Higgs Theory Overview

Howard E. Haber
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Outline

- Where is the Higgs boson?
- The nature of EWSB Dynamics
- The Decoupling Limit
- Main goals of the Higgs Hunter
- Precision Higgs Physics at the LC
- Where do we go from here?

Motherhood and apple pie preamble

The number one priority of particle physics today is to discover the dynamics responsible for electroweak symmetry breaking (EWSB). In the Standard Model (SM), this dynamics is achieved by the self-interactions of a complex scalar doublet of fields. But, is this the end of physics (until we reach the Planck scale)?

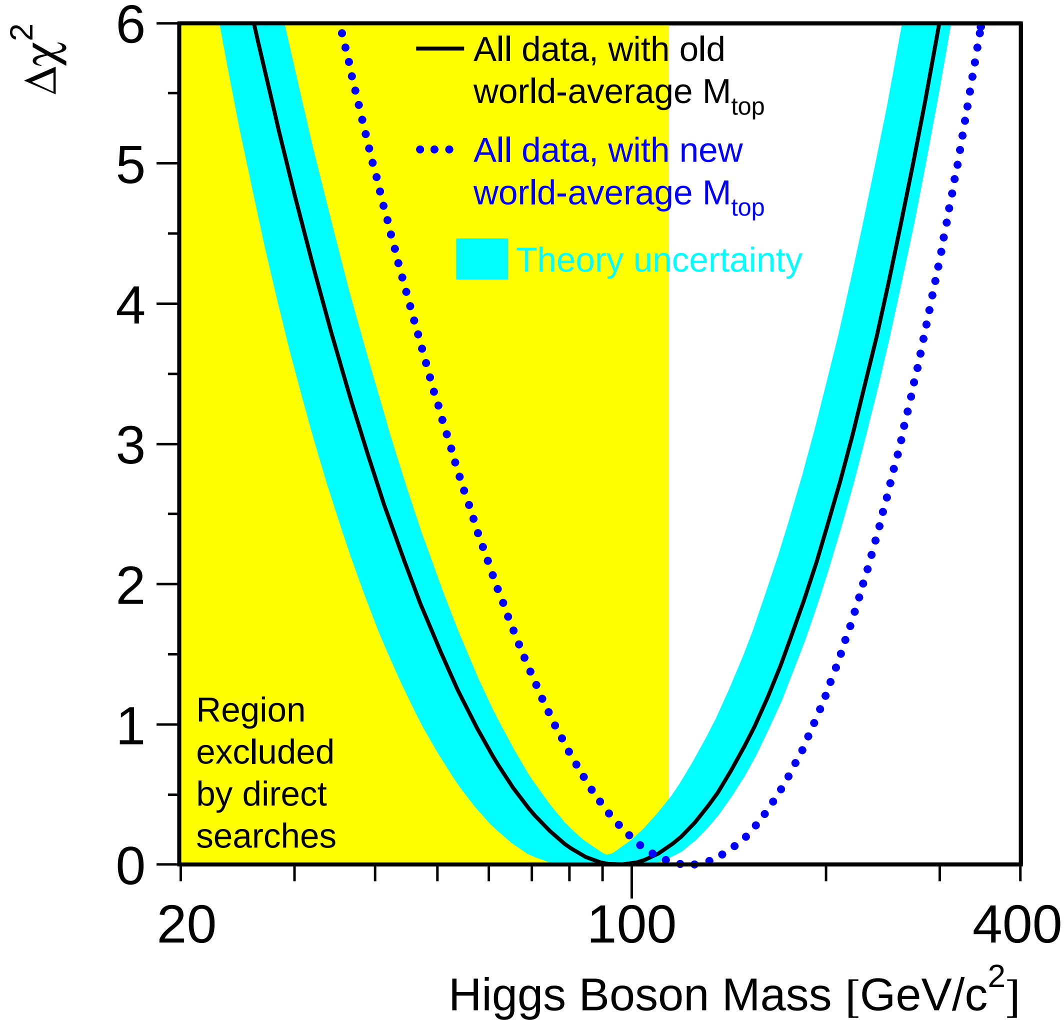
It is hard to imagine a fundamental theory of elementary particles and their interactions with no explanation for the origin of the large hierarchy of mass scales from the electroweak to the Planck scale. Thus, most theorists expect new physics beyond the SM at the TeV-scale to emerge and provide the connection between these two disparate mass scales ("naturalness principle").

To fully probe the nature of EWSB and the associated new TeV-scale physics, one must conduct experiments at the LHC and the Linear Collider (LC).

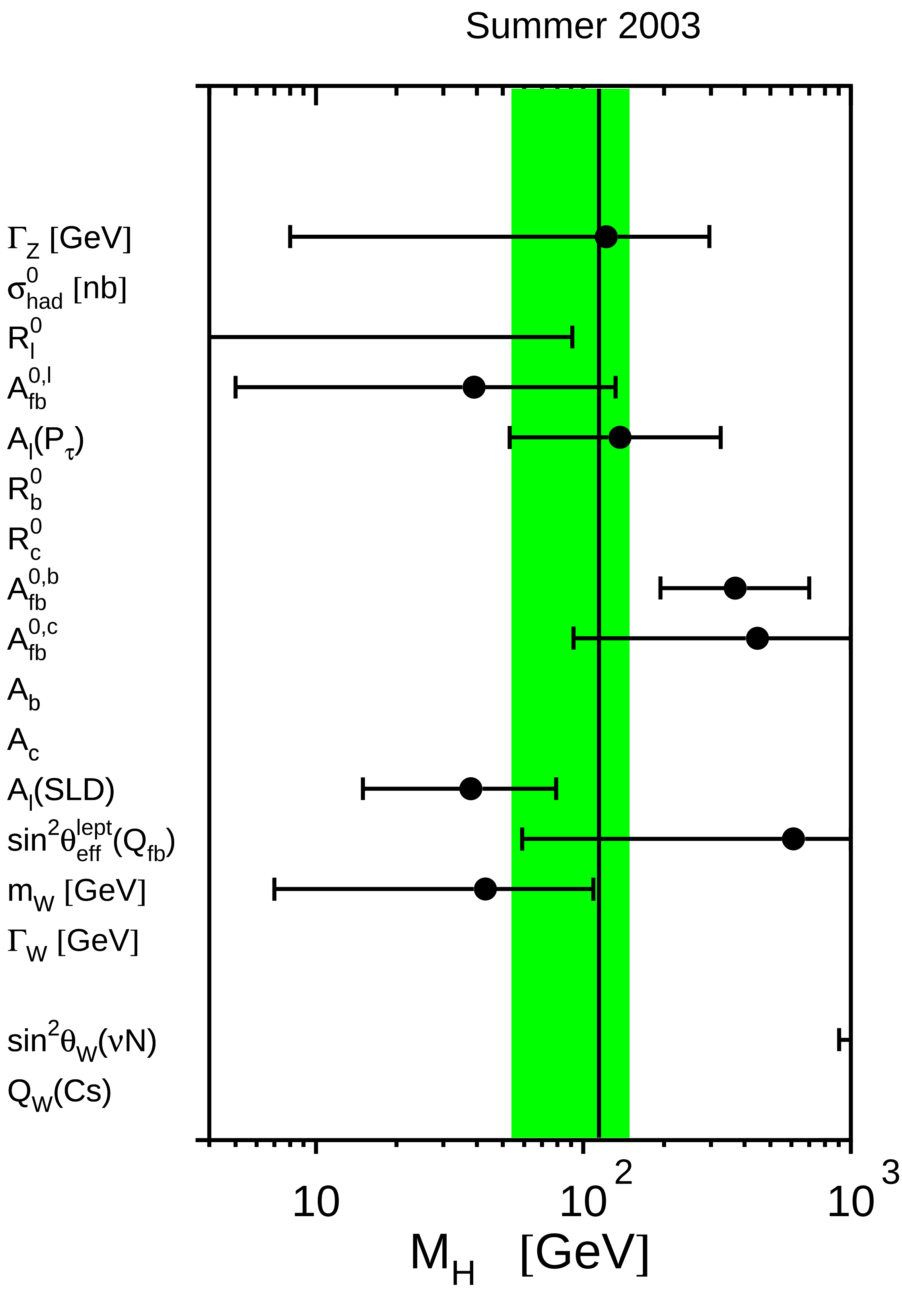
Where is the Higgs Boson?

LEPEWWG SM fits to precision electroweak data

$m_h < 251$ GeV at 95% CL



The *blueband* plot shows $\Delta\chi^2 \equiv \chi^2 - \chi^2_{\min}$ as a function of m_h.



Summer 2003
Γ_Z [GeV]
σ^0_{had} [nb]
R^0_l
$A^{0,l}_{fb}$
$A_l(P_\tau)$
R^0_b
R^0_c
$A^{0,b}_{fb}$
$A^{0,c}_{fb}$
A_b
A_c
A_l(SLD)
$\sin^2\theta^{lept}_{eff}(Q_{fb})$
m_W [GeV]
Γ_W [GeV]
$\sin^2\theta_W(\nu N)$
Q_W(Cs)
10
10^2
10^3
M_H [GeV]

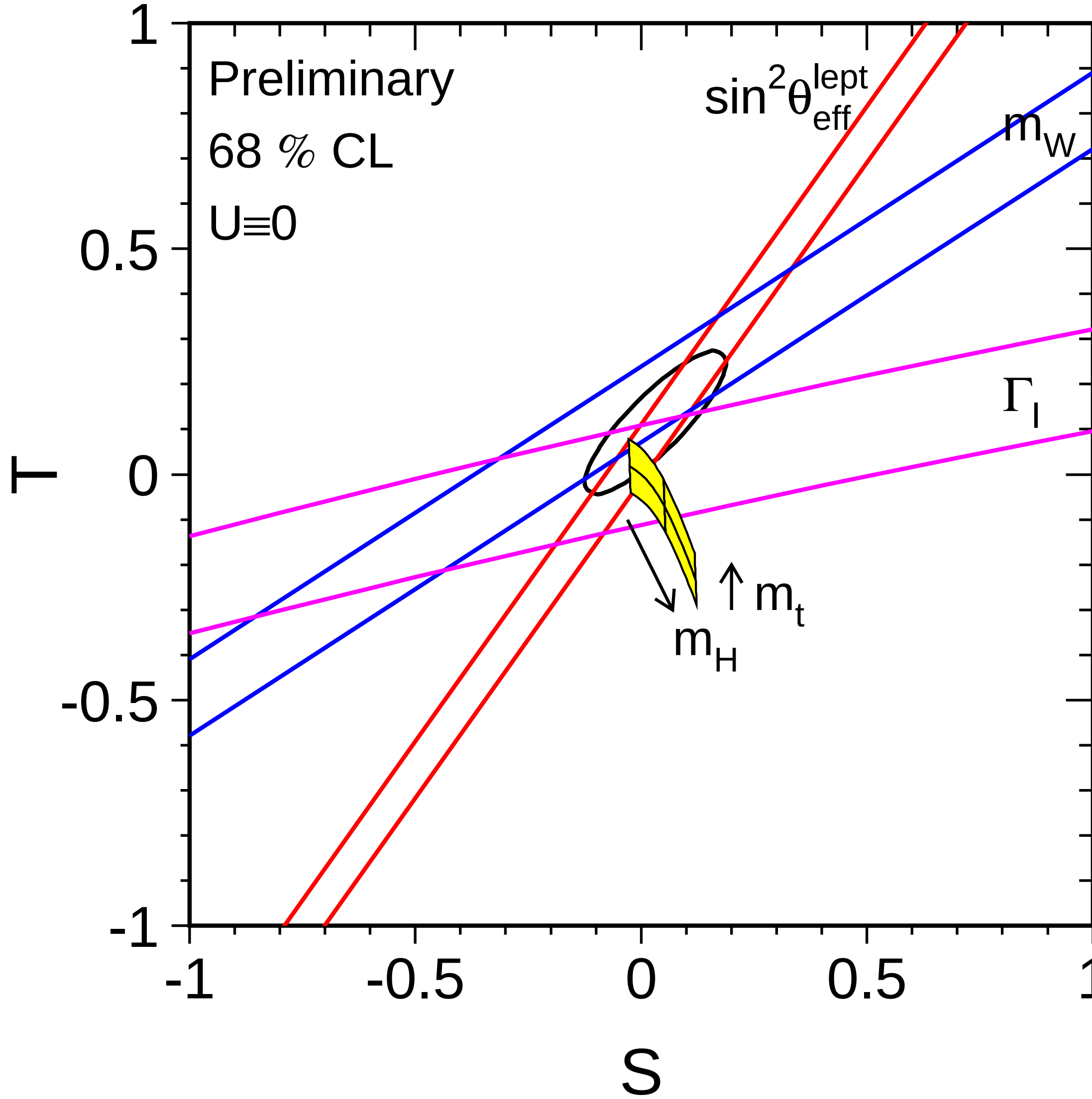
Can a Light Higgs Boson be avoided?

Possible interpretations of the global fit to precision electroweak data:

1. consistent with the SM (up to statistical fluctuations);
2. internally inconsistent.

In the second case, it is not clear how to constrain the Higgs mass without a theory beyond the SM to resolve the inconsistency. However, one probably expects significant new physics effects below the TeV-scale.

In the first case, one can use the data to constrain theories of new physics (whose low-energy effective theory closely approximates the Standard Model). An example of such a procedure employs the S and T parameters of Peskin and Takeuchi, under the assumption that the main effects of the new physics enters through the modification of the W and Z boson self-energies.



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).

What is the nature of EWSB dynamics?

- Weakly-coupled scalar dynamics?
- Strongly-coupled dynamics of a new sector?
- Extra-dimensional?

In all cases, it is critical to identify the energy scale at which the SM breaks down. New physics beyond the SM can be of two types:

- decoupling

The effects on the SM global fit scales as m_Z^2/M^2, where M is a scale characteristic of the new physics. example: supersymmetric particles, with soft-SUSY-breaking masses of $\mathcal{O}(M)$.

- non-decoupling

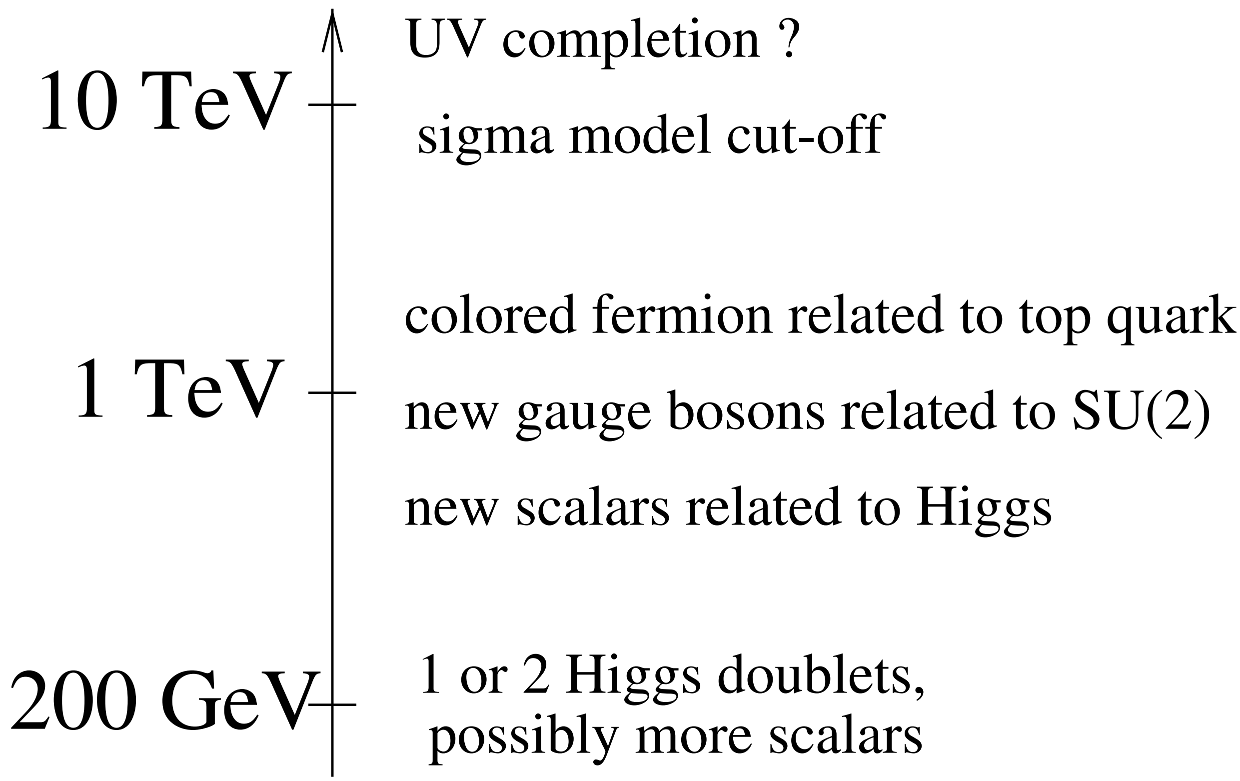
Effects on the SM global fit do not vanish as the characteristic scale $M \to \infty$. examples: (i) fourth-generation fermion; (ii) technicolor.

The success of the SM global fit places stronger constraints on non-decoupling new physics. Nevertheless, some interesting constraints on decoupling physics can also be obtained.

The little hierarchy problem: tension between the SM global fit constraints and the requirements of naturalness.

The four main theoretical approaches are:

- Higgs bosons of low-energy supersymmetry
- Little Higgs models



- extra-dimensional theories of electroweak symmetry breaking

  including "Higgsless" models in which there is no light Higgs scalar in the spectrum.

- Strongly-coupled EWSB sectors of various kinds, including top-color, fat Higgs, ...

In the presence of non-decoupling physics, it is essential to prove that precision electroweak constraints are satisfied. So, look for the fine print.

Note that many models of EWSB yield a lightest Higgs boson whose properties are nearly identical to those of the Standard Model Higgs boson (the so-called decoupling limit).

Thus, to probe the physics of EWSB, one must either:

- detect deviations of the lightest CP-even Higgs boson from the decoupling limit

AND/OR

- directly observe the additional degrees of freedom associated with the EWSB sector.

The latter is expected to be connected with the TeV-scale physics responsible for a natural explanation of the electroweak scale.

Examples:

- non-minimal Higgs states (additional CP-even neutral scalars, CP-odd scalars and charged scalars)
- supersymmetric particles
- new gauge bosons
- vector-like fermions
- Kaluza-Klein excitations
- radions

Approaching the decoupling limit

As an example, consider the MSSM Higgs sector. If we only keep the leading $\tan\beta$-enhanced radiative corrections, then for $m_A \gg m_Z$ (approaching the decoupling limit),

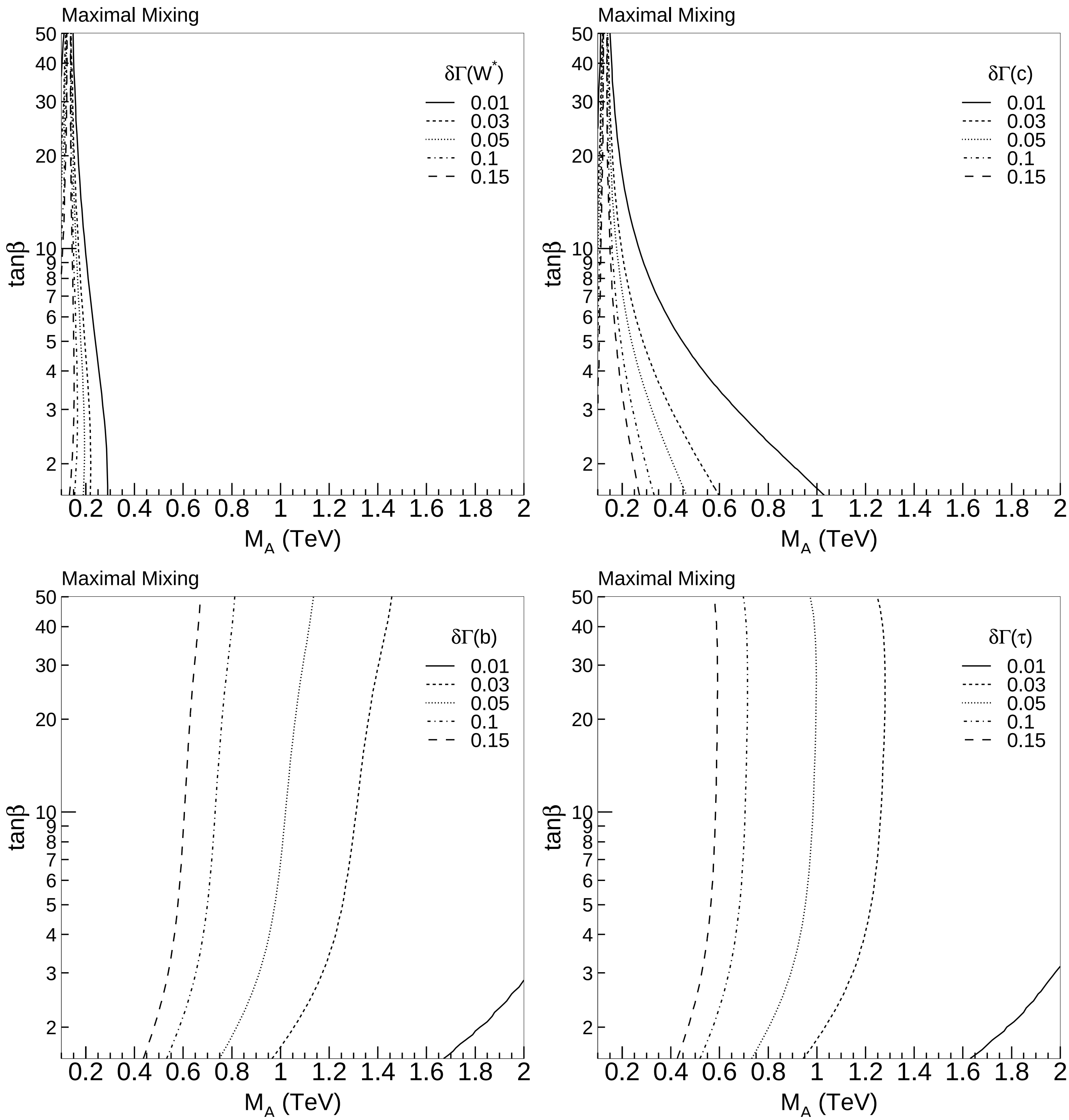
$$\frac{g^2_{hVV}}{g^2_{h_{\rm SM}VV}} \simeq 1 - \frac{c^2 m_Z^4 \sin^2 4\beta}{4m_A^4}\,,$$

$$\frac{g^2_{htt}}{g^2_{h_{\rm SM}tt}} \simeq 1 + \frac{c m_Z^2 \sin 4\beta \cot\beta}{m_A^2}\,,$$

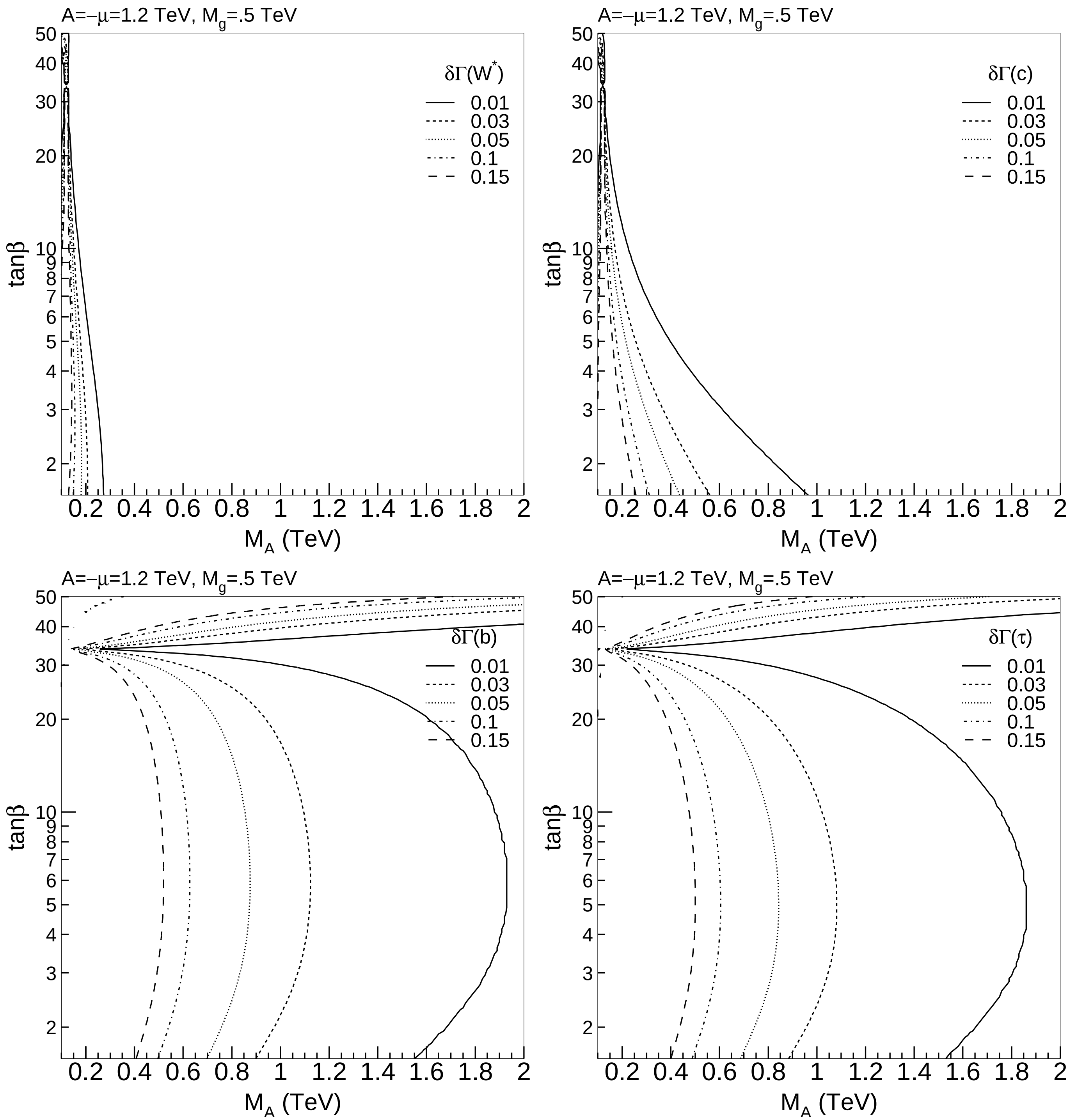
$$\frac{g^2_{hbb}}{g^2_{h_{\rm SM}bb}} \simeq 1 - \frac{4c m_Z^2 \cos 2\beta}{m_A^2}\left[\sin^2\beta - \frac{\Delta_b}{1+\Delta_b}\right]\,,$$

where $c \equiv 1 + \mathcal{O}(g^2)$ and $\Delta_b \equiv \tan\beta \times \mathcal{O}(g^2)$ [g is a generic gauge or Yukawa coupling]. The quantities c and Δ_b depend on the MSSM spectrum. The approach to decoupling is fastest for the h couplings to vector boson pairs and slowest for the couplings to down-type quarks.

Thus, deviations from the decoupling limit implicitly contain information about the EWSB sector and the associated TeV-scale dynamics.



Deviations of Higgs partial widths from their SM values in the maximal-mixing scenario (Carena, Haber, Logan and Mrenna [CHLM]).



Deviations of Higgs partial widths from their SM values in the large μ and A_t scenario, with $A_t = -\mu = 1.2$ TeV. (CHLM)

Main goals of the Higgs Hunter

A program of Higgs physics at colliders must address

- Discovery reach of colliders (Tevatron, LHC, LC, ...) for the SM Higgs boson
- How many Higgs states are there?
- Assuming one Higgs-like state is discovered
  - Is it a Higgs boson?
  - Is it the SM Higgs boson?
- How will evidence emerge for a non-minimal Higgs sector?
  - deviations from SM Higgs behavior
  - discovery reach for the non-minimal Higgs states?
- Challenge of the decoupling limit
  - in which the lightest Higgs state closely resembles $h_{\rm SM}$

To fully address many of these questions will require a program of precision Higgs measurements.

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

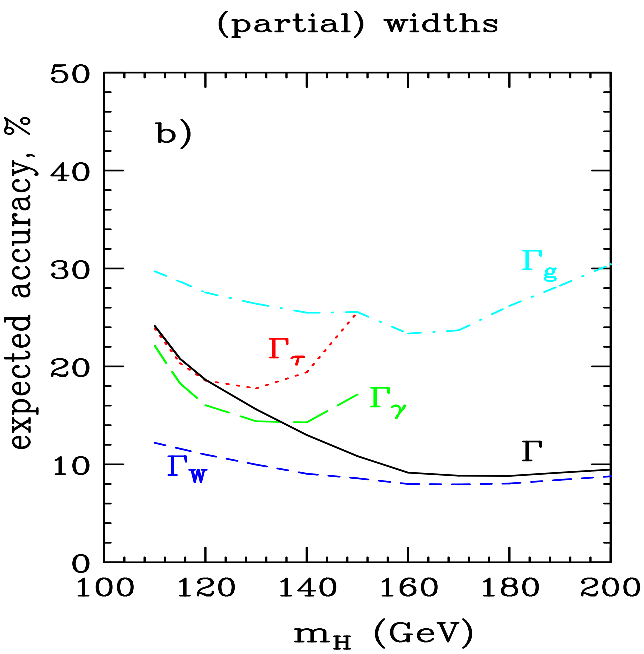
If nature chooses a path far from the decoupling limit, the challenges are of a different nature.

- Are there light scalar states that are associated with electroweak symmetry breaking dynamics? (Is it just an extended Higgs sector far from the decoupling limit? If yes, one expects numerous light Higgs states accessible to both the LHC and LC.)
- Can one identify the source of electroweak symmetry breaking dynamics and any associated phenomena?

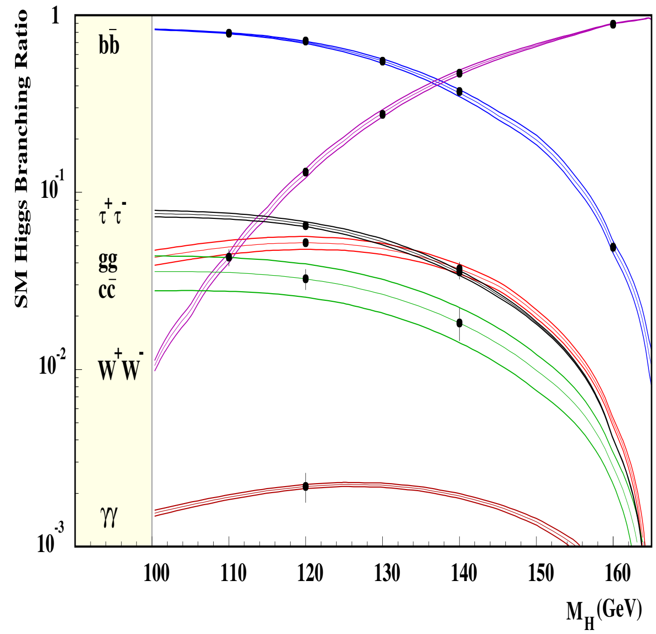
Precision Higgs Physics

A program of precision measurements will begin at the LHC and will reach maturity at the LC.

LHC



LC



Higgs production at the LC is mainly due to

- Higgs-strahlung ($e^+e^- \to Z^* \to Zh_{\rm SM}$)
- Vector boson fusion ($e^+e^- \to \nu\bar{\nu}W^*W^* \to \nu\bar{\nu}h_{\rm SM}$)
- Radiation off the top quark ($e^+e^- \to t\bar{t}h_{\rm SM}$)

Precision Higgs physics at the LC

- Results from the American Linear Collider Collaboration

	$m_{h_{\rm SM}} = 120$ GeV		$m_{h_{\rm SM}} = 140$ GeV	
	BR	δBR/BR	BR	δBR/BR
$h_{\rm SM} \to b\bar{b}$	$(69 \pm 2.0)\%$	2.9%	$(34 \pm 1.3)\%$	3.8%
$h_{\rm SM} \to WW^*$	$(14 \pm 1.3)\%$	10%	$(51 \pm 1.5)\%$	3.0%
$h_{\rm SM} \to c\bar{c}$	$(2.8 \pm 1.1)\%$	39%	$(1.4 \pm 0.64)\%$	44%
$h_{\rm SM} \to gg$	$(5.2 \pm 0.93)\%$	18%	$(3.5 \pm 0.79)\%$	23%
$h_{\rm SM} \to \tau^+\tau^-$	$(7.1 \pm 0.56)\%$	8.0%	$(3.6 \pm 0.38)\%$	10%

Predicted branching ratio precisions in the LCD Large detector and typical vertex detector configuration for 500 fb^{-1} and $\sqrt{s} = 500$ GeV. [Brau, Wassail and Potter]

- Results from the European LC studies

Higgs coupling	δBR/BR	$\delta g/g$	$\mathcal{L}$ (fb^{-1})
hWW	5.1%	1.2%	500
hZZ	—	1.2%	500
$ht\bar{t}$	—	2.2%	1000
$hb\bar{b}$	2.4%	2.1%	500
$hc\bar{c}$	8.3%	3.1%	500
$h\tau\tau$	5.0%	3.2%	500
$h\mu\mu$	$\sim 30\%$	$\sim 15\%$	1000
hgg	5.5%		500
$h\gamma\gamma$	16%		1000
hhh	—	$\sim 20\%$	1000

Expected fractional uncertainties for LC measurements of Higgs branching ratios [BR($h \to XX$)] and couplings [g_{hXX}], for various choices of final state XX, assuming $m_h = 120$ GeV. In all but two cases, the analysis is based on $\sqrt{s} = 500$ GeV. Results for $ht\bar{t}$ and $h\mu\mu$ are based on $\sqrt{s} = 800$ GeV. [Battaglia, Boos, DeRoeck, Desch, and others]

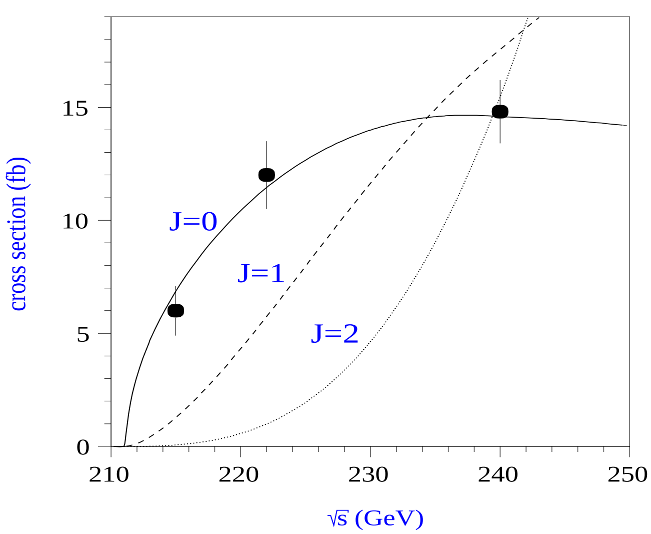
Beware: theoretical uncertainty in $h_{\rm SM}c\bar{c}$ $[h_{\rm SM}b\bar{b}]$ coupling due to uncertainty in m_c $[m_b]$ and α_s is about 12% [1.8%].

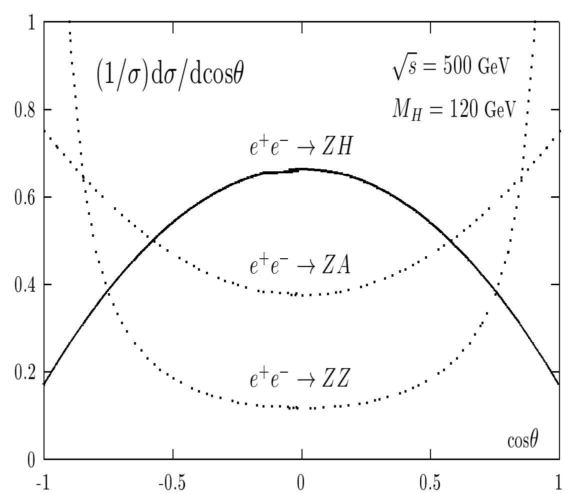
Other precision measurements:

- Total width: use $\Gamma_{\rm tot} = \Gamma_{h_{\rm SM}WW}/{\rm BR}(h_{\rm SM} \to WW^*)$. $\delta\Gamma/\Gamma \simeq 6\%$ for $m_{h_{\rm SM}} = 120$ GeV.

- Spin and CP quantum number

- Reconstructing the Higgs potential. For $m_{h_{\rm SM}} = 120$ GeV, using $e^+e^- \to Zh^* \to Zhh$ $(h = h_{\rm SM})$, one can measure $\delta g_{hhh}/g_{hhh} \simeq 20\%$.





The Higgs studies at the LC are somewhat mature. There is a significant program of precision Higgs studies that has examined the SM Higgs boson and the Higgs boson of MSSM.

Are we done?

Of course not!! There are at least three major directions that require particular attention.

- Improving the precision Higgs studies. Examples: (i) new channels; (ii) more realistic assessment of systematic errors.
- Going beyond minimality assumptions. Examples: (i) enlarged Higgs sectors; (ii) CP-violating Higgs sectors.
- Changing the (MS)SM Higgs paradigm. Examples: (i) little Higgs models; (ii) extra-dimensional EWSB.

Where do we go from here?

Consider the two alternatives:

- Close to the decoupling limit

The properties of the lightest CP-even scalar are close to those of the SM Higgs boson.

- Far from the decoupling limit

EWSB dynamics produces no state that closely resembles the SM Higgs boson.

Close to the decoupling limit, the precision Higgs studies are essential. Small deviations from the SM encode the physics of EWSB and new physics beyond the SM.

Far from the decoupling limit, one will probably have many light states with a rich phenomenology. One needs further theoretical study to see if there are viable counter-examples (new Higgsless theories?).

Marching orders for theorists

- New approaches in EWSB dynamics have resulted in an explosion of new models. Can we begin to systematize the attendant phenomenology with an eye toward finding some universal features?

- How can precision Higgs studies be used to distinguish among these new approaches? Look for examples where conventional assumptions fail.

- Our cosmological friends want some connections. What, if any, are the best hooks between EWSB and advances in cosmological theory?

- Refine and extend the studies of the complementarity of the LHC and LC searches for EWSB dynamics. Previous works have focused almost exclusively on the precision Higgs studies.