Outline of Lecture II

- SM Higgs boson physics depends just on $M_H$: $M_H$ highly constrained!
- **Quantum effects** leading players in constraining $M_H$:
  - $\rightarrow$ branching ratios (see end of last lecture): important corrections;
  - $\rightarrow$ 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:

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

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

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

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

QCD corrections dominant:

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

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

$$
\Delta_t = \left( \frac{\alpha_s(M_H)}{\pi} \right)^2 \left[ 1.57 - \frac{2}{3} \ln \frac{M_H^2}{m_t^2} + \frac{1}{9} \ln^2 \frac{\bar{m}_q^2(M_H)}{M_H^2} \right]
$$
Consist of both virtual and real corrections:
• Large Logs absorbed into $\overline{MS}$ quark mass

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

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

where (from renormalization group equation)

$$f(x) = \left( \frac{25}{6} x \right)^{\frac{12}{25}} [1 + 1.014x + \ldots] \text{ for } m_c < \mu < m_b$$

$$f(x) = \left( \frac{23}{6} x \right)^{\frac{12}{23}} [1 + 1.175x + \ldots] \text{ for } m_b < \mu < m_t$$

$$f(x) = \left( \frac{7}{2} x \right)^{\frac{4}{7}} [1 + 1.398x + \ldots] \text{ for } \mu > m_t$$

• Large corrections, when $M_H \gg m_Q$

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

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:

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

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

\[
A^H_q(\tau) = \frac{3}{2} \tau [1 + (1 - \tau)f(\tau)]
\]

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

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 $\Gamma(H \rightarrow gg(q), q\bar{q}g)$ agrees with $m_t \gg M_H$ result at 10%

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

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

Dominant soft/collinear radiation do not resolve the Higgs boson coupling to gluons $\rightarrow$ QCD corrections are just a (big) rescaling factor
NLO QCD corrections almost $60 - 70\%$ of LO result in the low mass region:

$$\delta(H \to gg)$$

$$\Gamma = \Gamma_{LO}(1+\delta)$$

$$\mu = M_H$$

$$M_t = 175 \text{ GeV}$$

solid line $\rightarrow$ full massive NLO calculation

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

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

$\rightarrow$ perturbative stabilization.
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
  \[
  M_i \to M_i \left( 1 + \frac{H}{v} \right) \quad (i = f, W, Z)
  \]
  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**
  \[
  \lim_{p_H \to 0} A(X \to Y + H) = \frac{1}{v} \sum_i M_i \frac{\partial}{\partial M_i} A(X \to Y)
  \]
  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:

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

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

\[
A_f^H = 2\tau \left[1 + (1 - \tau)f(\tau)\right]
\]

\[
A_W^H(\tau) = -\left[2 + 3\tau + 3\tau(2 - \tau)f(\tau)\right]
\]

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

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 \(\sim 1 - 3\%\).
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.

\[
M_W, M_Z \rightarrow \quad \begin{array}{c}
\text{H} \\
W,Z \\
W,Z
\end{array}
\]

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

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

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

- New physics at the scale \( \Lambda \) will appear as higher dimension effective operators.
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.

$m_W = 80.399 \pm 0.023$ GeV

$m_t = 173.3 \pm 1.1$ GeV

\[ \downarrow \]

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

$M_H < 158$ (185) GeV

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

$M_H > 114.4$ GeV (LEP)

$M_H \neq 158 - 175$ 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 $\Lambda$. The Higgs sector of the SM actually contains two unknowns: $M_H$ and $\Lambda$.

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

$\rightarrow$ $M_H$ 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 ($s \gg M_V^2$)

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

($V^i_L =$ longitudinal weak gauge boson; $\omega^i =$ associated Goldstone boson).

Example: $W_L^+ W_L^- \to W_L^+ W_L^-$

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

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

$$\Downarrow$$

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

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

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

\[ \downarrow \]

\[ |a_l|^2 = \text{Im}(a_l) \quad \longrightarrow \quad |\text{Re}(a_l)| \leq \frac{1}{2} \]

Most constraining condition for \( W^+_L W^-_L \rightarrow W^+_L W^-_L \) from

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

\[ |\text{Re}(a_0)| \leq \frac{1}{2} \quad \longrightarrow \quad M_H < 870 \text{ GeV} \]

Best constraint from coupled channels \((2W^+_L W^-_L + Z_L Z_L)\):

\[ a_0 \xrightarrow{s \gg \frac{M_H^2}{8\pi v^2}} - \frac{5M_H^2}{32\pi v^2} \quad \longrightarrow \quad M_H < 780 \text{ GeV} \]
Observe that: if there is no Higgs boson, i.e. $M_H \gg s$:

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

Imposing the unitarity constraint $\sqrt{s} < 1.8$ TeV

Most restrictive constraint $\sqrt{s} < 1.2$ 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 $\lambda$ is more complicated:

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

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

Still, for large $\lambda$ (↔ 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 → $\lambda(Q)$ hits a pole → triviality

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

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

where we have set $Q \rightarrow \Lambda$ and $Q_0 \rightarrow v$. 
Vacuum stability: $\lambda(Q) > 0$

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

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

from where a first rough lower bound is derived:

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

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:

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

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

\begin{itemize}
  \item CMSSM/NUHM1 (different choice of soft SUSY breaking mass terms);
  \item all available data (exp.) and all known corrections (th.) included in fit;
  \item most masses accessible to early LHC, several within reach of ILC.
\end{itemize}

(MasterCode by Buchmüller et al., ’09)
The Higgs bosons of the MSSM: example of 2HDM

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

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

and (super)potential (Higgs part only):

$$
V_H = (|\mu|^2 + m_u^2)|\Phi_u|^2 + (|\mu|^2 + m_d^2)|\Phi_d|^2 - \mu B\epsilon_{ij}(\Phi_u^i \Phi_d^j + \text{h.c.}) + \frac{g^2 + g'^2}{8} (|\Phi_u|^2 - |\Phi_d|^2)^2 + \frac{g^2}{2} |\Phi_u \Phi_d|^2
$$

The EW symmetry is spontaneously broken by choosing:

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

normalized to preserve the SM relation:

$$
M_W^2 = g^2 (v_u^2 + v_d^2)/4 = g^2 v^2/4.
$$
Five physical scalar/pseudoscalar degrees of freedom:

\[
\begin{align*}
    h^0 &= - (\sqrt{2} \text{Re}\Phi_d^0 - v_d) \sin \alpha + (\sqrt{2} \text{Re}\Phi_u^0 - v_u) \cos \alpha \\
    H^0 &= (\sqrt{2} \text{Re}\Phi_d^0 - v_d) \cos \alpha + (\sqrt{2} \text{Re}\Phi_u^0 - v_u) \sin \alpha \\
    A^0 &= \sqrt{2} \left( \text{Im}\Phi_d^0 \sin \beta + \text{Im}\Phi_u^0 \cos \beta \right) \\
    H^\pm &= \Phi_d^\pm \sin \beta + \Phi_u^\pm \cos \beta
\end{align*}
\]

where \( \tan \beta = v_u/v_d \).

All masses can be expressed (at tree level) in terms of \( \tan \beta \) and \( M_A \): 

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

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

Notice: tree level upper bound on \( M_h \): \( M_h^2 \leq M_Z^2 \cos 2\beta \leq M_Z^2 \).
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 $M_S \equiv (M_{t_1}^2 + M_{t_2}^2)/2$ while $X_t$ is the top squark mixing parameter:

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

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

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

$$D_R^t = 2/3 \sin^2 \theta_W M_Z^2 \cos 2\beta$$

$M_t = 175 \pm 5$ GeV

$M_{\text{SUSY}} = m_A = 1$ TeV

$\mu = -200$ GeV
Higgs boson couplings to SM gauge bosons:

Some phenomelogically important ones:

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

where \( g_V = 2M_V/v \) for \( V = W, Z \), and

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

Notice: \( g_{AZZ} = g_{AWW} = 0 \), \( g_{H\pm ZZ} = g_{H\pm WW} = 0 \)

Decoupling limit: \( M_A \gg M_Z \rightarrow \left\{ \begin{array}{l} M_h \simeq M_h^{\text{max}} \\ M_H \simeq M_{H\pm} \simeq M_A \end{array} \right. \)

\[ \cos^2(\beta - \alpha) \simeq \frac{M_Z^4 \sin^2 4\beta}{M_A^4} \rightarrow \left\{ \begin{array}{l} \cos(\beta - \alpha) \rightarrow 0 \\ \sin(\beta - \alpha) \rightarrow 1 \end{array} \right. \]

The only low energy Higgs is \( h \simeq H_{SM} \).
Higgs boson couplings to quarks and leptons:

Yukawa type couplings, $\Phi_u$ to up-component and $\Phi_d$ to down-component of $SU(2)_{L}$ fermion doublets. Ex. (3rd generation quarks):

$$L_{Yukawa} = h_t [\bar{t} P_L t \Phi^0_u - \bar{t} P_L b \Phi^+_u] + h_b [\bar{b} P_L b \Phi^0_d - \bar{b} P_L t \Phi^-_d] + h.c.$$  

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

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

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

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

  $\delta M_{ij}$ $\rightarrow$ corrections to the CP-even scalar mass matrix.

- **Corrections to** 3rd generation Higgs-fermion Yukawa couplings.

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

  \[
  m_b = \frac{h_b v}{\sqrt{2}} \cos \beta \left( 1 + \frac{\delta h_b}{h_b} + \frac{\Delta h_b \tan \beta}{h_b} \right) \equiv \frac{h_b v}{\sqrt{2}} \cos \beta (1 + \Delta_b)
  \]

  \[
  m_t = \frac{h_t v}{\sqrt{2}} \sin \beta \left( 1 + \frac{\delta h_t}{h_t} + \frac{\Delta h_t \tan \beta}{h_t} \right) \equiv \frac{h_t v}{\sqrt{2}} \sin \beta (1 + \Delta_t)
  \]
MSSM Higgs boson branching ratios, possible scenarios:
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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.