The Higgs Boson in/at the SM/LHC and Beyond

Sven Heinemeyer, IFCA (Santander)

Jaca, 05/2007

1. The Higgs Boson in the SM
2. The Higgs Boson in the MSSM

The Higgs Boson in/at the SM/LHC and Beyond (II)

Sven Heinemeyer, IFCA (Santander)

Jaca, 05/2007

1. The Higgs Boson in the SM
2. The Higgs Boson in the MSSM

The Higgs Boson in/at the SM/LHC and Beyond (II)

Sven Heinemeyer, IFCA (Santander)

Jaca, 05/2007

1. Motivation for SUSY
2. MSSM Higgs Theory
3. Electroweak Precision Observables
4. MSSM Higgs boson Searches at LEP
5. MSSM Higgs boson Searches at the Tevatron
6. MSSM Higgs boson Searches at the LHC
7. MSSM Higgs boson precision physics at the ILC

1. Motivation for SUSY

The Standard Model (SM) cannot be the ultimate theory

– The SM does not contain gravity

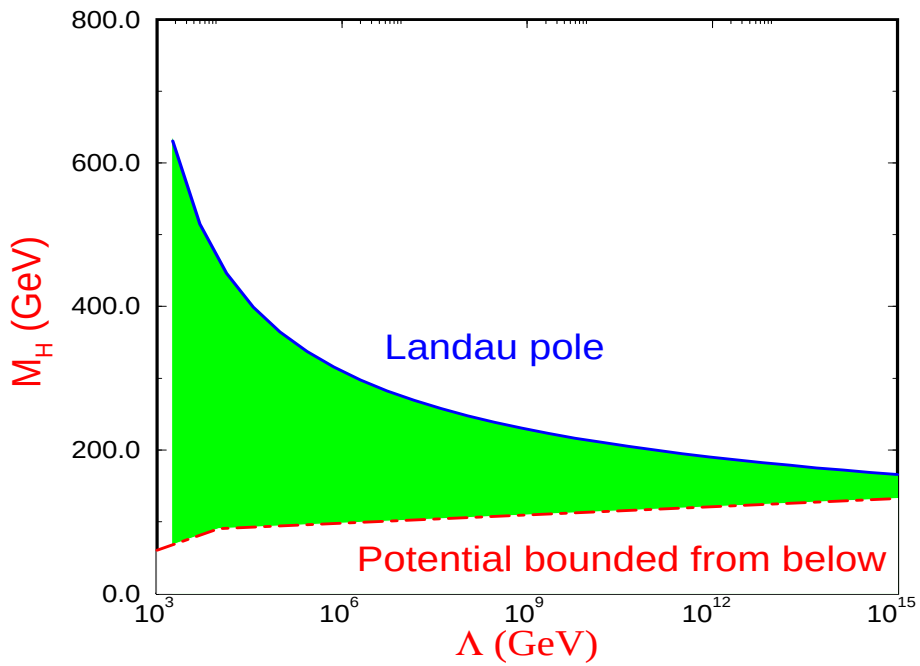
– Further problems: Hierarchy problem

Up to which energy scale Λ can the SM be valid?

– $\Lambda < M_{\rm Pl}$: inclusion of gravity effects necessary

– stability of Higgs potential: $\Rightarrow$

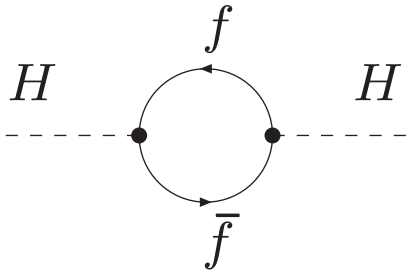
– Hierarchy problem :
Higgs mass unstable
w.r.t. quantum corrections
$\delta M_H^2 \sim \Lambda^2$
(but what does this mean?)



Mass is what determines the properties of the free propagation of a particle

Free propagation:

inverse propagator: $i(p^2 - M_H^2)$

Loop corrections: 

inverse propagator: $i(p^2 - M_H^2 + \Sigma_H^f)$

QM: integration over all possible loop momenta k

dimensional analysis:

$$\Sigma_H^f \sim N_f \, \lambda_f^2 \int d^4k \left(\frac{1}{k^2 - m_f^2} + \frac{2m_f^2}{(k^2 - m_f^2)^2} \right)$$

for $\Lambda \to \infty$: $$\Sigma_H^f \sim N_f \, \lambda_f^2 \left(\underbrace{\int \frac{d^4k}{k^2}}_{\sim \Lambda^2} + 2m_f^2 \underbrace{\int \frac{dk}{k}}_{\sim \ln \Lambda} \right)$$

$\Rightarrow$ quadratically divergent!

For $\Lambda = M_{\text{Pl}}$:

$$\Sigma_H^f \approx \delta M_H^2 \sim M_{\text{Pl}}^2 \quad \Rightarrow \quad \delta M_H^2 \approx 10^{30}\, M_H^2$$

(for $M_H \lesssim 1$ TeV)

– no additional symmetry for $M_H = 0$

– no protection against large corrections

$\Rightarrow$ Hierarchy problem is instability of small Higgs mass to large corrections in a theory with a large mass scale in addition to the weak scale

E.g.: Grand Unified Theory (GUT): $\delta M_H^2 \approx M_{\text{GUT}}^2$

Note however: there is another fine-tuning problem in nature, for which we have no clue so far – cosmological constant

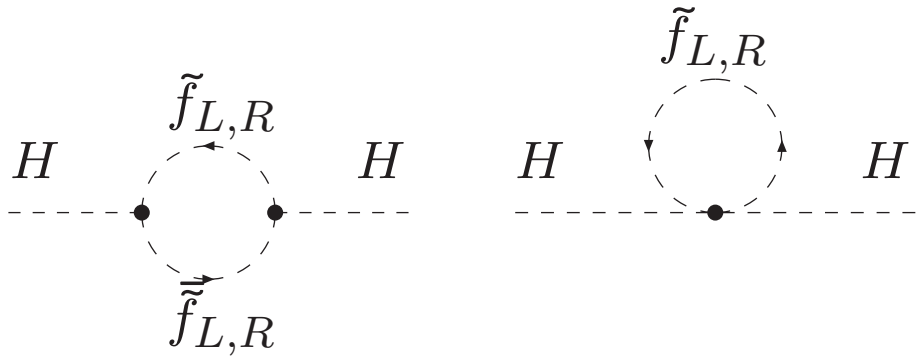
Supersymmetry:

Symmetry between fermions and bosons

$$\begin{aligned} Q|\text{boson}\rangle &= |\text{fermion}\rangle \\ Q|\text{fermion}\rangle &= |\text{boson}\rangle \end{aligned}$$

Effectively: SM particles have SUSY partners (e.g. $f_{L,R} \to \tilde{f}_{L,R}$)

SUSY: additional contributions from scalar fields:



$$\Sigma_H^{\tilde{f}} \sim N_{\tilde{f}}\, \lambda_{\tilde{f}}^2 \int d^4k \left(\frac{1}{k^2 - m_{\tilde{f}_L}^2} + \frac{1}{k^2 - m_{\tilde{f}_R}^2} \right) + \text{ terms without quadratic div.}$$

for $\Lambda \to \infty$: $\quad \Sigma_H^{\tilde{f}} \sim N_{\tilde{f}}\, \lambda_{\tilde{f}}^2\, \Lambda^2$

$\Rightarrow$ quadratic divergences cancel for

$$N_{\tilde{f}_L} = N_{\tilde{f}_R} = N_f$$
$$\lambda^2_{\tilde{f}} = \lambda^2_f$$

complete correction vanishes if furthermore

$$m_{\tilde{f}} = m_f$$

Soft SUSY breaking: $m^2_{\tilde{f}} = m^2_f + \Delta^2, \quad \lambda^2_{\tilde{f}} = \lambda^2_f$

$$\Rightarrow \Sigma_H^{f+\tilde{f}} \sim N_f \, \lambda^2_f \, \Delta^2 + \ldots$$

$\Rightarrow$ correction stays acceptably small if mass splitting is of weak scale

$\Rightarrow$ realized if mass scale of SUSY partners

$$M_{\text{SUSY}} \lesssim 1 \text{ TeV}$$

$\Rightarrow$ SUSY at TeV scale provides attractive solution of hierarchy problem

Supersymmetry (SUSY) : Symmetry between

$$\text{Bosons} \leftrightarrow \text{Fermions}$$

$$Q\ |\text{Fermion}\rangle \rightarrow |\text{Boson}\rangle$$
$$Q\ |\text{Boson}\rangle \rightarrow |\text{Fermion}\rangle$$

Simplified examples:

$$Q\ |\text{top},\ t\rangle \rightarrow |\text{scalar top},\ \tilde{t}\rangle$$
$$Q\ |\text{gluon},\ g\rangle \rightarrow |\text{gluino},\ \tilde{g}\rangle$$

$\Rightarrow$ each SM multiplet is enlarged to its double size

Unbroken SUSY: All particles in a multiplet have the same mass

Reality: $m_e \neq m_{\tilde{e}} \Rightarrow$ SUSY is broken . . .

. . . via soft SUSY-breaking terms in the Lagrangian (added by hand)

SUSY particles are made heavy: $\boxed{M_{\text{SUSY}} = \mathcal{O}(1\ \text{TeV})}$

Supersymmetry: Motivation

The SM is in a pretty good shape.

Why MSSM? (Is it worth to double the particle spectrum?)

1.) Stability of the Higgs mass against higher-order corr.

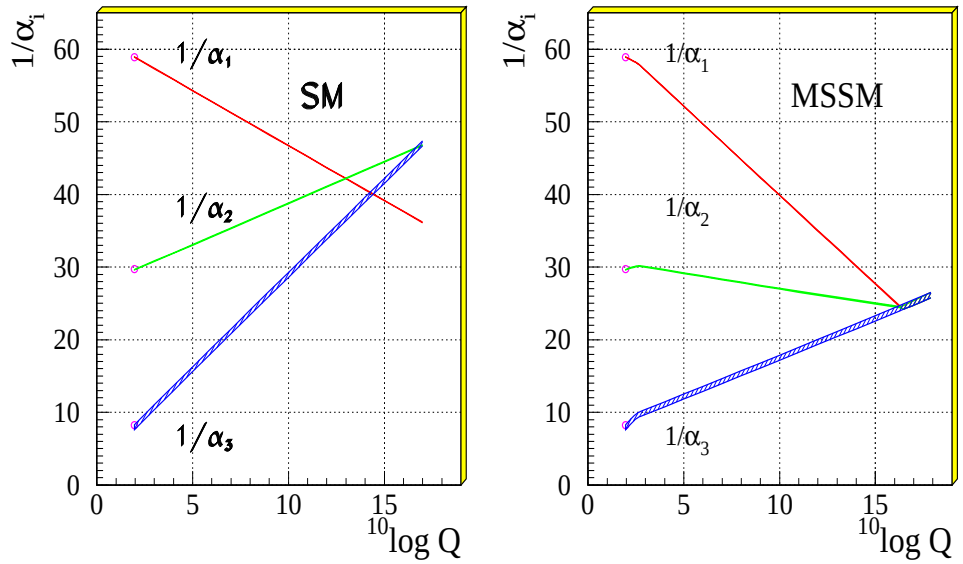
2.) Unification of gauge couplings: Not possible in the SM, but in the MSSM (although it was not designed for it.)

3.) Spontaneous symmetry breaking via Higgs mechanism is automatic in SUSY GUTs

4.) SUSY provides CDM candidate

5.) . . .

Unification of the Coupling Constants in the SM and the minimal MSSM



[*Amaldi, de Boer, Fürstenau '92*]

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin } 1 \text{ / Spin } 0$$

$$\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^{0}_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

$\tilde{t}/\tilde{b}$ sector of the MSSM: (scalar partner of the top/bottom quark)

Stop, sbottom mass matrices ($X_t = A_t - \mu^*/\tan\beta$, $X_b = A_b - \mu^* \tan\beta$):

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t^* \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

$$\mathcal{M}^2_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + DT_{b_1} & m_b X_b^* \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m^2_{\tilde{b}_1} & 0 \\ 0 & m^2_{\tilde{b}_2} \end{pmatrix}$$

mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

soft SUSY-breaking parameters A_t, A_b also appear in ϕ-$\tilde{t}/\tilde{b}$ couplings

$$SU(2) \text{ relation} \Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$$

$\Rightarrow$ relation between $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$

2. MSSM Higgs Theory

Comparison with SM case:

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

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \tilde{H} = i\sigma_2 H^\dagger, \quad H \to \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \tilde{H} \to \begin{pmatrix} v \\ 0 \end{pmatrix}$$

In SUSY: term $\bar{Q}_L H^\dagger$ 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

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

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

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

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

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:

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

$\Rightarrow$ $m_h \leq M_Z$ at tree level

$\Rightarrow$ Light Higgs boson h required in SUSY

Measurement of m_h, Higgs couplings

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

Higgs couplings, tree level:

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

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

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

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

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

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

$\Rightarrow$ $g_{hVV} \leq g^{\text{SM}}_{HVV}$, $\quad g_{hVV}$, g_{HVV}, g_{hAZ} cannot all be small

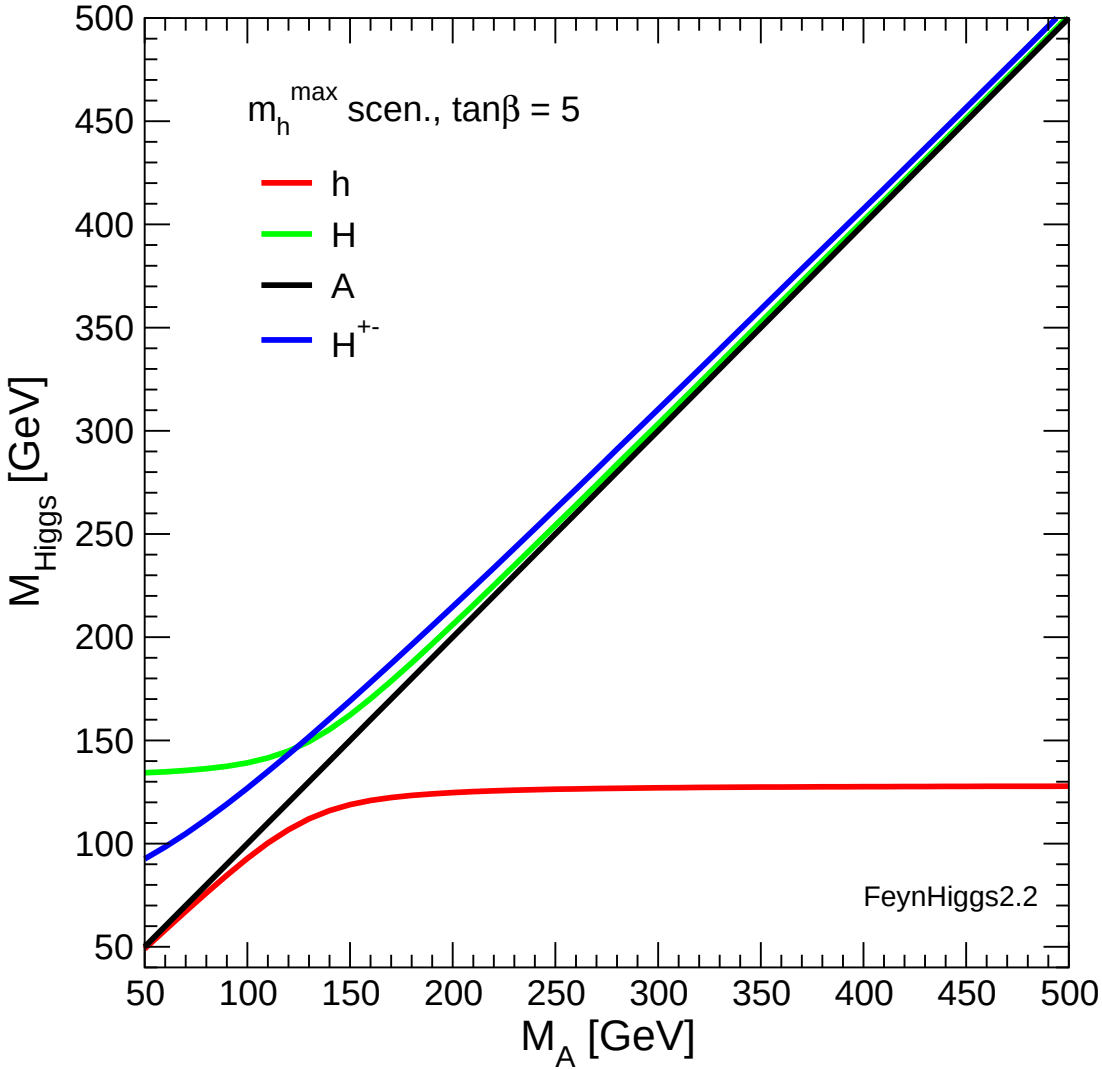
$g_{hb\bar{b}}, g_{h\tau^+\tau^-}$: significant suppression or enhancement w.r.t. SM coupling possible

The decoupling limit:

For $M_A \gtrsim 150$ GeV:

The lightest MSSM Higgs is SM-like

The heavy MSSM Higgses: $M_A \approx M_H \approx M_{H^\pm}$



of course there are exceptions . . .

Higgs mass bounds in SUSY theories

MSSM predicts upper bound on M_h:

tree-level bound: $m_h < M_Z$, excluded by LEP Higgs searches!

Large radiative corrections:

Yukawa couplings: $\frac{\mathrm{e}\, m_t}{2 M_W s_\mathrm{W}}$, $\frac{\mathrm{e}\, m_t^2}{M_W s_\mathrm{W}}$, ...

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

The MSSM Higgs sector is connected to all other sector 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

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 $m_t = 170.9 \pm 1.8$ GeV

(including theoretical uncertainties from unknown higher orders)

$\Rightarrow$ observable at the LHC

Obtained with:

FeynHiggs

[*S.H., W. Hollik, G. Weiglein '98, '00, '02*]

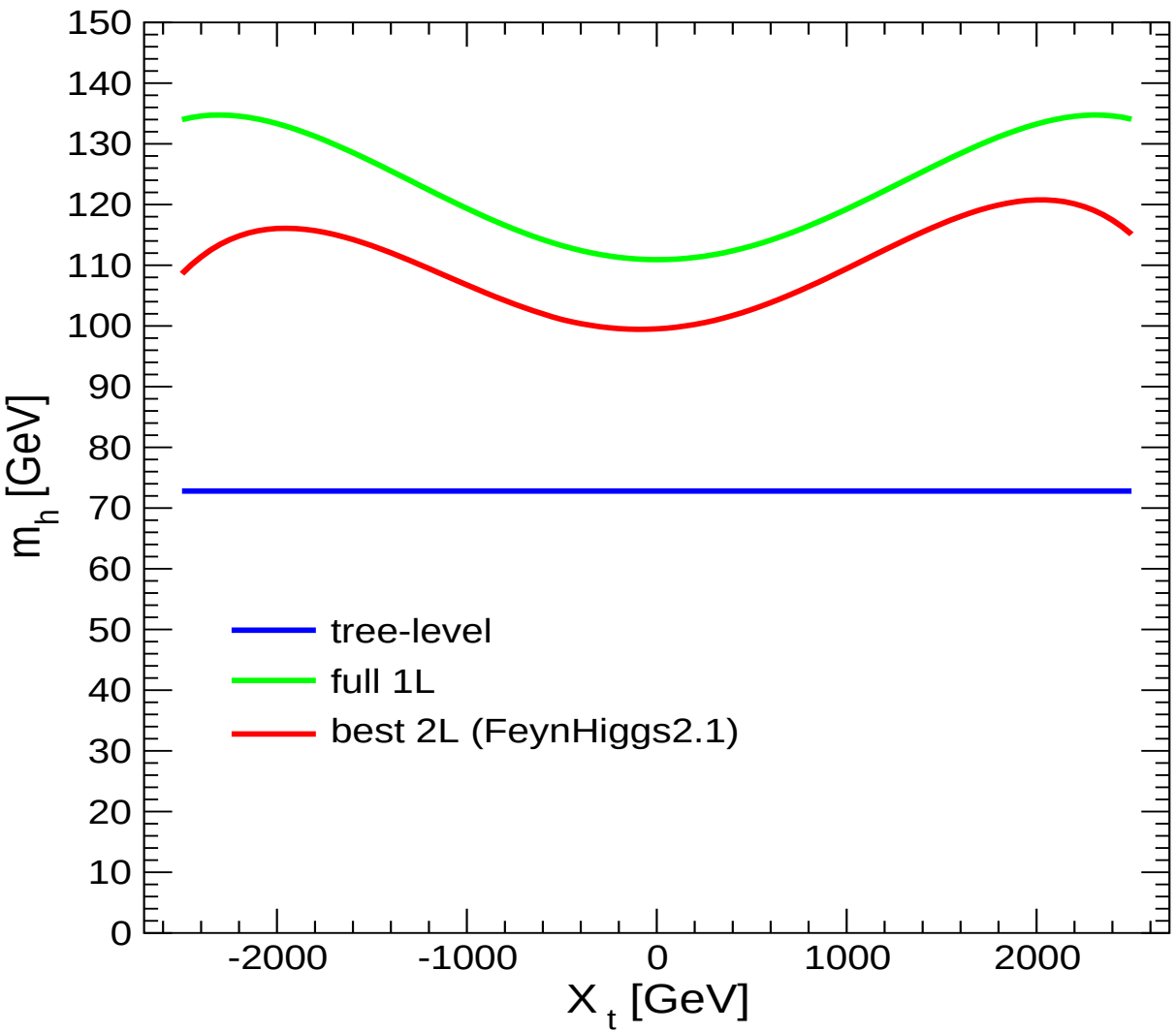
[*T. Hahn, S.H., W. Hollik, G. Weiglein '03 – '07*]

`www.feynhiggs.de`

$\rightarrow$ all Higgs masses, couplings, BRs (easy to link, easy to use :-)

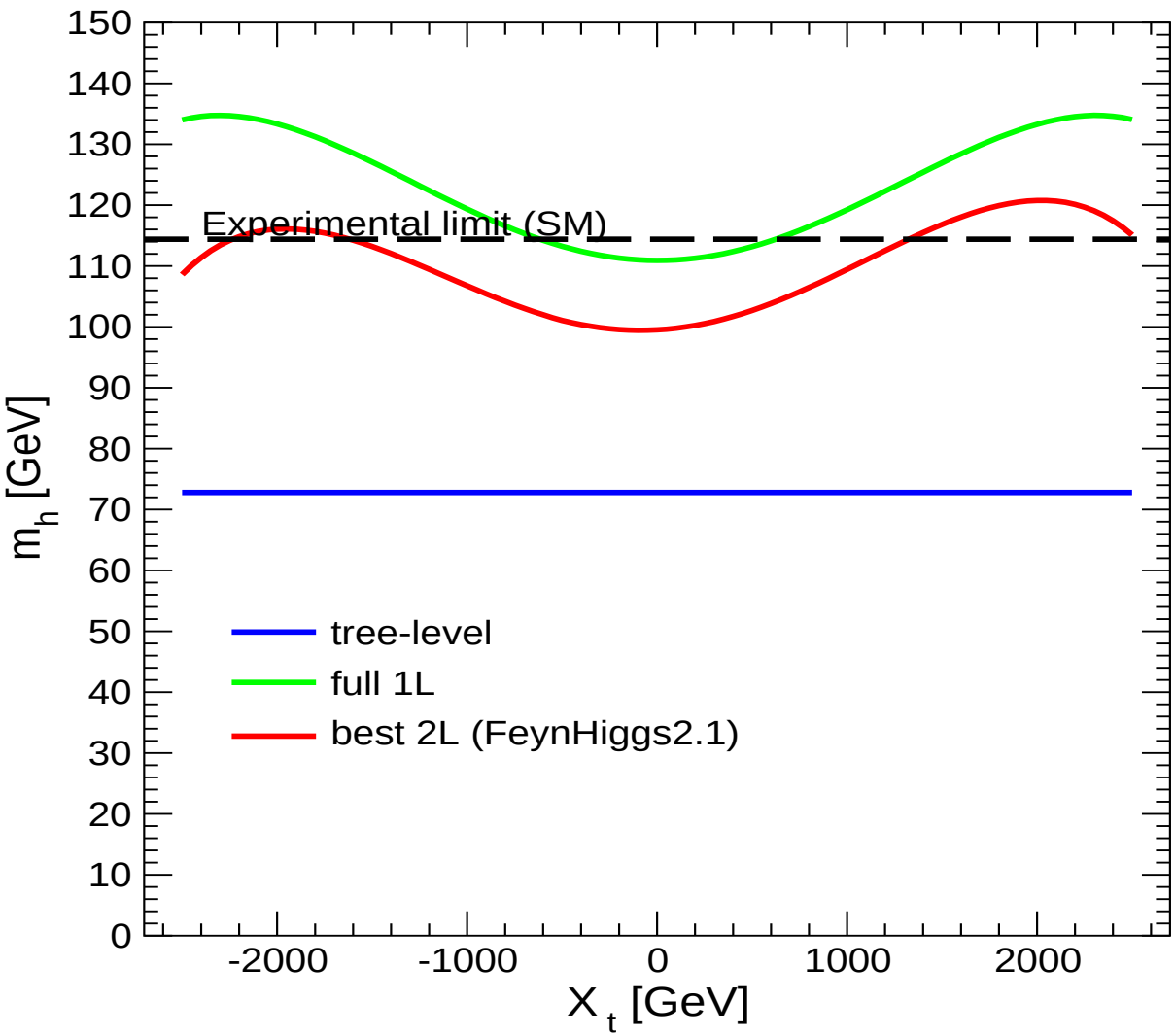
Effects of the two-loop corrections to the lightest Higgs mass:

Example for one set of MSSM parameters



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

Example for one set of MSSM parameters



Comparison with experimental limits

⇒ strong impact on bound on SUSY parameters

Remaining theoretical uncertainties in prediction for M_h in the MSSM:

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

– From unknown higher-order corrections:
$\Rightarrow \Delta M_h \approx 3$ GeV

– From uncertainties in input parameters

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

$\Delta m_t \approx 2$ GeV $\Rightarrow \Delta M_h \approx 2$ GeV

Higgs couplings, production cross sections

$\Rightarrow$ also affected by large SUSY loop corrections

. . . see below

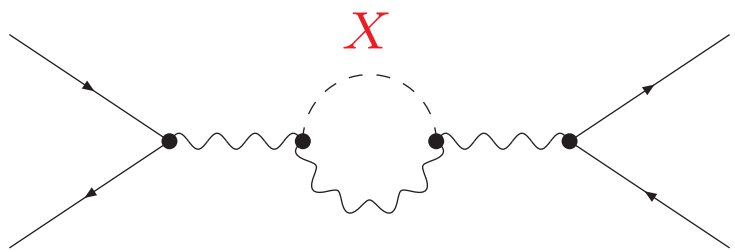
3. Electroweak Precision Observables (EWPO):

Comparison of electro-weak precision observables with theory:

EW Precision data:		Theory:
$M_W, \sin^2\theta_{\text{eff}}, a_\mu$	$\leftrightarrow$	SM, MSSM , . . .

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections, e.g. H



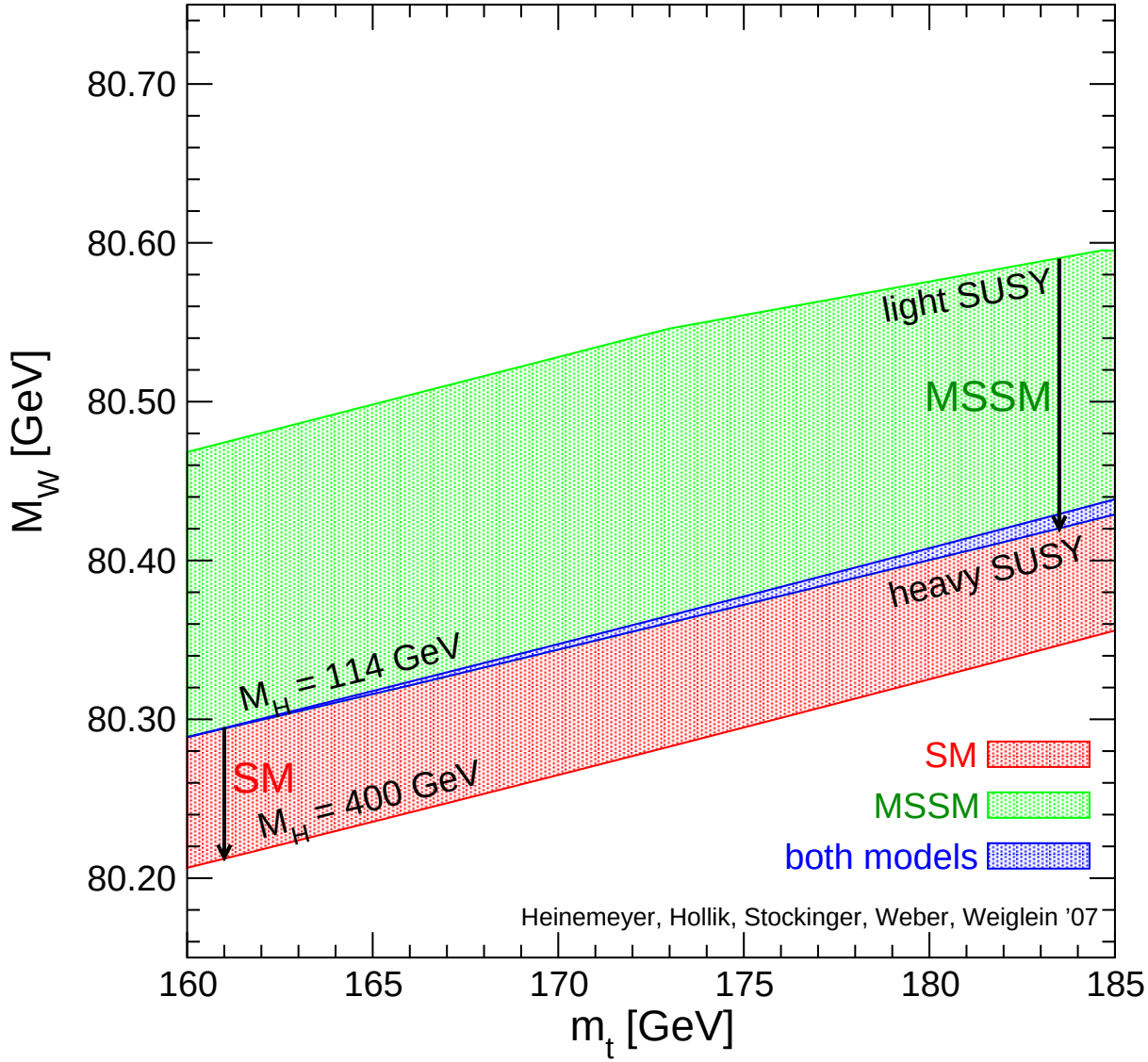
$\Downarrow$

SM: limits on SUSY masses, . . .

Very high accuracy of measurements and theoretical predictions needed

Example: Prediction for M_W in the SM and the MSSM :

[S.H., W. Hollik, D. Stockinger, A.M. Weber, G. Weiglein '07]



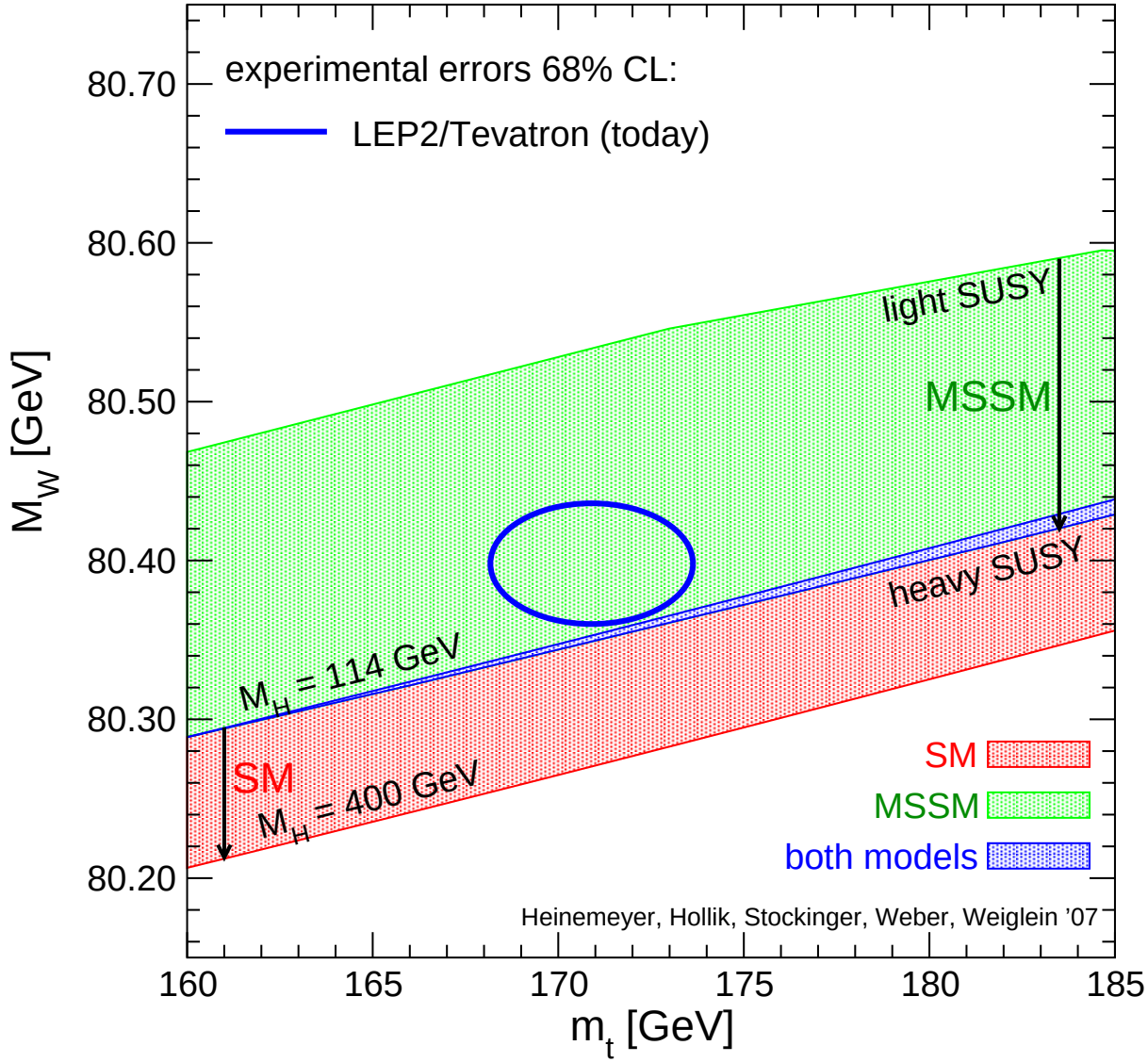
MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of $M_H^{\rm SM}$

Example: Prediction for M_W in the SM and the MSSM :

[S.H., W. Hollik, D. Stockinger, A.M. Weber, G. Weiglein '07]



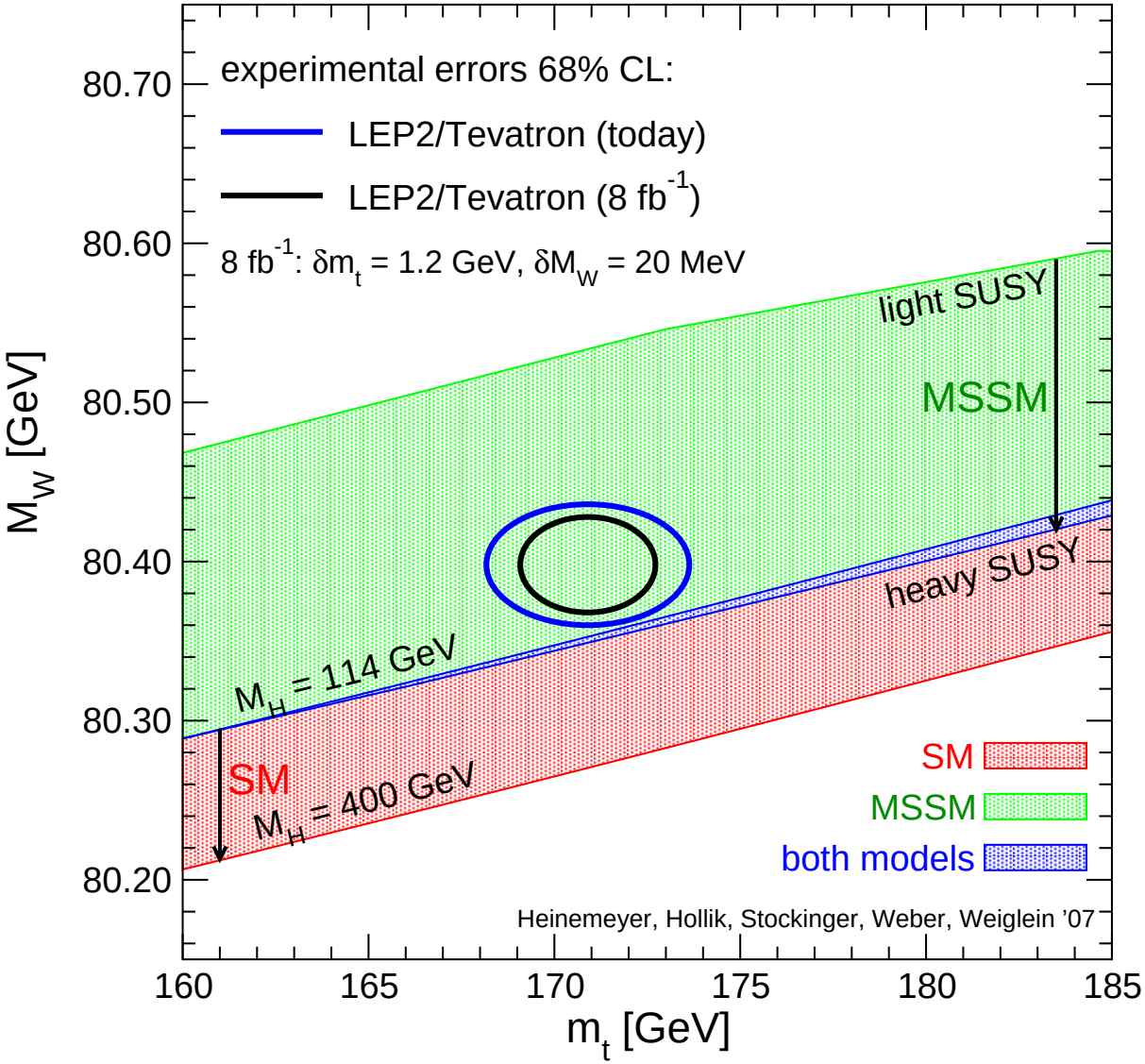
MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of $M_H^{\rm SM}$

Example: Prediction for M_W in the SM and the MSSM :

[*S.H., W. Hollik, D. Stockinger, A.M. Weber, G. Weiglein '07*]



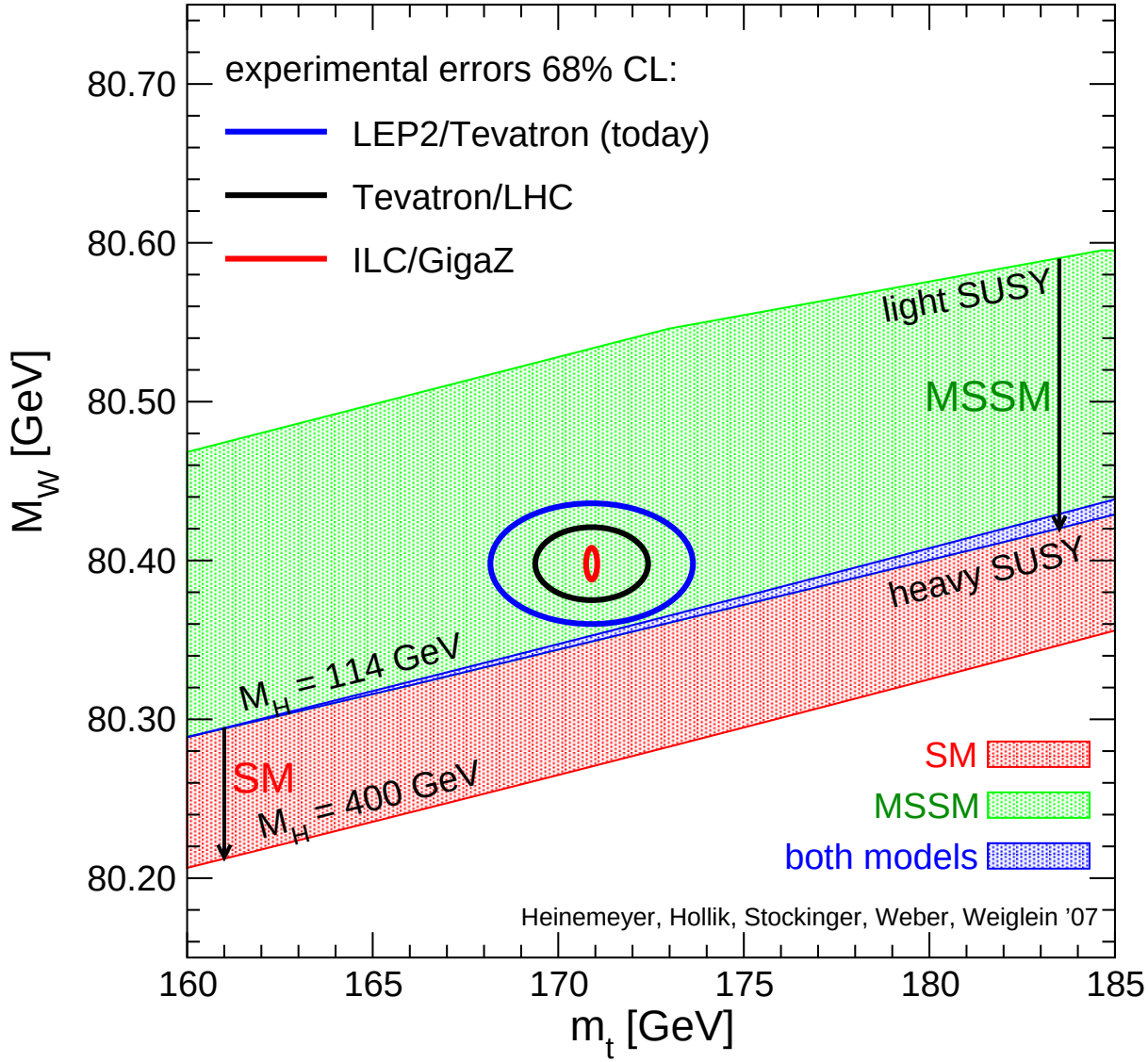
MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of M_H^{SM}

Example: Prediction for M_W in the SM and the MSSM :

[*S.H., W. Hollik, D. Stockinger, A.M. Weber, G. Weiglein '07*]



MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

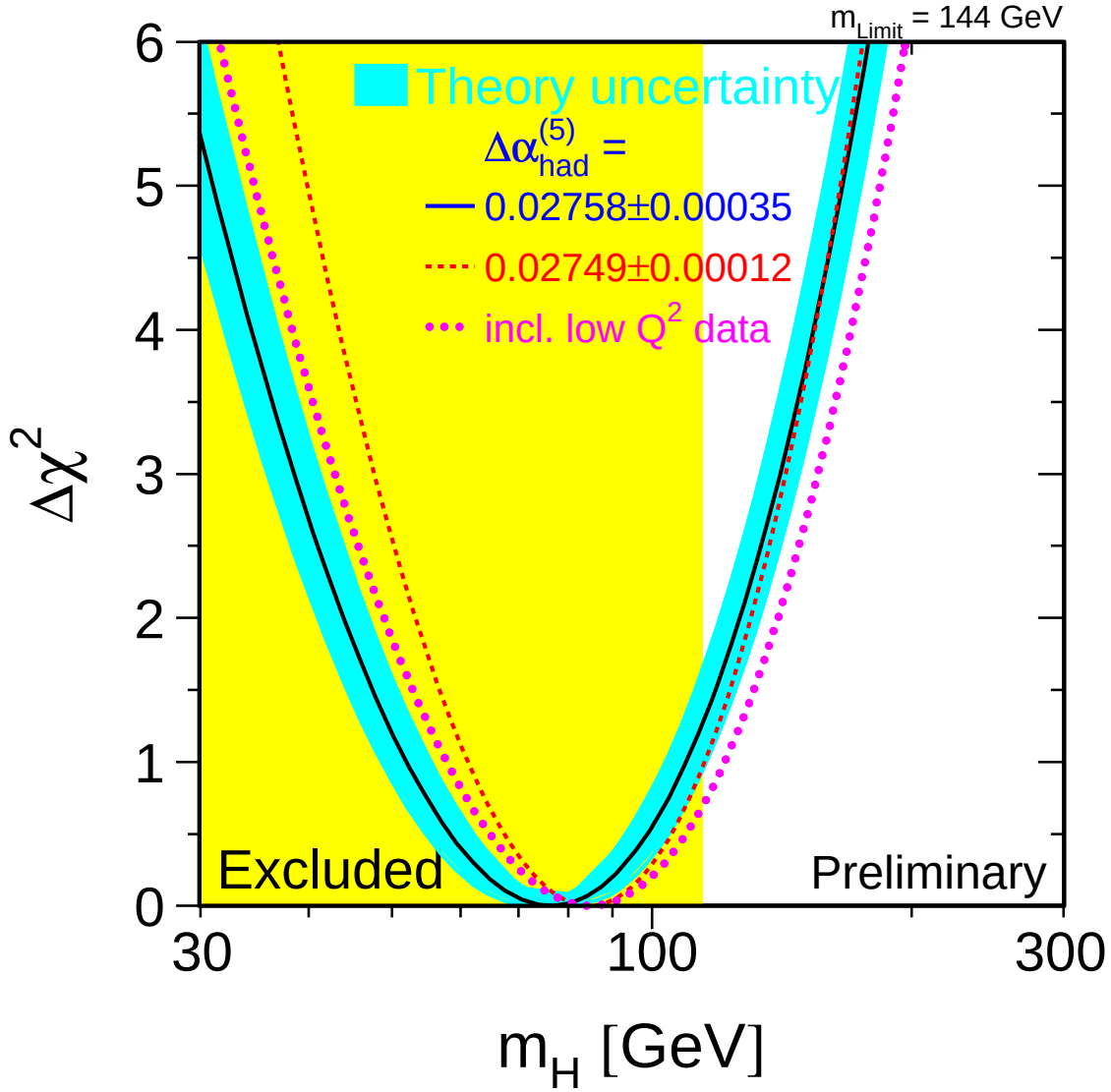
SM band:
variation of $M_H^{\rm SM}$

Global fit to all SM data:

[*LEPEWWG '07*]

$\Rightarrow M_H = 76^{+33}_{-24}$ GeV

$M_H < 144$ GeV, 95% C.L.



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of Higgs mechanism

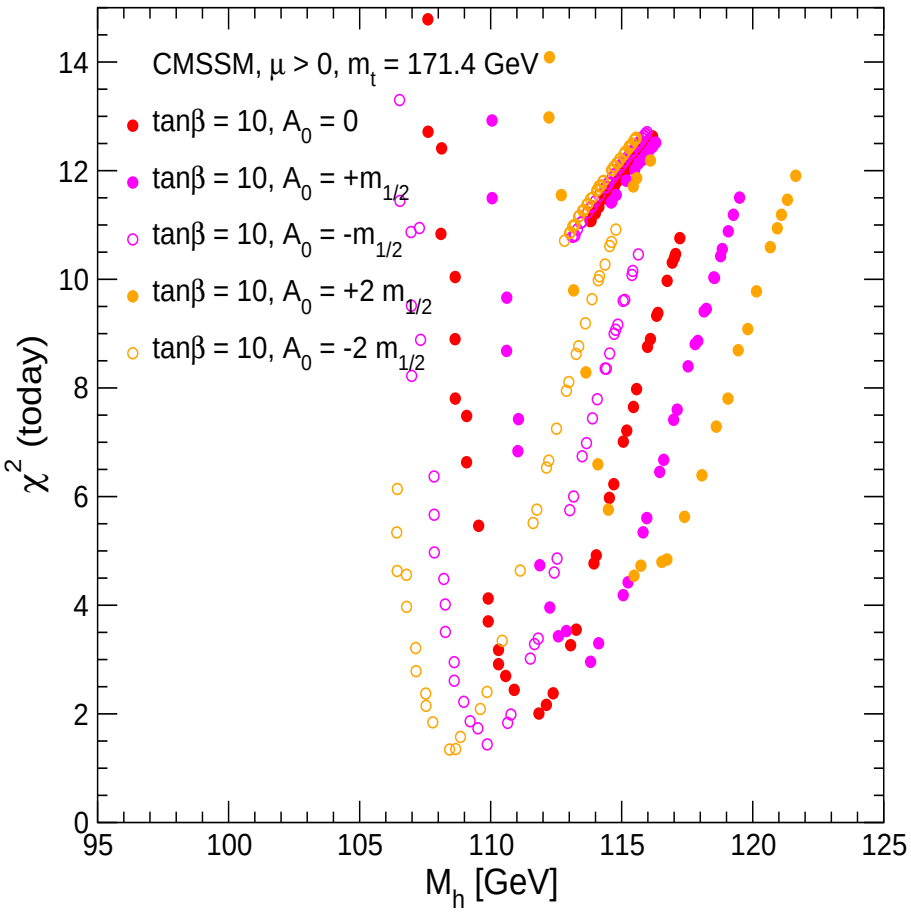
$\Rightarrow$ Higgs boson seems to be light – too light?

CMSSM/mSUGRA: "blue band" for M_h

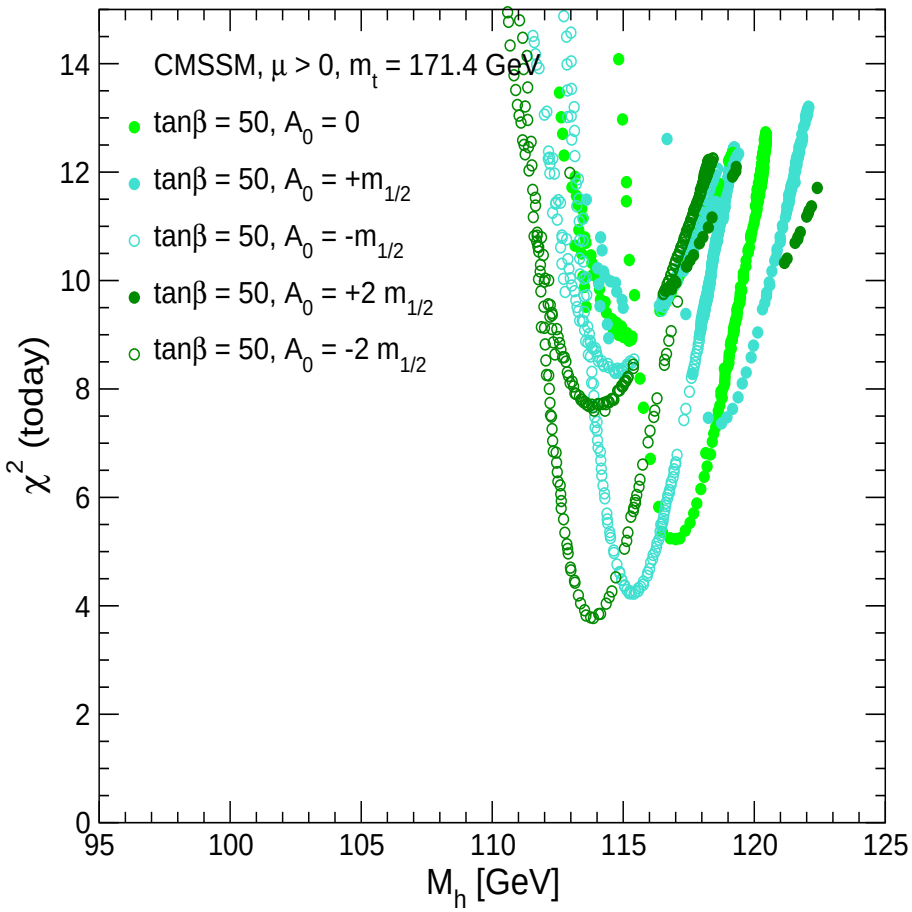
[*J. Ellis, S.H., K. Olive, A.M. Weber, G. Weiglein '07*]

Fit with M_W, $\sin^2\theta_{\text{eff}}$, Γ_Z, $(g-2)_\mu$, BR$(b \to s\gamma)$ and other BPO

$\tan\beta = 10$



$\tan\beta = 50$

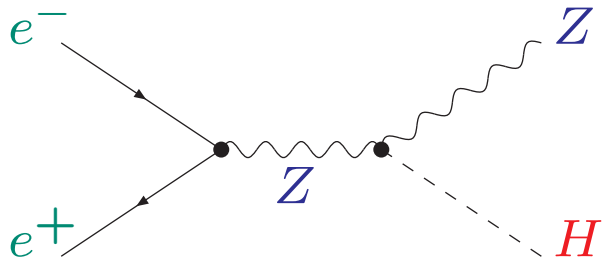


Best M_h value $\sim$ 110–115 GeV $\Rightarrow$ much "better" than in the SM

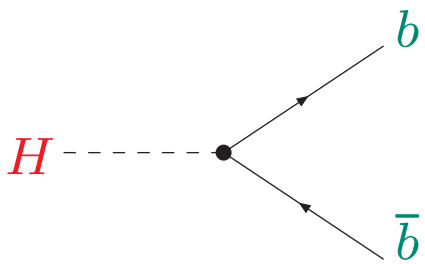
4. MSSM Higgs boson search at LEP:

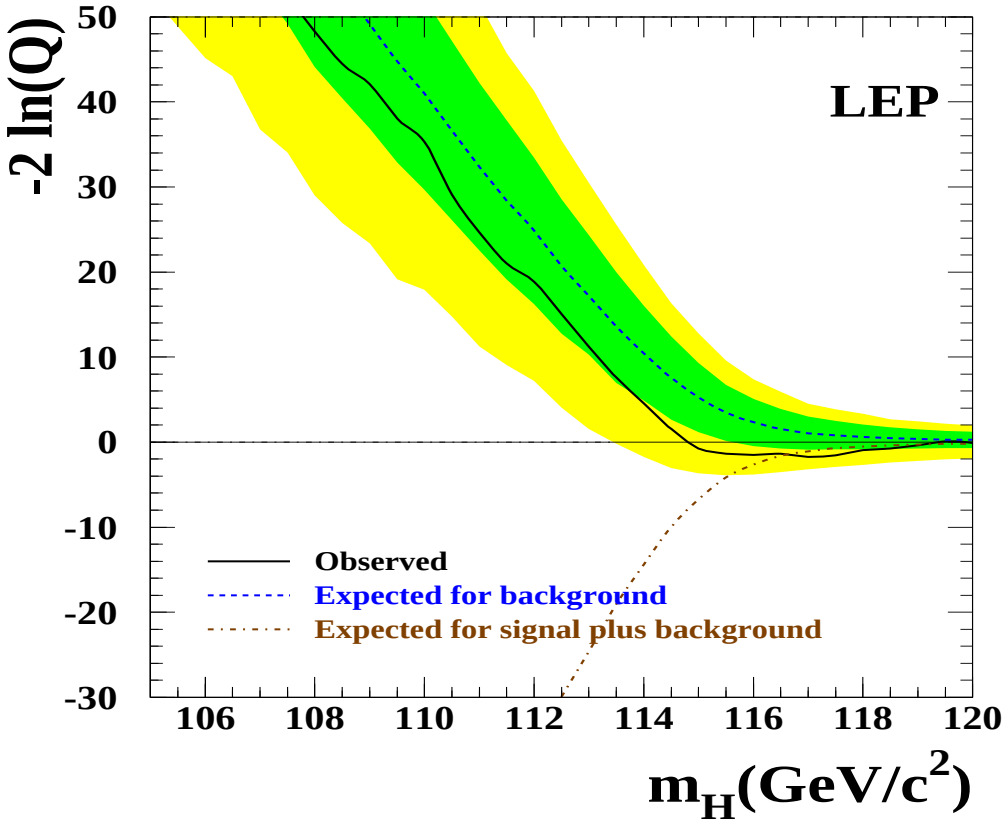
Search for the Standard Model Higgs at LEP: [*LEP Higgs WG '03*]

Dominant production process:
$e^+e^- \to ZH$:



Dominant decay process: $H \to b\bar{b}$





Exclusion limit, 95% C.L.: $M_H > 114.4$ GeV (expected: 115.3 GeV)

(LEP has seen exactly as many Higgs-like events as could be expected for $M_H \approx 116$ GeV , not more, not less)

Search for the MSSM Higgs bosons:

Situation is more involved due to many SUSY parameters

→ investigate benchmark scenarios:

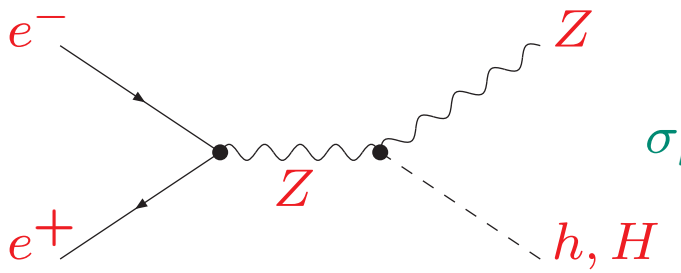
→ Vary only M_A and $\tan\beta$
→ Keep all other SUSY parameters fixed

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*]

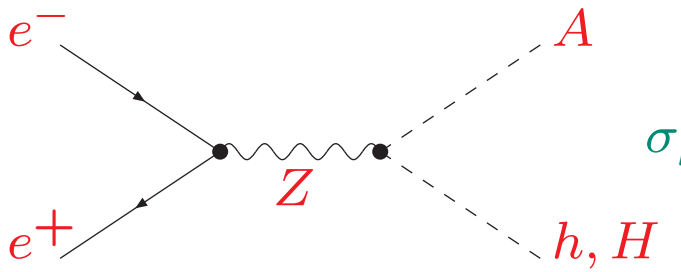
Search for neutral SUSY Higgs bosons:

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



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

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

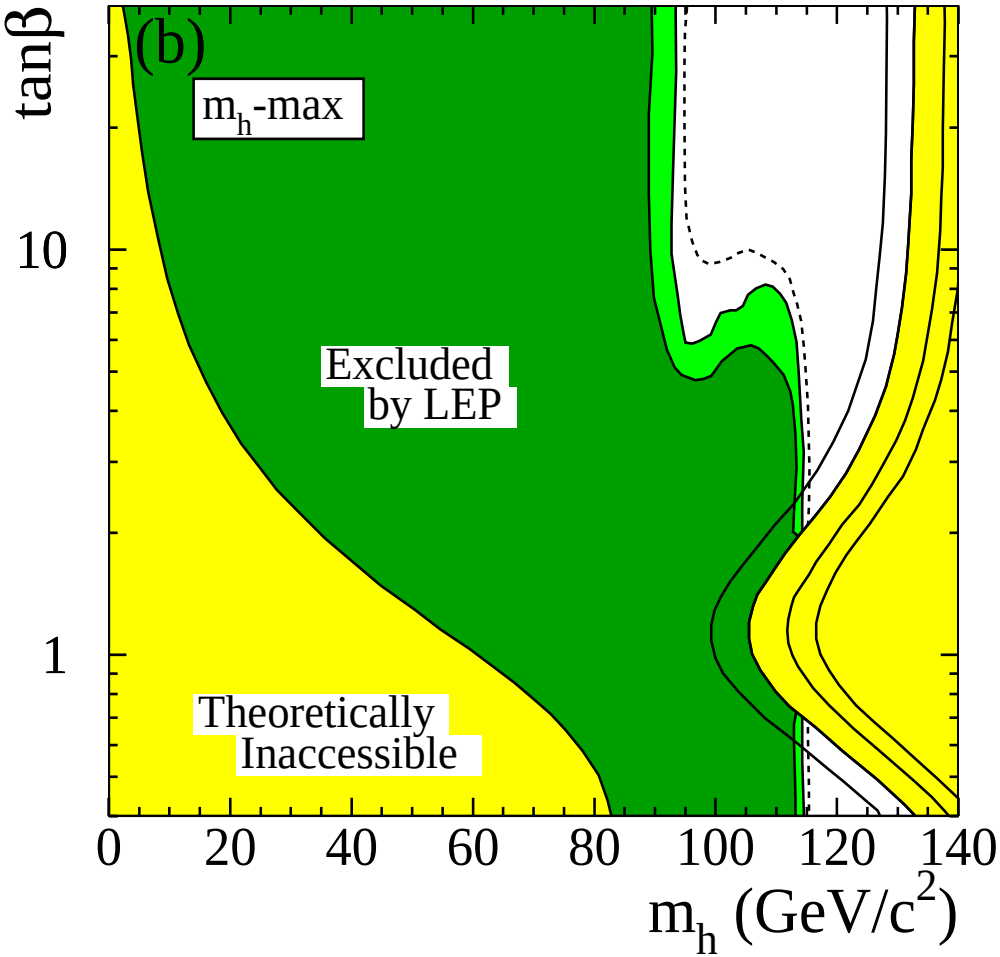


$$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

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:

$$0.7 < \tan\beta < 2.0$$

Note: this exclusion bound assumes

m_t, M_{SUSY} fixed, $m_t = 174.3$ GeV, $M_{\text{SUSY}} = 1$ TeV

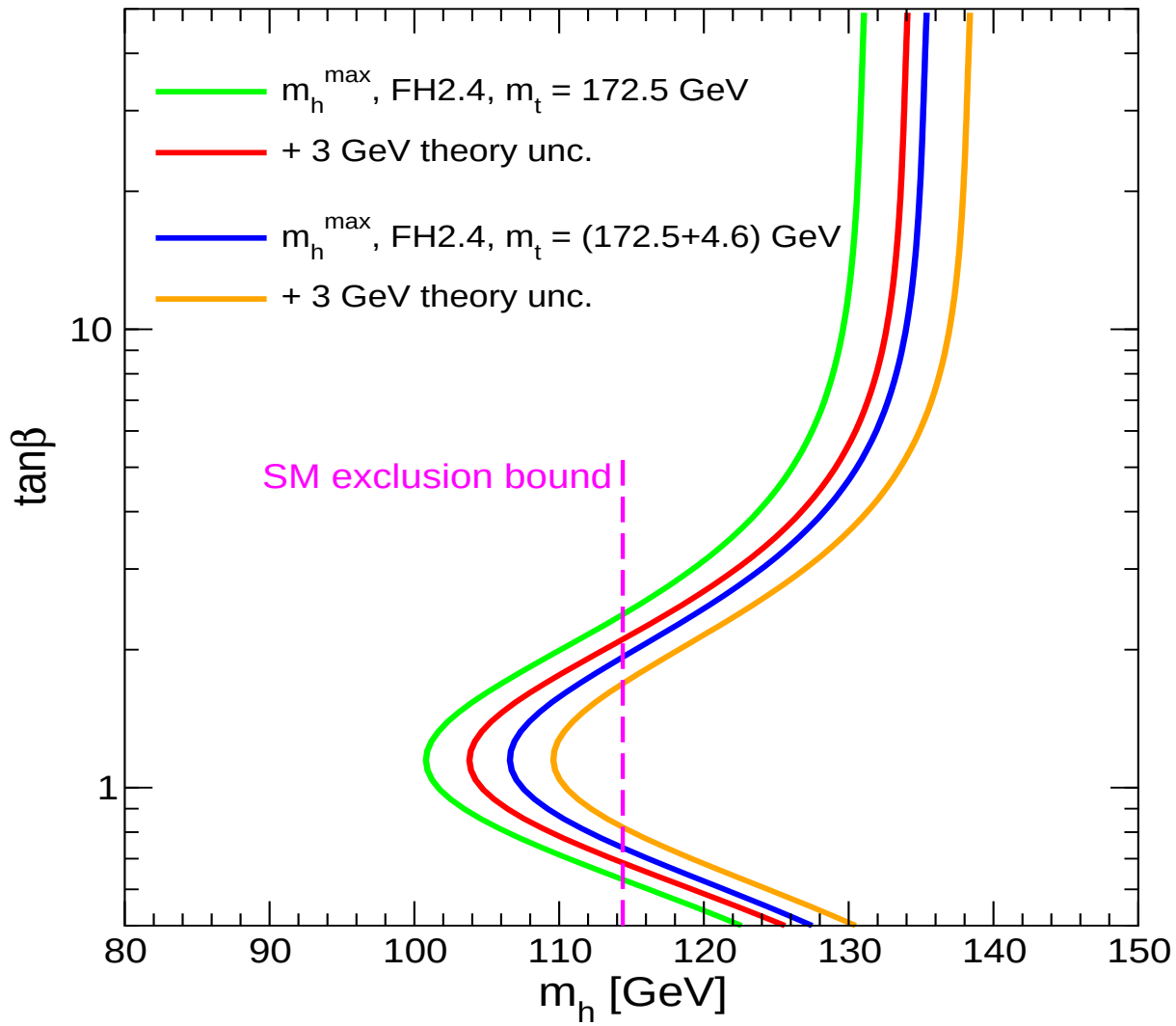
no theoretical uncertainties included

Note: new m_t value: $m_t = 170.9 \pm 1.8$ GeV [*Tevatron EWWG '07*]

parametric uncertainty: $\delta M_h^{\text{para}} \approx \delta m_t$

Effect of new corrections and $m_t \to m_t + 2\,\sigma_{m_t}$

[*S.H., W. Hollik, G. Weiglein '05*]



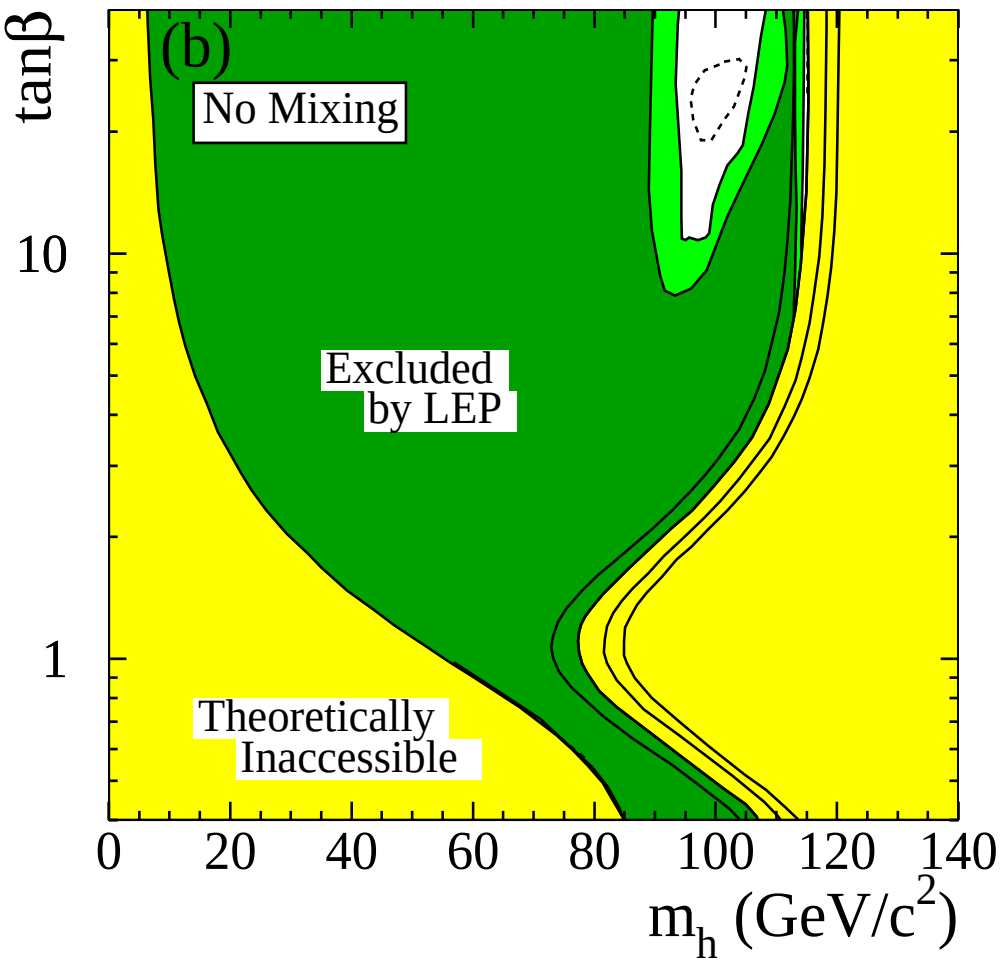
$\Rightarrow$ precise knowledge of m_t important!

$\Rightarrow$ Low $\tan\beta$ LEP exclusion region can vary strongly

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)

5. MSSM Higgs boson search at the Tevatron

Tevatron MSSM Higgs searches (I): Search for a "SM-like" light Higgs:

Prediction in "simplified" versions of the MSSM:
($m_t^{\rm exp} = 170.9$ GeV, $\delta m_t^{\rm exp} = 1.8$ GeV, $M_{\rm SUSY} \lesssim$ few TeV)
[A. Dedes, S.H., S. Su, G. Weiglein '03] [S.H., W. Hollik, G. Weiglein '04,'05]

	max. m_h [GeV]	$\delta m_h/\delta m_t$	for $m_t^{\rm exp} + 2\delta m_t$
mSUGRA/CMSSM	124.5	0.65	126.9
mGMSB	118.8	0.70	121.3
mAMSB	120.5	0.58	122.6

Exclusion potential of the Tevatron: $M_H^{\rm SM} \lesssim 130$ GeV

mSUGRA/CMSSM, mGMSB, mAMSB: no suppression of hVV coupling
$\Rightarrow$ SM bound applies

$\Rightarrow$ Tevatron can exclude mSUGRA/CMSSM, mGMSB, mAMSB, ...

$\Rightarrow$ potentially huge impact on search strategies at LHC

Possible problem in SUSY:

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

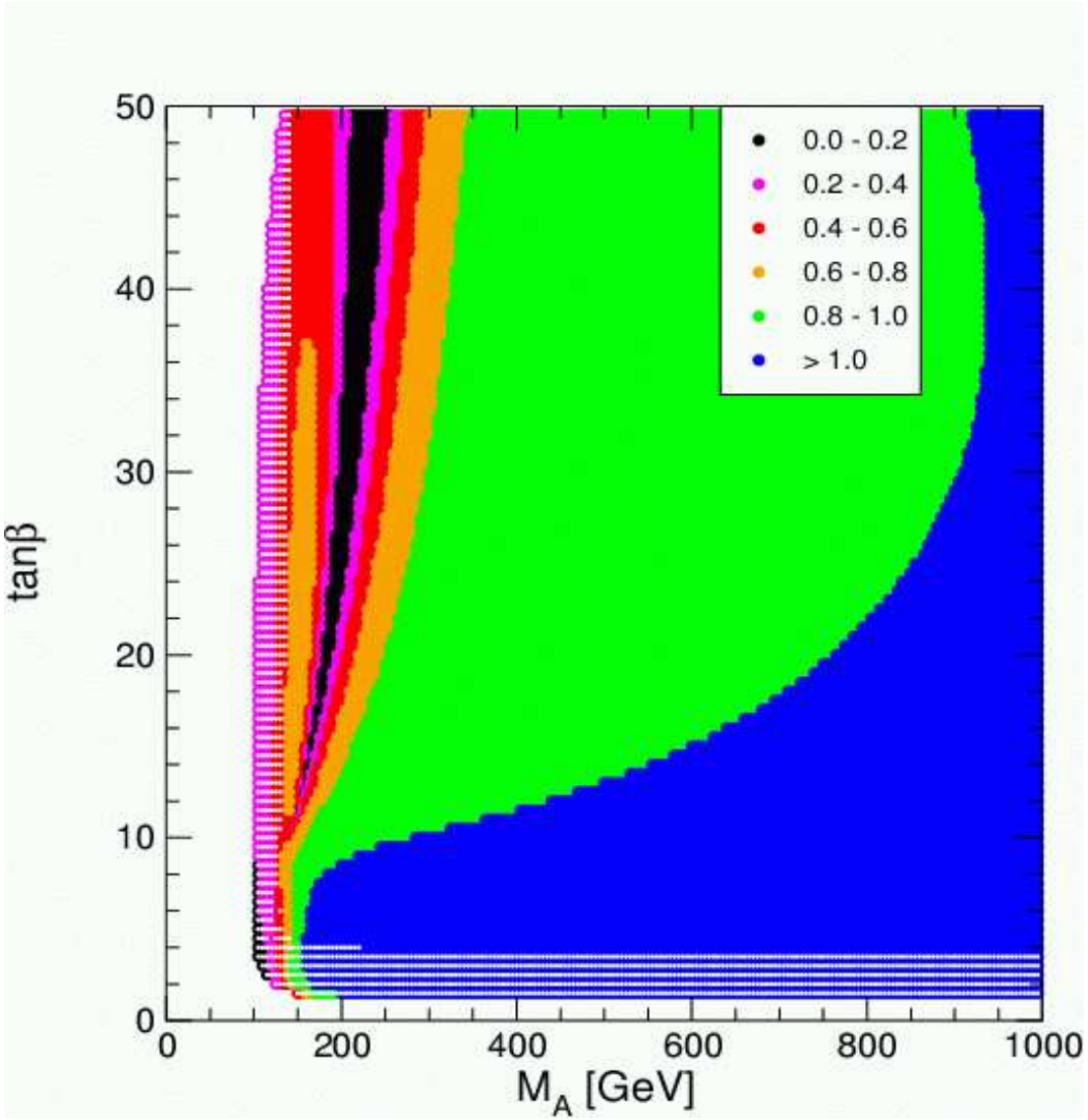
can be strongly suppressed

$\to$ "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

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



Tevatron MSSM Higgs searches (II): "Heavy" MSSM Higgs bosons

Search modes:

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

Strong enhancement compared to the SM:

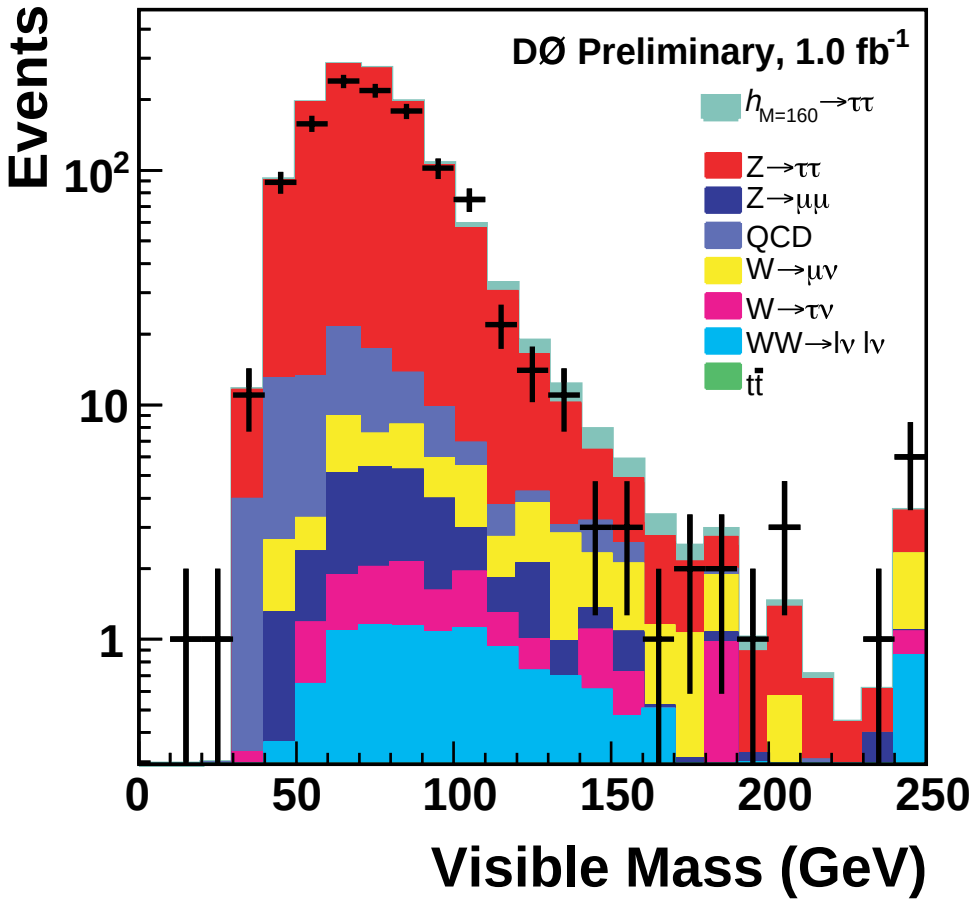
$$\sigma(b\bar{b}A) \times \mathrm{BR}(A \to b\bar{b}) \simeq \sigma(b\bar{b}A)_{\mathrm{SM}} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2+9}$$

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

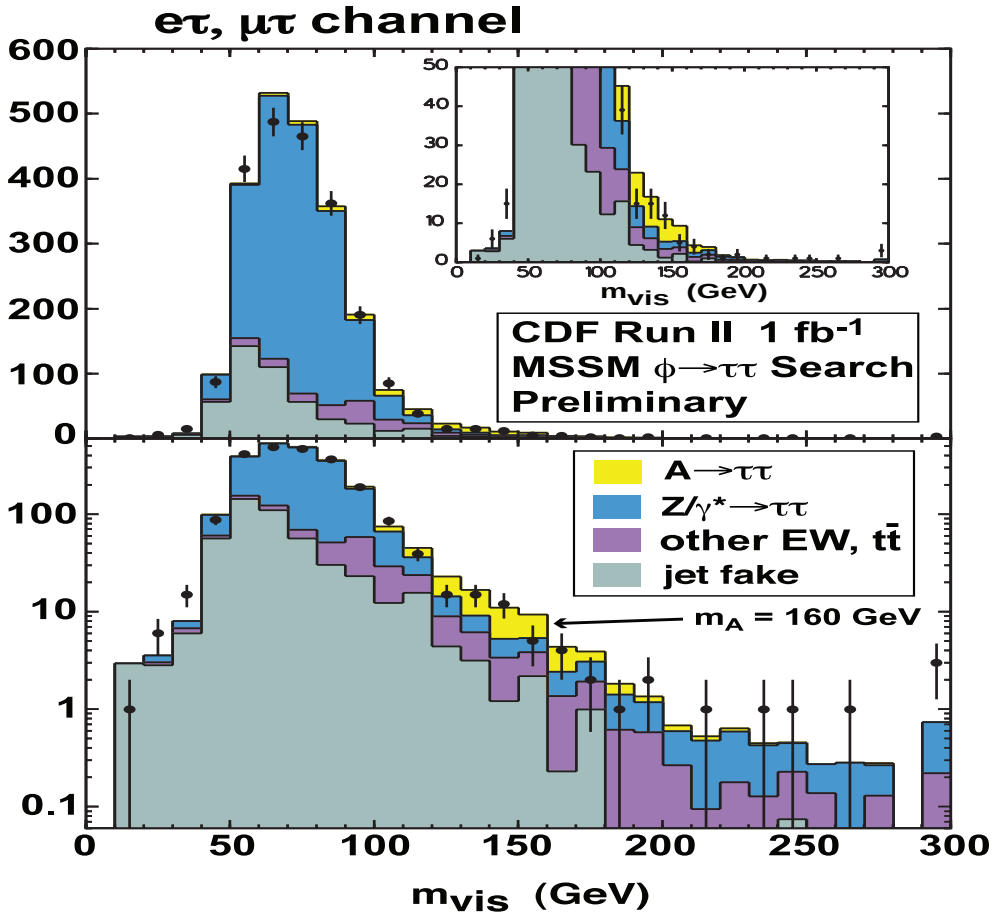
$$\Delta_b = \frac{2\alpha_s}{3\pi} m_{\tilde{g}}\,\mu\,\tan\beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{\alpha_t}{4\pi} A_t\,\mu\,\tan\beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)$$

Either $H \approx A$ or $h \approx A \Rightarrow$ another factor of 2

Existing Tevatron analyses: $H/A \to \tau\tau$ (1 fb^{-1}):



[D0 '07]

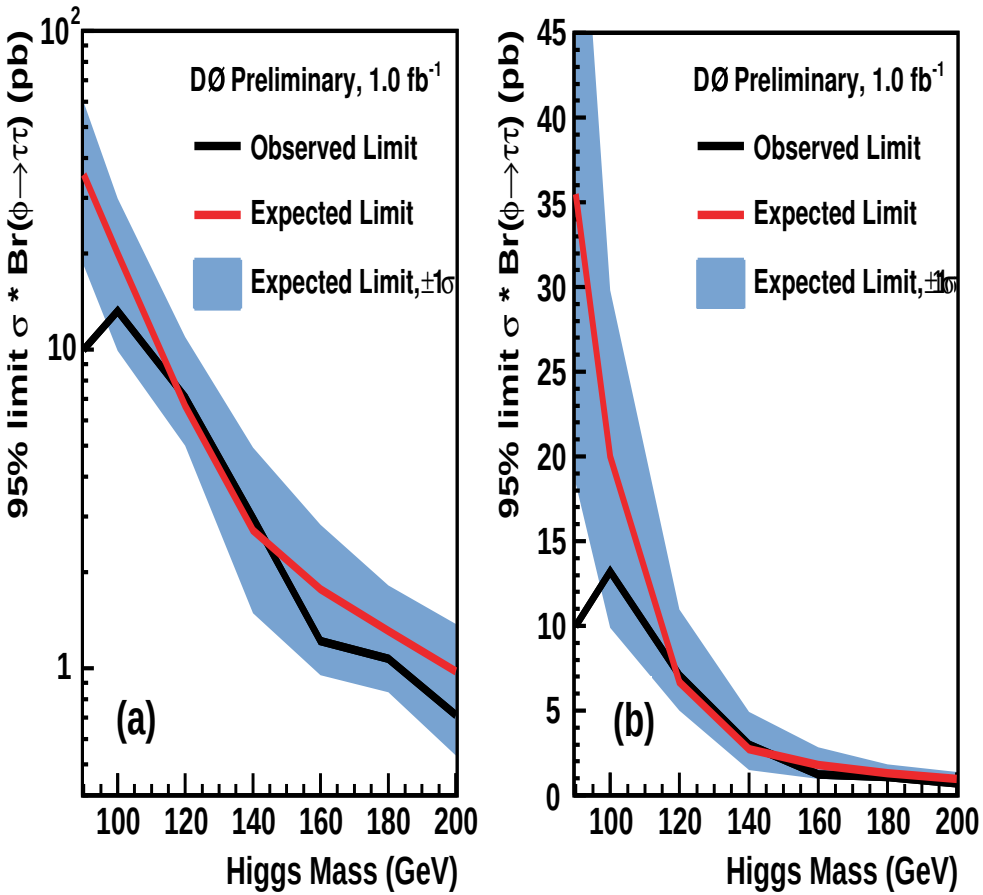


[CDF '07]

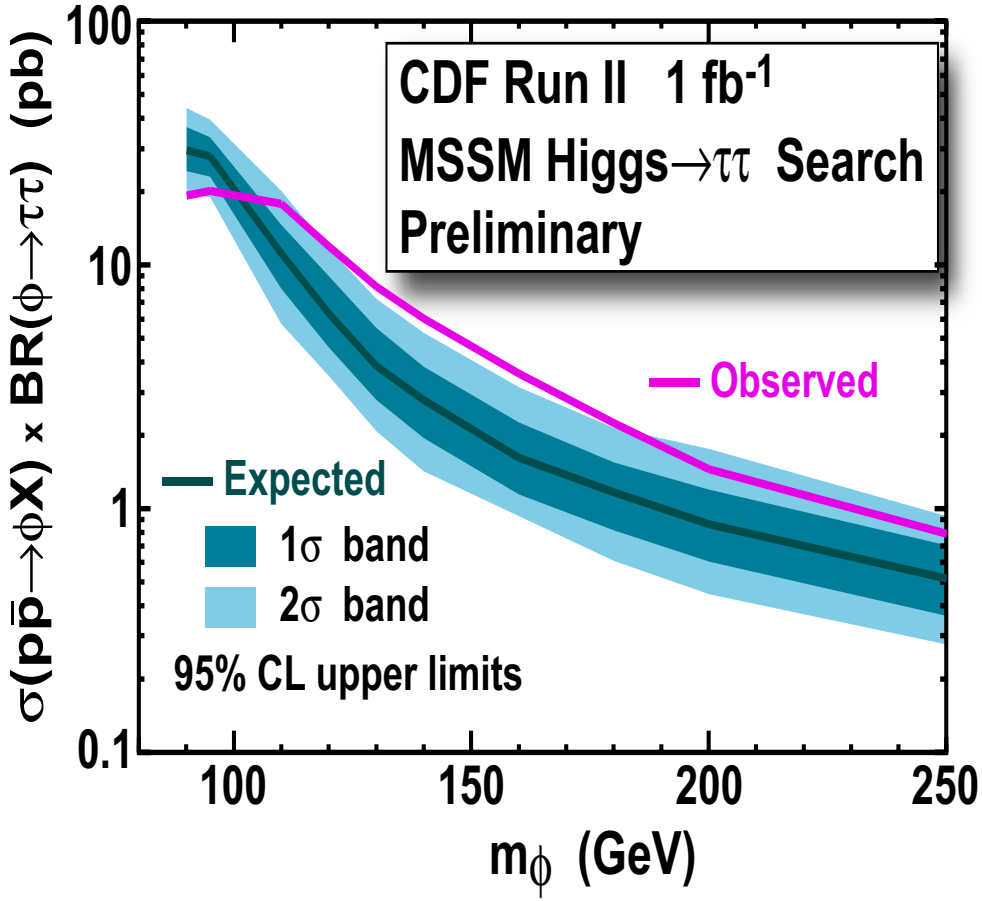
⇒ Bounds on the MSSM parameter space for low M_A, high $\tan\beta$:

CDF excess? D0 missing events?

Existing Tevatron analyses: $H/A \to \tau\tau$ (1 fb^{-1}):



[D0 '07]

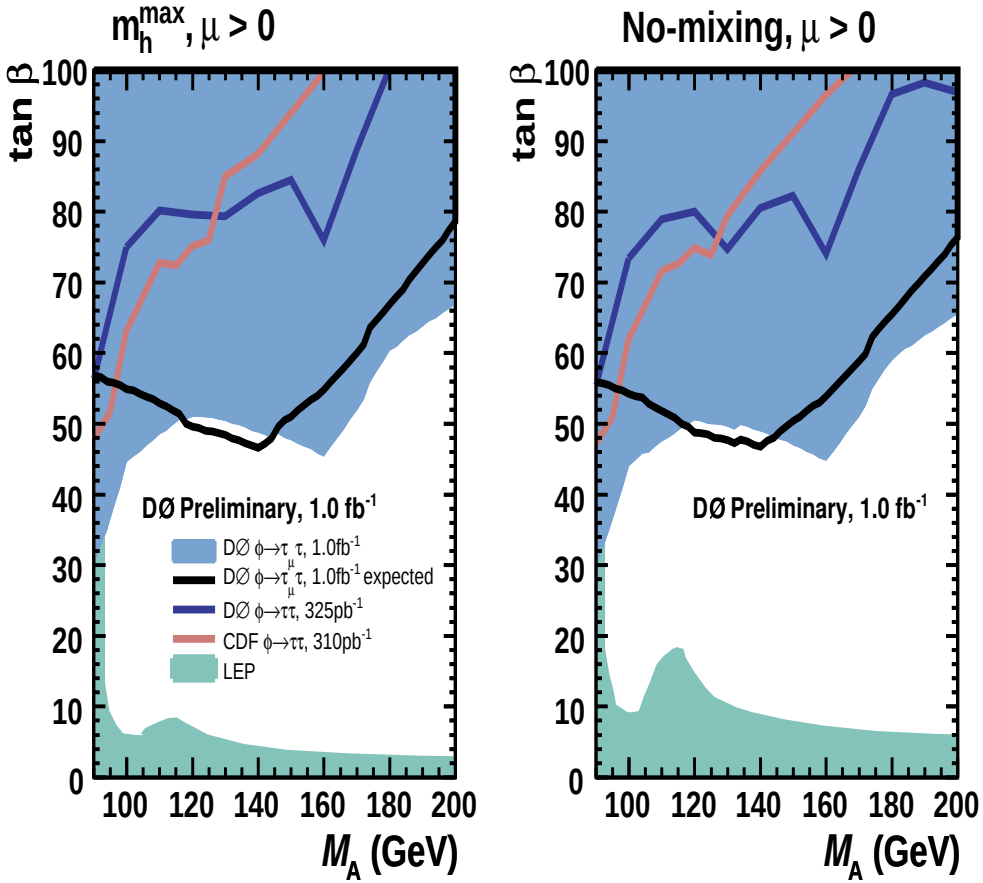


[CDF '07]

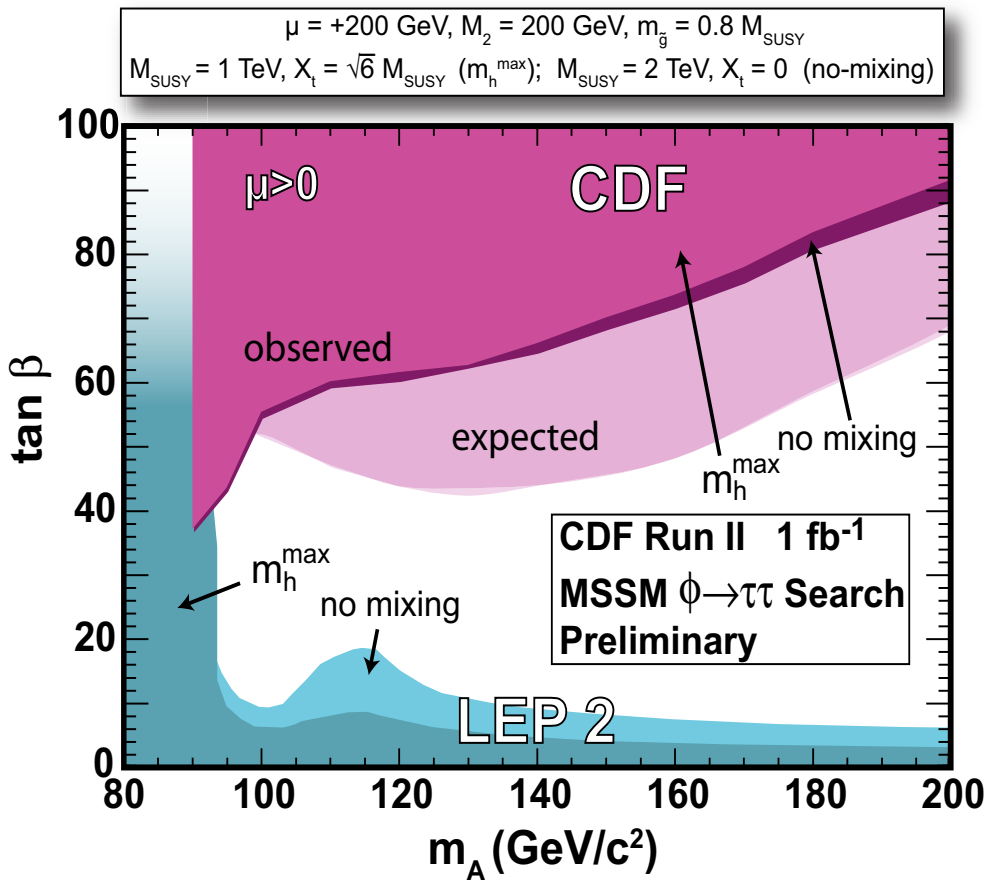
⇒ Bounds on the MSSM parameter space for low M_A, high $\tan\beta$:

CDF excess? D0 missing events?

Existing Tevatron analyses: $H/A \to \tau\tau$ (1 fb^{-1}):



[D0 '07]



[CDF '07]

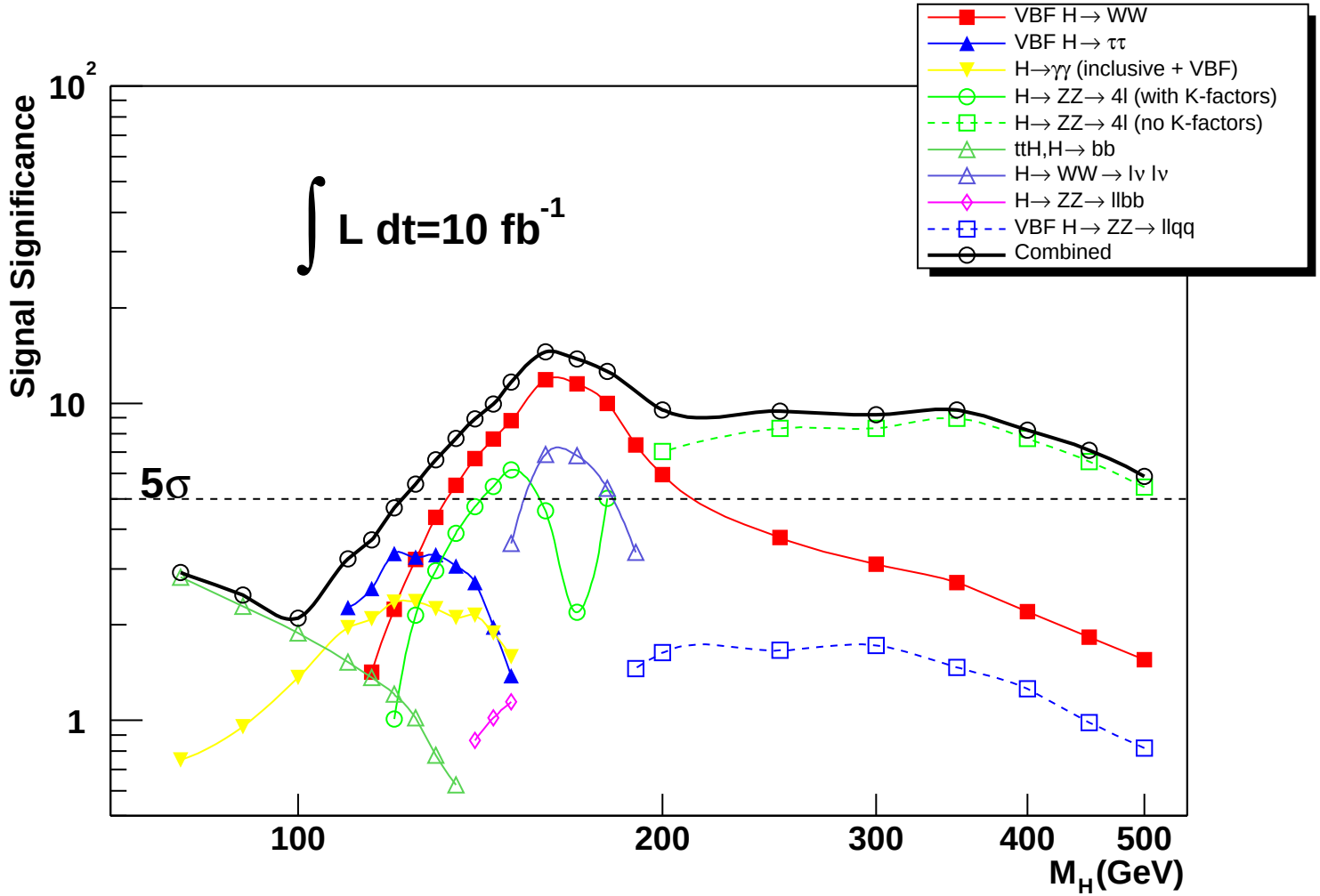
⇒ Bounds on the MSSM parameter space for low M_A, high $\tan\beta$:

CDF excess? D0 missing events?

6. MSSM Higgs boson search at the LHC

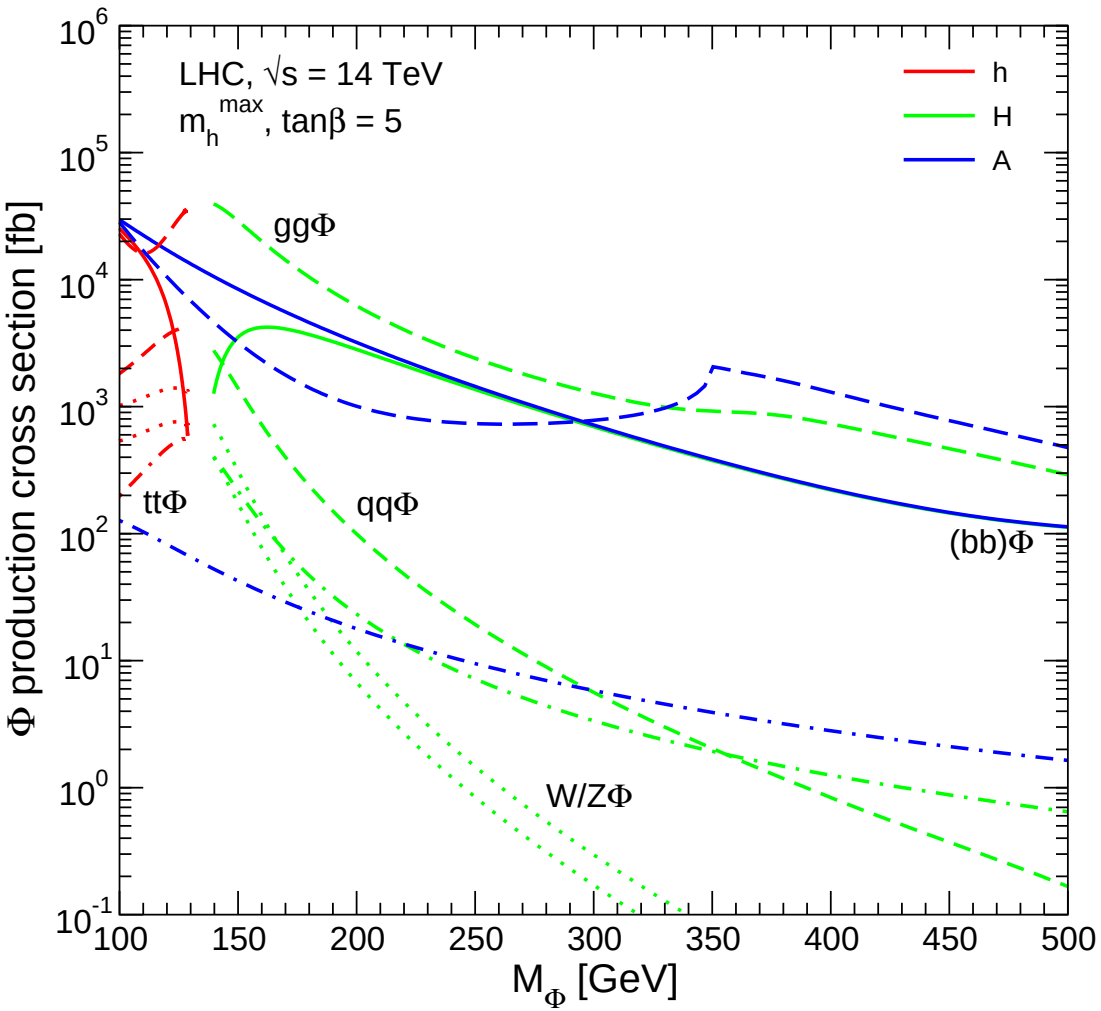
SM Higgs search at the LHC: ⇒ full parameter space accessible

[*ATLAS '05*]



Situation is a bit more complicated for SUSY Higgses ($\phi = h, H, A$)

[*T. Hahn, S.H., F. Maltoni, G. Weiglein, S. Willenbrock '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: $b\bar{b}\phi$

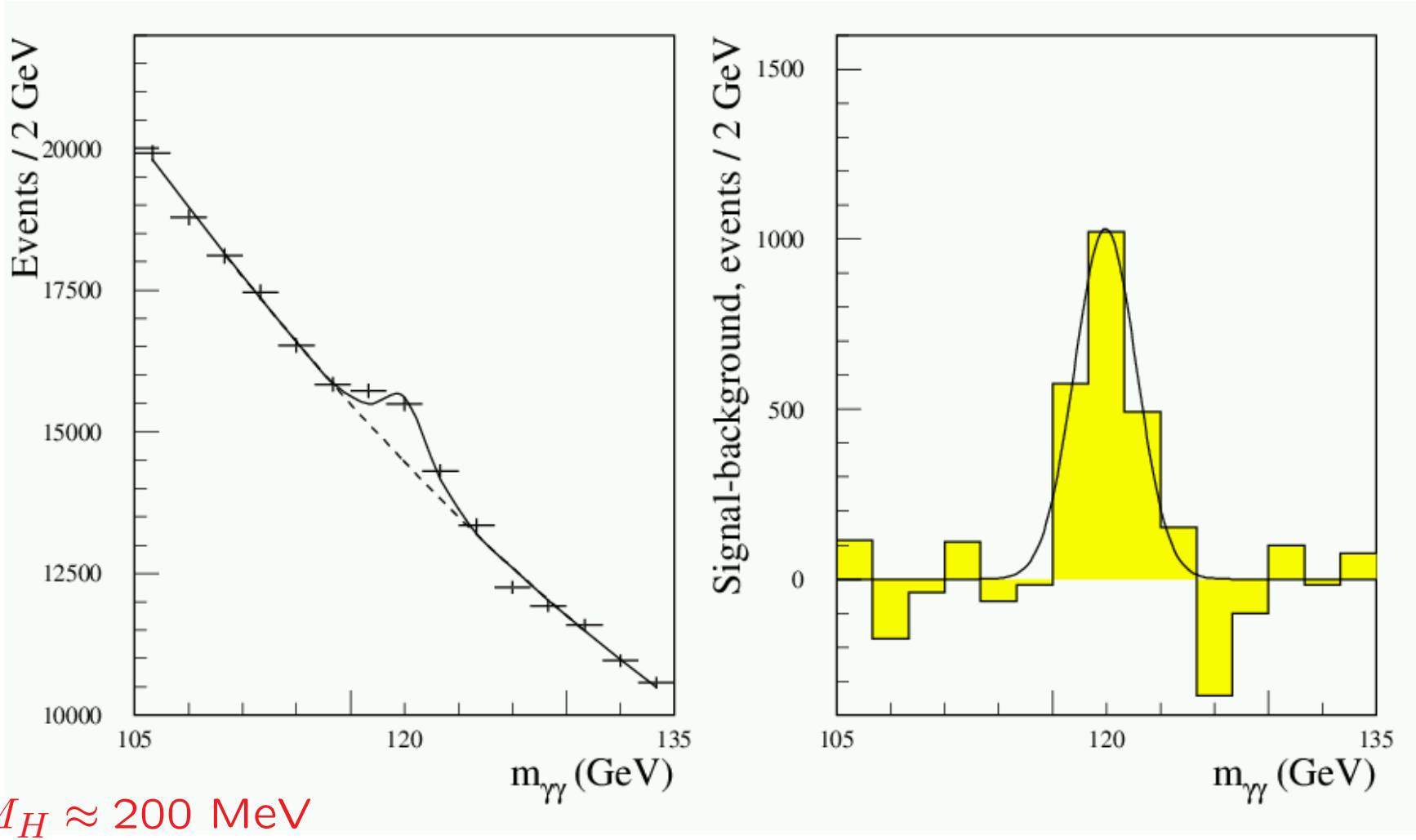
Search for the lightest MSSM Higgs at the LHC:

$\Rightarrow$ full parameter accessible But there might be problems . . .

Step 2: Measurement of the mass

Best channel for mass measurement in the SM: $H \to \gamma\gamma$

[*ATLAS '99*]



$\Rightarrow \delta M_H \approx 200$ MeV

Possible problem in SUSY:

$$gg \to h \to \gamma\gamma$$

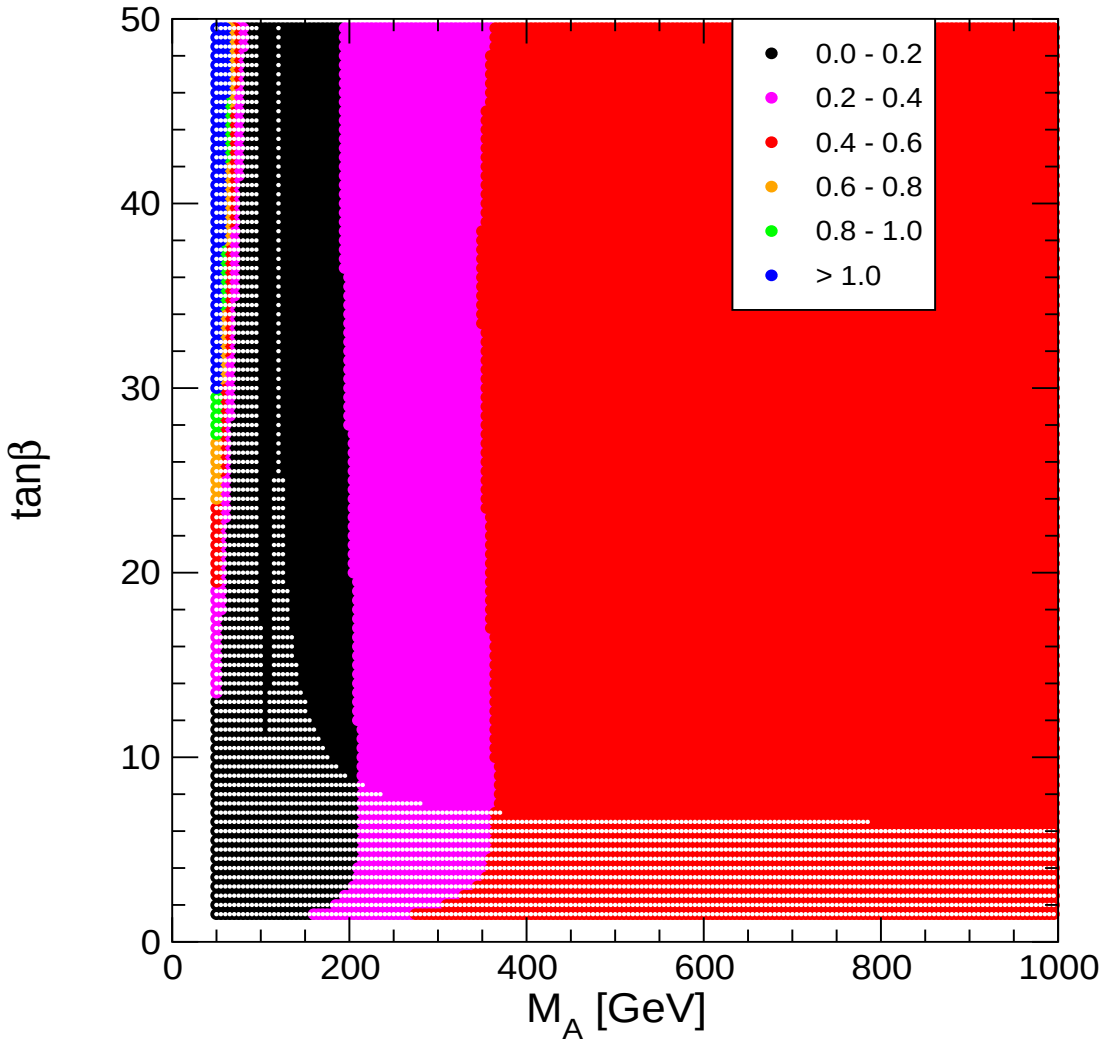
can be strongly suppressed

$\longrightarrow$ "gluophobic Higgs scenario"

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

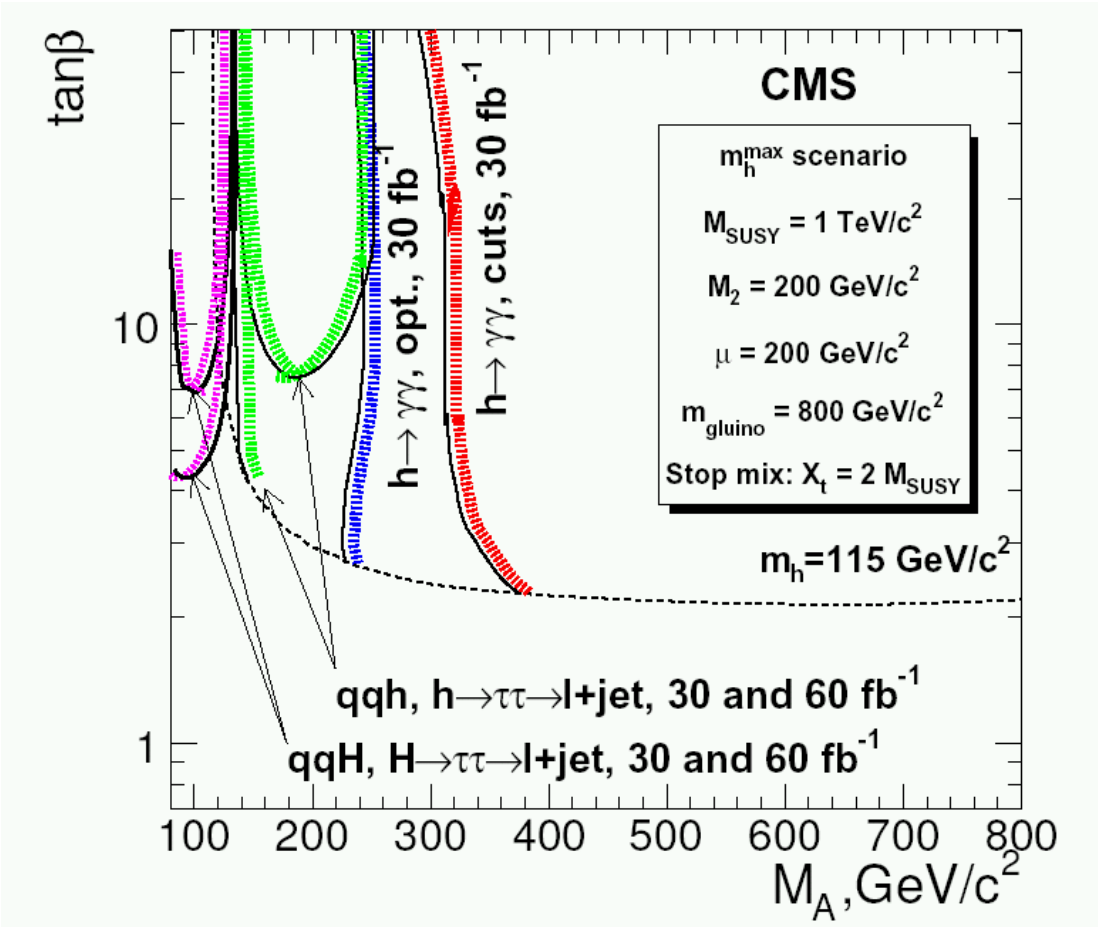
$\Rightarrow$ Strong suppression of $gg \to h \to \gamma\gamma$ possible over the whole parameter space

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



And even in the "nice" $m_h^{\max}$ scenario there might be problems:

[*CMS '06*]



Measurement possible only for $M_A \gtrsim 250$ GeV

$\Rightarrow \delta M_h \approx 200$ MeV

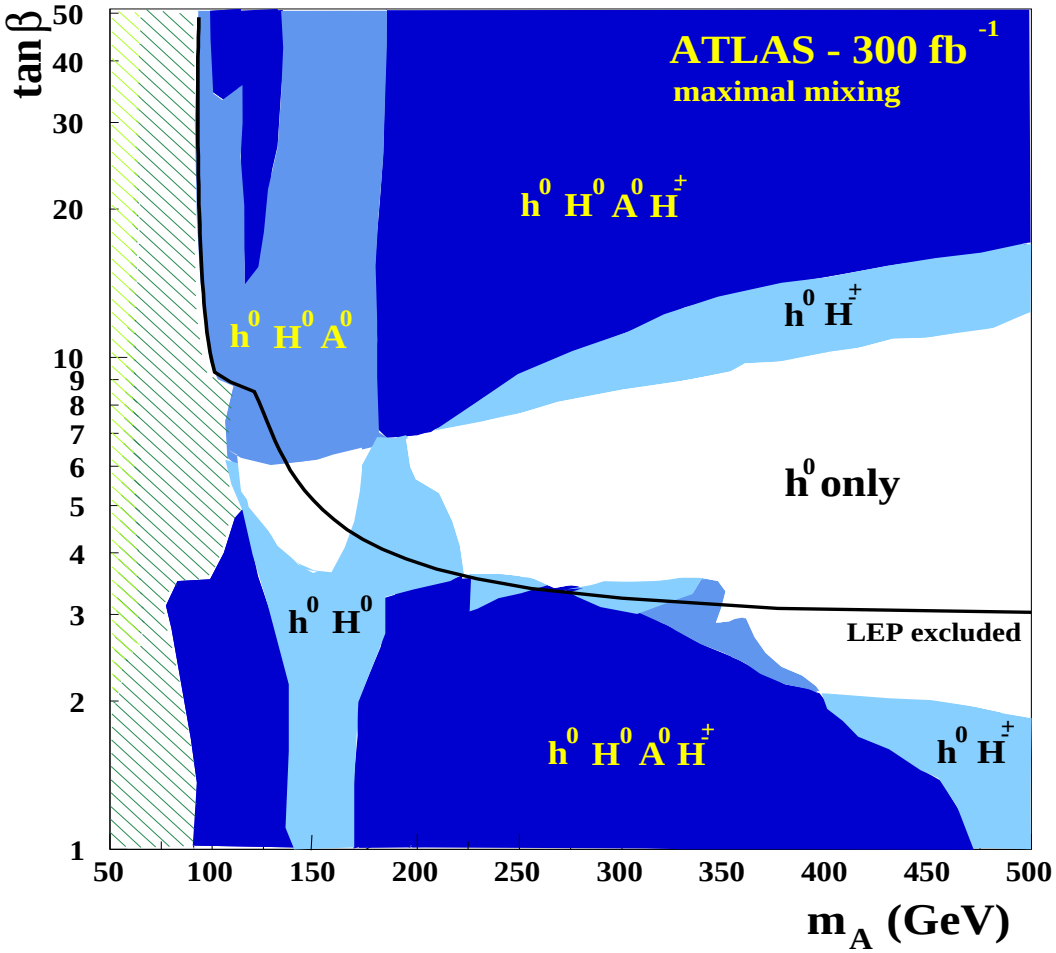
other channels:

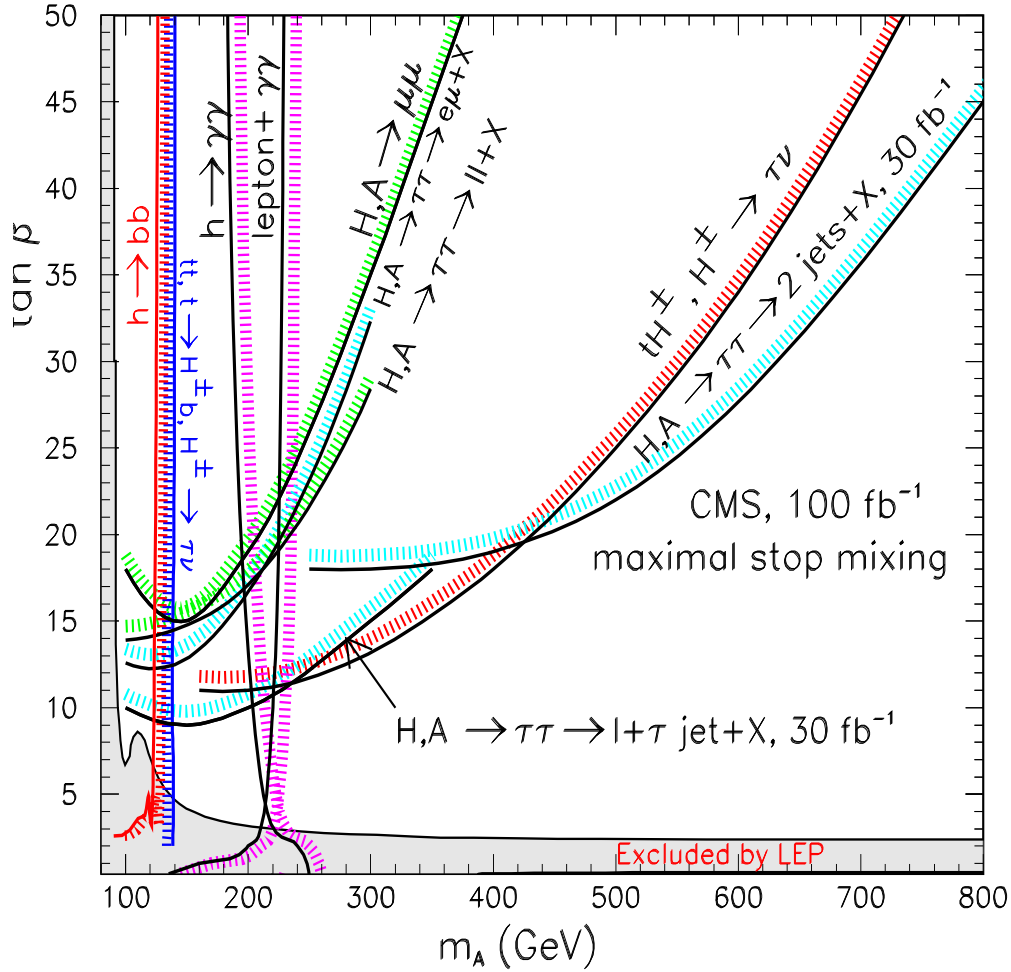
$h \to ZZ^* \to 4\mu$ ($M_h \gtrsim 130$ GeV)

otherwise: $\delta M_h \gtrsim 1 - 2$ GeV

"Heavy" MSSM Higgs searches:

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"

Most powerful search modes for heavy MSSM Higgs bosons:

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

Enhancement factors compared to the SM case:

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

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

$\Rightarrow$ Δ_b effects so far neglected by ATLAS/CMS

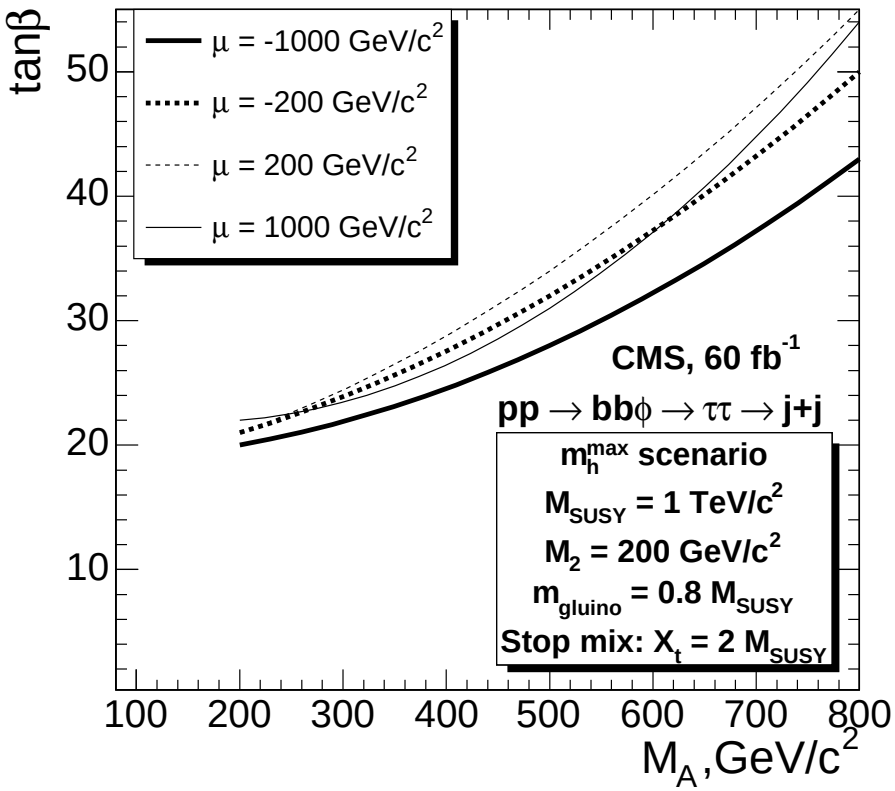
also relevant for $\mathrm{BR}(H/A \to \tau^+\tau^-)$, $\mathrm{BR}(H^\pm \to \tau\nu_\tau)$

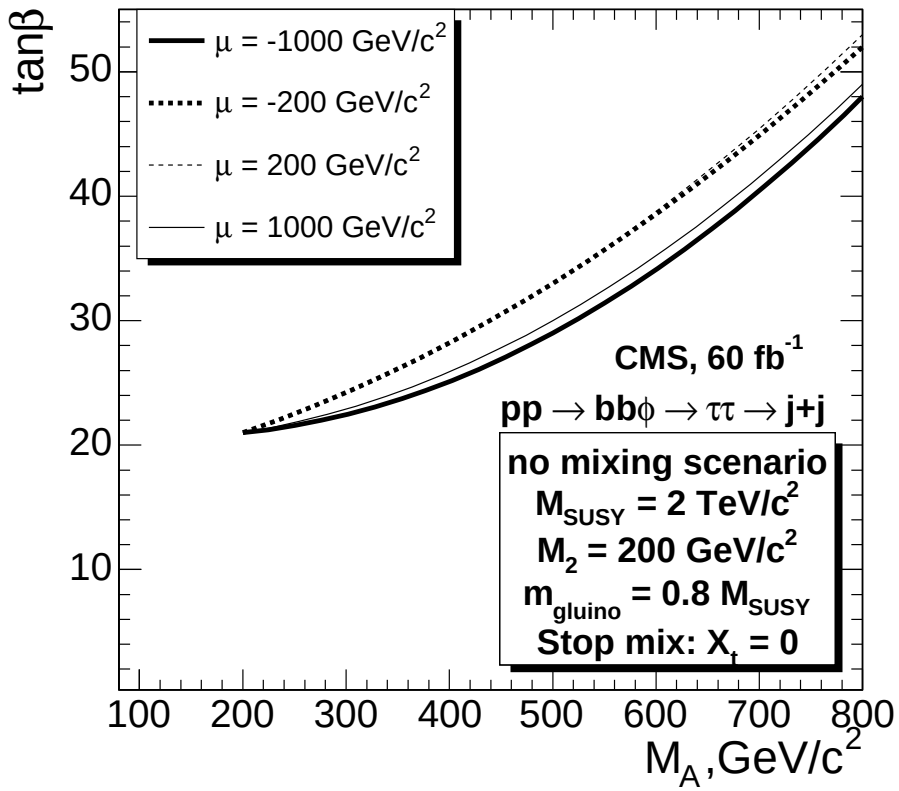
also relevant: correct evaluation of $\Gamma(H/A/H^\pm \to \mathrm{SUSY})$

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

Dependence of LHC wedge from $b\bar{b} \to H/A \to \tau^+\tau^- \to 2\,\text{jets}$ on μ:

[*S.H., A. Nikitenko, G. Weiglein et al. '06*]





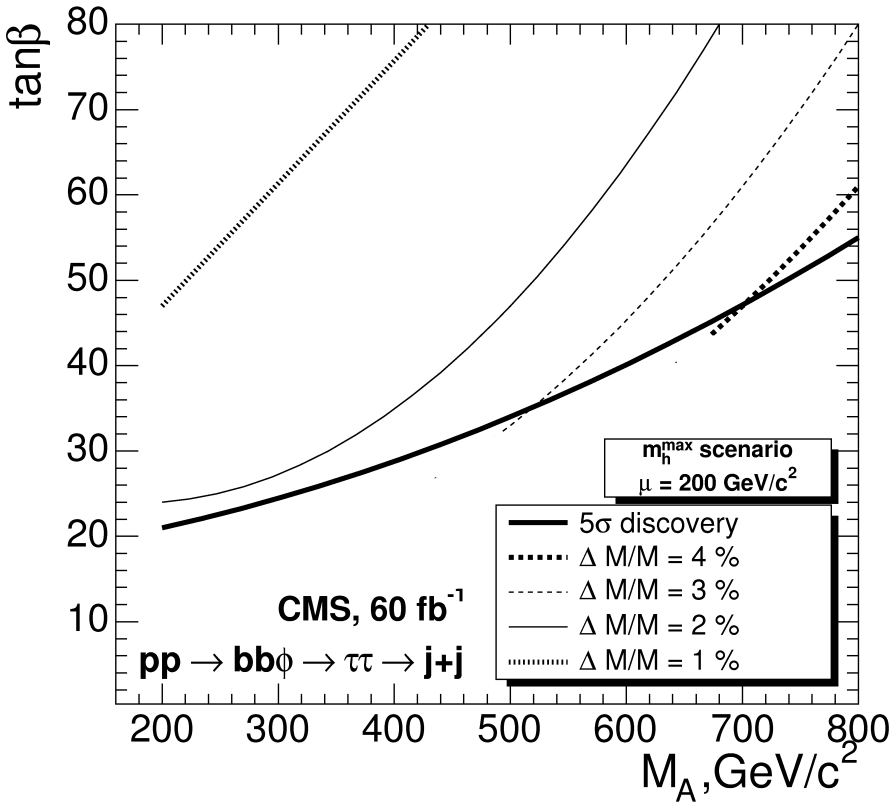
⇒ now based on full CMS simulation

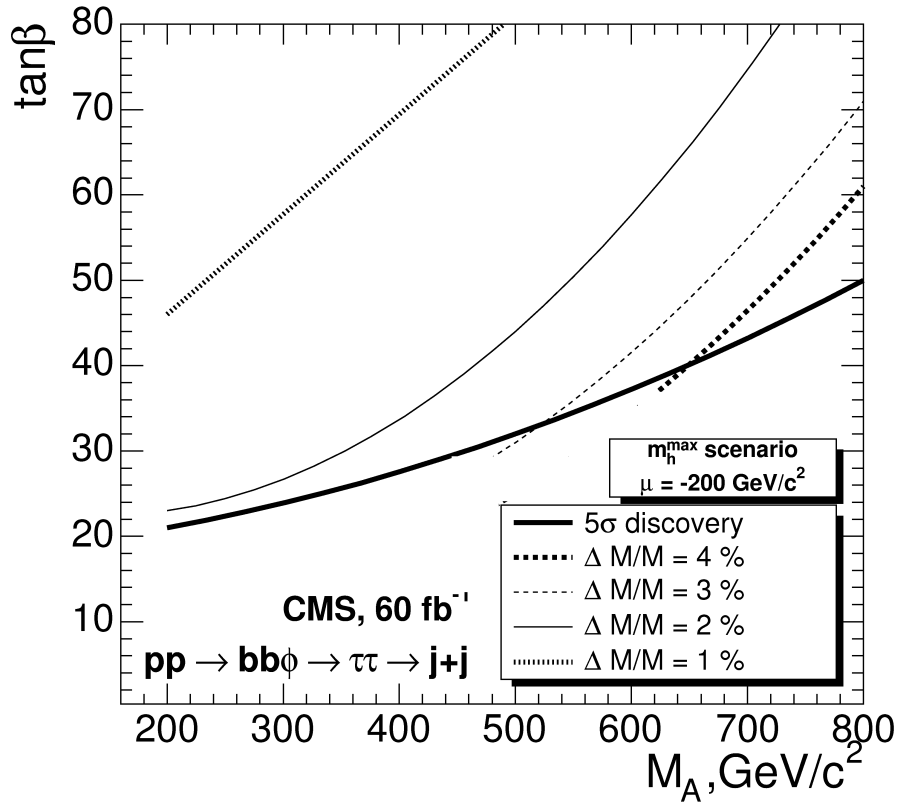
⇒ non-negligible variation with the sign and absolute value of μ

(→ numerical compensations in production and decay)

Precision of $\delta M/M$ from $b\bar{b} \to H/A \to \tau^+\tau^- \to 2\,\text{jets}$:

[*S.H., A. Nikitenko, G. Weiglein et al. '06*]





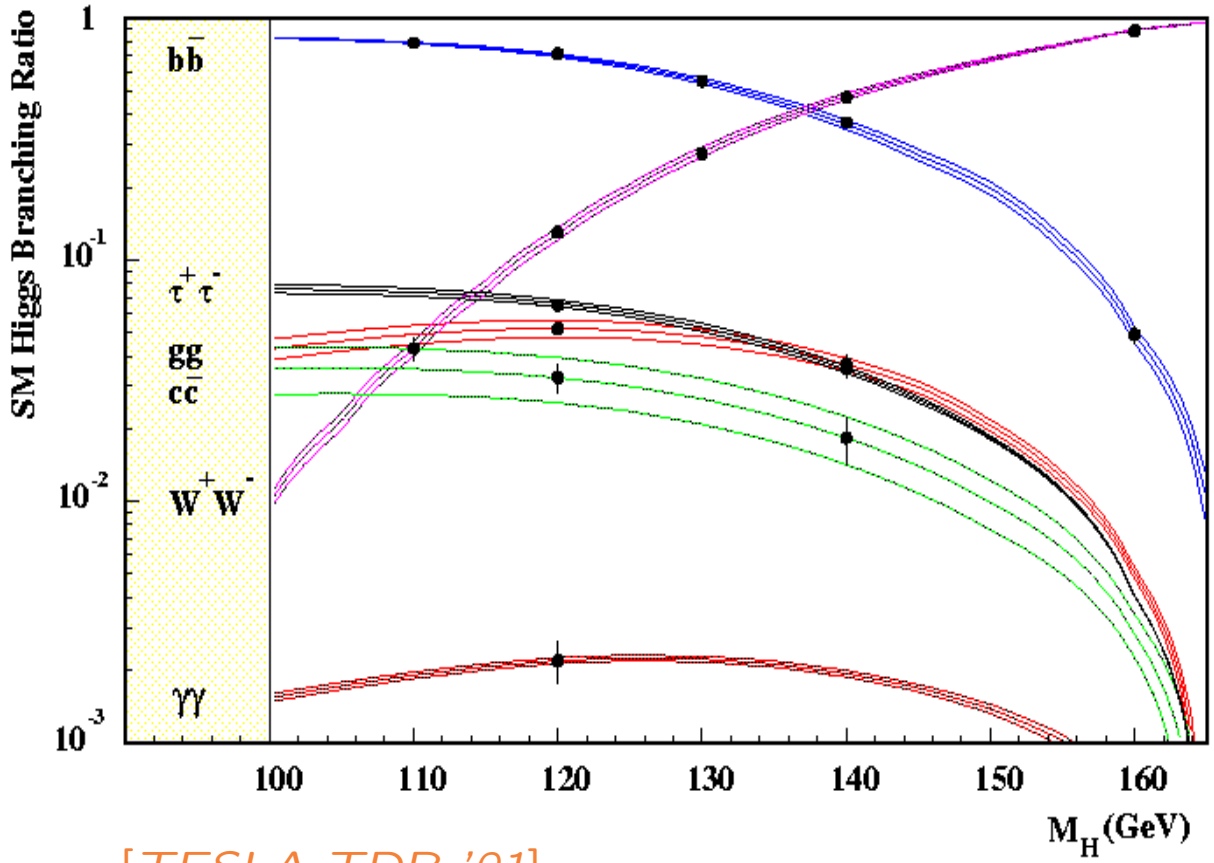
⇒ now based on full CMS simulation

⇒ high precision measurement of heavy Higgs boson masses possible

7. MSSM Higgs boson precision physics at the ILC

SM Higgs @ ILC:
Precise measurement of:

1. Higgs boson mass, $\delta M_H \approx 50$ MeV
2. Higgs boson width (direct/indirect)
3. Higgs boson couplings, $\mathcal{O}$ (few%) $\Rightarrow$
4. Higgs boson quantum numbers: spin, . . .



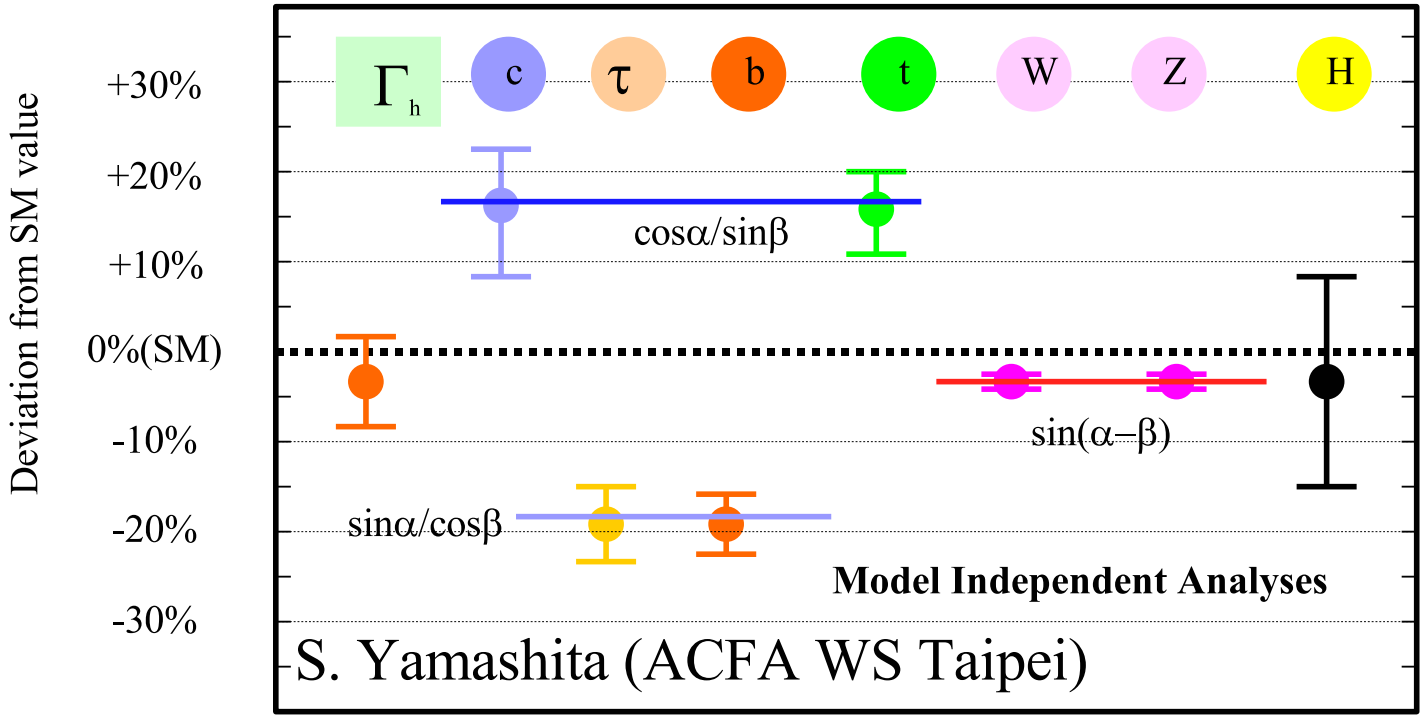
[*TESLA TDR '01*]

But do we need the ILC precision?

YES! To discriminate between the SM and extensions

Example I: Higgs couplings in the MSSM:

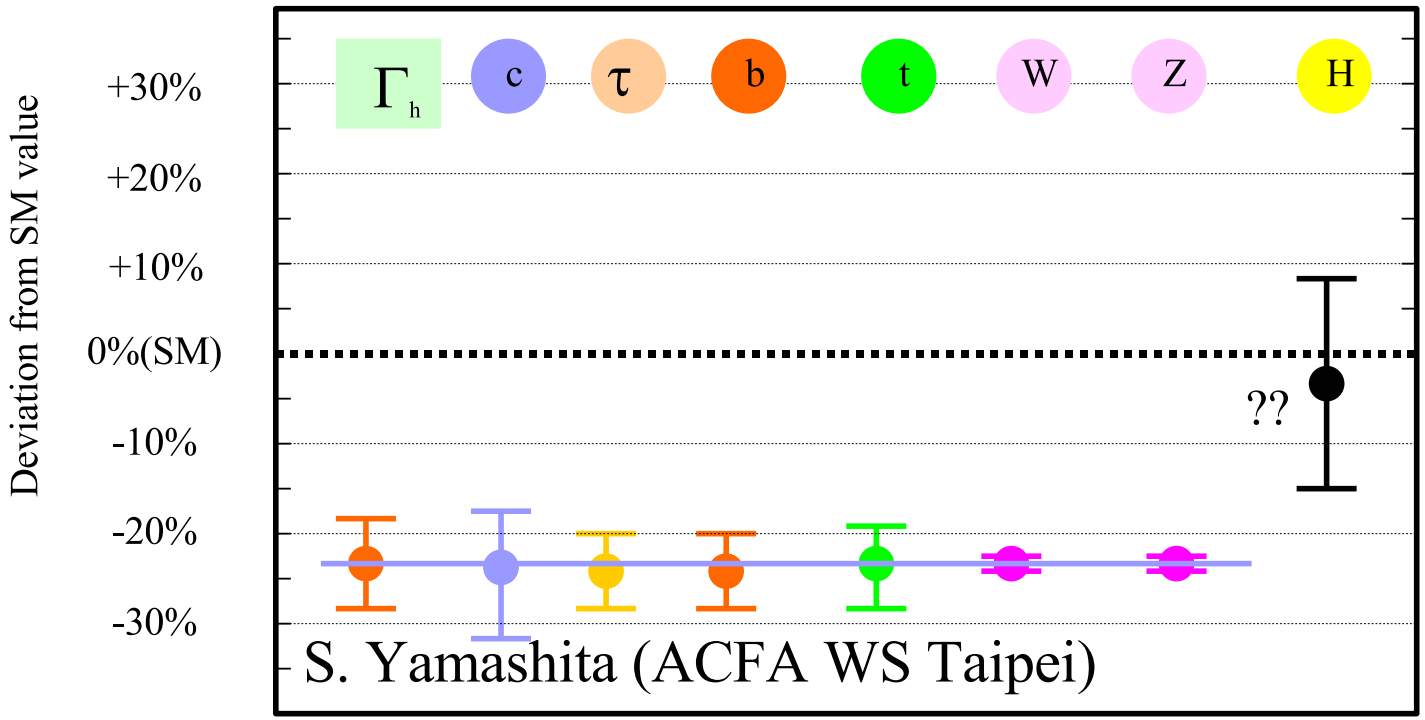
"Normal" MSSM scenario:



⇒ measurable deviations over large parts of the parameter space

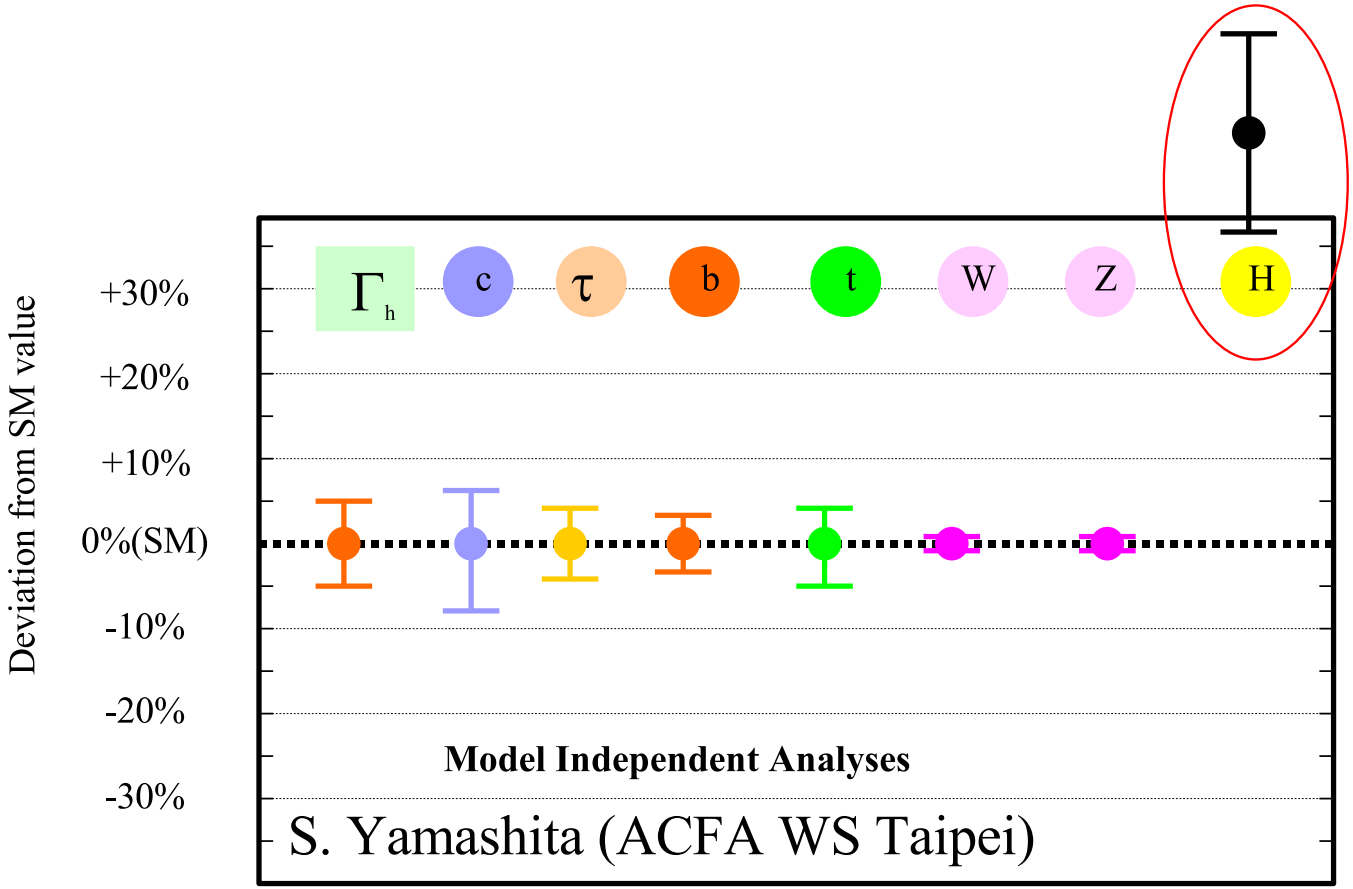
Example II: Higgs couplings in model with extra dimensions:

Effects of Kaluza Klein towers:



⇒ measurable deviations over large parts of the parameter space

Example III: Higgs couplings in a baryogenesis motivated SM extension:



⇒ Only Higgs self coupling deviates, measurement possible!

Tricky scenario:

The LHC finds only a SM-like Higgs and nothing else

Q: Do we still need the ILC?

Tricky scenario:

The LHC finds only a SM-like Higgs and nothing else

Q: Do we still need the ILC?

A: Of course!

Tricky scenario:

The LHC finds only a SM-like Higgs and nothing else

Q: Do we still need the ILC?

A: Of course! Or better: even more!

The ILC provides:

– precise Higgs coupling measurements

– precision observable measurements with the GigaZ option

⇒ Only the ILC can find deviations from the SM predictions via the various precision measurements

⇒ Only the ILC can point towards extensions of the SM

Outlook

- The quest for electroweak symmetry breaking continues!
- Low-energy Supersymmetry continues to be our best bet for physics beyond the Standard Model
- Data rules:

  We need experimental information from Tevatron, LHC, ILC, ν experiments, dark matter searches, low-energy experiments, ... to verify / falsify our ideas about electroweak symmetry breaking, the Higgs, extensions of the SM, ...
- The experiments in the next years will bring a decisive test of our ideas about the Higgs and electroweak symmetry breaking

$\Rightarrow$ Very exciting prospects for the coming years

Expect the unexpected!

Interested in Theory Predictions?

Interested in

- theory predictions for the Tevatron?
- theory predictions for the LHC?
- theory predictions for the ILC?
- phenomenology analyses in Higgs/SUSY?

⇒ You can do your PhD at IFCA (Santander, Spain)

contact: Sven.Heinemeyer @ cern.ch

Santander, Spain: (15 minutes by foot from the institute :-)

contact: Sven.Heinemeyer @ cern.ch