SUSY: From the Basics to Phenomenology

Sven Heinemeyer, IFCA (CSIC, Santander)

Dubna, 07/2009

1. SUSY Lagrangian and algebra

2. The MSSM and simplified versions

3. The Higgs sector of the MSSM

4. SUSY at the LHC and the ILC

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SUSY lectures (III):
The Higgs sector of the MSSM

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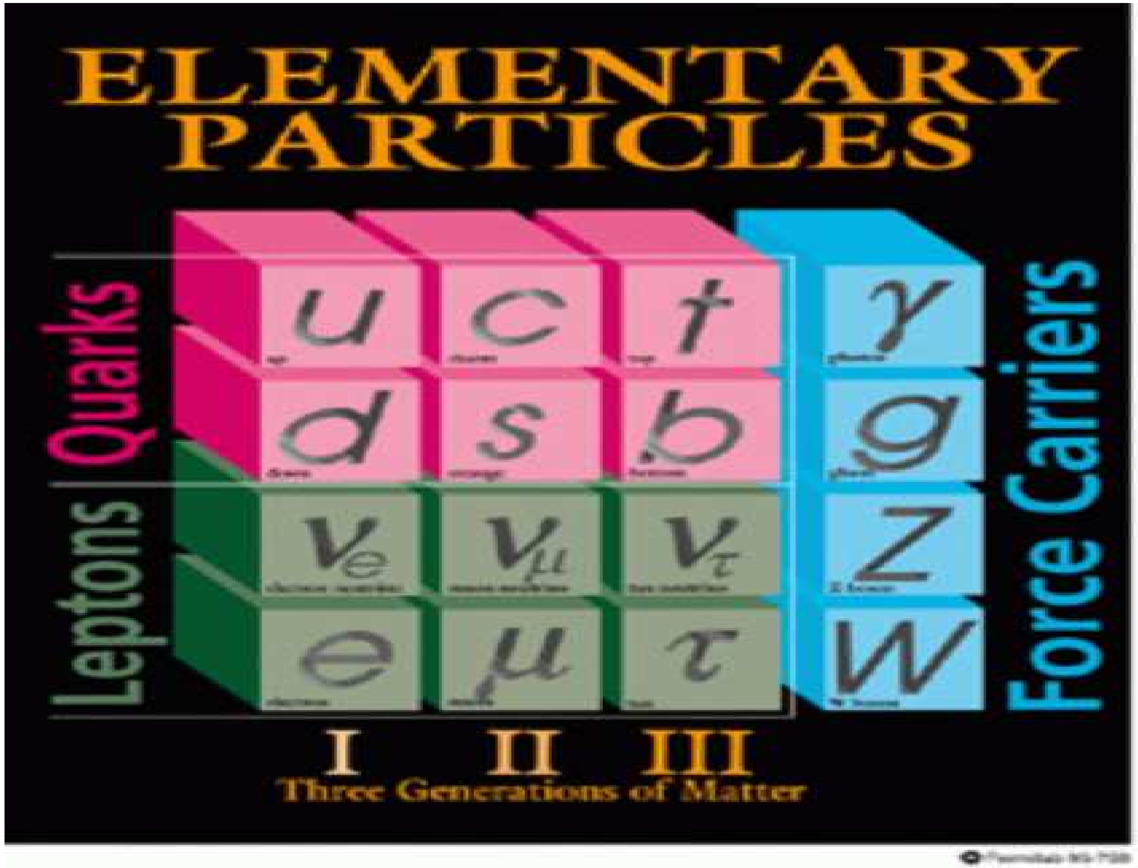
1. The Higgs sector of the SM
2. MSSM Higgs theory
3. The lightest MSSM Higgs boson
4. The heavy MSSM Higgs bosons

1. The SM and the Higgs boson

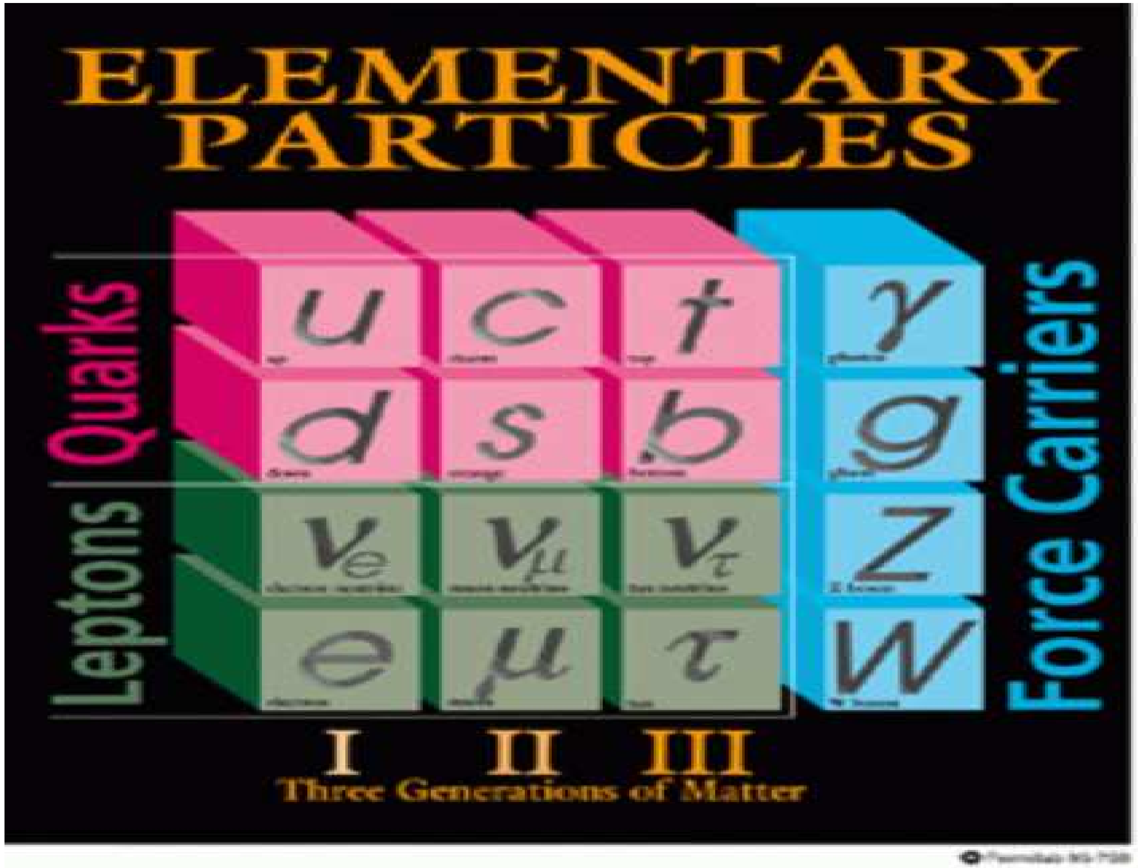
Current status of knowledge: the Standard Model (SM)



$\Rightarrow$ all particles experimentally seen

1. The SM and the Higgs boson

Current status of knowledge: the Standard Model (SM)



⇒ all particles experimentally seen

⇒ but one particle is missing . . .

Problem:

Gauge fields Z, W^+, W^- are massive

explicite mass terms in the Lagrangian $\Leftrightarrow$ breaking of gauge invariance

Solution: Higgs mechanism

scalar field postulated, mass terms from coupling to Higgs field

Higgs sector in the Standard Model:

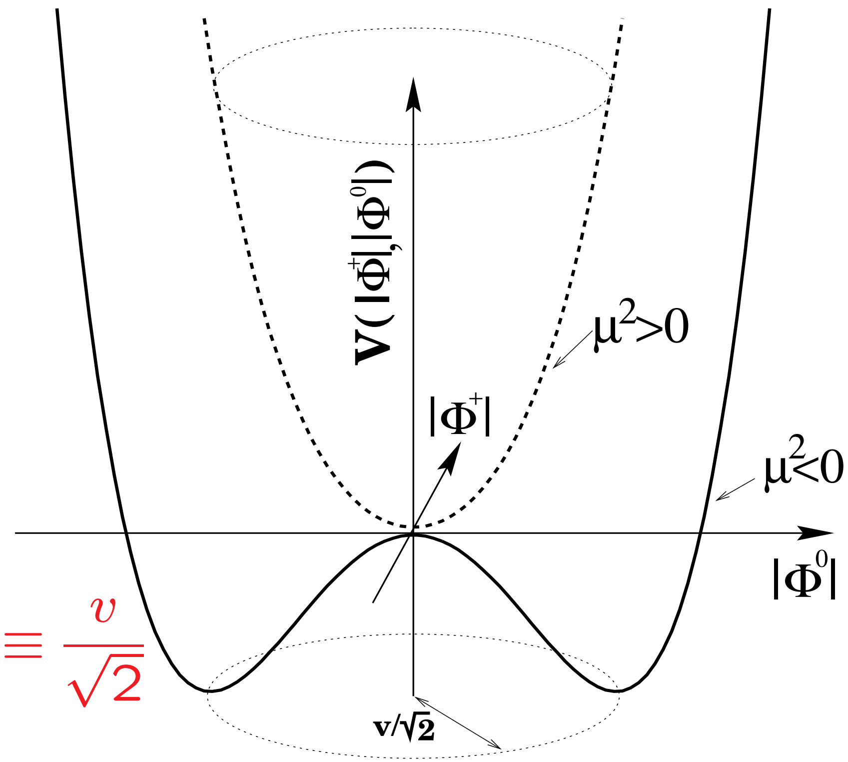
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential:

$$V(\phi) = \mu^2 \left|\Phi^\dagger \Phi\right| + \lambda \left|\Phi^\dagger \Phi\right|^2, \quad \lambda > 0$$

$\mu^2 < 0$: Spontaneous symmetry breaking

minimum of potential at $|\langle \Phi_0 \rangle| = \sqrt{\frac{-\mu^2}{2\,\lambda}} \equiv \frac{v}{\sqrt{2}}$



$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad \text{(unitary gauge)}$$

H: elementary scalar field, Higgs boson

Lagrange density:

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = \quad & (D_\mu \Phi)^\dagger (D^\mu \Phi) \\ & - g_d \bar{Q}_L \Phi d_R \; - \; g_u \bar{Q}_L \Phi_c u_R \\ & - V(\Phi) \end{aligned}$$

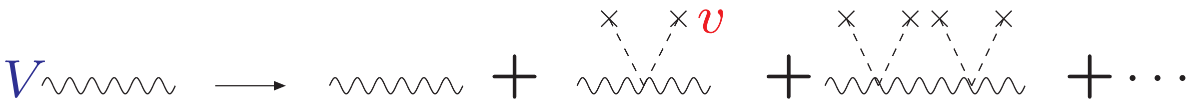
with

$$\begin{aligned} iD_\mu &= i\partial_\mu - g_2 \vec{I}\vec{W}_\mu - g_1 Y B_\mu \\ \Phi_c &= i\sigma_2 \Phi^\dagger \qquad\qquad Q_L \sim \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \; \Phi \sim \begin{pmatrix} 0 \\ v \end{pmatrix}, \; \Phi_c \sim \begin{pmatrix} v \\ 0 \end{pmatrix} \end{aligned}$$

Gauge invariant coupling to gauge fields

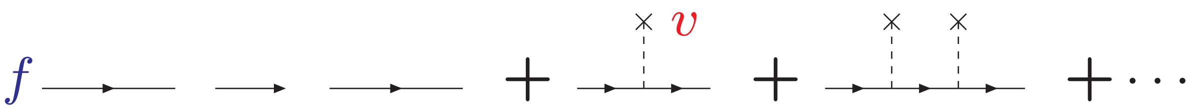
$\Rightarrow$ mass terms for gauge bosons and fermions

1.) $VV\Phi\Phi$ coupling:



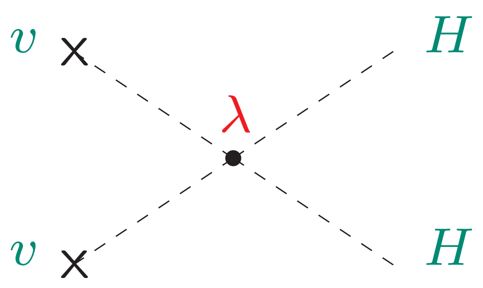
$$\frac{1}{q^2} \to \frac{1}{q^2} + \sum_j \frac{1}{q^2}\left[\left(\frac{gv}{\sqrt{2}}\right)^2 \frac{1}{q^2}\right]^j = \frac{1}{q^2 - M^2} \; : \; M^2 = g^2\frac{v^2}{2} \qquad \Rightarrow M \propto g$$

2.) fermion mass terms: Yukawa couplings:



$$\frac{1}{\not{q}} \to \frac{1}{\not{q}} + \sum_j \frac{1}{\not{q}}\left[\frac{g_f v}{\sqrt{2}}\frac{1}{\not{q}}\right]^j = \frac{1}{\not{q} - m_f} \; : \; m_f = g_f\frac{v}{\sqrt{2}} \qquad \Rightarrow m_f \propto g_f$$

3.) mass of the Higgs boson: self coupling



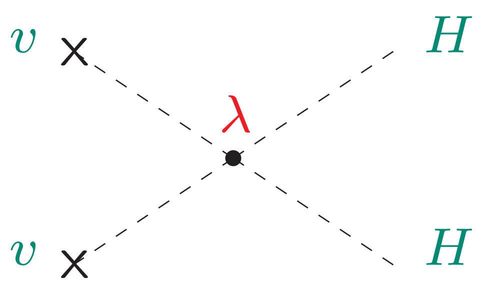
. . .

$$\lambda = M_H^2/v$$

$M_H = v\sqrt{\lambda}$ free parameter

$\rightarrow$ last unknown parameter of the SM

3.) mass of the Higgs boson: self coupling



. . .

$\lambda = M_H^2/v$

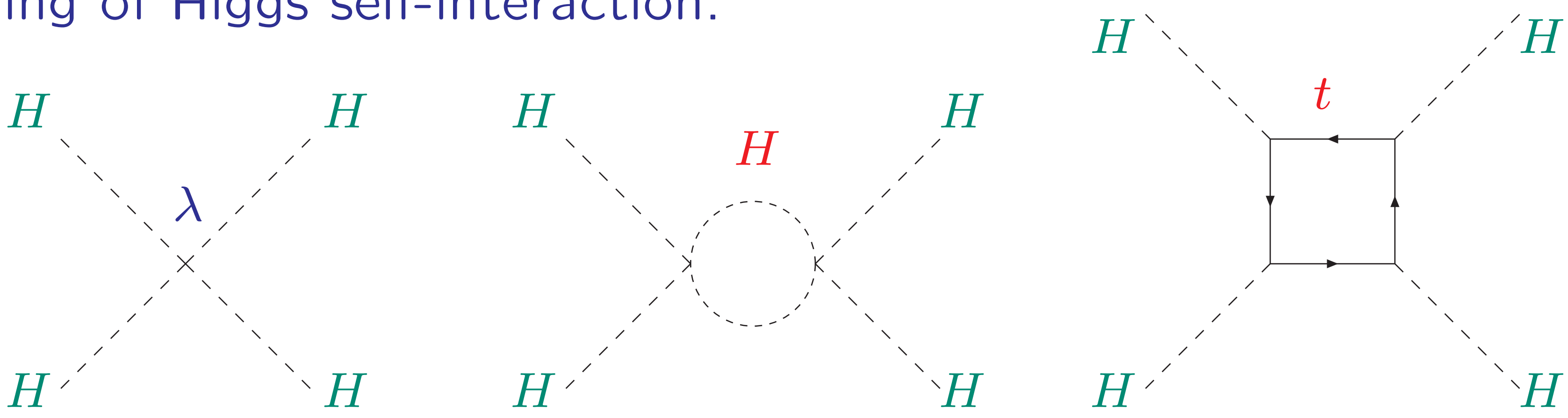
$M_H = v\sqrt{\lambda}$ free parameter

$\rightarrow$ last unknown parameter of the SM

$\Rightarrow$ establish Higgs mechanism $\equiv$ find the Higgs $\oplus$ measure its couplings

What else do we know about the SM Higgs boson?

Running of Higgs self-interaction:



Renormalization group equation:

$$\frac{d\,\lambda}{d\,t} = \frac{3}{8\,\pi^2}\left[\lambda^2 + \lambda g_t^2 - g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right] \;, \qquad t = \log\left(\frac{Q^2}{v^2}\right)$$

Two conditions:

1.) avoid Landau pole (for large $\lambda \sim M_H^2$)

2.) avoid vacuum instability (for small/negative λ)

1.) avoid Landau pole (for large $\lambda \sim M_H^2$)

$$\frac{d\,\lambda}{d\,t} = \frac{3}{8\,\pi^2}\left[\lambda^2\right]$$

$$\Rightarrow \qquad \lambda(Q^2) = \frac{\lambda(v^2)}{1 - \frac{3\lambda(v^2)}{8\,\pi^2}\log\left(\frac{Q^2}{v^2}\right)}$$

$$\lambda(\Lambda) < \infty \;\Rightarrow\; M_H^2 \leq \frac{8\,\pi^2\,v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)}$$: upper bound on M_H

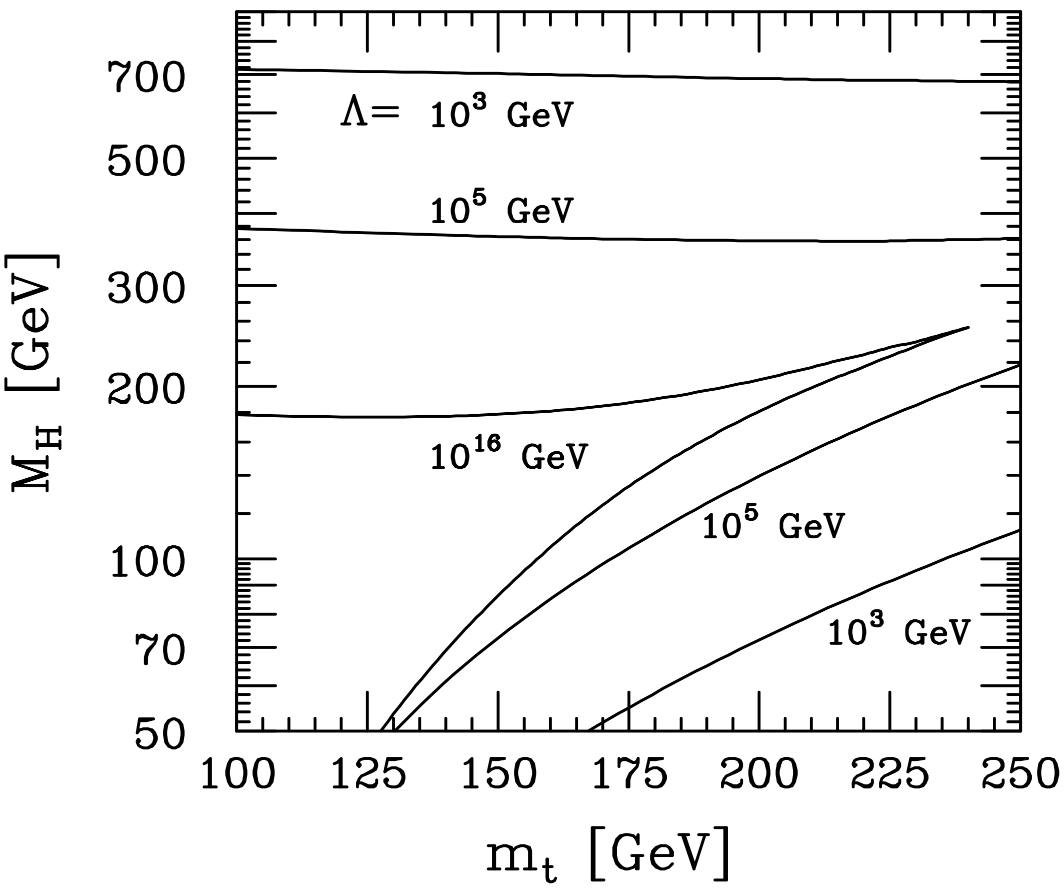
2.) avoid vacuum instability (for small/negative λ): $V(v) < V(0) \Rightarrow \lambda(\Lambda) > 0$

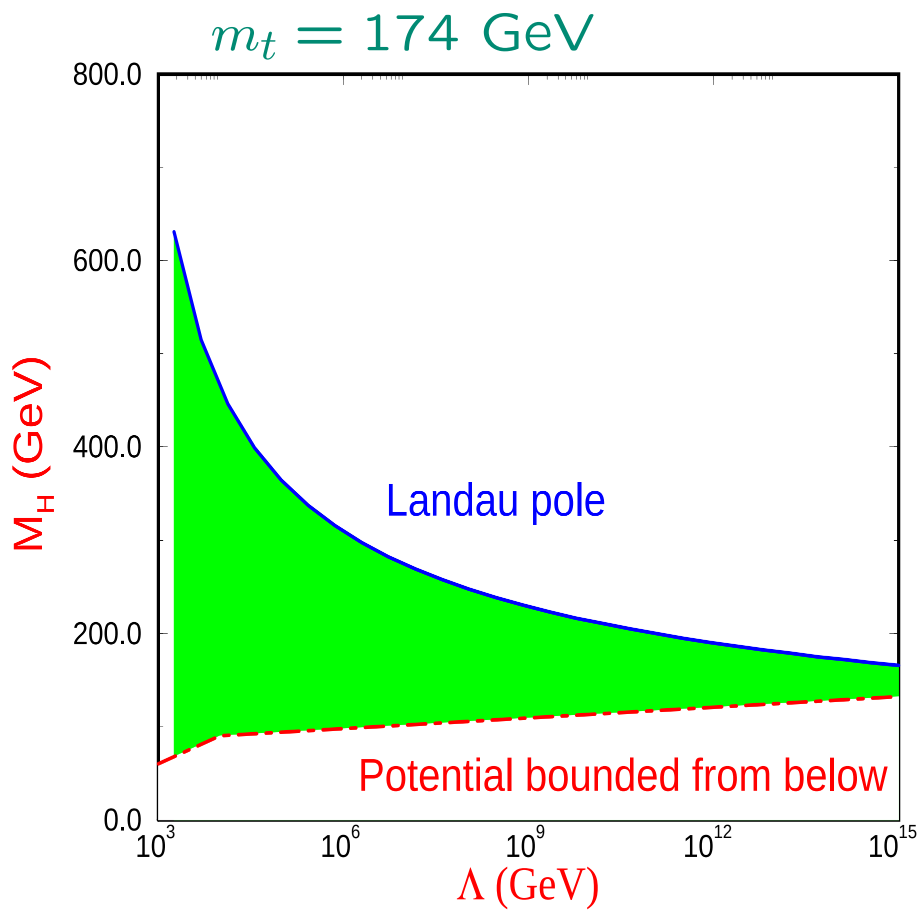
$$\frac{d\,\lambda}{d\,t} = \frac{3}{8\,\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

$$\Rightarrow \qquad \lambda(Q^2) = \lambda(v^2)\frac{3}{8\,\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]\log\left(\frac{Q^2}{v^2}\right)$$

$$\lambda(\Lambda) > 0 \;\Rightarrow\; M_H^2 > \frac{v^2}{4\,\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]\log\left(\frac{\Lambda^2}{v^2}\right)$$: lower bound

Both limits combined:





Λ: scale up to which the SM is valid

$\Lambda = M_{\text{GUT}} \Rightarrow 130\text{ GeV} \lesssim M_H \lesssim 180\text{ GeV}$

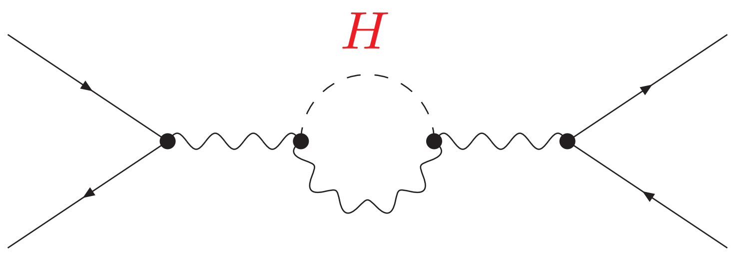
Electroweak Precision Observables (EWPO):

Comparison of electro-weak precision observables with theory:

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

$\Downarrow$

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



$\Downarrow$

SM: limits on M_H

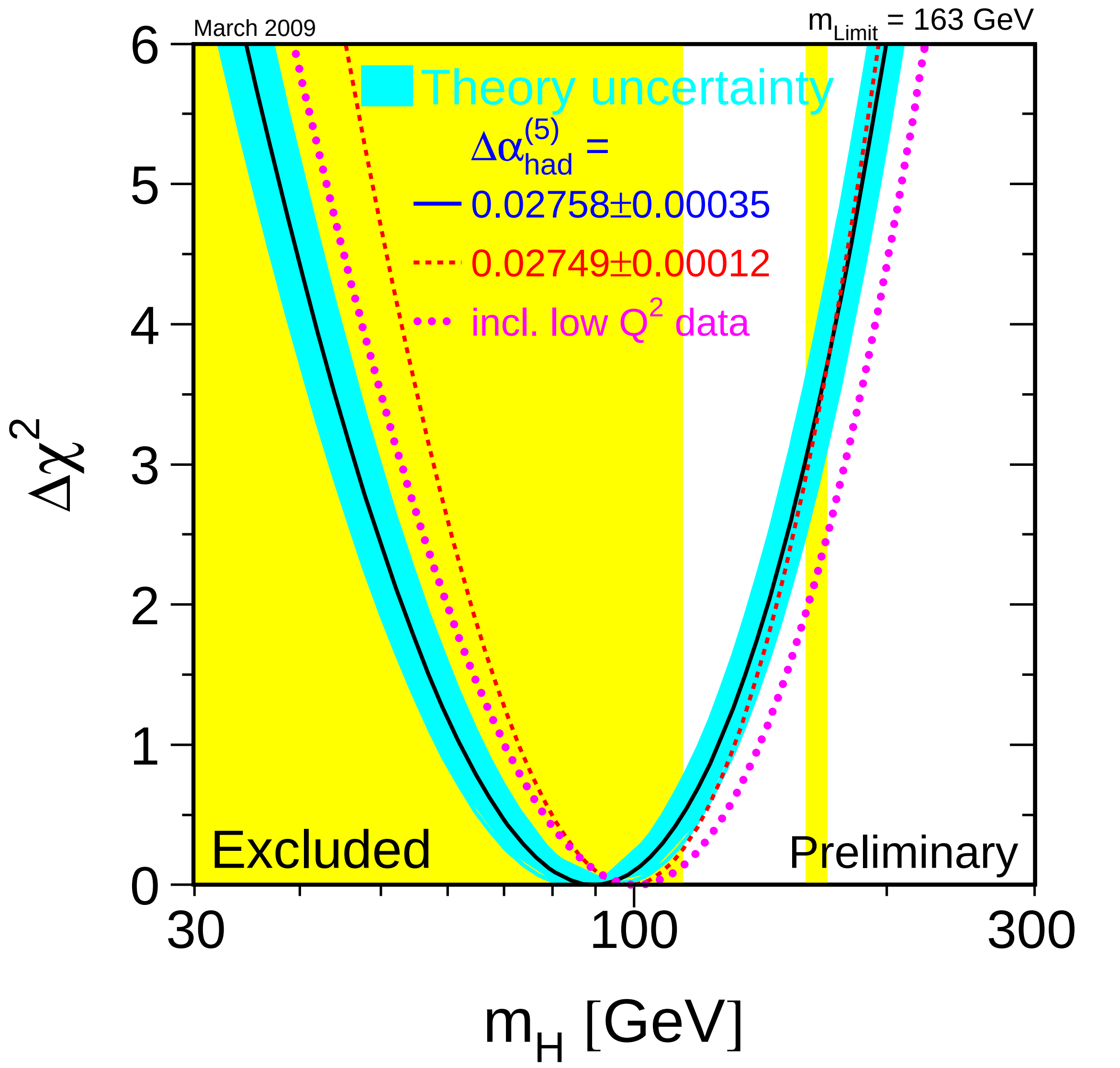
Very high accuracy of measurements and theoretical predictions needed

Global fit to all SM data:

[*LEPEWWG '09*]

$\Rightarrow M_H = 90^{+36}_{-27}$ GeV

$M_H < 163$ 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, $M_H \lesssim 160$ GeV

Properties of the SM Higgs boson

1.) Decay to fermions:

coupling:

$$g_{f\bar{f}H} = \left[\sqrt{2}\,G_\mu\right]^{1/2} m_f$$

decay width:

$$\Gamma(H \to f\bar{f}) = N_c \frac{G_\mu\, M_H}{4\sqrt{2}\,\pi} m_f^2(M_H^2) \left(1 - 4\frac{m_f^2}{M_H^2}\right)^{3/2}$$

with N_c = number of colors

Bulk of QCD corrections for decays to quarks are mapped into

$$m_q^2(\text{pole}) \to m_q^2(M_H^2)$$

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

2.) Decay to heavy gauge bosons ($V = W, Z$):

coupling:

$$g_{VVH} = 2\left[\sqrt{2}\,G_\mu\right]^{1/2} M_V^2$$

on-shell decay width ($M_H > 2M_V$):

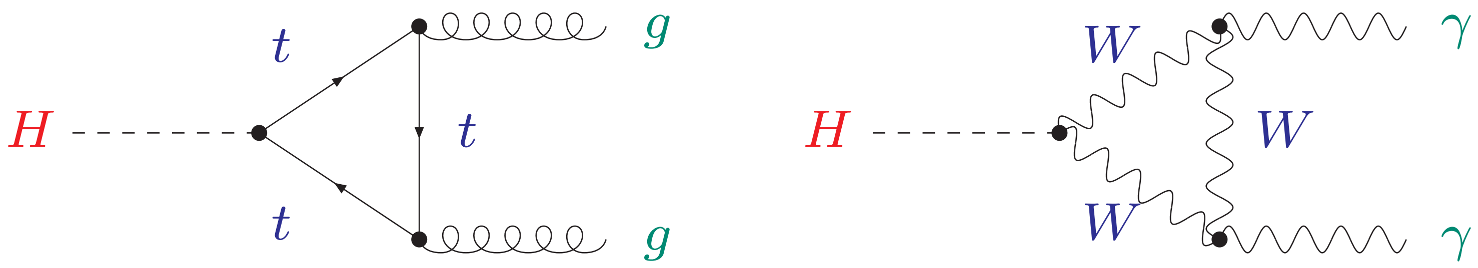
$$\Gamma(H \to VV) = \delta_V \frac{G_\mu M_H^3}{16\sqrt{2}\,\pi}\left(1 - 4\frac{M_V^2}{M_H^2} + 12\frac{M_V^4}{M_H^4}\right)\left(1 - 4\frac{M_V^2}{M_H^2}\right)^{1/2}$$

with $\delta_{W,Z} = 2, 1$

off-shell decay width ($M_H < 2M_V$):

$$\Gamma(H \to VV^*) = \delta'_V \frac{3G_\mu^2 M_H}{16\,\pi^3} M_V^4 \times \text{Integral}$$

3.) Decay to massless gauge bosons (gg, $\gamma\gamma$):



$$\Gamma(H \to gg) = \frac{G_\mu \, \alpha_s^2(M_H^2) \, M_H^3}{36\sqrt{2}\,\pi^3} \left[1 + C \frac{\alpha_s(\mu)}{\pi} \right]$$

via the top quark loop with

$$C = \frac{215}{12} - \frac{23}{6} \log\left(\frac{\mu^2}{M_H^2}\right) + \mathcal{O}(\alpha_s)$$

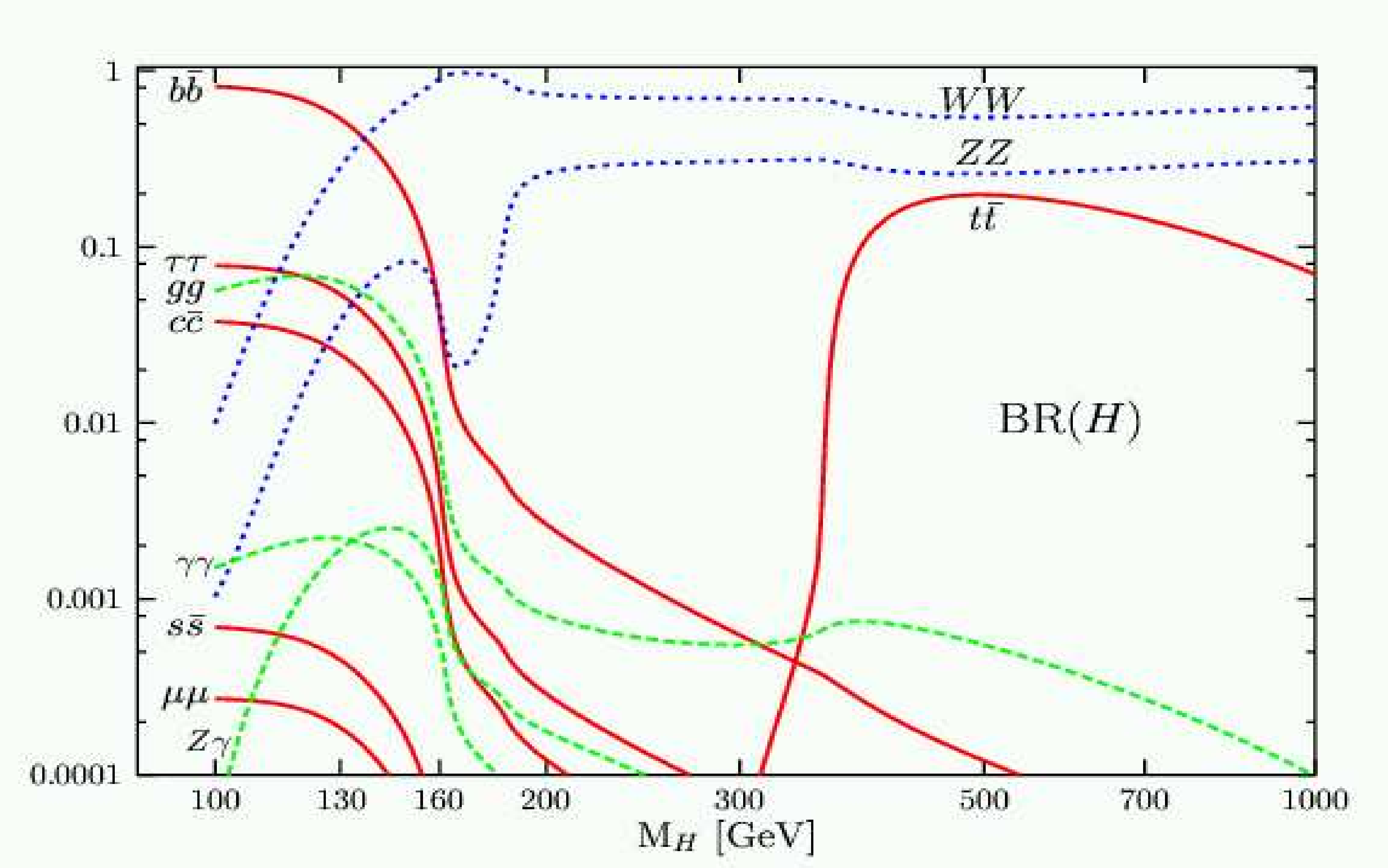
⇒ huge QCD corrections

$$\Gamma(H \to \gamma\gamma) = \frac{G_\mu \, \alpha^2 \, M_H^3}{128\sqrt{2}\,\pi^3} \left| \frac{4}{3} e_t^2 - 7 \right|^2$$

via the top quark and W boson loop

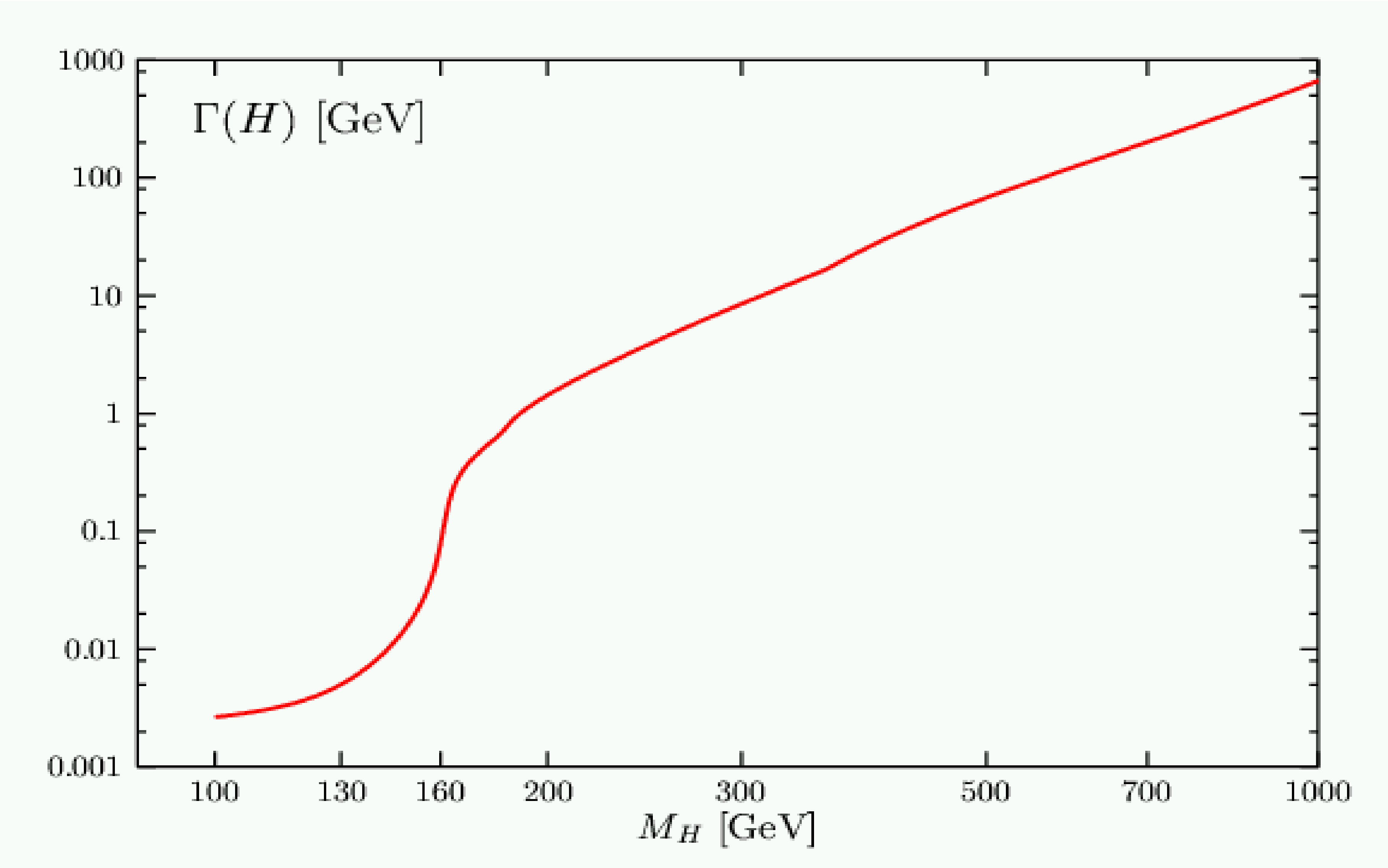
Overview of the branching ratios:

[*taken from hep-ph/0503172*]



The total SM Higgs boson width:

[*taken from hep-ph/0503172*]



2. MSSM Higgs Theory

Comparison with SM case:

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

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

In SUSY: term $\bar{Q}_L \Phi^\dagger$ 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 → [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, $m_{\mathrm{H}^\pm}$: no free parameters, can be predicted

In lowest order:

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

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

$\phi_1 - \phi_2$ basis:

$$M_{\text{Higgs}}^{2,\text{tree}} = \begin{pmatrix} m_{\phi_1}^2 & m_{\phi_1\phi_2}^2 \\ m_{\phi_1\phi_2}^2 & m_{\phi_2}^2 \end{pmatrix} =$$

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

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

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

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:

$$
\begin{aligned}
g_{hVV} &= \sin(\beta-\alpha)\, g_{HVV}^{\rm SM}, \quad V = W^{\pm}, Z \\
g_{HVV} &= \cos(\beta-\alpha)\, g_{HVV}^{\rm SM} \\
g_{hAZ} &= \cos(\beta-\alpha)\, \frac{g'}{2\cos\theta_W} \\
g_{hb\bar{b}}, g_{h\tau^+\tau^-} &= -\frac{\sin\alpha}{\cos\beta}\, g_{Hb\bar{b},H\tau^+\tau^-}^{\rm SM} \\
g_{ht\bar{t}} &= \frac{\cos\alpha}{\sin\beta}\, g_{Ht\bar{t}}^{\rm SM} \\
g_{Ab\bar{b}}, g_{A\tau^+\tau^-} &= \gamma_5 \tan\beta\, g_{Hb\bar{b}}^{\rm SM}
\end{aligned}
$$

$\Rightarrow$ $g_{hVV} \le g_{HVV}^{\rm SM}$, 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

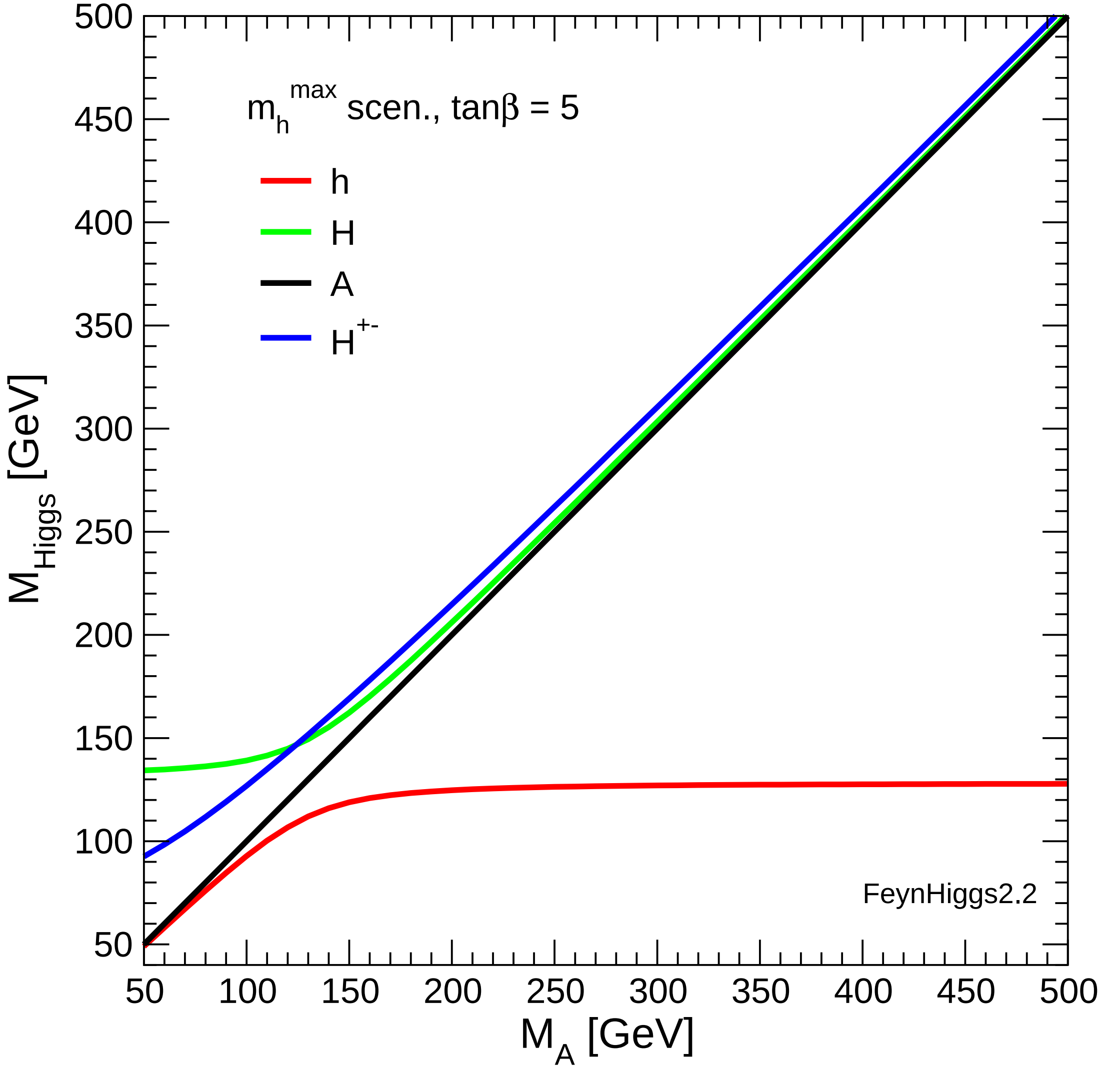
The decoupling limit:

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 . . .



3. 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: $\longrightarrow$ excursion

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

$\Rightarrow$ 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

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.

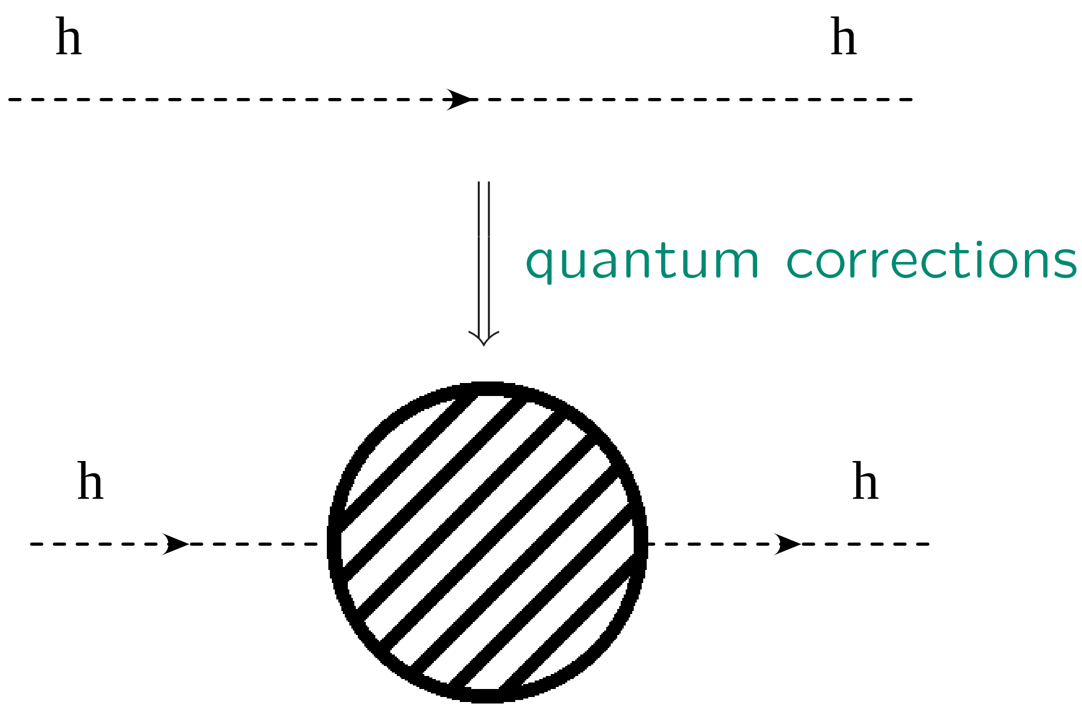
$\Rightarrow$ Pole of the propagator corresponds to zeroth of the inverse propagator.

Inverse propagator:

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

Problem: quantum corrections

Higgs propagator:

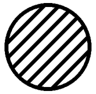


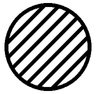
Inverse propagator:

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

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

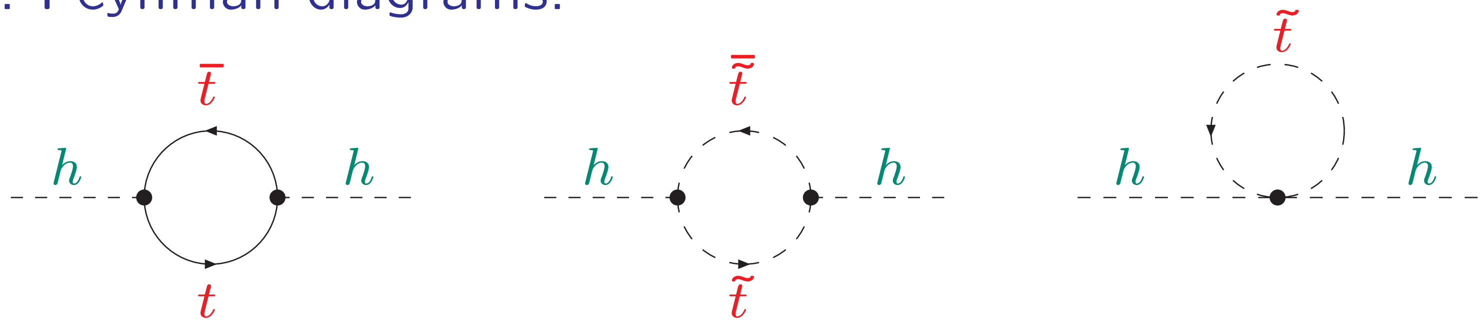
Calculation of the blob:

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

 : 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 GeV)

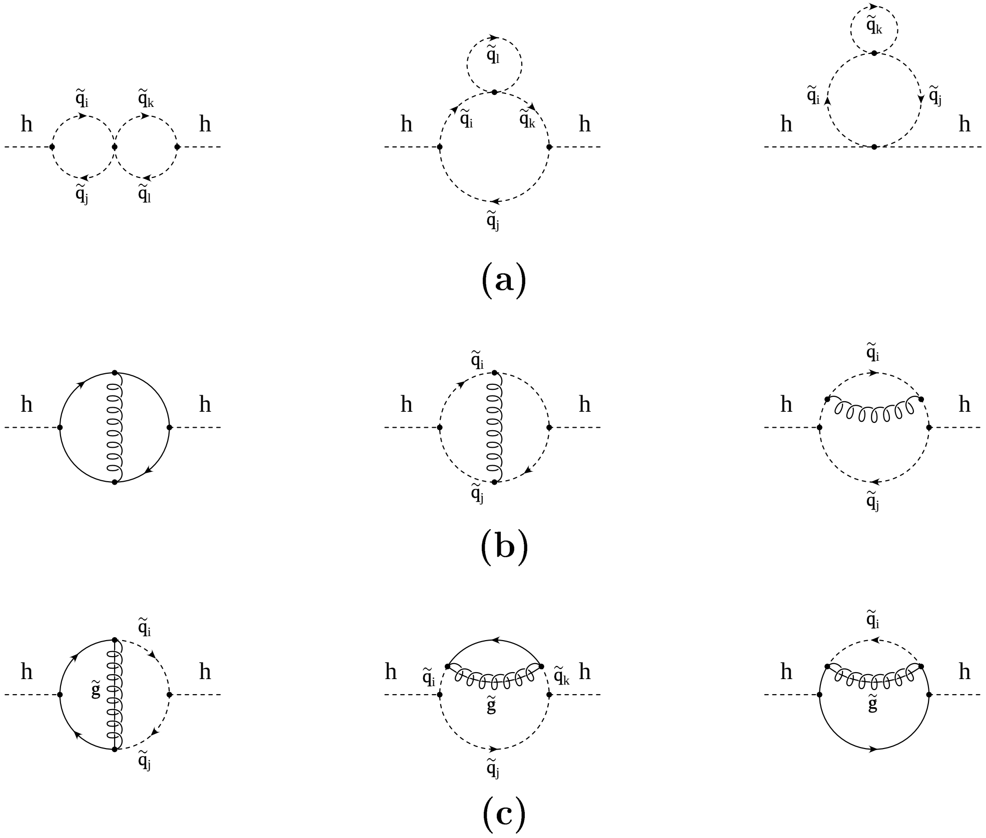
$\Rightarrow$ 2-Loop calculation necessary!

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 programs

['98 - '09:] $\Rightarrow$ 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 $m_t = 173.1 \pm 1.3\,\text{GeV}$

(including theoretical uncertainties from unknown higher orders)
$\Rightarrow$ observable at the LHC

Obtained with:

FeynHiggs

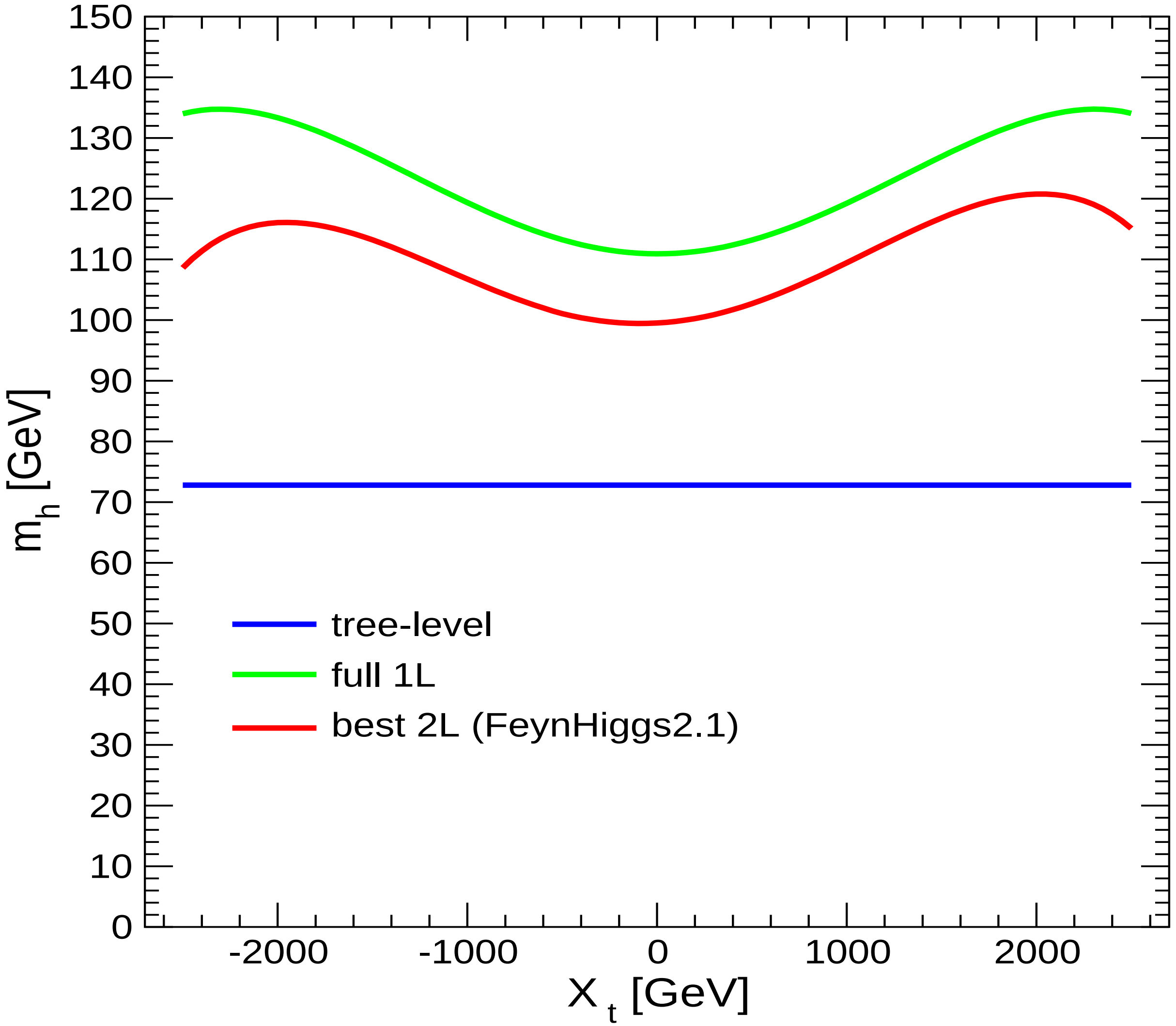
[*S.H., W. Hollik, G. Weiglein '98 – '02*]
[*T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '03 – '09*]

`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:

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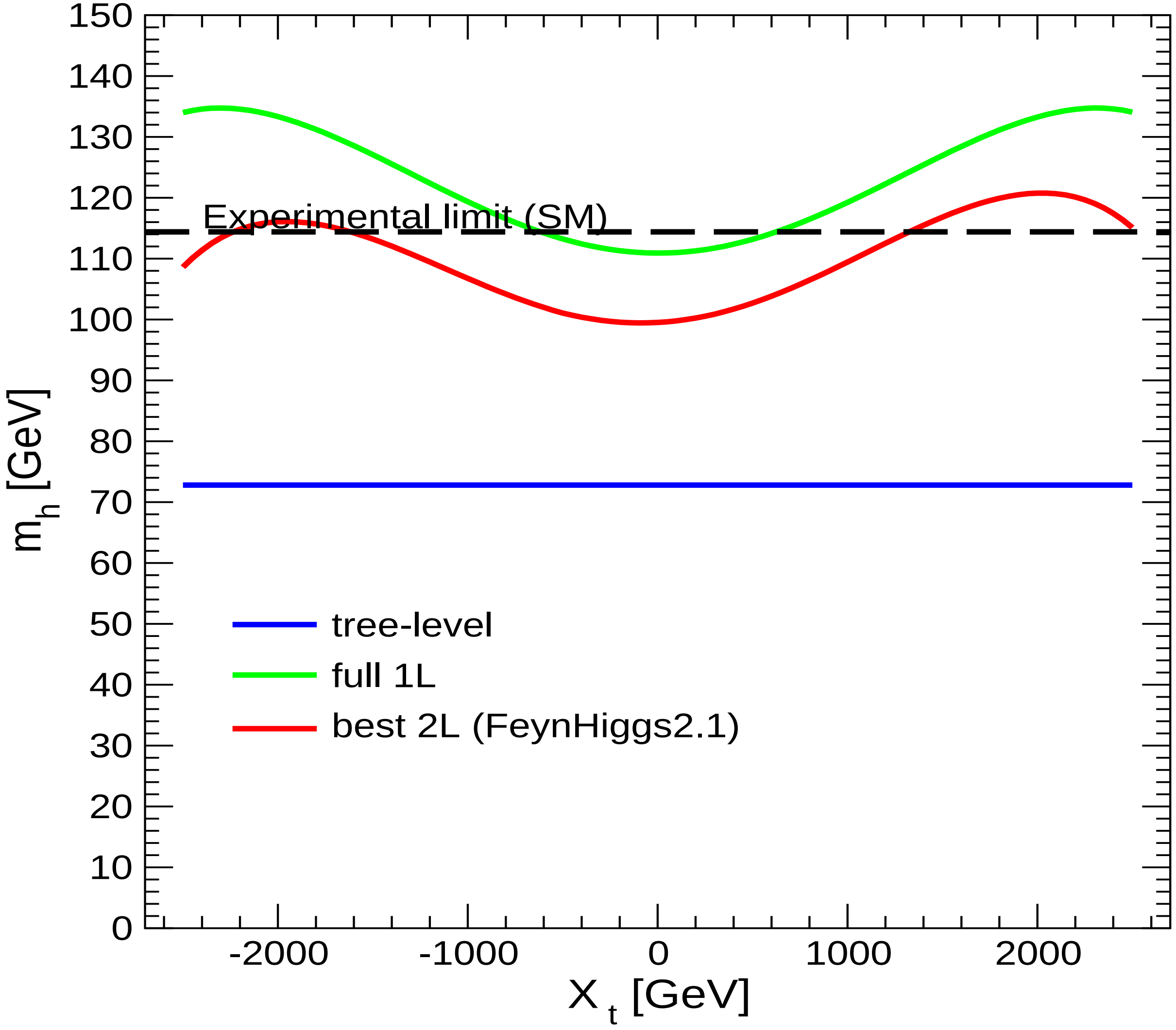


Comparison with experimental limits

$\Rightarrow$ 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

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

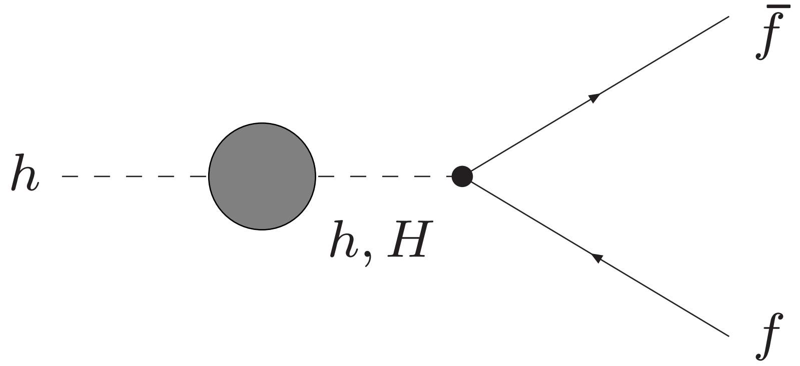
  $\Delta m_t \approx 1$ GeV $\Rightarrow \Delta M_h \approx 1$ GeV

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:



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

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

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 $\tan\beta$

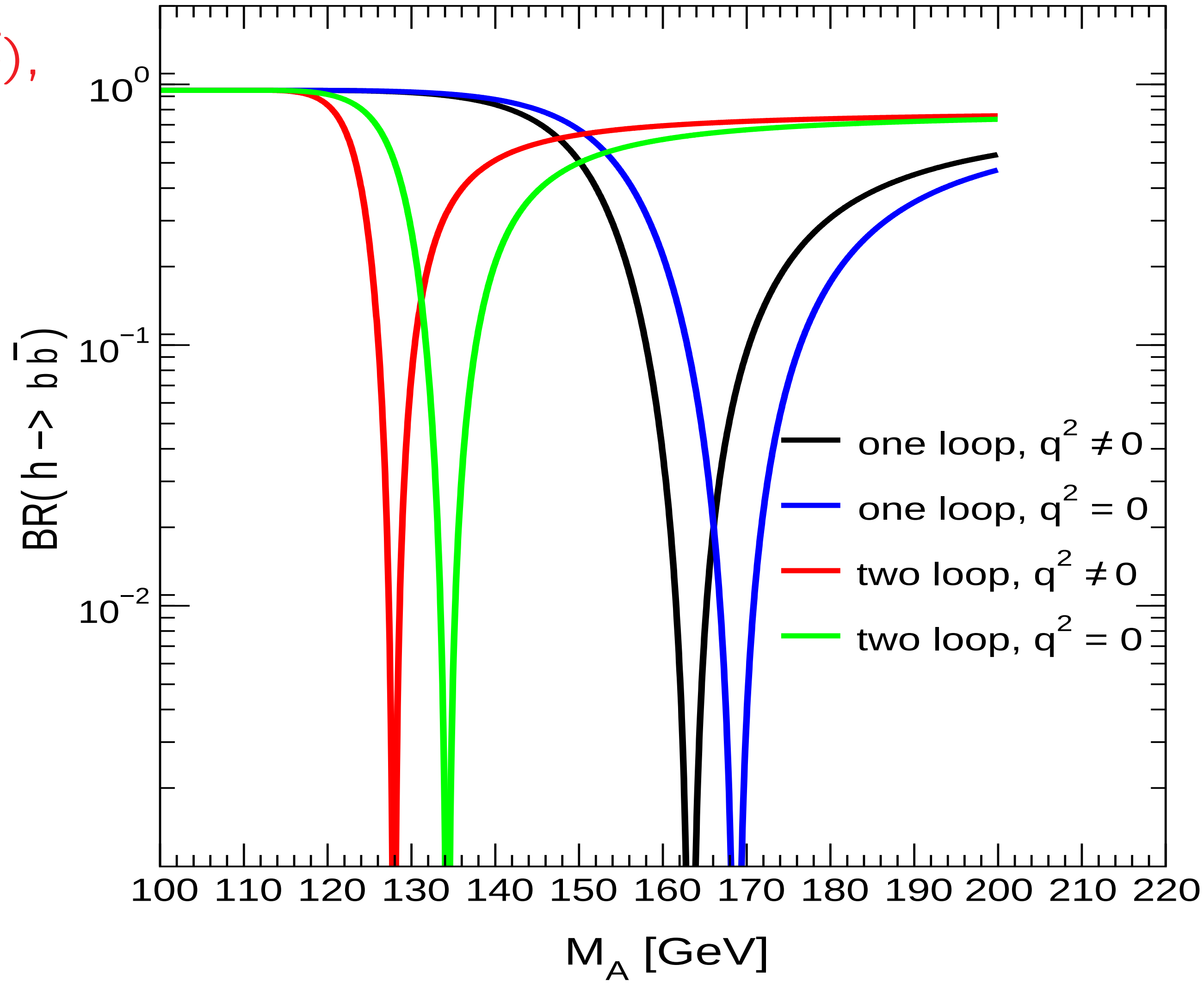
Effective $hf\bar{f}$ coupling can go to zero for large $\hat{\Sigma}_{\rm hH}$

$\Rightarrow$ "Pathological regions"

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

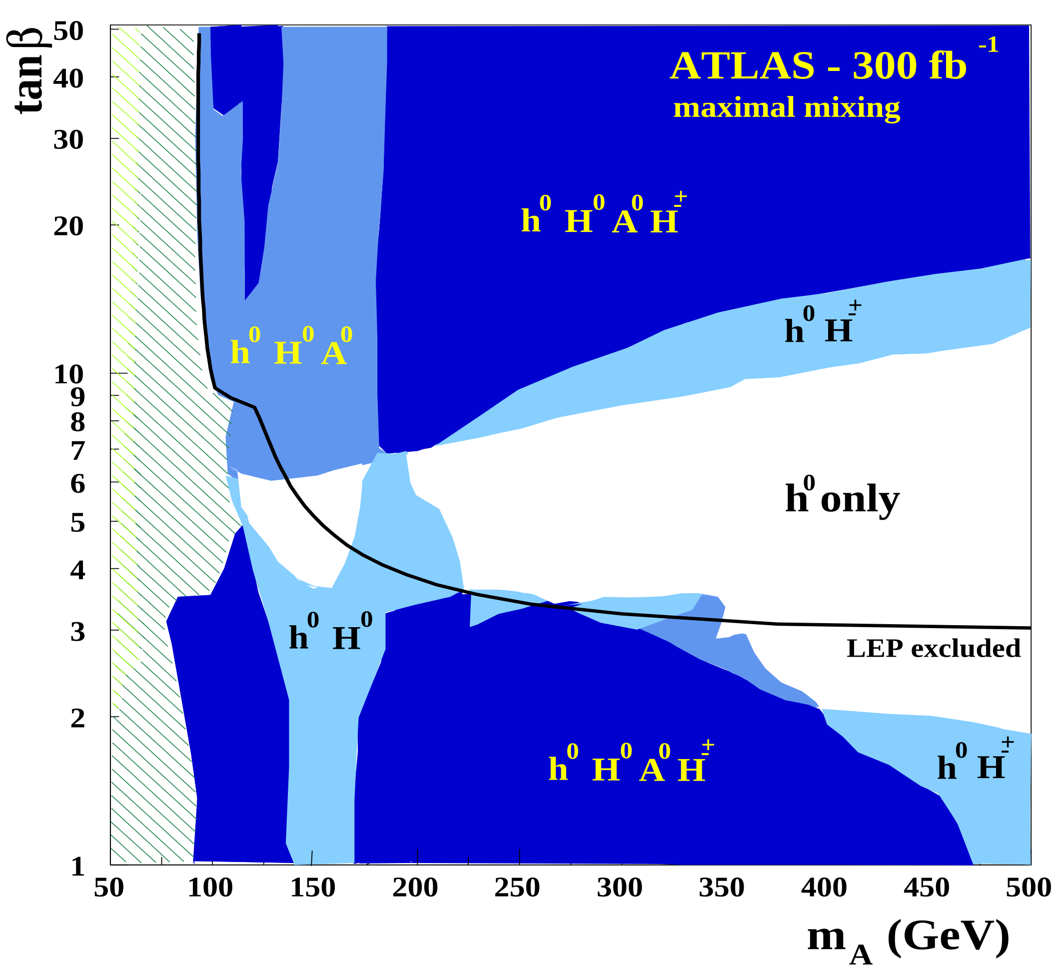
$\Rightarrow$ Suppression of BR$(h \to b\bar{b})$,
BR$(h \to \tau\tau)$, . . .

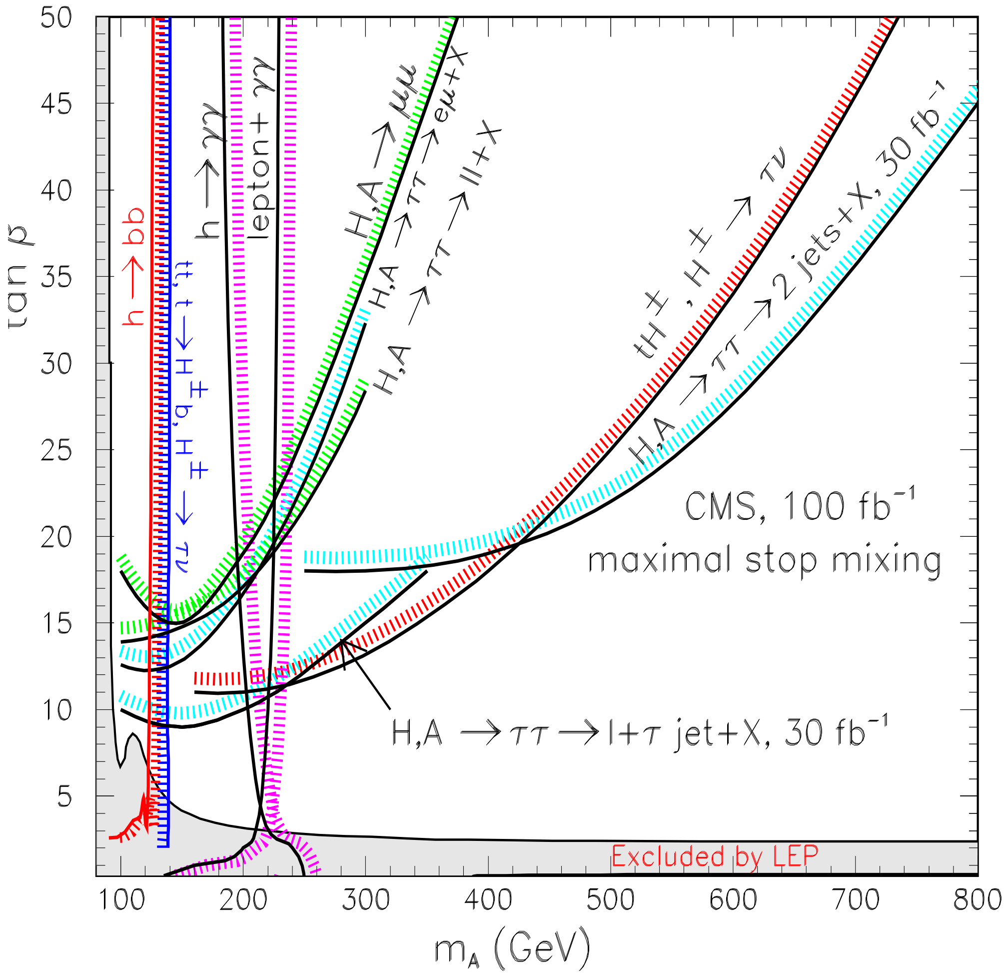
[*S.H., W. Hollik, G. Weiglein '00*]



4. The heavy MSSM Higgs bosons

MSSM Higgs discovery contours in M_A–$\tan\beta$ plane
($m_h^{\max}$ benchmark scenario): [ATLAS '99] [CMS '03]

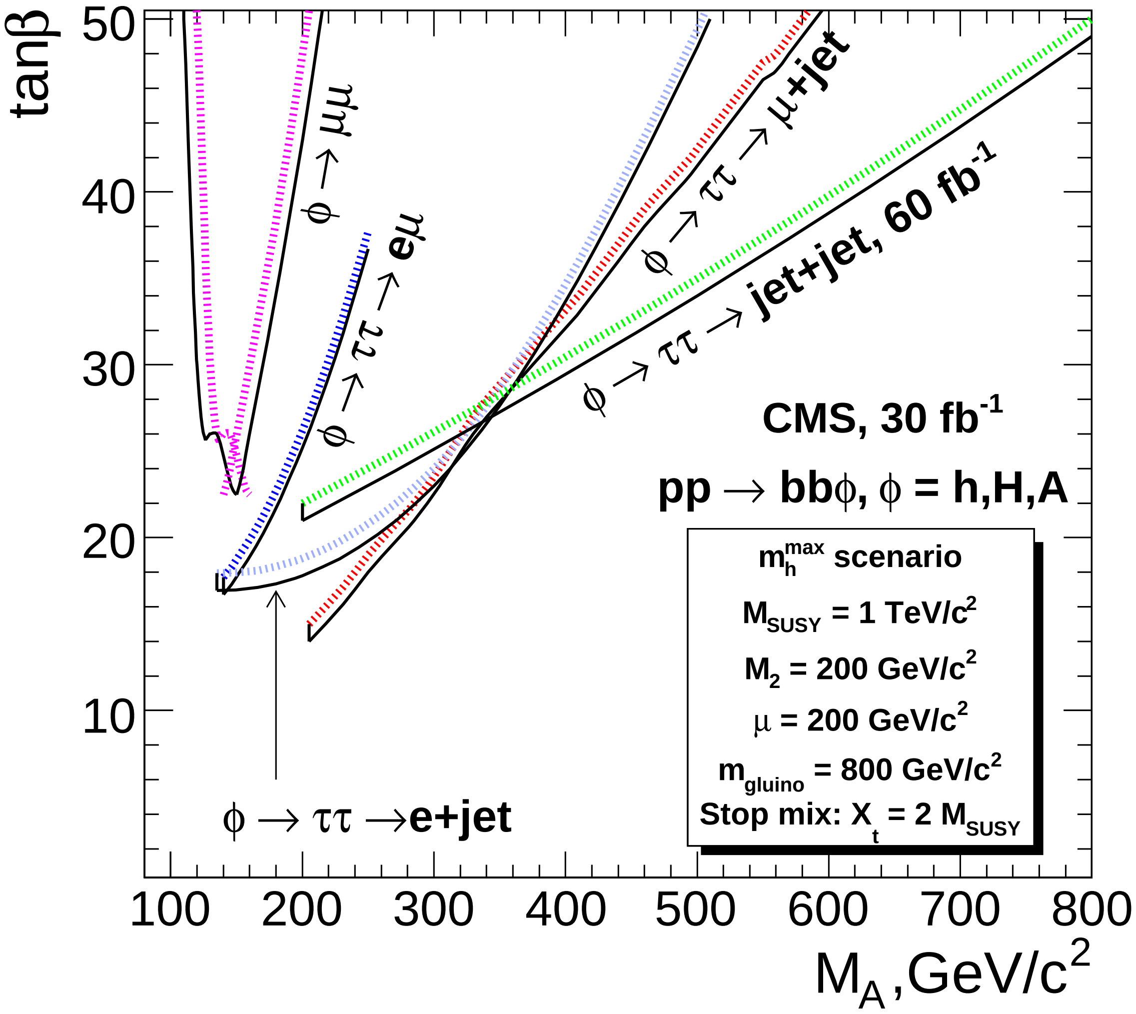




areas where only h is observable ⇒ "LHC wedge"

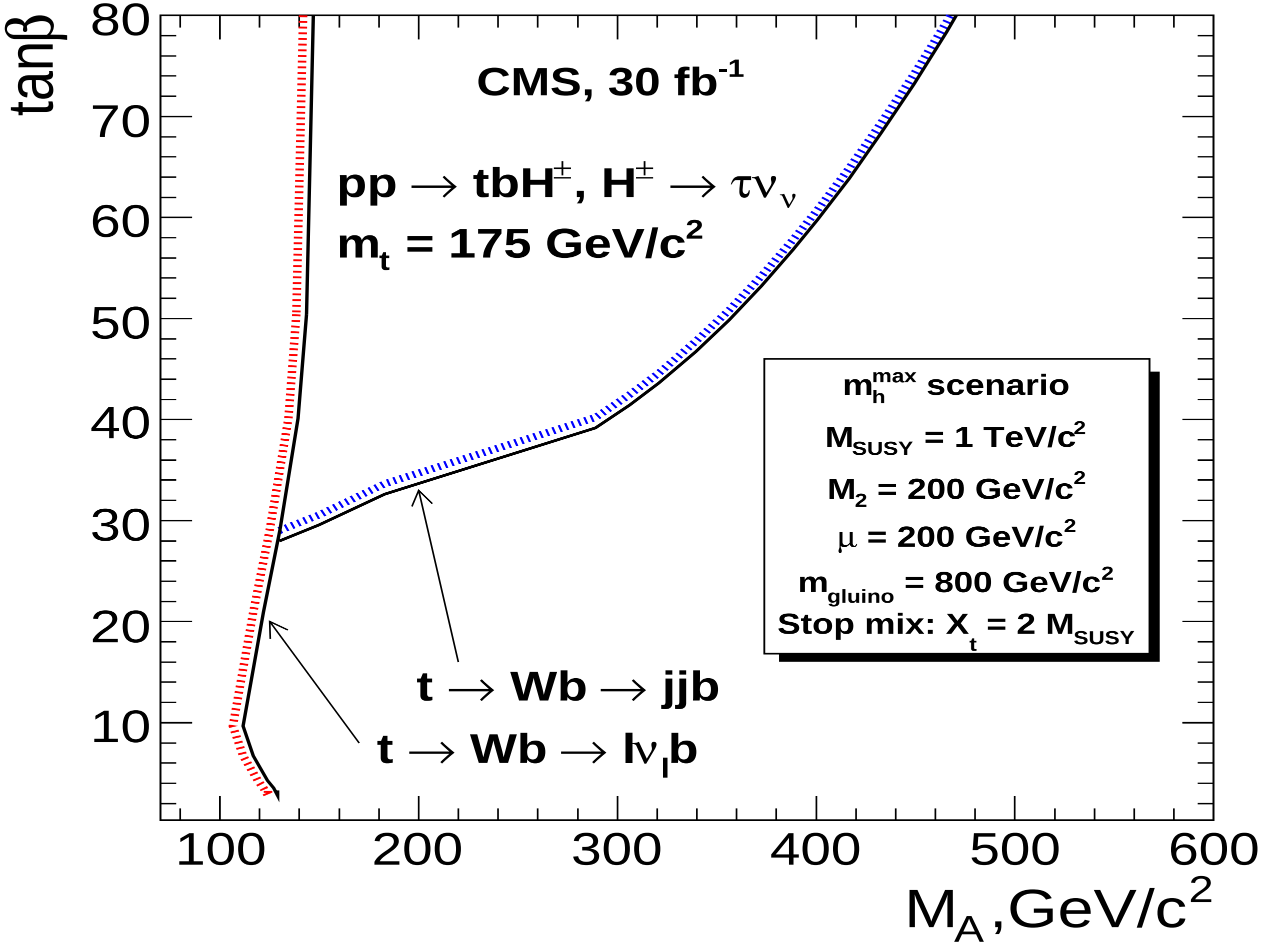
Latest results for neutral heavy Higgs bosons:

MSSM Higgs discovery contours in M_A–$\tan\beta$ plane $(\Phi = H, A)$
($m_h^{\rm max}$ 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:

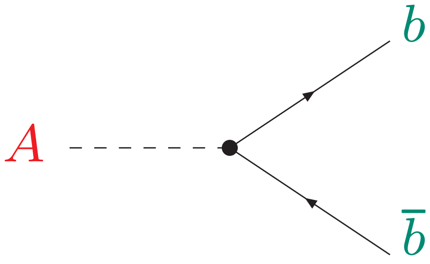
$$M_{H^\pm} < m_t$$

heavy charged Higgs:

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

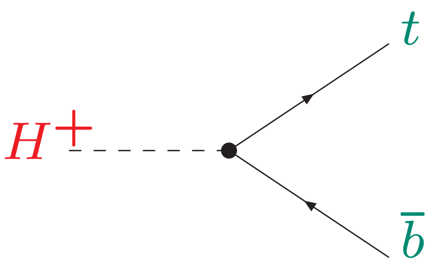
Differences compared to the SM Higgs:

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

Most powerful search modes for heavy MSSM Higgs bosons:

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

Enhancement factors compared to the SM case:

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

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

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

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

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

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

Suggestion for new benchmark scenarios:

[*M. Carena, S.H., C. Wagner, G. Weiglein '05*]

→ investigate benchmark scenarios:

→ Vary only M_A and $\tan\beta$ (large!)
→ Keep all other SUSY parameters fixed

→ Vary in addition μ: $\mu = \pm 1000, \pm 500, \pm 200$ GeV
(if perturbativity allows)

1. m_h^{max} scenario:
   → obtain conservative $\tan\beta$ exclusion bounds ($X_t = 2\,M_{\text{SUSY}}$)

   A_t large ⇒ large $\mathcal{O}(\alpha_t)$ contribution to Δ_b

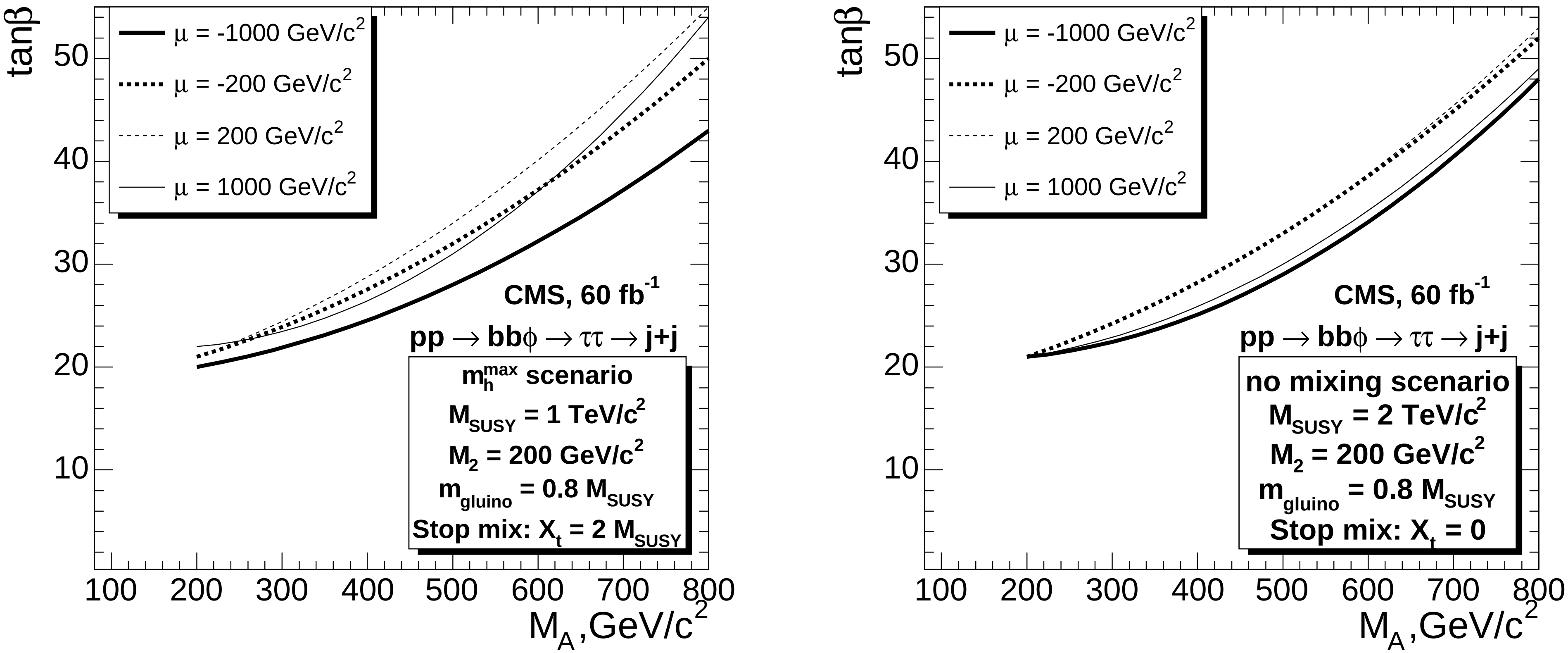
2. no-mixing scenario
   → no mixing in the scalar top sector ($X_t = 0$)

   A_t small ⇒ small $\mathcal{O}(\alpha_t)$ contribution to Δ_b

   ⇒ large difference to m_h^{max} scenario

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

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

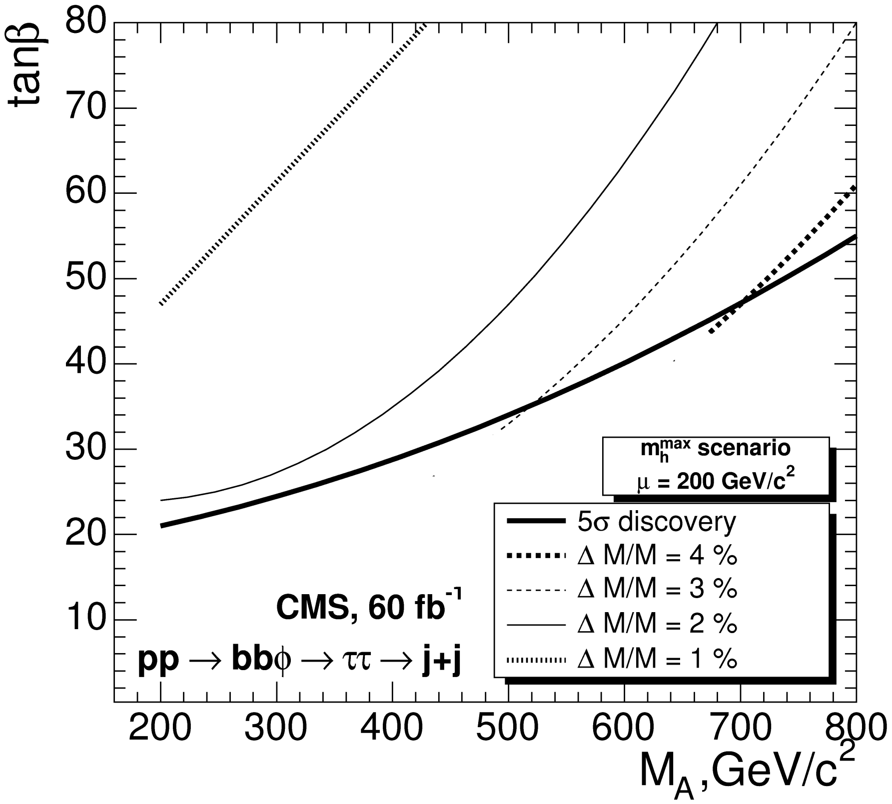


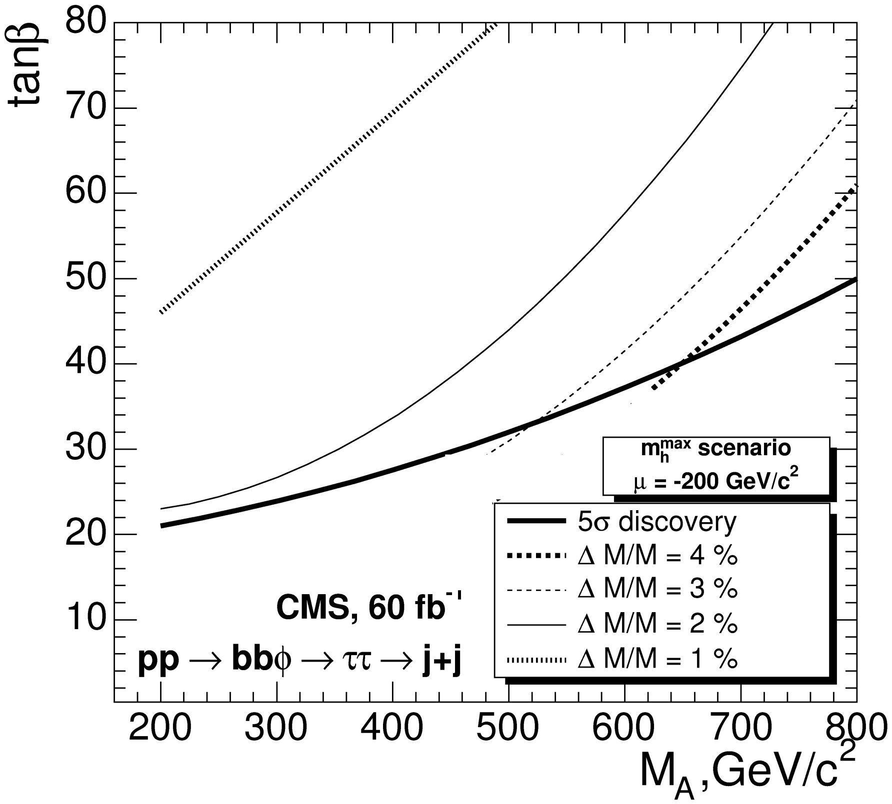
⇒ now based on full CMS simulation

⇒ non-negligible variation with the sign and absolute value of μ
(→ numerical compensations in production and decay)

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

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



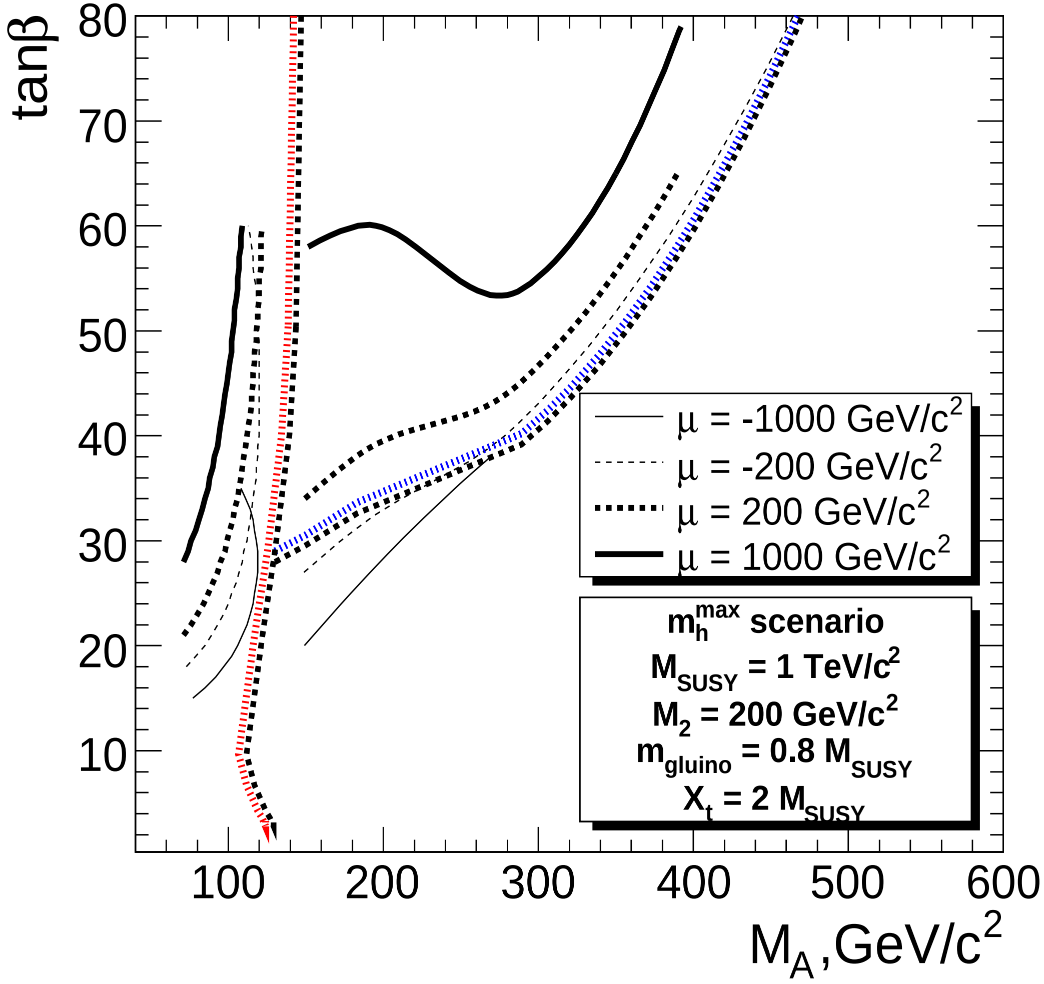


⇒ now based on full CMS simulation

⇒ high precision measurement of heavy Higgs boson masses possible

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

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



→ note: M_A–$\tan\beta$ plane

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

Back-up

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)

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

Effects of complex parameters in the Higgs sector:

Complex parameters enter via loop corrections:

– μ : Higgsino mass parameter

– $A_{t,b,\tau}$: trilinear couplings $\Rightarrow X_{t,b,\tau} = A_{t,b} - \mu^* \{\cot\beta\,, \tan\beta\}$ complex

– $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)

– $m_{\tilde{g}}$: gluino mass

$\Rightarrow$ can induce $\mathcal{CP}$-violating effects

Result:

$$(A, H, h) \to (h_3, h_2, h_1)$$

with

$$M_{h_3} > M_{h_2} > M_{h_1}$$

Propagator/Mass matrix at tree-level:

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

Propagator / mass matrix with higher-order corrections
($\to$ Feynman-diagrammatic approach):

$$M_{hHA}^2(q^2) = \begin{pmatrix} q^2 - m_A^2 + \hat{\Sigma}_{AA}(q^2) & \hat{\Sigma}_{AH}(q^2) & \hat{\Sigma}_{Ah}(q^2) \\ \hat{\Sigma}_{HA}(q^2) & q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hA}(q^2) & \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

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

$\hat{\Sigma}_{Ah}, \hat{\Sigma}_{AH} \neq 0 \Rightarrow$ $\mathcal{CP}$V, $\mathcal{CP}$-even and $\mathcal{CP}$-odd fields can mix

$\Rightarrow$ complex roots of $\det(M_{hHA}^2(q^2))$: $\mathcal{M}_{h_i}^2 (i = 1, 2, 3)$: $\mathcal{M}^2 = M^2 - iM\Gamma$