

SUSY Higgses at the LHC

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SUSY and Higgs: the framework

- 1. The Higgs spectrum in the MSSM**
- 2. Higgs decay and production at the LHC**
- 3. Difficult scenarios in the conventional MSSM**
- 4. Beyond the conventional MSSM**
- 5. Conclusion**

SUSY and Higgs: the framework

Up to now, the focus was mainly on the Higgs sector of the
Minimal Supersymmetric Standard Model (MSSM):

- minimal gauge group: $SU(3) \times SU(2) \times U(1)$,
- minimal particle content: 3 fermion families and 2 Φ doublets,
- $R=(-1)^{(2S+L+3B)}$ parity is conserved,
- minimal set of terms (masses, couplings) breaking “softly” SUSY.

To reduce the number of the (too many in general) free parameters:

- impose phenomenological constraints: O(20) free parameters,
- unified models, O(5) parameters (mSUGRA: $m_0, m_{\frac{1}{2}}, A_0, \tan \beta, \epsilon_\mu$),
- in general sparticles assumed to be heavy: decouple from Higgs.

First summarize Higgs phenomenology in this (rather simple) model.

- there are still tricky scenarios which need further analyses....
- the impact of light SUSY particles might be important...
- the impact of relaxing some MSSM assumptions can be huge...

1. The MSSM Higgs sector

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 scalar potential V_H (comes from 3 sources: D, F and $\mathcal{L}_{\text{soft}}$ terms):

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

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

- quartic couplings fixed by gauge couplings, only 3 free parameters.
- $\bar{m}_{1,2}^2$ real, phase of $B\mu$ rotated away, $\Rightarrow V_H$ (MSSM) conserves CP.
- to have SSB, we need $\bar{m}_{1,2,3} \neq 0$, i.e. SUSY breaking. Connection!

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 ,

\Rightarrow Radiative EWSB: symmetry breaking more natural and elegant than in SM.

1. The Higgs spectrum: Higgs masses

- Develop in terms of components $H_1 = (H_1^0, H_1^-), H_2 = (H_2^+, H_2^0)$

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

Three dof to make $W_L^\pm, Z_L \Rightarrow 5$ physical states left out: h, H, A, H^\pm

The obtained physical Higgs masses and mixing angle are then:

$$M_A^2 = -2\bar{m}_3^2 / \sin 2\beta, \quad M_{H^\pm}^2 = M_A^2 + M_W^2$$
$$M_{h,H}^2 = \frac{1}{2} \left[M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta} \right]$$
$$\tan 2\alpha = \tan 2\beta (M_A^2 + M_Z^2) / (M_A^2 - M_Z^2)$$

While the mixing angle for the CP-odd and charged fields is simply β .

Only two free parameters at the tree level: $\tan \beta, M_A$

We have important constraint on the MSSM Higgs boson masses:

$$M_h \leq \min(M_A, M_Z) \cdot |\cos 2\beta| \leq M_Z, \quad M_{H^\pm} > M_W, \quad M_H > M_A \dots$$

$M_A \gg M_Z$: decoupling regime, all Higgses heavy except for h .

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

1. 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

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

$\propto m_t^4, \log(m_{\tilde{t}}^2/m_t^2)$, and large: $\frac{M_h^{\max} \rightarrow M_Z + 40 \text{ GeV}}{M_h^{\min} \rightarrow M_Z} \gtrsim 115 \text{ GeV}$

Ellis+Ridolfi+Zwirner; Haber+Hempfling; Okada+Yanagida+Yamagushi.

- Full one-loop corrections available: μ, A_t, A_b enter as new parameters and M_h is maximal (minimal) for $A_t \sim 2M_{\tilde{Q}}(0)$.

Dabelstein; Bagger et al.; Pokorski et al.; Brignole et al.;

- Approximate dominant two-loop corrections in EPA approach:
 - dominant QCD RC large but absorbed by $m_t|^{pole} \rightarrow m_t|^{\overline{MS}}$.
 - Yukawa corrections rather small in the limit $M_h = 0$.

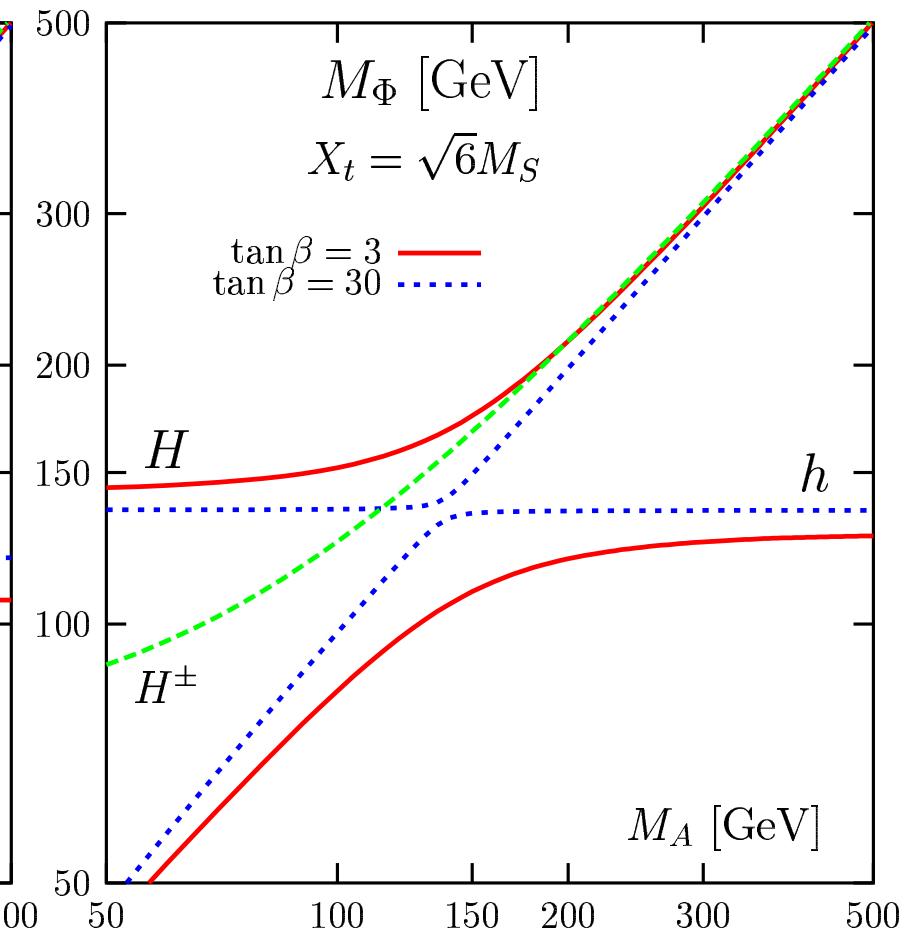
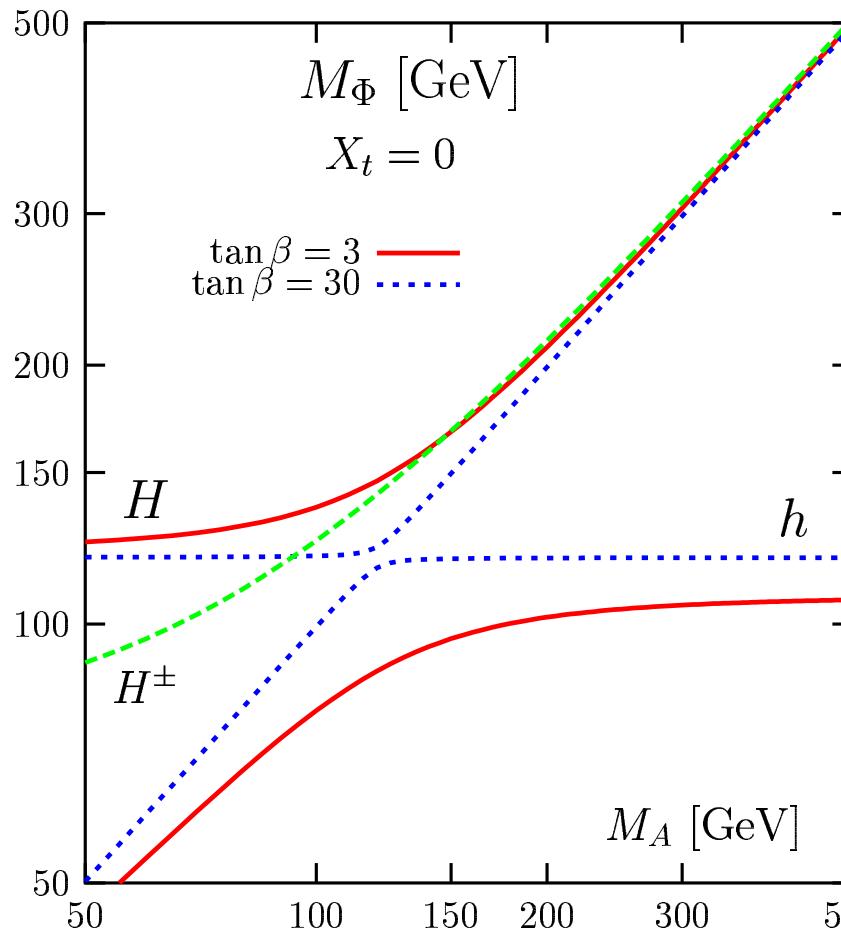
Carena+Espinosa+Quiros+Wagner; Haber+Hempfling; Heinemeyer et al;

1. The Higgs spectrum: Higgs masses

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

$\mathcal{O}(\alpha_t \alpha_S)$, $\mathcal{O}(\alpha_t^2)$, $\mathcal{O}(\alpha_b \alpha_S)$... with squark mixing and gluino loops, ...

Brignole+Degrassi+Slavich+Zwirner; Heinemeyer+Hollik+Weiglein; Martin



1. MSSM Higgs couplings

Higgs decays and cross sections strongly depend on couplings.

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

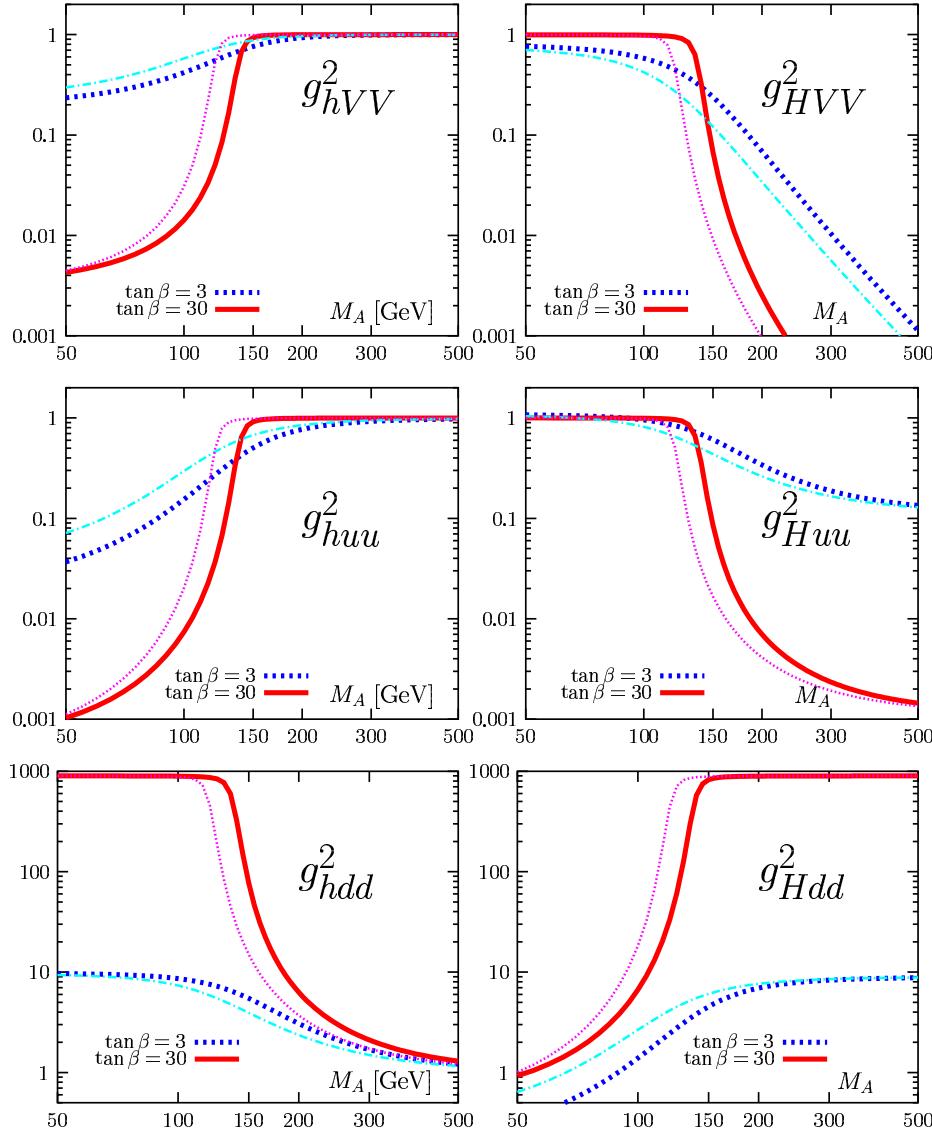
Φ	$g_{\Phi \bar{u} u}$	$g_{\Phi \bar{d} d}$	$g_{\Phi VV}$
h	$\frac{\cos \alpha}{\sin \beta} \rightarrow 1$	$\frac{\sin \alpha}{\cos \beta} \rightarrow 1$	$\sin(\beta - \alpha) \rightarrow 1$
H	$\frac{\sin \alpha}{\sin \beta} \rightarrow 1/\tan \beta$	$\frac{\cos \alpha}{\cos \beta} \rightarrow \tan \beta$	$\cos(\beta - \alpha) \rightarrow 0$
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 $\tan \beta > 1$: couplings to d enhanced, couplings to u suppressed.
- For $\tan \beta \gg 1$: couplings to b quarks ($m_b \tan \beta$) very strong.
- For $M_A \gg M_Z$: h couples like the SM Higgs boson and H like A .

In decoupling limit: MSSM reduces to SM but with a light Higgs.

1. MSSM Higgs couplings

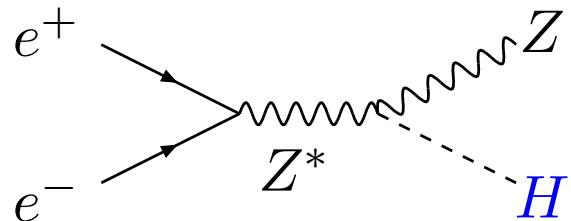
Including radiative corrections just as in the case of the Higgs masses:



1. The Higgs spectrum: SM limit and constraints

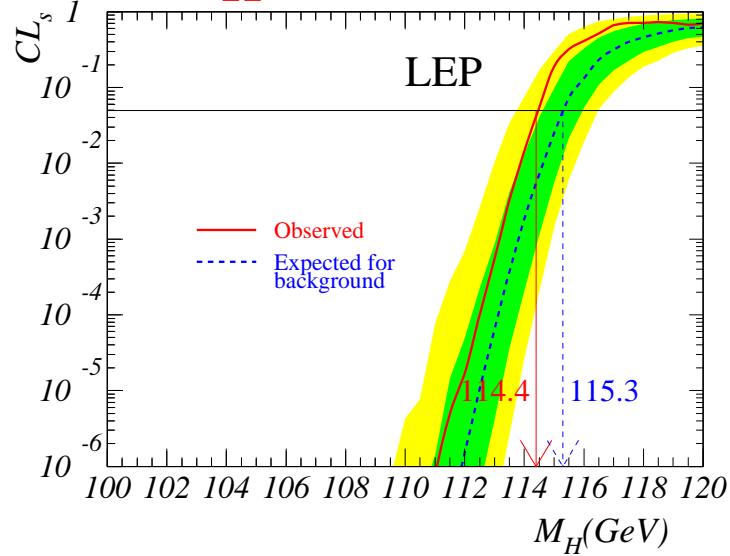
Direct searches at LEP:

H looked for in $e^+e^- \rightarrow ZH$



We have a limit at 95% CL:

$$M_H > 114.4 \text{ GeV}$$

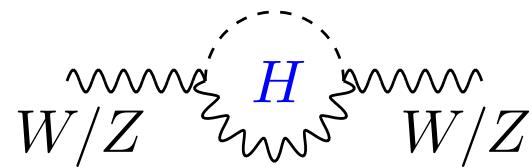


Absolute mass bound in MSSM:

$$M_h, M_A \gtrsim M_Z$$

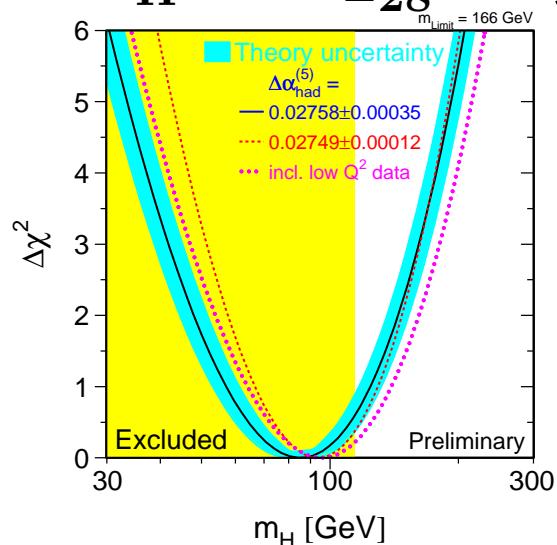
Indirect Higgs searches:

H contributes to RC to W/Z masses:



Fit the EW precision measurements:

$$\text{we obtain } M_H = 85^{+39}_{-28} \text{ GeV, or}$$

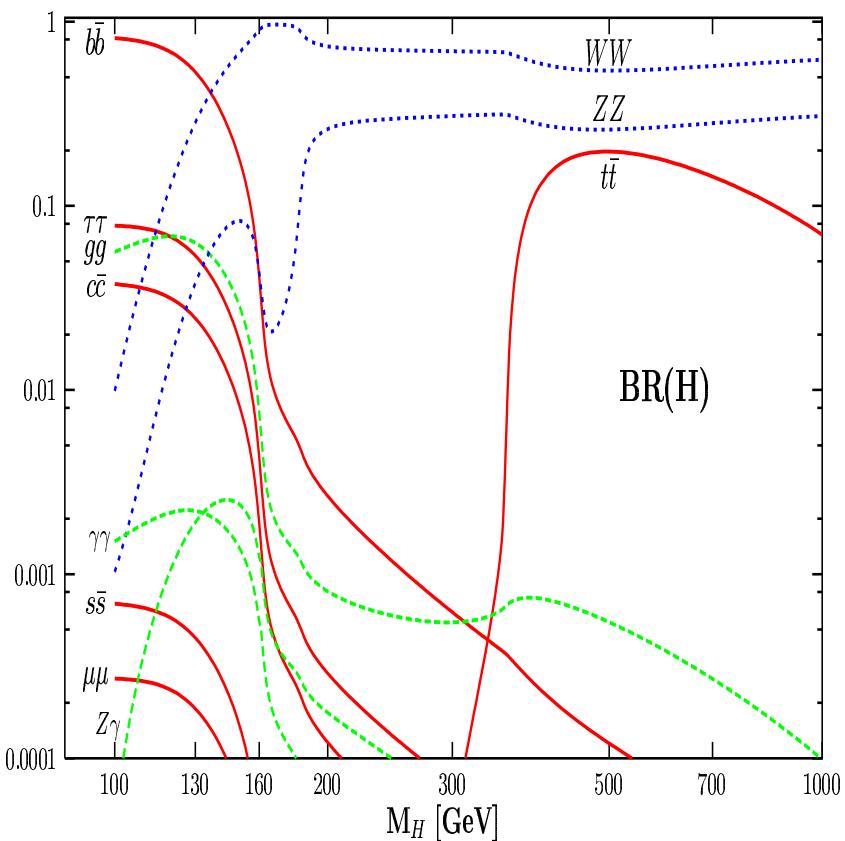


$$M_H \lesssim 166 \text{ GeV at 95% CL}$$

$$\text{MSSM: } M_h \lesssim 140 \text{ GeV}$$

2. Higgs decays: summary in SM

Higgs decays in the SM:

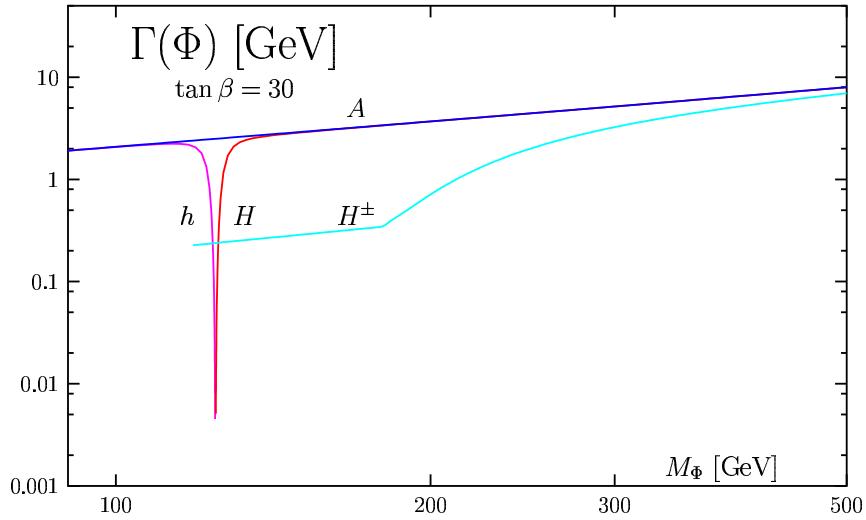
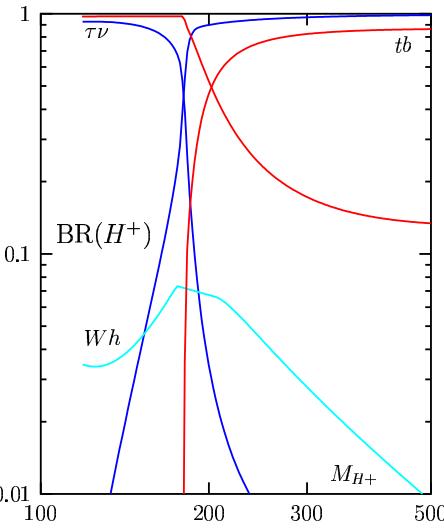
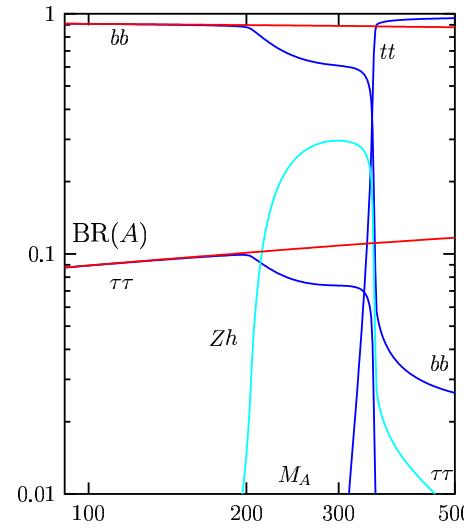
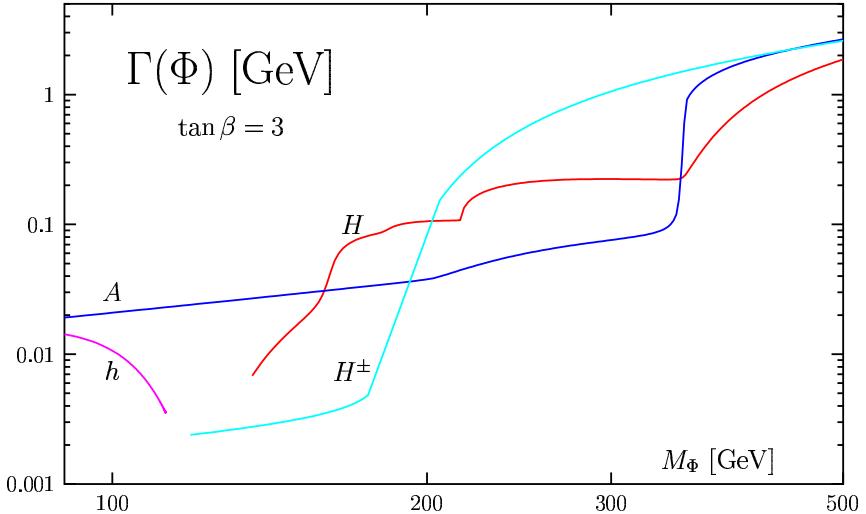
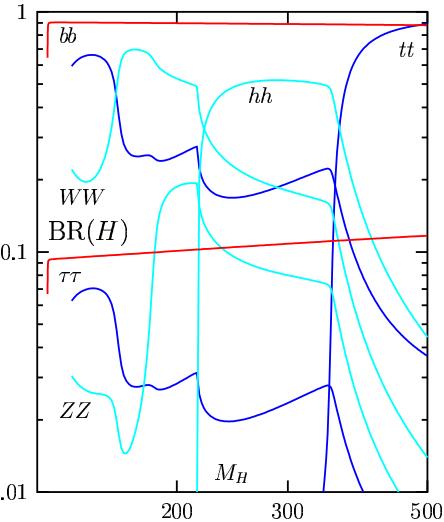
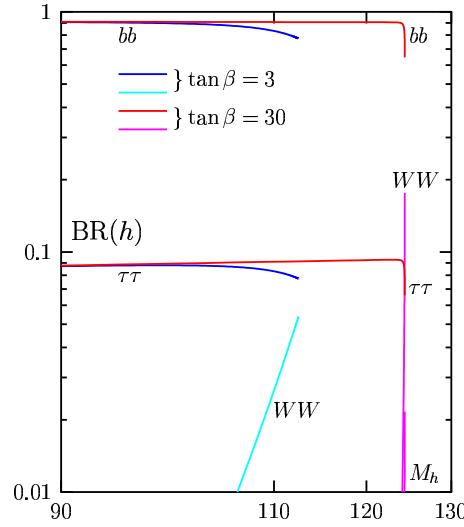


General features in MSSM:

- h : same as H_{SM} in general
(in particular in decoupling limit)
 $h \rightarrow b\bar{b}$ and $\tau^+\tau^-$ same or enhanced
- A : only $b\bar{b}$, $\tau^+\tau^-$ and $t\bar{t}$ decays
(no VV decays, hZ suppressed).
- H : same as A in general
(WW , ZZ , hh decays suppressed).
- H^\pm : $\tau\nu$ and $t\bar{b}$ decays
(depending if $M_{H^\pm} <$ or $> m_t$).

Possible new effects from SUSY

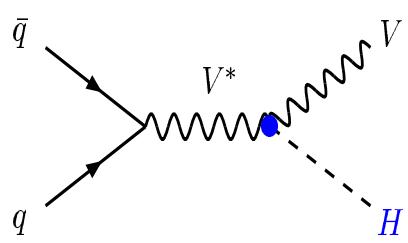
2. Higgs decays: BRs and widths



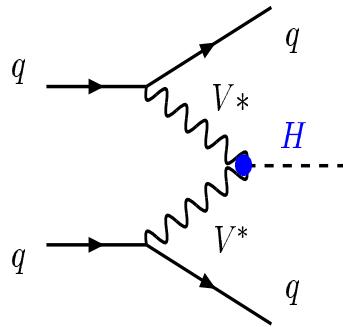
2. Production at the LHC

SM production mechanisms

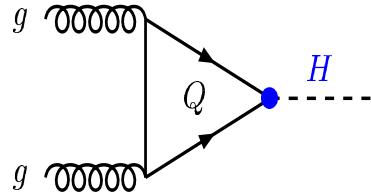
Higgs–strahlung



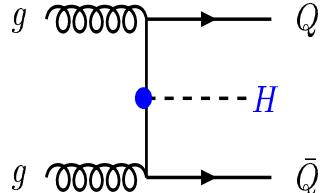
Vector boson fusion



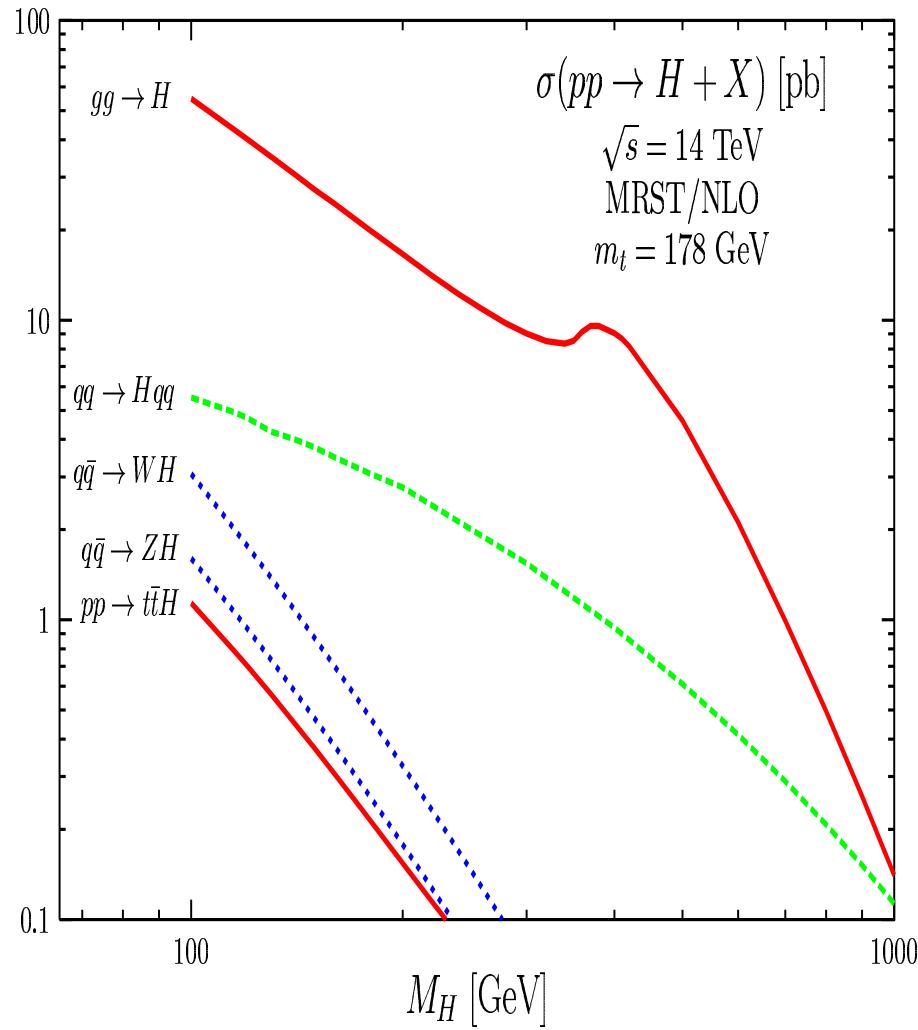
gluon–gluon fusion



in association with $Q\bar{Q}$



Cross sections at the LHC



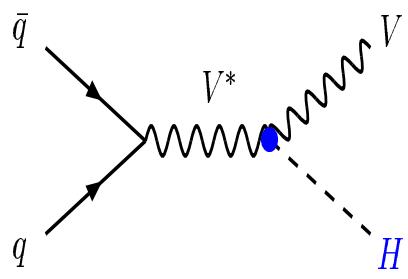
**There are also subleading processes, $gg \rightarrow HH$, etc...
... and maybe some new SUSY processes (see later)....**

2. Production at the LHC: MSSM case

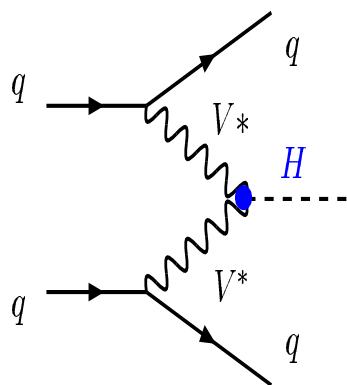
SM production mechanisms

[assuming heavy sparticles]

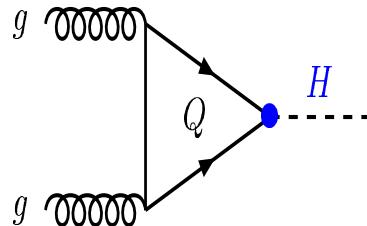
Higgs-strahlung



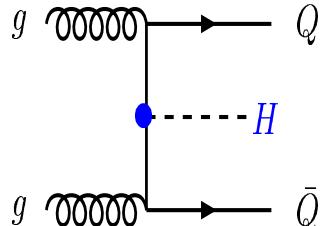
Vector boson fusion



gluon-gluon fusion



in association with $Q\bar{Q}$



What is different in MSSM

- All work for CP-even h, H bosons.
- in ΦV , $q\bar{q}\Phi$ h/H complementary
- $\sigma(h) + \sigma(H) = \sigma(H_{SM})$
- additionnal mechanism: $q\bar{q} \rightarrow A+h/H$
- For $gg \rightarrow \Phi$ and $pp \rightarrow t\bar{t}\Phi$
 - include the contr. of b-quarks
 - dominant contr. at high $\tan\beta$!
- For pseudoscalar A boson:
 - CP: no ΦA and $q\bar{q}A$ processes
 - $gg \rightarrow A$ and $pp \rightarrow b\bar{b}A$ 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 $pp \rightarrow t\bar{b}H$

2. Production at LHC: cross sections

Summary of higher order calculations in MSSM (for SM ask: R. Harlander)

For h/H : same processes as for SM Higgs (esp. for $M_A \gg M_Z$) but:

- Include b-loop contributions to $gg \rightarrow h/H$ and new $gg \rightarrow A$

K-factors only at NLO ($\sim 1.5\text{--}2$) **AD+Graudenz+Spira+Zerwas**

- Include b -final states in $pp \rightarrow b\bar{b} + h/H$ (dominant at high $\tan \beta$)

large K-factors at NLO (50%) **Zerwas et al.; Dawson et al.;**

- Additional SUSY-QCD corrections in $pp \rightarrow V + h/H; qq + h/H$:
rather small at NLO (a few %) for heavy \tilde{q}/\tilde{g} **AD+Spira**

For A : rates including K-factors approx the same as above for h/H

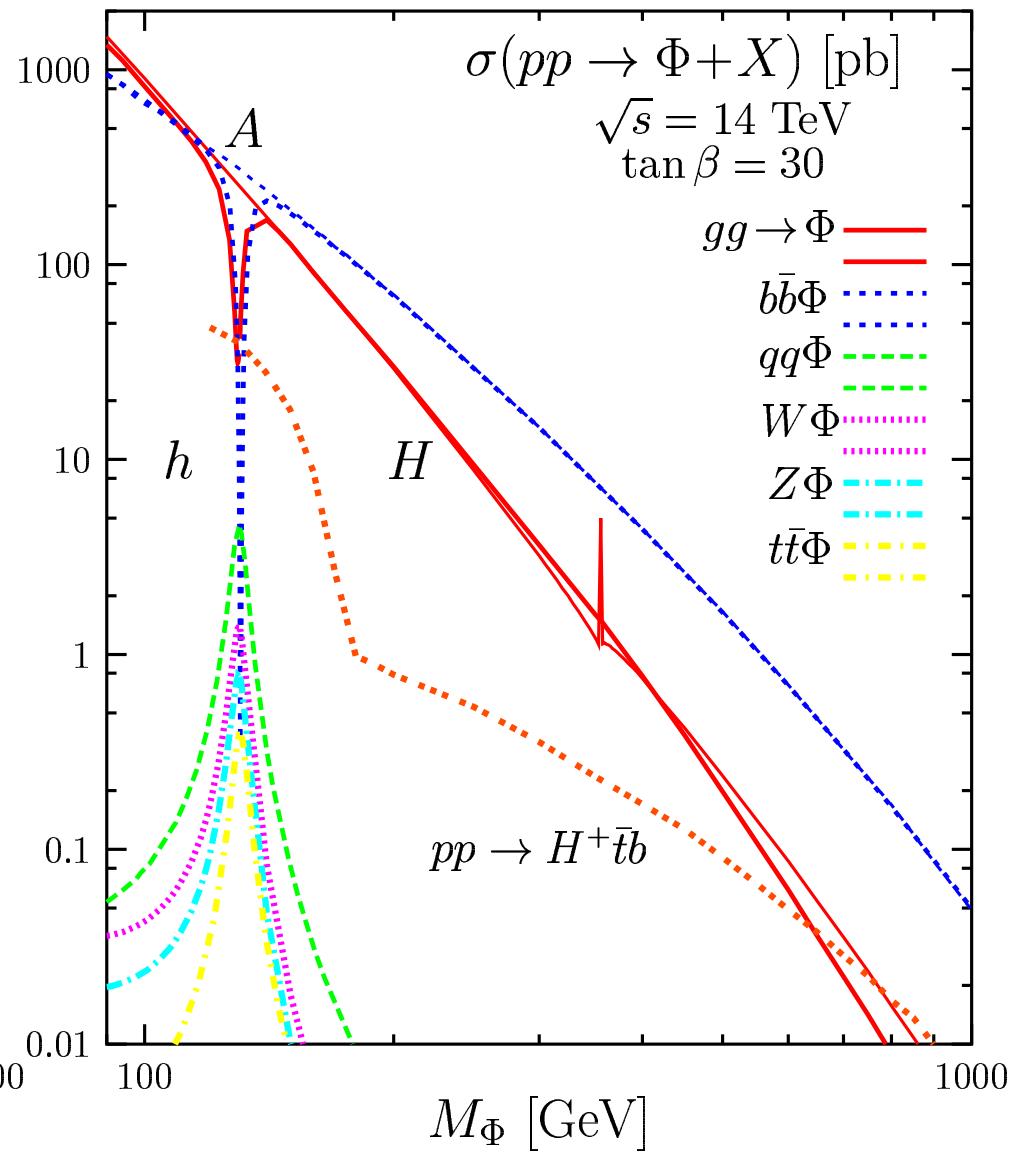
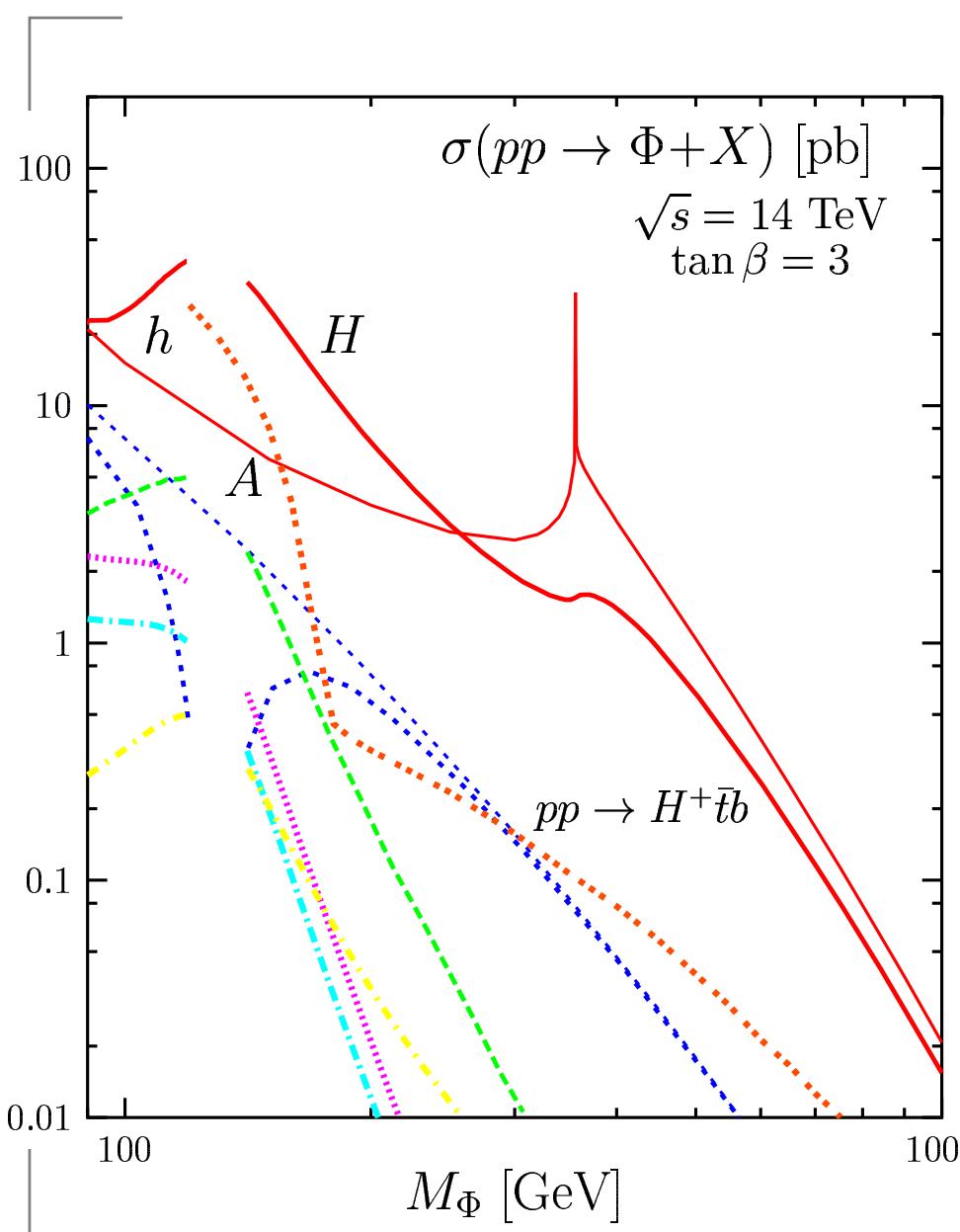
For H^\pm : main process is $pp \rightarrow tt^{(*)} \rightarrow tbH^\pm$ in general

relevant corrections known exactly at NLO **Plehn; Zhou; Kidonakis**

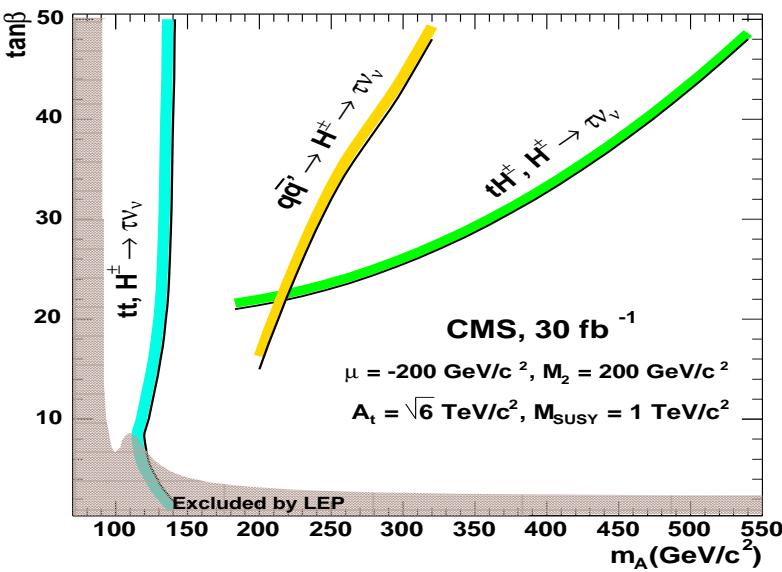
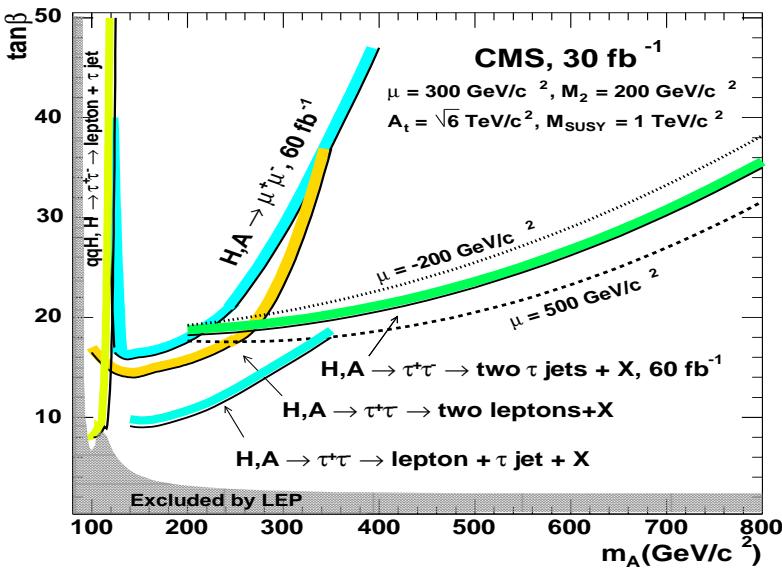
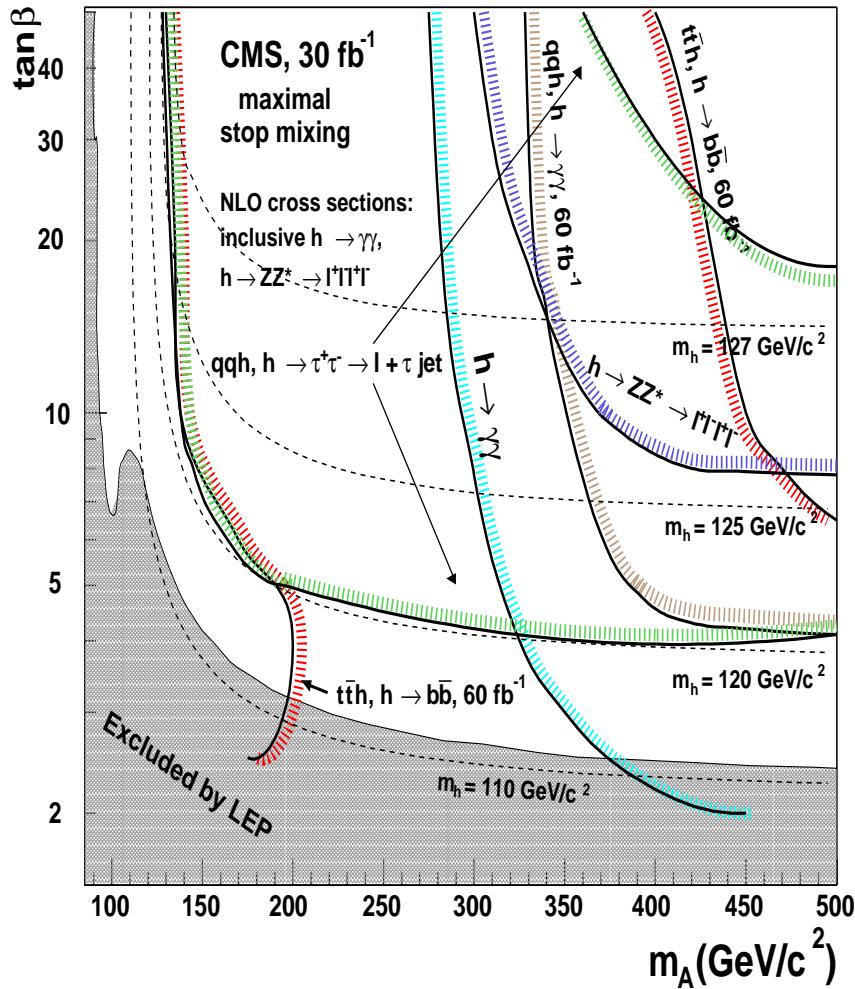
h, H, A, H^\pm decays: well under control including SUSY+NLO corrections

summarized in the program **HDECAY** **AD+Kalinowski+Spira**

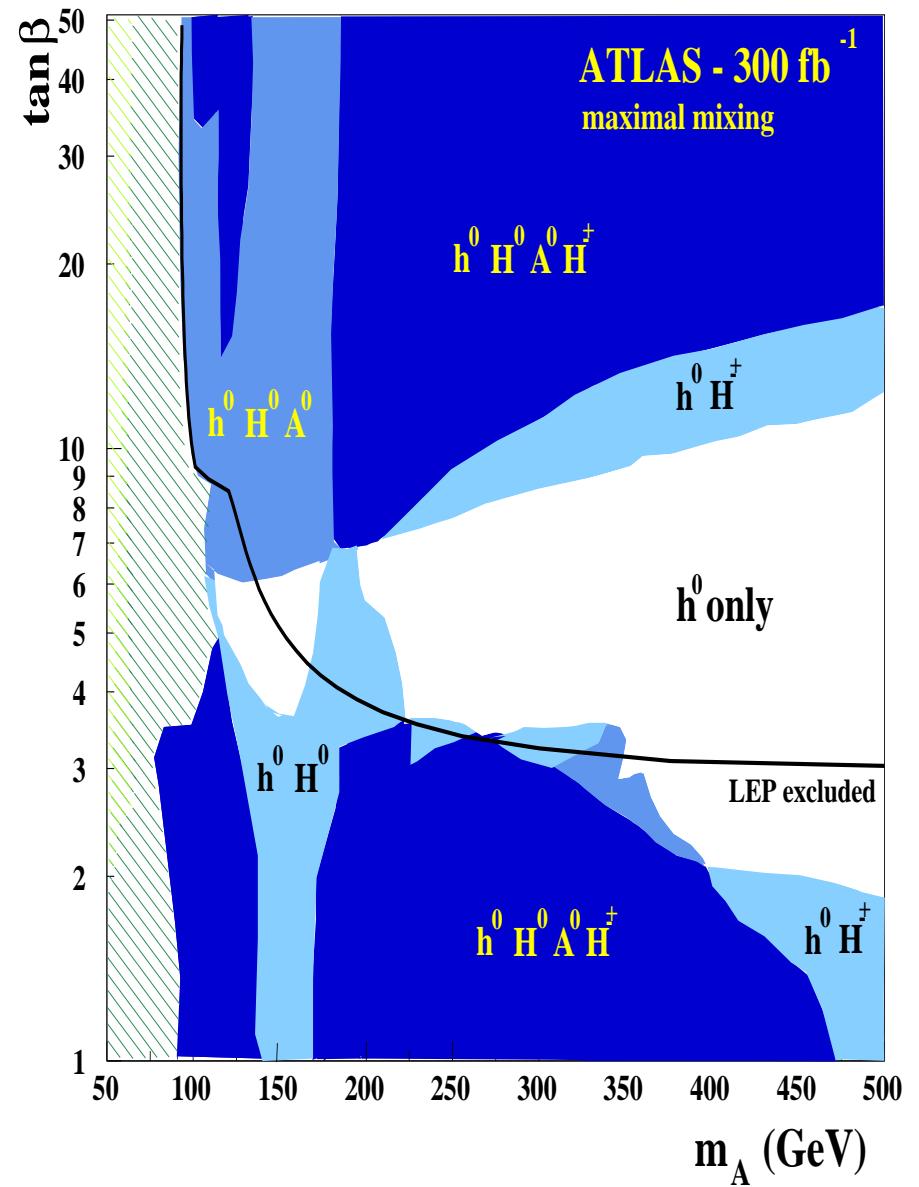
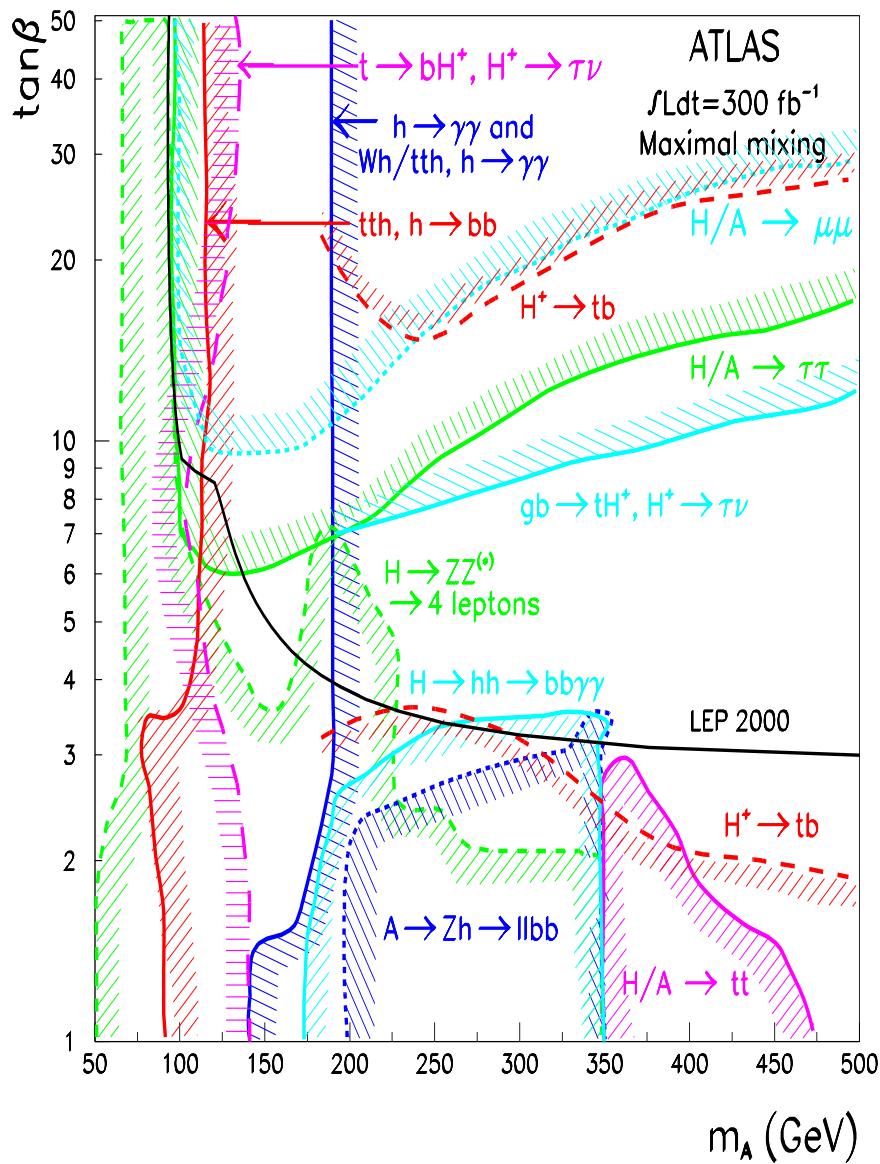
2. Production at LHC: cross sections



2. Production at LHC: detection



2. Production at LHC: detection



2. Production at LHC: measurements

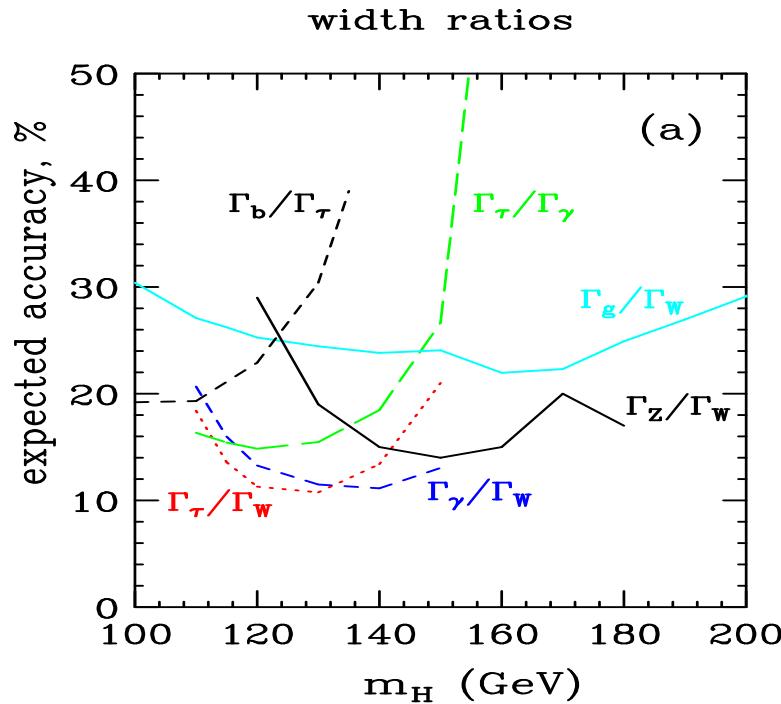
Lightest Higgs: as in SM

Higgs mass $h \rightarrow \gamma\gamma, ZZ^*$

Higgs spin/CP numbers

Higgs couplings from $\sigma \times \text{BR}$

Higgs self couplings hopeless...



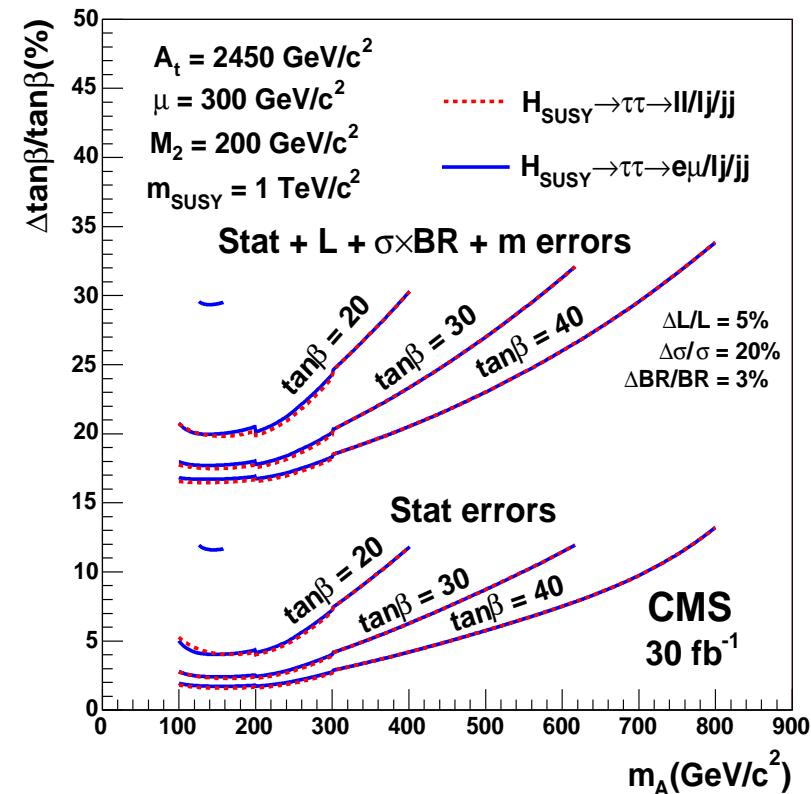
M. Dührssen et al. (2004).

Heavy Higgses

Masses from $H/A \rightarrow \mu^+ \mu^-$

$\tan \beta$ in $pp \rightarrow H/A + b\bar{b}$

H/A separation difficult



3. Difficult scenarios in the MSSM

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

- There is the "bad luck" scenario in which only h is observed:
 - looks SM-like at the 10% level (and $M_{\text{SUSY}} \gtrsim 3 \text{ TeV...}$): SM
- There are scenarii where searches are different from standard 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 $\sigma(gg \rightarrow h \rightarrow \gamma\gamma)$ smaller than in SM.
 - Higgses can be produced with sparticles ($pp \rightarrow \tilde{t}\tilde{t}^*h, \dots$).
 - Cascade decays of SUSY particles into Higgs bosons....
- SUSY decays, if allowed, might alter the search strategies:
 - $h \rightarrow \chi_1^0 \chi_1^0, \tilde{\nu} \tilde{\nu}$ are still possible in non universal models...
 - Decays of A, H, H^\pm into χ_i^\pm, χ_i^0 are possible but can be useful...

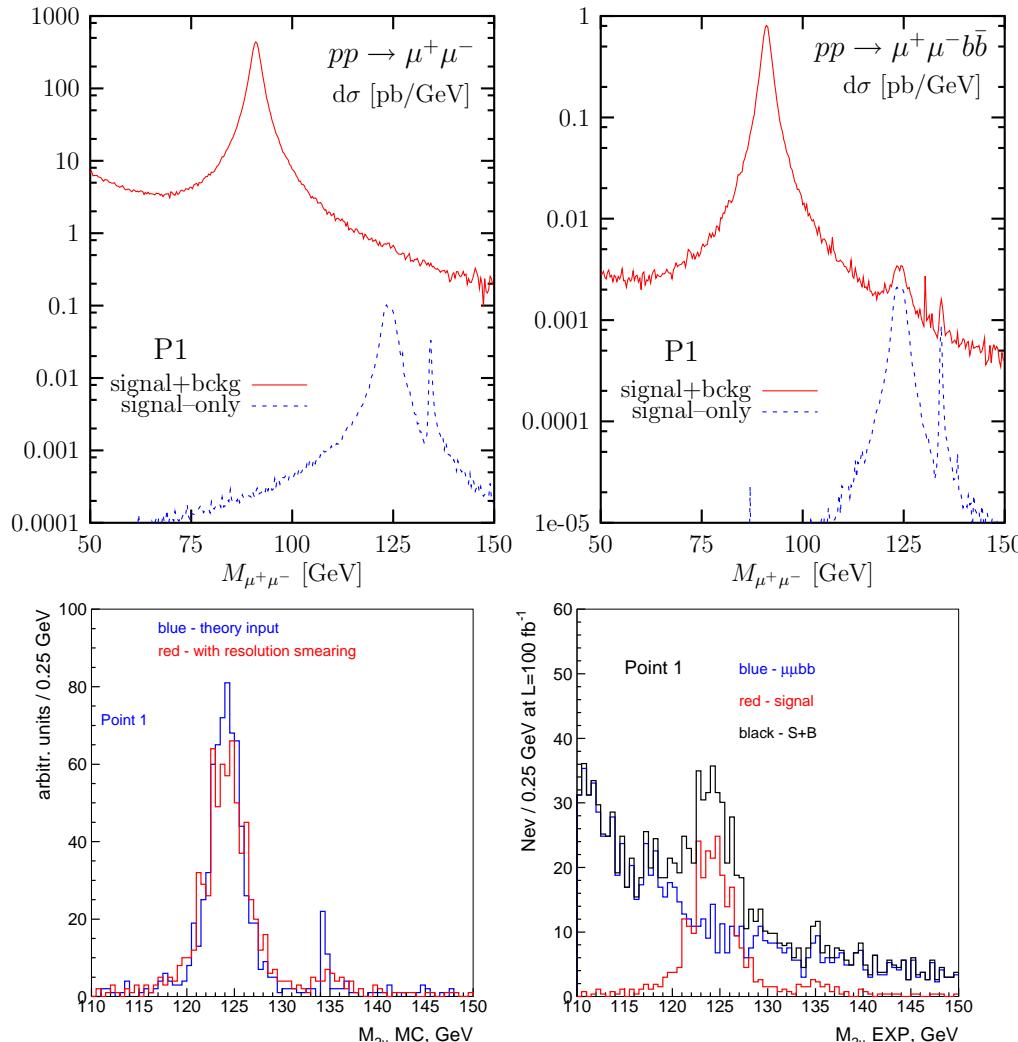
Be prepared for the unexpected!

3. Difficult scenarios: intense coupling regime

- There are scenarii where searches are different from standard case:
 - The intense coupling regime: h, H, A almost mass degenerate....

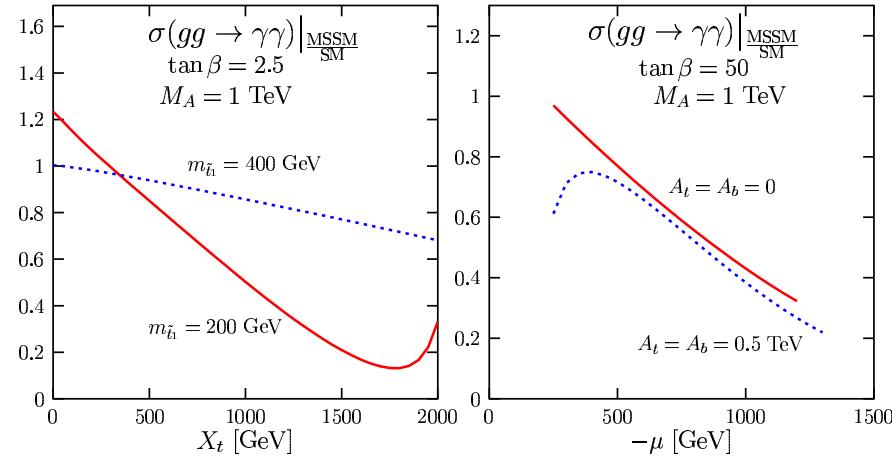
E. Boos,
A. Nikitenko,

.....

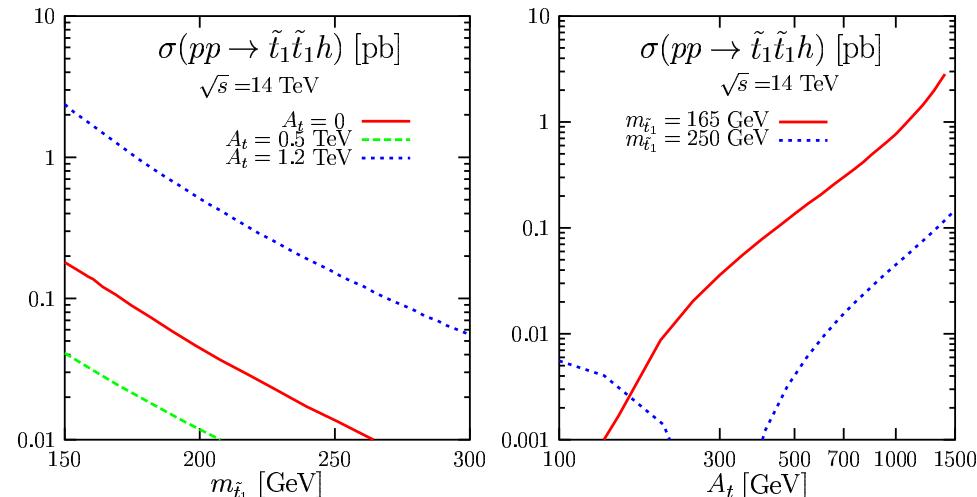


3. Difficult scenarios: light stops

- SUSY particles might play an important role in production/decay:
 - light \tilde{t} loops might make $\sigma(gg \rightarrow h \rightarrow \gamma\gamma)$ smaller than in SM.



- Higgses can be produced with sparticles ($pp \rightarrow \tilde{t}\tilde{t}^* h, \dots$).

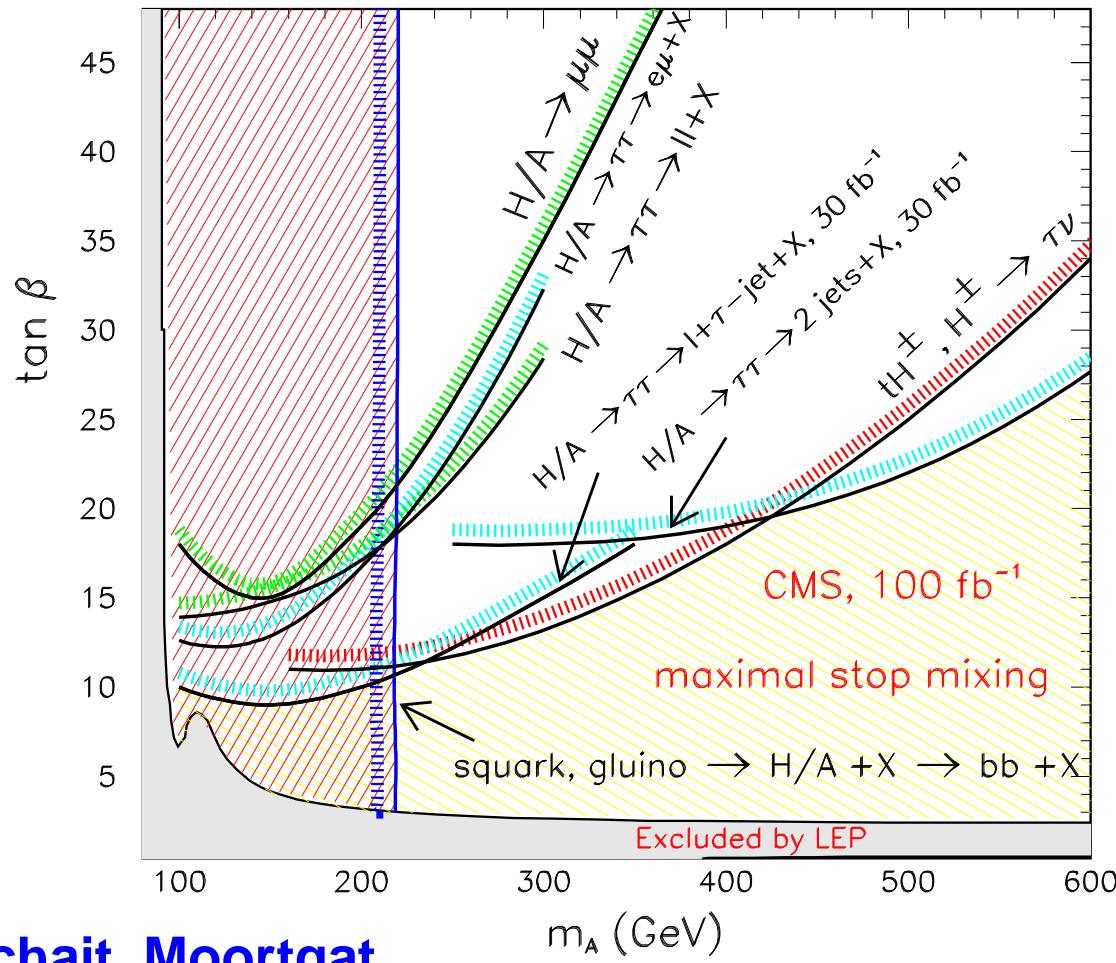


JL. Kneur,
G. Moultaka,
S. Moretti,

....

3. Difficult scenarios: SUSY cascade decays

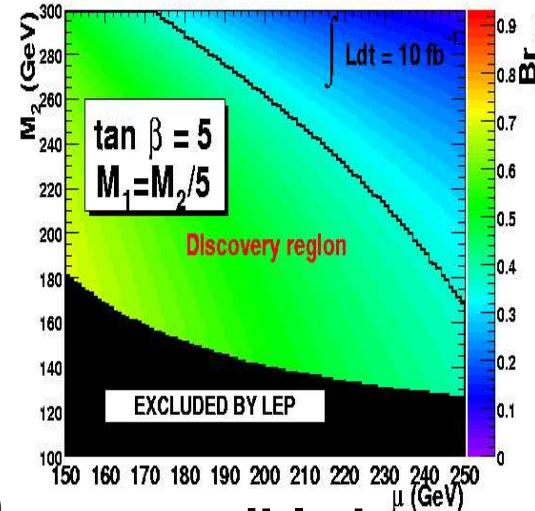
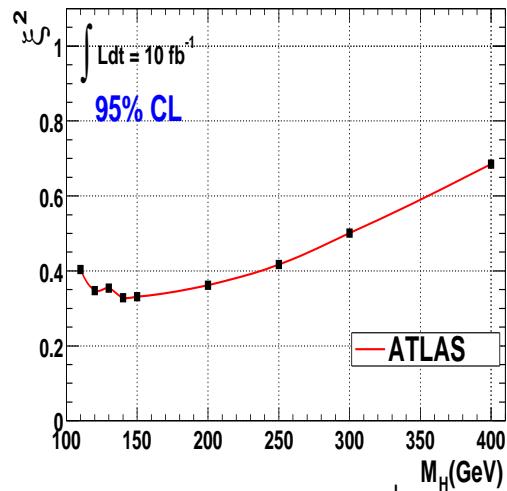
- SUSY particles might play an important role in production/decay:
 - Cascade decays of SUSY particles into Higgs bosons....



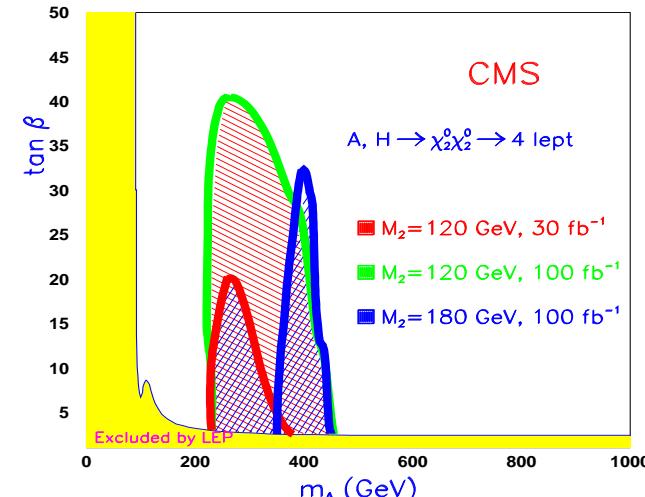
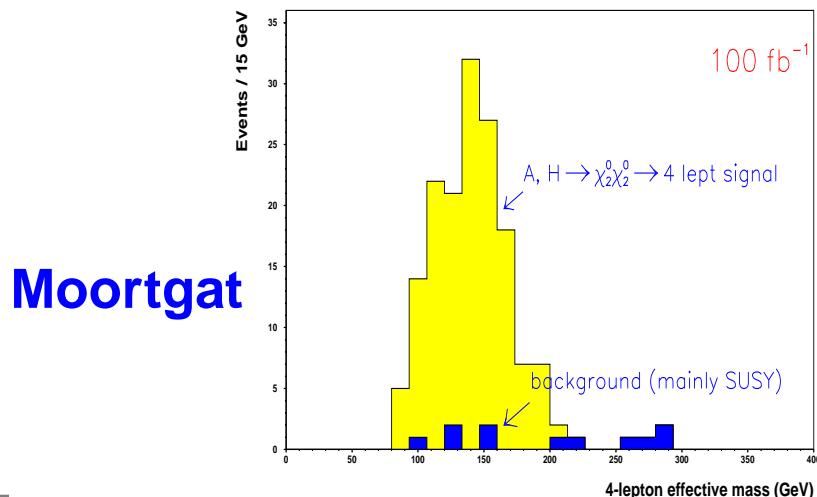
Datta, Guchait, Moortgat,

3. Difficult scenarios: decays into SUSY

- SUSY decays, if allowed, might alter the search strategies:
 - $h \rightarrow \chi_1^0 \chi_1^0, \tilde{\nu} \tilde{\nu}$ are still possible in non universal models...



- Decays of A, H, H^\pm into χ_i^\pm, χ_i^0 are possible but can be useful...



Bélanger,
Boudjema,
Donato
Godbole,
Rosier Lee

4. Beyond the conventional MSSM: CP–violation

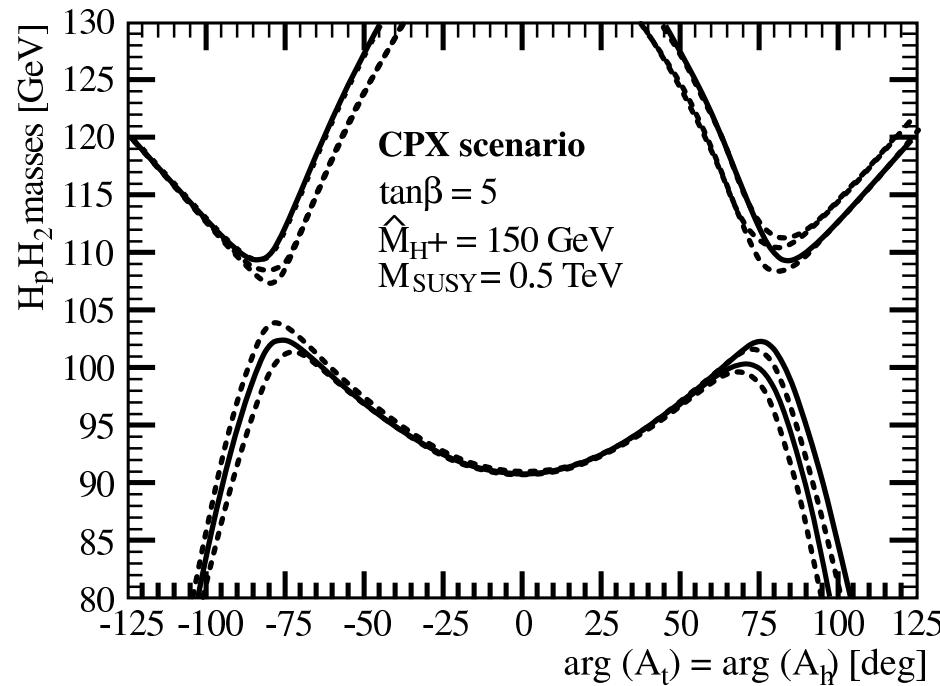
Life can be even more complicated in extensions of the MSSM

We can allow for some amount of CP–violation in eg. M_i , μ and 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 H_1, H_2, H_3 CP mixtures
- determination of Higgs spectrum slightly more complicated,
- possibility of a light H_1 that has escaped detection at LEP2.



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

4. Beyond the conventional MSSM: 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...

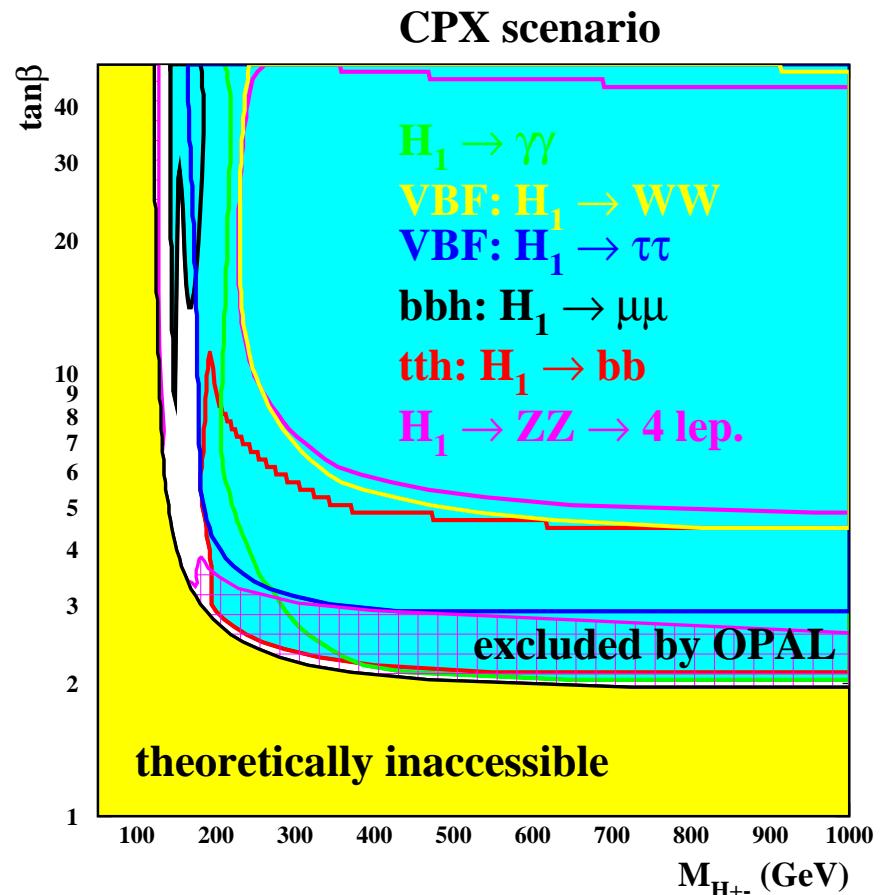
All Higgses escape detection

Still, there is the possibility

$t \rightarrow H^+ b$ with $H^+ \rightarrow h W^*$

(Godbole, Guchait, Roy).

M. Schumacher →



Regions of MSSM parameter space not covered by ATLAS/CMS:
more work is still needed....

4. Beyond the conventional MSSM: 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 an additional singlet field S , $\langle S \rangle \propto \mu$

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

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

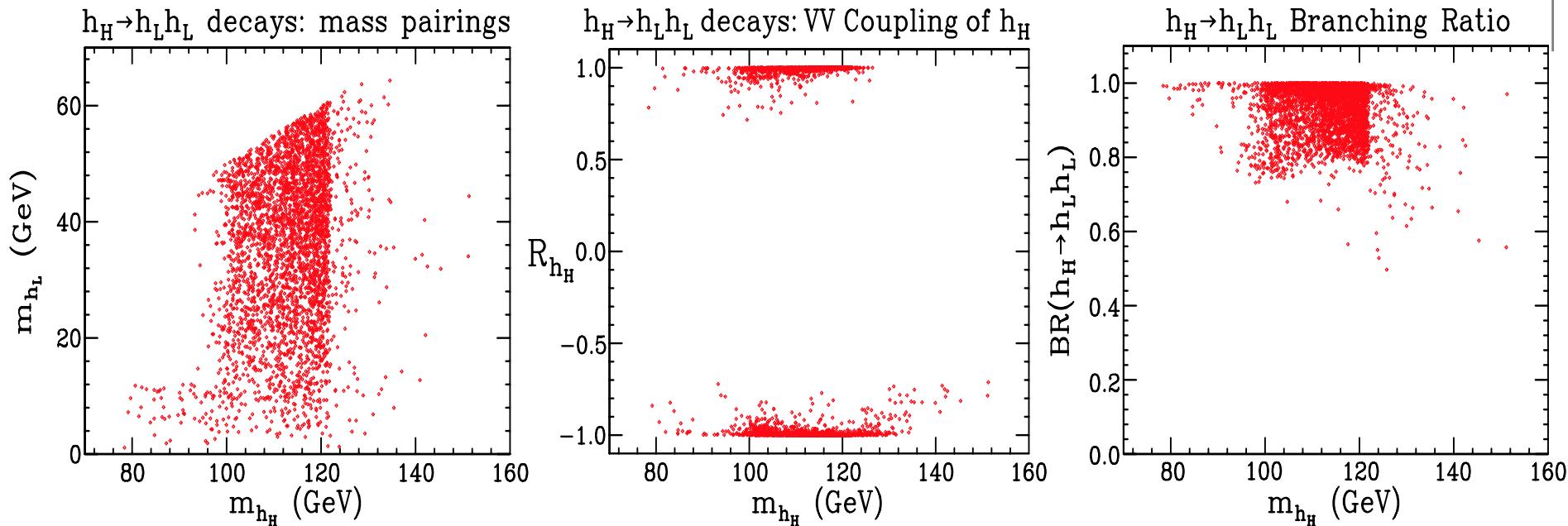
- additional parameters enter in Higgs masses and couplings
 - less constrained model, more flexibility,
- the bound on lightest Higgs boson mass is higher than in MSSM
 - less fine-tuning is needed to cope with LEP..
- possibility of a light Higgs which has escaped detection at LEP2
 - rich phenomenology: low energy constraints, DM,

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...)

4. Production in extended scenarios



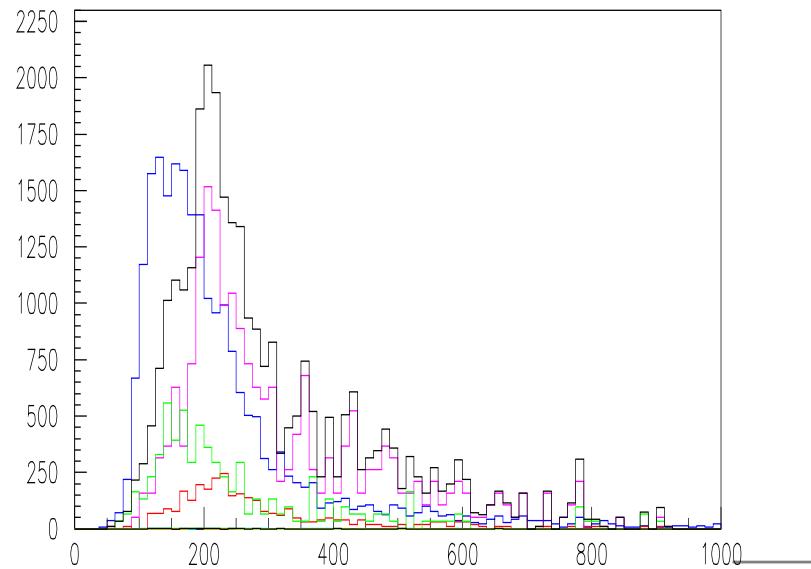
Searches very difficult at the LHC:

$$p \rightarrow W^*W^* \rightarrow h_2qq$$

— $h_1 \rightarrow a_1a_1 \rightarrow b\bar{b}\tau\tau \times 500.$

— total background.

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



5. Conclusion?

The LHC will tell!