Research on the Theory of the Terascale

Howard Haber
SCIPP Theory

January 23, 2018

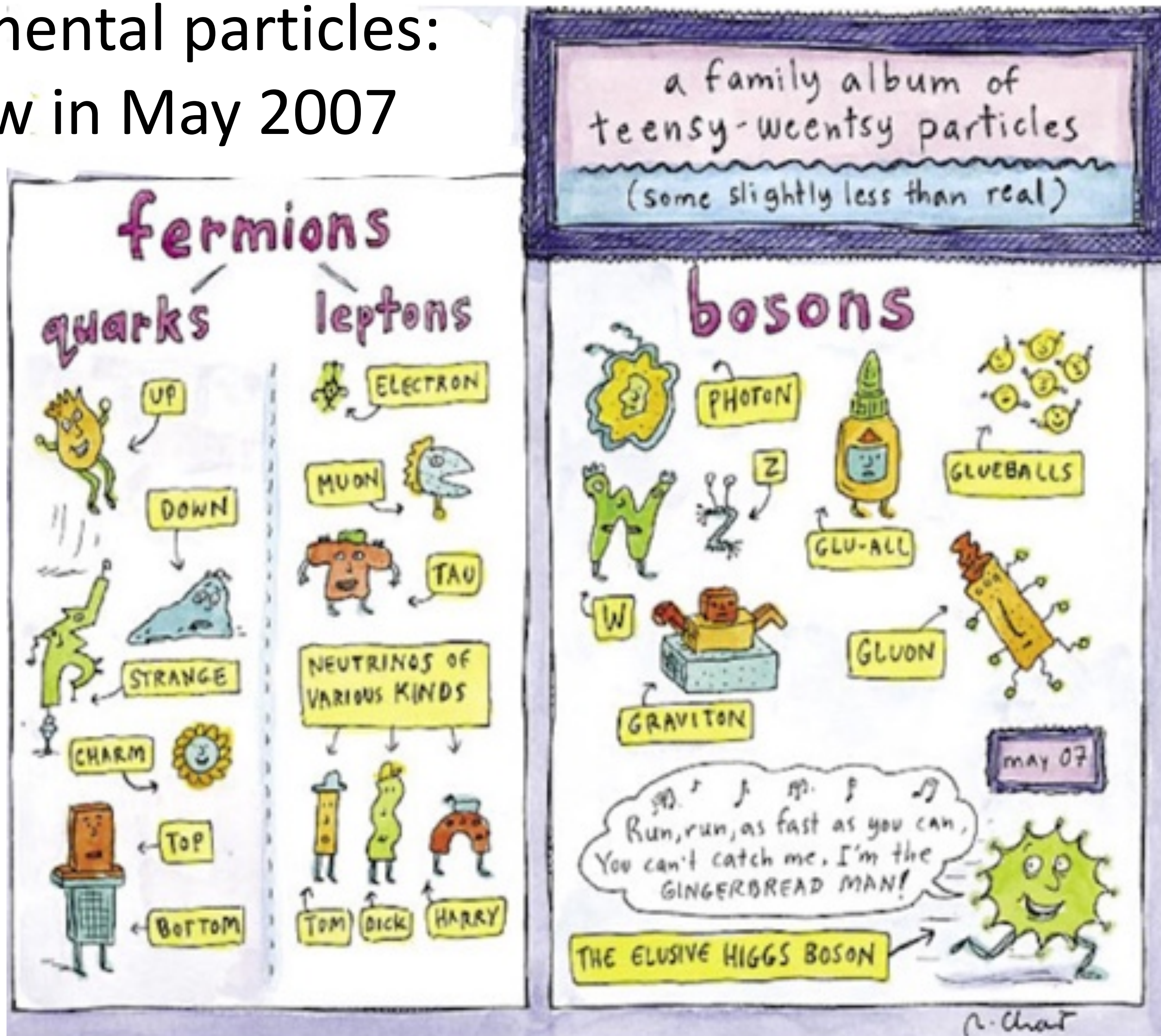
For further details, check out my webpage:
http://scipp.ucsc.edu/~haber/

SCIPP Particle Theory Group

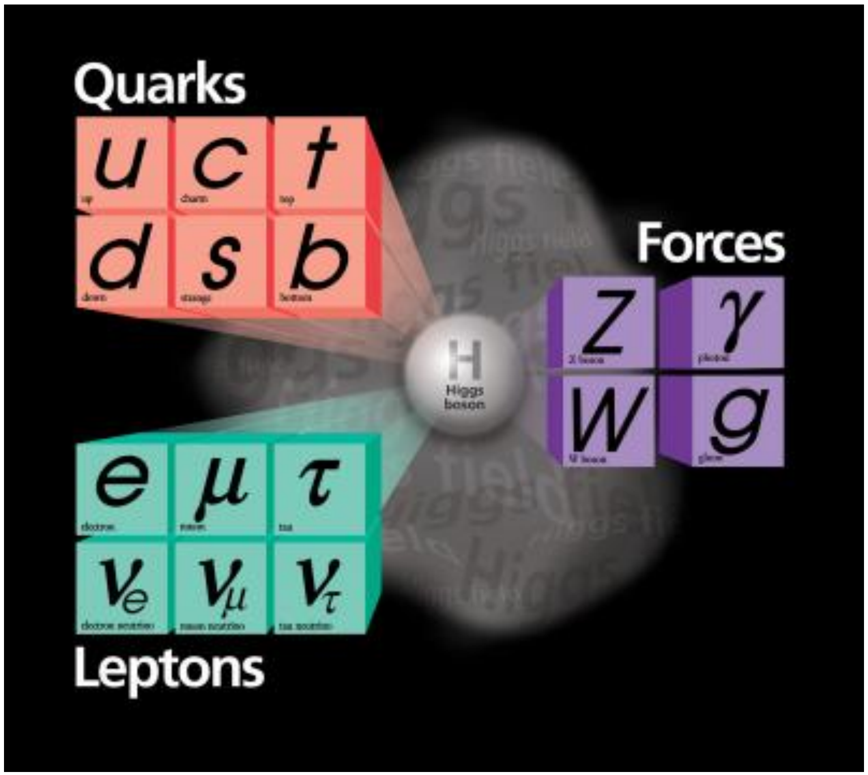
- Michael Dine: supersymmetry, string theory, and the early universe
- Howard Haber: Higgs bosons, collider physics, new physics beyond the Standard Model at the terascale (including supersymmetry)
- Stefano Profumo: Theories of particle dark matter and their implications for astrophysics and collider phenomenology
- New faculty hires: The Physics Department voted to support two new faculty hires, specializing in theoretical particle physics (if successful, new faculty members would start in July 2018)

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 in May 2007



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, one 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.

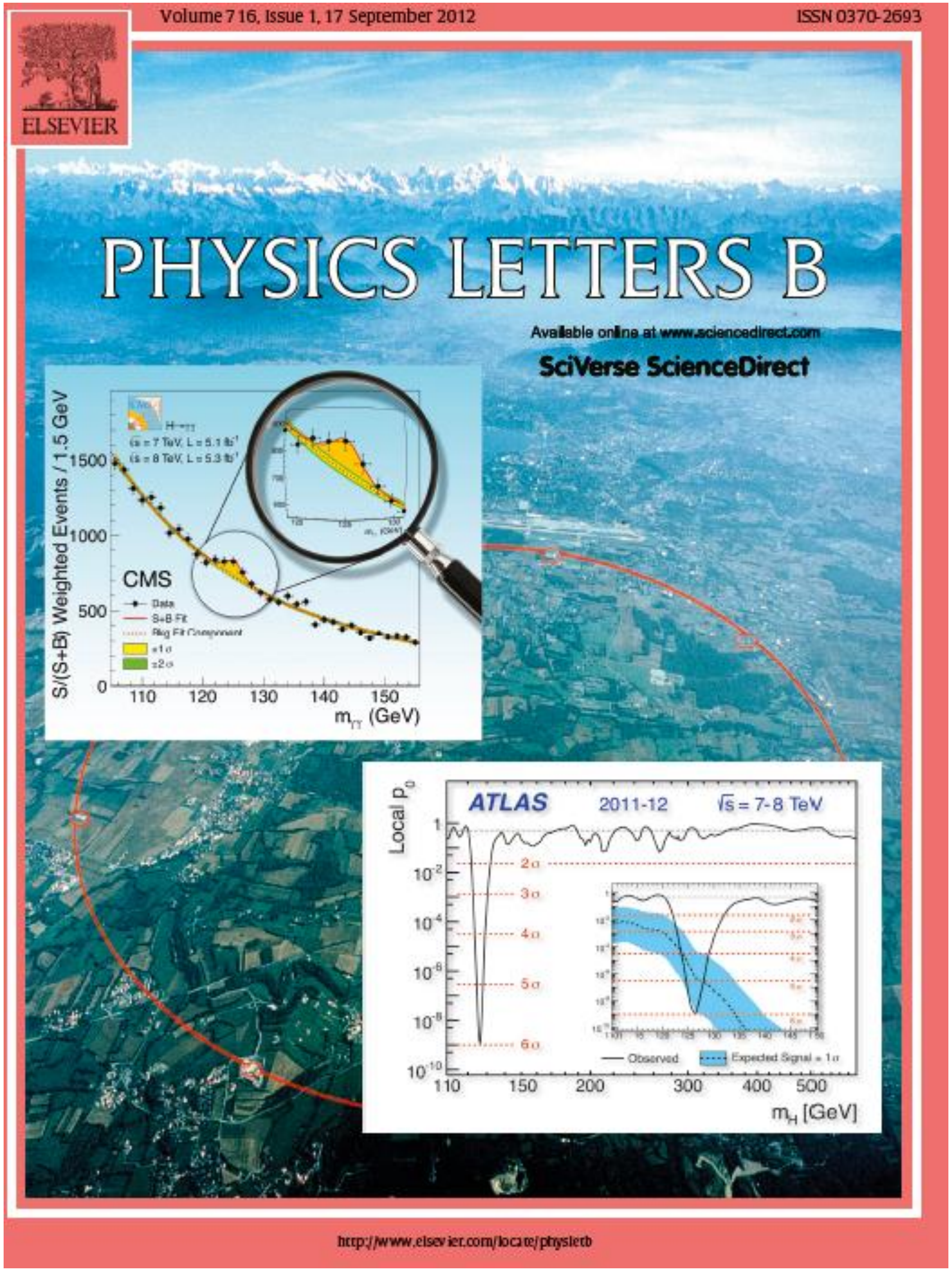
The discovery papers are published two months later In Physics Letters B.

<u>ATLAS Collaboration:</u>

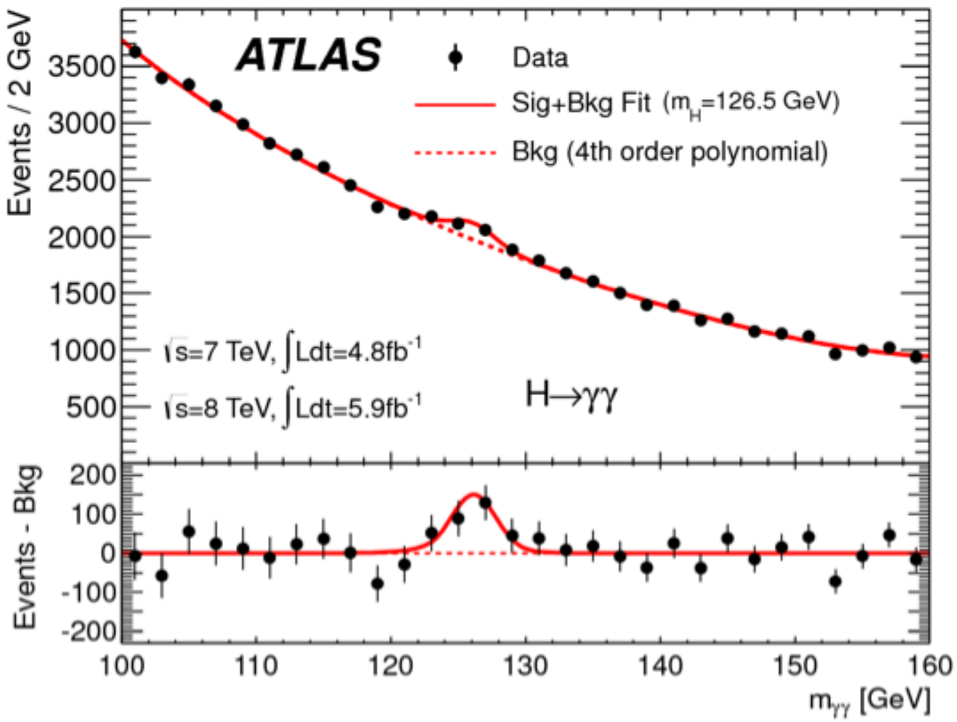
Physics Letters B716 (2012) 1—29

<u>CMS Collaboration:</u>

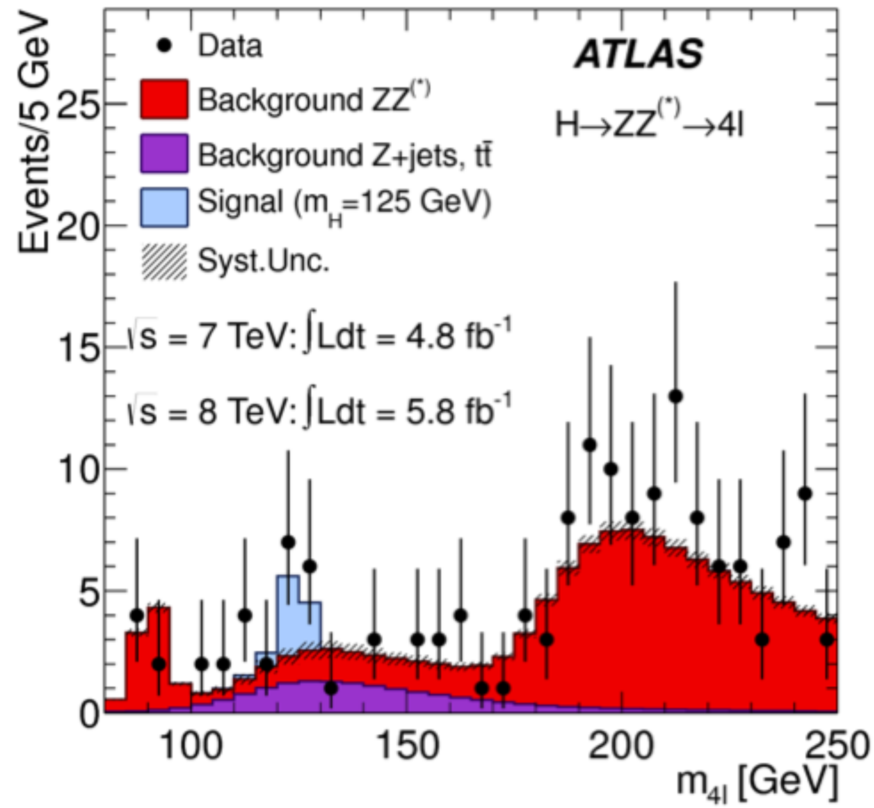
Physics Letters B716 (2012) 30—61



A boson is discovered at the LHC by the ATLAS Collaboration



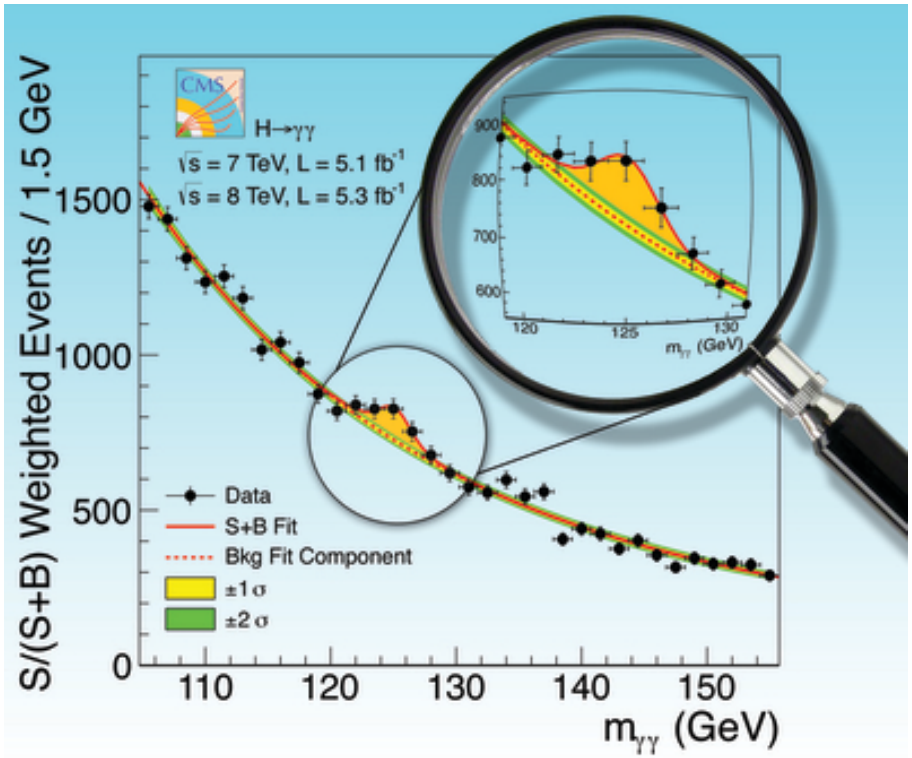
Invariant mass distribution of diphoton candidates for the combined 7 TeV and 8 TeV data samples. The result of a fit to the data of the sum of a signal component fixed to m_H = 126.5 GeV and a background component described by a fourth-order Bernstein polynomial is superimposed. The bottom inset displays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



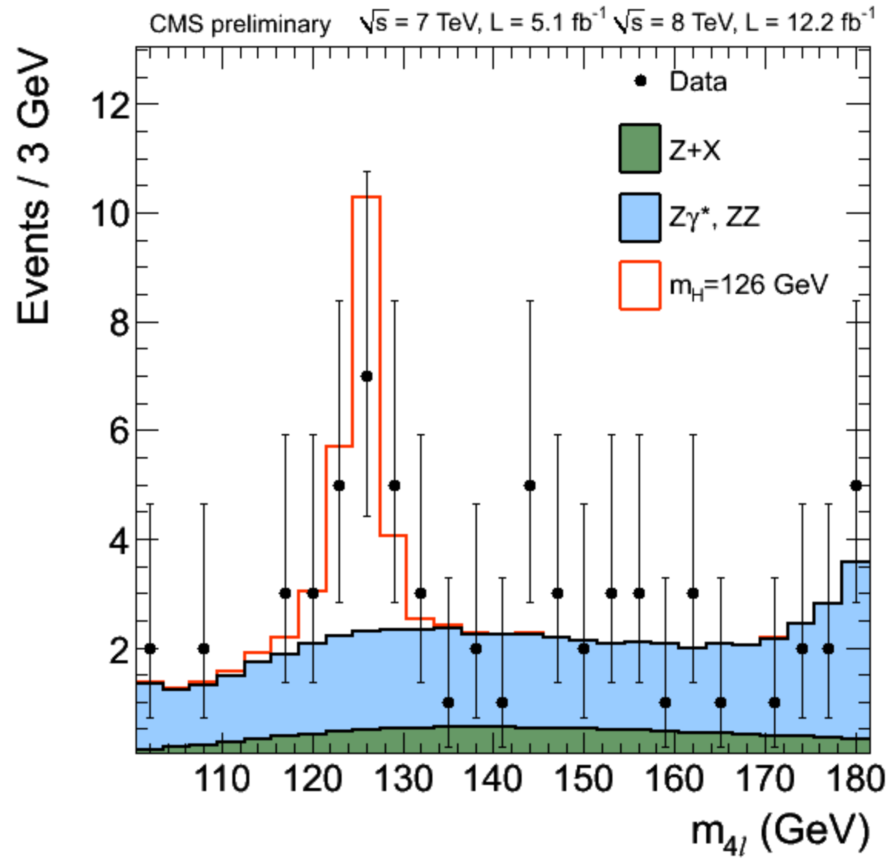
The distribution of the four-lepton invariant mass, m_{4l}, for the selected candidates, compared to the background expectation in the 80 to 250 GeV mass range, for the combination of the 7 TeV 8 TeV data. The signal expectation for a Higgs boson with m_H=125 GeV is also shown.

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

A boson is discovered at the LHC by the CMS Collaboration

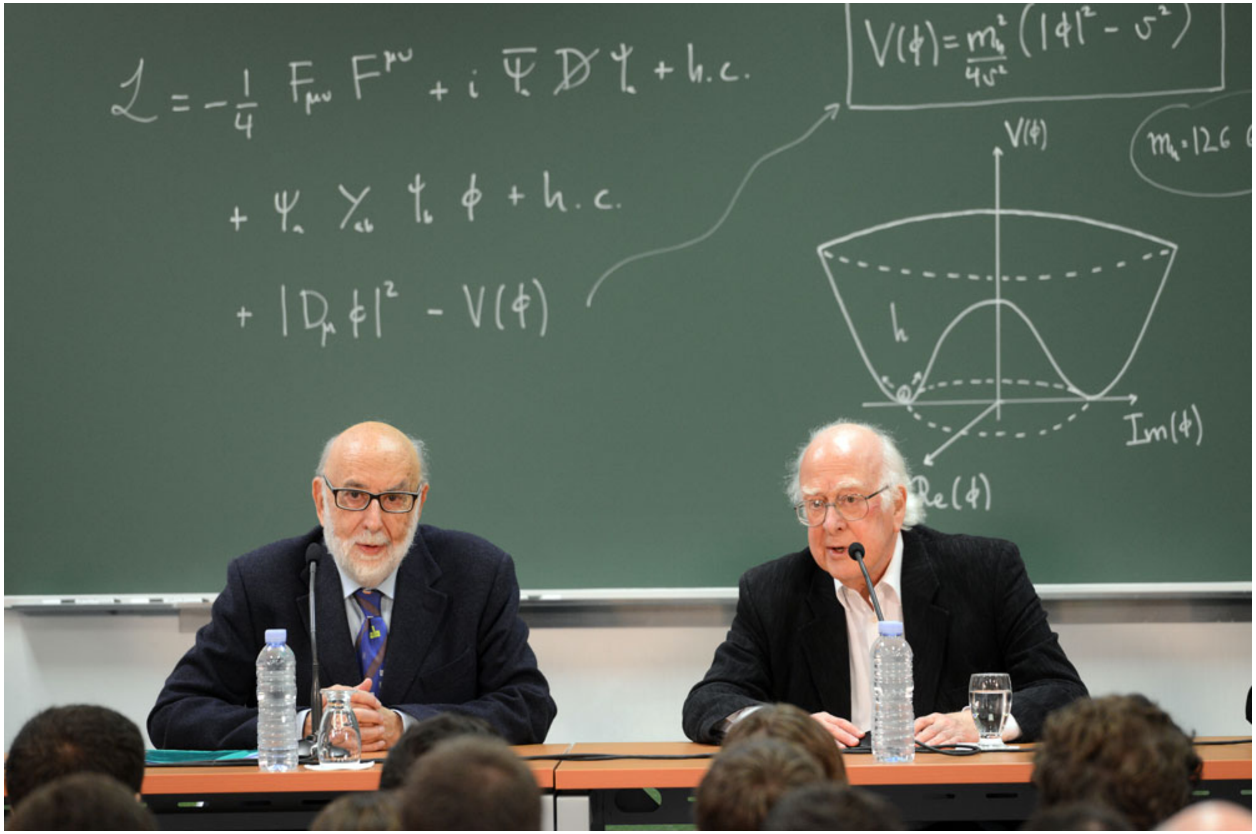


The diphoton invariant mass distribution with each event weighted by the S/(S+B) value of its category. The lines represent the fitted background and signal, and the colored bands represent the ±1 and ±2 standard deviation uncertainties in the background estimate. The inset shows the central part of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

Winners of the 2013
Nobel Prize in Physics

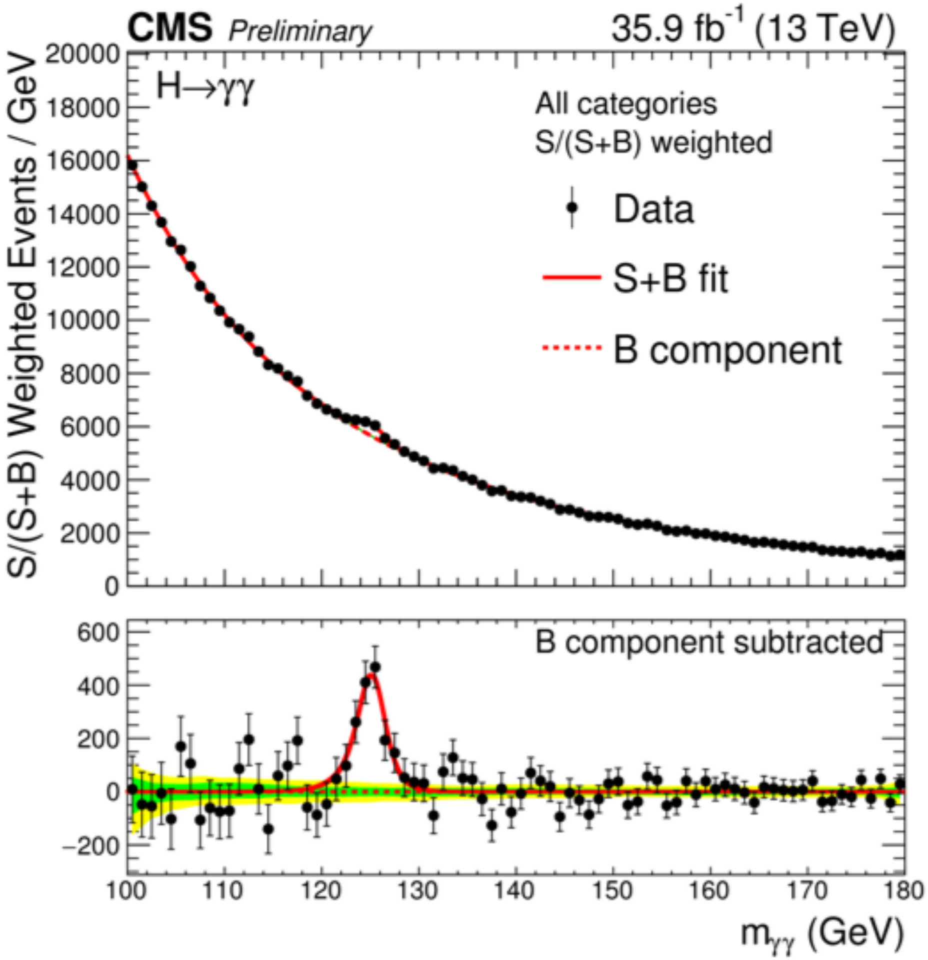


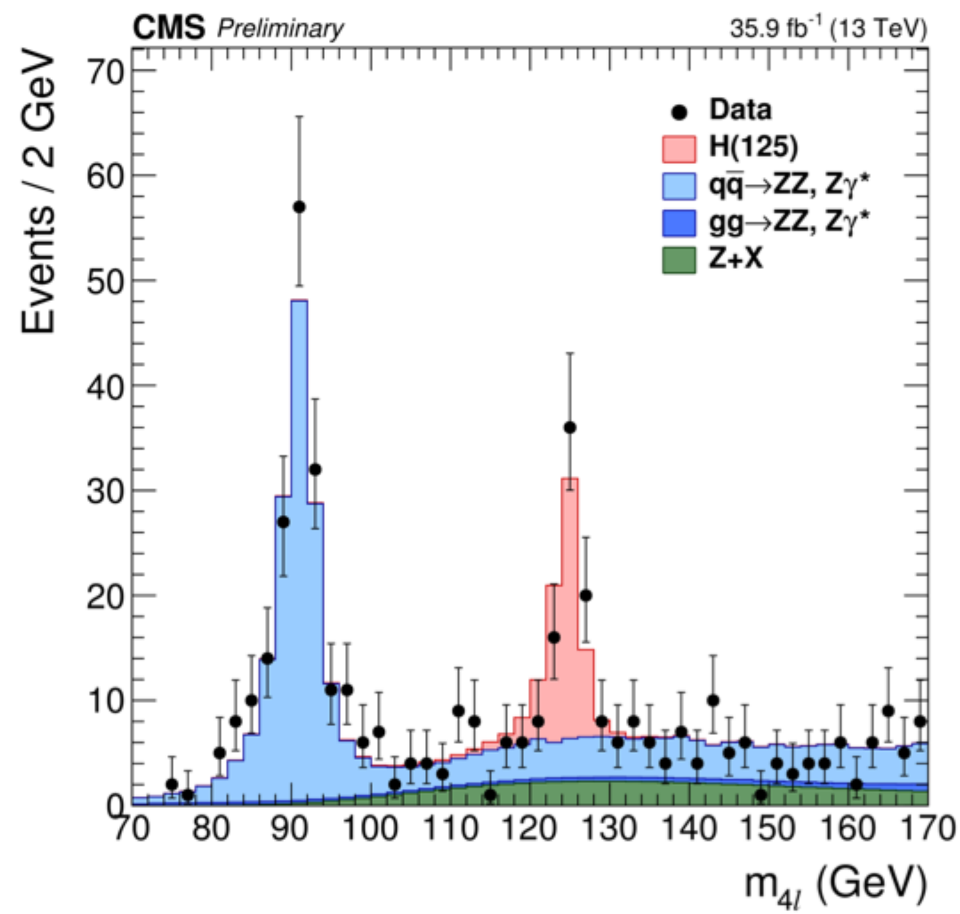
François Englert

and

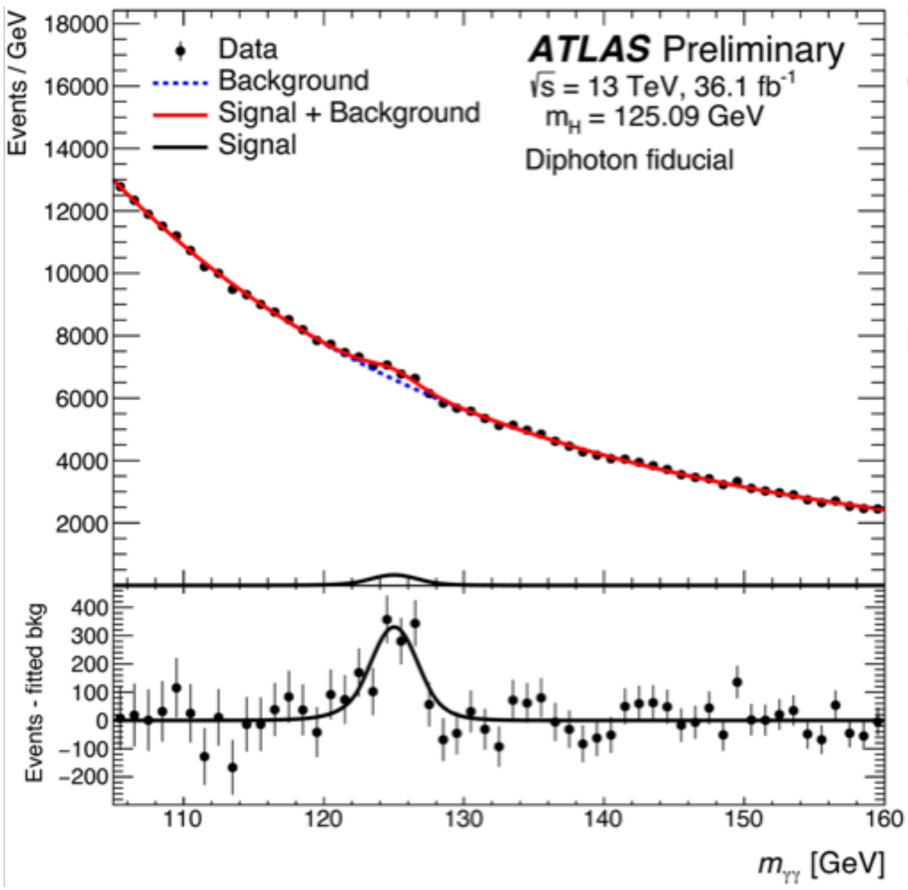
Peter Higgs

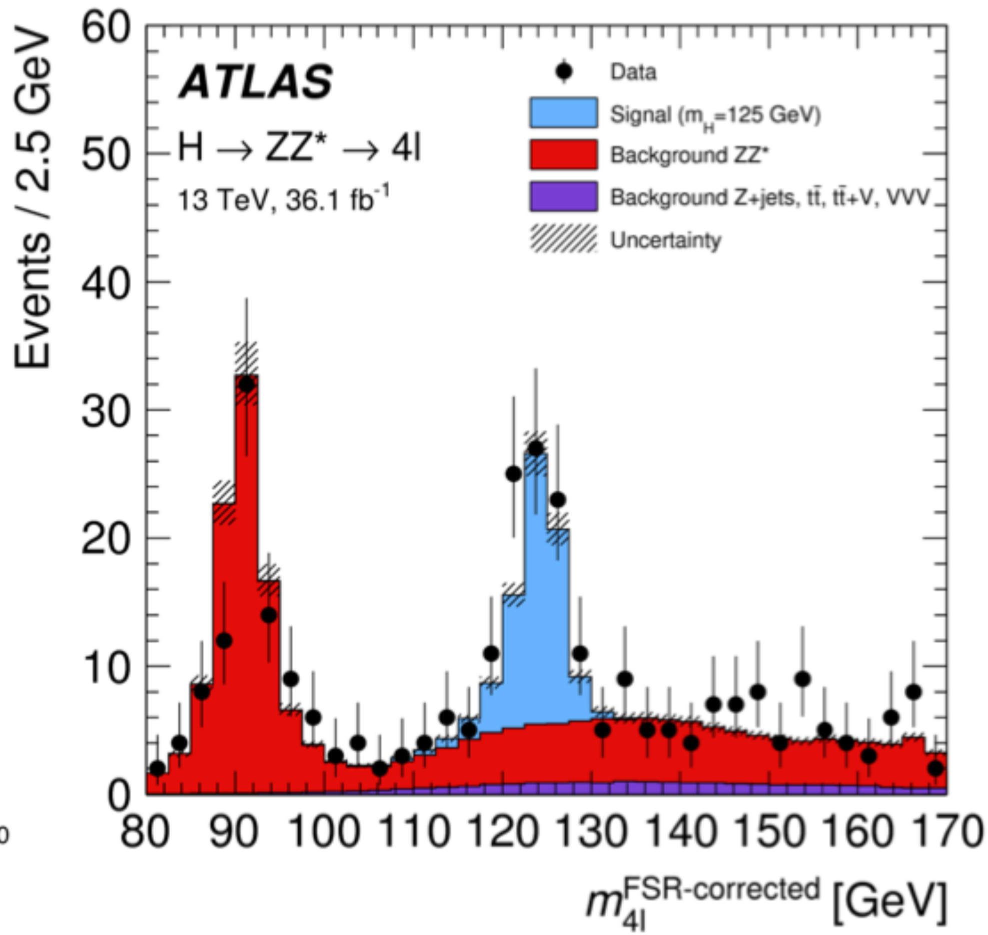
CMS Run-2 observations of the Higgs boson





ATLAS Run-2 observations of the Higgs boson





Higgs production at hadron colliders

At hadron colliders, the relevant processes are

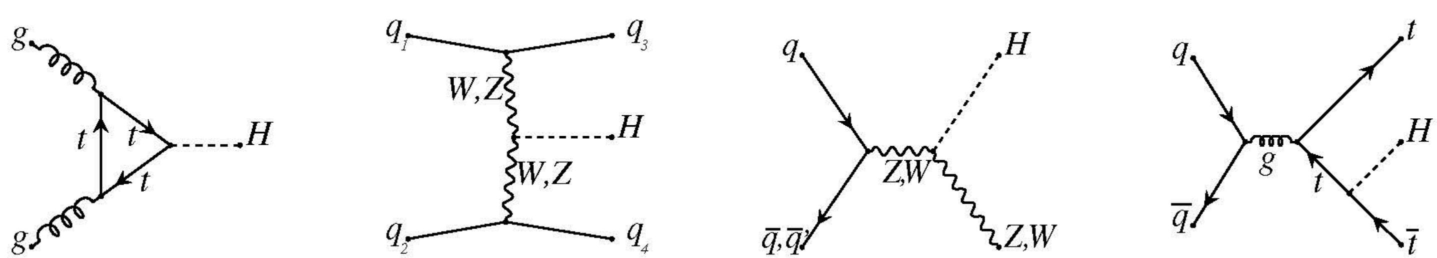
$$gg \to h^0\,, \quad h^0 \to \gamma\gamma\,, VV^{(*)}\,,$$

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

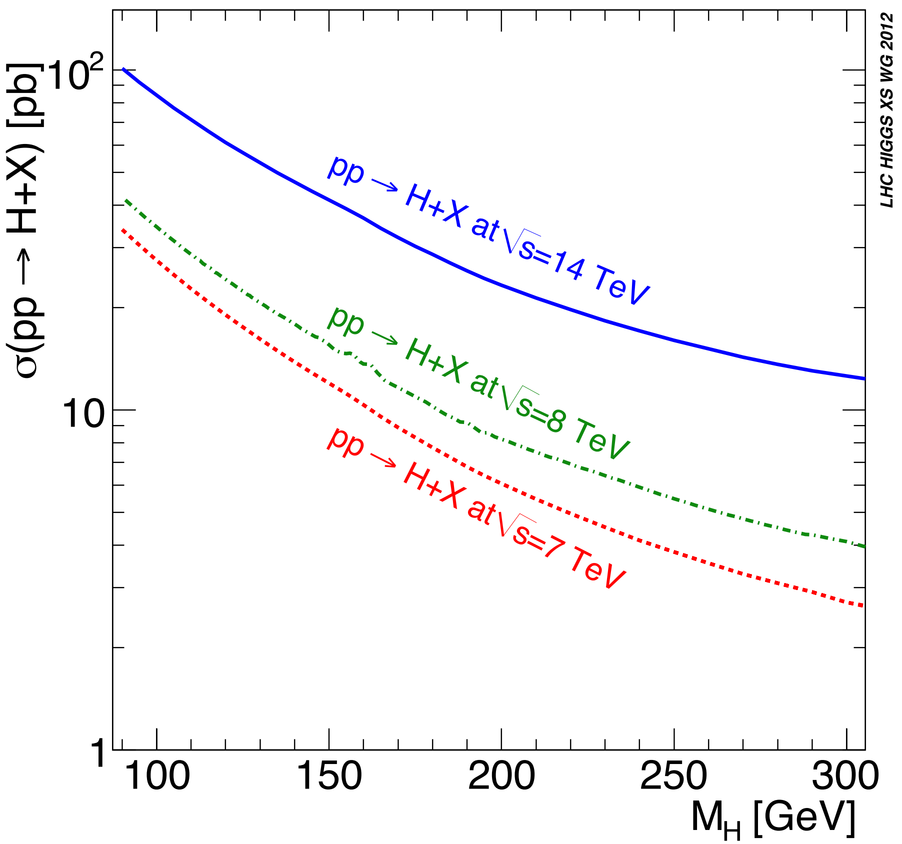
$$q\bar{q}^{(\prime)} \to V^{(*)} \to Vh^0\,, \quad h^0 \to b\bar{b}\,, WW^{(*)}\,,$$

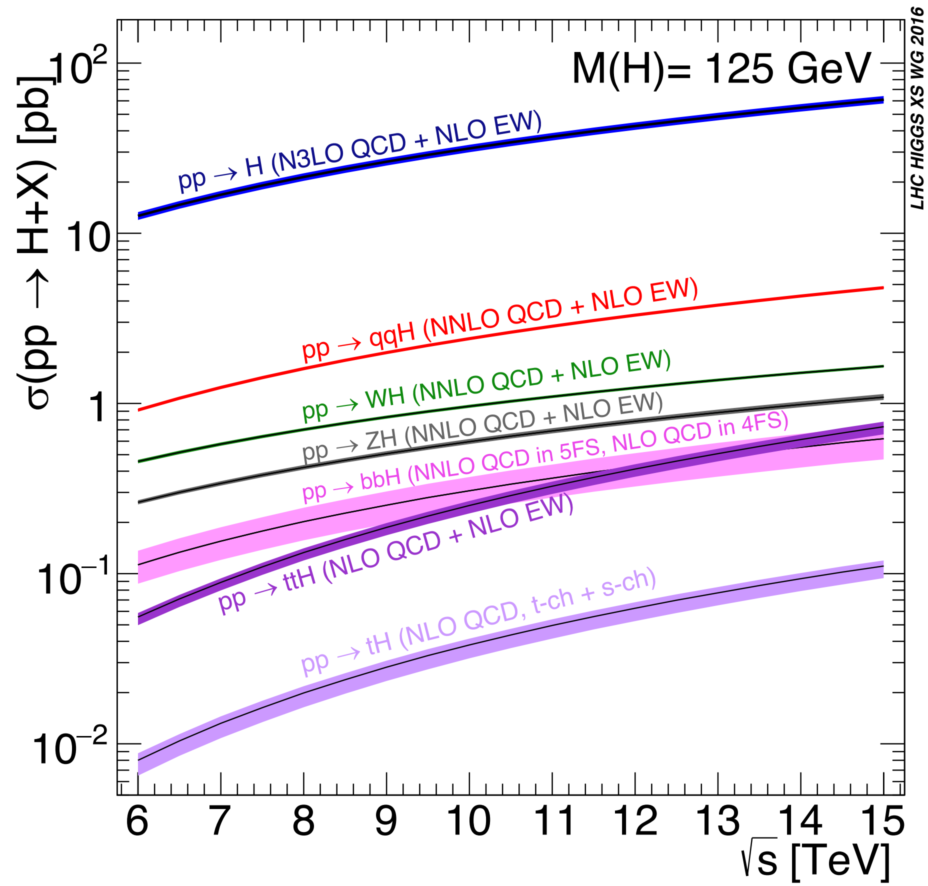
$$gg, q\bar{q} \to t\bar{t}h^0, \quad h^0 \to b\bar{b},\, \gamma\gamma,\, WW^{(*)}\,.$$

where $V = W$ or Z.



Higgs boson production cross sections at a pp collider

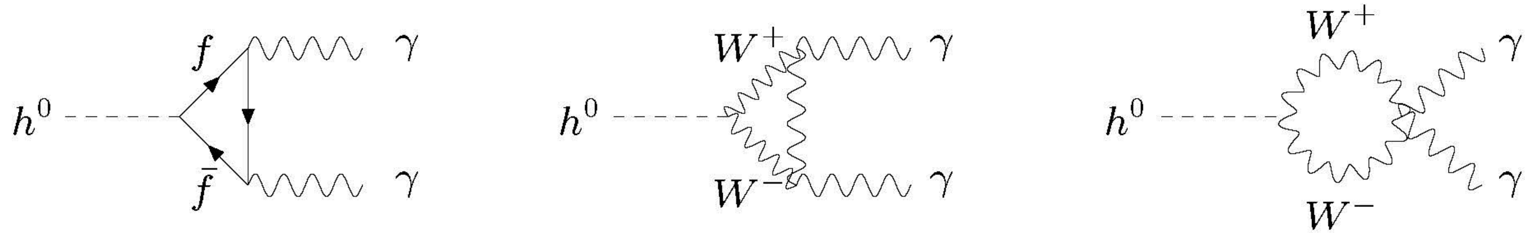




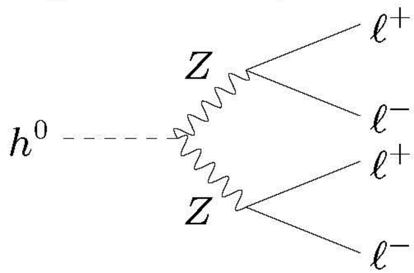
With 36 fb^{-1} of data delivered by the LHC to both ATLAS and CMS in 2015—2016 at a center of mass energy of 13 TeV, roughly 1.8×10^6 Higgs bosons per experiment were produced, assuming the Higgs mass is 125 GeV. Still to be analyzed: 50 fb^{-1} of 2017 data and at least another 50 fb^{-1} od data in 2018.

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

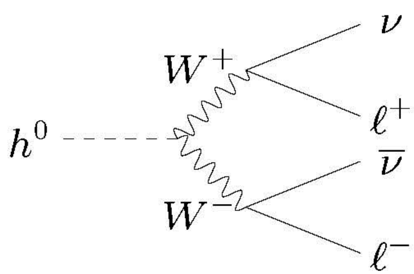
1. The rare decay $h^0 \to \gamma\gamma$ is the most promising signal.



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.



Higgs boson decay channels observed at the LHC

Higgs boson decay mode	Branching ratio (for $m_h = 125\ GeV$)
$h^0 \rightarrow \mathbf{bb}$	0.582
$h^0 \rightarrow \tau^+ \tau^-$	6.27×10^{-2}
$h^0 \rightarrow \ell^+ \ell^- \nu\nu$ ($\ell = e$ or μ)	1.06×10^{-2}
$h^0 \rightarrow \gamma\gamma$	2.27×10^{-3}
$h^0 \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ ($\ell = e$ or μ)	1.24×10^{-4}

Taken from https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR#Branching_Ratios

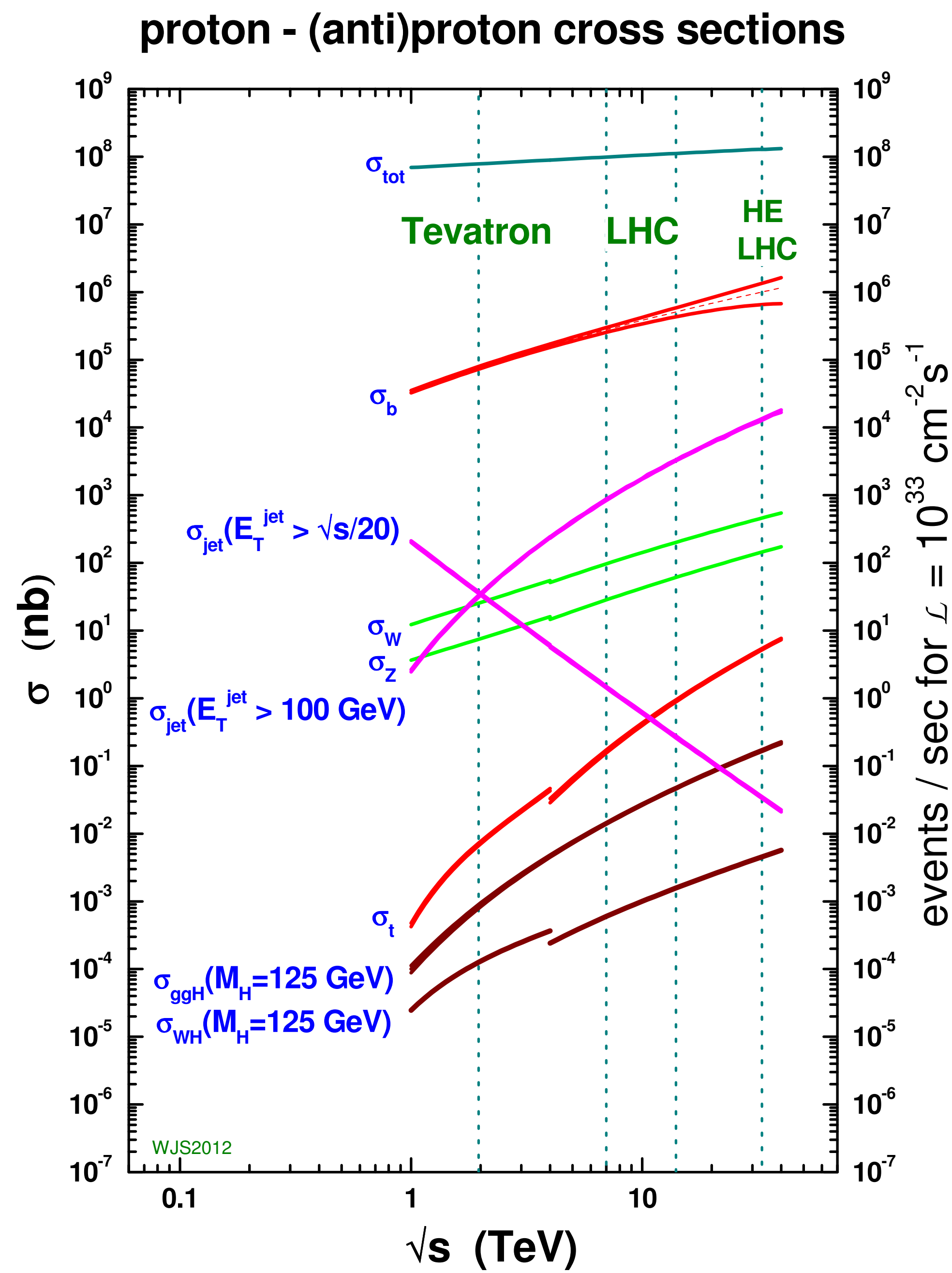
<u>Remarks</u>:

1. $h^0 \rightarrow WW^*$ is observed primarily via the $\ell^+ \nu\, \ell^- \nu$ ($\ell = e$ or μ) final state.
2. $h^0 \rightarrow ZZ^*$ is observed primarily via the $\ell^+ \ell^- \ell^+ \ell^-$ ($\ell = e$ or μ) final state.

In the decays to the diboson final state, kinematics dictates that one of the vector bosons is off-shell (i.e., "virtual") and is thus indicated by a superscript star.

Question: why not search inclusively for Higgs bosons 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.

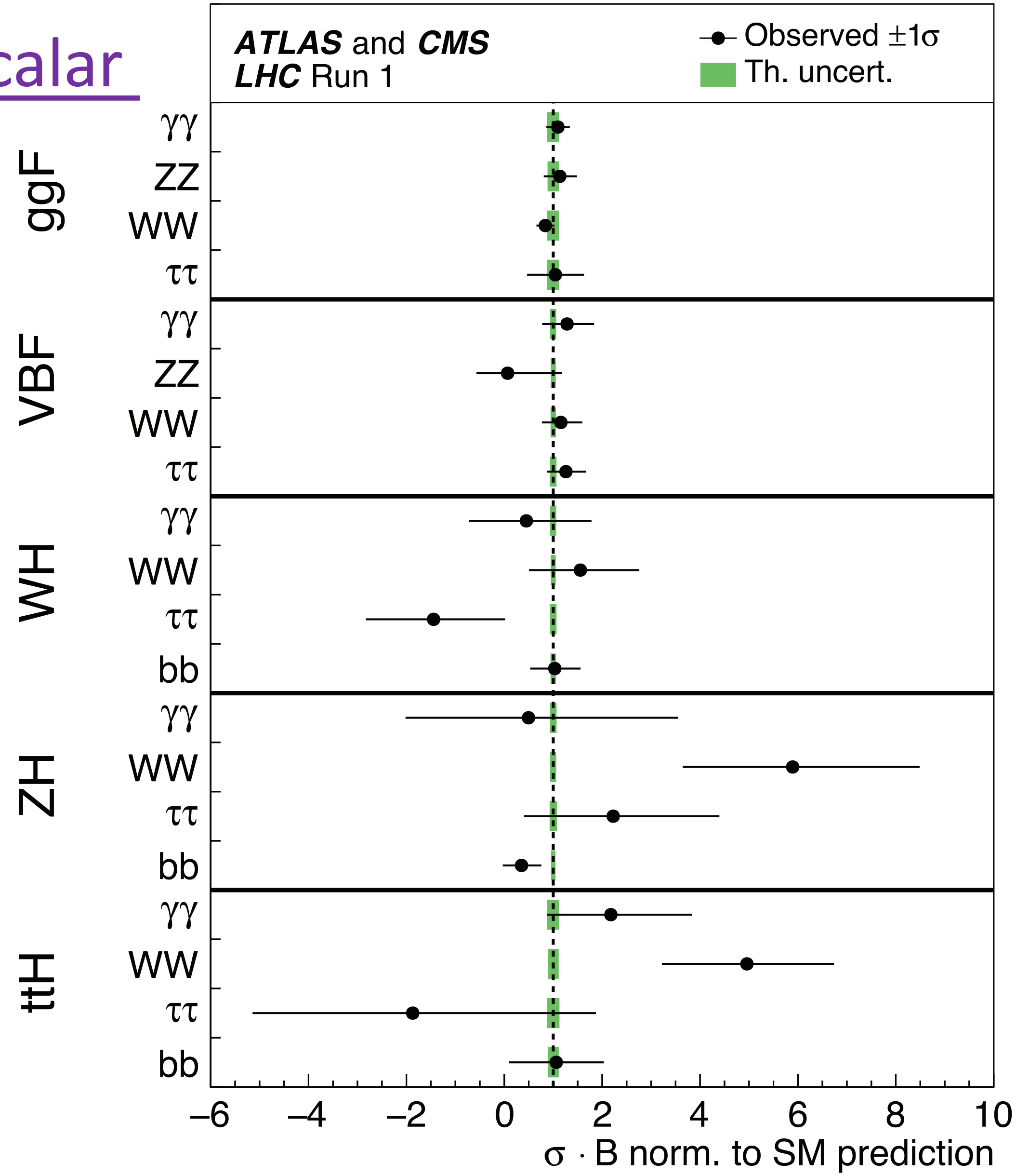


Is the observed 125 GeV scalar the SM Higgs boson?

After the end of Run-1 of the LHC (2011—2013), the ATLAS and CMS Collaborations provided a combined analysis of the Higgs boson data.

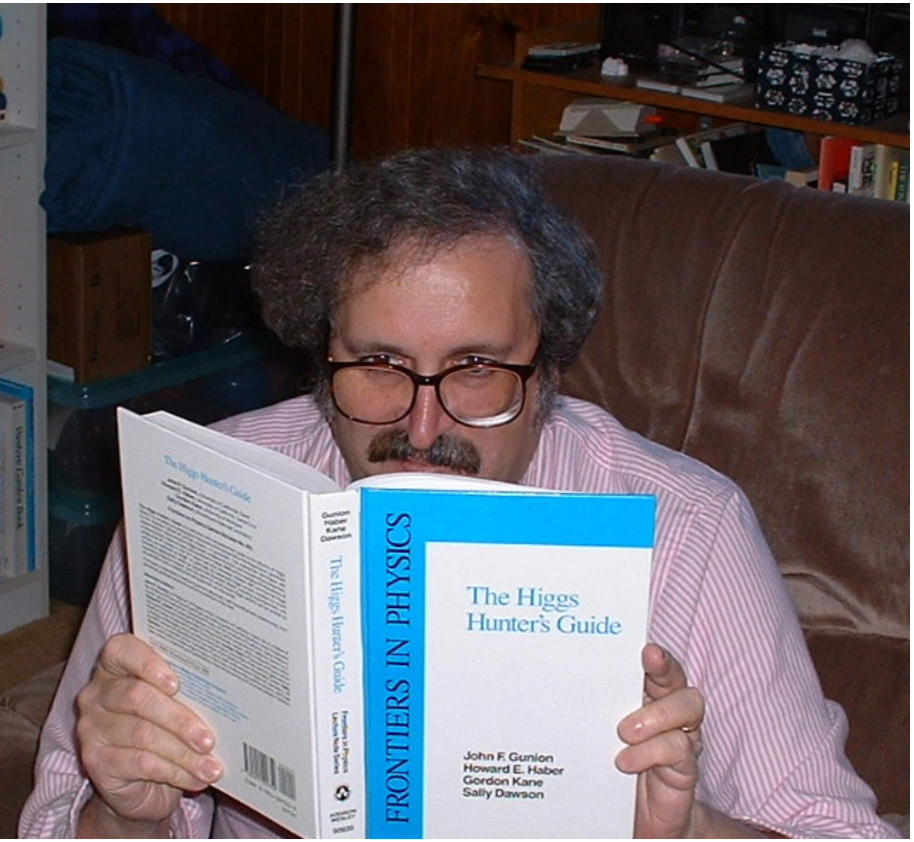
The properties of the Higgs boson are consistent with Standard Model predictions (given the statistical power of the Higgs boson data).

The Higgs data taken at Run-2 of the LHC (2015—2016) have confirmed the Run-1 observations (with potential deviations from the Standard Model further reduced).

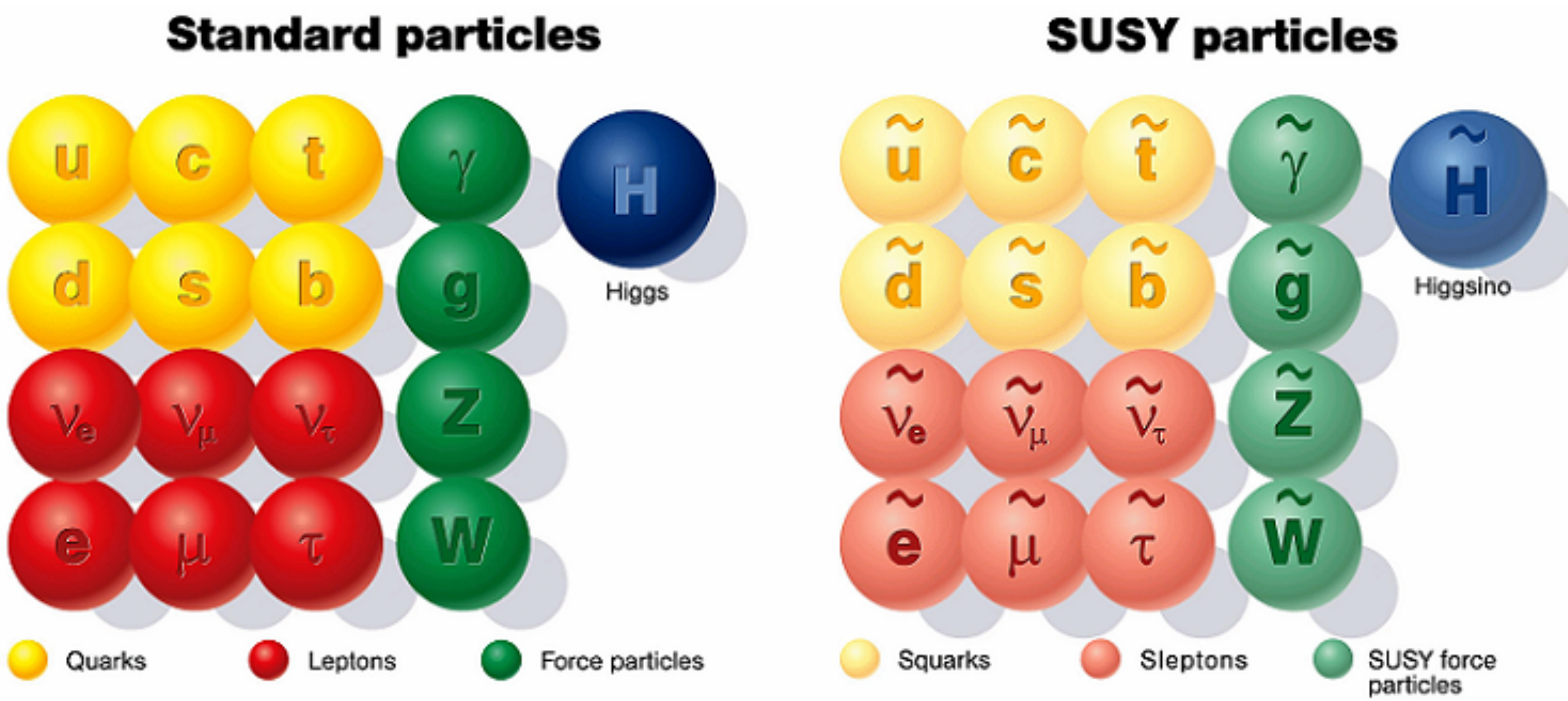


Taken from G. Aad et al. [ATLAS, CMS Collaborations], Phys. Rev. Letters **114**, 191803 (2015).

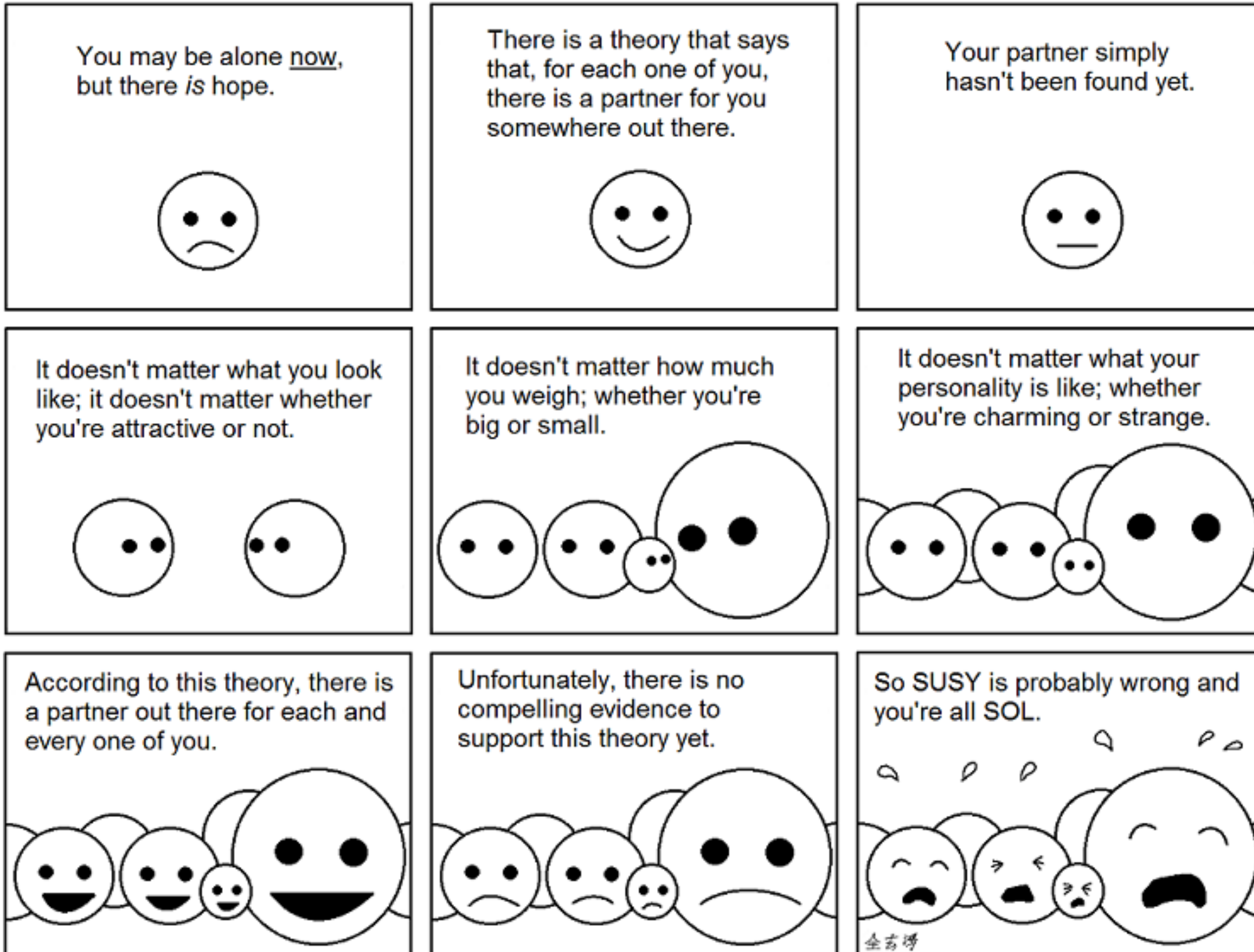
Research program 1: theory and phenomenology of Higgs bosons



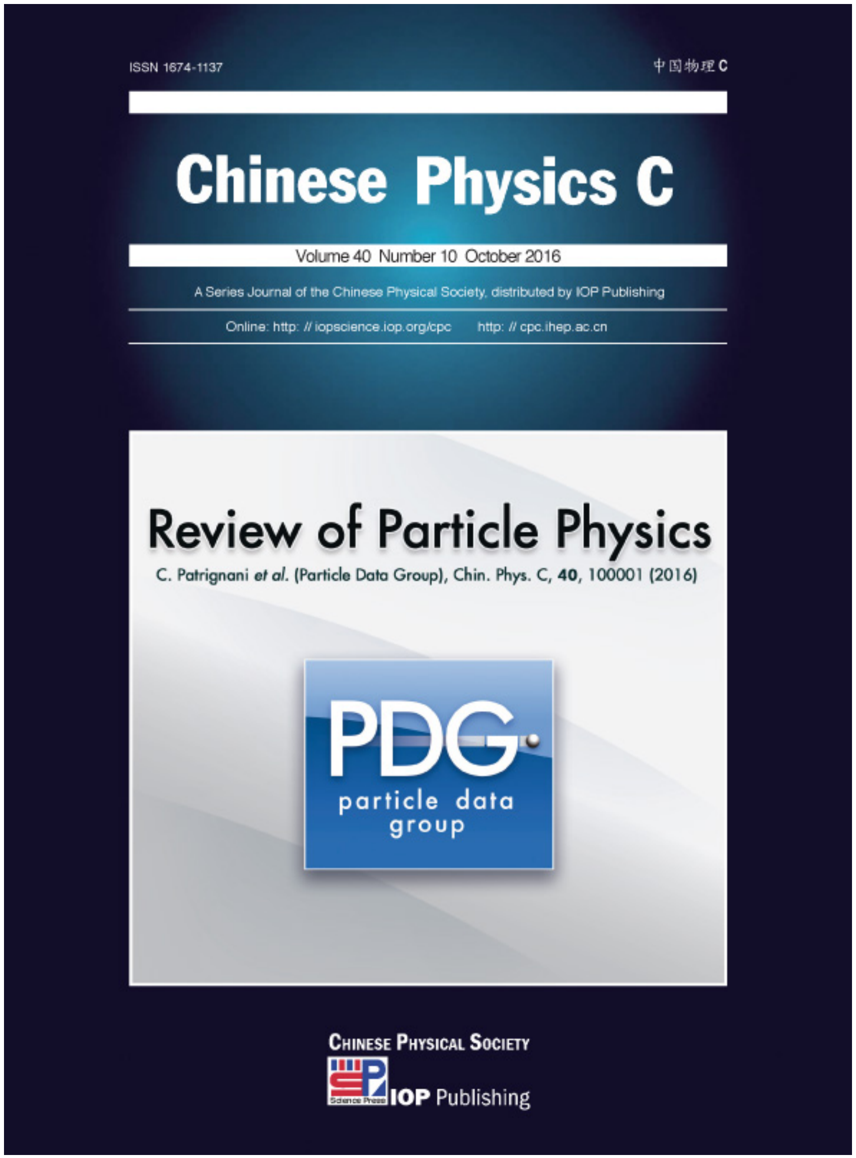
Research program 2: theory and phenomenology of TeV-scale supersymmetry (SUSY)



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) and 2017 update [http://pdg.lbl.gov/2017/reviews/rpp2017-rev-susy-1-theory.pdf].


You may be alone now, but there is hope.
There is a theory that says that, for each one of you, there is a partner for you somewhere out there.
Your partner simply hasn't been found yet.
It doesn't matter what you look like; it doesn't matter whether you're attractive or not.
It doesn't matter how much you weigh; whether you're big or small.
It doesn't matter what your personality is like; whether you're charming or strange.
According to this theory, there is a partner out there for each and every one of you.
Unfortunately, there is no compelling evidence to support this theory yet.
So SUSY is probably wrong and you're all SOL.

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



112. Supersymmetry, Part I (Theory)

Revised September 2017 by Howard E. Haber (UC Santa Cruz).

112.1. Introduction

Supersymmetry (SUSY) is a generalization of the space-time symmetries of quantum field theory that 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, $M_P \sim 10^{19}$ 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, $M_{EW} \sim 100$ GeV, and 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)

2017 Publications

Supersymmetric Theory and Models
H.E. Haber and L. Stephenson Haskins, arXiv:1712.05926 [hep-ph], to appear in the Proceedings of the 2016 Theoretical Advanced Study Institute (TASI-2016).

Multi-Higgs doublet models: physical parametrization, sum rules and unitarity bounds
M.P. Bento, H.E. Haber, J.C. Romão and J.P. Silva, JHEP **1711**, 095 (2017).

The Impact of Two-Loop Effects on the Scenario of MSSM Higgs Alignment without Decoupling
H.E. Haber, S. Heinemeyer and T. Stefaniak, Eur. Phys. J. C. **77**, 142 (2017).

High scale flavor alignment in two-Higgs doublet models and its phenomenology
S. Gori, H.E. Haber and E. Santos, JHEP **1706**, 110 (2017).

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**, 67 (2017).

Future Higgs Studies: A Theorist's Outlook
H.E. Haber, arXiv:1701.01922 [hep-ph], in the Proceedings of the 6th International Workshop on the Prospects for Charged Higgs Discovery at Colliders, PoS(CHARGED2016)029.

UCSC graduate student authors in red; UCSC post doctoral fellow authors in orange.

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?

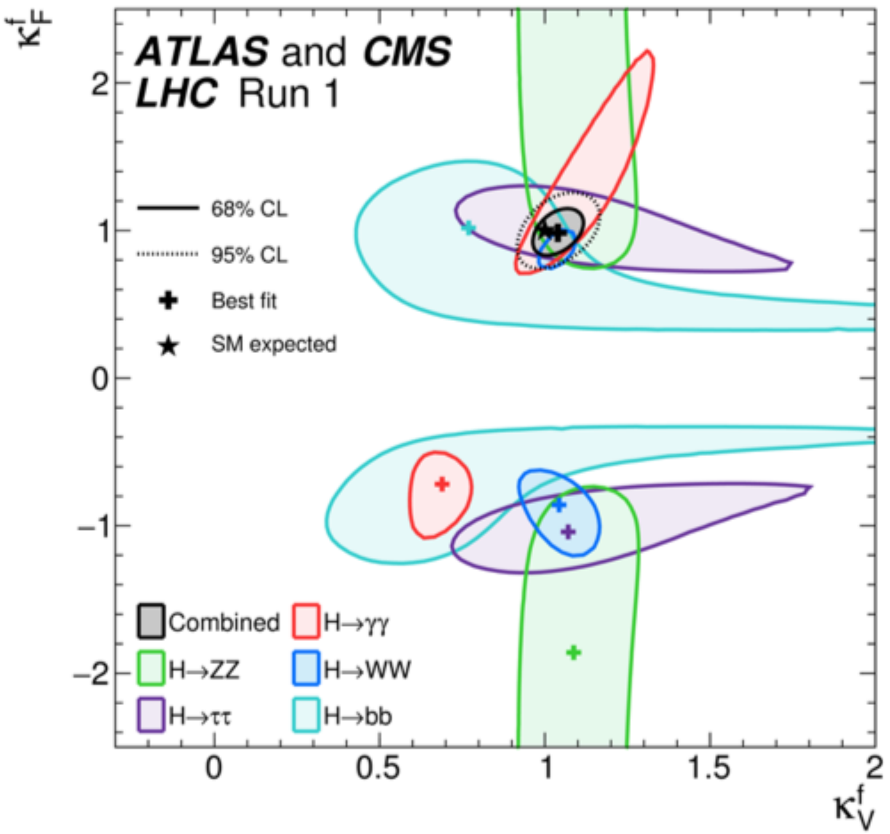
- Adding new scalar states can alleviate the metastability of the vacuum, allowing the Higgs-sector-extended SM to be valid all the way up to the Planck scale.

- Extended Higgs sectors can provide a dark matter candidate.

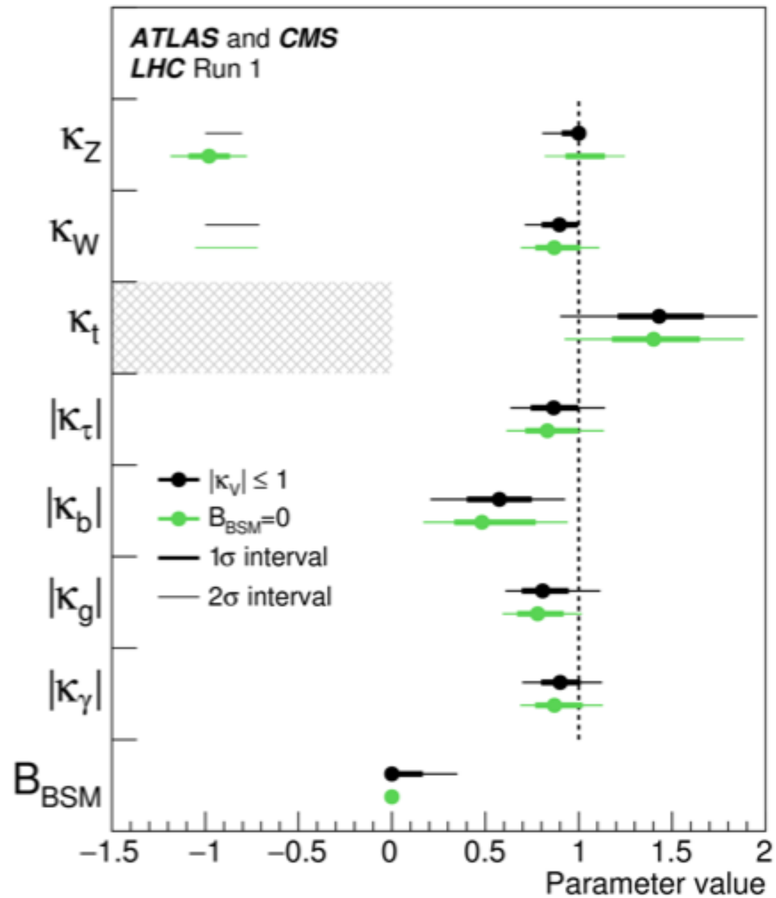
- Extended Higgs sectors can provide new sources of CP violation (which may be useful in baryogenesis).

- 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 (κ_F^f ,κ_V^f) plane for the combination of ATLAS and CMS and for the individual decay channels, as well as for their global combination (κ_F versus κ_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).

A tale of two alignment mechanisms

1. Higgs field alignment

In the limit in which one of the Higgs mass eigenstate fields is approximately aligned with the direction of the scalar doublet vacuum expectation value (vev) in field space, the tree-level properties of corresponding scalar mass eigenstate approximate those of the SM Higgs boson.

2. Flavor alignment

The quark mass matrices arise from the Higgs-fermion Yukawa couplings when the neutral Higgs fields acquire vevs. In the case of flavor alignment, the diagonalization of the quark mass matrices simultaneously diagonalize the neutral Higgs quark interactions, which implies the absence of tree-level Higgs-mediated FCNCs in hadron physics.

Higgs field alignment with or without decoupling

1. The decoupling limit

Approximate Higgs field alignment is most naturally achieved in the decoupling limit, where there is a new mass parameter, $M \gg v$, such that all physical Higgs masses with one exception are of $\mathcal{O}(M)$. The Higgs boson, with $m_h \sim \mathcal{O}(v)$, is SM-like, due to approximate alignment.

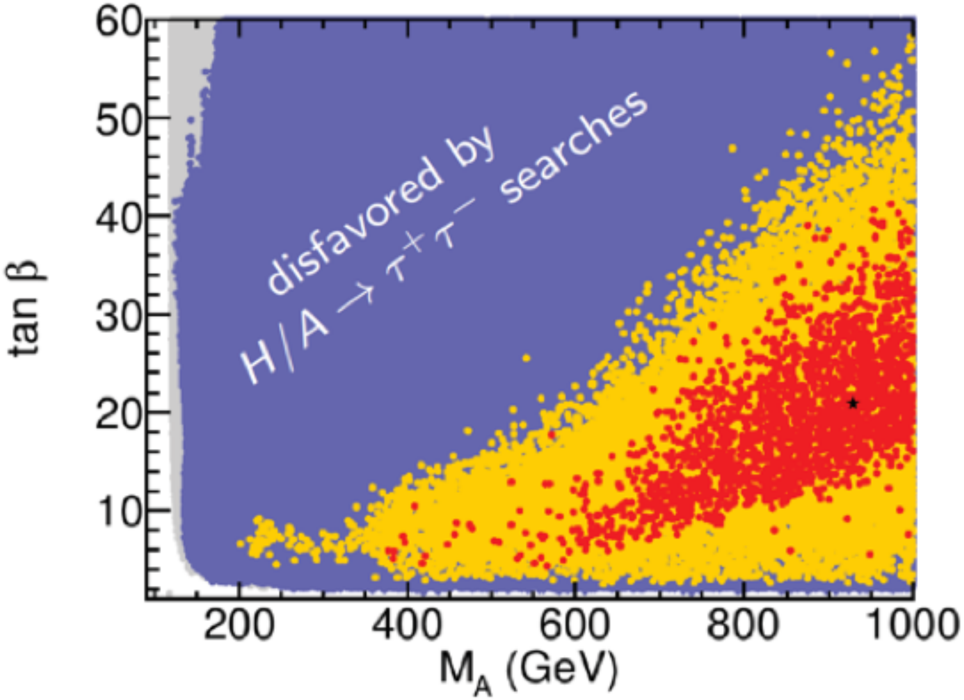
2. Higgs field alignment without decoupling[4]

In models of alignment without decoupling (due to suppressed scalar mixing), the masses of all Higgs scalars (both SM-like and non-SM-like) can be of $\mathcal{O}(v)$. Hence, the non-SM Higgs scalars may be more easily accessible at the LHC. In some theories, this can be achieved by a symmetry (e.g., the inert doublet model). In most cases, approximate alignment is an accidental (fine-tuned?) region of the model parameter space.

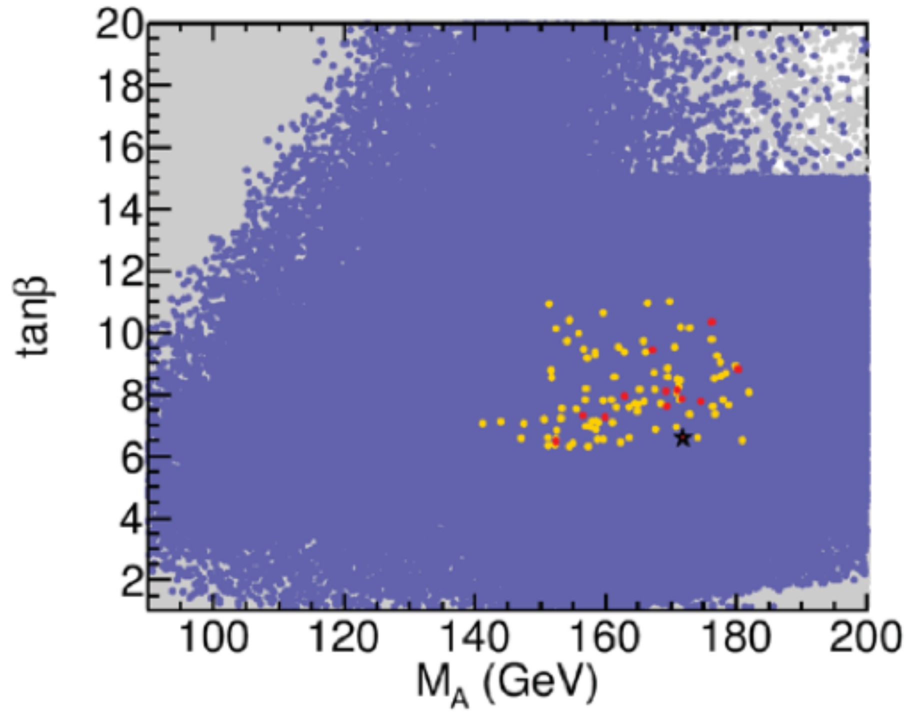
[4] J.F. Gunion and H.E. Haber, hep-ph/0207010; N. Craig, J. Galloway and S. Thomas, arXiv:1305.2424.

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, Eur. Phys. J. C. **77**, 142 (2017).

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 S. Gori, H.E. Haber and E. Santos, JHEP **1706**, 110 (2017), new contributions to these days were considered in the two Higgs doublet model (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.

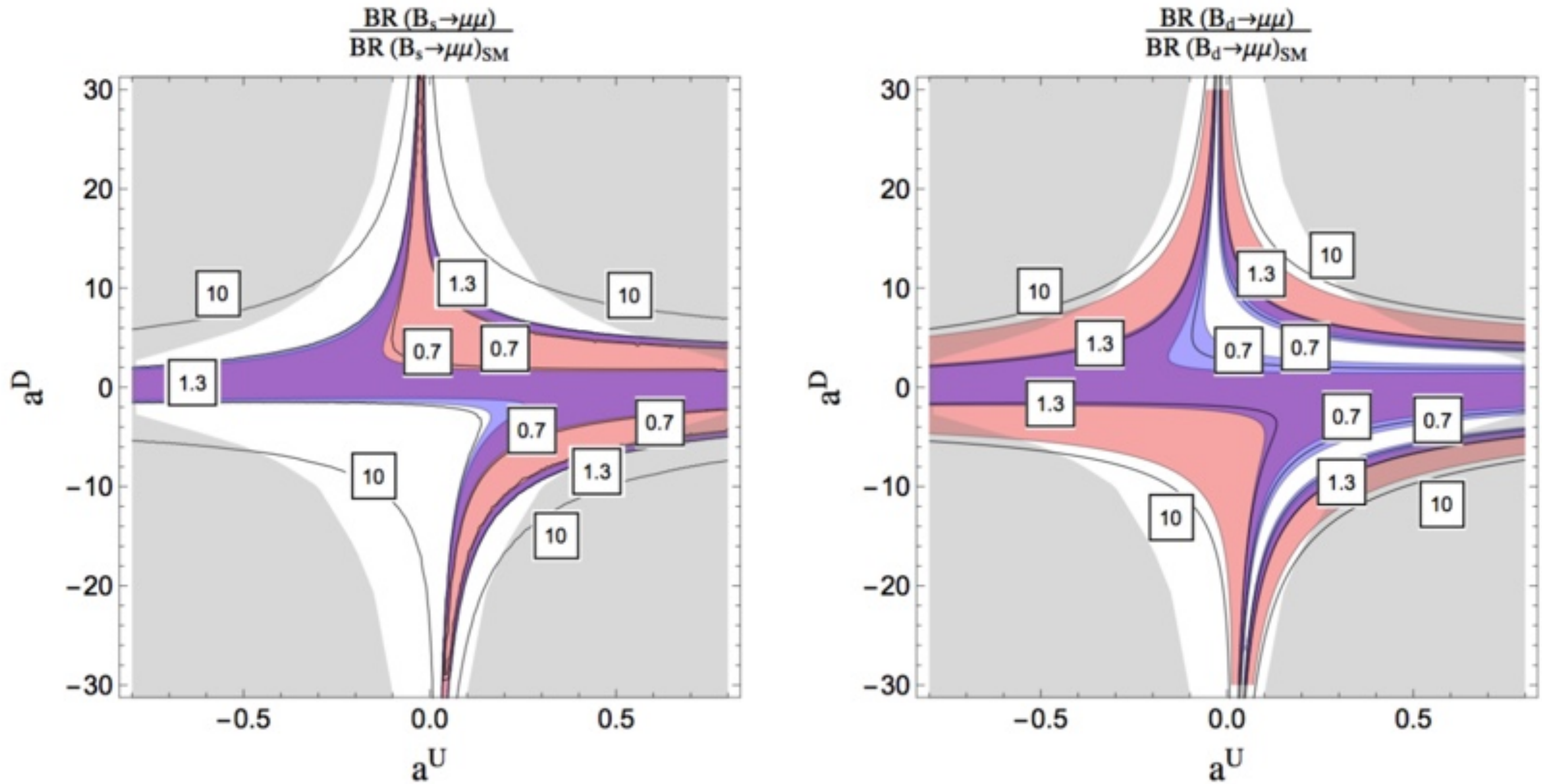


Figure 7. Leading log prediction for the branching ratios for $B_s \to \mu^+\mu^-$ (left panel) and $B_d \to \mu^+\mu^-$ (right panel) relative the SM, as a function of a^U and a^D, with fixed $\tan\beta = 10$, $\cos(\beta - \alpha) = 0$, and $m_A = m_H = 400$ GeV. The regions in pink are allowed at the 2σ level by the present measurements. The purple shaded regions are anticipated 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 Yukawa couplings below $M_{\rm P}$.

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.

Recent Ph.D. student (co-advised with Michael Dine) and her thesis project

Laurel Stephenson Haskins (2017): Supersymmetry , Inflation and Dark Matter

Current position

Post Doctoral Research Associate at the Racah Institute of Physics at the Hebrew University of Jerusalem

We collaborated on two projects:

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

2. H.E. Haber and L. Stephenson Haskins, *Supersymmetric Theory and Models*, arXiv:1712.05926 [hep-ph], to appear in the Proceedings of the Theoretical Advanced Study Institute (TASI-2016).

Supersymmetric Theory and Models

Howard E. Haber[1] and Laurel Stephenson Haskins[1,2]

[1] *Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064, USA*

[2] *Racah Institute of Physics, Hebrew University, Jerusalem 91904, Israel*

In these introductory lectures, we review the theoretical tools used in constructing supersymmetric field theories and their application to physical models. We first introduce the technology of two-component spinors, which is convenient for describing spin-$\frac{1}{2}$ fermions. After motivating why a theory of nature may be supersymmetric at the TeV energy scale, we show how supersymmetry (SUSY) arises as an extension of the Poincaré algebra of spacetime symmetries. We then obtain the representations of the SUSY algebra and discuss its simplest realization in the Wess-Zumino model. In order to have a systematic approach for obtaining supersymmetric Lagrangians, we introduce the formalism of superspace and superfields and recover the Wess-Zumino Lagrangian. These methods are then extended to encompass supersymmetric abelian and non-abelian gauge theories coupled to supermatter. Since supersymmetry is not an exact symmetry of nature, it must ultimately be broken. We discuss several mechanisms of SUSY-breaking (both spontaneous and explicit) and briefly survey various proposals for realizing SUSY-breaking in nature. Finally, we construct the the Minimal Supersymmetric extension of the Standard Model (MSSM), and consider the implications for the future of SUSY in particle physics.

Contents

Ongoing and Future Activities

- Natural alignment without decoupling (with P. Draper and F. D'Eramo)
  - Achieving a SM-like Higgs boson without fine-tuning.
- Implications of 2HDM high energy flavor alignment (with S. Gori)
  - Neutral Higgs mediated flavor violation in the lepton sector.
- Mass degeneracies in extended Higgs sectors (with P. Osland…)
- Unitarity and Sum rules in extended Higgs sectors (with J.P. Silva,…)
- Basis-invariant treatment of the 3HDM (with V. Keus)
- Phenomenological aspects of more general 2HDMs (with J. Connell,…)
  - 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.

Various projects are waiting for the right Ph.D. student…