Introduction to Electroweak Symmetry Breaking

Howard E. Haber

Workshop on the Future of Higgs Physics

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Outline

- Dynamics of Electroweak Symmetry Breaking
- The Standard Model Higgs Boson
- Where Does the Standard Model Break Down?
- Higgs Bosons in Low-Energy Supersymmetry
- The Challenge of the Decoupling Limit

The Standard Model of Particle Physics

The observed fundamental particles

spin-1/2 “matter” fermions

- three generations of quarks

$$\begin{pmatrix} u \\ d \end{pmatrix} \qquad \begin{pmatrix} c \\ s \end{pmatrix} \qquad \begin{pmatrix} t \\ b \end{pmatrix}$$

- three generations of leptons

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

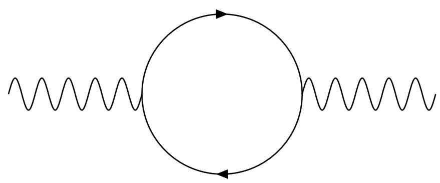
- plus the corresponding antiparticles

spin-1 gauge bosons

- eight gluons (g) mediate the strong interactions
- photon (γ) mediates electromagnetism
- $W^\pm$ and Z^0 mediate the weak interactions

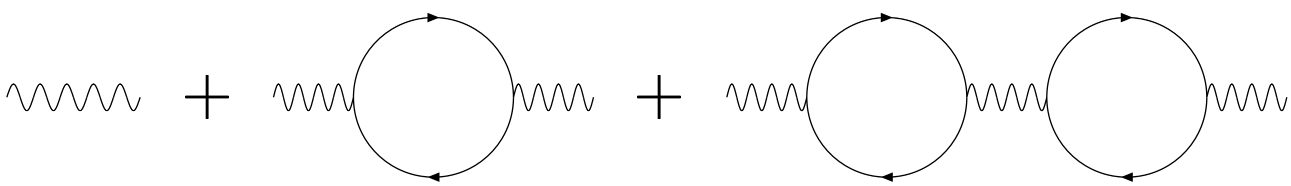
What's missing?

What is the origin of the $W^{\pm}$ and Z boson masses? Gauge boson masses are initially massless, but when quantum corrections are included, a mass may be generated. If one defines:



$$i\,\Pi(q^2)$$

the total propagation is the sum of a geometric series



$$+ \ldots \quad = \quad \frac{i}{q^2[1+\Pi(q^2)]}$$

The pole at $q^2 = 0$ is shifted to a non-zero value if:

$$\Pi(q^2) \underset{q^2 \to 0}{\simeq} \frac{-g^2 v^2}{q^2}\,.$$

Then $q^2[1 + \Pi(q^2)] = q^2 - g^2 v^2$, corresponding to a gauge boson mass of gv.

What dynamics generates the Goldstone bosons?

Interpretation of gauge boson mass generation:

In the sum over intermediate states, there is the propagation of a massless excitation, corresponding to a spin 0 state, called the Goldstone boson. This state could be either an elementary scalar boson or a bound state massless scalar.

Experimental Observation:

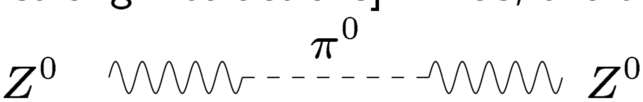
$m_W = 80.436 \pm 0.037$ GeV

$m_Z = 91.1875 \pm 0.0021$ GeV

The Z and $W^{\pm}$ couple to neutral and charged weak currents

$$\mathcal{L}_{\rm int} = g_Z j_\mu^Z Z^\mu + g_W (j_\mu^W W^{+\mu} + {\rm h.c.})\,.$$

which are known to create neutral and charged pions from the vacuum. In the absence of quark masses, the pions are massless bound states of $q\bar{q}$ [they are Goldstone bosons of chiral symmetry which is spontaneously broken by the strong interactions]. Thus, the diagram:



yields $\Pi(q^2) = -g_Z^2 f_\pi^2/q^2$, where $f_\pi = 93$ MeV is the amplitude for creating a pion from the vacuum.

Thus, $m_Z = g_Z f_\pi$. Similarly $m_W = g_W f_\pi$. Thus,

$$\frac{m_W}{m_Z} = \frac{g_W}{g_Z} \equiv \cos\theta_W \simeq 0.88$$

which is remarkably close to the measured ratio. Unfortunately, since $g_Z \simeq 0.37$ we find $m_Z = 35$ MeV, which is too small by a factor of 2600. We need another source for the Goldstone bosons.

> The quest for electroweak symmetry breaking is the search for the dynamics that generates the Goldstone bosons that are the source of mass for the W and Z.

Possible choices for EWSB dynamics

- weakly-interacting self-coupled elementary (Higgs) scalar dynamics

- strong-interaction dynamics among new fermions (mediated perhaps by gauge forces)

Both mechanisms generate new phenomena with significant experimental consequences.

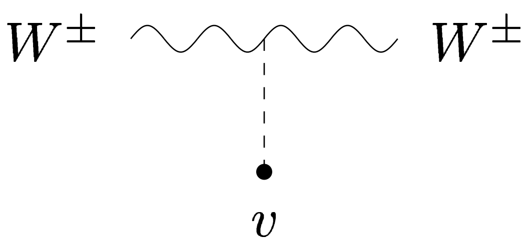
The missing piece of the Standard Model

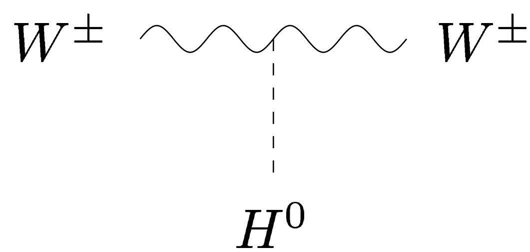
The Standard Model posits a new sector of "matter" consisting of self-interacting scalar fields that carry electroweak quantum numbers (and thus couple to the $W^\pm$ and Z^0). The simplest model consists of a complex doublet of scalar fields, with four degrees of freedom. The scalar potential is chosen so that in the ground state, the neutral scalar field takes on a constant non-zero value, $v = 246$ GeV.

A scalar field with electroweak quantum numbers with a constant non-zero vacuum value breaks the electroweak symmetry. One finds three Goldstone bosons (exactly massless), which are absorbed by the $W^\pm$ and Z. Now, v plays the role of f_π, so we get $m_Z = g_Z v \simeq 91$ GeV. One scalar degree of freedom is left over—this is the Higgs boson. It is a neutral CP-even scalar boson, whose interactions are precisely predicted, but whose mass is unknown (it is proportional to the strength of the scalar self-coupling—the only unknown parameter of the model).

Mass generation and Higgs couplings in the Standard Model

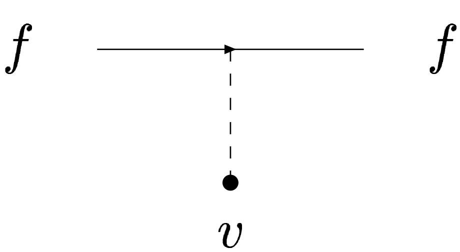
Gauge bosons acquire mass via interaction with the Higgs vacuum condensate.

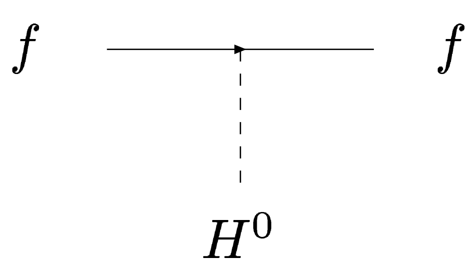




Thus, $g_{HW^+W^-} = 2m_W^2/v$. That is, Higgs couplings are proportional to mass.

Before electroweak symmetry breaking, Standard Model fermions are massless. The quarks and charged leptons acquire mass as well:

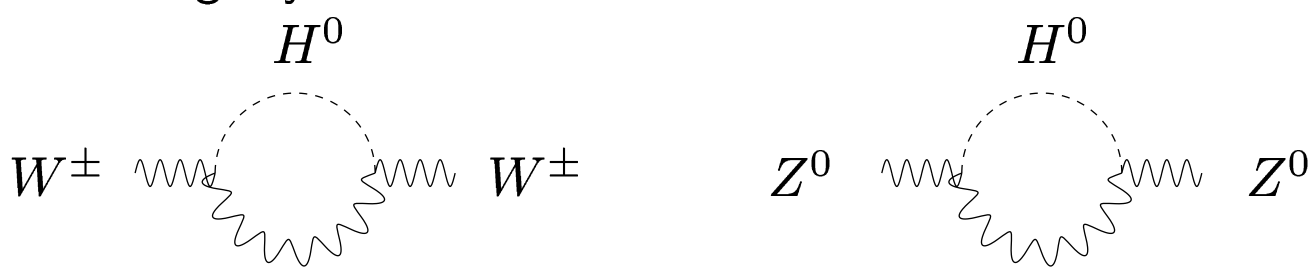




We again find a Higgs coupling proportional to mass: $g_{Hf\bar{f}} = m_f/v$.

Precision tests of the Standard Model

Very precise tests of the Standard Model were possible given the large sample of 2×10^7 Z-boson decays observed at LEP. 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:

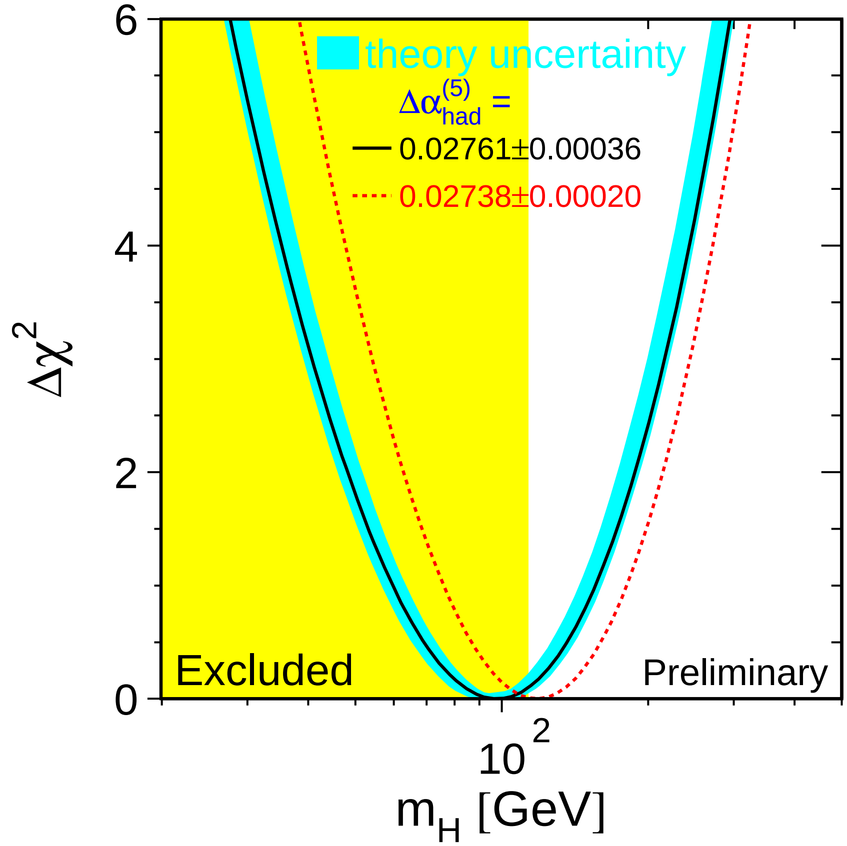


The m_H dependence of the above radiative corrections is logarithmic. Nevertheless, a global fit of many electroweak observables can determine the preferred value of m_H (assuming that the Standard Model is the correct description of the data).

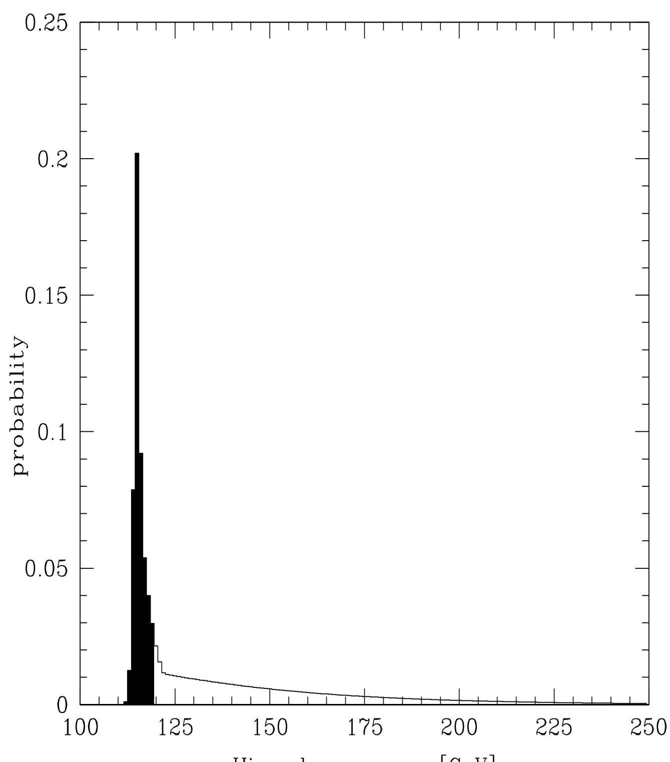
A recent analysis [LEP EW Working Group; Moriond 2001]:

$$m_H = 98^{+58}_{-38}\ \mathrm{GeV} \quad \mathrm{OR} \quad m_H < 212\ \mathrm{GeV}\ [at\ 95\%\ \mathrm{CL}]$$

with $\chi^2 = 25/15$ $[P = 4\%]$.



theory uncertainty
$\Delta\alpha^{(5)}_{had}$ =
0.02761±0.00036
0.02738±0.00020
Excluded
Preliminary
$\Delta\chi^2$
m_H [GeV]
10^2
0
2
4
6



probability
Higgs boson mass [GeV]
0
0.05
0.1
0.15
0.2
0.25
100
125
150
175
200
225
250

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].

Peskin and Wells [hep-ph/0101342] have recently argued that 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 that can be detected at future colliders (LHC and/or the a high-energy e^+e^- linear collider [LC])

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

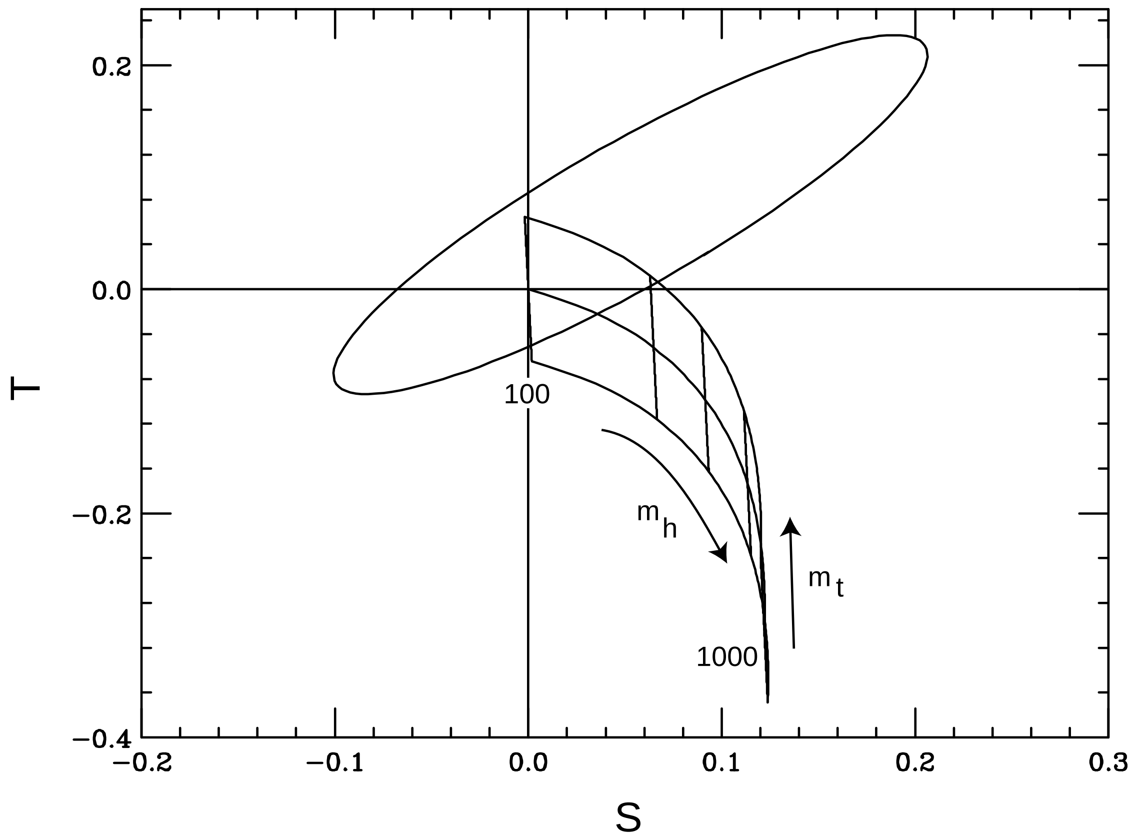


Figure 1: Fit of the precision electroweak data to the MSM plus the S, T parameters described in the text. The fit is based on the values of m_W, $\sin^2\theta_w^{\rm eff}$, and Γ_ℓ shown in Table 1. The ellipse shows the 68% two-dimensional confidence region ($1.5\,\sigma$). The banana-shaped figure shows the central value of a fit to the MSM for $m_t = 174.3 \pm 5.1$ GeV and m_h varying from 100 to 1000 GeV, with m_h = 200, 300, 500 GeV marked with vertical bands. An active version of this figure can be obtained by downloading the additional files deposited with the eprint.

Although the 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).

Where does the Standard Model Break Down?

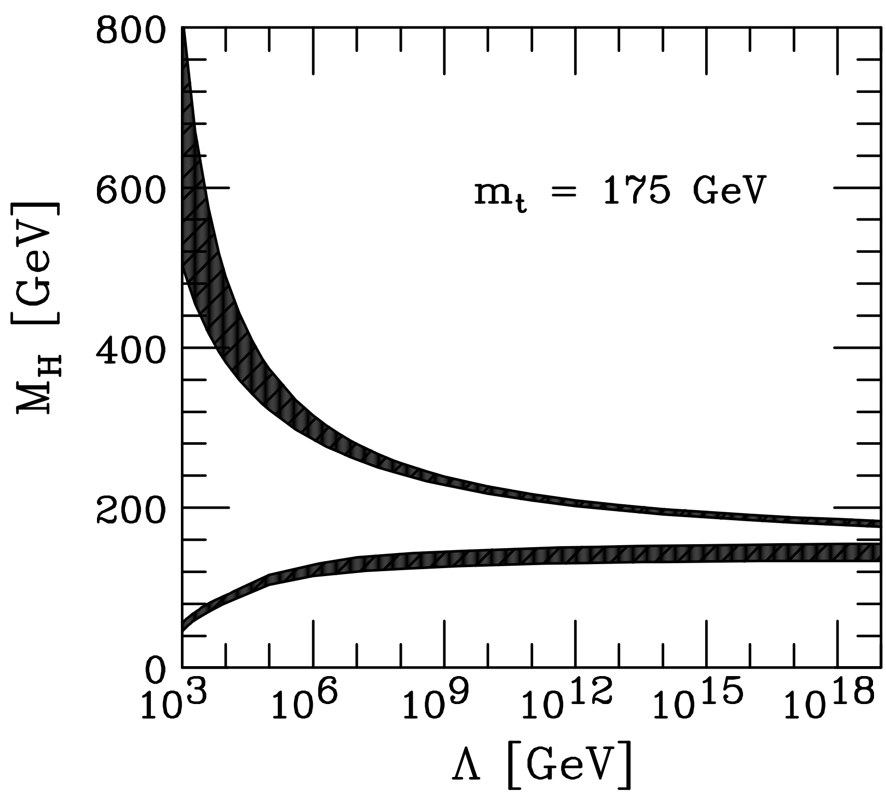
The Standard Model (SM) describes quite accurately physics near the electroweak symmetry breaking scale [$v = 246$ GeV]. But, the SM is only a "low-energy" approximation to a more fundamental theory.

- The Standard Model cannot be valid at energies above the Planck scale, $M_{\rm PL} \simeq 10^{19}$ GeV, where gravity can no longer be ignored.

- Neutrinos are exactly massless in the Standard Model. But, recent experimental observations of neutrino mixing imply that neutrinos have very small masses ($m_\nu/m_e \lesssim 10^{-7}$). Neutrino masses can be incorporated in a theory whose fundamental scale is $M \gg v$. Neutrino masses of order v^2/M are generated, which suggest that $M \sim 10^{15}$ GeV.

- When radiative corrections are evaluated, one finds:
  - The Higgs potential is unstable at large values of the Higgs field ($|\Phi| > \Lambda$) if the Higgs mass is too small.
  - The value of the Higgs self-coupling runs off to infinity at an energy scale above Λ if the Higgs mass is too large.

  This is evidence that the Standard Model must break down at energies above Λ.



Problems with Elementary Scalar Fields

How can one understand the large hierarchy of energy scales from v to $M_{\rm PL}$ in the context of the SM? If the SM is superseded by a more fundamental theory at an energy scale Λ, one expects scalar squared-masses to exhibit quadratic sensitivity to Λ, in contrast to fermions which exhibit only logarithmic sensitivity to Λ. That is,

$$m_H^2 = (m_H^2)_0 + K\frac{g^2}{4\pi}\Lambda^2$$

$(m_H^2)_0$ is a parameter of the fundamental theory, $K \sim \mathcal{O}(1)$ is determined by low-energy physics. The *natural* value for the scalar squared-mass is roughly $g^2\Lambda^2$. Thus,

$$\Lambda \simeq 4\pi m_H/g \sim \mathcal{O}(1 \text{ TeV})$$

What new physics is lurking at the TeV scale?

Low-Energy Supersymmetry

Introduce supersymmetry: for every fermion, there is a boson of equal mass and vice versa. Now, compute the self-energy of an elementary scalar. Supersymmetry relates it to the self-energy of a fermion, which is only logarithmically logarithmically sensitive to the fundamental high energy scale. Conclusion: quadratic sensitivity is removed! The hierarchy problem is resolved.

However, no super-partner (degenerate in mass with the corresponding SM particle) has ever been seen. Supersymmetry, if it exists in nature, must be a broken symmetry. Previous arguments then imply that:

> The scale of supersymmetry-breaking must be of order 1 TeV or less, if supersymmetry is associated with the scale of electroweak symmetry breaking.

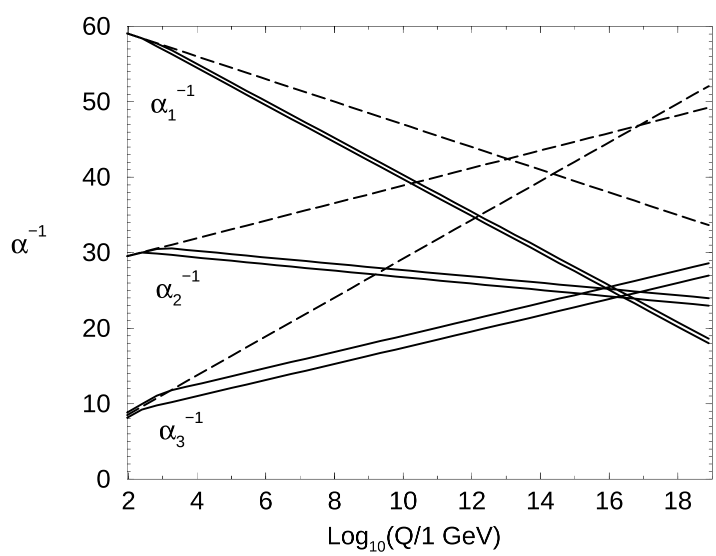
What has been gained? The problem of the electroweak symmetry breaking scale is now replaced with the question of the origin of low-energy supersymmetry breaking [a difficult task, not yet solved—many approaches but no compelling model]. But, in principle one can extend the model of low-energy supersymmetry all the way up to $M_{\rm PL}$ with no theoretical impediments.

Benefits of Low-Energy Supersymmetry

- In low-energy SUSY theories, quadratic sensitivity to Λ is replaced by quadratic sensitivity to the SUSY-breaking scale.

- Provides a framework for the hierarchy of energy scales between the scale of electroweak symmetry breaking and the Planck scale ($M_{\rm PL} \simeq 10^{19}$ GeV), which characterizes the fundamental scale of gravity.

- Unification of the three gauge couplings at $\sim 10^{16}$ GeV.



Electroweak Symmetry Breaking and Low-Energy Supersymmetry

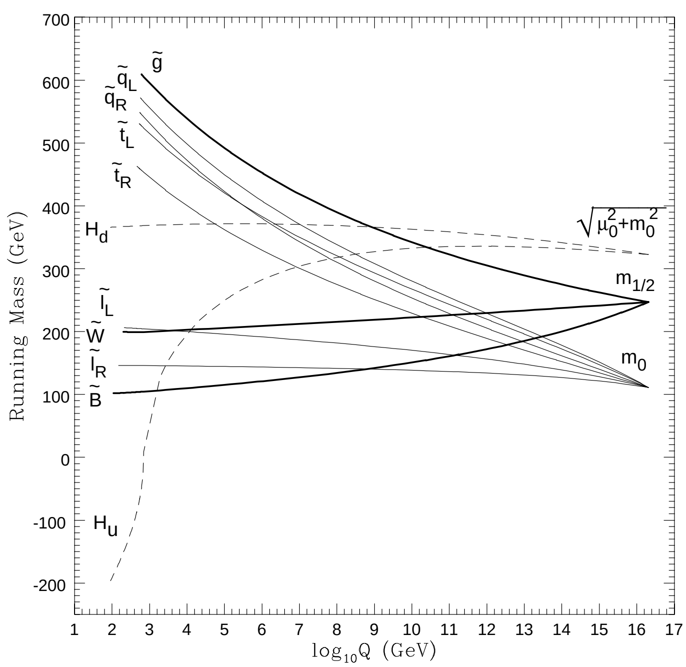
The Minimal Supersymmetric Standard Model (MSSM)

• Add a second complex Higgs doublet

• Add corresponding super-partners and allow for all possible supersymmetric interactions (consistent with B and L)

• Add supersymmetry-breaking (subject to experimental limits on super-partner masses)

Electroweak symmetry breaking is radiatively generated.



Higgs sector of the MSSM

Two complex doublets have eight degrees of freedom. Two neutral scalar components acquire vacuum expectation values: v_1 and v_2. The two scalar provide three Goldstone bosons that are absorbed by the $W^\pm$ and Z. The gauge boson masses fix the value of $v_1^2 + v_2^2 = 246$ GeV, while the ratio $\tan\beta \equiv v_2/v_1$ remains a free parameter. There are five remaining physical scalar degrees of freedom:

- $H^\pm$: a charged Higgs pair
- h^0, H^0: two CP-even Higgs scalars ($m_h \leq m_H$), and a CP-even Higgs mixing angle α
- A^0: a CP-odd Higgs scalar

All Higgs masses and couplings can be expressed in terms of two parameters usually chosen to be m_A and $\tan\beta$.

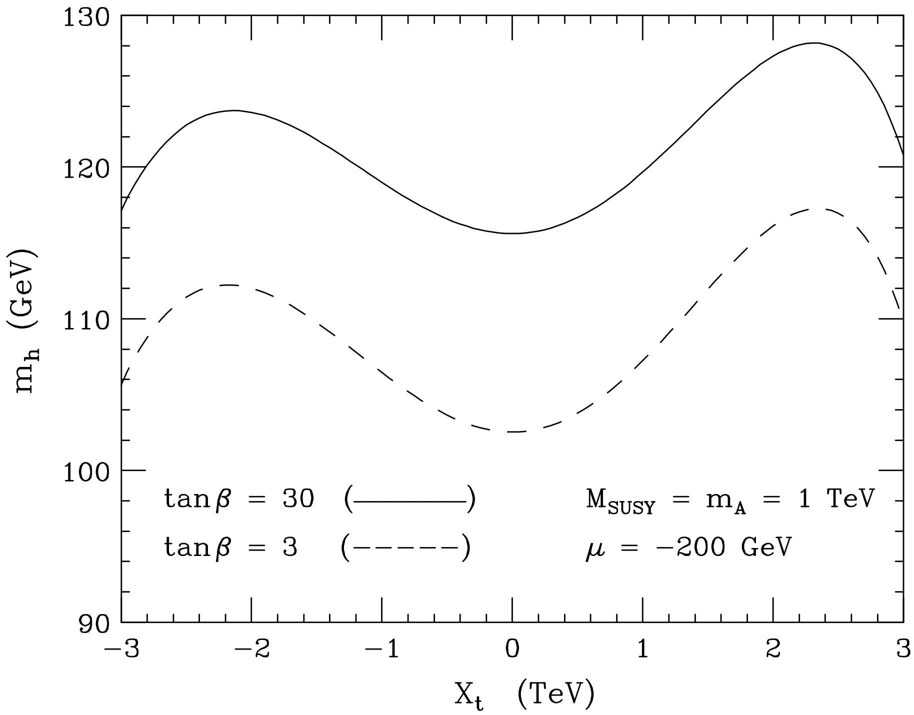
- When $m_A \gg m_Z$, one finds that h^0 exhibits couplings identical to that of the Standard Model Higgs boson, while the other Higgs states H^0, A^0 and $H^\pm$ are all heavy and roughly degenerate in mass. This is called the decoupling limit.

- Due to supersymmetric relations among couplings, one finds that $m_h \leq m_Z$ (a result already 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 cancelation, which would have been exact if supersymmetry were unbroken):

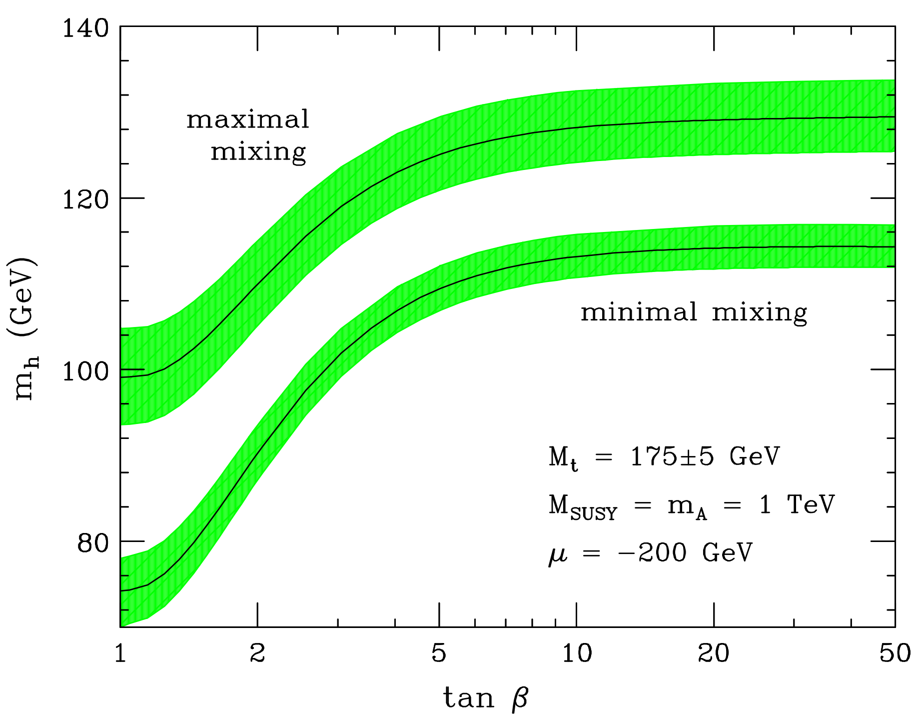
$$m_h^2 \lesssim m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right],$$

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

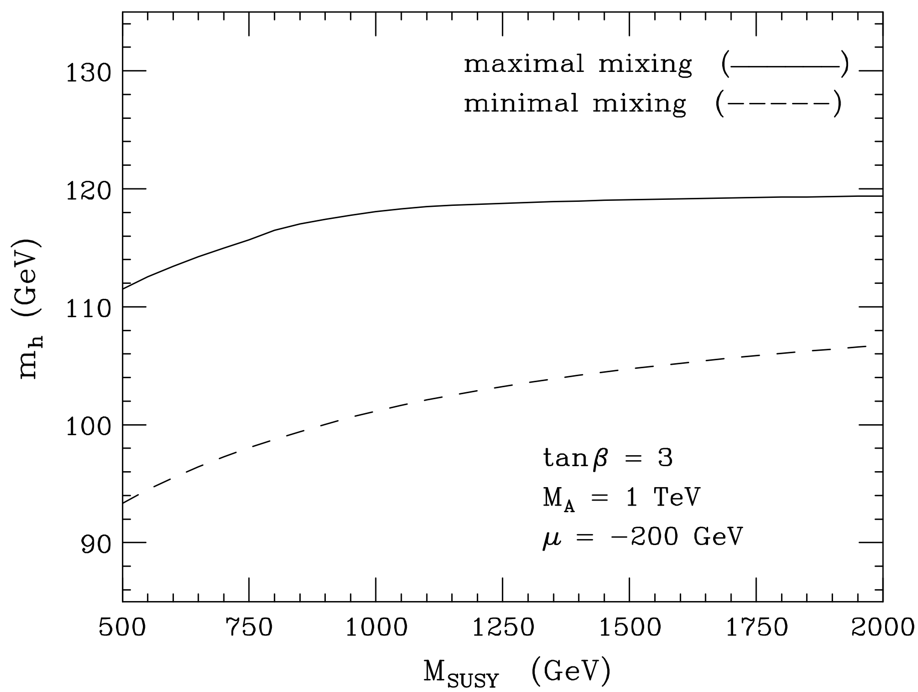
End result: $m_h \lesssim 130$ GeV [assuming that the top-squark mass is no heavier than about 2 TeV].



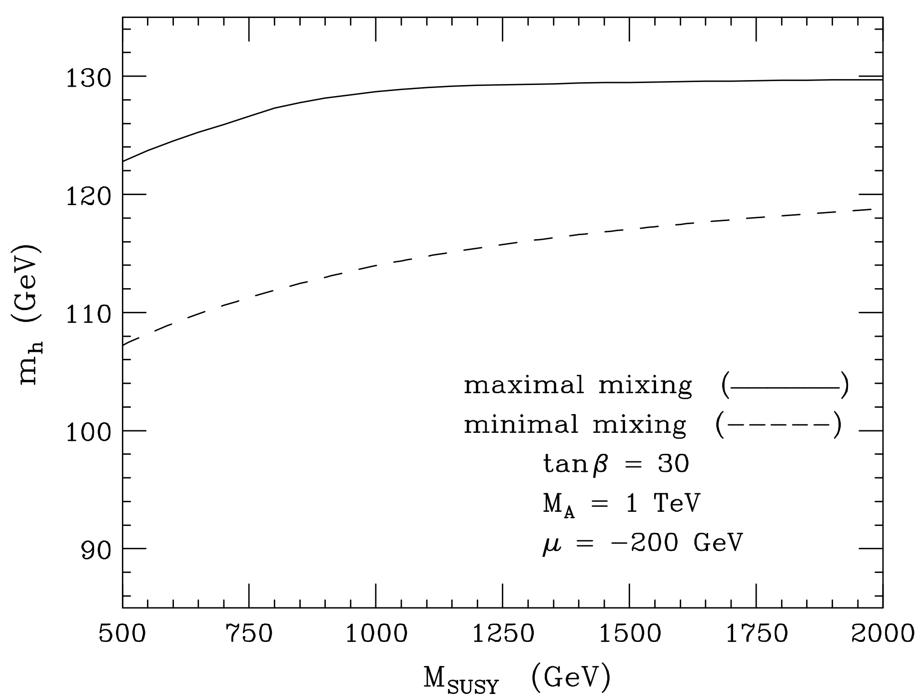
tan β = 30 (———)
tan β = 3 (- - - - -)
M_SUSY = m_A = 1 TeV
μ = −200 GeV
m_h (GeV)
X_t (TeV)



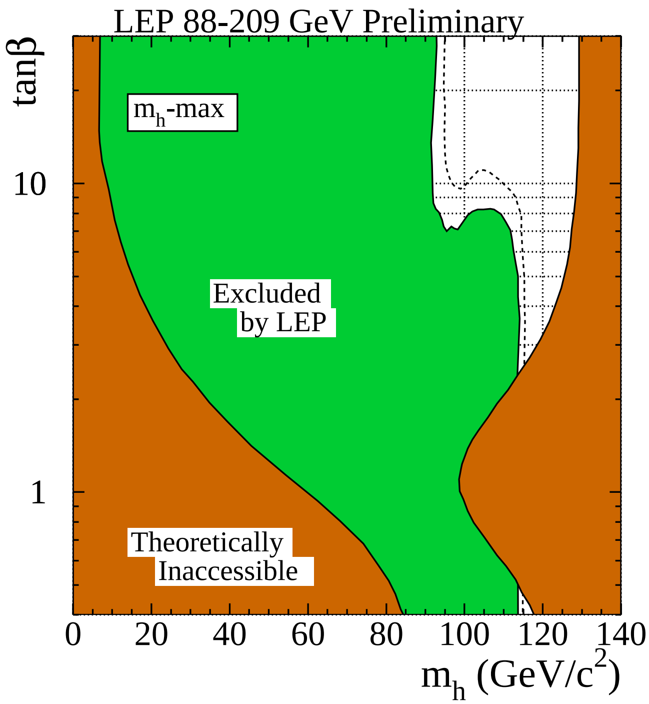
maximal
mixing
minimal mixing
M_t = 175±5 GeV
M_SUSY = m_A = 1 TeV
μ = −200 GeV
m_h (GeV)
tan β

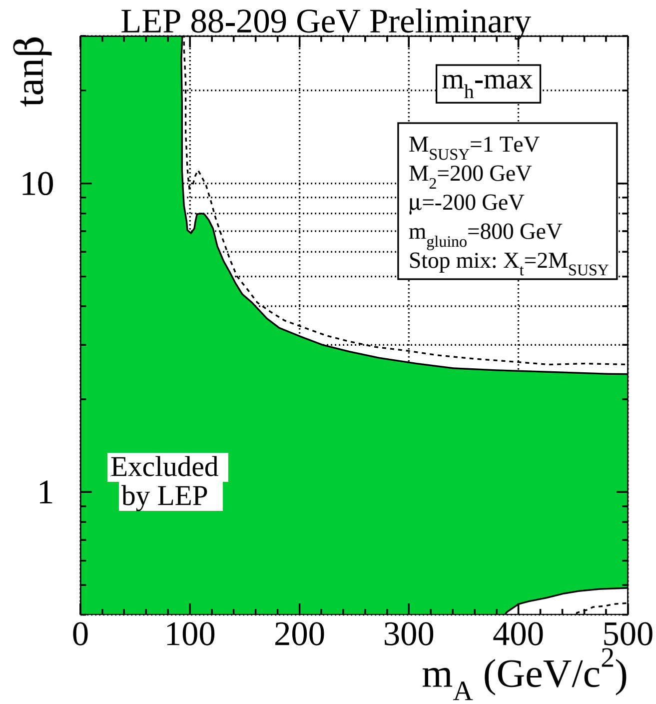


maximal mixing (———)
minimal mixing (-----)
tanβ = 3
M_A = 1 TeV
μ = −200 GeV
m_h (GeV)
M_SUSY (GeV)



maximal mixing (———)
minimal mixing (-----)
tanβ = 30
M_A = 1 TeV
μ = −200 GeV
m_h (GeV)
M_SUSY (GeV)





Present status of the LEP Higgs Search [95% CL limits]

- Standard Model Higgs boson: $m_H > 113.5$ GeV
- Charged Higgs boson: $m_{H^\pm} > 78.5$ GeV
- MSSM Higgs: $m_h > 91.0$ GeV; $m_A > 91.9$ GeV

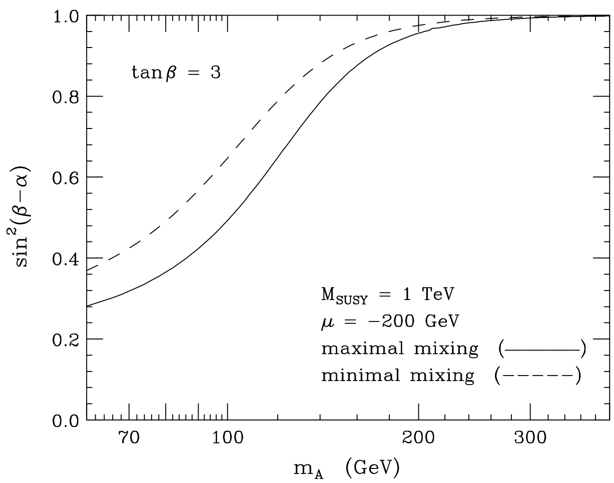
At large $\tan\beta$, supersymmetric radiative corrections can also have a significant impact on the Higgs branching ratios. Example: the dominant decay mode $h \to b\bar{b}$ is suppressed in some regions of MSSM Higgs parameter space.

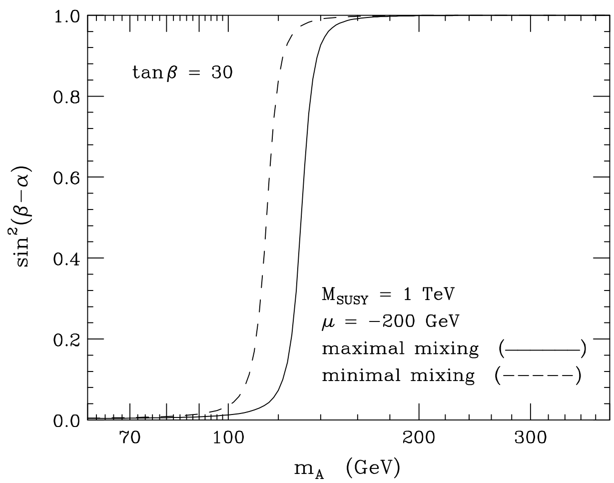
The Decoupling Limit

In the limit $m_A \gg m_Z$, tree-level Higgs masses are given by:

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

Thus, $m_A \simeq m_H \simeq m_{H^\pm}$, up to corrections of $\mathcal{O}(m_Z^2/m_A)$, and $\cos(\beta - \alpha) = 0$ up to corrections of $\mathcal{O}(m_Z^2/m_A^2)$.





This is the decoupling limit, in which the effective low-energy theory below the scale of m_A is a theory with an effective Higgs sector consisting of one SM-like CP-even Higgs boson, h^0.

MSSM Tree-Level Higgs Couplings

Higgs couplings to gauge bosons: suppression factors

$\cos(\beta-\alpha)$	$\sin(\beta-\alpha)$	no angle factor
$H^0W^+W^-$	$h^0W^+W^-$	
H^0ZZ	h^0ZZ	
ZA^0h^0	ZA^0H^0	$ZH^+H^-, \gamma H^+H^-$
$W^\pm H^\mp h^0$	$W^\pm H^\mp H^0$	$W^\pm H^\mp A^0$

CP-even Higgs couplings to fermion pairs [relative to m_f/v]

$$h^0 b\bar{b}: \quad -\frac{\sin\alpha}{\cos\beta} = 1\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\,,$$

$$h^0 t\bar{t}: \quad \frac{\cos\alpha}{\sin\beta} = 1\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)\,,$$

$$H^0 b\bar{b}: \quad \frac{\cos\alpha}{\cos\beta} = \cos(\beta-\alpha) + \tan\beta\,\sin(\beta-\alpha)\,,$$

$$H^0 t\bar{t}: \quad \frac{\sin\alpha}{\sin\beta} = \cos(\beta-\alpha) - \cot\beta\,\sin(\beta-\alpha)\,.$$

In particular, tree-level couplings of h^0 are precisely those of the Standard Model Higgs boson when $\cos(\beta-\alpha)=0$.

The decoupling limit still applies when radiative corrections are taken into account, although the rate of approach to decoupling may be significantly altered. For example, including the leading radiative corrections, one finds the following $b\bar{b}$ Higgs couplings:

$$h^0 b\bar{b}: \qquad -\frac{\sin\alpha}{\cos\beta}\left(\frac{1}{1+\Delta_b}\right)\left[1-\frac{\Delta_b}{\tan\alpha\tan\beta}\right],$$

$$H^0 b\bar{b}: \qquad \frac{\cos\alpha}{\cos\beta}\left(\frac{1}{1+\Delta_b}\right)\left[1+\frac{\Delta_b\tan\alpha}{\tan\beta}\right],$$

where $\Delta_b \sim \alpha_s \tan\beta\, f(M_S)$, and $f(M_S)$ is a dimensionless function of supersymmetric masses. In the decoupling limit:

$$\cot\alpha = -\tan\beta - \frac{2m_Z^2}{m_A^2}\tan\beta\cos 2\beta + \mathcal{O}\left(\frac{m_Z^4}{m_A^4}\right).$$

Thus, in the decoupling limit, the $hb\bar{b}$ coupling differs from its SM value by a factor of $\mathcal{O}(m_Z^2 \tan\beta / m_A^2)$. Decoupling is delayed by a factor of $\tan\beta$.

Challenge of the Decoupling Limit

- The decoupling limit is very general. Many models with non-minimal Higgs sectors possess a decoupling limit, in which the properties of the lightest CP-even Higgs boson are nearly indistinguishable from those of the SM Higgs boson.

- Discovery of the SM-like Higgs boson is not sufficient to reveal the underlying EWSB dynamics.

- It is crucial to find evidence for Higgs physics beyond the SM Higgs boson. Either one must directly discover the non-minimal Higgs states (perhaps difficult, if they are too heavy), or one must detect deviations from SM Higgs predictions.

- In the latter case, precision Higgs measurements are essential for detecting deviations from the SM of branching ratios, coupling strengths, cross-sections, *etc.*

Precision Higgs Boson Measurements

The LHC will provide the first set of Higgs boson measurements, and will achieve some degree of accuracy. However, a robust program of precision Higgs physics requires a lepton collider.

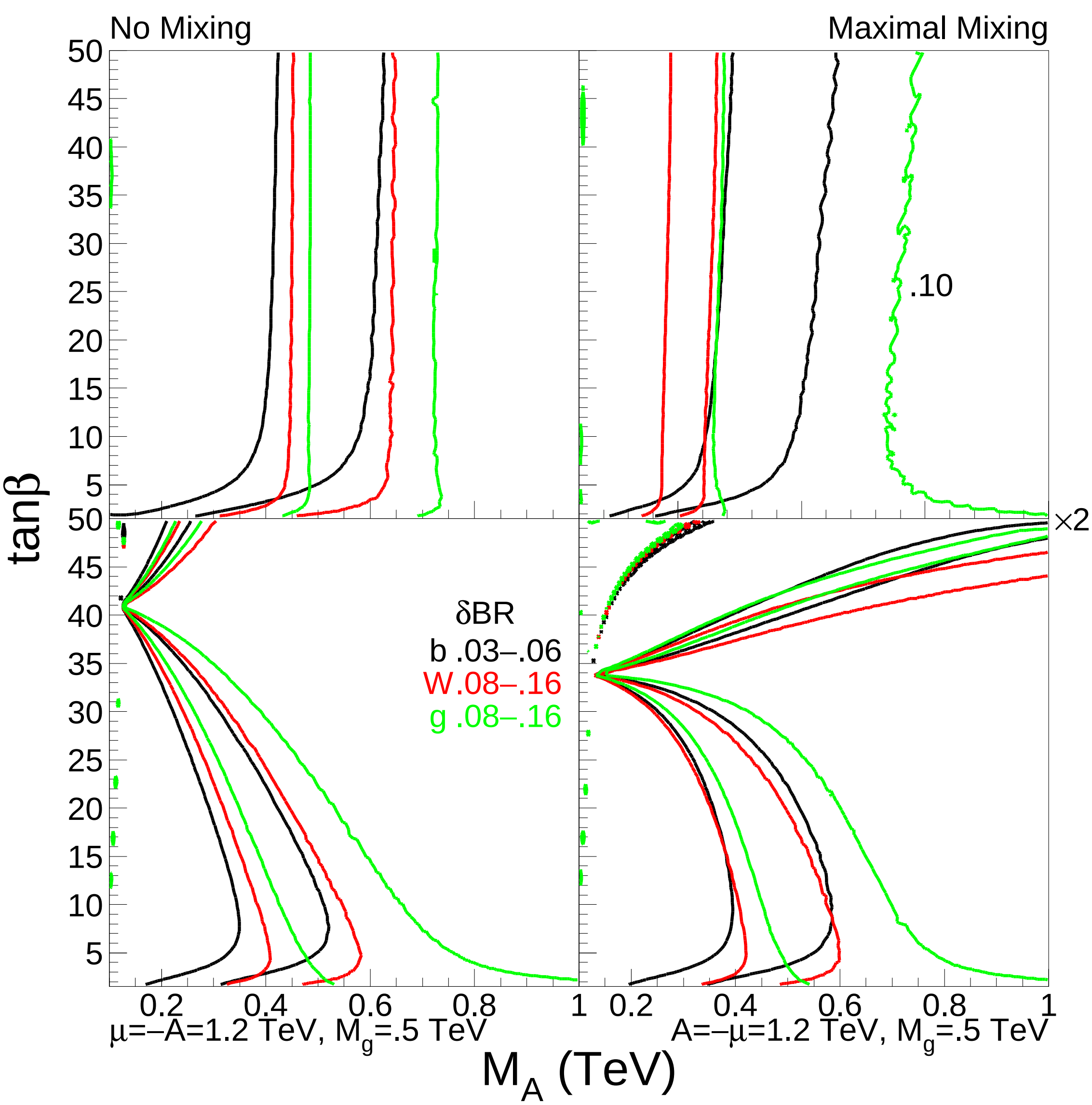
Expectations for precision of LC measurements of branching ratios (BRs) [Battaglia and Desch]

final state	$m_H = 120$ GeV	$m_H = 140$ GeV
h^0, $H^0 \to b\bar{b}$	± 0.024	± 0.026
h^0, $H^0 \to \tau^+\tau^-$	± 0.050	± 0.080
h^0, $H^0 \to c\bar{c}$	± 0.085	± 0.190
h^0, $H^0 \to gg$	± 0.055	± 0.140
h^0, $H^0 \to WW^*$	± 0.051	± 0.025

Relative accuracy in the determination of Higgs boson decay branching ratios, assuming 500 fb^{-1} at an e^+e^- CM energy of 350 GeV.

Implications for the MSSM Higgs sector [Carena, Haber, Logan, and Mrenna]

Contours of $\delta\mathrm{BR} \equiv [\mathrm{BR}_{\mathrm{MSSM}} - \mathrm{BR}_{\mathrm{SM}}]/\mathrm{BR}_{\mathrm{SM}}$ in the m_A—$\tan\beta$ plane for different MSSM parameter scenarios.



Conclusions

• The Standard Model is not yet complete. The nature of the dynamics responsible for EWSB remains unresolved.

• There are strong hints that a weakly-coupled elementary Higgs boson exists in nature. (Loopholes still exist—nature may be trickier than expected by naive theorists.)

• Strong theoretical arguments based on hierarchy and naturalness suggest that the Standard Model must be superseded by a more fundamental theory at an energy scale of order 1 TeV. This new physics is intimately connected with the dynamics of electroweak symmetry breaking.

• Low-Energy Supersymmetry is a leading candidate for the TeV-scale physics beyond the Standard Model.

• Nature may still have some surprises up her sleeve. Perhaps extra dimensions will be revealed by experiments at future colliders. One can only begin to imagine how EWSB could fit into such a scenario.

Conclusions (continued)

- If weakly-coupled Higgs bosons exist, it is essential to find evidence for departures from SM Higgs predictions. Such departures will reveal crucial information about the nature of the EWSB dynamics.

- The decoupling limit presents a severe challenge for future Higgs studies. A program of precision Higgs measurements will begin at the LHC, but will only truly blossom at a future high energy e^+e^- collider.

- Ultimately, one must discover the TeV-scale dynamics associated with EWSB $e.g.$, low-energy supersymmetry and/or new particles and phenomena associated with new strong dynamics. Future colliders at the TeV-scale should be prepared for a very rich menu of new phenomena.

- But what if there is only a SM Higgs boson and no evidence for new physics beyond the SM? . . .