The Higgs sector of the MSSM

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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

Many thanks to Sven Heinemeyer

1. The building of the Higgs sector in the MSSM

Comparison with SM case:

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

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

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

Superpotential is holomorphic function of chiral superfields, i.e. depends only on φ_i, not on φ_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]

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

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

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

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{} |H_1 \bar{H}_2|^2$$

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)

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

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

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

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

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

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

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

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

Input parameters: (to be determined experimentally)

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

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

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

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

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

$\Rightarrow$ 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

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

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

In lowest order:

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

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

$\phi_1 - \phi_2$ basis:

$$M^{2,\text{tree}}_{\text{Higgs}} = \begin{pmatrix} m^2_{\phi_1} & m^2_{\phi_1\phi_2} \\ m^2_{\phi_1\phi_2} & m^2_{\phi_2} \end{pmatrix} =$$

$$\begin{pmatrix} M_A^2 \sin^2\beta + M_Z^2 \cos^2\beta & -(M_A^2 + M_Z^2)\sin\beta\cos\beta \\ -(M_A^2 + M_Z^2)\sin\beta\cos\beta & M_A^2\cos^2\beta + M_Z^2\sin^2\beta \end{pmatrix}$$

$$\Big\Downarrow \leftarrow \text{Diagonalization}, \alpha$$

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

Tree-level result for m_h, m_H:

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

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

$\Rightarrow$ Light Higgs boson h required in SUSY

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

Measurement of m_h, Higgs couplings

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

Higgs couplings, tree level:

$$g_{hVV} = \sin(\beta-\alpha)\, g^{\rm SM}_{HVV}, \qquad V = W^\pm, Z$$

$$g_{HVV} = \cos(\beta-\alpha)\, g^{\rm SM}_{HVV}$$

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

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

$$g_{ht\bar{t}} = \frac{\cos\alpha}{\sin\beta}\, g^{\rm SM}_{Ht\bar{t}}$$

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

$\Rightarrow$ $g_{hVV} \leq g^{\rm SM}_{HVV}$, $\quad g_{hVV}$, 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: $M_A >> M_Z$

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

The lightest MSSM Higgs is SM-like

$-\frac{\sin\ \alpha}{\cos\beta} \to 1,\ \frac{\cos\ \alpha}{\sin\beta} \to 1,\ \sin(\beta-\alpha) \to 1$
$\Rightarrow g_{hVV} \to g_{HVV}^{\text{SM}},\ g_{hf\bar{f}} \to g_{Hf\bar{f}}^{\text{SM}}$

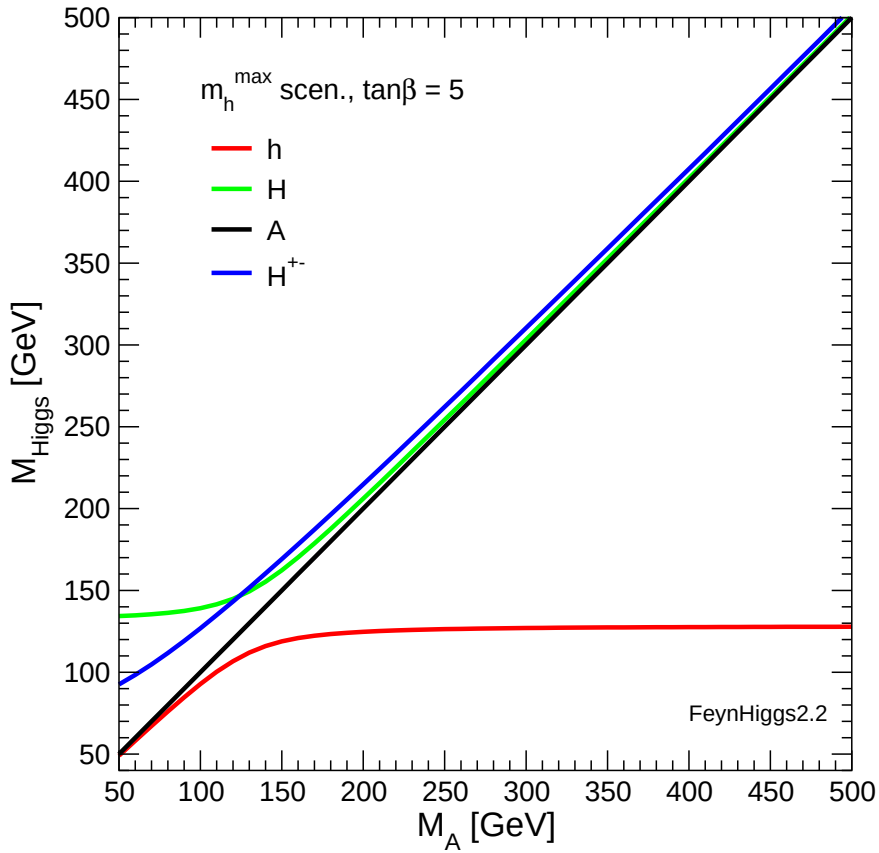
Effectively, $h \approx H_{SM}$

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: MSSM $\to$ SM (Higgs sector)

Decoupling effective at $M_A \gtrsim 150$ GeV:



2. The lightest MSSM Higgs boson

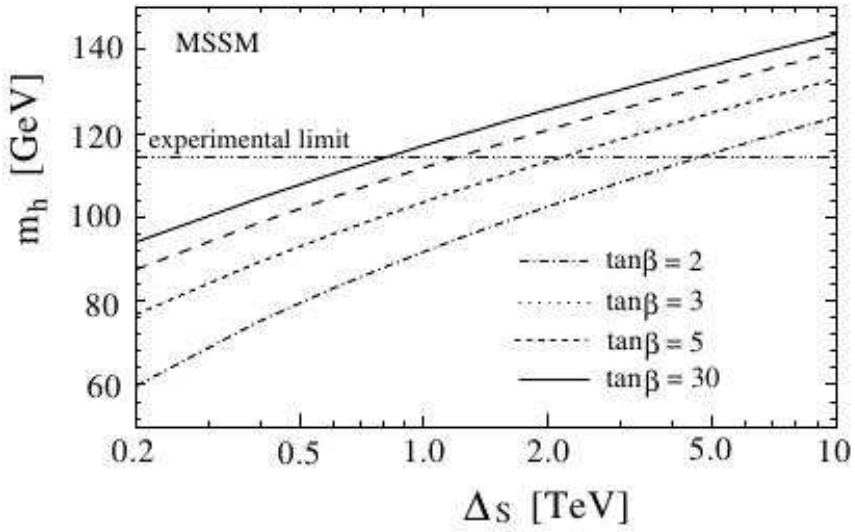
MSSM predicts upper bound on m_h:

tree-level bound: $m_h < M_Z$,

excluded by LEP Higgs searches!

Large radiative corrections:

Mainly from large Yukawa couplings: top the largest, . . .



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

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

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

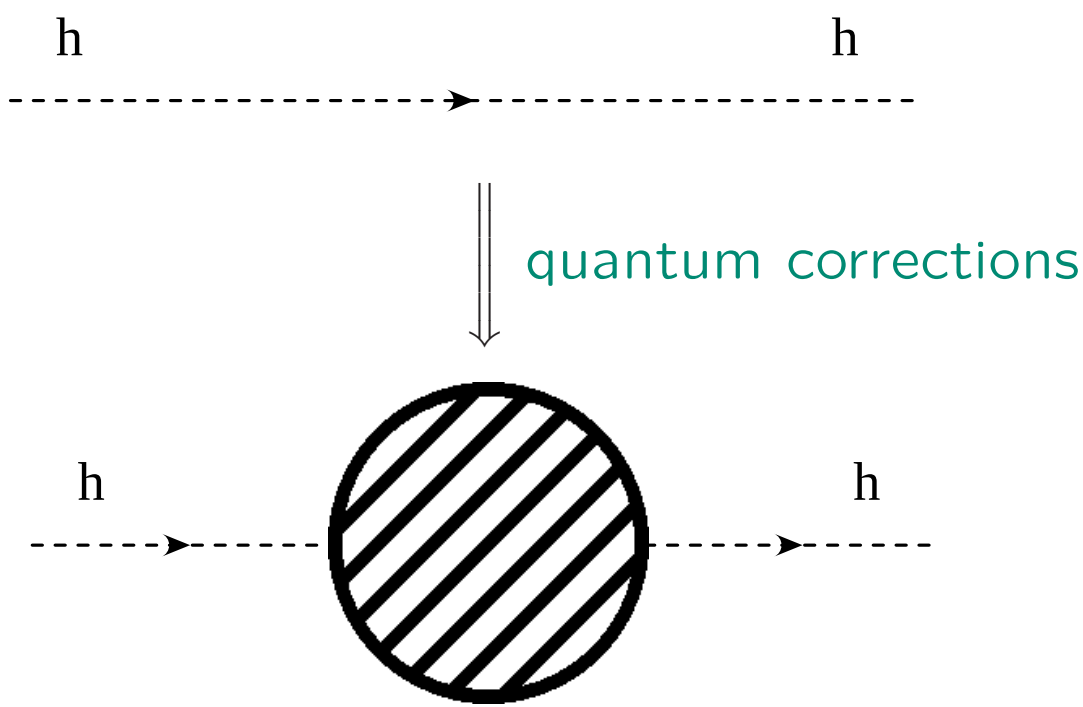
The MSSM Higgs sector is connected to all other sectors via loop corrections
(especially to the scalar top sector)

Present status of M_h prediction in the MSSM:

Complete one-loop and 'almost complete' two-loop result available

Quantum corrections to Higgs mass

Higgs propagator:



Inverse propagator:

$$-i(q^2 - m^2) \quad \longrightarrow \quad -i\left(q^2 - m^2 + \hat{\Sigma}_h(q^2)\right)$$

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

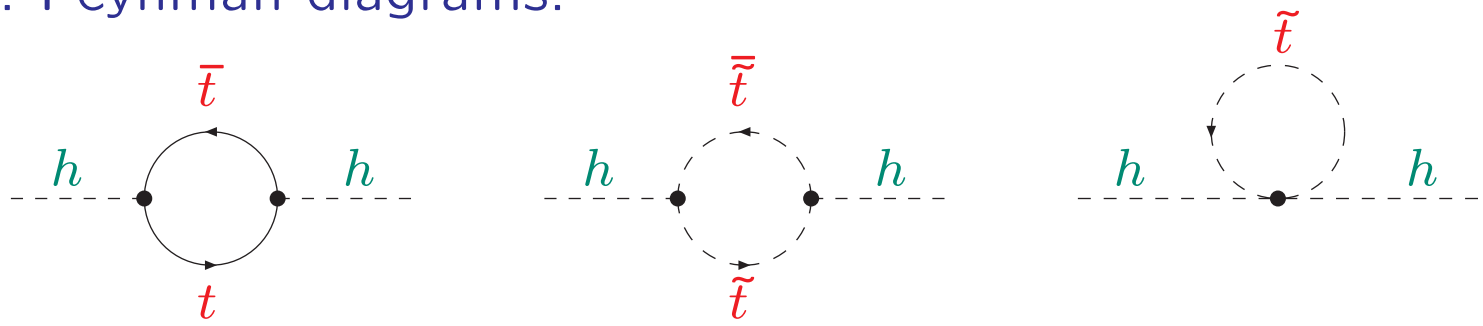
Calculation of the blob:

 $= \hat{\Sigma}(q^2) = \hat{\Sigma}^{(1)}(q^2) + \hat{\Sigma}^{(2)}(q^2) + \ldots$

 : 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: $\mathcal{O}(50\ \text{GeV})$

$\Rightarrow$ 2-Loop calculation necessary!

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

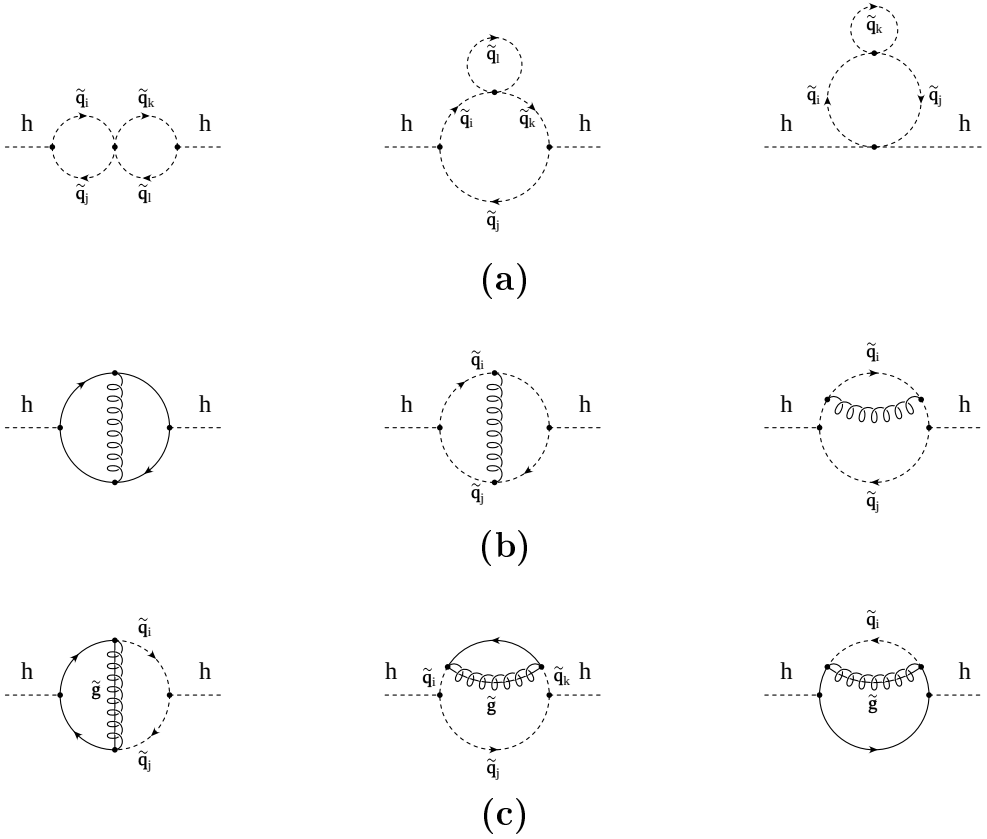
[*S. H., W. Hollik, G. Weiglein '98*]

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

(a) pure scalar diagrams
(b) diagrams with gluonexchange
(c) diagrams with gluinoexchange

Quite complicated calculation ...
$\Rightarrow$ Need for computer algebra programms

['98 - '11:] $\Rightarrow$ 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
($\rightarrow$ 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

$\Rightarrow$ 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, μ, $m_{\tilde{g}}$, M_2

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

for $m_t = 173.2 \pm 0.9$ GeV

(including theoretical uncertainties from unknown higher orders)

$\Rightarrow$ observable at the LHC

Obtained with:

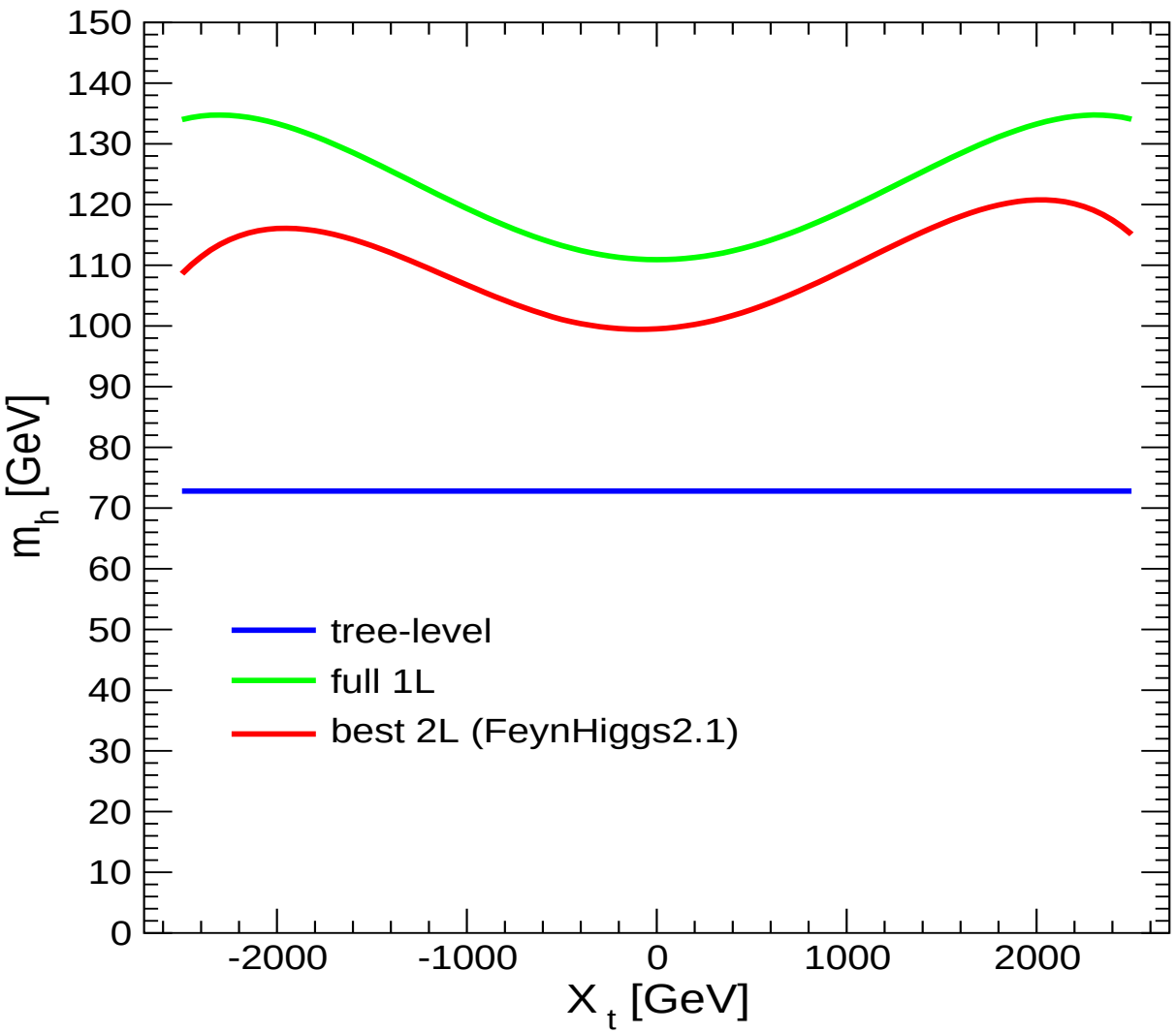
FeynHiggs

`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:
$\Rightarrow \Delta M_h \approx 3$ GeV

– From uncertainties in input parameters

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

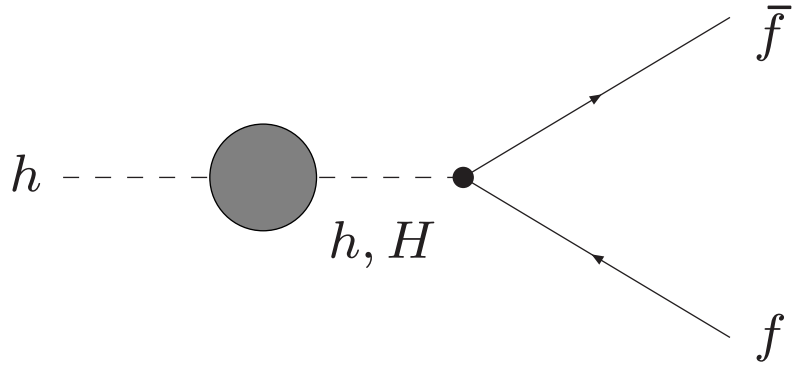
$\Delta m_t \approx 1$ GeV $\Rightarrow \Delta M_h \approx 1$ GeV

Higgs couplings, production cross sections

$\Rightarrow$ also affected by large SUSY loop corrections

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

$hf\bar{f}$ coupling:



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

$\Rightarrow$ Effective $hf\bar{f}$ coupling can vanish for large $\hat{\Sigma}_{\mathsf{hH}}$

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

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

Relevant difference MSSM/SM:

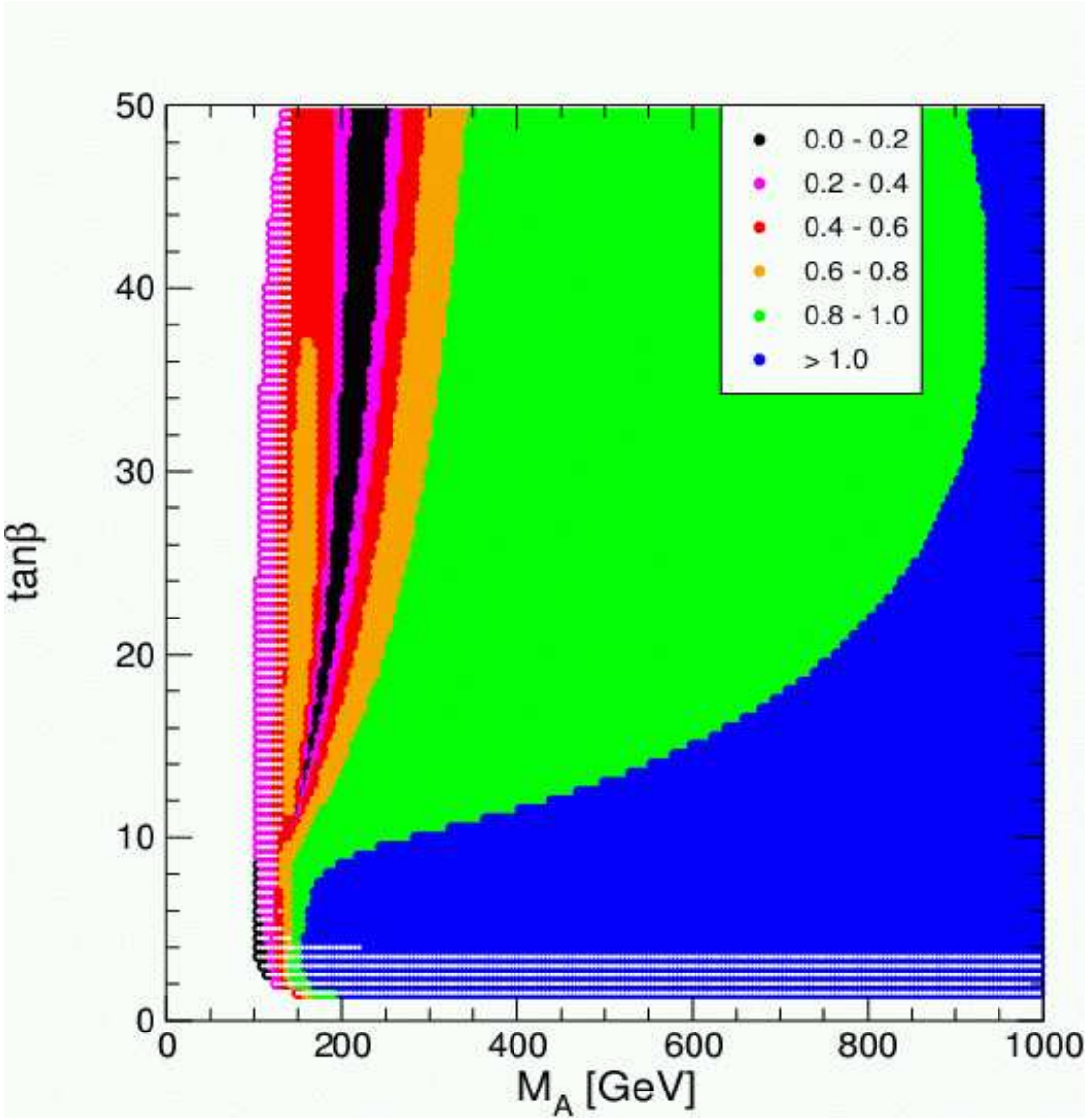
$$h \to b\bar{b}$$

can be strongly suppressed in SUSY

$\to$ "Small α_{eff} scenario"

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

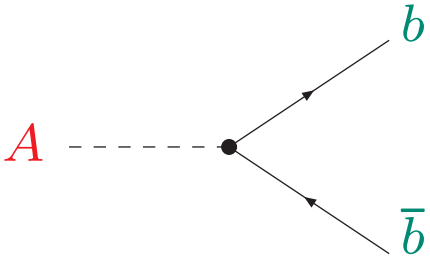
$\Rightarrow$ Strong suppression of $h \to b\bar{b}$ possible, up to $M_A \lesssim 350$ GeV



3. The heavy MSSM Higgs bosons

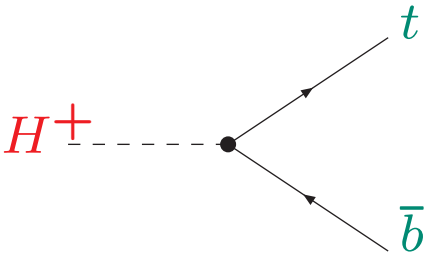
Differences compared to the SM Higgs:

Additional enhancement factors compared to the SM case:



$$y_b \quad \longrightarrow \quad y_b \, \frac{\tan\beta}{1+\Delta_b}$$

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



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

$$\Delta_b = \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \, \mu \, \tan\beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}})$$

$$+ \frac{\alpha_t}{4\pi} A_t \, \mu \, \tan\beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)$$

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

Search for the MSSM Higgs bosons:

Situation is more involved due to many SUSY parameters

→ investigate benchmark scenarios:

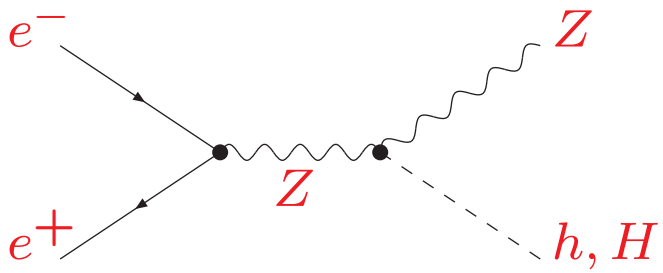
→ Vary only M_A and $\tan\beta$
→ Keep all other SUSY parameters fixed

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 α_{eff} scenario
   → $hb\bar{b}$ coupling $\sim \sin\alpha_{\text{eff}}/\cos\beta$ can be zero: $\alpha_{\text{eff}} \to 0$:
   main decay mode vanishes, important search channel vanishes
4. gluophobic Higgs scenario
   → hgg 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:

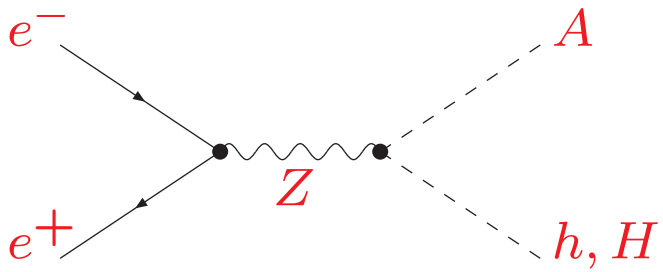
$e^+e^- \to Zh, ZH$



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

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

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



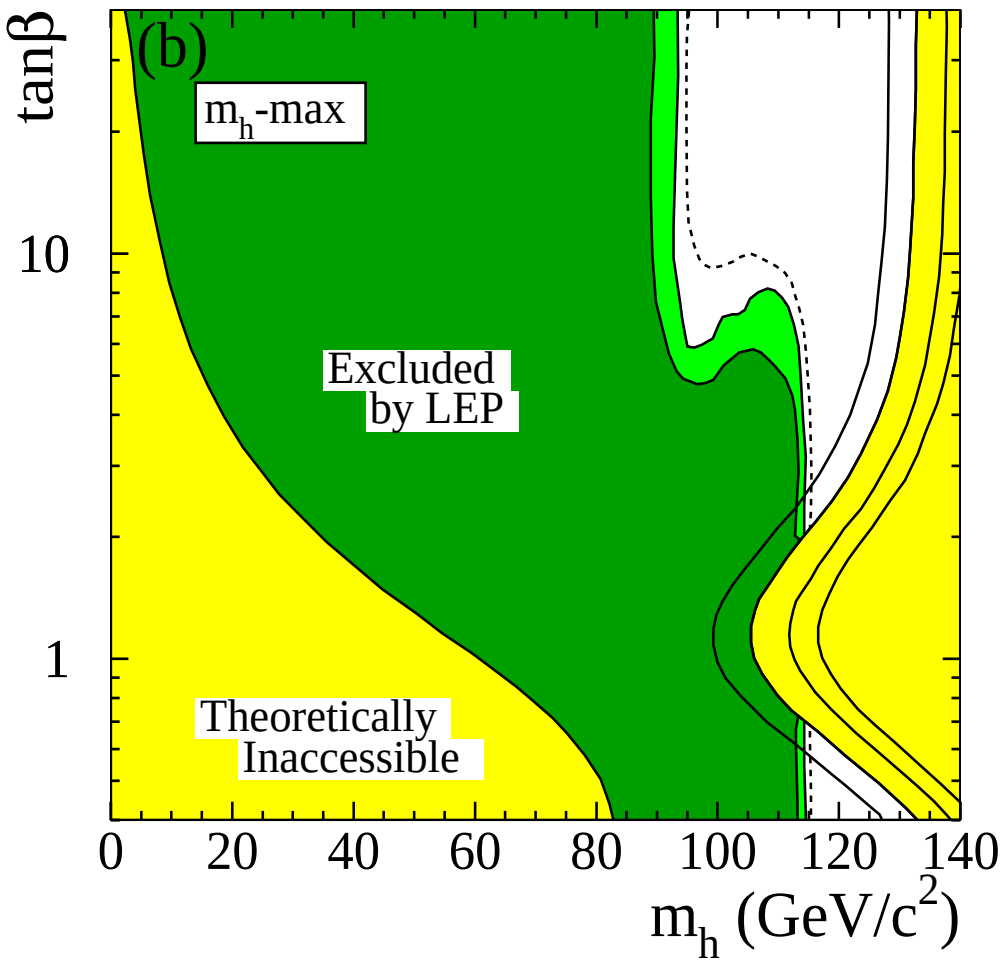
$$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

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

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):

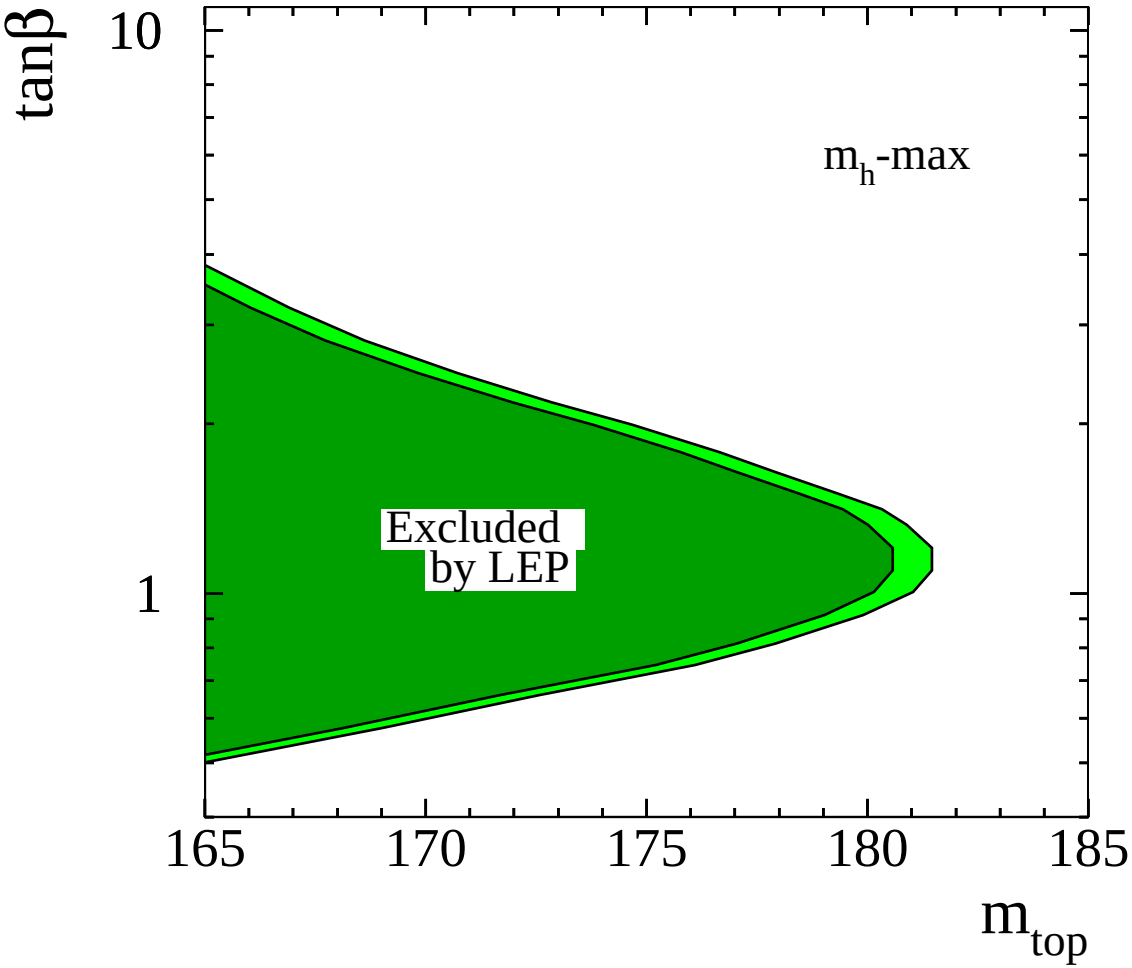


$m_h > 92.8$ GeV
(expected: 94.9 GeV), 95% C.L.

$M_A > 93.4$ 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 $\sin^2(\beta - \alpha_{\rm eff}) \ll 1$

"Excluded" $\tan\beta$ region:



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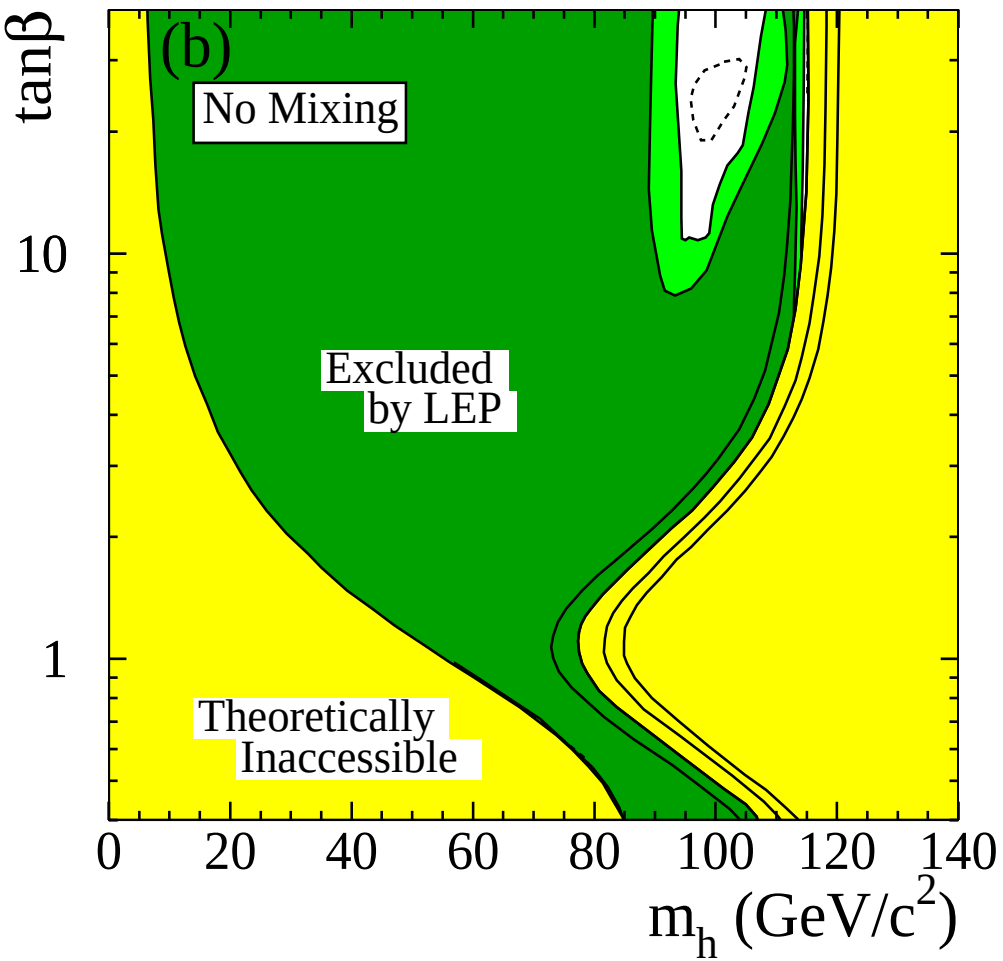
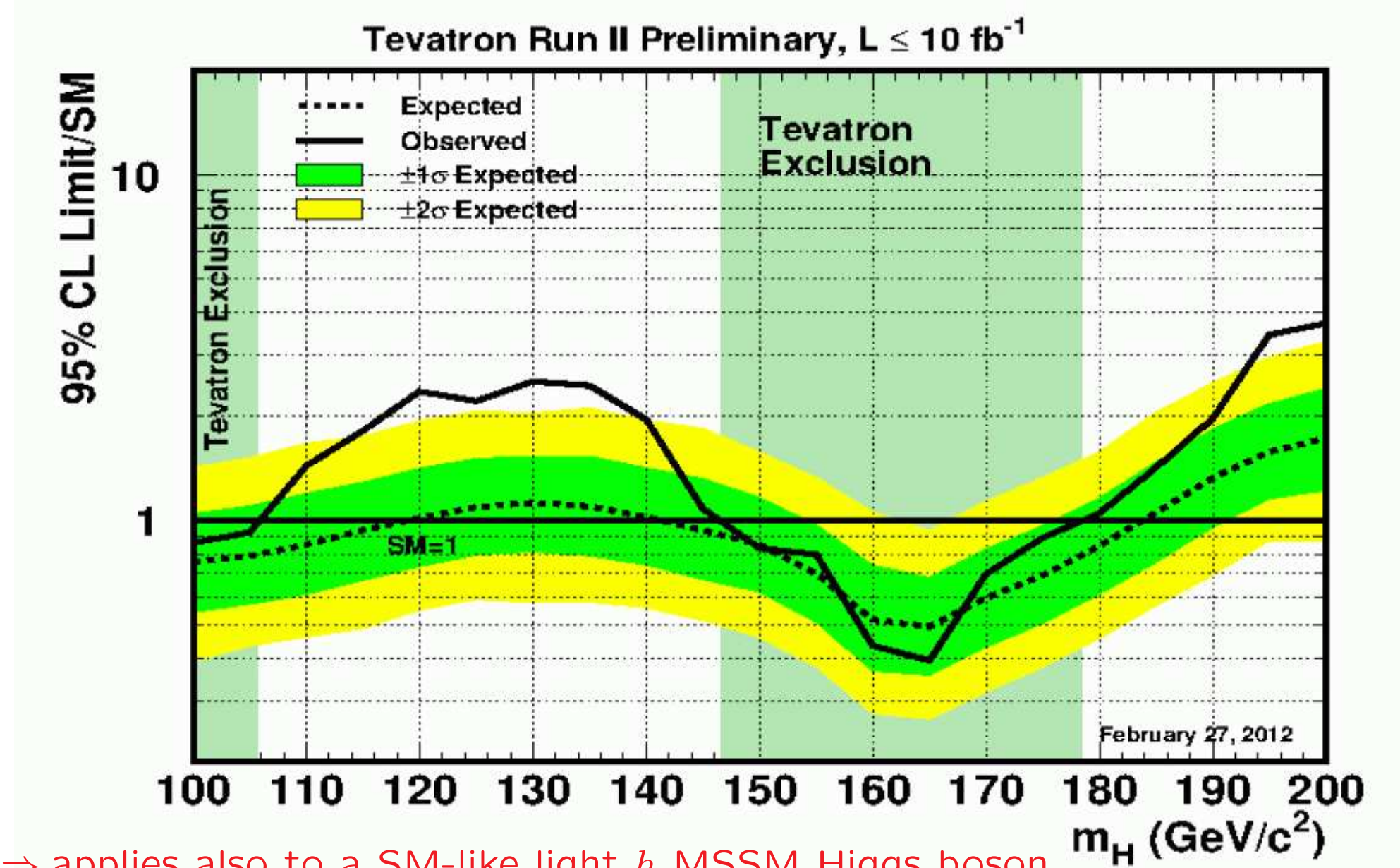
no-mixing scenario ($m_t = 174.3$ GeV, $M_{\text{SUSY}} = 1$ TeV):



$m_h > 93.6$ 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



$\Rightarrow$ applies also to a SM-like light h MSSM Higgs boson

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

Search modes:

$$b\,\bar{b} \to \phi\, b\,\bar{b}\ , \quad \phi = H, A$$
$$p\,\bar{p} \to \phi \to \tau^+\,\tau^-\ , \quad \phi = H, A$$

Strong enhancement compared to the SM:

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

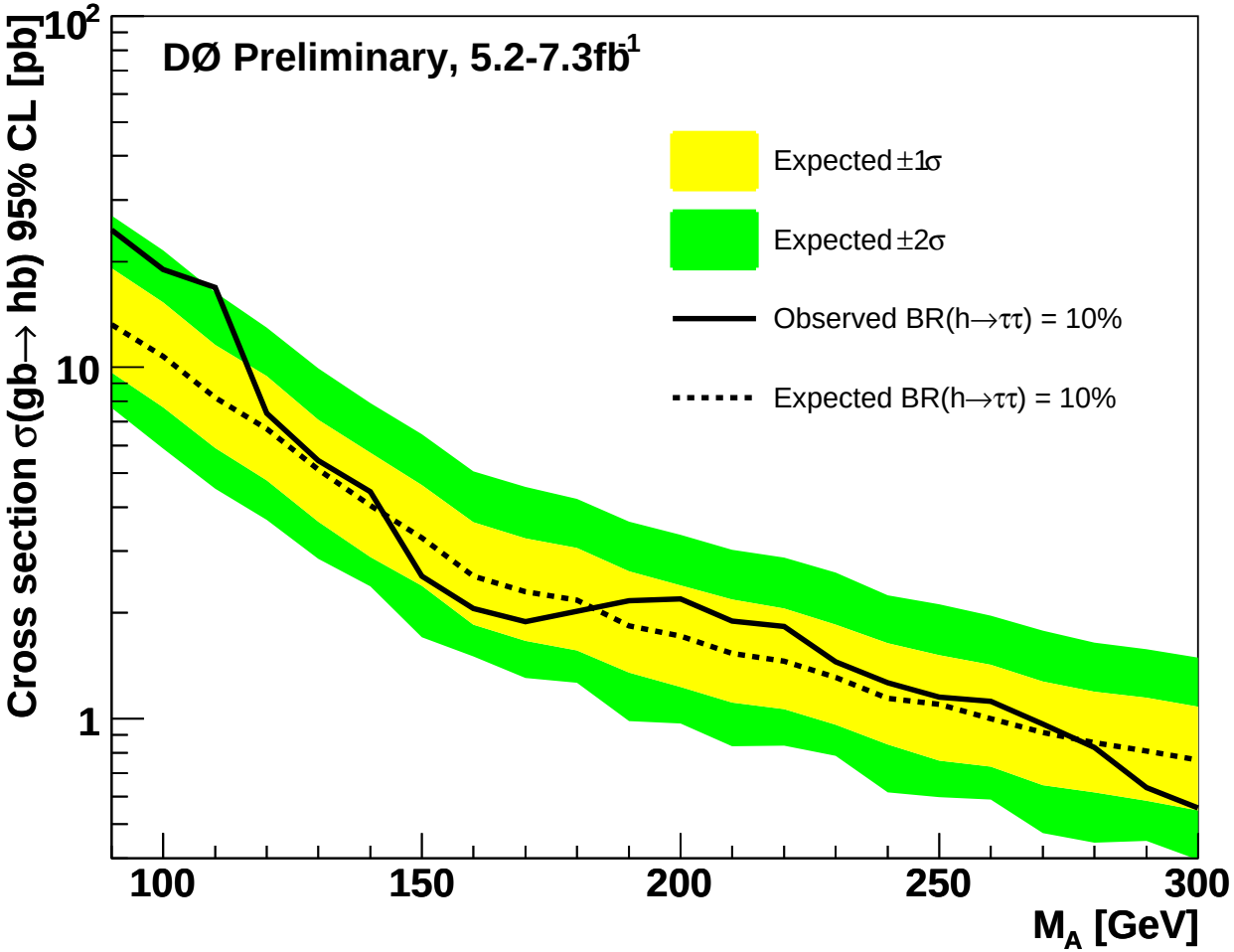
$$\sigma(gg, b\bar{b} \to A) \times \mathrm{BR}(A \to \tau^+\tau^-) \simeq \sigma(gg, b\bar{b} \to A)_{\mathrm{SM}} \frac{\tan^2\beta}{(1+\Delta_b)^2+9}$$

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

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

Example: $p\bar{p} \to h/H/A \to \tau^+\tau^-$ at DØwith $\sim 7\,\mathrm{fb}^{-1}$

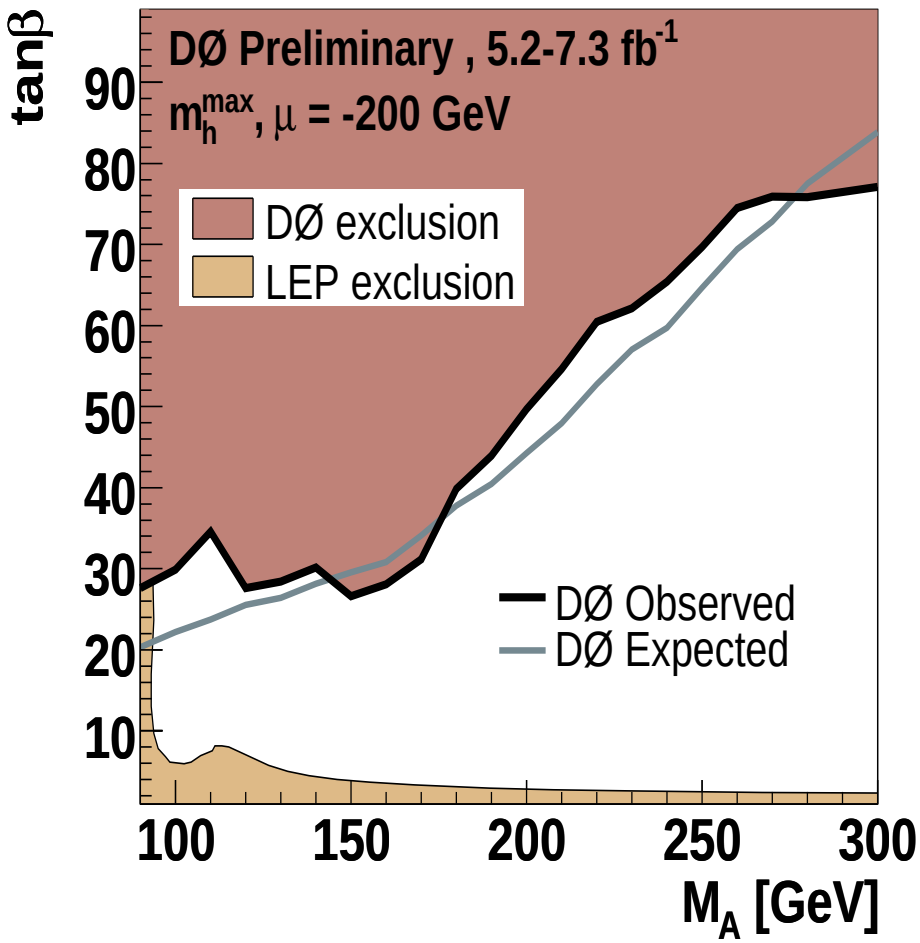
[*DØ'11*]

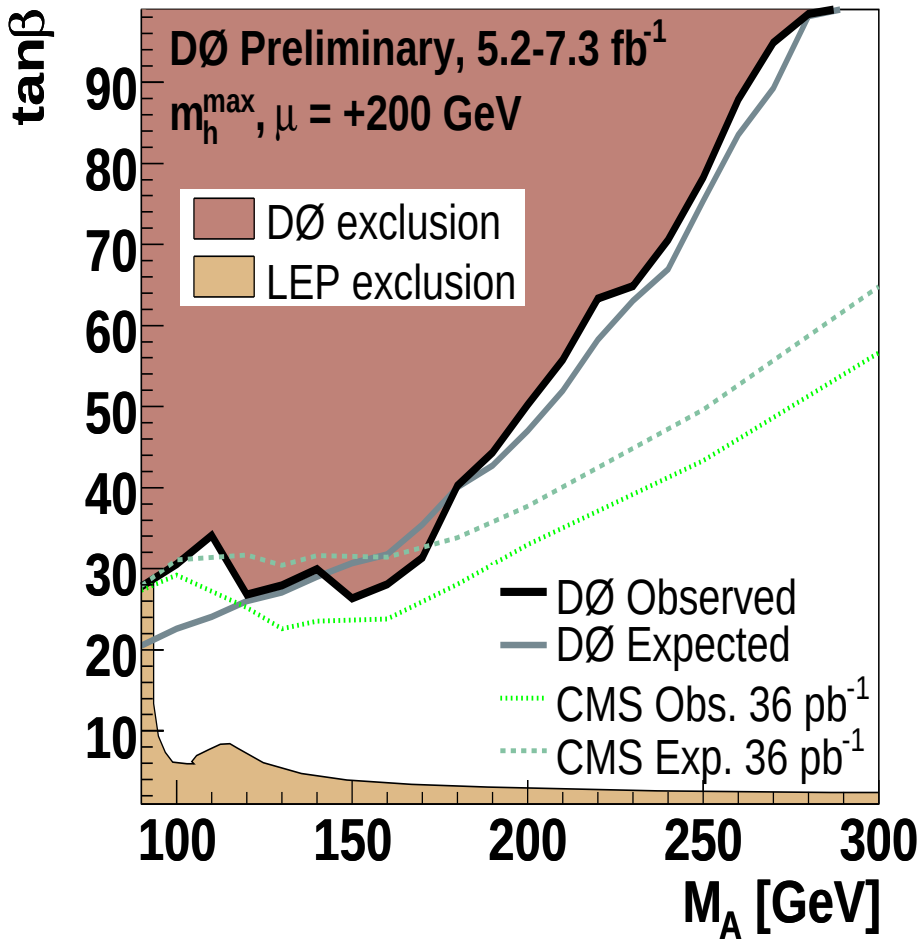


$\Rightarrow$ model independent limit on $\sigma \times$ BR

Example: $p\bar{p} \to h/H/A \to \tau^+\tau^-$ at DØwith $\sim 7\,\text{fb}^{-1}$

[*DØ'11*]





$\Rightarrow$ 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

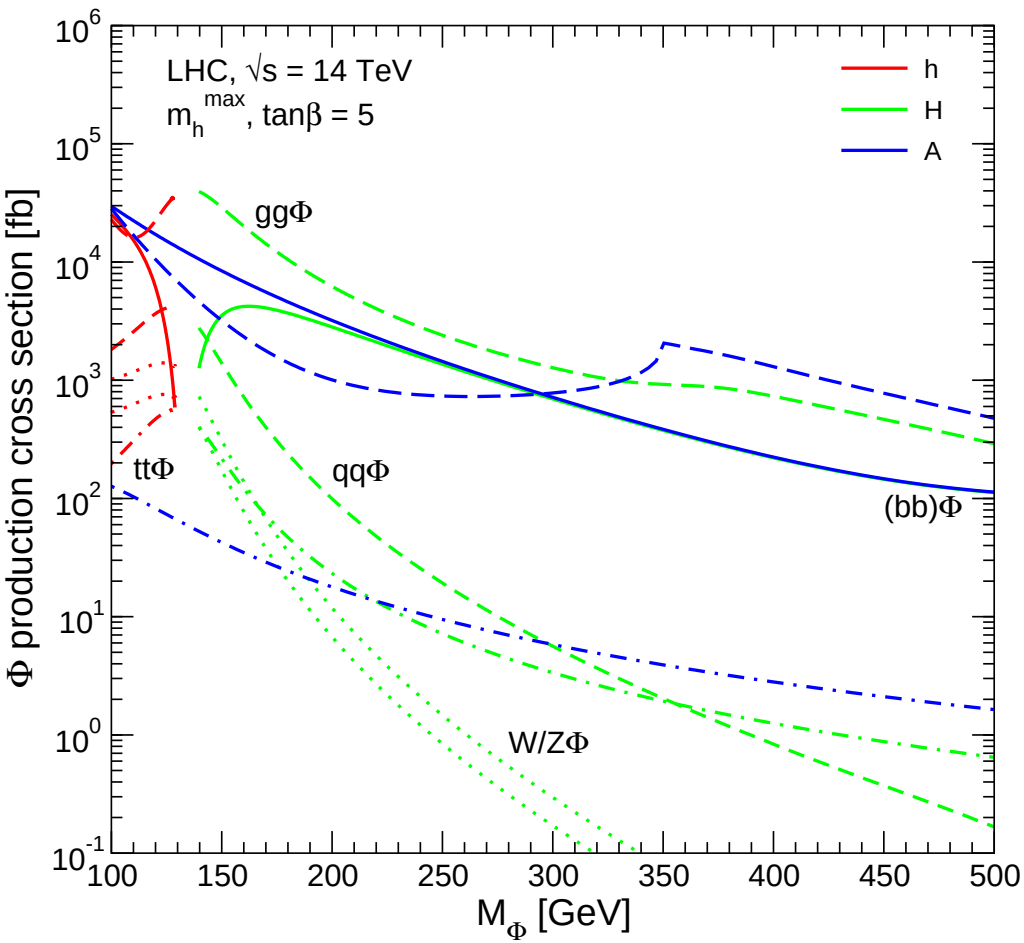
1. Light MSSM Higgs boson in the decoupling limit:
   $\longrightarrow$ SM Higgs searches apply
   $\longrightarrow$ keep in mind the upper limit of 135 GeV
   $\Rightarrow$ no limits beyond LEP so far!

2. Light MSSM Higgs boson "before" the decoupling limit:
   $\longrightarrow$ dedicated search necessary
   $\longrightarrow$ SM-like search with reduced couplings
   $\longrightarrow$ therefore reduced $\sigma \times$ BR

3. Heavy MSSM Higgs boson:
   $\longrightarrow$ dedicated search
   $\Rightarrow$ model independent results on $\sigma \times$ BR
   $\Rightarrow$ 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: $gg \to \phi$

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

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

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

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

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

$$b\bar{b} \to H/A \to \tau^+\tau^- + X$$
$$gb \to tH^\pm + X, \;\; H^\pm \to \tau\nu_\tau$$
$$pp \to t\bar{t} \to H^\pm + X, \;\; H^\pm \to \tau\nu_\tau$$

Most powerful modes due to enhancement factors compared to SM:

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

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

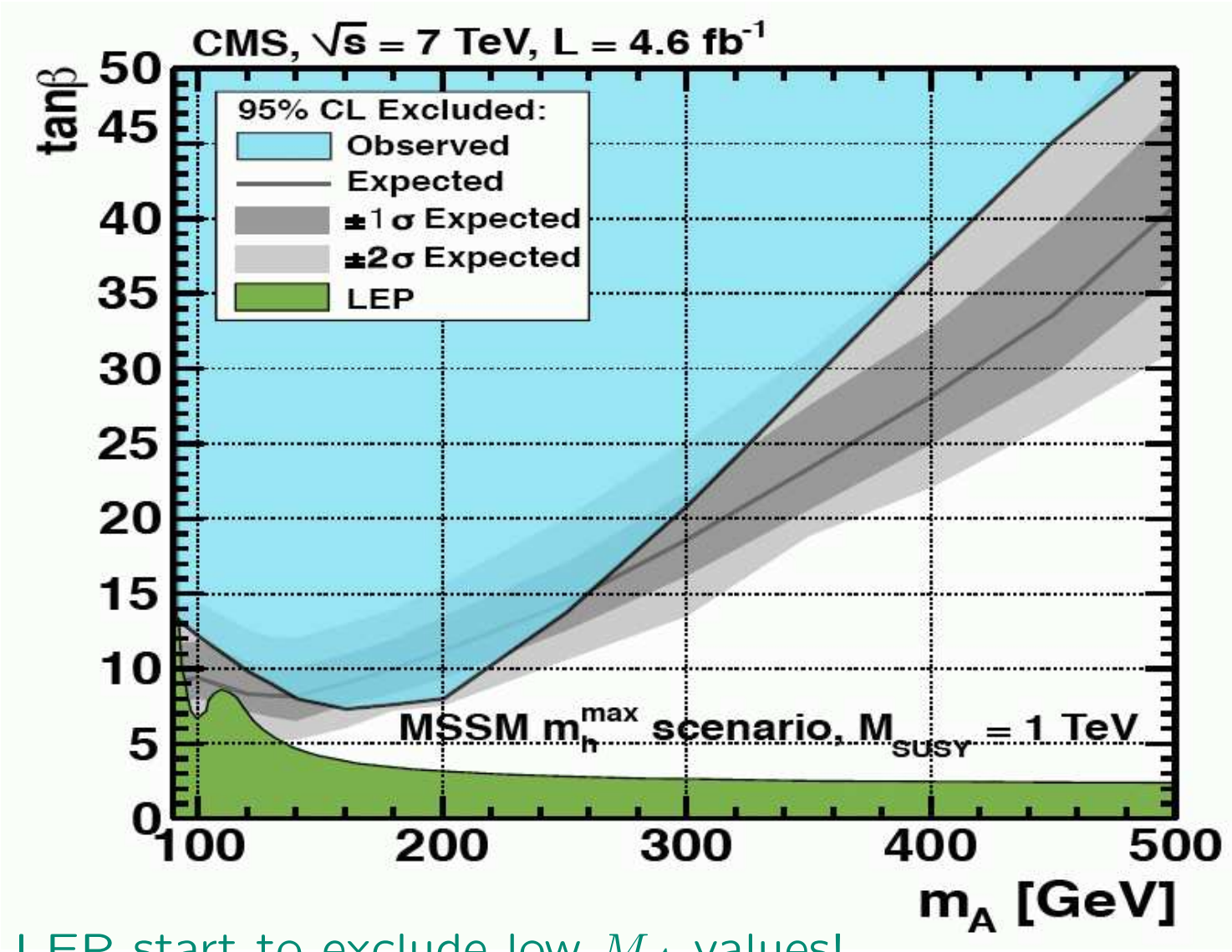
$\Rightarrow$ Δ_b effects (often neglected by ATLAS/CMS analyses)

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

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

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

Latest CMS results in search for the heavy MSSM Higgses: [*CMS '11*]



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

$\Rightarrow$ small "excess" around $M_A \approx 300$ GeV

Back-up

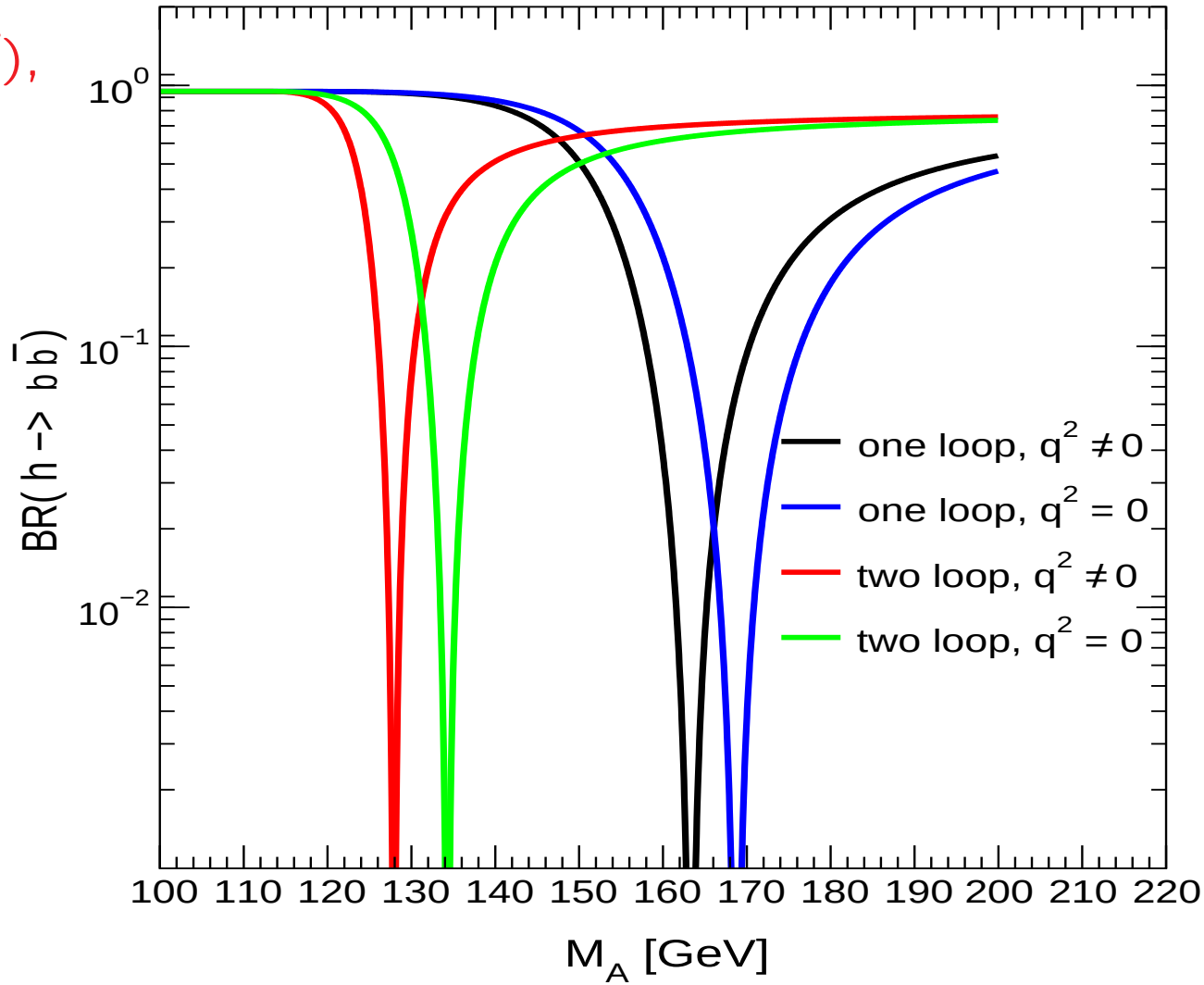
Effective $hf\bar{f}$ coupling can go to zero for large $\hat{\Sigma}_{hH}$

$\Rightarrow$ "Pathological regions"

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

$\Rightarrow$ Suppression of BR($h \to b\bar{b}$), BR($h \to \tau\tau$), ...

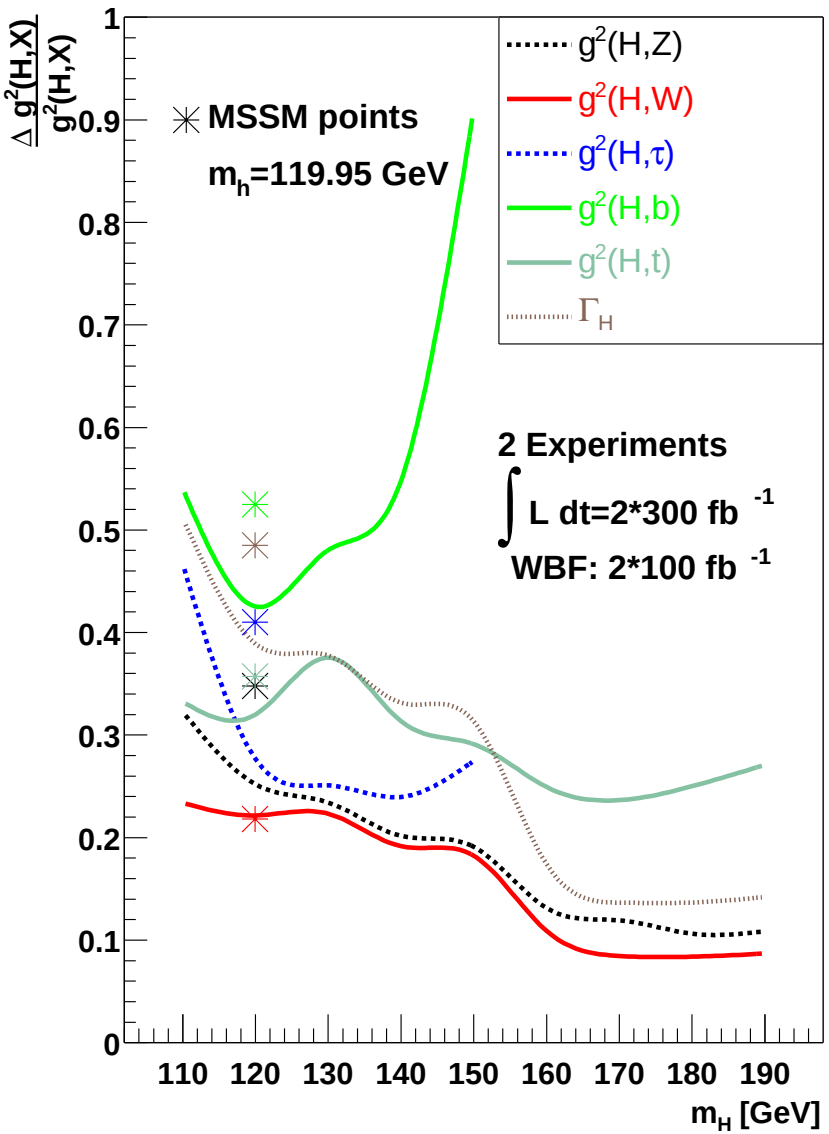
[*S.H., W. Hollik, G. Weiglein '00*]



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 $\tan\beta$:

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

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

BR$(h \to VV^*) \approx 1/2$ SM

BR$(h \to \gamma\gamma) \approx 1/2$ SM

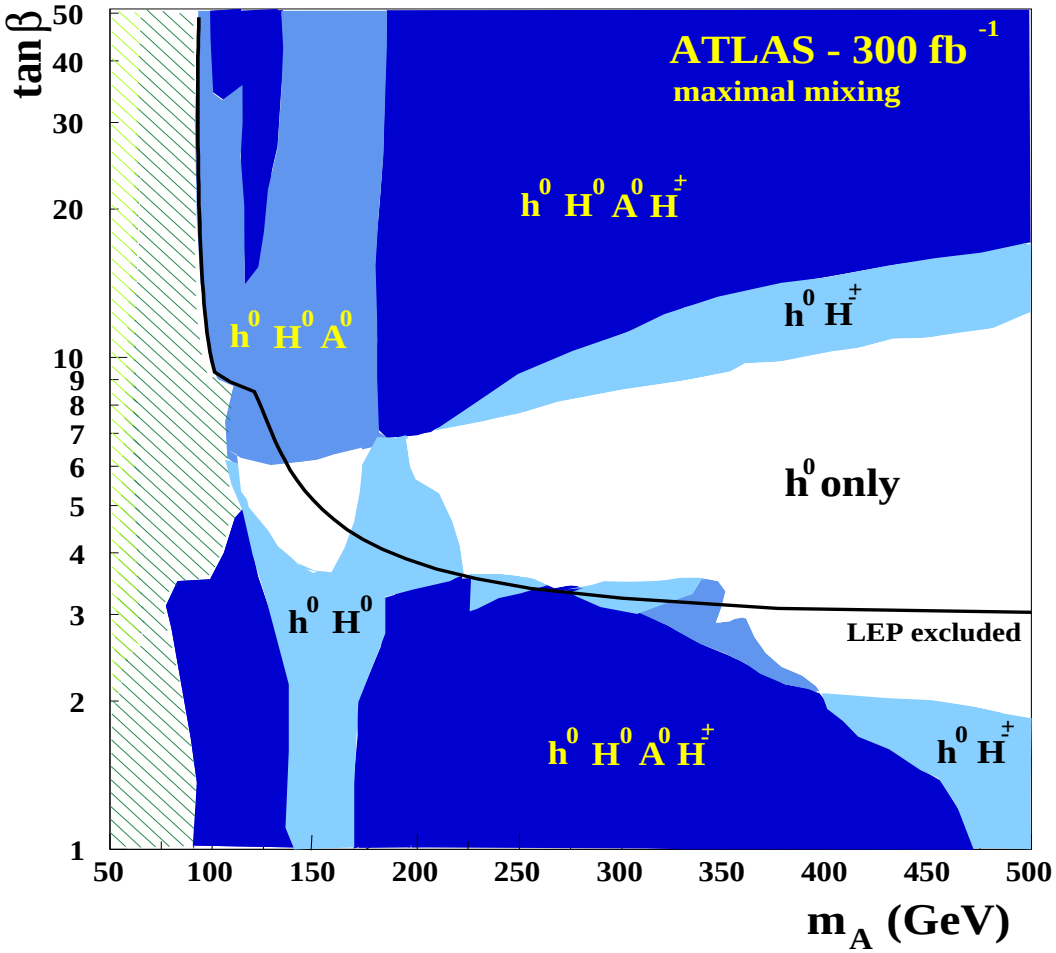
BR$(h \to gg) \approx 1/5$ SM

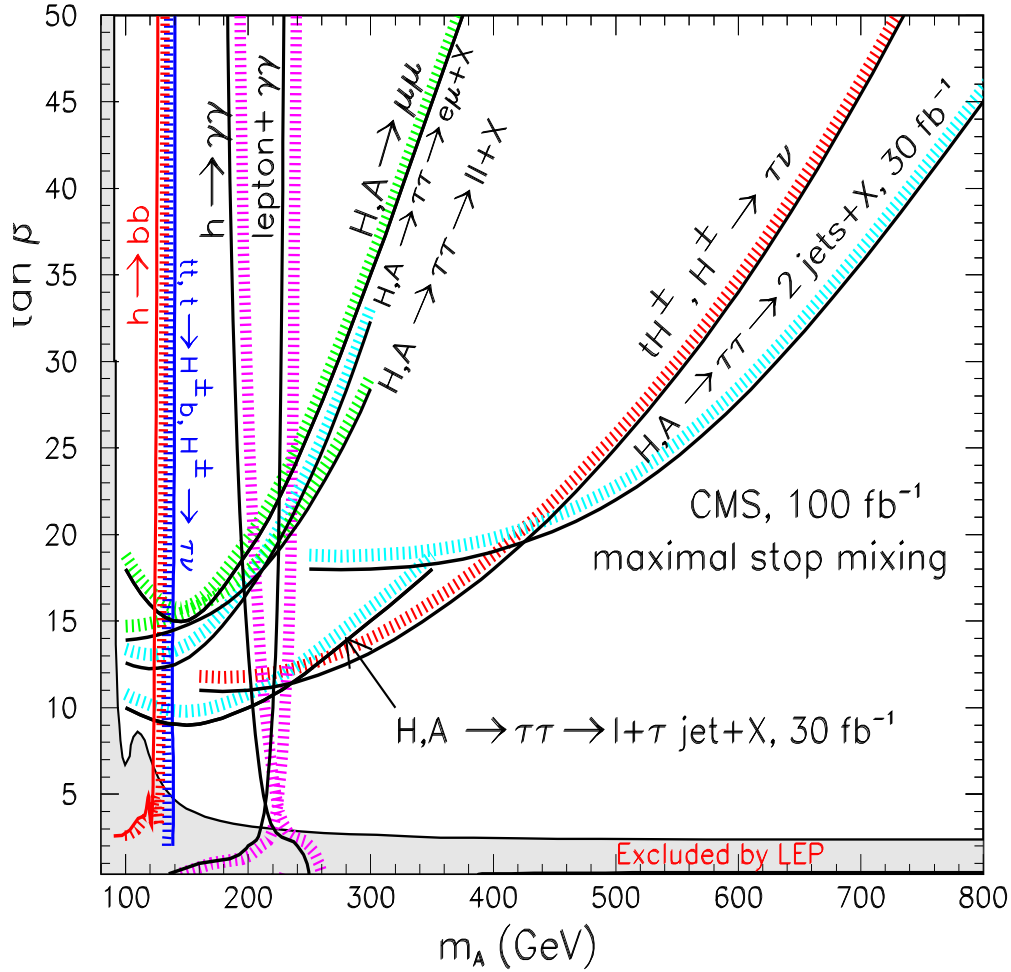
$\Rightarrow$ not too bad . . .

$\Rightarrow$ more analyses needed!

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]

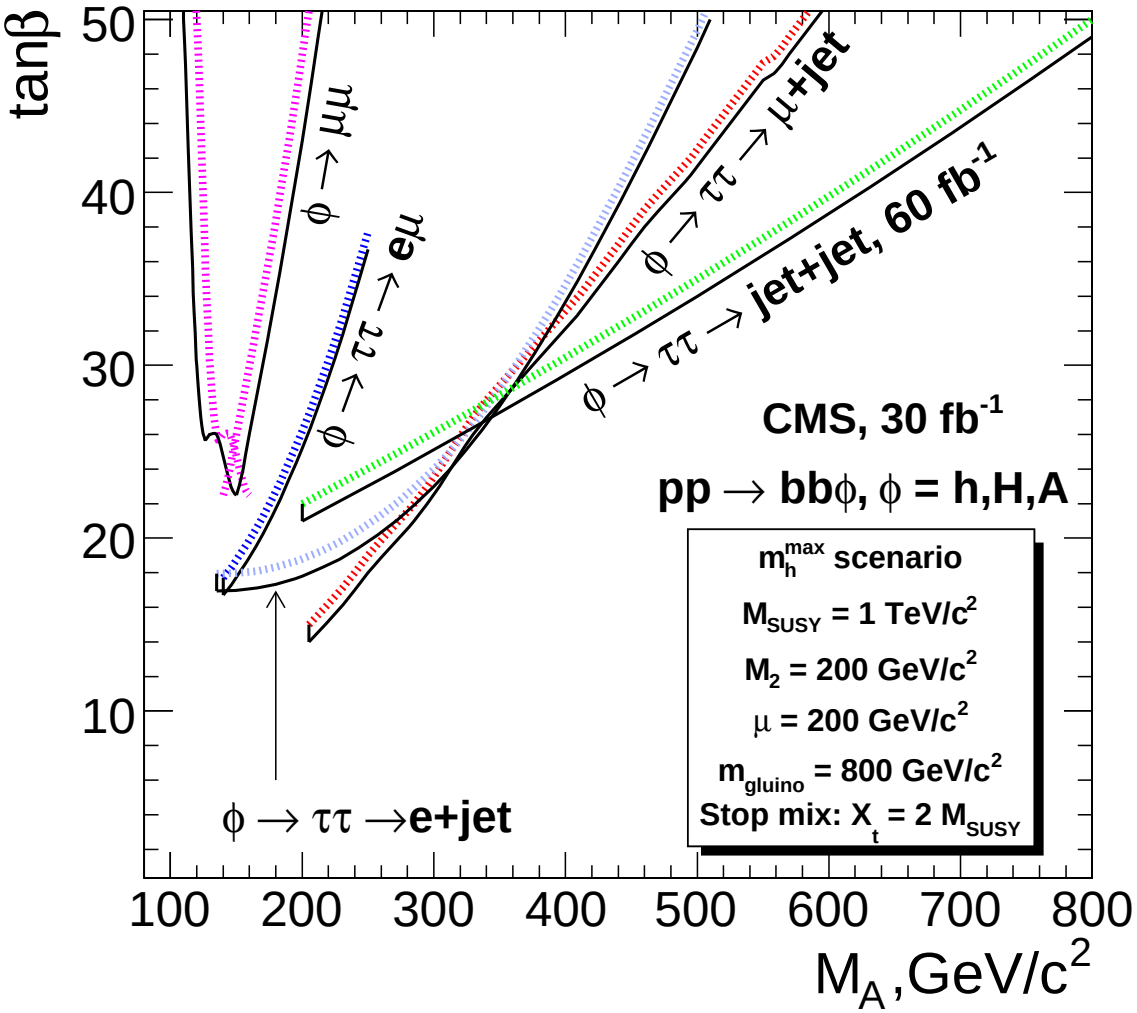




areas where only h is observable $\Rightarrow$ "LHC wedge"

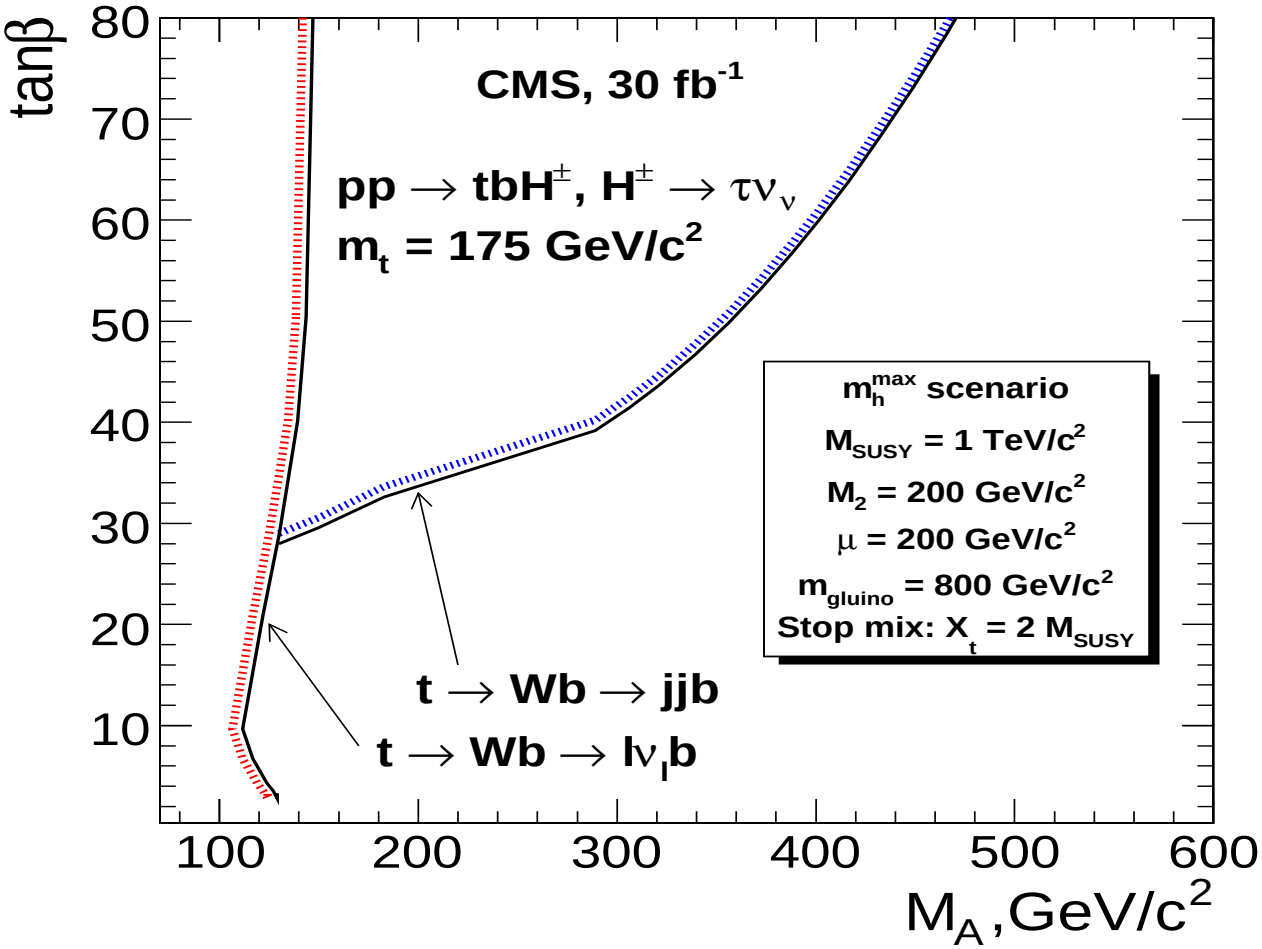
Latest results for neutral heavy Higgs bosons:

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:

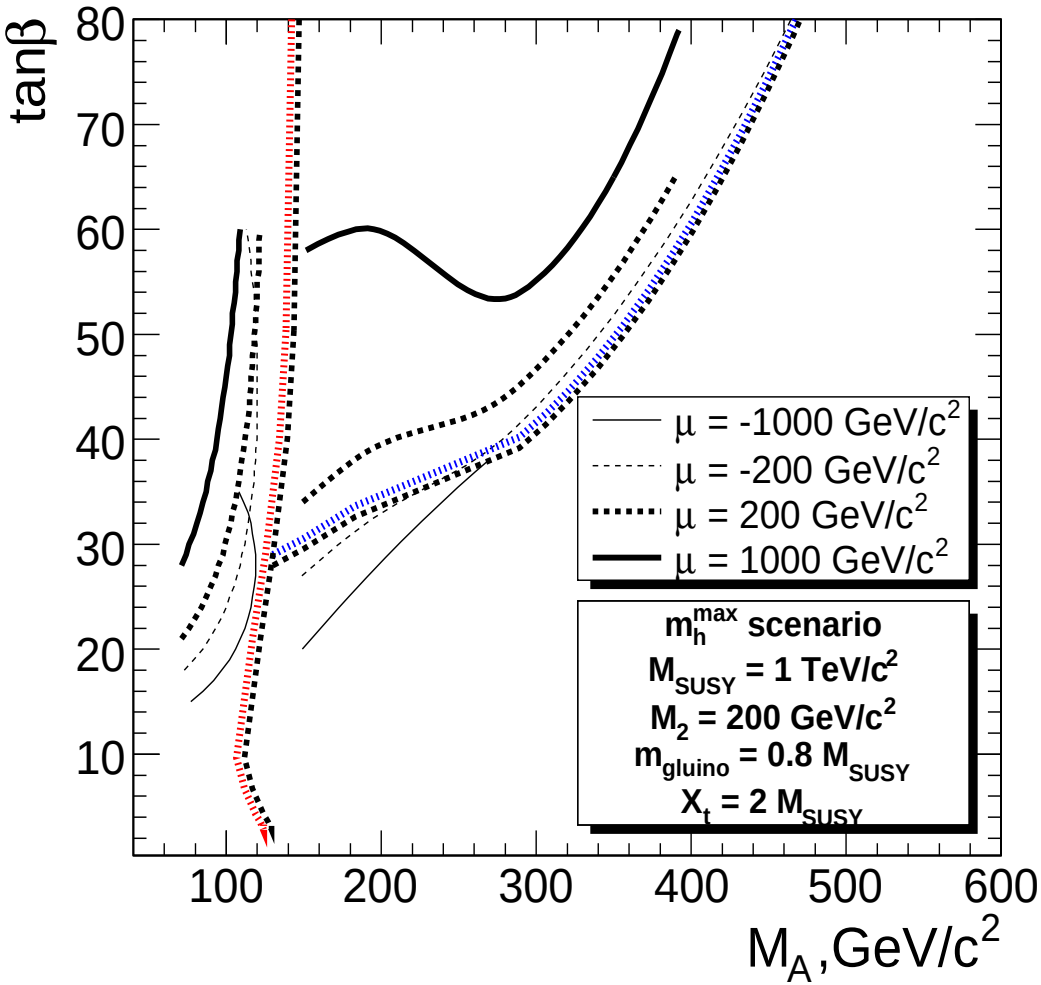
$$M_{H^\pm} < m_t$$

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!

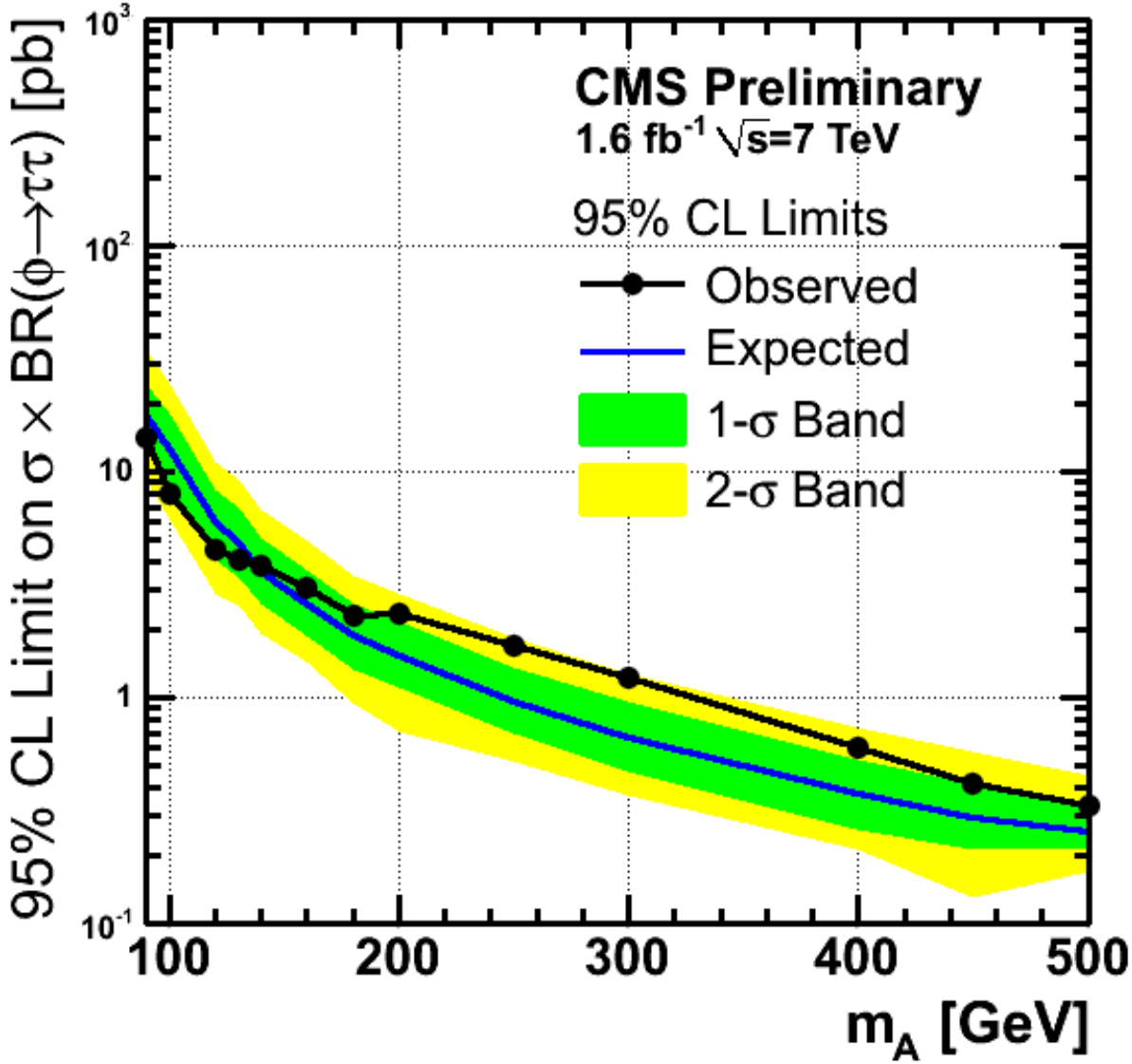
inclusion of Δ_b effects

heavy charged Higgs:

PTDR in "the middle"

new results partially substantially worse

Latest CMS resuls for model independent limits: [*CMS '11*]



⇒ small "excess" around $M_A \gtrsim 300$ 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

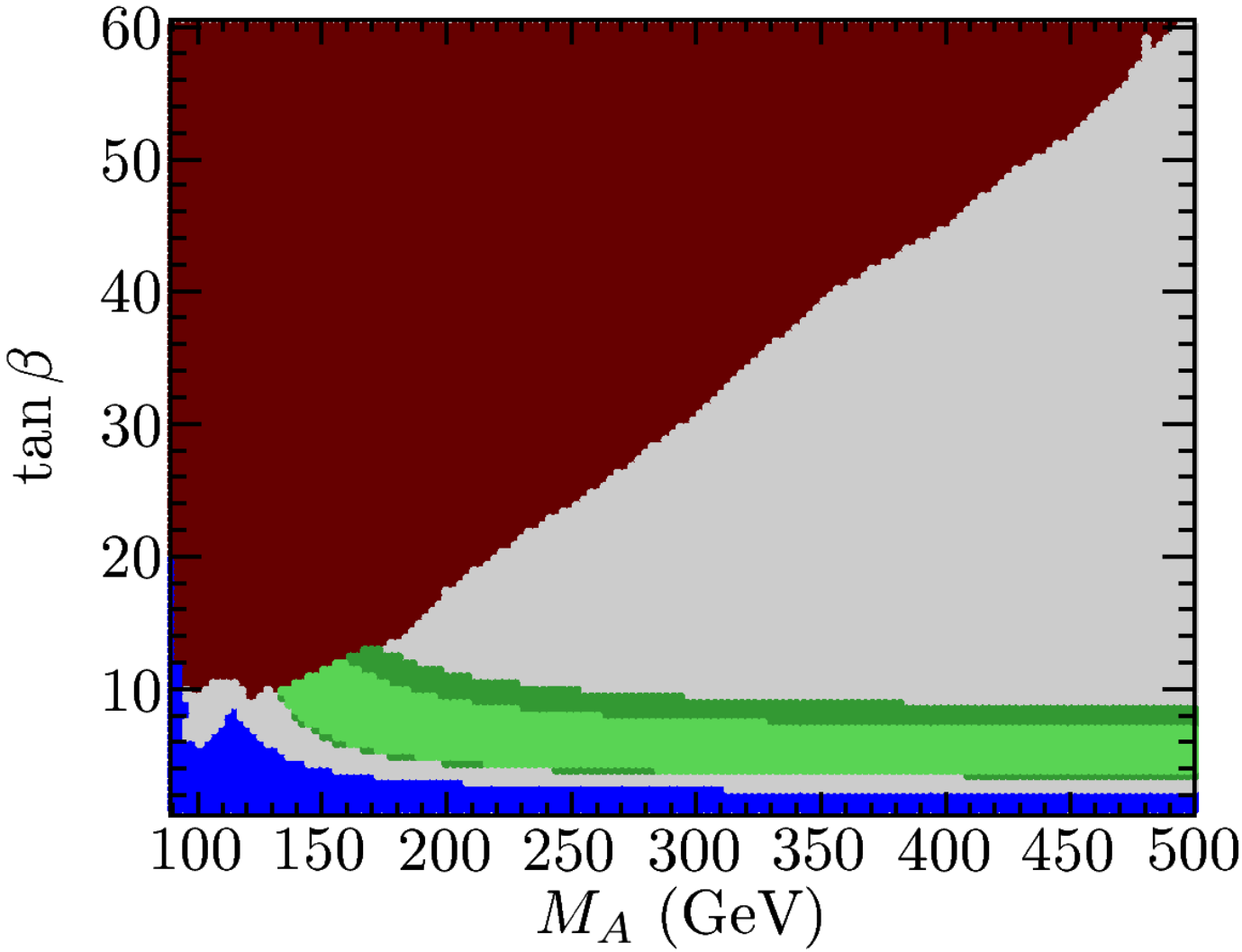
Most of them analyzed them in the framework of SUSY

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*]

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



$\Rightarrow$ green are allowed by Higgs "excess"

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

	Limits without $M_h = 125$			Limits with $M_h = 125$		
M_{SUSY}	$\tan\beta$	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

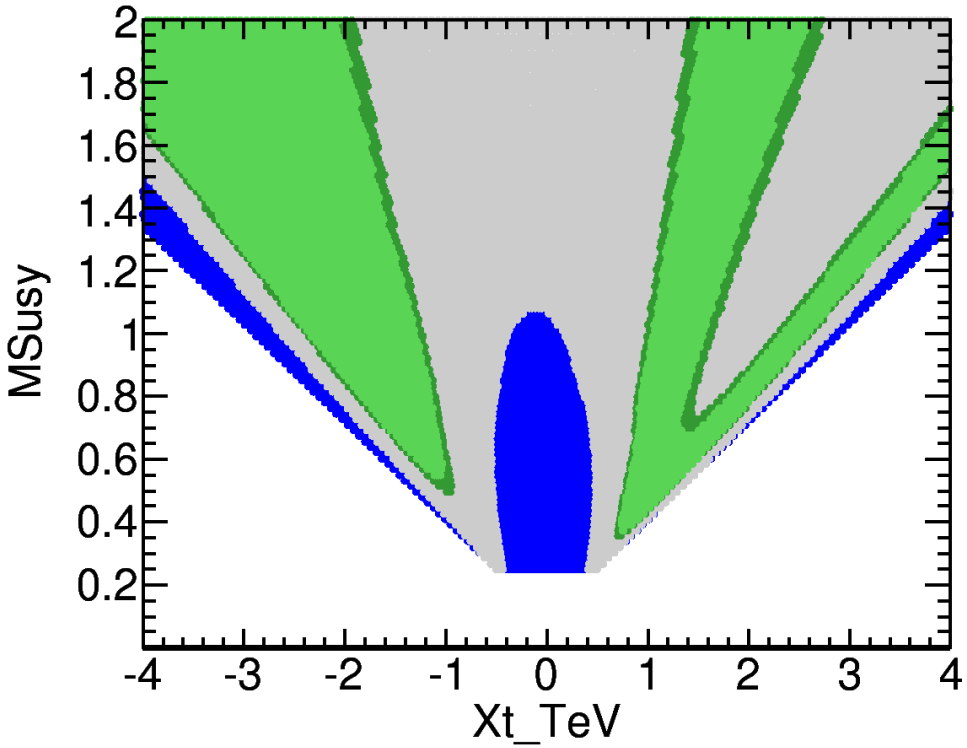
$\Rightarrow$ new conservative limits obtained!

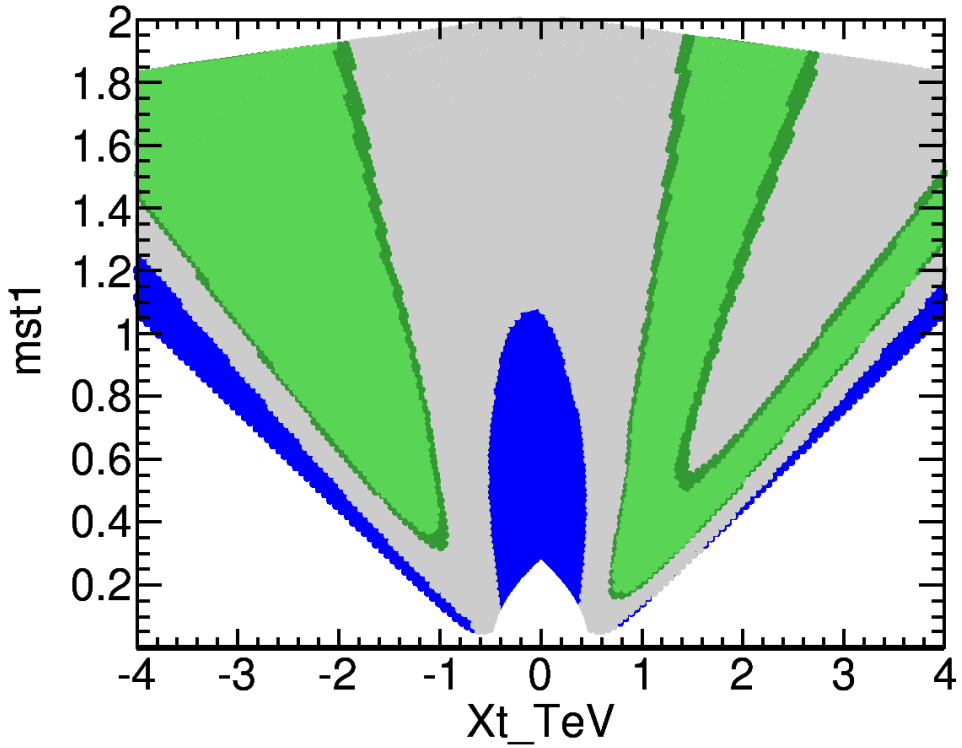
$\Rightarrow$ only small margin left for $t \to H^+ b$

Limits on stop masses:

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

$m_h^{\max}$ scenario:





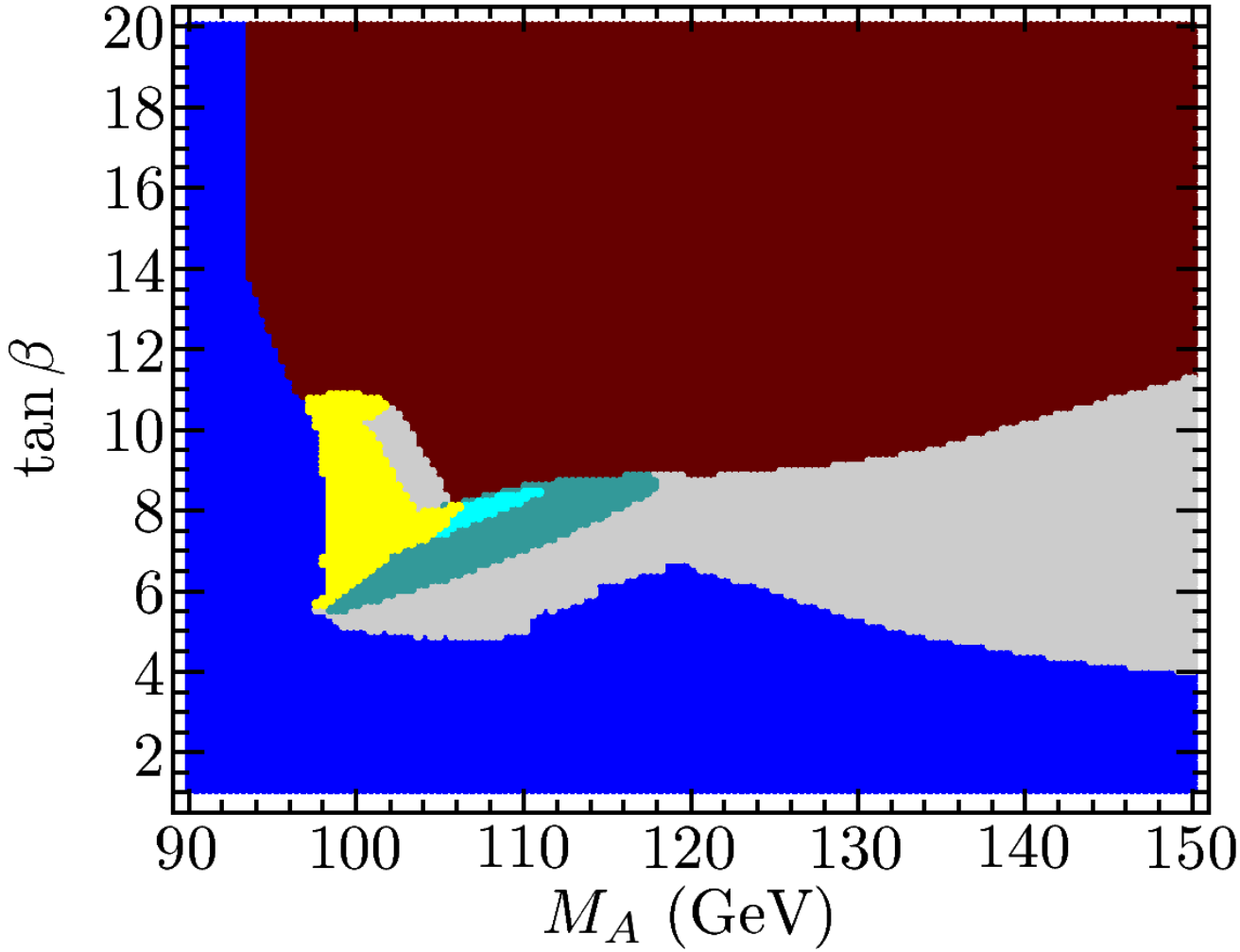
$\Rightarrow$ green are allowed by Higgs "excess"

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

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

A "heavy" SUSY Higgs at 125 GeV? [S.H., O. Stal, G. Weiglein '11]

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



Possible: $M_h = 98$ GeV, $M_H = 125$ GeV, ...