Research on the Theory of the Terascale

Howard Haber

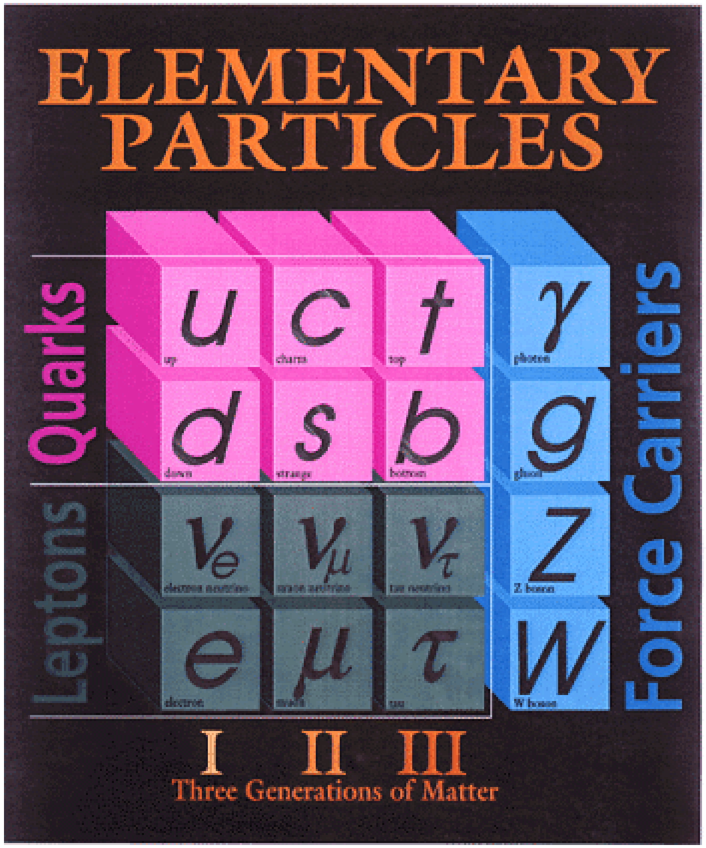
SCIPP Theory

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 of Particle Physics

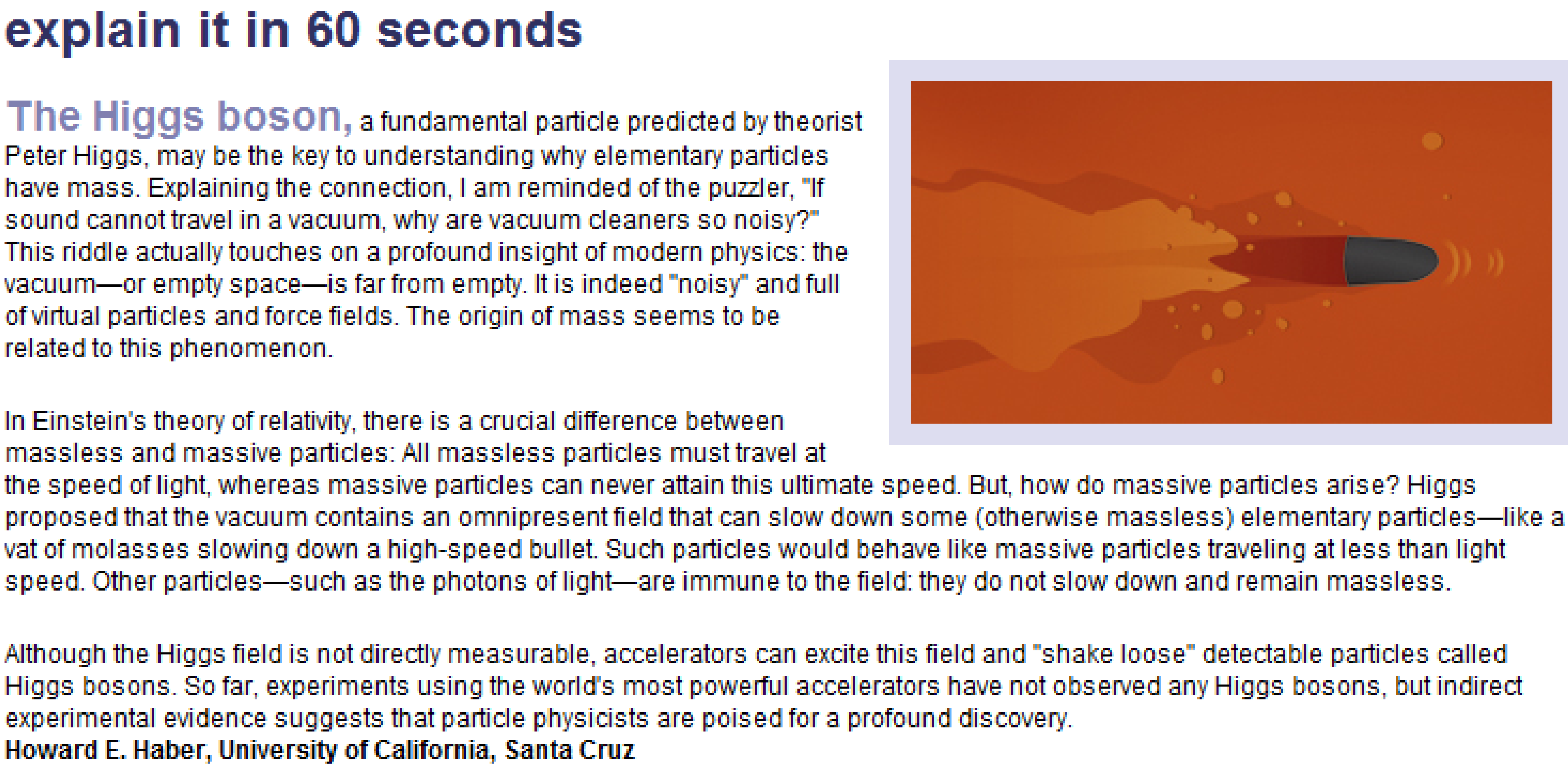


The elementary particles consists of three generations of spin-1/2 quarks and leptons and the gauge bosons of SU(3)xSU(2)xU(1).

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

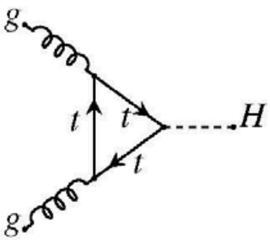
$$gg \to h^0\,, \quad h^0 \to \gamma\gamma\,, VV^{(*)}\,,$$

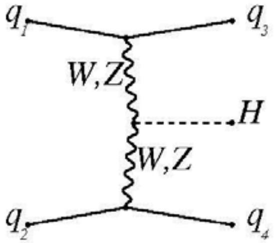
$$qq \to qqV^{(*)}V^{(*)} \to qqh^0, \quad h^0 \to \gamma\gamma,\, \tau^+\tau^-,\, VV^{(*)}\,,$$

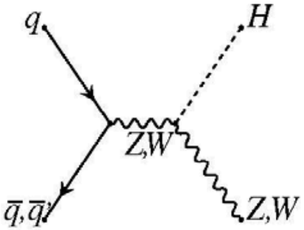
$$q\bar{q}^{(\prime)} \to V^{(*)} \to Vh^0\,, \quad h^0 \to b\bar{b}\,, WW^{(*)}\,,$$

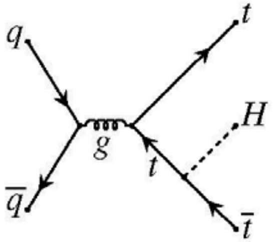
$$gg, q\bar{q} \to t\bar{t}h^0, \quad h^0 \to b\bar{b},\, \gamma\gamma,\, WW^{(*)}\,.$$

where $V = W$ or Z.



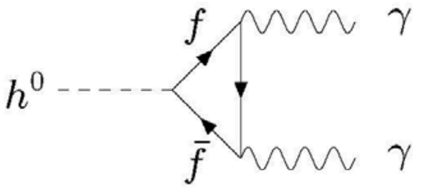


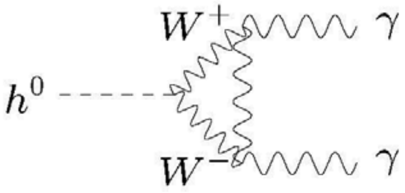


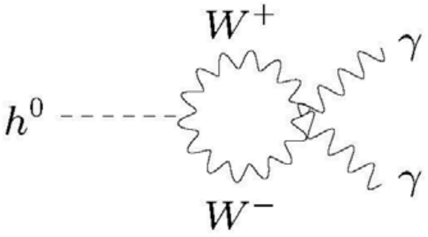


SM Higgs decays at the LHC for $m_h \sim 125$ GeV

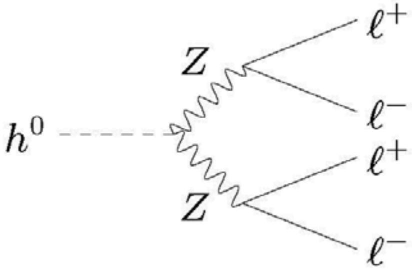
1. The rare decay $h^0 \to \gamma\gamma$ is the most promising signal.



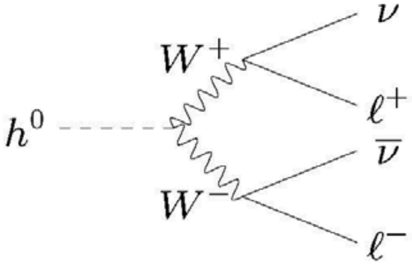




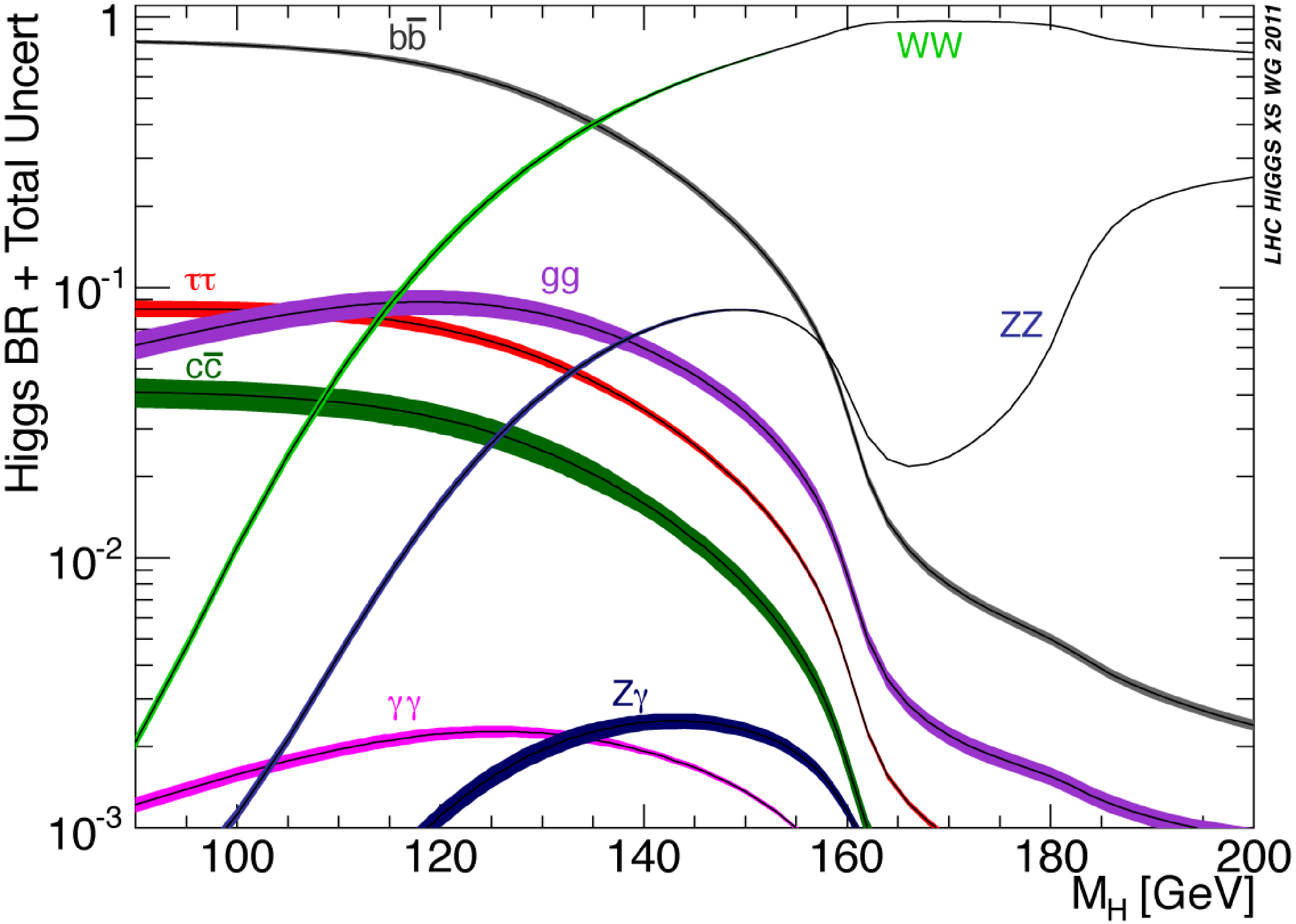
2. The so-called golden channel, $h^0 \to ZZ \to \ell^+\ell^-\ell^+\ell^-$ (where one or both Z bosons are off-shell) is a rare decay for $m_h \sim 125$ GeV, but is nevertheless visible.



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.



Probability of Higgs boson decay channels



The LHC discovery of 4 July 2012

The CERN update of the search for the Higgs boson, simulcast at ICHEP-2012 in Melbourne, Australia

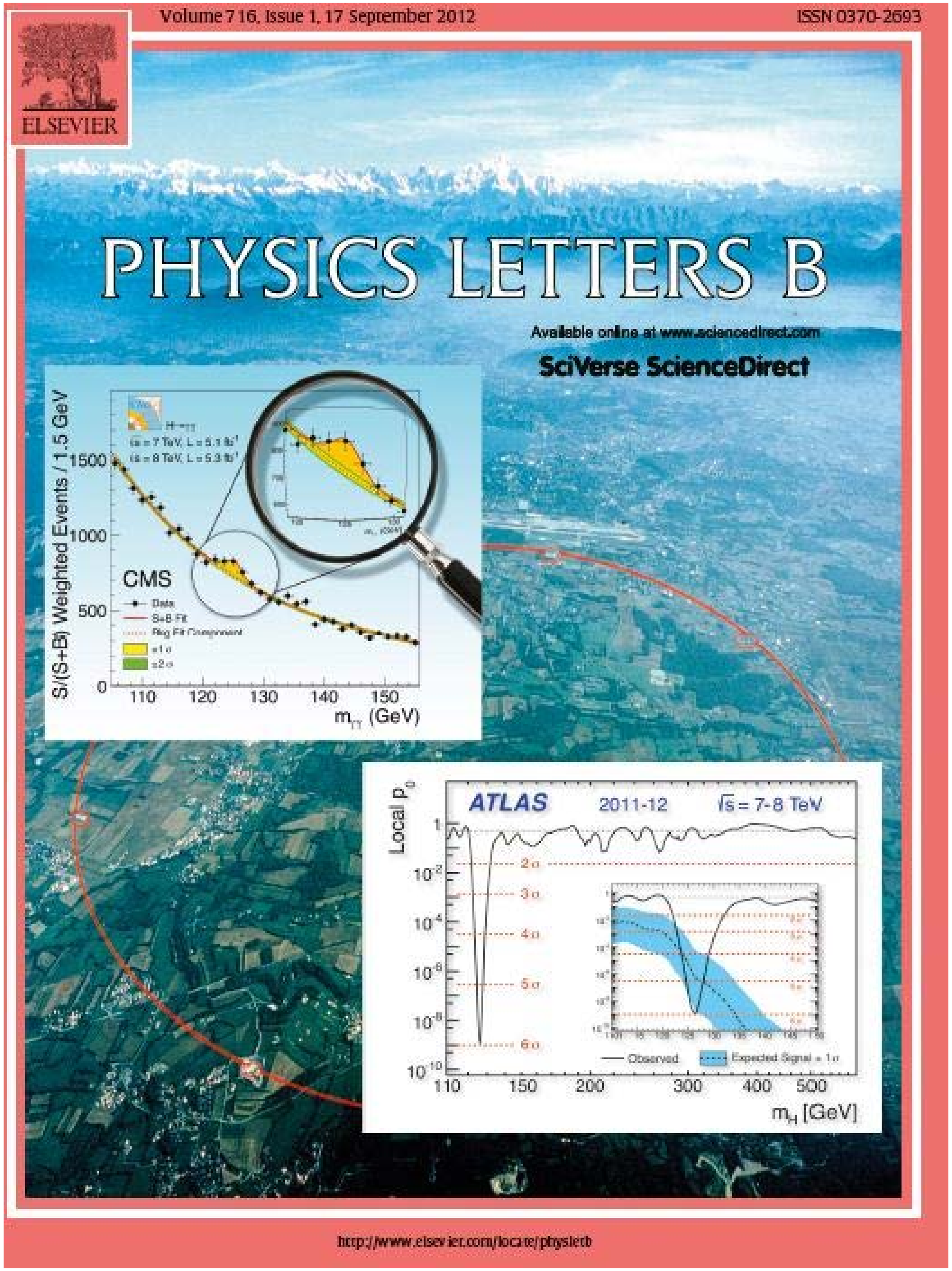
The discovery of the new boson is published in Physics Letters B.

ATLAS Collaboration:

Physics Letters B716 (2012) 1—29

CMS Collaboration:

Physics Letters B716 (2012) 30—61



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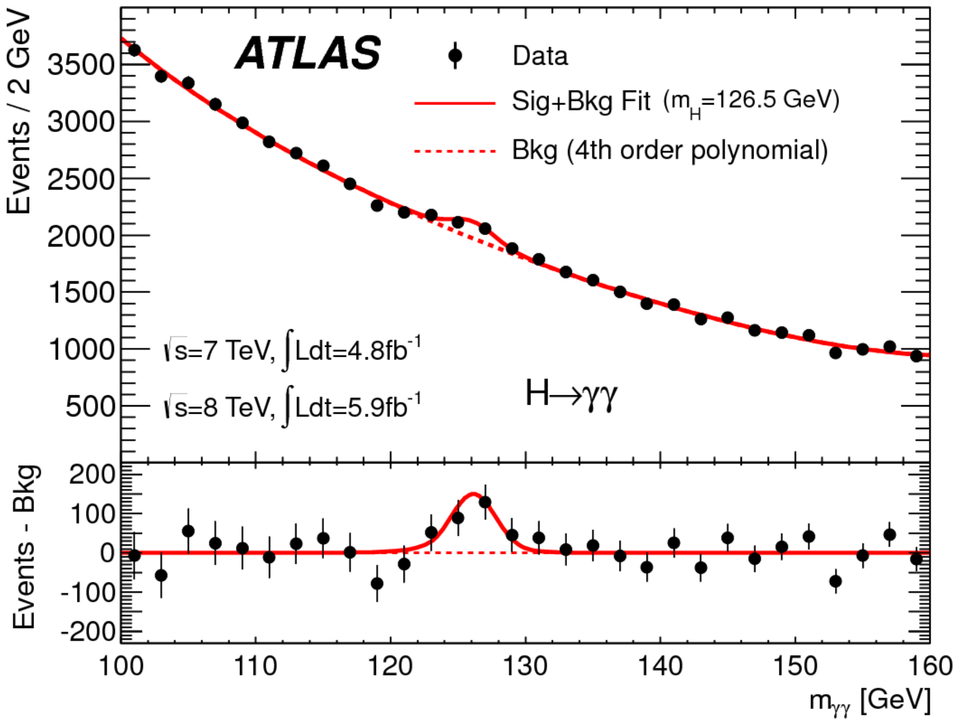
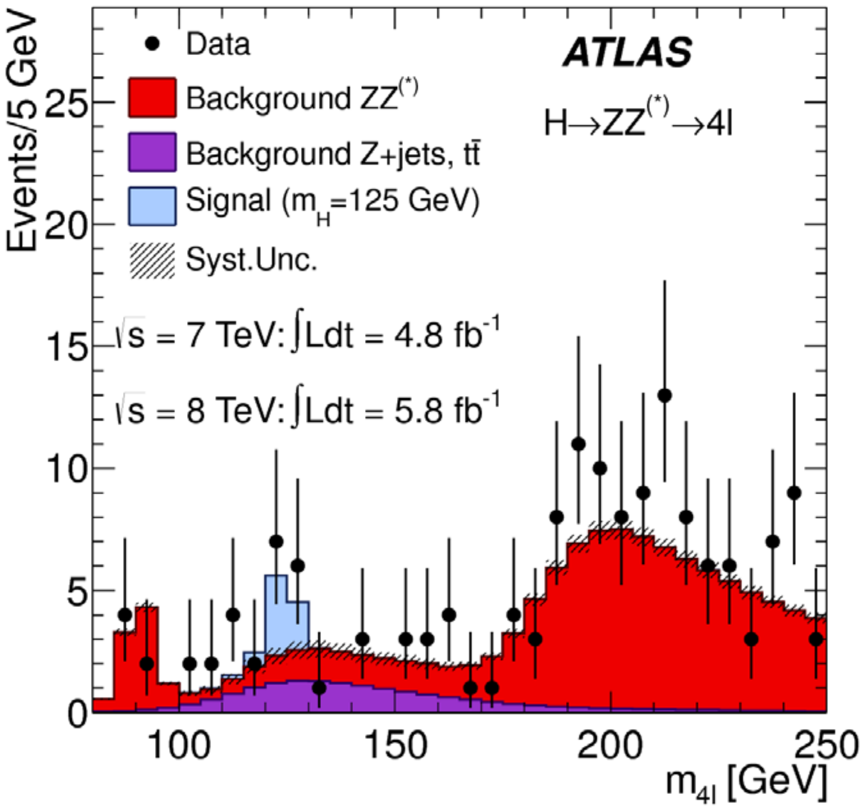
A boson is discovered at the LHC by the ATLAS Collaboration



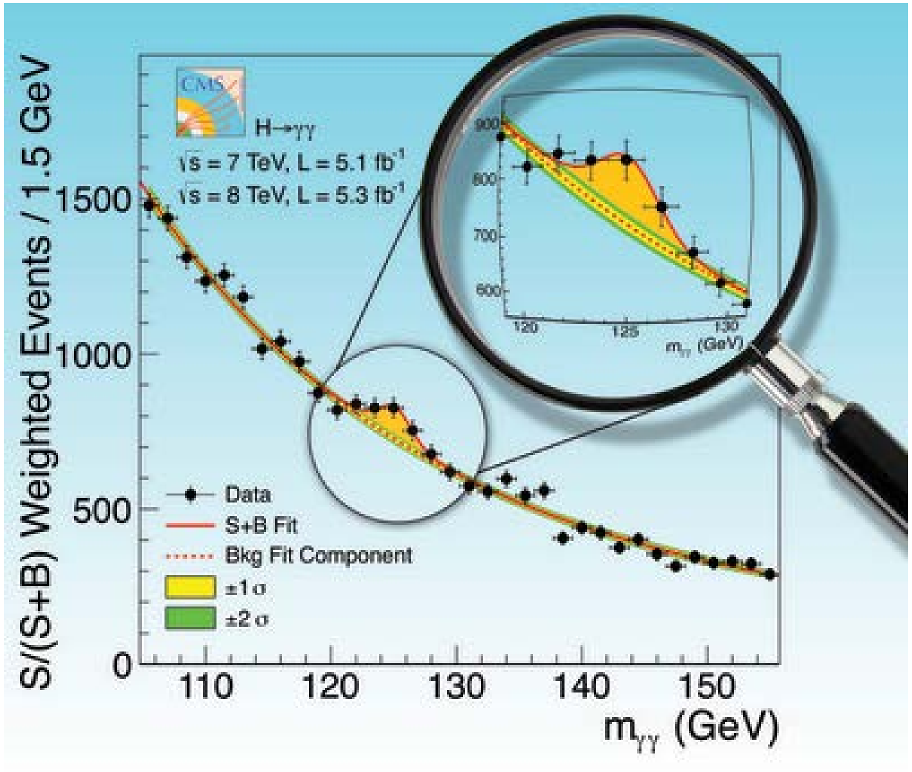
Invariant mass distribution of diphoton candidates for the combined 7 TeV and 8 TeV data samples. The result of a fit to the data of the sum of a signal component fixed to m_H = 126.5 GeV and a background component described by a fourth-order Bernstein polynomial is superimposed. The bottom inset displays the residuals of the data with respect to the fitted background component.



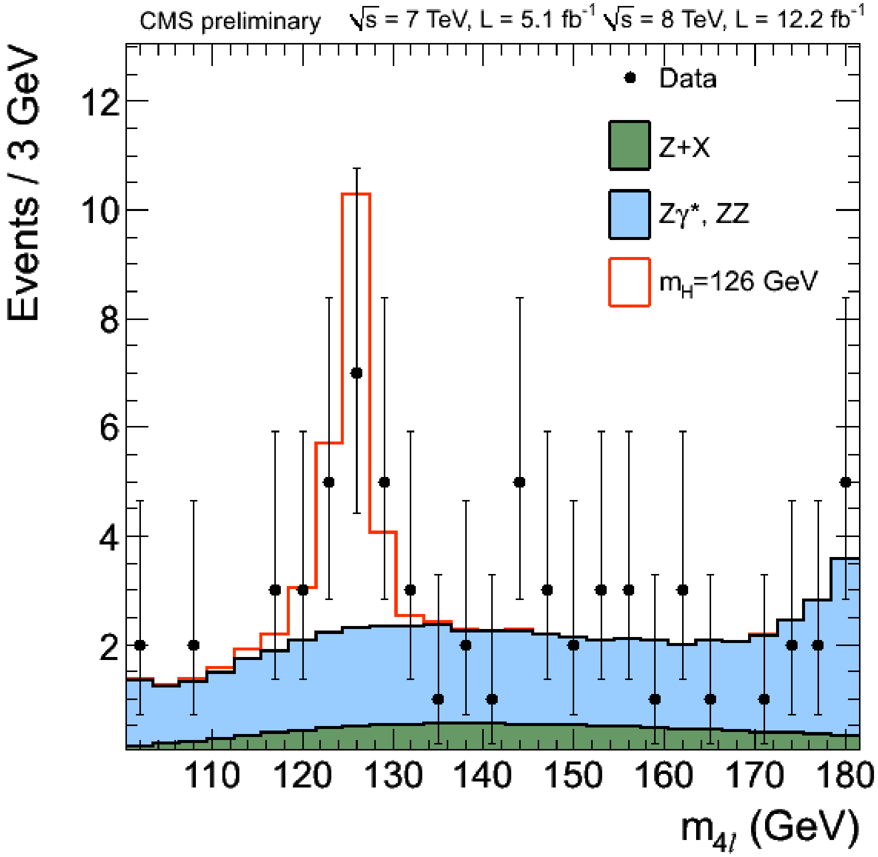
The distribution of the four-lepton invariant mass, m_{4l}, for the selected candidates, compared to the background expectation in the 80 to 250 GeV mass range, for the combination of the 7 TeV 8 TeV data. The signal expectation for a Higgs boson with m_H=125 GeV is also shown.

(Taken from Physics Letters B716 (2012) 1-29.)

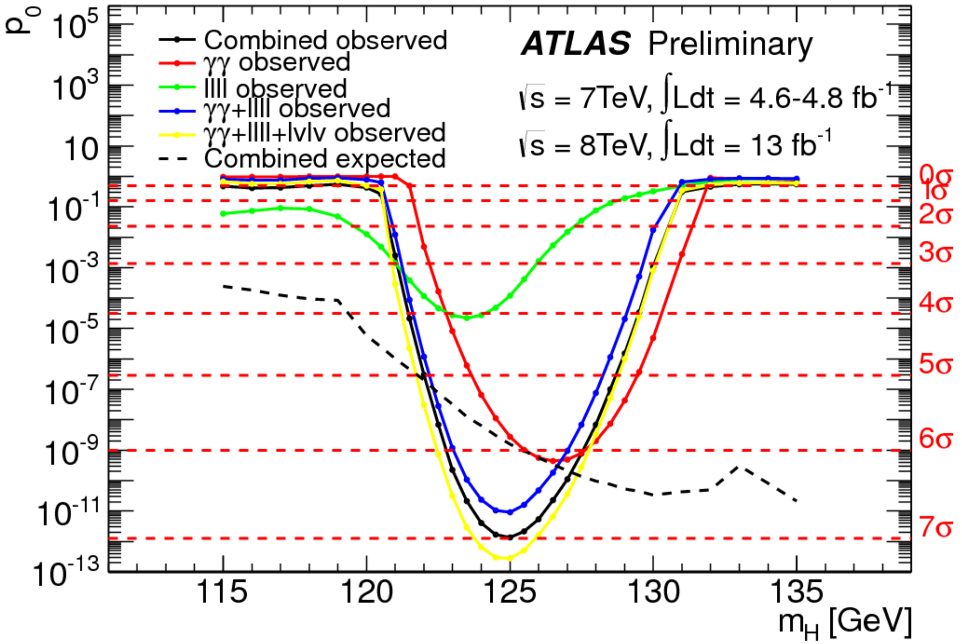
A boson is discovered at the LHC by the CMS Collaboration



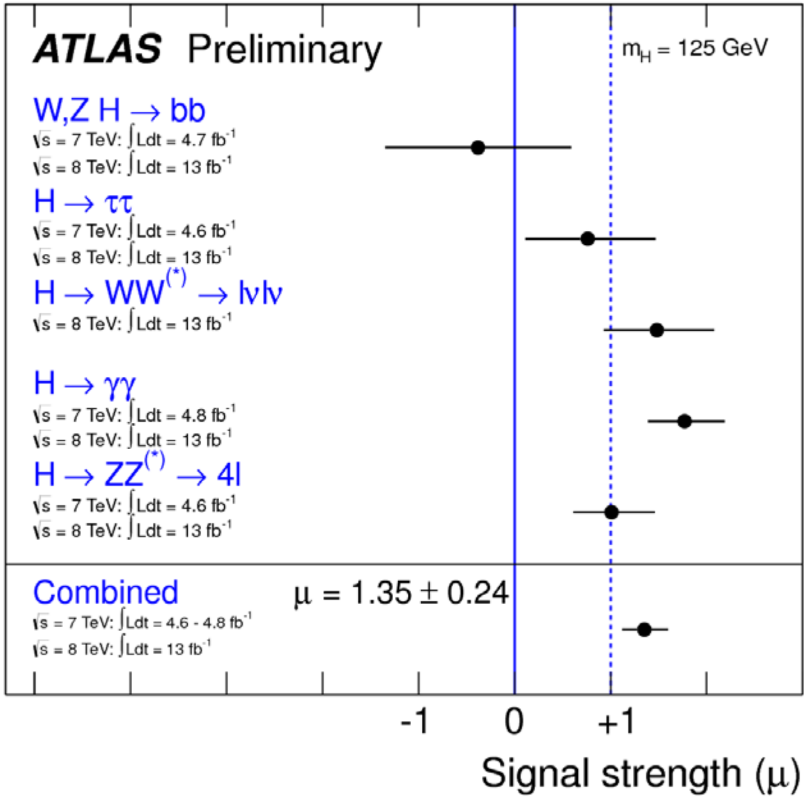
The diphoton invariant mass distribution with each event weighted by the S/(S+B) value of its category. The lines represent the fitted background and signal, and the colored bands represent the ±1 and ±2 standard deviation uncertainties in the background estimate. The inset shows the central part of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



Distribution of the four-lepton invariant mass for the ZZ→4 leptons analysis. The points represent the data, the filled histograms represent the background, and the open histogram shows the signal expectation for a Higgs boson of mass m_H = 126 GeV, added to the background expectation. Taken from https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12041TWiki.

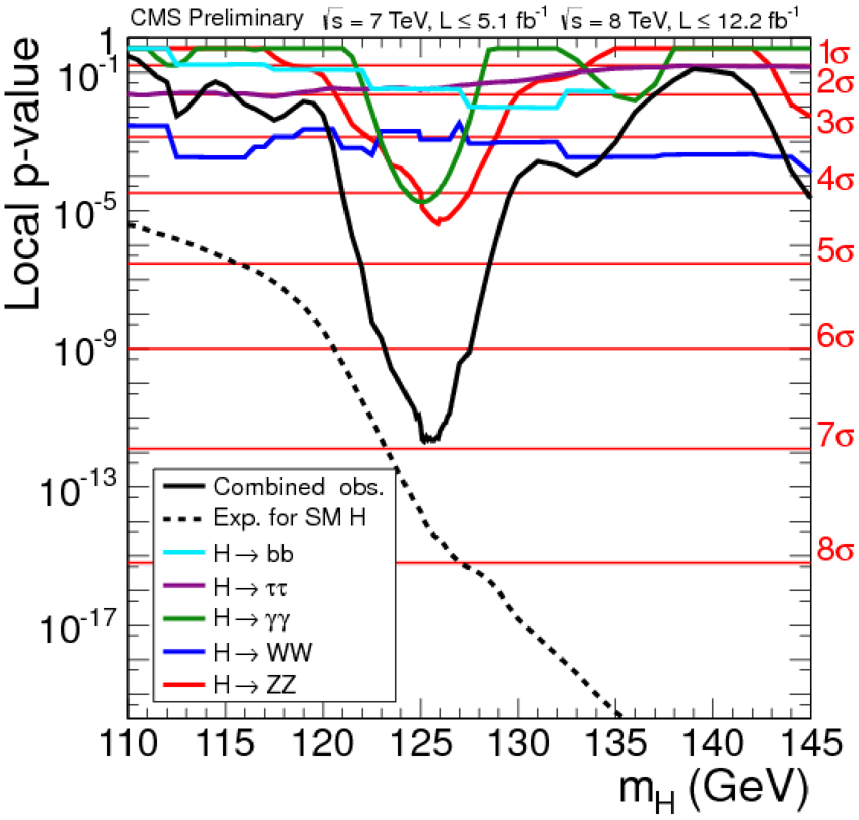


The local probability p_0 for a background-only experiment to be more signal-like as a function of m_h for various cases of combinations: H→γγ (red line); H → ZZ* → llll (green line); combination of H→γγ and H → ZZ*→ llll (blue line); combination of H→γγ and H → ZZ* → llll and H->WW*->lvlv (magenta line); and the combination of all channels, including H → bb and H →ττ (black line). The dashed black curve shows the median expected local p_0 under the hypothesis of a Standard Model Higgs boson production signal at that mass for the combination of all channels.

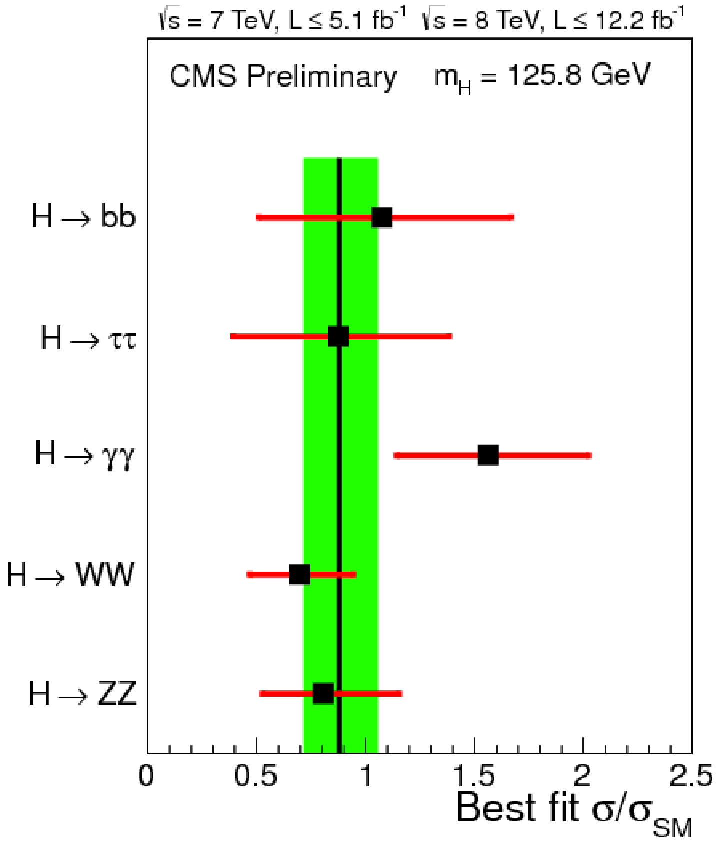


Summary of the individual and combined best-fit values of the strength parameter for a Higgs boson mass hypothesis of 125 GeV. The ATLAS γγ signal strength deviates from the Standard Model prediction by 2.4 σ.

Taken from ATLAS-CONF-2012-170, 13 December 2012.



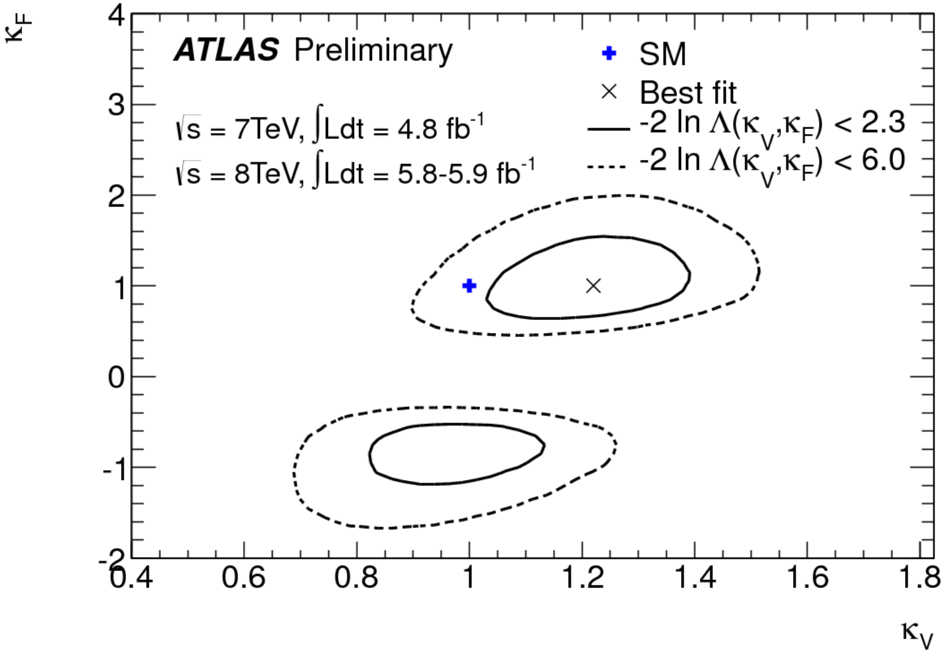
The observed local *p*-value p_0 for five subcombinations by decay mode and the overall combination as a function of the SM Higgs boson mass. The dashed lines show the expected local *p*-value $p_0(m_H)$, should a Higgs boson with a mass m_H exist.



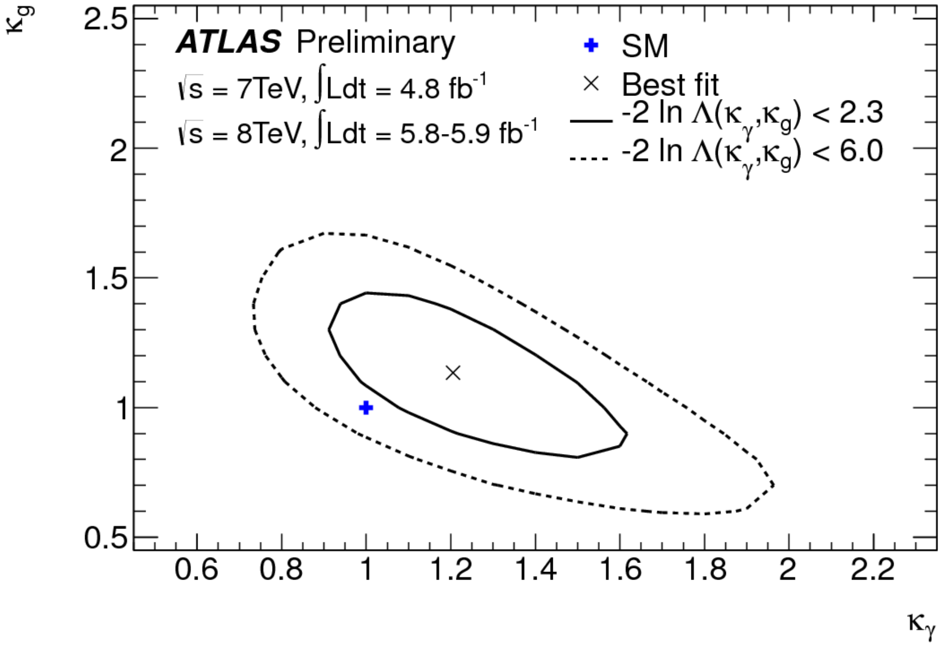
Values of $\hat{\mu} = \sigma/\sigma_{SM}$ for the combination (solid vertical line) and for sub-combinations grouped by decay mode (points). The vertical band shows the overall $\hat{\mu}$ value 0.88 ± 0.21. The horizontal bars indicate the $\pm 1\sigma$ uncertainties (both statistical and systematic) on the $\hat{\mu}$ values for individual channels.

Taken from CMS-PAS-HIG-12-045, 16 November 2012.

How well does ATLAS Higgs data fit the Standard Model expectations for Higgs couplings?



Top figure: Fits for 2-parameter benchmark models probing different Higgs coupling strength scale factors for fermions and vector bosons, under the assumption that there is a single coupling for all fermions t, b, τ (κ_F) and a single coupling for vector bosons (κ_V).

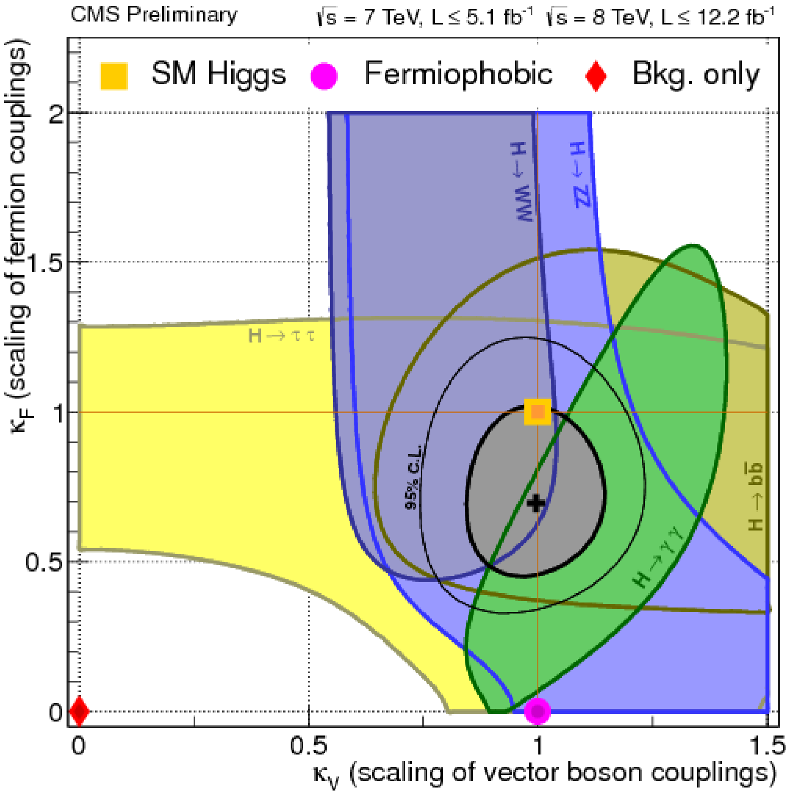


Bottom figure: Fits for benchmark models probing for contributions from non-Standard Model particles: probing only the gg → H and H→ γγ loops, assuming no sizable extra contribution to the total width. The magnitudes of the ggH and γγH couplings relative to their Standard Model values are denoted by κ_g and κ_γ.

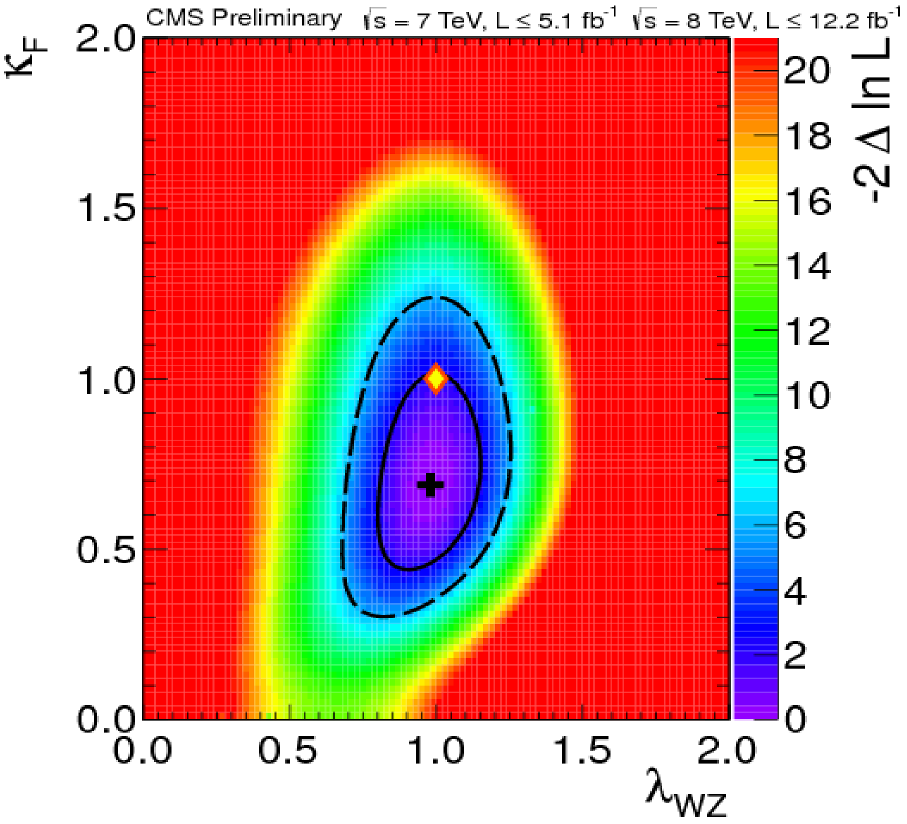
Reference:

ATLAS-CONF-2012-127 (September 9, 2012)

How well does CMS Higgs data fit the Standard Model expectations for Higgs couplings?



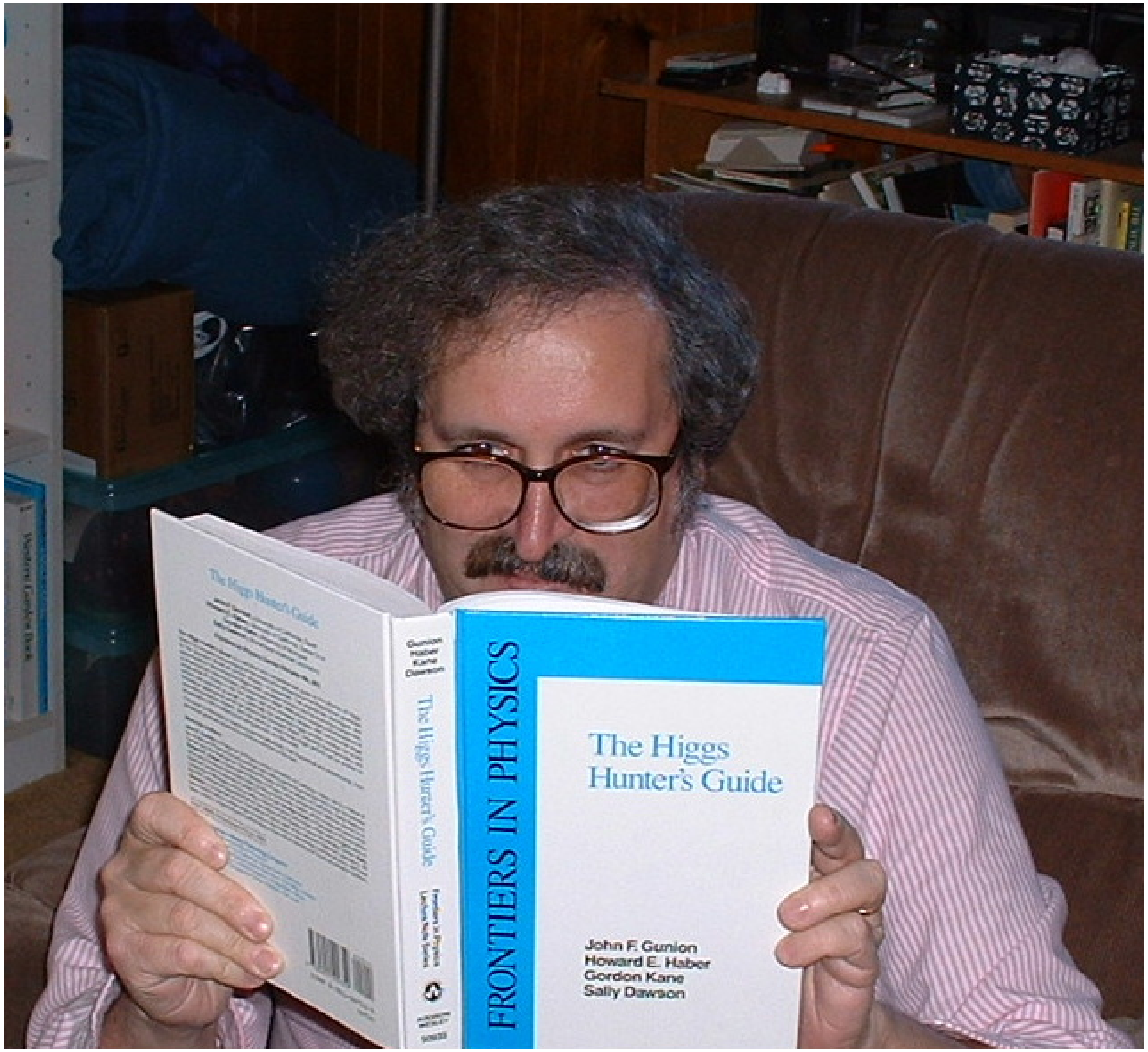
Tests of fermion and vector boson couplings of the Higgs boson. The Standard Model (SM) expectation is (κ_V , κ_F)=(1,1).



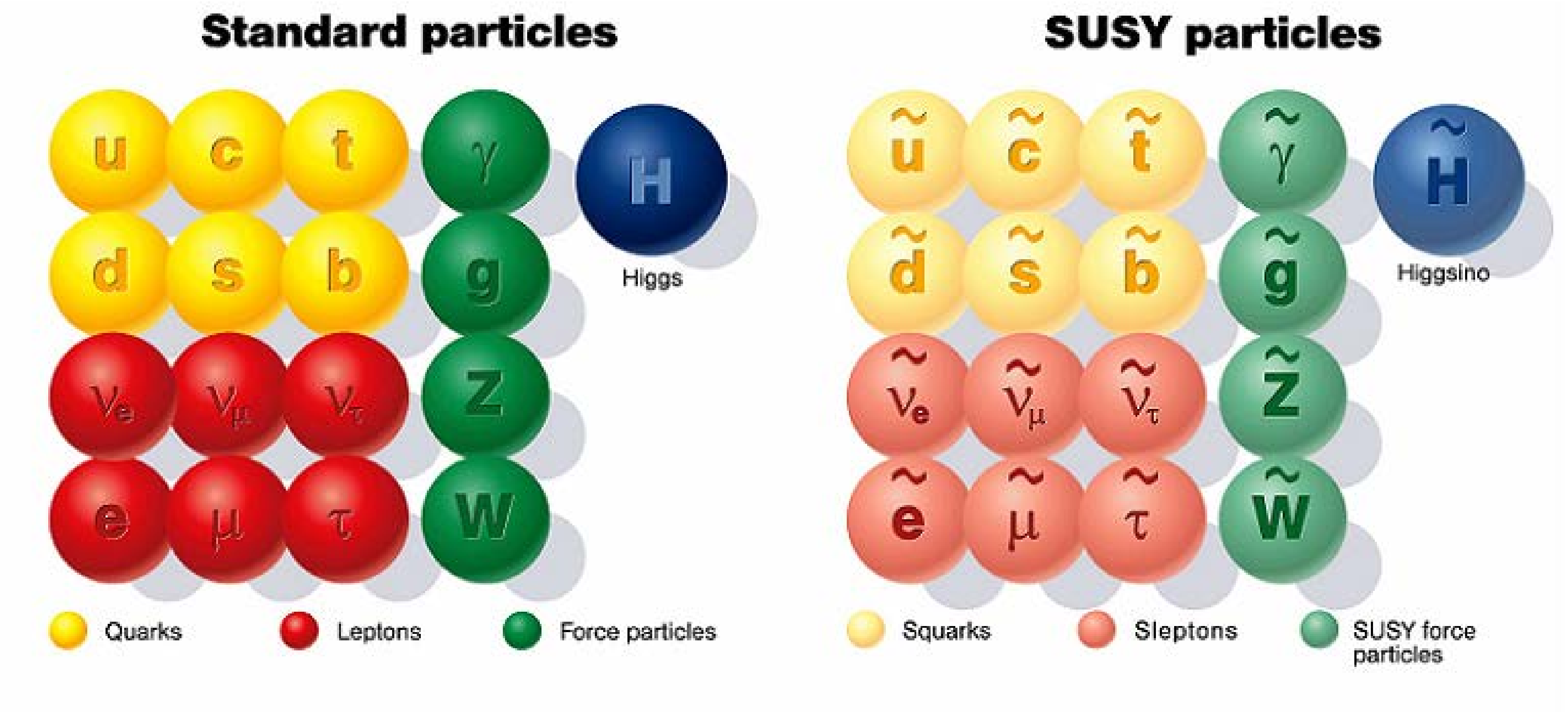
Test of custodial symmetry: the Standard Model expectation is $\lambda_{WZ} = \kappa_W / \kappa_Z = 1$.

Taken from: CMS-PAS-HIG-12-045, 16 November 2012.

Research program 1: theory and phenomenology of Higgs bosons



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

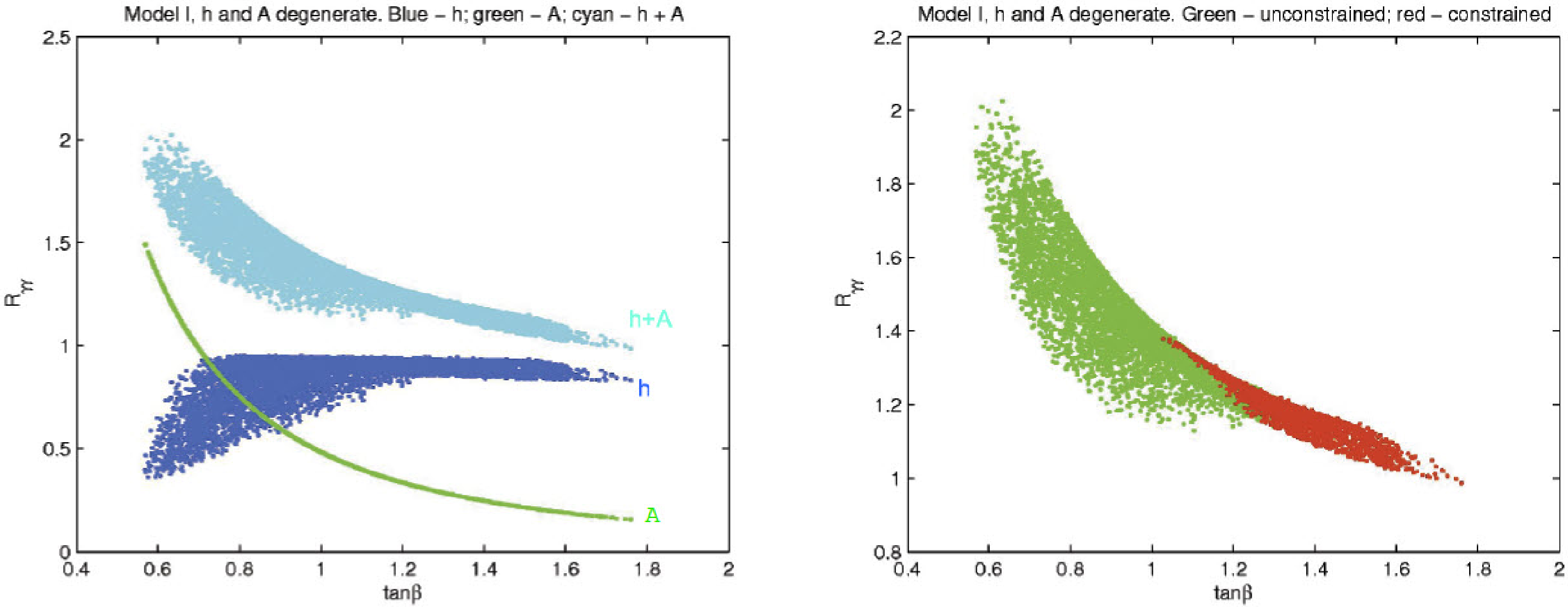


For a review, see H.E. Haber, *Supersymmetry Theory*, The 2012 Review of Particle Physics, in J. Beringer *et al.* [Particle Data Group], Phys. Rev. D**86**, 010001 (2012).

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)

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



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.

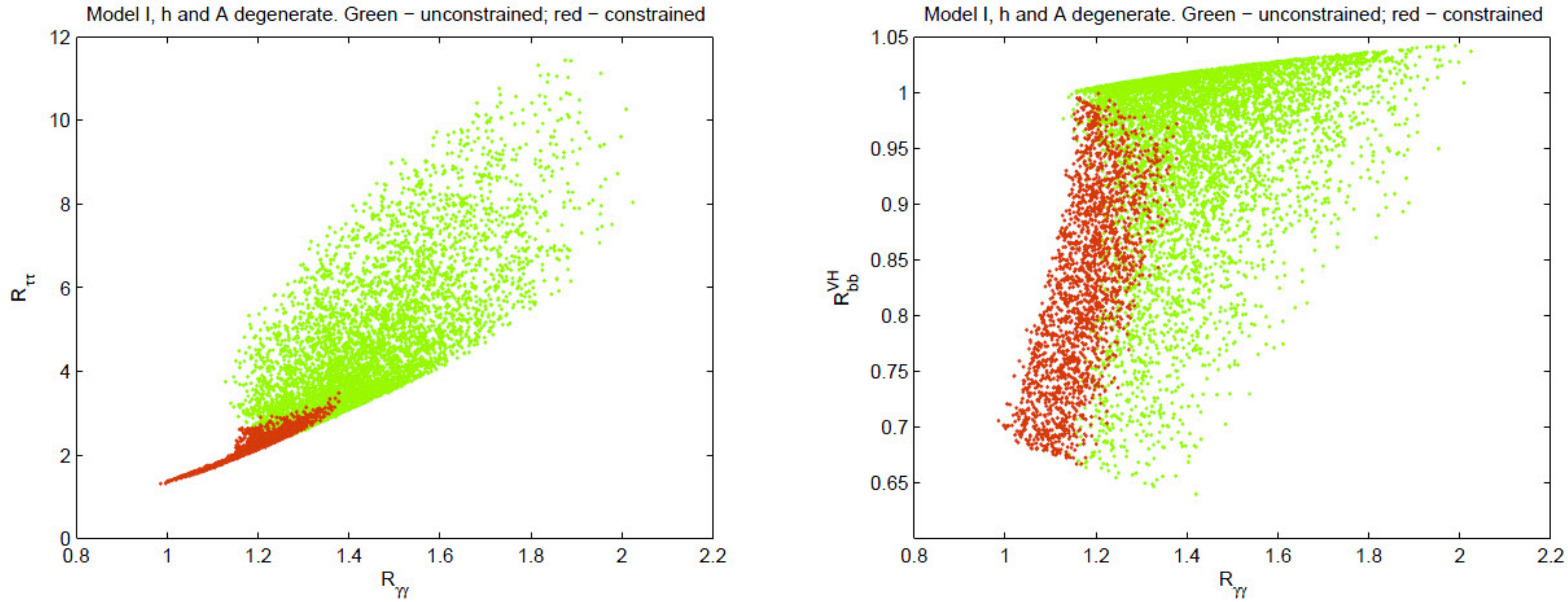
The enhancement occurs in the parameter regime of $\tan\beta \lesssim 1.5$ and $\sin(\beta-\alpha)$ near 1.

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,'' arXiv:1211.3131 [hep-ph], Phys. Rev. D in press.

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.



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

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

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.

Simulation of a precision measurements of SUSY coupling relations at a high-intensity LHC using the monojet signal

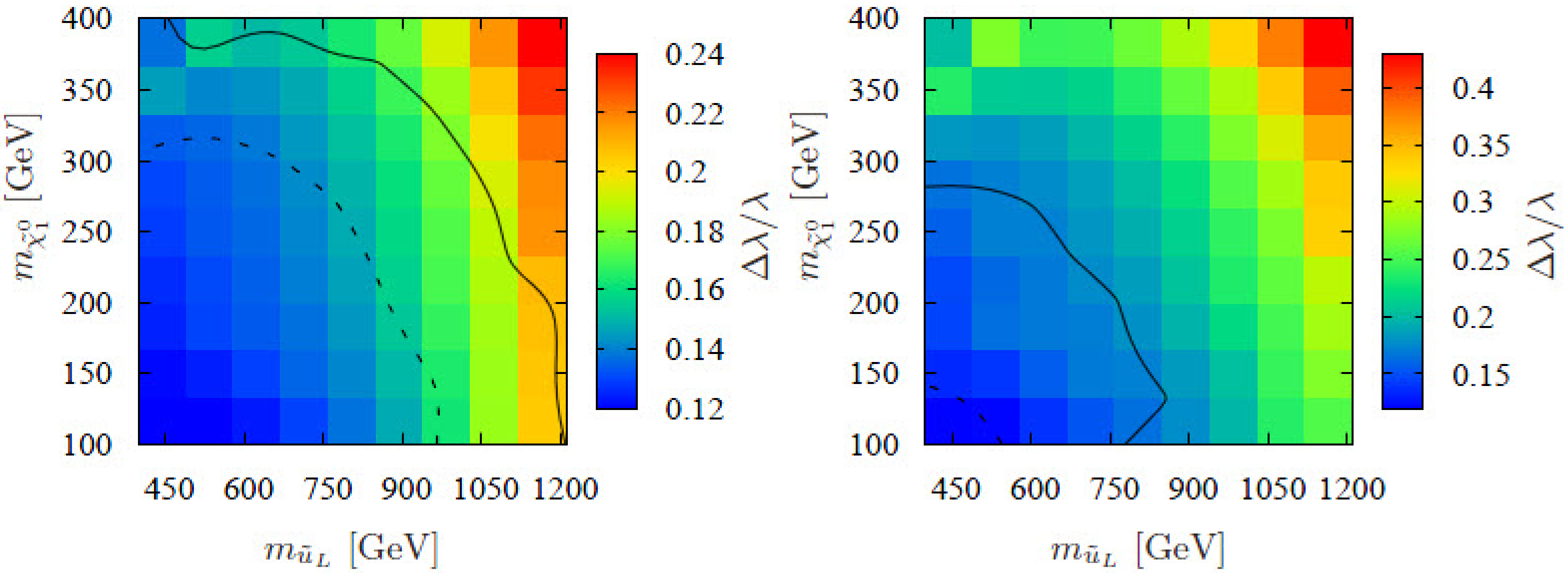


Figure 9: Fractional precision to which the $\tilde\chi_1^0\tilde q_L q$ coupling λ can be reconstructed as function of the squark and $\tilde\chi_1^0$ mass. The left (right) figure employs our optimistic (conservative) estimate for the SM background uncertainties. The solid and dashed black lines correspond to $S/\sqrt{B}$ ($S/\sqrt{7B}$) of 5σ and 10σ, respectively.

Taken from B.C. Allanach, S. Grab and H.E. Haber, JHEP 1101, 138 (2011)

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 UED (universal extra dimensions) theories

Eddie Santos: Renormalization group running in the general CP-violating two-Higgs doublet model; predictions for a lower limit on the energy scale at which new physics must enter

Implication of the Higgs data for the stability of the vacuum

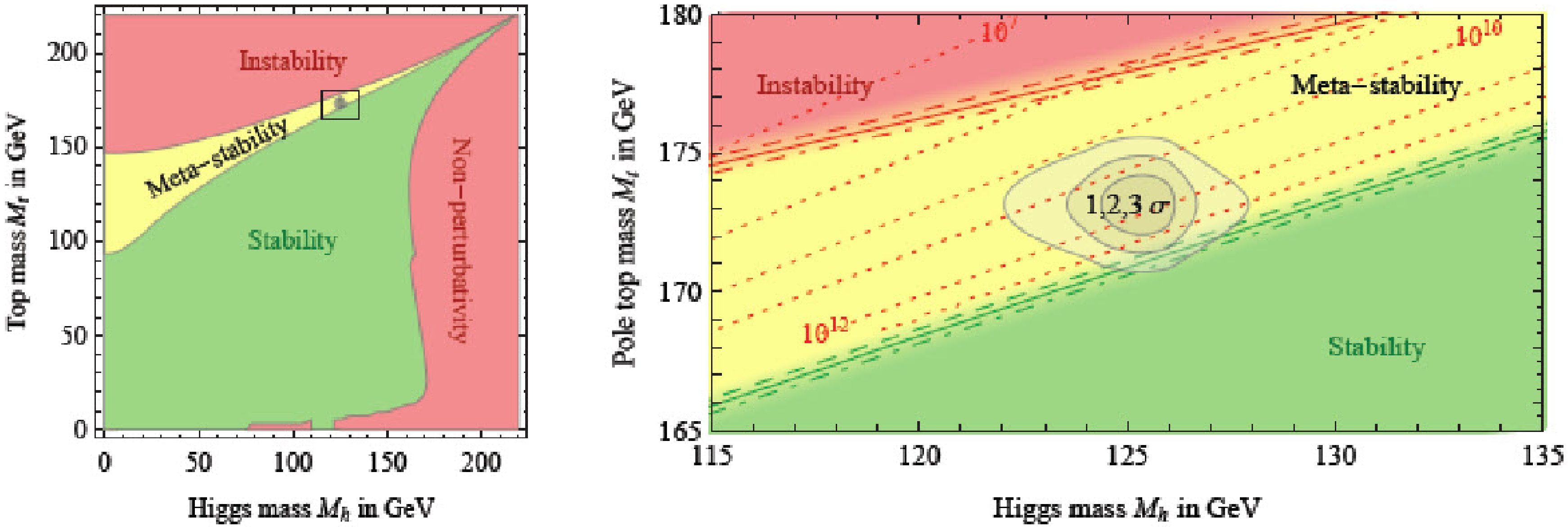
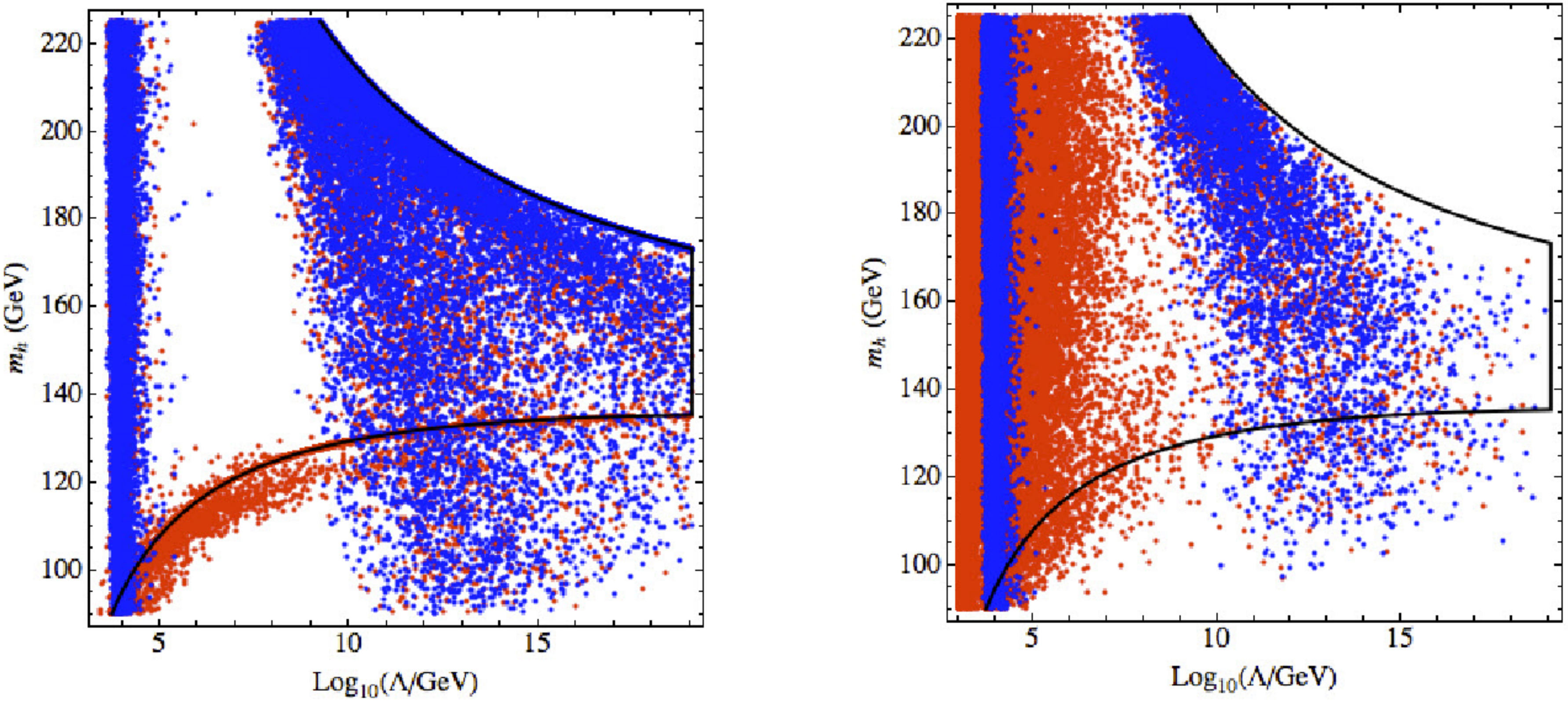


Figure 5: *Regions of absolute stability, meta-stability and instability of the SM vacuum in the* M_t–M_h *plane.* **Right**: *Zoom in the region of the preferred experimental range of* M_h *and* M_t *(the gray areas denote the allowed region at 1, 2, and 3σ). The three boundaries lines correspond to*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