Research on the Theory of the Terascale

Howard Haber

SCIPP Theory

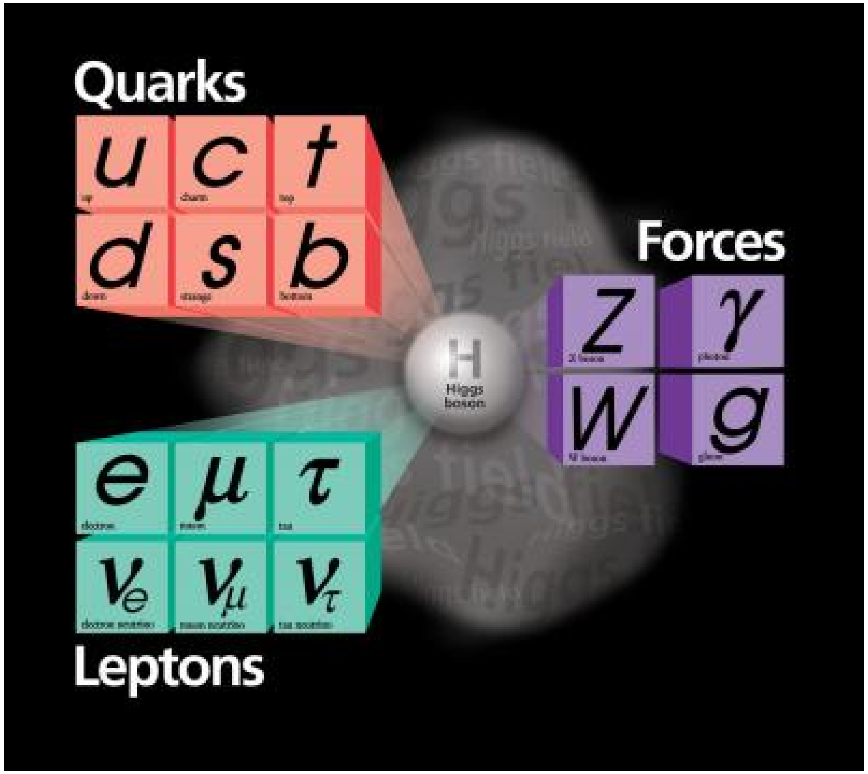
January 13, 2014

SCIPP Particle Theory Group

- **Thomas Banks:** supersymmetry, string theory, gravity, and the early universe
- **Michael Dine:** supersymmetry, string theory, and the early universe
- **Howard Haber:** Higgs bosons, collider physics, new physics beyond the Standard Model at the terascale (including supersymmetry)
- **Stefano Profumo:** Theories of particle dark matter and their implications for astrophysics and collider phenomenology

In addition, Anthony Aguirre and Joel Primack work on a variety of topics overlapping particle theory and astroparticle theory, including dark matter, early universe cosmology, inflation, …

The Standard Model (SM) of Particle Physics

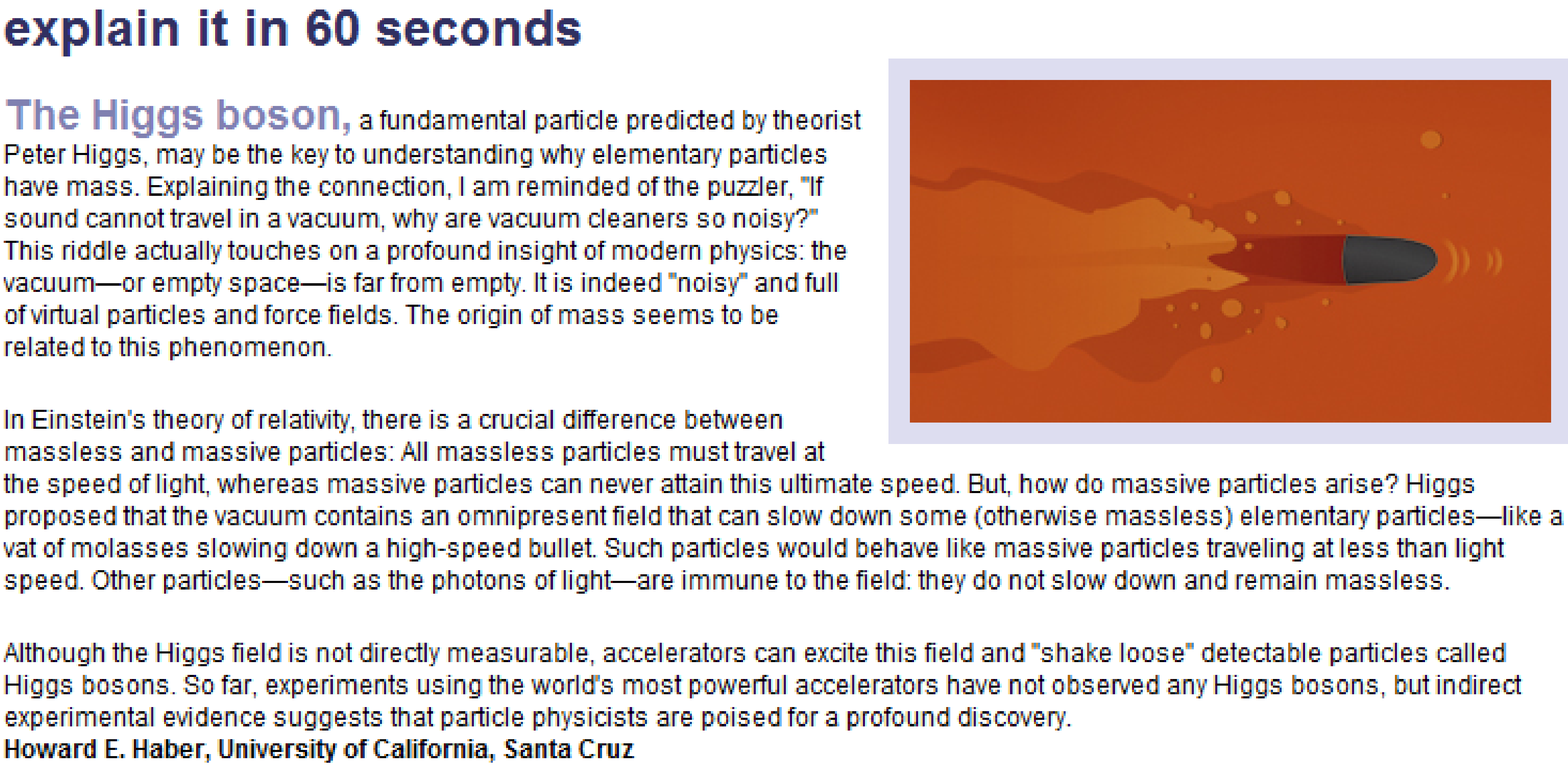


The elementary particles consists of three generations of spin-1/2 quarks and leptons and the gauge bosons of SU(3)xSU(2)xU(1).

Technically, massive neutrinos require an extension of the Standard Model, but most likely the relevant scale of the new physics lies way beyond the terascale.

Origin of mass for elementary particles

Naively, an SU(3)xSU(2)xU(1) gauge theory yields massless gauge bosons and massless quarks and leptons, in conflict with observation. The Standard Model introduces the Higgs mechanism for mass generation. The gauge invariance is spontaneously broken. In the simplest implementation, a spinless physical Higgs scalar is predicted.



explain it in 60 seconds

The Higgs boson, a fundamental particle predicted by theorist Peter Higgs, may be the key to understanding why elementary particles have mass. Explaining the connection, I am reminded of the puzzler, "If sound cannot travel in a vacuum, why are vacuum cleaners so noisy?" This riddle actually touches on a profound insight of modern physics: the vacuum—or empty space—is far from empty. It is indeed "noisy" and full of virtual particles and force fields. The origin of mass seems to be related to this phenomenon.

In Einstein's theory of relativity, there is a crucial difference between massless and massive particles: All massless particles must travel at the speed of light, whereas massive particles can never attain this ultimate speed. But, how do massive particles arise? Higgs proposed that the vacuum contains an omnipresent field that can slow down some (otherwise massless) elementary particles—like a vat of molasses slowing down a high-speed bullet. Such particles would behave like massive particles traveling at less than light speed. Other particles—such as the photons of light—are immune to the field: they do not slow down and remain massless.

Although the Higgs field is not directly measurable, accelerators can excite this field and "shake loose" detectable particles called Higgs bosons. So far, experiments using the world's most powerful accelerators have not observed any Higgs bosons, but indirect experimental evidence suggests that particle physicists are poised for a profound discovery.

Howard E. Haber, University of California, Santa Cruz

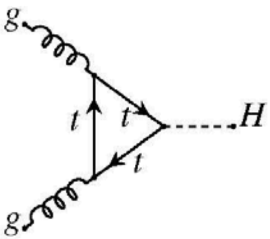
From Symmetry Magazine, volume 3, issue 6, August 2006

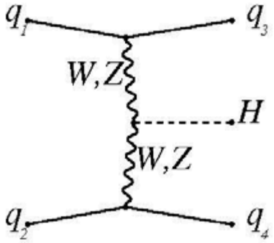
Higgs production at hadron colliders

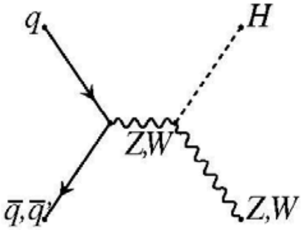
At hadron colliders, the relevant processes are

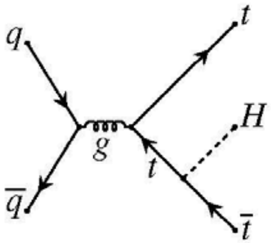
$$
\begin{aligned}
& gg \to h^0 \,, \quad h^0 \to \gamma\gamma \,, VV^{(*)} \,, \\
& qq \to qqV^{(*)}V^{(*)} \to qqh^0, \quad h^0 \to \gamma\gamma, \tau^+\tau^-, VV^{(*)} \,, \\
& q\bar{q}^{(\prime)} \to V^{(*)} \to Vh^0 \,, \quad h^0 \to b\bar{b} \,, WW^{(*)} \,, \\
& gg, q\bar{q} \to t\bar{t}h^0, \quad h^0 \to b\bar{b}, \gamma\gamma, WW^{(*)} \,.
\end{aligned}
$$

where $V = W$ or Z.

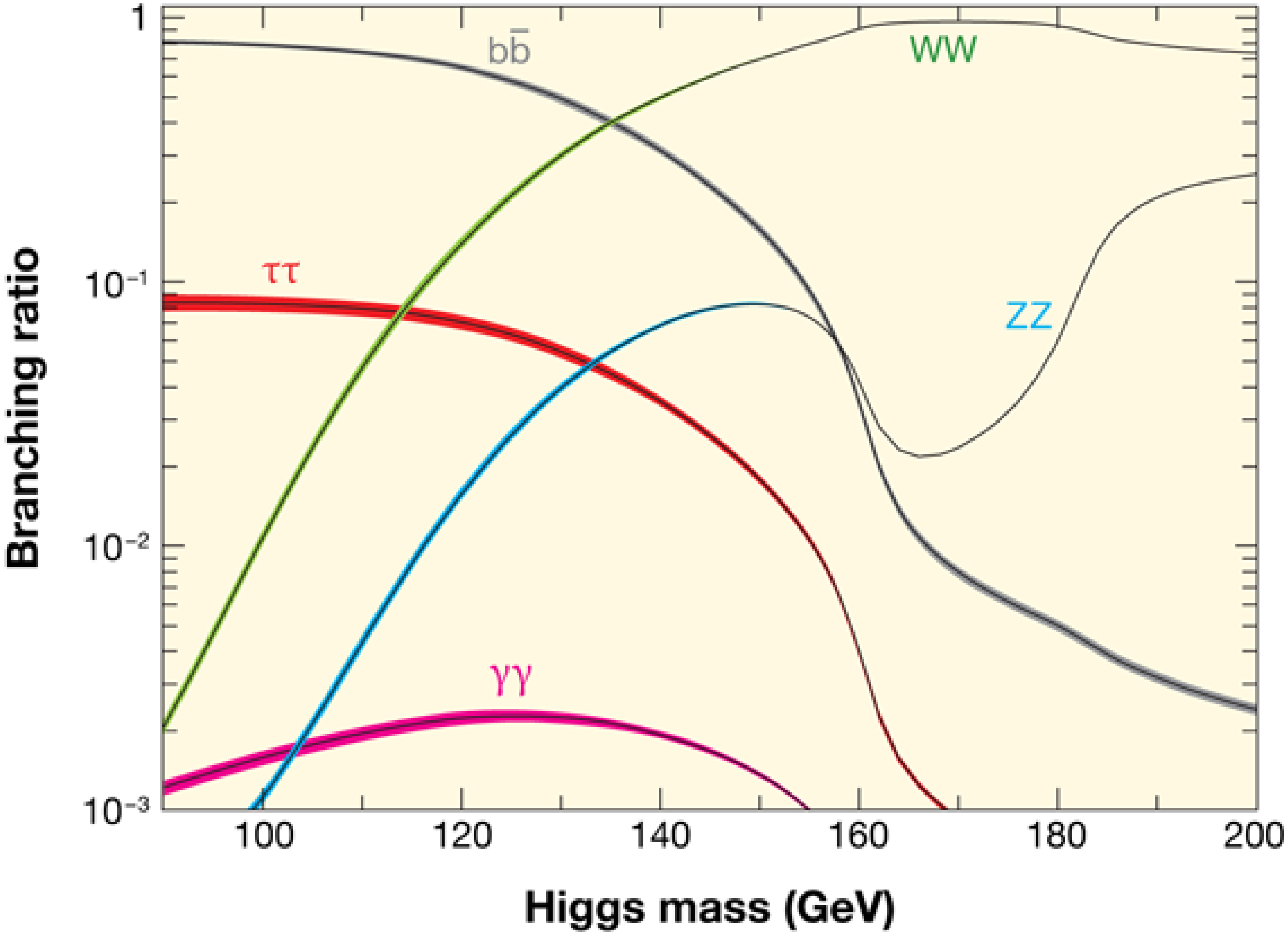




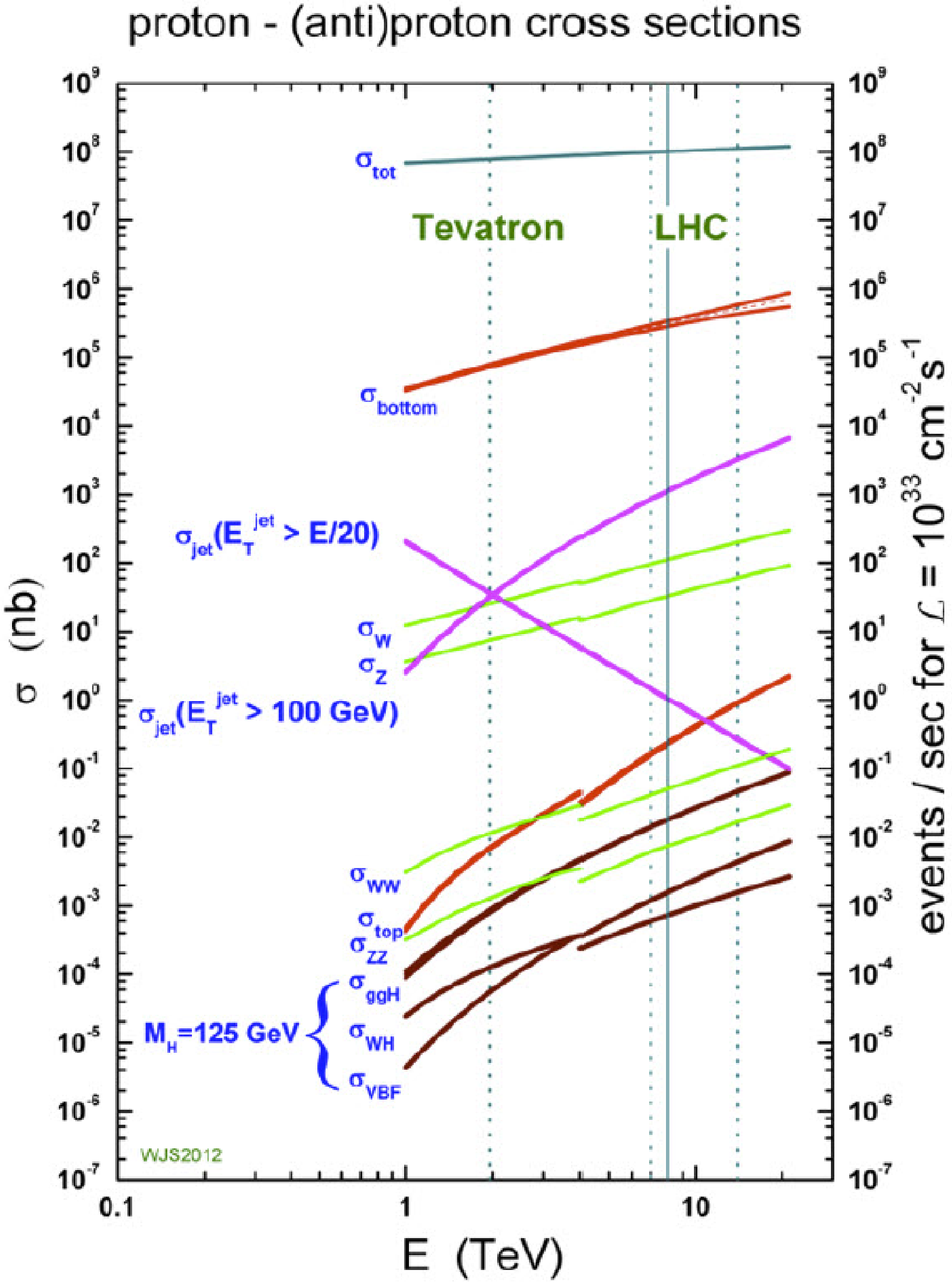




Probability of Higgs boson decay channels



Question: why not search for Higgs bosons produced in gluon-gluon fusion that decay into a pair of b-quarks?

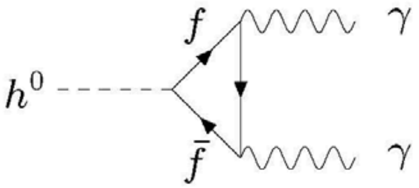


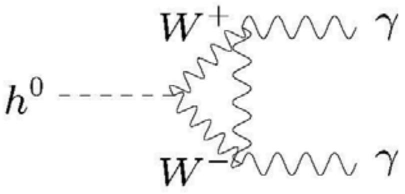
<u>Answer</u>: The Standard Model background is overwhelming. There are more than 10^7 times as many b-quark pairs produced in proton-proton collisions as compared to b-quark pairs that arise from a decaying Higgs boson.

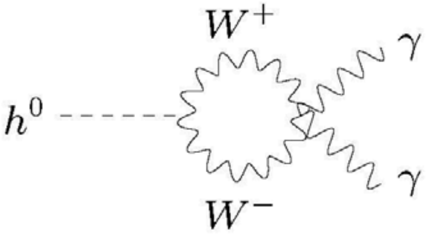
Roughly 250,000 Higgs bosons per experiment were produced at the LHC from 2010—2013.

SM Higgs decays at the LHC for $m_h \sim 125$ GeV

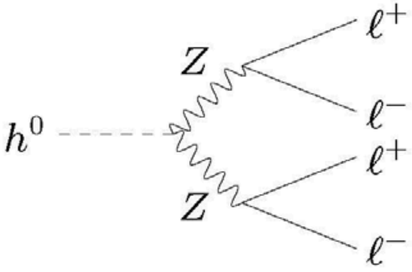
1. The rare decay $h^0 \to \gamma\gamma$ is the most promising signal.



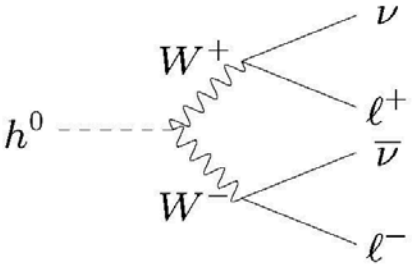




2. The so-called golden channel, $h^0 \to ZZ \to \ell^+\ell^-\ell^+\ell^-$ (where one or both Z bosons are off-shell) is a rare decay for $m_h \sim 125$ GeV, but is nevertheless visible.



3. The channel, $h \to WW^* \to \ell^+\nu\ell^-\overline{\nu}$ is also useful, although it does not provide a good Higgs mass determination.



On July 4, 2012, the discovery of a new boson is announced which may be the long sought after Higgs boson.

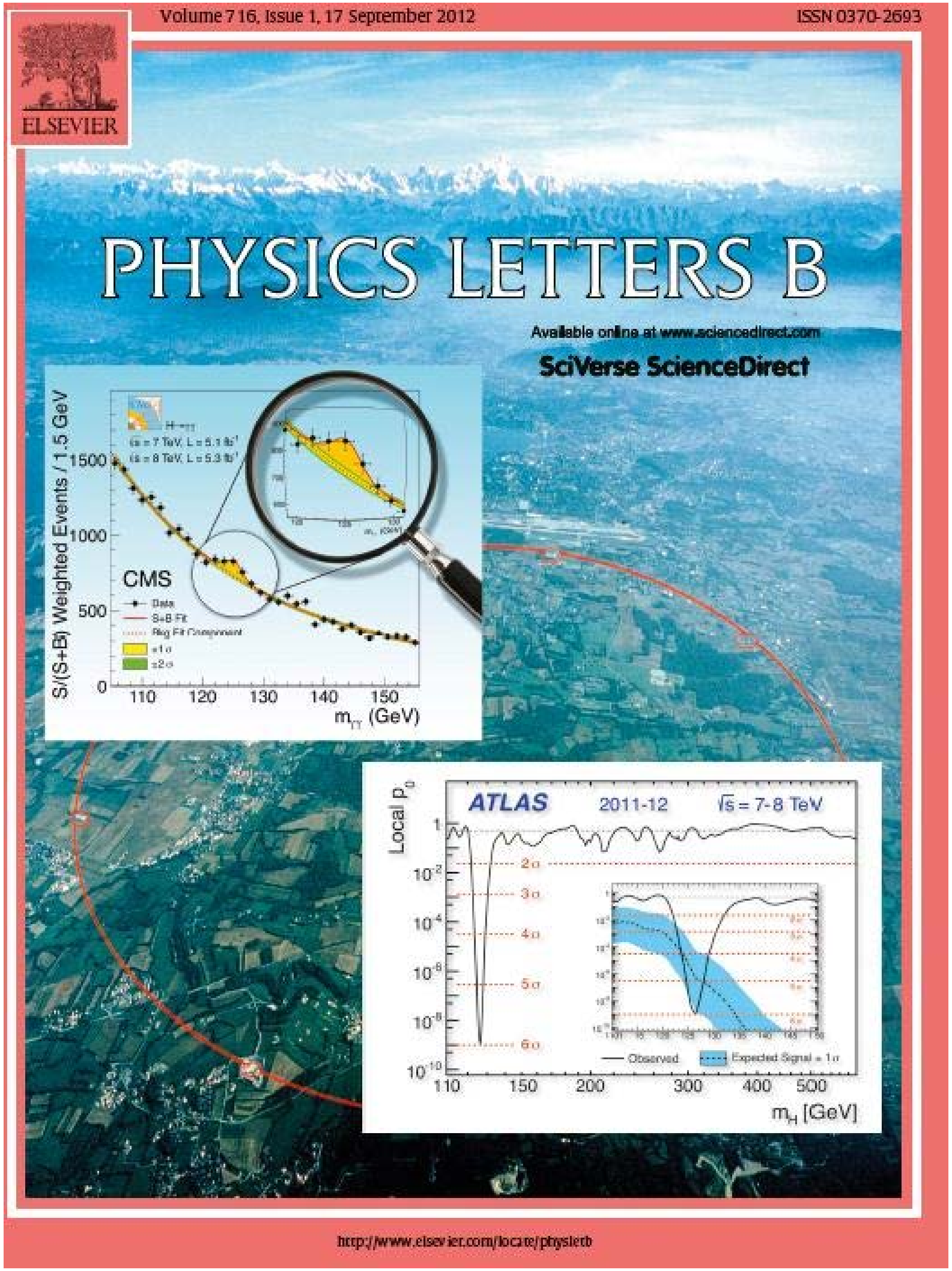
The discovery papers are published two months later In Physics Letters B.

<u>ATLAS Collaboration:</u>

Physics Letters B716 (2012) 1—29

<u>CMS Collaboration:</u>

Physics Letters B716 (2012) 30—61



Volume 716, Issue 1, 17 September 2012
ISSN 0370-2693

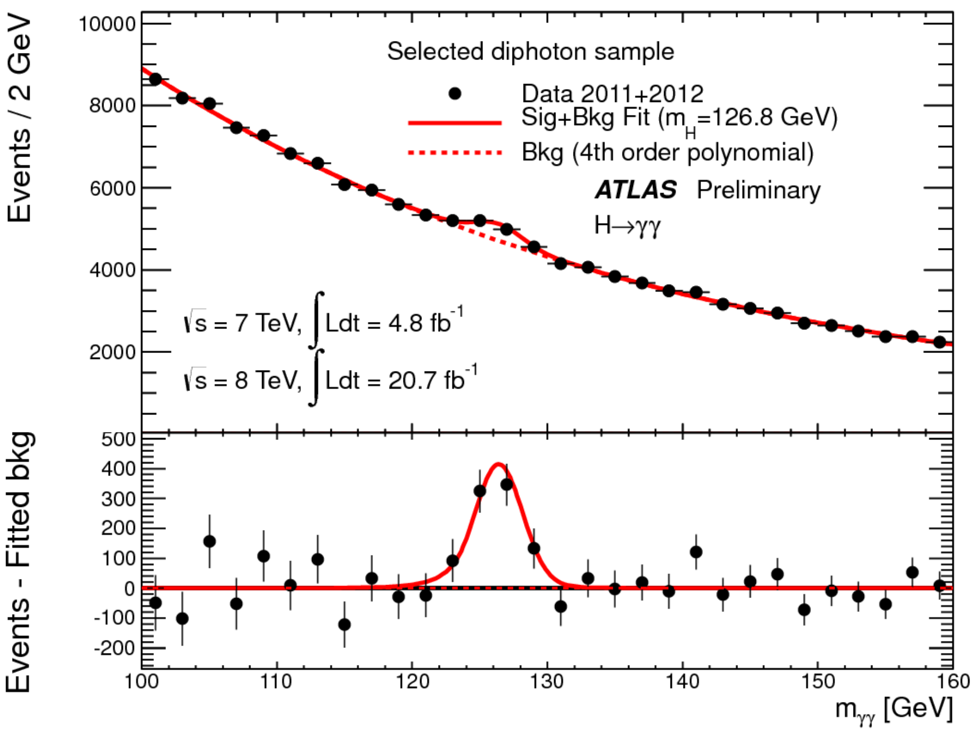
ELSEVIER

PHYSICS LETTERS B

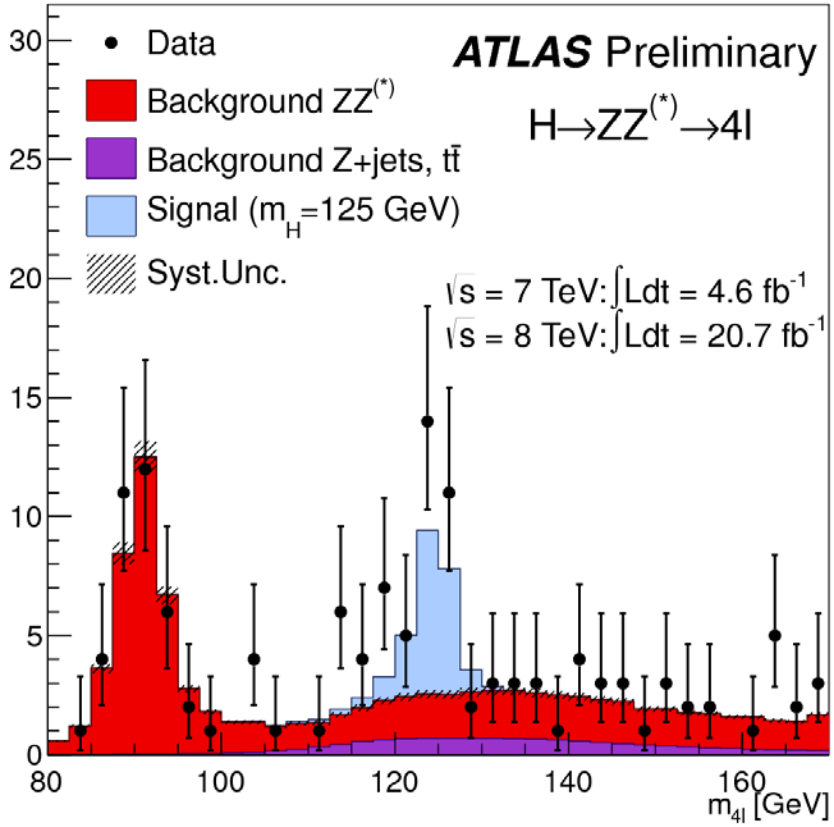
Available online at www.sciencedirect.com
SciVerse ScienceDirect

http://www.elsevier.com/locate/physletb

A boson is discovered at the LHC by the ATLAS Collaboration

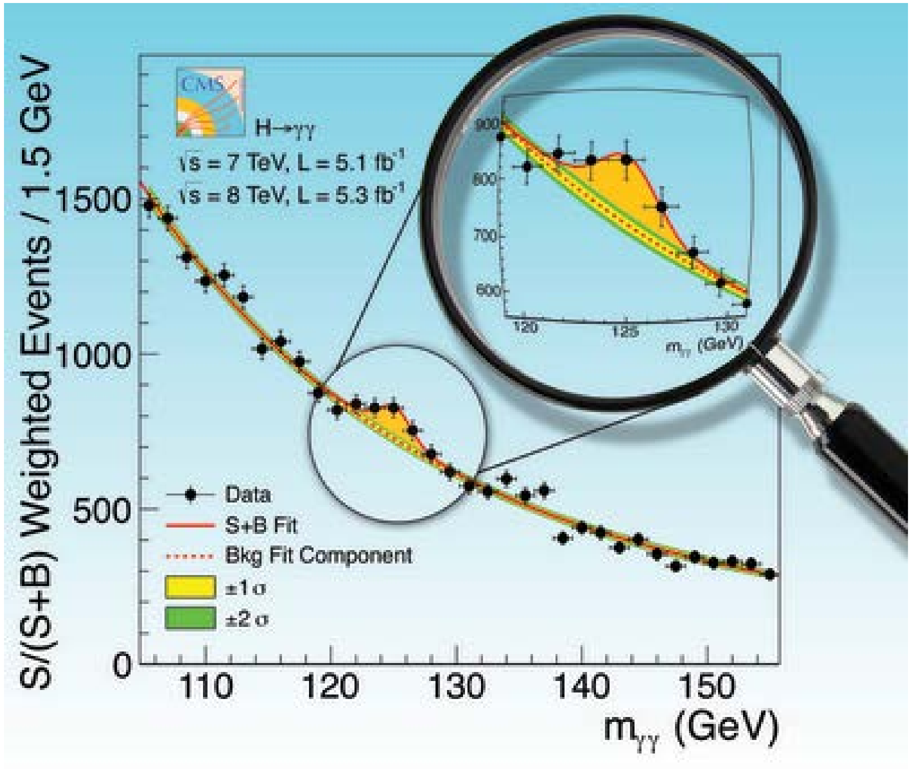


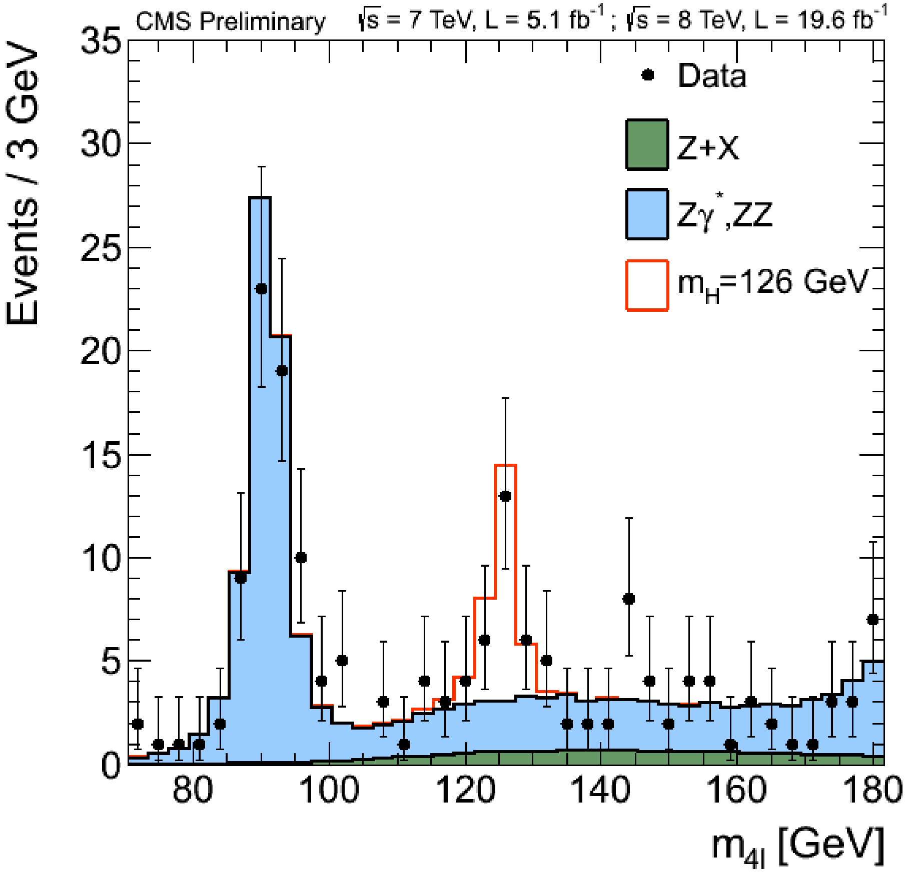
Invariant mass distribution of diphoton candidates for the combined 7 TeV and 8 TeV data samples. The result of a fit to the data of the sum of a signal component fixed to m_H = 126.8 GeV and a background component described by a fourth-order Bernstein polynomial is superimposed. The bottom inset displays the residuals of the data with respect to the fitted background component. Taken from ATLAS-CONF-2013-012 (March, 2013).



The distribution of the four-lepton invariant mass for the selected candidates, compared to the background expectation in the 80 to 170 GeV mass range, for the combination of the 7 TeV 8 TeV data. The signal expectation for a Higgs boson with m_H=125 GeV is also shown. Taken from ATLAS-CONF-2013-013 (March, 2013).

A boson is discovered at the LHC by the CMS Collaboration

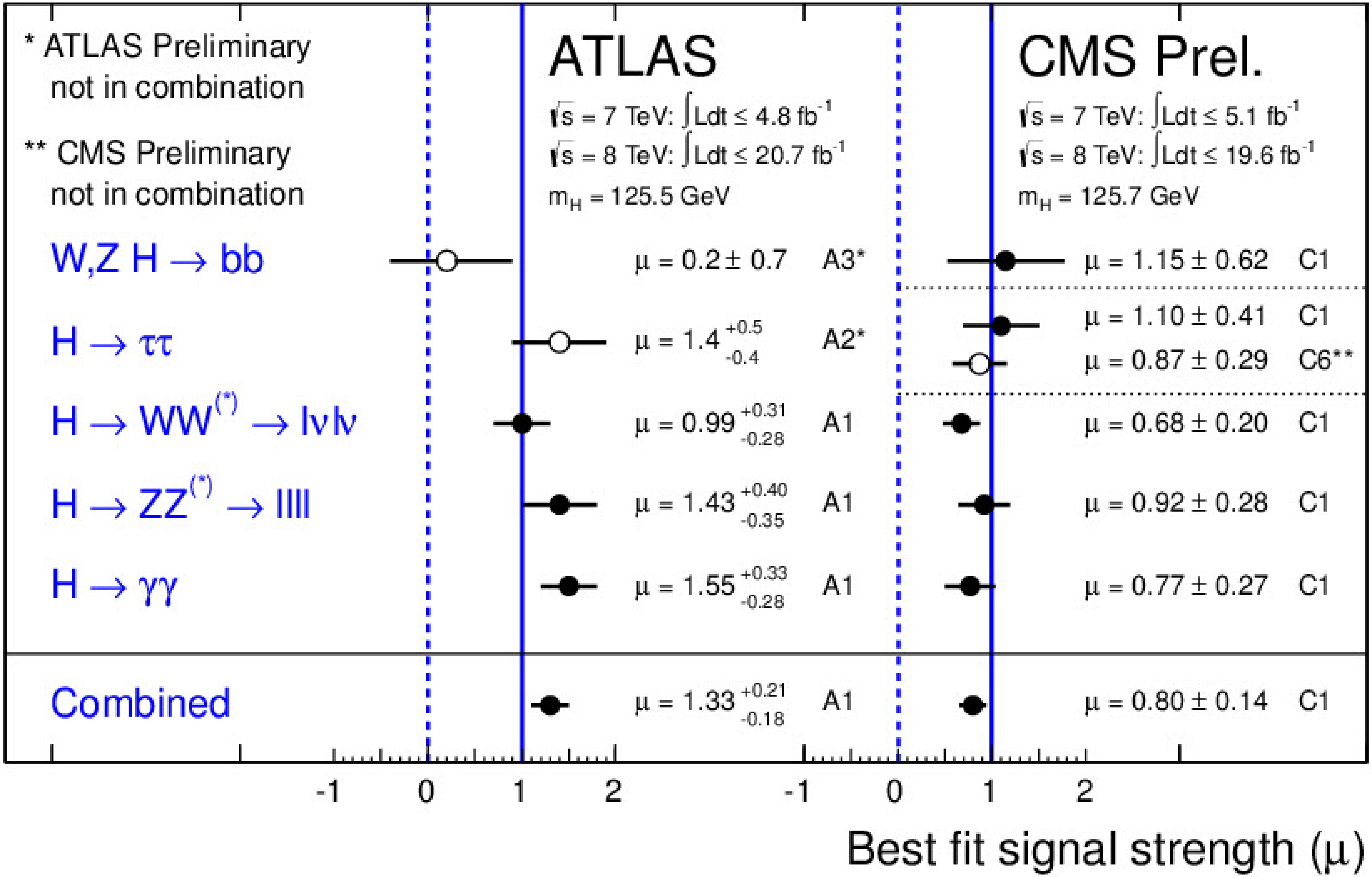




The diphoton invariant mass distribution with each event weighted by the S/(S+B) value of its category. The lines represent the fitted background and signal, and the colored bands represent the ±1 and ±2 standard deviation uncertainties in the background estimate. The inset shows the central part of the unweighted invariant mass distribution. Taken from Physics Letters **B716** (2012) 30—61.

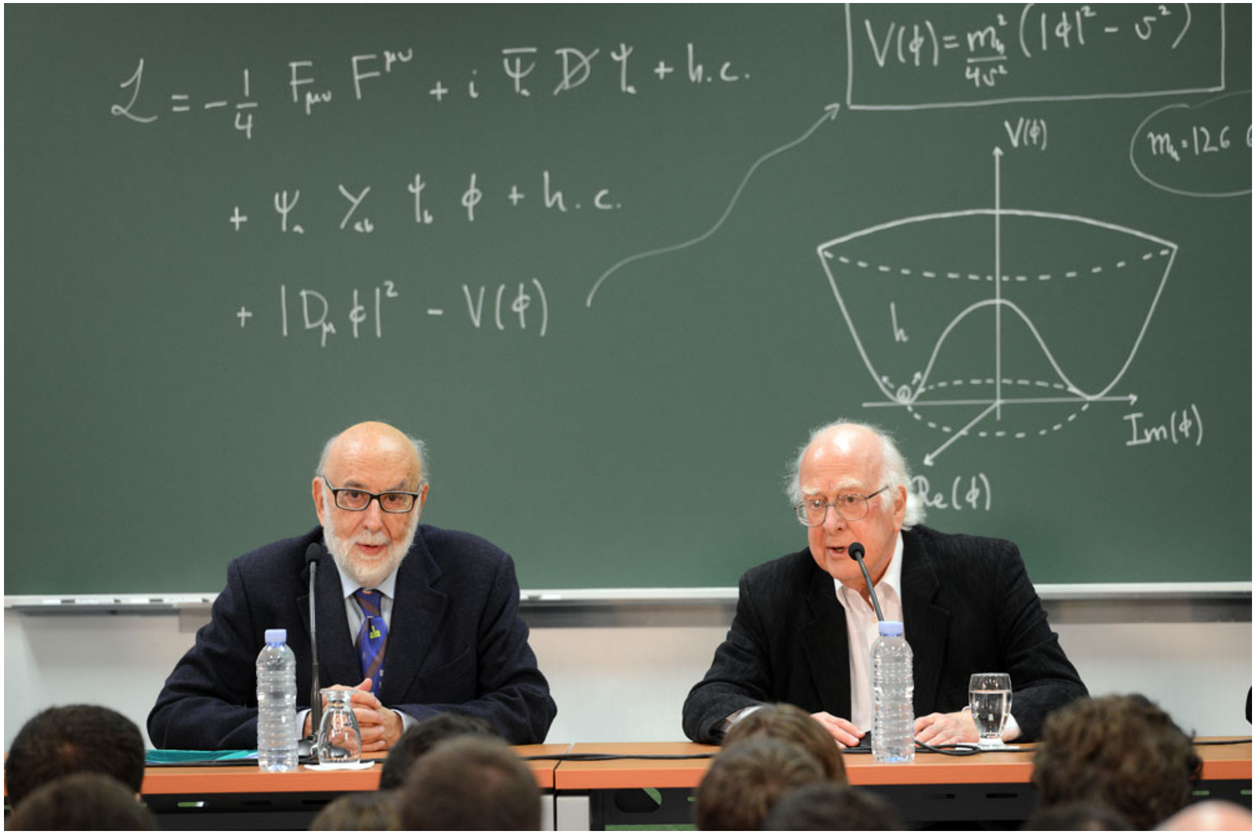
Distribution of the four-lepton reconstructed mass in full mass range for the sum of the 4e, 4μ, and 2e2μ channels. Points represent the data, shaded histograms represent the background and unshaded histogram the signal expectations. The expected distributions are presented as stacked histograms. The measurements are presented for the sum of the data collected at √s = 7 TeV and √s = 8 TeV. [70-180] GeV range - 3 GeV bin width. Taken from CMS-PAS-HIG-13-002 (March, 2013).

A Standard Model—like Higgs boson?



The signal strengths measured by the ATLAS and CMS experiments in the five principal Higgs channels and their combination. Taken from the Higgs review appearing in the 2013 partial update for the 2014 edition of the *Review of Particle Physics* [http://pdg.lbl.gov/2013/reviews/rpp2013-rev-higgs-boson.pdf].

Winners of the 2013 Nobel Prize in Physics

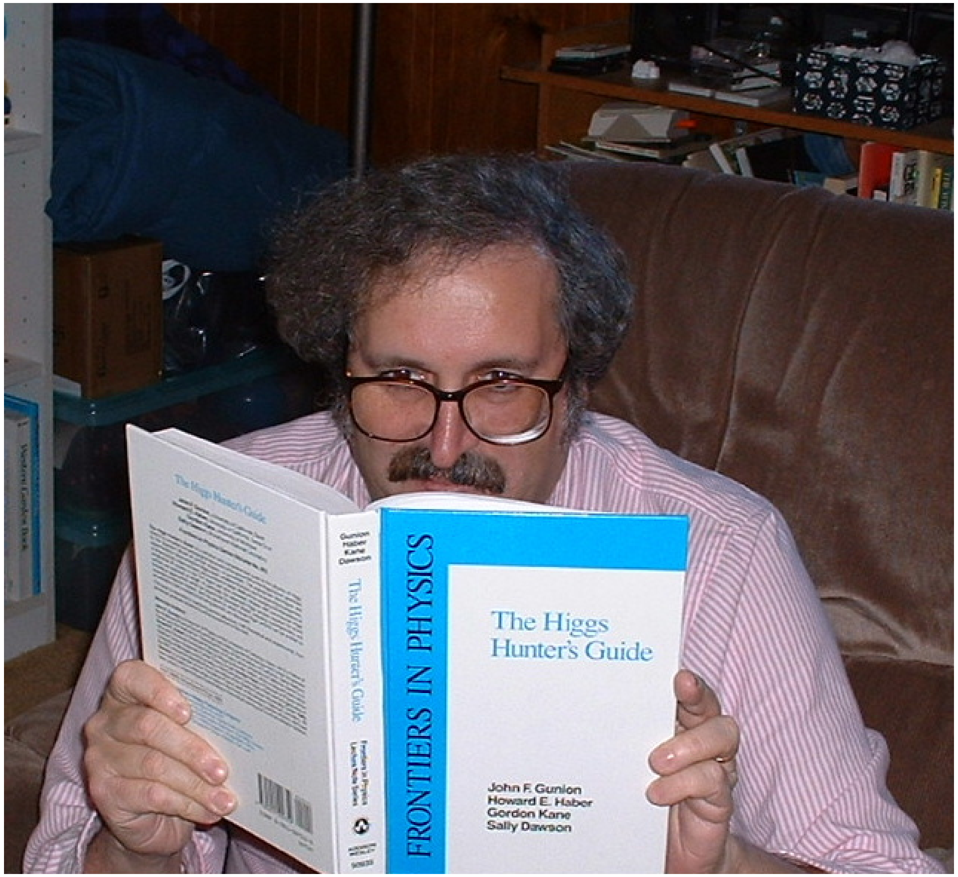


François Englert

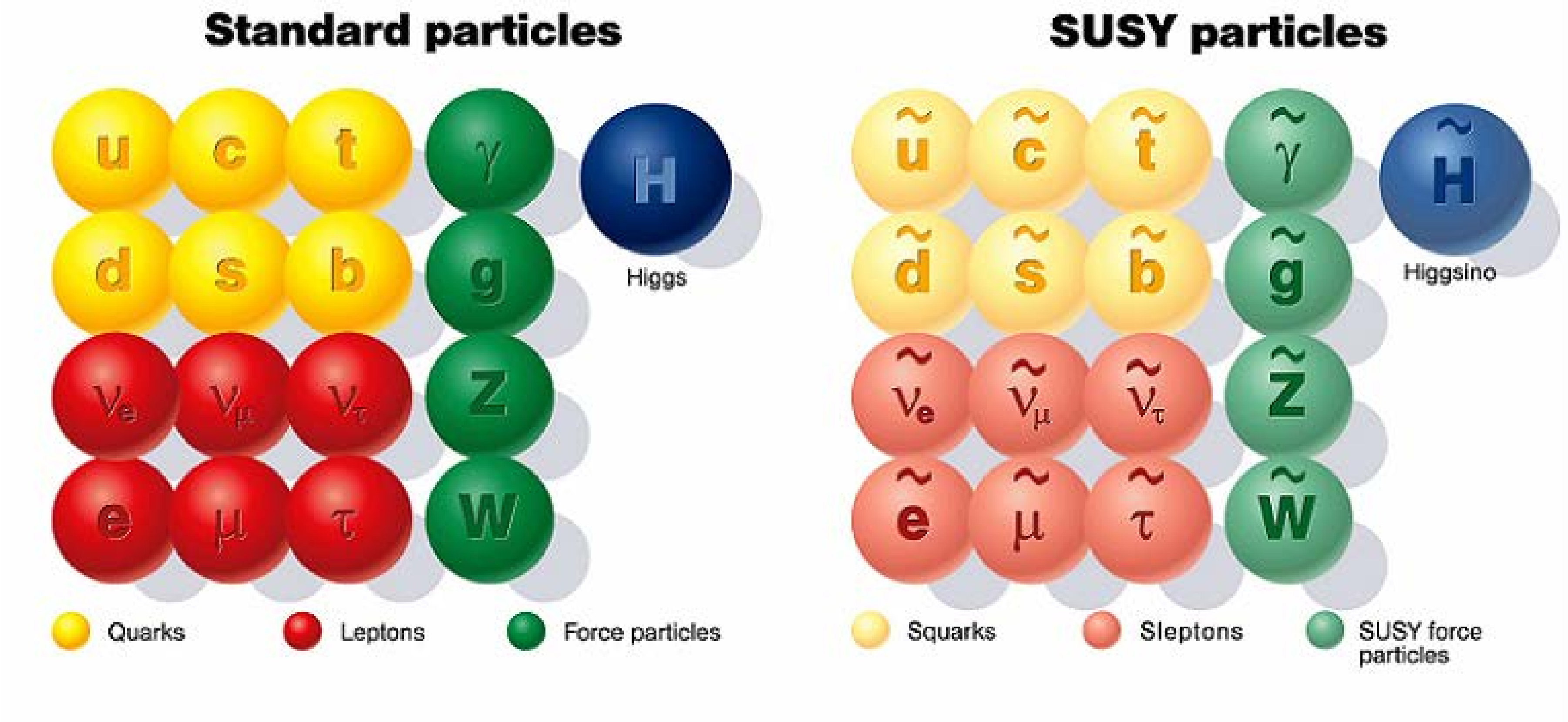
and

Peter Higgs

Research program 1: theory and phenomenology of Higgs bosons



Research program 2: theory and phenomenology of TeV-scale supersymmetry (SUSY)

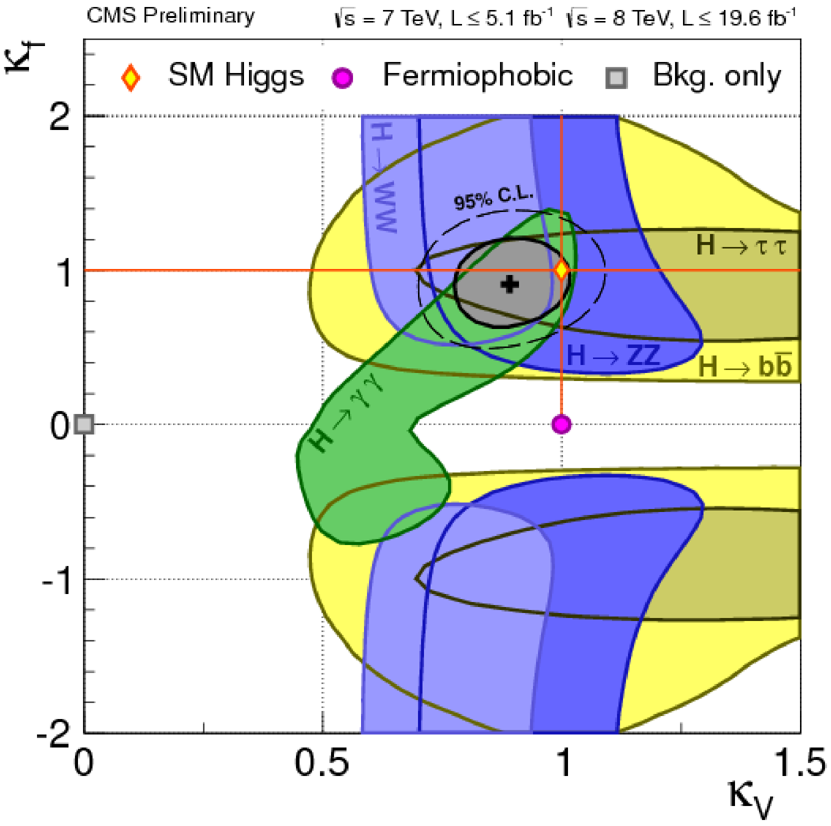


For a review, see H.E. Haber, *Supersymmetry Theory*, in the 2013 partial update for the 2014 edition of the *Review of Particle Physics*, to be published by the Particle Data Group [http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-1-theory.pdf].

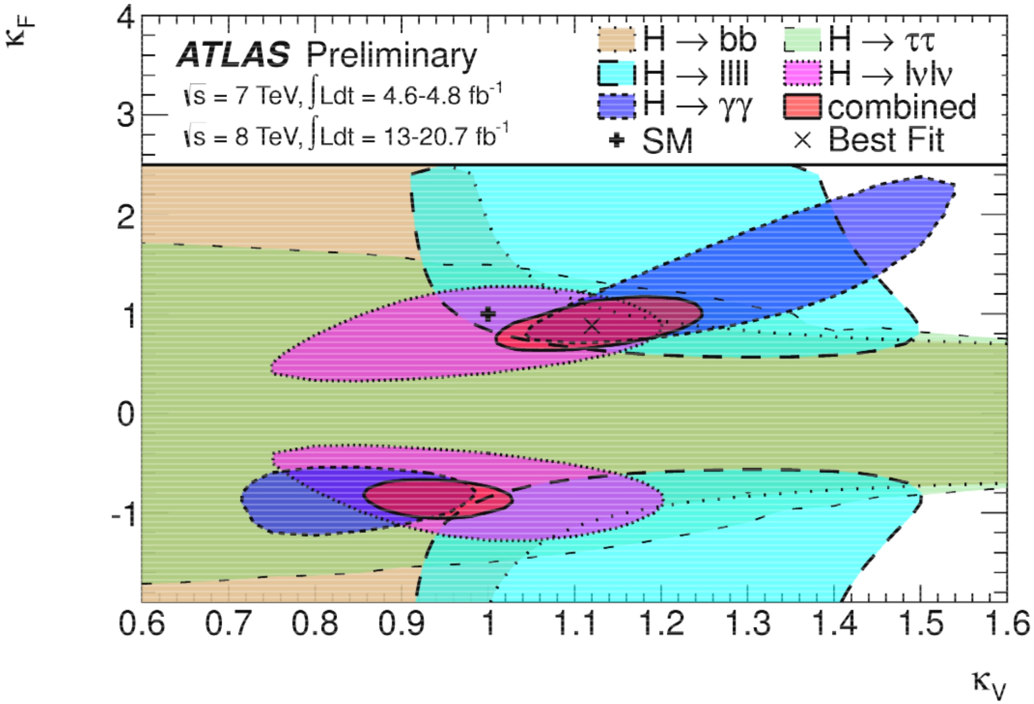
Research program 3: explorations of the Terascale at present and future colliders (LHC and ILC)

- Studies of the non-minimal Higgs sector
- Precision measurements of new physics observables
- Distinguishing among different theoretical interpretations of new physics signals
- Employing the ILC as a precision Higgs factory
- Terascale footprints of lepton-number-violating physics (e.g. R-parity-violation or the SUSY seesaw)
- New sources for CP-violation (Higgs and/or SUSY mediated)

Search for deviations from SM-Higgs couplings to fermions and WW/ZZ



Taken from CMS-PAS-HIG-130-005 (March, 2013)



Fits for 2-parameter benchmark models probing different coupling strength scale factors for fermions and vector bosons, assuming only SM contributions to the total width: (a) Correlation of the coupling scale factors κ_F and κ_V; (b) the same correlation, overlaying the 68% CL contours derived from the individual channels and their combination; (c) coupling scale factor κ_V (κ_F is profiled); (d) coupling scale factor κ_F (κ_V is profiled). The dashed curves in (c) and (d) show the SM expectation. The thin dotted lines in (c) indicate the continuation of the likelihood curve when restricting the parameters to either the positive or negative sector of κ_F.

Taken from ATLAS-CONF-2013-034 (March, 2013)

Implications of a SM-like Higgs boson

The SM employs a minimal Higgs sector with one Higgs doublet. But, why should nature choose such a minimal structure? The supersymmetric extension of the SM employs two Higgs doublets. Other approaches beyond the SM can employ more complicated scalar sectors.

The decoupling limit (heavy mass decoupling) [Haber and Nir]

In many extended Higgs sectors, one can take a certain mass parameter M large. For $M \gg v$, most Higgs states become heavy. The effective Higgs theory at an energy scale below M is that of the SM Higgs boson!

The alignment limit (weak coupling decoupling) [Craig, Galloway, Thomas]

In all extended Higgs sectors, one can take the limit where one or more Higgs self-couplings vanish. In this case, there exists a scalar mass-eigenstate that aligns with $\mathrm{Re}(H_1^0 - v/\sqrt{2})$, where $\langle H_1^0 \rangle = v/\sqrt{2}$, which behaves precisely as a SM Higgs boson.

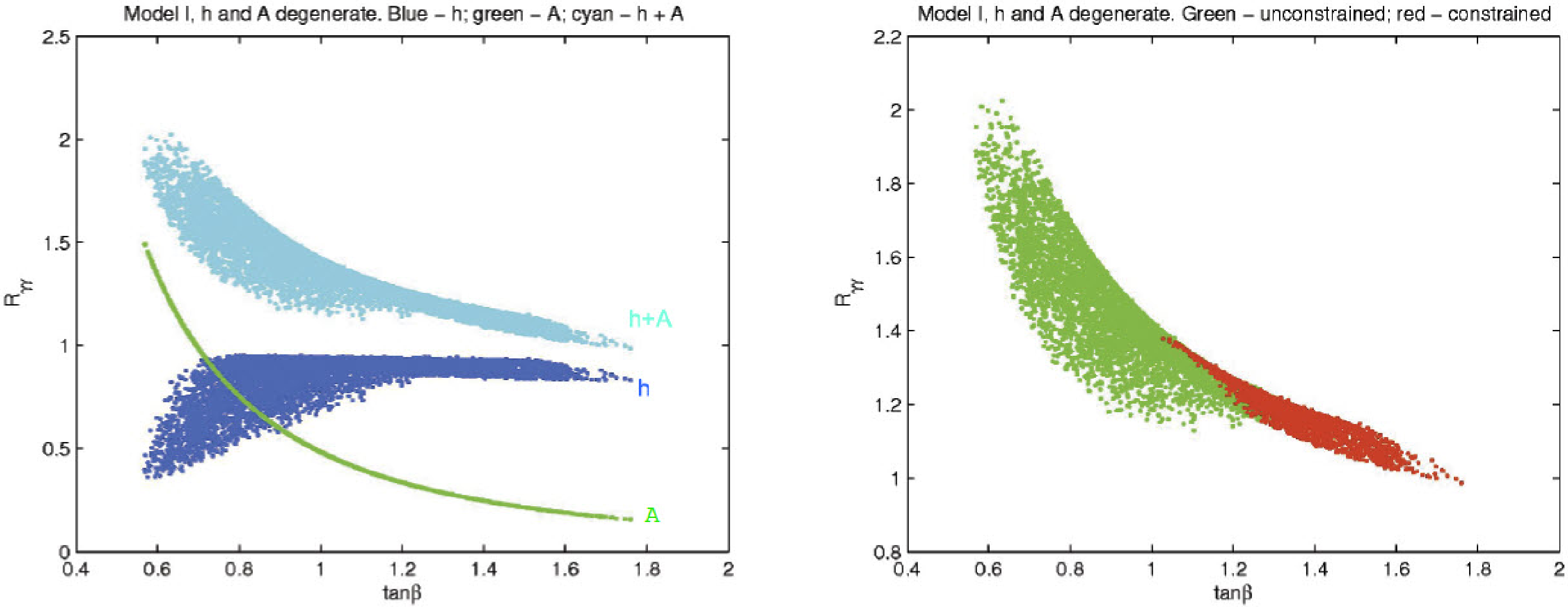
Example: Approaching the decoupling/alignment limit in the 2HDM

Couplings of the SM-like Higgs boson h normalized to those of the SM Higgs boson, in the decoupling/alignment limit of the most general two-Higgs-doublet model (2HDM). The normalization of the pseudoscalar coupling of h to fermions is relative to the corresponding scalar coupling. The Z_i are related to the coefficients of the Higgs scalar potential, the ρ_i are complex 3×3 matrices that govern the Higgs-quark Yukawa couplings, and $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$ parameterize neutral Higgs mixing. In the decoupling/alignment limit, s_{12}, $s_{13} \ll 1$. In the alignment limit we also have Z_{6R}, $Z_{6I} \ll 1$.

Higgs interaction	2HDM coupling	decoupling/alignment limit
$hW^+W^-\,, hZZ$	$c_{12}c_{13}$	$1 - \frac{1}{2}s_{12}^2 - \frac{1}{2}s_{13}^2$
hhh		$1 - 3(s_{12}Z_{6R} - s_{13}Z_{6I})/Z_1$
$hhhh$		$1 - 4(s_{12}Z_{6R} - s_{13}Z_{6I})/Z_1$
$h\overline{D}D$	$c_{12}c_{13}\mathbb{1} - s_{12}\rho_R^D - c_{12}s_{13}\rho_I^D$	$\mathbb{1} - s_{12}\rho_R^D - s_{13}\rho_I^D$
$ih\overline{D}\gamma_5 D$	$s_{12}\rho_I^D - c_{12}s_{13}\rho_R^D$	$s_{12}\rho_I^D - s_{13}\rho_R^D$
$h\overline{U}U$	$c_{12}c_{13}\mathbb{1} - s_{12}\rho_R^U - c_{12}s_{13}\rho_I^U$	$\mathbb{1} - s_{12}\rho_R^U - s_{13}\rho_I^U$
$ih\overline{U}\gamma_5 U$	$-s_{12}\rho_I^U + c_{12}s_{13}\rho_R^U$	$-s_{12}\rho_I^U + s_{13}\rho_R^U$

A precision Higgs program can detect small deviations from SM Higgs couplings and thus probe the structure of the extended Higgs sector.

An enhanced $\gamma\gamma$ signal due to mass-degenerate h^0 and A^0:


Model I, h and A degenerate. Blue – h; green – A; cyan – h + A

Model I, h and A degenerate. Green – unconstrained; red – constrained

Left panel: $R_{\gamma\gamma}$ as a function of $\tan\beta$ for h (blue), A (green), and the total observable rate (cyan), obtained by summing the rates with intermediate h and A, for the unconstrained scenario.

Right panel: Total rate for $R_{\gamma\gamma}$ as a function of $\tan\beta$ for the constrained (red) and unconstrained (green) scenarios.

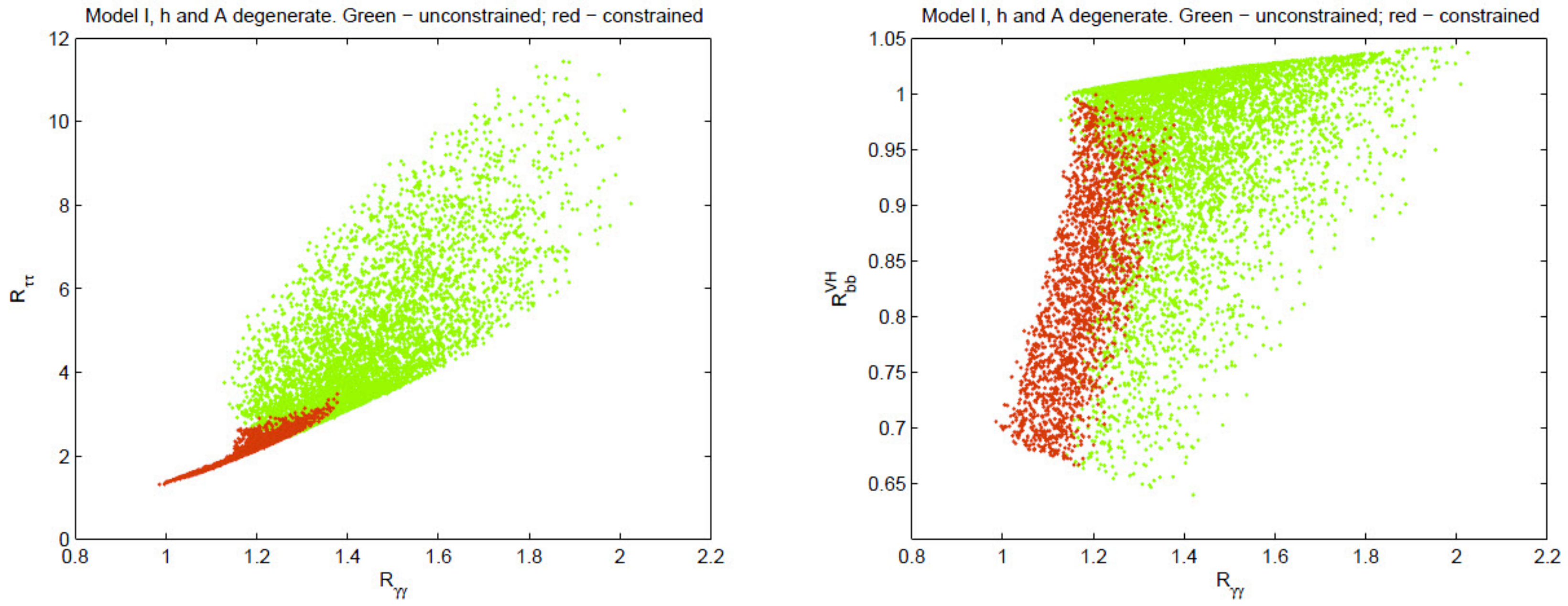
The enhancement occurs in the parameter regime of $\tan\beta \lesssim 1.5$ and $\sin(\beta-\alpha)$ near 1.

Taken from P.M. Ferreira, H.E. Haber, R. Santos and J.P. Silva, ``Mass-degenerate Higgs bosons at 125 GeV in the Two-Higgs-Doublet Model,'' Phys. Rev. **D87**, 055009 (2013).

An enhanced $\gamma\gamma$ signal in the mass-degenerate scenario yields two associated predictions that must be confirmed by experiment if this framework is to be consistent.

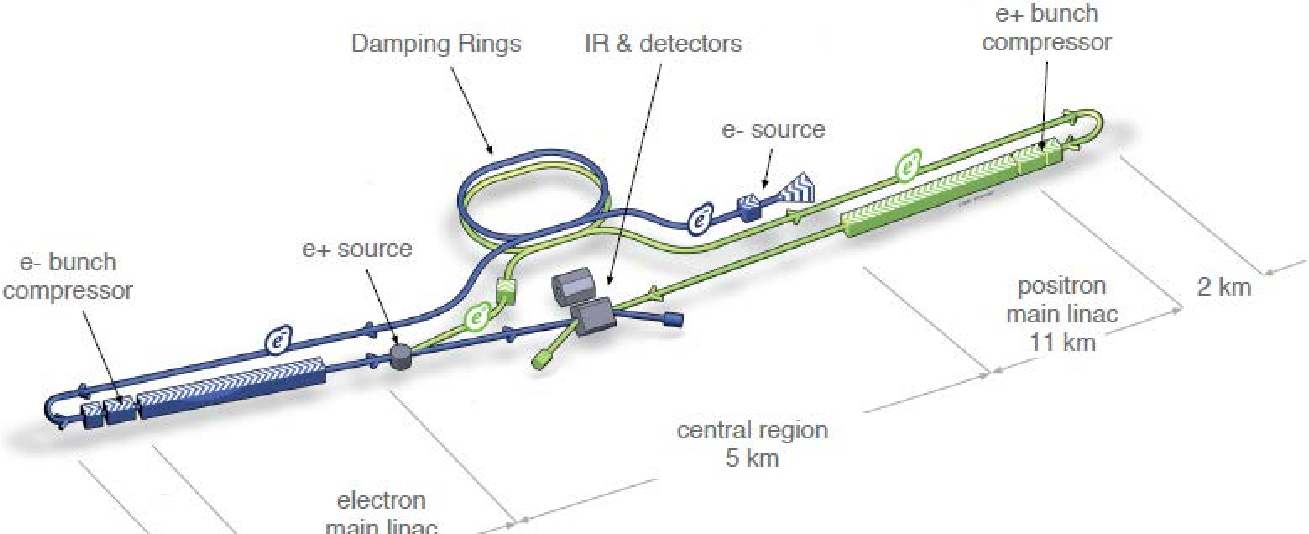
1. The inclusive $\tau^+\tau^-$ signal is enhanced with respect to the SM due to the production of A via gg fusion.

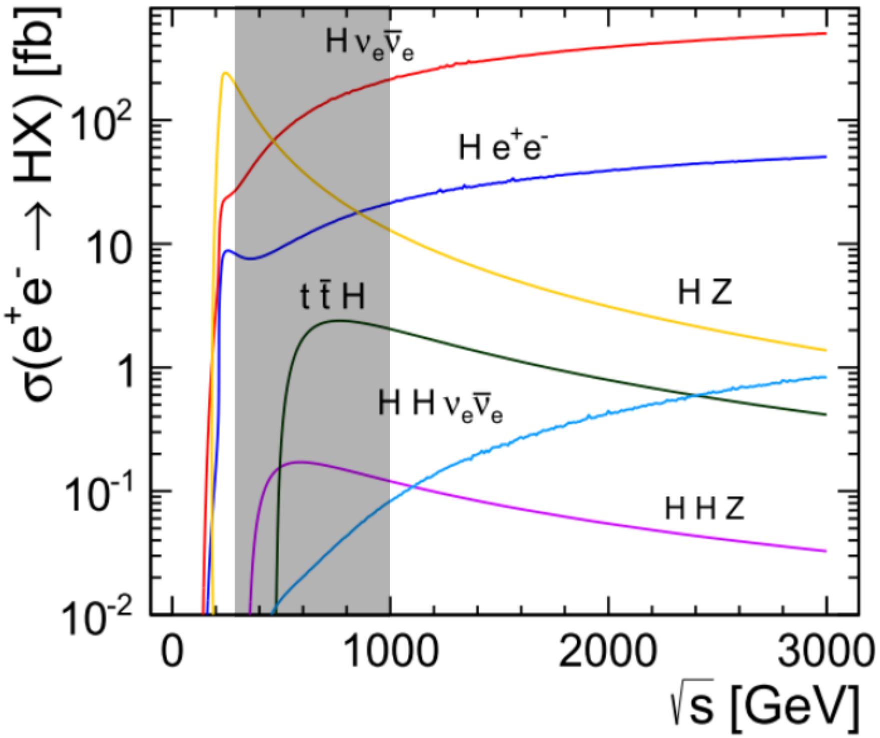
2. The exclusive $b\bar{b}$ signal due to the production of Higgs bosons in association with W or Z is close to its SM value but is not enhanced.



Left panel: Total $R_{\tau\tau}$ (h and A summed) as a function of $R_{\gamma\gamma}$ for the constrained (red) and unconstrained (green) scenarios. Right panel: R_{bb}^{VH} (h and A summed) as a function of $R_{\gamma\gamma}$ for the constrained (red) and unconstrained (green) scenarios.

$ILC: \; e^+e^-$ Linear Collider at 250 GeV $< \sqrt{s} <$ 1000 GeV

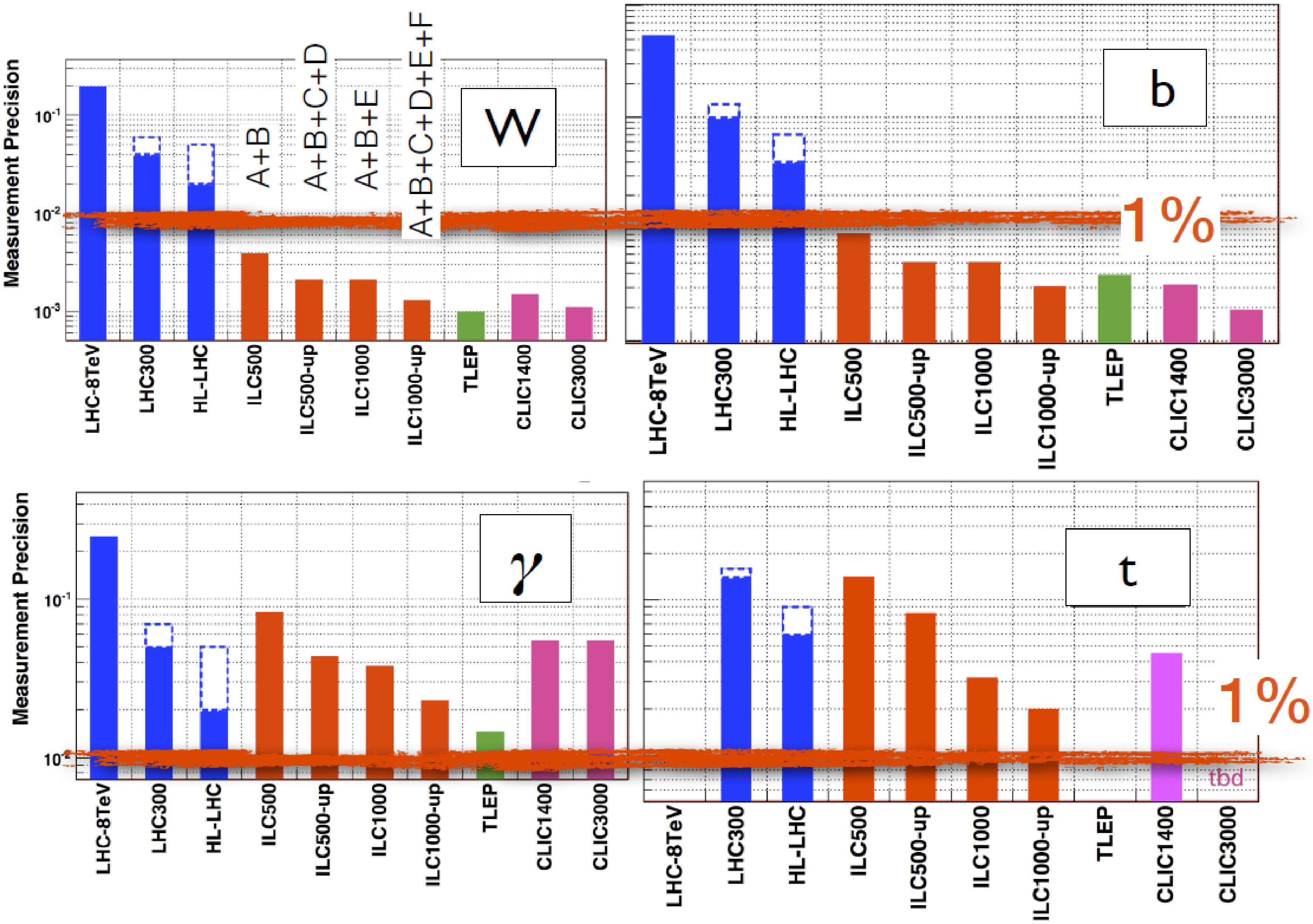




Summary of expected accuracies for Higgs cross sections and branching ratios at the ILC, taken from the *ILC Higgs White Paper* (D.M. Asner et al., arXiv:1310.0763 [hep-ph]) and contributed to the Proceedings of the 2013 Snowmass Community Planning Study.

	ILC(250)	ILC500	ILC(1000)	ILC(LumUp)
process	$\Delta\sigma/\sigma$			
$e^+e^- \to ZH$	2.6 %	2.0 %	2.0 %	1.0 %
$e^+e^- \to \nu\bar{\nu}H$	11 %	2.3 %	2.2 %	1.1 %
$e^+e^- \to t\bar{t}H$	-	28 %	6.3 %	3.8 %
mode	ΔBr/Br			
$H \to ZZ$	19 %	7.5 %	4.2 %	2.4 %
$H \to WW$	6.9 %	3.1 %	2.5 %	1.3 %
$H \to b\bar{b}$	2.9 %	2.2 %	2.2 %	1.1 %
$H \to c\bar{c}$	8.7 %	5.1 %	3.4 %	1.9 %
$H \to gg$	7.5 %	4.0 %	2.9 %	1.6 %
$H \to \tau^+\tau^-$	4.9 %	3.7 %	3.0 %	1.6 %
$H \to \gamma\gamma$	34 %	17 %	7.9 %	4.7 %
$H \to \mu^+\mu^-$	100 %	100 %	31 %	20 %

Precision in kappa by facility



My recent Ph.D. students and their thesis projects

Douglas Pahel (2005): CP-Violating Effects in W and Z Boson Pair Production at the the ILC in the Minimal Supersymmetric Standard Model

John Mason (2008): Hard supersymmetry-breaking "wrong-Higgs" couplings of the MSSM

Deva O'Neil (2009): Phenomenology of the Basis-Independent CP-Violating Two-Higgs Doublet Model

Where are they now?

D. Pahel – working in industry
J. Mason – following a three-year post doctoral research associate in particle theory at Harvard University, John accepted a position as an assistant professor of physics at Western State College of Colorado
D. O'Neil – assistant professor of physics at Bridgewater College (in Virginia)

My current Ph.D. students and their projects

Laura Daniel: Precision measurements of couplings at the LHC and tests of theories of UED (universal extra dimensions).

Eddie Santos: Renormalization group running in the general CP-violating two-Higgs doublet model; predictions for Higgs-mediated flavor changing neutral current processes.

I am also working with:

Laurel Stephenson Haskins: Puzzle in the relation between the quark anomalous dimension and the mass anomalous dimension in supersymmetric non-abelian gauge theory.

Implication of the Higgs data for the stability of the vacuum

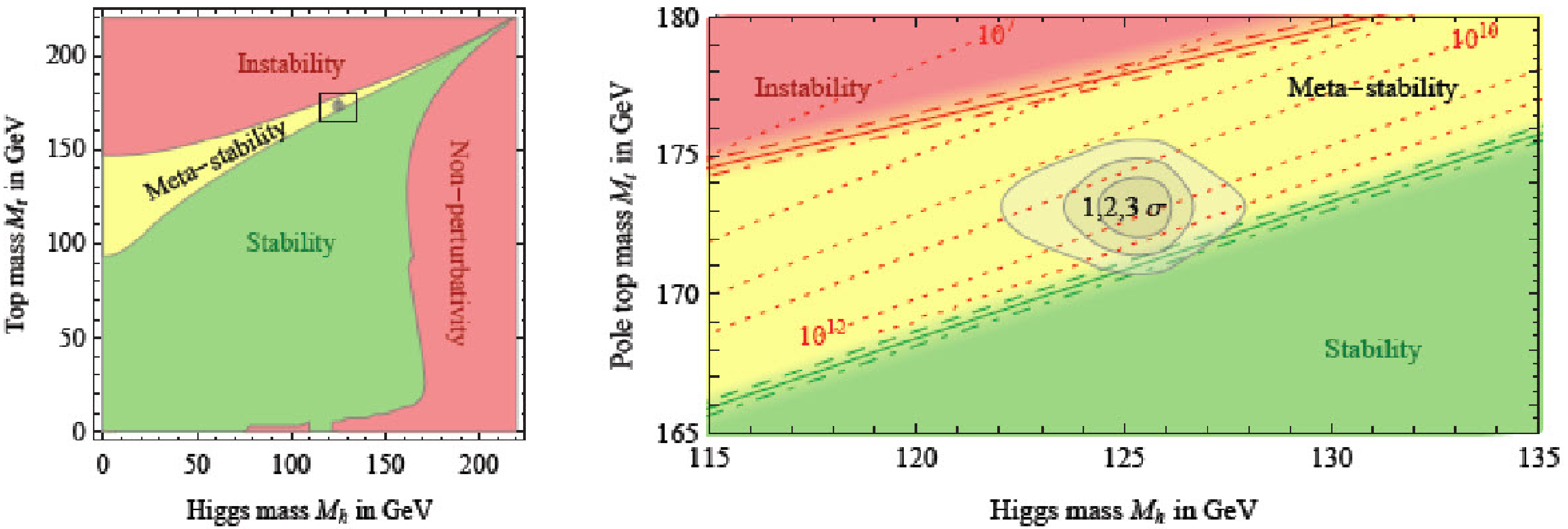


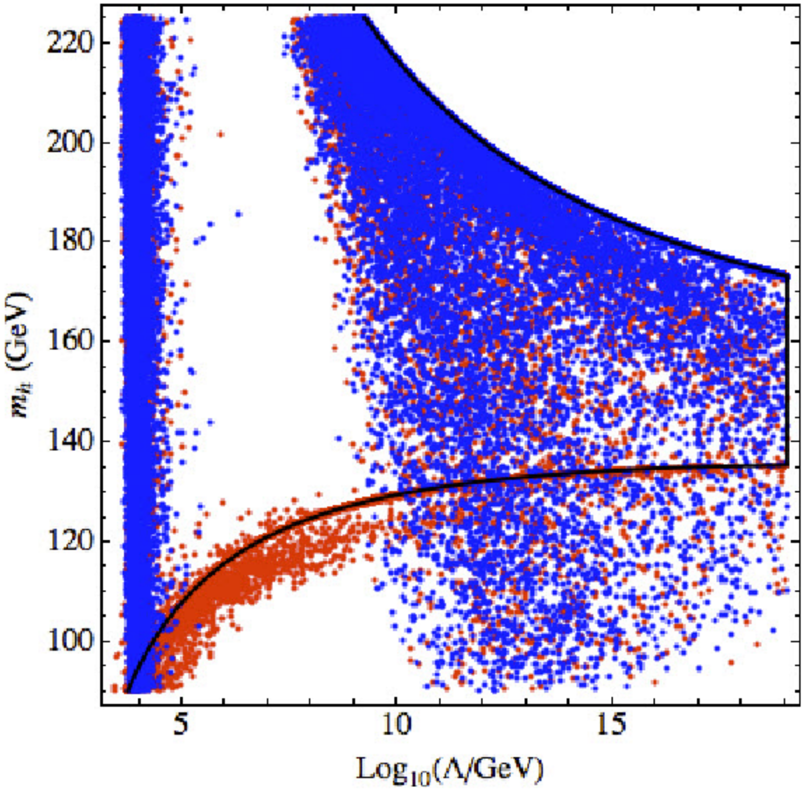
Figure 5: *Regions of absolute stability, meta-stability and instability of the SM vacuum in the* M_t–M_h *plane.* **Right**: *Zoom in the region of the preferred experimental range of* M_h *and* M_t *(the gray areas denote the allowed region at 1, 2, and* 3σ*). The three boundaries lines correspond to* $\alpha_s(M_Z) = 0.1184 \pm 0.0007$*, and the grading of the colors indicates the size of the theoretical error. The dotted contour-lines show the instability scale* Λ *in* GeV *assuming* $\alpha_s(M_Z) = 0.1184$.

Taken from G. Degrassi et al., arXiv:1205.6497

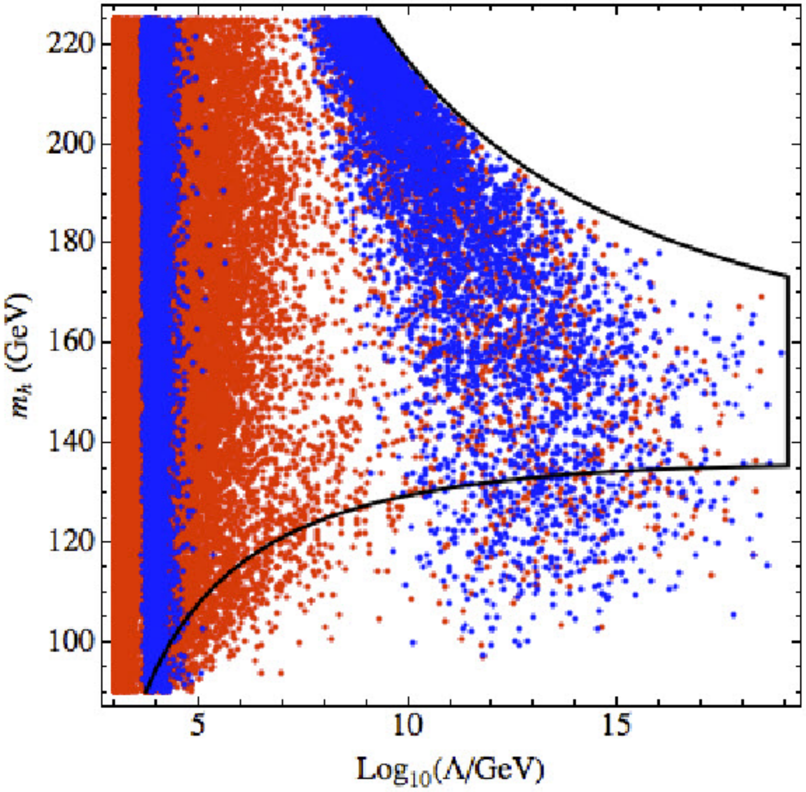
Stability up to the Planck scale is possible in the two-Higgs-doublet model (2HDM)

A partial scan over 2HDM parameter space

α=0



α=0.8



red—stability bound blue—Landau pole