B-physics and Low-Energy Supersymmetric Models

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Outline

1. **Low-Energy Supersymmetric Models**
2. Flavour in a Low-energy Supersymmetric Model
3. B-physics in a Low-energy Supersymmetric Model

What is Supersymmetry (SUSY)?

… A Symmetry!

- *The* symmetry algebra generalizing the Poincaré group to anticommutators:

$$\left\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\right\} = 2\sigma^\mu_{\alpha\dot{\alpha}} P_\mu \quad ; \quad (N = 1 \text{ SUSY} \rightarrow \text{chirality})$$

- To define a SUSY model, work with Supermultiplets (Superfields).

… Relating Fermions and Bosons:

$N = 1$ Supermultiplets:

- Chiral Supermultiplets ("matter") → 1 Complex Scalar Field (A) + 1 Weyl Spinor (ψ):

$$\hat{\Phi} \supset \begin{pmatrix} A \\ \psi \end{pmatrix} \quad ; \quad \hat{\Phi}^+ \supset \begin{pmatrix} A^+ \\ \bar{\psi} \end{pmatrix}$$

- Vector Supermultiplets ("gauge") → 1 Weyl spinor (λ) + 1 Vector Field (A^μ):

$$\hat{V} \supset \begin{pmatrix} \lambda \\ A^\mu \end{pmatrix}$$

What is Supersymmetry (SUSY)? *(continued)*

How to define a SUSY Lagrangian?

- Usual kinetic terms for all the fields;
- Gauge interactions (chiral × gauge):

  determined by the gauge symmetry!
- "Yukawa" couplings (chiral × chiral):

  → Constrained by symmetries;

  → Encoded in the **superpotential**:

  $$W = \lambda_i \hat{\Phi}_i + \frac{\mu_{ij}}{2} \hat{\Phi}_i \hat{\Phi}_j + \frac{g_{ijk}}{3} \hat{\Phi}_i \hat{\Phi}_j \hat{\Phi}_k$$

  (at most cubic for renormalizability; holomorphic);

⇒ scalar potential: $\mathcal{V}(\Phi_i) = \left| \frac{\partial W}{\partial \hat{\Phi}_j} (\Phi_i) \right|^2 + gauge$

⇒ Yukawa interactions: $\mathcal{L}_{\Phi_i \psi_j \psi_k} = -\frac{\partial^2 W}{\partial \hat{\Phi}_j \partial \hat{\Phi}_k} (\Phi_i)\, \psi_j \psi_k$

We can build a (N=1) SUSY *model!*

Why are SUSY models so interesting?

Supersymmetry has unique properties with respect to renormalization

- **"Non-renormalization" theorems**:
  For $N = 1$ SUSY, the superpotential receives no quantum corrections;
  $\Rightarrow$ Only Wave-function renormalization;
  $\Rightarrow$ Radiative corrections at most logarithmic
  (under certain conditions).

- At the diagrammatic level:
  Cancellations between scalar/pseudoscalar diagrams;
  between superpartner contributions.

In particular: No quadratic divergences for scalar squared masses!

Bridge towards gravity

Gauging supersymmetry $\Rightarrow$ Supergravity $\supset$ General Relativity
(Non renormalizable).

$\Rightarrow$ *SUSY is an ideal framework to connect low and high-energy scales.*

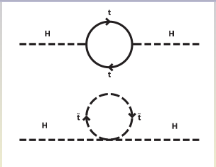
Why introduce SUSY at the TeV scale?

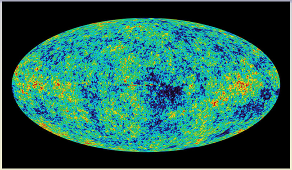
Several reasons to expect New Physics at the TeV scale:

- **Hierarchy problem** of the SM:
  - $\rightarrow m^2_{\text{Higgs}} \sim \Lambda^2_{EW}$ a natural requirement (exp. fits/unitarity,...);
  - $\rightarrow$ radiative corrections quadratically sensitive to SM cutoff;

$$\Rightarrow \begin{cases} \text{New Physics close to the EW scale; or} \\ \text{Fine-tune the counterterms (unnatural).} \end{cases}$$

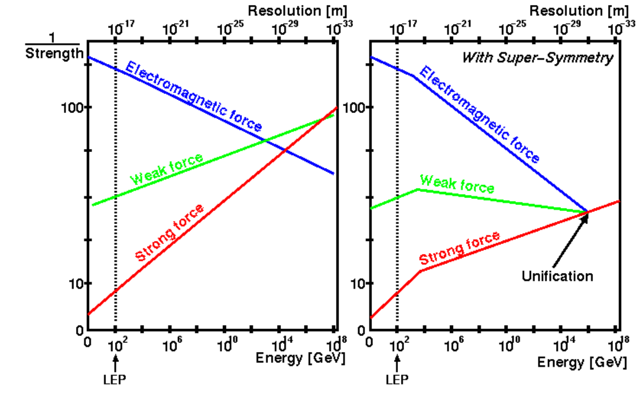
- **Dark Matter**: WIMP scenario
  - $\rightarrow$ A stable weakly-interacting particle at the EW scale.





$\Rightarrow$ New physics: $\rightarrow$ Strongly-interacting models (Technicolour, Little Higgs,...);
$\rightarrow$ Extra-dimensions (Large/warped,...);
$\rightarrow$ Supersymmetry.

Why introduce SUSY at the TeV scale? *(continued)*



Unification of the Gauge couplings:

- Nice feature in the SM… and does not work so bad!
- Supersymmetry: extension up to the GUT scale works! (bonus)

Supersymmetric Standard Model

Field Content:

Reproduce all the SM field content:

1. **Three Families of Lepton/Quark Superfields**:
   $$\hat{L}_L,\ \hat{E}^c_R = \text{(leptons+sleptons)}, \quad \hat{Q}_L,\ \hat{U}^c_R,\ \hat{D}^c_R = \text{(quarks+squarks)}.$$
2. **Two (Higgs+higgsinos) Doublets** (at least… + singlets?): $\hat{H}_u,\ \hat{H}_d$
   coupling respectively to u-like fields and d-like fields;
   Electroweak Symmetry Breaking $\Rightarrow$ v.e.v.'s v_u, v_d $\rightarrow$ parameter $\tan\beta \equiv \frac{v_u}{v_d}$.
3. **(Vector+gaugino) fields** for all the gauge groups $(SU(3)_c \times SU(2)_L \times U(1)_Y)$:
   $\hat{B},\ \hat{W}^a,\ \hat{A}^c$.

Superpotential:

$$W = \mu \hat{H}_u.\hat{H}_d + Y_u \hat{Q}_L.\hat{H}_u \hat{U}^c_R - Y_d \hat{Q}_L.\hat{H}_d \hat{D}^c_R - Y_e \hat{L}_L.\hat{H}_d \hat{E}^c_R \quad +(L/B)\text{-}\textbf{violating terms}!$$

- **R-parity**: $\rightarrow$ forbids the (L/B)-violating terms (imposed by hand);
  $\rightarrow$ stabilizes the Lightest Supersymmetric Particle (Dark Matter candidate).

BUT… This fails! Low-energy Particle Physics is not supersymmetric!

$\Rightarrow$ *Supersymmetry must be broken.*

Supersymmetry Breaking

- Theoretically possible.
- Phenomenologically difficult to implement:
  SUSY broken in hidden/secluded sector then mediated to the Standard sector…
- **Realistic models exist** (mediation through gravitational effects, gauge fields,…)…
  …Which one to choose?

Soft Supersymmetry Breaking

Add the most general SUSY-breaking terms (close to the EW scale)

- Parametrizing a spontaneous SUSY-breaking;
- Leading to at-most-logarithmic quantum corrections
  (preserve solution to the Hierarchy problem).

$$\Rightarrow \begin{cases} \text{Masses squared for all the scalars;} \\ \text{W-like interactions for the scalars;} \\ \text{Masses for the gauginos.} \end{cases}$$

PROBLEM: Large number of new free parameters!

At last we have the MSSM!

Next-to-Minimal SuperSymmetric Model (NMSSM)

- Additional Gauge-Singlet superfield $\hat{S}$ *[Fayet (1975)]*
- Superpotential ($\mathbb{Z}_3$ symmetry: scale invariant):

$$W = \frac{\kappa}{3}\hat{S}^3 + \lambda \hat{S}\hat{H}_u.\hat{H}_d + Y_u \hat{Q}_L.\hat{H}_u \hat{U}^c_R - Y_d \hat{Q}_L.\hat{H}_d \hat{D}^c_R - Y_e \hat{L}_L.\hat{H}_d \hat{E}^c_R$$

- v.e.v. $\langle S \rangle = s \quad \Rightarrow \quad \mu_{eff} = \lambda s$ (solution to the μ-problem)
- + Soft terms…

Particle Content of the NMSSM:

- SM particles: quarks, leptons, gauge bosons;
- Extended Higgs Sector:
  1. 3 neutral scalars: h_1, h_2, h_3;
  2. 2 neutral pseudoscalars: A_1, A_2;
  3. 1 charged scalar: $H^{\pm}$;
- SUSY particles:
  1. Sfermions: supersymmetric partners (scalar fields) of quarks and leptons;
  2. Charginos (charged fermions): $\chi^{\pm}_{1,2}$
  3. Neutralinos (neutral fermions): $\chi^{o}_{1,\ldots,5}$
  4. Gluinos: supersymmetric partners of the gluons.

A word about SUSY phenomenology...

Several constraints to consider...

- Vacuum stability / Electroweak Symmetry Breaking;
- Collider constraints on direct searches of the new particles (LEP);
- Cosmological constraints (Dark Matter relic density);
- Precision measurements ($(g-2)_\mu$, Z-pole,...) / Flavour observables;
- Perturbativity of the couplings up to the GUT scale;
- Choose a specific pattern of SUSY-Breaking?

Example: Little Fine-tuning Problem

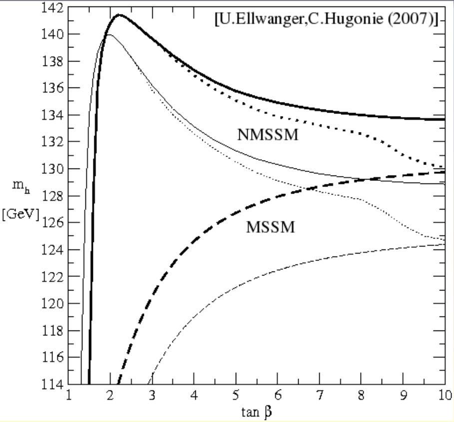
Upper Bound on the Lightest Higgs Mass:

i) Tree level (NMSSM)

$$m_{h_1}^2 \leq M_Z^2 \left[\left(\frac{1 - \tan^2\beta}{1 + \tan^2\beta} \right)^2 + \frac{2\lambda^2}{g_1^2 + g_2^2} \frac{4\tan^2\beta}{(1 + \tan^2\beta)^2} \right] \quad ; \quad \lambda(M_{GUT}) < \infty \Rightarrow \lambda(M_Z) \leq 0.7$$

ii) + Radiative corrections

+ Possible scenarii (invisible light singlet Higgs, light CP-odd Higgs scenario?)



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Supersymmetry and Flavour Physics

What does Supersymmetry tell us about Flavour physics?

Not Much. . .

Only that we should have a more complicated spectrum, so potentially new loops involved in radiative decays.

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Observables involve only SM particles and no significant deviation from SM predictions has been noted:

All looks consistent with the simple Yukawa structure.

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Supersymmetry-Breaking and Flavour Physics

What does Supersymmetry-Breaking tell us about Flavour physics?

Too Much!

→ New sources of flavour violation ($[U(3)]^5 \to U(1)_L \times U(1)_B$)
in the sfermion sector: soft terms $m^{2\,ff'}_{Sf.}$ and $(A_i Y_i)^{ff'}$

$$\mathcal{M}^2_{\tilde U} = \begin{pmatrix} m^{2\,ff'}_Q + Y^{*\,fk}_u Y^{f'k}_u v_u^2 + \frac{y_Q g'^2 - 2t_{3U} g^2}{8}\left(v_u^2 - v_d^2\right)\delta^{ff'} & \left[(A_u Y_u)^{ff'} v_u - \mu Y^{ff'}_u v_d\right]^* \\ (A_u Y_u)^{f'f} v_u - \mu Y^{f'f}_u v_d & m^{2\,f'f}_U + Y^{*\,kf'}_u Y^{kf}_u v_u^2 + y_U \frac{g'^2}{8}\left(v_u^2 - v_d^2\right)\delta^{ff'} \end{pmatrix}$$

What does Flavour physics tell us about Supersymmetry-Breaking?

Too Little!

The Yukawa structure is sufficient to explain what flavour violation is observed.

⇒ New sources of flavour-violation are constrained. / A Mechanism is necessary to protect flavour violation in the SUSY-breaking terms.

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Solutions to the "MSSM Flavour Problem"?

Universal Soft-Breaking terms

- Motivated by a **mSugra** setup: gravitational interactions supposedly flavour-blind;
- Soft-breaking terms are **universal** (proportional to $\mathbb{I}$) at some high-energy scale (GUT);
- However no flavour symmetry $\Rightarrow$ **flavour-violating effects generated at the loop level**.

GMSB-like scenarii

- Breakdown of flavour symmetry assumed to be controlled by some dynamics; Breaking scale $\Lambda_{\text{Fl.}}$;
- SUSY-Breaking scale $\Lambda_{\text{SUSY}} < \Lambda_{\text{Fl.}}$;
  $\Rightarrow$ **Yukawa Flavour structure** frozen and enforced at Λ_{SUSY};
- Natural scenario in Gauge-mediated SUSY-Breaking.

Solutions to the "MSSM Flavour Problem"? *(continued)*

Minimal Flavour Violation

- Sfermion mass-matrices **diagonalizable simultaneously** with the fermion Yukawa couplings (at some scale Λ_{MFV});
- Radiative corrections still generate some new flavour-violating effects.

Other possibilities?

- Yukawa couplings vanish at high energy (except perhaps for the 3rd generation) and are generated by the soft-breaking terms;
- (...)

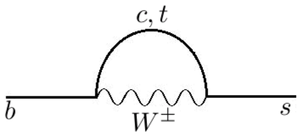
+ *Same comments apply to CP-violation!*

Outline

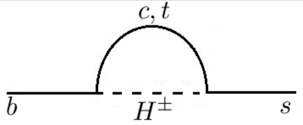
Flavour-changing loops

New Particles ⇒ New flavour-changing loops:

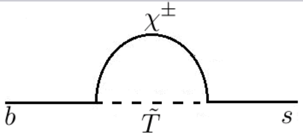
→ *SM-like contributions*



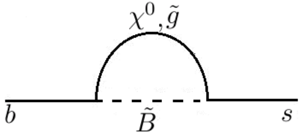
→ *2 Higgs Doublet Model contributions*



→ SUSY *charged loops*



→ SUSY *Flavour-Changing Neutral Currents*



Flavour-changing loops *(continued)*

Are the New Contributions really relevant?

- New particle massive (from direct searches)
  $\Rightarrow$ Contribution heavily suppressed;
- Large uncertainty on hadronic processes.

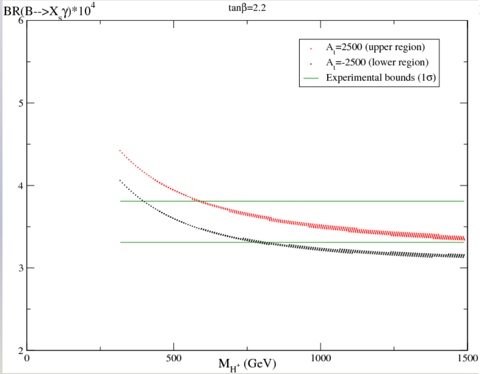
$\Rightarrow$ New contributions negligible *a priori*...

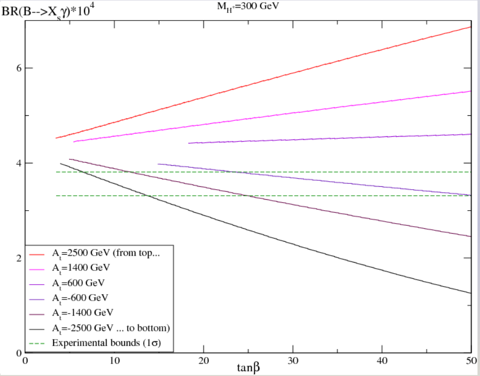
Enhancement factors

- Light charged Higgs;
- Large $\tan\beta$: All the SUSY effects enhanced
  $\rightarrow$ "Hall-Ratazzi-Sarid effect": resum the one-loop effects in the Yukawa / mass sector *Ex:* $Y_b = \frac{m_b^{obs}}{v_d(1+\varepsilon_b \tan\beta)}$
- Light CP-odd Higgs (NMSSM only):
  $\rightarrow$ Enhanced Higgs-penguin (4-fermion operators).

$\Rightarrow$ Constrained scenarii!

$BR(\bar{B} \to X_s \gamma)$: Leading effects

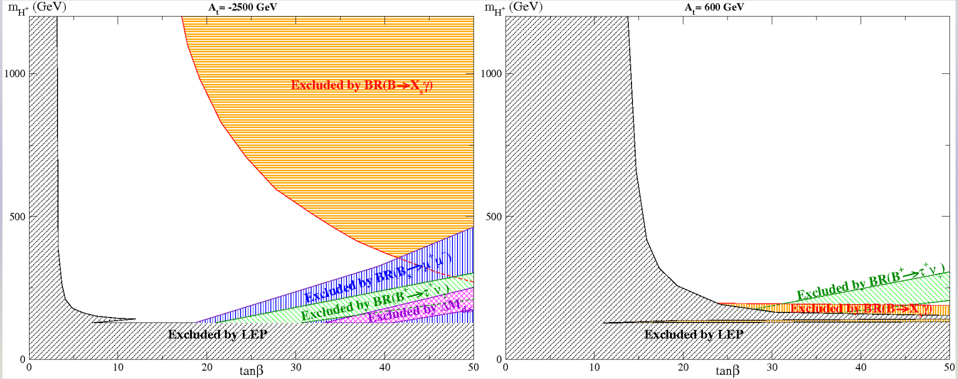




Two main enhancing effects

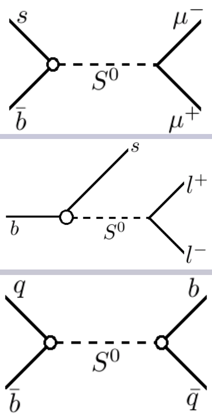
- **Light Charged Higgs** lead to large (positive) contributions;
- **Large** $\tan\beta$ enhance the SUSY contributions; sign depends on $\mu \cdot A_t$:
  $\to$ constructive/destructive effect with $H^{\pm}$?

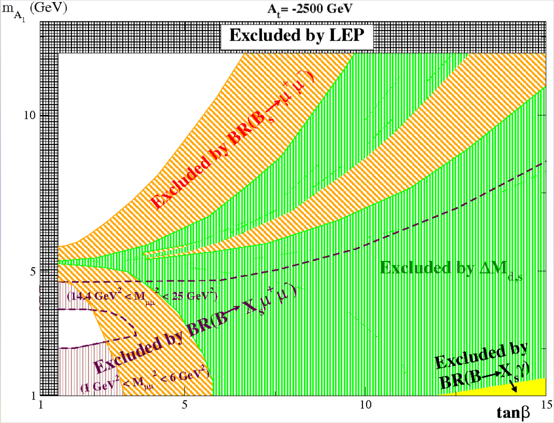
Plane $(\tan\beta, m_{H^\pm})$: B-Physics versus LEP



- Large $\tan\beta$ severely constrained because of the SUSY contribution to B-observables.
- However, SUSY effects can be "switched off" by small trilinear couplings;
- Yet, LEP constraints (from Higgs searches) become more relevant.

Light Pseudoscalar Scenario (NMSSM)





- $BR(\bar{B}_s \to \mu^+\mu^-)$ particularly constraining;
- "Pole" regions are always excluded;
- Effect enhanced for large $\tan\beta$;
- For small A_t, LEP constraints restrict the large $\tan\beta$ region.