SMR 1773 - 12

SCHOOL ON PHYSICS AT LHC: "EXPECTING LHC"
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Higgs bosons searches at LHC
Part III

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The Higgs at the LHC

Abdelhak DJOUADI (LPT Orsay)

- **The Higgs boson in the Standard Model**
- **The SM Higgs at the LHC**
- **The Higgs boson in SUSY theories**
- **The SUSY Higgs bosons at the LHC**

1. **Beyond the SM and SUSY**
2. **The Higgs sector of the MSSM**
3. **SUSY Higgs decays**
4. **SUSY Higgs production at the LHC**

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:

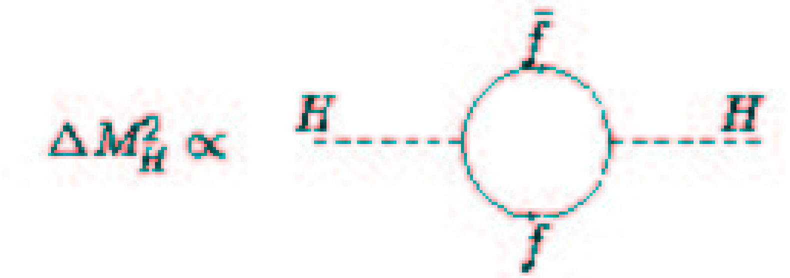
- **Too many free parameters (19!) in the model, put by hand...**
- **No satisfactory explanation for $\mu^2 < 0$ (put ad hoc).**
- **Does not include the fourth fundamental force, gravity, ..**
- **Does not say anything about the masses of the neutrinos.**
- **No real unification of the three gauge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

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

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 $\mathbf{M_{\rm GUT}}$ 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: $M_H^2|^{\rm Physical} = M_H^2|^0 + \Delta M_H^2$+ 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 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.

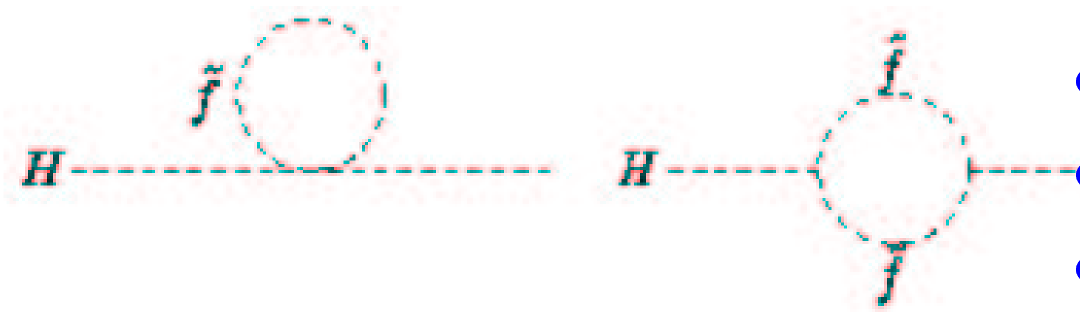
Photon and fermion masses protected by gauge and chiral symmetry,

.... 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



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

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

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 $M_S \gg 1$ TeV the fine tunning problem is back!!!

1. BSM & SUSY: SUSY

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

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

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 $H_1 = \binom{H_1^0}{H_1^-}$ and $H_2 = \binom{H_2^+}{H_2^0}$.

- 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

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

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 $V_H{}^{\min}$ breaks $G_{SM} \to U(1)_{QED}$ (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:

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

2. The Higgs spectrum: scalar potential

Some remarks on this scalar potential:

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

- **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

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

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 $\mathbf{H^\pm}$:

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

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 $\mathbf{M_Z}$ and should have been seen at LEP2

(we have $\sqrt{\mathbf{s}}_{\rm LEP2} \sim \mathbf{200\ GeV} \ > \mathbf{M_h + M_Z} \sim \mathbf{180}$ 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 $\mathbf{htt}$ and $\mathbf{h\tilde{t}\tilde{t}}$ couplings.

$\Rightarrow$ Calculation of radiative corrections to $\mathbf{M_h}$ 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 $m_t|^{\rm pole} \to m_t|^{\overline{\rm MS}}$.

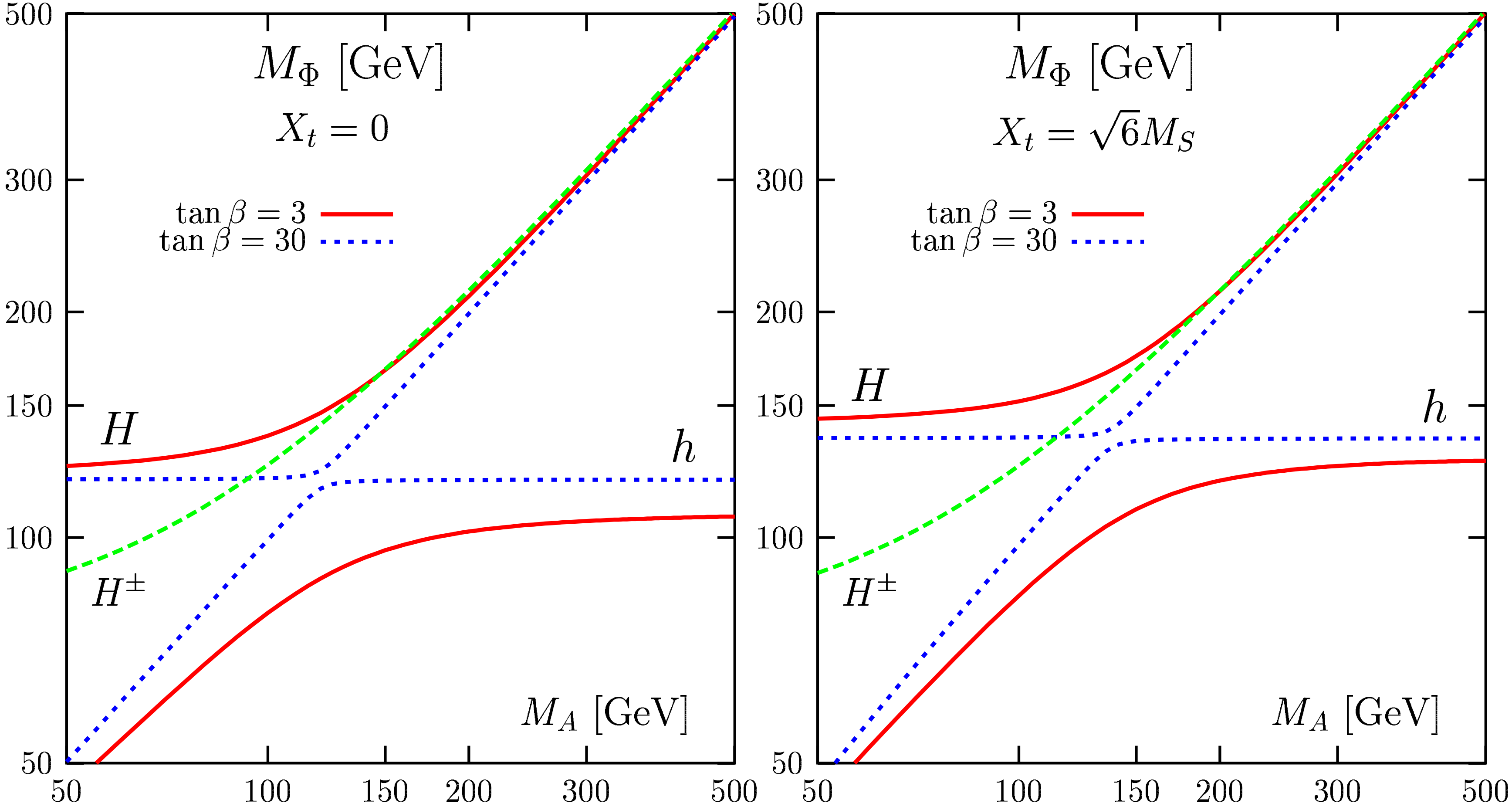
– Yukawa corrections rather small in the limit $M_h = 0$.

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. Higgs Decays

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)**

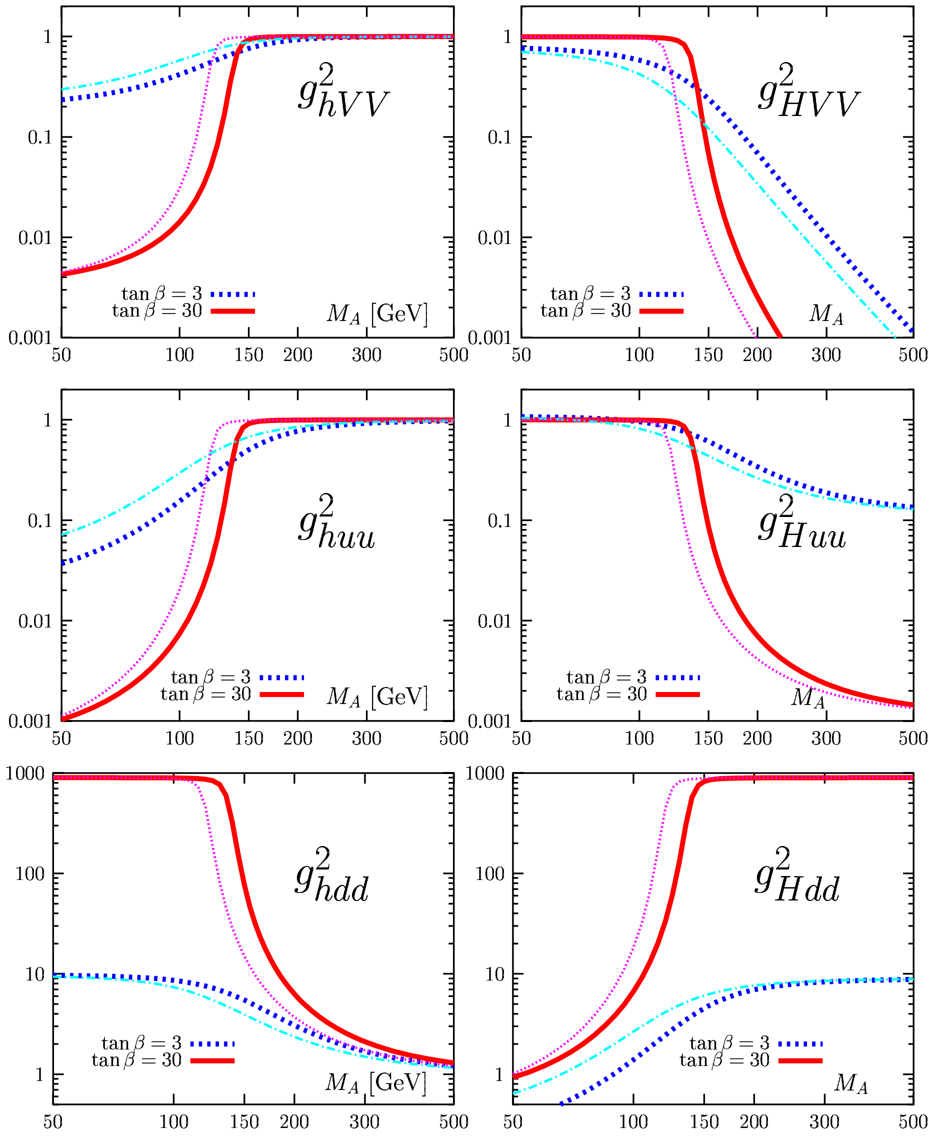
– **For $\tan\beta > 1$: cplgs to d enhanced, cplgs to u suppressed.**

– **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.**

3. Decays: SUSY Higgs couplings

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



3. Decays: MSSM Higgs particles

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 ($h/A/H \to b\bar{b}, h \to gg)$.

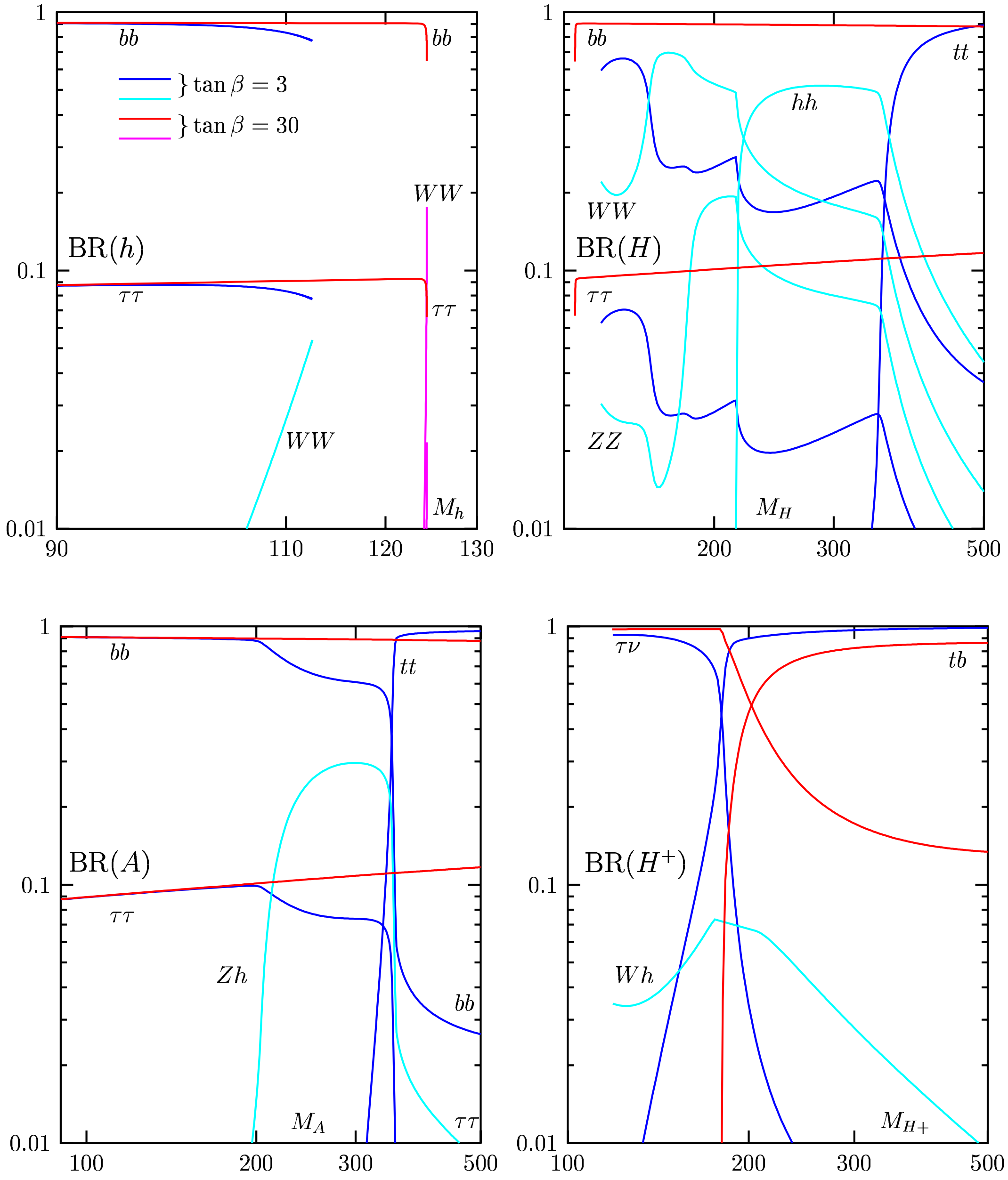
– Decays into sparticles if kinematically allowed significant:

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

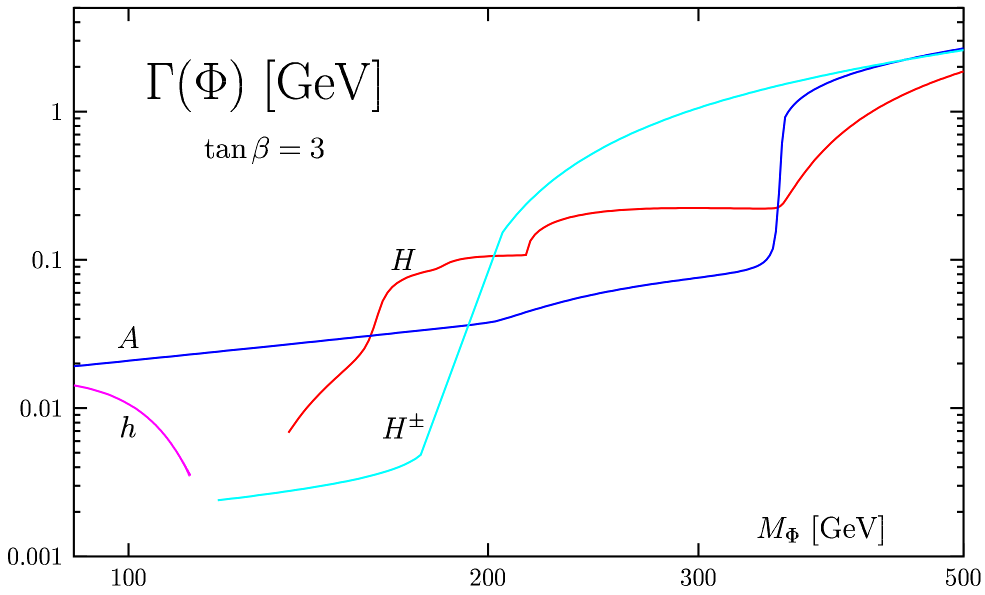
$H, A \to \chi_i^+\chi_j^-, \chi_i^0\chi_j^0$ and $H^\pm \to \chi_i^0\chi_j^\pm$ important for low $\tan\beta$.

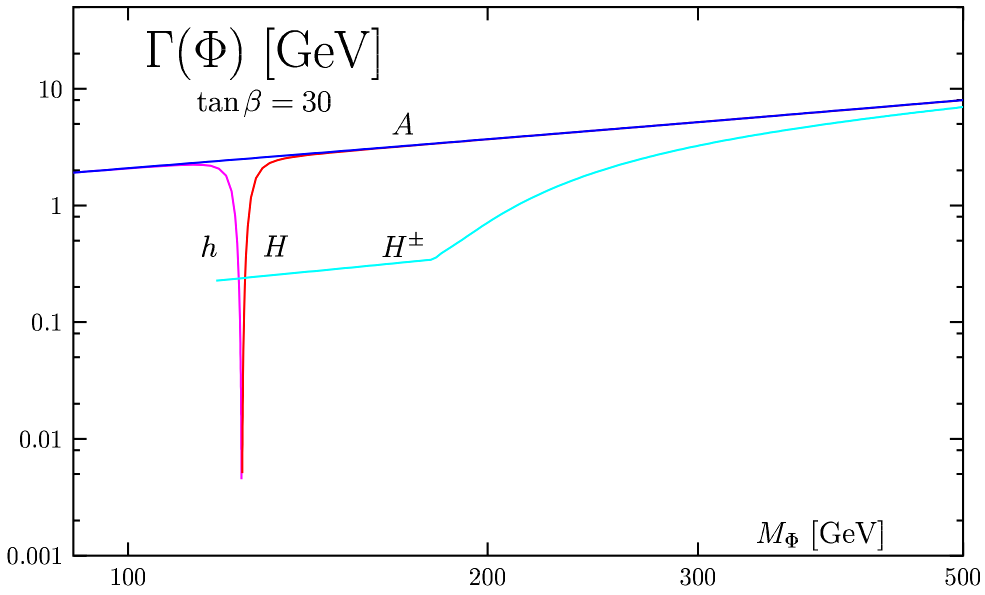
Total decay widths: Small compared to SM (no V_L contribution).

3. Decays: BR MSSM Higgs particles



3. Decays: MSSM Higgs particle widths



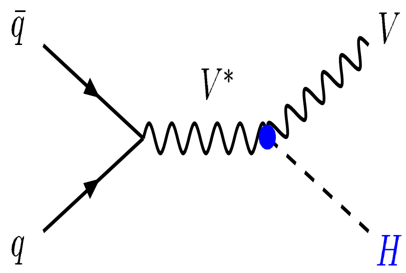


4. Production at LHC

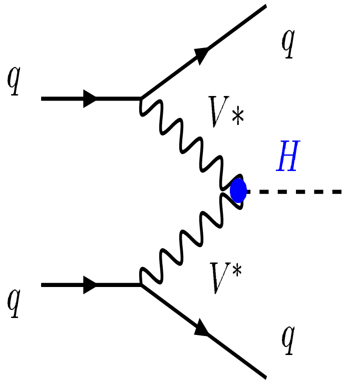
SM production mechanisms

[assuming heavy sparticles]

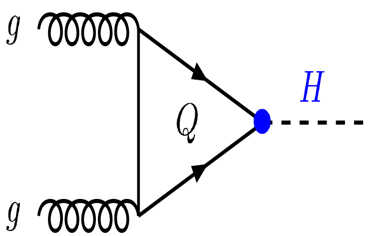
Higgs–strahlung



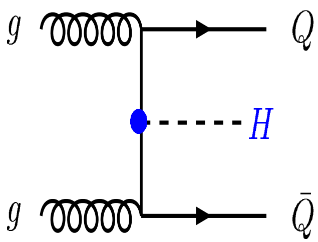
Vector boson fusion



gluon–gluon fusion



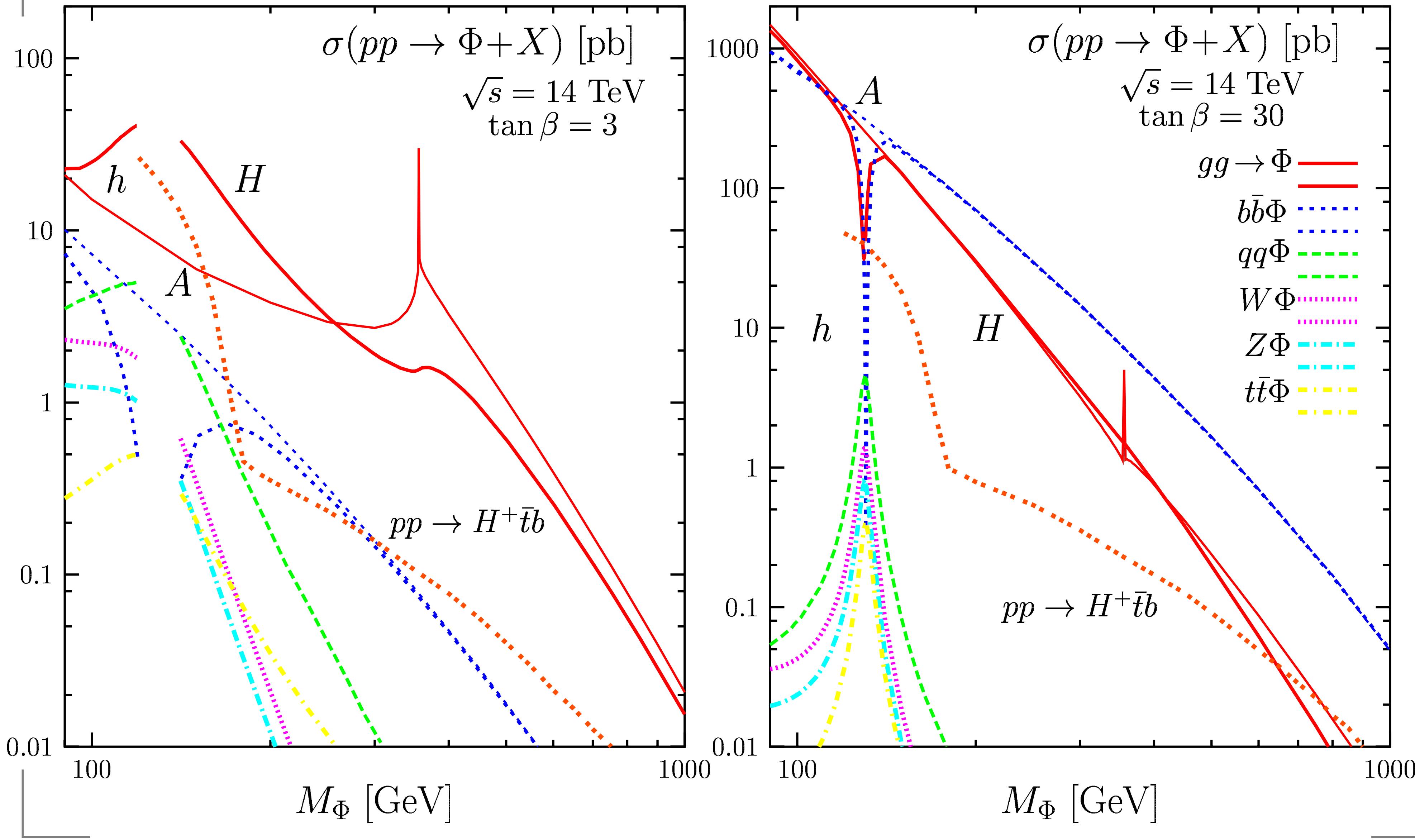
in associated with $Q\bar{Q}$



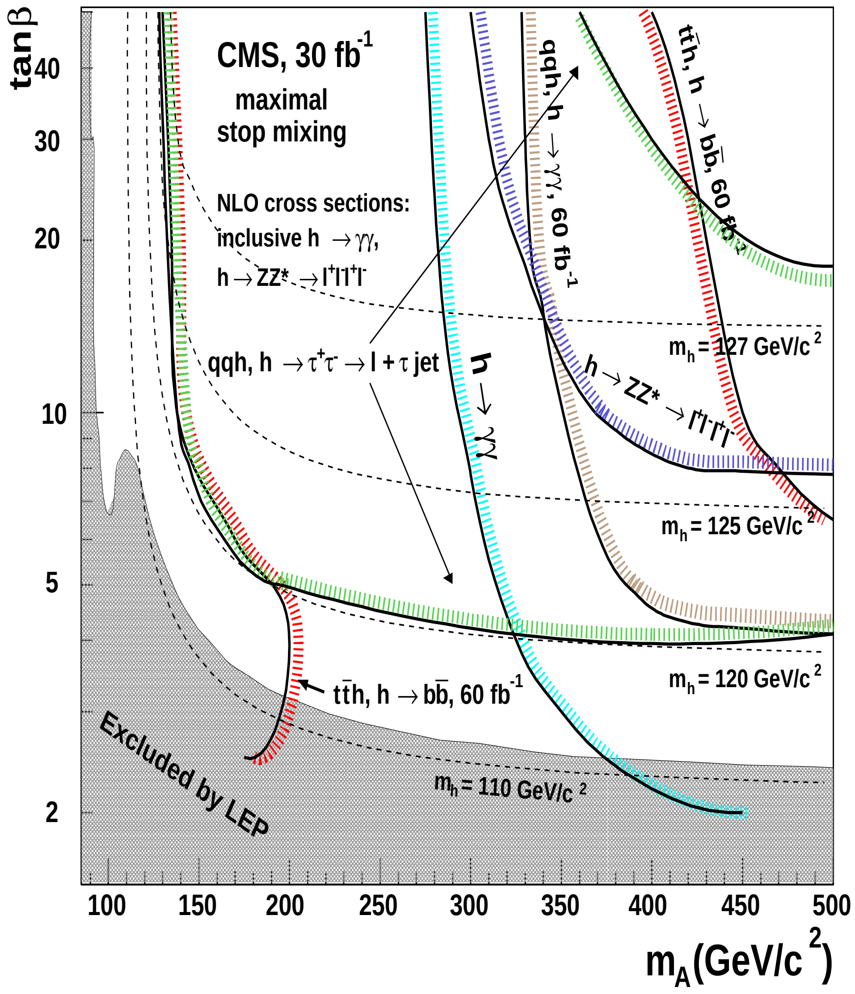
What is different in MSSM

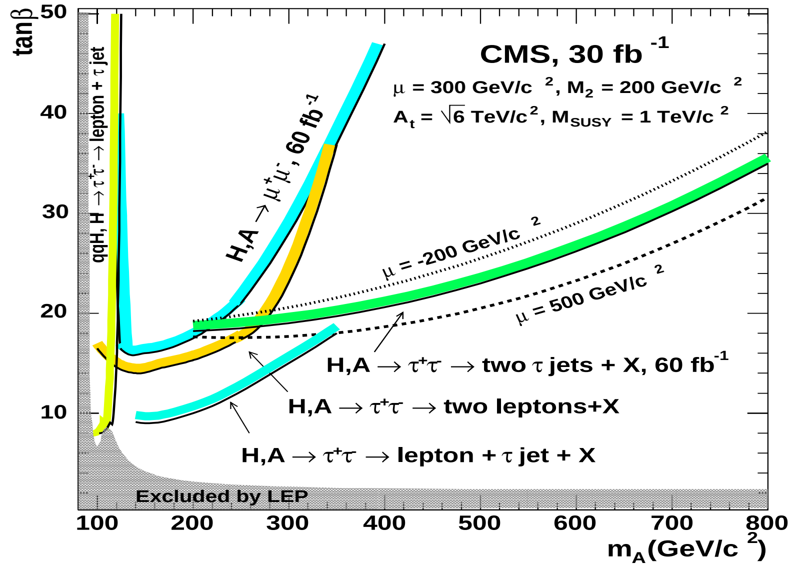
- **All work for CP–even h,H bosons.**
- **– in $\Phi\mathbf{V}$, $\mathbf{qq}\Phi$ h/H complementary**
- **–** $\sigma(\mathbf{h}) + \sigma(\mathbf{H}) = \sigma(\mathbf{H_{SM}})$
- **– aditionnal mechanism: q$\bar{q} \to$A+h/H**
- **For** $gg \to \Phi$ **and** $pp \to tt\Phi$
- **– include the contr.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

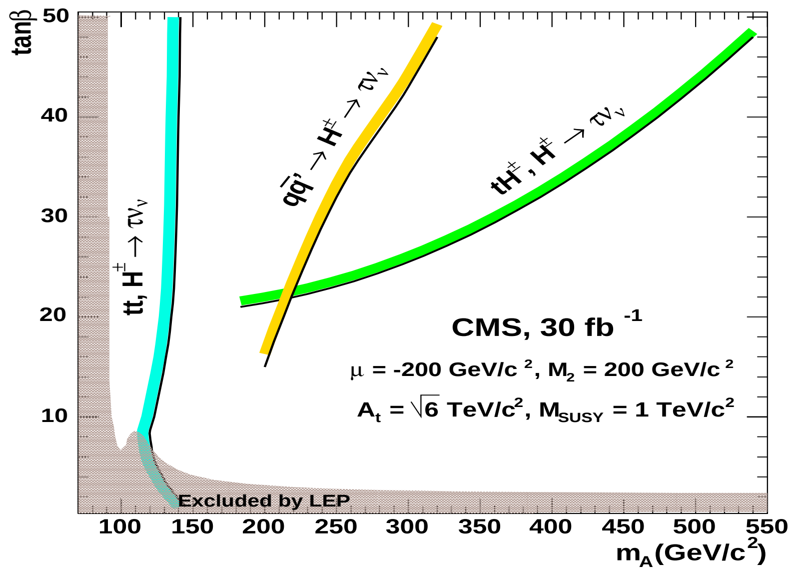
4. Production at LHC: cross sections



4. Production at LHC: detection







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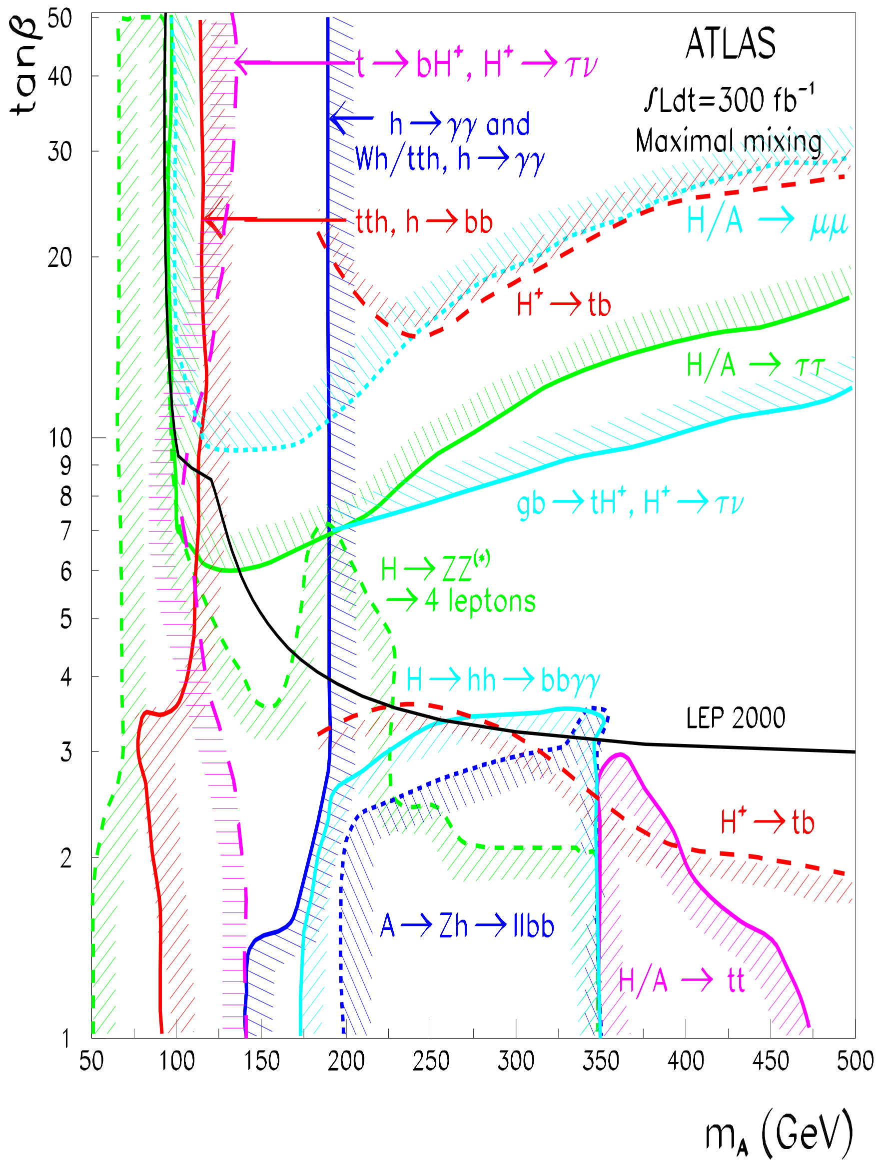

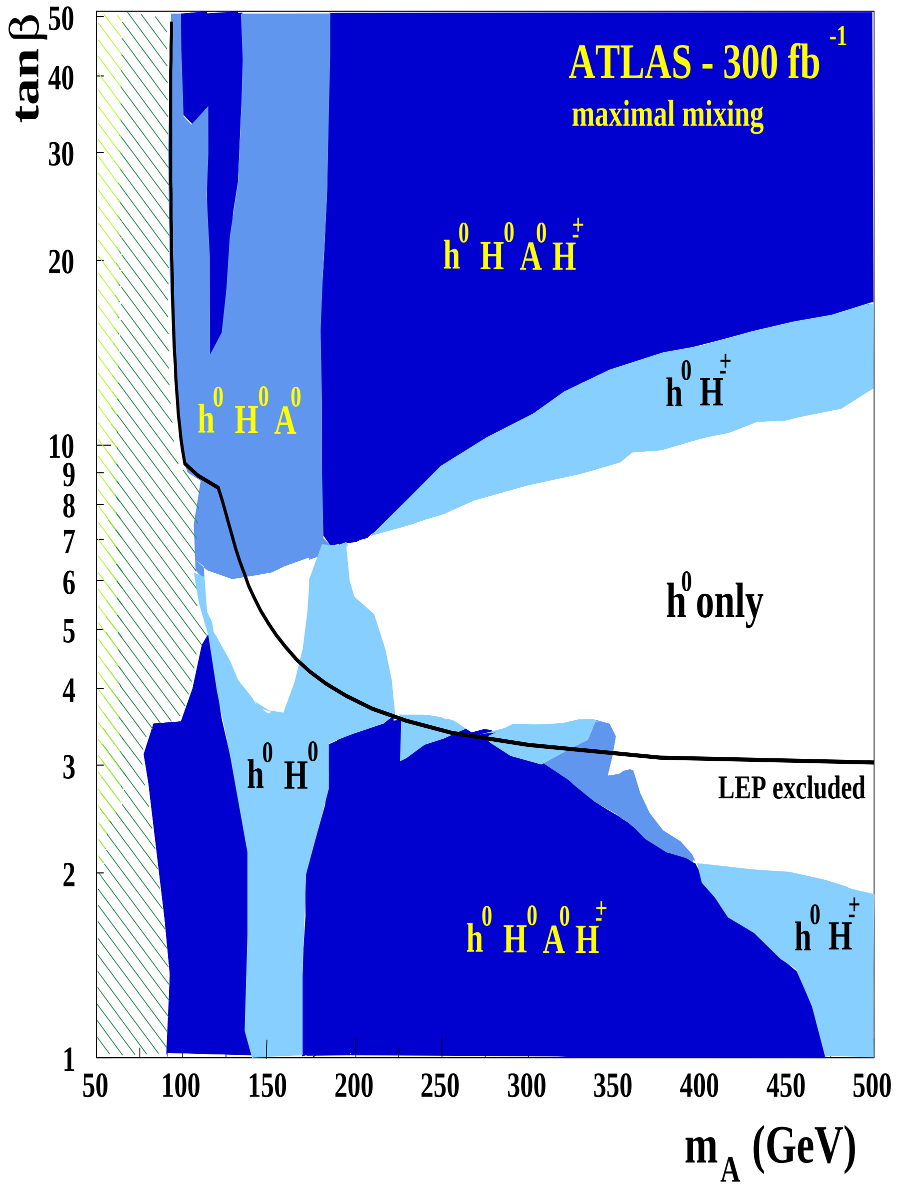

4. Production at LHC: warnings

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:**

– $h \to \chi_1^0\chi_1^0, \tilde{\nu}\tilde{\nu}$ 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!

4. Production at LHC: warnings

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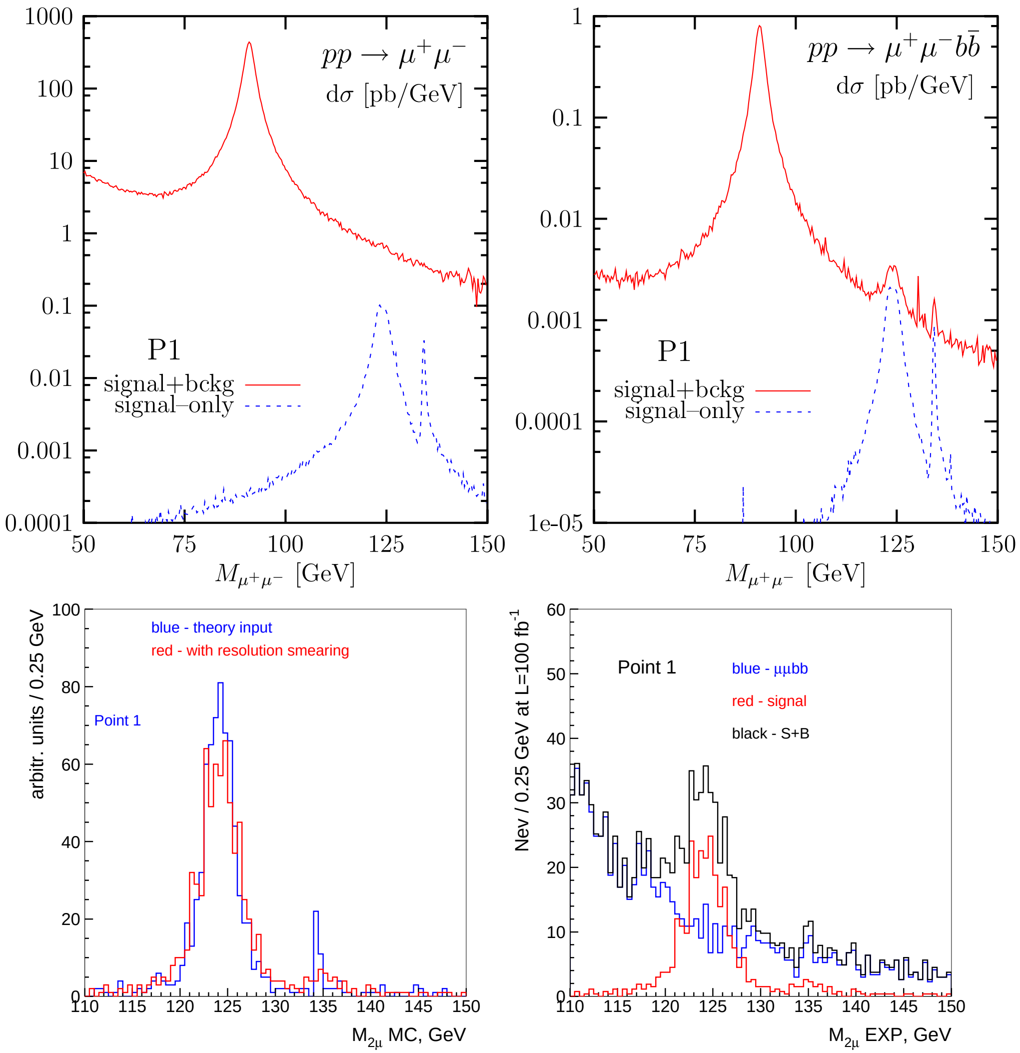

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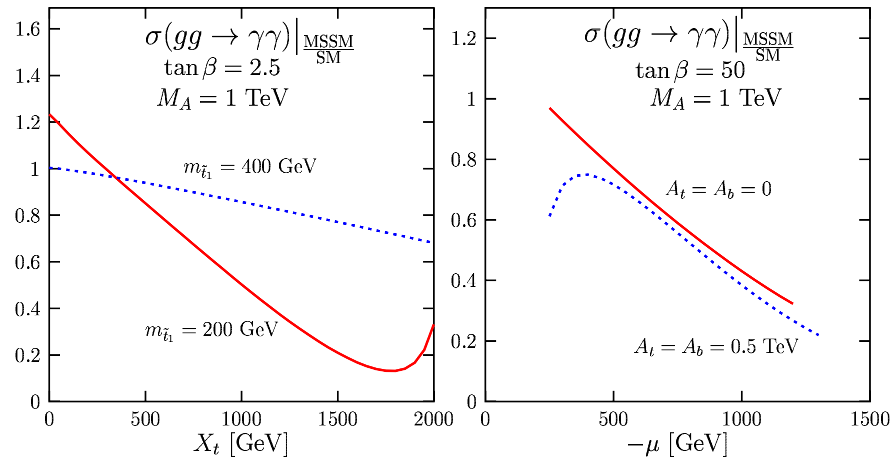
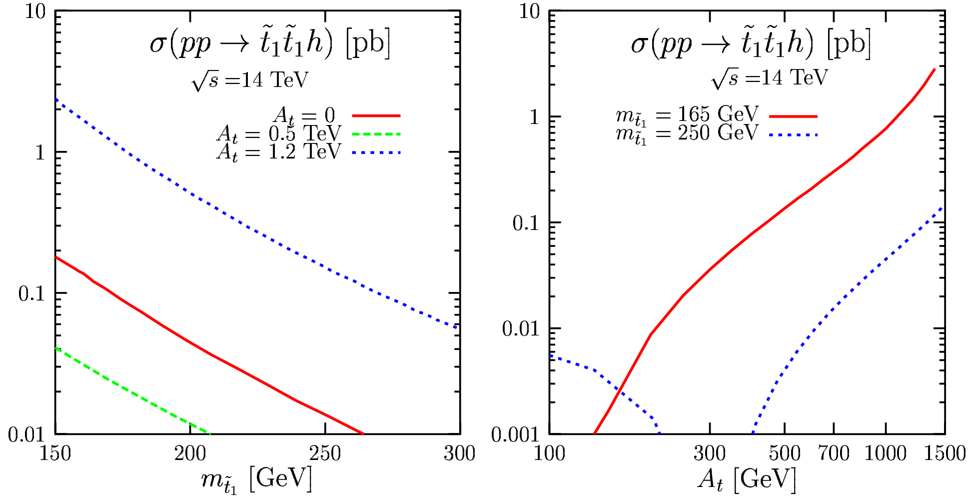


– Higgsses can be produced with sparticles ($pp \to \tilde{t}\tilde{t}^* h$,..).



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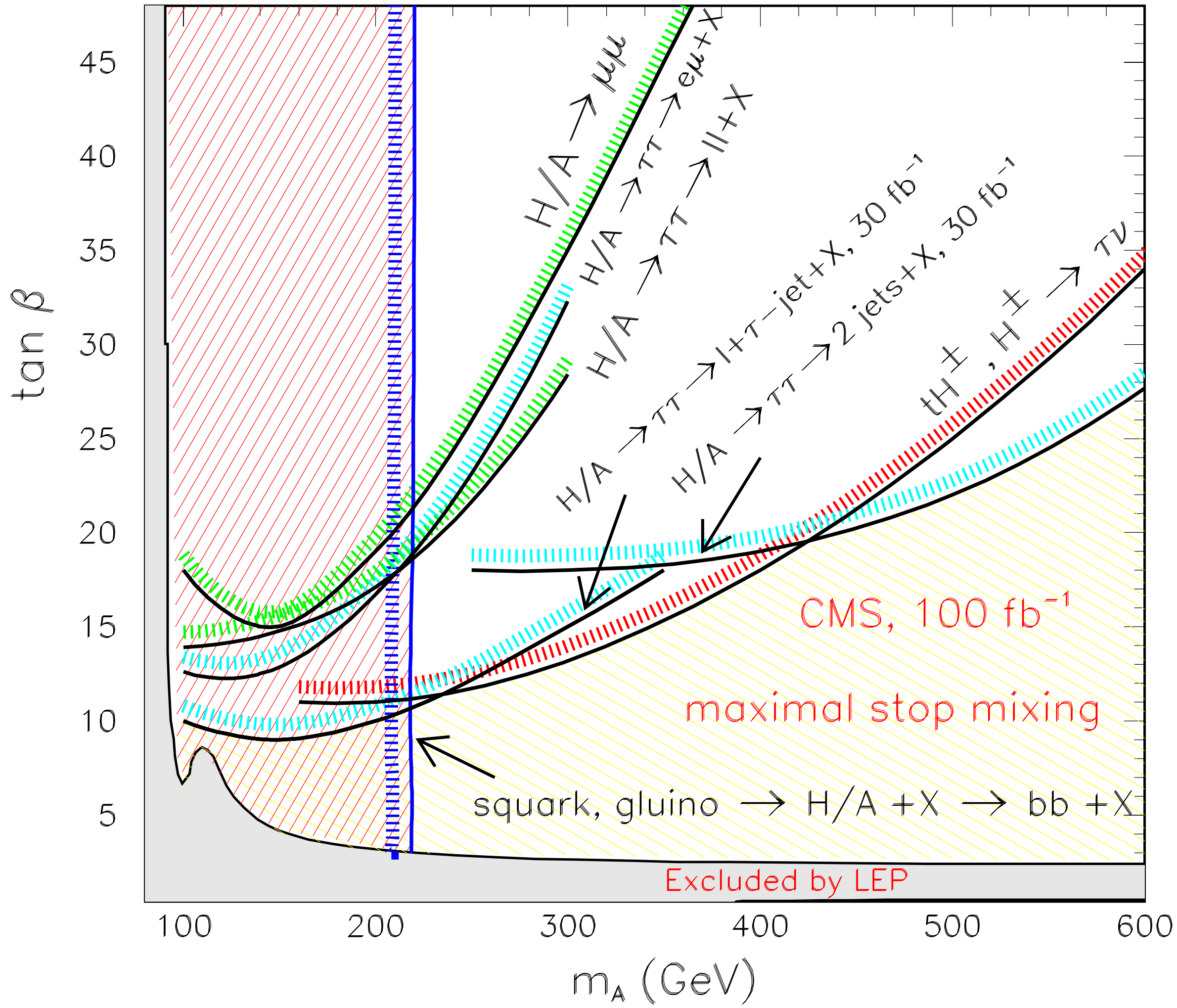

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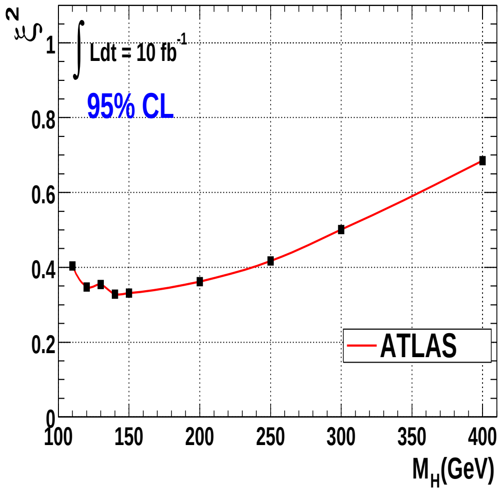
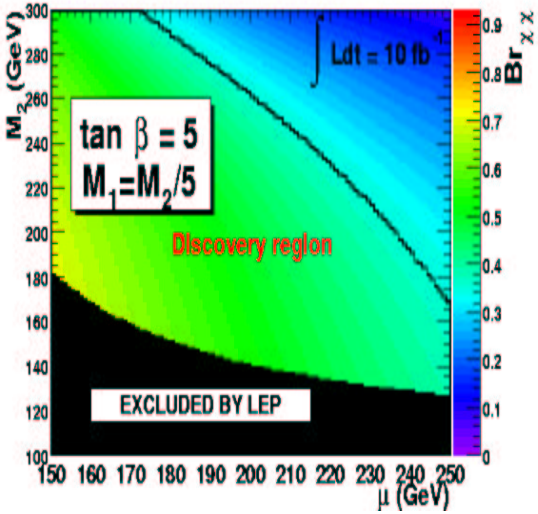
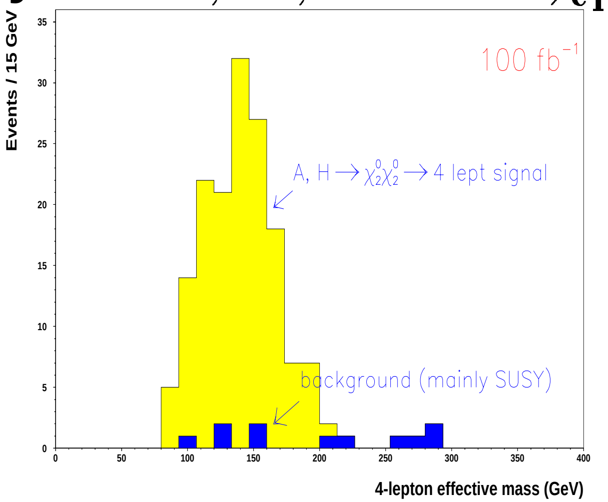
- **SUSY decays, if allowed, might alter the search strategies:**

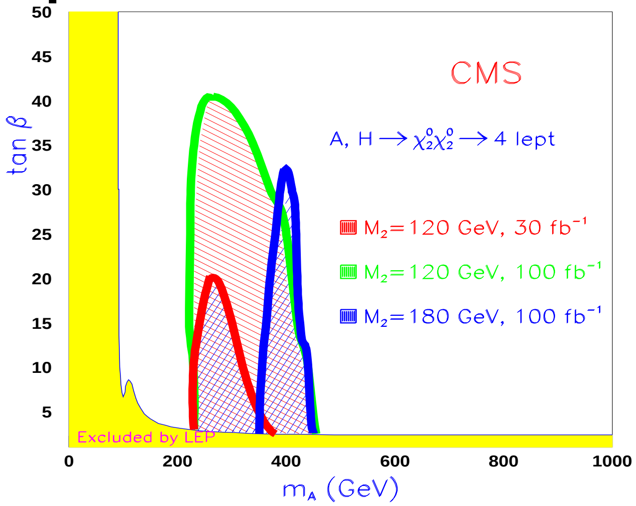
– $h \to \chi_1^0 \chi_1^0, \tilde{\nu}\tilde{\nu}$ **are still possible in non universal models...**





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

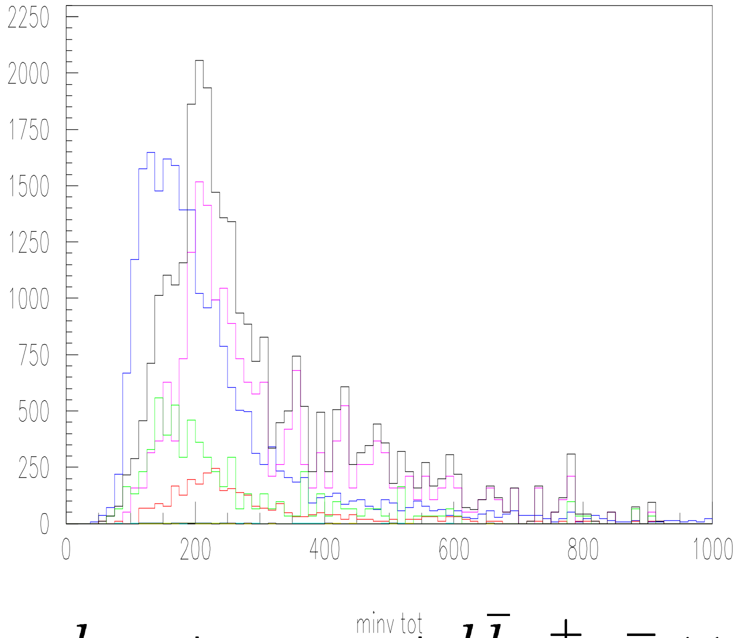




4. Production at LHC: warnings

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.**



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

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

—— **total background.**

Conclusion?

The LHC will tell!