Higgs and SUSY

Howard E. Haber
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IPPP
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Higgs and SUSY

SUSY and Higgs

King Henry and
Thomas Becket

Thomas Becket and
King Henry

Outline

1. Theoretical framework for electroweak symmetry breaking (EWSB)

   - weakly coupled vs. strongly coupled EWSB dynamics
   - principle of naturalness
   - Higgs physics as a window to physics beyond the Standard Model

2. Manifestations of the Higgs boson

   - Standard Model (SM) Higgs boson
   - The two Higgs doublet model (2HDM)
   - The Higgs sector of the MSSM
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   - The decoupling limit

3. Present status of the Higgs boson

- Ruling out the SM Higgs boson
  - Precision electroweak constraints
  - Collider searches for the Higgs boson
- Discovering the SM-like Higgs boson
  - What does the present CERN data tell us?
  - implications for a new energy scale beyond the SM
  - implications for supersymmetry and naturalness

4. Outlook and conclusions

Framework for Electroweak Symmetry Breaking (EWSB)

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) $v = 2m_W/g = (246\ \text{GeV})^2$ [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, . . .]

The Principle of Naturalness

JULY 1, 1939 PHYSICAL REVIEW VOLUME 56

On the Self-Energy and the Electromagnetic Field of the Electron

V. F. WEISSKOPF
University of Rochester, Rochester, New York
(Received April 12, 1939)

In 1939, Weisskopf announces in the abstract to this paper that "the self-energy of charged particles obeying Bose statistics is found to be quadratically divergent"….

…. and concludes that in theories of elementary bosons, new phenomena must enter at an energy scale of order m/e (e is the relevant coupling)—the first application of naturalness.

which is about 10^{-58} times smaller than the classical electron radius. The "critical length" of the positron theory is thus infinitely smaller than usually assumed.

The situation is, however, entirely different for a particle with Bose statistics. Even the Coulombian part of the self-energy diverges to a first approximation as $W_{st}\sim e^2h/(mca^2)$ and requires a much larger critical length that is $a=(hc/e^2)^{-\frac{1}{2}}\cdot h/(mc)$, to keep it of the order of magnitude of mc^2. This may indicate that a theory of particles obeying Bose statistics must involve new features at this critical length, or at energies corresponding to this length; whereas a theory of particles obeying the exclusion principle is probably consistent down to much smaller lengths or up to much higher energies.

Principle of naturalness in modern times

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

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

- The Higgs boson is an approximate Goldstone boson—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 2001–2011 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),

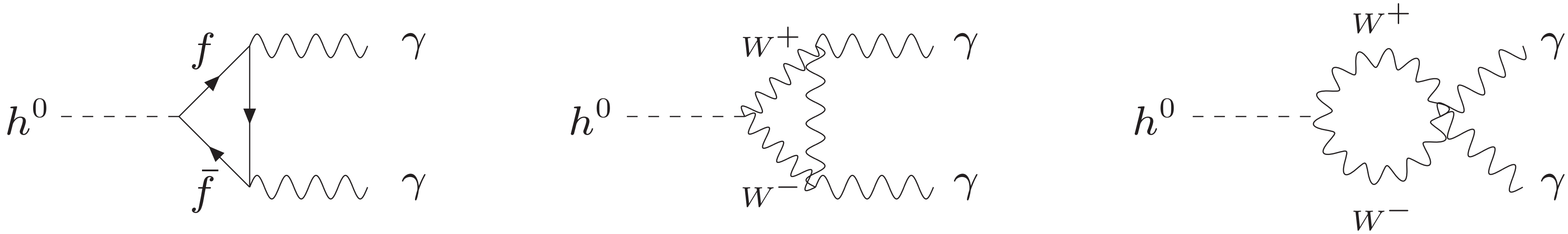
Vertex	Coupling
hVV	$2m_V^2/v$
$hhVV$	$2m_V^2/v^2$
hhh	$3m_h^2/v$
$hhhh$	$3m_h^2/v^2$
$hf\bar{f}$	m_f/v

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.

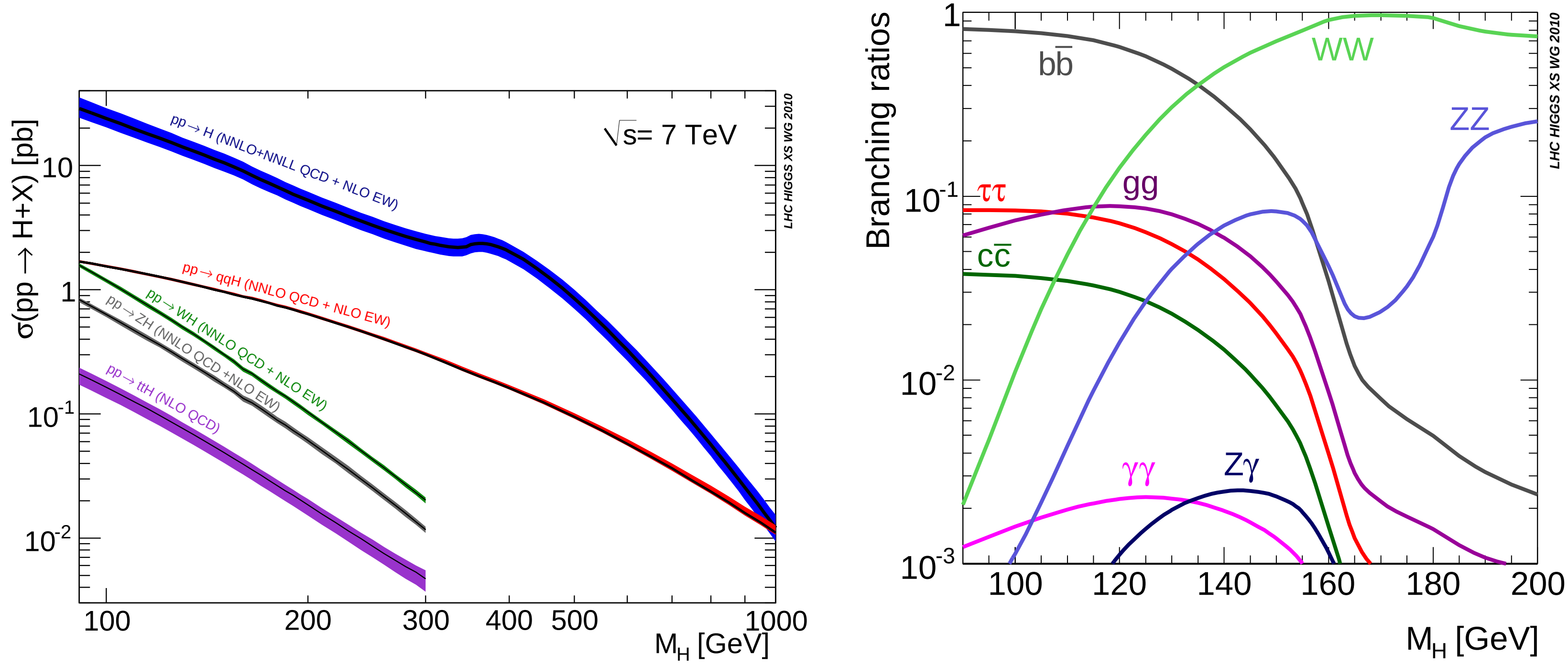
Importance of the loop-induced Higgs couplings for the LHC Higgs program

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

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

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 $m_h \simeq 125$ GeV, the main discovery channel for the Higgs boson at the LHC is via the rare decay $h^0 \to \gamma\gamma$.



SM Higgs cross-sections at the LHC at $\sqrt{s} = 7$ TeV [left pane] and the SM Higgs branching rations [right pane], taken from the LHC Higgs Cross Section Working Group, available at `https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections`.

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:

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

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

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

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.

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, which 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 $\tan\beta$.

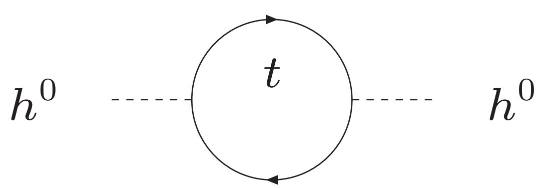
At tree level,

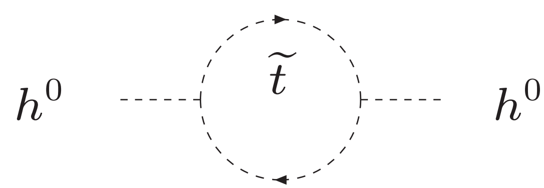
$$m_{H^\pm}^2 = m_A^2 + m_W^2\,,$$
$$m_{H,h}^2 = \tfrac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2+m_Z^2)^2 - 4m_Z^2 m_A^2\cos^2 2\beta}\;\right)\,,$$

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):

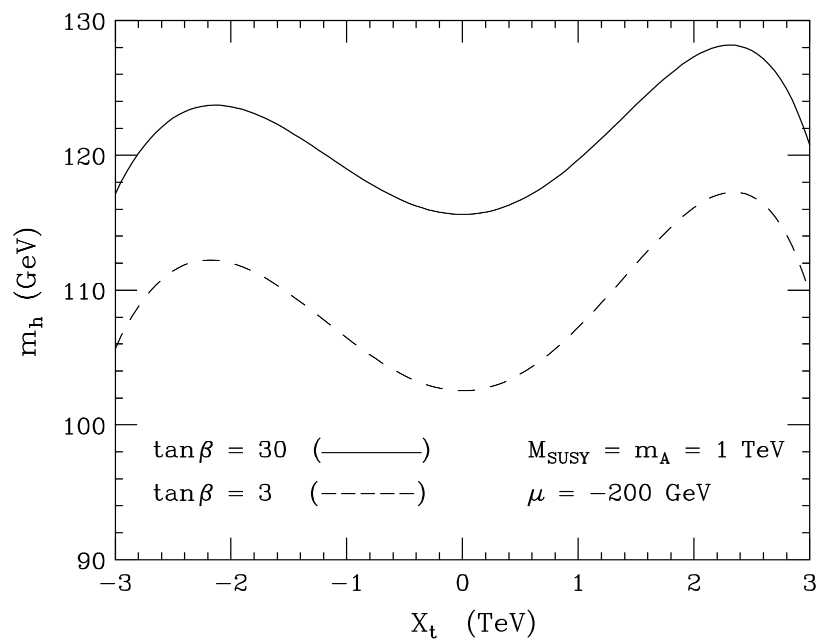


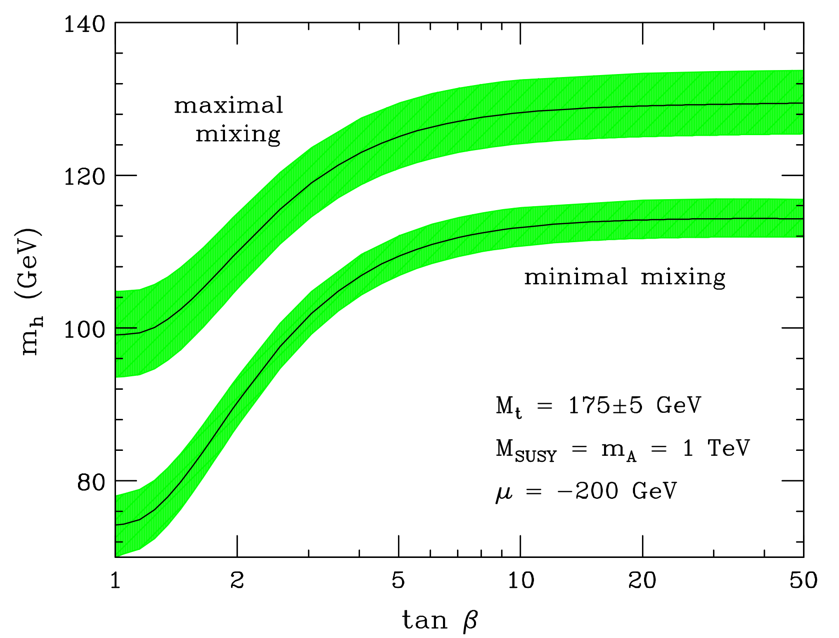


$$m_h^2 \lesssim m_Z^2\cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]\,,$$

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, $(m_h)_{\rm max} \simeq 130$ GeV, for $\tan\beta \gg 1$ and $m_A \gg m_Z$.

Higgs bosons in models beyond the MSSM

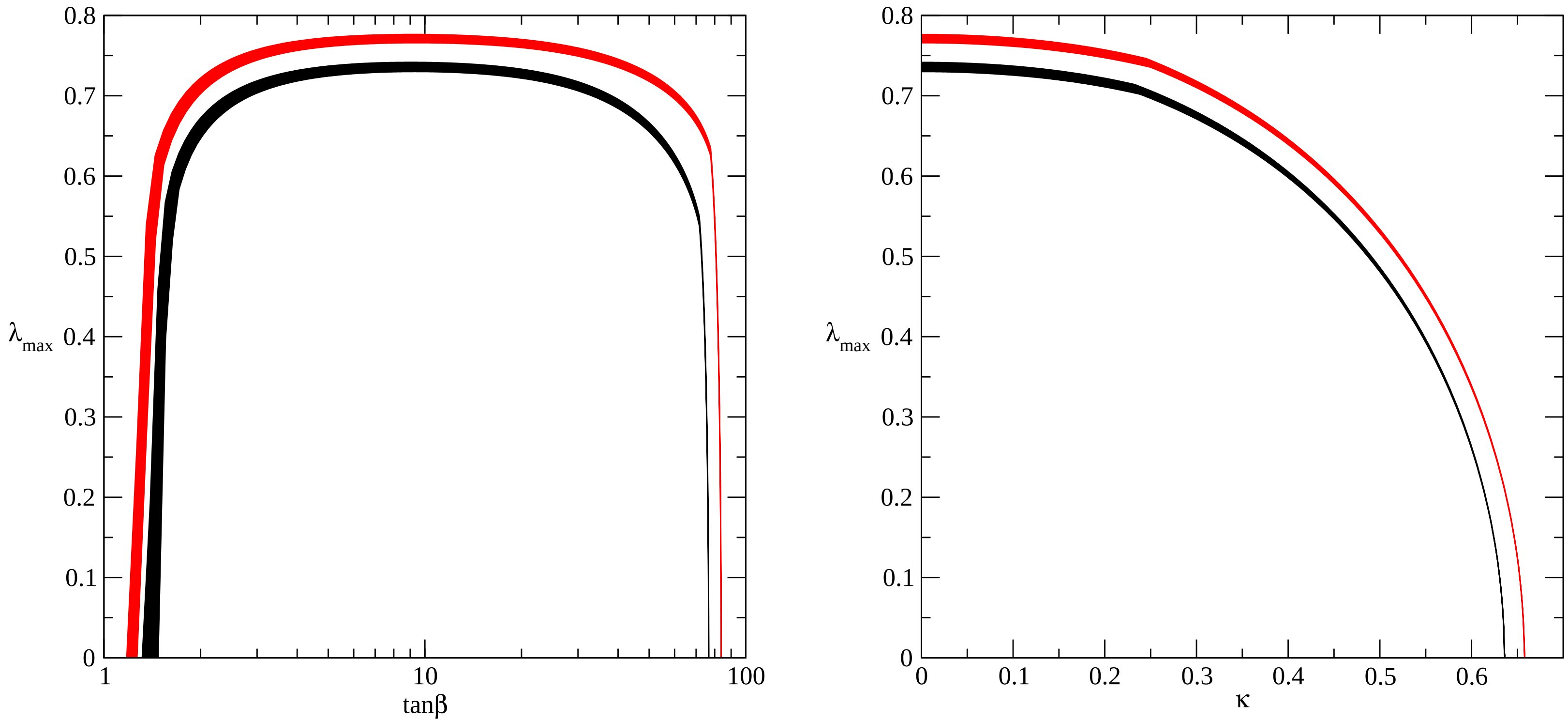
Why go beyond the MSSM? The LEP Higgs mass bounds have already made adherents of the MSSM uncomfortable, as the mass of h^0 must be somewhat close to its maximally allowed value, which requires rather heavy stop masses and significant stop mixing. The absence of observed SUSY particles just emphasizes 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 $B_sS^2 + \lambda A_\lambda SH_uH_d$ can modify the bounds on the lightest Higgs mass. First, we consider the case of no dimensionful parameters, i.e. $\mu = \mu_s = B_s = 0$.

If one imposes the requirement that there should be no Landau pole in λ below the Planck scale, then $\lambda \lesssim \lambda_{\rm max} \lesssim 0.75$.



The left panel shows the upper bound on λ as a function of $\tan\beta$ for a fixed $\kappa = 0.01$. The right panel shows how $\lambda_{\rm max}$ depends on κ for a fixed value of $\tan\beta = 10$. The red and black contours correspond to a heavy and light SUSY spectrum, respectively. Taken from U. Ellwanger, C. Hugonie and A. M. Teixeira, Phys. Rept. **496** (2010) 1.

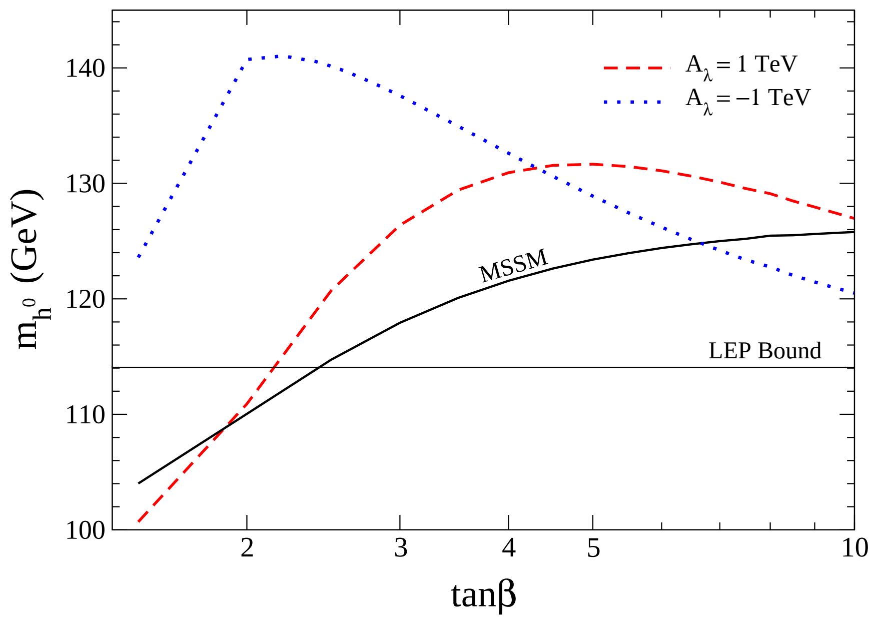
Including one-loop radiative corrections, the upper bound on the SM-like CP-even Higgs boson of the NMSSM is:

$$m_h^2 \lesssim m_Z^2 \cos^2 2\beta + \tfrac{1}{2}\lambda^2 v^2 \sin^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right].$$

Since $\frac{1}{2}\lambda_{\rm max}^2 v^2 \lesssim (130~{\rm GeV})^2$, the presence of the additional term allows for somewhat larger values of the SM-like Higgs boson mass as compared to the MSSM case. The maximal value of the mass is achieved for $\tan\beta \sim 2$ where the NMSSM contribution to the mass proportional to λ^2 dominates.

One of the motivations of the NMSSM is to eliminate the need for dimensionful couplings in the superpotential. The scalar component of $\hat{S}$ acquires a vacuum expectation value, in which case $\lambda\langle S\rangle$ plays the role of the μ parameter of the MSSM. Dermisek and Gunion have advocated the NMSSM as a way for hiding the SM-like Higgs due to new decay modes into a pair of very light CP-odd scalars.

Recently there has been a revival in interest in the more general NMSSM, in which the dimensionful parameters of the superpotential are retained. Such models have been shown to reduce the fine-tuning involved in establishing the EWSB scale. The upper bound for the Higgs mass is again modified; a typical result is shown below:



Mass of the SM-like Higgs boson for $\mu_S = 2$ TeV, $\mu = 500$ GeV, $m_{\tilde{t}} = M_{\tilde{g}} = 1$ TeV, $A_t = 2.5$ TeV and $\kappa = 0$. Taken from A. Delgado et. al., Phys. Rev. Lett. **105**, 091802 (2010).

Similar results have been found by G. Ross and Schmidt-Hoberg and by Hall, Pinner and Ruderman. More on this later.

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:

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

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

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^0ff 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} from $[\lambda_{h^0bb}]_{\rm SM}$

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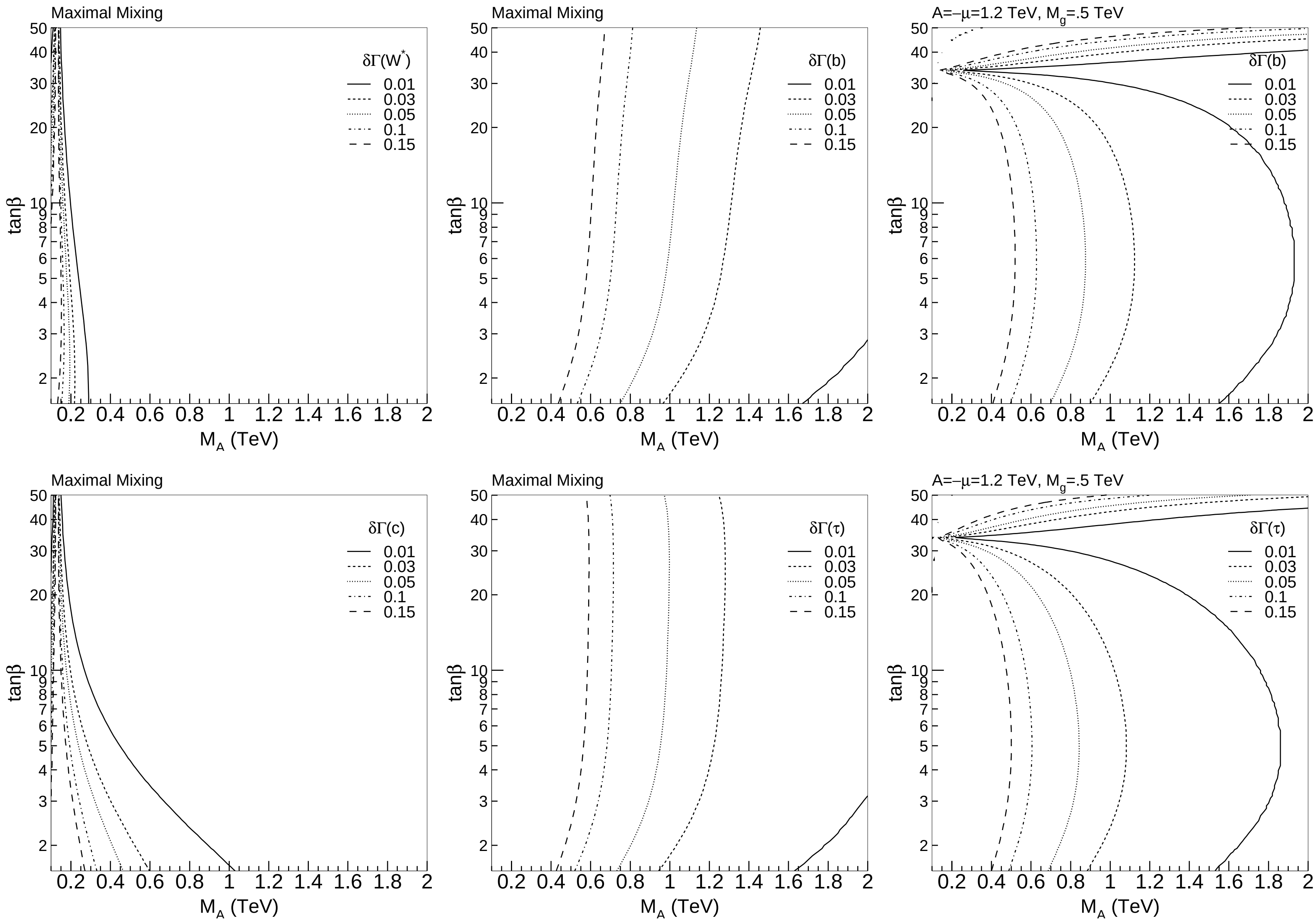


Deviations of Higgs partial widths from their SM values in two different MSSM scenarios (Carena, Haber, Logan and Mrenna).

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.

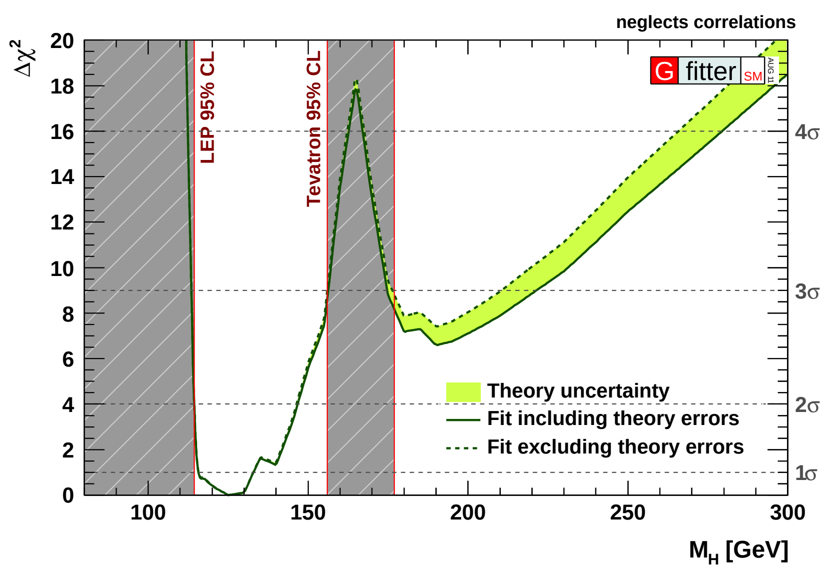
*However, if some terms of the Higgs potential are absent, it is possible that no decoupling limit may exist. In this case, the only way to have very large Higgs masses is to have large Higgs self-couplings.

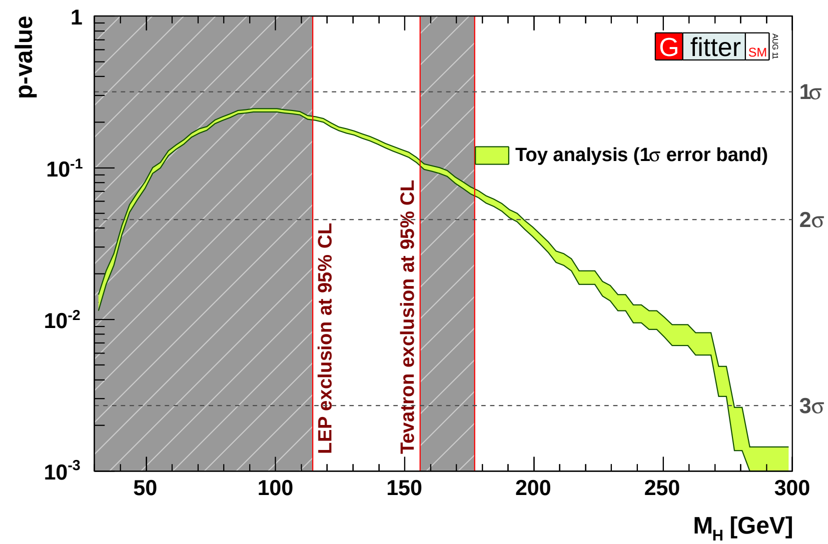
The Higgs boson—where are we now?

Ruling out the SM Higgs boson

1. Constraints from precision electroweak data.

In the SM, virtual Higgs exchange contributes to precision electroweak observables, primarily through small shifts in the W and Z self-energies.





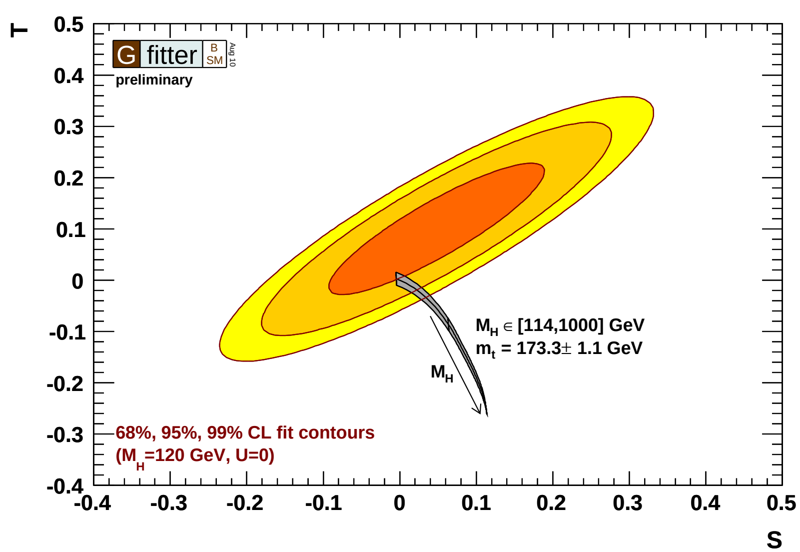
This implies that the SM Higgs boson, if it exists, lies in a mass region between 114 GeV and 150 GeV.

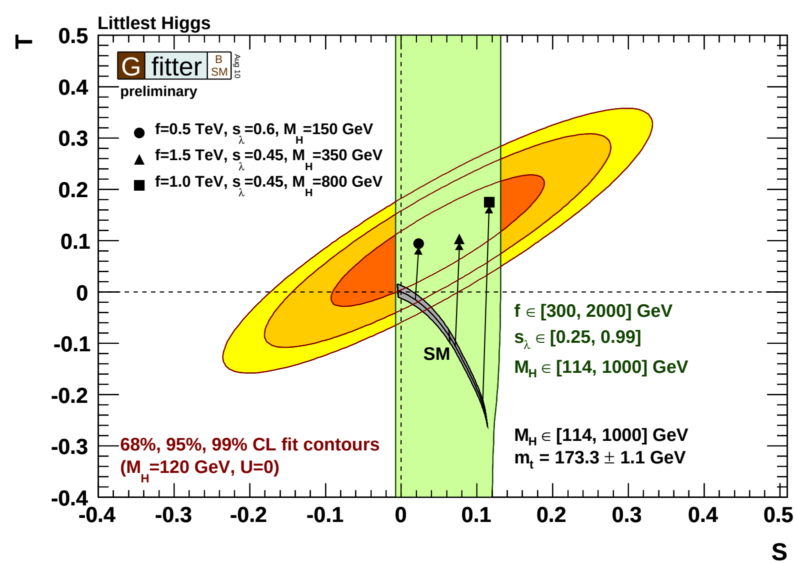
If BSM physics exists, then additional corrections to precision electroweak observables arise that can compensate the effects of a heavier Higgs boson (or no Higgs boson at all!). In many cases, these effects can be parameterized in terms of two quantities, S and T

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

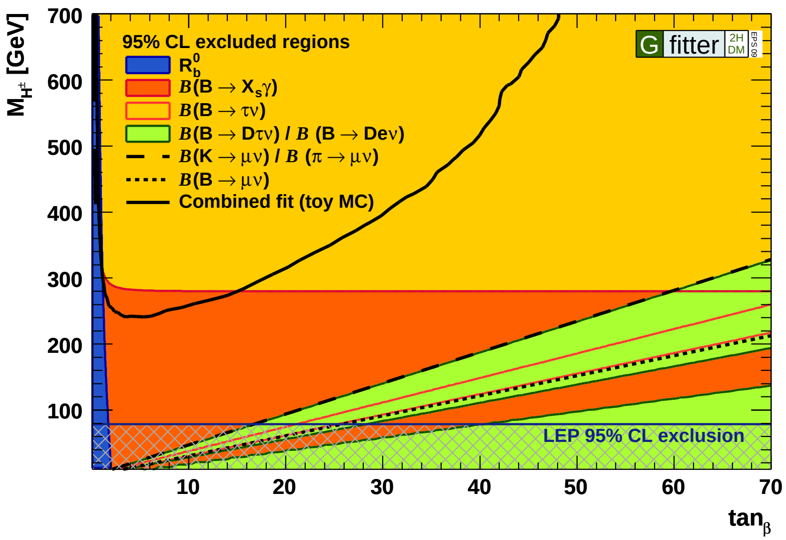
$$\frac{\overline{\alpha}}{4\overline{s}_Z^2\overline{c}_Z^2}\,S \equiv \frac{\Pi^{\rm new}_{ZZ}(m_Z^2)-\Pi^{\rm new}_{ZZ}(0)}{m_Z^2} - \left(\frac{\overline{c}_Z^2-\overline{s}_Z^2}{\overline{c}_Z\overline{s}_Z}\right)\frac{\Pi^{\rm new}_{Z\gamma}(m_Z^2)}{m_Z^2} - \frac{\Pi^{\rm new}_{\gamma\gamma}(m_Z^2)}{m_Z^2}\,,$$

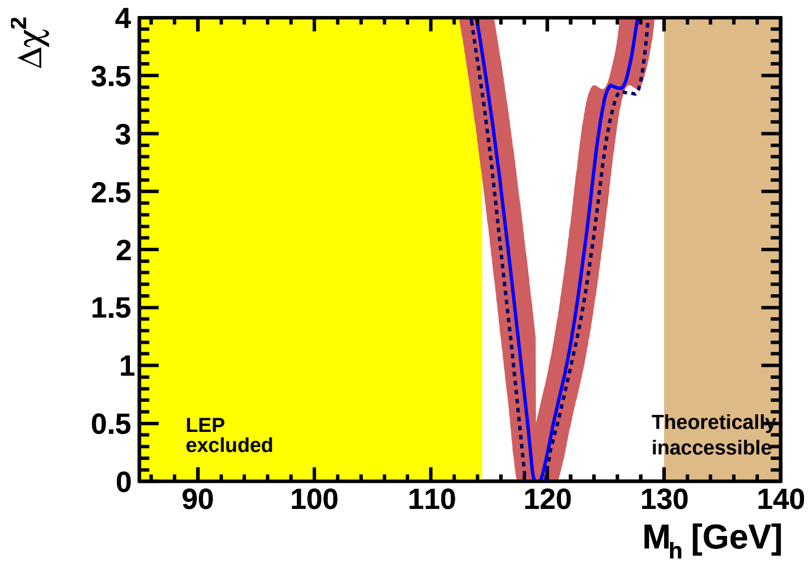
where $s \equiv \sin\theta_W$, $c \equiv \cos\theta_W$, and barred quantities are defined in the $\overline{\rm MS}$ scheme evaluated at m_Z. The $\Pi^{\rm new}_{V_aV_b}$ are the new physics contributions to the one-loop V_a—V_b vacuum polarization functions [Peskin and Takeuchi].





Precision electroweak constraints can also be applied to the 2HDM and the MSSM.



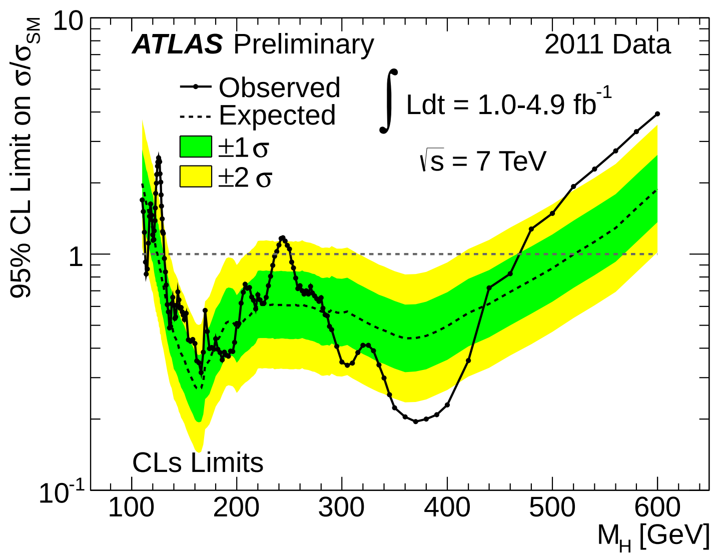


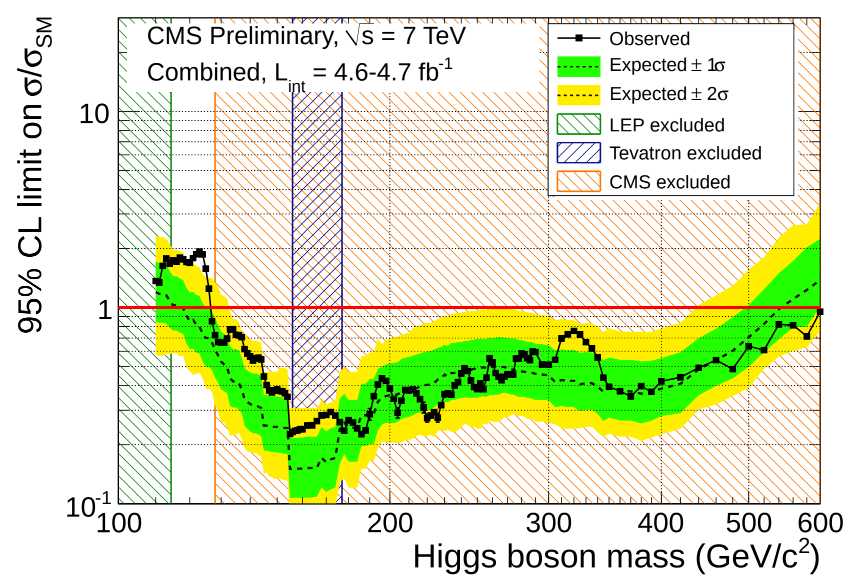
The left-hand plot provides constraints on the Type-II 2HDM.

The right-hand plot [update of a plot shown in O. Buchmüller et al., Eur. Phys. J. **C71**, 1634 (2011)] shows Higgs mass constraints in the NUHM1 extension of the CMSSM (with non-universal Higgs mass parameters).

2. Higgs mass bounds from collider searches.

From 1989–2000, experiments at LEP searched for $e^+e^- \to Z \to h^0 Z$ (where one of the Z-bosons is on-shell and one is off-shell). No significant evidence was found leading to a lower bound on the SM Higgs mass $m_h > 114.4\ \mathrm{GeV}$ at 95% CL. Searches at the Tevatron and LHC extend the 95% excluded region of Higgs masses. On December 13, 2011 the following plots were shown:





The excluded mass region above the LEP SM Higgs mass bound obtained by CMS is:

$$\boxed{127\ [128]\ \mathrm{GeV} < m_h < [525]\ 600\ \mathrm{GeV} \quad \text{at} \ \ 95\%\ [99\%]\ \mathrm{CL}.}$$

ATLAS also rules out SM Higgs masses in the range $112.7\ \mathrm{GeV} < m_h < 115.5\ \mathrm{GeV}$ at 95% CL. Taken at face value, these results imply that if the SM Higgs exists, its mass is most likely to lie in the range:

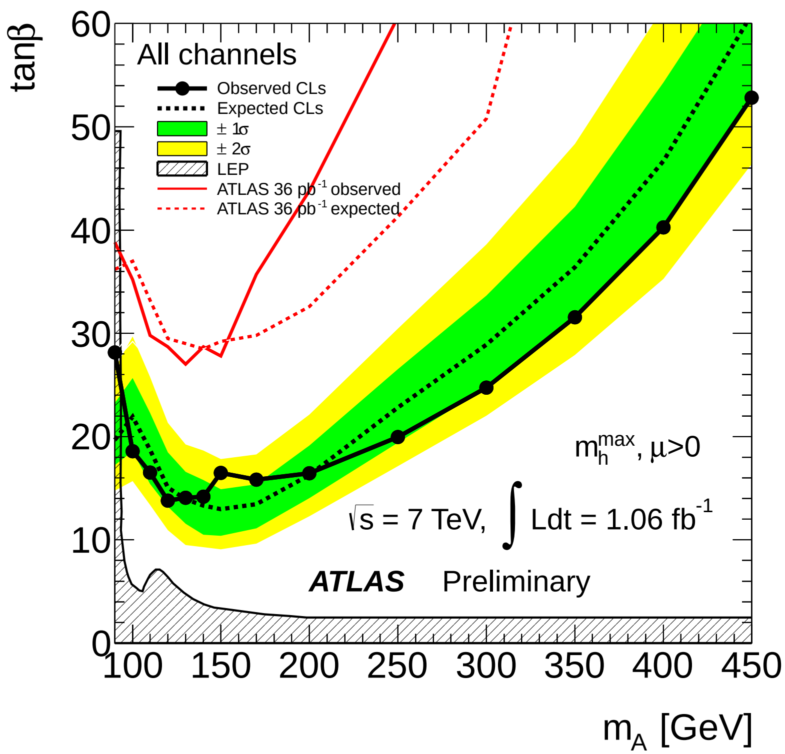
$$115.5\ \mathrm{GeV} \lesssim m_h \lesssim 127\ \mathrm{GeV}\,,$$

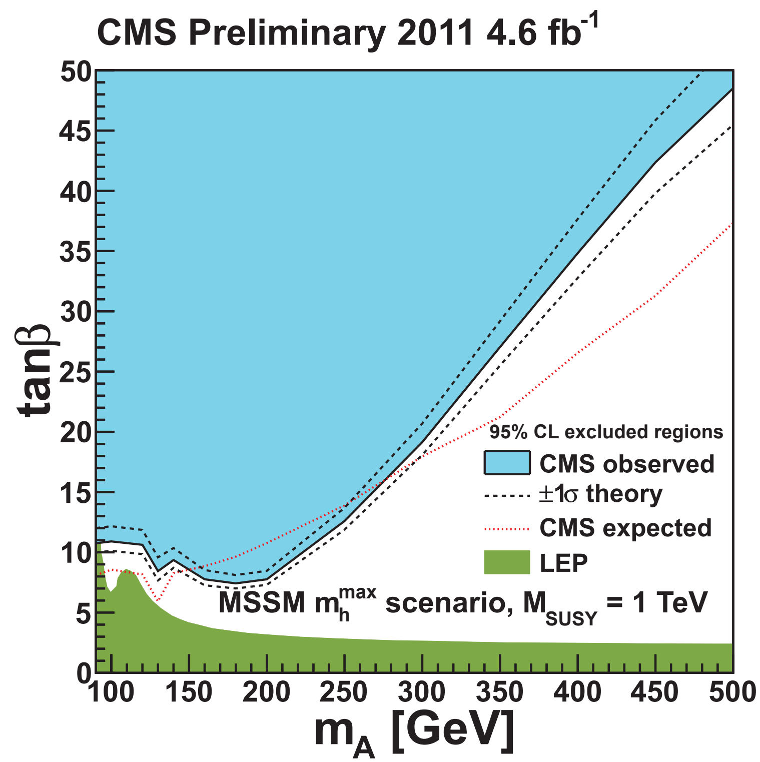
which is consistent with the constraints from precision electroweak data, or in the range $m_h > 600$ GeV, in conflict with precision electroweak data.

This is the main achievement of the 2011 LHC Higgs search!! (More on the tantalizing hint that the LHC searches have caught a glimpse of the Higgs boson in a moment.)

The above mass range is also consistent with the expectations of the MSSM Higgs sector in the decoupling limit (modulo naturalness issues that may be alleviated in non-minimal extensions of the MSSM). Of course, the parameter space of the MSSM Higgs sector extends beyond the decoupling regime.

In particular, the LHC search for MSSM Higgs bosons has produced interesting limits in the non-decoupling regime, where $m_A \lesssim 150$ GeV.

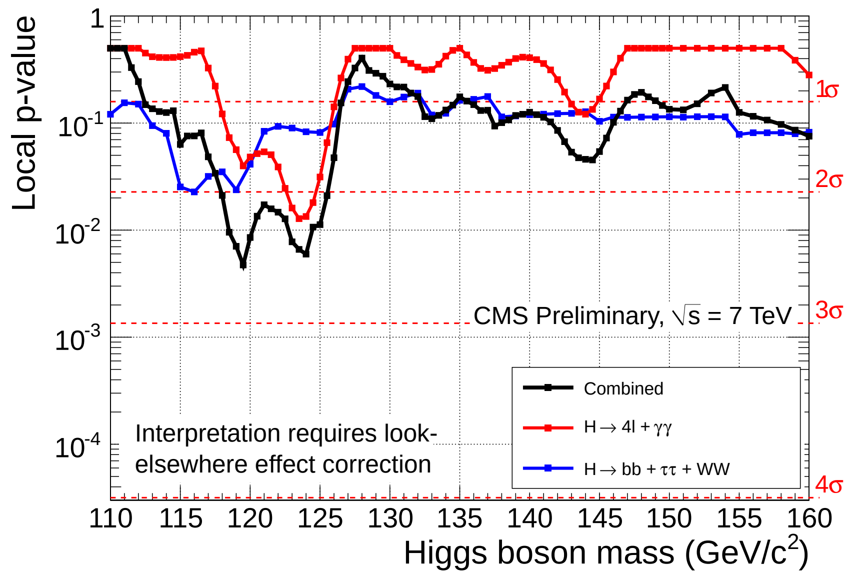


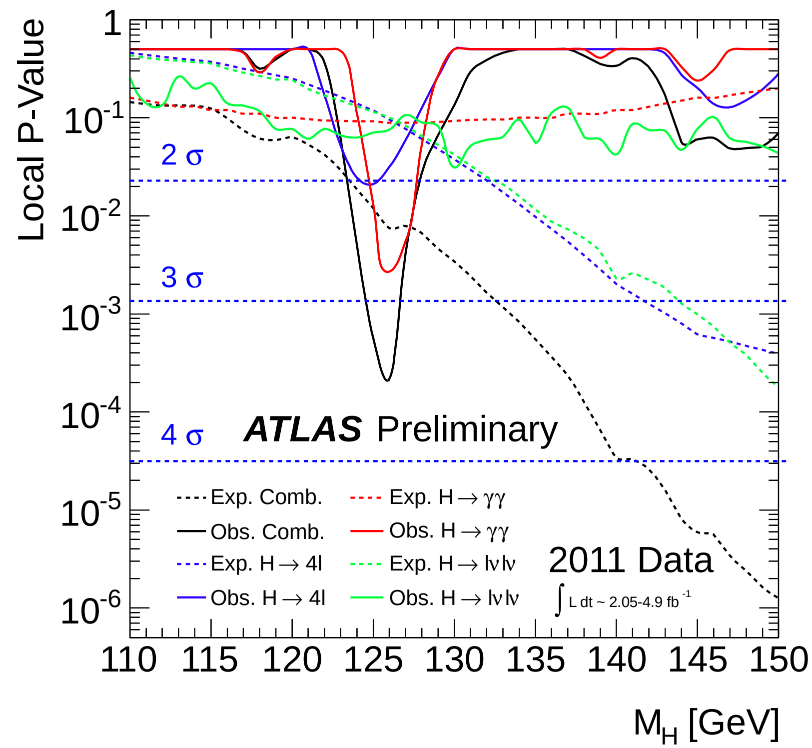


With more data, LHC data can be used to rule out more of the $\tan\beta$–m_A plane. However, in the region of large m_A and moderate $\tan\beta$, it will be difficult to detect H^0, A^0 and $H^\pm$ even with a significant increase of luminosity. This is the infamous *LHC wedge region*, where only the SM-like h^0 of the MSSM can be observed.

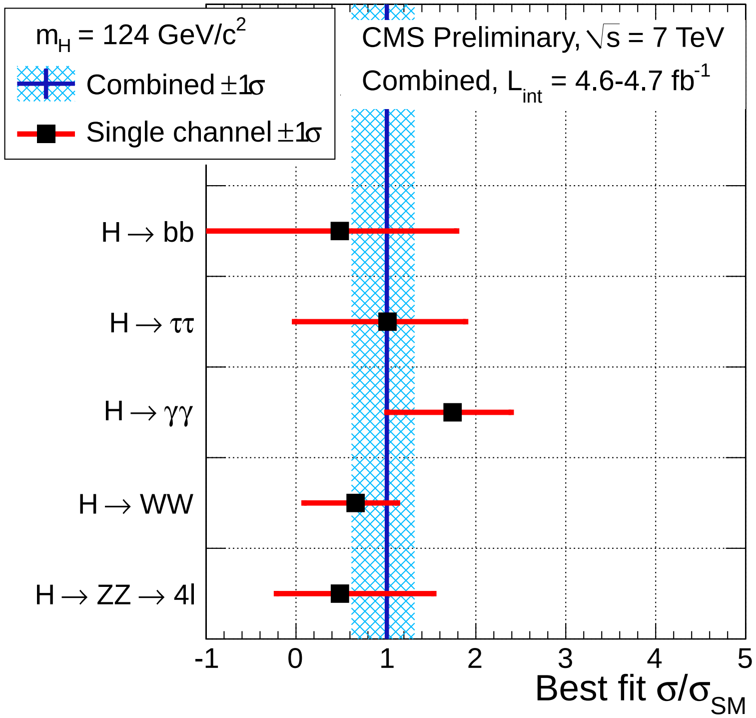
Discovering the SM-like Higgs boson

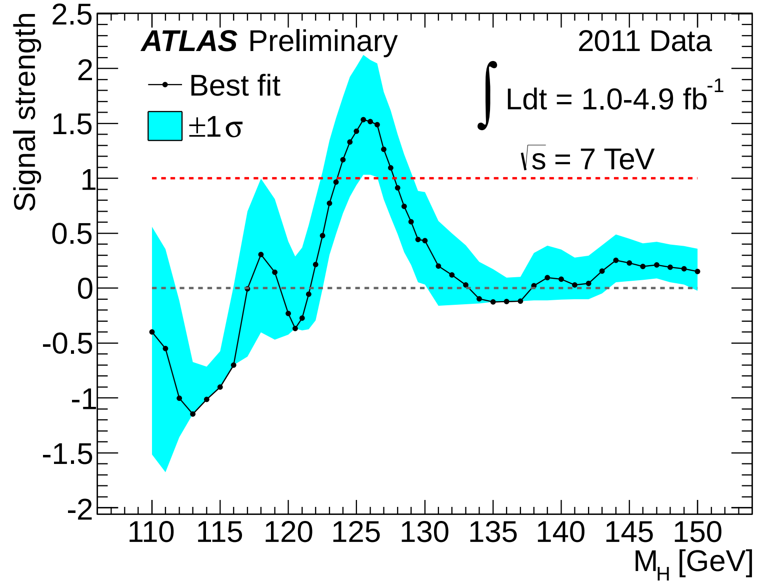
1. What does the present LHC data suggest? Results from ATLAS-CONF-2011-163 and CNS PAS HIG-11-032, released on 13 December 2011, show the consistency of the LHC data with the background-only hypothesis.





Have we caught the first glimpse of a SM-like Higgs boson whose mass is $m_h \simeq 125$ GeV?



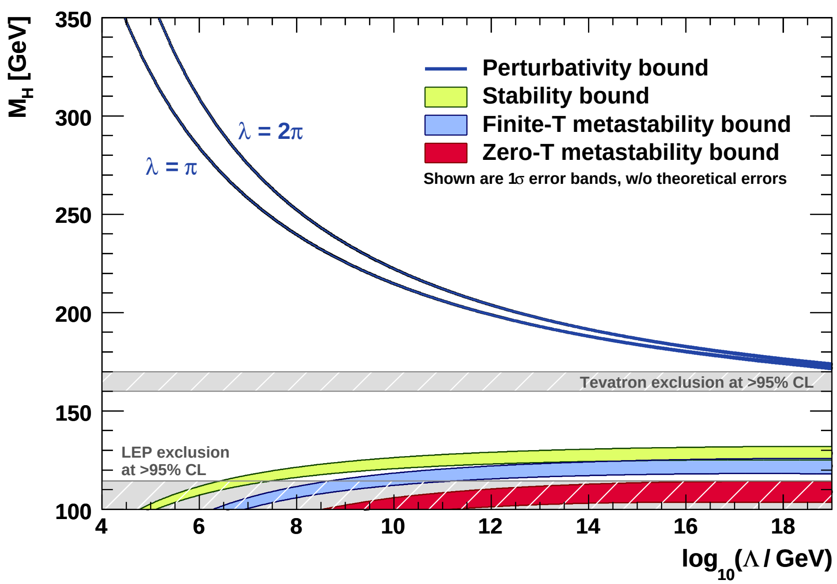


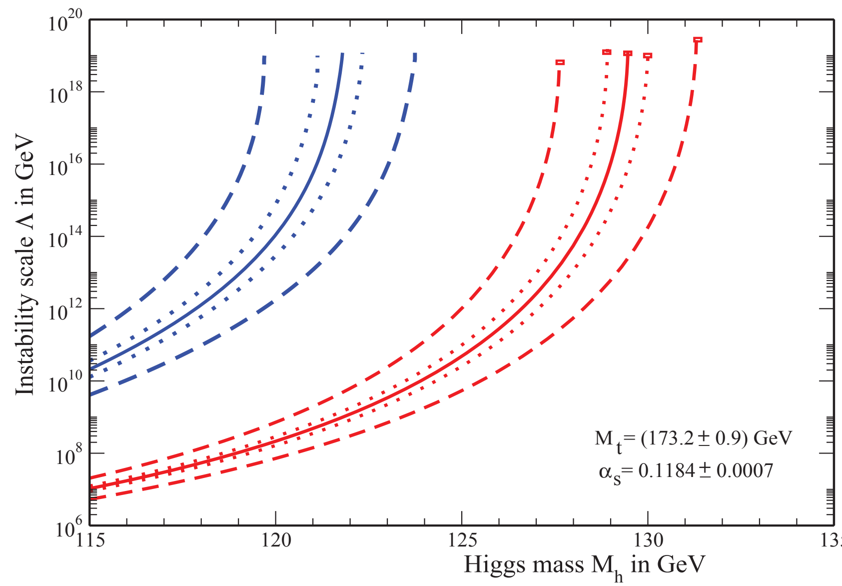
If yes, then its production rate times branching ratio is consistent with that of a SM Higgs, within the experimental uncertainty. Of course, it is premature to call this an *observation* (and certainly it is not yet a *discovery*). Nevertheless, it is a tantalizing hint whose significance will be revealed, if all goes well, in 2012.

Implications of a SM-like Higgs boson with $m_h \sim 125$ GeV

1. Implications for the Standard Model

For a SM Higgs mass below about 130 GeV, the Higgs potential develops an instability at field values of $\Phi \sim \Lambda < M_{\rm PL}$. Either new physics beyond the SM must enter at the scale Λ or below, or the EWSB ground state is not the global minimum. The latter is consistent with observation if the lifetime of the EWSB ground state is sufficiently long.

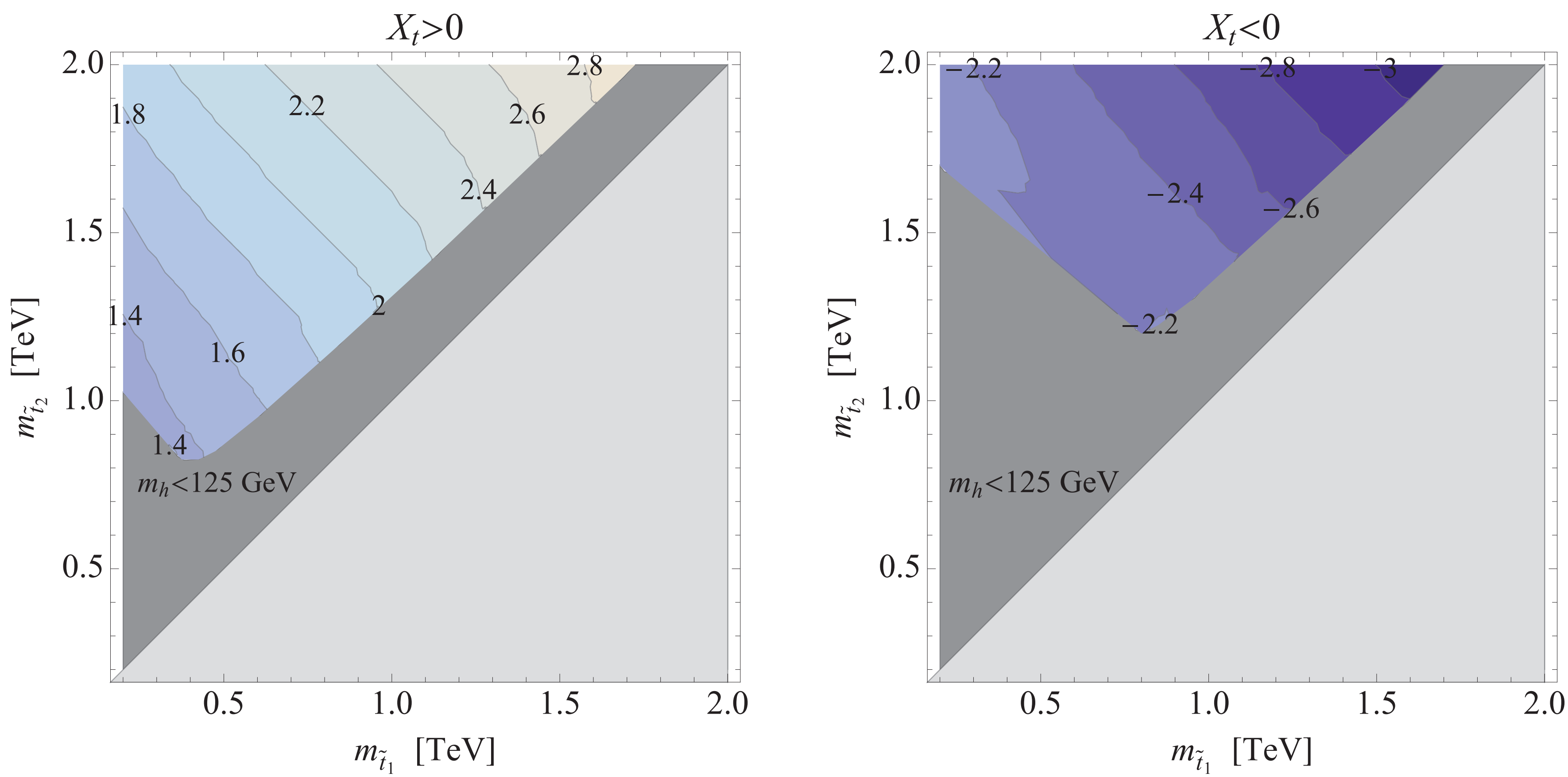




The left pane, taken from J. Ellis et al., Phys. Lett. **679** (2009) 369, updates the triviality and metastability plots for the SM Higgs boson. The right pane, taken from J. Elias-Miró et al., arXiv:1112.3022, focuses in on a Higgs mass range of interest.

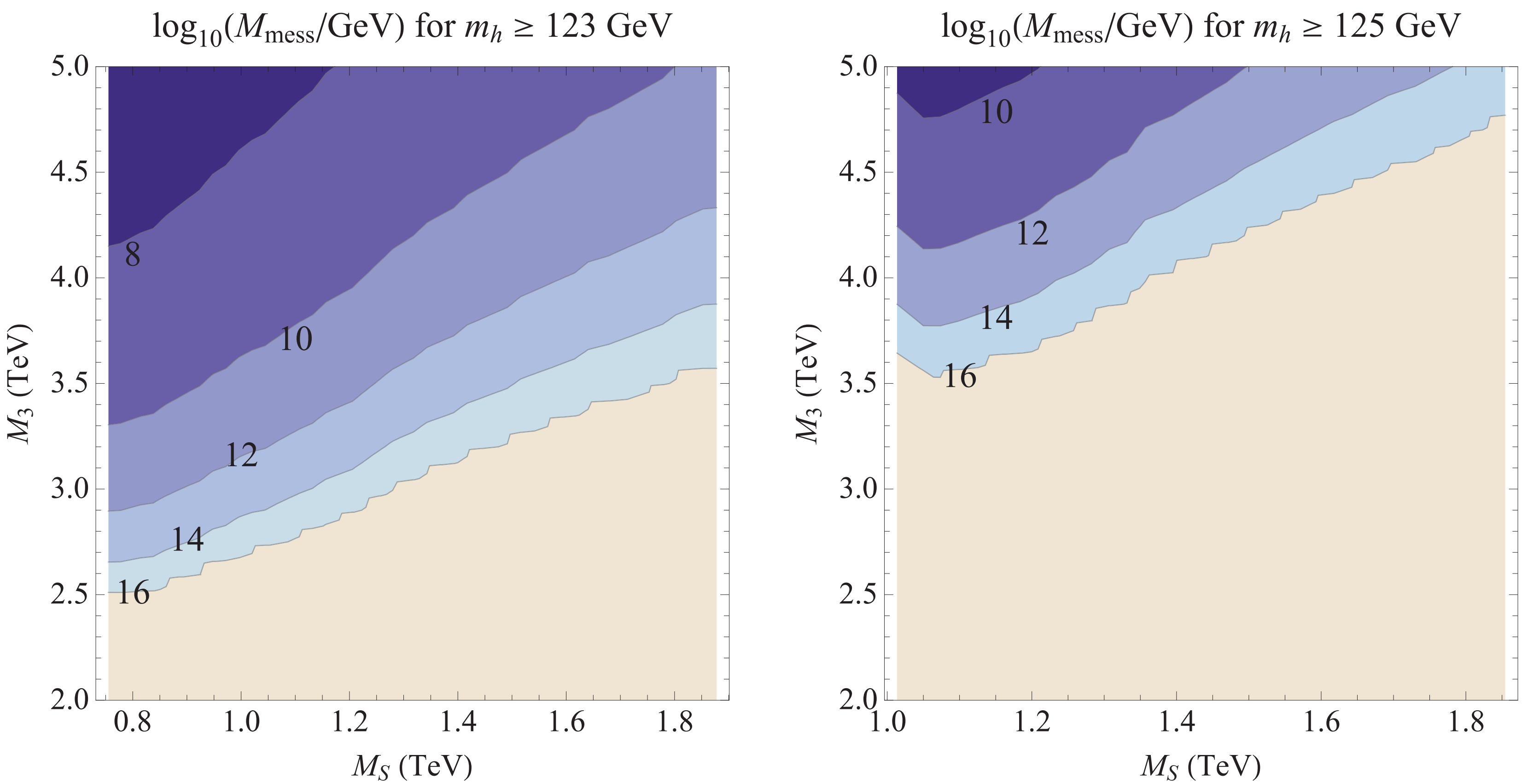
2. Implications for the MSSM

To achieve $m_h \sim 125$ GeV, the radiative corrections to the Higgs mass must be sufficiently large. This places bounds on $\tan\beta$ and the stop masses and mixing. For example, Draper, Meade, Reece and Shih (arXiv:1112.3068) find $\tan\beta \gtrsim 3.5$ and



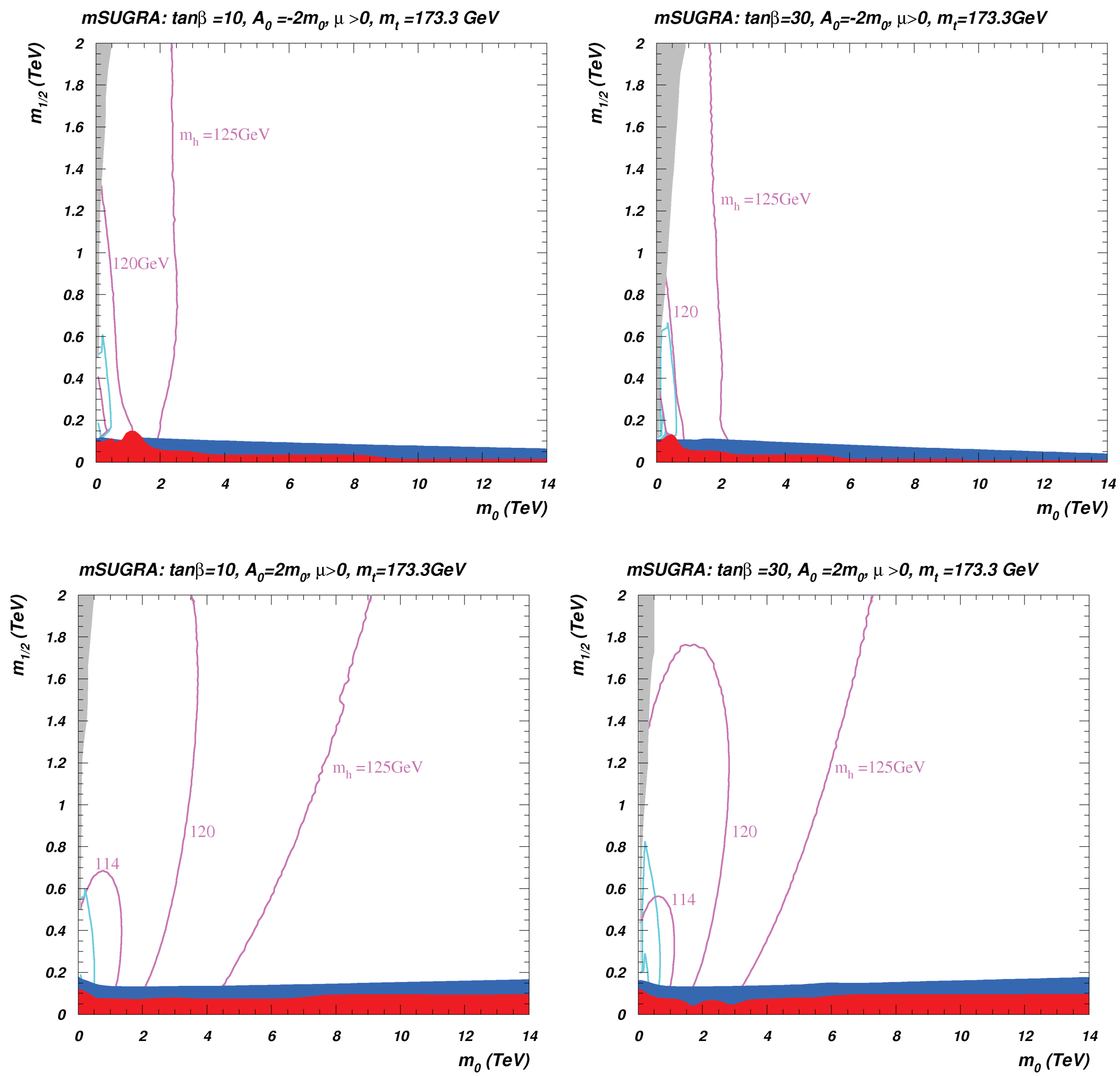
Contour plot of X_t in the plane of the physical stop masses. Here, $X_t = A_t - \mu \cot\beta$ is fixed to be the minimum positive or negative solution to $m_h = 125$ GeV, respectively.

The rather large values of the stop mixing parameter $X_t = A_t - \mu \cot\beta$ imposes severe restrictions on gauge mediated SUSY-breaking models, where A_t is typically zero at the messenger scale. To get large enough A_t requires a high messenger scale (in which case sufficiently large A_t can be generated by RG-running) and/or a large gaugino mass parameter M_3.



Messenger scale required to produce sufficiently large $|A_t|$ through RG-running as a function of gaugino mass parameter M_3 and $M_S \equiv (m_{\tilde{t}_1} m_{\tilde{t}_2})^{1/2}$. Taken from Draper, Meade, Reece and Shih, arXiV:1112.3068.

In mSUGRA models, $m_h \sim 125$ GeV requires a rather heavy SUSY spectrum, which is consistent with the present non-observation of SUSY signals at LHC. For example, Baer, Barger and Mustafayev (arXiv:1112.3017) find:



3. Implications for naturalness in SUSY models

For $m_h \sim 125$ GeV, the size of the stop masses and mixing larger than one would have expected if SUSY is responsible for the scale of EWSB. Similar conclusions have been drawn based on the absence of SUSY events in present LHC data. This is sometimes referred as the *little hierarchy problem*, which seems to require an effective SUSY-breaking scale that is an order of magnitude larger than the EWSB scale.

To address this issue, one must answer the following questions:

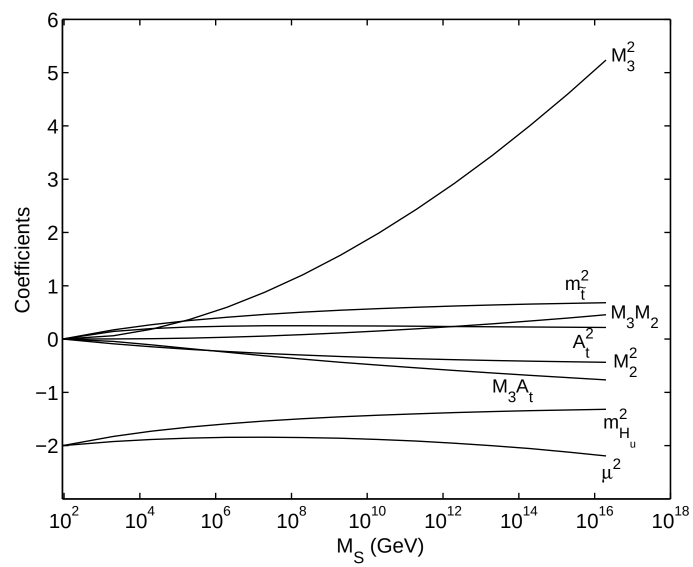
- How does one quantify the degree of naturalness of a SUSY model?

- Given current LHC data, what model assumptions underlie the claim for the little hierarchy?

The minimum conditions for the scalar potential yield an expression for the vacuum expectation values in terms of scalar potential parameters. This can be converted into a formula that expresses m_Z^2 as a sum of terms that depend on low-energy scalar potential parameters. This formula can be re-expressed in terms of high-energy parameters (which reflect the fundamental SUSY-breaking model at some messenger scale M_S) using RG-running. Generically, one has

$$m_Z^2 = \sum_{i,j} c_{ij}(\tan\beta, M_S) m_i(M_S) m_j(M_S) \, .$$

where the coefficients in the MSSM are (note the sensitivity to the gluino and stop masses):

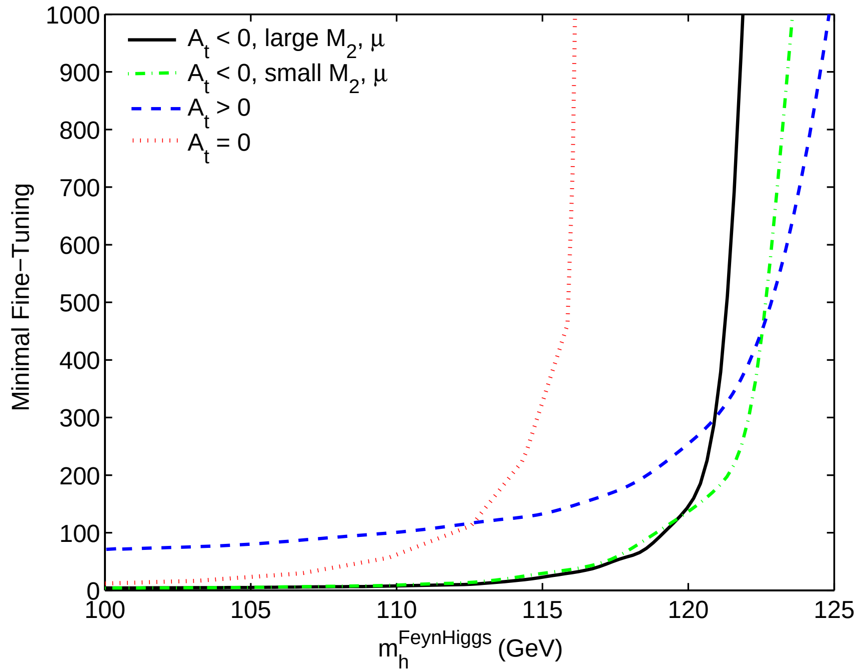


The coefficients c_{ij} for $\tan\beta = 10$, taken from R. Essig and J.-F. Fortin, JHEP **04** (2008) 073.

Following Barbieri and Giudice, one can define the fine tuning sensitivity of m_Z^2 with respect to a parameter a_i by

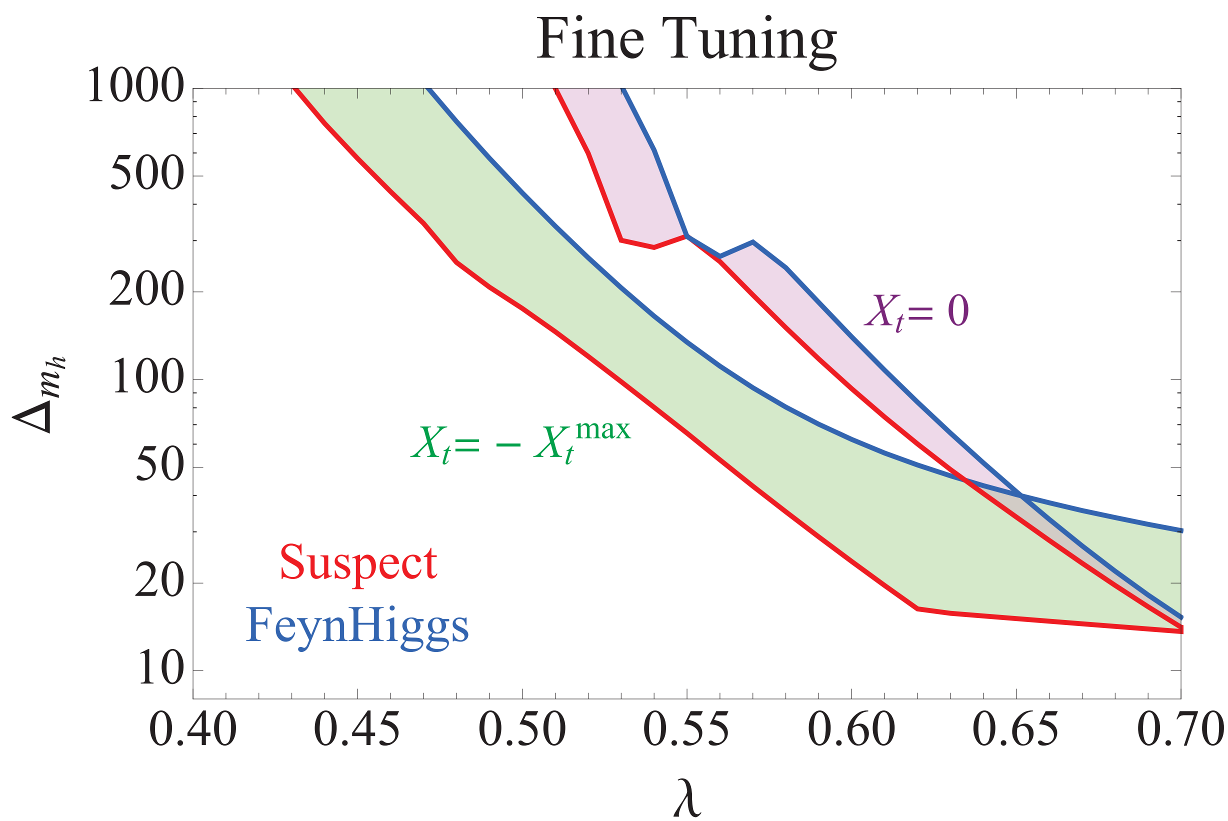
$$\Delta(m_Z^2, a_i) = \left| \frac{\partial \log m_Z^2}{\partial \log a_i} \right| .$$

The fine tuning measure is often defined as $\max\ \Delta(m_Z^2, a_i)$. In the present context, it is more useful to define the fine tuning measure by $\Delta \equiv \left\{ \sum_i \left[|\Delta(m_Z^2, m_i^2(M_S)) \right]^2 \right\}^{1/2}$.



Fine tuning is minimized subject to the constraint on m_h. For details, see R. Essig and J.-F. Fortin, JHEP **04** (2008) 073.

The MSSM with $m_h \sim 125$ GeV is therefore very fined-tuned, since $\Delta \gg 1$. The fine tuning can be significantly alleviated in the NMSSM and even more so if dimensional parameters are included in the superpotential, as advocated by G. Ross and K. Schmidt-Hoberg, and more recently by L.J. Hall and collaborators.



The necessary tuning to achieve $m_h = 126$ GeV as a function of λ, withe $\tan\beta = 2$. Larger values of λ allow for lighter stops and hence much less fine tuning. Taken from L.J. Hallm D. Pinner and J.T. Ruderman, arXiv:1112.2703.

Outlook—where are we headed?

The discovery of the Higgs boson may be imminent. With another 15 fb^{-1} of LHC data anticipated by next summer, the current hints for the Higgs boson will be clarified, with a possible 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?

Measuring Higgs boson properties will be critical in order to determine:

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

Possible scenarios for the Higgs search

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 surely encourage all supersymmetric enthusiasts.

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

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 . . .?