Research on the Theory of the TeV energy scale (Terascale)

Howard Haber
SCIPP Theory
January 22, 2020

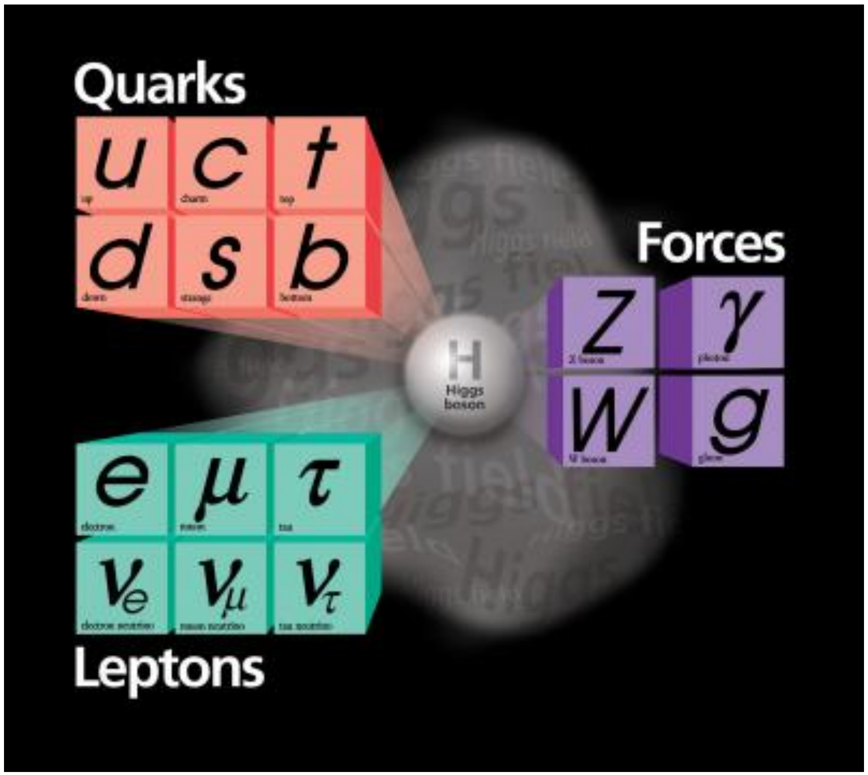
For further details, check out my webpage:
http://scipp.ucsc.edu/~haber/

SCIPP Particle Theory Group

- Michael Dine: supersymmetry, string theory, instantons, axions, inflation and the early universe
- Stefania Gori: phenomenology of new physics beyond the Standard model, dark matter and dark sectors, Higgs physics
- 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
- Wolfgang Altmannshofer: Flavor physics theory and phenomenology, CP violation, neutrino physics, Higgs physics

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, the gauge bosons of SU(3)xSU(2)xU(1), and the Higgs boson.

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.

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

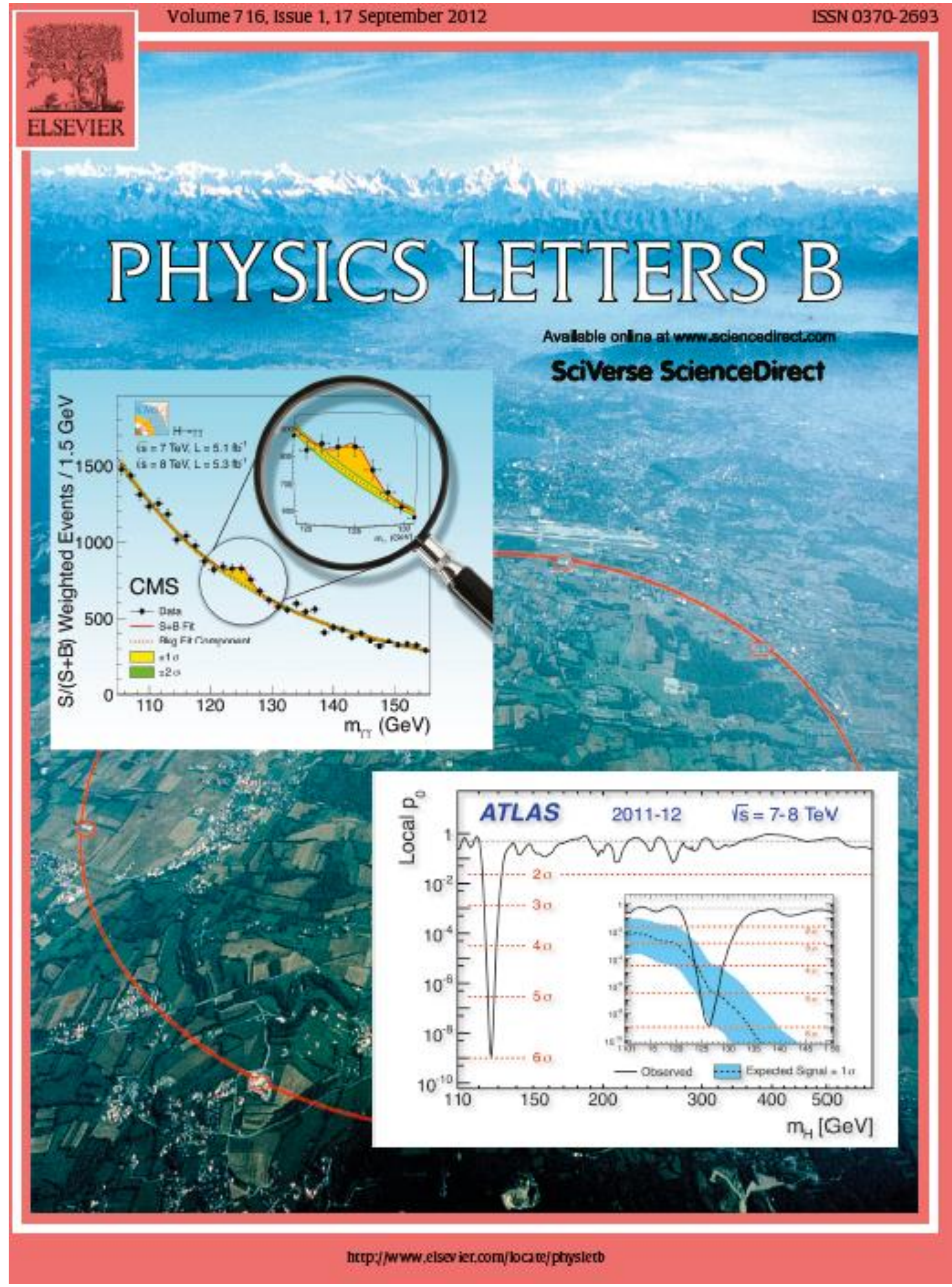
The discovery papers are published two months later In Physics Letters B.

<u>ATLAS Collaboration:</u>

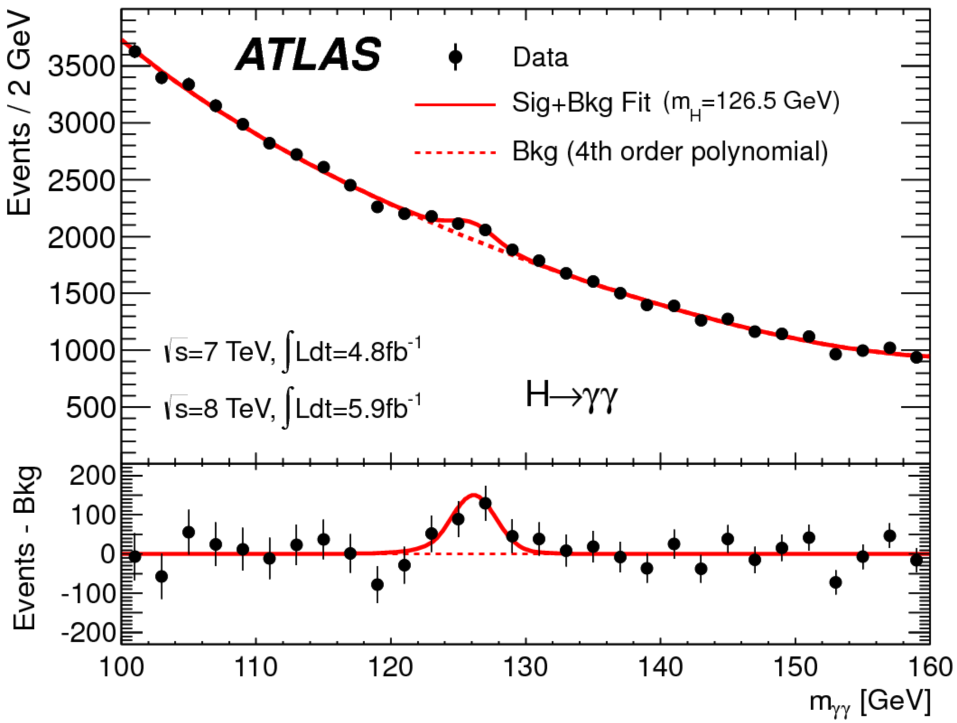
Physics Letters B716 (2012) 1—29

<u>CMS Collaboration:</u>

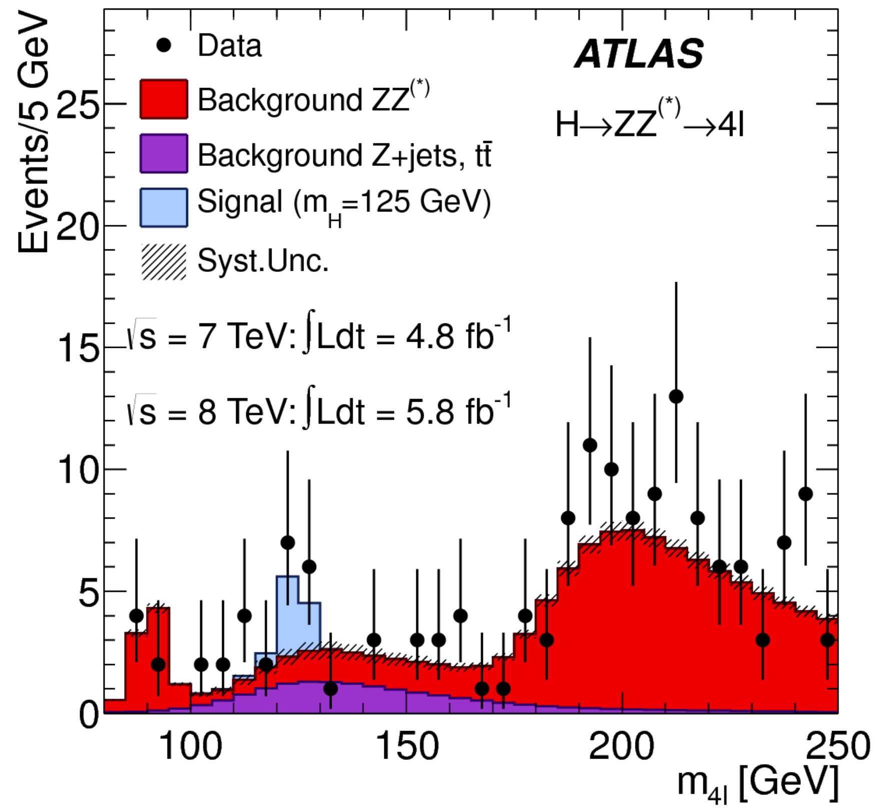
Physics Letters B716 (2012) 30—61



A boson is discovered at the LHC by the ATLAS Collaboration



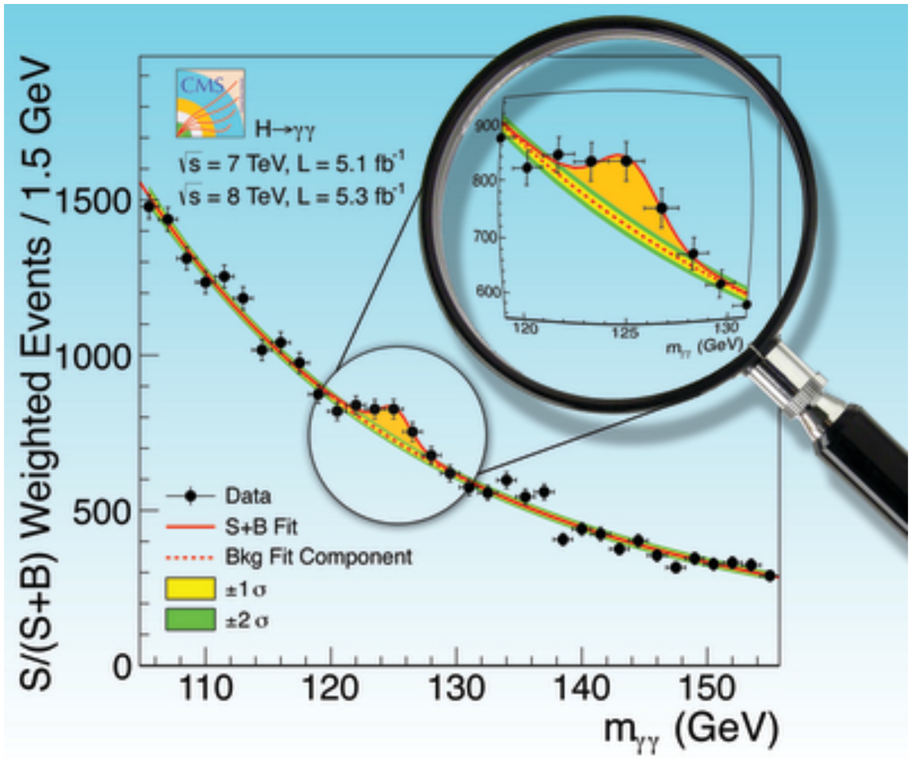
Invariant mass distribution of diphoton candidates for the combined 7 TeV and 8 TeV data samples. The result of a fit to the data of the sum of a signal component fixed to m_H = 126.5 GeV and a background component described by a fourth-order Bernstein polynomial is superimposed. The bottom inset displays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

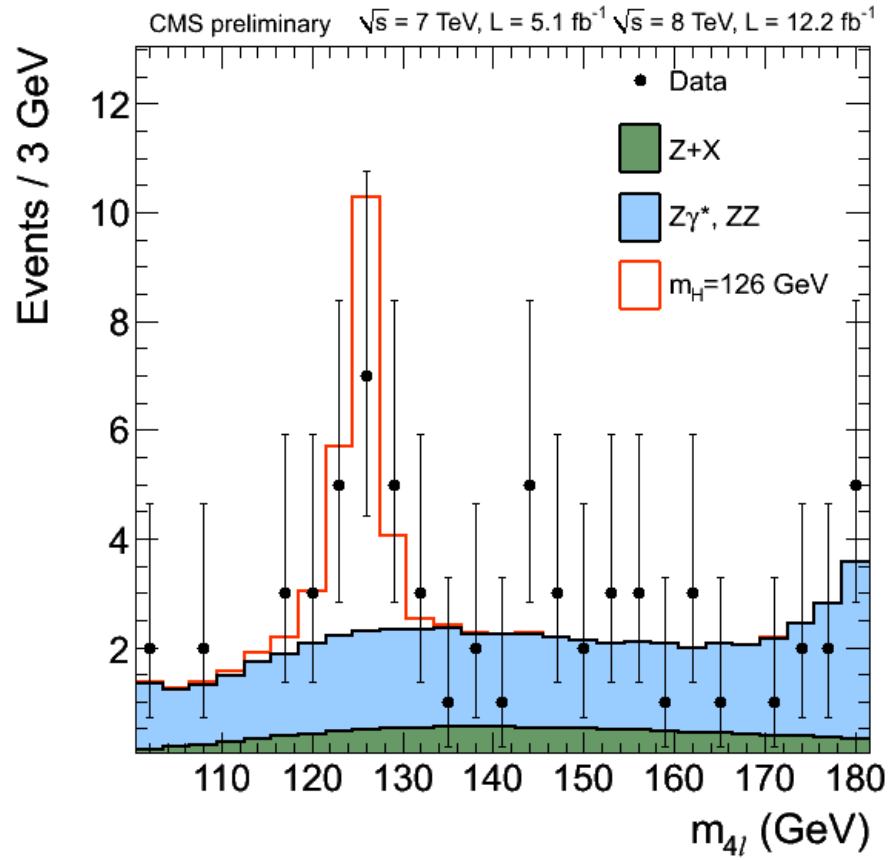


The distribution of the four-lepton invariant mass, m_{4l}, for the selected candidates, compared to the background expectation in the 80 to 250 GeV mass range, for the combination of the 7 TeV 8 TeV data. The signal expectation for a Higgs boson with m_H=125 GeV is also shown.

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

A boson is discovered at the LHC by the CMS Collaboration

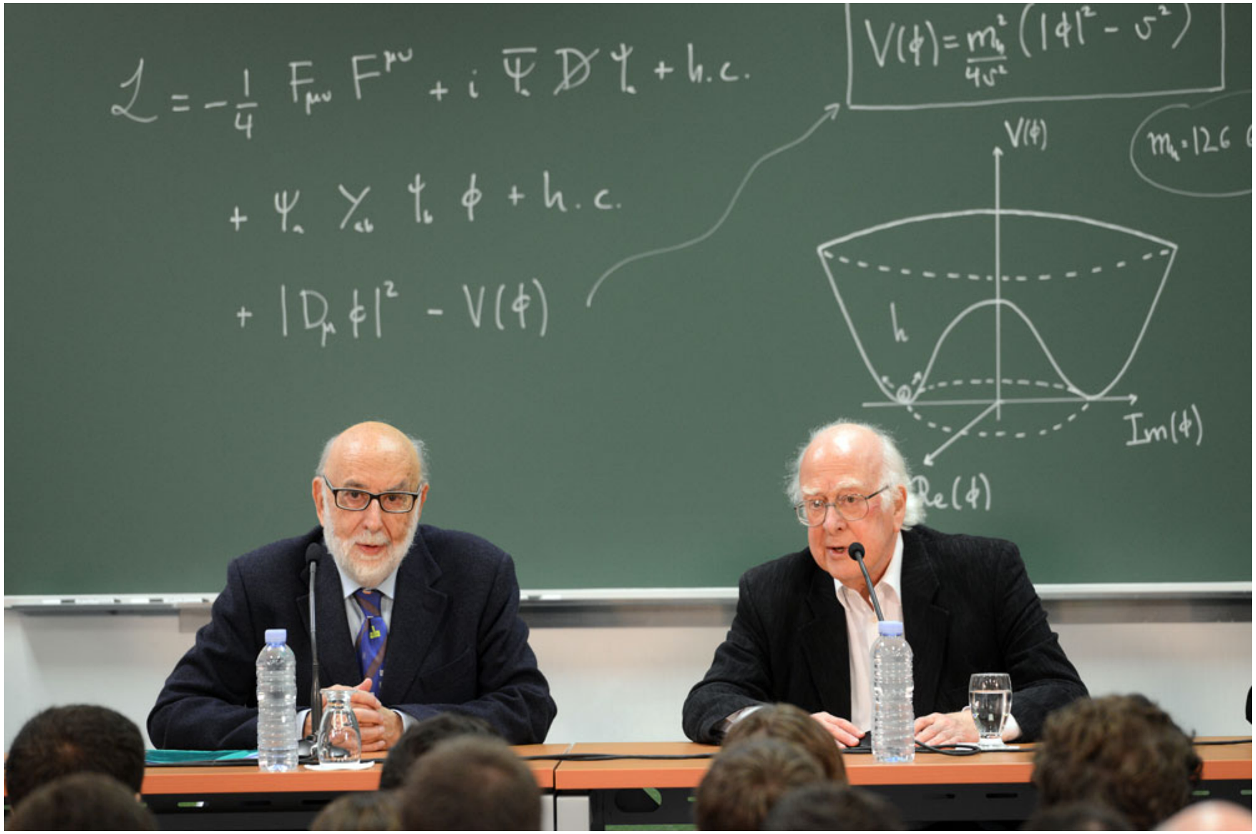




The diphoton invariant mass distribution with each event weighted by the S/(S+B) value of its category. The lines represent the fitted background and signal, and the colored bands represent the ±1 and ±2 standard deviation uncertainties in the background estimate. The inset shows the central part of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

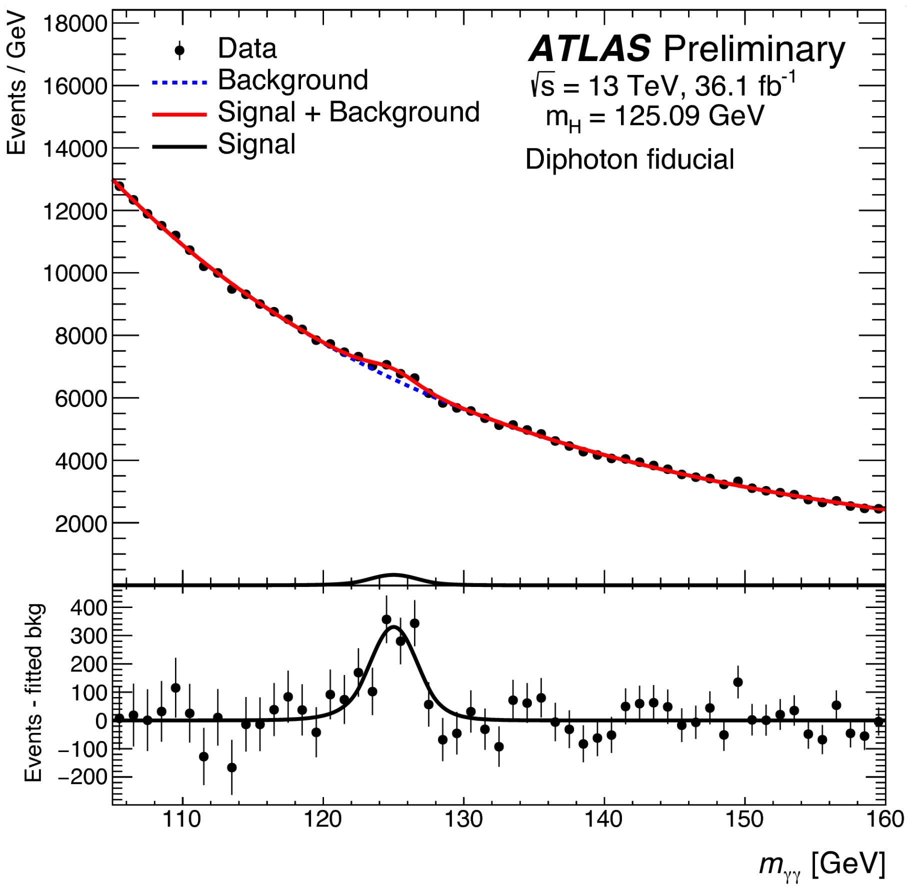


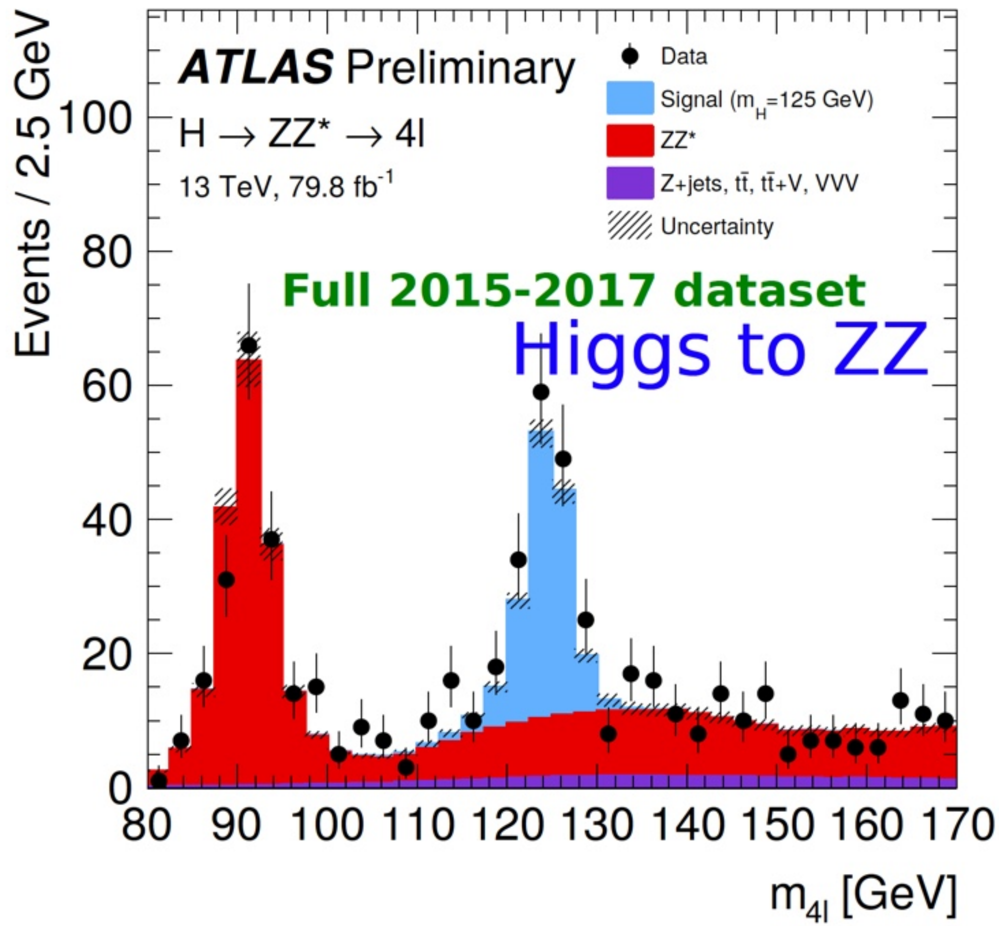
François Englert

and

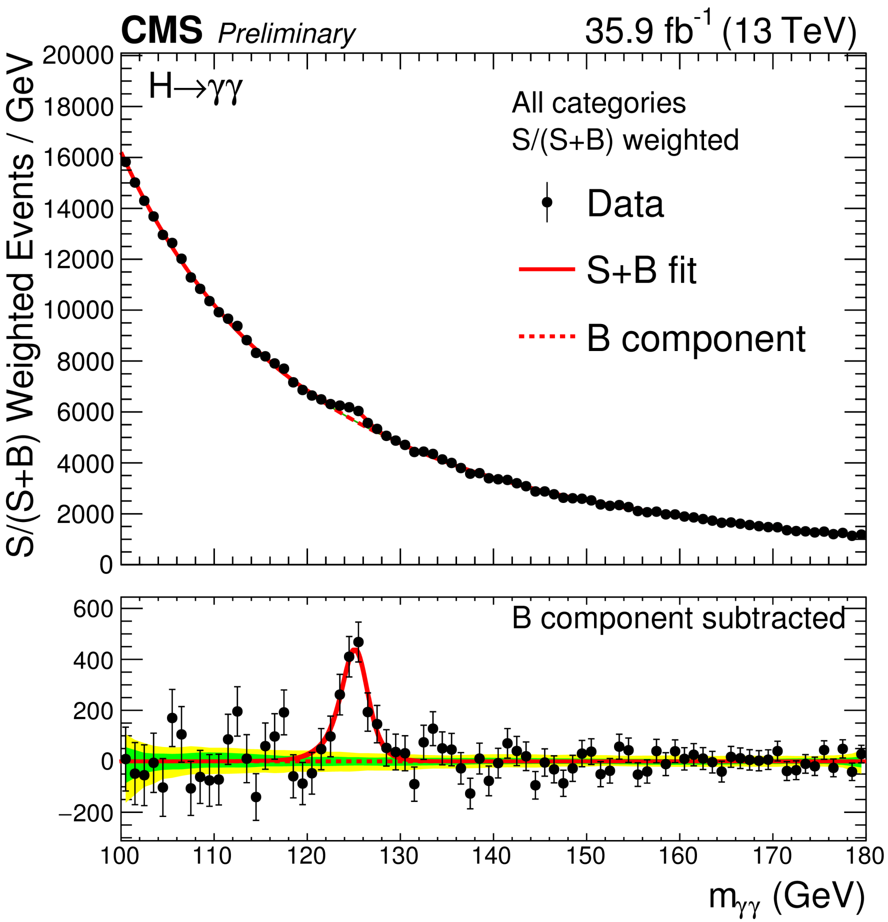
Peter Higgs

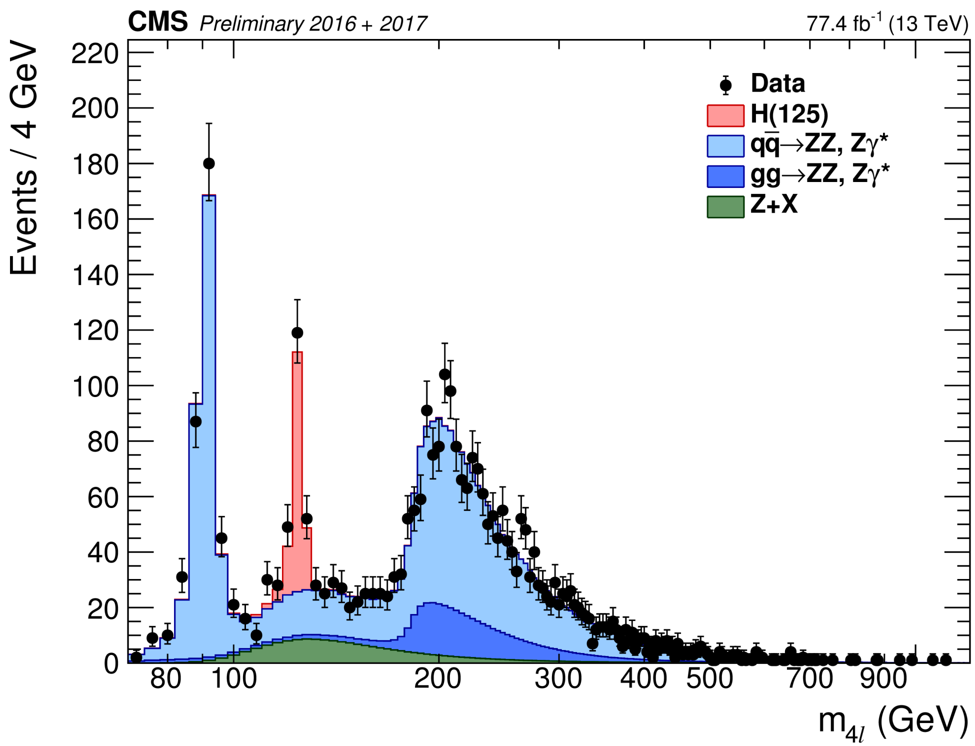
ATLAS Run-2 observations of the Higgs boson





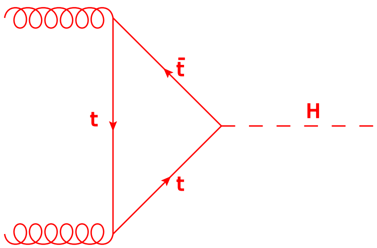
CMS Run-2 observations of the Higgs boson



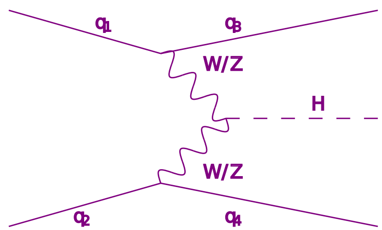


ATLAS observed Higgs boson interactions

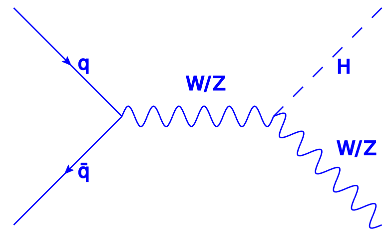
Higgs production mechanisms



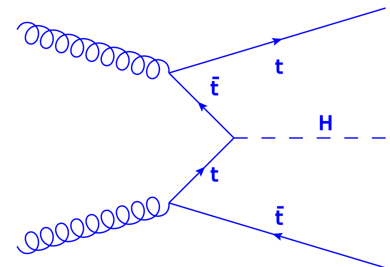
ggF
Run 1



VBF
Run 1 (ATLAS+CMS)
Run 2 (ATLAS alone)

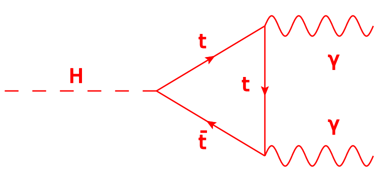


VH
2018

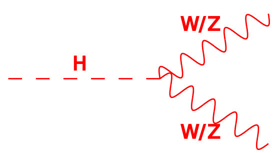


ttH
2018

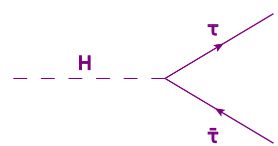
Higgs decay modes



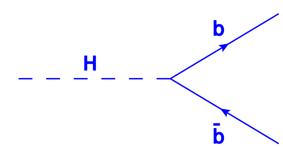
Hγγ
Run 1



HWW/HZZ
Run 1

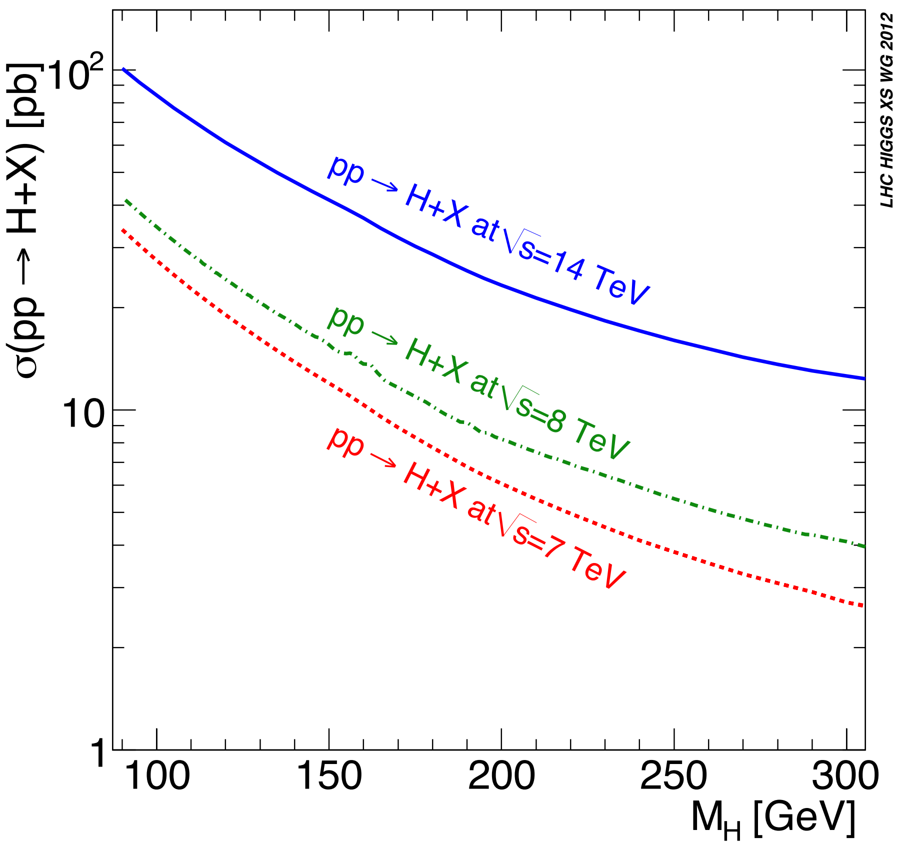


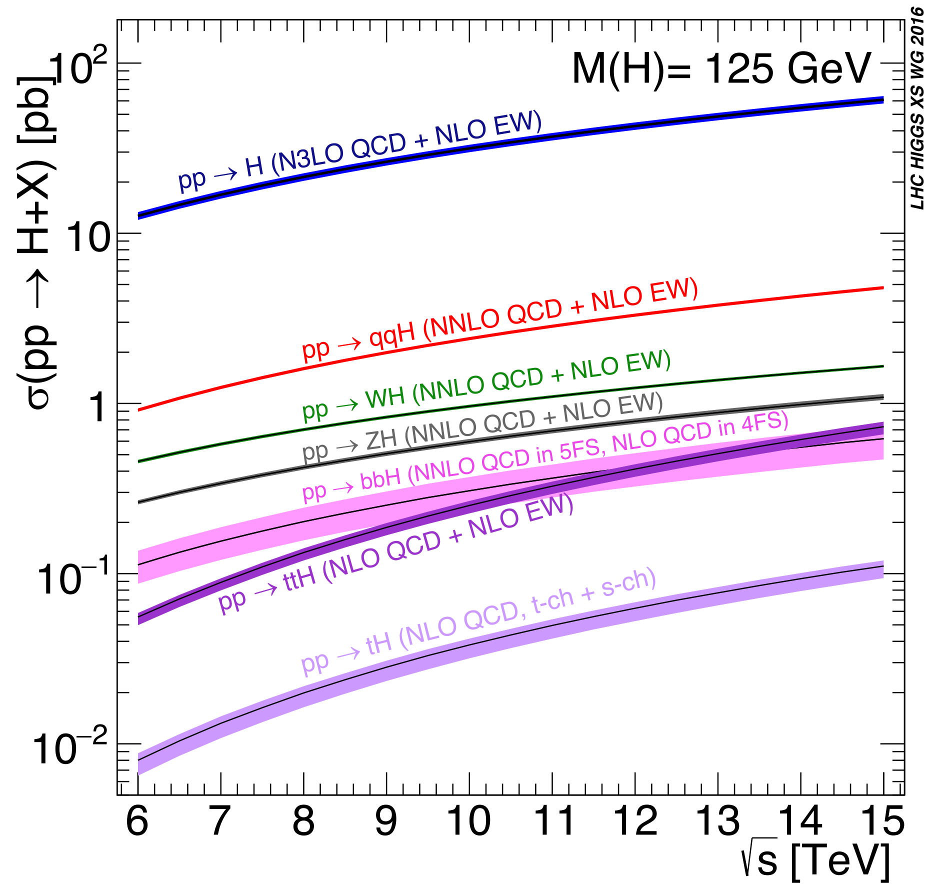
Hττ
Run 1 (ATLAS+CMS)
2018 (ATLAS alone)



Hbb
2018

Higgs boson production cross sections at a pp collider





With nearly 150 fb^{-1} of data delivered by the LHC in Run 2 to both ATLAS and CMS in 2015—2018 at a center of mass energy of 13 TeV, roughly 7.5 million Higgs bosons per experiment were produced, assuming the Higgs mass is 125 GeV.

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
$H^0 \rightarrow \boldsymbol{\tau}^+ \boldsymbol{\tau}^-$	6.27×10^{-2}
$h^0 \rightarrow \boldsymbol{\ell}^+ \boldsymbol{\ell}^- \boldsymbol{\nu\nu}$ ($\boldsymbol{\ell} = \boldsymbol{e}$ or $\boldsymbol{\mu}$)	1.06×10^{-2}
$h^0 \rightarrow \boldsymbol{\gamma\gamma}$	2.27×10^{-3}
$h^0 \rightarrow \boldsymbol{\ell}^+ \boldsymbol{\ell}^- \boldsymbol{\ell}^+ \boldsymbol{\ell}^-$ ($\boldsymbol{\ell} = \boldsymbol{e}$ or $\boldsymbol{\mu}$)	1.24×10^{-4}

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

Remarks:

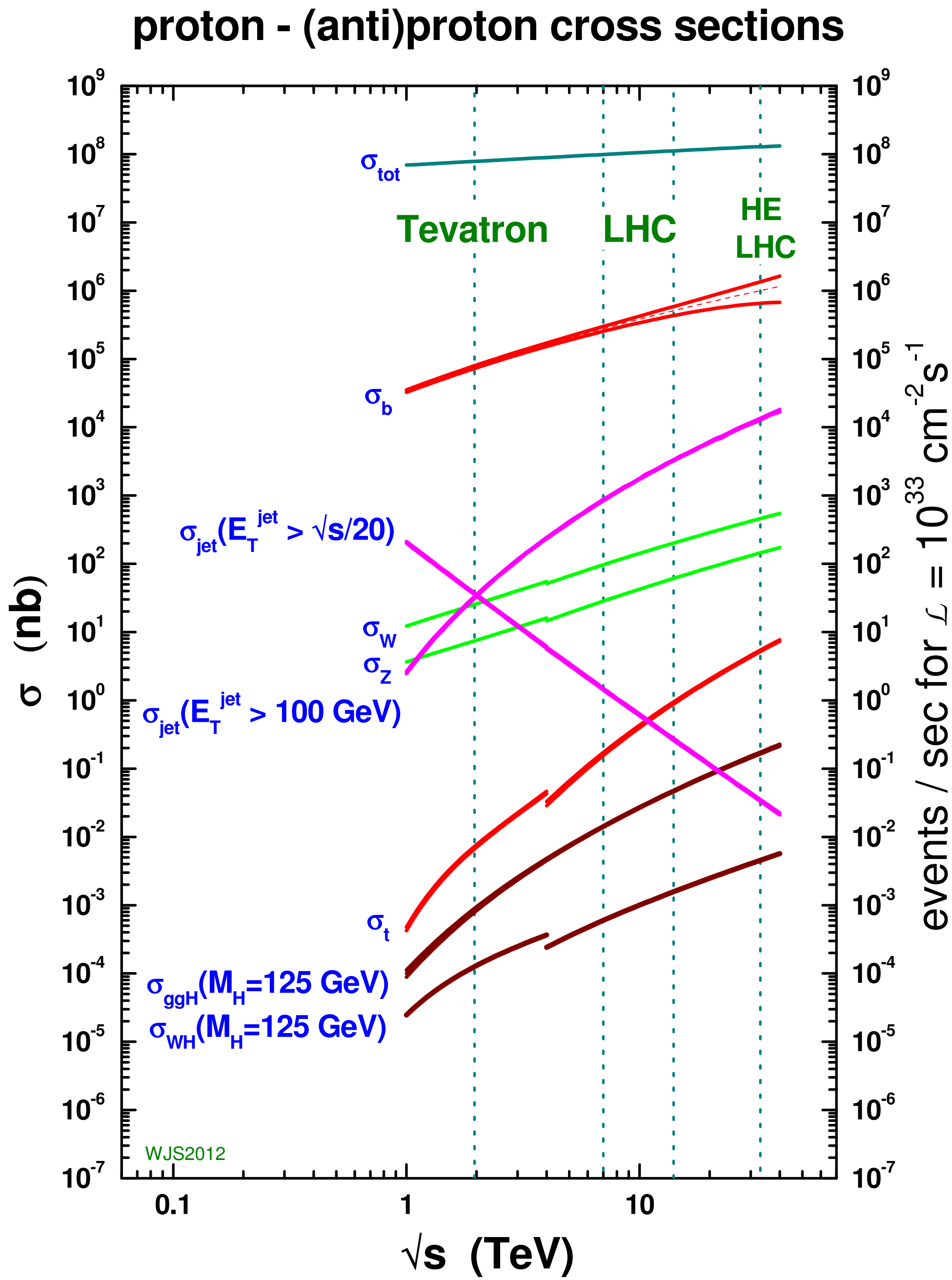
1. $h^0 \rightarrow WW^*$ is observed primarily via the $\boldsymbol{\ell}^+ \boldsymbol{\nu} \boldsymbol{\ell}^- \boldsymbol{\nu}$ ($\boldsymbol{\ell} = \boldsymbol{e}$ or $\boldsymbol{\mu}$) final state.
2. $h^0 \rightarrow ZZ^*$ is observed primarily via the $\boldsymbol{\ell}^+ \boldsymbol{\ell}^-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

Nevertheless, the observation of H → bb in the VH channel was confirmed by ATLAS and CMS in 2018!

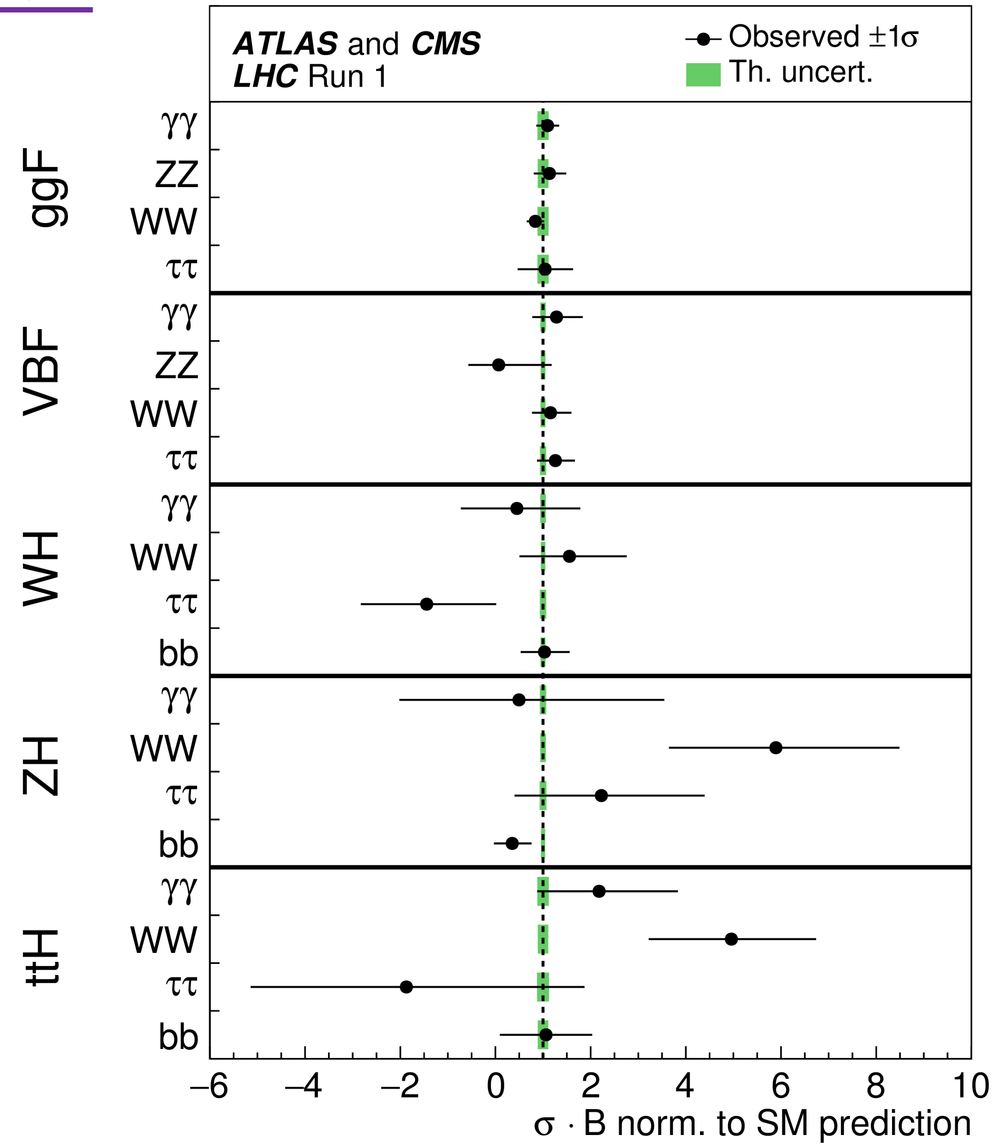


Is the observed 125 GeV scalar the SM Higgs boson?

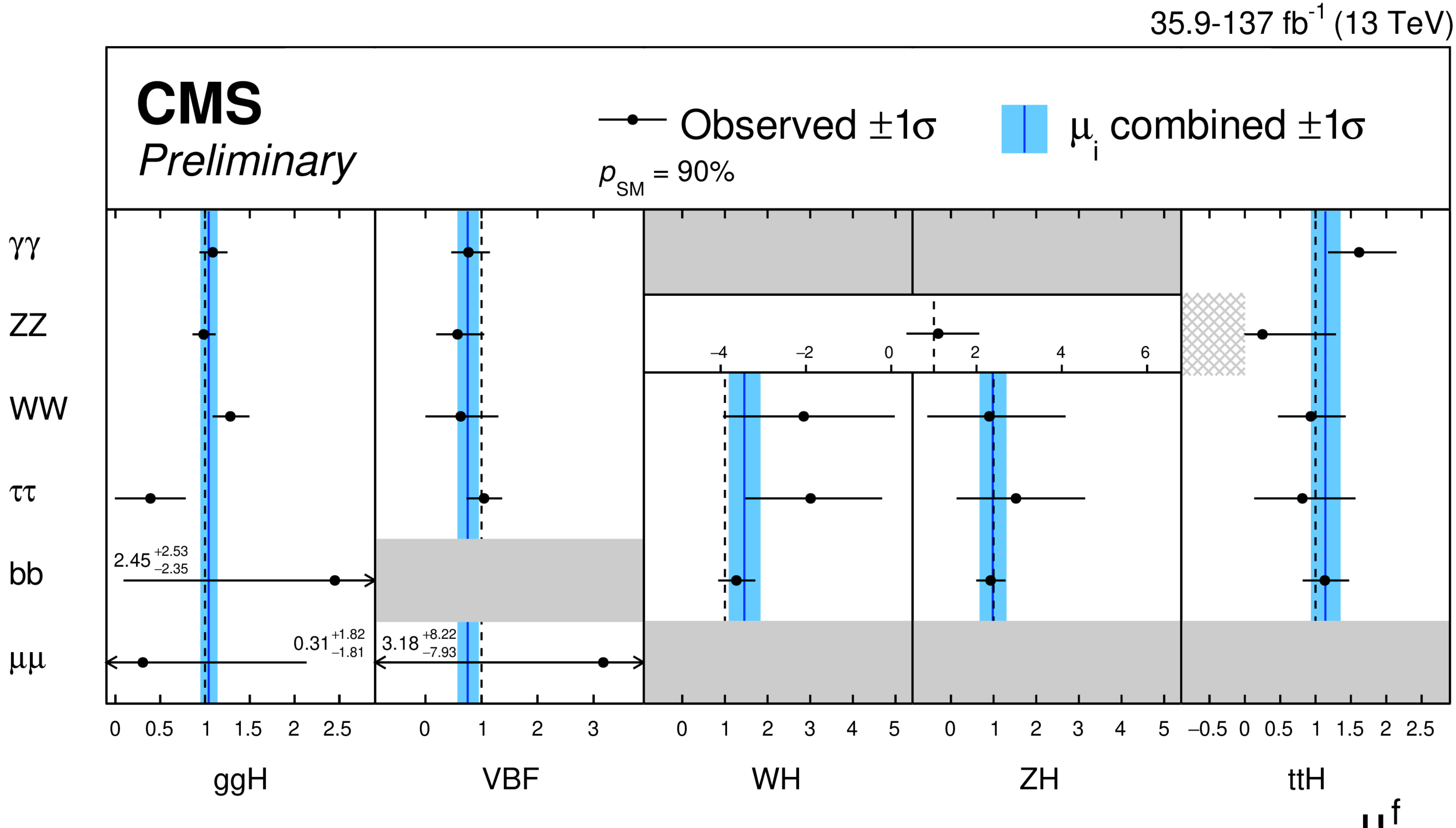
After the end of Run-1 of the LHC (2011—2013), the ATLAS and CMS Collaborations provided a combined analysis of the Higgs boson data.

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

The Higgs data taken at Run-2 of the LHC (2015—2018) have confirmed the Run-1 observations (with potential deviations from the Standard Model further reduced).

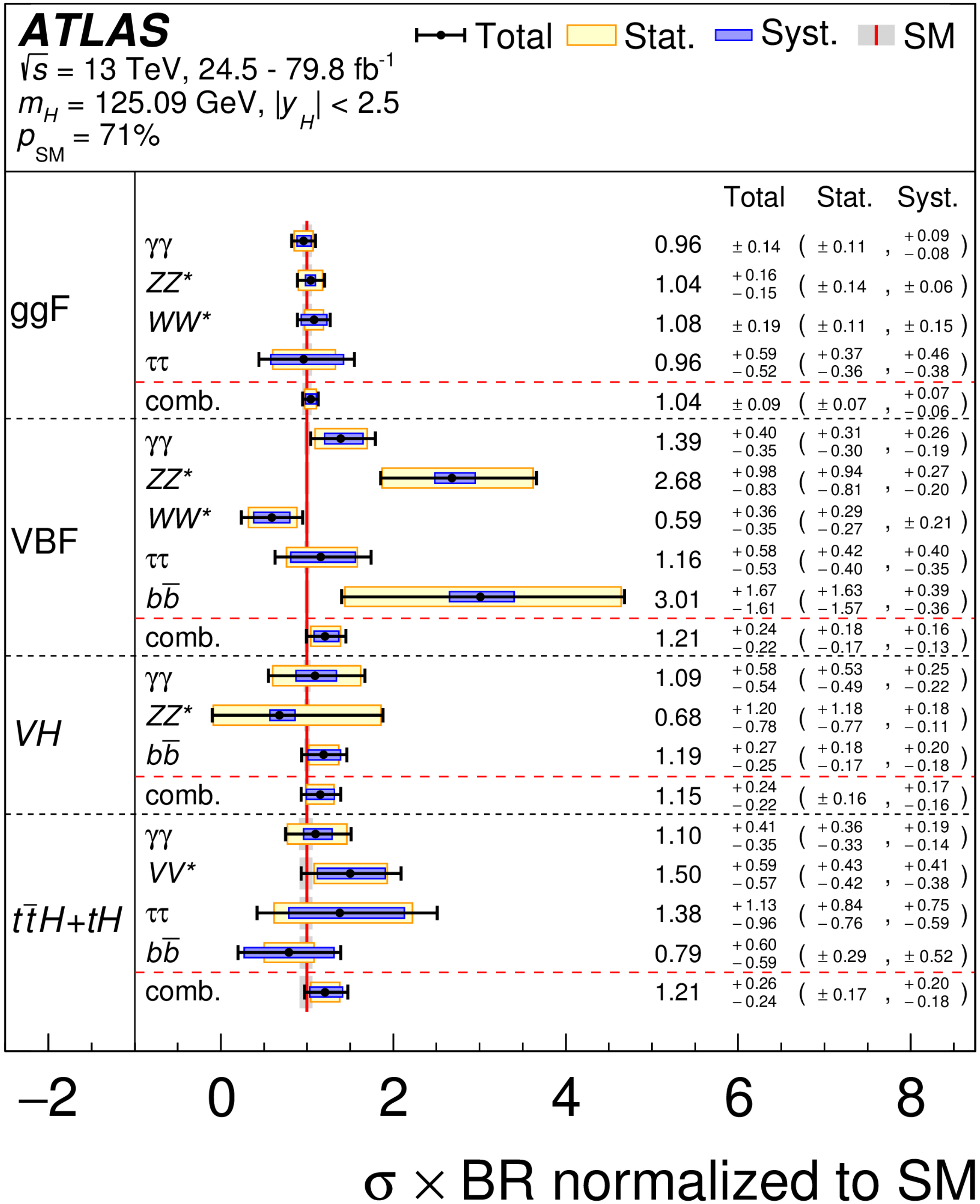


Taken from G. Aad *et al.* (ATLAS and CMS Collaborations) JHEP **1608** (2016) 045.



Taken from CMS Collaboration, CMS-PAS-HIG-19-005 (January, 2020).

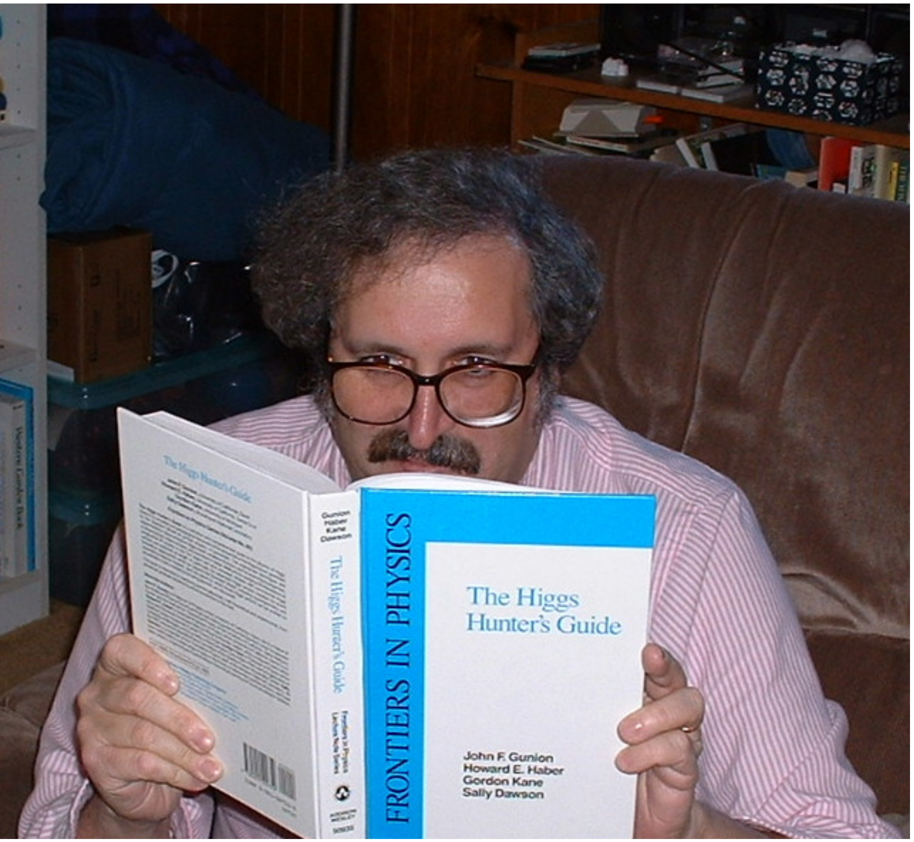
Signal strength modifiers for the production times decay mode, μ^f_i. The black points and horizontal error bars show the best-fit values and 1σ confidence intervals, respectively. The arrows indicate cases where the confidence intervals exceed the scale of the horizontal axis. The gray filled boxes indicate signal strength modifiers which are not included in the model, while the gray hatched box indicates the region for which the sum of signal and background becomes negative in the fit for μ^{ZZ}_{ttH}. In the $\mathrm{H}\to\mathrm{ZZ}$ decay mode, a common modifier is fit to the WH and ZH production modes. The measured value and 1σ confidence interval for each production cross section modifier, μ_i, from the combination across decay channels, is indicated by the blue vertical line, and the blue bands, respectively. The indicated p-value is given for the production times decay mode signal strength modifiers.



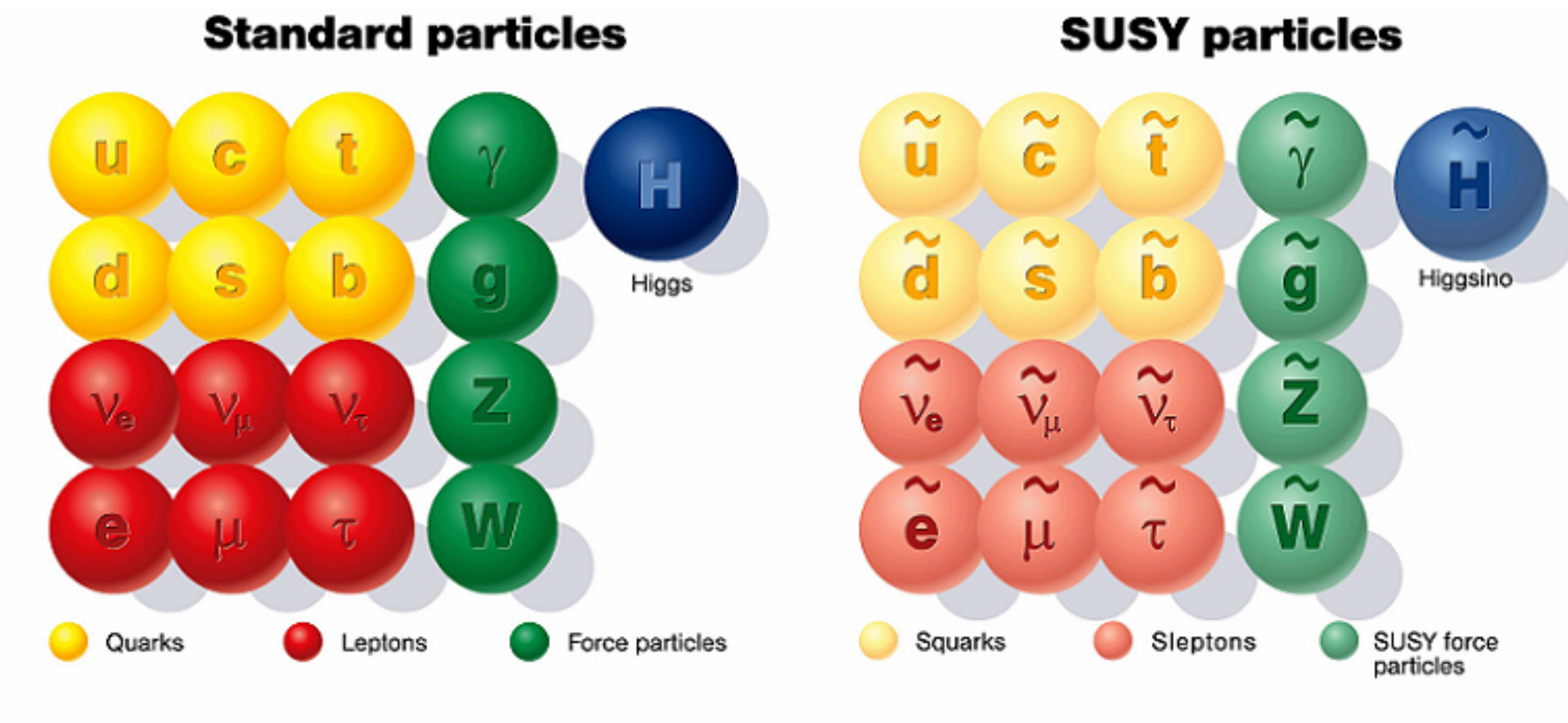
Taken from ATLAS collaboration, Phys. Rev. **D** 101, 012002 (2020) [arXiv:1909.02845].

Cross sections times branching fraction for ggF, VBF, VH and tt̄H+tH production in each relevant decay mode, normalized to their SM predictions. The values are obtained from a simultaneous fit to all channels. The cross sections of the ggF, $H \to b\bar{b}$, VH, $H \to WW^*$ and VH, $H \to \tau\tau$ processes are fixed to their SM predictions. Combined results for each production mode are also shown, assuming SM values for the branching fractions into each decay mode. The black error bars, blue boxes and yellow boxes show the total, systematic, and statistical uncertainties in the measurements, respectively. The gray bands show the theory uncertainties in the predictions.

Research program 1: theory and phenomenology of Higgs bosons

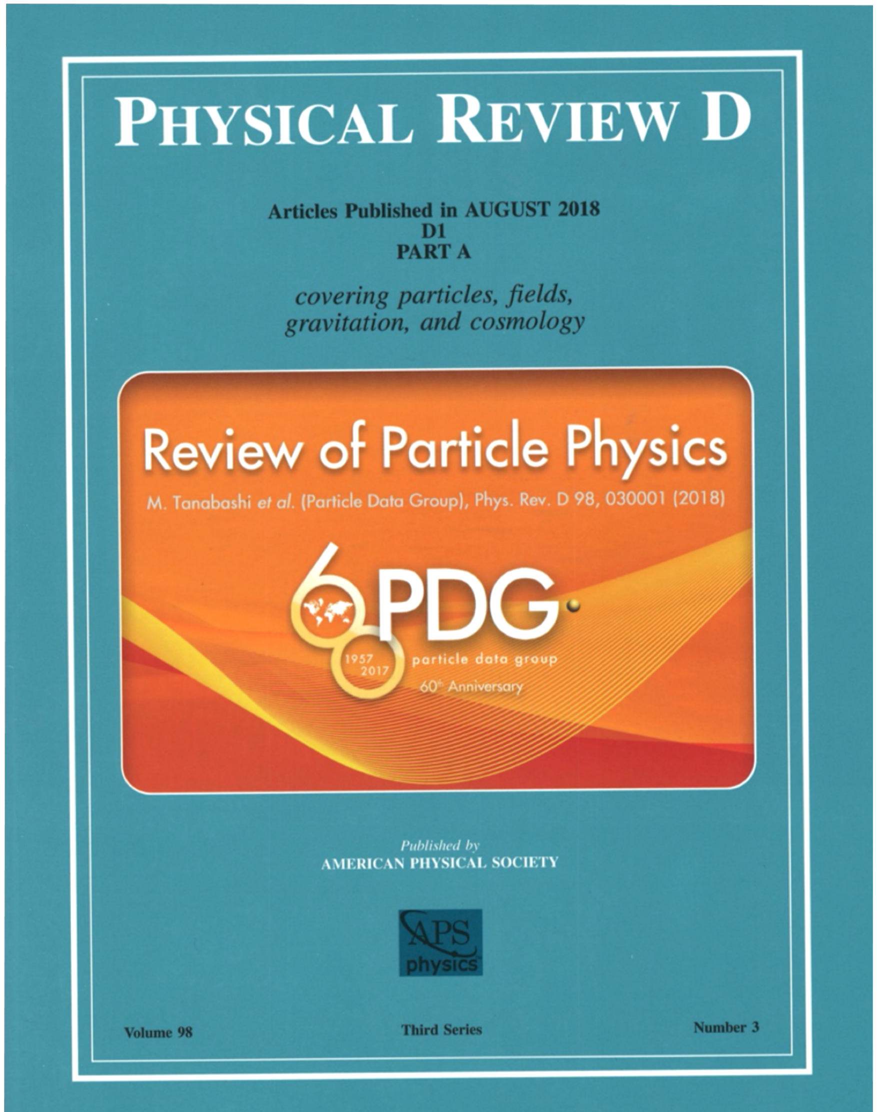


Research program 2: theory and phenomenology of TeV-scale supersymmetry (SUSY)



For a review, see H.E. Haber, *Supersymmetry Theory*, in M. Tanabashi et al. [Particle Data Group Collaboration], *Review of Particle Physics*, Phys. Rev. D **98**, 030001 (2018) pp. 790—806. The most recent 2019 update in collaboration with B.C. Allanach can be found at: http://pdg.lbl.gov/2019/reviews/rpp2019-rev-susy-1-theory.pdf.

As a member of the Particle Data Group, I am the author of the biennial Supersymmetry Theory review. This review was recently updated in collaboration with B.C. Allanach.



109. Supersymmetry, Part I (Theory)

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

109.1. 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

electroweak symmetry breaking, provides
origin and the stability of the gauge hiera

At present, there is no unambiguous
the breakdown of the Standard Model a
The expectations for new TeV-scale phy
Model are based primarily on three theo
a theory with an elementary scalar field
strength λ (e.g., a quartic scalar self-cou
coupling or the square of a Yukawa co
respect to quantum corrections requires
cutoff roughly of order $(16\pi^2/\lambda)^{1/2}m$, b
must enter [14]. A significantly larger e
an unnatural fine-tuning of parameters t
theory. Applying this argument to the St
expectation of new physics at the TeV sca

Second, the unification of the three Sta
at a very high energy close to the Planc
physics beyond the Standard Model (wh
of the gauge couplings above the electro
minimal supersymmetric extension of the
where superpartner masses lie below a fe
of successful gauge coupling unification [1

Third, the existence of dark matter, wh
one quarter of the energy density of the u
within the Standard Model of particle p
stable weakly-interacting massive particle
interaction rate are governed by new ph
TeV-scale can be consistent with the obse
(this is the so-called WIMP miracle, which
lightest supersymmetric particle, if stable
not the unique) candidate for the dark ma
of dark matter can be found in Ref. 23.

109.2. Structure of the MSSM

The minimal supersymmetric extensio
consists of the fields of the two-Higgs-d
Standard Model and the corresponding
particle and its superpartner together fo
corresponding field content of the superm

Research program 3: explorations of the Terascale at the LHC and at future colliders

- 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)

Recent Publications

Basis-independent treatment of the C2HDM
R. Boto, T.V. Fernandes, H.E. Haber, J.C. Romão and J.P. Silva, arXiv:2001.01430 [hep-ph]

Symmetries and mass degeneracies in the scalar sector
H.E. Haber, O.M. Ogreid, Per Osland and M.N. Rebelo, JHEP **1901** (2019) 042.

Heavy Higgs boson decays in the alignment limit of the 2HDM
B. Grzadkowski, H.E. Haber, O.M. Ogreid and Per Osland, JHEP **1812** (2018) 056.

Multi-Higgs doublet models: the Higgs-fermion couplings and their sum rules
M.P. Bento, H.E. Haber, J.C. Romão and J.P. Silva, JHEP **1810** (2018) 143.

Approximate Higgs alignment without decoupling
H.E. Haber, in the Proceedings of the 53th Rencontres de Moriond, QCD Session, March 17—24, 2018, in La Thuile, Aosta Valley, Italy, edited by E. Augé, J. Dumarchez and J. Trân Thanh Vân (ARISF Publishers, France, 2018) pp. 139–142.

Supersymmetric theory and models
H.E. Haber and L. Stephenson Haskins, arXiv:1712.05926 [hep-ph], in Chapter 6 of *TASI 2016: Anticipating the Next Discoveries in Particle Physics*, edited by Rouven Essig and Ian Low (World Scientific, Singapore, 2018) pp. 355--499.

UCSC graduate student authors in red.

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?

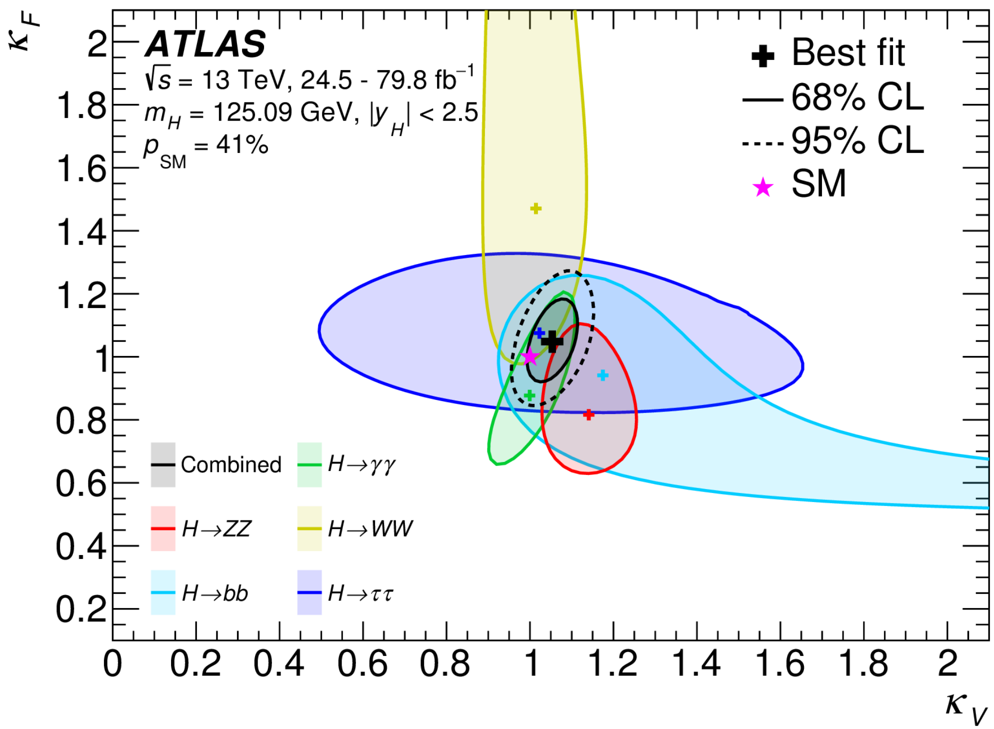
- Adding new scalar states can alleviate the metastability of the vacuum, allowing the Higgs-sector-extended SM to be valid all the way up to the Planck scale.

- Extended Higgs sectors can provide a dark matter candidate.

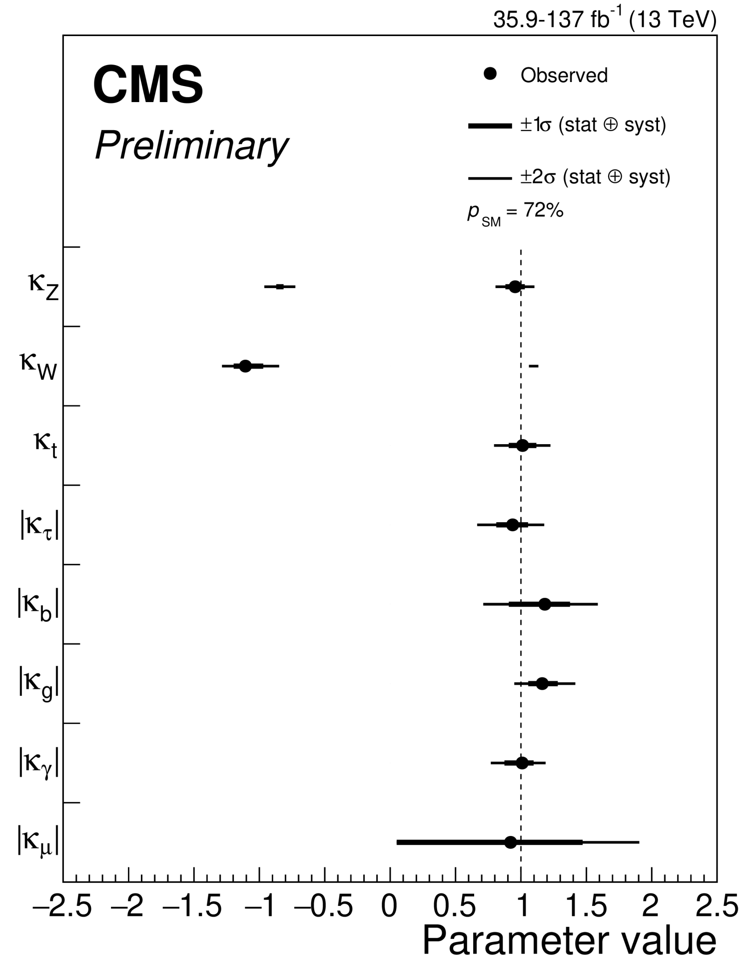
- Extended Higgs sectors can provide new sources of CP violation (which may be useful in baryogenesis).

- 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, κ_V) plane for the individual decay channels and the combined fit, assuming that the coupling strengths to fermions and vector bosons to be positive. No contributions from invisible or undetected Higgs boson decays are assumed. The best-fit value for each measurement is indicated by a cross while the SM hypothesis is indicated by a star. Taken from ATLAS collaboration, Phys. Rev. **D** 101, 012002 (2020).



Summary of the κ framework model assuming that there are no additional BSM contributions to the Higgs boson width, i.e. BR_{BSM}=0. The points indicate the best fit values while the thick and thin horizontal bars show the 1σ and 2σ CL intervals, respectively. Taken from CMS Collaboration, CMS-PAS-HIG-19-005 (January, 2020).

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. If flavor alignment is realized, then the diagonalization of the quark mass matrices simultaneously diagonalize the neutral Higgs quark interactions, which implies the absence of tree-level Higgs-mediated flavor-changing neutral currents 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.

Evidence for new physics beyond the SM in B decays to muon pairs?

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

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

which should be compared with the SM predictions,

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

In S. Gori, H.E. Haber and E. Santos, JHEP **1706** (2017) 110, new contributions to these decays 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.

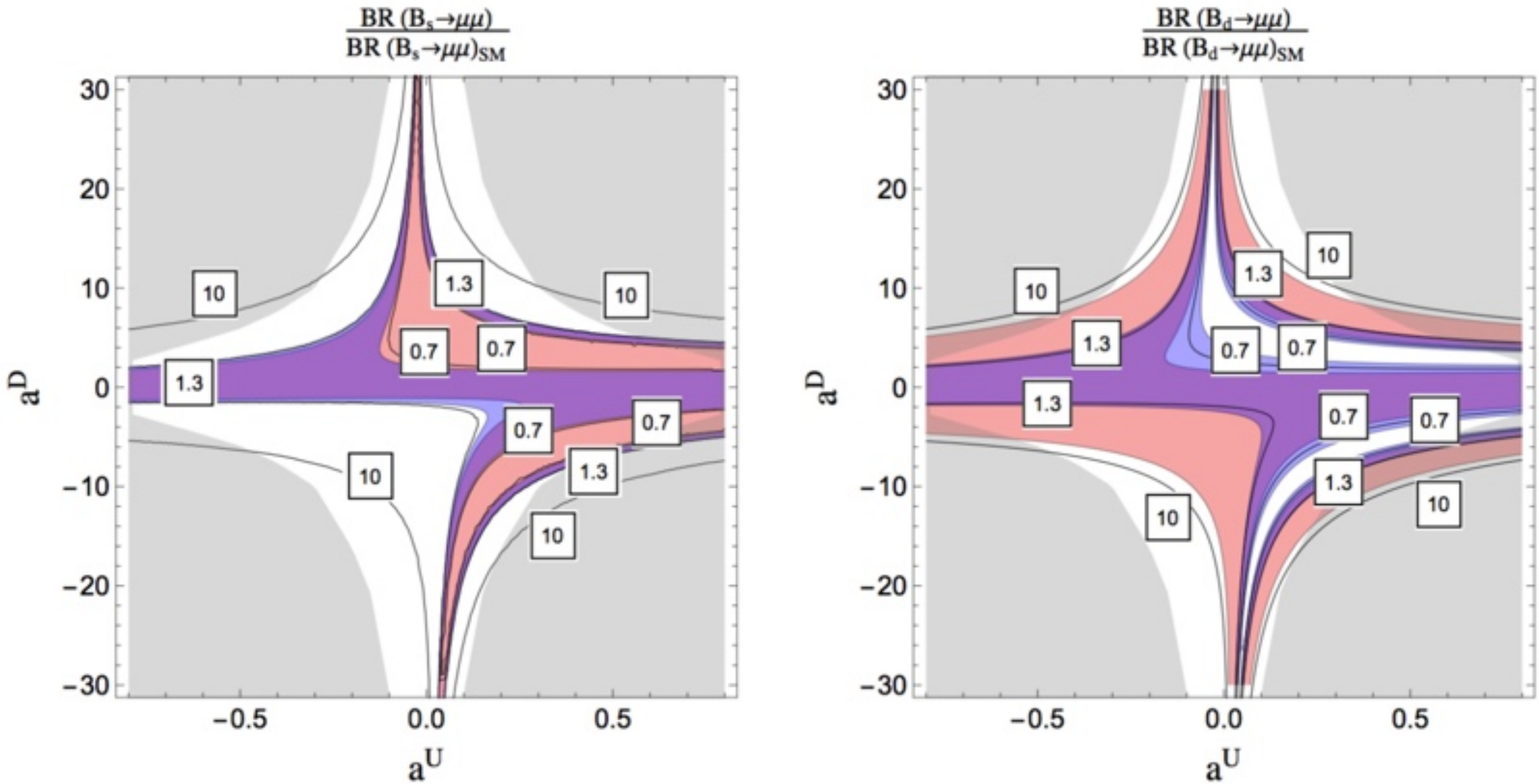


Figure 7. Leading log prediction for the branching ratios for $B_s \to \mu^+\mu^-$ (left panel) and $B_d \to \mu^+\mu^-$ (right panel) relative the SM, as a function of a^U and a^D, with fixed $\tan\beta = 10$, $\cos(\beta - \alpha) = 0$, and $m_A = m_H = 400$ GeV. The regions in pink are allowed at 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_{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; initially found employment in Silicon Valley.

E. Santos – presently works for Google

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

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

First postdoctoral position

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

Current position

Working in data science in San Francisco

We collaborated on two projects:

1. M. Dine, P. Draper, H.E. Haber and L. Stephenson 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], in Chapter 6 of *TASI 2016: Anticipating the Next Discoveries in Particle Physics*, edited by Rouven Essig and Ian Low (World Scientific, Singapore, 2018) pp. 355--499.

Supersymmetric Theory and Models

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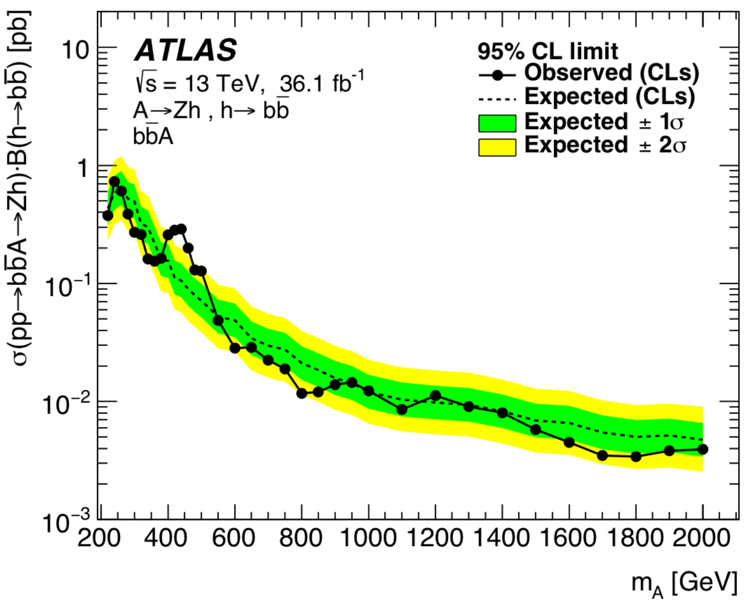
In these introductory lectures, we review the theoretical tools used in constructing supersymmetric field theories and their application to physical models. We first introduce the technology of two-component spinors, which is convenient for describing spin-$\frac{1}{2}$ fermions. After motivating why 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

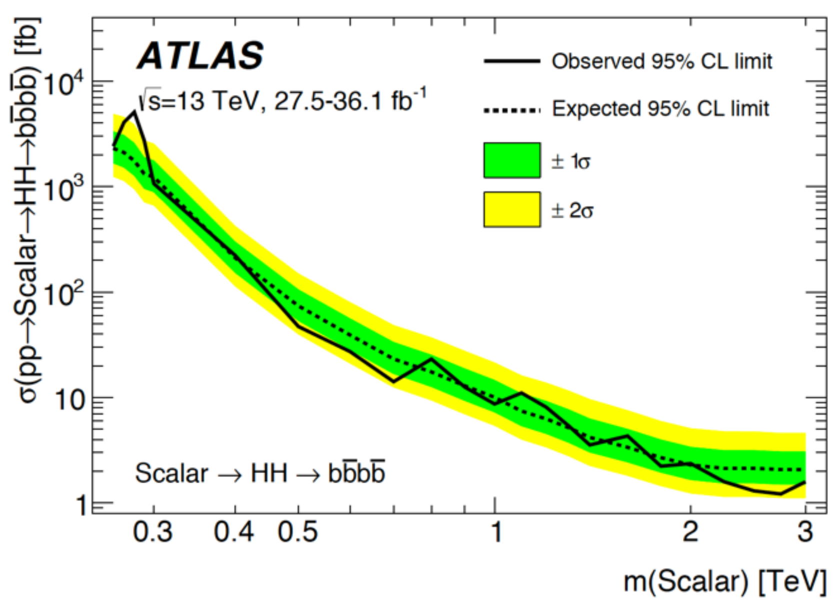
My current Ph.D. students and their projects

- 2HDM high energy flavor alignment (with S. Gori and E. Shahly)
  - Neutral Higgs-mediated flavor violation in the lepton sector.

- Phenomenological aspects of more general 2HDMs (with J. Connell and P. Ferreira)
  - Exploring some (local) $3\boldsymbol{\sigma}$ deviations in ATLAS searches for new Higgs bosons, with implications for the flavor-aligned 2HDM.



ATLAS Collaboration, JHEP **1803** (2018) 174



ATLAS Collaboration, JHEP **1901** (2019) 030

Other Ongoing and Future Activities

- Natural alignment without decoupling (with P. Draper,…)
  - Achieving a SM-like Higgs boson without fine-tuning.
- Theoretical studies of the CP-violating 2HDM (with J.P. Silva,…)
- Basis-invariant treatment of the 3HDM (with V. Keus)
- P-even CP-violating signals in scalar-mediated processes (with V. Keus, and T. Stefaniak)
- Higgs alignment at one loop (with S.J.D. King and H. Patel)
- Higgs alignment in 2HDM effective field theory
- Higgs alignment in the Georgi-Machacek model (with P. Ferreira, H. Logan and Y. Wu)

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