Physique au LHC: théorie

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- **SUSY au LHC**

1. **BSM, SUSY et le MSSM**
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1. SUSY and the MSSM

The SM has many attractive theoretical/experimental features:

- Based on gauge principle, unitary, perturbative, renormalisable $\cdots$
- Once M_H fixed: everything is predictible with great accuracy.
- And has passed all experimental tests up to now.

But the model has too many shortcomings:

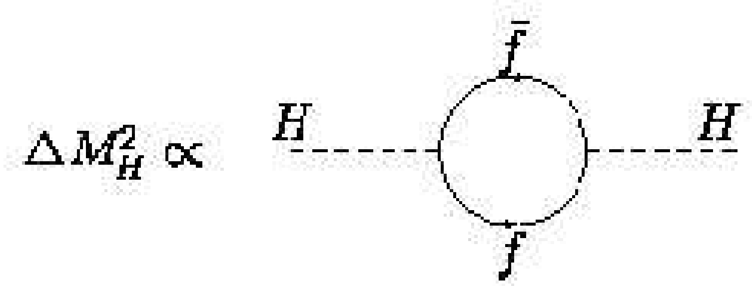
- Too many free parameters (19!) in the model, put by hand...
- No satisfactory explanation for $\mu^2 < 0$ (put ad hoc).
- Does not include the fourth fundamental force, gravity, ..
- Does not say anything about the masses of the neutrinos.
- No real unification of the three gauge interactions.
- Does not explain the baryon asymmetry in the universe.
- There is no stable, weak, massive particle for dark matter.

And above all that, there is the hierarchy or naturalness problem.

1. BSM & SUSY: the hierarchy problem

Radiative corrections to the Higgs boson mass in the SM

Let us first consider the fermion loop contribution to M_H^2



Using a cut–off Λ (see excercises later) one obtains:

$$\Delta M_H^2 = N_f \frac{\lambda_f^2}{8\pi^2}\left[-\Lambda^2 + 6 m_f^2 \log\frac{\Lambda}{m_f} - 2m_f^2 \right] + \mathcal{O}(1/\Lambda^2)$$

We have thus a quadratic divergence, $\Delta M_H^2 \sim \Lambda^2$.

Divergence is independent of M_H, and does not disappear if $M_H = 0$:

The choice $M_H = 0$ does not increase the symmetry of $\mathcal{L}_{\rm SM}$.

If we fix the cut–off Λ to $M_{\rm GUT}$ or M_P: $\Rightarrow M_H \sim 10^{14}$ to 10^{17} GeV!

The Higgs boson mass prefers to be close to the very high scale:

This is the hierarchy problem.

1. BSM & SUSY: the hierarchy problem

But we want a light Higgs ($\mathrm{M_H} \lesssim 1$ TeV) for unitarity etc... reasons.

We need thus to make: $\mathrm{M_H^2}|^{\mathrm{Physical}} = \mathrm{M_H^2}|^{\mathbf{0}} + \mathbf{\Delta}\mathrm{M_H^2}$+ countreterm

And adjust this counterterm with a precision of 10^{-30} (30 digits)

This fine-tunning would be very unnatural...

In SM, besides fermion loops, there are also contributions to $\mathrm{M_H}$

from the massive gauge bosons and from the Higgs boson itself:

$$\Rightarrow \mathbf{\Delta}\mathrm{M_H^2} \propto [3(\mathrm{M_W^2} + \mathrm{M_Z^2} + \mathrm{M_H^2})/4 - \sum \mathrm{m_f^2}](\mathbf{\Lambda}^2/\mathrm{M_W^2})$$

We can adjust the unknown $\mathrm{M_H}$ so that the quadratic divergence

disappears (would be a prediction for Higgs mass, $\mathrm{M_H} \sim 200$ GeV).

However: does not work at two–loop level or at higher orders....

Summary: the problem of the quadratic divergences to $\mathrm{M_H}$ is there.

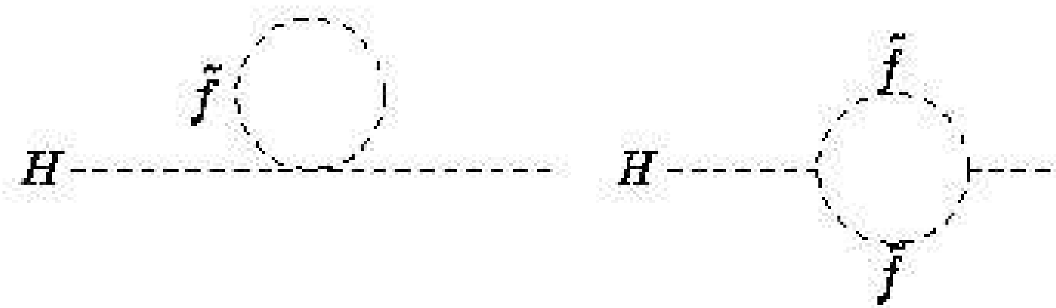
Photon and fermion masses protected by gauge and chiral symmetry,

.... but here is no symmetry which protects $\mathrm{M_H}$ in the SM.

1. BSM & SUSY: the hierarchy problem

Imagine now that you have additional scalar particles:

Add the contributions of scalar fermion partner loops to ΔM_H^2



- $\lambda_f^2 = -\lambda_S$.
- $N_S = N_f$ **(nb: 2 scalars).**
- $m_1 = m_2 = m_S$.
- **Add f+S contributions.**

$$\Delta M_H^2\Big|^{\rm tot} = \frac{\lambda_f^2 N_f}{4\pi^2}\left[(m_f^2 - m_S^2)\log\left(\frac{\Lambda}{m_S}\right) + 3m_f^2 \log\left(\frac{m_S}{m_f}\right)\right]$$

The quadratic divergences have disappeared in the sum!! (same job for W/Z/H). Logarithmic divergence still there, but contribution small.

No divergences at all if in addition $m_S = m_f$ (exact SUSY)!

$\Rightarrow$ Symmetry fermions–scalars $\to$ no divergence in Λ^2

“Supersymmetry” no divergences at all: M_H is protected!

Note that if $M_S \gg 1\ \text{TeV}$ the fine tunning problem is back!!!

1. BSM & SUSY: SUSY

SUSY: symmetry relating fermions s=$\frac{1}{2}$ and bosons s=0,1

$$\mathcal{Q}|\mathrm{fermion}>=|\mathrm{boson}> \ , \ \ \mathcal{Q}|\mathrm{boson}>=|\mathrm{fermion}>$$

is the most attractive extension of SM also for other reasons

- **Links internal and space–time symmetries: larger for S matrix..**
- **If SUSY is gauged $\Rightarrow \mathrm{s}=\frac{3}{2},2 \Rightarrow$ link with 4th force, gravity...**
- **Naturally present in Superstrings (theory of everything?).**
- **The spectrum of superparticles fixes unification of couplings and $\not{P}$.**
- **Possibility of unifying the fermion Yukawa couplings at $M_{\rm GUT}$.**
- **The LSP can have the right relic density and solve the DM problem.**
- **Radiative breaking of the EW symmetry: $\mu^2>0$ at $M_{\rm GUT}, <0$ at $M_{\rm EW}$**

$\cdots$ **and all this at once** $\cdots$ **But we need $M_{\rm SUSY} \sim \mathcal{O}$(TeV)!**

otherwise, back to the hierarchy, dark matter and unification problems $\cdots$

1. BSM & SUSY: SUSY

Drawback: no satisfactory way to break SUSY spontaneously

Solution: SUSY–breaking occurs in a hidden sector of particles with no (or very tiny) couplings to the visible sector of the MSSM.

If mediating interaction is flavor–blind, universal breaking terms.

Examples: gravity (mSUGRA), gauge (GMSB) mediation ...

Many breaking schemes but none is fully satisfactory at the moment:

$\Rightarrow$ Explicit breaking by hand (also with several possibilities...).

- **We need SUSY breaking at low energy to solve the problems:**

– Quadratic divergences in the Higgs sector.

– Unification of the coupling constants of $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$.

– Dark Matter problem (existence of a massive stable particle), etc.

- **In the breaking, we still need to preserve: gauge invariance, renormalizability, and no quadratic divergence (soft SUSY–breaking).**

$\Rightarrow$ “Low energy SUSY” $\equiv$ effective theory at low energy.

1. BSM & SUSY: the MSSM

The MSSM is the most economic low energy SUSY extension of SM

It is based on the following assumptions:

• **Minimal gauge group:** $\mathrm{G_{SM} = SU(3)_C \times SU(2)_L \times U(1)}$.

The SM spin–1 gauge bosons [$\mathrm{B}, \mathbf{W_{1-3}}$ **and** $\mathbf{g_{1-8}}$] **and their spin–**$\frac{1}{2}$

gaugino partners $[\tilde{\mathrm{b}}, \tilde{\mathrm{w}}_{\mathbf{1-3}}, \tilde{\mathrm{g}}_{\mathbf{1-8}}]$ **are in vector superfields.**

Superfields	$\mathbf{SU(3)_C}$	$\mathbf{SU(2)_L}$	$\mathbf{U(1)_Y}$	Particle content
$\mathbf{\hat{G}^a}$	8	1	0	$\mathbf{G^{\mu}}, \tilde{\mathbf{g}}$
$\mathbf{\hat{W}^i}$	1	3	0	$\mathbf{W_i^{\mu}}, \tilde{\omega}_{\mathbf{i}}$
$\mathbf{\hat{B}}$	1	1	0	$\mathbf{B^{\mu}}, \tilde{\mathbf{b}}$

Charged winos mix with higgsinos to form the two charginos $\chi^{\pm}_{1,2}$

Bino and neutral wino mix with higgsinos to form 4 neutralinos $\chi^0_{1,2,3,4}$

Gluinos do not mix with anybody....

1. BSM & SUSY: the MSSM

• **Minimal particle content:**

– Three fermion generations [as in SM no $\nu_{\rm R}$...] and their spin–0 SUSY partners, the sfermions $\tilde{\rm f}_{\rm L}, \tilde{\rm f}_{\rm R}$, combined in chiral supermultiplets.

– No chiral anomalies ($\sum_{\rm f} {\rm Q_f} \equiv 0$) and fermion mass generation in a SUSY invariant way (no conjugate ${\rm H}^*$ field for u–quarks), we need: two chiral superfields with ${\rm Y}=+1$ and ${\rm Y}=-1$.

Superfield	$\mathbf{SU(3)_C}$	$\mathbf{SU(2)_L}$	$\mathbf{U(1)_Y}$	Particle content
$\hat{Q}$	3	2	$\frac{1}{3}$	(u_L, d_L), $(\tilde{u}_L, \tilde{d}_L)$
$\hat{U}^c$	$\overline{3}$	1	$-\frac{4}{3}$	$\overline{u}_R$, $\tilde{u}^*_R$
$\hat{D}^c$	$\overline{3}$	1	$\frac{2}{3}$	$\overline{d}_R$, $\tilde{d}^*_R$
$\hat{L}$	1	2	-1	(ν_L, e_L), $(\tilde{\nu}_L, \tilde{e}_L)$
$\hat{E}^c$	1	1	2	$\overline{e}_R$, $\tilde{e}^*_R$
$\hat{H}_1$	1	2	-1	$(H_1, \tilde{h}_1)$
$\hat{H}_2$	1	2	1	$(H_2, \tilde{h}_2)$

1. BSM & SUSY: the MSSM

• R–parity conservation:

To eliminate terms violating B and L numbers (and proton decay):

Discrete and multiplicative symmetry called R-parity or $\mathbf{R_p}$:

$$\mathbf{R_p = (-1)^{2s+3B+L}}$$

Then $R = +1$ for all ordinary SMparticles

$R = -1$ for all the SUSY particles

The consequences of $\mathbf{R_p}$ conservation are very important:

– SUSY particles always produced in pairs.

– SUSY particles decay into an odd number of SUSY particles.

– The lightest SUSY particle (LSP) is absolutely stable.

1. BSM & SUSY: the MSSM

At this stage, we have a globally supersymmetric Lagrangian.

- **Everything is specified by SUSY and gauge invariance.**
- **No additional parameter compared to SM.**
- **Only freedom, the choice of the Superpotential.**

The most general Superpotential compatible with SUSY, gauge invariance, renormalizability and R–parity conservation is:

$$\mathbf{W} = \sum_{\rm i,j=gen} Y^u_{ij}\, \hat{u}^i_R \hat{H}_2 . \hat{Q}^j + Y^d_{ij}\, \hat{d}^i_R \hat{H}_1 . \hat{Q}^j + Y^l_{ij}\, \hat{l}^i_R \hat{H}_1 . \hat{L}^j + \mu \hat{H}_1 . \hat{H}_2$$

- $Y^{u,d,l}_{ij}$ **denote the Yukawa couplings among the three generations (and which simply a generalisation of the SM Yukawa interaction).**
- μ **supersymmetric Higgs–higgsino parameter with dimension of mass (it is thus a supersymmetric parameter, see later....).**

1. BSM & SUSY: the unconstrained MSSM

• **Soft SUSY breaking:**

To explicitely break Supersymmetry without reintroducing the quadratic divergences (the so–called soft SUSY–breaking), we add by hand a collection of soft terms (of dimension two and three):

$$\mathcal{L}_{\rm gaugino} = \frac{1}{2}\left[\mathbf{M_1 \tilde{b}\tilde{b} + M_2 \Sigma_{a=1}^{3} \tilde{w}^a \tilde{w}_a + M_3 \Sigma_{a=1}^{8} \tilde{g}^a \tilde{g}_a} \; + \; {\rm h.c.}\right]$$

$$\mathcal{L}_{\rm sf.} = \mathbf{\Sigma_i m^2_{\tilde{Q},i} \tilde{Q}_i^\dagger \tilde{Q}_i + m^2_{\tilde{L},i} \tilde{L}_i^\dagger \tilde{L}_i + m^2_{\tilde{u},i} |\tilde{u}_{R_i}|^2 + m^2_{\tilde{d},i} |\tilde{d}_{R_i}|^2 + m^2_{\tilde{l},i} |\tilde{l}_{R_i}}$$

$$\mathcal{L}_{\rm Higgs} = \mathbf{m_2^2 H_2^\dagger H_2 + m_1^2 H_1^\dagger H_1 + B\mu(H_2.H_1} + {\rm h.c.})$$

$$\mathcal{L}_{\rm tr.} = \mathbf{\Sigma_{i,j}\Big[A^u_{ij} Y^u_{ij} \tilde{u}_{R_i} H_2.\tilde{Q}_j + A^d_{ij} Y^d_{ij} \tilde{d}_{R_i} H_1.\tilde{Q}_j + A^l_{ij} Y^l_{ij} \tilde{l}_{R_i} H_1.\tilde{L}_j +}$$

A rather complicated and problematic potential indeed!

• **Too many parameters and thus not very predictive.**

• **Leads generically to a problematic phenomenology.**

1. BSM & SUSY: the unconstrained MSSM

In the most general case (mixing and phases): 105 free parameters!

- **complex gaugino masses M_1, M_2, M_3 : 6**
- **3×3 hermitian mass matrices $m_{\tilde{F}}$: 45**
- **3×3 complex trilinear coupling matrices A_f : 54**
- **2×2 matrix for the bilinear B coupling : 4**
- **Higgs masses squared, $m^2_{H_1}, m^2_{H_2}$: 2**

111–6 (due to constraints from symmetries and Higgs sector)=105.

For "generic" sets of these parameters, leads to severe problems:

- **large flavor changing neutral currents [FCNC]**
- **unacceptable amount of additional CP–violation**
- **color and/or charge breaking minima**
- **an incorrect value of the Z boson mass, etc......**

We need more constrained MSSMs

1. BSM & SUSY: the phenomenological MSSM

A phenomenologically viable MSSM is defined by assuming:

- **all soft SUSY–breaking parameters are real (no new CP viol).**
- **Mass and trilinear cpls. for sfermions diagonal (no FCNC)**
- **1st/2d sfermion generation universality (no pb. with Kaons)**

Phenomenological MSSM (pMSSM) with 22 free parameters:

$\tan\beta$: **the ratio of the vevs of the two–Higgs doublet fields.**

$m^2_{H_u}, m^2_{H_d}$: **the Higgs mass parameters squared.**

M_1, M_2, M_3: **the bino, wino and gluino mass parameters.**

$m_{\tilde{q}}, m_{\tilde{u}_R}, m_{\tilde{d}_R}, m_{\tilde{l}}, m_{\tilde{e}_R}$: **1st/2d generation sfermion mass para.**

$m_{\tilde{Q}}, m_{\tilde{t}_R}, m_{\tilde{b}_R}, m_{\tilde{L}}, m_{\tilde{\tau}_R}$: **third generation sfermion mass para.**

A_t, A_b, A_τ: **the third generation trilinear couplings.**

A_u, A_d, A_e: **the first/second generation trilinear couplings.**

1. BSM & SUSY: the constrained MSSM

In fact:

- **You can trade $m^2_{H_u}, m^2_{H_d}$ with more "physical" μ and M_A**

(in fact: μ^2 and $B\mu$ can be determined from ESWB, see later).

- **A_u, A_d, A_e in general not relevant for phenomenology.**

(enter only in "light" flavor physics: $(g-2)_\mu$, neutron edm, ...).

- **If you focus on a given sector (Higgs, gauginos, sfermions):**

only few parameters to deal with and model indep. analyses....

$\Rightarrow$ **phenomenologically more viable model than general MSSM**

- **You can also use common soft–SUSY breaking terms in many cases**

($m_{\tilde{q}} = m_{\tilde{u}_R} = m_{\tilde{d}_R}$; $m_{\tilde{Q}}, m_{\tilde{t}_R}, m_{\tilde{b}_R}$; A_t, A_b, A_τ; etc..)

and one ends with an even more restrictive set of parameters, $\lesssim 10$.

$\Rightarrow$ **much more predictive model than general MSSM**

1. BSM & SUSY: the constrained MSSM

Almost all problems of MSSM solved at once if soft SUSY–breaking parameters obey a set of universal boundary conditions at $M_{\rm GUT}$.

Underlying assumption: SUSY–breaking occurs in a hidden sector communicating with visible sector through gravitational interactions.

$\Rightarrow$ Universal soft terms emerge if interactions are "flavor–blind":

Besides $g_{1,2,3}$ unification which fix the scale $\rm M_{GUT} \sim \mathbf{2 \cdot 10^{16}}$ GeV:

Unification of gaugino, scalar masses and trili. couplings at $\rm Q = M_{GUT}$

Universal gaugino masses: $\mathbf{M_1 = M_2 = M_3 \equiv m_{1/2}}$

Universal scalar masses: $\mathbf{M_{\tilde{Q}_i} = M_{\tilde{L}_i} = M_{H_i} \equiv m_0}$

Universal trilinear couplings: $\mathbf{A^u_{ij} = A^d_{ij} = A^l_{ij} \equiv A_0\, \delta_{ij}}$

Also: B and μ^2 from requiring of EWSB and minimization of $V_{\rm Higgs}$

$$\mu^{\mathbf{2}} = \tfrac{\mathbf{1}}{\mathbf{2}}[\tan \mathbf{2}\beta(\mathbf{m^2_{H_u}} \tan\beta - \mathbf{m^2_{H_d}} \cot\beta) - \mathbf{M_Z^2}]$$

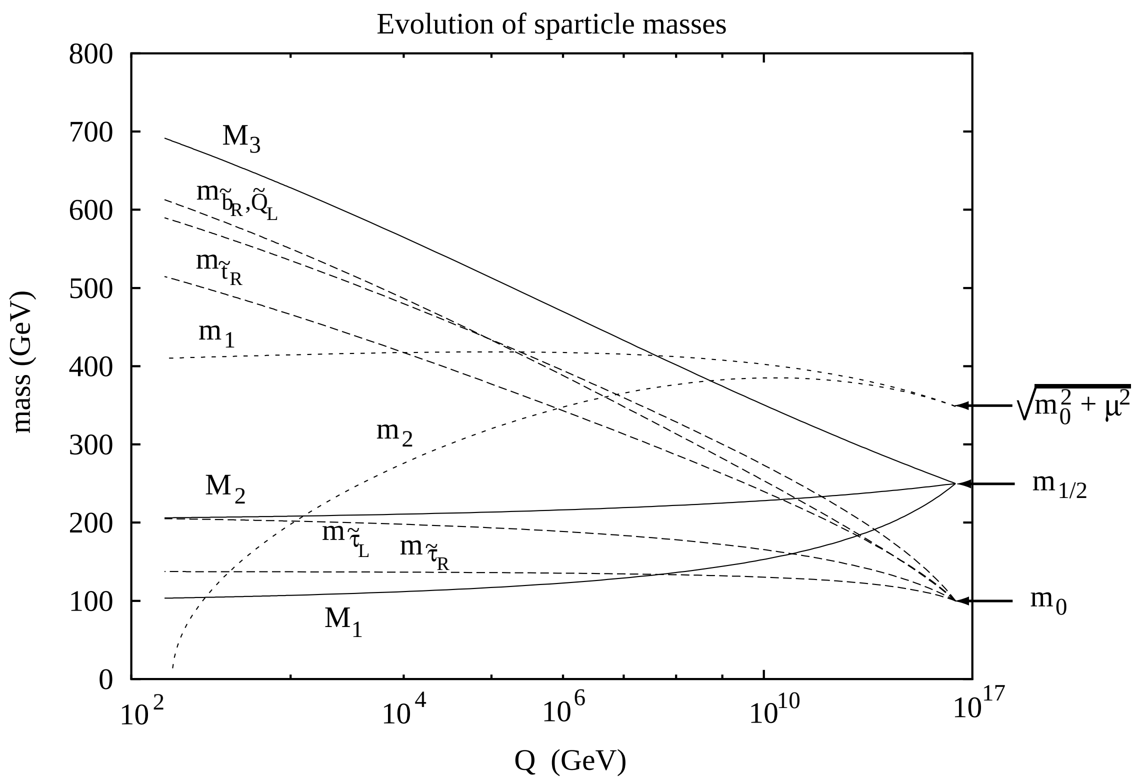
$$\mathbf{B}\mu = \tfrac{\mathbf{1}}{\mathbf{2}} \sin \mathbf{2}\beta[\mathbf{m^2_{H_u}} + \mathbf{m^2_{H_d}} + \mathbf{2}\mu^{\mathbf{2}}]$$

1. BSM & SUSY: the constrained MSSM

Only 4.5 param: $\tan\beta$, $\mathbf{m_{1/2}}$, $\mathbf{m_0}$, $\mathbf{A_0}$, $\text{sign}(\mu)$

All soft breaking parameters at M_S are obtained through RGEs.

With $\mathrm{M_{GUT}} \sim \mathbf{2 \cdot 10^{16}}$ GeV and $\mathrm{M_{SUSY}} \sim \sqrt{\mathbf{m_{\tilde{t}_L} m_{\tilde{t}_R}}}$:



Radiative EWSB occurs since $\mathrm{M^2_{H_2}} < \mathbf{0}$ at scale $\mathrm{M_Z}$ $(\mathbf{t}/\tilde{\mathbf{t}}$ loops$)$

⇒ EWSB more natural in MSSM ($\mu^2 < 0$ from RGEs) than in SM!

1. BSM & SUSY: the constrained MSSM

In GMSB, SSB transmitted to MSSM fields via SM gauge interactions.

- **Hidden sector for SUSY–break. contains messengers fields, $n_{\hat{q}}/n_{\hat{l}}$ quark/lepton-like pairs coupled to a gauge singlet chiral superfield $\hat{S}$.**
- **The spotential is $W = \lambda \hat{S}\hat{q}\hat{\bar{q}} + \lambda \hat{S}\hat{l}\hat{\bar{l}}$ with $\hat{S}$ havings vevs. s and f_S**
- **SSB are generated by (1or2) loop corrections at scale $M_{\rm mes} = \lambda s$**

$$\mathbf{M_G(M_{mes}) = \frac{\alpha_G(M_{mes})}{4\pi} \Lambda\, g(\frac{\Lambda}{M_{mes}}) \sum_m N_R^G(m)}$$

$$\mathbf{m_s^2(M_{mes}) = 2\Lambda^2 f(\frac{\Lambda}{M_{mes}}) \sum_{m,G} (\frac{\alpha_G(M_{mes})}{4\pi})^2 N_R^G(m) C_R^G(s)}$$

$\mathbf{A_f(M_{mes}) \simeq 0}$ **(generated at two–loops).**

with $\mathbf{\Lambda = f_s/s, G = {\rm U(1), SU(2), SU(3)}}$, m and s label messengers and scalars; f/g are one/two loop functions; N/C are Dynkin/Casimirs..

Thus, in the GMSB model there are six basic input parameters

$$\mathbf{\tan\beta\ ,\ sign(\mu)\ ,\ M_{mes}\ ,\ \Lambda\ ,\ n_{\hat{q}}\ ,\ n_{\hat{l}}}$$

plus the mass of the very light gravitino (which is the LSP).

1. BSM & SUSY: the constrained MSSM

In AMSB, SUSY breaking occurs also in hidden sector (e.g. extra dims) and is transmitted to visible sector via (e.g. super–Weyl) anomalies.

Gaugino, scalar masses and trilinear couplings are simply related to the scale dependence of the gauge and matter kinetic functions.

In terms of gravitino mass $\mathrm{m_{3/2}}$, β functions for $\mathrm{g_a}$ and $\mathrm{Y_i}$ couplings and anomalous dimensions γ_i of chiral superfields, SSB terms are:

$$\mathrm{M_a} = \frac{\beta_{\mathrm{g_a}}}{\mathrm{g_a}} \mathrm{m_{3/2}}\ , \ \mathrm{A_i} = \frac{\beta_{\mathrm{Y_i}}}{\mathrm{Y_i}} \mathrm{m_{3/2}}$$

$$\mathrm{m_i^2} = -\frac{1}{4}\left(\Sigma_\mathrm{a} \frac{\partial \gamma_\mathrm{i}}{\partial \mathrm{g_a}} \beta_{\mathrm{g_a}} + \Sigma_\mathrm{k} \frac{\partial \gamma_\mathrm{i}}{\partial \mathrm{Y_k}} \beta_{\mathrm{Y_k}}\right) \mathrm{m_{3/2}^2}$$

RG invariant equations valid at any scale (make a predictive model).

(μ^2 and $B\mu$ terms are obtained as usual by requiring EWSB).

However, picture spoiled by tachyonic sleptons $m_{\tilde{L}}^2 < 0$ in general!

$\Rightarrow$ add a non anomalous contribution to soft masses $c_i m_0^2$ to m_i^2

In minimal AMSB with a universal m_0, $c_i = 1$, the inputs are:

$$\mathbf{m_0}\ ,\ \mathbf{m_{3/2}}\ ,\ \tan\beta\ ,\ \mathrm{sign}(\mu) \ \mathrm{and}\ \mathbf{c_i}$$

2. The MSSM Higgs spectrum

In MSSM with two Higgs doublets $H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$ and $H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$.

- To cancel the chiral anomalies introduced by the new $\tilde{h}$ field.
- Give separately masses to d and u fermions in SUSY invariant way.

The terms contributing to scalar potential V_H come from 3 sources:

D terms (scalar inter.), F terms (Superpotential) and soft–SUSY breaking

$$V_H = \bar{m}_1^2|H_1|^2 + \bar{m}_2^2|H_2|^2 - \bar{m}_3^2\epsilon_{ij}(H_1^i H_2^j + \text{h.c.})$$
$$+ \frac{g_2^2+g_1^2}{8}(|H_1|^2 - |H_2|^2)^2 + \frac{1}{2}g_2^2|H_1^* H_2|^2$$

with $\overline{m}_1^2 = |\mu|^2 + m_1^2,\ \overline{m}_2^2 = |\mu|^2 + m_2^2,\ \overline{m}_3^2 = B\mu$

- Develop in terms of components $H_1 = (H_1^0, H_1^-)$,$H_2 = (H_2^+, H_2^0)$
- Now require $V_H{}^{\text{min}}$ breaks $G_{\text{SM}} \to U(1)_{\text{QED}}$ (neutral component).

$$\langle 0 | \text{Re}(H_1^0) | 0 \rangle = v_1,\ \ \langle 0 | \text{Re}(H_2^0) | 0 \rangle = v_2,\ \ \tan\beta = v_2/v_1,\ v_1^2 + v_2^2 = v^2$$

The relevant part of the scalar potential is then simply given by:

$$V_H = \overline{m}_1^2|H_1^0|^2 + \overline{m}_2^2|H_2^0|^2 + \overline{m}_3^2(H_1^0 H_2^0 + \text{hc}) + \frac{M_Z^2}{4v^2}(|H_1^0|^2 - |H_2^0|^2)^2$$

2. The Higgs spectrum: scalar potential

Some remarks on this scalar potential:

$$V_H = \overline{m}_1^2 |H_1^0|^2 + \overline{m}_2^2 |H_2^0|^2 + \overline{m}_3^2 (H_1^0 H_2^0 + \mathrm{hc}) + \frac{M_Z^2}{4v^2} (|H_1^0|^2 - |H_2^0|^2)^2$$

- **Quartic couplings fixed in terms of the gauge couplings, only 3 free parameters: $\overline{m}_1^2, \overline{m}_2^2, \overline{m}_3^2$ (6 para and a phase in a general 2HDM).**
- **$m_{1,2}^2 + |\mu|^2$ real, only $B\mu$ can be complex. But any phase in $B\mu$ can be absorbed in phases of $H_1, H_2 \Rightarrow V_H$ (MSSM) conserves CP.**
- **If $B\mu$ is zero, all other terms are positive and thus $V_H = 0$ only if $\langle H_1^0 \rangle = \langle H_2^0 \rangle = 0$. To have SSB (without CCB), we need $\overline{m}_{1,2,3} \neq 0$**

$\Rightarrow$ **Connection of gauge symmetry breaking and SUSY breaking!!**

More precisely: in SM, SSB takes place with ad hoc choice $\mu^2 < 0$.

In MSSM, $m_{H_i}^2 > 0$ at $M_{\rm GUT}$ but $t/\tilde{t}$ in RGE make $m_{H_i}^2 < 0$ at M_Z: radiative breaking of the electroweak symmetry (i.e. through RC).

$\Rightarrow$ **Symmetry breaking more natural and elegant than in SM.**

2. The Higgs spectrum: Higgs masses

To obtain the physical Higgs fields and their masses from potential V_H, develop $H_1 = \binom{H_1^0}{H_1^-}$ and $H_2 = \binom{H_2^+}{H_2^0}$ into real (CP-even+charged H) and imaginary (CP-odd H+Goldstones) and diagonalize 2×2 mass matrices

$$\mathcal{M}_{ij}^2 = \frac{1}{2} \partial^2 V_H / \partial H_i \partial H_j \big|_{\langle \mathrm{Re}(H_{1,2}^0) \rangle = v_{1,2}, \langle \mathrm{Im}(H_{1,2}^0) \rangle = 0, \langle H_{1,2}^\pm \rangle = 0}$$

The obtained physical masses and mixing angle are (see excercise):

$$M_A^2 = -\bar{m}_3^2 (\tan\beta + \cot\beta) = -2\bar{m}_3^2 / \sin 2\beta$$

$$M_{h,H}^2 = \frac{1}{2} \left[M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2)^2 - 4 M_A^2 M_Z^2 \cos^2 2\beta} \right]$$

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

The mixing angle α which rotates the CP-even fields ($-\frac{\pi}{2} \leq \alpha \leq 0$)

$$\tan 2\alpha = \frac{2\mathcal{M}_{12}}{\mathcal{M}_{11} - \mathcal{M}_{22}} = \frac{-(M_A^2 + M_Z^2) \sin 2\beta}{(M_Z^2 - M_A^2) \cos 2\beta} = \tan 2\beta \, \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}$$

While the mixing angle for the CP–odd and charged fileds is simply β.

2. The Higgs spectrum: Higgs masses

We have an important constraint on the lightest MSSM h boson mass:

$$\mathbf{M_h \leq \min(M_A, M_Z) \cdot |\cos 2\beta| \leq M_Z}$$

besides some other (also important) relations for H,A and $\mathrm{H^{\pm}}$:

$$\mathbf{M_H > \max(M_A, M_Z) \ \ \text{and} \ \ M_{H^\pm} > M_W}$$

If we send M_A to infinity, we will have for Higgs masses and α:

$$\mathbf{M_h \sim M_Z |\cos 2\beta| \ , \ M_H \sim M_{H^\pm} \sim M_A \ , \qquad \alpha \sim \frac{\pi}{2} - \beta}$$

This is the decoupling regime: all Higgses are heavy except for h.

The h boson is lighter than $\mathrm{M_Z}$ and should have been seen at LEP2

(we have $\sqrt{\mathrm{s}}_{\mathrm{LEP2}} \sim \mathbf{200\ GeV} \ > \mathrm{M_h + M_Z} \sim \mathbf{180}$ GeV).

So what happened in this case? Maybe the MSSM is already ruled out?

No! This relation holds only at first order (tree–level) and there are

strong couplings involved, in particular the htt and $\mathrm{h\tilde{t}\tilde{t}}$ couplings.

$\Rightarrow$ Calculation of radiative corrections to $\mathrm{M_h}$ necessary.

2. The Higgs spectrum: Higgs masses

Radiative corrections very important in the MSSM Higgs sector!

A large activity for the RC calculation in the last 15 years.

- **Dominant corrections are due to top (s)quark at one-loop level**

$$\Delta M_h^2 = \frac{3g^2}{2\pi^2}\frac{m_t^4}{M_W^2}\log\frac{m_{\tilde{t}}^2}{m_t^2}$$

It depends on m_t^4 and $\log(m_{\tilde{t}}^2/m_t^2)$, and is large: $\xrightarrow{M_h^{max} \to M_Z+40}$ GeV!

This explains why the h boson has not been observed at LEP2.

- **The full one–loop corrections have been calculated:**

– the parameters μ, A_t and A_b appear at the subleading level.

– the h boson mass is maximal (minimal) for $A_t \sim 2M_{\tilde{Q}}(0)$.

- **Approximate calculation for the dominant two–loop radiative corrections (in the effective potential approach; see SH again):**

– dominant QCD RC large but absorbed by $m_t|^{\rm pole} \to m_t|^{\overline{\rm MS}}$.

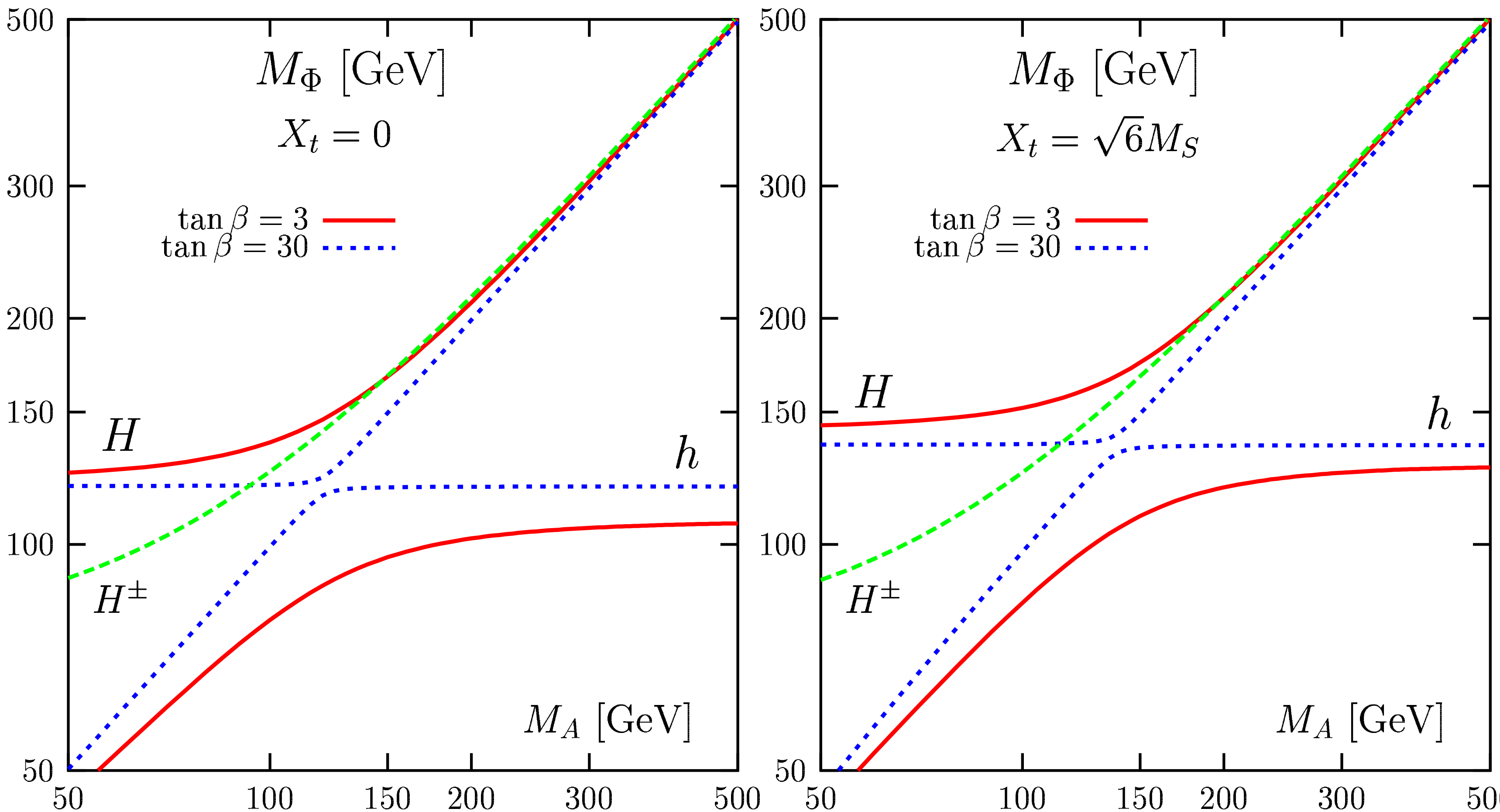
– Yukawa corrections rather small in the limit $M_h = 0$.

2. The Higgs spectrum: Higgs masses

- **Using full 1–loop and the 2–loop RC in effective potential approach:**

– $\mathcal{O}(\alpha_t \alpha_S)$: **including squark mixing and gluino loops.**

– $\mathcal{O}(\alpha_t^2)$: **including mixing and** $\mathcal{O}(\alpha_b \alpha_S), \mathcal{O}(\alpha_\tau \alpha_S)$.



3. SUSY spectrum and constraints

Determination of spectrum:

– RGEs (two loops, numerics)

– EWSB and $V_{\rm soft}$ (iterations)

– Masses, couplings, RC

Sophisticated RGE programs:

– example of SuSpect

(Kneur, Moultaka, AD)

– other programs also exist:

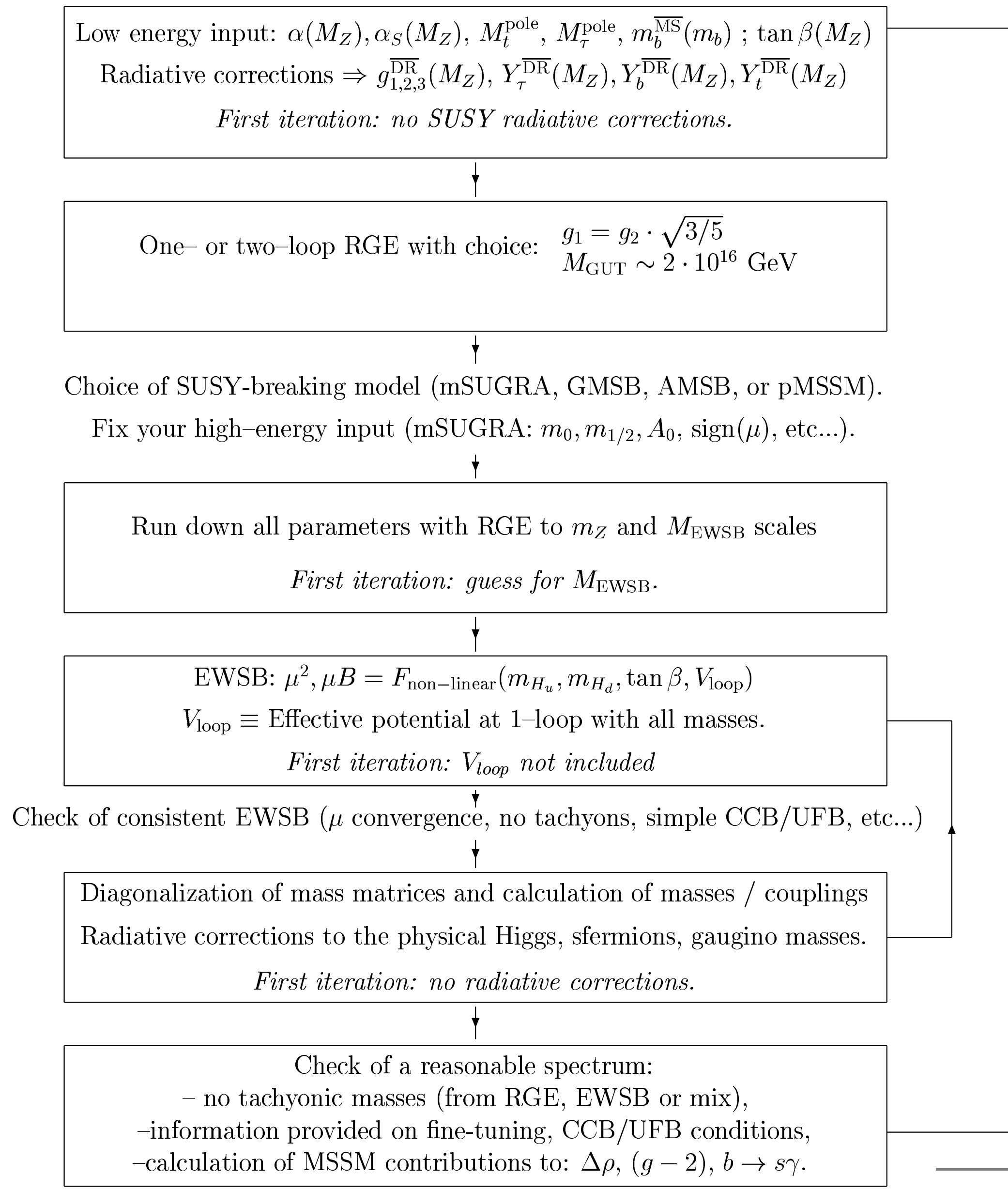
(Isajet, SoftSUSY, Spheno, ...)

Viable parameter space:

– choose inputs, param. scan

– impose known constraints

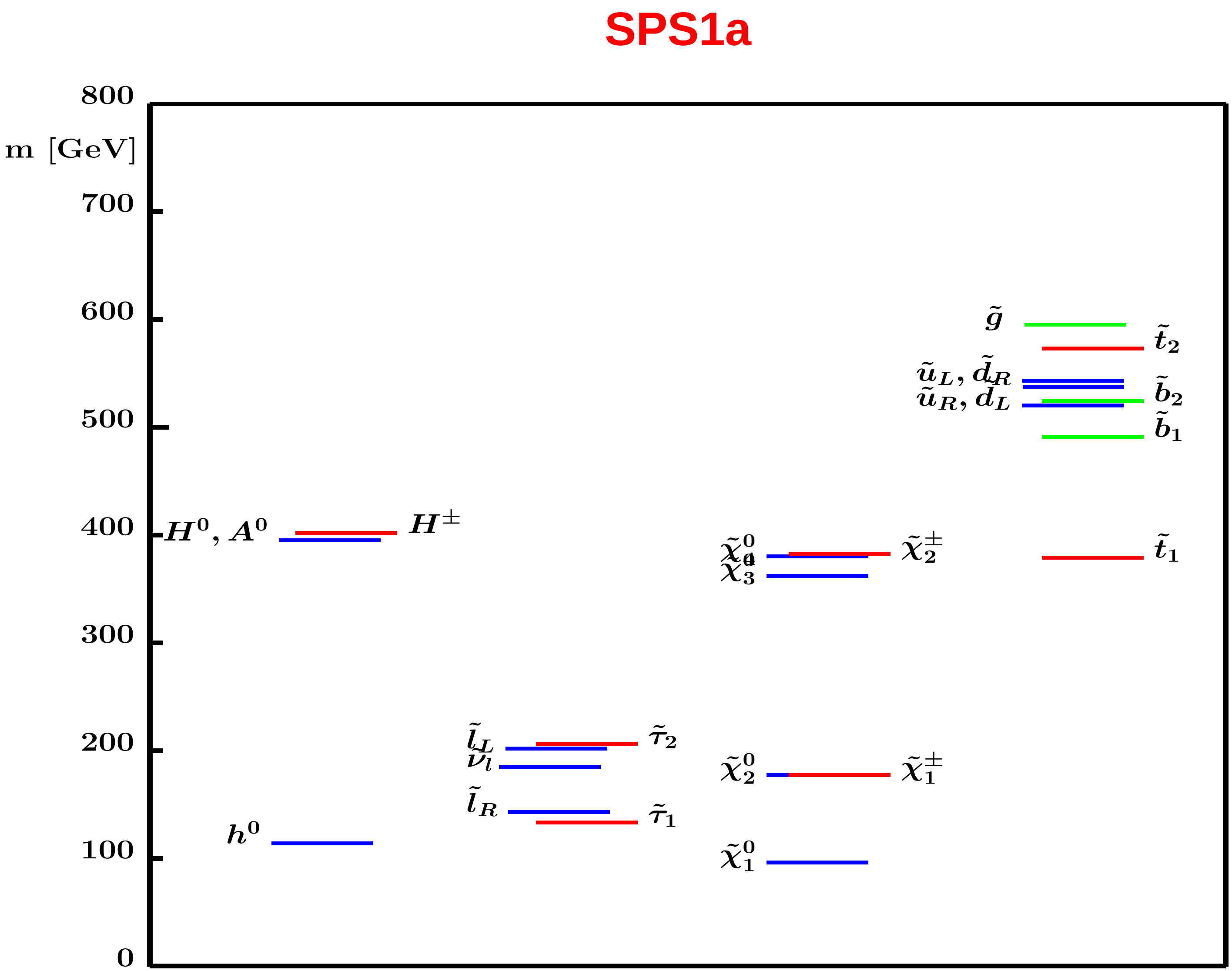
(Th, Experimental, DM, ...)



3. SUSY spectrum: Theoretical constraints

- **No RGE problems:**
  - **Perturbative couplings/No Landau poles**
  - **Non tachyonic sfermions (in particular for 3d generation)**
  - **Consistent unification of gauge couplings**
- **Proper implementation of EWSB:**
  - **Non tachyonic A boson or μ parameter**
  - **Convergent/stable value of μ after several iterations**
  - **Vacuum non CCB nor UFB**
- **Reasonnable SUSY spectrum:**
  - **Non tachyonic sfermions from mixing**
  - **Higgs masses not NaN**
  - **The LSP is the lightest neutralino χ_1^0**

3. SUSY spectrum: example of spectrum



3. SUSY spectrum: direct experimental constraints

Bounds from $\tilde{P}$ searches:

- **Bounds from LEPI/LEPII:**
  $m_{\tilde{\chi}_1^\pm} \gtrsim 104$ GeV
  $m_{\tilde{f}} \gtrsim 100$ GeV
  with $\tilde{f} = \tilde{t}_1, \tilde{b}_1, \tilde{l}^\pm, \tilde{\nu}$
- **Bounds from the Tevatron:**
  $m_{\tilde{g}} \gtrsim 300$ GeV
  $m_{\tilde{q}_{1,2}} \gtrsim 260$ GeV
  with $\tilde{q} = \tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}$
- **Possible refinements:**
  – **(almost) stable** χ_1^+ **at LEPII**
  – **degenerate** $\tilde{t}_1, \tilde{\tau}_1$ **with LSP**
  – $\tilde{t}_1$ **with large** Δm **at Tevatron**

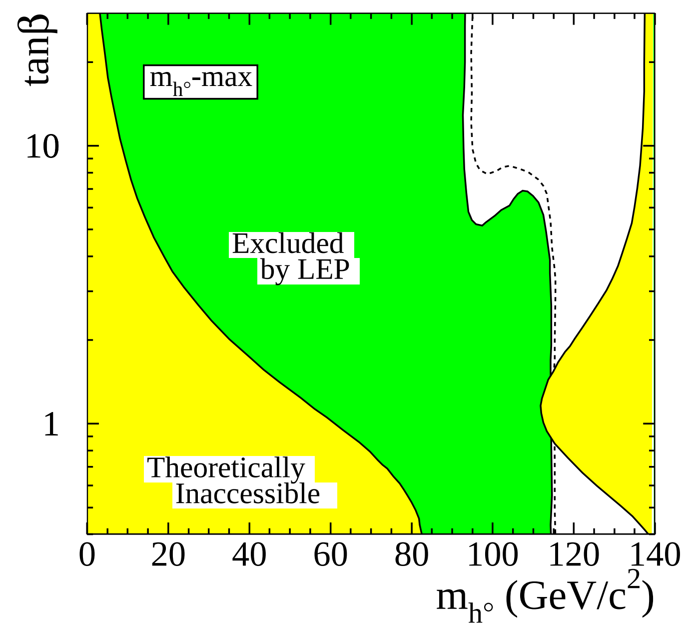
Bounds from Higgs searches at LEPII:

$M_A \gg M_Z \Rightarrow M_h > 114$ **GeV**

$M_A \sim M_Z \Rightarrow M_h, M_A \gtrsim 92$ **GeV**

– **Slightly depend on** m_t, H **mixing, ...**

– **Include a** $\Delta^{\rm th} M_h \sim 3$ **GeV error.**



(Excluded boundary to be fitted)

Note: include 1.7σ Higgs signal??

3. SUSY spectrum: indirect experimental constraints

- **High precision electroweak measurements: agree with SM**

  Large $(\tilde{t}, \tilde{b})$ mass splitting might generate large contributions:

  $\Delta^{\rm SUSY}\rho = \Pi_{ZZ}(0)/M_Z^2 - \Pi_{WW}(0)/M_W^2 \lesssim 2.2 \cdot 10^{-3}$

  (loose constraints from direct SUSY contributions to $Zb\bar{b}$ vertex)

- **The $(g-2)_\mu$ constraint: 2.5σ away from SM (only e^+e^- data)**

  Might be accounted for by $\tilde{\mu}$–χ^0 and $\tilde{\nu}_\mu$–$\chi^\pm$ loop contributions

  $1.06 \cdot 10^{-9} \leq \frac{1}{2} g_\mu^{\rm SUSY} \leq 4.36 \cdot 10^{-9}$

  (OK with SM if+ τ data: $-5.7 \cdot 10^{-10} \leq \frac{1}{2} g_\mu^{\rm SUSY} \leq 4.7 \cdot 10^{-9}$)

- **The $b \to s\gamma$ constraint: experimental value agrees with SM**

  Strong constraints on the t–$H^\pm$ and $\tilde{t}$–$\chi^\pm$ loop contributions

  $2.65 \cdot 10^{-4} \leq B(b \to s\gamma) \leq 4.45 \cdot 10^{-4}$

  (might be aleviated with a small amount of flavor violation)

- **The $b \to s\ell^+\ell^-$ constraint: not very stringent in mSUGRA yet**

3. SUSY spectrum: the dark matter constraint

- **WMAP measurement of temperature anisotropies in CMB, ...**

  $\Omega_{\rm DM}\, h^2 \simeq 0.113 \pm 0.009 \Rightarrow 0.09 \leq \Omega_{\rm DM}\, h^2 \leq 0.14$ **at 99% CL**

- **In the MSSM, LSP neutralino χ_1^0 is best candidate for CDM**

  – electrically neutral and (often maybe too) weakly interacting

  – stable if R–parity is conserved

  – massive: $m_{\chi_1^0} \gtrsim 50$ GeV in constrained models (mSUGRA)

- **Calculation of $\Omega_{\chi_1^0}\, h^2 \propto \langle v\sigma(\chi\chi \to {\rm SM\, part.})\rangle^{-1}$ complicated:**
  - **Many final states ($\Phi = h, H, A, H^{\pm}$; $f = \ell, q; V = W, Z, \gamma$)**

    $$\chi_1^0\chi_1^0 \to f\bar{f}, VV, \Phi_i\Phi_j, \Phi_i V \;\; {\rm etc....}$$

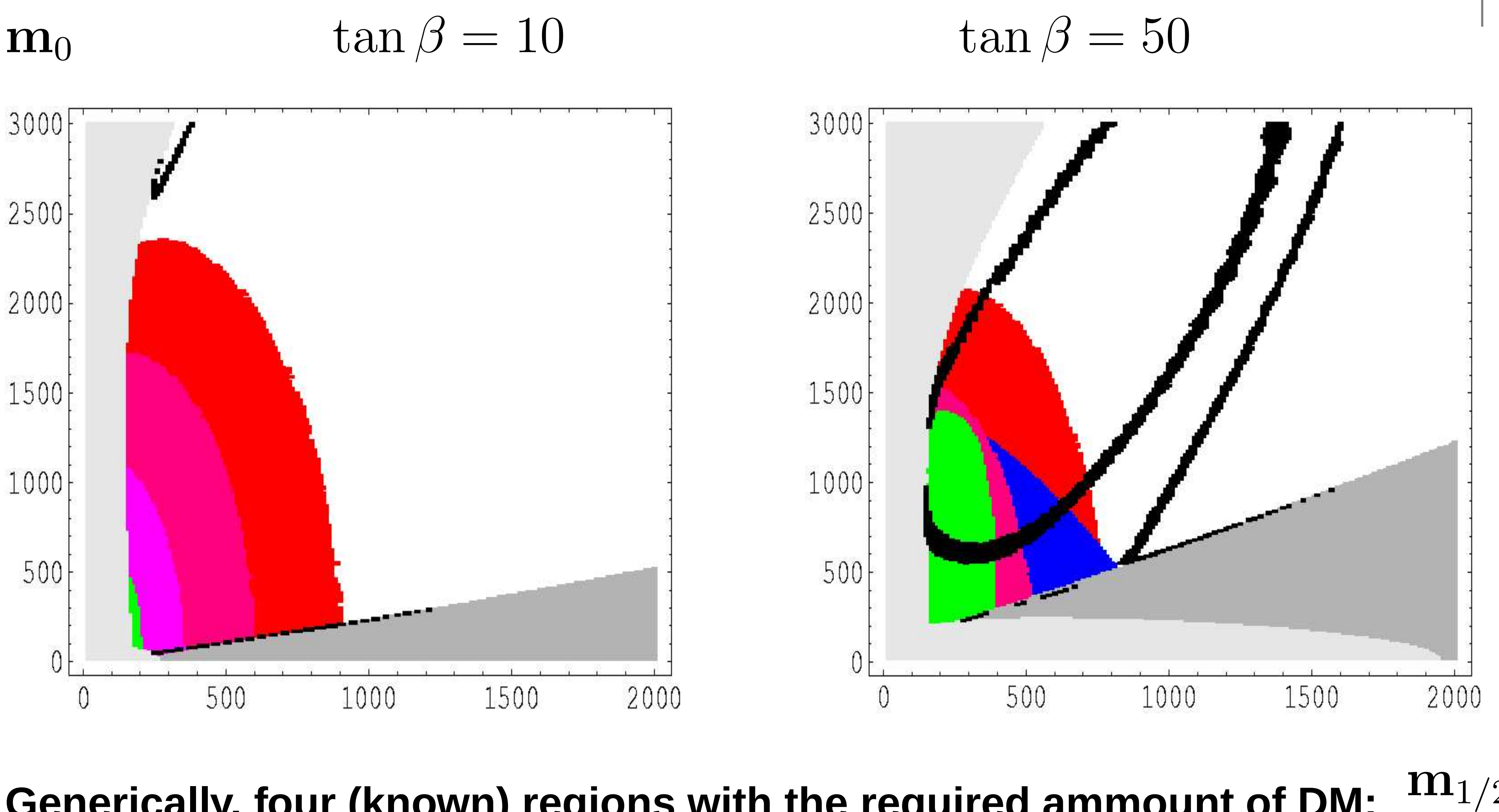
  - **Several channels are present; for example in $\chi_1^0\chi_1^0 \to f\bar{f}$:**
    t–channel $\tilde{f}$, s–channel Z and s–channel A, h, H exchanges

  - **Co-annihilation processes with NLSP taken into account:**

$$\chi_1^0 + \tilde{P} \to X + Y \;\; {\rm and} \;\; \tilde{P} + \tilde{P}^{(*)} \to X + Y \;\; {\rm if}\; m_{\tilde{P}} \sim m_\chi$$

3. SUSY spectrum: an example of a scan

An $(m_{1/2}, m_0)$ scan with $A=0, \mu>0, m_t=172.5$ GeV:

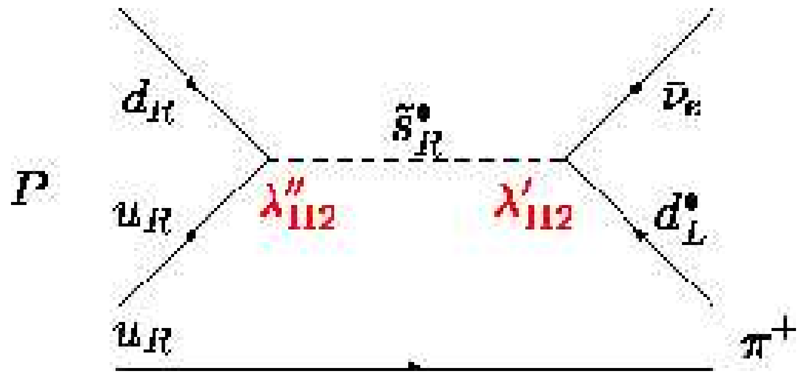


Generically, four (known) regions with the required ammount of DM:

bulk region (excluded), focus point, co-annihilation, A/h pole regions

4. Extensions of MSSM: Rp violation

To avoid fast P decay, we do not need both L and B conservation



In most general W, include ΔL=1 or ΔB=1 interactions:

$$\mathbf{W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{e}_k + \lambda'_{ijk}L_iQ_j\bar{d}_k + \mu'_iL_iH_u}$$
$$\mathbf{W_{\Delta B=1} = \frac{1}{2}\lambda''_{ijk}\bar{u}_i\bar{d}_j\bar{d}_k}$$

P decay modes and experimental limits on $\not{B}$ and $\not{L}$ imply $\lambda^{','',}_{ijk} \ll 1$.

- **However, at least 45 new parameters in the general case.**
- **no stable LSP and thus no SUSY DM candidate...**
- **But, rich phenomenology (e.g. s channel sfermion production)**
- **enters in neutrino phenomenology and adresses small ν masses**

4. Extensions of the MSSM: CP violation

One can allow for some CP–violating parameters, in particular:

- **Complex M_1, M_2, M_3 (some phases rotated away) and μ**
- **Complex trilinear A_f couplings, in particular A_f.**

The MSSM Higgs sector stays CP–conserving at the tree–level but complex parameters enter at the one–loop level through μ and A_t.

- **CP violation is needed for (direct) baryogenesis in MSSM**
- **However, many new parameters will enter in the general case**
- **Complicates the determination of spectrum but less fine-tunning!**
- **Strongly constrained by data ($n_{\rm edm}$..) and needs cancelations**
- **No sign yet of any additionnaly from $\not{C}P$ in B–factories etc...**

One can also allow for flavor non–diagonal interactions, howver:

- **Parameters strongly constrained from FCNC, K, B physics...**
- **Only adds complications/parameters (no theory motivation)...**

4. Extensions of the MSSM: NMSSM

The μ problem: μ enters EWSB and the determination of $\mathrm{M_Z}$.

It must be of order SUSY–breaking parameters such as $\mathrm{M_{H_1}}, \mathrm{M_{H_2}}$.

But μ is a SUSY preserving parameter, comes from $\mathbf{W} \propto \mu \hat{\mathbf{H}}_1 \hat{\mathbf{H}}_2$,

and, a priori, no reason for having $\mu \propto \mathrm{M_Z}, \mathrm{M_{SUSY}} \ll \mathrm{M_{GUT}}$....

Solution: μ is related to a vev of an additional field S with $\langle S \rangle = s$

NMSSM: introduce a gauge singlet superfield $\hat{S}$ into superpotential

$$\mathbf{W} = \mathbf{W}_{\mathrm{MSSM}} + \lambda \hat{\mathbf{H}}_1 \hat{\mathbf{H}}_2 \hat{\mathbf{S}} + \frac{1}{3} \kappa \hat{\mathbf{S}}$$

Extended spectrum in NMSSM compared to MSSM:

- **one additional neutralino state: $\Rightarrow \chi^0_{1,\ldots,5}$**
- **two additional Higgs particles $\Rightarrow \mathbf{H_1}, \mathbf{H_2}, \mathbf{H_3},\ \mathbf{A_1}, \mathbf{A_2},\ \mathbf{H^+}, \mathbf{H^-}$**

$\Rightarrow$ less constrained and fine tuned model, richer phenomenology...

Ex: upper bound on h mass is $\mathrm{M_h^{NMSSM}} = \mathrm{M_h^{MSSM}} + 20$–40 GeV.

LEP searches bounds are not valid and h lighter than 100 GeV.

4. Extensions of the MSSM: ESSM

An even more extended model with richer phenomenology is the E_6SSM

– based on low–energy matter content of 27 repr. of the E_6 group

– there are also two additional non Higgs scalar doublets.

It has a very elegant solution to the μ problem of the MSSM

$$\mathbf{E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\psi \times U(1)_\chi \to G_{\rm SM} \times U(1)'}$$

extra U(1)' allows for $\lambda \mathbf{S H_1 H_2}$ interaction which generates effective μ

The model has very nice features:

– gives a solution to the μ problem with less fine-tuning as in NMSSM

– gauge coupling unification at $M_{\rm GUT}$ with a reasonable α_s value

– a full unification of all forces including gravity possible is at M_P

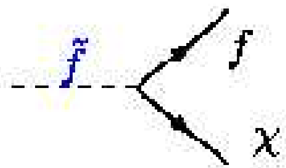
.... and very rich phenomenology:

– extended Higgs sector and possibility of a light Z' gauge boson

– extra light matter in anomaly representation of dimension 27 of E_6

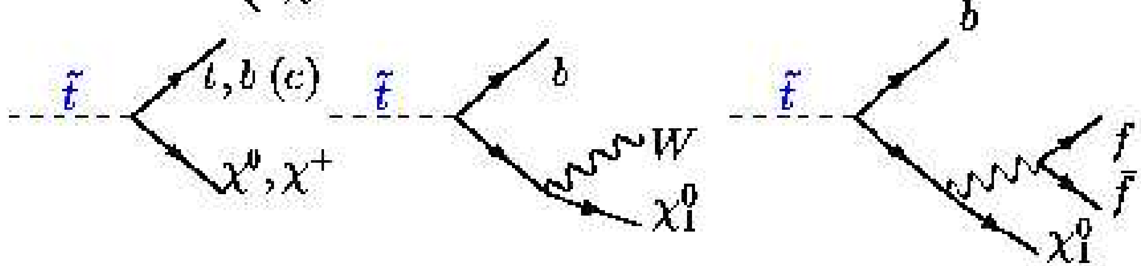
5. Decays and Production of sparticles

Squarks and Sleptons

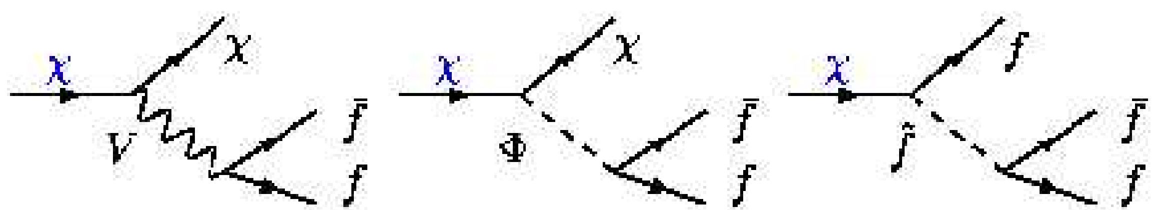


$f \equiv \ell, q = u, d, s, c$ and $Q = t, b$

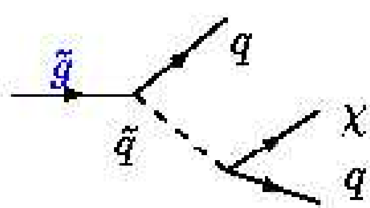
$\chi \equiv \chi_i^0, \chi_i^\pm, \tilde{g}$



Charginos and neutralinos



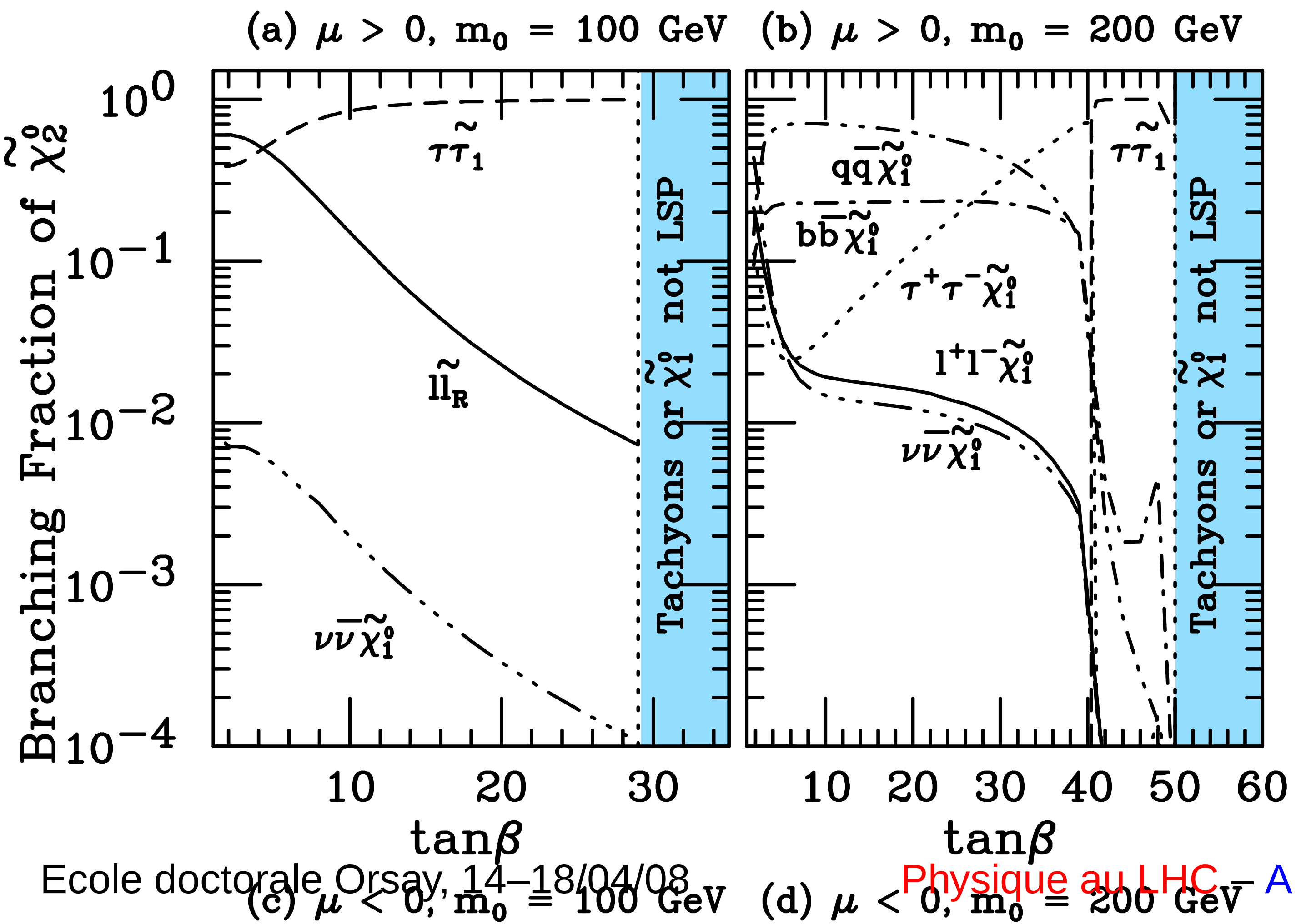
Gluinos



5. Decays: possible decays of sparticles

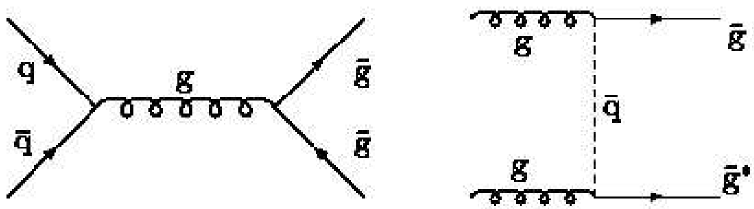
- Possibility of cascade decays: $\tilde{q} \to q + \chi_2^0 \to q + \chi_1^0 f\bar{f}$.
- Signature in usual MSSM: $\not{E}_T$ from escaping χ_1^0 LSPs.
- In GMSB, signature is due to NLSP $(\chi_1^0, \tilde{\tau}_1) \to \tilde{G} + (\gamma, \tau)$.

Example of final state decay in mSUGRA: χ_2^0

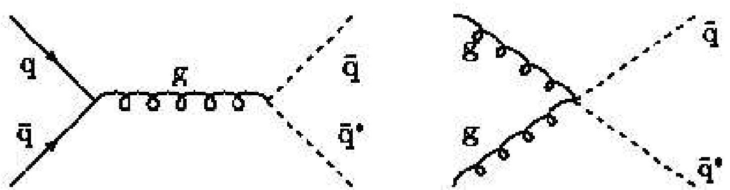


5. Production of SUSY particles

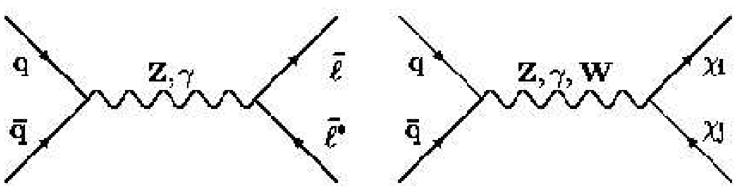
- **Gluino production**



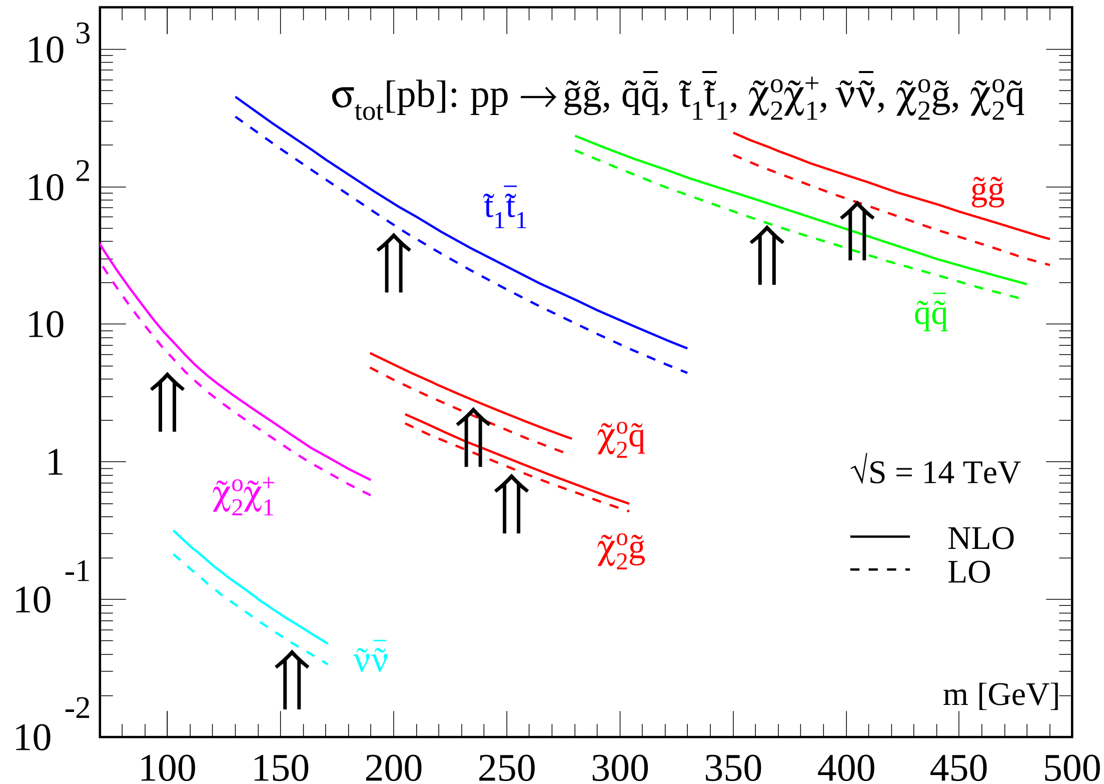
- **Squark production**



- **$\chi/\tilde{\ell}$ production**

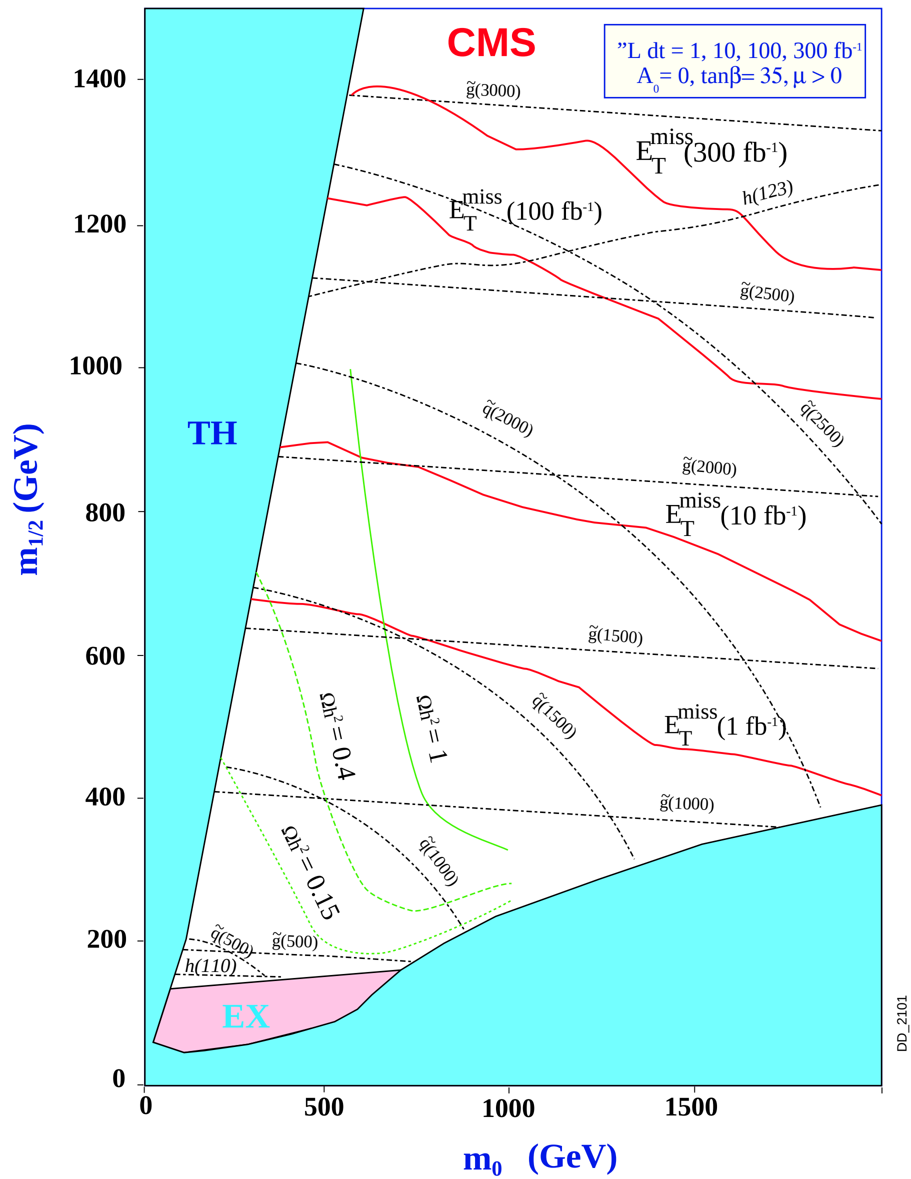


Cross sections at the LHC



5. Sparticle discovery reach at the LHC

The CMS $\tilde{q},\tilde{g}$ mass reach in E_T^{miss} + jets inclusive channel for various integrated luminosities



6. SUSY Higgs Decays and Production

Higgs decays (and cross sections) strongly depend on couplings

Couplings in terms of $\mathrm{H_{SM}}$ and their values in decoupling limit:

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\sin\alpha}{\cos\beta} \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\frac{\sin\alpha}{\sin\beta} \to 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$	0

– **The couplings of $H^{\pm}$ have the same intensity as those of A.**

– **Couplings of h, H to VV are suppressed; no AVV couplings (CP)**

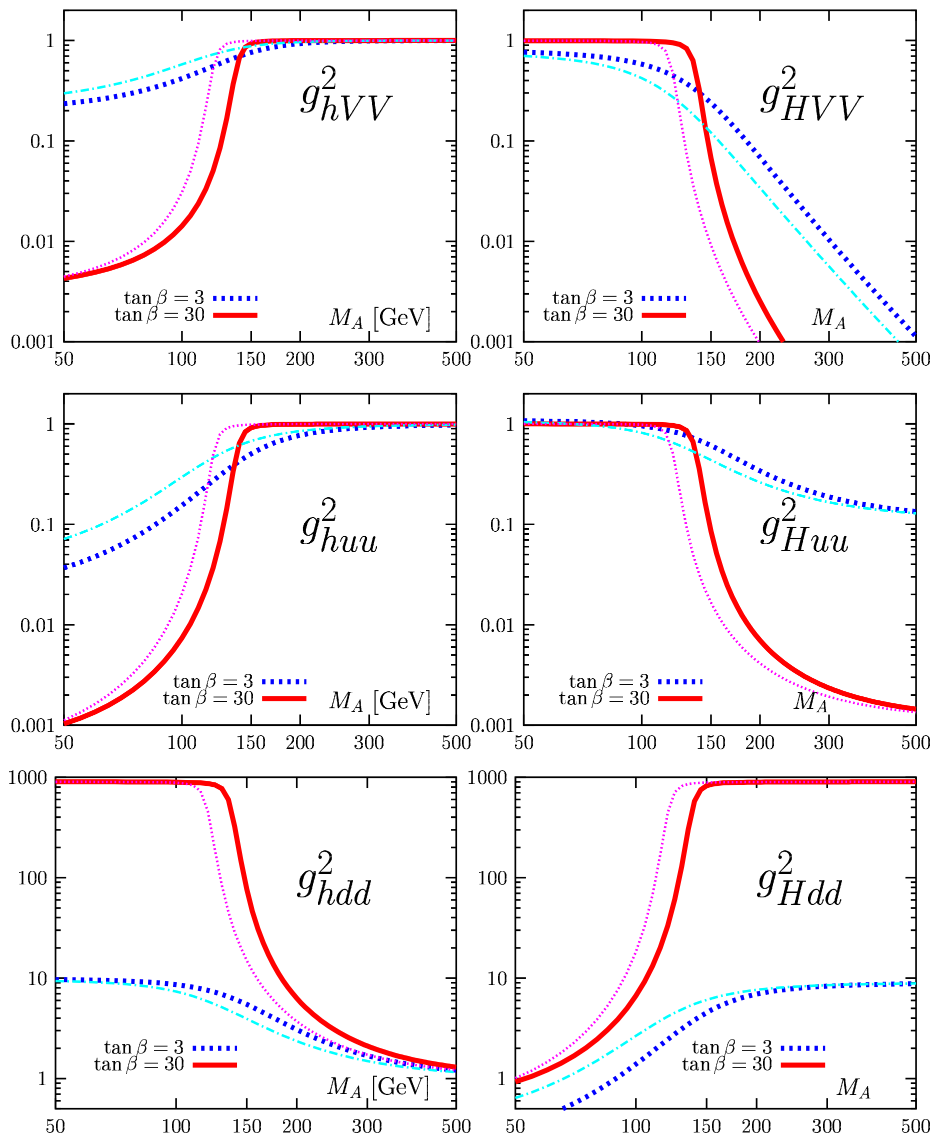
– **For $\tan\beta > 1$: cplgs to d enhanced, cplgs to u suppressed.**

– **For $\tan\beta \gg 1$: couplings to b quarks b ($m_b \tan\beta$) very strong.**

– **For $M_A \gg M_Z$: h couples like the SM Higgs boson and H like A.**

6. Higgs decays: SUSY Higgs couplings

Including radiative corrections just as in the case of the Higgs masses:



6. Higgs decays: channels

General features in Higgs decays

- h: **same as $H_{\rm SM}$ in general (in particular in decoupling limit)**

  $h \to b\bar{b}$ **and** $\tau^+\tau^-$ **potentially enhanced (**$\tan\beta \gtrsim 3$**).**
- A: **only** $b\bar{b}, \tau^+\tau^-$ **and** $t\bar{t}$ **decays (no** VV, hZ **suppressed).**
- H: **same as** A **in general** $(WW, ZZ, hh$ **decays suppressed).**
- $H^\pm$: $\tau\nu$ **and** tb **decays (depending if** $M_{H^\pm} < $ **or** $> m_t$**).**

Possible new effects

– Although suppressed, decays into $V\Phi$ **and/or** VV **possible.**

– 3–body decays important ($h \to WW^*, H/A \to tt^*, H^+ \to tb^* ...)$

– SUSY particle loops might be important ($h/A/H \to b\bar{b}, h \to gg)$**.**

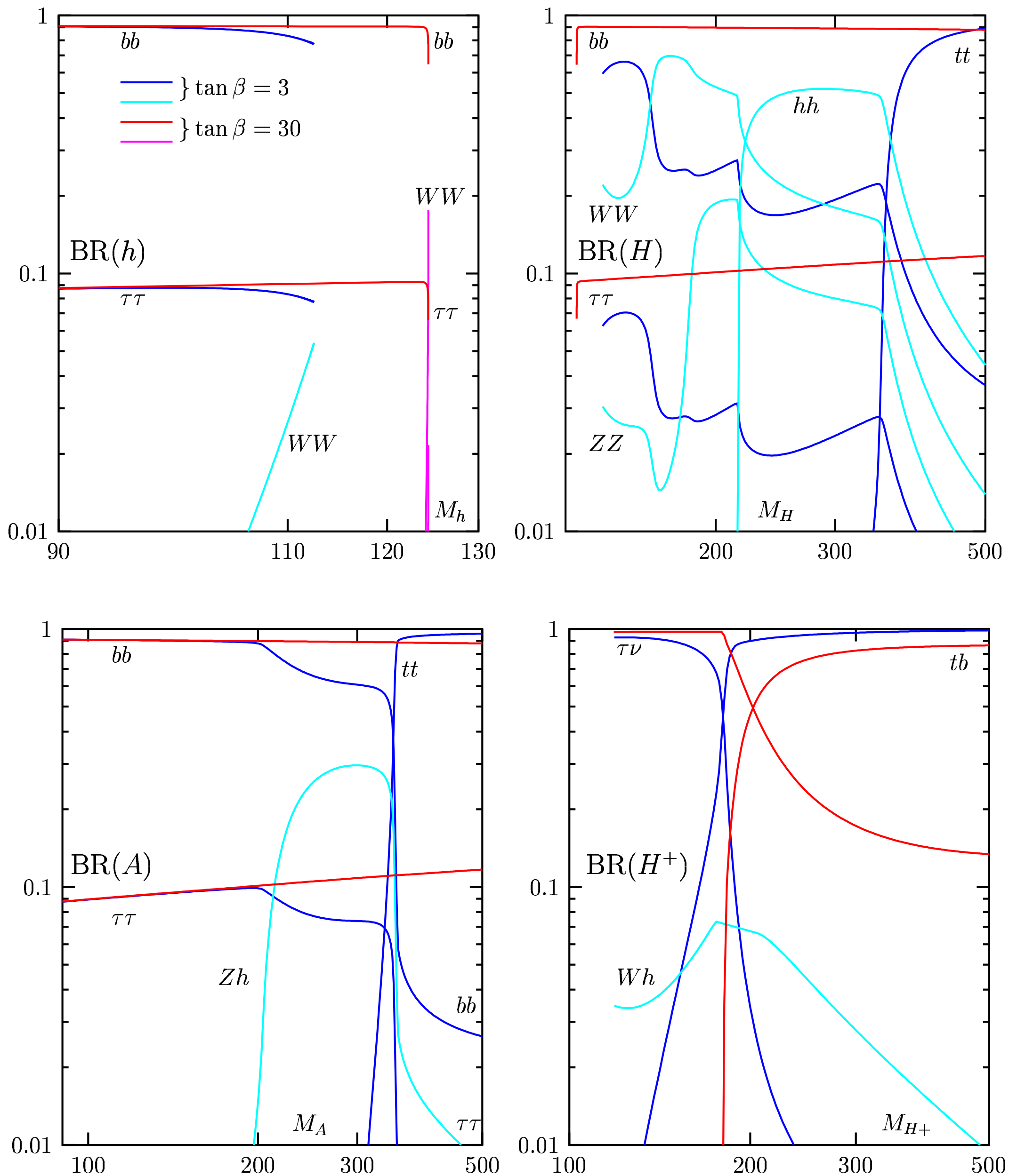
– Decays into sparticles if kinematically allowed significant:

$h \to \chi_1^0\chi_1^0$ **still possible in non universal MSSMs.**

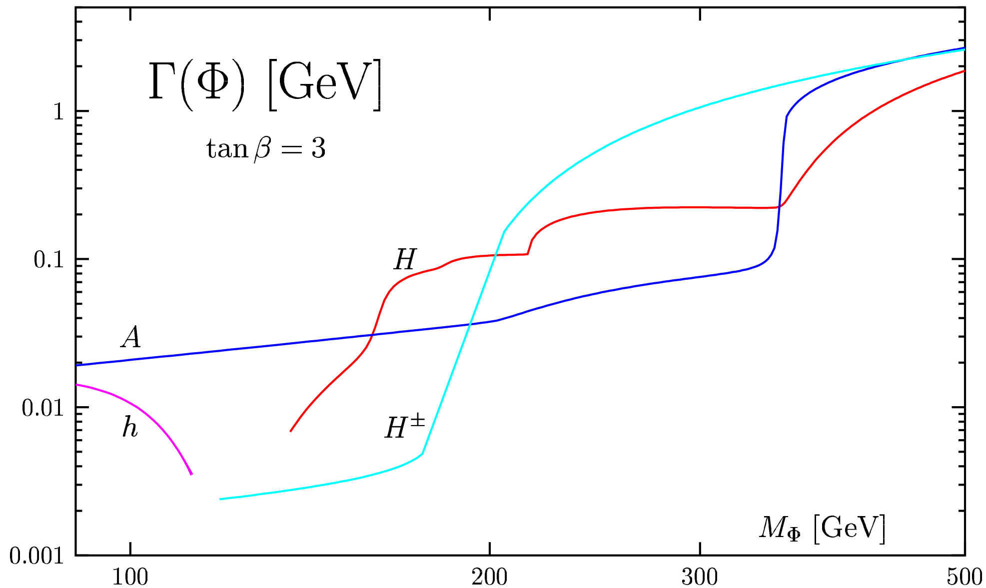
$H, A \to \chi_i^+\chi_j^-, \chi_i^0\chi_j^0$ **and** $H^\pm \to \chi_i^0\chi_j^\pm$ **important for low** $\tan\beta$**.**

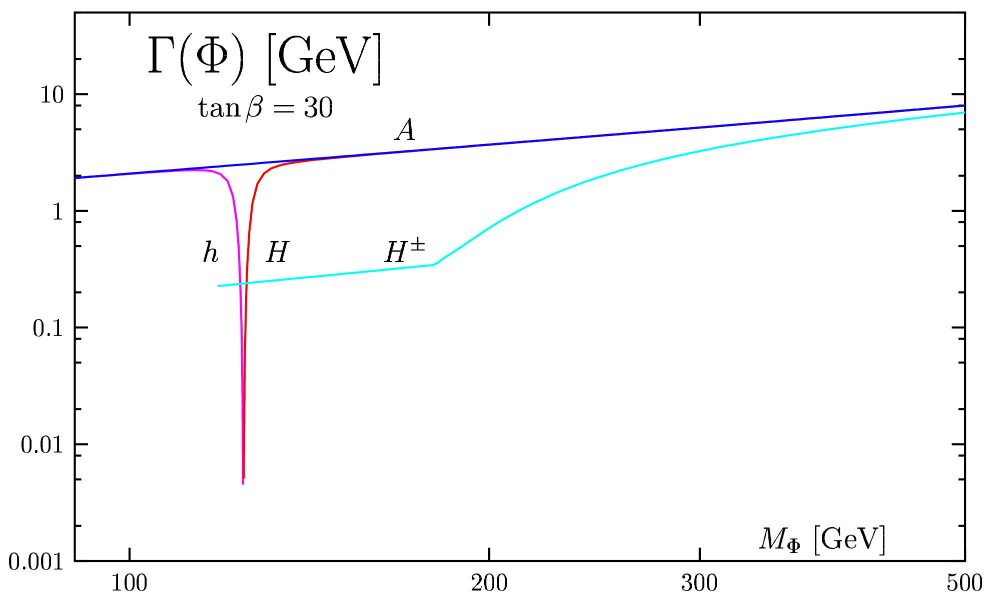
Total decay widths: Small compared to SM (no V_L **contribution).**

6. Higgs Decays: BRs



6. Higgs decays: total widths

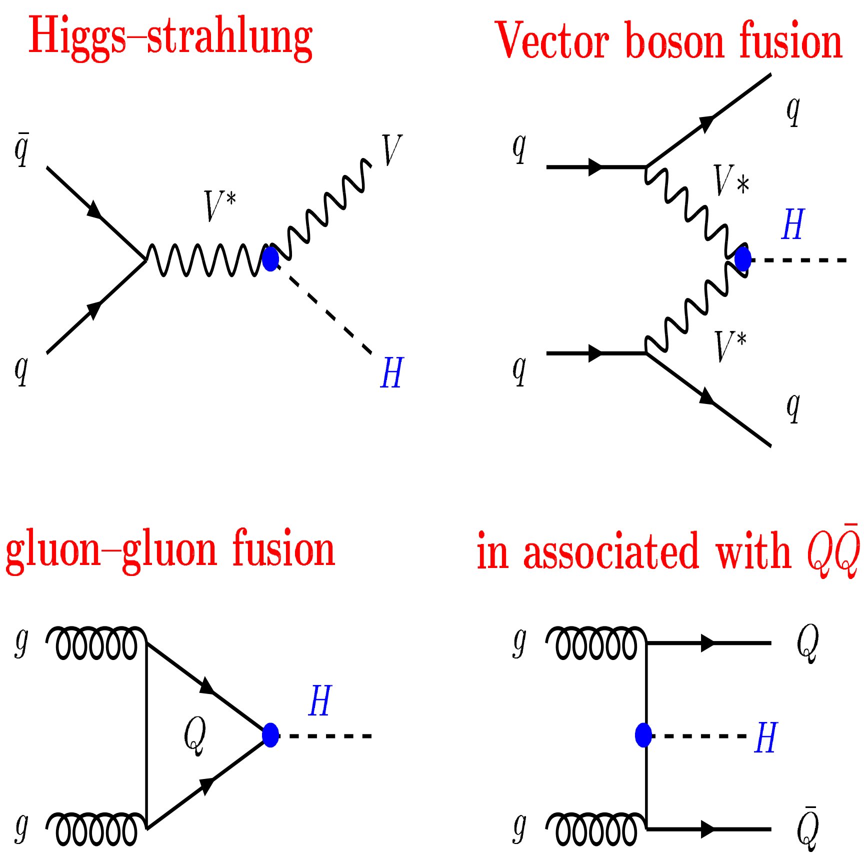




6. Higgs production at LHC

SM production mechanisms

[assuming heavy sparticles]



What is different in MSSM

- **All work for CP–even h,H bosons.**

– in ΦV, $qq\Phi$ h/H complementary

– $\sigma(\mathbf{h}) + \sigma(\mathbf{H}) = \sigma(\mathbf{H_{SM}})$

– aditionnal mechanism: q$\bar{q}\rightarrow$A+h/H

- **For $gg \rightarrow \Phi$ and $pp \rightarrow tt\Phi$**

– include the contr. of b–quarks

– dominant contr. at high $\tan\beta$!

- **For pseudoscalar A boson:**

– CP: no ΦA and qqA

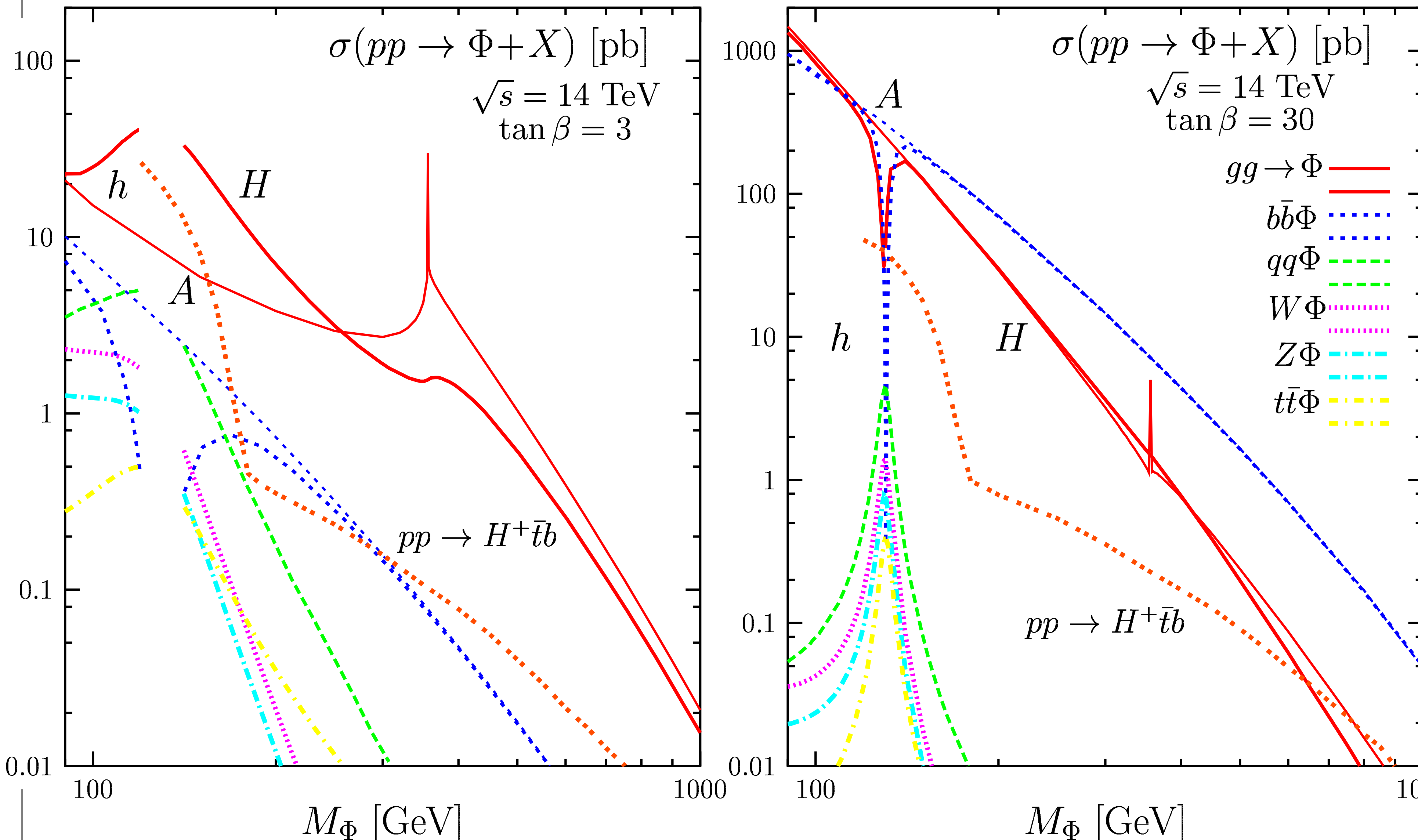
– $gg \rightarrow A$ and $pp \rightarrow bbA$ dominant.

- **For charged Higgs boson:**

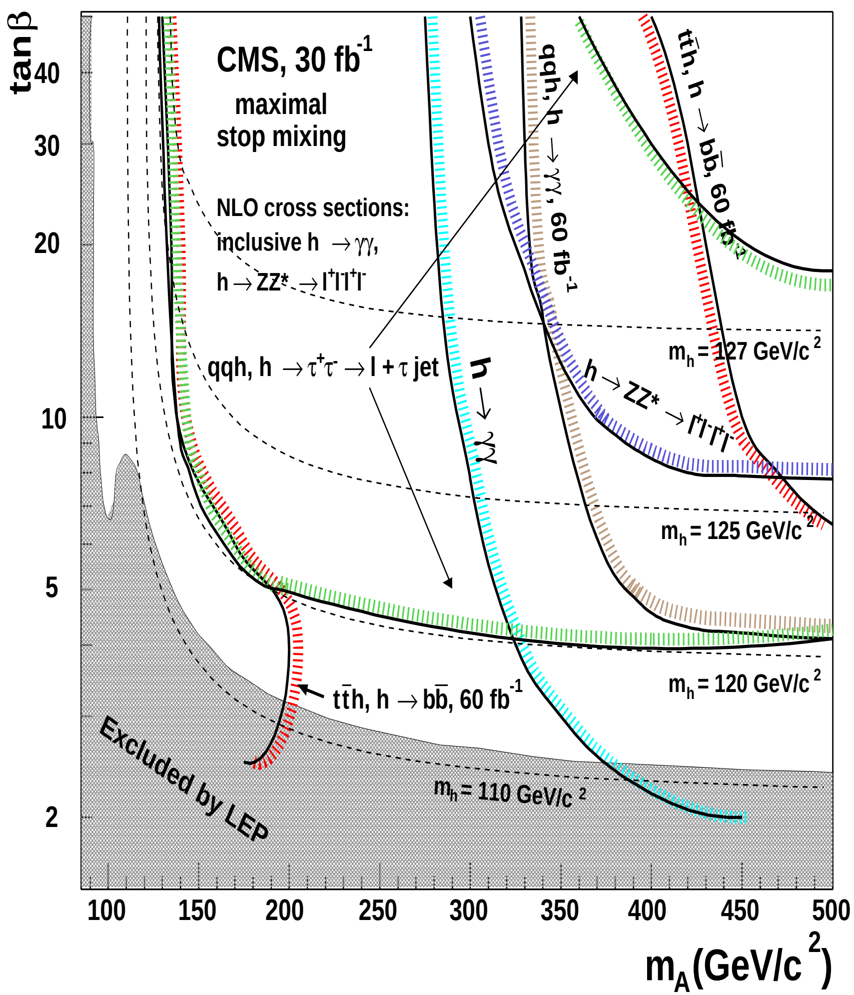
– $M_H \lesssim m_t$: $pp \rightarrow t\bar{t}$ with $t \rightarrow H^+b$

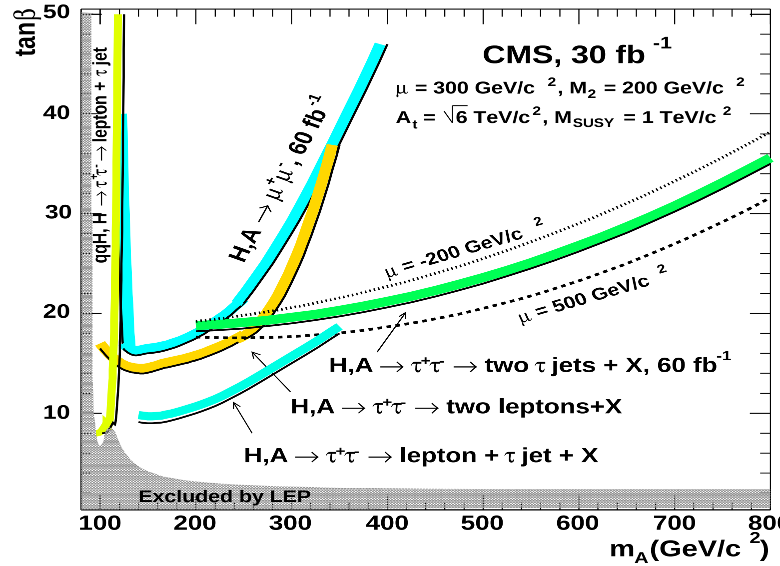
– $M_H \gtrsim m_t$: continuum $pp \rightarrow t\bar{b}H^-$

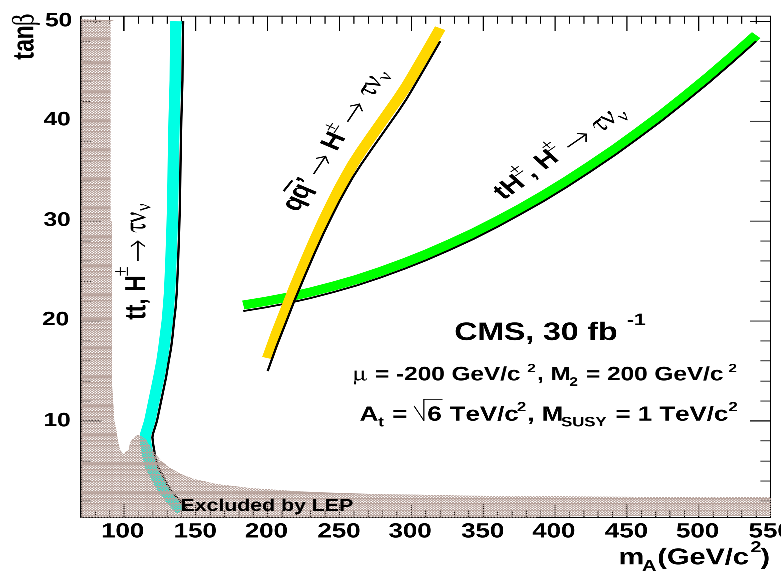
6. Higgs production: cross sections



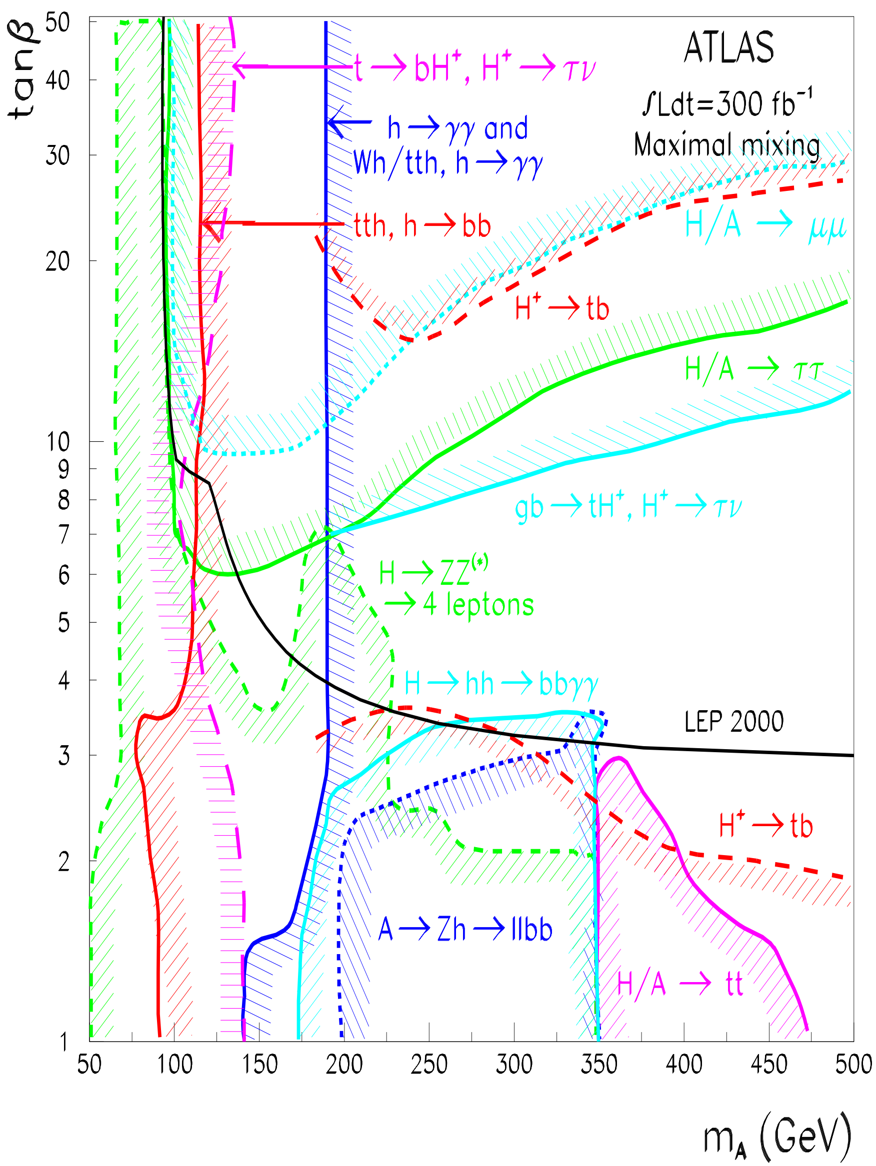
6. Higgs production: detection

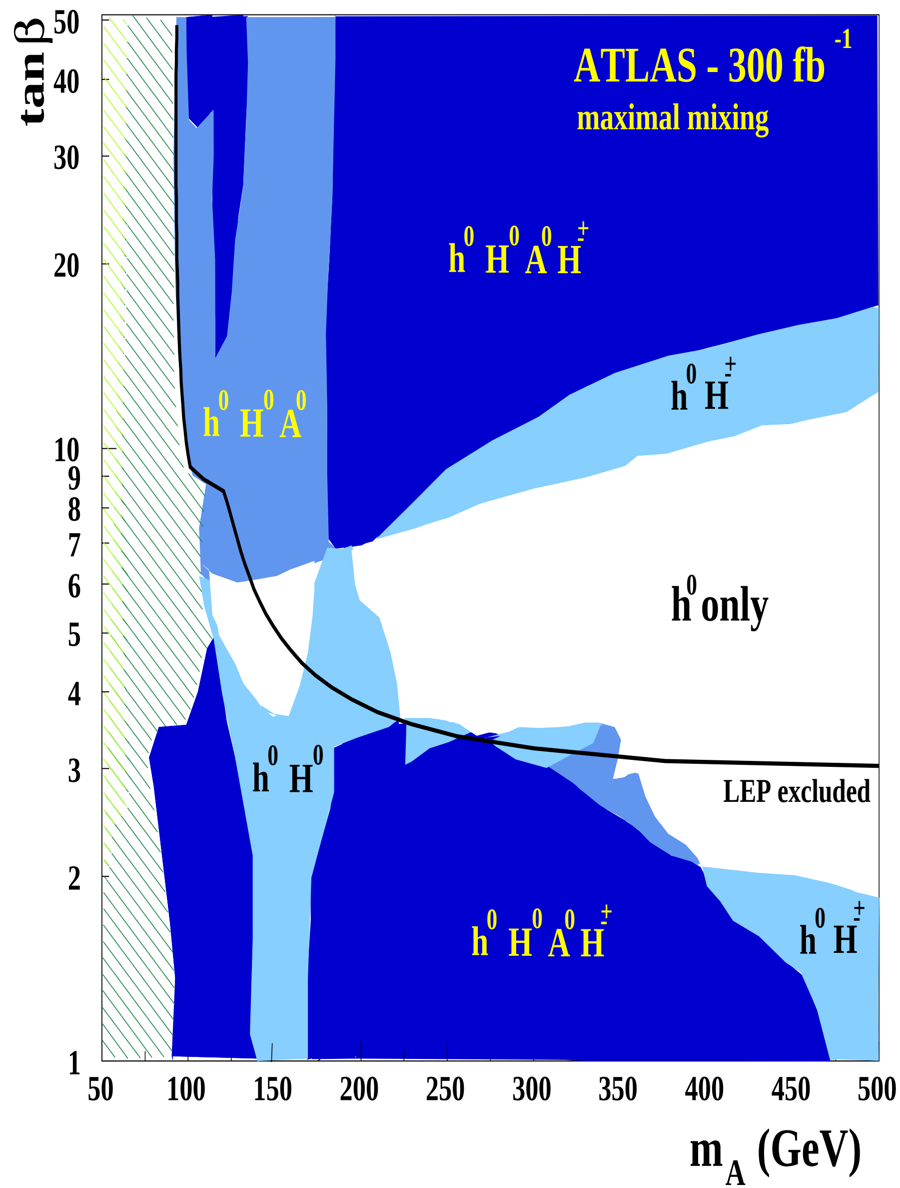






6. Higgs production: detection





7. Higgs in non minimal scenarios

However: life can be much more complicated even in the MSSM

- **There are scenarii where searches are different from the SM case:**

– The intense coupling regime: h,H,A almost mass degenerate....

- **SUSY particles might play an important role in production/decay:**

– light $\tilde{t}$ loops might make $\sigma(gg \to h \to \gamma\gamma)$ smaller than in SM.

– Higgsses can be produced with sparticles ($pp \to \tilde{t}\tilde{t}^* h$,..).

– Cascade decays of SUSY particles into Higgs bosons....

- **SUSY decays, if allowed, might alter the search strategies:**

– $h \to \chi_1^0 \chi_1^0, \tilde{\nu}\tilde{\nu}$ are still possible in non universal models...

– Decays of $A, H, H^{\pm}$ into $\chi_i^{\pm}, \chi_i^0$ are possible but can be useful...

Life can be even more complicated in extensions of the MSSM

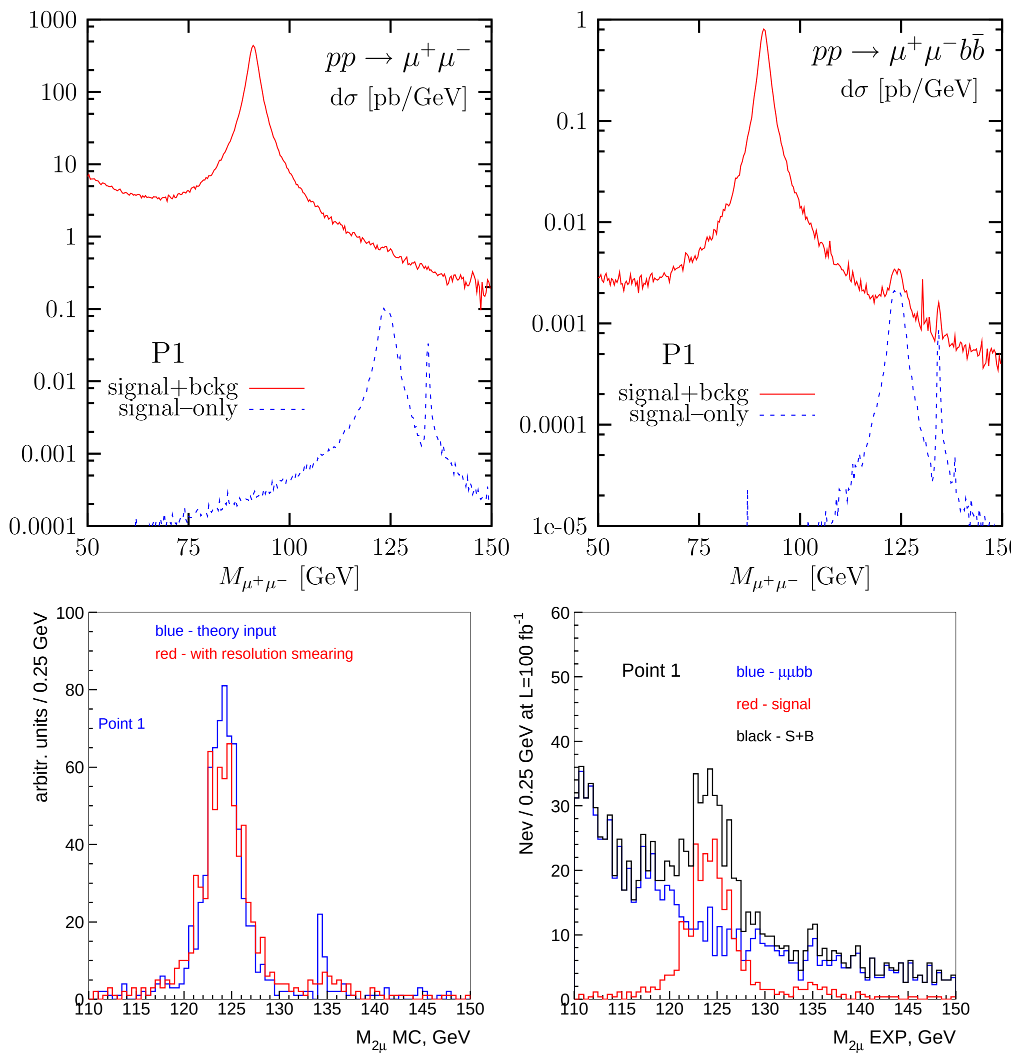
- **CP violation in the Higgs sector which changes the spectrum.**
- **NMSSM with an additional Higgs singlet and difficult Higgs decays.**

Be prepared for the unexpected!

7. Higgs in non minimal scenarios

- **There are scenarii where searches are different from the SM case:**

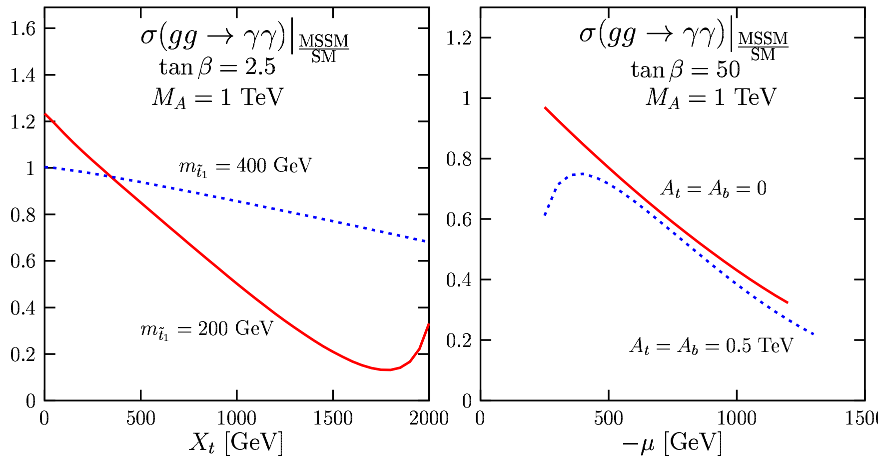
– The intense coupling regime: h,H,A almost mass degenerate....



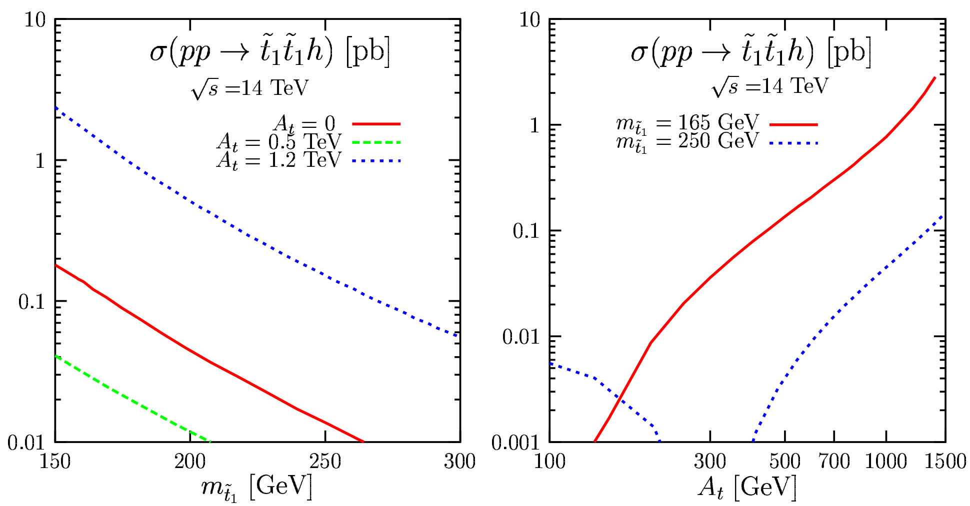
7. Higgs in non minimal scenarios

- **SUSY particles might play an important role in production/decay:**

– light $\tilde{t}$ loops might make $\sigma(gg \to h \to \gamma\gamma)$ smaller than in SM.



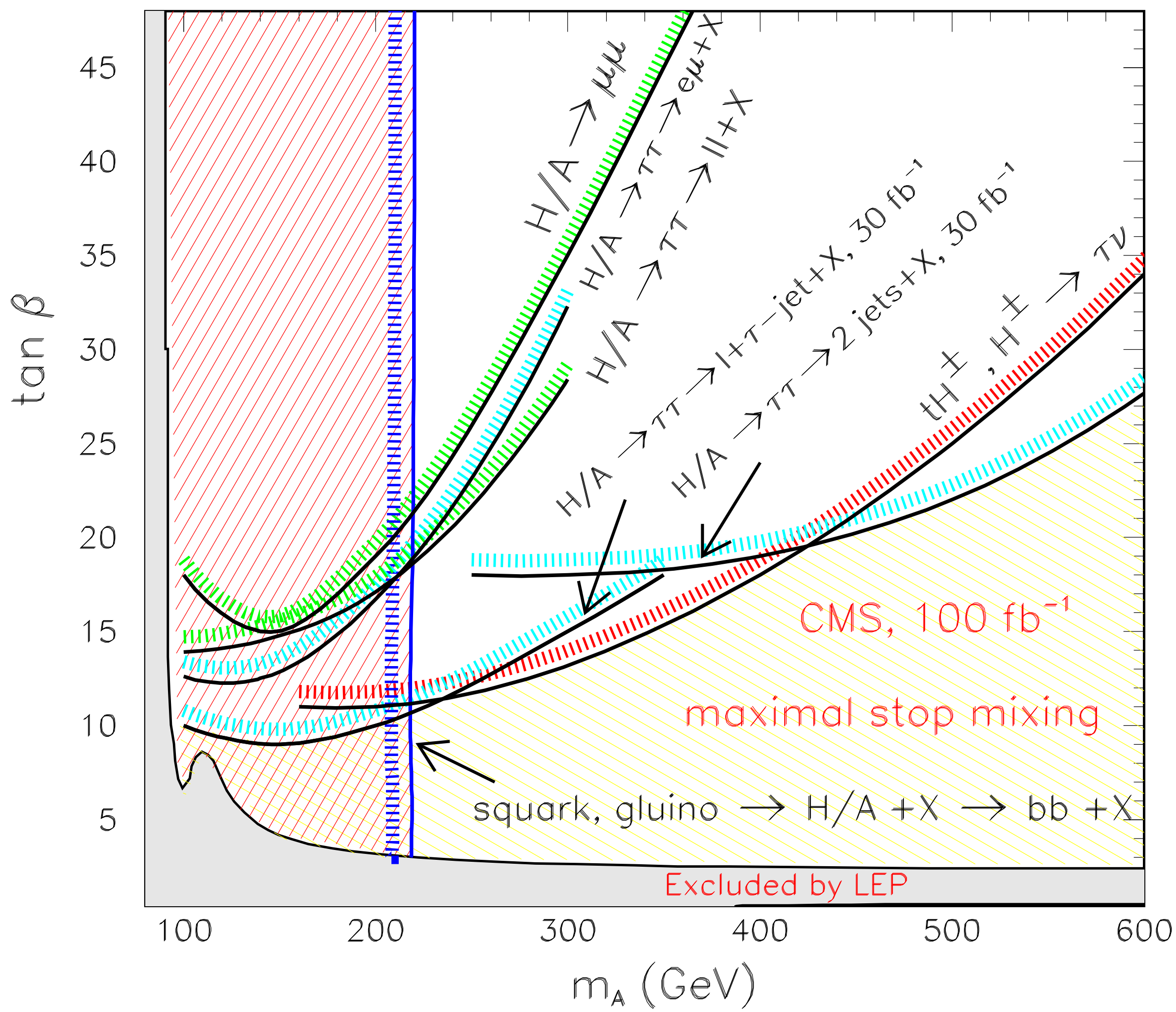
– Higgsses can be produced with sparticles ($pp \to \tilde{t}\tilde{t}^{*}h$,..).



7. Higgs in non minimal scenarios

- **SUSY particles might play an important role in production/decay:**

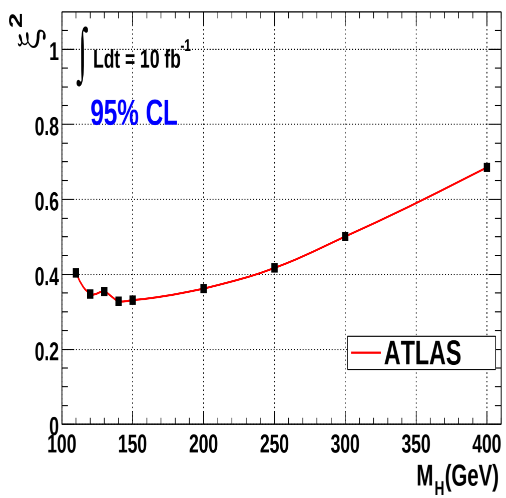
– Cascade decays of SUSY particles into Higgs bosons....

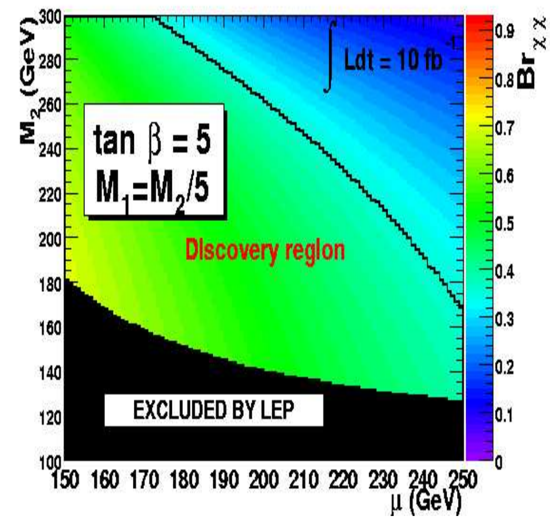


7. Higgs in non minimal scenarios

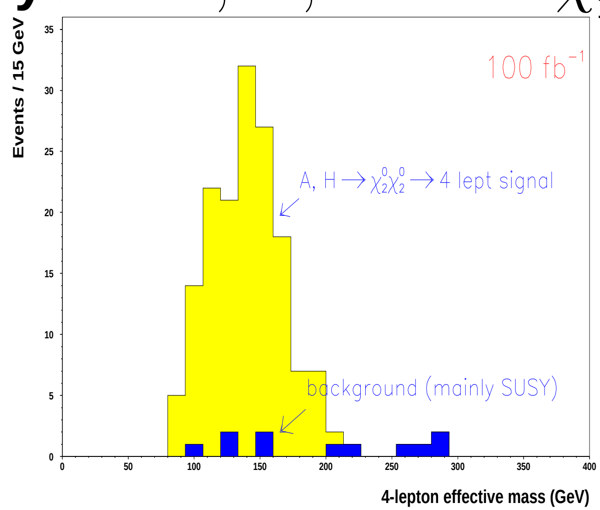
- **SUSY decays, if allowed, might alter the search strategies:**

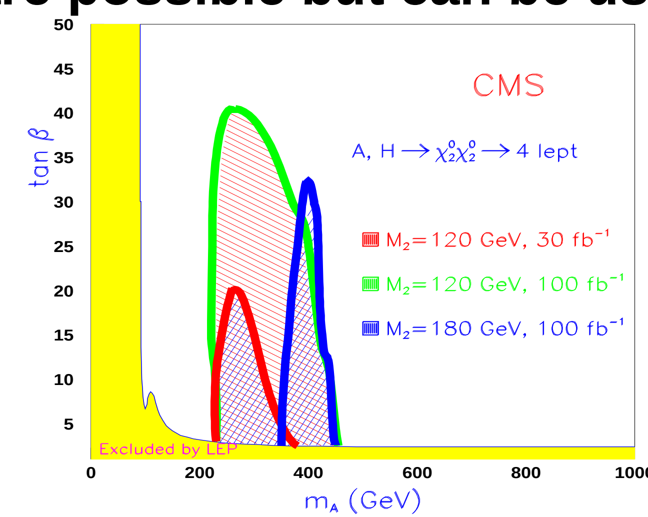
– $\mathrm{h} \to \chi_1^0 \chi_1^0, \tilde{\nu}\tilde{\nu}$ **are still possible in non universal models...**





– **Decays of** $\mathrm{A}, \mathrm{H}, \mathrm{H}^\pm$ **into** $\chi_i^\pm, \chi_i^0$ **are possible but can be useful...**





7. Higgs in non minimal scenarios: CP–violation

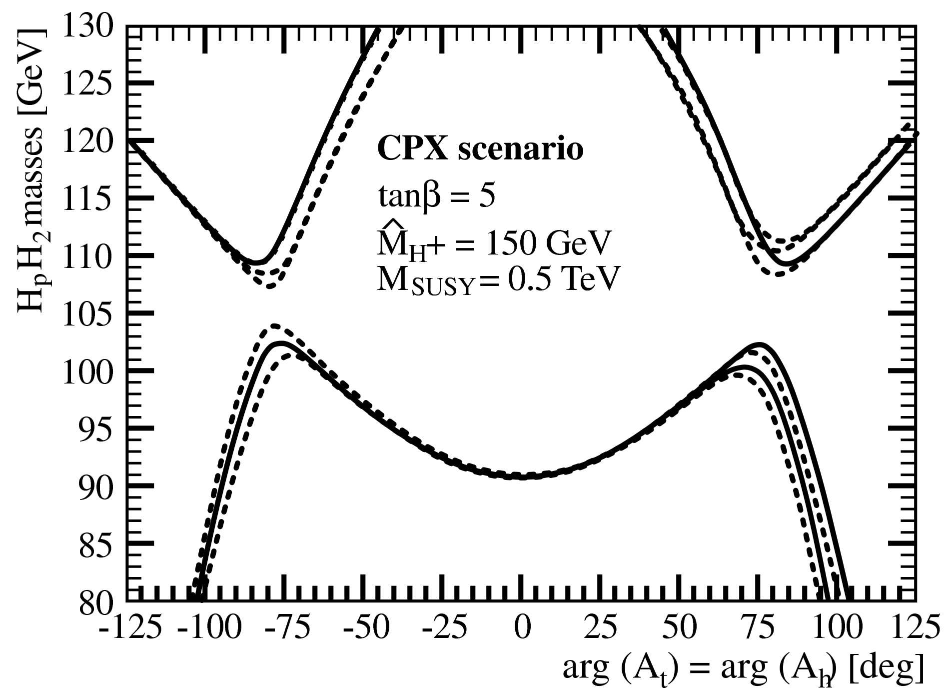
Life can be even more complicated in extensions of the MSSM

We can allow for some amount of CP–violation in eg. $\mathbf{M_i}$, μ and $\mathbf{A_f}$

Higgs sector: CP–conserving at tree level $\Rightarrow$ CP–violating at one–loop

Good to address the issue of baryogenesis at the electroweak scale....

- **h, H,A are not CP definite states and $\mathbf{h_1, h_2, h_3}$ CP mixtures**
- **determination of Higgs spectrum slightly more complicated,**
- **possibility of a light $\mathbf{h_1}$ that has escaped detection at LEP2.**



Carena et al, Choi+Drees et al, Pilaftsis et al, Ellis et al, Haber+Gunion, Krawczyk et al, Osland et al, Heinemeyer et al, Moretti et al, ...

7. Higgs in non minimal scenarios: CP–violation

The CPX scenario:

(Carena et al, Ellis et al,)

h_1 light but weak cplgs to W,Z

$h_2 \rightarrow h_1 h_1$ decays allowed

h_3 couplings to VV reduced...

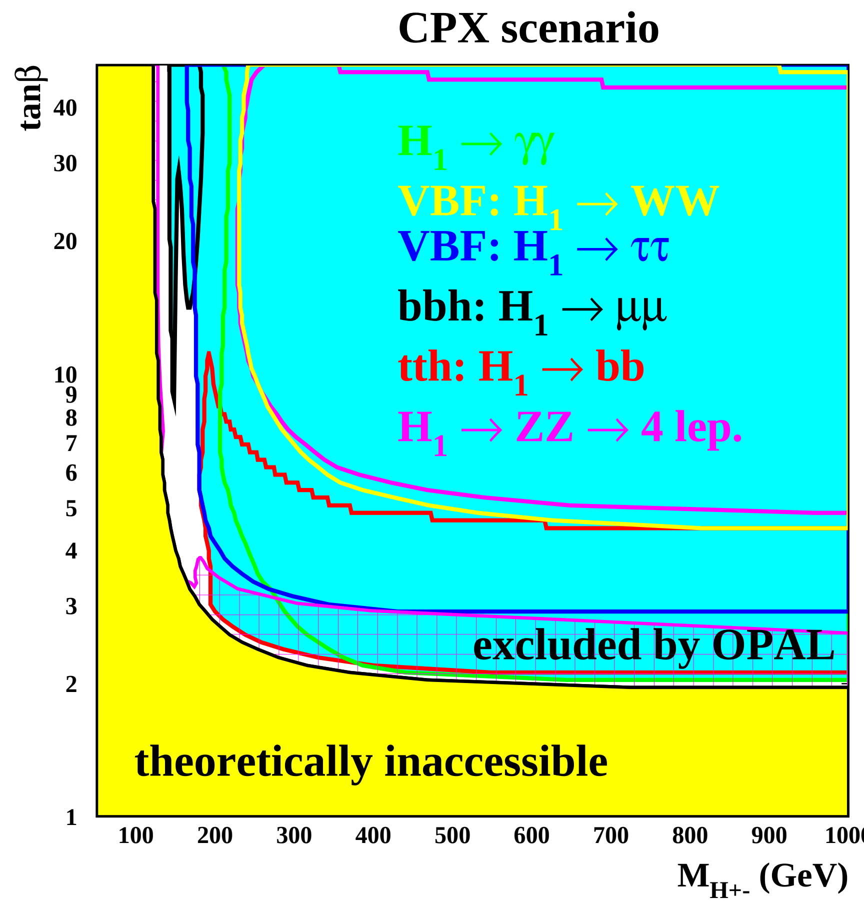
All Higgses escape detection

Still, there is the possibility

$t \rightarrow H^+ b$ with $H^+ \rightarrow hW^*$

(Godbole, Guchait, Roy).

M. Schumacher $\longrightarrow$



Regions of MSSM parameter space not covered by ATLAS/CMS:

more work is still needed....

7. Higgs in non minimal scenarios: the NMSSM

The next-to-minimal SSM is becoming the "standard" MSSM these days..

MSSM problem: μ is SUSY-preserving but $\mathcal{O}(M_Z)$; a priori no reason

Solution, μ related to the vev of singlet field, $\langle S \rangle \propto \mu$ **Kim+Nilles**

NMSSM: introduce a gauge singlet in Superpotential: $\lambda \hat{H}_1 \hat{H}_2 \hat{S} + \frac{1}{3}\hat{S}$

Nilles et al, Frere et al, Ellis et al, Drees, Ellwanger et al, King et al, ...

SUSY spectrum extended by χ_5^0 and two neutral Higgs particles h_3, a_2

- **additional parameters enter in Higgs masses and couplings**

  less constrained model, more flexibility, ...

- **the bound on lightest Higgs boson mass is higher than in MSSM**

  less fine-tuning is needed to cope with LEP..

- **possibility of a light Higgs which has escaped detection at LEP2**

possibility of a light Higgs which has escaped detection at LEP2

  rich phenomenology: low energy constraints, DM, ...

- **Note: constrained NMSSM, less freedom than in mSUGRA ...**

7. Higgs in non minimal scenarios: the NMSSM

The NMSSM with universal boundary conditions at GUT scale:

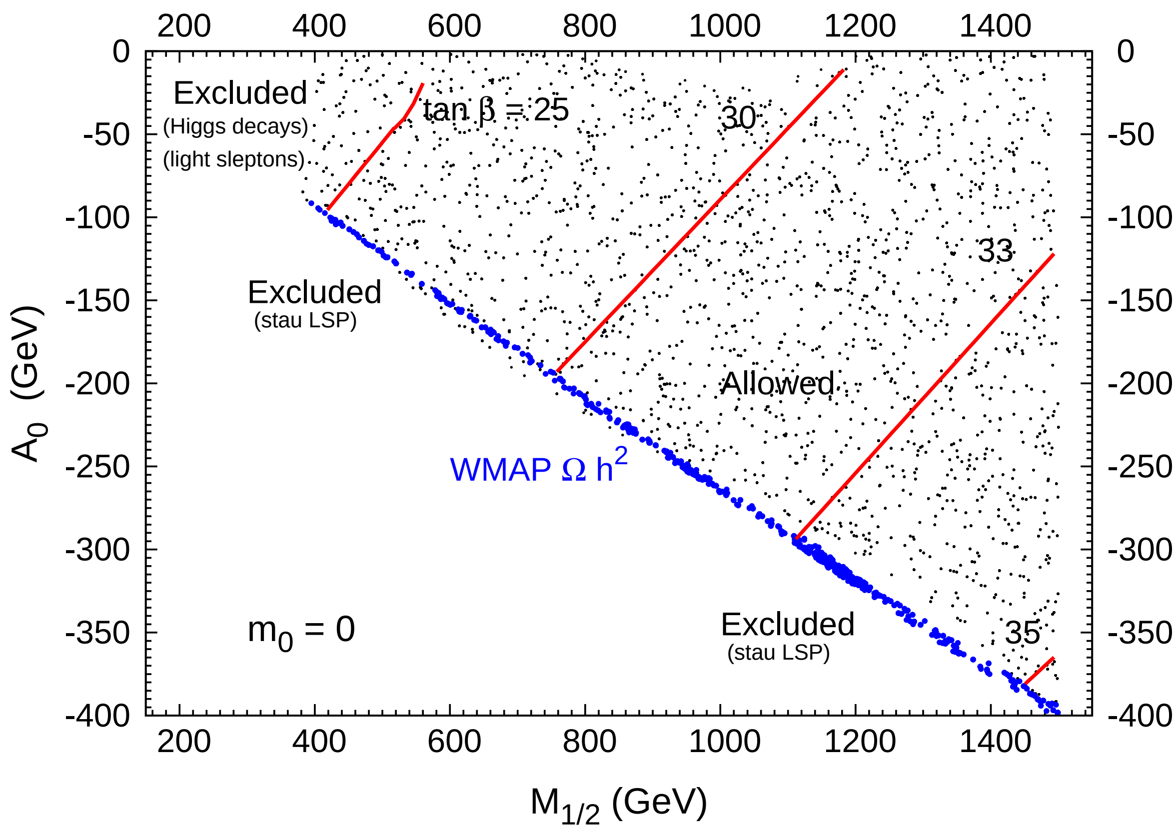
In principle: $\mathbf{M_{1/2}, m_0, A_0, \lambda, \tan\beta}$ **as free parameters**

With constraints: proper EWSB+LEP Higgs+low energy+ WMAP

only one cNMSSM free parameter: $\mathbf{m_0 \sim 0}$ **and** $\lambda \lesssim \mathbf{0.01}$

The parameters $\mathbf{A_0}$ **and** $\tan\beta$ **are related to** $\mathbf{M_{1/2}}$

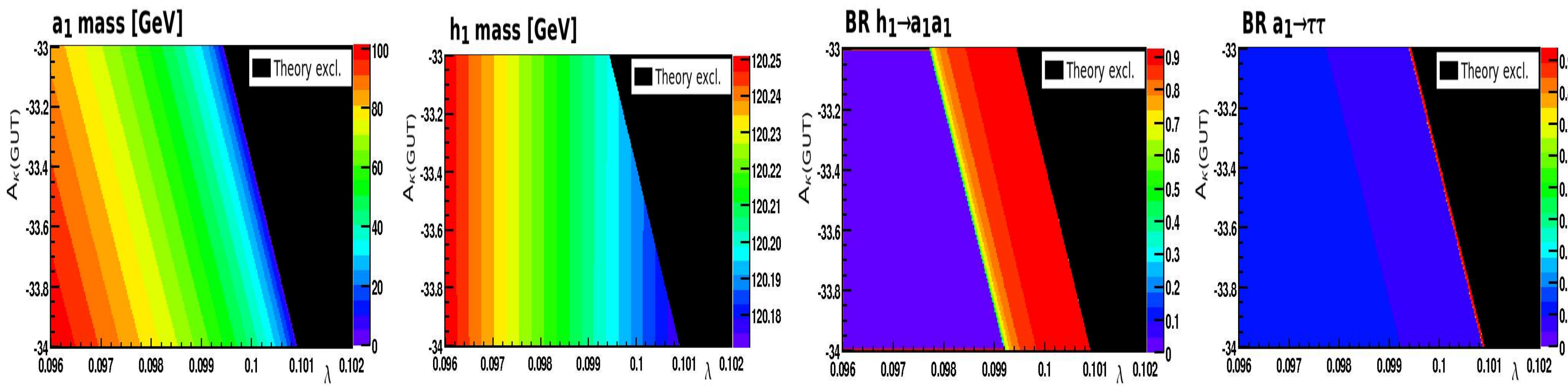
Ellwanger, Teixeira, AD (2008)



4. Production in NMSSM

But life can be even more complicated with LHC Higgs searches:

the possibility of missing all Higgs bosons is not yet ruled out!
(Ellwanger, Hugonie, Gunion, Moretti; King..., Nevzorov..., Barger...)

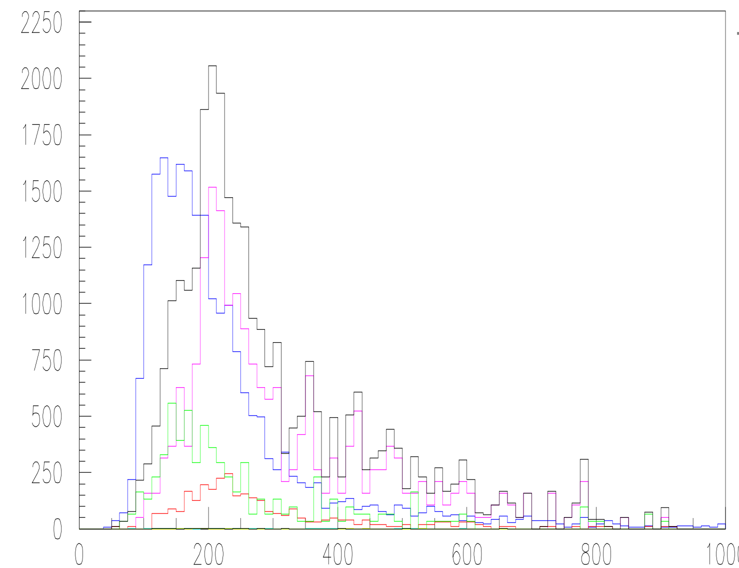


Recently, some benchmark scenarios for NMSSM Higgs searches

have been proposed: AD, Drees, Rottlander, M. Schumacher, et al., ...

- h_1 **is SM–like and** a_1 **light:** $h_1 \to a_1 a_1$ **with** $a_1 \to b\bar{b}$ **and/or** $\tau^+\tau^-$
- h_2 **is SM–like and** h_1 **light:** $h_2 \to h_1 h_1$ **with** $h_1 \to b\bar{b}$
- **All Higgs are light (NMSSM ICR): reduced couplings to VV, etc...**

7. Higgs in non minimal scenarios: NMSSM



Higgs $\rightarrow$ Higgs+Higgs $\rightarrow 4\mathrm{b}, 2\mathrm{b}2\tau$

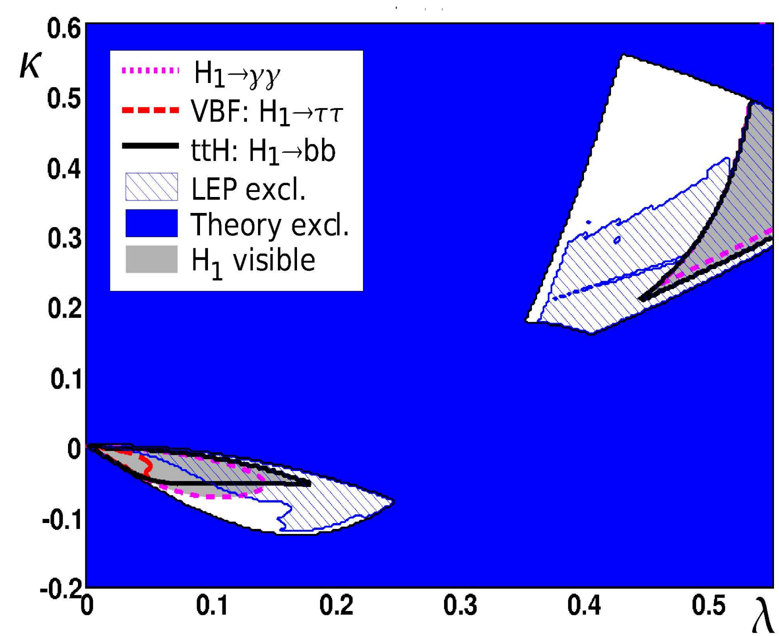
searches very difficult at the LHC:

$pp \rightarrow qq \rightarrow\rightarrow W^*W^*qq \rightarrow h_1 qq$

——– $h_1 \rightarrow a_1 a_1 \rightarrow b\bar{b}\tau\tau \times 500$.

——– total background.

(Ellwanger..., Baffioni+D.Zerwas)



Higgs $\rightarrow$ Higgs+Higgs $\rightarrow 4\tau \rightarrow 4\ell\mathrm{X}$

also difficult but detection possible

(Nikitenko .., Schumacher+Rottlander)

Example of scan for light h_1

using VBF + all h_1 decay channels

(same for all Higgsses can be done)

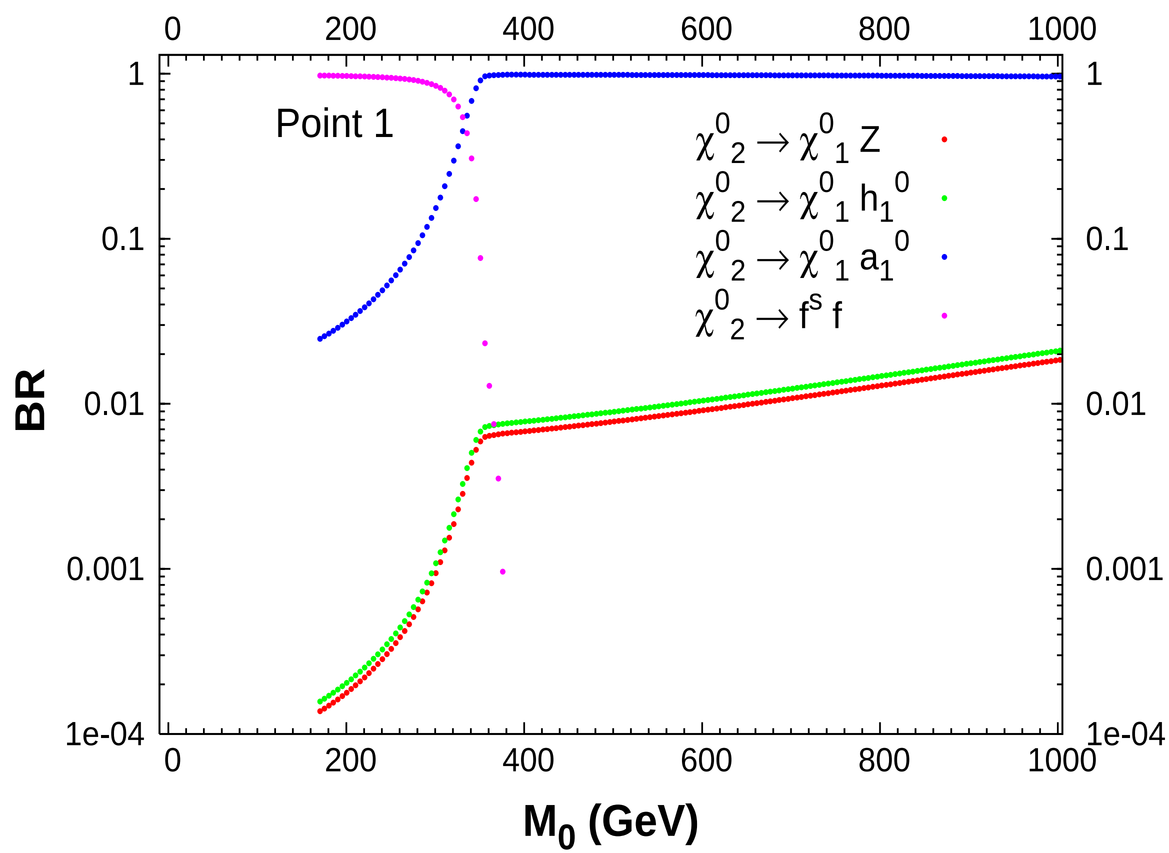
(Schumacher+Rottlander)

7. Higgs in non minimal scenarios

A possible rescue in both the CPV MSSM and NMSSM might come from SUSY particle cascade decays into Higgs bosons. In particular:

$$\mathbf{pp \to \tilde{q}\tilde{q}, \tilde{g}\tilde{g}, \tilde{g}\tilde{q} \to \chi + X \text{ with } \chi_2^0 \to \chi_1^0 + Higgs}$$

Example for one of the NMSSM benchmark points with light a_1:



Ellwanger ea

7. Invisible Higgs??

There are many scenarios in which a Higgs boson would decay invisibly

- **In MSSM, Higgs $\to \chi_1^0 \chi_1^0, \tilde{\nu}\tilde{\nu},$ etc.. as already discussed.**
- **In MSSM with $R\!\!\!/_p$: Higgs $\to$ JJ could be dominant.** **Valle ea**
- **The SM when minimaly extended to contain a singlet field (which decouples from f/V), $H \to SS$ can be dominant** **Bij, Wells ea,..**
- **In large extra dimensions H mixing with graviscalars.** **Gunion ea**

... or very different couplings to fermions and bosons...

- **Radion mixing in warped extra dimension models: supressed f/V couplings and Higgs decays to radions** **Hewett+ Rizzo, Gunion ea**
- **Presence of new quarks which alter production** **Moreau ea**

... Many possible surprises/difficult scenarios.......