Higgs Boson Phenomenology
Lecture II

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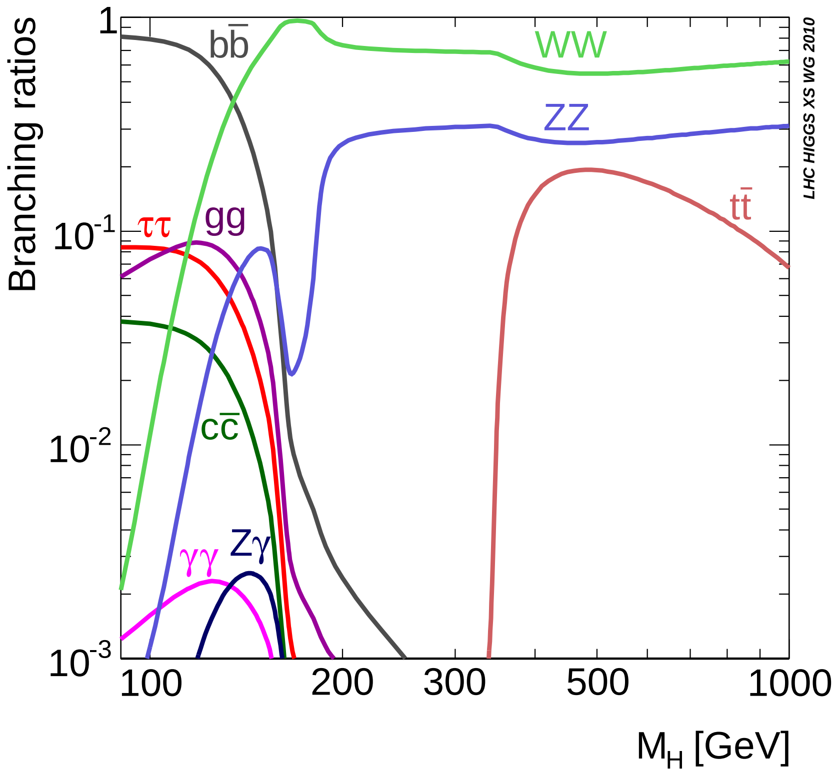
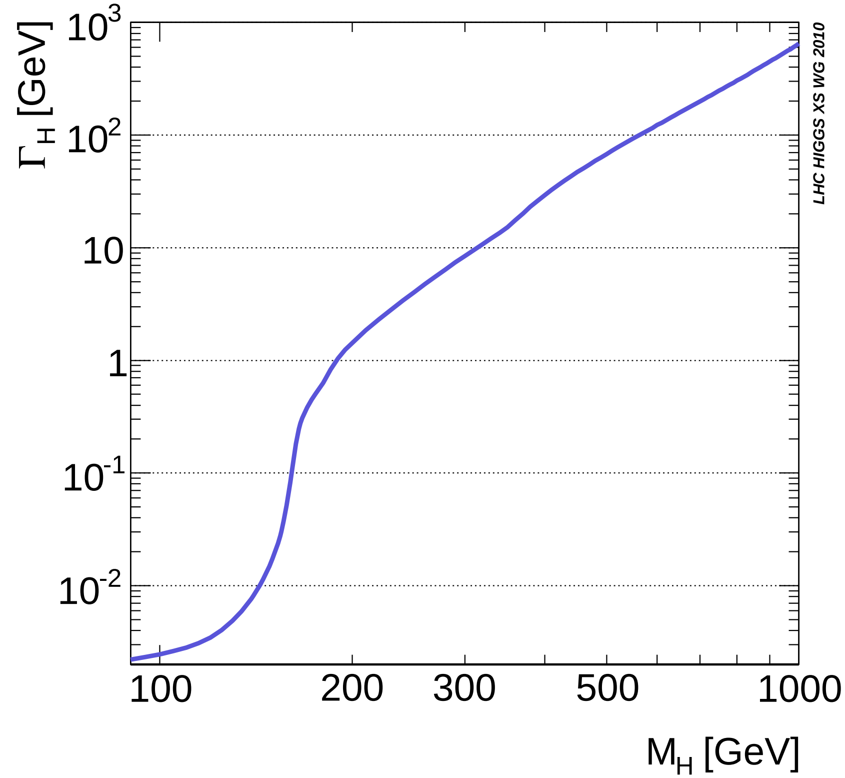
Outline of Lecture II

- SM Higgs boson physics depends just on M_H: M_H highly constrained!
- Quantum effects leading players in constraining M_H:
  $\longrightarrow$ branching ratios (see end of last lecture): important corrections;
  $\longrightarrow$ EW precision fits: M_H only unknown.
- SM Higgs so contrained that it can point to scale of new physics.
- Beyond SM Higgs: MSSM (useful example of an extended Higgs sector) and more.
- Need data! and need to understand them ....

SM Higgs boson decay branching ratios and width





Observe difference between light and heavy Higgs

These curves include: tree level + QCD and EW loop corrections.

Tree level decays: $H \to f\bar{f}$ and $H \to VV$

At lowest order:

$$\Gamma(H \to f\bar{f}) = \frac{G_F M_H}{4\sqrt{2}\pi} N_{cf} m_f^2 \beta_f^3$$

$$\Gamma(H \to VV) = \frac{G_F M_H^3}{16\sqrt{2}\pi} \delta_V \left(1 - \tau_V + \frac{3}{4}\tau_V^2\right) \beta_V$$

($\beta_i = \sqrt{1-\tau_i}$, $\tau_i = 4m_i^2/M_H^2$, $\delta_{W,Z} = 2, 1$, $(N_c)_{l,q} = 1, 3$)

Ex.1: Higher order corrections to $H \to q\bar{q}$

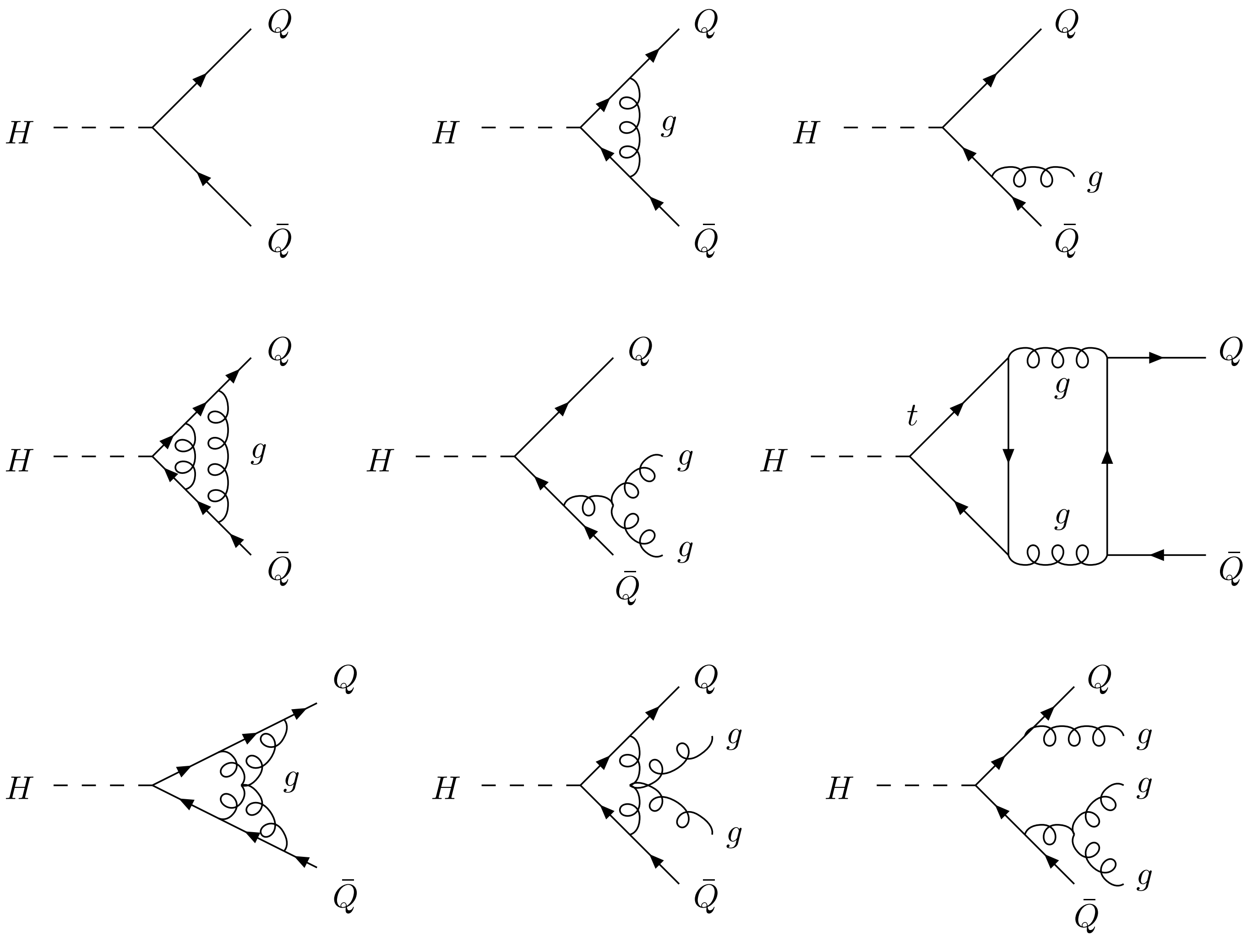
QCD corrections dominant:

$$\Gamma(H \to q\bar{q})_{\rm QCD} = \frac{3G_F M_H}{4\sqrt{2}\pi} \bar{m}_q^2(M_H) \beta_q^3 \left[\Delta_{QCD} + \Delta_t\right]$$

$$\Delta_{QCD} = 1 + 5.67\frac{\alpha_s(M_H)}{\pi} + (35.94 - 1.36 N_F)\left(\frac{\alpha_s(M_H)}{\pi}\right)^2 + \cdots$$

$$\Delta_t = \left(\frac{\alpha_s(M_H)}{\pi}\right)^2 \left[1.57 - \frac{2}{3}\ln\frac{M_H^2}{m_t^2} + \frac{1}{9}\ln^2\frac{\bar{m}_q^2(M_H)}{M_H^2}\right] + \cdots$$

Consist of both virtual and real corrections, e.g.:



- Large Logs absorbed into $\overline{MS}$ quark mass

$$\text{Leading Order}: \quad \bar{m}_Q(\mu) = \bar{m}_Q(m_Q) \left(\frac{\alpha_s(\mu)}{\alpha_s(m_Q)} \right)^{\frac{2b_0}{\gamma_0}}$$

$$\text{Higher order}: \quad \bar{m}_Q(\mu) = \bar{m}_Q(m_Q) \frac{f\left(\alpha_s(\mu)/\pi\right)}{f\left(\alpha_s(m_Q)/\pi\right)}$$

where (from renormalization group equation)

$$\begin{aligned}
f(x) &= \left(\frac{25}{6}x\right)^{\frac{12}{25}} [1 + 1.014x + \ldots] \quad \text{for} \quad m_c < \mu < m_b \\
f(x) &= \left(\frac{23}{6}x\right)^{\frac{12}{23}} [1 + 1.175x + \ldots] \quad \text{for} \quad m_b < \mu < m_t \\
f(x) &= \left(\frac{7}{2}x\right)^{\frac{4}{7}} [1 + 1.398x + \ldots] \quad \text{for} \quad \mu > m_t
\end{aligned}$$

- Large corrections, when $M_H \gg m_Q$

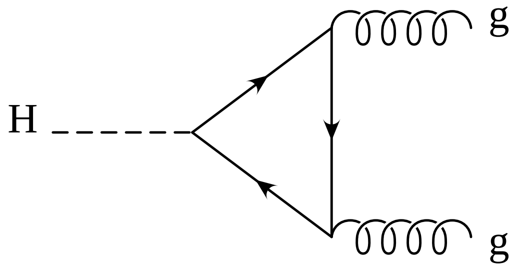
$$m_b(m_b) \simeq 4.2\,\text{GeV} \longrightarrow \bar{m}_b(M_h \simeq 100\,\text{GeV}) \simeq 3\,\text{GeV}$$

Branching ratio smaller by almost a factor 2.

- Main uncertainties: $\alpha_s(M_Z)$, pole masses: $m_c(m_c)$, $m_b(m_b)$.

Ex. 2: Higher order corrections $\Gamma(H\to gg)$

Start from tree level:



$$\Gamma(H\to gg)=\frac{G_F\alpha_s^2 M_H^3}{36\sqrt{2}\pi^3}\left|\sum_q A_q^H(\tau_q)\right|$$

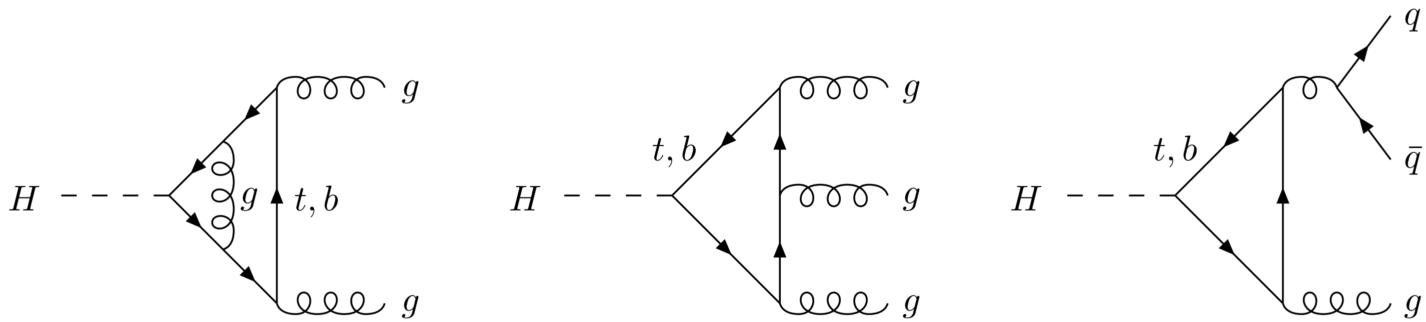
where $\tau_q = 4m_q^2/M_H^2$ and

$$A_q^H(\tau)=\frac{3}{2}\tau\left[1+(1-\tau)f(\tau)\right]$$

$$f(\tau)=\begin{cases}\arcsin^2\frac{1}{\sqrt{\tau}} & \tau\geq 1\\ -\frac{1}{4}\left[\ln\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}-i\pi\right]^2 & \tau<1\end{cases}$$

Main contribution from top quark $\longrightarrow$ optimal situation to use Low Energy Theorems to add higher order corrections.

QCD corrections dominant:



Difficult task since decay is already a loop effect.

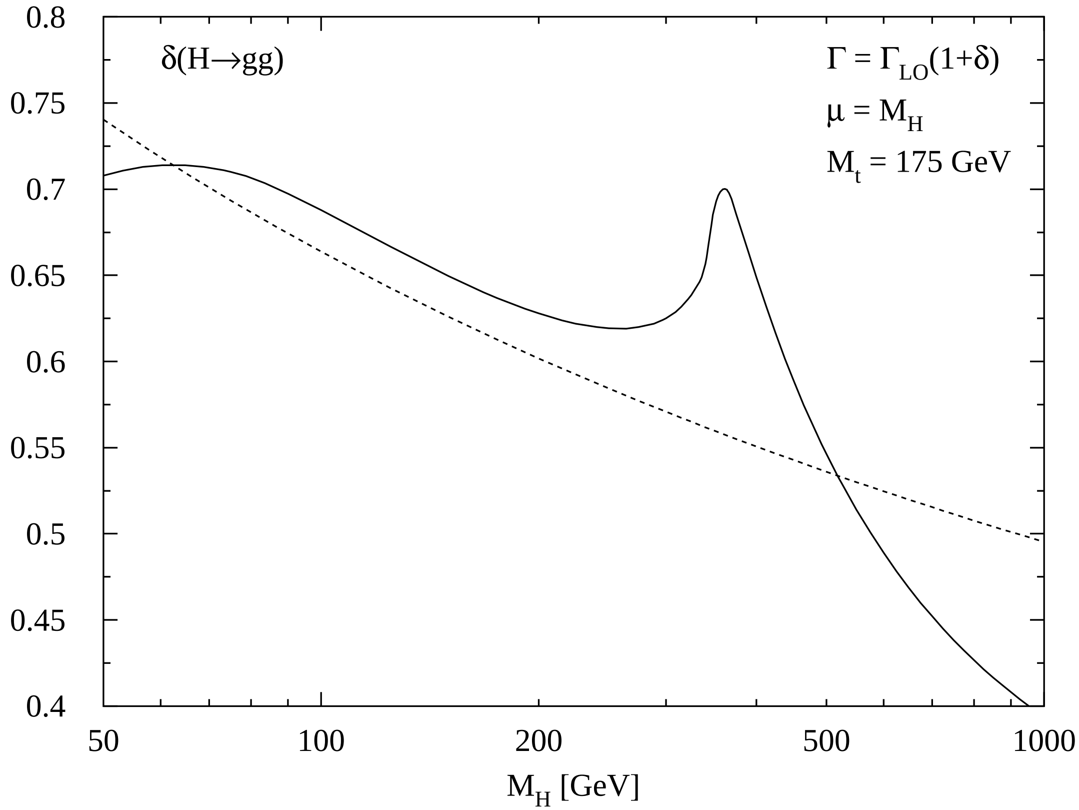
However, full massive calculation of $\Gamma(H \to gg(q), q\bar{q}g)$ agrees with $m_t \gg M_H$ result at 10%

$$\Gamma(H \to gg(q), q\bar{q}g) = \Gamma_{LO}(\alpha_s^{(N_L)}(M_H)) \left[1 + E^{(N_L)} \frac{\alpha_s^{(N_L)}}{\pi}\right]$$

$$E^{(N_L)} \stackrel{M_H^2 \ll 4m_q^2}{\longrightarrow} \frac{95}{4} - \frac{7}{6} N_L$$

Dominant soft/collinear radiation do not resolve the Higgs boson coupling to gluons $\longrightarrow$ QCD corrections are just a (big) rescaling factor

NLO QCD corrections almost $60-70\%$ of LO result in the low mass region:



solid line $\longrightarrow$ full massive NLO calculation

dashed line $\longrightarrow$ heavy top limit $(M_H^2 \ll 4m_t^2)$

NNLO corrections calculated in the heavy top limit: add 20%

$\longrightarrow$ perturbative stabilization. Residual theoretical uncertainty $\simeq 10\%$.

Low-energy theorems, in a nutshell.

- Observing that:

  In the $p_H \to 0$ limit: the interactions of a Higgs boson with the SM particles arise by substituting

$$M_i \longrightarrow M_i \left(1 + \frac{H}{v}\right) \quad (i = f, W, Z)$$

  In practice: Higgs taken on shell ($p_H^2 = M_H^2$), and limit $p_H \to 0$ is limit of small Higgs masses (e.g.: $M_H^2 \ll 4m_t^2$).

- Then

$$\lim_{p_H \to 0} \mathcal{A}(X \to Y + H) = \frac{1}{v} \sum_i M_i \frac{\partial}{\partial M_i} \mathcal{A}(X \to Y)$$

  very convenient!

- Equivalent to an Effective Theory described by:

$$\mathcal{L}_{eff} = \frac{\alpha_s}{12\pi} G^{a\mu\nu} G^a_{\mu\nu} \frac{H}{v} (1 + O(\alpha_s))$$

  including higher order QCD corrections.

For completeness:

$$\Gamma(H\to\gamma\gamma)=\frac{G_F\alpha^2M_H^3}{128\sqrt{2}\pi^3}\left|\sum_f N_{cf}e_f^2A_f^H(\tau_f)+A_W^H(\tau_W)\right|^2$$

where ($f(\tau)$ as in $H\to gg$):

$$\begin{aligned} A_f^H &= 2\tau\left[1+(1-\tau)f(\tau)\right] \\ A_W^H(\tau) &= -\left[2+3\tau+3\tau(2-\tau)f(\tau)\right] \end{aligned}$$

$$\Gamma(H\to Z\gamma)=\frac{G_F^2M_W^2\alpha M_H^3}{64\pi^4}\left(1-\frac{M_Z^2}{M_H^2}\right)^3\left|\sum_f A_f^H(\tau_f,\lambda_f)+A_W^H(\tau_W,\lambda_W)\right|^2$$

where the form factors $A_f^H(\tau,\lambda)$ and $A_W^H(\tau,\lambda)$ can be found in the literature (see, e.g., M. Spira, hep-ph/9705337).

For both decays, both QCD and EW corrections are very small ($\simeq 1-3\%$).

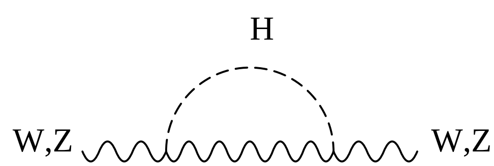
EW precision fits: perturbatively calculate observables in terms of few parameters:

$$M_Z, G_F, \alpha(M_Z), M_W, m_f, (\alpha_s(M_Z))$$

extracted from experiments with high accuracy. Only SM unknown: M_H.

- SM needs Higgs boson to cancel infinities, e.g.

$$M_W, M_Z \longrightarrow$$



- Finite logarithmic contributions survive, e.g. radiative corrections to $\rho = M_W^2/(M_Z^2 \cos^2\theta_W)$:

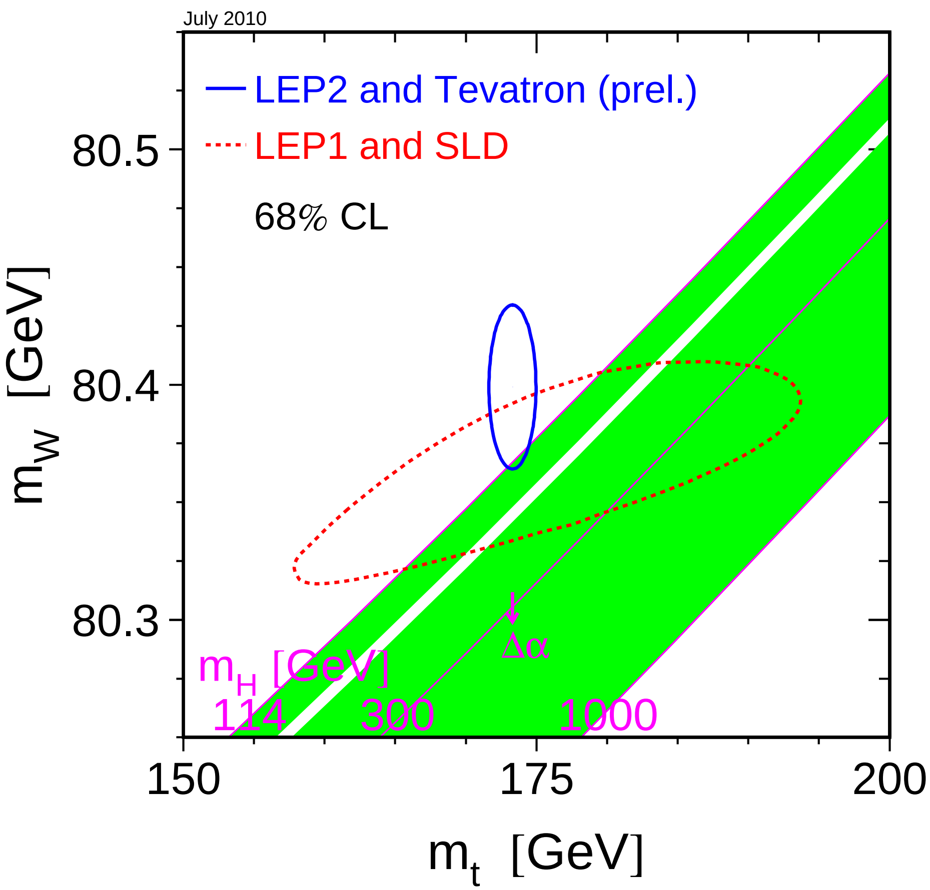
$$\rho = 1 - \frac{11 g^2}{96\pi^2 \tan^2\theta_W} \ln\left(\frac{M_H}{M_W}\right)$$

Main effects in oblique radiative corrections (S,T-parameters)

- Same constraints apply to any model of new physics.

SM Higgs-boson mass range: constrained by EW precision fits

Increasing precision will continue to provide an invaluable tool to test the consistency of the SM and its extensions.



$$m_W = 80.399 \pm 0.023 \text{ GeV}$$

$$m_t = 173.3 \pm 1.1 \text{ GeV}$$

$$\Downarrow$$

$$M_H = 89^{+35}_{-26} \text{ GeV}$$

$$M_H < 158\,(185) \text{ GeV}$$

plus exclusion limits (95% c.l.):

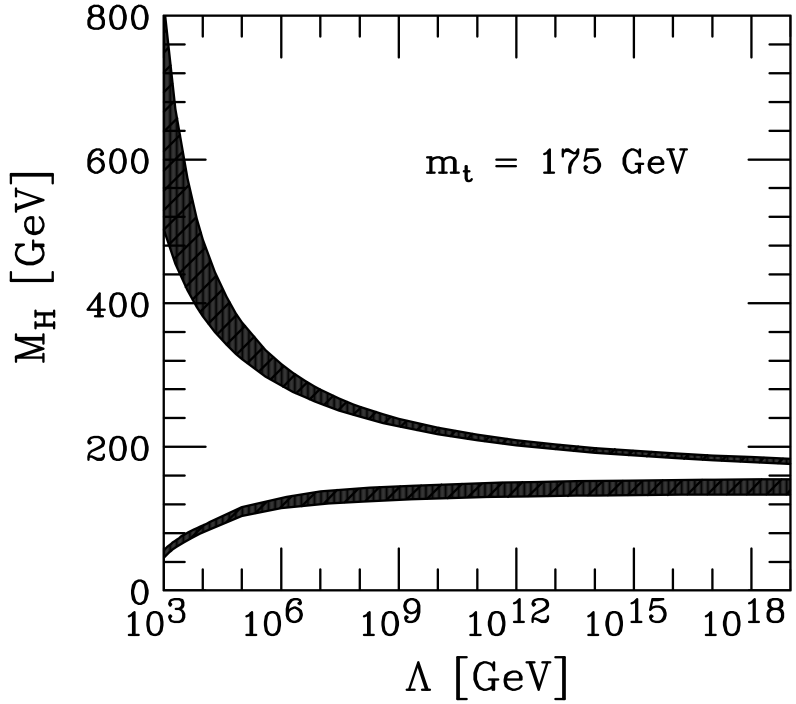
$$M_H > 114.4 \text{ GeV (LEP)}$$

$$M_H \neq 158 - 175 \text{ GeV (Tevatron)}$$

focus is now on exclusion limits and discovery!

Other theoretical constraints on M_H in the Standard Model

SM as an effective theory valid up to a scale Λ. The Higgs sector of the SM actually contains two unknowns: $\boxed{M_H \text{ and } \Lambda}$.



Bounds given by:

- $\longrightarrow$ unitarity
- $\longrightarrow$ triviality
- $\longrightarrow$ vacuum stability
- $\longrightarrow$ fine tuning

$\boxed{M_H^2 = 2\lambda v^2}$ $\longrightarrow$ M_H determines the weak/strong coupling behavior of the theory, i.e. the limit of validity of the perturbative approach.

Unitarity: longitudinal gauge boson scattering cross section at high energy grows with M_H.

Electroweak Equivalence Theorem:

in the high energy limit ($s \gg M_V^2$)

$$\mathcal{A}(V_L^1 \dots V_L^n \to V_L^1 \dots V_L^m) = (i)^n(-i)^m \mathcal{A}(\omega^1 \dots \omega^n \to \omega^1 \dots \omega^m) + O\left(\frac{M_V^2}{s}\right)$$

(V_L^i=longitudinal weak gauge boson; ω^i=associated Goldstone boson).

Example: $\boxed{W_L^+ W_L^- \to W_L^+ W_L^-}$

$$\mathcal{A}(W_L^+ W_L^- \to W_L^+ W_L^-) \sim -\frac{1}{v^2}\left(-s - t + \frac{s^2}{s - M_H^2} + \frac{t^2}{t - M_H^2}\right)$$

$$\mathcal{A}(\omega^+ \omega^- \to \omega^+ \omega^-) = -\frac{M_H^2}{v^2}\left(\frac{s}{s - M_H^2} + \frac{t}{t - M_H^2}\right)$$

$$\Downarrow$$

$$\mathcal{A}(W_L^+ W_L^- \to W_L^+ W_L^-) = \mathcal{A}(\omega^+ \omega^- \to \omega^+ \omega^-) + O\left(\frac{M_W^2}{s}\right)$$

Using partial wave decomposition:

$$\mathcal{A} = 16\pi \sum_{l=0}^{\infty} (2l+1) P_l(\cos\theta) a_l$$

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s} |\mathcal{A}^2| \quad \longrightarrow \quad \sigma = \frac{16\pi}{s} \sum_{l=0}^{\infty} (2l+1)|a_l|^2 = \frac{1}{s} \mathrm{Im}\left[\mathcal{A}(\theta = 0)\right]$$

$$\Downarrow$$

$$\boxed{|a_l|^2 = \mathrm{Im}(a_l)} \quad \longrightarrow \quad \boxed{|\mathrm{Re}(a_l)| \leq \tfrac{1}{2}}$$

Most constraining condition for $W_L^+ W_L^- \rightarrow W_L^+ W_L^-$ from

$$a_0(\omega^+\omega^- \rightarrow \omega^+\omega^-) = -\frac{M_H^2}{16\pi v^2}\left[2 + \frac{M_H^2}{s - M_H^2} - \frac{M_H^2}{s}\log\left(1 + \frac{s}{M_H^2}\right)\right) \xrightarrow{s \gg M_H^2} -\frac{M_H^2}{8\pi v^2}$$

$$\boxed{|\mathrm{Re}(a_0)| < \tfrac{1}{2}} \quad \longrightarrow \quad \boxed{M_H < 870\ \mathrm{GeV}}$$

Best constraint from coupled channels $(2W_L^+ W_L^- + Z_L Z_L)$:

$$a_0 \xrightarrow{s \gg M_H^2} -\frac{5M_H^2}{32\pi v^2} \quad \longrightarrow \quad \boxed{M_H < 780\ \mathrm{GeV}}$$

Observe that: if there is no Higgs boson, i.e. $M_H \gg s$:

$$a_0(\omega^+\omega^- \to \omega^+\omega^-) \xrightarrow{M_H^2 \gg s} -\frac{s}{32\pi v^2}$$

Imposing the unitarity constraint $\longrightarrow$ $\boxed{\sqrt{s_c} < 1.8 \text{ TeV}}$

Most restrictive constraint $\longrightarrow$ $\boxed{\sqrt{s_c} < 1.2 \text{ TeV}}$

$$\Downarrow$$

New physics expected at the TeV scale

Exciting !!

this is the range of energies of both Tevatron and LHC

Triviality: a $\lambda\phi^4$ theory cannot be perturbative at all scales unless $\lambda = 0$.

In the SM the scale evolution of λ is more complicated:

$$32\pi^2 \frac{d\lambda}{dt} = 24\lambda^2 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 24y_t^4 + \cdots$$

($t = \ln(Q^2/Q_0^2)$, $y_t = m_t/v$ $\rightarrow$ top quark Yukawa coupling).

Still, for large λ ($\leftrightarrow$ large M_H) the first term dominates and (at 1-loop):

$$\lambda(Q) = \frac{\lambda(Q_0)}{1 - \frac{3}{4\pi^2}\lambda(Q_0)\ln\left(\frac{Q^2}{Q_0^2}\right)}$$

when Q grows	$\longrightarrow$	$\lambda(Q)$ hits a pole $\rightarrow$ triviality

Imposing that $\lambda(Q)$ is finite, gives a scale dependent bound on M_H:

$$\boxed{\frac{1}{\lambda(\Lambda)} > 0 \quad \longrightarrow \quad M_H^2 < \frac{8\pi^2 v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)}}$$

where we have set $Q \rightarrow \Lambda$ and $Q_0 \rightarrow v$.

Vacuum stability: $\boxed{\lambda(Q) > 0}$

For small λ ($\leftrightarrow$ small M_H) the last term in $d\lambda/dt = \ldots$ dominates and:

$$\lambda(\Lambda) = \lambda(v) - \frac{3}{4\pi^2} y_t^4 \log\left(\frac{\Lambda^2}{v^2}\right)$$

from where a first rough lower bound is derived:

$$\boxed{\lambda(\Lambda) > 0 \quad \longrightarrow \quad M_H^2 > \frac{3v^2}{2\pi^2} y_t^4 \log\left(\frac{\Lambda^2}{v^2}\right)}$$

More accurate analyses use 2-loop renormalization group improved V_{eff}.

Fine-tuning: M_H is unstable to ultraviolet corrections

$$M_H^2 = (M_H^0)^2 + \frac{g^2}{16\pi^2}\Lambda^2 \cdot \text{constant} + \text{ higher orders}$$

$M_H^0 \rightarrow$ fundamental parameter of the SM
$\Lambda \rightarrow$ UV-cutoff scale

Unless $\Lambda \simeq$ EW-scale, fine-tuning is required to get $M_H \simeq$ EW-scale.

More generally, the all order calculation of V_{eff} would give:

$$\bar{\mu}^2 = \mu^2 + \Lambda^2 \sum_{n=0}^{\infty} c_n(\lambda_i) \log^n(\Lambda/Q)$$

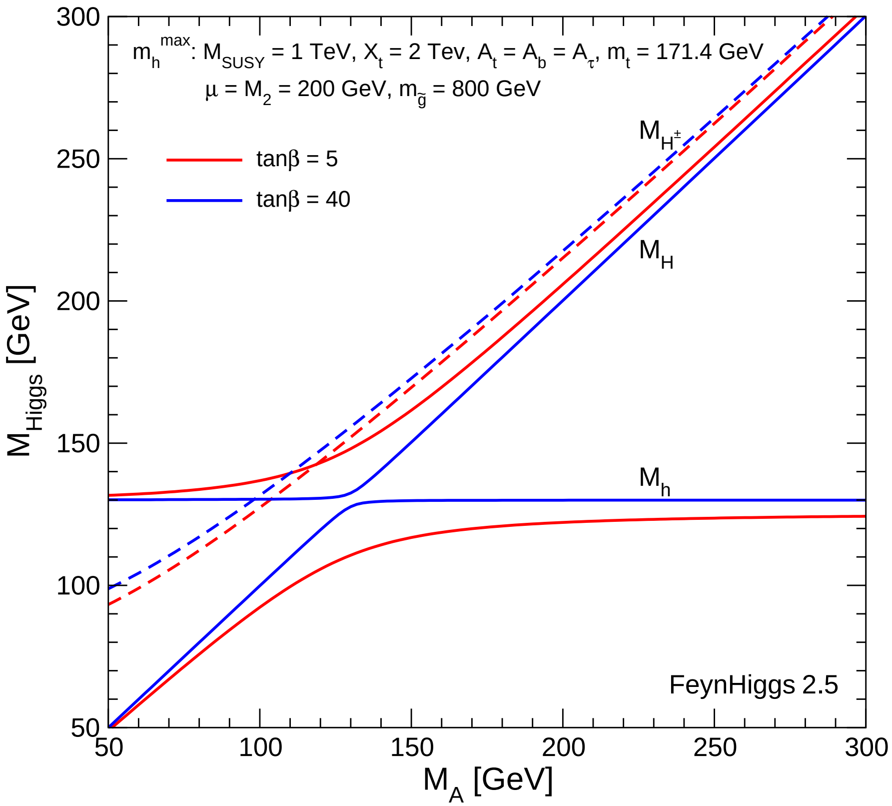
Veltman condition: the absence of large quadratic corrections is guaranteed by:

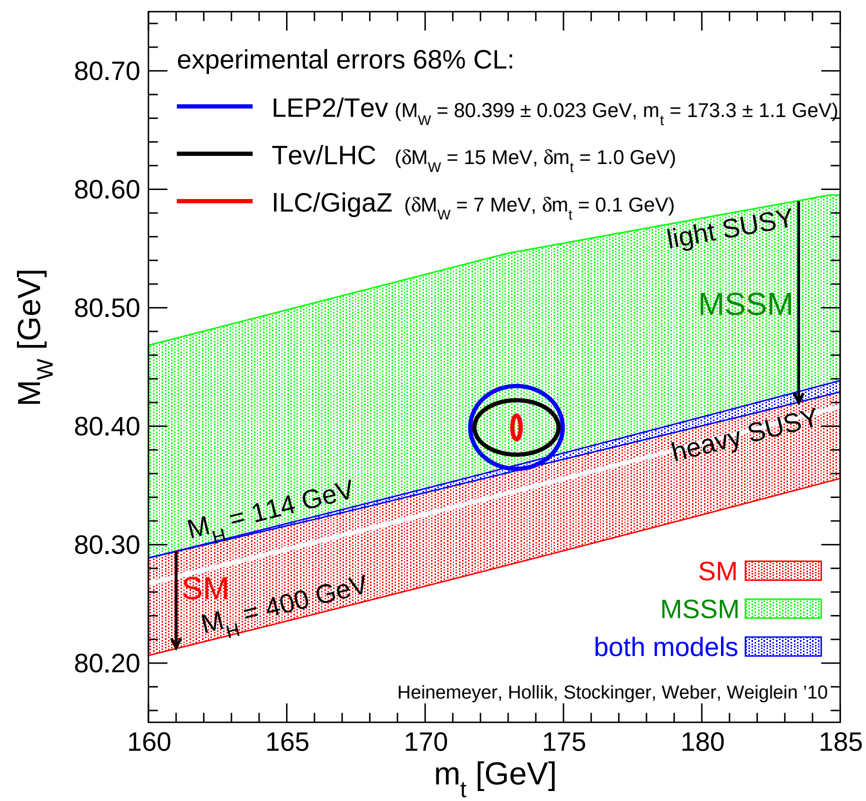
$$\sum_{n=0}^{\infty} c_n(\lambda_i) \log^n(\Lambda/M_H) = 0 \quad \text{or better} \sum_{n=0}^{n_{max}} c_n(\lambda_i) \log^n(\Lambda/M_H) < \frac{v^2}{\Lambda^2}$$

where: $n_{max} = 0, 1, 2 \longrightarrow \Lambda \simeq 2, 15, 50$ TeV.

Beyond SM: new physics at the TeV scale can be a better fit

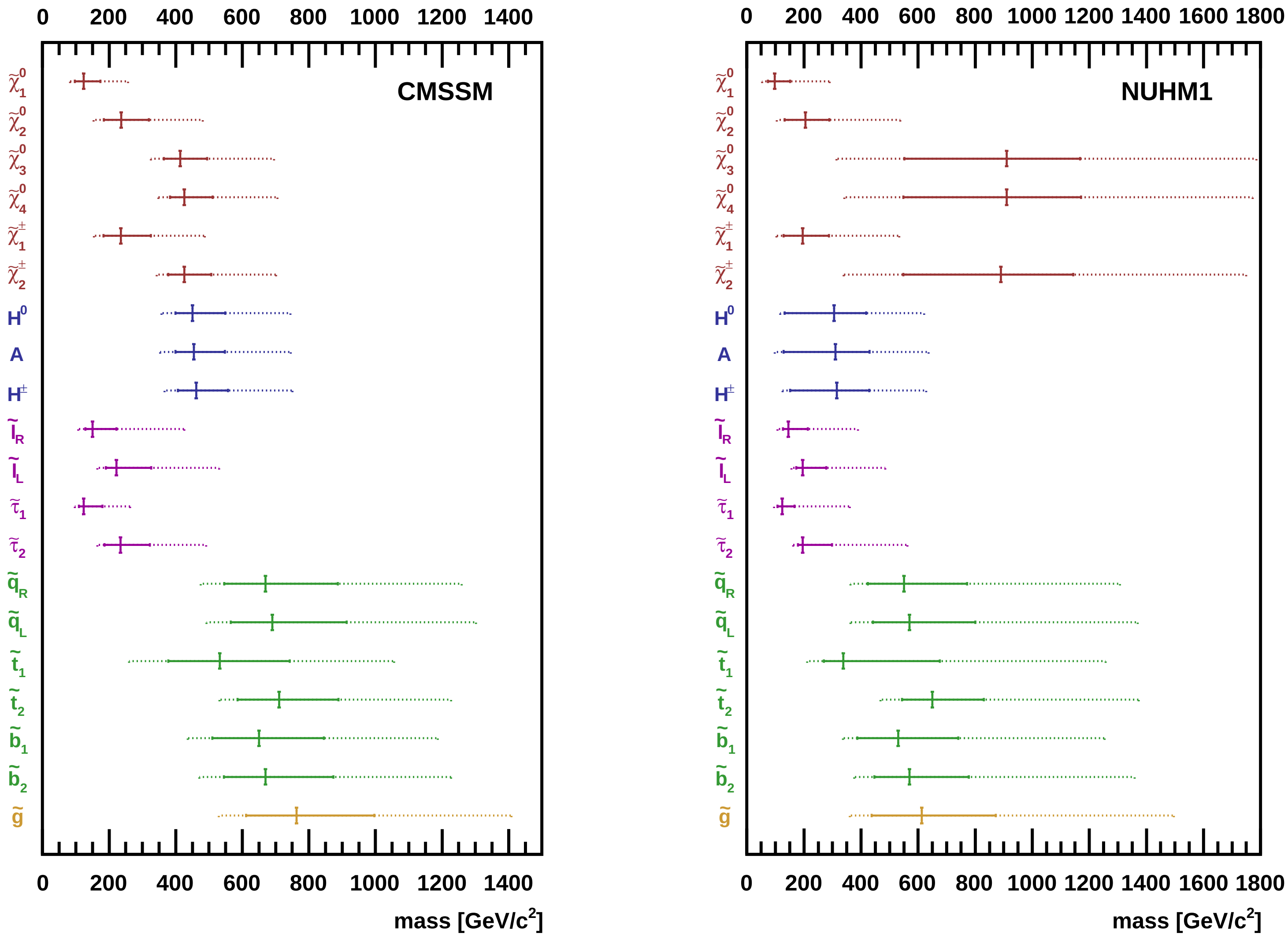
Ex. 1: MSSM





- ▷ a light scalar Higgs boson, along with a heavier scalar, a pseudoscalar and a charged scalar;
- ▷ similar although less constrained pattern in any 2HDM;
- ▷ MSSM main uncertainty: unknown masses of SUSY particles.
- ▷ precise measurement of mass spectrum and couplings will be crucial.

... mass spectrum at a glance ... (MasterCode by Buchmüller et al., '09)



▷ CMSSM/NUHM1 (different choice of soft SUSY breaking mass terms);

▷ all available data (exp.) and all known corrections (th.) included in fit;

▷ most masses accessible to early LHC, several within reach of ILC.

The Higgs bosons of the MSSM: example of 2HDM

Two complex $SU(2)_L$ doublets, with hypercharge $Y=\pm 1$:

$$\Phi_u = \begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix} \quad , \quad \Phi_d = \begin{pmatrix} \phi_d^0 \\ \phi_d^- \end{pmatrix}$$

and (super)potential (Higgs part only):

$$\begin{aligned} V_H &= (|\mu|^2 + m_u^2)|\Phi_u|^2 + (|\mu|^2 + m_d^2)|\Phi_d|^2 - \mu B \epsilon_{ij}(\Phi_u^i \Phi_d^j + h.c.) \\ &+ \frac{g^2 + g'^2}{8}\left(|\Phi_u|^2 - |\Phi_d|^2\right)^2 + \frac{g^2}{2}|\Phi_u^\dagger \Phi_d|^2 \end{aligned}$$

The EW symmetry is spontaneously broken by choosing:

$$\langle \Phi_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_u \end{pmatrix} \quad , \quad \langle \Phi_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d \\ 0 \end{pmatrix}$$

normalized to preserve the SM relation: $\boxed{M_W^2 = g^2(v_u^2 + v_d^2)/4 = g^2 v^2/4}$.

Five physical scalar/pseudoscalar degrees of freedom:

$$
\begin{aligned}
h^0 &= -(\sqrt{2}\mathrm{Re}\Phi_d^0 - v_d)\sin\alpha + (\sqrt{2}\mathrm{Re}\Phi_u^0 - v_u)\cos\alpha \\
H^0 &= (\sqrt{2}\mathrm{Re}\Phi_d^0 - v_d)\cos\alpha + (\sqrt{2}\mathrm{Re}\Phi_u^0 - v_u)\sin\alpha
\end{aligned}
$$

$$A^0 = \sqrt{2}\left(\mathrm{Im}\Phi_d^0\sin\beta + \mathrm{Im}\Phi_u^0\cos\beta\right)$$

$$H^\pm = \Phi_d^\pm\sin\beta + \Phi_u^\pm\cos\beta$$

where $\boxed{\tan\beta = v_u/v_d}$.

All masses can be expressed (at tree level) in terms of $\boxed{\tan\beta \text{ and } M_A}$:

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

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

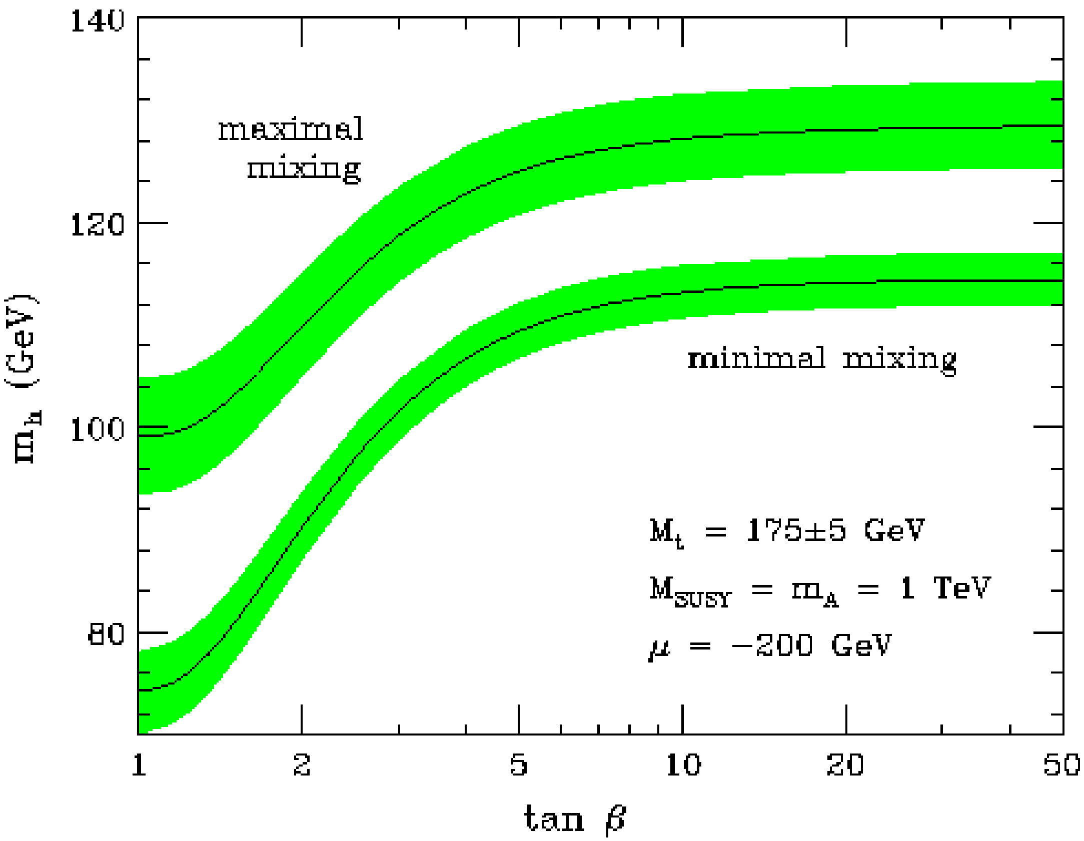
Notice: tree level upper bound on M_h: $\boxed{M_h^2 \leq M_Z^2\cos 2\beta \leq M_Z^2}$!

Higgs masses greatly modified by radiative corrections.

In particular, the upper bound on M_h becomes:

$$M_h^2 \leq M_Z^2 + \frac{3g^2 m_t^2}{8\pi^2 M_W^2}\left[\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right]$$

where $M_S \equiv (M_{\tilde{t}_1}^2 + M_{\tilde{t}_2}^2)/2$ while X_t is the top squark mixing parameter:



$$\begin{pmatrix} M_{Q_t}^2 + m_t^2 + D_L^t & m_t X_t \\ m_t X_t & M_{R_t}^2 + m_t^2 + D_R^t \end{pmatrix}$$

with $X_t \equiv A_t - \mu \cot\beta$.

$$D_L^t = (1/2 - 2/3 \sin\theta_W) M_Z^2 \cos 2\beta$$
$$D_R^t = 2/3 \sin^2\theta_W M_Z^2 \cos 2\beta$$

Higgs boson couplings to SM gauge bosons:

Some phenomelogically important ones:

$$g_{hVV} = g_V M_V \sin(\beta-\alpha) g^{\mu\nu} \quad , \quad g_{HVV} = g_V M_V \cos(\beta-\alpha) g^{\mu\nu}$$

where $g_V = 2M_V/v$ for $V = W, Z$, and

$$g_{hAZ} = \frac{g\cos(\beta-\alpha)}{2\cos\theta_W}(p_h - p_A)^\mu \quad , \quad g_{HAZ} = -\frac{g\sin(\beta-\alpha)}{2\cos\theta_W}(p_H - p_A)^\mu$$

Notice: $\boxed{g_{AZZ} = g_{AWW} = 0}$, $\boxed{g_{H^\pm ZZ} = g_{H^\pm WW} = 0}$

Decoupling limit: $\boxed{M_A \gg M_Z} \longrightarrow \begin{cases} M_h \simeq M_h^{max} \\ M_H \simeq M_{H^\pm} \simeq M_A \end{cases}$

$$\cos^2(\beta-\alpha) \simeq \frac{M_Z^4 \sin^2 4\beta}{M_A^4} \longrightarrow \begin{cases} \cos(\beta-\alpha) \to 0 \\ \sin(\beta-\alpha) \to 1 \end{cases}$$

The only low energy Higgs is $h \simeq H_{SM}$.

Higgs boson couplings to quarks and leptons:

Yukawa type couplings, Φ_u to up-component and Φ_d to down-component of $SU(2)_L$ fermion doublets. Ex. (3^{rd} generation quarks):

$$\mathcal{L}_{Yukawa} = h_t \left[\bar{t}P_L t\Phi_u^0 - \bar{t}P_L b\Phi_u^+\right] + h_b \left[\bar{b}P_L b\Phi_d^0 - \bar{b}P_L t\Phi_d^-\right] + \text{h.c.}$$

and similarly for leptons. The corresponding couplings can be expressed as ($y_t, y_b \to$ SM):

$$\begin{aligned}
g_{ht\bar{t}} &= \frac{\cos\alpha}{\sin\beta} y_t = \left[\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)\right] y_t \\
g_{hb\bar{b}} &= -\frac{\sin\alpha}{\cos\beta} y_b = \left[\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\right] y_b \\
g_{Ht\bar{t}} &= \frac{\sin\alpha}{\sin\beta} y_t = \left[\cos(\beta-\alpha) - \cot\beta\sin(\beta-\alpha)\right] y_t \\
g_{Hb\bar{b}} &= \frac{\cos\alpha}{\cos\beta} y_b = \left[\cos(\beta-\alpha) + \tan\beta\sin(\beta-\alpha)\right] y_b \\
g_{At\bar{t}} &= \cot\beta y_t \quad , \quad g_{Ab\bar{b}} = \tan\beta y_b \\
g_{H^\pm t\bar{b}} &= \frac{g}{2\sqrt{2}M_W}\left[m_t\cot\beta(1+\gamma_5) + m_b\tan\beta(1-\gamma_5)\right]
\end{aligned}$$

Notice: consistent decoupling limit behavior.

Higgs couplings modified by radiative corrections

Most important effects:

- Corrections to $\cos(\beta-\alpha)$: crucial in decoupling behavior.

$$\cos(\beta-\alpha) = K\left[\frac{M_Z^2 \sin 4\beta}{2M_A^2} + \mathcal{O}\left(\frac{M_Z^4}{M_A^4}\right)\right]$$

where

$$K \equiv 1 + \frac{\delta\mathcal{M}_{11}^2 - \delta\mathcal{M}_{22}^2}{2M_Z^2 \cos 2\beta} - \frac{\delta\mathcal{M}_{12}^2}{M_Z^2 \sin 2\beta}$$

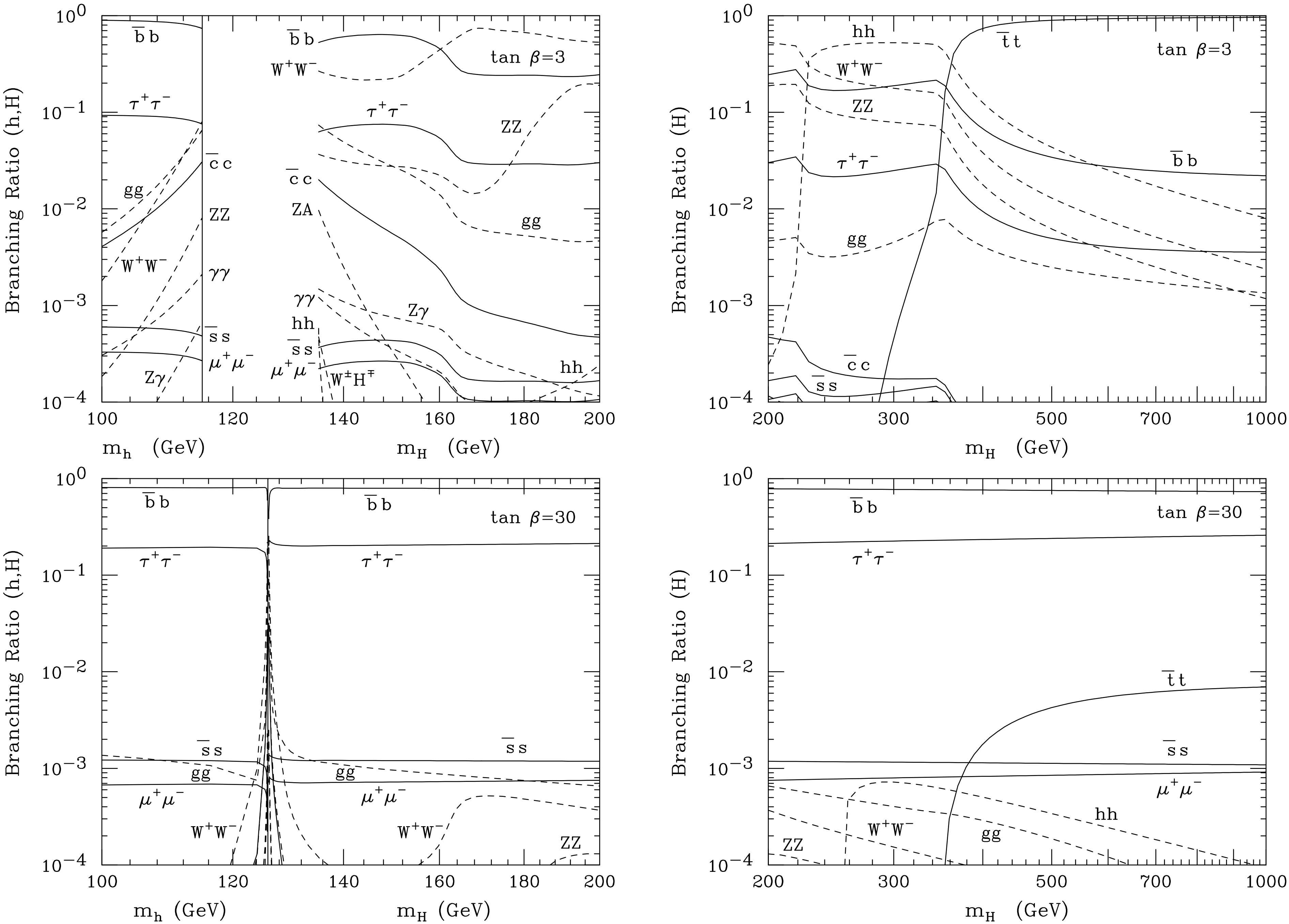
$\delta\mathcal{M}_{ij} \longrightarrow$ corrections to the CP-even scalar mass matrix.

- Corrections to 3$^{\rm rd}$ generation Higgs-fermion Yukawa couplings.

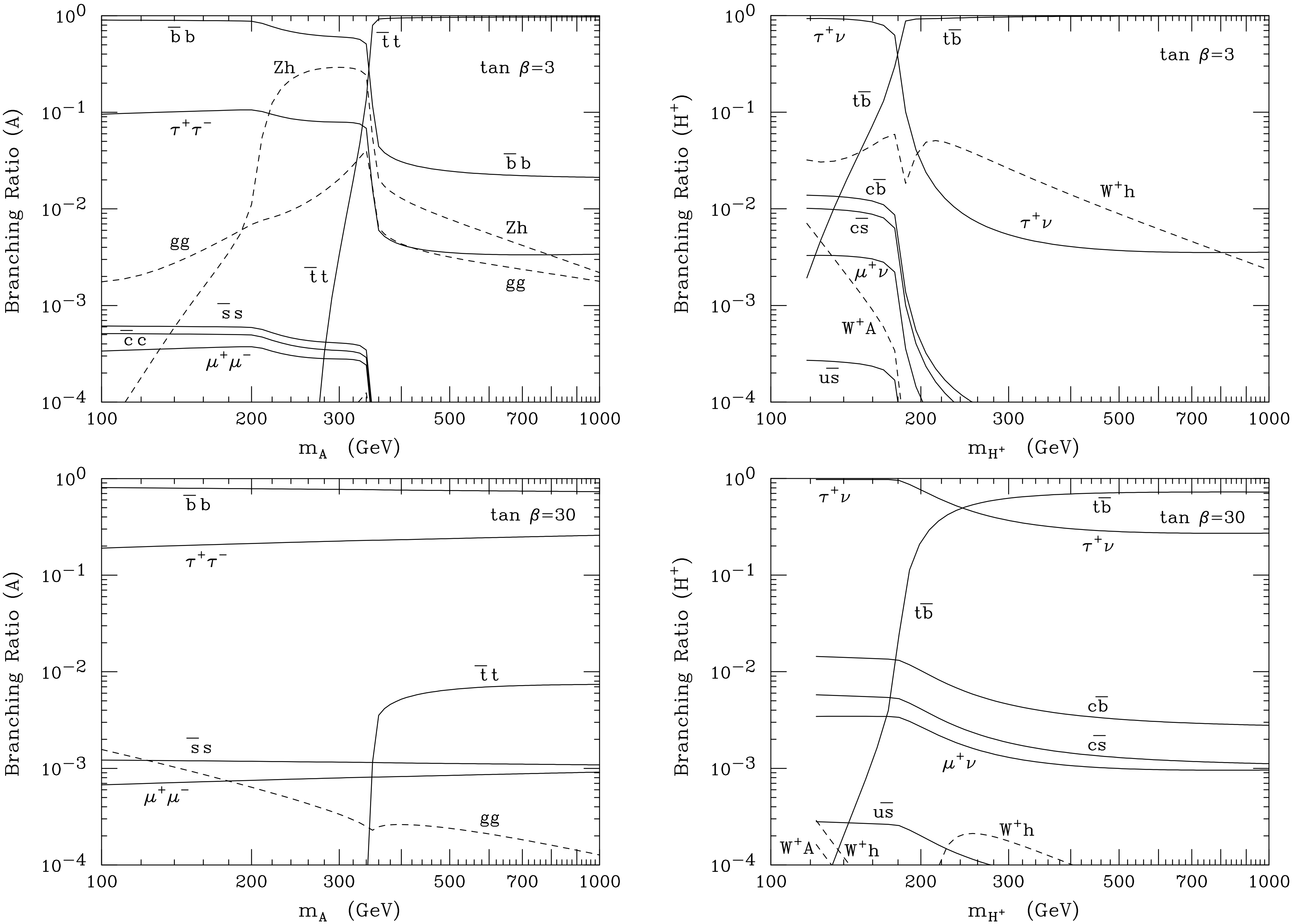
$$-\mathcal{L}_{eff} = \epsilon_{ij}\left[(h_b+\delta h_b)\bar{b}_R H_d^i Q_L^j + (h_t+\delta h_t)\bar{t}_R H_u^j Q_L^i\right] + \Delta h_t \bar{t}_R Q_L^k H_d^{k*} + \Delta h_b \bar{b}_R Q_L^k H_u^{k*} + \text{h.c.}$$

$$\begin{aligned} m_b &= \frac{h_b v}{\sqrt{2}} \cos\beta \left(1 + \frac{\delta h_b}{h_b} + \frac{\Delta h_b \tan\beta}{h_b}\right) \equiv \frac{h_b v}{\sqrt{2}} \cos\beta (1+\Delta_b) \\ m_t &= \frac{h_t v}{\sqrt{2}} \sin\beta \left(1 + \frac{\delta h_t}{h_t} + \frac{\Delta h_t \tan\beta}{h_t}\right) \equiv \frac{h_t v}{\sqrt{2}} \sin\beta (1+\Delta_t) \end{aligned}$$

MSSM Higgs boson branching ratios, possible scenarios:

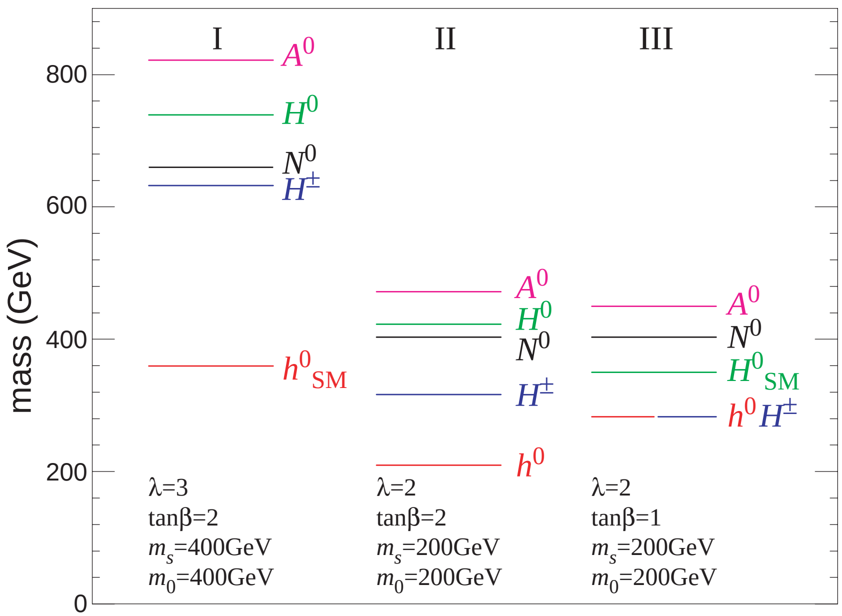


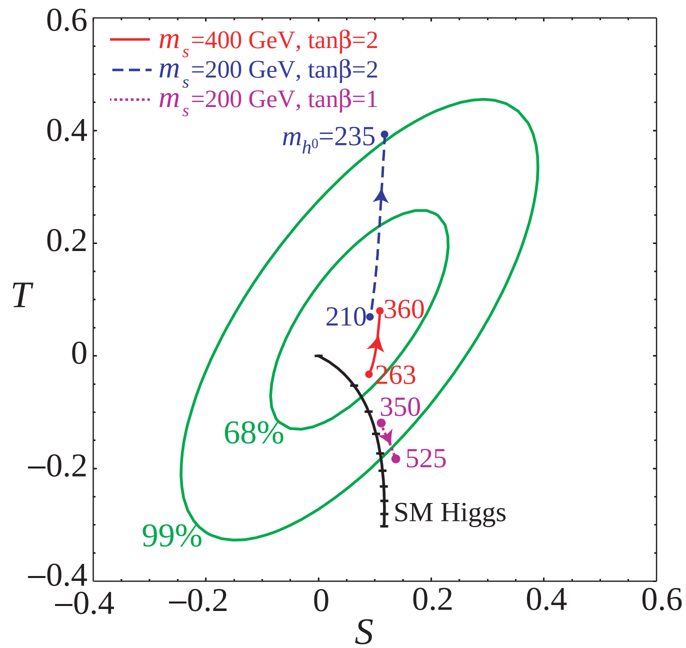
MSSM Higgs boson branching ratios, possible scenarios:



Beyond SM: new physics at the TeV scale can be a better fit

Ex. 2: "Fat Higgs" models





(Harnik, Kribs, Larson, and Murayama, PRD 70 (2004) 015002)

▷ supersymmetric theory of a composite Higgs boson;

▷ moderately heavy lighter scalar Higgs boson, along with a heavier scalar, a pseudoscalar and a charged scalar;

▷ consistent with EW precision measurements without fine tuning.