Research on the Theory of the Terascale

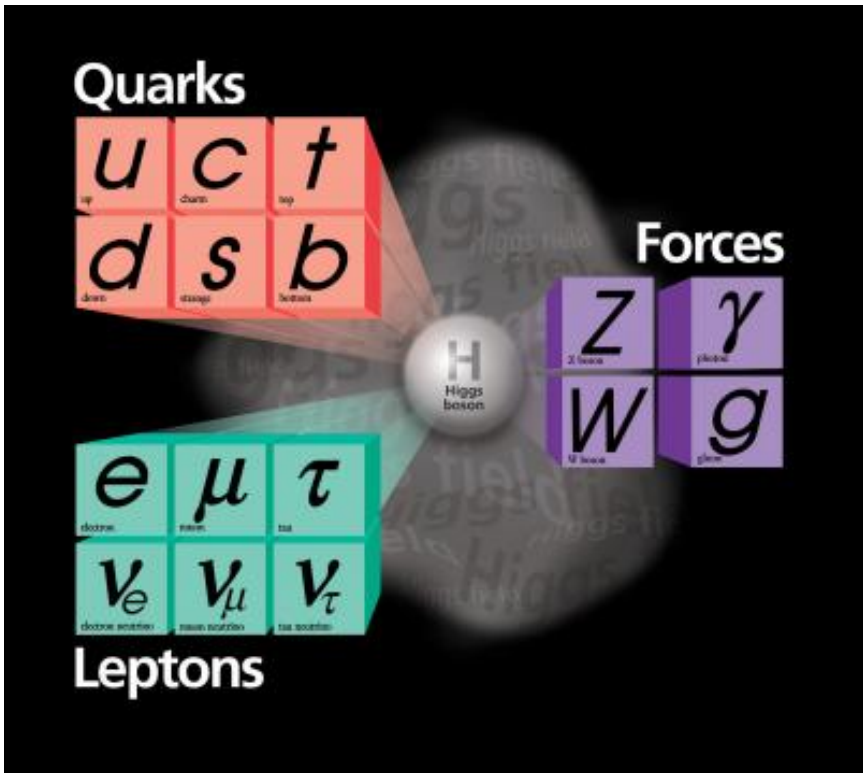
Howard Haber
SCIPP Theory
January 11, 2016

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

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

The Standard Model (SM) of Particle Physics



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

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

Origin of mass for elementary particles

Naively, an SU(3)xSU(2)xU(1) gauge theory yields massless gauge bosons and massless quarks and leptons, in conflict with observation. The Standard Model 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.

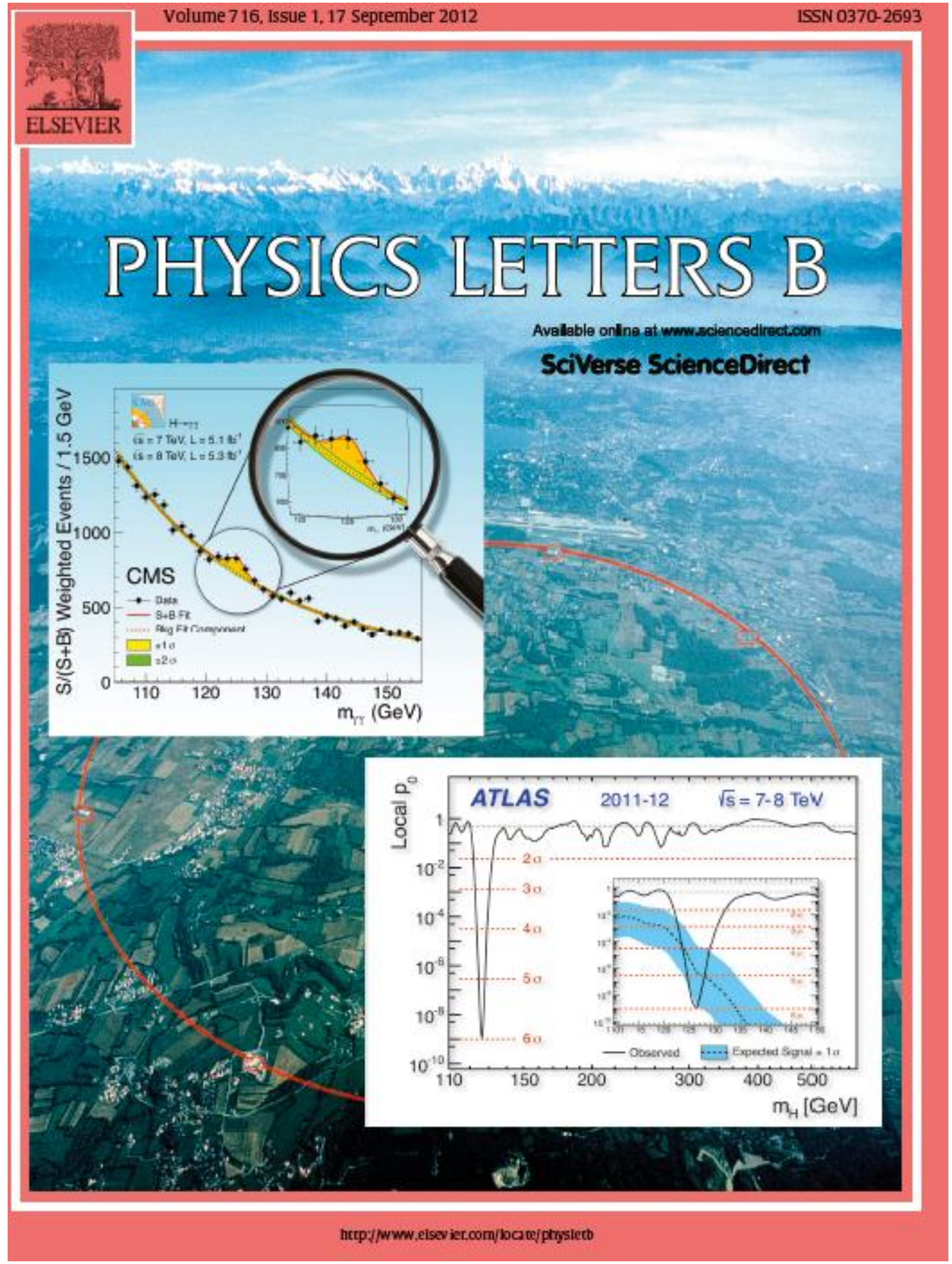
The discovery papers are published two months later In Physics Letters B.

<u>ATLAS Collaboration:</u>

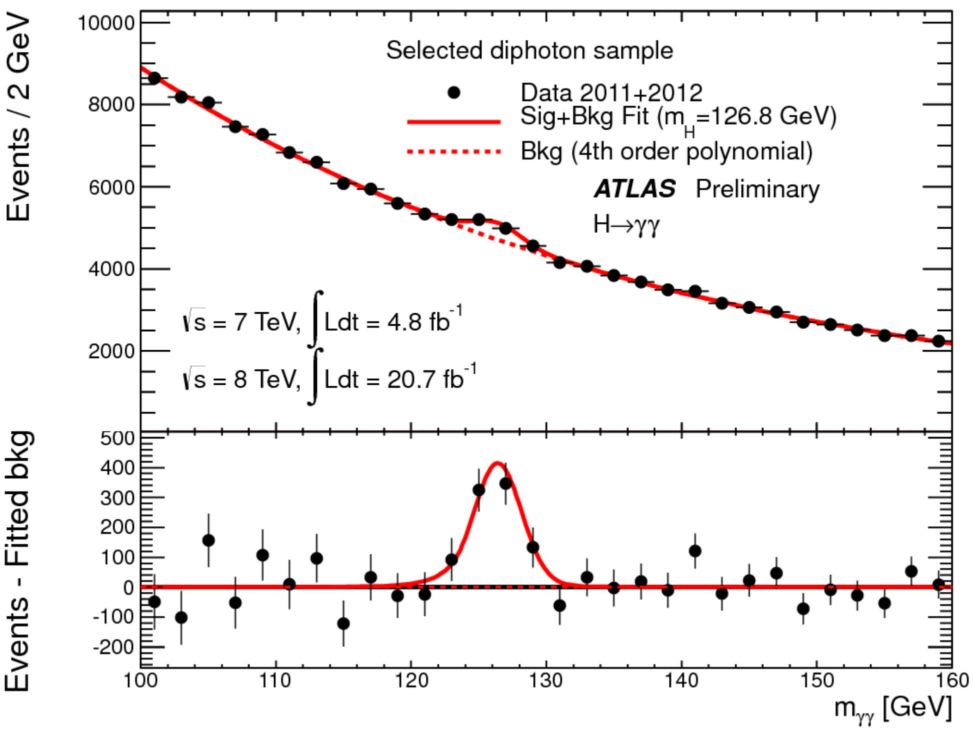
Physics Letters B716 (2012) 1—29

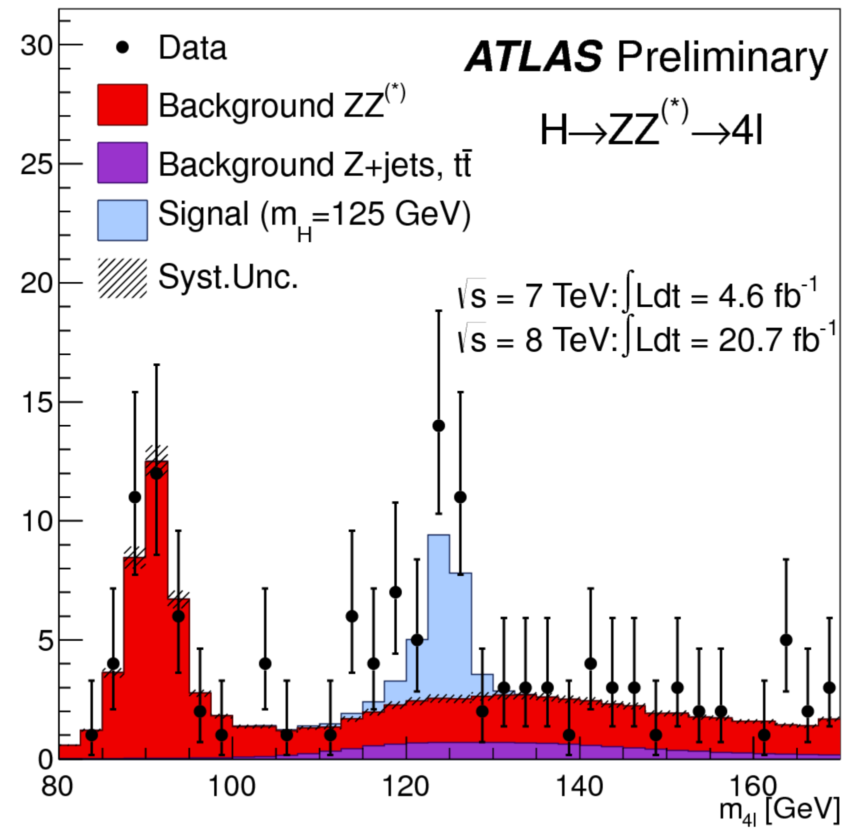
<u>CMS Collaboration:</u>

Physics Letters B716 (2012) 30—61



A boson is discovered at the LHC by the ATLAS Collaboration

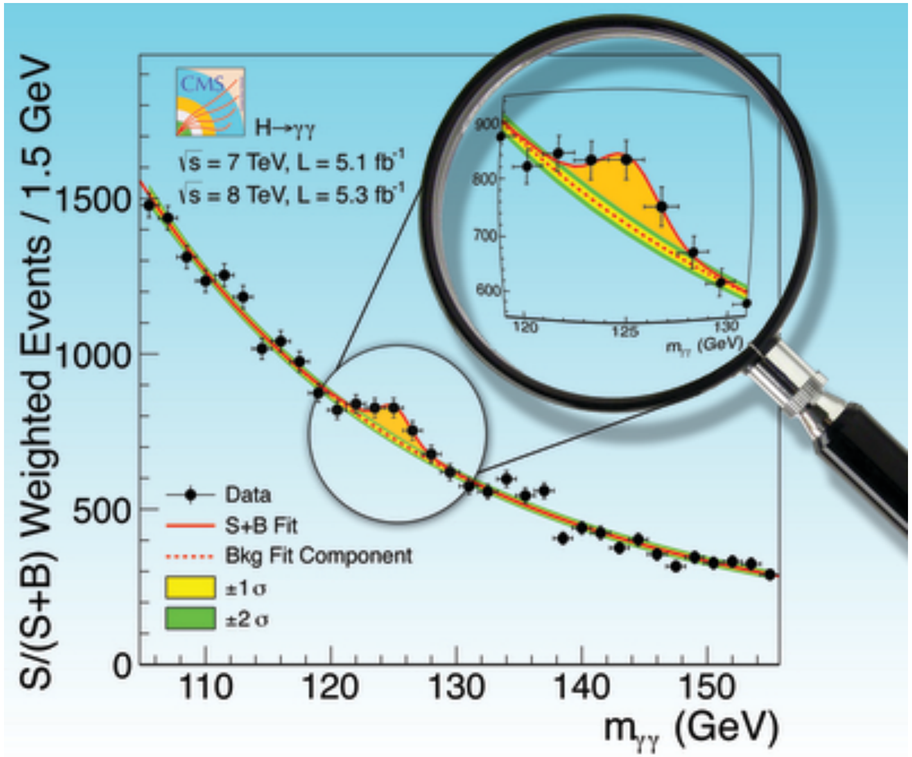


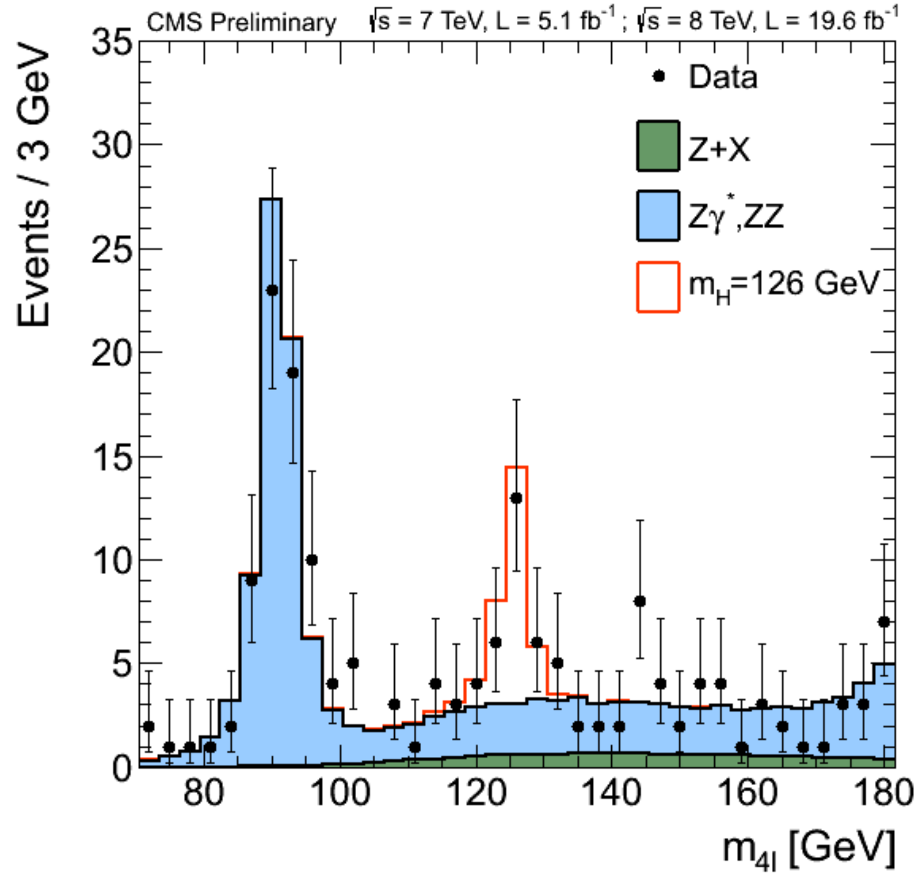


Invariant mass distribution of diphoton candidates for the combined 7 TeV and 8 TeV data samples. The result of a fit to the data of the sum of a signal component fixed to m_H = 126.8 GeV and a background component described by a fourth-order Bernstein polynomial is superimposed. The bottom inset displays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

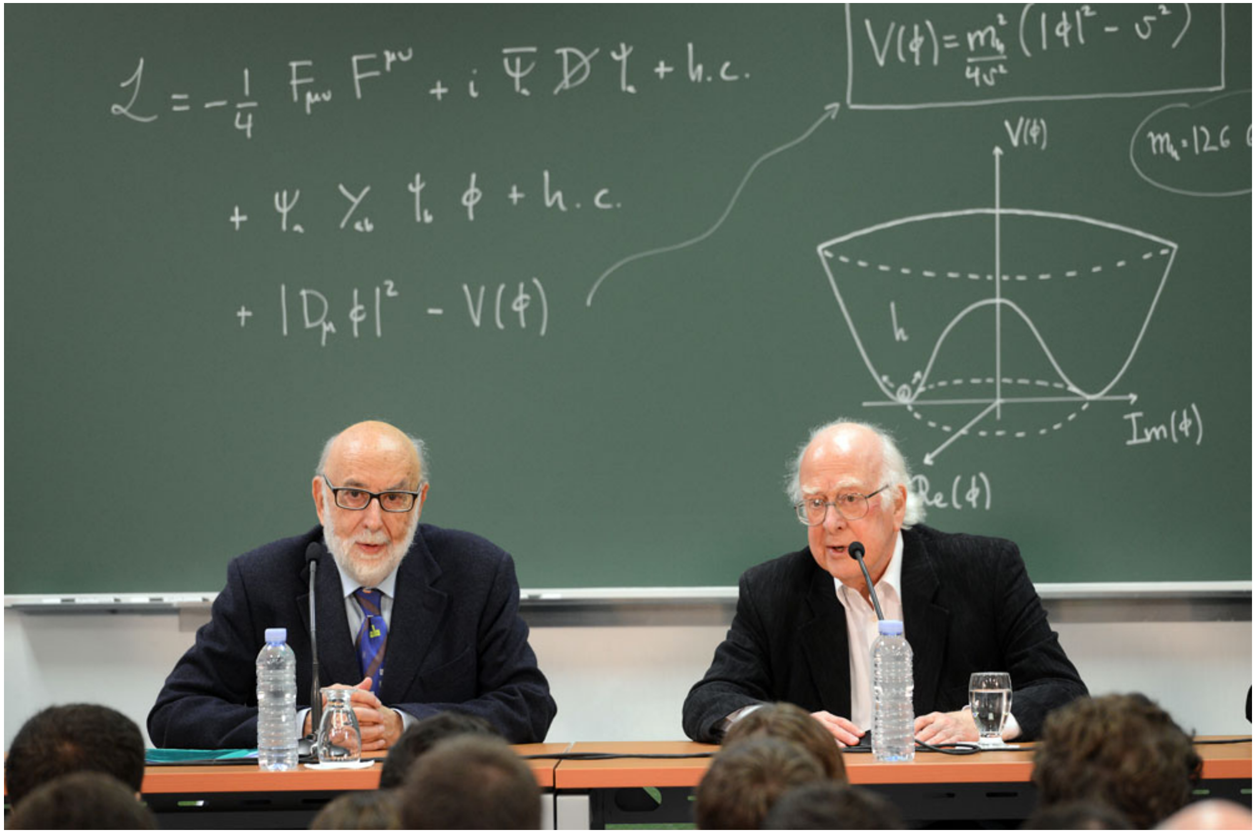




The diphoton invariant mass distribution with each event weighted by the S/(S+B) value of its category. The lines represent the fitted background and signal, and the colored bands represent the ±1 and ±2 standard deviation uncertainties in the background estimate. The inset shows the central part of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

Higgs production at hadron colliders

At hadron colliders, the relevant processes are

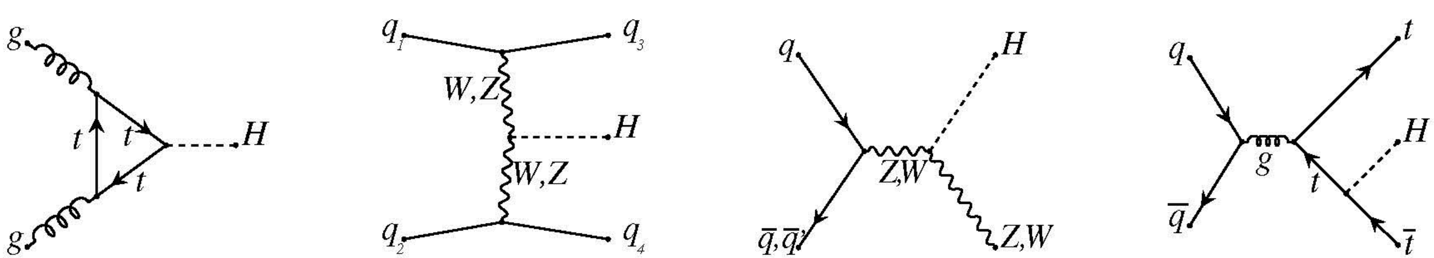
$$gg \to h^0\,, \quad h^0 \to \gamma\gamma\,, VV^{(*)}\,,$$

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

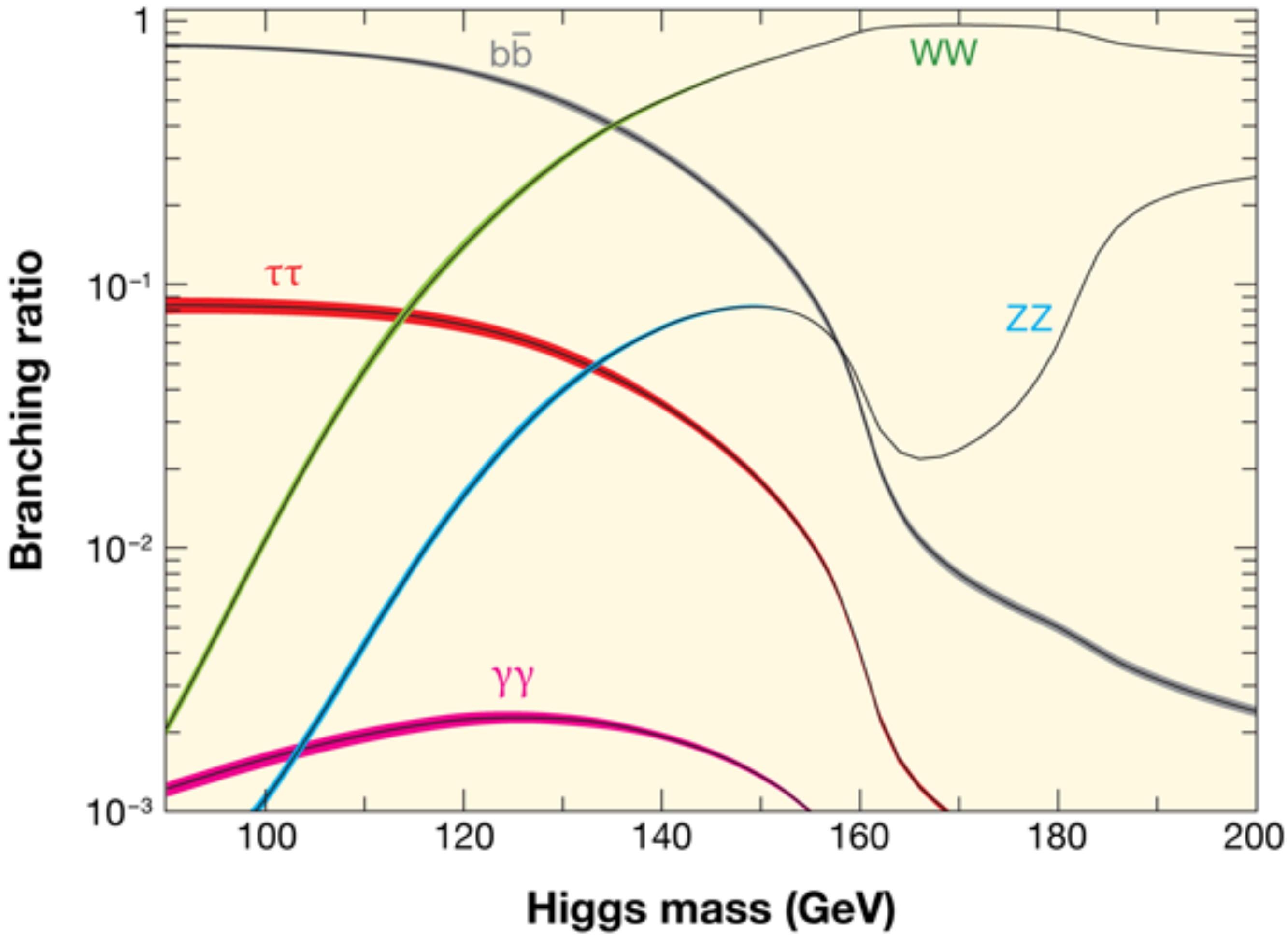
$$q\bar{q}^{(\prime)} \to V^{(*)} \to Vh^0\,, \quad h^0 \to b\bar{b}\,, WW^{(*)}\,,$$

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

where $V = W$ or Z.



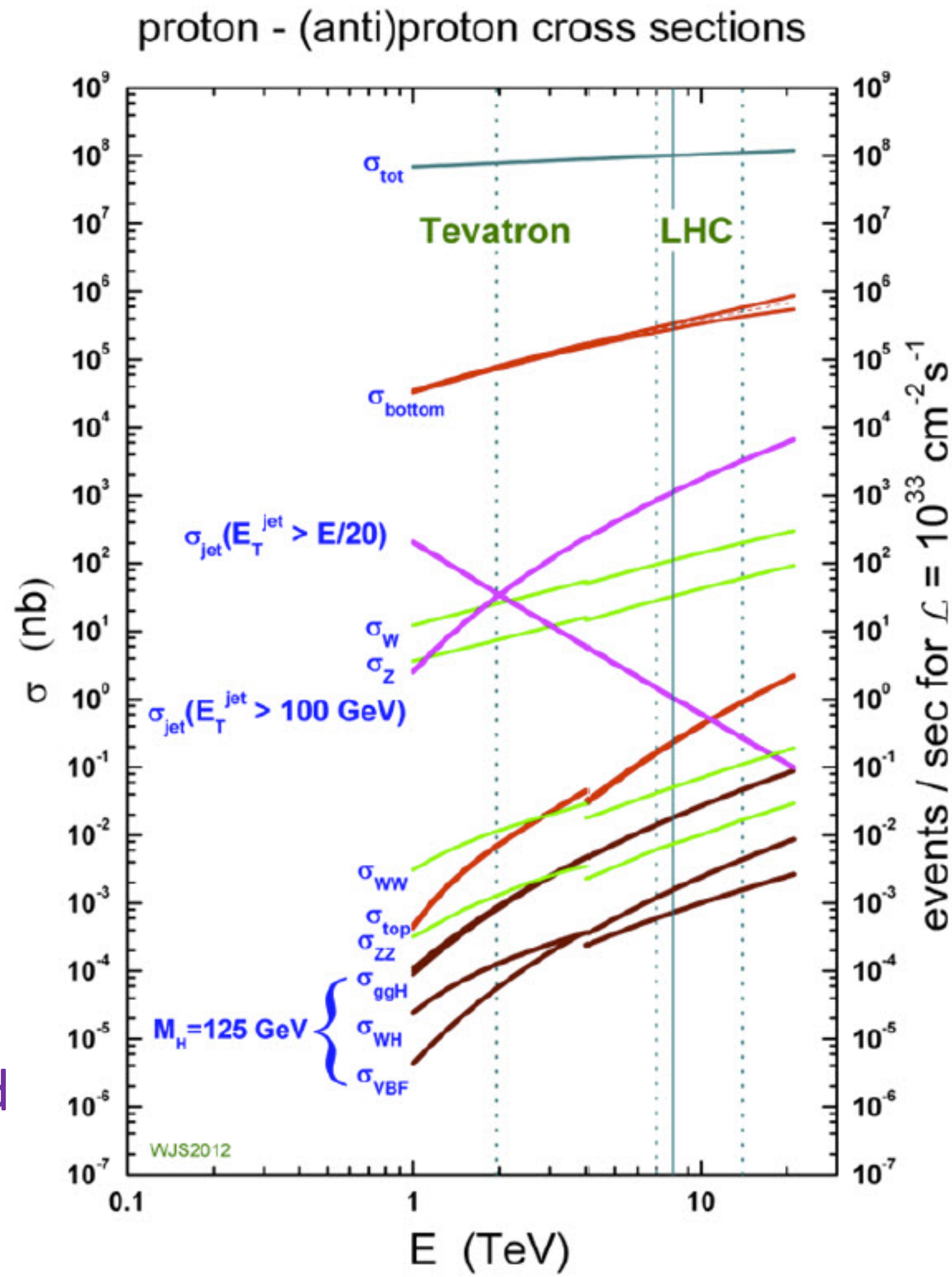
Probability of Higgs boson decay channels



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

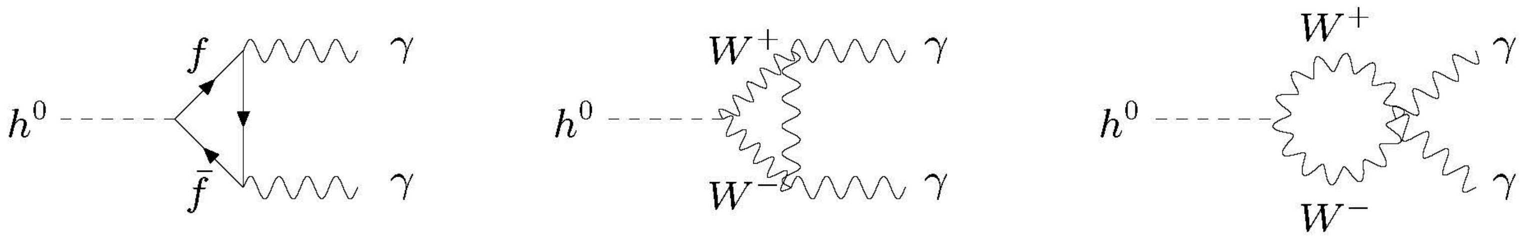
Answer: The Standard Model background is overwhelming. There are more than 10^7 times as many b-quark pairs produced in proton-proton collisions as compared to b-quark pairs that arise from a decaying Higgs boson.

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

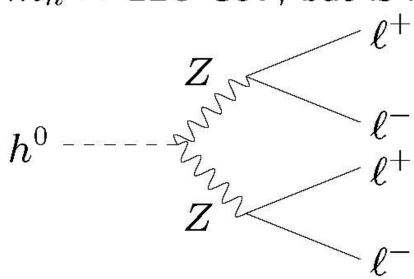


SM Higgs decays at the LHC for $m_h \sim 125$ GeV

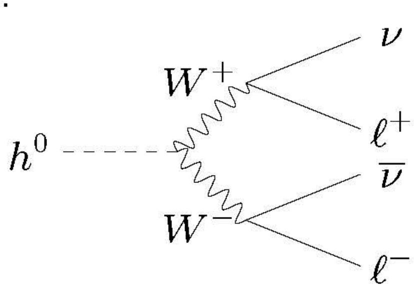
1. The rare decay $h^0 \longrightarrow \gamma\gamma$ is the most promising signal.



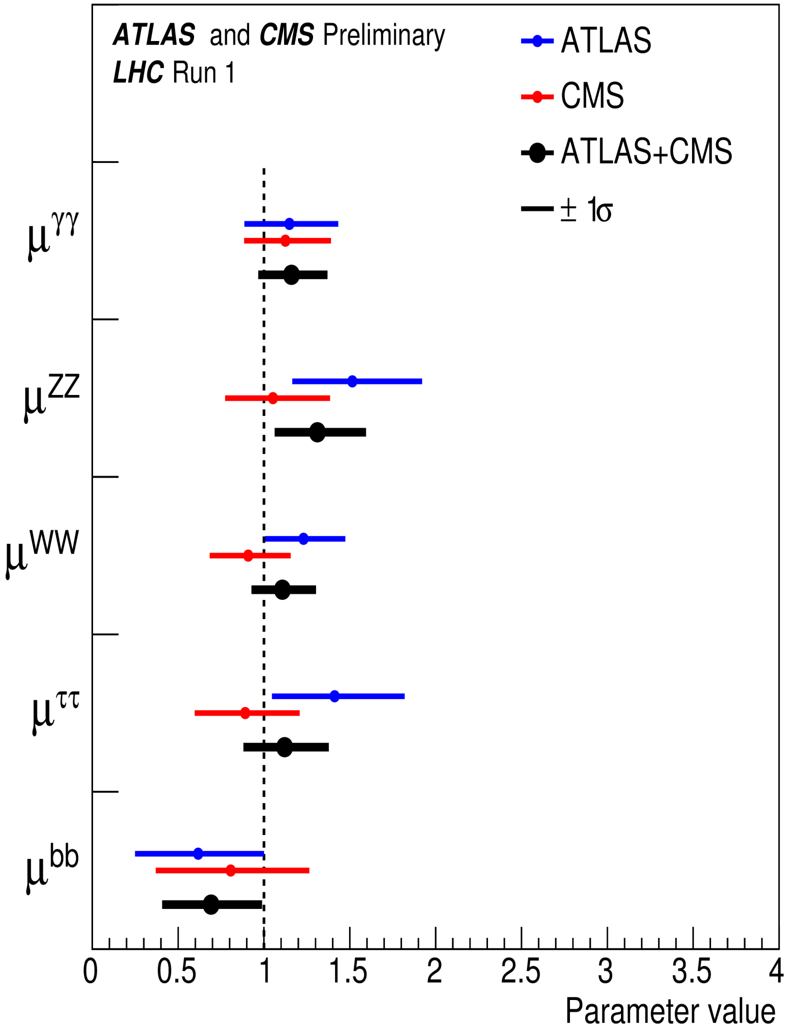
2. The so-called golden channel, $h^0 \longrightarrow ZZ \longrightarrow \ell^+\ell^-\ell^+\ell^-$ (where one or both Z bosons are off-shell) is a rare decay for $m_h \sim 125$ GeV, but is nevertheless visible.

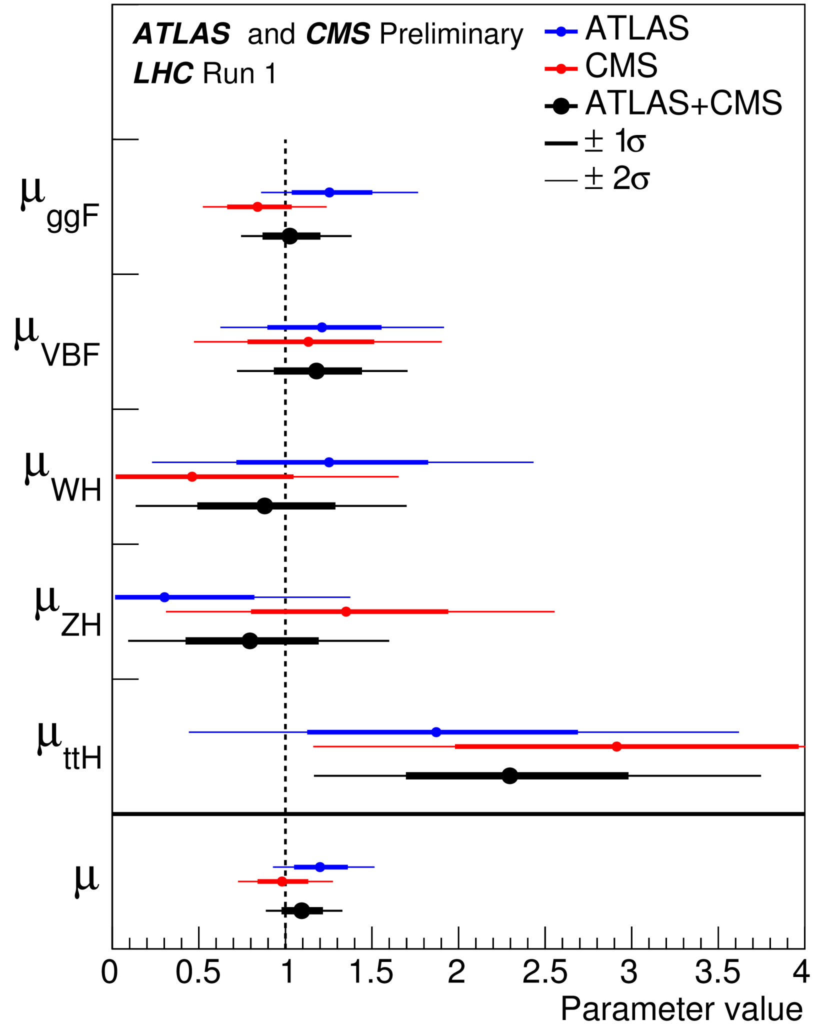


3. The channel, $h \longrightarrow WW^* \longrightarrow \ell^+\nu\ell^-\overline{\nu}$ is also useful, although it does not provide a good Higgs mass determination.



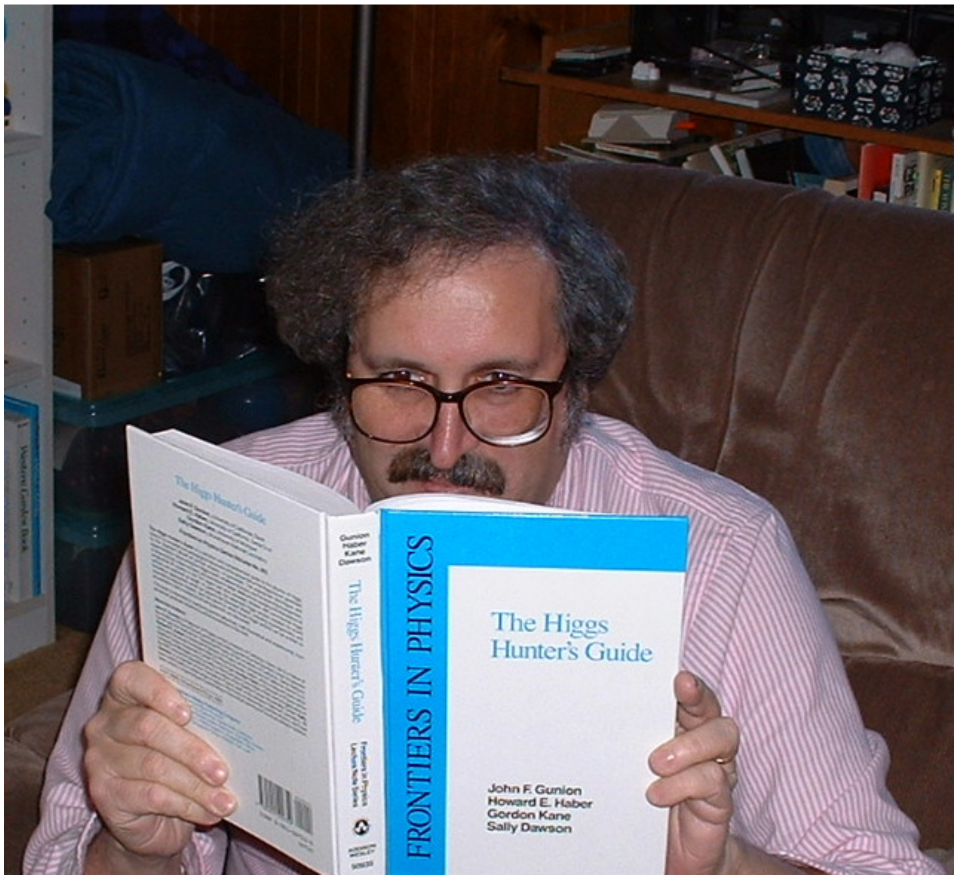
Is the observed scalar at 125 GeV the SM Higgs boson?



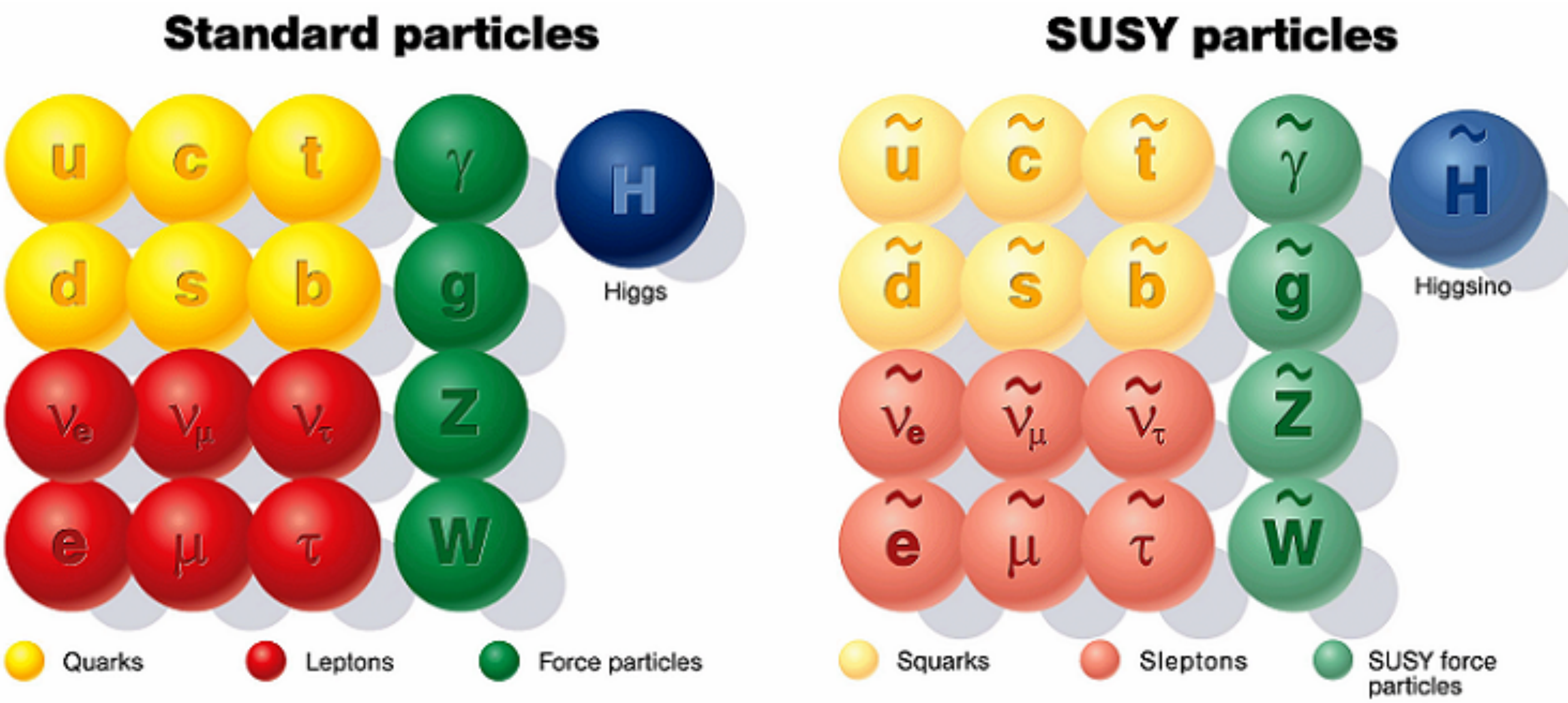


Best-fit results for the decay [left] and production [right] signal strengths (normalized to the SM predicted values) for the combination of ATLAS and CMS. The error bars indicate the 1σ (thick lines) and 2σ (thin lines) intervals. Reference: ATLAS-CONF-2015-044; CMS-PAS-HIG-15-002.

Research program 1: theory and phenomenology of Higgs bosons

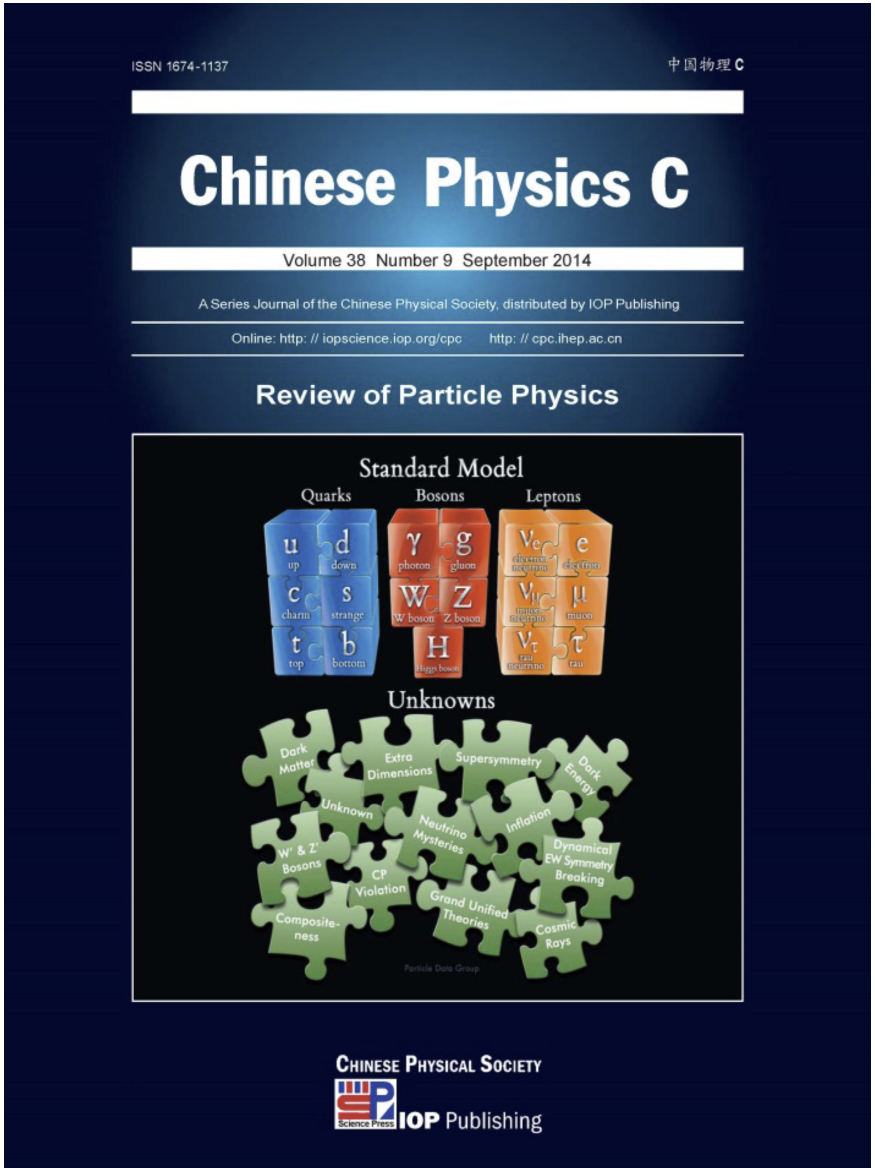


Research program 2: theory and phenomenology of TeV-scale supersymmetry (SUSY)



For a review, see H.E. Haber, *Supersymmetry Theory*, in K.A. Olive et al. [Particle Data Group Collaboration], *Review of Particle Physics*, Chin. Phys. C **38**, 090001 (2014); and in the 2015 partial update for the 2016 edition, available on the web shortly.

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



BRODERICK 79 PR D19 1046 J.J. Broderick *et al.* (VPI)
BARTLETT 78 PR D18 2253 D.F. Bartlett, D. Soo, M.G. White (COLO, PRIN)
CARRIGAN 78 PR D17 1754 R.A. Carrigan, B.P. Strauss, G. Giacomelli (FNAL+)
HOFFMANN 78 LNC 23 357 H. Hoffmann *et al.* (CERN, ROMA)
PRICE 78 PR D18 1382 P.B. Price *et al.* (UCB, HOUS)
HAGSTROM 77 PRL 38 729 R. Hagstrom (LBL)
CARRIGAN 76 PR D13 1823 R.A. Carrigan, F.A. Nezrick, B.P. Strauss (FNAL)
DELL 76 LNC 15 269 G.F. Dell *et al.* (CERN, BNL, ROMA, ADEL)
ROSS 76 LBL 4665 R.R. Ross (LBL)
STEVENS 76B PR D14 2207 D.M. Stevens *et al.* (VPI, BNL)
ZRELOV 76 CZJP B26 1306 V.P. Zrelov *et al.* (JINR)
ALVAREZ 75 LBL 4260 L.W. Alvarez (LBL)
BURKE 75 PL 60B 113 D.L. Burke *et al.* (MICH)
CABRERA 75 Thesis B. Cabrera (STAN)
CARRIGAN 75 NP B91 279 R.A. Carrigan, F.A. Nezrick (FNAL)
Also PR D3 56 R.A. Carrigan, F.A. Nezrick (FNAL)
EBERHARD 75 PR D11 3099 P.H. Eberhard *et al.* (LBL, MPIM)
EBERHARD 75B LBL 4289 P.H. Eberhard (LBL)
FLEISCHER 75 PRL 35 1412 R.L. Fleischer, R.N.F. Walker (GESC, WUSL)
FRIEDLANDER 75 PRL 35 1167 M.W. Friedlander (WUSL)
GIACOMELLI 75 NC 28A 21 G. Giacomelli *et al.* (BGNA, CERN, SACL+)
PRICE 75 PRL 35 487 P.B. Price *et al.* (UCB, HOUS)
CARRIGAN 74 PR D10 3867 R.A. Carrigan, F.A. Nezrick, B.P. Strauss (FNAL)
CARRIGAN 73 PR D8 3717 R.A. Carrigan, F.A. Nezrick, B.P. Strauss (FNAL)
ROSS 73 PR D8 698 R.R. Ross *et al.* (LBL, SLAC)
Also PR D4 3260 P.H. Eberhard *et al.* (LBL, SLAC)
Also SCI 167 701 L.W. Alvarez *et al.* (LBL, SLAC)
BARTLETT 72 PR D6 1817 D.F. Bartlett, M.D. Lahana (COLO)
GUREVICH 72 PL 38B 549 I.I. Gurevich *et al.* (KIAE, NOVO, SERP)
Also JETP 34 917 L.M. Barkov, I.I. Gurevich, M.S. Zolotorev (KIAE+)
Translated from ZETF 61 1721.
Also PL 31B 394 I.I. Gurevich *et al.* (KIAE, NOVO, SERP)
FLEISCHER 71 PR D4 24 R.L. Fleischer *et al.* (GESC)
KOLM 71 PR D4 1285 H.H. Kolm, F. Villa, A. Odian (MIT, SLAC)
PARKER 70 APJ 160 383 E.N. Parker (CHIC)
SCHATTEN 70 PR D1 2245 K.H. Schatten (NASA)
FLEISCHER 69 PR 177 2029 R.L. Fleischer *et al.* (GESC, FSU)
FLEISCHER 69B PR 184 1393 R.L. Fleischer *et al.* (GESC, UNCS, GSCO)
FLEISCHER 69C PR 184 1398 R.L. Fleischer, P.B. Price, R.T. Woods (GESC)
Also JAP 41 958 R.L. Fleischer *et al.* (GESC)
CARITHERS 66 PR 149 1070 W.C.J. Carithers, R.J. Stefanski, R.K. Adair
AMALDI 63 NC 28 773 E. Amaldi *et al.* (ROMA, UCSD, CERN)
GOTO 63 PR 132 387 E. Goto, H.H. Kolm, K.W. Ford (TOKY, MIT, BRAN)
PETUKHOV 63 NP 49 87 V.A. Petukhov, M.N. Yakimenko (LEBD)
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FIDECARO 61 NC 22 657 M. Fidecaro, G. Finocchiaro, G. Giacomelli (CERN)
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OTHER RELATED PAPERS

GROOM 86 PRPL 140 323 D.E. Groom (UTAH)
Review

Supersymmetric Particle Searches

SUPERSYMMETRY, PART I (THEORY)

Revised October 2013 by Howard E. Haber (UC Santa Cruz).

I.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, $M_P \approx 10^{19}$ 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 with no fine-tuning of parameters, and provide 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 size of the supersymmetry-breaking masses. Thus, a theory of *weak-scale supersymmetry*, where the effective scale of supersymmetry breaking is tied to the scale of electroweak symmetry breaking, provides a *natural* framework for the origin and the stability of the gauge hierarchy [7–10].

The Standard Model cannot be the correct theory of fundamental particles and their interactions (applicable at all energy scales). However, no unambiguous experimental results currently exist that imply that the Standard Model breaks down at the TeV scale. The expectations of new physics beyond

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)

2015 Publications

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, arXiv:1511.03682 [hep-ph].

On the Alignment Limit of the NMSSM Higgs Sector
M. Carena, H. E. Haber, I. Low, N.R. Shah and C.E.M. Wagner, arXiv:1510.09137 [hep-ph].

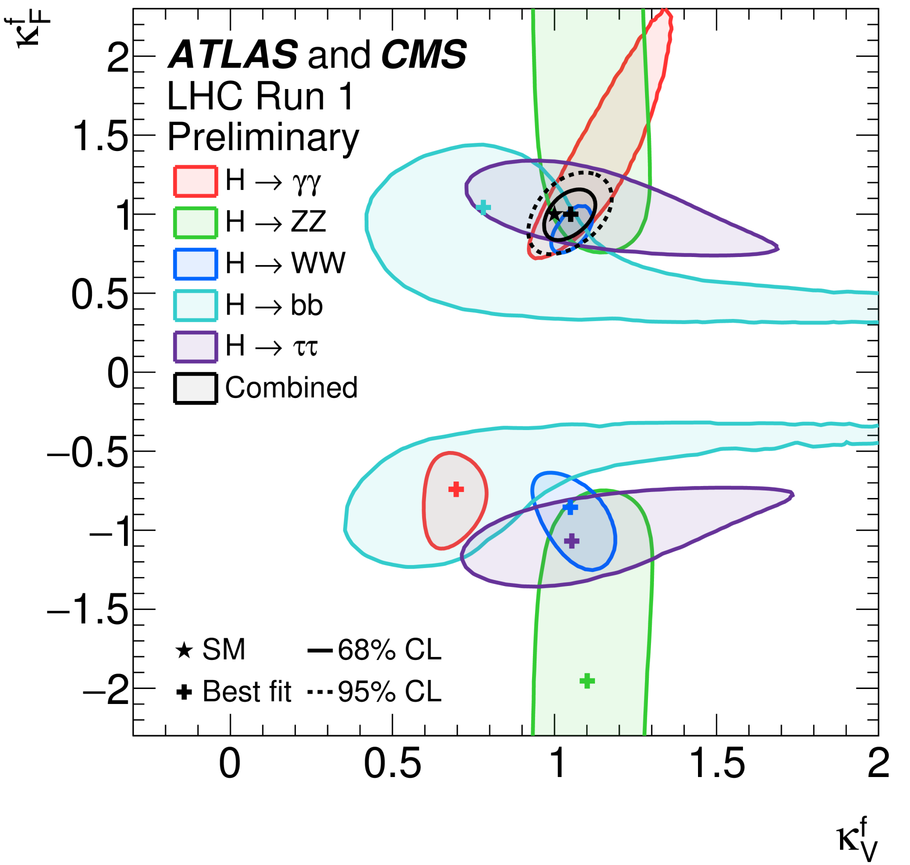
New LHC Benchmarks for the CP-conserving Two-Higgs-Doublet Model
H.E. Haber and O. Stål, Eur. Phys. J. C **75**, 491 (2015).

Scrutinizing the Alignment Limit in Two-Higgs-Doublet Models. Part 1: m_h = 125 GeV
J. Bernon, J.F. Gunion, H.E. Haber, Y. Jiang and S. Kraml, Phys. Rev. D **92**, 075004 (2015) .

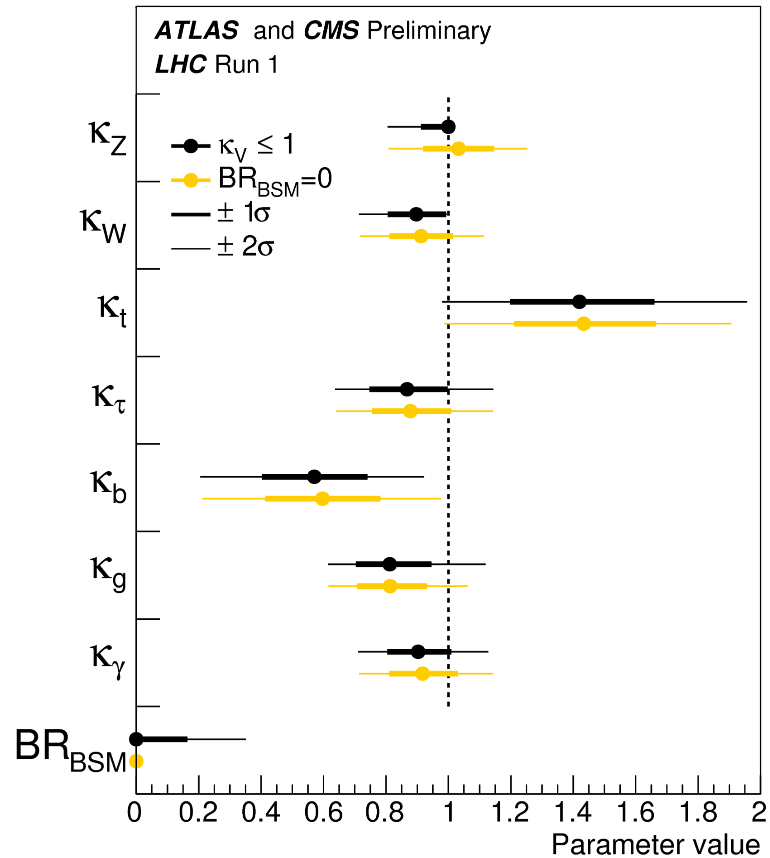
Preserving the validity of the Two-Higgs Doublet Model up to the Planck scale
P. Ferreira, H.E. Haber and E. Santos, Phys. Rev. D **92**, 033003 (2015).

Complementarity Between Non-Standard Higgs Boson Searches and Precision Higgs Boson Measurements in the MSSM
M. Carena, H.E. Haber, I. Low, N.R. Shah and C.E.M. Wagner, Phys. Rev. D **91**, 035003 (2015).

Search for deviations from SM-Higgs couplings



2D test statistics q(κ_V, κ_F) scan. Negative log-likelihood contours of κ_F^f versus κ_V^f 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, with $\kappa_V \leq 1$, where κ_V stands for κ_Z or κ_W, or without 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 ATLAS-CONF-2015-044; CMS-PAS-HIG-15-002 (September, 2015)

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.

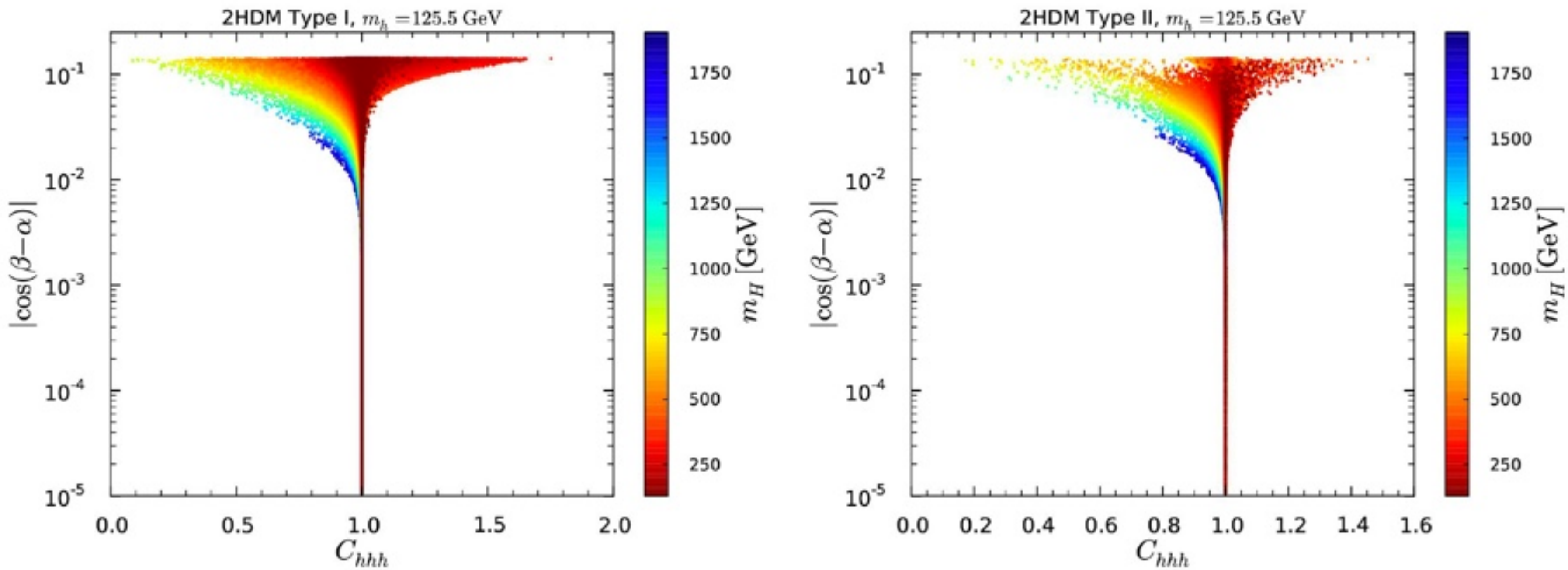
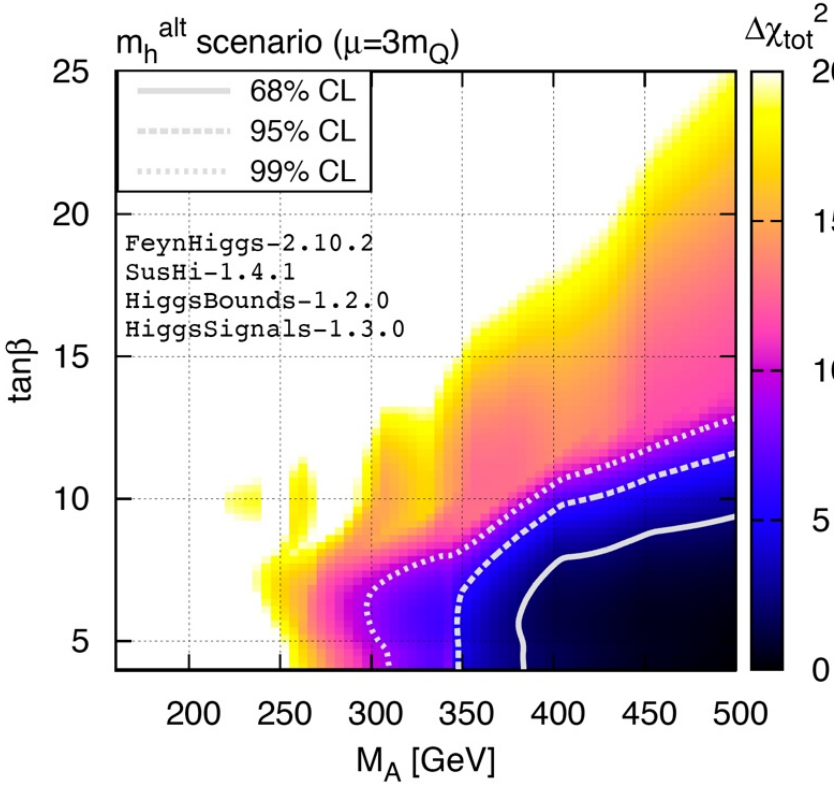
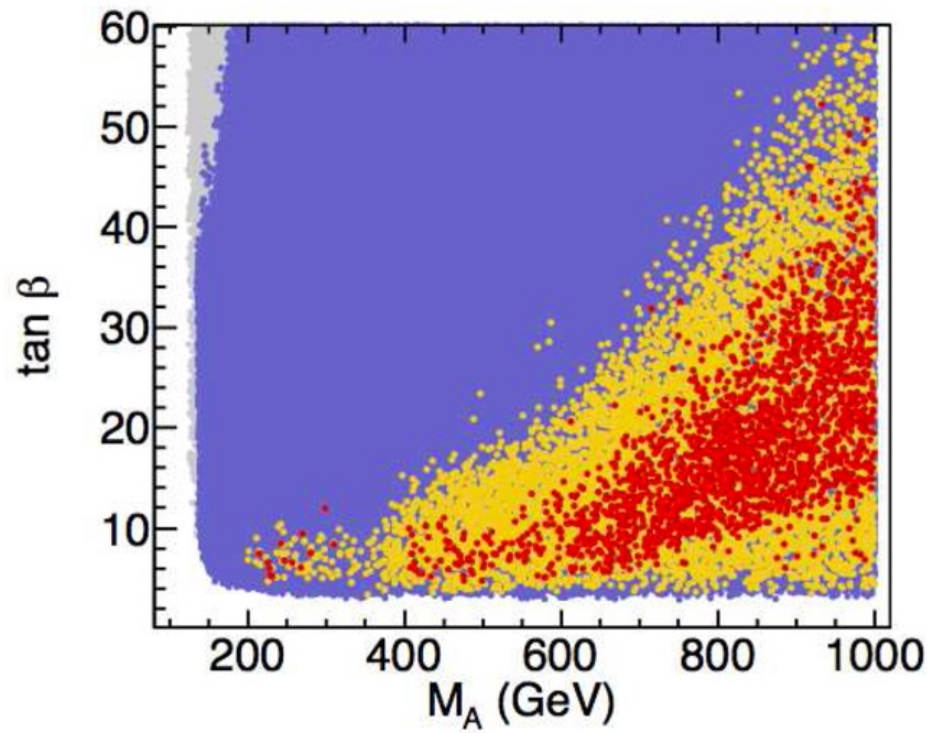


Figure 8: $|c_{\beta-\alpha}|$ versus the reduced triple Higgs coupling C_{hhh} in Type I (left) and Type II (right) with m_H color code. Points are ordered from high to low m_H values.

In the alignment limit, significant deviations from SM behavior can be seen in the triple Higgs coupling in certain regions of the two Higgs doublet model parameter space. Taken from J. Bernon et al., Phys. Rev. D **92**, 075004 (2015) .



Allowed region of MSSM Higgs parameter space in the m_h^{alt} scenario where 2HDM alignment without decoupling is achieved for tan$\beta \sim 10$ due to one-loop radiative corrections.



A 7 parameter pMSSM scan to generalize the constraints on the m_h^{alt} scenario. Red points are with 1σ of the best fit point and yellow points are within 2σ of the best fit point.

[T. Stefaniak and collaborators, after revisiting the results obtained by M. Carena et al.]

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

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 assistant professor of physics at Western State College of Colorado

D. O’Neil – assistant 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.

Current Ph.D. students

Laurel Stephenson Haskins:

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).

Ongoing and Future Activities

- Partially Natural 2HDM (with P. Draper and J. Ruderman)
  - Implementing the second fine tuning of the 2HDM with a symmetry.
- Implications of 2HDM flavor alignment at a very high energies (with S. Gori and E. Santos)
  - Generating manageable flavor violation at the electroweak scale via renormalization group running.
- LHC Benchmarks for more general 2HDMs (with T. Stefaniak)
  - Putting in CP violation and $\mathbf{Z_2}$ symmetry breaking effects in the 2HDM in the HiggsSignals program.
- Higgs alignment in the radiatively corrected 2HDM revisited (with T. Stefaniak)
  - A more comprehensive scan of the pMSSM parameter space.
- Implications of evidence for new physics in Run II of the LHC
  - Co-convening the Higgs sessions of the KITP Workshop, *Experimental Challenges for the LHC Run II* (March 28—June 3)

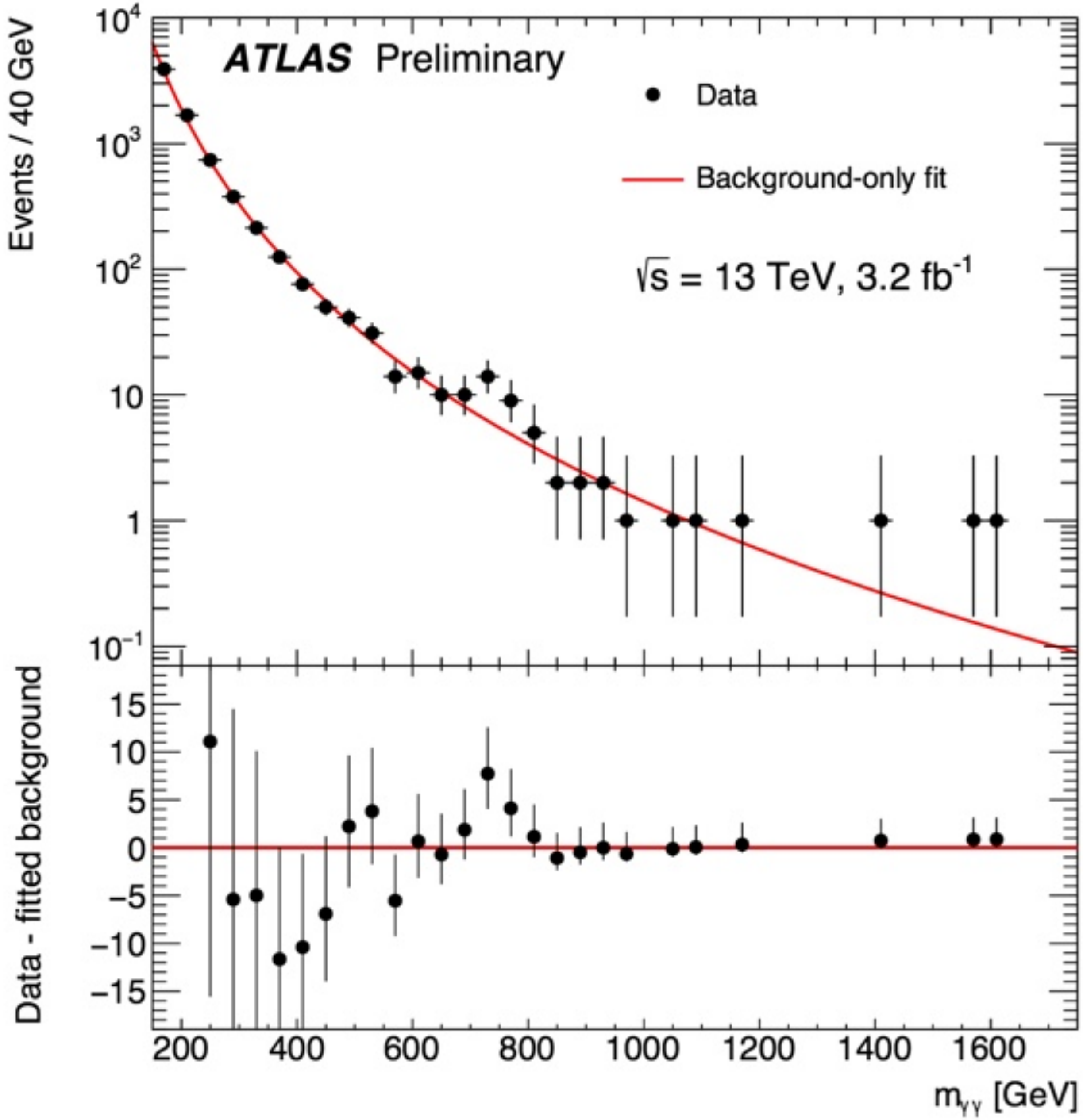
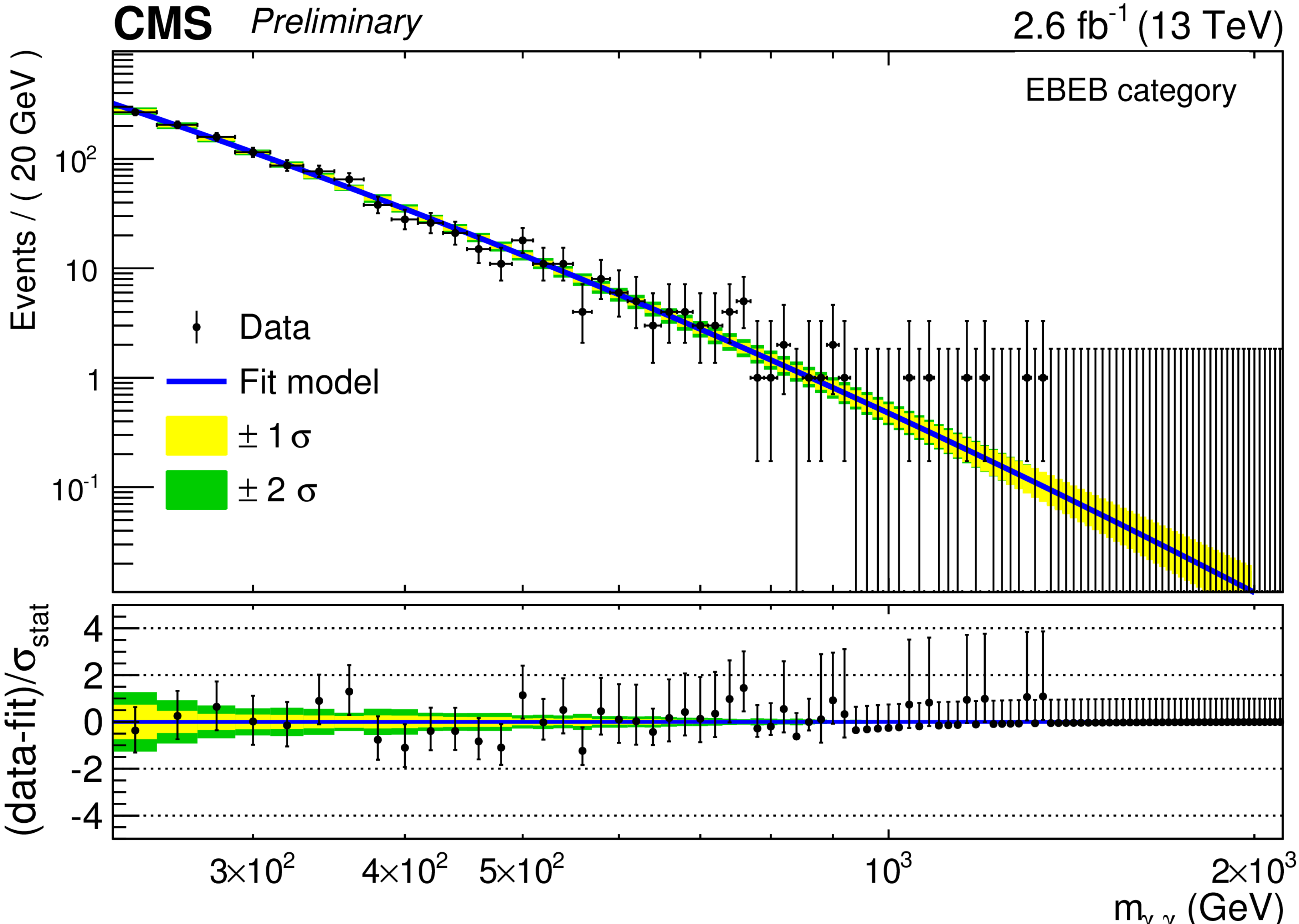
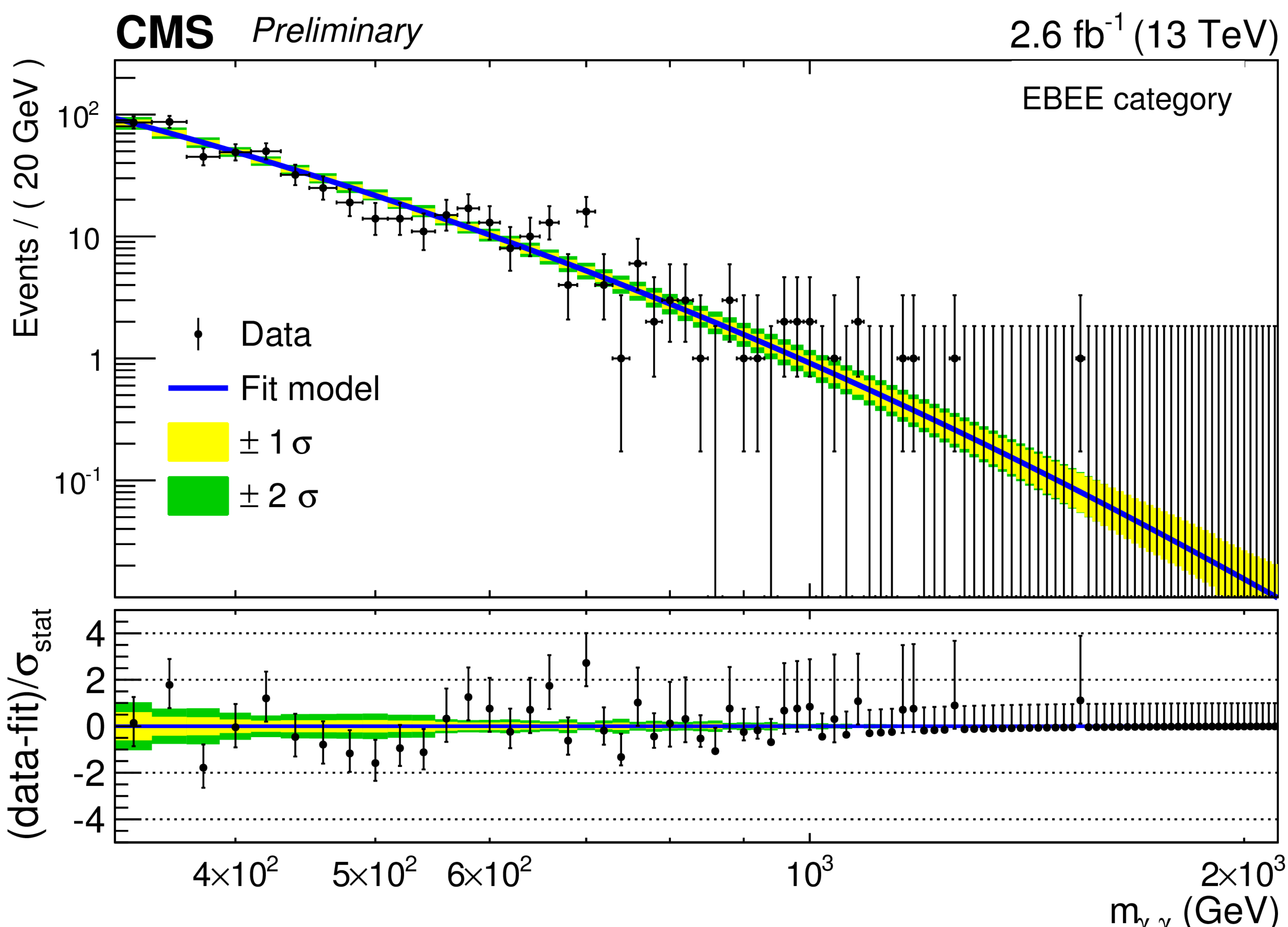


Figure 1: Invariant mass distribution of the selected diphoton events. Residual number of events with respect to the fit result are shown in the bottom pane. The first two bins in the lower pane are outside the vertical plot range.



CMS Preliminary
2.6 fb-1 (13 TeV)
EBEB category
Events / (20 GeV)
Data
Fit model
± 1 σ
± 2 σ
(data-fit)/σstat
3×10^2
4×10^2
5×10^2
10^3
2×10^3
mγγ (GeV)



CMS Preliminary
2.6 fb^{-1} (13 TeV)
EBEE category
Events / (20 GeV)
Data
Fit model
± 1 σ
± 2 σ
(data-fit)/σ_{stat}
$m_{\gamma\gamma}$ (GeV)