

# The Higgs sector of the MSSM

*María José Herrero, IFT-UAM (Madrid)*

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1. The building of the Higgs sector in the MSSM
2. The lightest MSSM Higgs boson
3. The heavy MSSM Higgs bosons
4. The Search for the MSSM Higgs bosons

## 1. The building of the Higgs sector in the MSSM

Comparison with SM case:

$$\mathcal{L}_{\text{SM}} = \underbrace{m_d \bar{Q}_L \Phi d_R}_{\text{d-quark mass}} + \underbrace{m_u \bar{Q}_L \Phi_c u_R}_{\text{u-quark mass}}$$

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \Phi_c = i\sigma_2 \Phi^*, \quad \Phi \rightarrow \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \Phi_c \rightarrow \begin{pmatrix} v \\ 0 \end{pmatrix}$$

In SUSY: term  $\bar{Q}_L \Phi^*$  not allowed

Superpotential is holomorphic function of chiral superfields, i.e. depends only on  $\varphi_i$ , not on  $\varphi_i^*$

No soft SUSY-breaking terms allowed for chiral fermions

$\Rightarrow H_d (\equiv H_1)$  and  $H_u (\equiv H_2)$  needed to give masses  
to down- and up-type fermions

Furthermore: two doublets also needed for cancellation of anomalies,  
quadratic divergences

## Enlarged Higgs sector: Two Higgs doublets

→ [C]

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states:  $h^0, H^0, A^0, H^\pm$

Goldstone bosons:  $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan \beta = \frac{v_2}{v_1}, \quad M_A^2 = -m_{12}^2(\tan \beta + \cot \beta)$$

## Enlarged Higgs sector: Two Higgs doublets with $\mathcal{CP}$ violation

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} e^{i\xi}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states:  $h^0, H^0, A^0, H^\pm$

2  $\mathcal{CP}$ -violating phases:  $\xi, \arg(m_{12}) \Rightarrow$  can be set/rotated to zero

Input parameters: (to be determined experimentally)

$$\tan \beta = \frac{v_2}{v_1}, \quad M_{H^\pm}^2$$

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} \quad \tan(2\alpha) = \tan(2\beta) \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}$$

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos \beta & \sin \beta \\ -\sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} \chi_1^0 \\ \chi_2^0 \end{pmatrix}, \quad \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos \beta & \sin \beta \\ -\sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

Three Goldstone bosons (as in SM):  $G^0, G^\pm$

→ longitudinal components of  $W^\pm, Z$

⇒ Five physical states:  $h^0, H^0, A^0, H^\pm$

$h, H$ : neutral,  $\mathcal{CP}$ -even,  $A^0$ : neutral,  $\mathcal{CP}$ -odd,  $H^\pm$ : charged

Gauge-boson masses:

$$M_W^2 = \frac{1}{2} g'^2 (v_1^2 + v_2^2), \quad M_Z^2 = \frac{1}{2} (g^2 + g'^2) (v_1^2 + v_2^2), \quad M_\gamma = 0$$

Parameters in MSSM Higgs potential  $V$  (besides  $g, g'$ ):

$$v_1, v_2, m_1, m_2, m_{12}$$

relation for  $M_W^2, M_Z^2 \Rightarrow 1$  condition

minimization of  $V$  w.r.t. neutral Higgs fields  $H_1^1, H_2^2 \Rightarrow 2$  conditions

$\Rightarrow$  only two free parameters remain in  $V$ , conventionally chosen as

$$\tan \beta = \frac{v_2}{v_1}, \quad M_A^2 = -m_{12}^2(\tan \beta + \cot \beta)$$

$\Rightarrow m_h, m_H, \text{mixing angle } \alpha, m_{H^\pm}$ : no free parameters, can be predicted

In lowest order:

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

Predictions for  $m_h$ ,  $m_H$  from diagonalization of tree-level mass matrix:

$\phi_1 - \phi_2$  basis:

$$M_{\text{Higgs}}^{2,\text{tree}} = \begin{pmatrix} m_{\phi_1}^2 & m_{\phi_1\phi_2}^2 \\ m_{\phi_1\phi_2}^2 & m_{\phi_2}^2 \end{pmatrix} =$$
$$\begin{pmatrix} M_A^2 \sin^2 \beta + M_Z^2 \cos^2 \beta & -(M_A^2 + M_Z^2) \sin \beta \cos \beta \\ -(M_A^2 + M_Z^2) \sin \beta \cos \beta & M_A^2 \cos^2 \beta + M_Z^2 \sin^2 \beta \end{pmatrix}$$

$\Downarrow \leftarrow$  Diagonalization,  $\alpha$

$$\begin{pmatrix} m_H^{2,\text{tree}} & 0 \\ 0 & m_h^{2,\text{tree}} \end{pmatrix}$$

Tree-level result for  $m_h$ ,  $m_H$ :

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

$\Rightarrow m_h^2 \leq M_Z^2 \cos^2 2\beta$  (the equality holds for  $M_A \gg M_Z$ )

$\Rightarrow$  Light Higgs boson  $h$  required in SUSY

In contrast to SM:  $m_{H_{SM}}$  and self-coupling  $\lambda = \frac{g^2 m_{H_{SM}}^2}{8M_W^2}$  are both unknown

Measurement of  $m_h$ , Higgs couplings

$\Rightarrow$  test of the theory (more directly than in SM)

## Higgs couplings, tree level:

$$g_{hVV} = \sin(\beta - \alpha) g_{HVV}^{\text{SM}}, \quad V = W^\pm, Z$$

$$g_{HVV} = \cos(\beta - \alpha) g_{HVV}^{\text{SM}}$$

$$g_{hAZ} = \cos(\beta - \alpha) \frac{g'}{2 \cos \theta_W}$$

$$g_{hb\bar{b}}, g_{h\tau^+\tau^-} = -\frac{\sin \alpha}{\cos \beta} g_{Hb\bar{b}, H\tau^+\tau^-}^{\text{SM}}$$

$$g_{ht\bar{t}} = \frac{\cos \alpha}{\sin \beta} g_{Ht\bar{t}}^{\text{SM}}$$

$$g_{Ab\bar{b}}, g_{A\tau^+\tau^-} = \gamma_5 \tan \beta g_{Hb\bar{b}}^{\text{SM}}$$

⇒  $g_{hVV} \leq g_{HVV}^{\text{SM}}$ ,  $g_{hVV}, g_{HVV}, g_{hAZ}$  cannot all be small

$g_{hb\bar{b}}, g_{h\tau^+\tau^-}$ : significant suppression or enhancement w.r.t. SM coupling possible

## The decoupling limit: $M_A \gg M_Z$

$$m_h^{\text{tree}} \rightarrow M_Z |\cos 2\beta|$$

The lightest MSSM Higgs is SM-like

$$\begin{aligned} -\frac{\sin \alpha}{\cos \beta} &\rightarrow 1, \quad \frac{\cos \alpha}{\sin \beta} \rightarrow 1, \quad \sin(\beta - \alpha) \rightarrow 1 \\ \Rightarrow g_{hVV} &\rightarrow g_{HVV}^{\text{SM}}, \quad g_{hff\bar{f}} \rightarrow g_{Hff\bar{f}}^{\text{SM}} \end{aligned}$$

Effectively,  $h \approx H_{SM}$

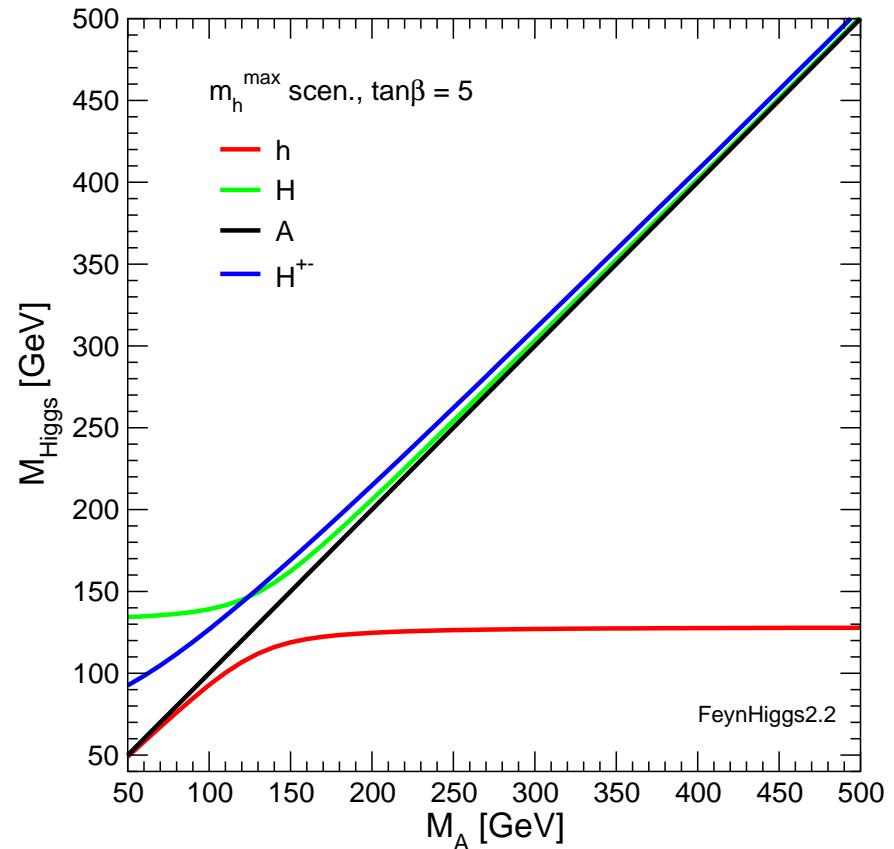
The heavy MSSM Higgses:

$$M_A \approx M_H \approx M_{H^\pm}$$

approximately degenerate and heavy

$A, H, H^\pm$  decouple from low energy physics:  $\text{MSSM} \rightarrow \text{SM}$  (Higgs sector)

Decoupling effective at  $M_A \gtrsim 150$  GeV:



## 2. The lightest MSSM Higgs boson

MSSM predicts upper bound on  $m_h$ :

tree-level bound:  $m_h < M_Z$ ,

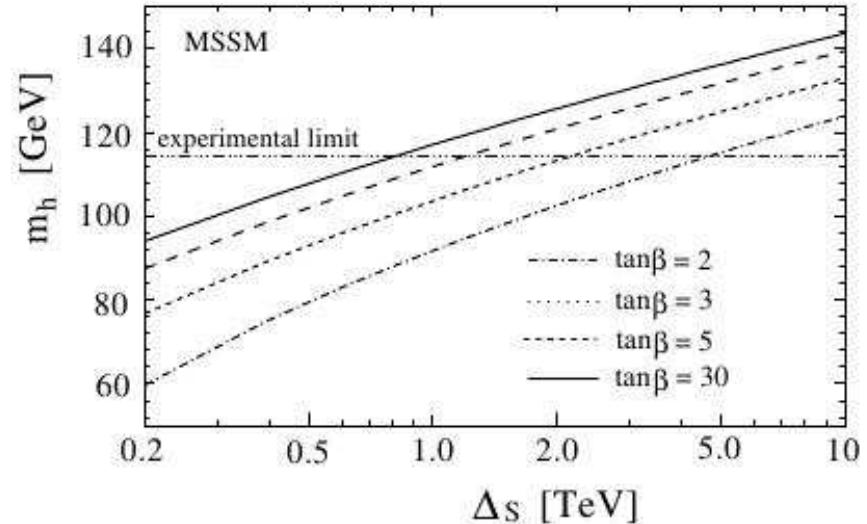
excluded by LEP Higgs searches!

Large radiative corrections:

Yukawa couplings:  $\frac{e m_t}{2 M_W s_W}$ ,  $\frac{e m_t^2}{M_W s_W}$ , ...

⇒ With dominant 1-loop corrections  
(and  $M_A \gtrsim 150$  GeV):

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3g^2}{8\pi^2} \frac{m_t^4}{M_W^2} \log \left( \frac{m_{\tilde{t}}^2}{m_t^2} \right)$$



Very relevant increase of  $m_h$   
with  $\Delta s = m_{\tilde{t}}$  and  $\tan\beta$   
Corrected  $m_h$  is OK with data

The MSSM Higgs sector is connected to all other sectors via loop corrections  
(especially to the scalar top sector)

Present status of  $M_h$  prediction in the MSSM:

Complete one-loop and ‘almost complete’ two-loop result available

## Excursion: Higgs mass calculations

### What is a mass

Definition: The mass of a particle is the pole of the propagator

Example: scalar particle

Propagator:

$$\frac{i}{q^2 - m^2}$$

$q^2$ : four-momentum squared

$m^2$ : constant in the Lagrangian

If one chooses  $q^2 = m^2$  then the propagator has a pole.

This  $q^2$  is then the mass of the particle.

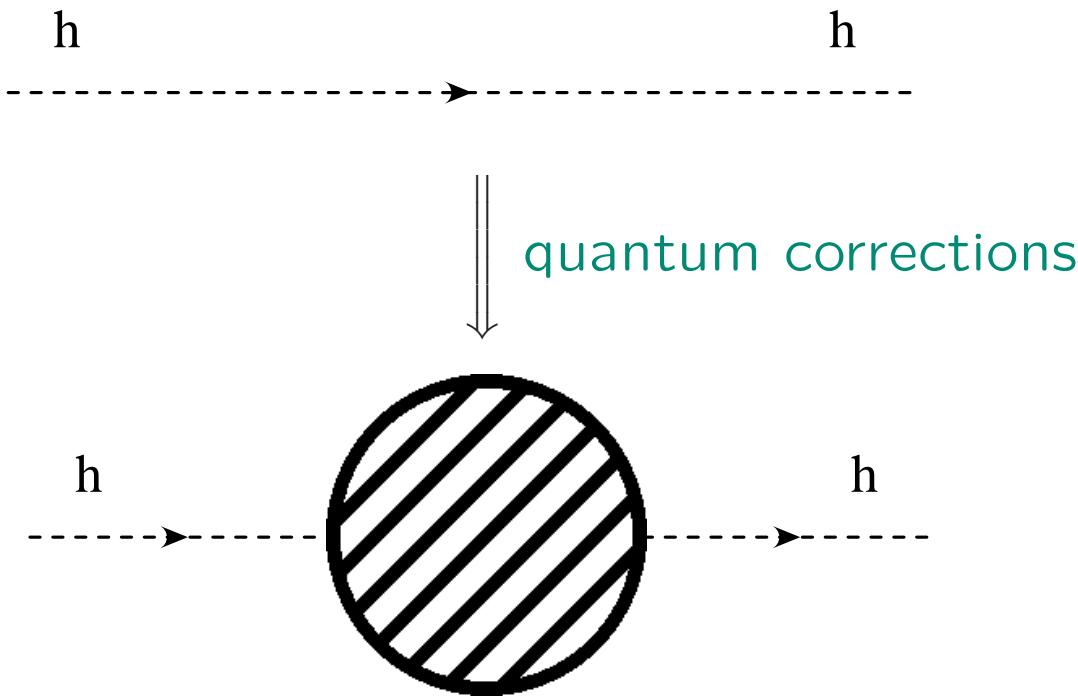
⇒ Pole of the propagator corresponds to zeroth of the inverse propagator.

Inverse propagator:

$$-i(q^2 - m^2)$$

## Problem: quantum corrections

Higgs propagator:



Inverse propagator:

$$-i(q^2 - m^2) \rightarrow -i(q^2 - m^2 + \hat{\Sigma}_h(q^2))$$

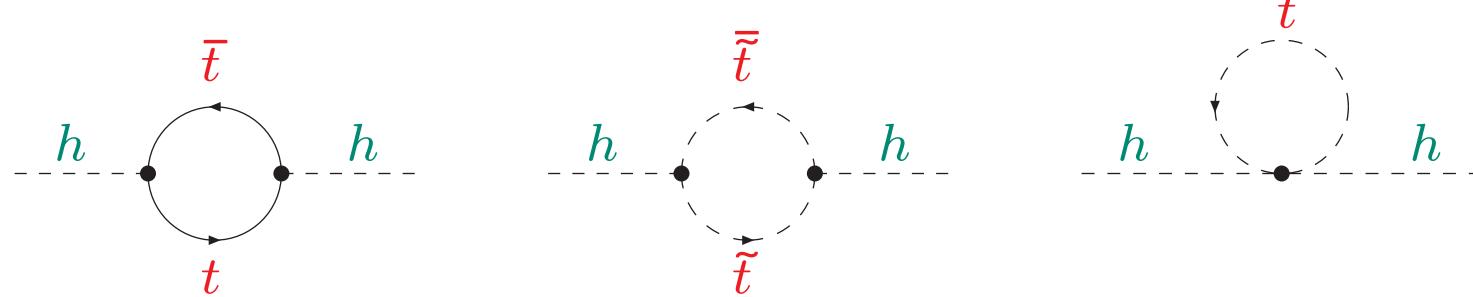
$\hat{\Sigma}_h(q^2)$ : renormalized Higgs self-energy

## Calculation of the blob:

$$\text{blob} = \hat{\Sigma}(q^2) = \hat{\Sigma}^{(1)}(q^2) + \hat{\Sigma}^{(2)}(q^2) + \dots$$

: all MSSM particles contribute  
main contribution:  $t/\tilde{t}$  sector ( $\tilde{t}$ : scalar top, SUSY partner of the  $t$ )

1-Loop: Feynman diagrams:



Dominant 1-loop corrections:  $\Delta m_h^2 \sim G_\mu m_t^4 \log \left( \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right)$

size of the corrections:  $\mathcal{O}(50 \text{ GeV})$

⇒ 2-Loop calculation necessary!

## 2-loop: $\hat{\Sigma}^{(2)}(0)$

[S. H., W. Hollik, G. Weiglein '98]

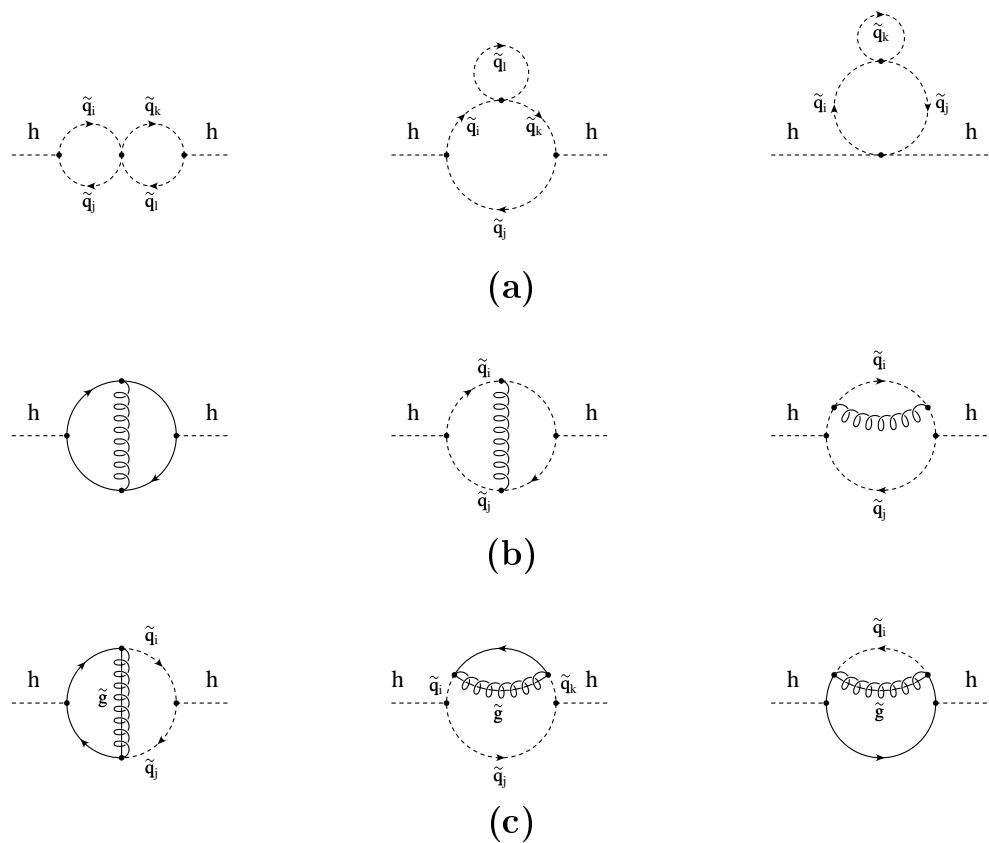
dominant contributions of  $\mathcal{O}(\alpha_t \alpha_s)$ :

- (a) pure scalar diagrams
- (b) diagrams with gluon exchange
- (c) diagrams with gluino exchange

Quite complicated calculation . . .

⇒ Need for computer algebra  
programms

['98 - '11:] ⇒ many more corrections  
calculated!



End of excursion: Higgs mass calculations

## Mixing of the $\mathcal{CP}$ -even Higgs bosons:

Propagator/Mass matrix at tree-level:

$$\begin{pmatrix} q^2 - m_H^2 & 0 \\ 0 & q^2 - m_h^2 \end{pmatrix}$$

Propagator / mass matrix with higher-order corrections  
(→ Feynman-diagrammatic approach):

$$M_{hH}^2(q^2) = \begin{pmatrix} q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$  ( $i, j = h, H$ ) : renormalized Higgs self-energies

$\mathcal{CP}$ -even fields can mix

⇒ complex roots of  $\det(M_{hH}^2(q^2))$ :  $\mathcal{M}_{h_i}^2$  ( $i = 1, 2$ ):  $\mathcal{M}^2 = M^2 - iM\Gamma$

## Upper bound on $M_h$ in the MSSM:

“Unconstrained MSSM”:

$M_A$ ,  $\tan \beta$ , 5 parameters in  $\tilde{t}$ - $\tilde{b}$  sector,  $\mu$ ,  $m_{\tilde{g}}$ ,  $M_2$

$$M_h \lesssim 135 \text{ GeV}$$

for  $m_t = 173.2 \pm 0.9 \text{ GeV}$

(including theoretical uncertainties from unknown higher orders)

⇒ observable at the LHC

Obtained with:

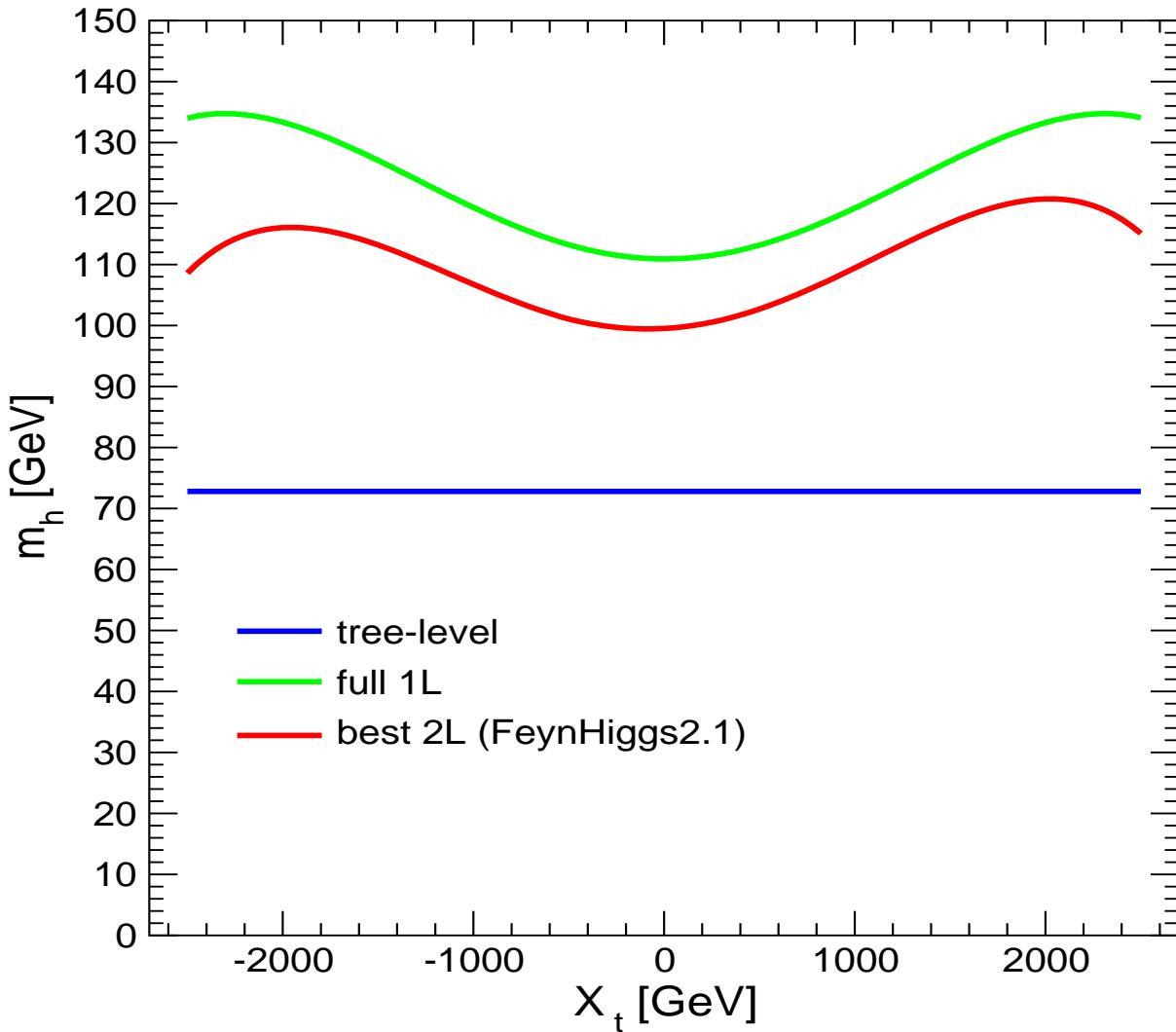
FeynHiggs

[www.feynhiggs.de](http://www.feynhiggs.de)

[T. Hahn, S. Heinemeyer., W. Hollik, H. Rzehak, G. Weiglein, K. Williams '98 – '11]

## Effects of the two-loop corrections to the lightest Higgs mass:

Example for one set of MSSM parameters



$$X_t = A_t - \mu \cot \beta$$

Typically,

1-loop corrections increase  $m_h$   
by  $\mathcal{O}(30 - 50)$  GeV

2-loop corrections decrease  $m_h$   
by  $\mathcal{O}(5 - 10)$  GeV

[S.Heinemeyer, W.Hollik, G.Weiglein '03]

## Remaining theoretical uncertainties in prediction for $M_h$ in the MSSM:

[*G. Degrassi, S. Heinemeyer., W. Hollik, P. Slavich, G. Weiglein '02*]

- From unknown higher-order corrections:

$$\Rightarrow \Delta M_h \approx 3 \text{ GeV}$$

- From uncertainties in input parameters

$$m_t, \dots, M_A, \tan \beta, m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{g}}, \dots$$

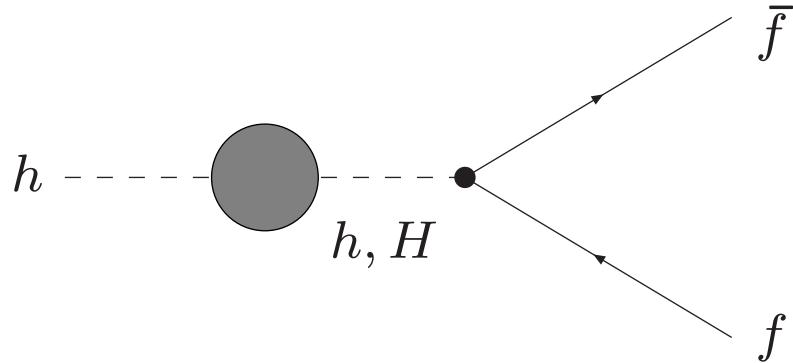
$$\Delta m_t \approx 1 \text{ GeV} \Rightarrow \Delta M_h \approx 1 \text{ GeV}$$

## Higgs couplings, production cross sections

⇒ also affected by large SUSY loop corrections

Extreme example:  $\Gamma(h \rightarrow b\bar{b}) \rightarrow 0$  via loop corrections possible

## $h f \bar{f}$ coupling:



$$A(h \rightarrow f\bar{f}) = \sqrt{Z_h} \left( \Gamma_h - \frac{\hat{\Sigma}_{hH}(M_h^2)}{M_h^2 - m_H^2 + \hat{\Sigma}_{HH}(M_h^2)} \Gamma_H \right)$$

⇒ Effective  $h f \bar{f}$  coupling can vanish for large  $\hat{\Sigma}_{hH}$

Gluino vertex corrections to  $h \rightarrow q\bar{q}$ :

⇒ ratio  $\Gamma(h \rightarrow \tau^+ \tau^-)/\Gamma(h \rightarrow b\bar{b})$  can significantly differ from SM value for large  $\tan \beta$

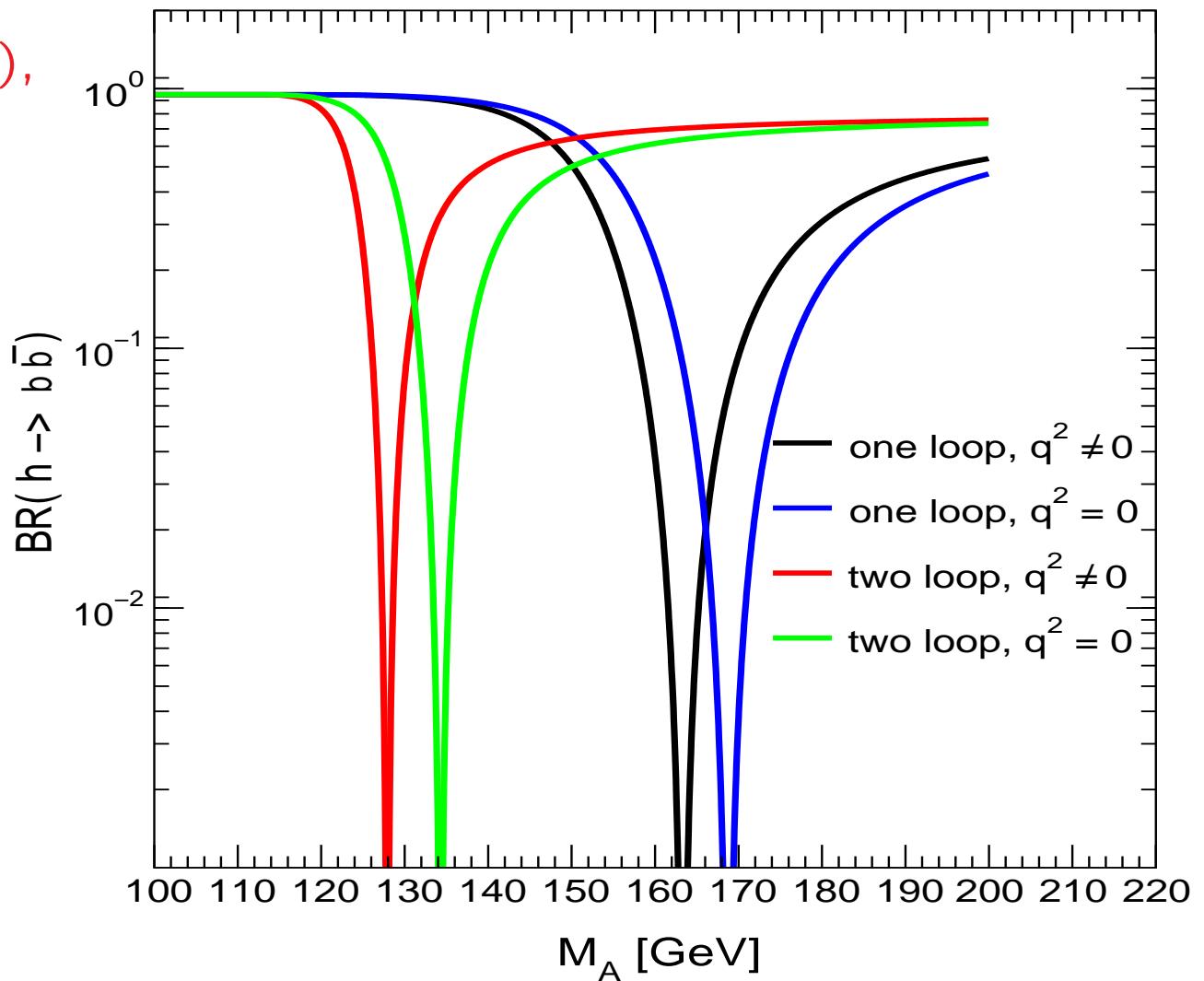
Effective  $h f \bar{f}$  coupling can go to zero for large  $\hat{\Sigma}_{hH}$

⇒ “Pathological regions”

[W. Loinaz, J. Wells '98] [M. Carena, S. Mrenna, C. Wagner '99]

⇒ Suppression of  $\text{BR}(h \rightarrow b\bar{b})$ ,  
 $\text{BR}(h \rightarrow \tau\tau)$ , ...

[S.H., W. Hollik, G. Weiglein '00]



## Possible problem in SUSY:

$$h \rightarrow b\bar{b}$$

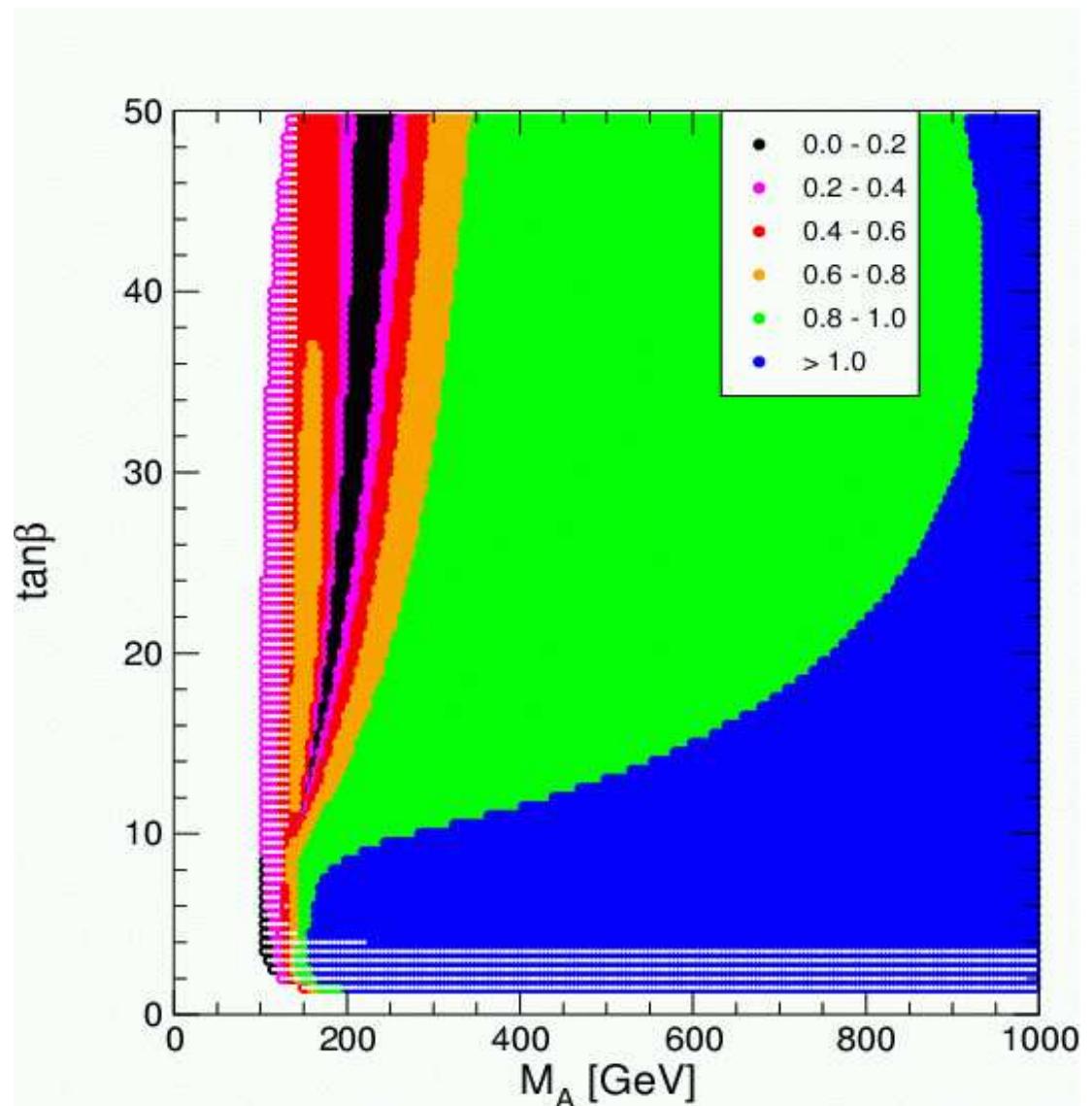
can be **strongly suppressed**

→ “Small  $\alpha_{\text{eff}}$  scenario”

[*M. Carena, S.H., C. Wagner,  
G. Weiglein '02*]

⇒ Strong suppression of  
 $h \rightarrow b\bar{b}$  possible,  
up to  $M_A \lesssim 350$  GeV

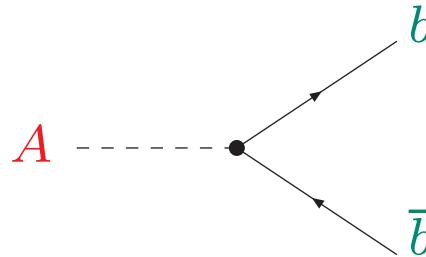
(not realized in  
mSUGRA/CMSSM, GMSB,  
AMSB, . . . )



### 3. The heavy MSSM Higgs bosons

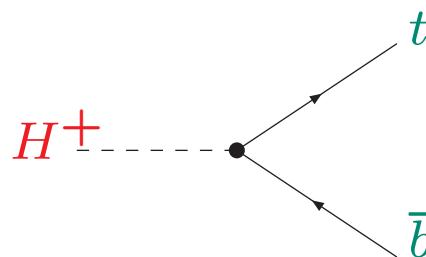
Differences compared to the SM Higgs:

Additional enhancement factors compared to the SM case:



$$y_b \rightarrow y_b \frac{\tan \beta}{1 + \Delta_b}$$

At large  $\tan \beta$ : either  $H \approx A$  or  $h \approx A$



$$y_b \frac{\tan \beta}{1 + \Delta_b}$$

$$\begin{aligned} \Delta_b &= \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu \tan \beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) \\ &+ \frac{\alpha_t}{4\pi} A_t \mu \tan \beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu) \end{aligned}$$

$\Rightarrow$  other parameters enter  $\Rightarrow$  strong  $\mu$  dependence

## Search for the MSSM Higgs bosons:

Situation is more involved due to many SUSY parameters

→ investigate benchmark scenarios:

- Vary only  $M_A$  and  $\tan\beta$
- Keep all other SUSY parameters fixed

### 1. $m_h^{\max}$ scenario:

→ obtain conservative  $\tan\beta$  exclusion bounds ( $X_t = 2 M_{\text{SUSY}}$ )

### 2. no-mixing scenario

→ no mixing in the scalar top sector ( $X_t = 0$ )

### 3. small $\alpha_{\text{eff}}$ scenario

→  $h b \bar{b}$  coupling  $\sim \sin \alpha_{\text{eff}} / \cos \beta$  can be zero:  $\alpha_{\text{eff}} \rightarrow 0$ :  
main decay mode vanishes, important search channel vanishes

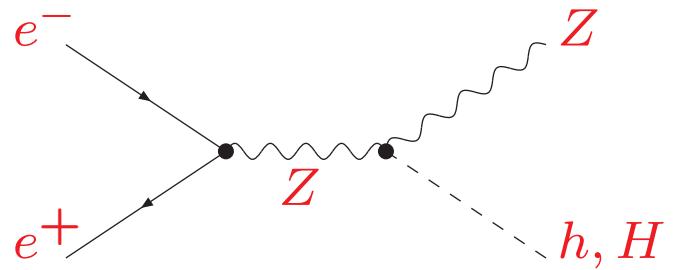
### 4. gluophobic Higgs scenario

→  $h gg$  coupling is small: main LHC production mode vanishes

[*M. Carena, S.H., C. Wagner, G. Weiglein '02*]

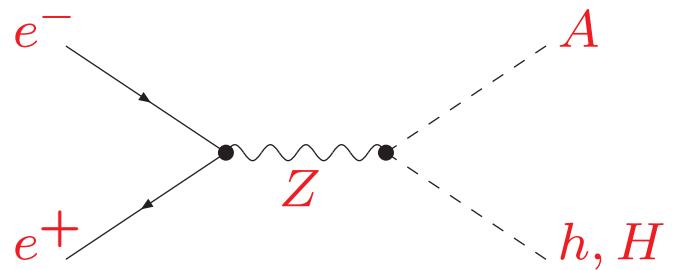
## Search for neutral SUSY Higgs bosons at LEP:

$e^+e^- \rightarrow Zh, ZH$



$$\sigma_{hZ} \approx \sin^2(\beta - \alpha_{\text{eff}}) \sigma_{hZ}^{\text{SM}}$$
$$\sigma_{HZ} \approx \cos^2(\beta - \alpha_{\text{eff}}) \sigma_{hZ}^{\text{SM}}$$

$e^+e^- \rightarrow Ah, AH$

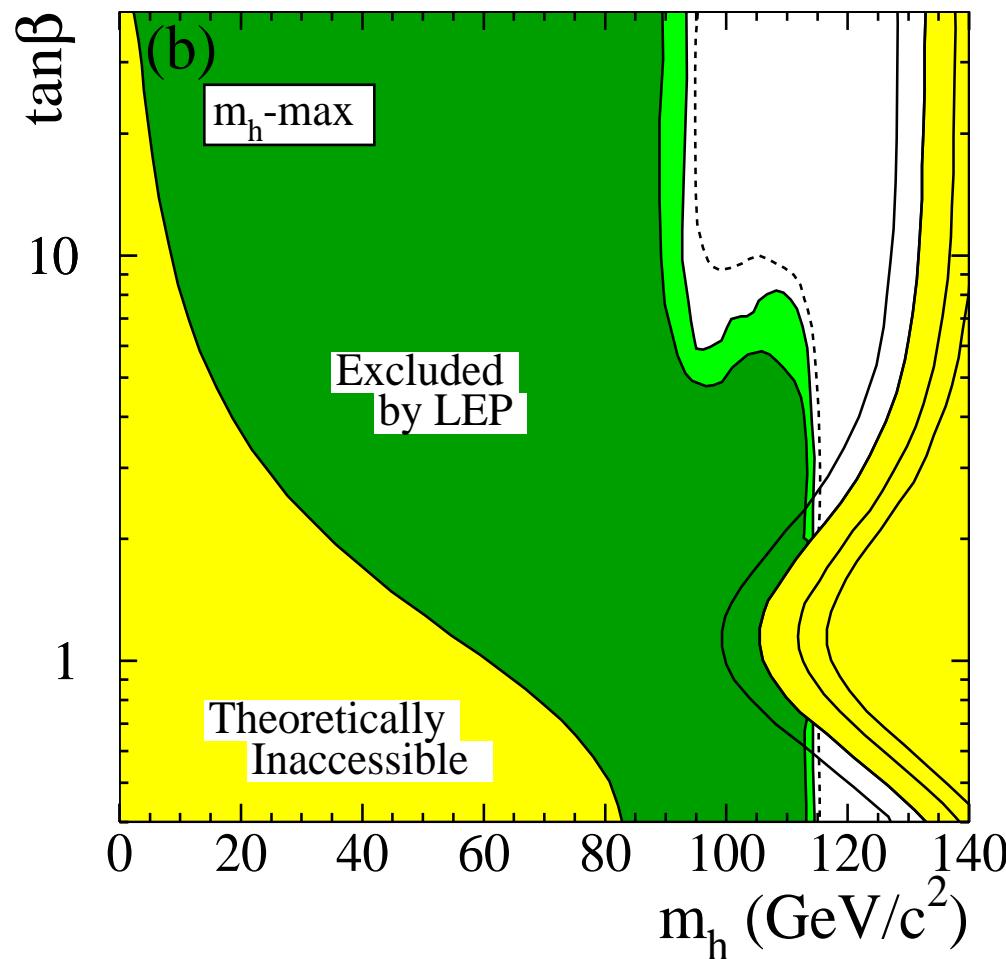


$$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}}) \sigma_{hZ}^{\text{SM}}$$
$$\sigma_{HA} \propto \sin^2(\beta - \alpha_{\text{eff}}) \sigma_{hZ}^{\text{SM}}$$

## Constraints from the Higgs search at LEP [LEP Higgs Working Group '06]

Experimental search vs. upper  $m_h$ -bound (*FeynHiggs 2.0*)

$m_h^{\max}$ -scenario ( $m_t = 174.3$  GeV,  $M_{\text{SUSY}} = 1$  TeV):

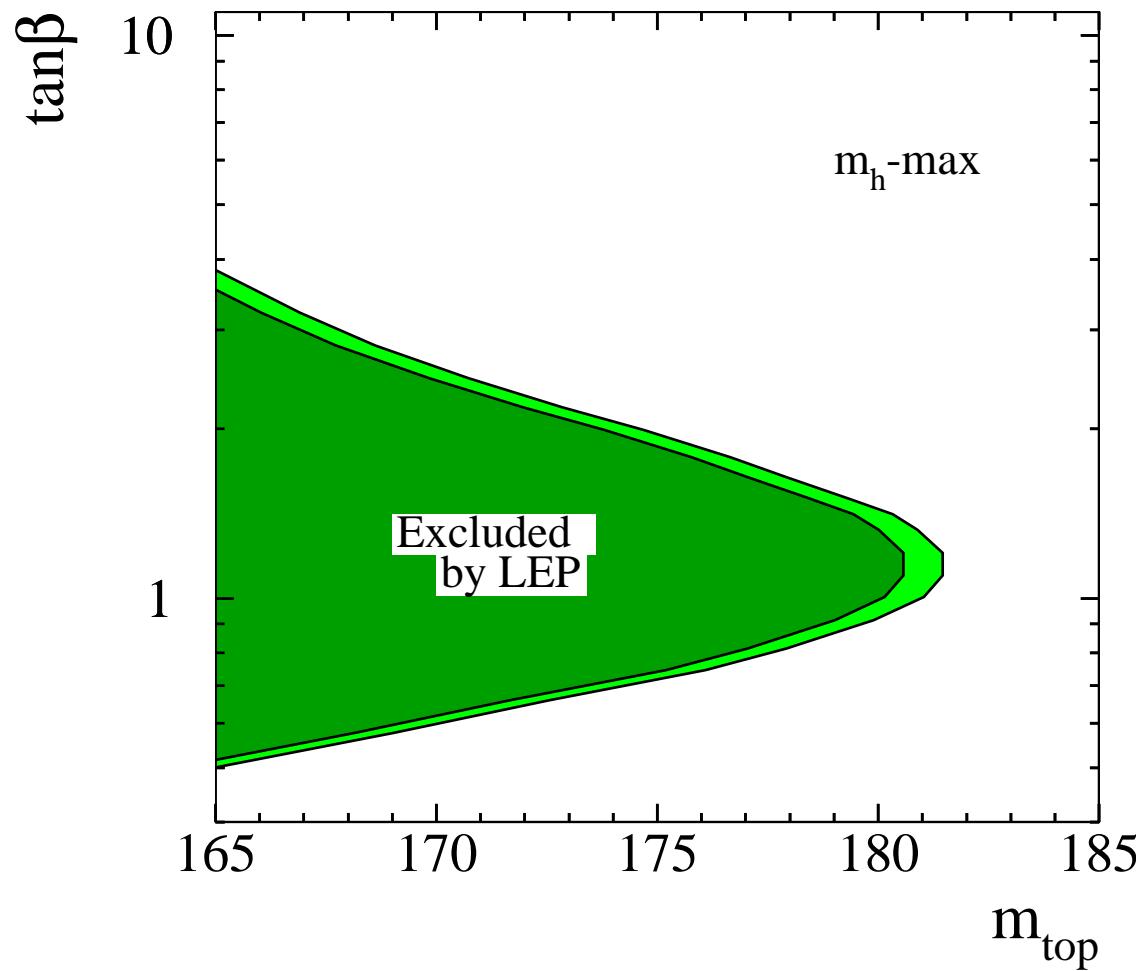


$m_h > 92.8$  GeV  
(expected: 94.9 GeV), 95% C.L.

$M_A > 93.4$  GeV  
(expected: 95.2 GeV)

Parameter region where experimental lower bound on  $M_h$  is significantly lower than SM bound,  $M_H > 114.4$  GeV, corresponds to  $\sin^2(\beta - \alpha_{\text{eff}}) \ll 1$

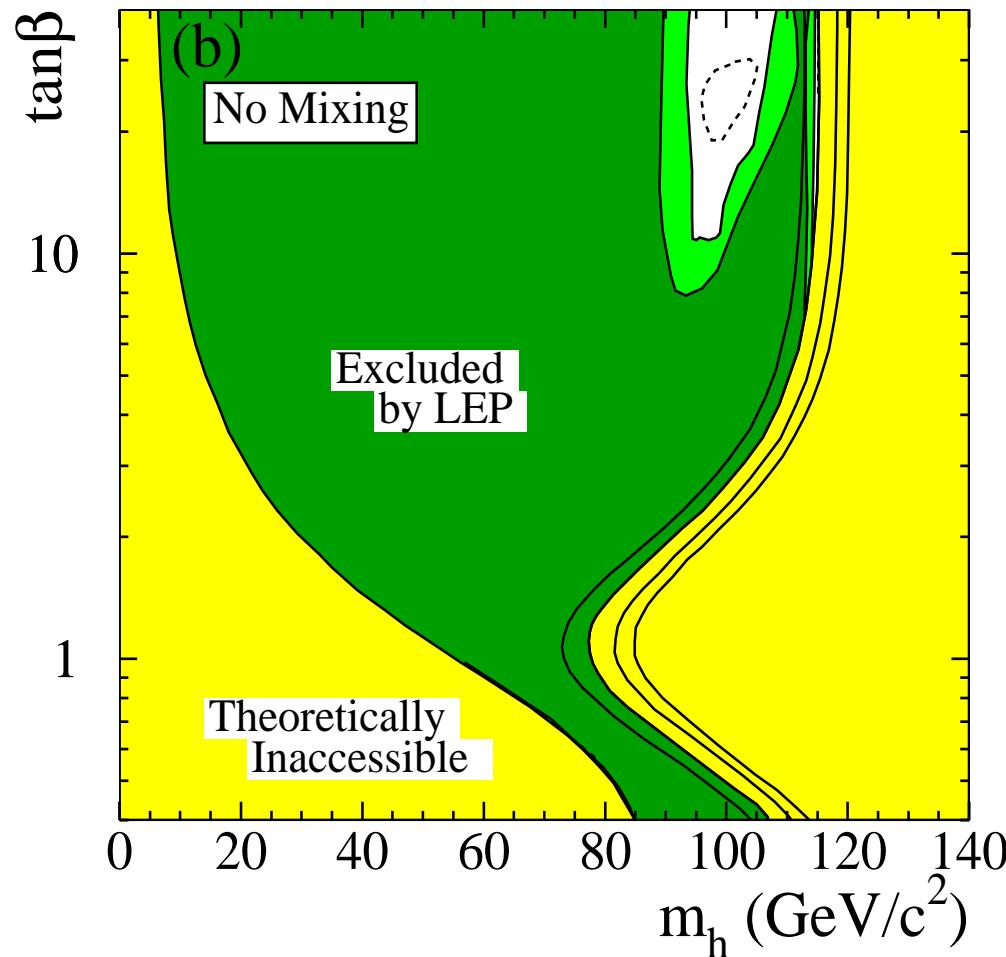
“Excluded”  $\tan\beta$  region:



## Constraints from the Higgs search at LEP [LEP Higgs Working Group '06]

Experimental search vs. upper  $m_h$ -bound (*FeynHiggs 2.0*)

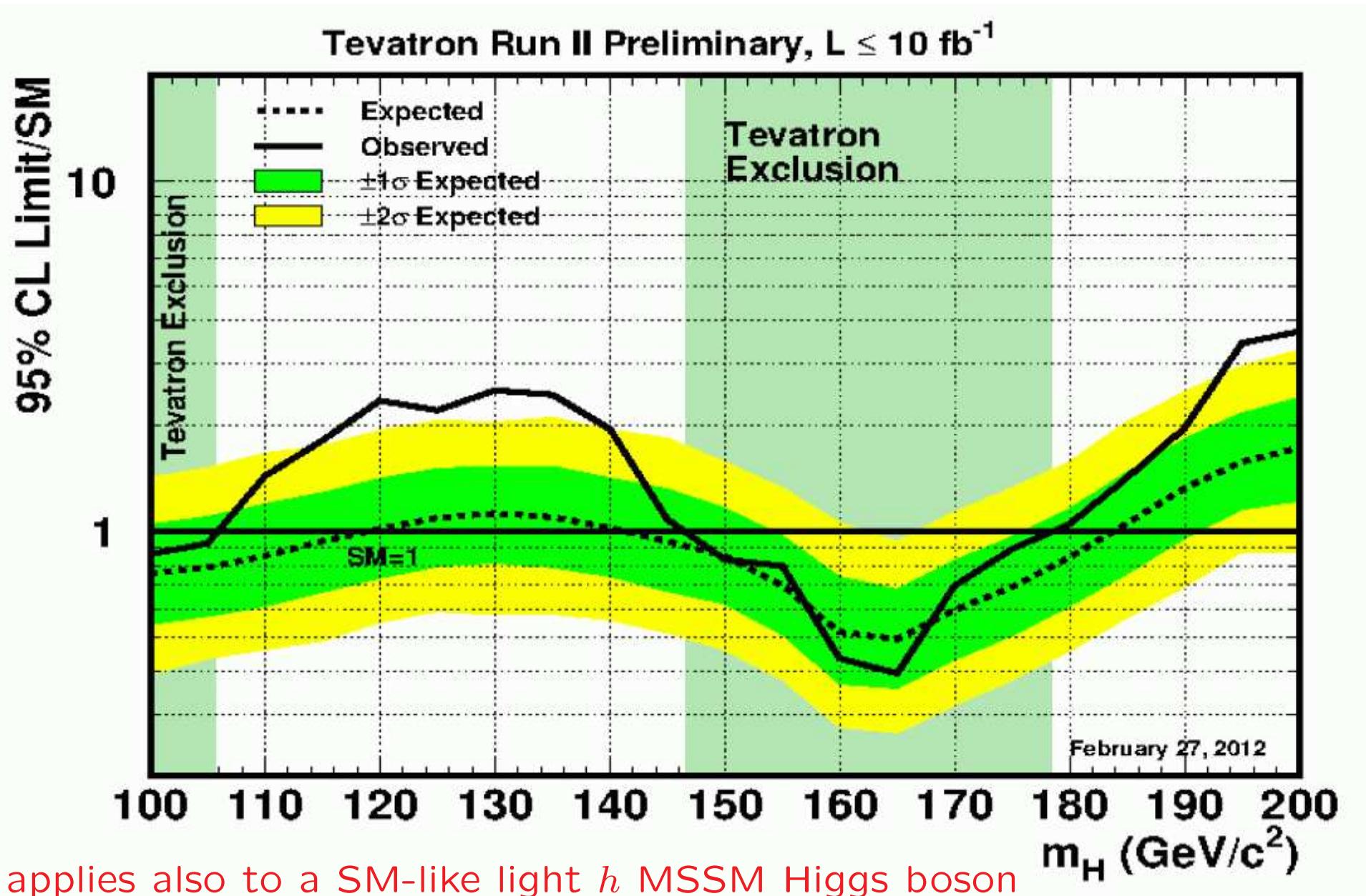
no-mixing scenario ( $m_t = 174.3$  GeV,  $M_{\text{SUSY}} = 1$  TeV):



$m_h > 93.6$  GeV  
(expected: 96.0 GeV), 95% C.L.

$M_A > 93.6$  GeV  
(expected: 96.4 GeV)

## MSSM Higgs searches at the Tevatron: The "light" $h$



## MSSM Higgs searches at the Tevatron: The "heavy" $H, A$

Search modes:

$$\begin{aligned} b\bar{b} \rightarrow \phi b\bar{b}, \quad \phi = H, A \\ p\bar{p} \rightarrow \phi \rightarrow \tau^+ \tau^-, \quad \phi = H, A \end{aligned}$$

Strong enhancement compared to the SM:

$$\sigma(b\bar{b}A) \times \text{BR}(A \rightarrow b\bar{b}) \simeq \sigma(b\bar{b}A)_{\text{SM}} \frac{\tan^2 \beta}{(1 + \Delta_b)^2} \times \frac{9}{(1 + \Delta_b)^2 + 9}$$

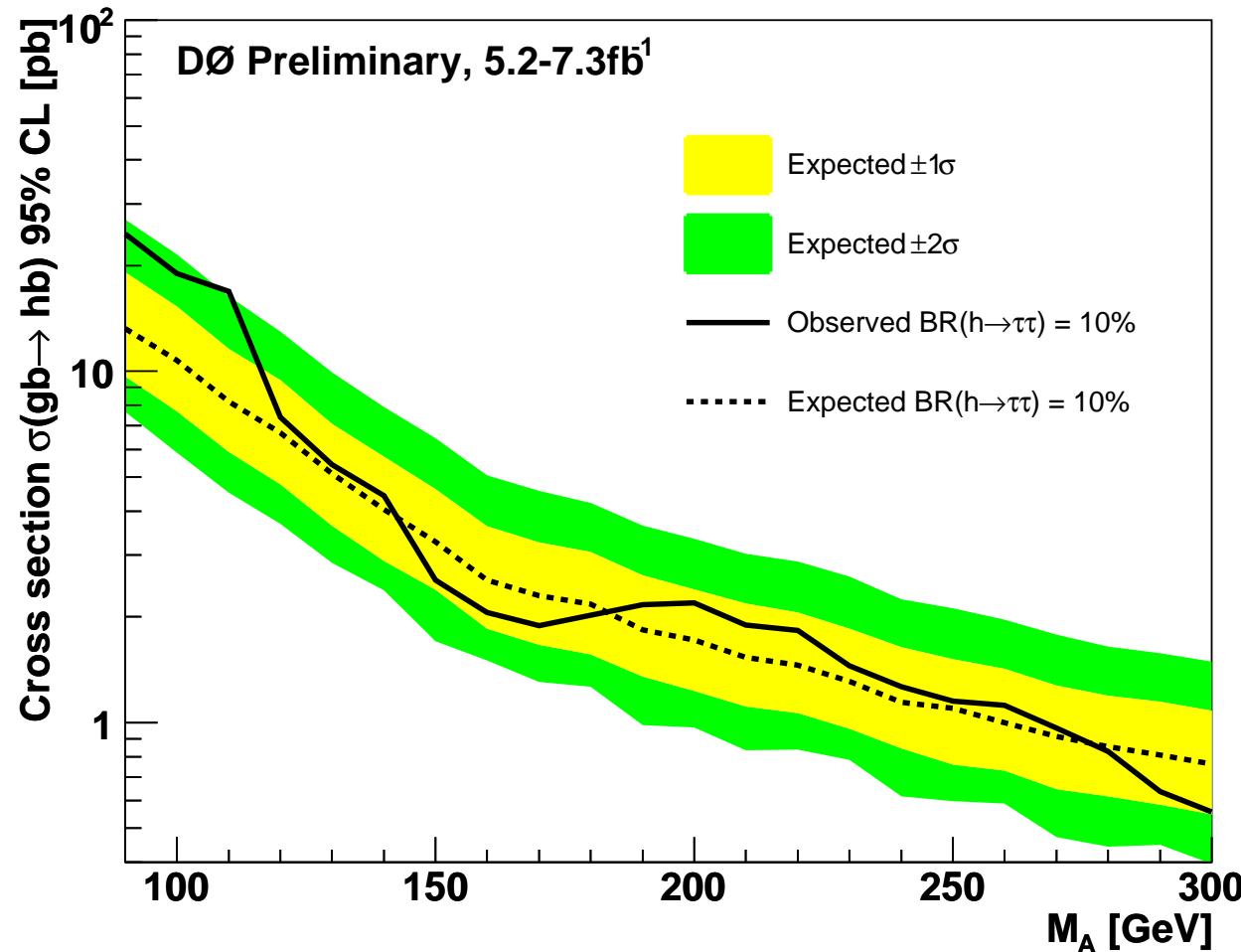
$$\sigma(gg, b\bar{b} \rightarrow A) \times \text{BR}(A \rightarrow \tau^+ \tau^-) \simeq \sigma(gg, b\bar{b} \rightarrow A)_{\text{SM}} \frac{\tan^2 \beta}{(1 + \Delta_b)^2 + 9}$$

$$\begin{aligned} \Delta_b &= \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu \tan \beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) \\ &+ \frac{\alpha_t}{4\pi} A_t \mu \tan \beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu) \end{aligned}$$

Typically, larger rates than in SM at large  $\tan \beta$

Example:  $p\bar{p} \rightarrow h/H/A \rightarrow \tau^+\tau^-$  at DØ with  $\sim 7 \text{ fb}^{-1}$

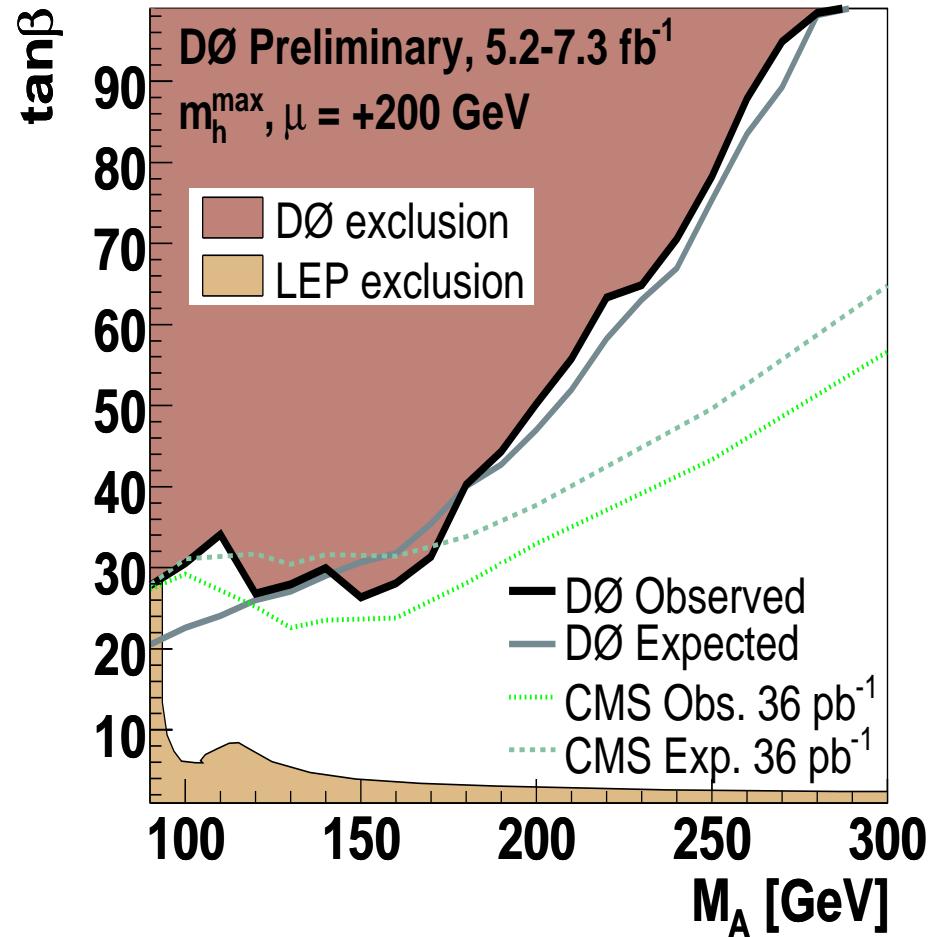
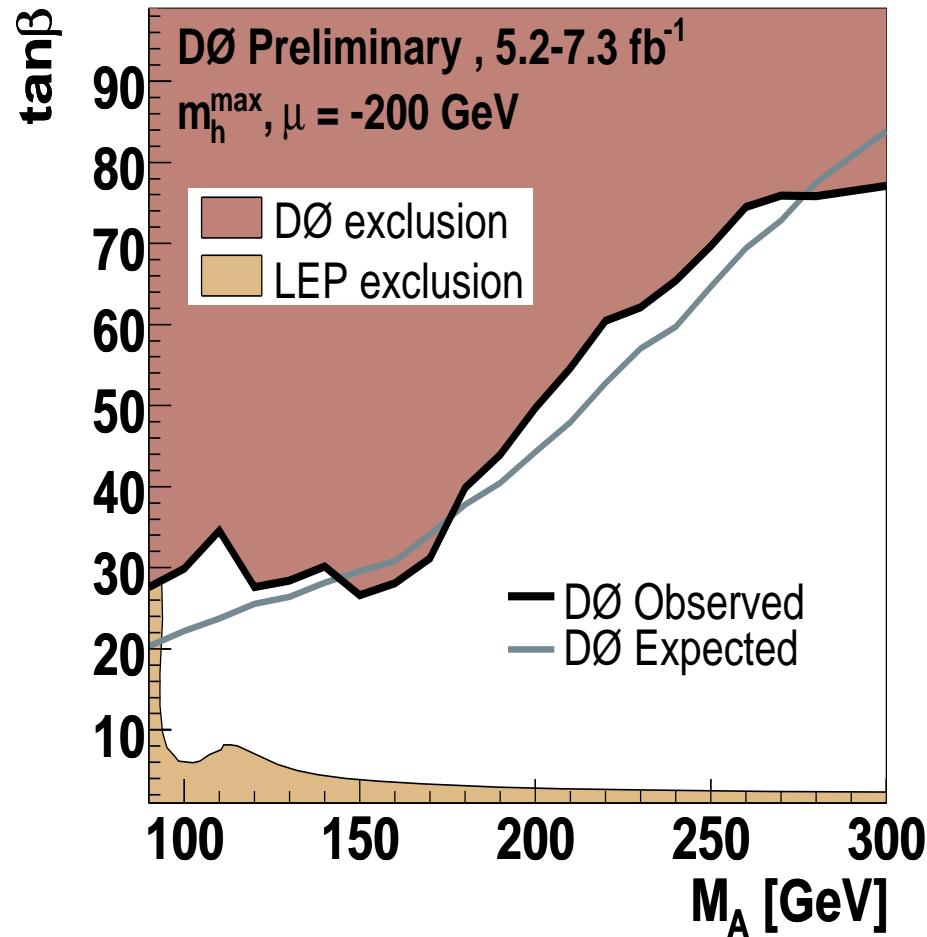
[DØ'11]



⇒ model independent limit on  $\sigma \times \text{BR}$

Example:  $p\bar{p} \rightarrow h/H/A \rightarrow \tau^+\tau^-$  at DØ with  $\sim 7 \text{ fb}^{-1}$

[DØ'11]



⇒ exclusion for light  $M_A$  and large  $\tan \beta$

## MSSM Higgs boson searches at the LHC

Searches are more involved than in SM due to many SUSY parameters

### 1. Light MSSM Higgs boson in the decoupling limit:

- SM Higgs searches apply
- keep in mind the upper limit of 135 GeV
- ⇒ no limits beyond LEP so far!

### 2. Light MSSM Higgs boson “before” the decoupling limit:

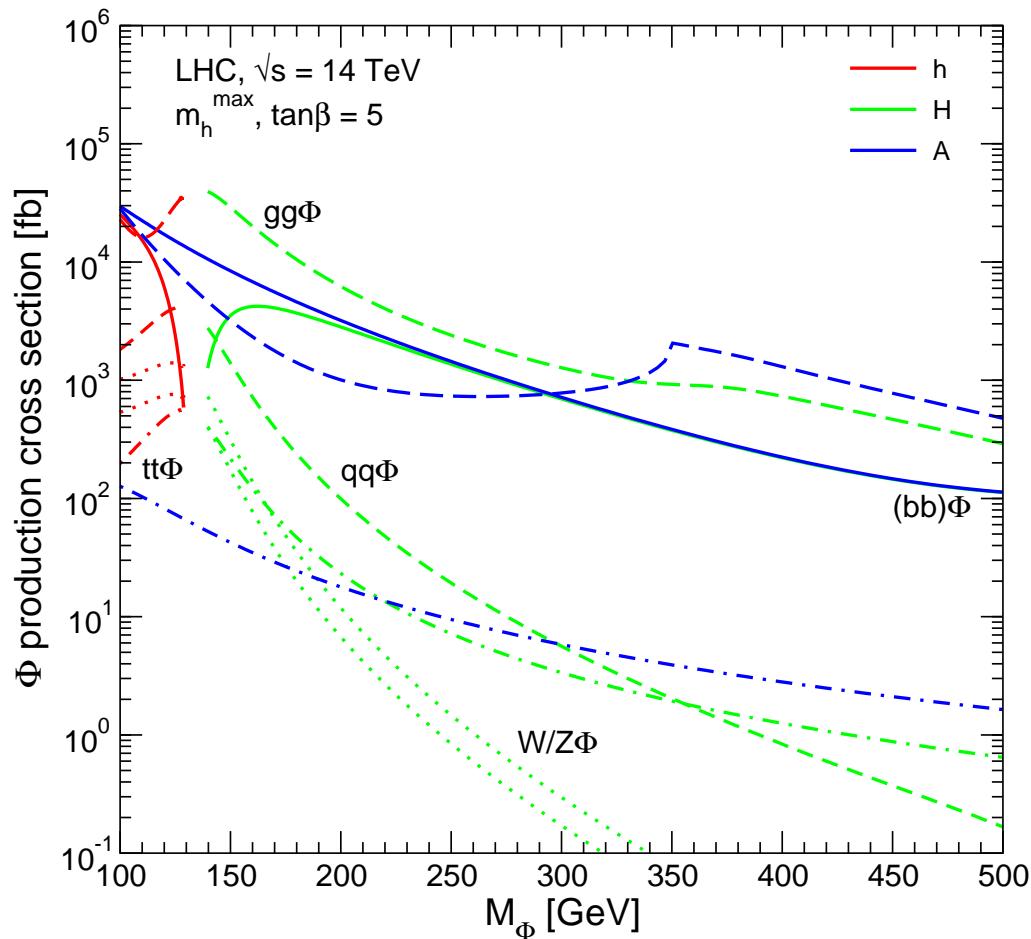
- dedicated search necessary
- SM-like search with reduced couplings
- therefore reduced  $\sigma \times \text{BR}$

### 3. Heavy MSSM Higgs boson:

- dedicated search
- ⇒ model independent results on  $\sigma \times \text{BR}$
- ⇒ specific MSSM results for  $H/A$

# Cross sections at LHC for neutral MSSM Higgses ( $\phi = h, H, A$ )

[*Tev4LHC Higgs working group report '06*]



gluon fusion:  $gg \rightarrow \phi$

weak boson fusion (WBF):  
 $q\bar{q} \rightarrow q'\bar{q}'\phi$

top quark associated  
production:  $gg, q\bar{q} \rightarrow t\bar{t}\phi$

weak boson associated  
production:  $q\bar{q}' \rightarrow W\phi, Z\phi$

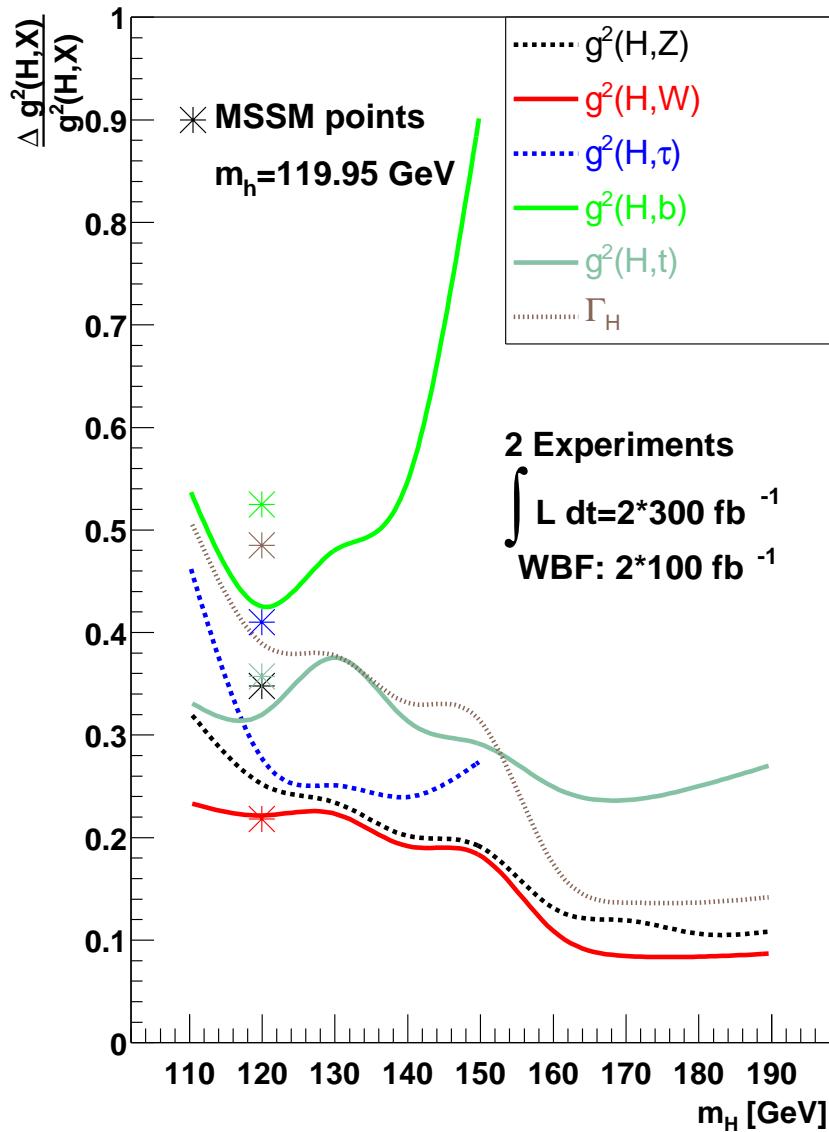
NEW:  $b\bar{b}\phi$

Search for the lightest  $h$  at the LHC:  $\Rightarrow$  full parameter accessible  
But there might be problems if strong suppression in effective  $b\bar{b}h$  coupling

## MSSM light Higgs couplings at the LHC:

One BSM example: one light MSSM Higgs

[M. Dührssen et al. '04]



scenario with low  $M_A$ , large  $\tan \beta$ :

$h \rightarrow b\bar{b}$  enhanced (but old analyses)

$h \rightarrow \tau^+ \tau^-$  enhanced

$\text{BR}(h \rightarrow VV^*) \approx 1/2 \text{ SM}$

$\text{BR}(h \rightarrow \gamma\gamma) \approx 1/2 \text{ SM}$

$\text{BR}(h \rightarrow gg) \approx 1/5 \text{ SM}$

⇒ not too bad ...

⇒ more analyses needed!

## LHC Higgs boson searches: the heavy $H, A, H^\pm$

$$\boxed{\begin{aligned} b\bar{b} &\rightarrow H/A \rightarrow \tau^+\tau^- + X \\ g\bar{b} &\rightarrow tH^\pm + X, \quad H^\pm \rightarrow \tau\nu_\tau \\ p\bar{p} &\rightarrow t\bar{t} \rightarrow H^\pm + X, \quad H^\pm \rightarrow \tau\nu_\tau \end{aligned}}$$

Most powerful modes due to enhancement factors compared to SM:

$$H/A : \frac{\tan^2 \beta}{(1 + \Delta_b)^2} \times \frac{\text{BR}(H \rightarrow \tau^+\tau^-) + \text{BR}(A \rightarrow \tau^+\tau^-)}{\text{BR}(H \rightarrow \tau^+\tau^-)_{\text{SM}}}$$

$$H^\pm : \frac{\tan^2 \beta}{(1 + \Delta_b)^2} \times \text{BR}(H^\pm \rightarrow \tau\nu_\tau)$$

$\Rightarrow \Delta_b$  effects (often neglected by ATLAS/CMS analyses)

also relevant for  $\text{BR}(H/A \rightarrow \tau^+\tau^-)$ ,  $\text{BR}(H^\pm \rightarrow \tau\nu_\tau)$

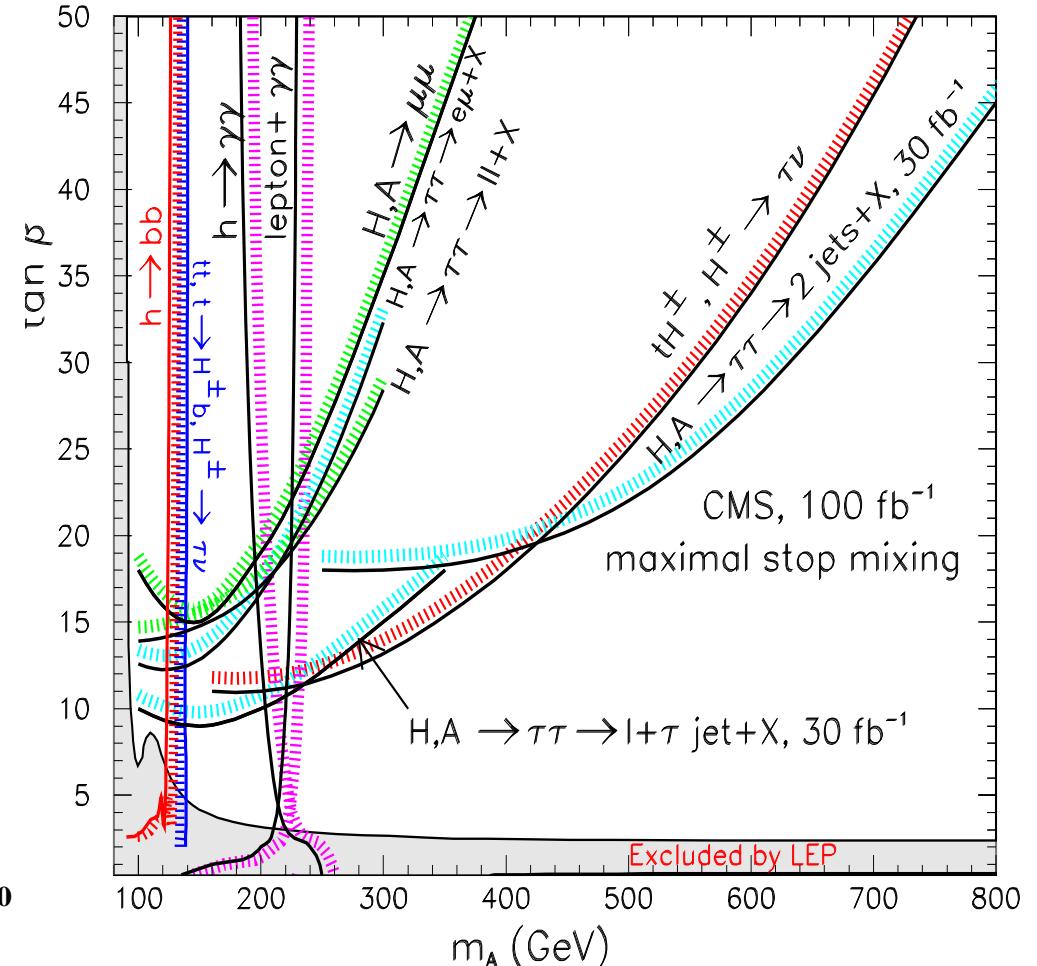
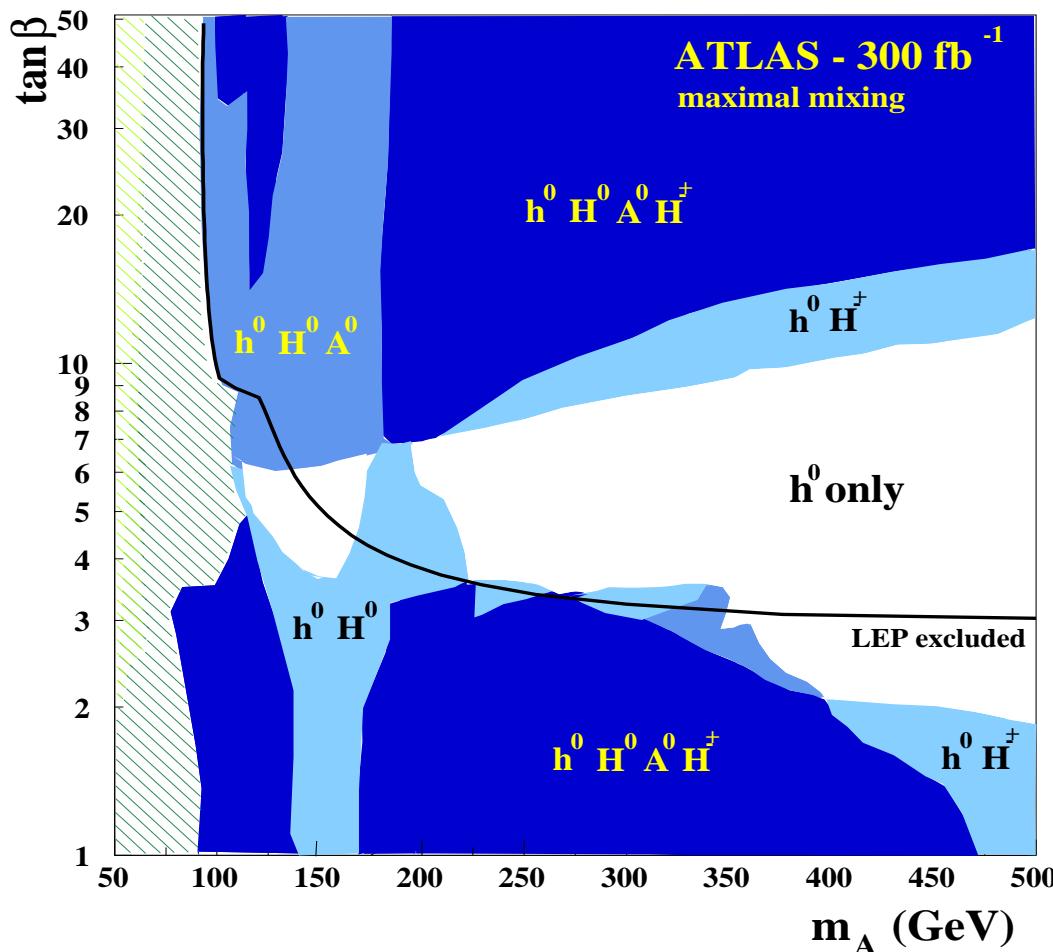
also relevant: correct evaluation of  $\Gamma(H/A/H^\pm \rightarrow \text{SUSY})$

$\Rightarrow$  additional effects on  $\text{BR}(H/A \rightarrow \tau^+\tau^-)$ ,  $\text{BR}(H^\pm \rightarrow \tau\nu_\tau)$

## Dedicated search for the heavy MSSM Higgs bosons

MSSM Higgs discovery contours in  $M_A$ - $\tan\beta$  plane

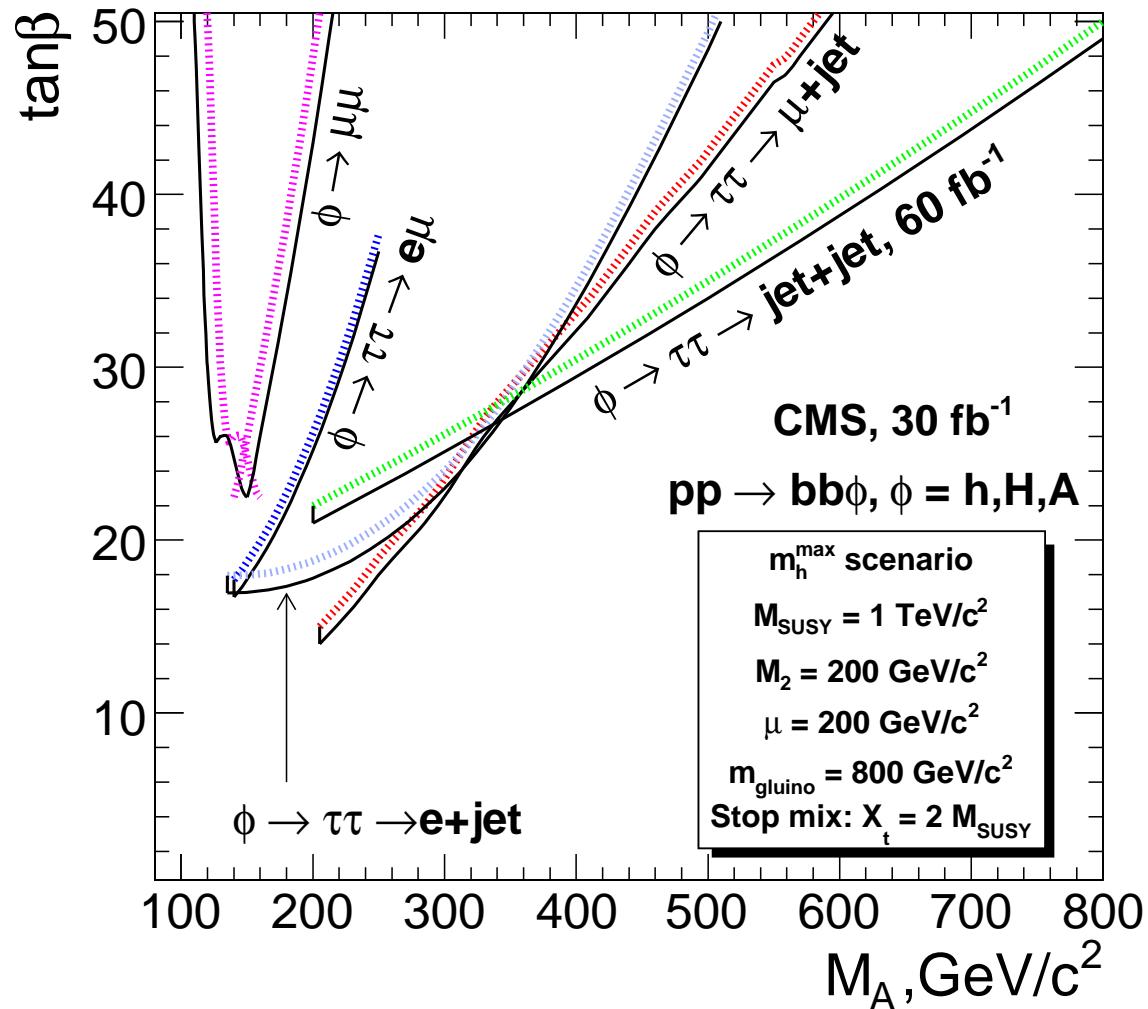
( $m_h^{\max}$  benchmark scenario): [ATLAS '99] [CMS '03]



areas where only  $h$  is observable  $\Rightarrow$  "LHC wedge"

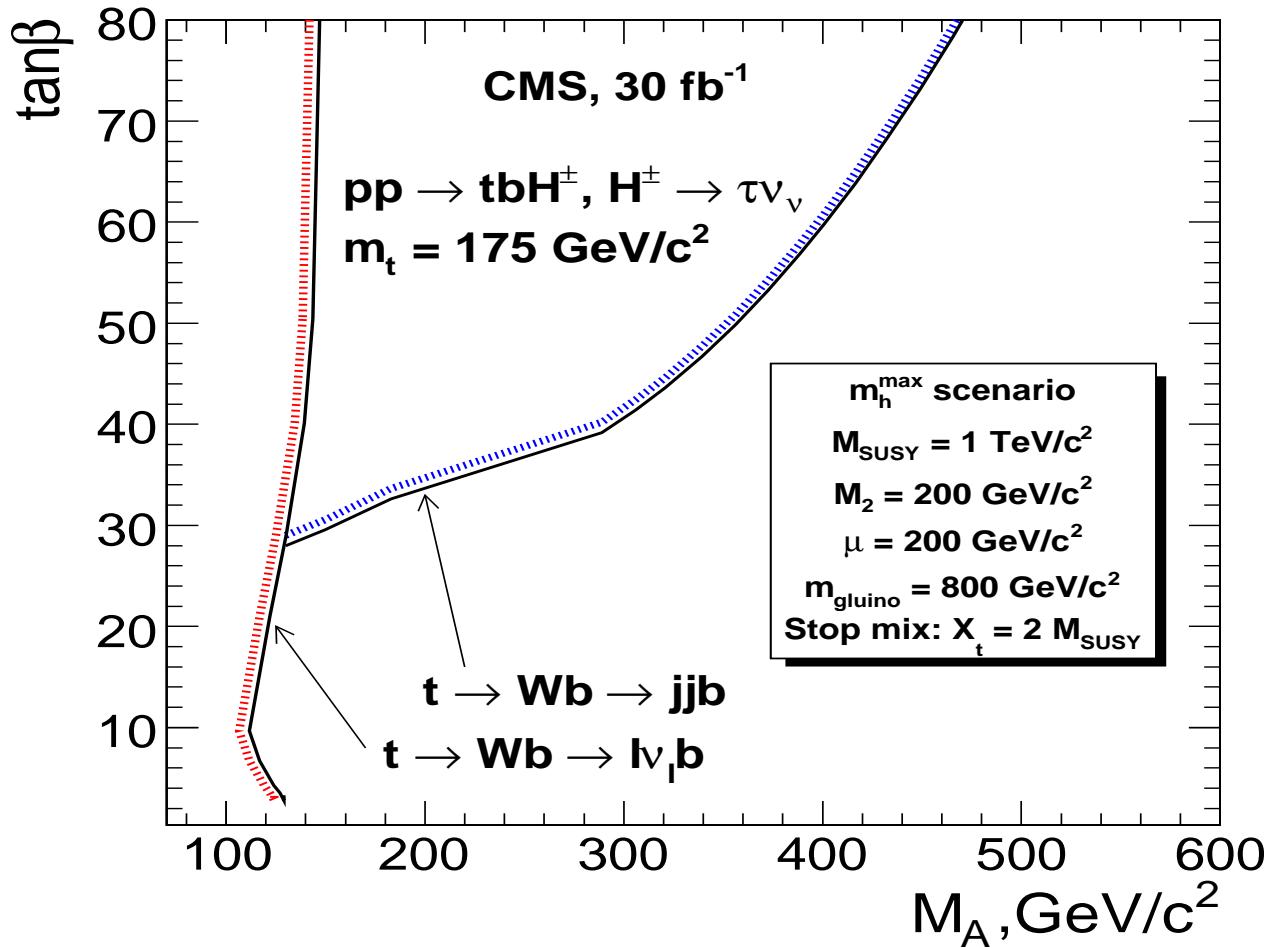
## Latest results for neutral heavy Higgs bosons:

MSSM Higgs discovery contours in  $M_A$ - $\tan\beta$  plane ( $\phi = H, A$ )  
( $m_h^{\max}$  benchmark scenario): [CMS PTDR '06]



## Charged Higgs boson searches:

MSSM Higgs discovery contours in  $M_A$ - $\tan\beta$  plane  
( $m_h^{\max}$  benchmark scenario): [CMS PTDR '06]



light charged Higgs:

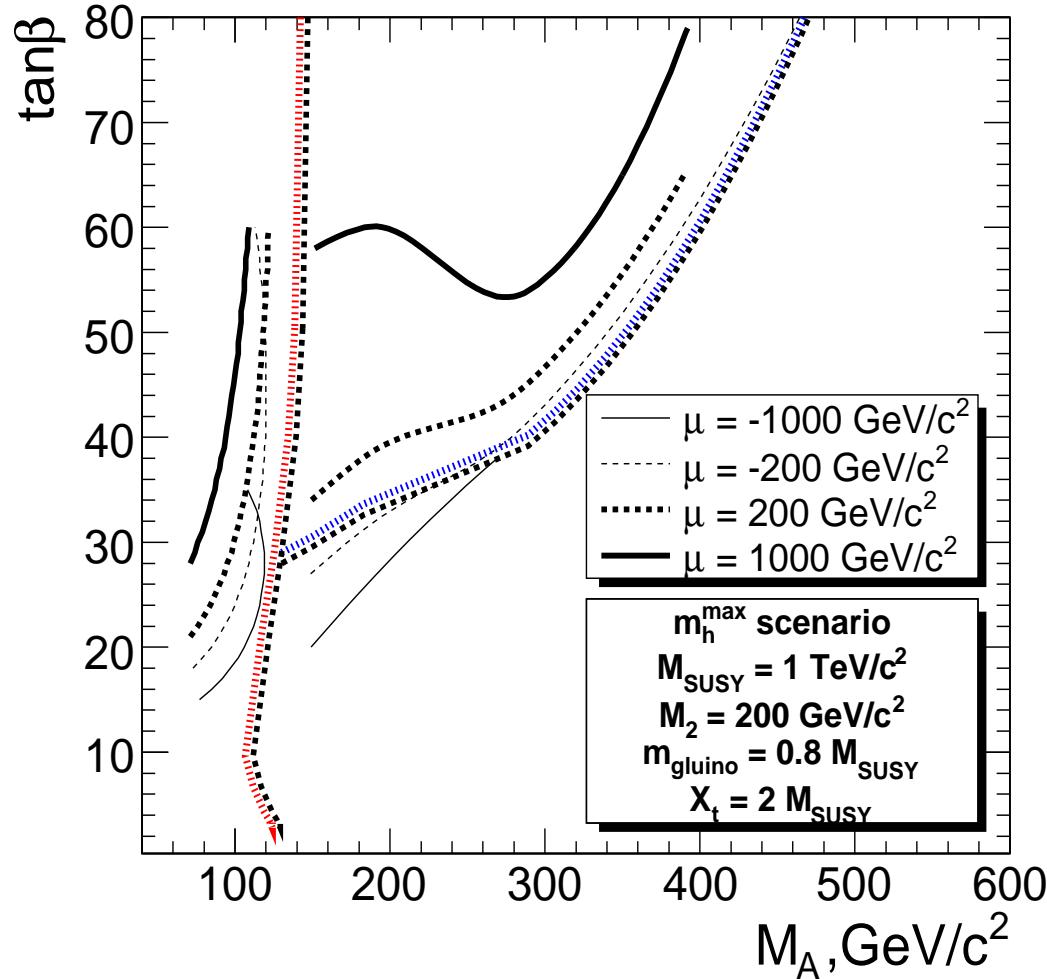
$$M_{H^\pm} < m_t$$

heavy charged Higgs:

$$M_{H^\pm} > m_t$$

# Charged Higgs: comparison with CMS PTDR ( $m_h^{\max}$ scenario):

[*M. Hashemi, S.H., R. Kinnunen, A. Nikitenko, G. Weiglein '07*]

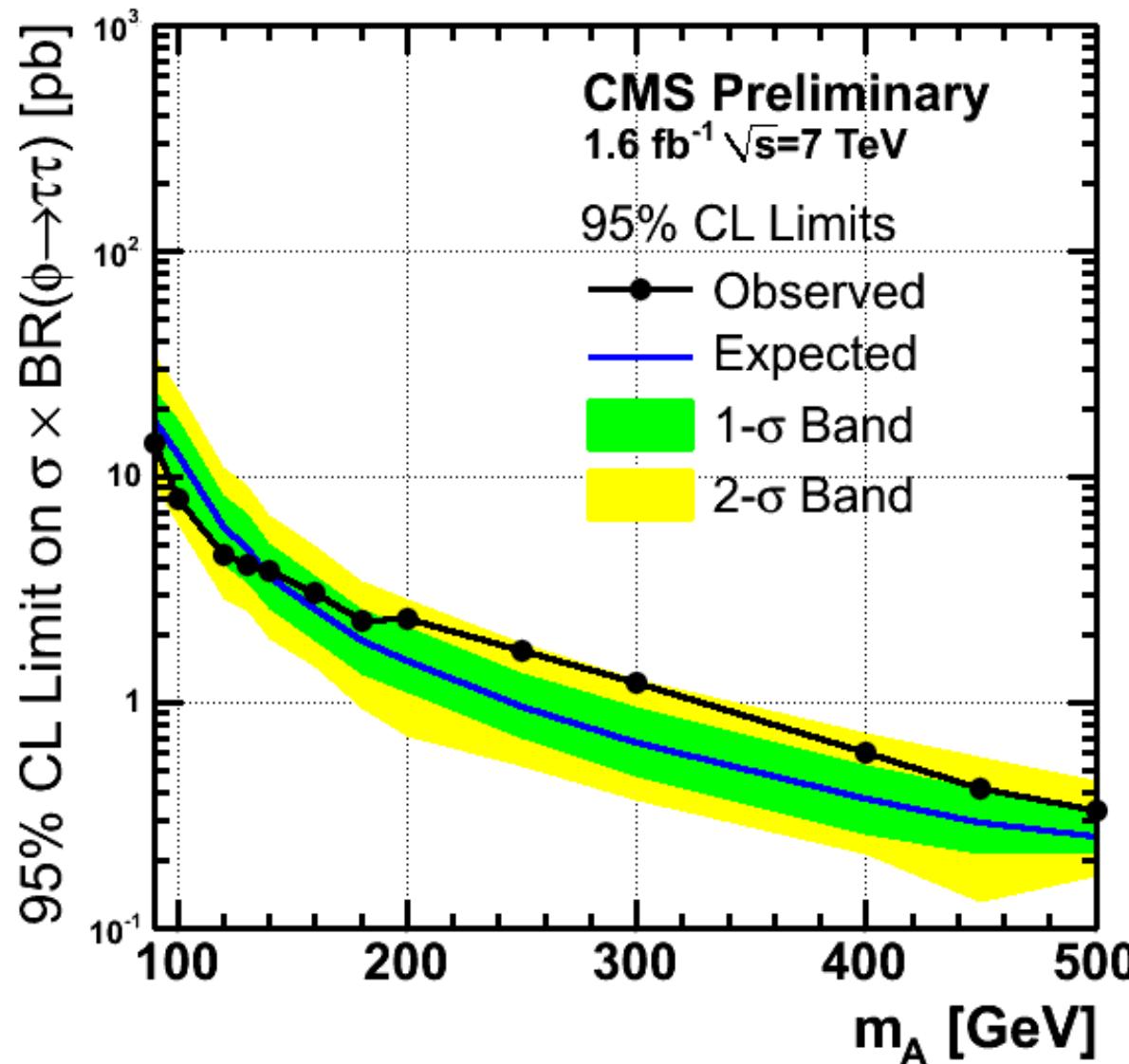


light charged Higgs:

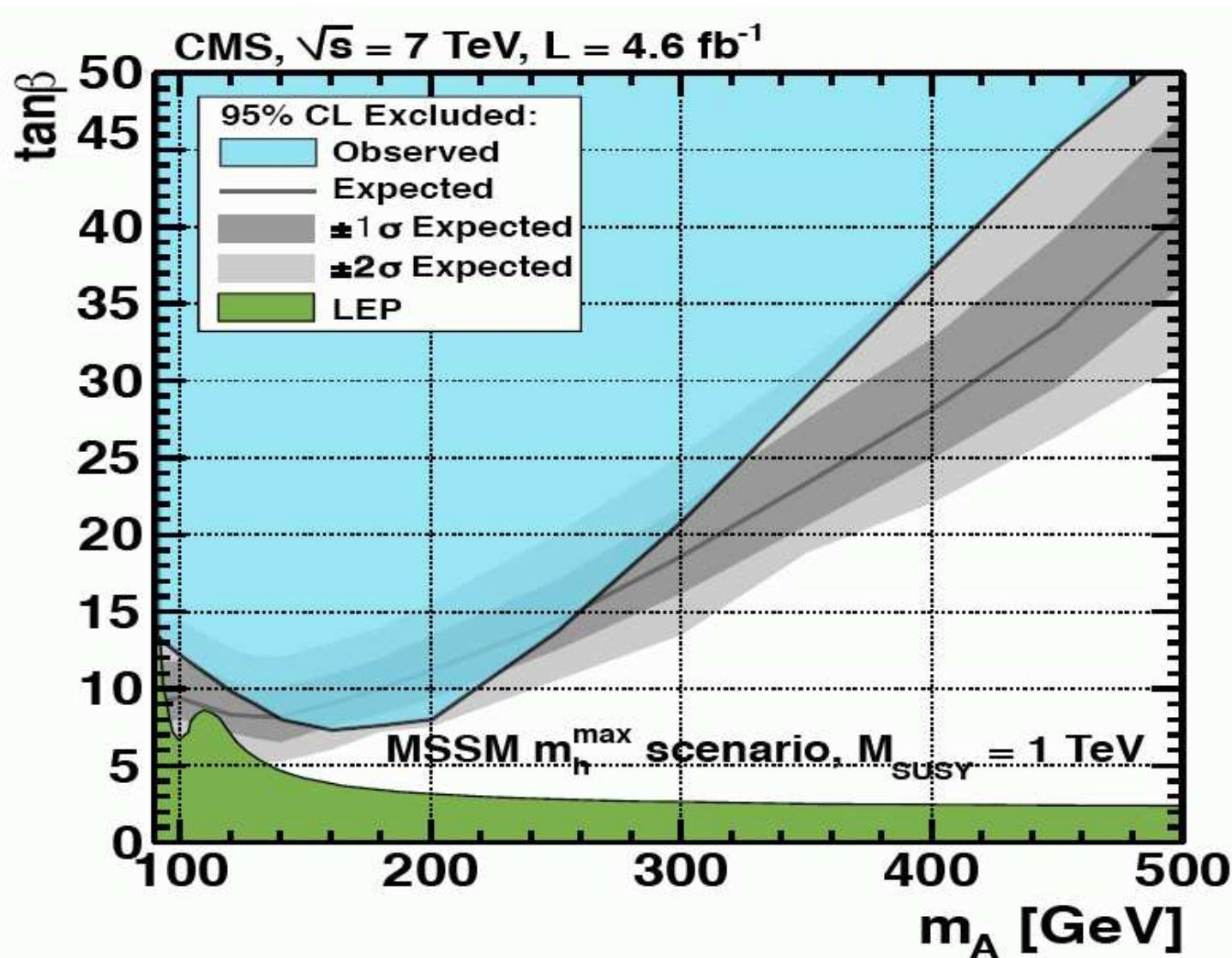
always worse than PTDR  
better  $M_{H^\pm}$  calculation!  
inclusion of  $\Delta_b$  effects

heavy charged Higgs:

PTDR in “the middle”  
new results partially  
substantially worse



⇒ small “excess” around  $M_A \gtrsim 300$  GeV



→ LHC  $\oplus$  LEP start to exclude low  $M_A$  values!

→ small “excess” around  $M_A \approx 300 \text{ GeV}$

## Implications of Higgs searches for SUSY

The latest results on ATLAS/CMS Higgs searches were presented on **13.12.2011** before **4pm**

On **14.12.2011** about **6** articles appeared on the arXiv, analyzing the implications

Most of them analyzed them in the framework of **SUSY**

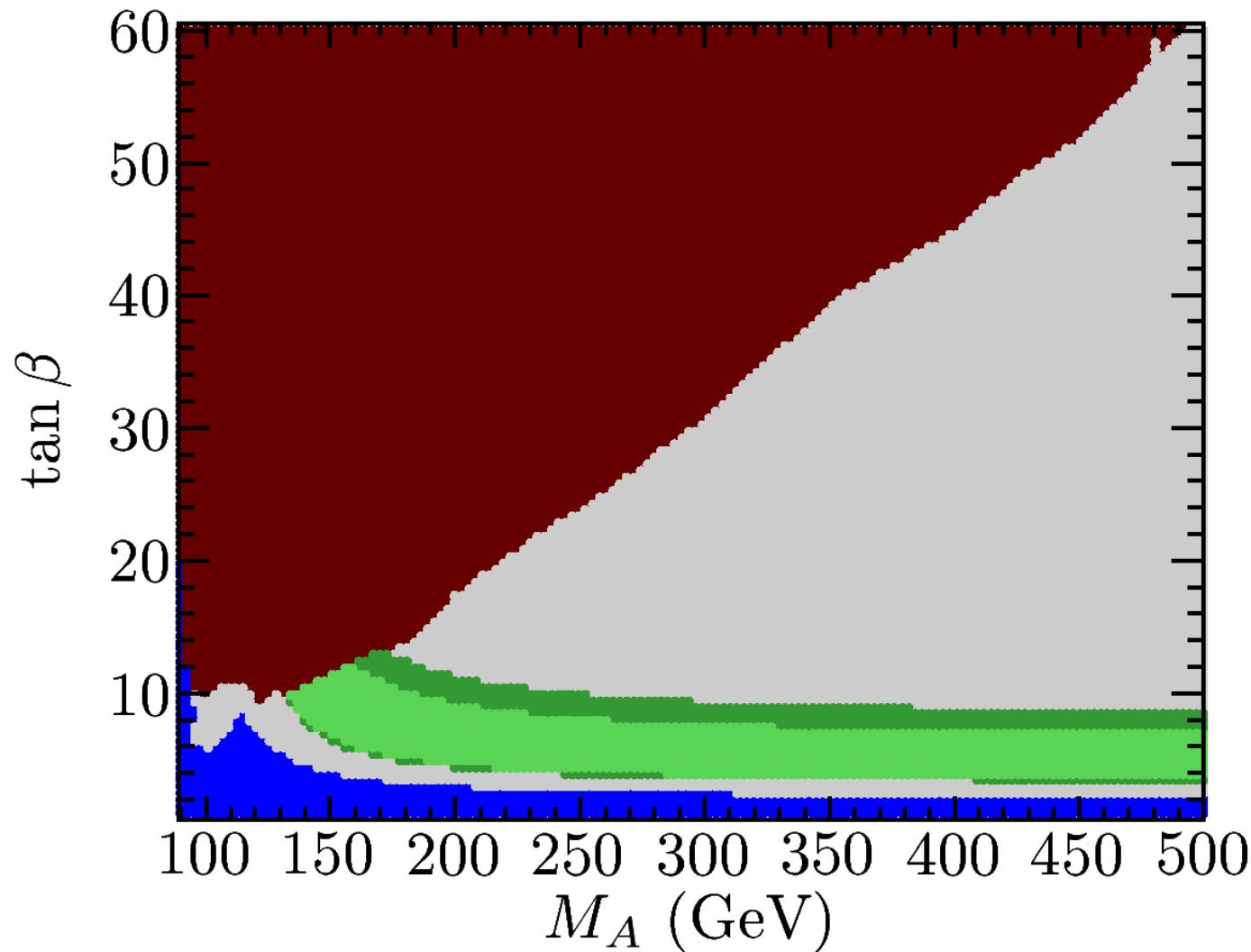
Here a few results from one **randomly picked article**:

[*arXiv:1112.3026 [hep-ph] (S.H., O. Stal, G. Weiglein)*]

$$M_h = 125 \pm 1(\text{exp.}) \pm 2(\text{theo.}) \text{ GeV}$$

First idea: new lower bounds on  $M_A$  and  $\tan \beta$  [S.H., O. Stal, G. Weiglein '11]

⇒ maximize all contributions:  $m_h^{\max}$  scenario



⇒ green are allowed by Higgs “excess”

First idea: new lower bounds on  $M_A$  and  $\tan \beta$  [S.H., O. Stal, G. Weiglein '11]

$M_{\text{SUSY}}$	Limits without $M_h = 125$			Limits with $M_h = 125$		
	$\tan \beta$	$M_A$	$M_{H^\pm}$	$\tan \beta$	$M_A$	$M_{H^\pm}$
500	2.7	94.5	123	4.5	139	159
1000	2.2	94.5	123	3.2	133	155
2000	2.0	94.5	123	2.9	130	152

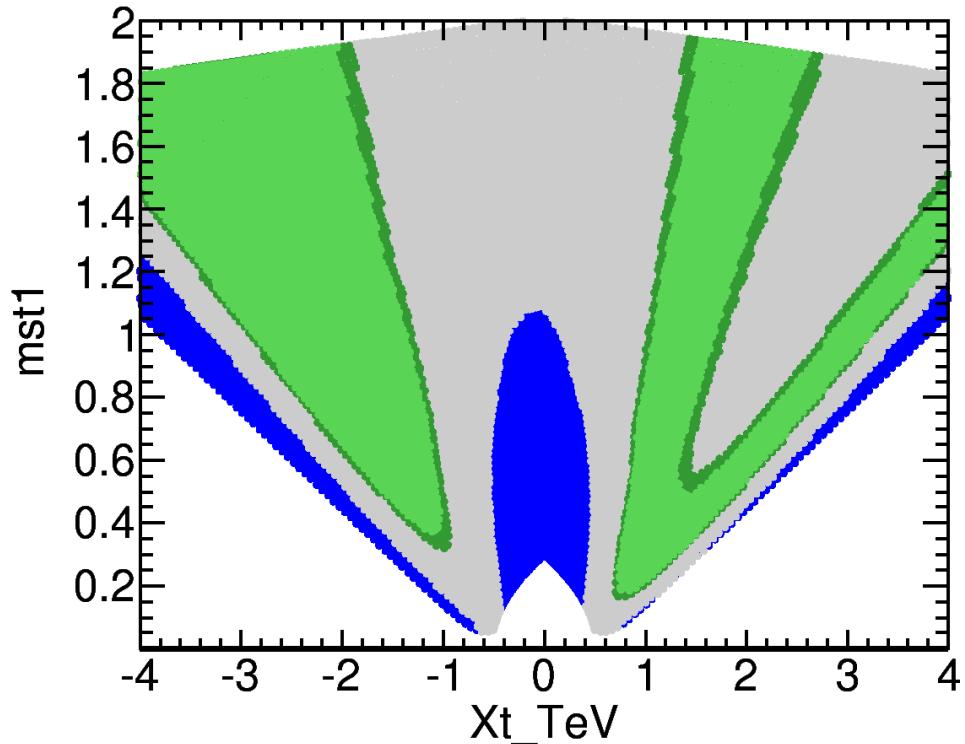
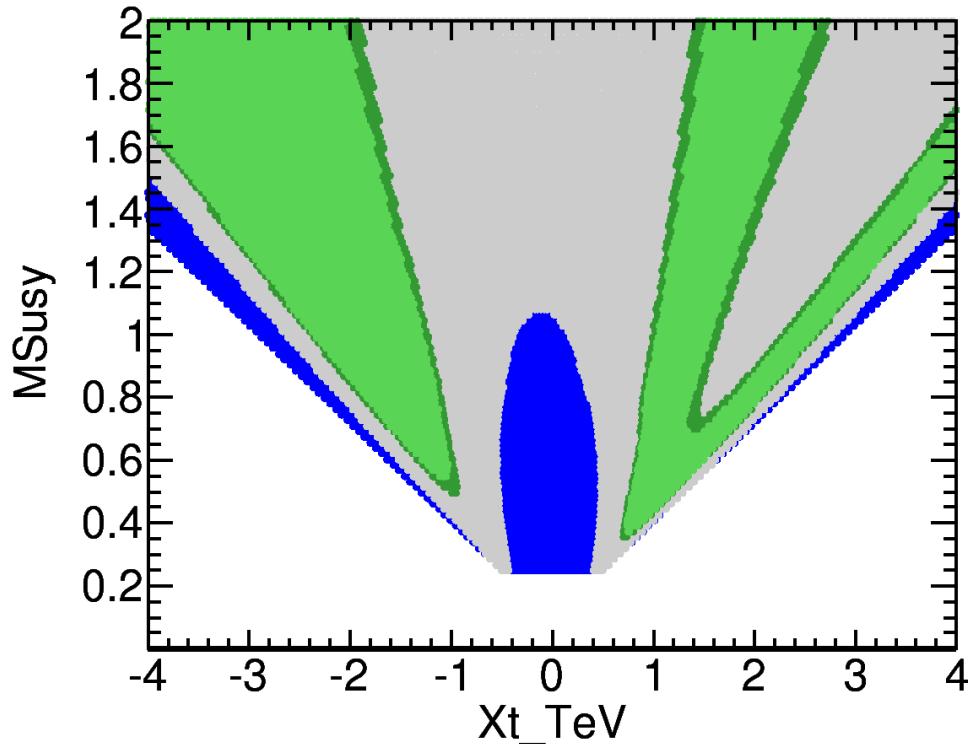
⇒ new conservative limits obtained!

⇒ only small margin left for  $t \rightarrow H^+ b$

## Limits on stop masses:

[S.H., O. Stal, G. Weiglein '11]

$m_h^{\max}$  scenario:

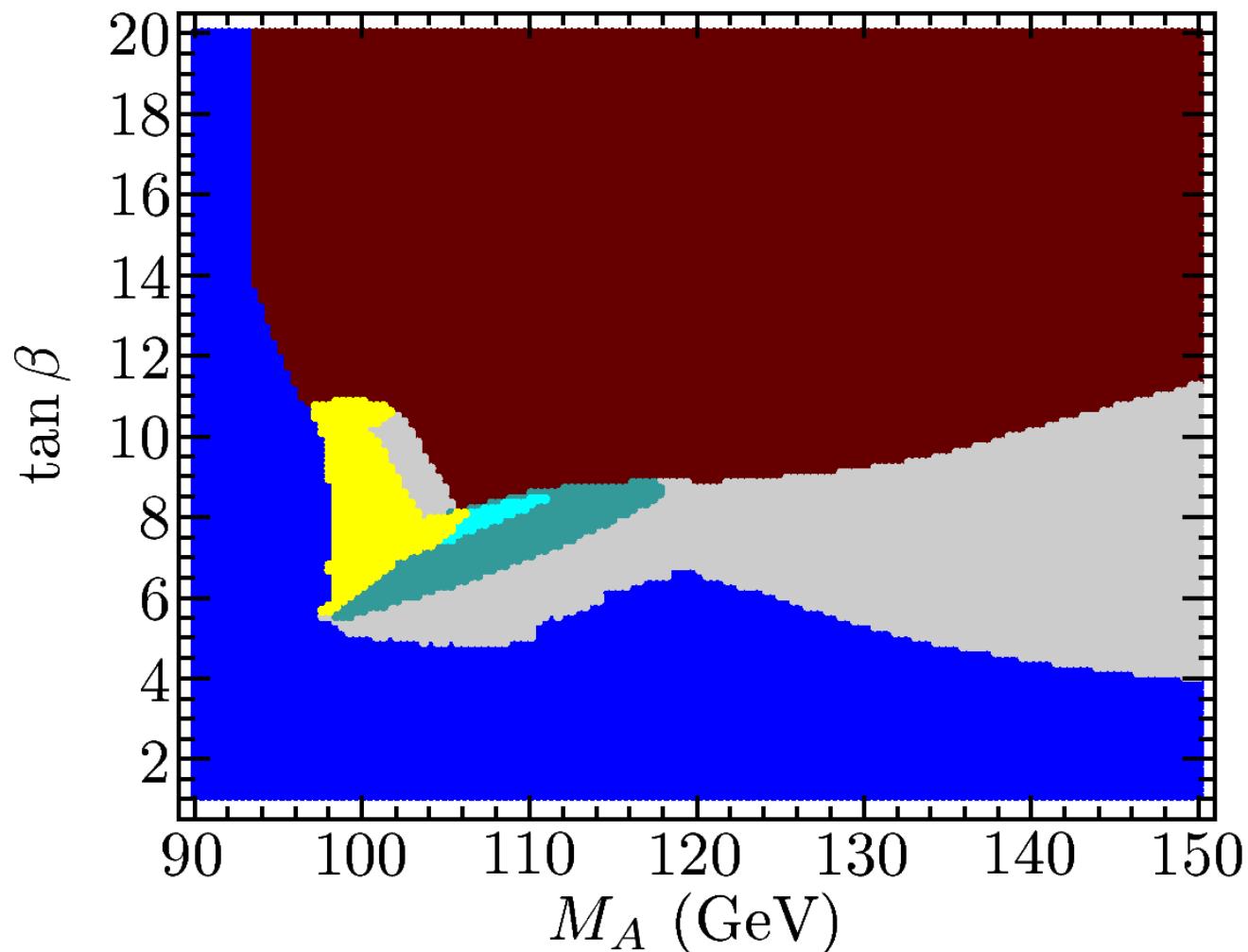


→ green are allowed by Higgs “excess”

$$m_{\tilde{t}_1} \gtrsim 150 \text{ GeV } (X_t > 0)$$

$$m_{\tilde{t}_1} \gtrsim 300 \text{ GeV } (X_t < 0) \text{ (preferred by } BR(b \rightarrow s\gamma))$$

$M_{\text{SUSY}} = \mu = 1 \text{ TeV}$ ,  $X_t = 2.3 \text{ TeV}$ , all Higgs limits taken into account:



Possible:  $M_h = 98 \text{ GeV}$ ,  $M_H = 125 \text{ GeV}$ , ...

Back-up