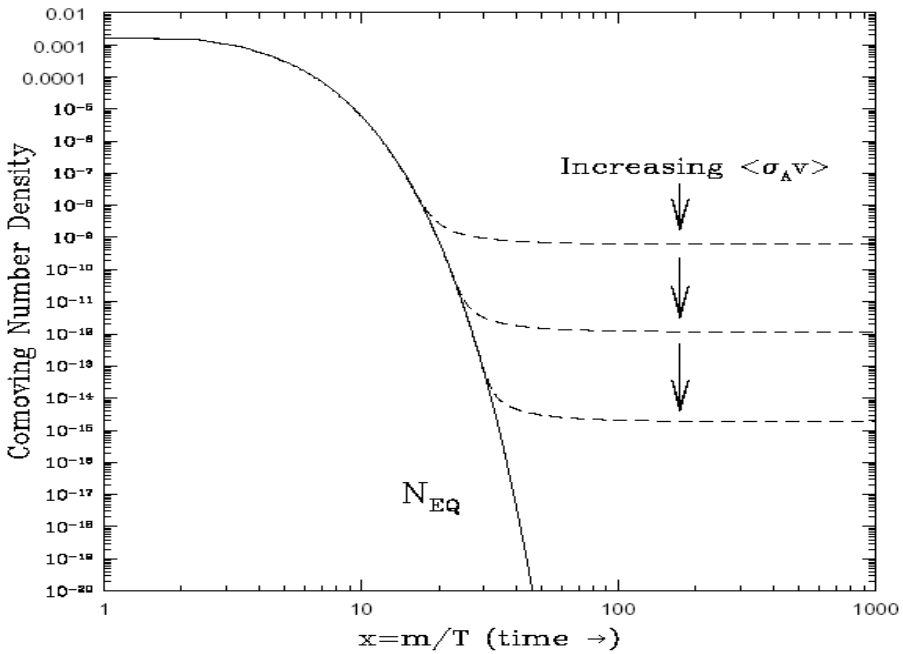
+ potentially large NLO contributions

IF enhanced by large $\tan\beta$ and/or $\ln(m_{sparticles}/M_W)$

e.g. approx.: $2.65 \leq 10^4 \cdot B.R.(b \to s\gamma) \leq 4.45$

+ constraint on amplitude sign! ($\simeq$ constraints on BR($b \to s\, l^+ l^-$) (i.e. requires SM sign)

Dark Matter relic density constraints:



•In early universe, “WIMP" (χ^0) are in thermal equilibrium

•As universe expanded and cool down, their density reduced through pair annihilation

•Eventually, density too low for annihilation to keep up with expansion rate: $\rightarrow T_{Freeze-out}$ (i.e. χ^0 decouple from SM)

$$\frac{dn}{dt} = -3Hn - \langle\sigma v\rangle[n^2 - n_{eq}^2]$$

Experimental (WMAP) evidence for Ωh^2

WMAP: $0.087 < \Omega h^2 < 0.138$: conservative (99% C.L.)

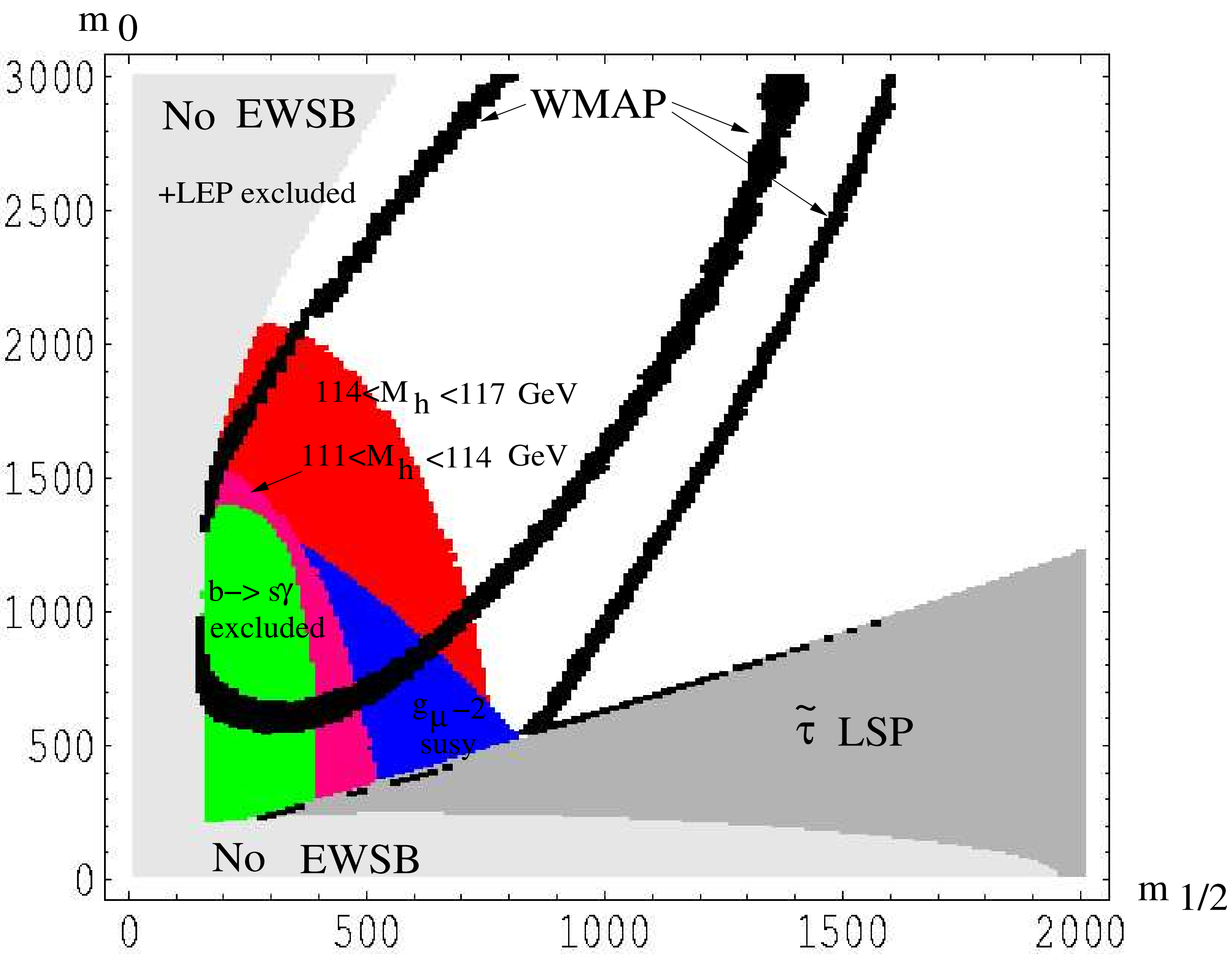
IF LSP $= \chi_0$: $\Omega_\chi h^2 \equiv$ relic density $\sim 3.10^{-27} cm^3 s^{-1} \times$
$[\langle\sigma(\chi_0\chi_0 \to all) + co - annihilation\ processes\rangle]^{-1}$

$\to \sigma$ large $\to \Omega h^2 \ll .1$ too small;
σ small $\to \Omega h^2$ too large

NB over 3000 processes $\sigma(\chi_0\chi_0 \to ...)$ can contribute!
But most relevant contributions depend on nature of LSP χ_1^0:
$\chi_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}_3 + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u$

e.g for $M_1 \ll \mu$, χ_1^0 is mainly “Bino", etc

Example of constraints in mSUGRA



$A_0 = 0$, $\tan\beta = 50$, $m_t = 173$ GeV. [Djouadi, Drees, JLK ’06]

Summary

-Problem of SUSY-breaking: no final convincing model
-would be better guide if a truly consistent picture of *dynamical* SUSY-breaking

-about 35 years of “waiting for SUSY": shall we start skepticism?
(and she missed already some rendez-vous: LEP1,2,TeVatron,..)

-embarassing fine tuning pbs, what if the spartners are very heavy, etc...
-embarassing flavor mixing, R-parity, etc

-On aimerait bien surfer avec SUSY sur la vague LHC!

LHC should guide our prejudices on SUSY-breaking models