Theoretical Aspects of Higgs Physics

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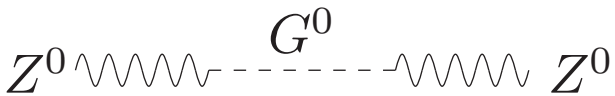
Berkeley workshop on searches for supersymmetry at the LHC

Outline

1. Theoretical framework for electroweak symmetry breaking (EWSB)
   - weakly coupled vs. strongly coupled EWSB dynamics
   - significance of the TeV scale
   - Higgs physics as a window to physics beyond the Standard Model
2. Standard Model (SM) Higgs boson
   - properties of the SM Higgs boson
   - implications of precision electroweak data
   - an upper Higgs mass bound
3. Extended Higgs sectors—2HDM, MSSM Higgs and beyond
   - The two-Higgs doublet model (2HDM)
   - Higgs sector of TeV-scale supersymmetry
   - The decoupling limit
4. Where do we stand? Where are we headed?

Framework for Electroweak Symmetry Breaking

The observed phenomena of the fundamental particles and their interactions can be explained by an SU(3)×SU(2)×U(1) gauge theory, in which the $W^{\pm}$, Z, quark and charged lepton masses arise from the interactions with (massless) Goldstone bosons $G^{\pm}$ and G^0, e.g.



The Goldstone bosons are a consequence of (presently unknown) EWSB dynamics, which could be ...

- weakly-interacting scalar dynamics, in which the scalar potential acquires a non-zero vacuum expectation value (vev) $v = 2m_W/g = (246\ \mathrm{GeV})^2$ [resulting in elementary Higgs bosons]

- strong-interaction dynamics (involving new matter and gauge fields) [technicolor, dynamical EWSB, Higgsless models, composite Higgs bosons, extra-dimensional symmetry breaking, ...]

Significance of the TeV Scale—Part 1

Let $\Lambda_{\rm EW}$ be energy scale of EWSB dynamics. For example:

- Elementary Higgs scalar ($\Lambda_{\rm EW} = m_h$).

- Strong EWSB dynamics ($e.g.$, $\Lambda_{\rm EW}^{-1}$ is the characteristic scale of bound states arising from new strong dynamics).

Consider $W_L^+ W_L^- \to W_L^+ W_L^-$ (L = longitudinal or equivalently, zero helicity) for $m_W^2 \ll s \ll \Lambda_{\rm EW}^2$. The corresponding amplitude, to leading order in g^2, but to all orders in the couplings that control the EWSB dynamics, is equal to the amplitude for $G^+ G^- \to G^+ G^-$ (where $G^\pm$ are the charged Goldstone bosons). The latter is universal, independent of the EWSB dynamics. This is a rigorous low-energy theorem.

Applying unitarity constraints to this amplitude yields a critical energy $\sqrt{s_c}$, above which unitarity is violated. This unitarity violation must be repaired by EWSB dynamics and implies that $\Lambda_{\rm EW} \lesssim \mathcal{O}\left(\sqrt{s_c}\right)$.

Unitarity of scattering amplitudes

Unitarity is equivalent to the conservation of probability in quantum mechanics. A violation of unitarity is tantamount to a violation of the principles of quantum mechanics—this is too sacred a principle to give up!

Consider the helicity amplitude $\mathcal{M}(\lambda_3\lambda_4\,;\,\lambda_1\lambda_2)$ for a $2 \to 2$ scattering process with initial [final] helicities λ_1, λ_2 [λ_3, λ_4]. The Jacob-Wick partial wave expansion is:

$$\mathcal{M}(\lambda_3\lambda_4\,;\,\lambda_1\lambda_2) = \frac{8\pi\sqrt{s}}{(p_i p_f)^{1/2}} e^{i(\lambda_i-\lambda_f)\phi} \sum_{J=J_0}^{\infty} (2J+1)\mathcal{M}^J_\lambda(s) d^J_{\lambda_i\lambda_f}(\theta)\,,$$

where p_i [p_f] is the incoming [outgoing] center-of-mass momentum, $\sqrt{s}$ is the center-of-mass energy, $\lambda \equiv \{\lambda_3\lambda_4\,;\,\lambda_1\lambda_2\}$ and

$$J_0 \equiv \max\{\lambda_i\,,\,\lambda_f\}\,, \quad \text{where} \quad \lambda_i \equiv \lambda_1 - \lambda_2\,, \quad \text{and} \quad \lambda_f \equiv \lambda_3 - \lambda_4\,.$$

Orthogonality of the d-functions allows one to project out a given partial wave amplitude. For example, for $W_L^+W_L^- \to W_L^+W_L^-$ (L stands for *longitudinal* and corresponds to $\lambda = 0$),

$$\mathcal{M}^{J=0} = \frac{1}{16\pi s}\int_{-s}^{0} dt\,\mathcal{M}(L,L\,;\,L,L)\,,$$

where $t = -\frac{1}{2}s(1-\cos\theta)$ in the limit where $m_W^2 \ll s$.

The $J = 0$ partial wave for $W_L^+ W_L^- \to W_L^+ W_L^-$ in the limit of $m_W^2 \ll s \ll \Lambda_{\rm EW}^2$ is equal to the corresponding amplitude for $G^+ G^- \to G^+ G^-$:

$$\mathcal{M}^{J=0} = \frac{G_F s}{16\pi\sqrt{2}}\,.$$

Partial wave unitarity implies that:

$$|\mathcal{M}^J|^2 \leq |\mathrm{Im}\ \mathcal{M}^J| \leq 1\,,$$

which gives

$$(\mathrm{Re}\ \mathcal{M}^J)^2 \leq |\mathrm{Im}\ \mathcal{M}^J| \left(1 - |\mathrm{Im}\ \mathcal{M}^J|\right) \leq \tfrac{1}{4}\,.$$

Setting $|\mathrm{Re}\ \mathcal{M}^{J=0}| \leq \frac{1}{2}$ yields $\sqrt{s_c}$. The most restrictive bound arises from the isospin zero channel $\sqrt{\frac{1}{6}}(2W_L^+ W_L^- + Z_L Z_L)$:

$$s_c = \frac{4\pi\sqrt{2}}{G_F} = (1.2\ \mathrm{TeV})^2\,.$$

Since unitarity cannot be violated, we conclude that $\Lambda_{\rm EW} \lesssim \sqrt{s_c}$. That is,

The dynamics of electroweak symmetry breaking must be exposed at or below the 1 TeV energy scale.

Significance of the TeV Scale—Part 2

How can we understand the magnitude of the EWSB scale? In the absence of new physics beyond the SM, its natural value would be the Planck scale (or perhaps the GUT scale or seesaw scale). The alternatives are:

- Naturalness is restored by a symmetry principle—supersymmetry at the TeV-scale—which ties the bosons to the more well-behaved fermions.

- The Higgs boson is an approximate Goldstone boson (generated by new TeV-scale physics)—the only other known mechanism for keeping an elementary scalar light.

- The Higgs boson is a composite scalar, with an inverse length of order the TeV-scale.

- The naturalness principle does not hold in this case. Unnatural choices for the EWSB parameters arise from other considerations (landscape?).

Higgs physics as a window to physics beyond the Standard Model (BSM)

Conventional wisdom from 2001–2010 was that if new physics did not appear in Run 2 of the Tevatron, then it would certainly show up in the first few fb^{-1} of LHC running. The Higgs search was likely to be a challenge, and any definitive discovery was relegated to a later date.

Today, the attitudes are reversed. The Higgs search is front and center, whereas it may take a longer time for a clear BSM signal to emerge. (Nevertheless, 2012 will be a very interesting year both for Higgs physics and BSM searches.)

Indeed, clarification of the mechanism of EWSB will likely be an essential step in the pursuit of BSM physics. The discovery the Higgs boson and its properties, and/or the exclusion of the Standard Model (SM) Higgs boson will have a profound impact on how we think about BSM physics.

The Higgs bosons can also couple to hidden sectors (which are singlets with respect to the SM) via the *Higgs portal*, $\mathscr{L}_{\rm int} = H^\dagger H f(\phi_{\rm hidden})$.

Higgs boson couplings in the Standard Model

At tree level (where $V = W^{\pm}$ or Z),

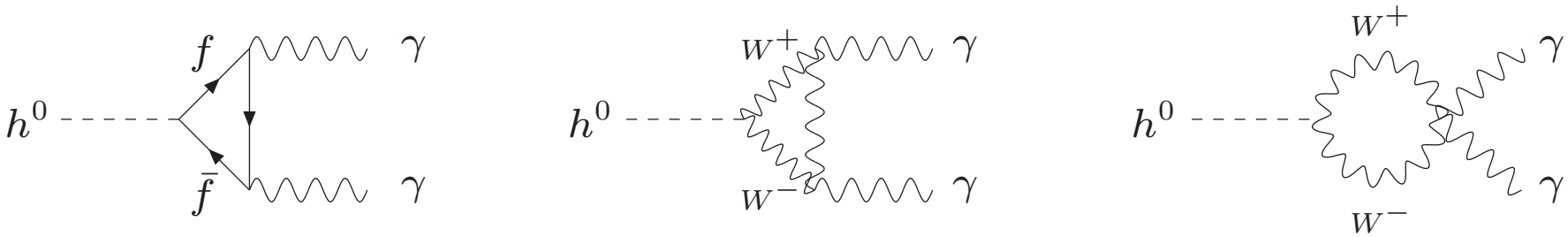
Vertex	Coupling
hVV	$2m_V^2/v$
$hhVV$	$2m_V^2/v^2$
hhh	$3m_h^2/v$
$hhhh$	$3m_h^2/v^2$
$hf\bar{f}$	m_f/v

At one-loop, the Higgs boson can couple to gluons and photons. Only particles in the loop with mass $\gtrsim \mathcal{O}(m_h)$ contribute appreciably.

One-loop Vertex	identity of particles in the loop
hgg	quarks
$h\gamma\gamma$	$W^{\pm}$, quarks and charged leptons
$hZ\gamma$	$W^{\pm}$, quarks and charged leptons

Higgs boson coupling to photons

At one-loop, the Higgs boson couples to photons via a loop of charged particles:



If charged scalars exist, they would contribute as well.

Importance of the loop-induced Higgs couplings for the LHC Higgs program

1. Dominant LHC Higgs production mechanism: gluon-gluon fusion. At leading order,

$$\frac{d\sigma}{dy}(pp \to h^0 + X) = \frac{\pi^2 \Gamma(h^0 \to gg)}{8 m_h^3} g(x_+, m_h^2) g(x_-, m_h^2) \,,$$

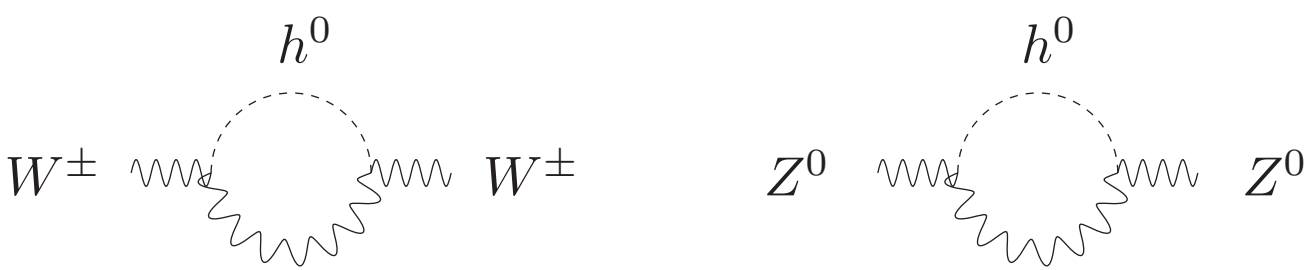
where $g(x, Q^2)$ is the gluon distribution function at the scale Q^2 and $x_\pm \equiv m_h e^{\pm y}/\sqrt{s}$, $y = \frac{1}{2} \ln \left(\frac{E+p_L}{E-p_L} \right)$.

2. For $m_h \simeq 120$ GeV, the discovery channel for the Higgs boson at the LHC is via the rare decay $h^0 \to \gamma\gamma$.

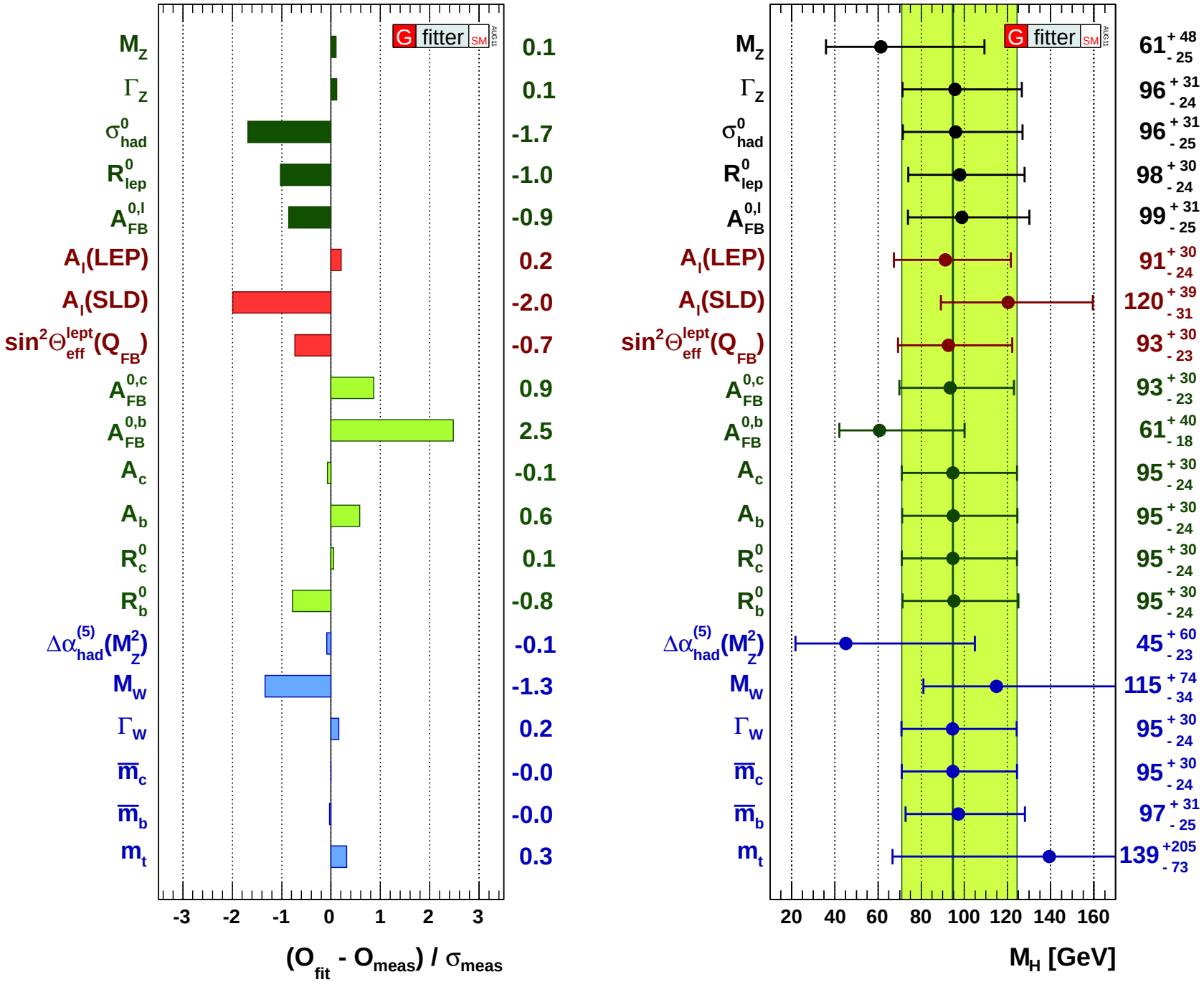
Expectations for the SM Higgs mass

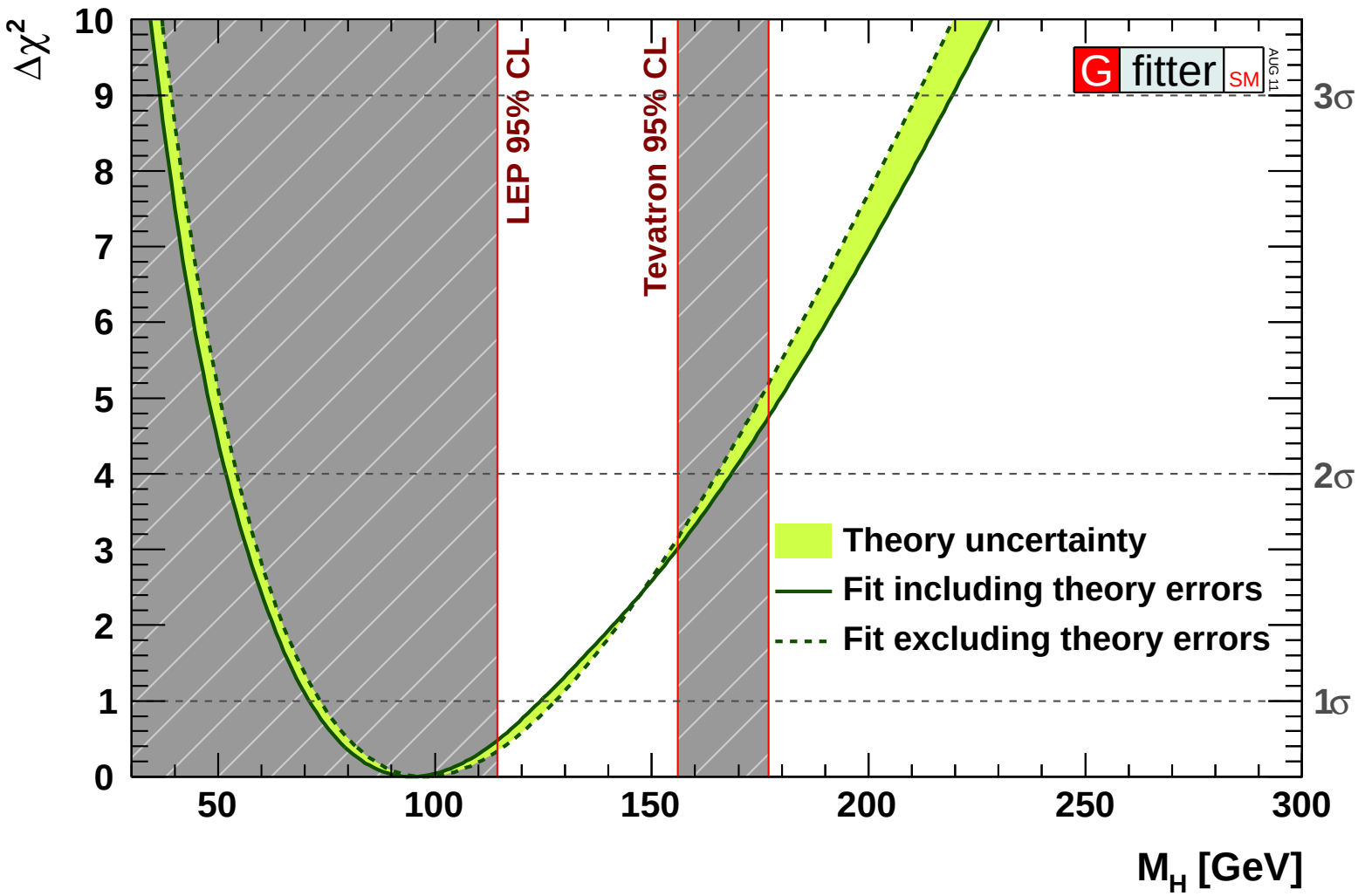
1. Consequences of precision electroweak data.

Very precise tests of the Standard Model are possible given the large sample of electroweak data from LEP, SLC and the Tevatron. Although the Higgs boson mass (m_h) is unknown, electroweak observables are sensitive to m_h through quantum corrections. For example, the W and Z masses are shifted slightly due to:



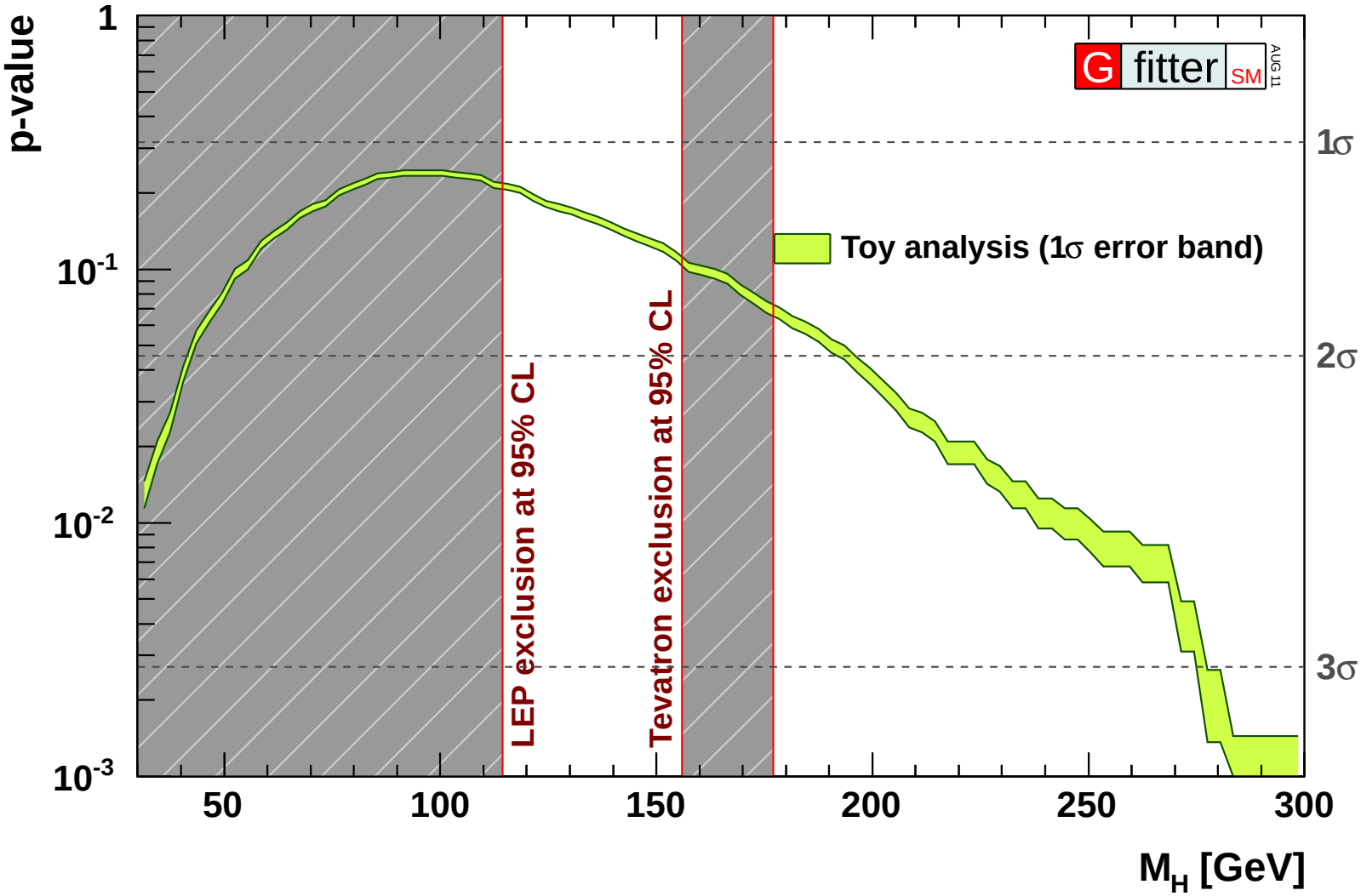
The m_h dependence of the above radiative corrections is logarithmic. Nevertheless, a global fit of many electroweak observables can determine the preferred value of m_h (assuming that the Standard Model is the correct description of the data).


G fitter SM
Aug11
M_Z 0.1
Γ_Z 0.1
σ^0_{had} -1.7
R^0_{lep} -1.0
$A^{0,l}_{FB}$ -0.9
A_l(LEP) 0.2
A_l(SLD) -2.0
$\sin^2\Theta^{lept}_{eff}(Q_{FB})$ -0.7
$A^{0,c}_{FB}$ 0.9
$A^{0,b}_{FB}$ 2.5
A_c -0.1
A_b 0.6
R^0_c 0.1
R^0_b -0.8
$\Delta\alpha^{(5)}_{had}(M^2_Z)$ -0.1
M_W -1.3
Γ_W 0.2
$\overline{m}_c$ -0.0
$\overline{m}_b$ -0.0
m_t 0.3
-3 -2 -1 0 1 2 3
$(O_{fit} - O_{meas}) / \sigma_{meas}$
G fitter SM
Aug11
M_Z 61^{+48}_{-25}
Γ_Z 96^{+31}_{-24}
σ^0_{had} 96^{+31}_{-25}
R^0_{lep} 98^{+30}_{-24}
$A^{0,l}_{FB}$ 99^{+31}_{-25}
A_l(LEP) 91^{+30}_{-24}
A_l(SLD) 120^{+39}_{-31}
$\sin^2\Theta^{lept}_{eff}(Q_{FB})$ 93^{+30}_{-23}
$A^{0,c}_{FB}$ 93^{+30}_{-23}
$A^{0,b}_{FB}$ 61^{+40}_{-18}
A_c 95^{+30}_{-24}
A_b 95^{+30}_{-24}
R^0_c 95^{+30}_{-24}
R^0_b 95^{+30}_{-24}
$\Delta\alpha^{(5)}_{had}(M^2_Z)$ 45^{+60}_{-23}
M_W 115^{+74}_{-34}
Γ_W 95^{+30}_{-24}
$\overline{m}_c$ 95^{+30}_{-24}
$\overline{m}_b$ 97^{+31}_{-25}
m_t 139^{+205}_{-73}
20 40 60 80 100 120 140 160
M_H [GeV]

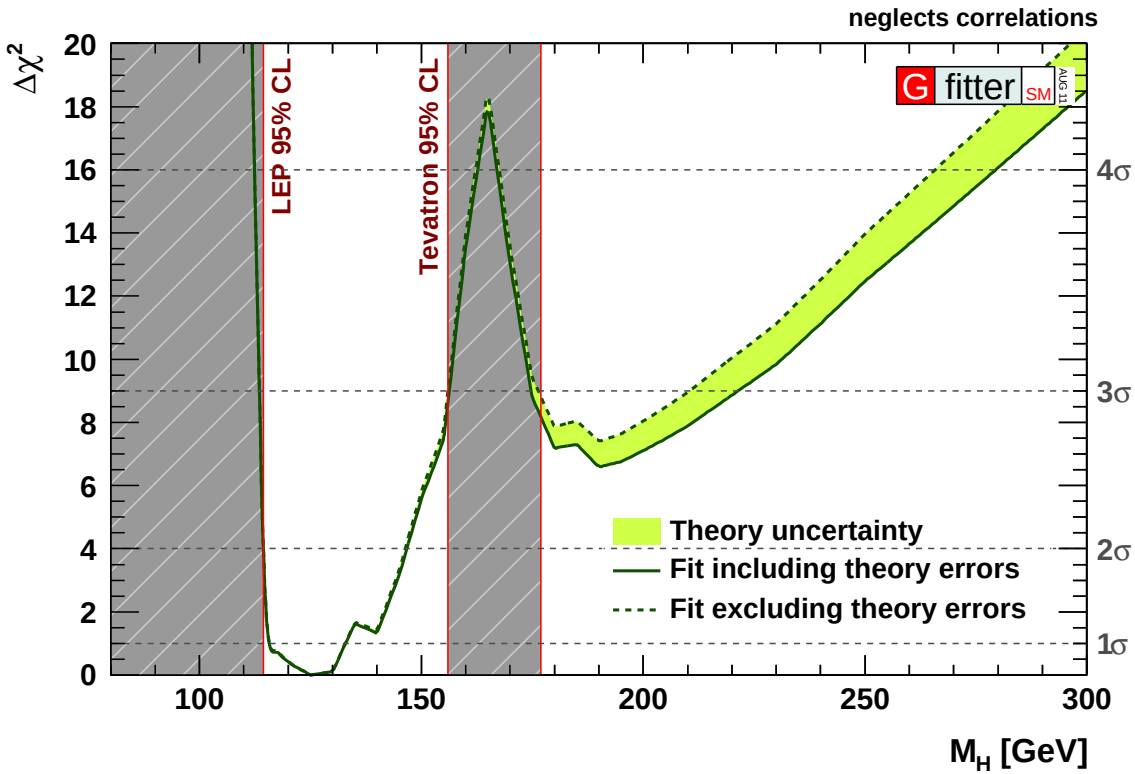


This result, which does *not* employ the direct Higgs search limits, corresponds to a upper bound of $m_h < 169$ GeV at 95% CL and $m_h < 200$ GeV at 99% CL. A similar result of the LEP Electroweak Working group quotes $m_h < 161$ GeV at 95% CL.

Moreover, the global fit to the SM is not too bad if 114 GeV $\lesssim m_h \lesssim$ 200 GeV.



Including the direct searches from LEP, Tevatron and the initial LHC Higgs search data prior to the summer of 2011, the GFITTER collaboration obtains a stronger constraint:



These results imply the existence of either:

- a SM-like Higgs boson with $114\ \mathrm{GeV} < m_h < 143\ \mathrm{GeV}$ at 95% CL; or
- new physics beyond the Standard Model, which provides additional corrections to precision electroweak observables that can compensate the effects of a heavier Higgs boson (or no Higgs boson at all!).

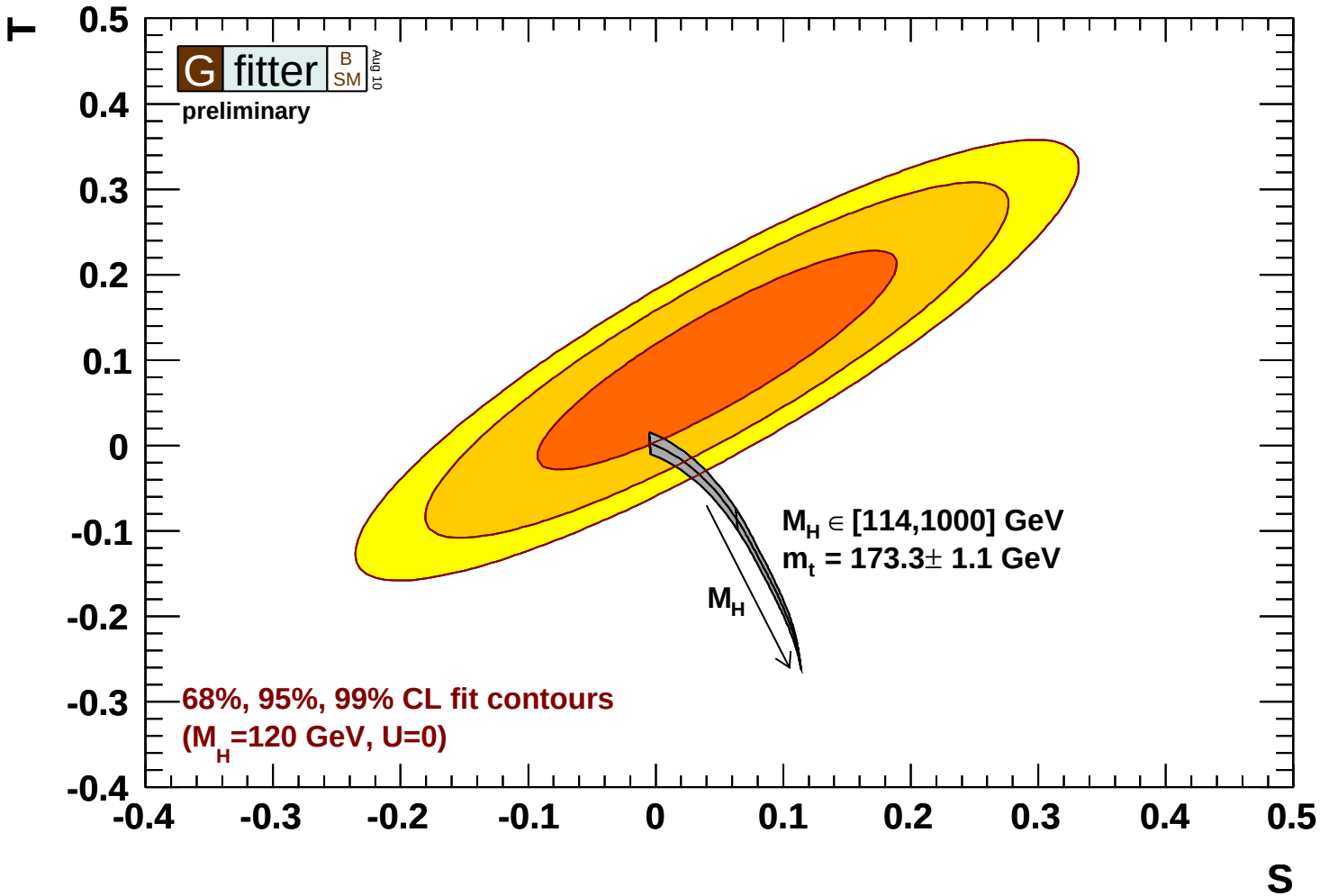
Can a Light Higgs Boson be avoided?

If new physics beyond the Standard Model (SM) exists, it almost certainly couples to W and Z bosons. Then, there will be additional shifts in the W and Z mass due to the appearance of new particles in loops. In many cases, these effects can be parameterized in terms of two quantities, S and T [Peskin and Takeuchi]:

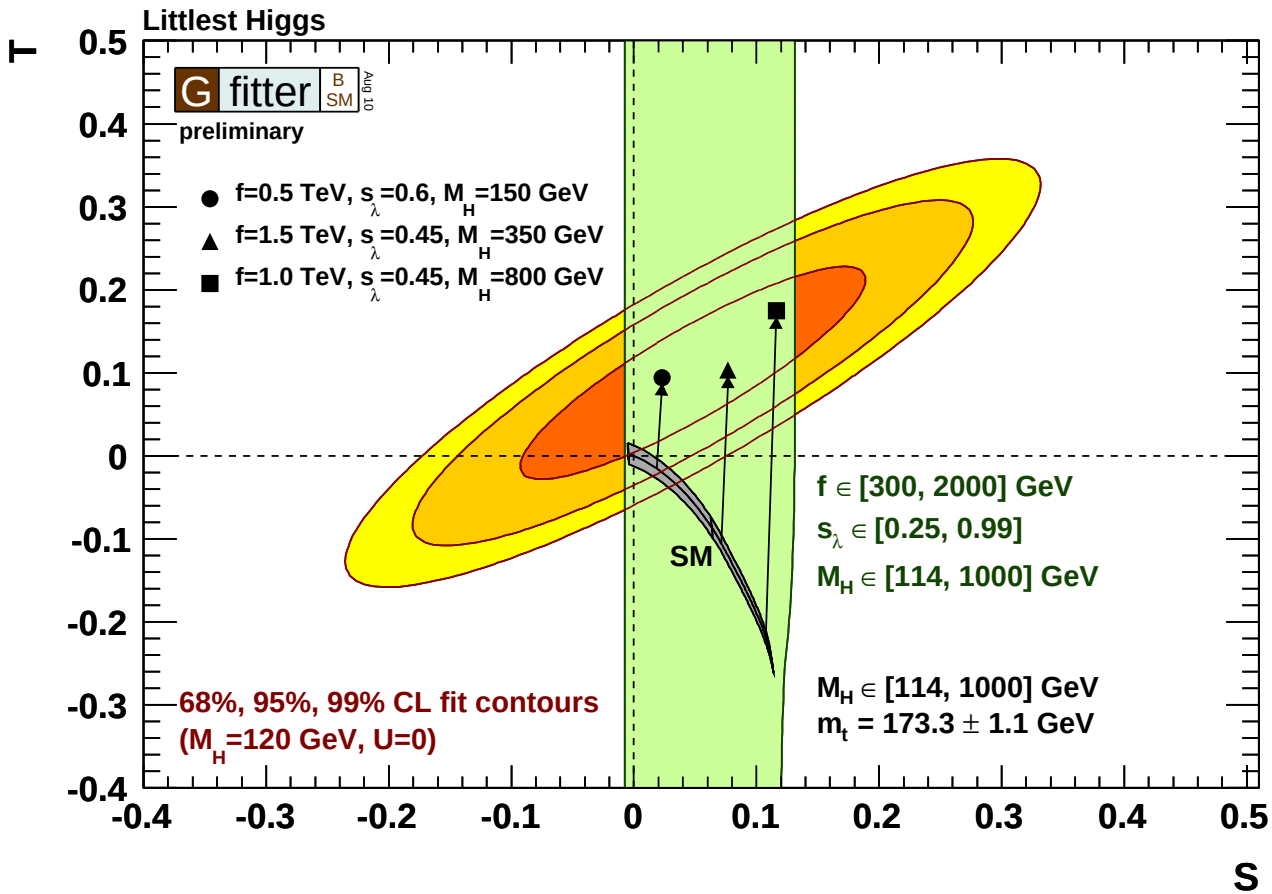
$$\overline{\alpha}\, T \equiv \frac{\Pi^{\rm new}_{WW}(0)}{m_W^2} - \frac{\Pi^{\rm new}_{ZZ}(0)}{m_Z^2}\,,$$

$$\frac{\overline{\alpha}}{4\overline{s}_Z^2\overline{c}_Z^2}\, S \equiv \frac{\Pi^{\rm new}_{ZZ}(m_Z^2) - \Pi^{\rm new}_{ZZ}(0)}{m_Z^2} - \left(\frac{\overline{c}_Z^2 - \overline{s}_Z^2}{\overline{c}_Z\overline{s}_Z}\right)\frac{\Pi^{\rm new}_{Z\gamma}(m_Z^2)}{m_Z^2} - \frac{\Pi^{\rm new}_{\gamma\gamma}(m_Z^2)}{m_Z^2}\,,$$

where $s \equiv \sin\theta_W$, $c \equiv \cos\theta_W$, and barred quantities are defined in the $\overline{\rm MS}$ scheme evaluated at m_Z. The $\Pi^{\rm new}_{V_aV_b}$ are the new physics contributions to the one-loop V_a—V_b vacuum polarization functions.



In order to avoid the conclusion of a light Higgs boson, new physics beyond the SM must be accompanied by a variety of new phenomena at an energy scale between 100 GeV and 1 TeV.



This new physics will be detected at future colliders

- either through direct observation of new physics beyond the SM
- or by improved precision measurements that can detect small deviations from SM predictions.

Although the precision electroweak data is suggestive of a weakly-coupled Higgs sector, one cannot definitively rule out another source of EWSB dynamics (although the measured S and T impose strong constraints on alternative approaches).

In alternative models of EWSB, there may be a scalar state with the properties of the Higgs boson that is significantly heavier.

Unitarity of $W_L^+ W_L^-$ scattering (which is violated in the SM in the absence of a Higgs boson) can be restored either by new physics beyond the Standard Model (e.g., the techni-rho of technicolor or Kaluza-Klein states of extra-dimensional models) or by the heavier Higgs boson itself.

Suppose we assume the latter. How heavy can this Higgs boson be?

2. Theoretical upper bound to the Higgs mass

Let us return to the unitarity argument. Consider the scattering process $W_L^+(p_1)W_L^-(p_2) \to W_L^+(p_3)W_L^-(p_4)$ at center-of-mass energies $\sqrt{s} \gg m_W$. Each contribution to the tree-level amplitude is proportional to

$$[\varepsilon_L(p_1) \cdot \varepsilon_L(p_2)]\,[\varepsilon_L(p_3) \cdot \varepsilon_L(p_4)] \sim \frac{s^2}{m_W^4}\,,$$

after using the fact that the helicity-zero polarization vector at high energies behaves as $\varepsilon_L^\mu(p) \sim p^\mu/m_W$. Due to the magic of gauge invariance and the presence of Higgs-exchange contributions, the bad high-energy behavior is removed, and one finds for s, $m_h^2 \gg m_W^2$:

$$\mathcal{M} = -\sqrt{2}G_F m_H^2 \left(\frac{s}{s-m_h^2} + \frac{t}{t-m_h^2}\right)\,.$$

Projecting out the $J = 0$ partial wave and taking $s \gg m_h^2$,

$$\mathcal{M}^{J=0} = -\frac{G_F m_h^2}{4\pi\sqrt{2}}\,.$$

Imposing $|\mathrm{Re}\ \mathcal{M}^J| \leq \frac{1}{2}$ yields an upper bound on m_h. The most stringent bound is obtained by all considering other possible final states such as $Z_L Z_L$, $Z_L h^0$ and $h^0 h^0$. The end result is:

$$\boxed{m_h^2 \leq \frac{4\pi\sqrt{2}}{3G_F} \simeq (700\ \mathrm{GeV})^2\,.}$$

This is a tree-level result that depends on the assumption that EWSB dynamics is perturbative (in contrast to our previous analysis of the unitary bound). If $m_h \gtrsim 700$ GeV, then the Higgs-self coupling, $\lambda = 2m_h^2/v^2$, is becoming large and our perturbative analysis is becoming suspect. Nevertheless, lattice studies suggest that an upper Higgs mass bound below 1 TeV remains valid even in the strong Higgs self-coupling regime.

Extended Higgs sectors: 2HDM, MSSM and beyond

For an arbitrary Higgs sector, the tree-level ρ-parameter is given by

$$\rho_0 \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 \quad \Longleftrightarrow \quad (2T+1)^2 - 3Y^2 = 1\,,$$

independently of the Higgs vevs, where T and Y specify the weak-isospin and the hypercharge of the Higgs representation to which it belongs. Y is normalized such that the electric charge of the scalar field is $Q = T_3 + Y/2$. The simplest solutions are Higgs singlets $(T, Y) = (0, 0)$ and hypercharge-one complex Higgs doublets $(T, Y) = (\frac{1}{2}, 1)$.

Thus, we shall consider non-minimal Higgs sectors consisting of multiple Higgs doublets (and perhaps Higgs singlets), but no higher Higgs representations, to avoid the fine-tuning of Higgs vevs.

Higgs boson phenomena beyond the SM

The two-Higgs-doublet model (2HDM) consists of two hypercharge-one scalar doublets. Of the eight initial degrees of freedom, three correspond to the Goldstone bosons and five are physical: a charged Higgs pair, $H^{\pm}$ and three neutral scalars.

In contrast to the SM, whereas the Higgs-sector is CP-conserving, the 2HDM allows for Higgs-mediated CP-violation. If CP is conserved, the Higgs spectrum contains two CP-even scalars, h^0 and H^0 and a CP-odd scalar A^0. Thus, new features of the extended Higgs sector include:

- Charged Higgs bosons
- A CP-odd Higgs boson (if CP is conserved in the Higgs sector)
- Higgs-mediated CP-violation (and neutral Higgs states of indefinite CP)

More exotic Higgs sectors allow for doubly-charged Higgs bosons, etc.

Higgs-fermion Yukawa couplings in the 2HDM

The 2HDM Higgs-fermion Yukawa Lagrangian is:

$$-\mathscr{L}_{\rm Y} = \overline{U}_L \Phi_a^{0\,*} h_a^U U_R - \overline{D}_L K^\dagger \Phi_a^- h_a^U U_R + \overline{U}_L K \Phi_a^+ h_a^{D\,\dagger} D_R + \overline{D}_L \Phi_a^0 h_a^{D\,\dagger} D_R + \text{h.c.}\,,$$

where K is the CKM mixing matrix, and there is an implicit sum over $a = 1, 2$. The $h^{U,D}$ are 3×3 Yukawa coupling matrices and

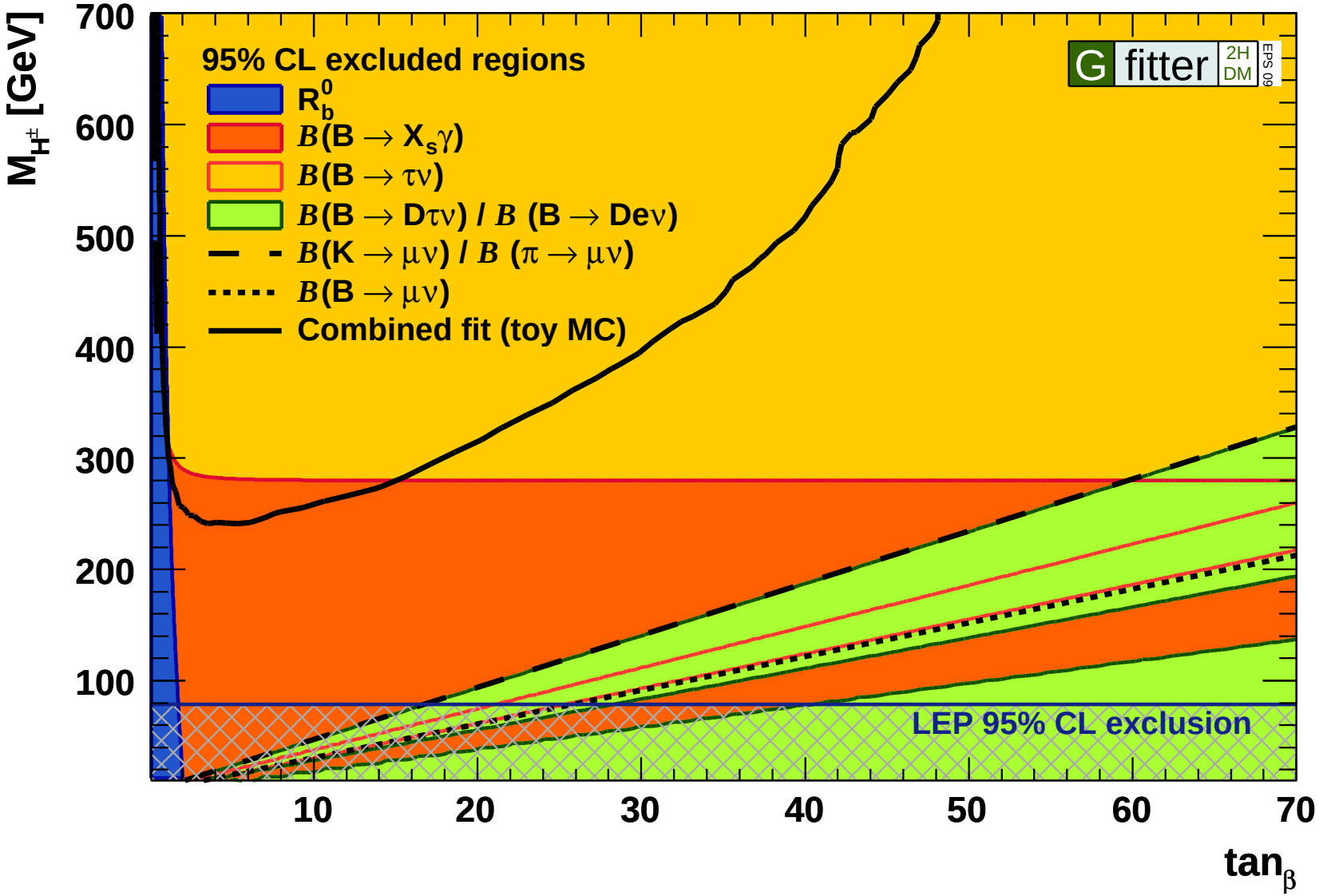
$$\langle \Phi_a^0 \rangle \equiv \frac{v_a}{\sqrt{2}}\,, \quad (a = 1, 2)\,, \qquad v^2 \equiv v_1^2 + v_2^2 = (246\ \text{GeV})^2\,.$$

If all terms are present, then tree-level Higgs-mediated flavor-changing neutral currents (FCNCs) and CP-violating neutral Higgs-fermion couplings are both present. Both can be avoided by imposing a discrete symmetry to restrict the structure of the Higgs-fermion Yukawa Lagrangian. Different choices for the discrete symmetry yield:

- Type-I Yukawa couplings: $h_2^U = h_2^D = 0$,
- Type-II Yukawa couplings: $h_1^U = h_2^D = 0$,

The parameter $\tan\beta = \langle \Phi_2^0 \rangle / \langle \Phi_1^0 \rangle$ governs the structure of the Higgs-fermion couplings. The parameter α emerges after diagonalizing the CP-even Higgs squared-mass matrix.

There are interesting experimental constraints on the Type-II 2HDM.



Tree-level Higgs couplings in the 2HDM

For simplicity, assume that CP-violation in the neutral Higgs sector can be neglected. Tree-level couplings of Higgs bosons with gauge bosons are often suppressed by an angle factor, either $\cos(\beta-\alpha)$ or $\sin(\beta-\alpha)$.

$\cos(\beta-\alpha)$	$\sin(\beta-\alpha)$	angle-independent
$H^0W^+W^-$	$h^0W^+W^-$	—
H^0ZZ	h^0ZZ	—
ZA^0h^0	ZA^0H^0	ZH^+H^- , γH^+H^-
$W^\pm H^\mp h^0$	$W^\pm H^\mp H^0$	$W^\pm H^\mp A^0$

Tree-level Higgs-fermion couplings may be either suppressed or enhanced with respect to the SM value, $gm_f/2m_W$. For Model-II Higgs-fermion Yukawa couplings, the couplings of H^0 and A^0 to $b\bar{b}$ and $\tau^+\tau^-$ are enhanced by a factor of $\tan\beta$ (in parameter regimes where the h^0 couplings approximate those of the SM).

Model-independent 2HDM studies

One can impose symmetries on the general 2HDM (e.g., discrete symmetries in the Yukawa sector or supersymmetry) to avoid potentially bad phenomenological consequences such as Higgs-mediated FCNCs. However, such symmetries are typically broken. If the breaking scale lies above the 2HDM masses, then the low-energy effective Higgs theory has the structure of the most general 2HDM.

In this case, the two complex Higgs doublets are effectively indistinguishable, and any physical 2HDM observable cannot depend on the basis choice that defines the Higgs doublets. In this framework, basis-dependent parameters such as $\tan\beta = v_2/v_1$ have no physical meaning.

Physical parameters of the model that are suitable for truly model-independent 2HDM studies, are most easily defined in the so-called Higgs basis, where one of the two Higgs doublet fields has no vacuum expectation value. [H.E. Haber and D. O'Neil, Phys. Rev. **D74**, 015018 (2006).]

The Higgs sector of the MSSM

The Higgs sector of the MSSM is a Type-II 2HDM, whose Yukawa couplings and Higgs potential are constrained by supersymmetry (SUSY). Minimizing the Higgs potential, the neutral components of the Higgs fields acquire vevs:

$$\langle H_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d \\ 0 \end{pmatrix}, \qquad \langle H_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_u \end{pmatrix},$$

where $v^2 \equiv v_d^2 + v_u^2 = 4m_W^2/g^2 = (246\ \mathrm{GeV})^2$. The ratio of the two vevs is an important parameter of the model:

$$\boxed{\tan\beta \equiv \frac{v_u}{v_d}}$$

The five physical Higgs particles consist of a charged Higgs pair $H^\pm$, one CP-odd scalar A^0, and two CP-even scalars h^0, H^0, obtained by diagonalizing All Higgs masses and couplings can be expressed in terms of two parameters usually chosen to be m_A and $\tan\beta$.

At tree level,

$$m_{H^\pm}^2 = m_A^2 + m_W^2 \,,$$
$$m_{H,h}^2 = \tfrac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - 4 m_Z^2 m_A^2 \cos^2 2\beta} \right) \,,$$

where α is the angle that diagonalizes the CP-even Higgs squared-mass matrix. Hence,

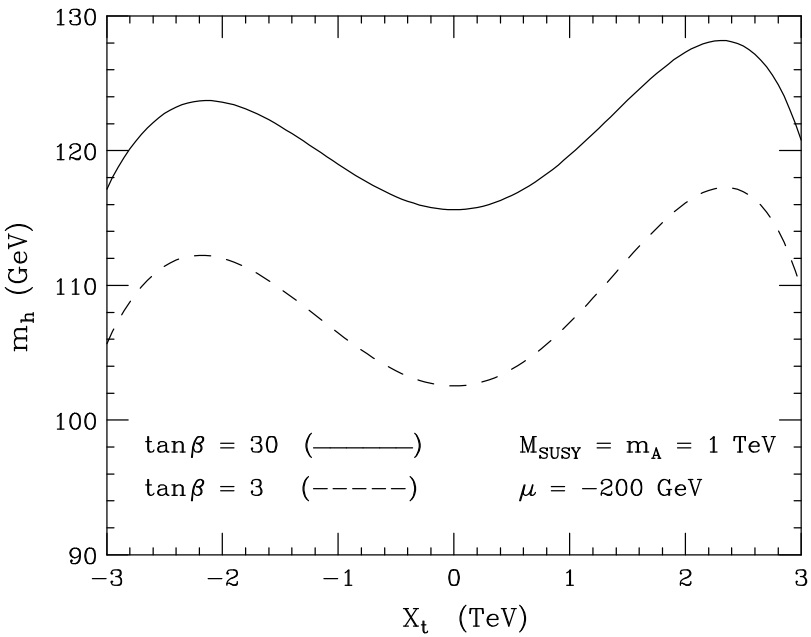
$$\boxed{m_h \leq m_Z |\cos 2\beta| \leq m_Z \,,}$$

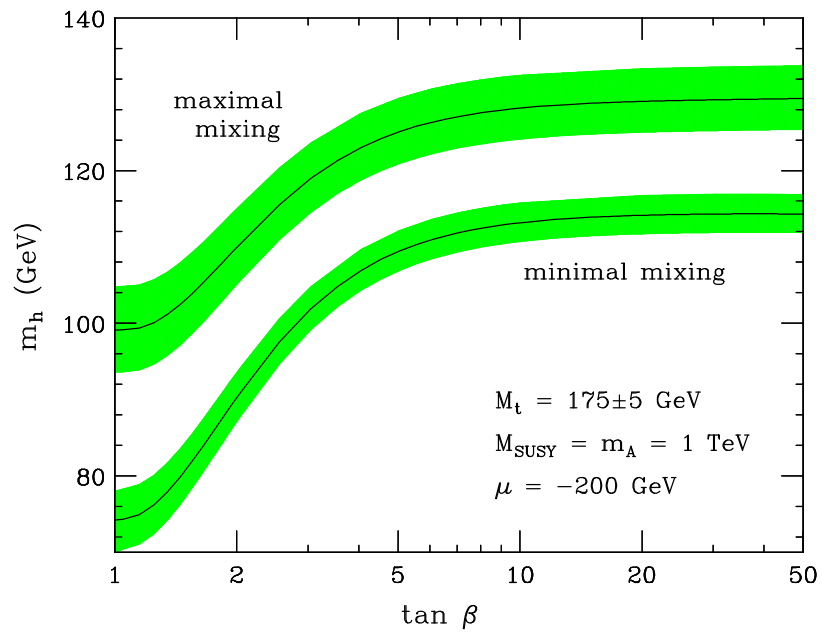
which is ruled out by LEP data. But, this inequality receives quantum corrections. The Higgs mass can be shifted due to loops of particles and their superpartners (an incomplete cancellation, which would have been exact if supersymmetry were unbroken):

$$m_h^2 \lesssim m_Z^2 + \frac{3 g^2 m_t^4}{8\pi^2 m_W^2} \left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right) \right] \,,$$

where $X_t \equiv A_t - \mu \cot\beta$ governs stop mixing and M_S^2 is the average top-squark squared-mass.

The state-of-the-art computation includes the full one-loop result, all the significant two-loop contributions, some of the leading three-loop terms, and renormalization-group improvements. The final conclusion is that $m_h \lesssim 130$ GeV [assuming that the top-squark mass is no heavier than about 2 TeV].



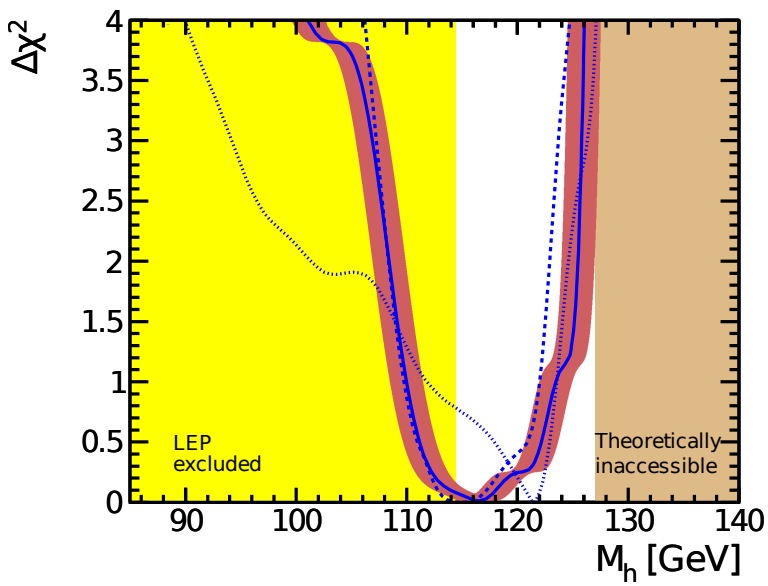


Maximal mixing corresponds to choosing the MSSM Higgs parameters in such a way that m_h is maximized (for a fixed $\tan\beta$). This occurs for $X_t/M_S \sim 2$. As $\tan\beta$ varies, m_h reaches is maximal value, $(m_h)_{\max} \simeq 130$ GeV, for $\tan\beta \gg 1$ and $m_A \gg m_Z$.

Consequences of precision electroweak data

- In the decoupling limit (with SUSY particles somewhat heavy), the effects of the heavy Higgs states and the SUSY particles decouple and the global SM fit applies.

- In the latter case, h^0 is a SM-like Higgs boson whose mass lies below about 130 GeV in the *preferred* Higgs mass range!



Higgs mass constraints in the NUHM1 extension of the CMSSM, with non-universal Higgs mass parameters [taken from O. Buchmüller et al., Eur. Phys. J. **C71**, 1634 (2011)].

Higgs bosons in models beyond the MSSM

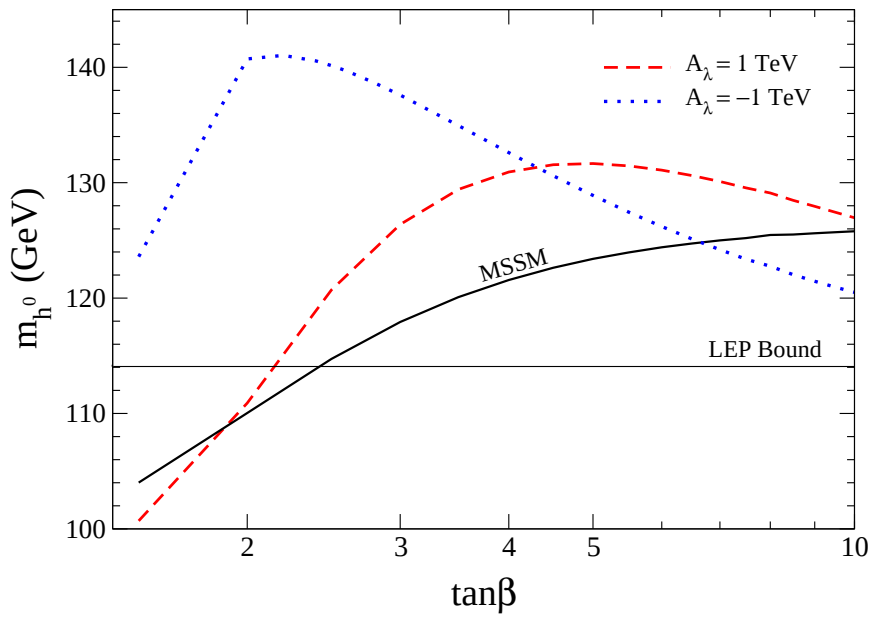
Why go beyond the MSSM? The LEP Higgs mass bounds have already made adherents of the MSSM uncomfortable, as the mass of h^0 must be somewhat close to its maximally allowed value, which requires rather heavy stop masses and significant stop mixing. The absence of observed SUSY particles just emphasizes this apparent *little hierarchy problem* that seems to require at least 1% fine-tuning of MSSM parameters to explain the magnitude of the EWSB scale.

In the NMSSM, a Higgs singlet superfield $\hat{S}$ is added to the MSSM. The corresponding superpotential terms,

$$(\mu + \lambda \hat{S})\hat{H}_u \hat{H}_d + \tfrac{1}{2}\mu_S \hat{S}^2 + \tfrac{1}{3}\kappa \hat{S}^3 \,,$$

and soft-SUSY-breaking terms $B_s S^2 + \lambda A_\lambda S H_u H_d$ add additional parameters to the model, which can modify the bounds on the lightest Higgs mass.

For example, in a recent paper by Delgado, Kolda, Olson and de la Puente,



Other authors (e.g. Dermisek and Gunion) have advocated NMSSM models as a way to partially alleviate the little hierarchy problem. More generally, there is a large literature (beginning with Haber and Sher in 1987) suggesting the possibility of relaxing the Higgs mass upper bound in extensions of the MSSM.

In 1993, Espinosa and Quiros showed that it was relatively easy to construct extended models with the lightest Higgs boson mass as large as 155 GeV. Other authors found ways to push this bound higher (although these are perhaps less interesting in light of present experimental Higgs search limits).

The Decoupling Limit

The Higgs boson serves as a window to BSM physics only if one can experimentally establish deviations of Higgs couplings from their SM values, or discover new scalar degrees of freedom beyond the SM-like Higgs boson.

The prospects to achieve this are challenging in general due to the decoupling limit. In extended Higgs models, most of the parameter space typically yields a neutral CP Higgs boson with SM-like tree-level couplings and additional scalar states that are somewhat heavier in mass (of order Λ), with small mass splittings of order m_Z^2/Λ. Below the scale Λ, the effective Higgs theory coincides with that of the SM.

This behavior is exhibited by the MSSM Higgs sector. In the limit of $m_A \gg m_Z$, the expressions for the Higgs masses and mixing angle simplify:

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta\,, \qquad m_H^2 \simeq m_A^2 + m_Z^2 \sin^2 2\beta\,,$$

$$m_{H^\pm}^2 = m_A^2 + m_W^2\,, \qquad \cos^2(\beta-\alpha) \simeq \frac{m_Z^4 \sin^2 4\beta}{4m_A^4}\,.$$

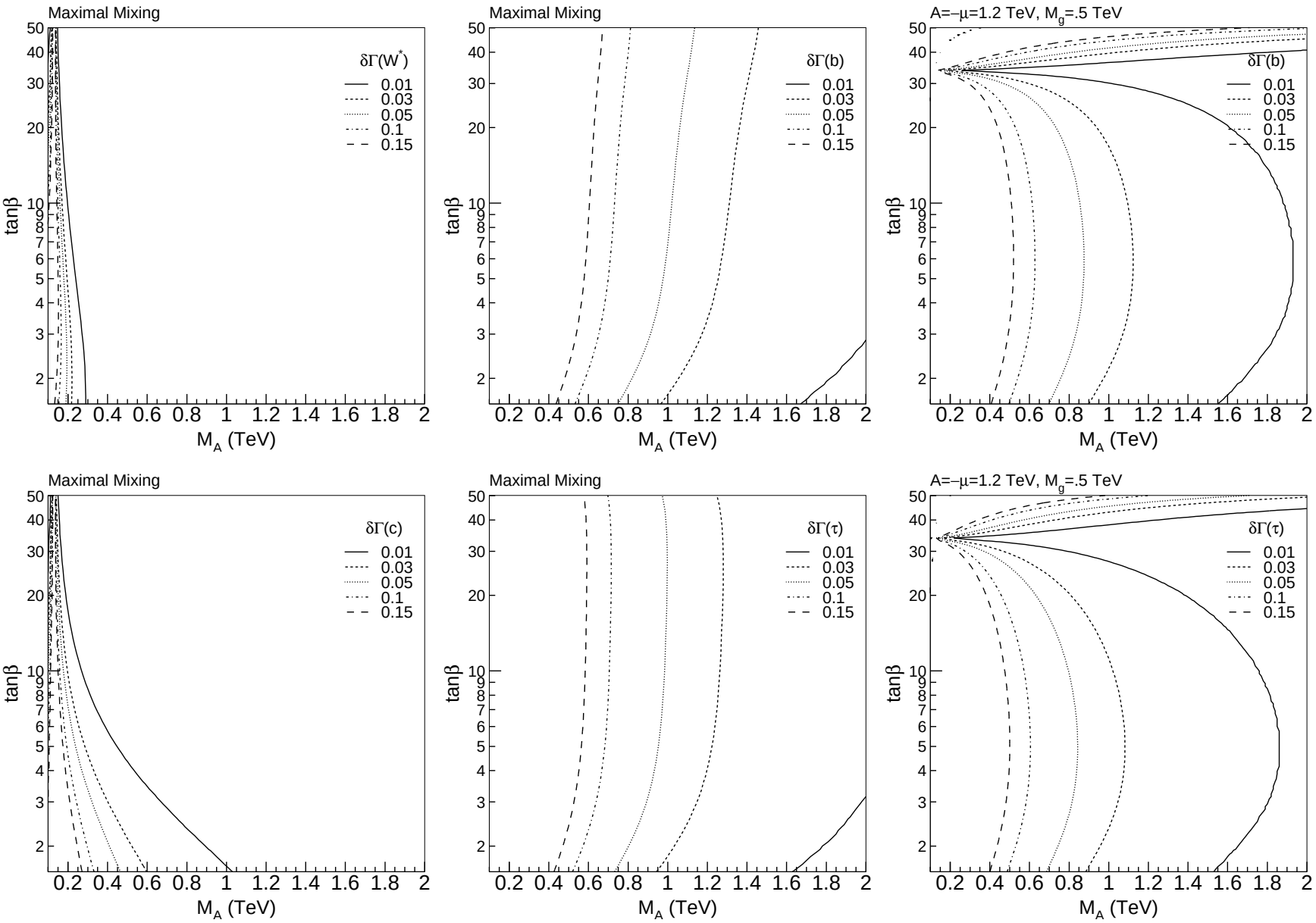
Two consequences are immediately apparent. First, $m_A \simeq m_H \simeq m_{H^\pm}$, up to corrections of $\mathcal{O}(m_Z^2/m_A)$. Second, $\cos(\beta-\alpha)=0$ up to corrections of $\mathcal{O}(m_Z^2/m_A^2)$. In general, in the limit of $\cos(\beta-\alpha)\to 0$, all the h^0 couplings to SM particles approach their SM limits. In particular, if λ_V is a Higgs coupling to vector bosons and λ_f is a Higgs couplings to fermions, then

$$\frac{\lambda_V}{[\lambda_V]_{\rm SM}} = 1 + \mathcal{O}\left(\frac{m_Z^4}{m_A^4}\right) ,$$
$$\frac{\lambda_f}{[\lambda_f]_{\rm SM}} = 1 + \mathcal{O}\left(\frac{m_Z^2}{m_A^2}\right) .$$

The behavior of the $h^0 ff$ coupling is seen from:

$$h^0 b\bar{b} \quad (\text{or } h^0\tau^+\tau^-): \qquad -\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) ,$$
$$h^0 t\bar{t}: \qquad \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha) ,$$

Note the extra $\tan\beta$ enhancement in the deviation of λ_{h^0bb}.



Deviations of Higgs partial widths from their SM values in two different MSSM scenarios (Carena, Haber, Logan and Mrenna).

Far from the decoupling limit, one typically finds that *all* Higgs bosons have a similar mass of $\mathcal{O}(v)$ and *none* of the neutral scalars are SM-like.

In the decoupling limit of a general 2HDM (where the neutral Higgs states h_1, h_2 and h_3 are not necessarily states of definite CP), the CP-violating and flavor-changing neutral Higgs couplings of the SM-like Higgs state h_1 are suppressed by factors of $\mathcal{O}(v^2/m_{2,3}^2)$. In contrast, the corresponding interactions of the heavy neutral Higgs bosons (h_2 and h_3) and the charged Higgs bosons ($H^\pm$) can exhibit CP-violating and flavor non-diagonal couplings.

The decoupling limit is a generic feature of extended Higgs sectors.*

- Thus, the observation of a SM-like Higgs boson does not rule out the possibility of an extended Higgs sector in the decoupling regime.
- Experimental exclusion of a SM Higgs boson does not preclude an extended Higgs sector in a non-decoupling regime.

*However, if some terms of the Higgs potential are absent, it is possible that no decoupling limit may exist. In this case, the only way to have very large Higgs masses is to have large Higgs self-couplings.

Where do we stand? Where are we headed?

No evidence for the Higgs boson has yet been observed. But, this is precisely what is expected, given the the SM global fits based on precision electroweak data. The LHC now begins to zero in on the Higgs mass range, $114\ \mathrm{GeV} < m_h < 145\ \mathrm{GeV}$, the region where the SM Higgs boson (if it exists) is likely to reside. With more that $5\ \mathrm{fb}^{-1}$ of data recorded in 2011, and another $15\ \mathrm{fb}^{-1}$ of data anticipated by next summer, there is some chance for evidence of the Higgs boson by the end of this year and an announcement of a discovery at ICHEP next summer.

If a candidate Higgs boson is discovered, one must then address the following questions:

- Is it a Higgs boson?
- Is it *the* SM Higgs boson?

The measurement of Higgs boson properties will be critical in order to answer these questions:

- mass, width, CP-quantum numbers (CP-violation?)
- Higgs cross sections
- branching ratios and Higgs couplings
- reconstructing the Higgs potential

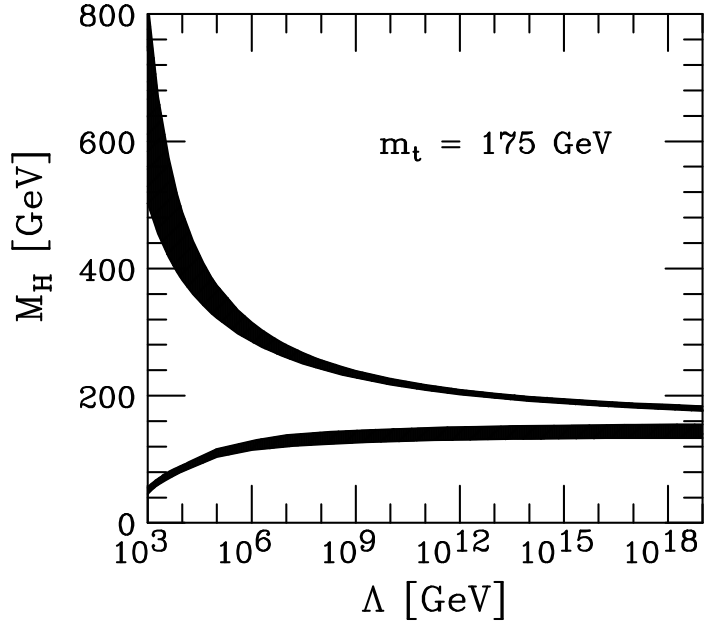
Scenarios and exit strategies

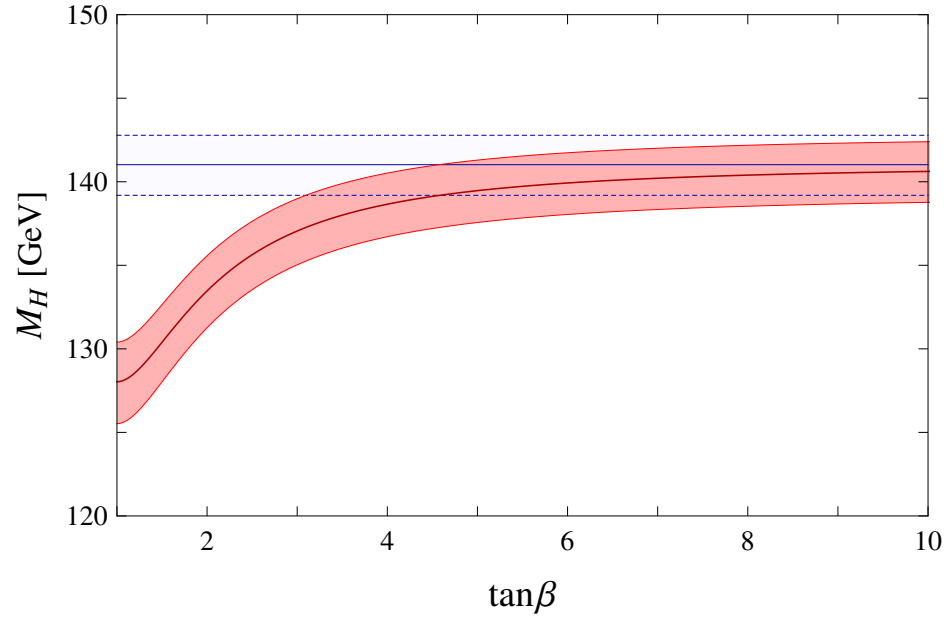
Possible scenarios include:

1. A SM-like Higgs boson is discovered. No evidence for BSM physics is evident.
2. A SM-like Higgs boson is discovered. Separate evidence for BSM physics emerges.
3. A light Higgs-like scalar is discovered, with properties that deviate from the SM.
4. A very heavy scalar state is discovered.
5. No Higgs boson candidate is discovered, and the entire mass range for a SM-like Higgs boson below 1 TeV is excluded.

In the last three cases, theoretical consistency implies that BSM physics must exist at the TeV energy scale that is observable at the LHC (with sufficient luminosity). Cases 4 and 5 would likely be incompatible with TeV-scale supersymmetry, whereas cases 2 and 3 would strongly encourage supersymmetric enthusiasts.

Case 1 would strongly cast doubts on the principle of naturalness. Nevertheless, is it still possible to learn about physics at higher mass scales?





Left-hand plot: The present-day theoretical uncertainties on the lower [Altarelli and Isidori; Casas, Espinosa and Quirós] and upper [Hambye and Riesselmann] Higgs mass bounds as a function of energy scale Λ at which the Standard Model breaks down, assuming $m_t = 175$ GeV and $\alpha_s(m_Z) = 0.118$. The shaded areas above reflect the theoretical uncertainties in the calculations of the Higgs mass bounds.

Right-hand plot: The SM Higgs mass prediction for theories where the boundary condition for the quartic coupling at 10^{14} GeV is fixed by the MSSM, and $\alpha_s(m_Z) = 0.1176$ and $m_t = 173.1 \pm 1.3$ GeV. The horizontal blue lines show the asymptotes of the prediction for large $\tan\beta$. Taken from L.J. Hall, Y. Nomura, JHEP **1003**, 076 (2010).

Conclusions

• The SM is not yet complete. The nature of the dynamics responsible for EWSB (and generating the Goldstone bosons that provide the longitudinal components of the massive $W^{\pm}$ and Z bosons) is not yet known.

• There are strong hints that a weakly-coupled elementary Higgs boson exists in nature (although loopholes still exist).

• If TeV-scale supersymmetry is responsible for EWSB, then the Higgs sector will be richer than in the SM. However, in the decoupling regime, it may be difficult to to detect deviations from SM Higgs properties at the LHC or evidence for new scalar states beyond the SM-like Higgs boson.

• Ultimately, one must discover the TeV-scale dynamics associated with EWSB, e.g. low-energy supersymmetry and/or new particles and phenomena responsible for creating the Goldstone bosons. So far, no evidence for physics BSM has been forthcoming.

• If there is only a Higgs boson and no evidence for new physics beyond the SM, then . . .?