# Research on the Theory of the Terascale

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SCIPP Theory
January 23, 2017

For further details, check out my webpage:
http://scipp.ucsc.edu/~haber/

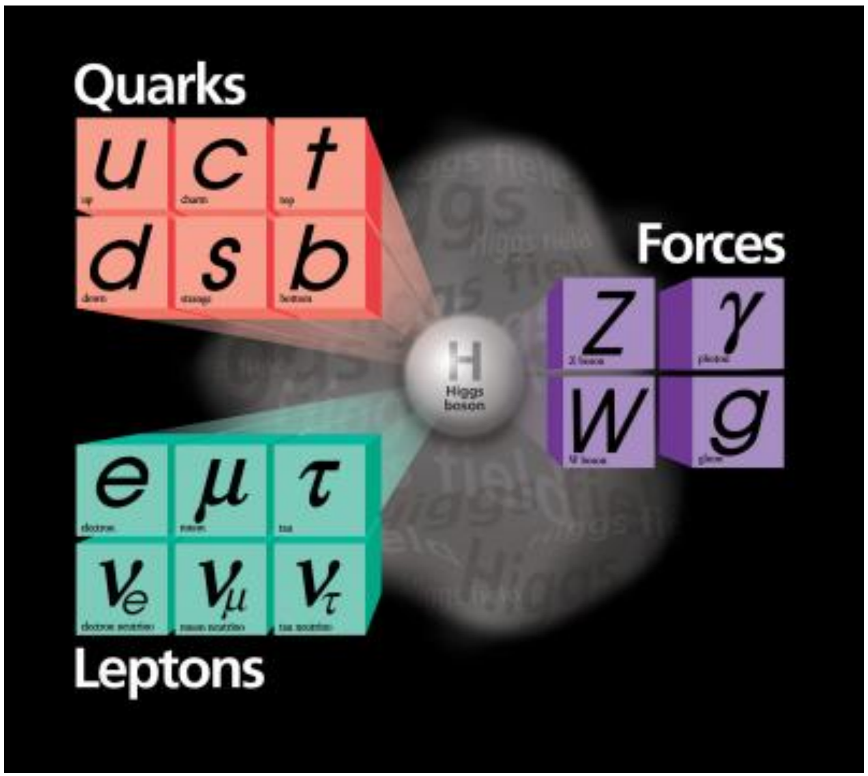
# SCIPP Particle Theory Group

- 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
- New faculty hire: The Physics Department is currently searching for a new faculty member, specializing in theoretical particle/particle-astro physics (perhaps starting in July 2017)

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, …

# Fundamental particles: the view before 2012

# 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 employs the Higgs mechanism for mass generation. The SU(2)xU(1) electroweak gauge invariance is spontaneously broken down to $U(1)_{EM}$, which yield the massive W and Z gauge bosons. 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

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

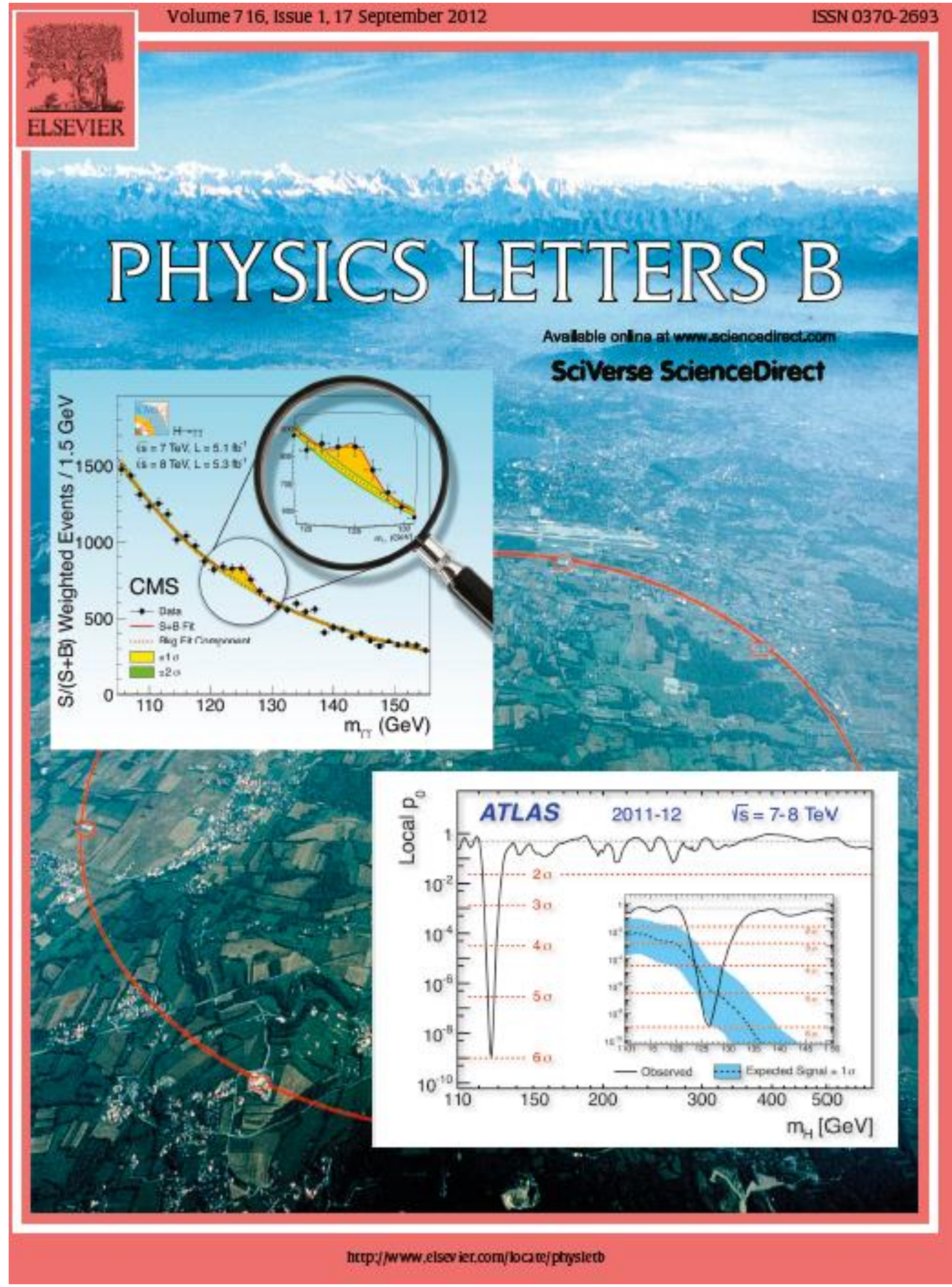
The discovery papers are published two months later In Physics Letters B.

<u>ATLAS Collaboration:</u>

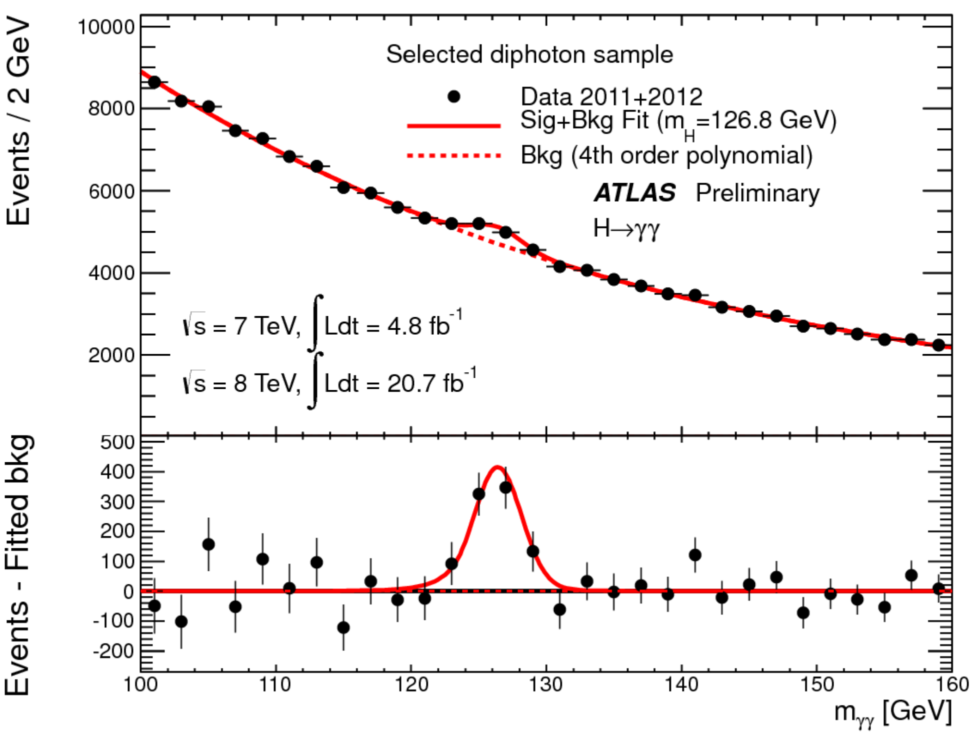
**Physics Letters B716 (2012) 1—29**

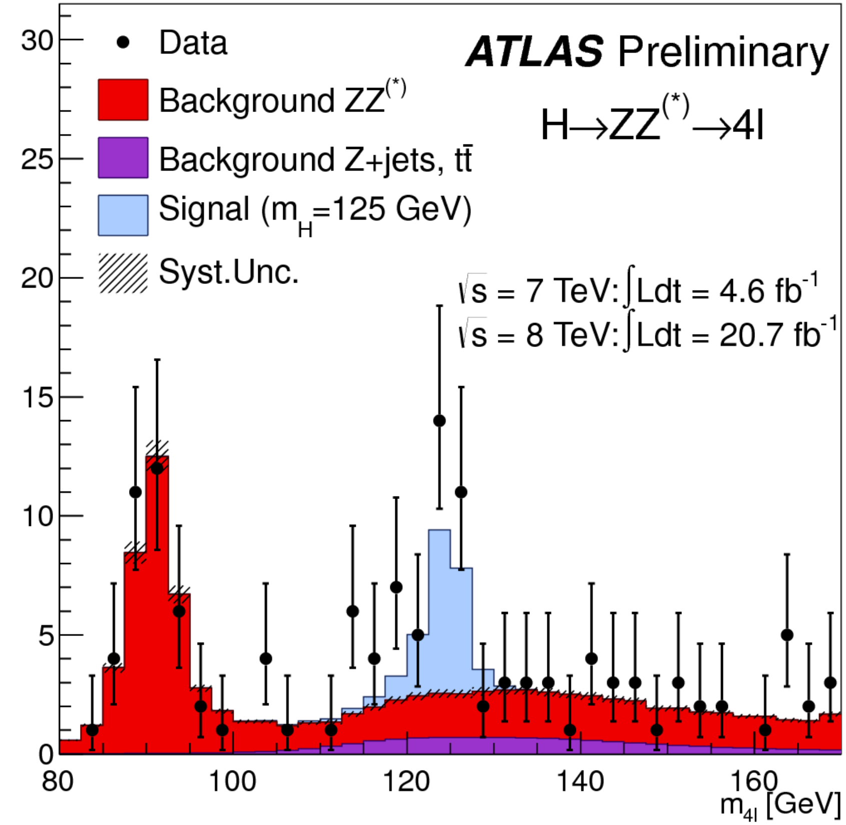
<u>CMS Collaboration:</u>

**Physics Letters B716 (2012) 30—61**



# A boson is discovered at the LHC by the ATLAS Collaboration

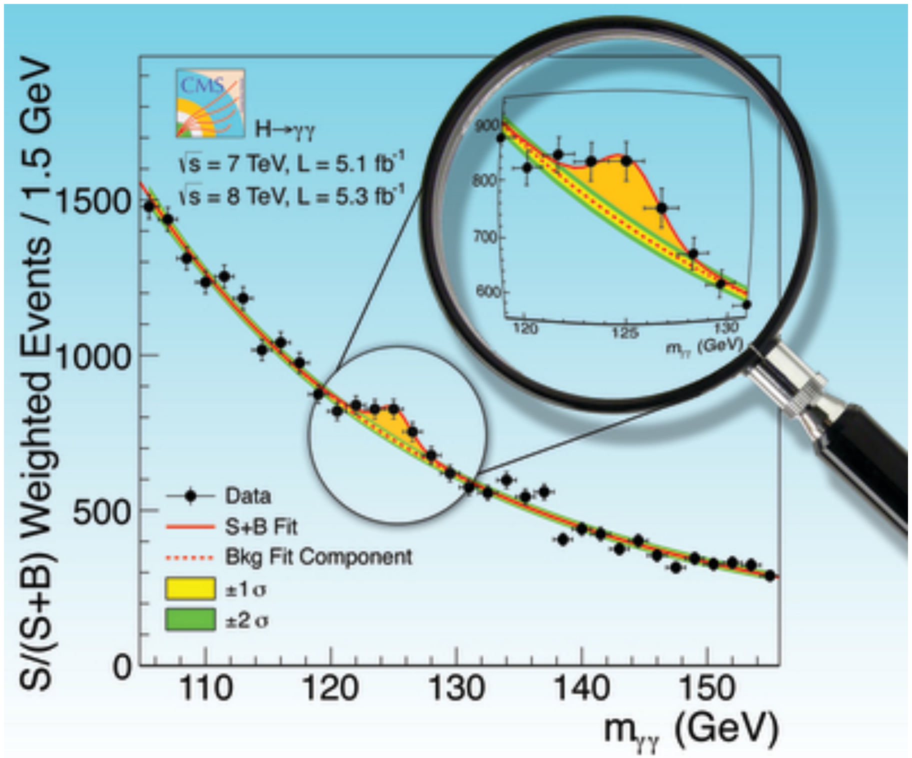


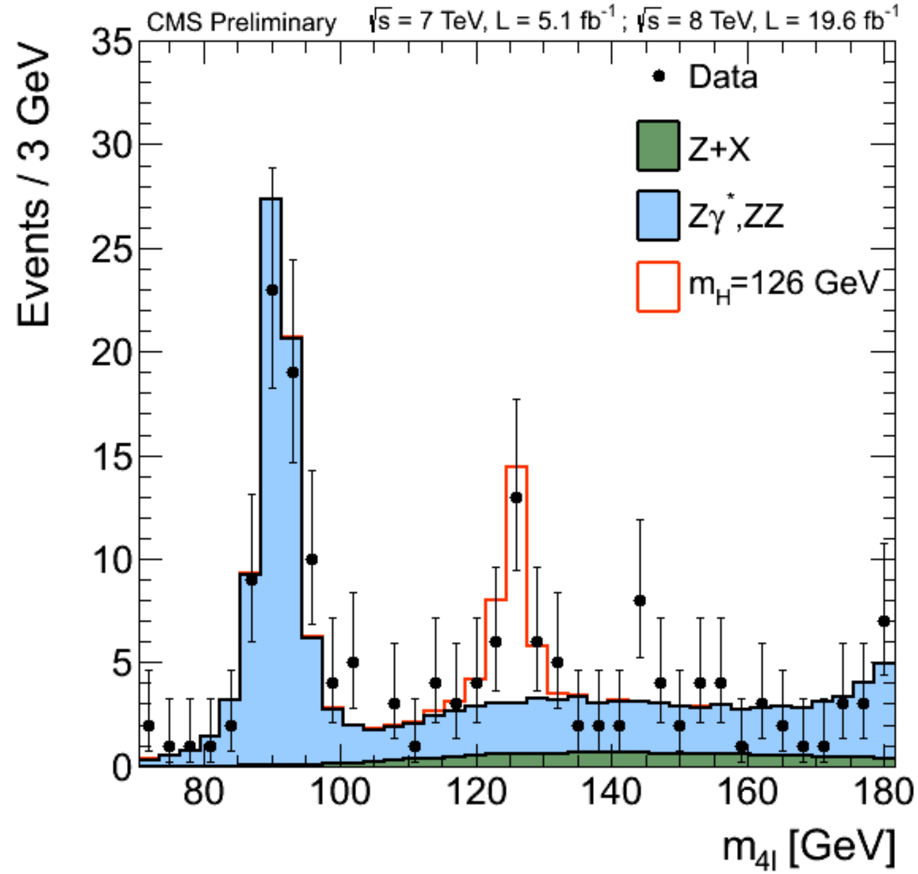

Invariant mass distribution of diphoton candidates for the combined 7 TeV and 8 TeV data samples. The result of a fit to the data of the sum of a signal component fixed to $m_H$ = 126.8 GeV and a background component described by a fourth-order Bernstein polynomial is superimposed. The bottom inset displays 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

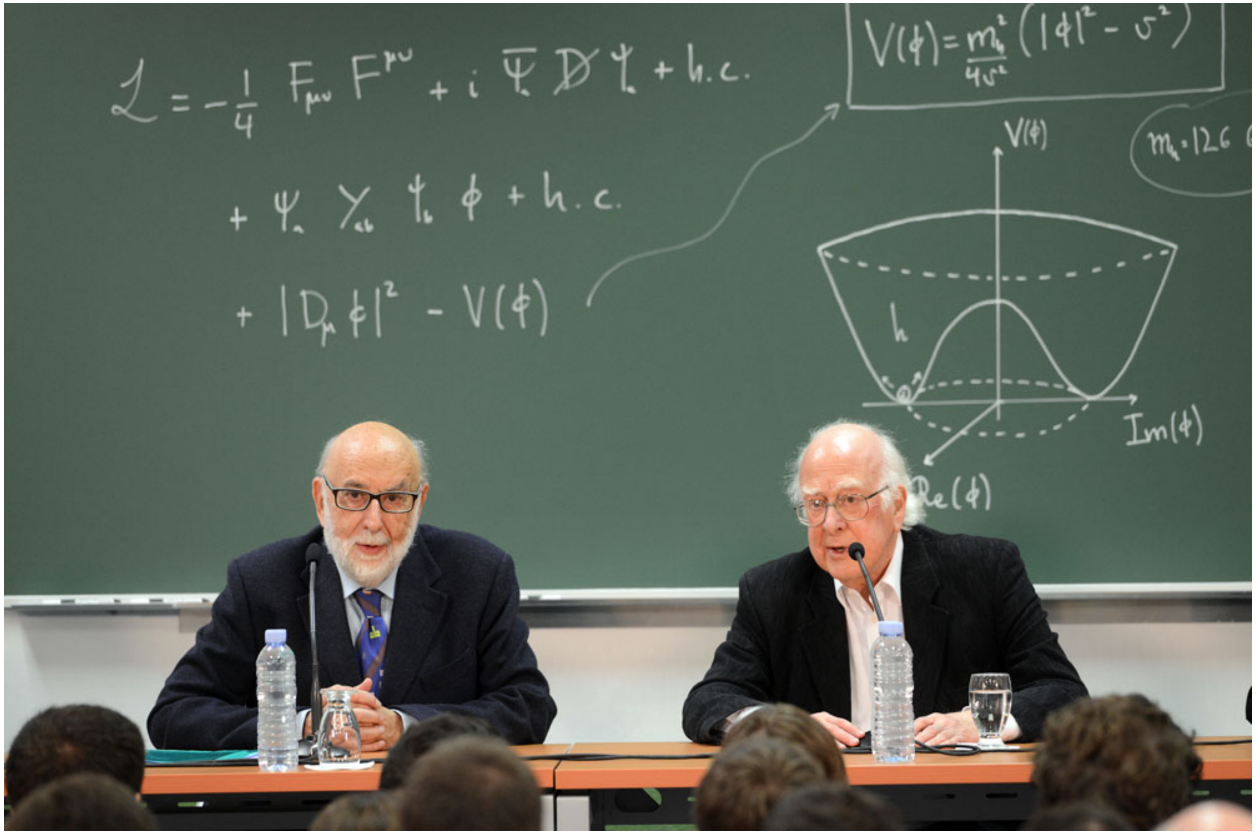



The diphoton invariant mass distribution with each event weighted by the S/(S+B) value of its category. The lines represent the fitted background and signal, and the colored bands represent the ±1 and ±2 standard deviation uncertainties in the background estimate. The inset shows the central part of 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).

# Winners of the 2013 Nobel Prize in Physics

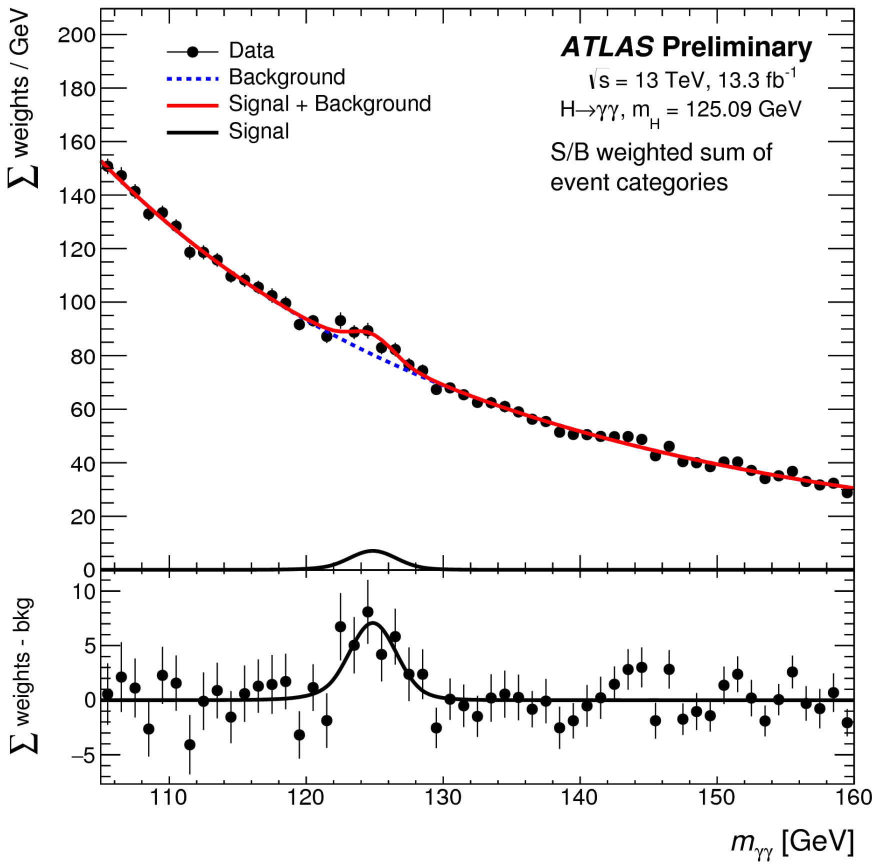


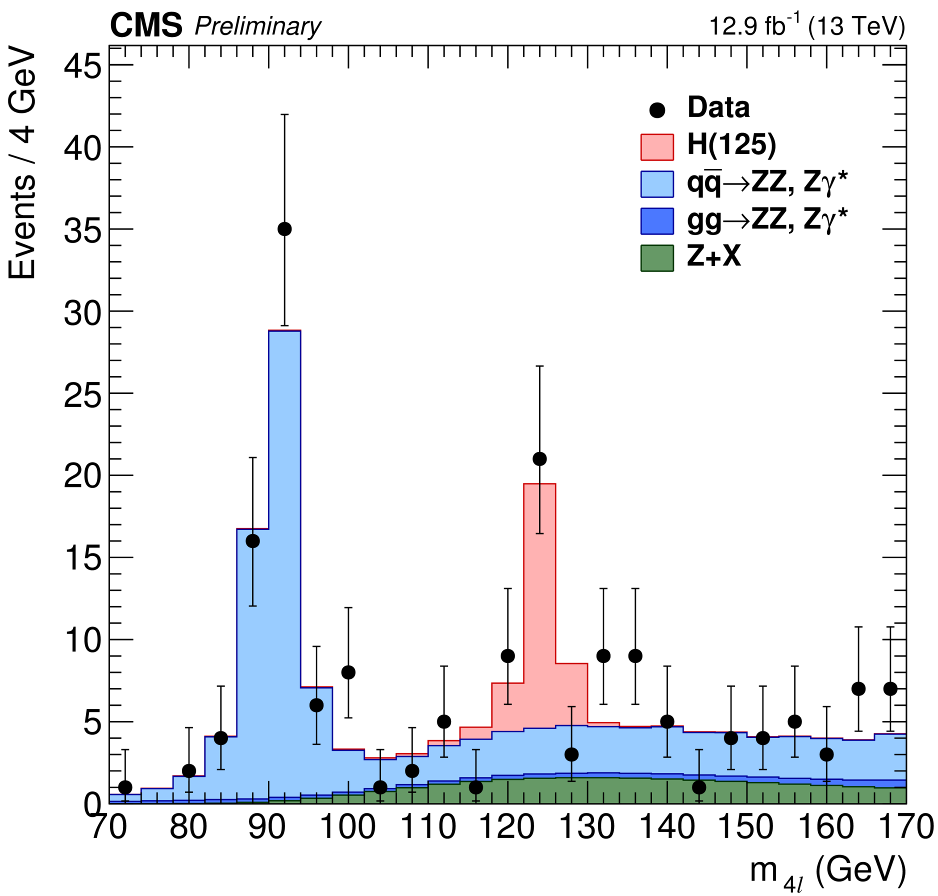

**François Englert**

**and**

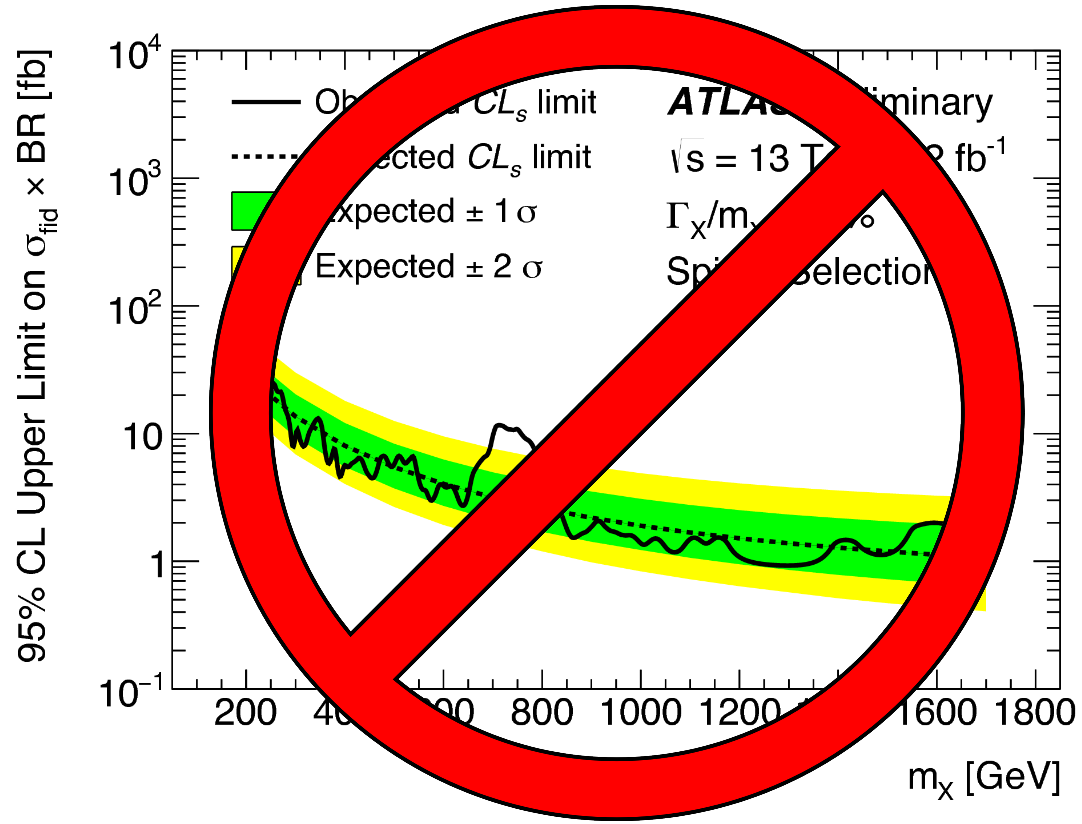
**Peter Higgs**

# In 2016, the Higgs boson was re-discovered…



and a second spin-0 state, was almost discovered…




…but with more data, it seems to have been a statistical fluke.

# Higgs production at hadron colliders

At hadron colliders, the relevant processes are

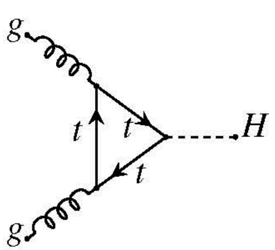
$$gg \to h^0 , \quad h^0 \to \gamma\gamma \, , VV^{(*)} \, ,$$

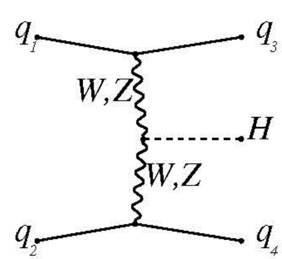
$$qq \to qqV^{(*)}V^{(*)} \to qqh^0, \quad h^0 \to \gamma\gamma, \, \tau^+\tau^-, \, VV^{(*)} \, ,$$

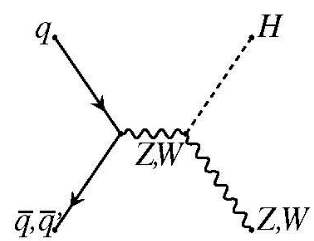
$$q\bar{q}^{(\prime)} \to V^{(*)} \to Vh^0 \, , \quad h^0 \to b\bar{b} \, , WW^{(*)} \, ,$$

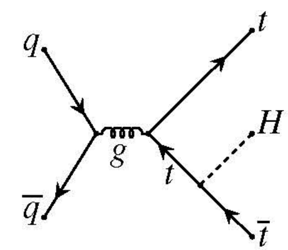
$$gg, q\bar{q} \to t\bar{t}h^0, \quad h^0 \to b\bar{b}, \, \gamma\gamma, \, WW^{(*)} \, .$$

where $V = W$ or $Z$.

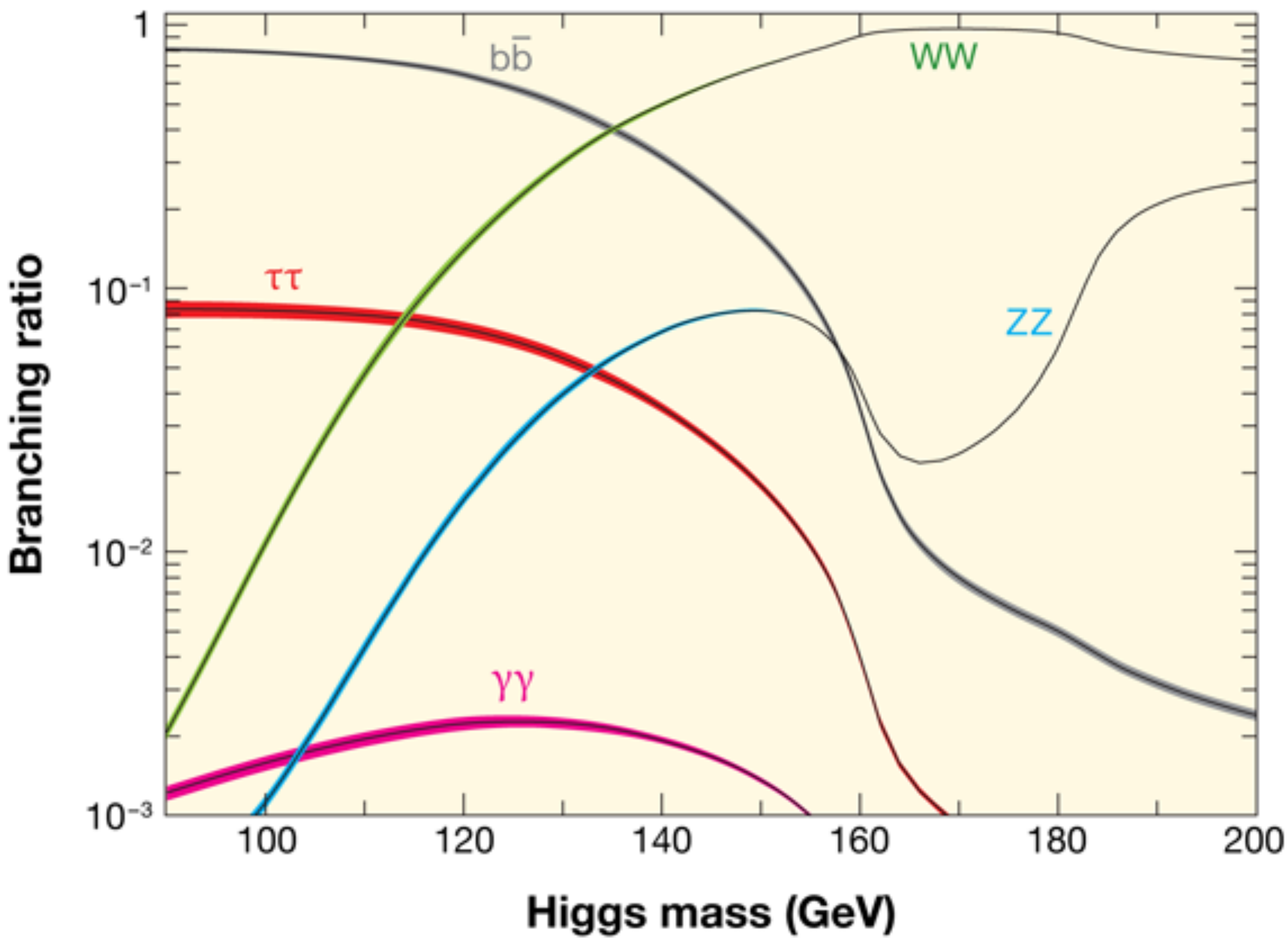


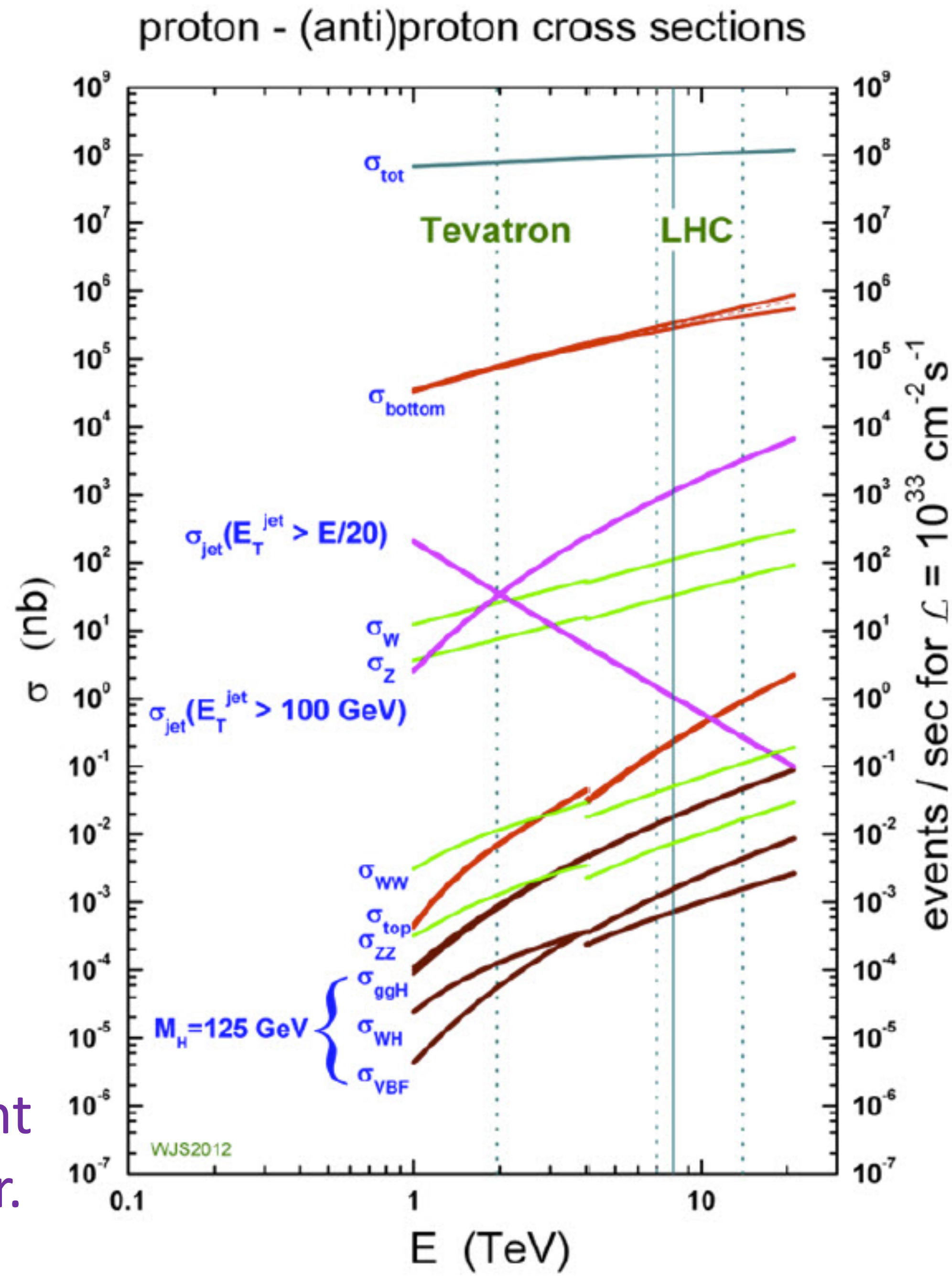
# Probability of Higgs boson decay channels



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

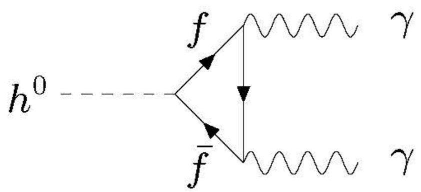
Answer: The Standard Model background is overwhelming. There are more than $10^7$ times as many b-quark pairs produced in proton-proton collisions as compared to b-quark pairs that arise from a decaying Higgs boson.

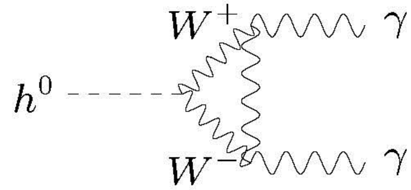
Roughly 250,000 Higgs bosons per experiment were produced at Run 1 of the LHC. The current Run 2 data set is ~4 times larger.

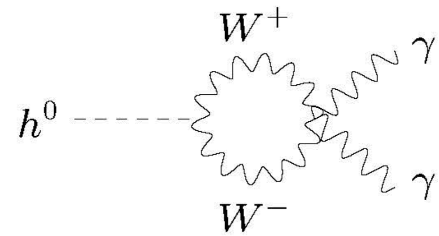


# SM Higgs decays at the LHC for $m_h \sim 125$ GeV

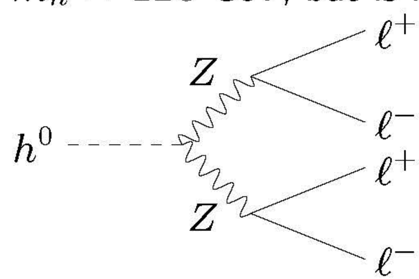
1. The rare decay $h^0 \to \gamma\gamma$ is the most promising signal.



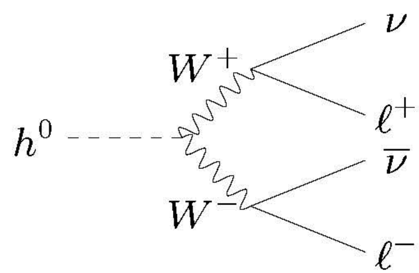




2. The so-called golden channel, $h^0 \to ZZ \to \ell^+\ell^-\ell^+\ell^-$ (where one or both $Z$ bosons are off-shell) is a rare decay for $m_h \sim 125$ GeV, but is nevertheless visible.




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.



# Is the observed scalar at 125 GeV the SM Higgs boson?

At the SUSY-16 conference last July, Eliot Lipeles summarized the results of the LHC Higgs experiments as follows:

## Summary

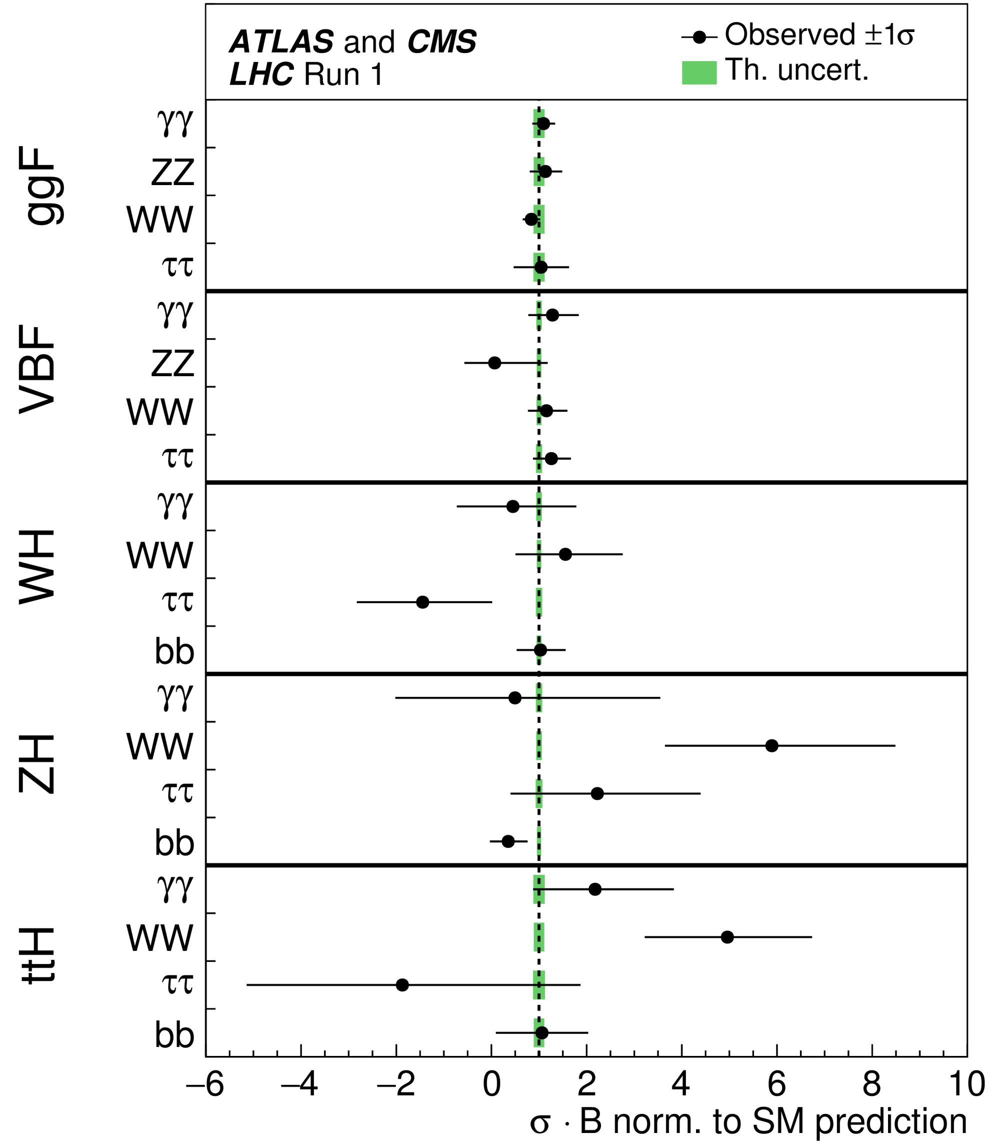
Penn
UNIVERSITY of PENNSYLVANIA

Four years ago today, a particle discovery was announced by ATLAS and CMS

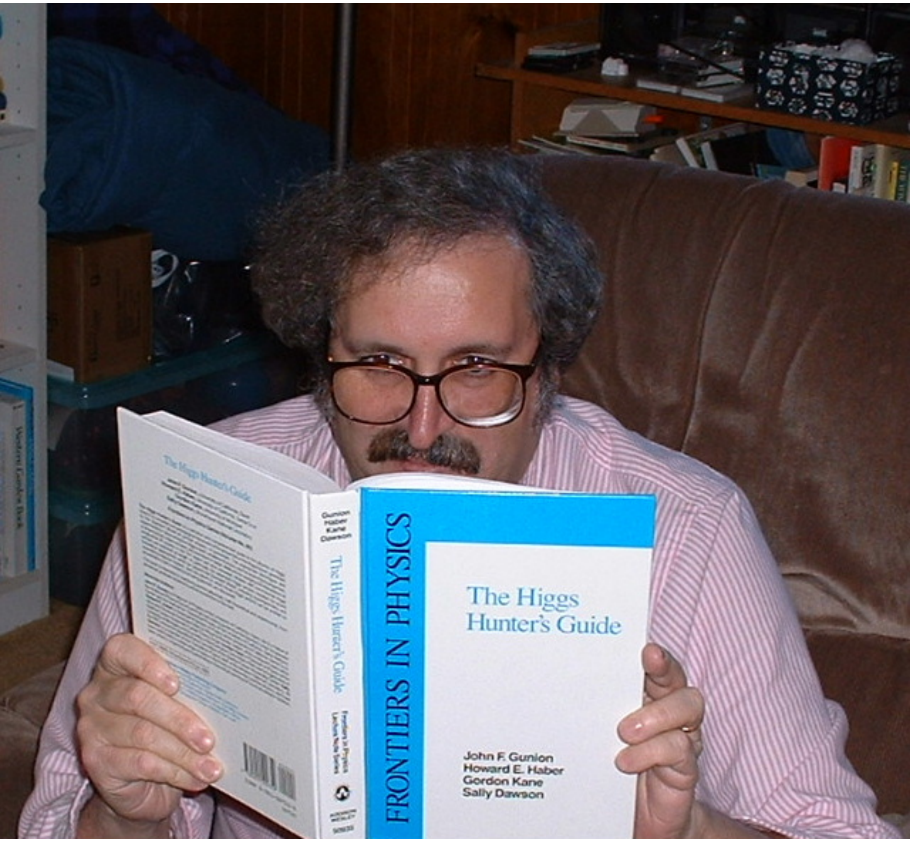
We now know this particle strongly resembles the SM Higgs boson

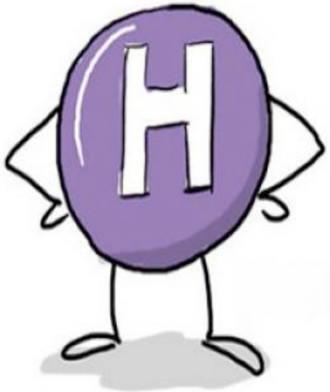
After Run 1 of the LHC, combined ATLAS/CMS Higgs data were strongly suggestive that the properties of Higgs boson were consistent with the predictions of the Standard Model (SM) of particle physics.

The Higgs boson of the SM is a loner; it is the only elementary spin 0 particle of the SM spectrum.

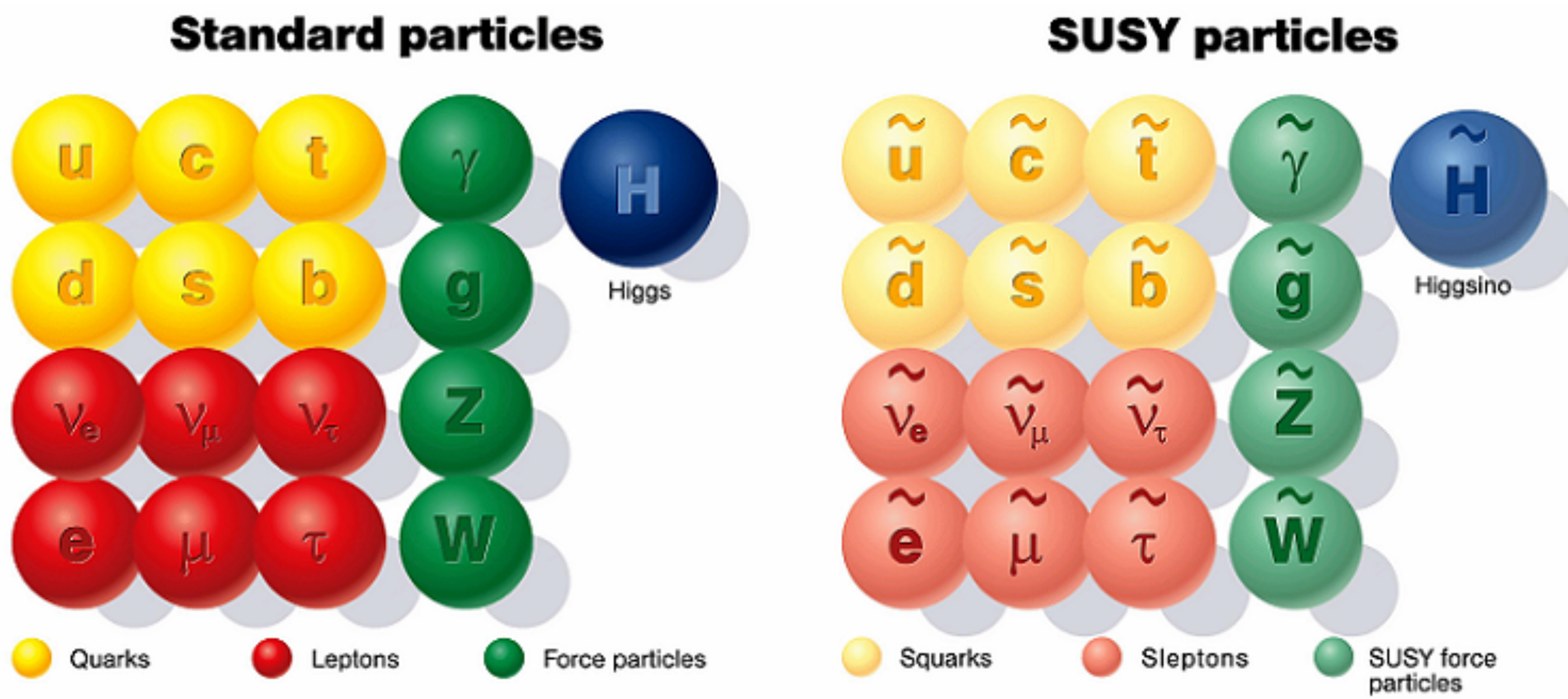


# Research program 1: theory and phenomenology of Higgs bosons



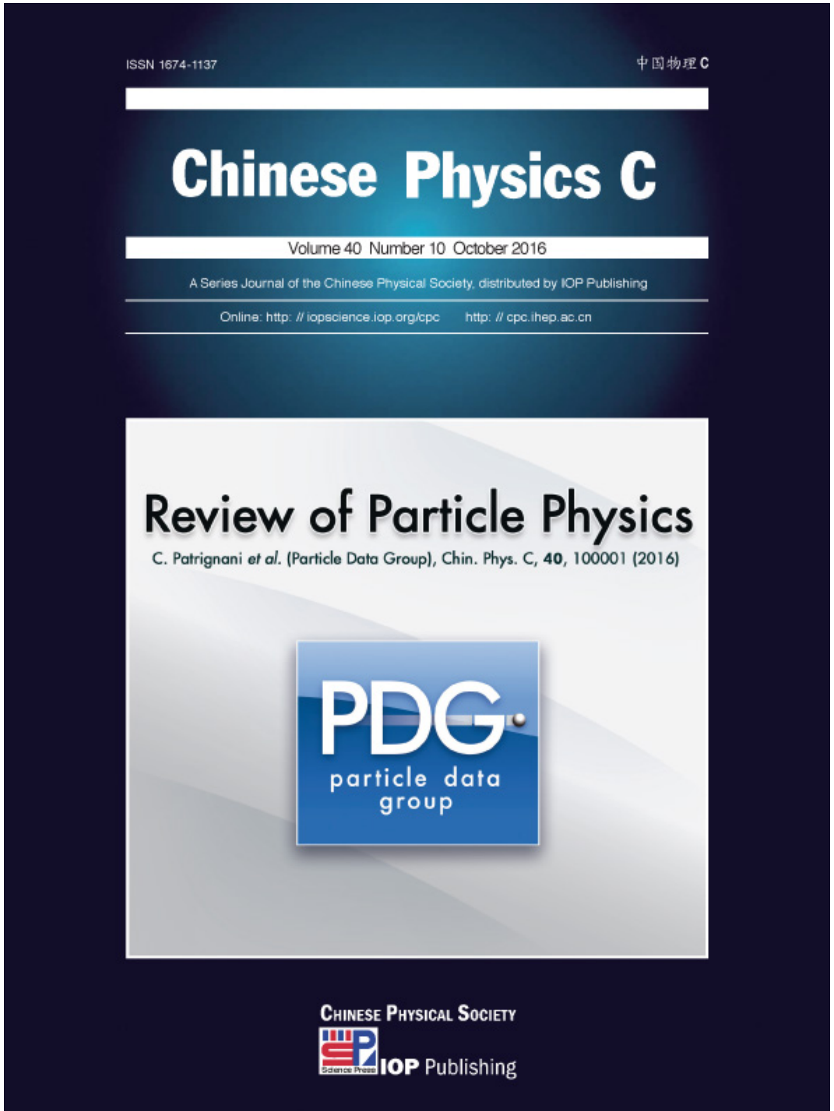




# Research program 2: theory and phenomenology of TeV-scale supersymmetry (SUSY)




For a review, see H.E. Haber, *Supersymmetry Theory*, in C. Patrignani et al. [Particle Data Group Collaboration], *Review of Particle Physics*, Chin. Phys. C **40**, 100001 (2016).

# As a member of the Particle Data Group, I am the author of the biennial Supersymmetry Theory review





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| | | Translated from ZETF 61 1721. | | |
| Also | | PL 31B 394 | I.I. Gurevich *et al.* | (KIAE, NOVO, SERP) |
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## Supersymmetric Particle Searches

### SUPERSYMMETRY, PART I (THEORY)

Revised September 2015 by Howard E. Haber (UC Santa Cruz).


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I.9. Extensions beyond the MSSM


***I.1. Introduction:*** Supersymmetry (SUSY) is a generalization of the space-time symmetries of quantum field theory which transforms fermions into bosons and vice versa [1]. The existence of such a non-trivial extension of the Poincaré symmetry of ordinary quantum field theory was initially surprising, and its form is highly constrained by theoretical principles [2]. Supersymmetry also provides a framework for the unification of particle physics and gravity [3–6] at the Planck energy scale, $M_P \approx 10^{19}$ GeV, where the gravitational interactions become comparable in magnitude to the gauge interactions. Moreover, supersymmetry can provide an explanation of the large hierarchy between the energy scale that characterizes electroweak symmetry breaking (of order 100 GeV) and the Planck scale [7–10]. The stability of this large *gauge hierarchy* with respect to radiative quantum corrections is not possible to maintain in the Standard Model without an *unnatural* fine-tuning of the parameters of the fundamental theory at the Planck scale. In contrast, in a supersymmetric extension of the Standard Model, it is possible to maintain the gauge hierarchy while providing a natural framework for elementary scalar fields.

If supersymmetry were an exact symmetry of nature, then particles and their *superpartners*, which differ in spin by half a unit, would be degenerate in mass. Since superpartners have not (yet) been observed, supersymmetry must be a broken symmetry. Nevertheless, the stability of the gauge hierarchy can still be maintained if the supersymmetry breaking is *soft* [11,12], and the corresponding supersymmetry-breaking mass parameters are no larger than a few TeV. Whether this is still plausible in light of recent supersymmetry searches at the LHC [13] will be discussed in Section I.7.

In particular, soft-supersymmetry-breaking terms of the Lagrangian involve combinations of fields with total mass dimension of three or less, with some restrictions on the dimension-three terms as elucidated in Ref. 11. The impact of the soft terms becomes negligible at energy scales much larger than the

# 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)

# 2016--2017 Publications

**Future Higgs Studies: A Theorist's Outlook**
H.E. Haber, arXiv:1701.01922 [hep-ph], to appear in the Proceedings of the Sixth International Workshop on the Prospects for Charged Higgs Discovery at Colliders (CHARGED 2016).

**The Light and Heavy Higgs Interpretation of the MSSM**
P. Bechtle, H.E. Haber, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein and L. Zeune, arXiv:1608.00638 [hep-ph], Eur. Phys. J. C. **77** (2017) in press.

**Theory in Supersymmetric QED: Infrared Divergences and Gauge Invariance**
M. Dine, P. Draper, H.E. Haber and L. Stephenson Haskins, Phys. Rev. D **94**, 095003 (2016) .

**Partially Natural Two Higgs Doublet Models**
J. Bernon, J.F. Gunion, H.E. Haber, Y. Jiang and S. Kraml, JHEP **06**, 124 (2016) .

**Scrutinizing the Alignment Limit in Two-Higgs-Doublet Models. Part 2: $m_H$=125 GeV**
J. Bernon, J.F. Gunion, H.E. Haber, Y. Jiang and S. Kraml, Phys. Rev. D **93**, 035027 (2016) .

**On the Alignment Limit of the NMSSM Higgs Sector**
M. Carena, H. E. Haber, I. Low, N.R. Shah and C.E.M. Wagner, Phys. Rev. D **93**, 035013 (2016) .

# Should we expect an extended Higgs sector beyond the SM?

- The fermion and gauge boson sectors of the SM are not of minimal form ("who ordered that?"). So, why should the spin-0 (scalar) sector be minimal?

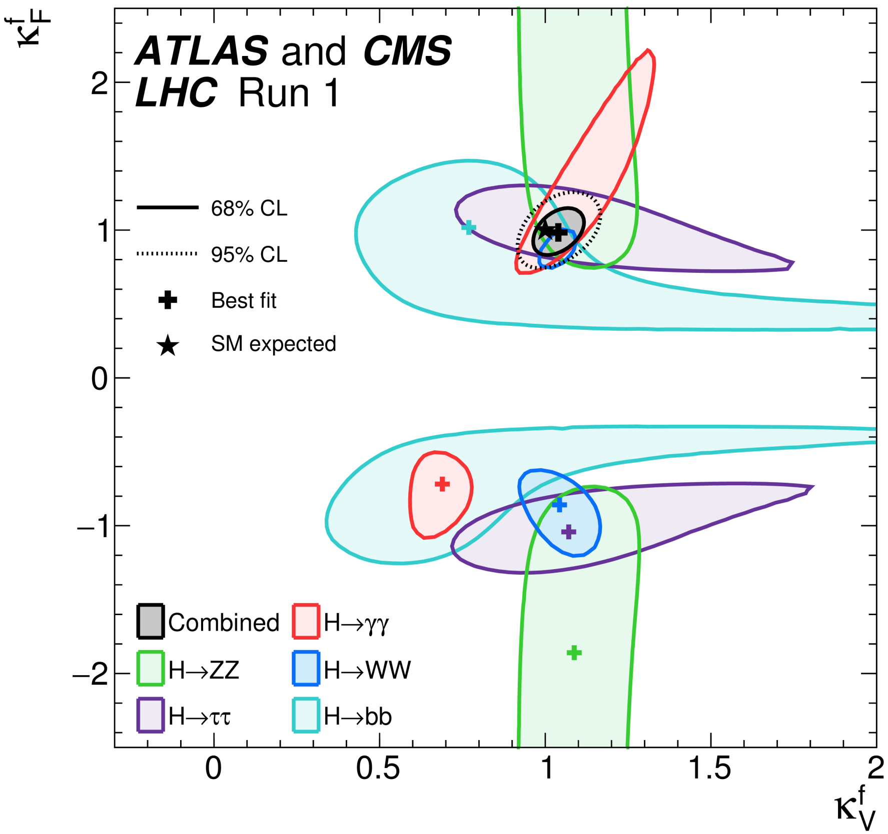
- Adding new scalar states can alleviate the metastability of the vacuum, allowing the Higgs-sector-extended SM to be valid all the way up to the Planck scale.

- Extended Higgs sectors can provide a dark matter candidate.

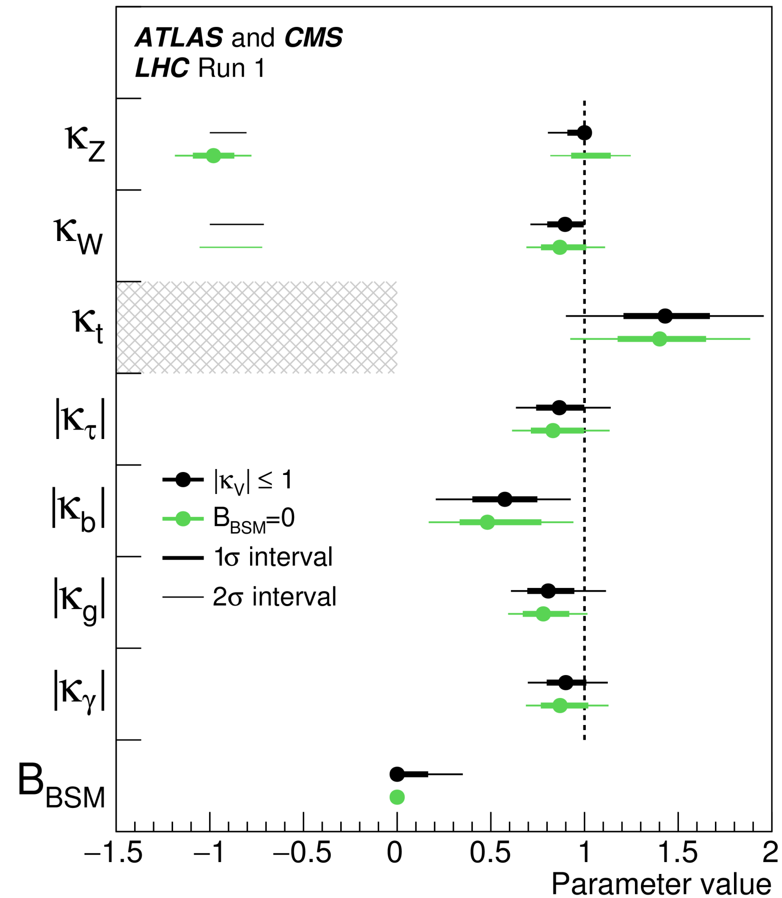
- Extended Higgs sectors can provide new sources of CP violation (which may be useful in baryogenesis).

- Models of physics beyond the SM often require additional scalar Higgs states. E.g., two Higgs doublets are required in the minimal supersymmetric extension of the SM (MSSM).

# Search for deviations from SM-Higgs couplings




Negative log-likelihood contours at 68% and 95% CL in the ($\kappa_F^f$ ,$\kappa_V^f$) plane for the combination of ATLAS and CMS and for the individual decay channels, as well as for their global combination ($\kappa_F$ versus $\kappa_V$ shown in black), without any assumptions on the sign of the coupling modifiers.




Fit results for the two parameterizations allowing BSM loop couplings; the first assumes that $B_{BSM} \geq 0$ with $|\kappa_V| \leq 1$ (V=W,Z), and the second one assumes that there are no additional BSM contributions to the Higgs boson width, i.e. $BR_{BSM}$=0. The measured results for the combination of ATLAS and CMS are reported together with their uncertainties. The error bars indicate the 1σ (thick lines) and 2σ (thin lines) intervals.

Taken from G. Aad et al. [ATLAS and CMS Collaborations], JHEP **08**, 045 (2016).

# Implications of a SM-like Higgs boson

Typically, none of the scalar states of an extended Higgs sector will resemble a SM-Higgs boson. However, a SM-like Higgs boson ($h_{\rm SM}$) can arise in two different ways:

- **The decoupling limit** (Haber and Nir 1990, Gunion and Haber 2003)

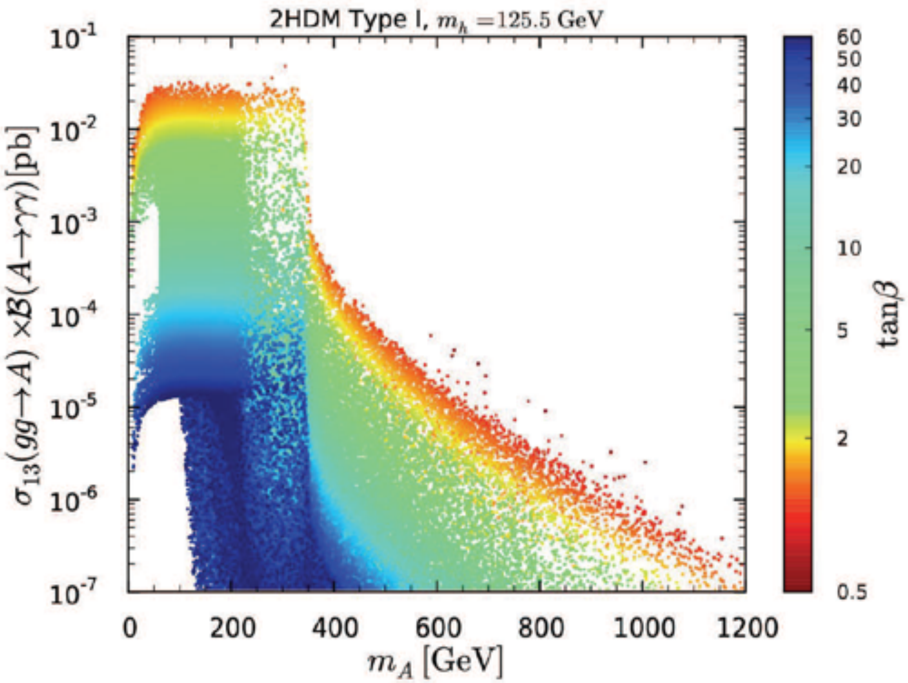
All but one of the scalar states ($h$) are very heavy (with masses of order $M \gg m_h$). Integrating out the heavy states below the mass scale $M$ yields an effective one-Higgs-doublet theory—i.e. the Standard Model, and $h \simeq h_{\rm SM}$.

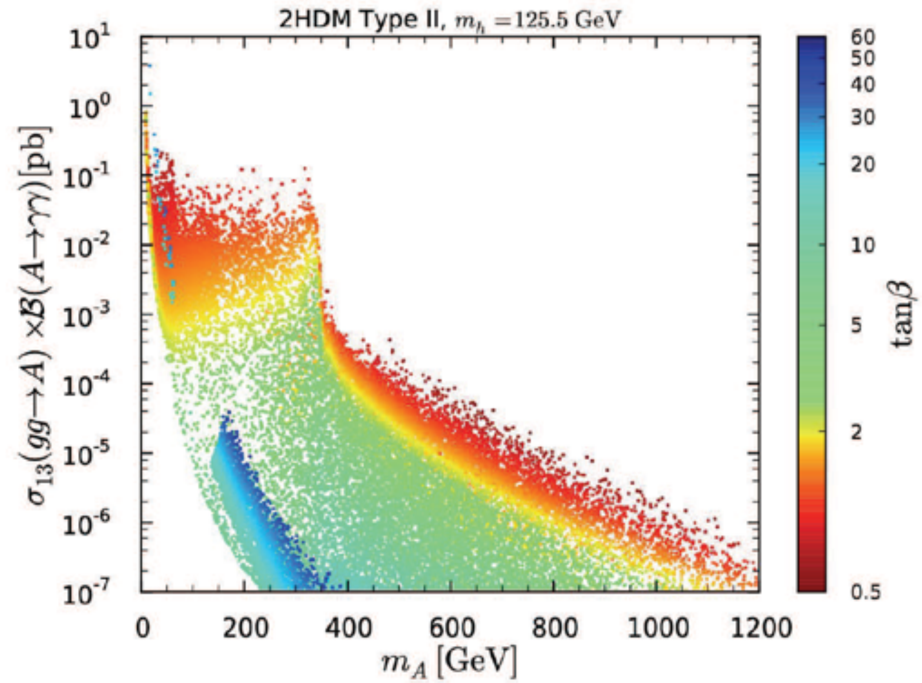
- **The alignment limit without decoupling** (Craig, Galloway, Thomas 2013, Haber 2013)

Electroweak symmetry breaking occurs when the vacuum value of a scalar field with electroweak quantum numbers is nonzero. In theories with multiple scalars, the scalar field vacuum expectation value points in some direction in the field space. If this direction is exactly aligned with one of the scalar mass-eigenstates $h$, then this scalar field will correspond to a state whose characteristics are precisely those of the SM Higgs boson. This alignment is automatically achieved in the decoupling limit. However, in special cases, the alignment limit can be attained even if all Higgs scalar masses are of the same order of magnitude.

# Projections for future LHC running

Taking the current Higgs data into account, we can project the possible values of new heavy Higgs boson cross sections. In these figures, we examined the possibility of discovering a new CP-odd scalar (in the 2HDM) that decayed into a pair of photons.

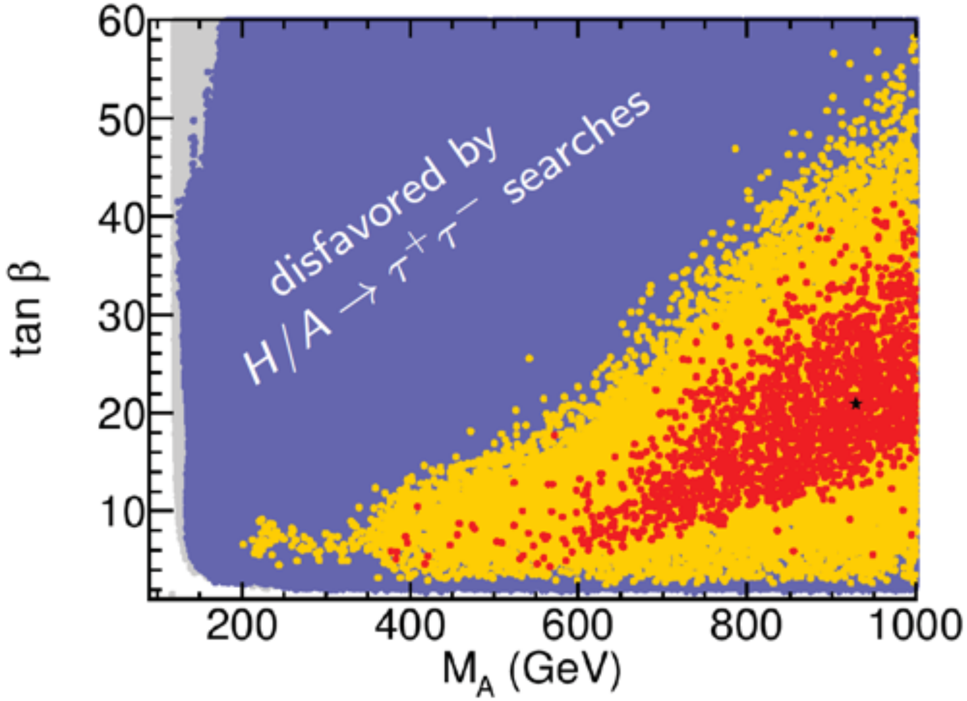


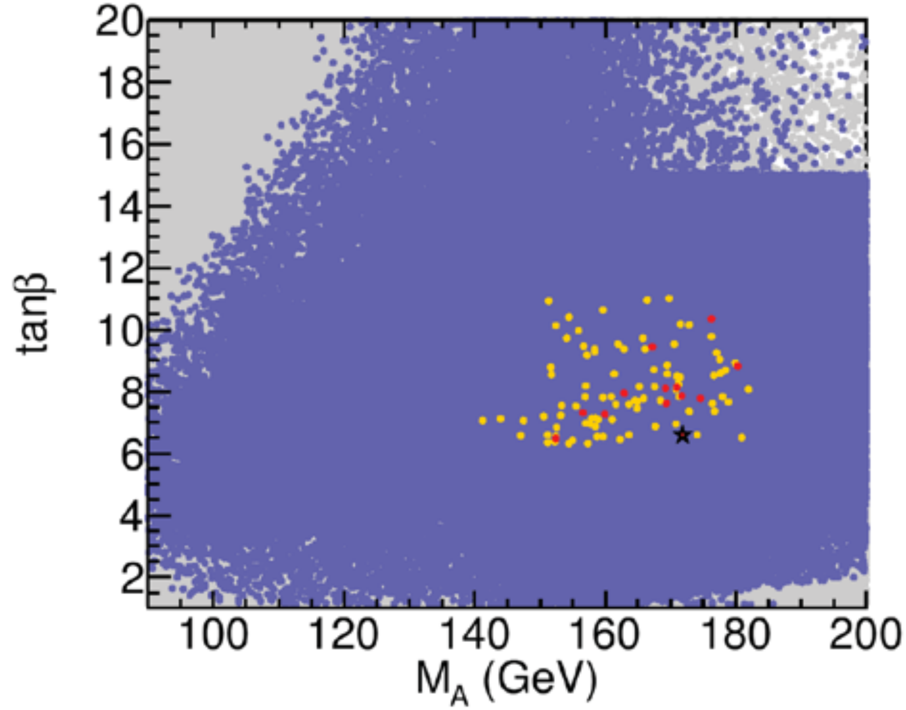

Taken from J. Bernon, J.F. Gunion, H.E. Haber, Y. Jiang and S. Kraml, Phys. Rev. D **92**, 075004 (2015) .

# Is alignment without decoupling possible in the MSSM Higgs sector?

If the Higgs boson is SM-like due to the fact that all Higgs bosons are very heavy, then it will be difficult to discover the heavy Higgs states in future LHC running.




If h is SM-like




If H is SM-like

A scan of the MSSM parameter space taken from P. Bechtle, H.E. Haber, S. Heinemeyer, O. Stål, T. Stefaniak, G.Weiglein and L. Zeune, arXiv:1608.00638

# Evidence for new physics beyond the SM (BSM) in B decays to muon pairs?

Recent results from LHCb and CMS at the LHC yield the following branching ratios (BR):

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{exp} = (2.8^{+0.7}_{-0.6}) \times 10^{-9},$$
$$\mathrm{BR}(B_d \to \mu^+\mu^-)_{exp} = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

which should be compared with the SM predictions,

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{SM} = (3.65 \pm 0.23) \times 10^{-9},$$
$$\mathrm{BR}(B_d \to \mu^+\mu^-)_{SM} = (1.06 \pm 0.09) \times 10^{-10},$$

In a paper soon to be posted on the arXiv by S. Gori, H.E. Haber and E. Santos, new contributions to these days are considered in the 2HDM where flavor alignment is imposed at very high energies. However, renormalization group running generates small flavor-changing neutral Higgs couplings that do not exist in the SM and can contribute to neutral B decays.

The present data already puts interesting constraints on the flavor alignment parameters $a^U$ and $a^D$ of our model.

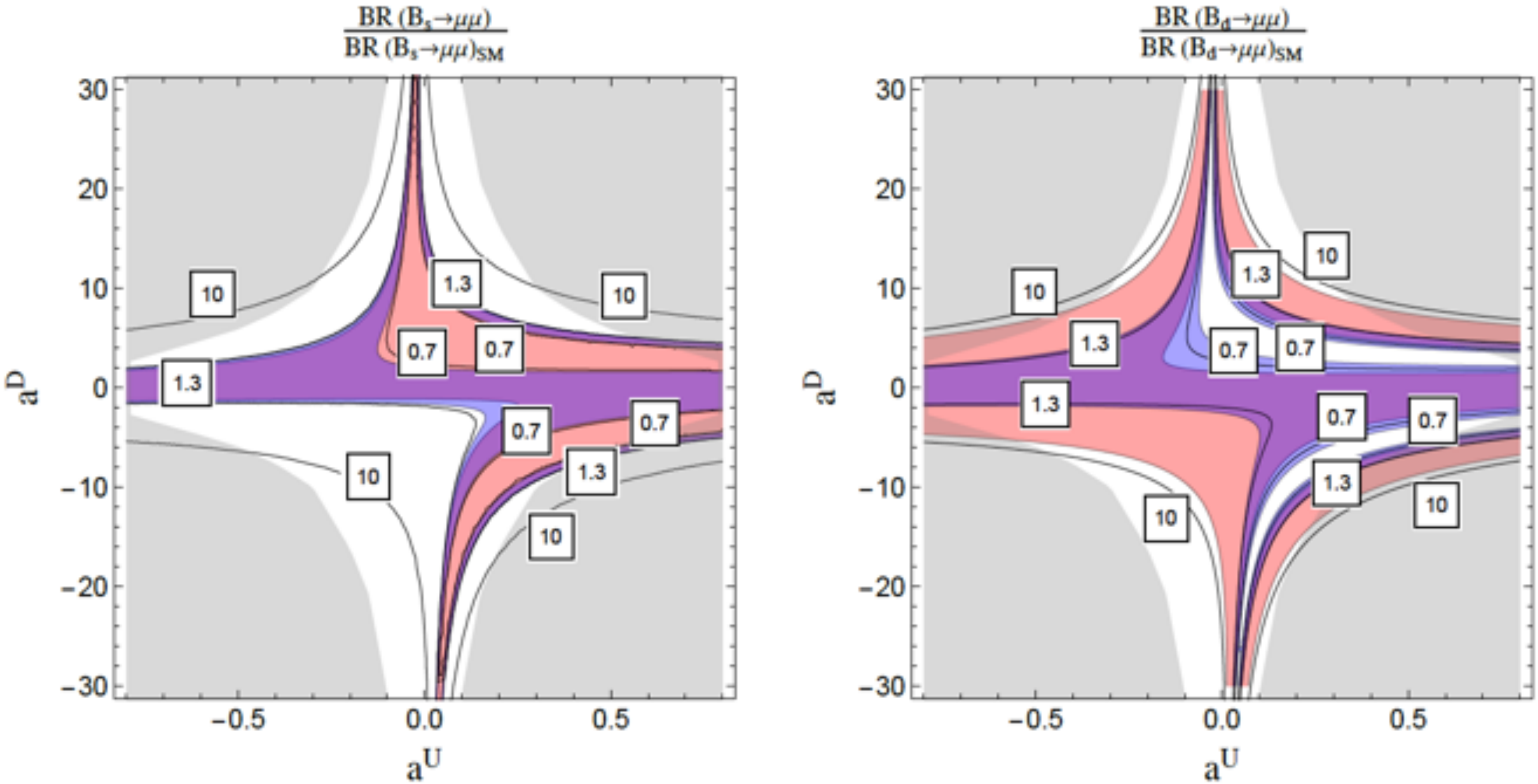



**Figure 8**. Leading log prediction for the branching ratios for $B_s \to \mu^+\mu^-$ (left panel) and $B_d \to \mu^+\mu^-$ (right panel) relative the the SM, as a function of $a^U$ and $a^D$. We fix $\tan\beta = 10$, $x = 0$, and $m_A = m_H = 400$ GeV. The red regions are the regions allowed at the $2\sigma$ level by the present measurements. The regions in blue denote the regions favored by the more precise HL-LHC measurements, assuming a measured central value equal to the SM prediction. The gray shaded regions produce Landau poles in the Yukawas below the high energy scale $\Lambda = M_{\rm P}$.

# My recent Ph.D. students and their thesis projects

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 (2HDM)

Laura Fava (2015): Precision Measurement of UED Coupling Constants Using Like-Sign Leptons at the LHC

Edward Santos (2015): Renormalization Group Constraints on the Two-Higgs Doublet Model

## Where are they now?

J. Mason – following a three-year post doctoral research associate in particle theory at Harvard University, John accepted a position as an associate professor of physics at Western State College of Colorado

D. O’Neil – associate professor of physics at Bridgewater College (in Virginia)

L. Fava and E. Santos – participated in the Insight Data Science Fellows Program; found employment in Silicon Valley.

# A collaboration with a current Ph.D. student

Laurel Stephenson Haskins:

I initially proposed to examine a puzzle in the relation between the quark anomalous dimension and the mass anomalous dimension in supersymmetric non-abelian gauge theory.

This project led to a more careful study of infrared divergences and gauge invariance in Supersymmetric QED (in collaboration with Michael Dine and Patrick Draper).

We demonstrated that the cancellation of infrared divergences in a physical quantity such as the electron mass takes place in a nontrivial way, amounting to a reorganization of the perturbative series from powers of $e^2$ to powers of e.

Laurel is graduating this year and will go on to post-doctoral research.

# Ongoing and Future Activities

- Natural alignment without decoupling (with P. Draper and F. D'ermo)
  - Achieving a SM-like Higgs boson without fine-tuning.
- Implications of 2HDM high energy flavor alignment (with S. Gori)
  - A closer look to neutral Higgs mediated flavor violation in the lepton sector.
- LHC Benchmarks for more general 2HDMs (with T. Stefaniak,…)
  - Examining CP violation and $\mathbf{Z_2}$ symmetry breaking effects in the 2HDM and its phenomenological consequences.
- Theoretical aspects of CP-violation in multi-Higgs models (with V. Keus, T. Stefaniak and S. Thomas)
  - CP properties of purely bosonic systems have some unexpected behaviors.

Other potential projects are waiting for the right Ph.D. student…