Physics at the LHC

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- **Standard Physics at the LHC**
- **The SM Higgs at the LHC**
- **SUSY and SUSY–Higgs at the LHC**

1. SUSY and The MSSM

2. Spectrum and constraints

3. Decays

4. Production

1. Beyond the SM & SUSY

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:

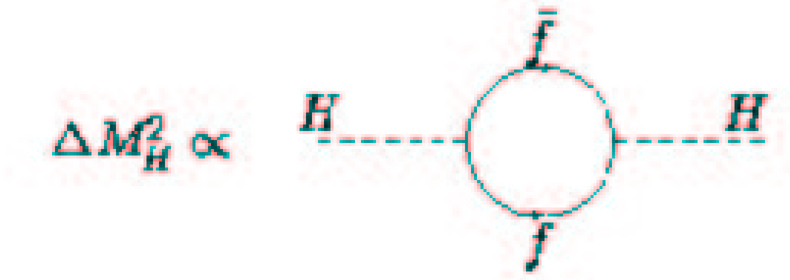
- **Too many free parameters (19!) in the model, put by hand...**
- **No satisfactory explanation for $\mu^2 < 0$ (put ad hoc).**
- **Does not include the fourth fundamental force, gravity, ..**
- **Does not say anything about the masses of the neutrinos.**
- **No real unification of the three gauge 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 $\mathbf{M_H^2}$



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

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

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

Divergence is independent of $\mathbf{M_H}$, and does not disappear if $\mathbf{M_H = 0}$:

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

If we fix the cut–off Λ to $\mathbf{M_{GUT}}$ or $\mathbf{M_P}$: $\Rightarrow$ $\mathbf{M_H} \sim 10^{14}$ 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 ($M_H \lesssim 1$ TeV) for unitarity etc... reasons.

We need thus to make: $M_H^2|^{\rm Physical} = M_H^2|^0 + \Delta M_H^2$+ counterterm

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 M_H

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

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

We can adjust the unknown M_H so that the quadratic divergence

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

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

Summary: the problem of the quadratic divergences to M_H is there.

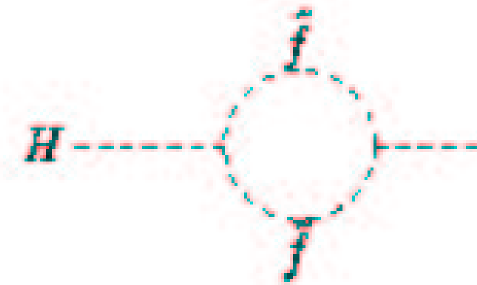
Photon and fermion masses protected by gauge and chiral symmetry,

.... but here is no symmetry which protects 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)!

⇒ Symmetry fermions–scalars → no divergence in Λ^2

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

Note that if $M_S \gg 1\,\mathrm{TeV}$ 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 $M_{\rm GUT}$.**
- **SUSY SO(10): extra space for a Majorana neutrino, see–saw $\to m_\nu$.**
- **Heavy neutrinos trigger baryogenesis via leptogenesis.**
- **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 $M_{\rm EW}$**

1. BSM & SUSY: SUSY

$\cdots$ and all this at once $\cdots$

But for this to work, we need to have $M_{\rm SUSY} \sim \mathcal{O}$(TeV)

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

Drawback: no satisfactory way to break SUSY yet $\Rightarrow$ breaking by hand

The Minimal Supersymmetric Standard Model (MSSM):

- **minimal gauge group $\rm G_{MSSM} = G_{SM}$,**
- **minimal particle content: 3 fermion families and 2 doublets of Φ,**
- **R–parity, $R=(-1)^{(2s+L+3B)}$, is conserved ($\not P$ and dark matter OK),**
- **minimal set of terms (masses, couplings) breaking "softly" SUSY.**

Result: too many free parameters:

– general case (CPV and mixing but R_p OK): O(100) new parameters,

– imposing phenomenological constraints: still O(20) free parameters,

– unified models, O(5) parameters (mSUGRA: $m_0, m_{\frac{1}{2}}, A_0, \tan\beta, \epsilon_\mu$).

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

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

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 ${V_H}^{\mathrm{min}}$ breaks $G_{\mathrm{SM}} \to U(1)_{\mathrm{QED}}$ (neutral component).

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

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

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

2. The Higgs spectrum: scalar potential

Some remarks on this scalar potential:

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

- **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_{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

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

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

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

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

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

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

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

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:

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

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

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

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

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

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 $\sqrt{\mathrm{s}}_{\mathrm{LEP2}} \sim 200 \ \mathrm{GeV} \ > \mathrm{M_h} + \mathrm{M_Z} \sim 180$ 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.

⇒ 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: $\underline{M_h^{\max}\to M_Z+40}$ 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 $m_t|^{\text{pole}} \to m_t|^{\overline{\text{MS}}}$.

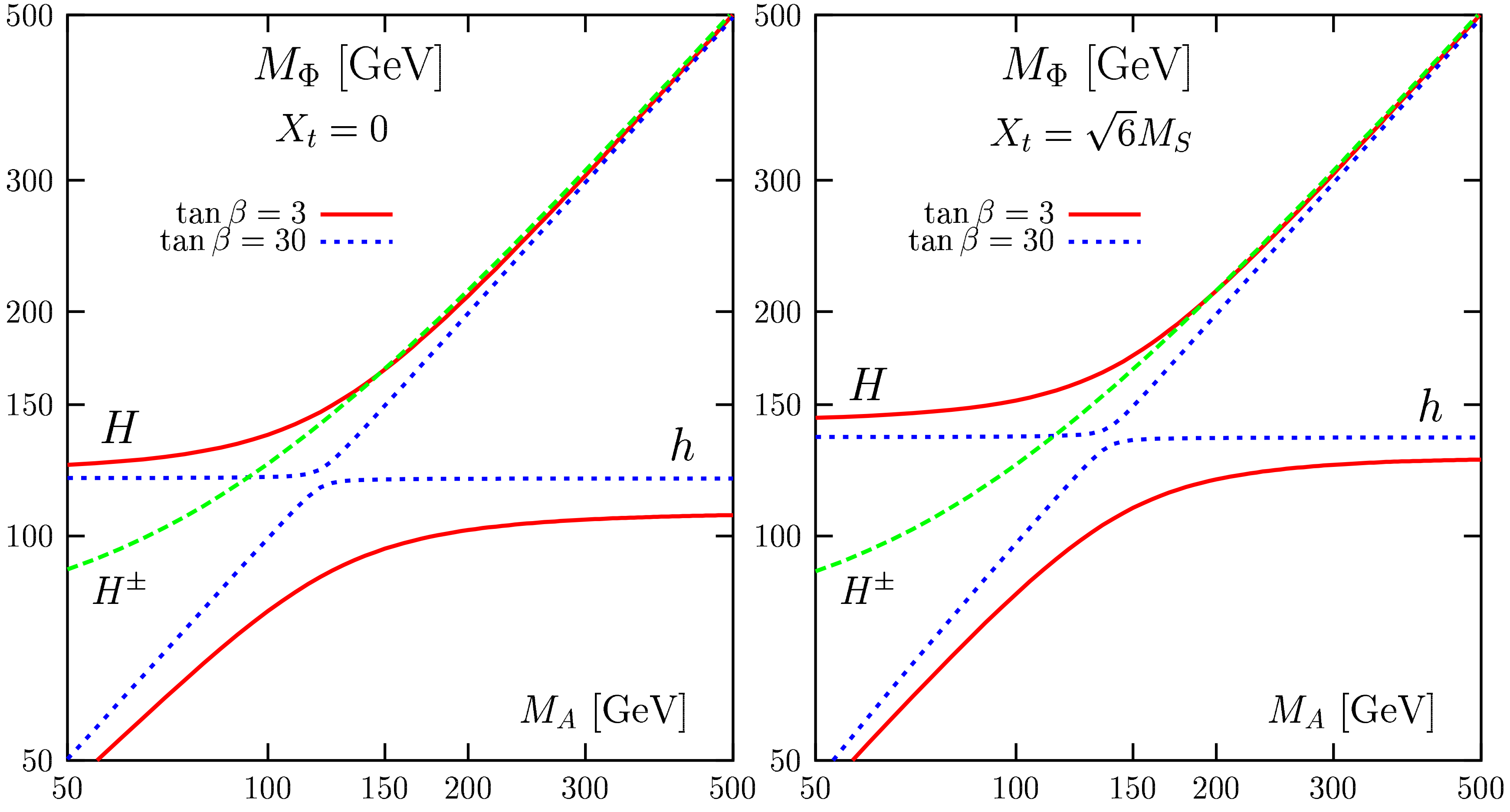
– Yukawa corrections rather small in the limit $M_h = 0$.

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 $\mathcal{O}(\alpha_b \alpha_S), \mathcal{O}(\alpha_\tau \alpha_S)$.



1. 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:

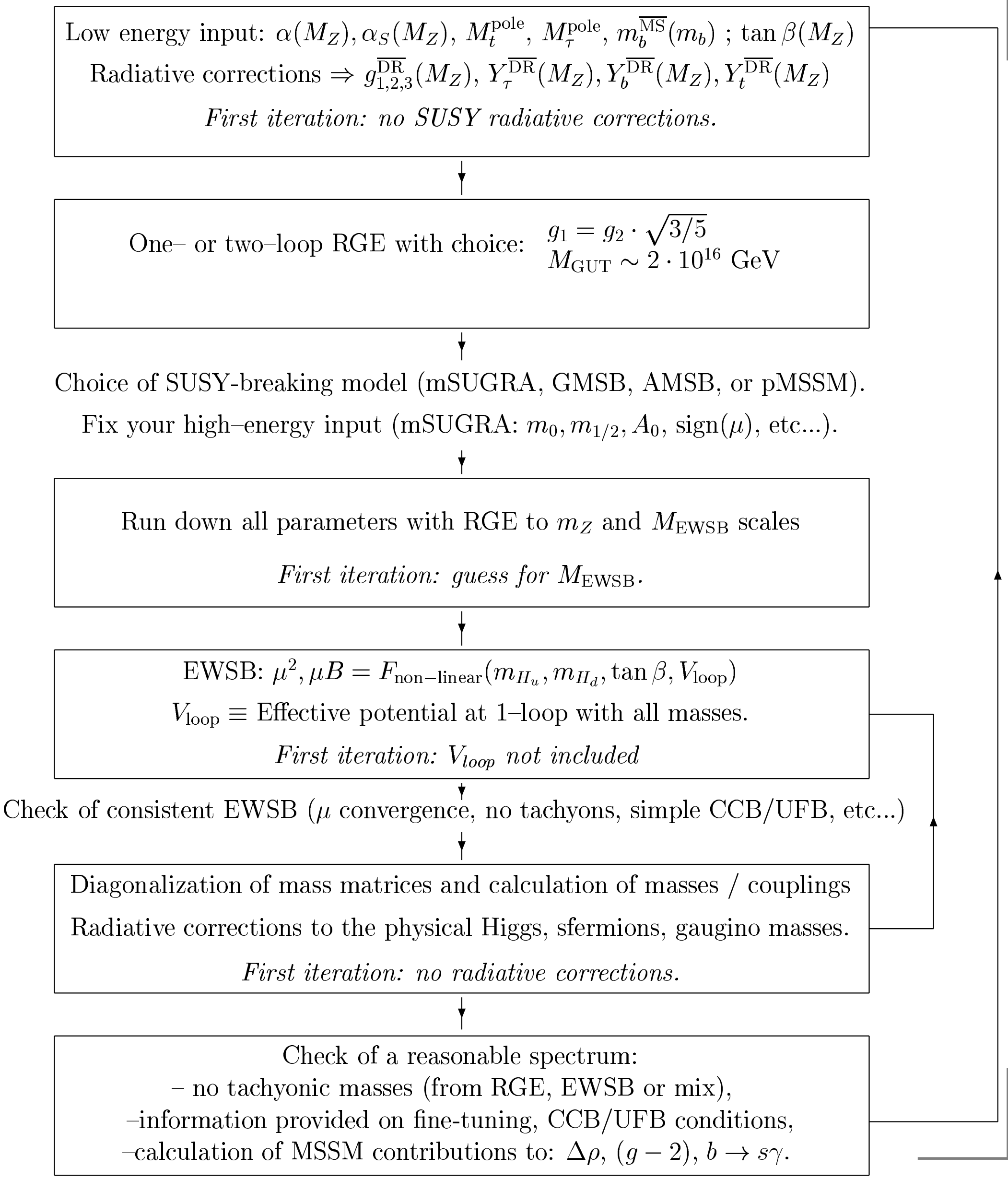
(Isajet, SoftSUSY, Spheno, ...)

Viable parameter space:

– choose inputs, param. scan

– impose known constraints

(Th, Experimental, DM, ...)



Low energy input: $\alpha(M_Z), \alpha_S(M_Z)$, $M_t^{\rm pole}$, $M_\tau^{\rm pole}$, $m_b^{\overline{\rm MS}}(m_b)$; $\tan\beta(M_Z)$

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

First iteration: no SUSY radiative corrections.

One– or two–loop RGE with choice: $g_1 = g_2 \cdot \sqrt{3/5}$, $M_{\rm GUT} \sim 2 \cdot 10^{16}$ GeV

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

Fix your high–energy input (mSUGRA: $m_0, m_{1/2}, A_0$, sign(μ), etc...).

Run down all parameters with RGE to m_Z and $M_{\rm EWSB}$ scales

First iteration: guess for $M_{\rm EWSB}$.

EWSB: $\mu^2, \mu B = F_{\rm non-linear}(m_{H_u}, m_{H_d}, \tan\beta, V_{\rm loop})$

$V_{\rm loop} \equiv$ Effective potential at 1–loop with all masses.

First iteration: V_{loop} not included

Check of consistent EWSB (μ convergence, no tachyons, simple CCB/UFB, etc...)

Diagonalization of mass matrices and calculation of masses / couplings

Radiative corrections to the physical Higgs, sfermions, gaugino masses.

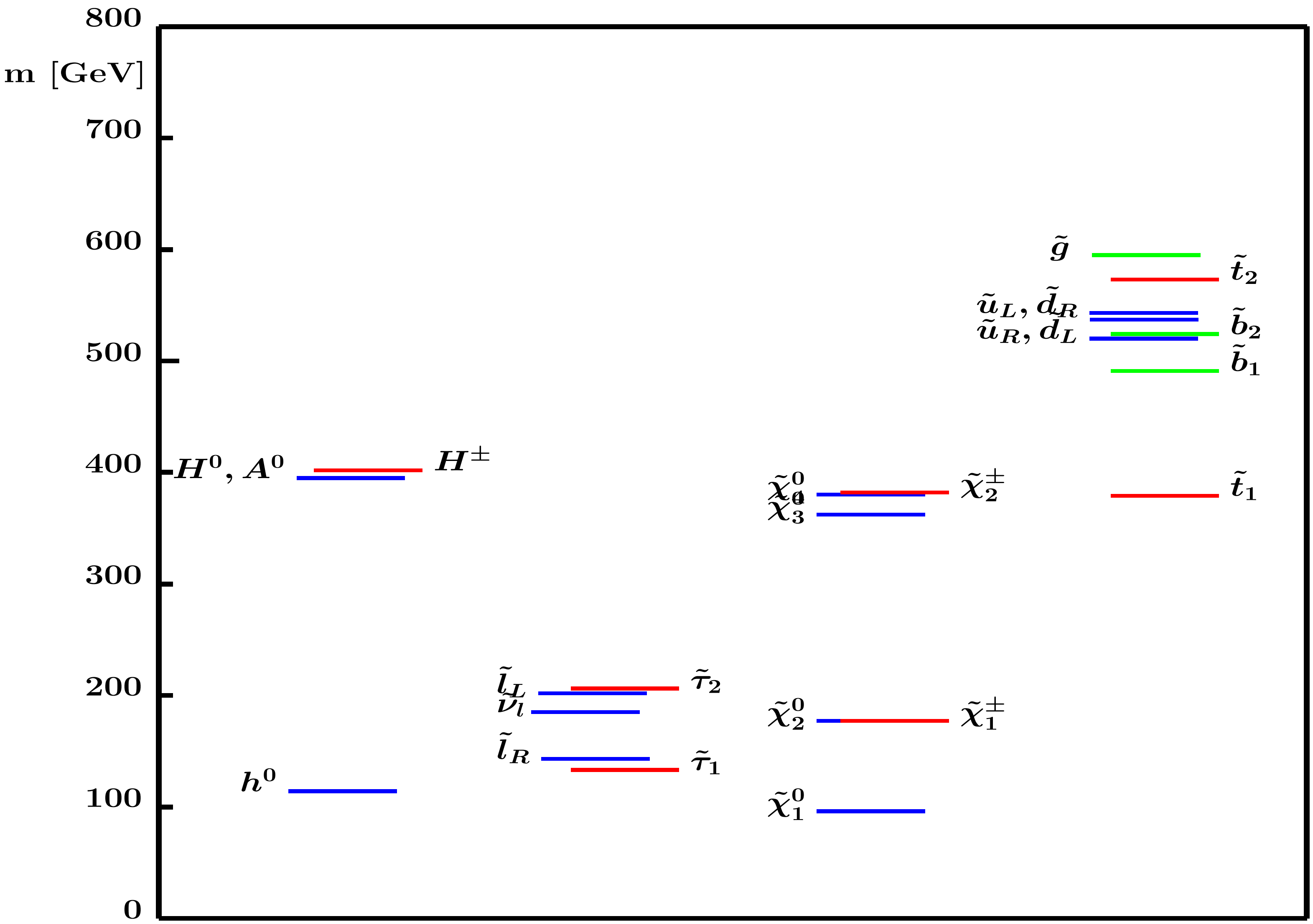
First iteration: no radiative corrections.

Check of a reasonable spectrum:
– no tachyonic masses (from RGE, EWSB or mix),
–information provided on fine-tuning, CCB/UFB conditions,
–calculation of MSSM contributions to: $\Delta\rho$, $(g-2)$, $b \to s\gamma$.

1. Spectrum and constraints: 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. Spectrum and constraints: example of spectrum



1. Spectrum/constraints: direct exper. 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

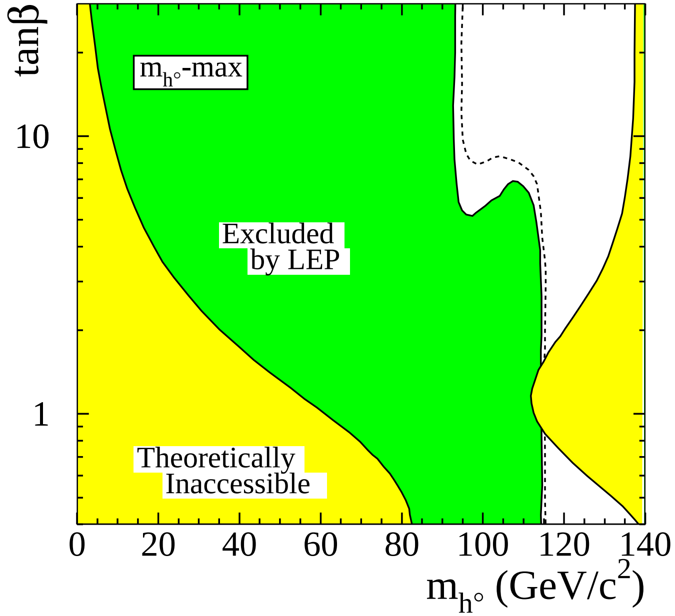
Bounds from Higgs searches at LEPII:

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

1. Spectrum/constraints: indirect exper. 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

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

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

- **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

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

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

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

1. Spectrum and constraints: 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 ($\Phi = h, H, A, H^\pm$; $f = \ell, q; V = W, Z, \gamma$)**

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

  - **Several channels are present; for example in $\chi_1^0\chi_1^0 \to f\bar{f}$:**

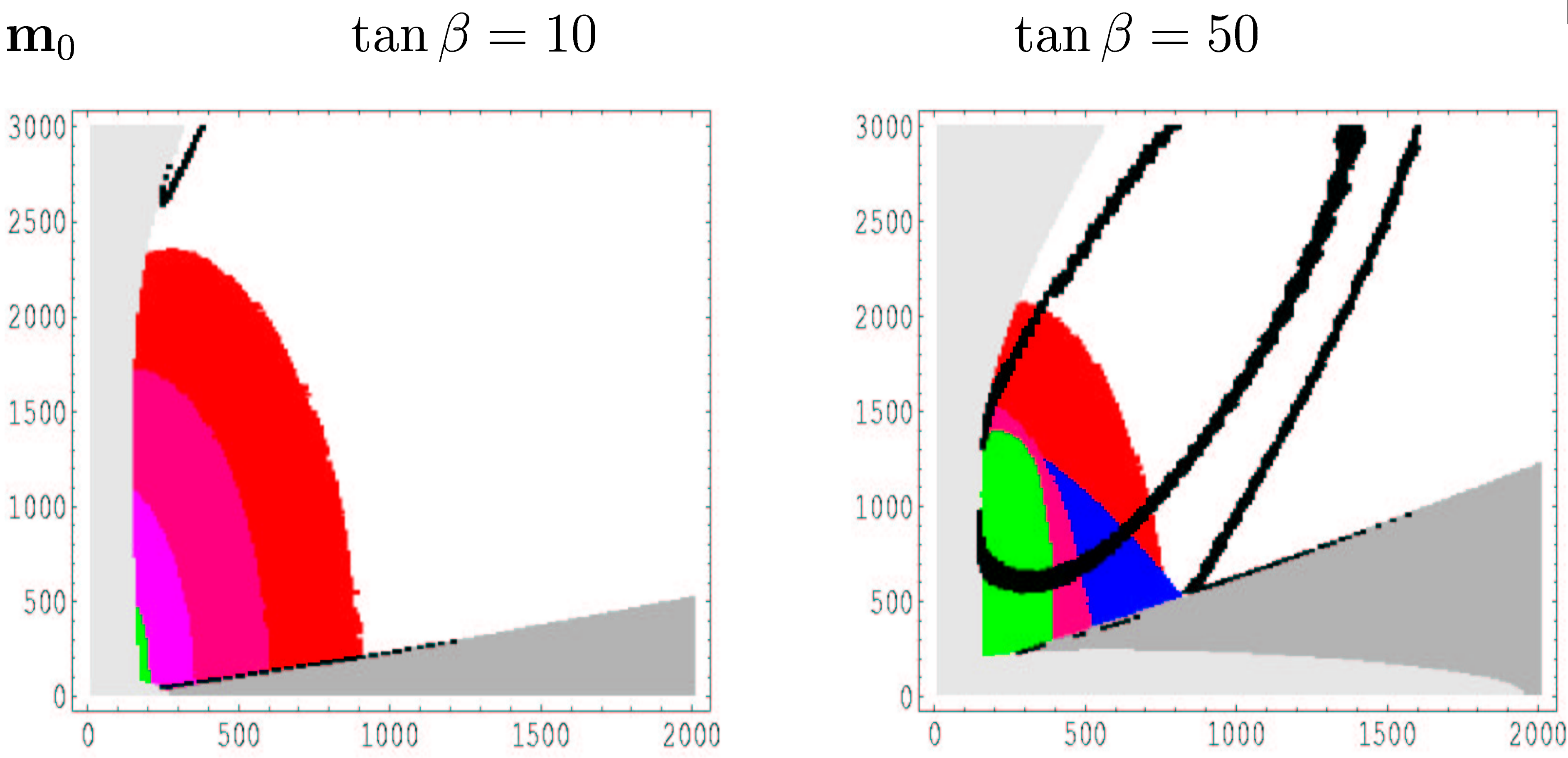
    t–channel $\tilde{f}$, s–channel Z and s–channel A, h, H exchanges

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

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

1. Spectrum and constraints: an example of a scan

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

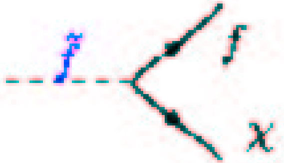


Generically, four (known) regions with the required ammount of DM:

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

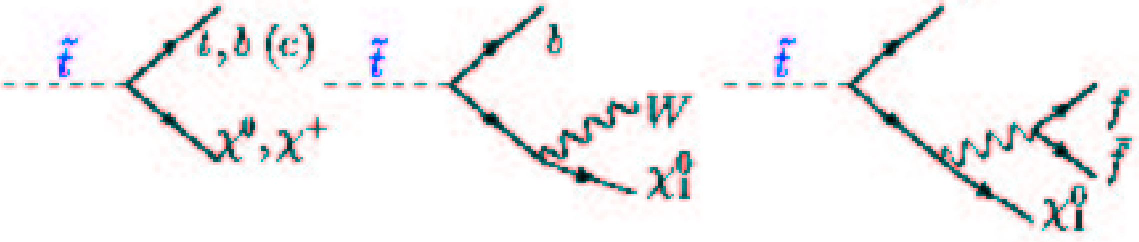
2. Decays of the Higgs and SUSY particles

Squarks and Sleptons



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

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



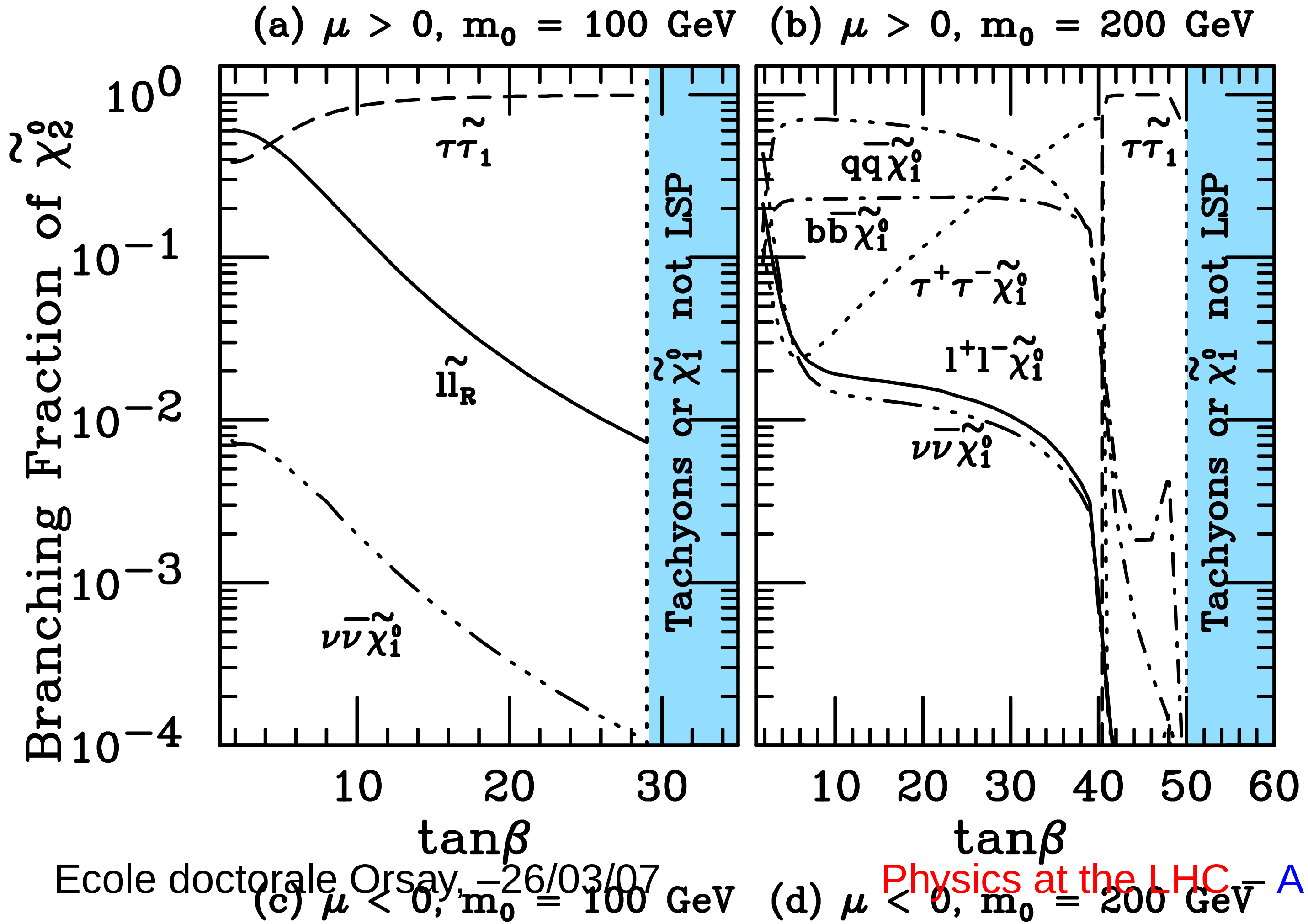
Charginos and neutralinos

Gluinos

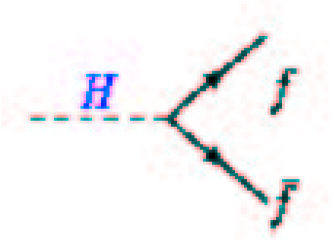
2. Decays: possible decays of sparticles

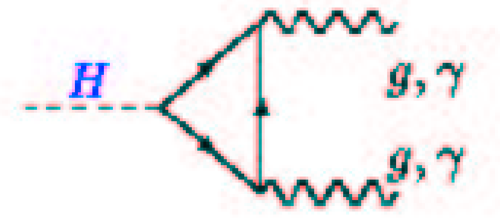
- **Possibility of cascade decays: $\tilde{q} \to q + \chi_2^0 \to q + \chi_1^0 f\bar{f}$.**
- **Signature in usual MSSM: $\not{E}_T$ from escaping χ_1^0 LSPs.**
- **In GMSB, signature is due to NLSP $(\chi_1^0, \tilde{\tau}_1) \to \tilde{G} + (\gamma, \tau)$.**

Example of final state decay in mSUGRA: χ_2^0



2. Decays: SM Higgs particle





- **“Low mass” range, $M_H \lesssim 130$ GeV:**

– $H \to b\bar{b}$ dominant, BR = 60–90%

– $H \to \tau^+\tau^-, c\bar{c}, gg$ BR= a few %

– $H \to \gamma\gamma, \gamma Z$, BR = a few permille.

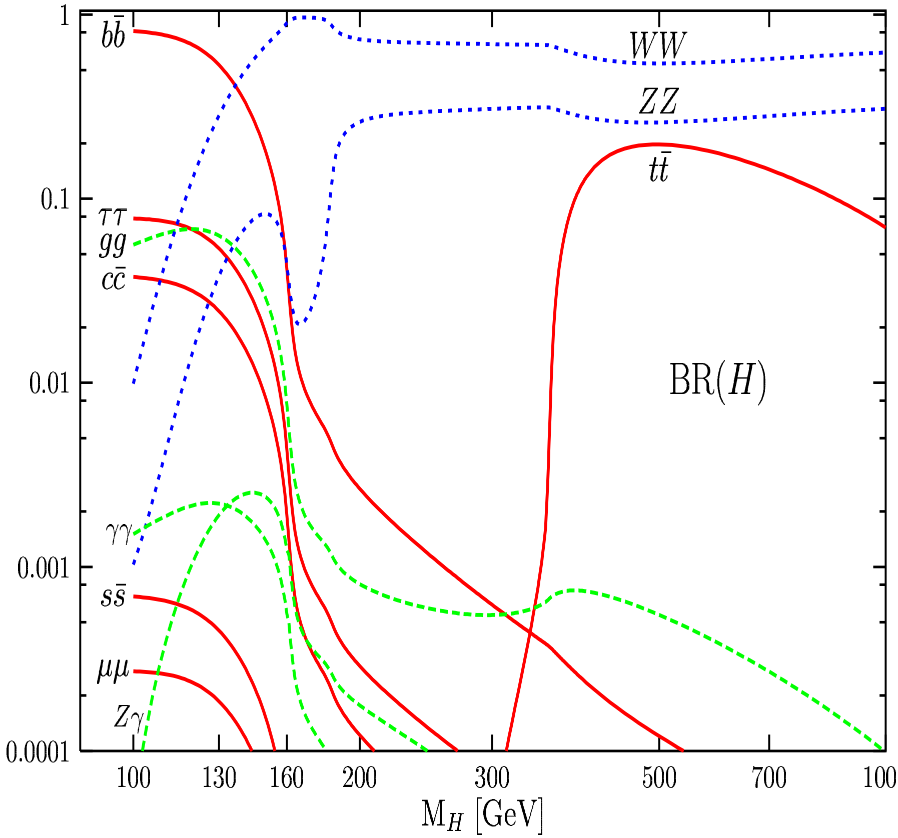
- **“High mass” range, $M_H \gtrsim 130$ GeV:**

– $\mathbf{H \to WW^*, ZZ^*}$ (BR $\to \frac{2}{3}$ or $\frac{1}{3}$),

– $H \to t\bar{t}$ for high M_H; BR $\lesssim 20\%$.

- **Total width: a few MeV to 100 GeV**

for M_H =100 to 700 GeV.



2. Decays: SUSY Higgs couplings

Higgs decays (and cross sections) strongly depend on couplings

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

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
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A	$1/\tan\beta$	$\tan\beta$	0

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

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2. Decays: MSSM Higgs particles

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Possible new effects

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

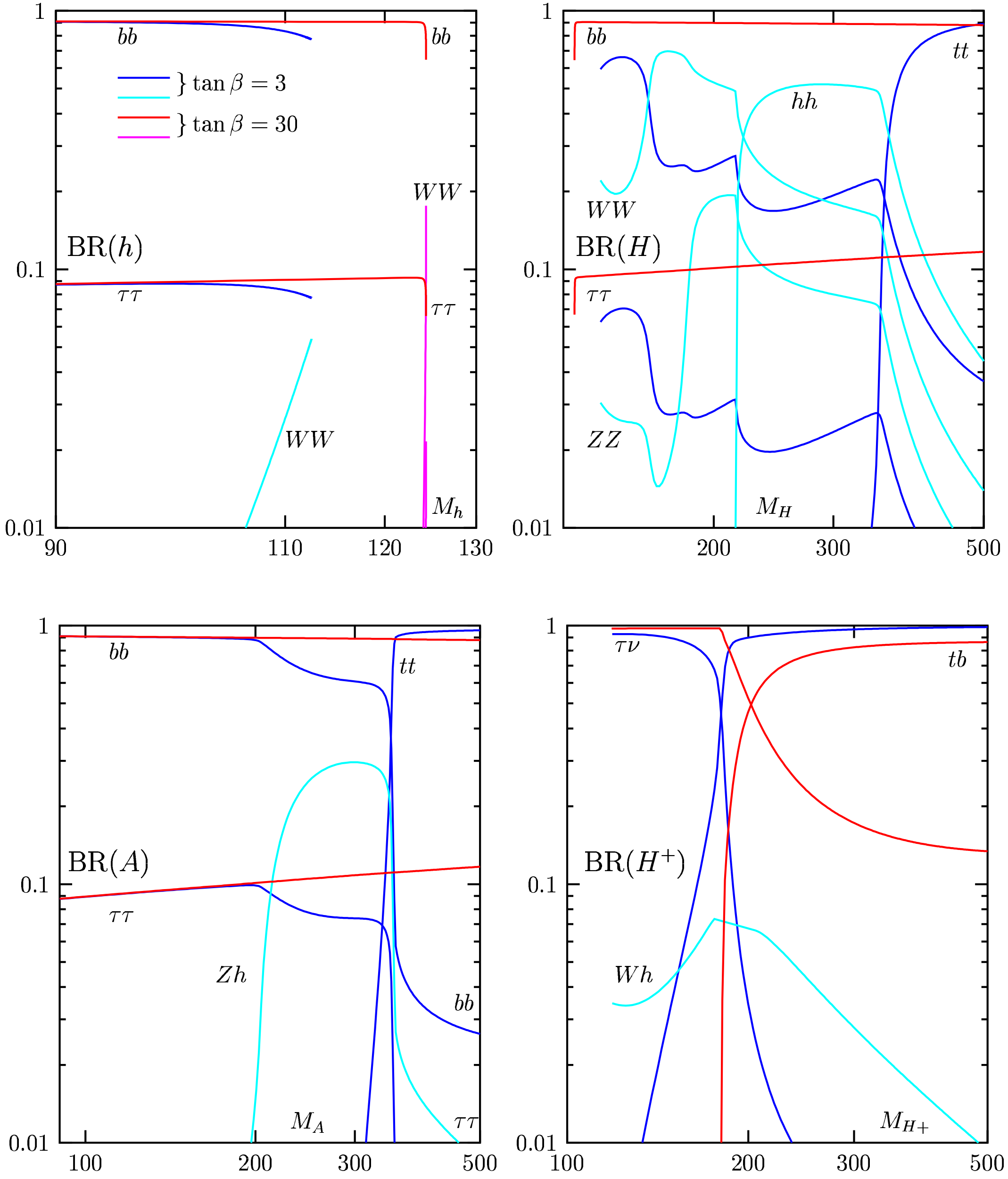
– Decays into sparticles if kinematically allowed significant:

$h \to \chi_1^0\chi_1^0$ **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.

2. Decays: BR MSSM Higgs particles



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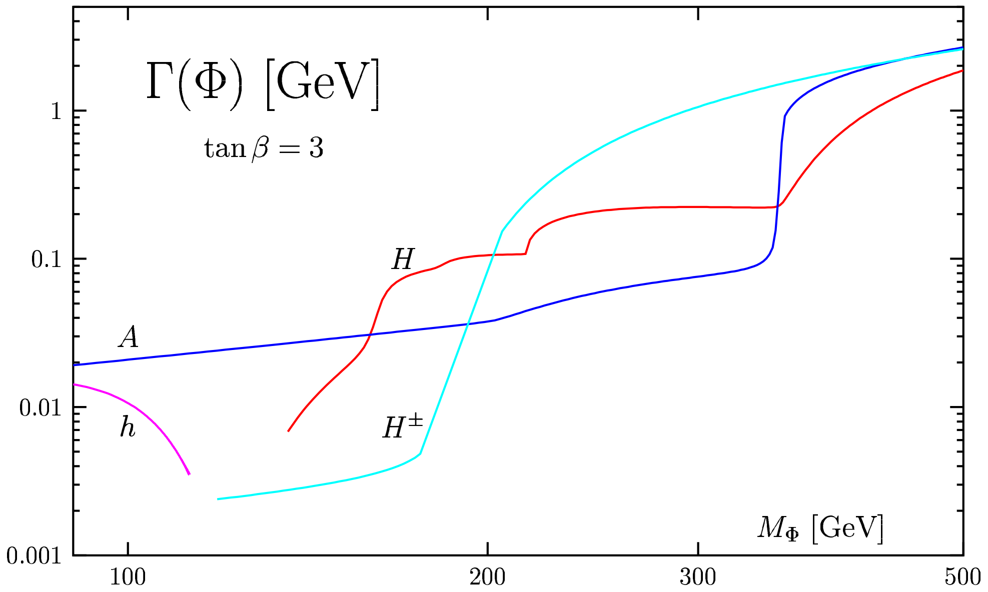
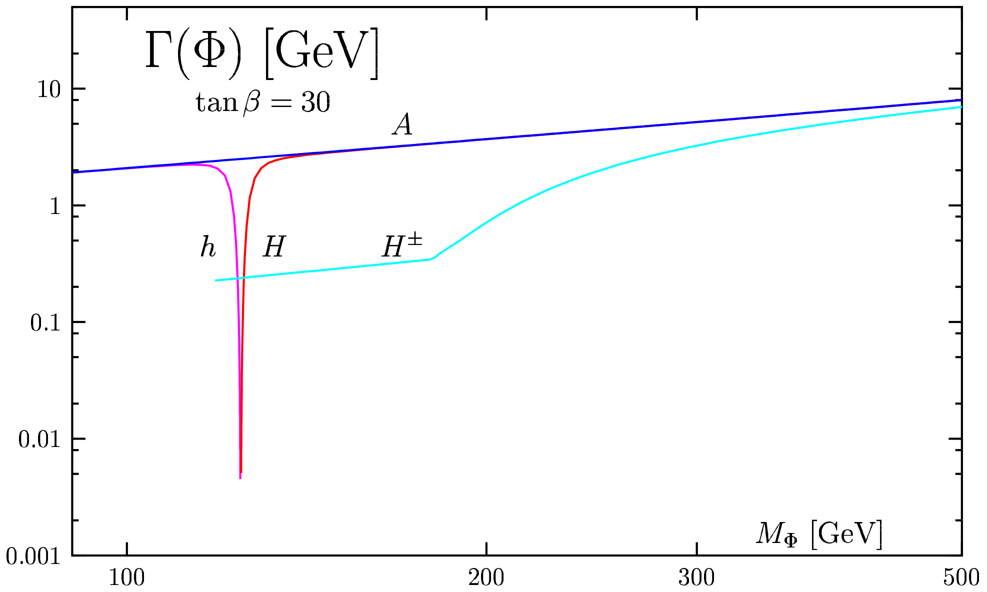
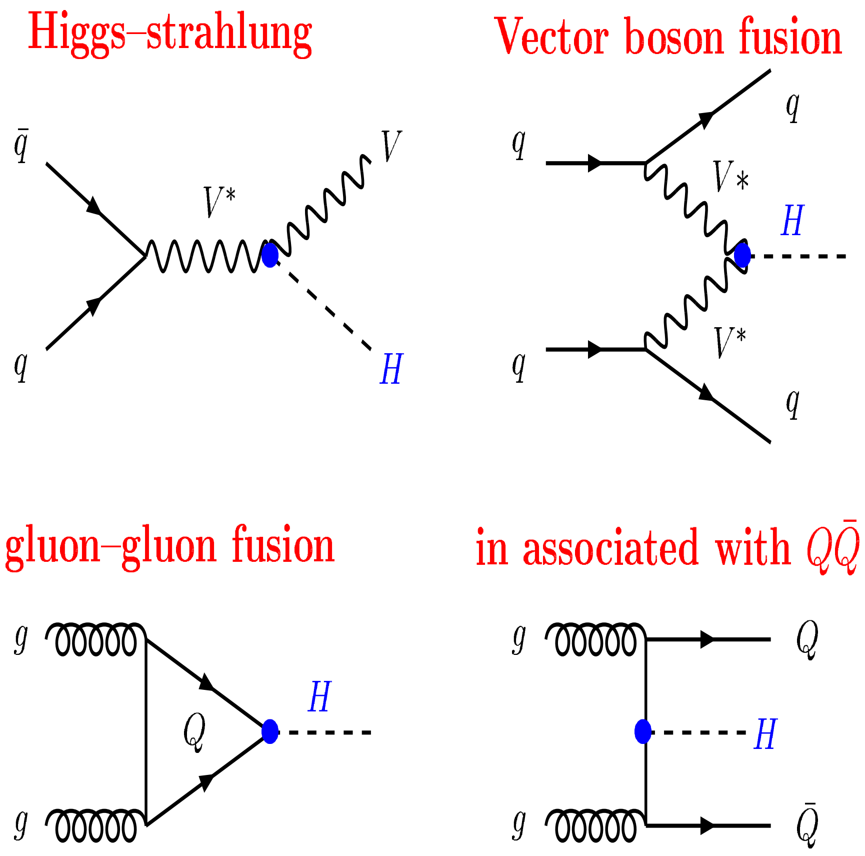


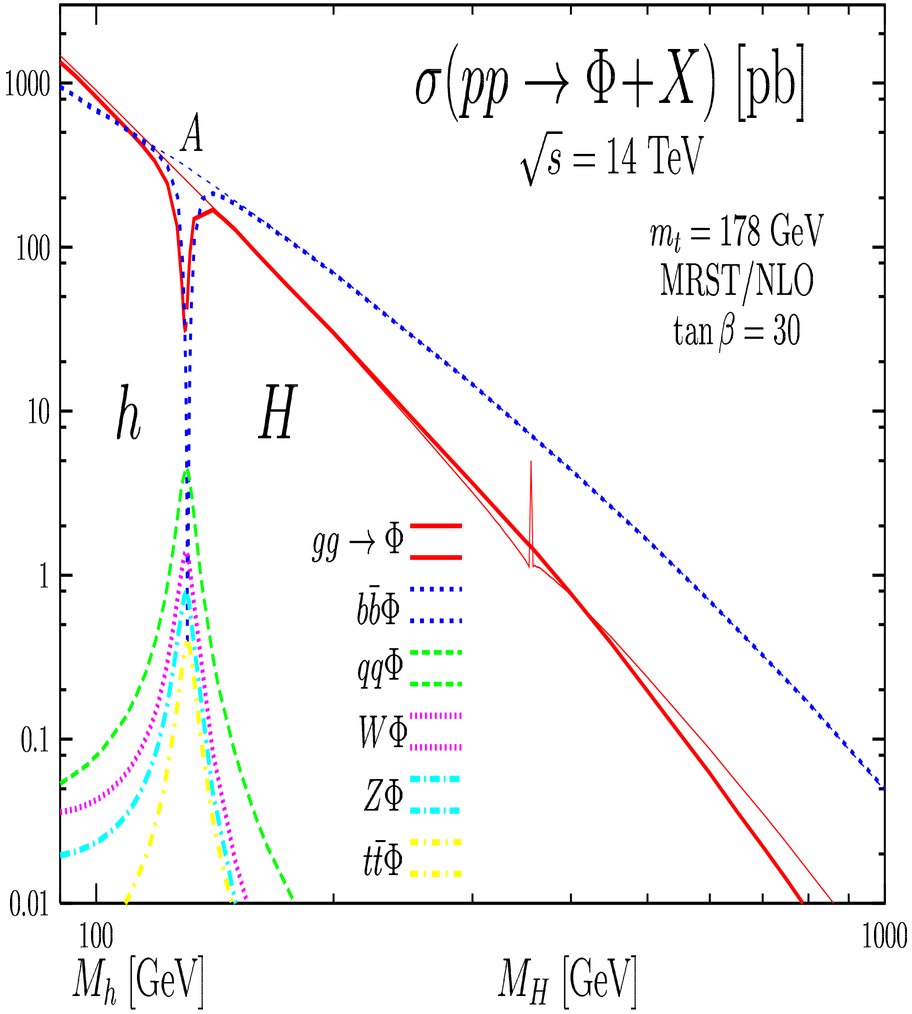


3. Production in $pp/p\bar{p}$: Higgs particles

Production mechanisms

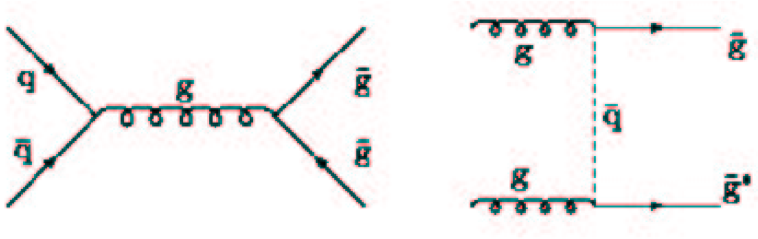


Cross sections at LHC

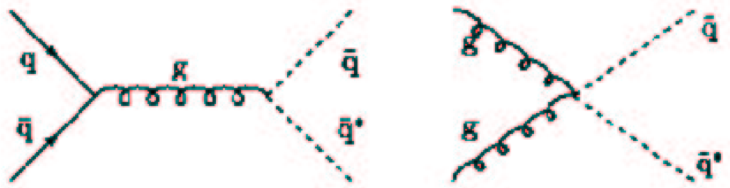


3. Production in $pp/p\bar{p}$: SUSY particles

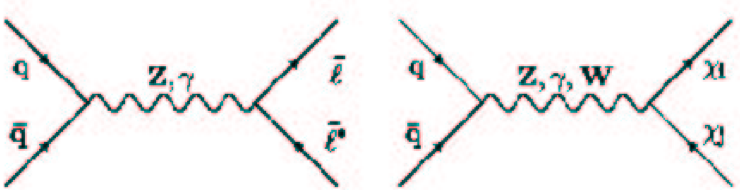
- **Gluino production**



- **Squark production**



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



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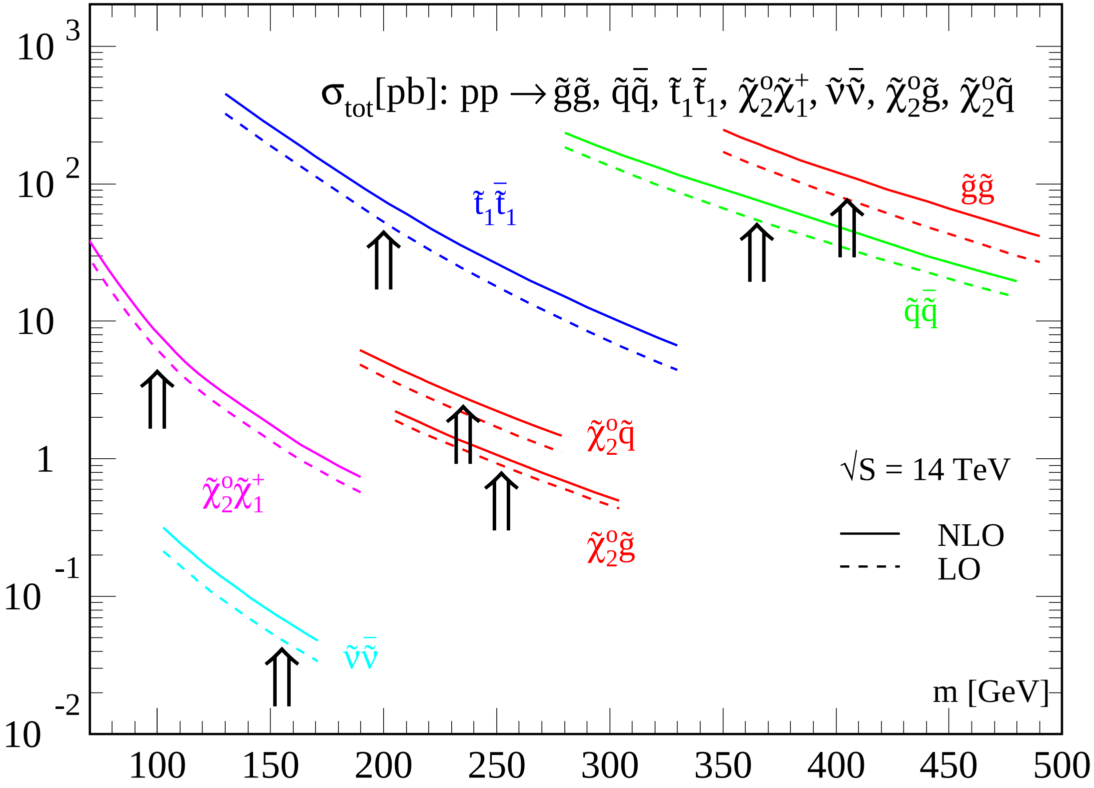
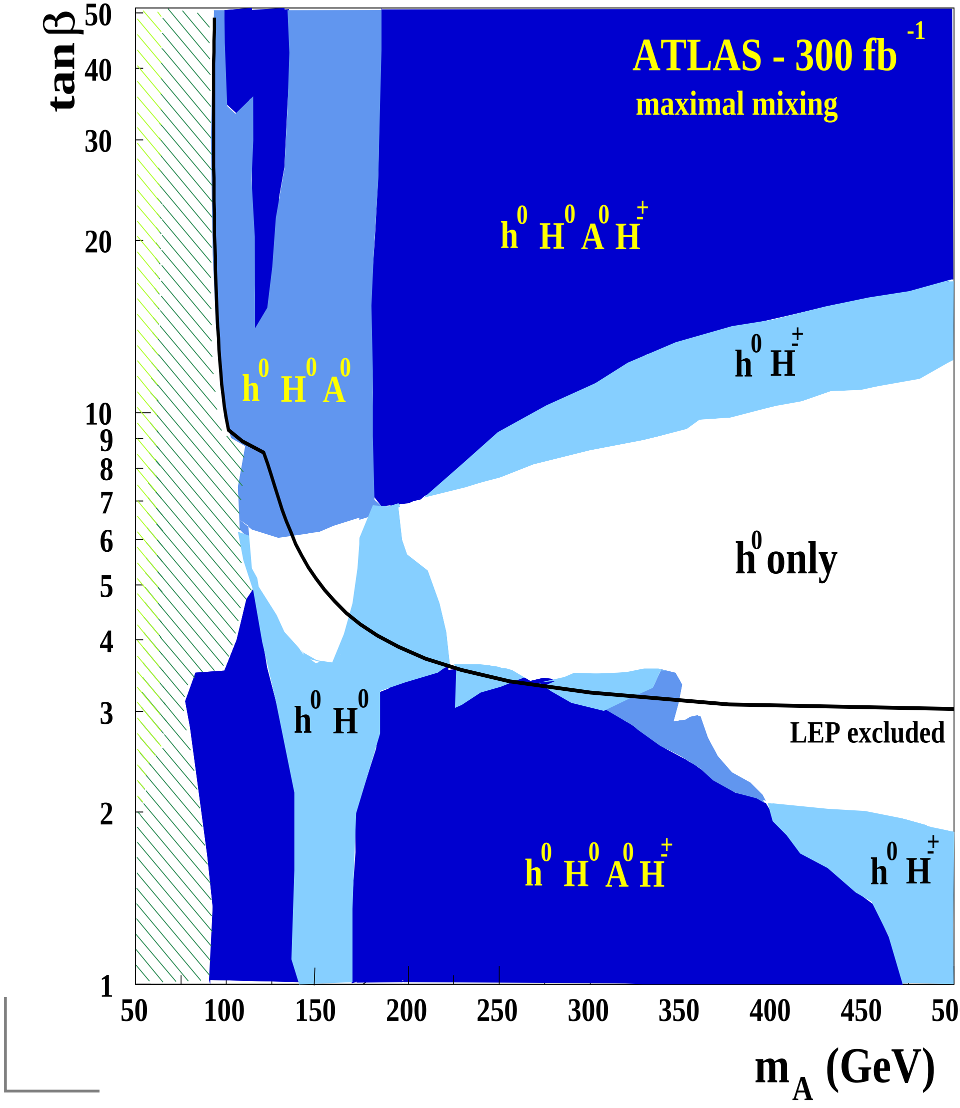
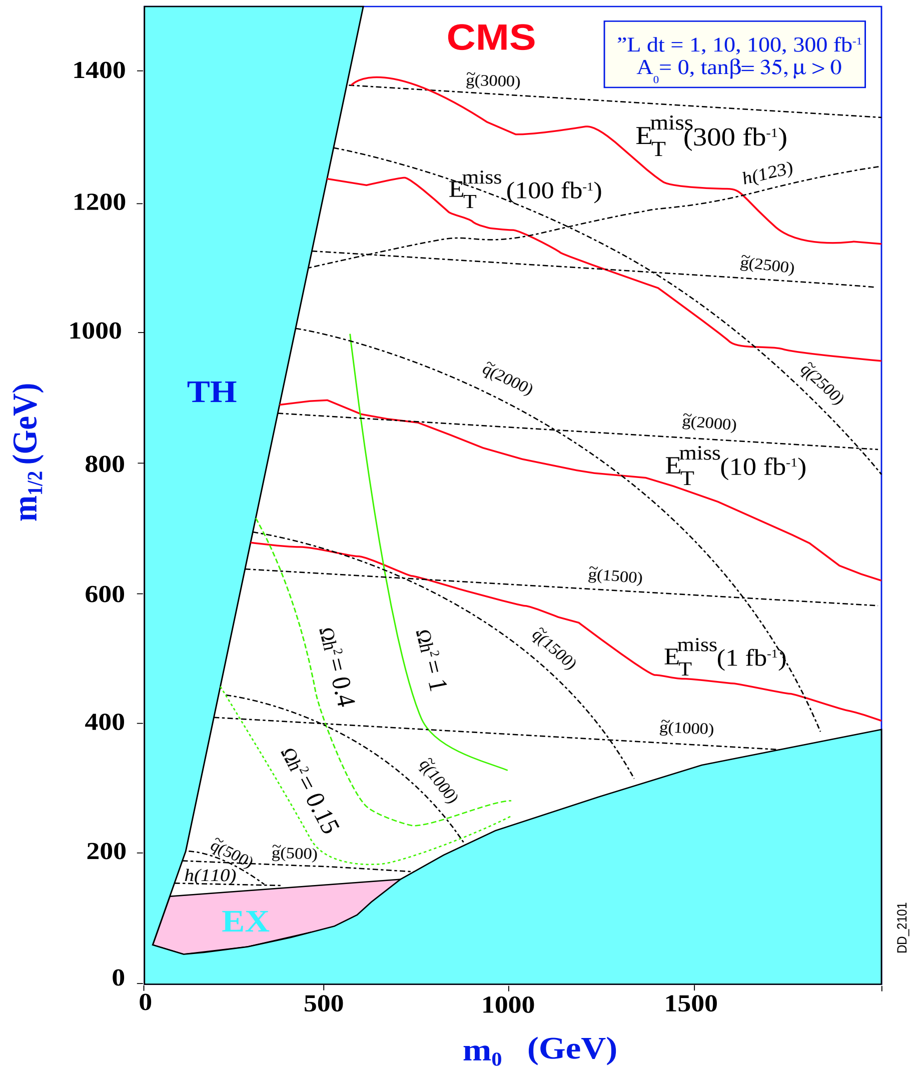


3. Discovery reach at the LHC:

Great discoveries are expected soon!

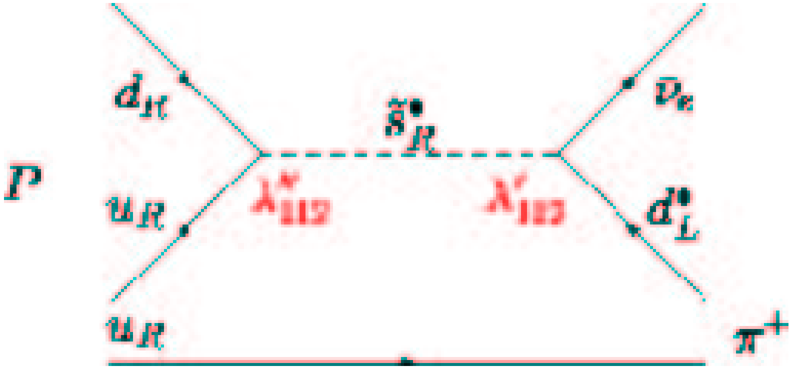
The CMS $\tilde{q},\tilde{g}$ mass reach in E_T^{miss}+ jets inclusive chann
for various integrated luminosities





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:

$$\mathbf{W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \mu'_i L_i H_u}$$

$$\mathbf{W_{\Delta B=1} = \frac{1}{2}\lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k}$$

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

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

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

- 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

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

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 $\mathrm{M_h^{NMSSM}} = \mathrm{M_h^{MSSM}} + \mathbf{20}$–40 GeV.

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

3. Higgs Decays

Higgs decays (and cross sections) strongly depend on couplings

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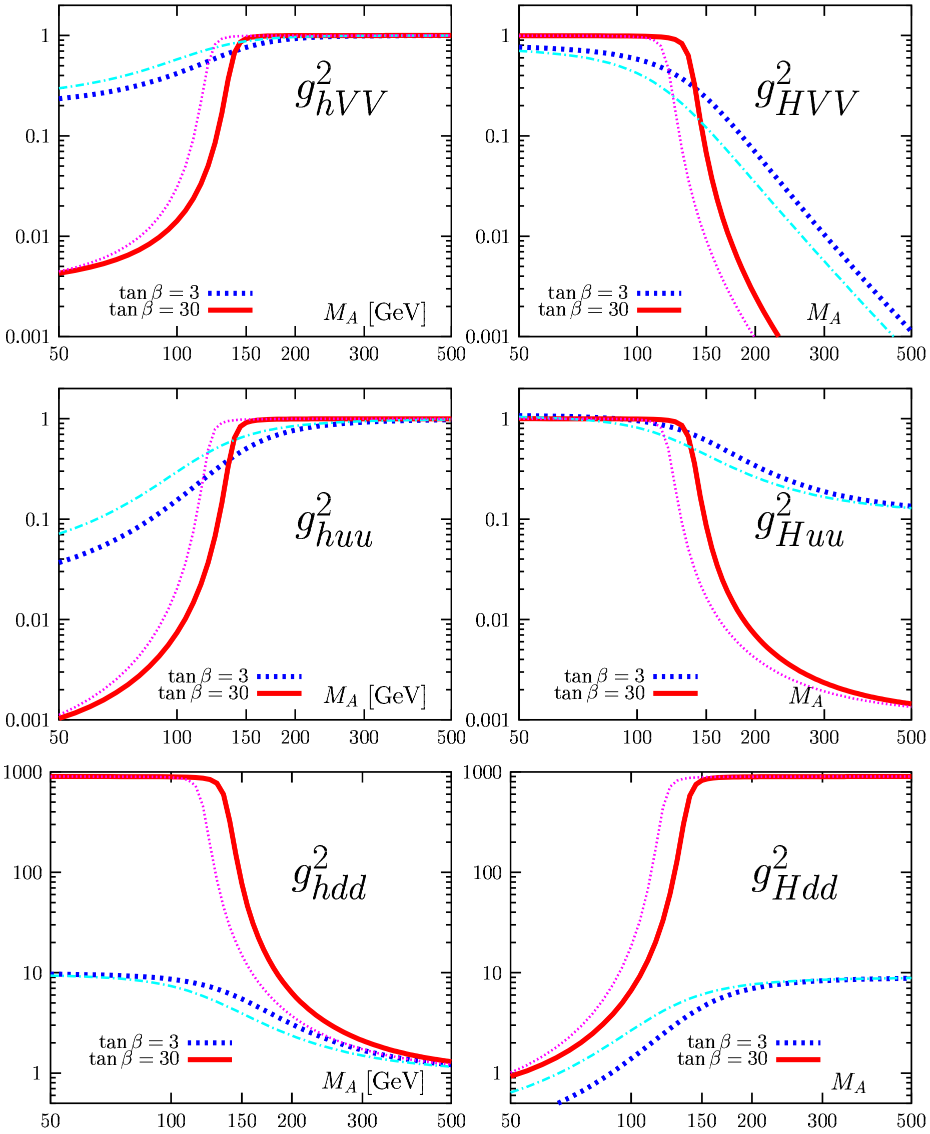
3. Decays: SUSY Higgs couplings

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



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

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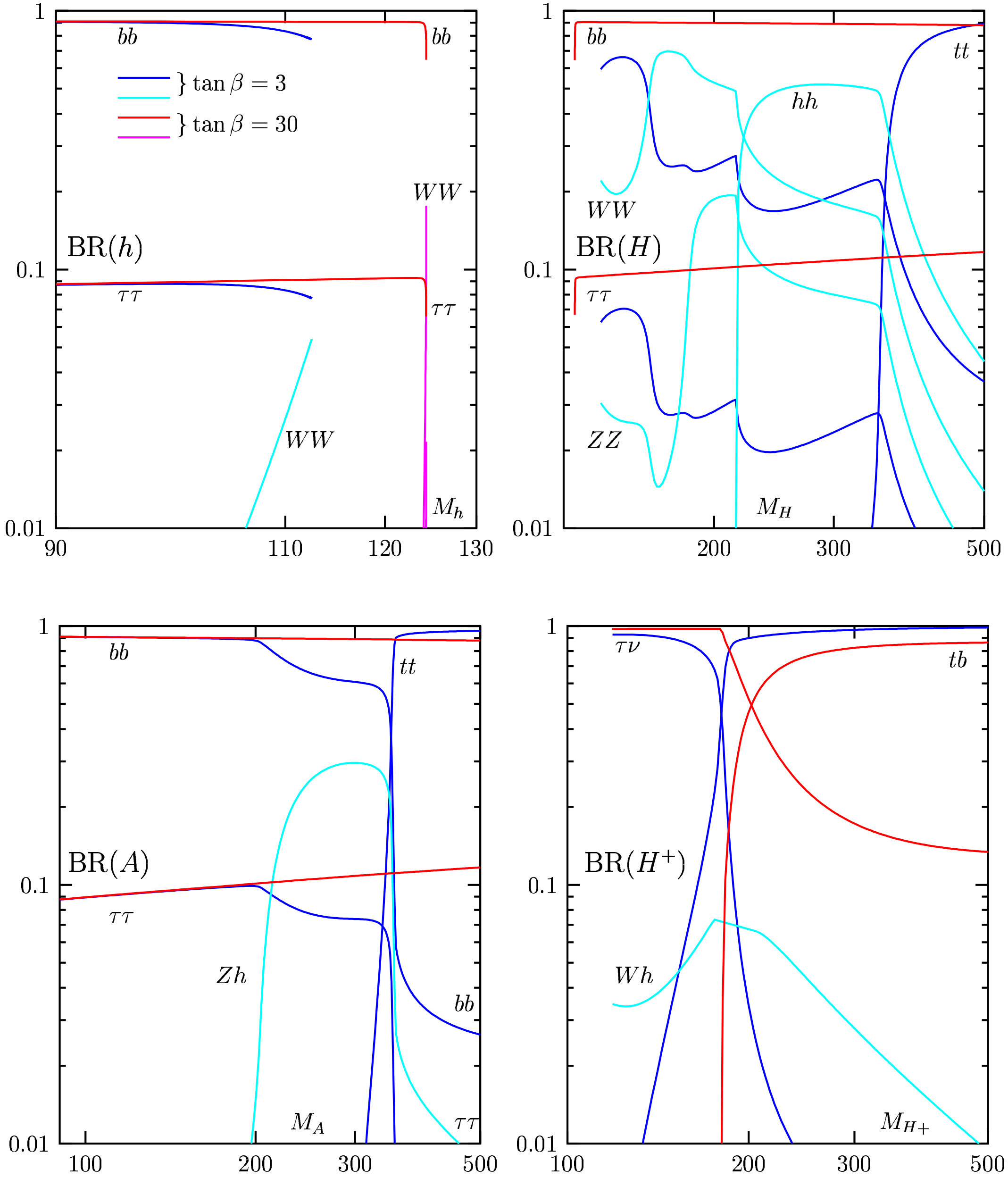

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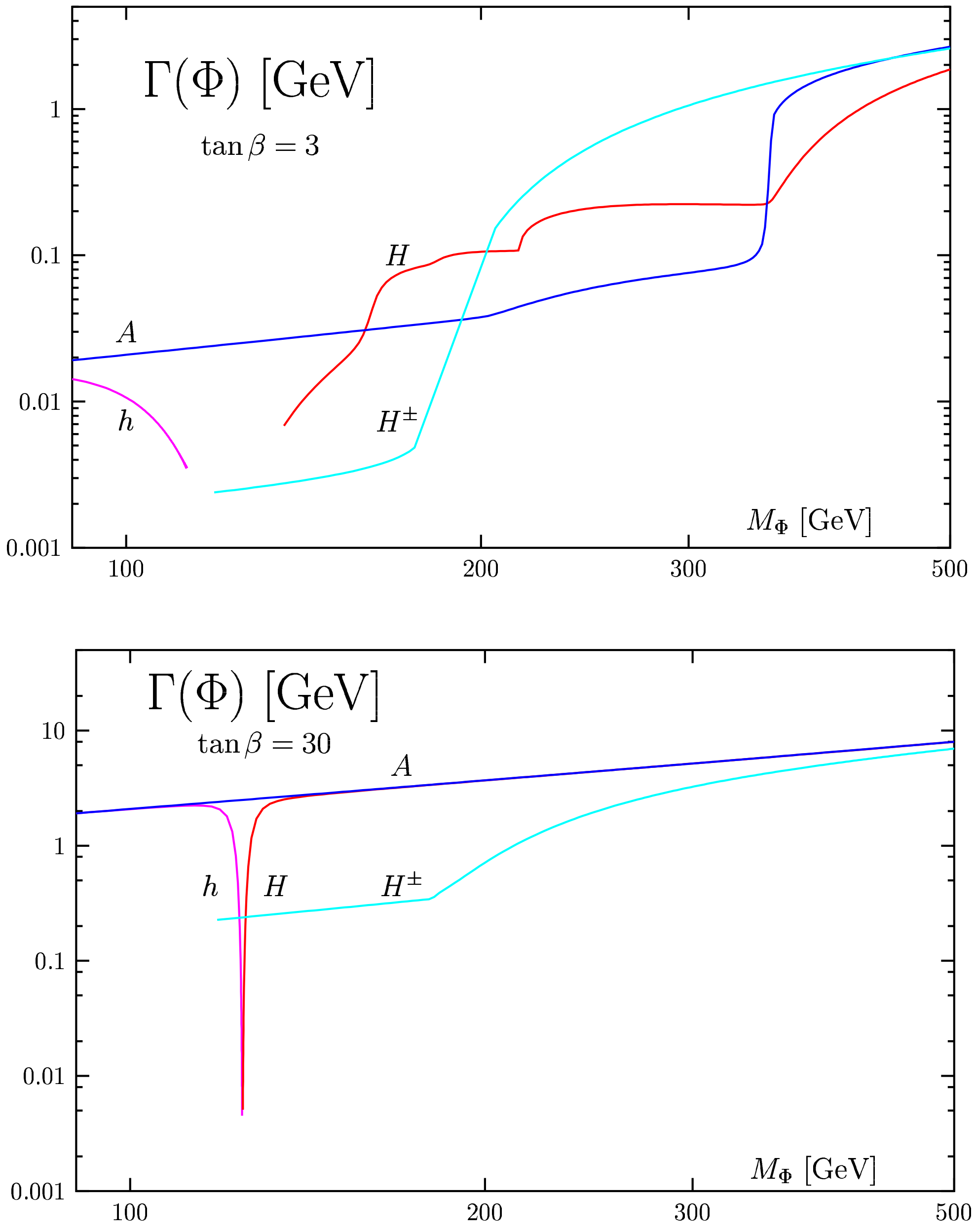
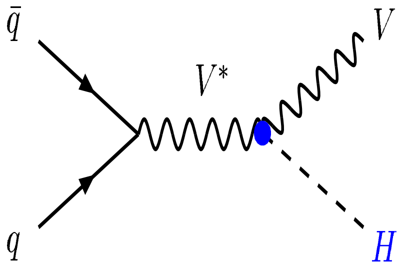


4. Production at LHC

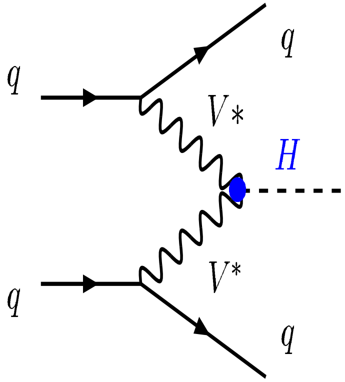
SM production mechanisms

[assuming heavy sparticles]

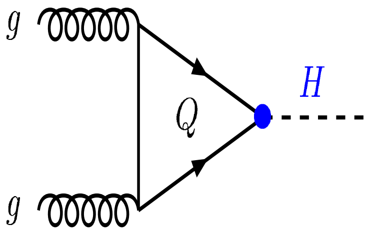
Higgs–strahlung



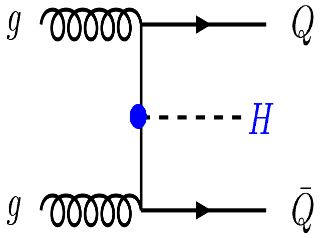
Vector boson fusion



gluon–gluon fusion



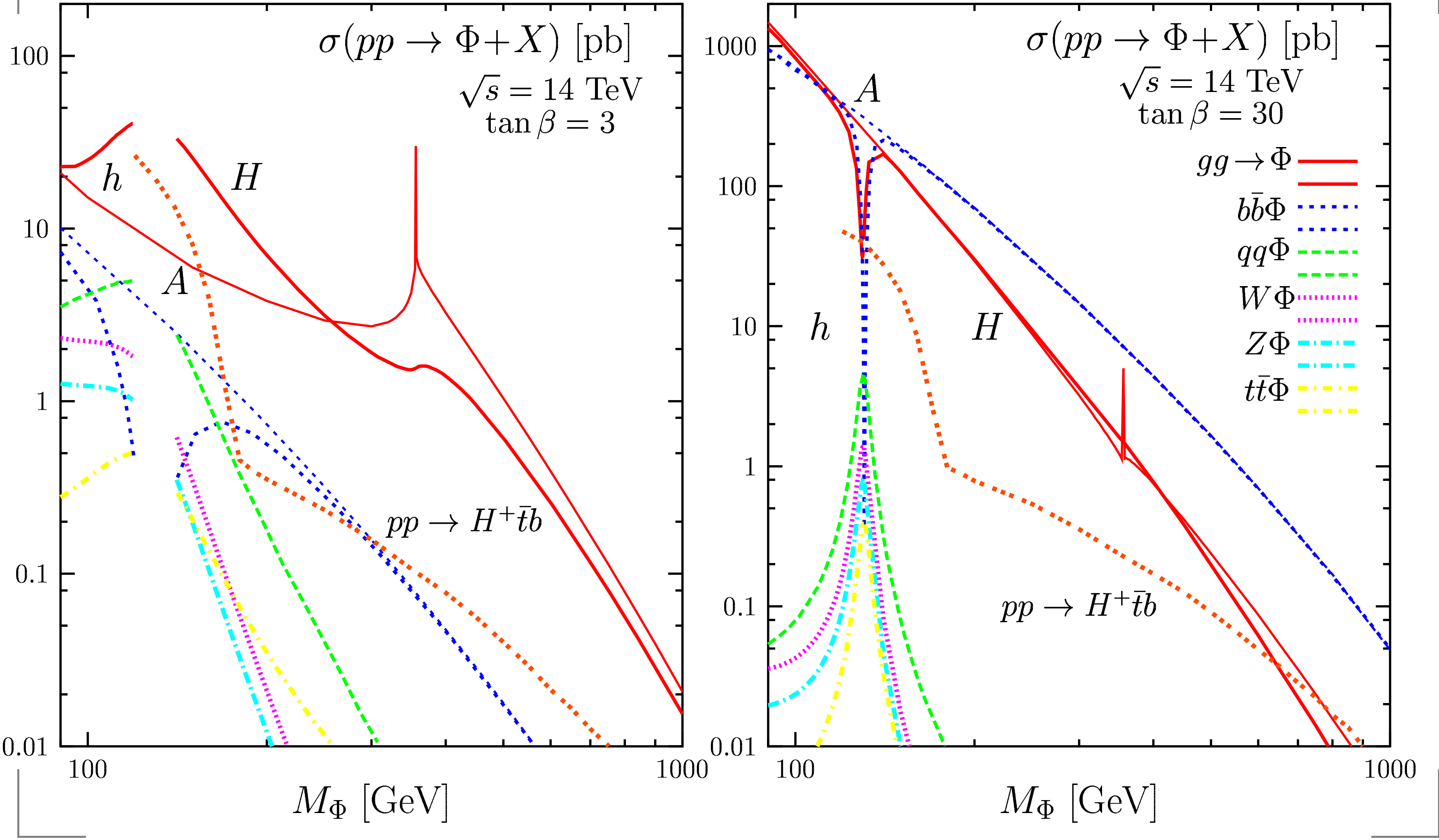
in associated with $Q\bar{Q}$



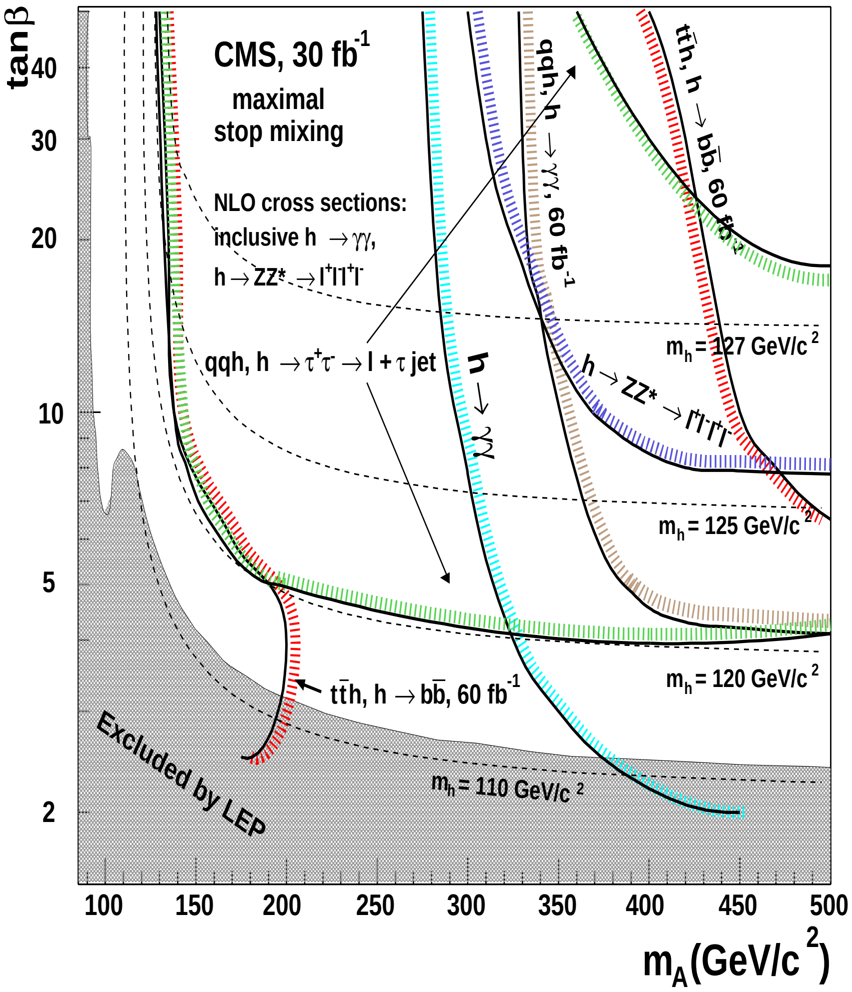
What is different in MSSM

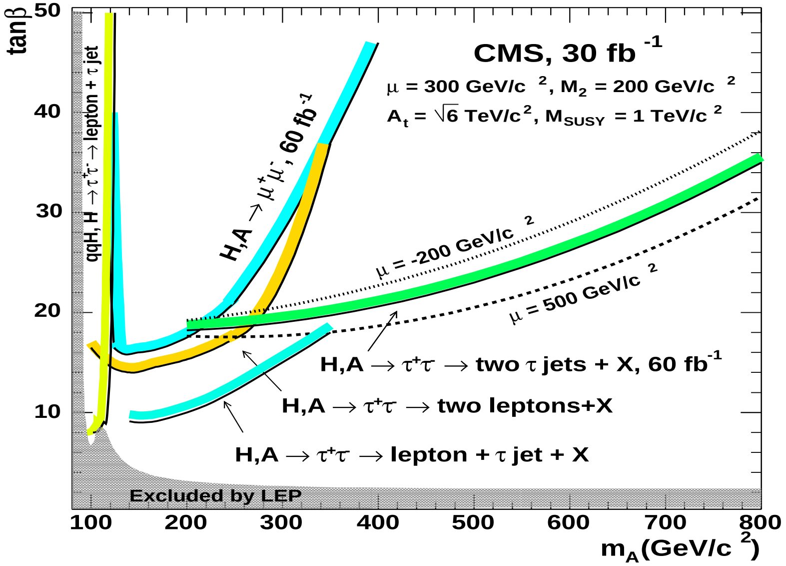
- **All work for CP–even h,H bosons.**
- **– in $\mathbf{\Phi V}$, $\mathbf{qq\Phi}$ h/H complementary**
- **–** $\sigma(\mathbf{h})+\sigma(\mathbf{H})=\sigma(\mathbf{H_{SM}})$
- **– aditionnal mechanism: q$\bar{q}\to$A+h/H**
- **For $gg\to\Phi$ and $pp\to tt\Phi$**
- **– include the contr. of b–quarks**
- **– dominant contr. at high $\tan\beta$!**
- **For pseudoscalar A boson:**
- **– CP: no $\mathbf{\Phi A}$ and $\mathbf{qqA}$**
- **– $gg\to A$ and $pp\to bbA$ dominant.**
- **For charged Higgs boson:**
- **– $\mathbf{M_H}\lesssim\mathbf{m_t}$: $pp\to t\bar{t}$ with $t\to H^+b$**
- **– $\mathbf{M_H}\gtrsim\mathbf{m_t}$: continuum $pp\to t\bar{b}H^-$**

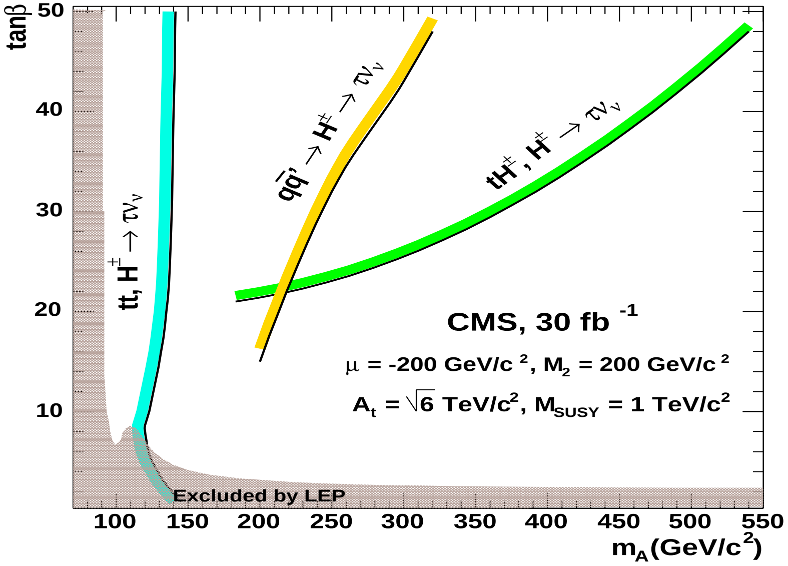
4. Production at LHC: cross sections



4. Production at LHC: detection







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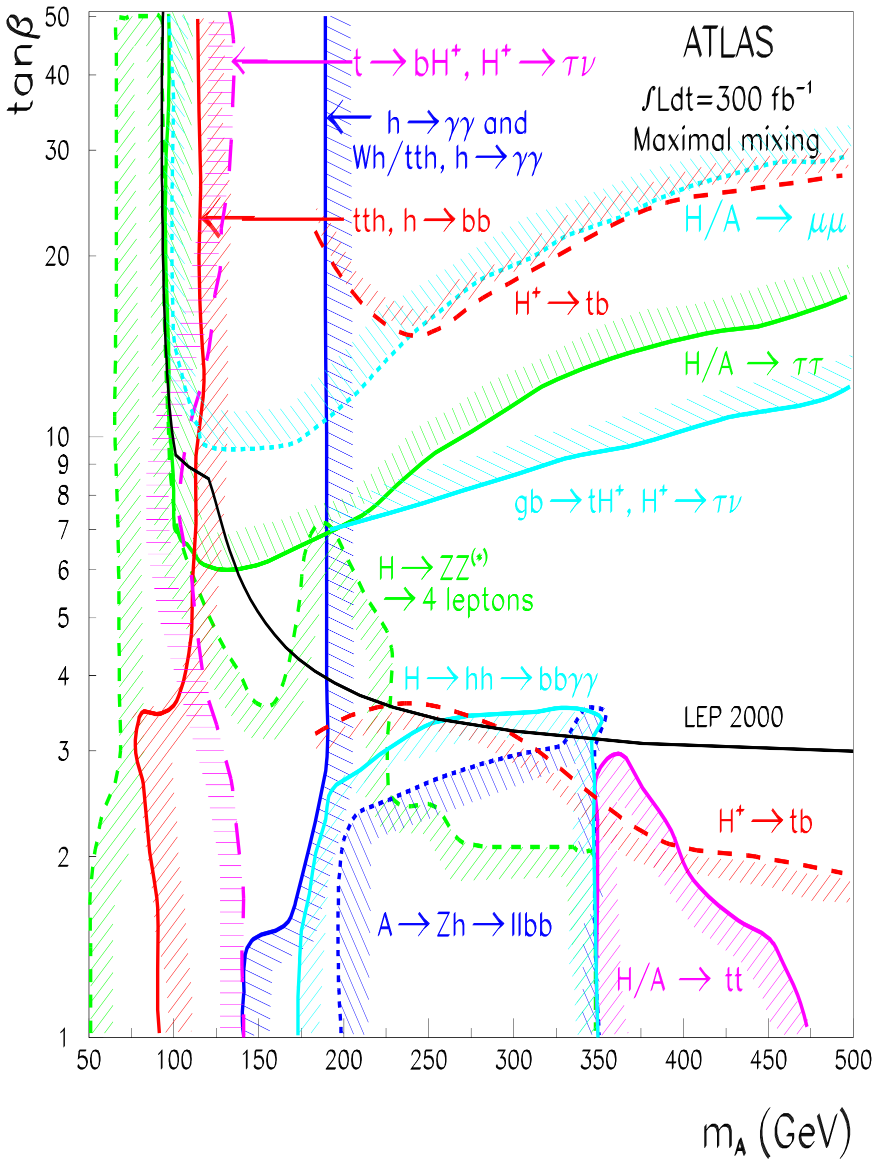

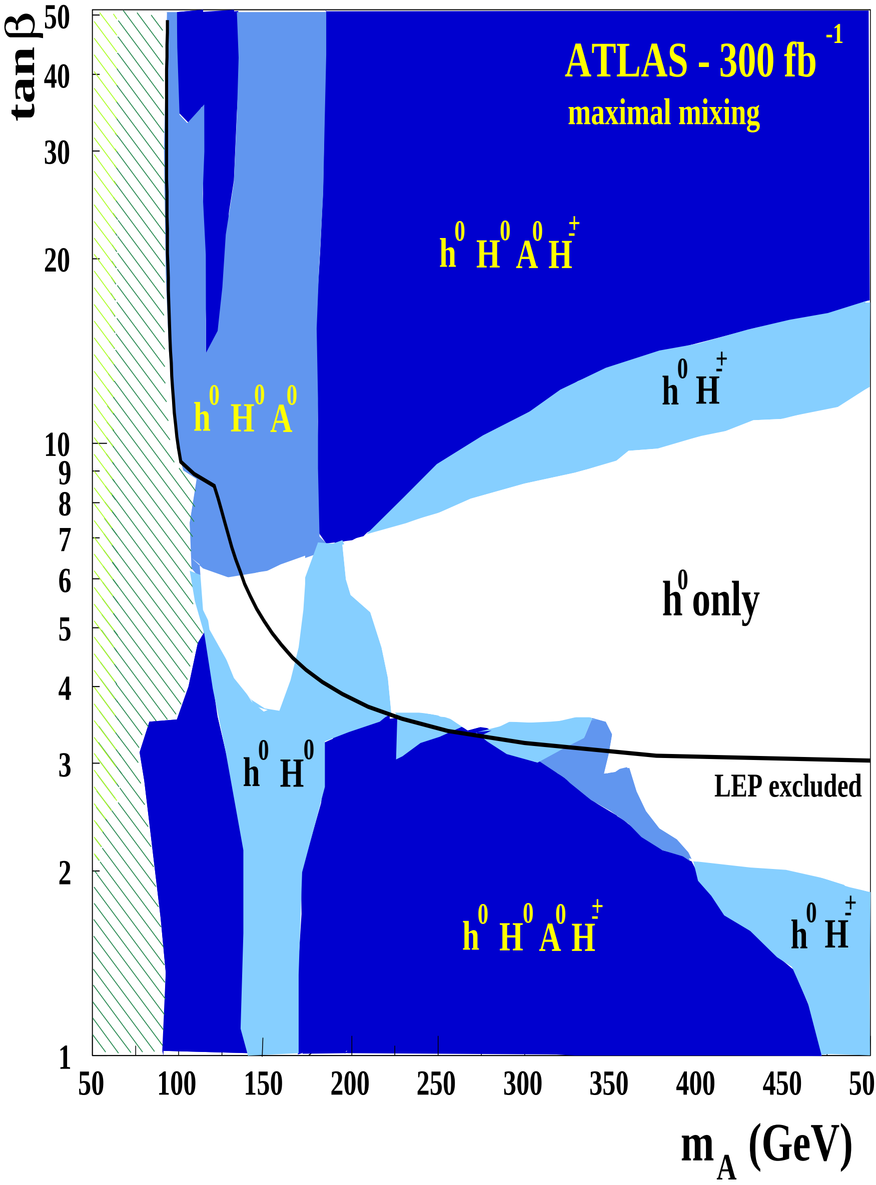

4. Production at LHC: warnings

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:

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

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- 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!

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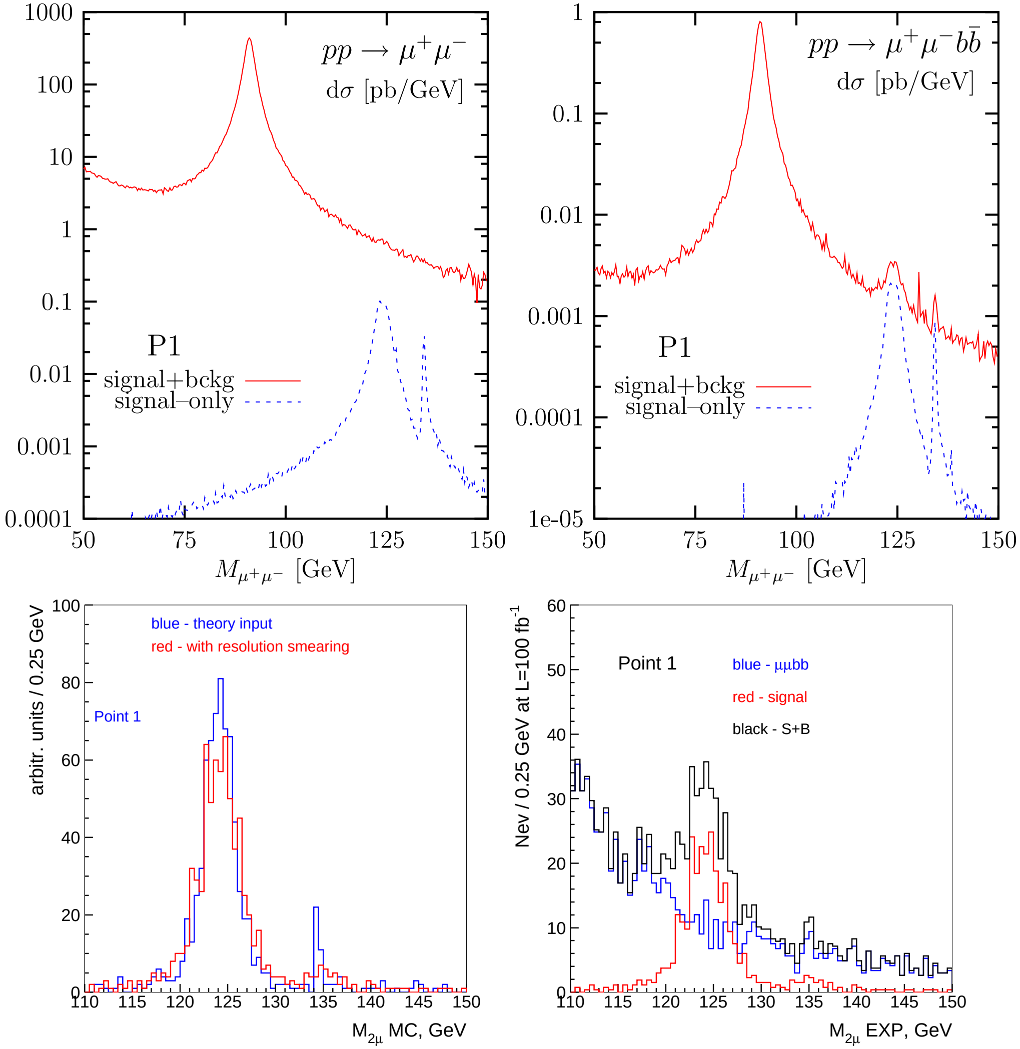

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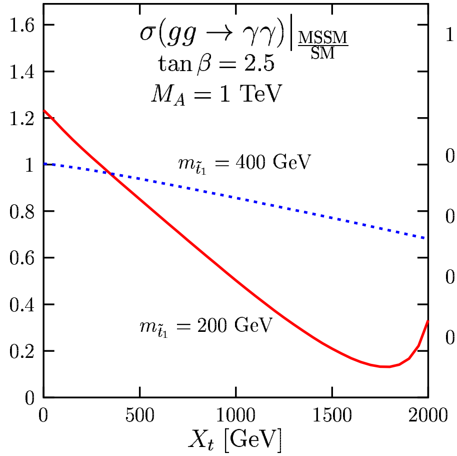

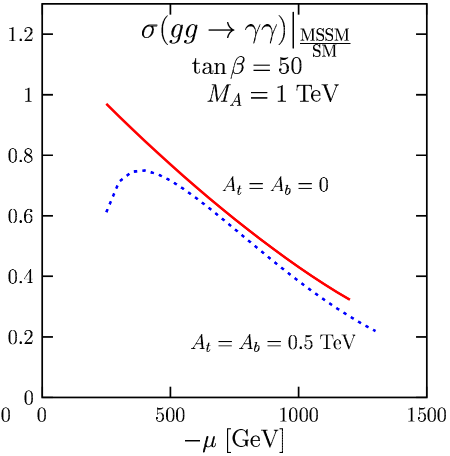

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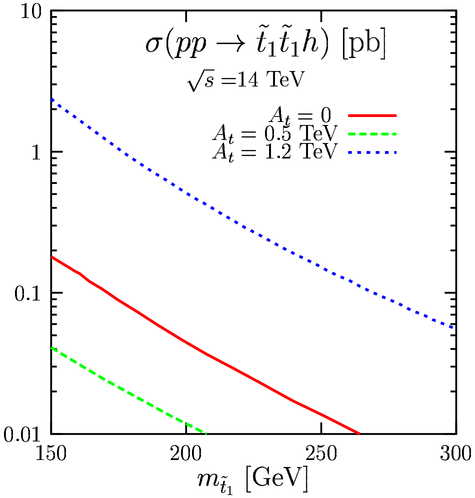

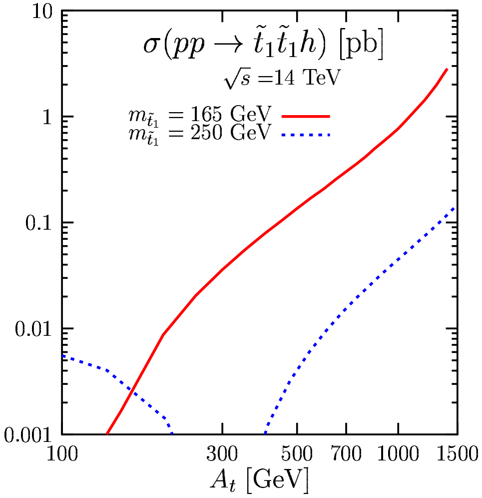

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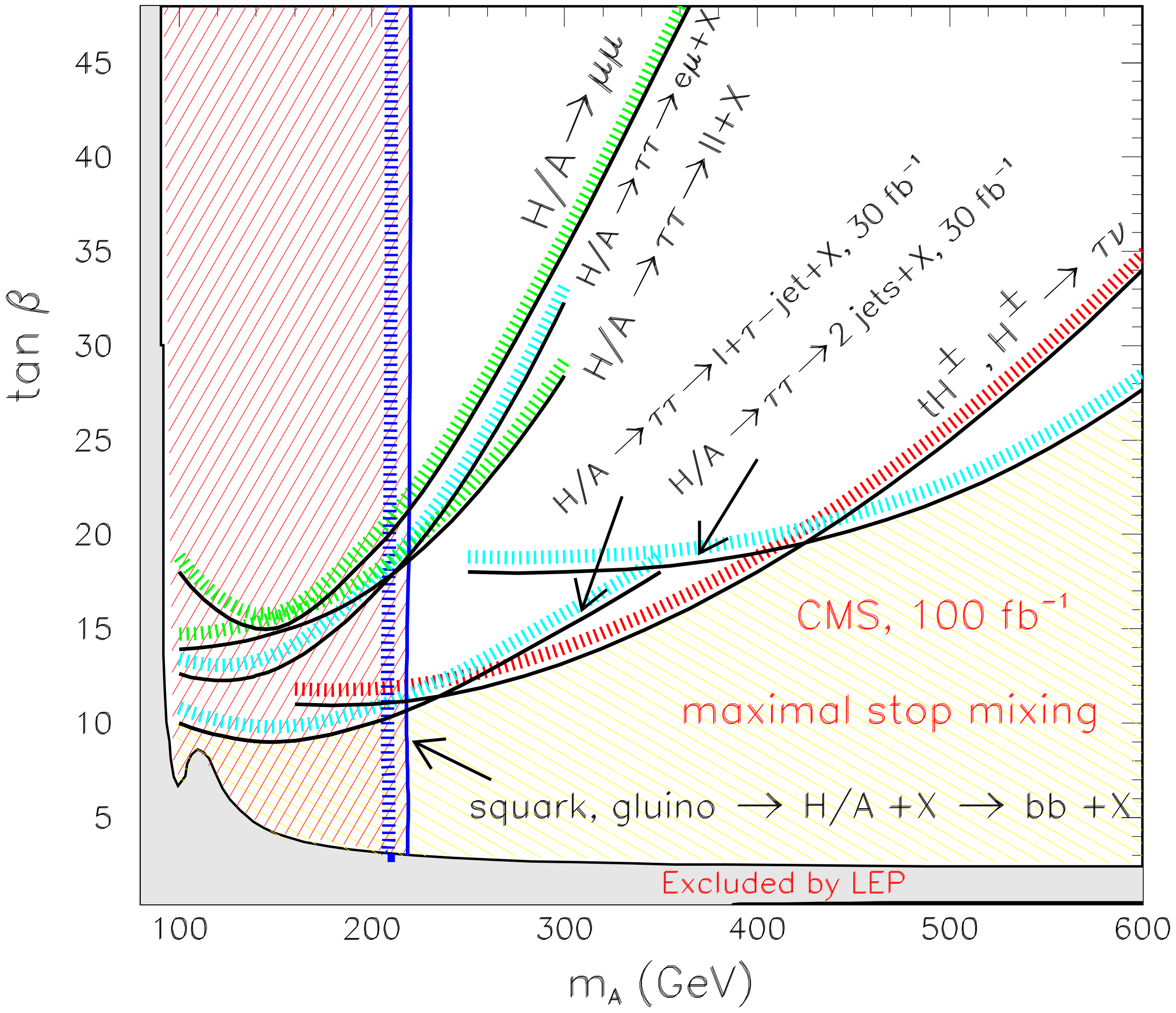

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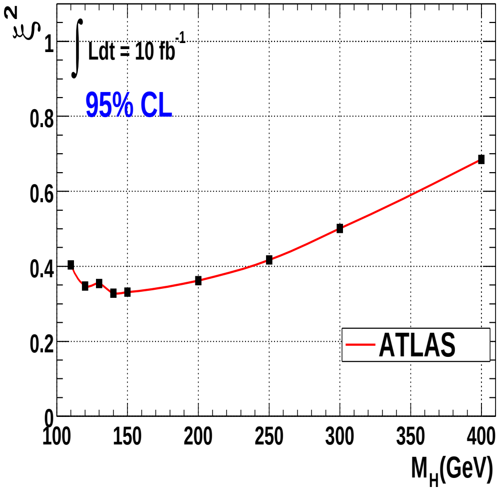

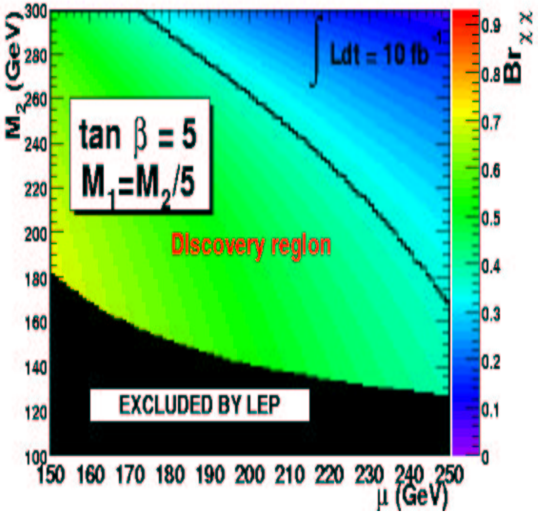

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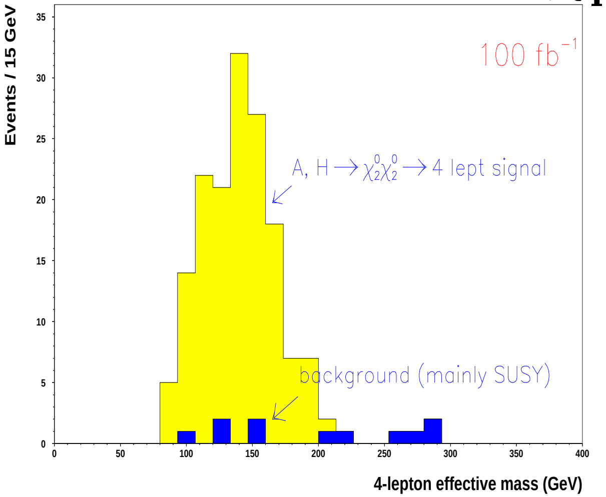

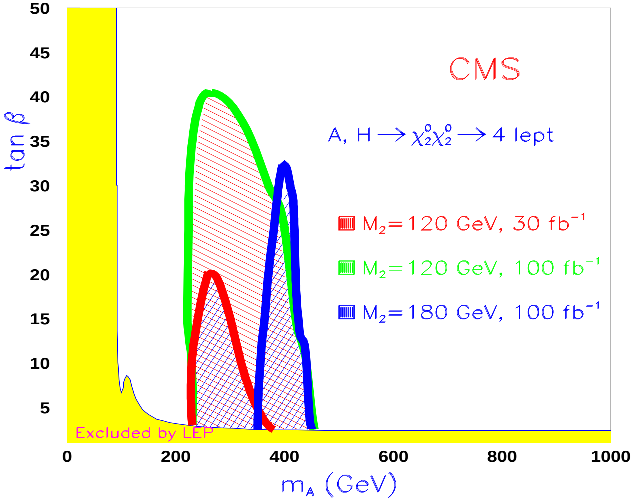

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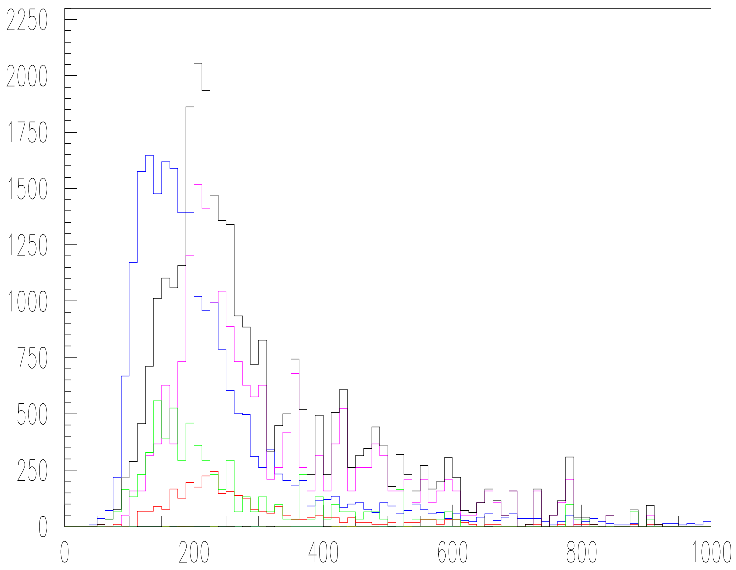

— $h_1 \to a_1 a_1 \to b\bar{b}\tau^+\tau^- \times 500$.

— $t\bar{t}$, — $\gamma^* \to e^+e^-, \mu\mu$, — $Z \to \tau^+\tau^-$,

— **total background.**

Conclusion?

The LHC will tell!