Research on the Theory of the Terascale

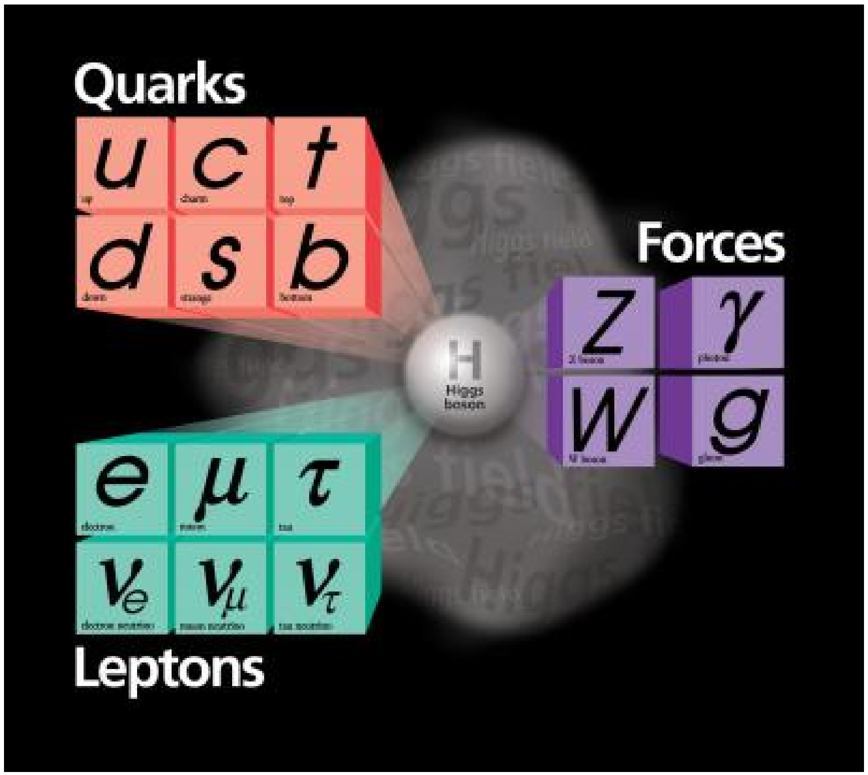
Howard Haber
SCIPP Theory
January 12, 2015

SCIPP Particle Theory Group

- Thomas Banks: supersymmetry, string theory, gravity, and the early universe
- Michael Dine: supersymmetry, string theory, and the early universe
- Howard Haber: Higgs bosons, collider physics, new physics beyond the Standard Model at the terascale (including supersymmetry)
- Stefano Profumo: Theories of particle dark matter and their implications for astrophysics and collider phenomenology

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

The Standard Model (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 introduces the Higgs mechanism for mass generation. The gauge invariance is spontaneously broken. In the simplest implementation, a spinless physical Higgs scalar is predicted.

explain it in 60 seconds

The Higgs boson, a fundamental particle predicted by theorist Peter Higgs, may be the key to understanding why elementary particles have mass. Explaining the connection, I am reminded of the puzzler, "If sound cannot travel in a vacuum, why are vacuum cleaners so noisy?" This riddle actually touches on a profound insight of modern physics: the vacuum—or empty space—is far from empty. It is indeed "noisy" and full of virtual particles and force fields. The origin of mass seems to be related to this phenomenon.

In Einstein's theory of relativity, there is a crucial difference between massless and massive particles: All massless particles must travel at the speed of light, whereas massive particles can never attain this ultimate speed. But, how do massive particles arise? Higgs proposed that the vacuum contains an omnipresent field that can slow down some (otherwise massless) elementary particles—like a vat of molasses slowing down a high-speed bullet. Such particles would behave like massive particles traveling at less than light speed. Other particles—such as the photons of light—are immune to the field: they do not slow down and remain massless.

Although the Higgs field is not directly measurable, accelerators can excite this field and "shake loose" detectable particles called Higgs bosons. So far, experiments using the world's most powerful accelerators have not observed any Higgs bosons, but indirect experimental evidence suggests that particle physicists are poised for a profound discovery.

Howard E. Haber, University of California, Santa Cruz

From Symmetry Magazine, volume 3, issue 6, August 2006

Higgs production at hadron colliders

At hadron colliders, the relevant processes are

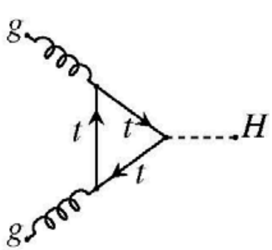
$$gg \to h^0\,, \quad h^0 \to \gamma\gamma\,, VV^{(*)}\,,$$

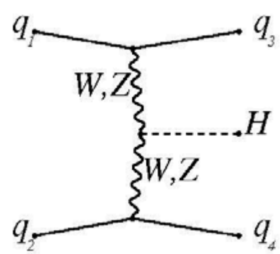
$$qq \to qqV^{(*)}V^{(*)} \to qqh^0, \quad h^0 \to \gamma\gamma,\, \tau^+\tau^-,\, VV^{(*)}\,,$$

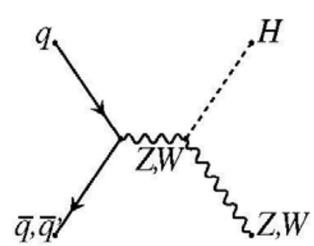
$$q\bar{q}^{(\prime)} \to V^{(*)} \to Vh^0\,, \quad h^0 \to b\bar{b}\,, WW^{(*)}\,,$$

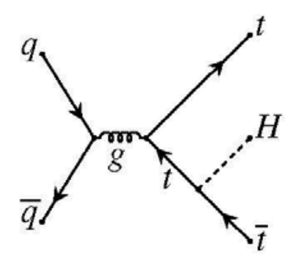
$$gg, q\bar{q} \to t\bar{t}h^0, \quad h^0 \to b\bar{b},\, \gamma\gamma,\, WW^{(*)}\,.$$

where $V = W$ or Z.

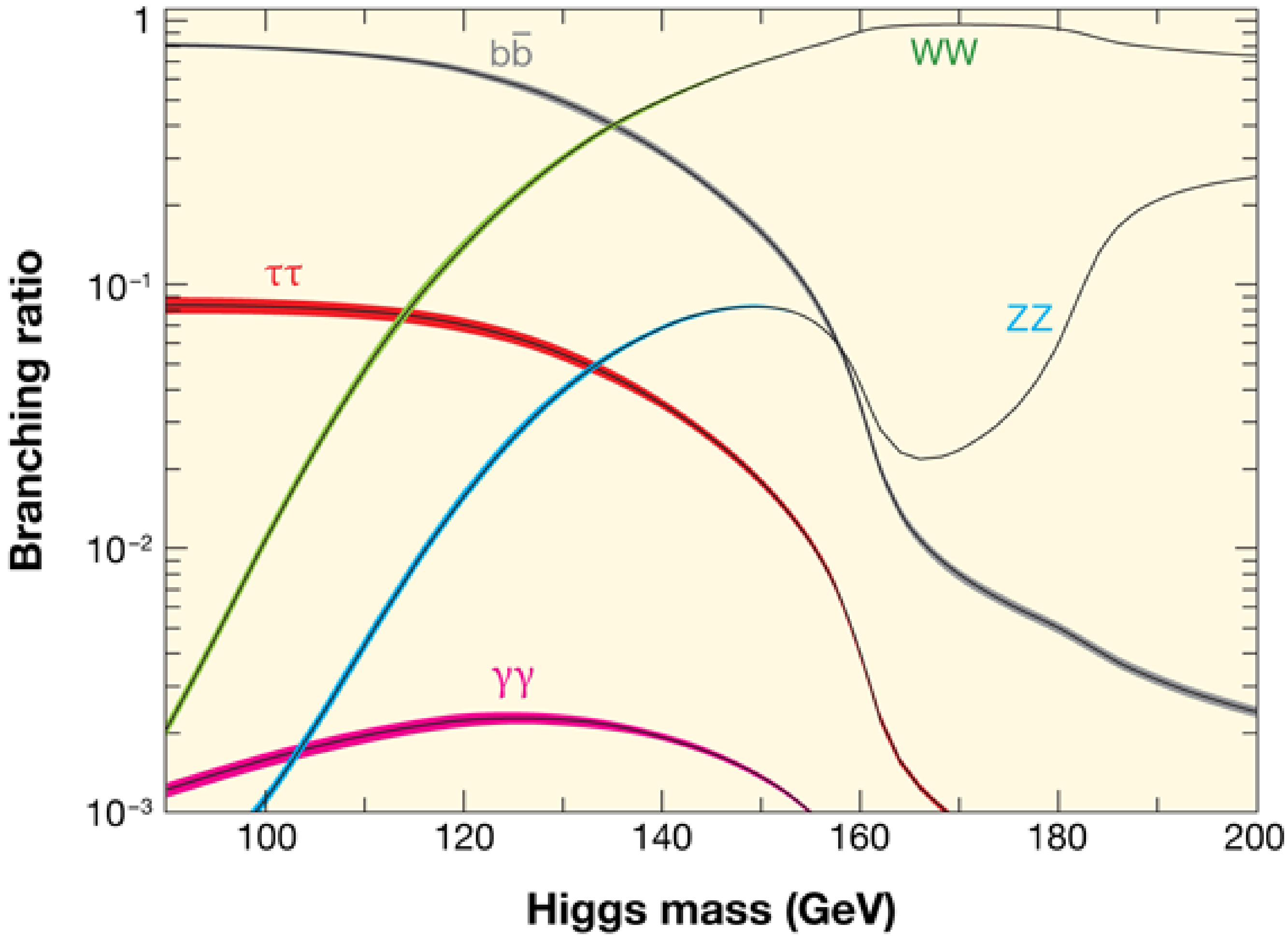








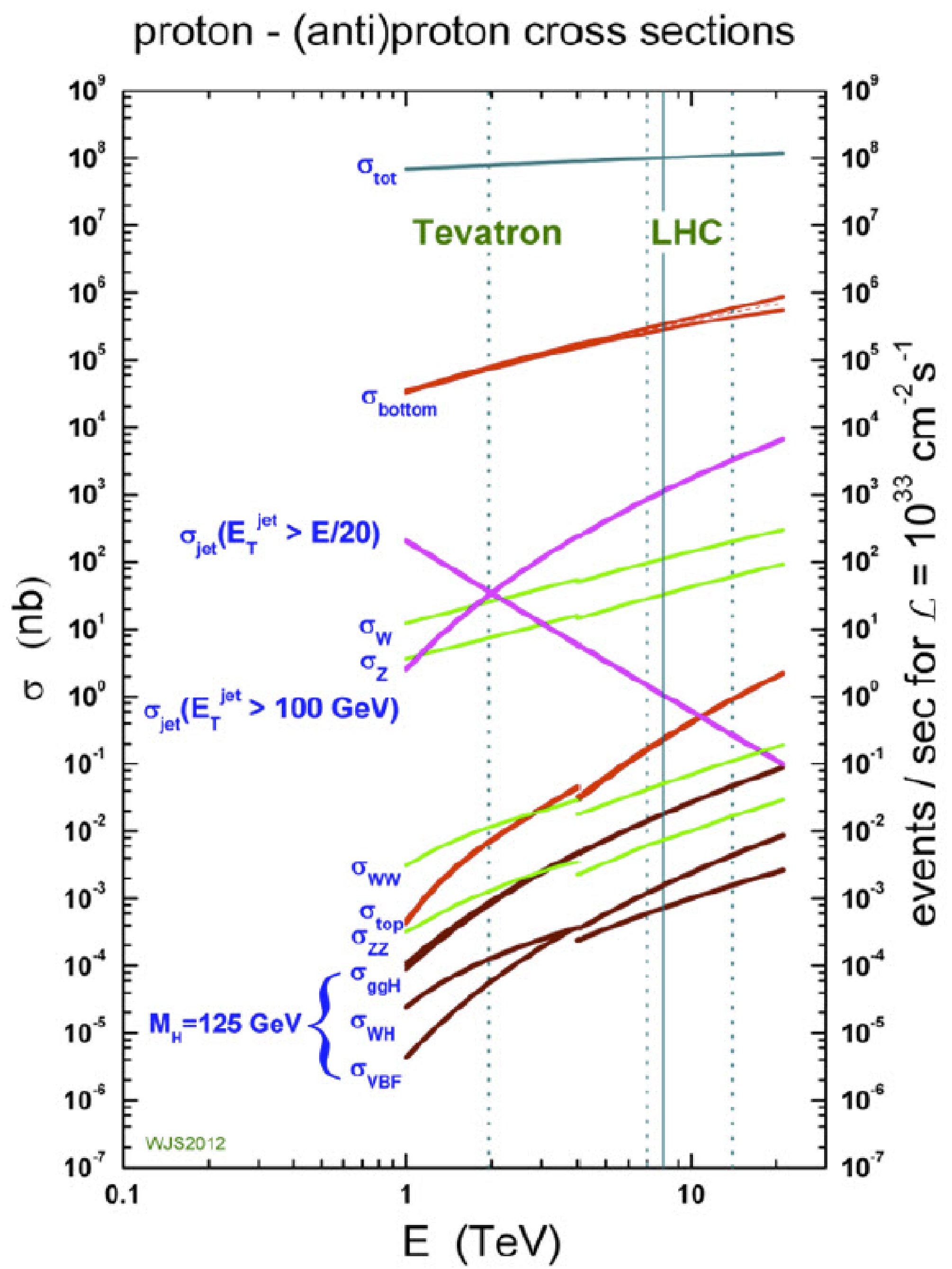
Probability of Higgs boson decay channels



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

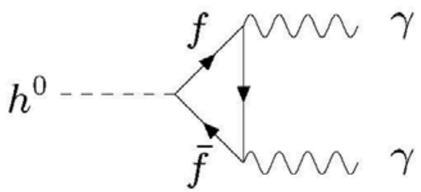
Answer: The Standard Model background is overwhelming. There are more than 10^7 times as many b-quark pairs produced in proton-proton collisions as compared to b-quark pairs that arise from a decaying Higgs boson.

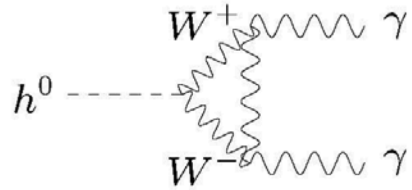
Roughly 250,000 Higgs bosons per experiment were produced at the LHC from 2010—2013.

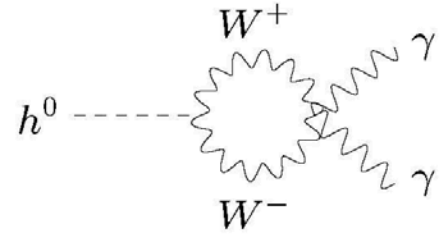


SM Higgs decays at the LHC for $m_h \sim 125$ GeV

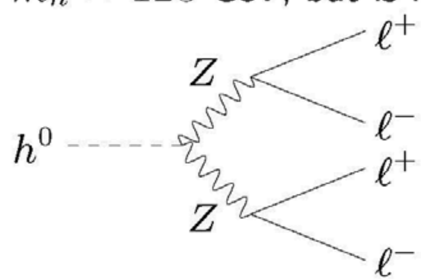
1. The rare decay $h^0 \to \gamma\gamma$ is the most promising signal.



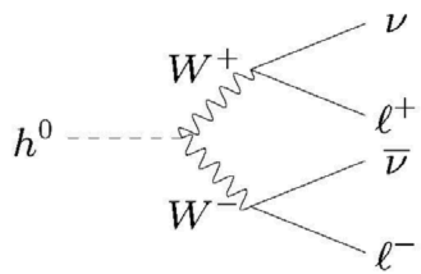




2. The so-called golden channel, $h^0 \to ZZ \to \ell^+\ell^-\ell^+\ell^-$ (where one or both Z bosons are off-shell) is a rare decay for $m_h \sim 125$ GeV, but is nevertheless visible.



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.



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

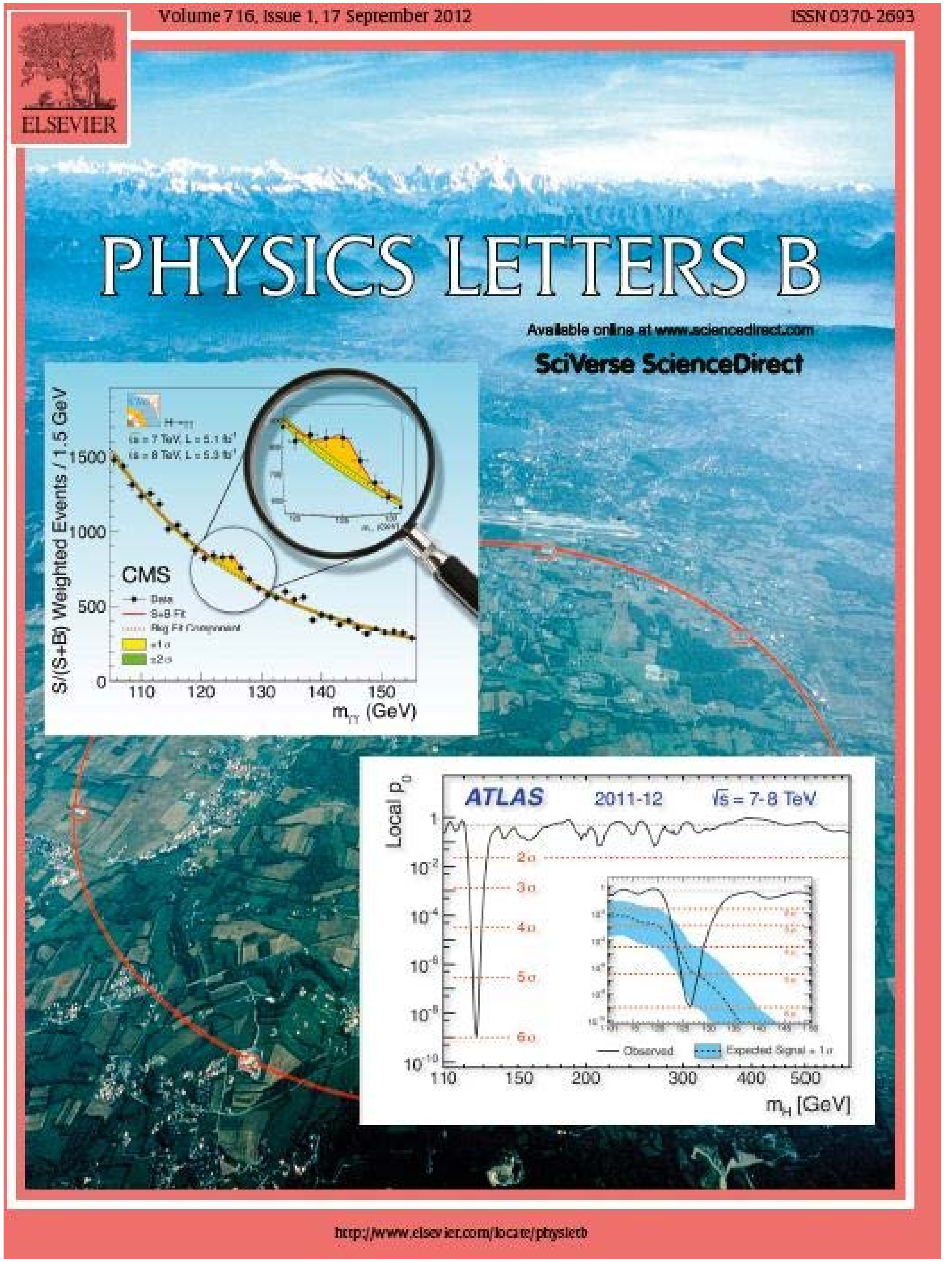
The discovery papers are published two months later In Physics Letters B.

<u>ATLAS Collaboration:</u>

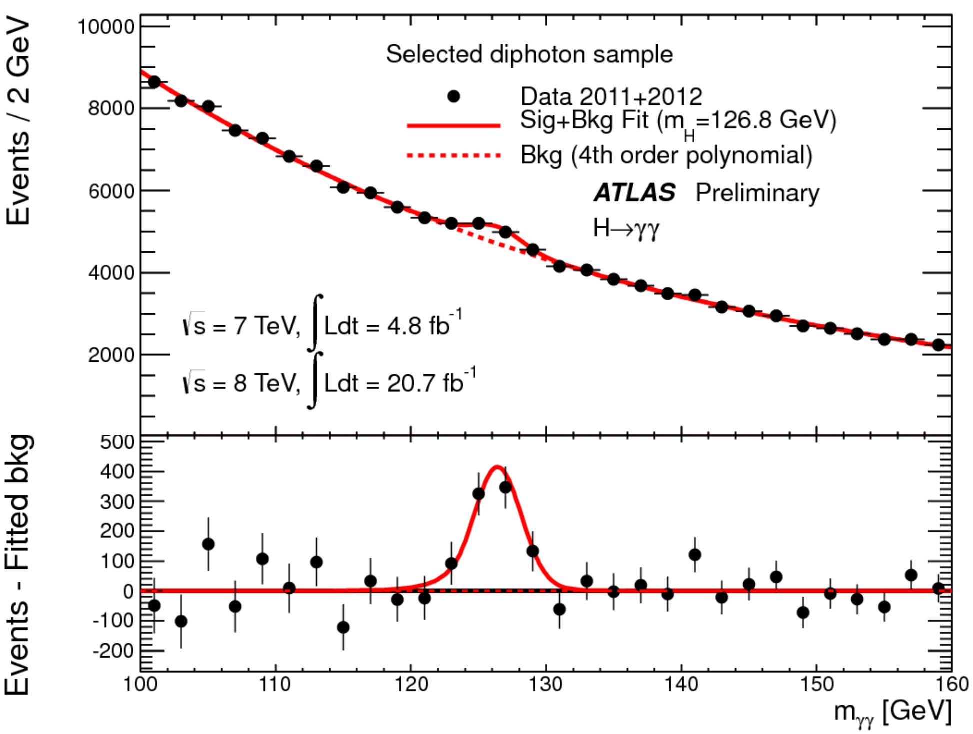
Physics Letters B716 (2012) 1—29

<u>CMS Collaboration:</u>

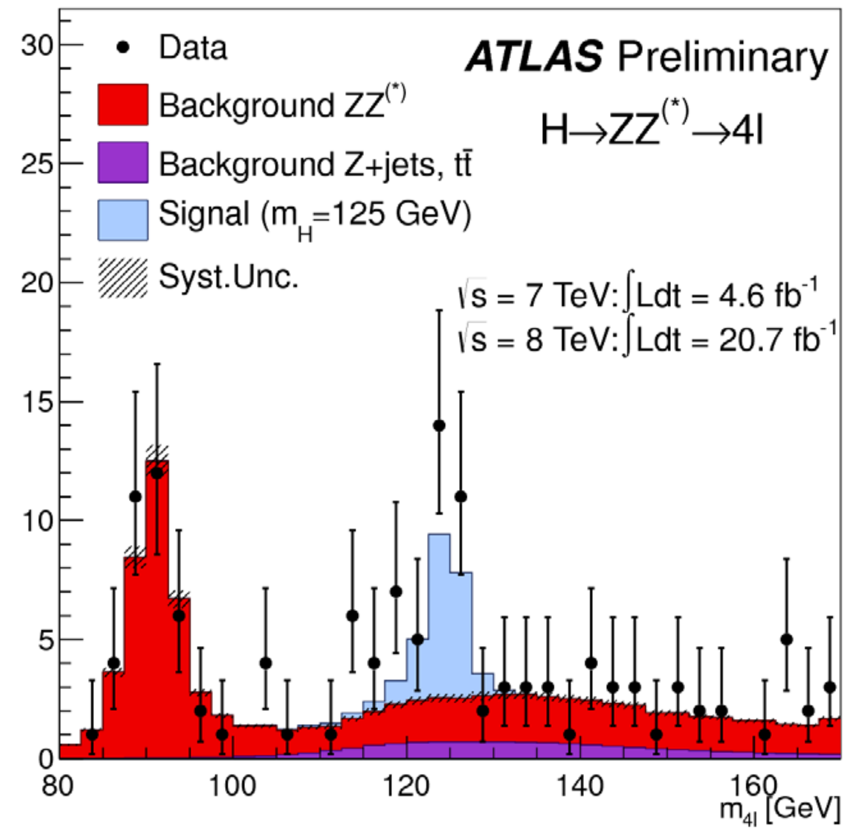
Physics Letters B716 (2012) 30—61



A boson is discovered at the LHC by the ATLAS Collaboration

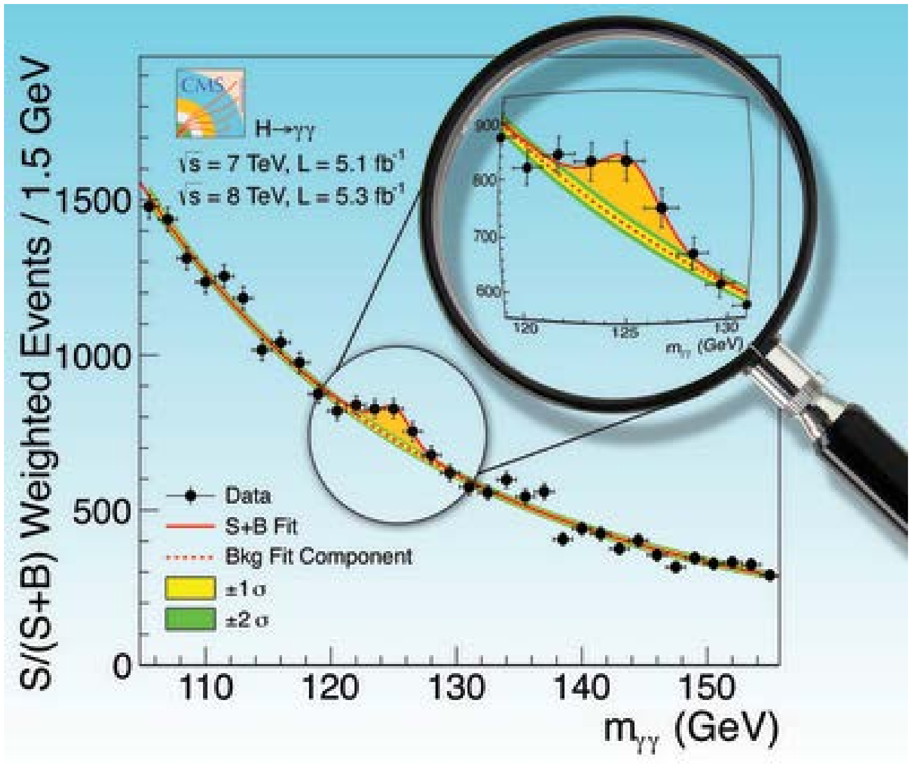


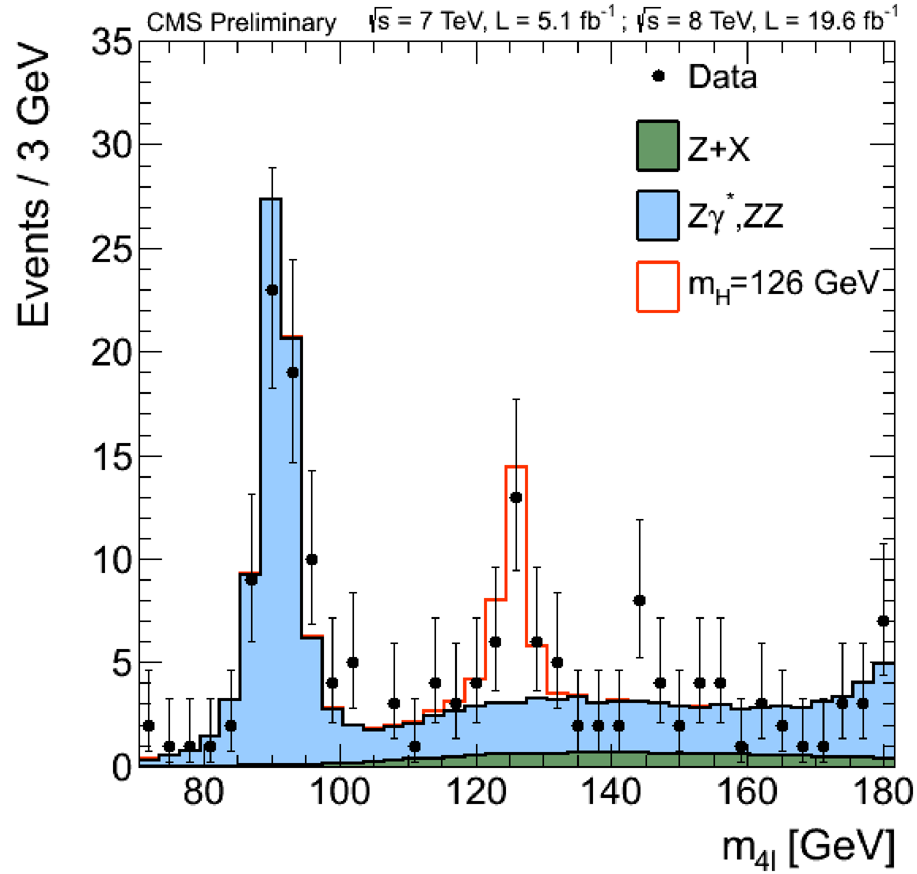
Invariant mass distribution of diphoton candidates for the combined 7 TeV and 8 TeV data samples. The result of a fit to the data of the sum of a signal component fixed to m_H = 126.8 GeV and a background component described by a fourth-order Bernstein polynomial is superimposed. The bottom inset displays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

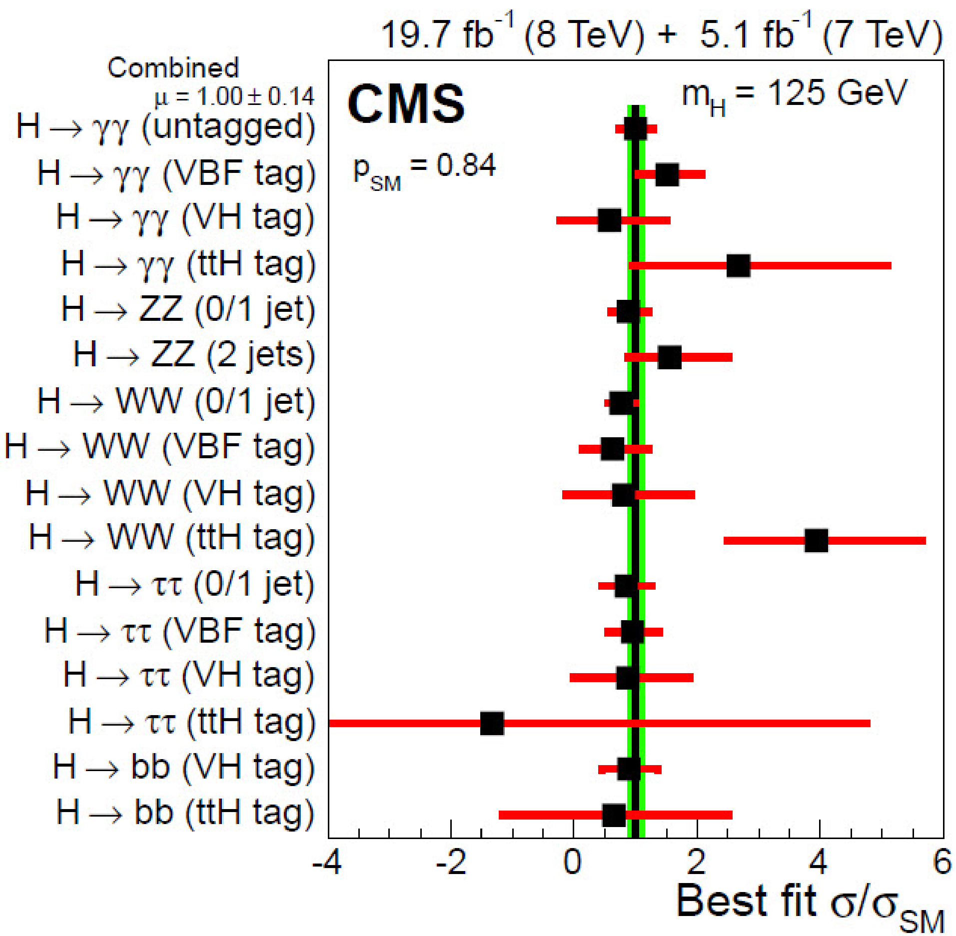




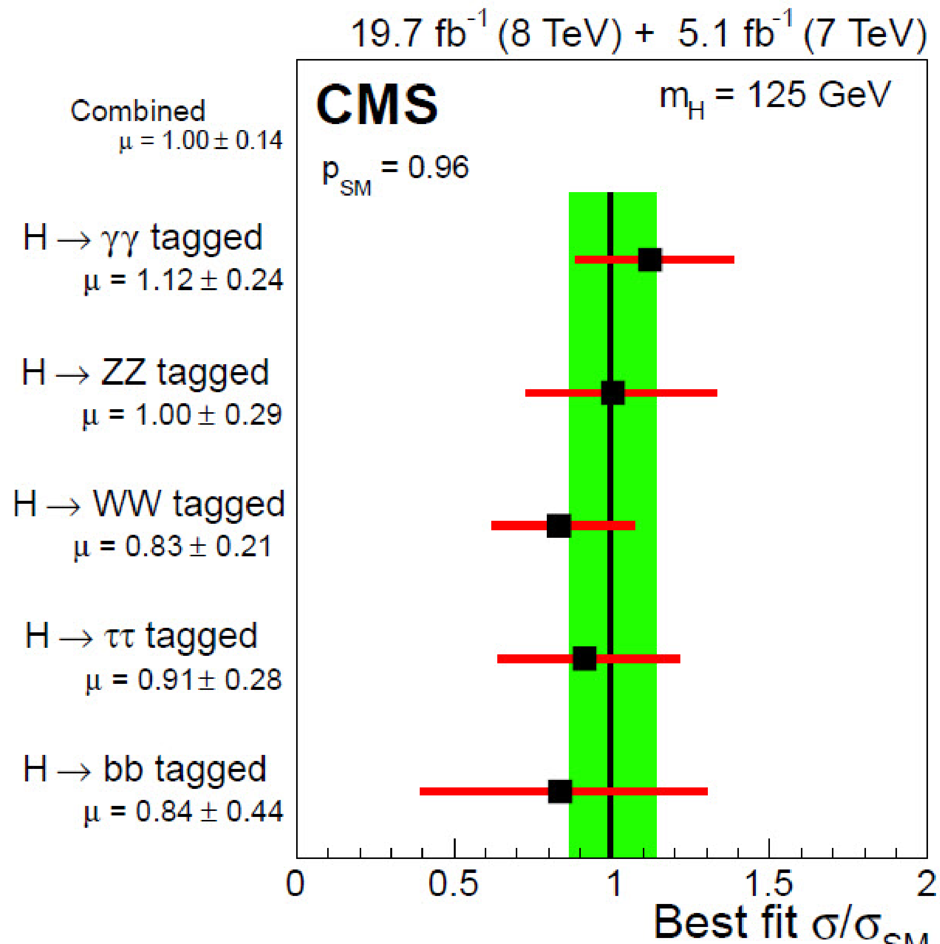
The diphoton invariant mass distribution with each event weighted by the S/(S+B) value of its category. The lines represent the fitted background and signal, and the colored bands represent the ±1 and ±2 standard deviation uncertainties in the background estimate. The inset shows the central part of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

CMS evidence for a Standard Model (SM)—like Higgs boson

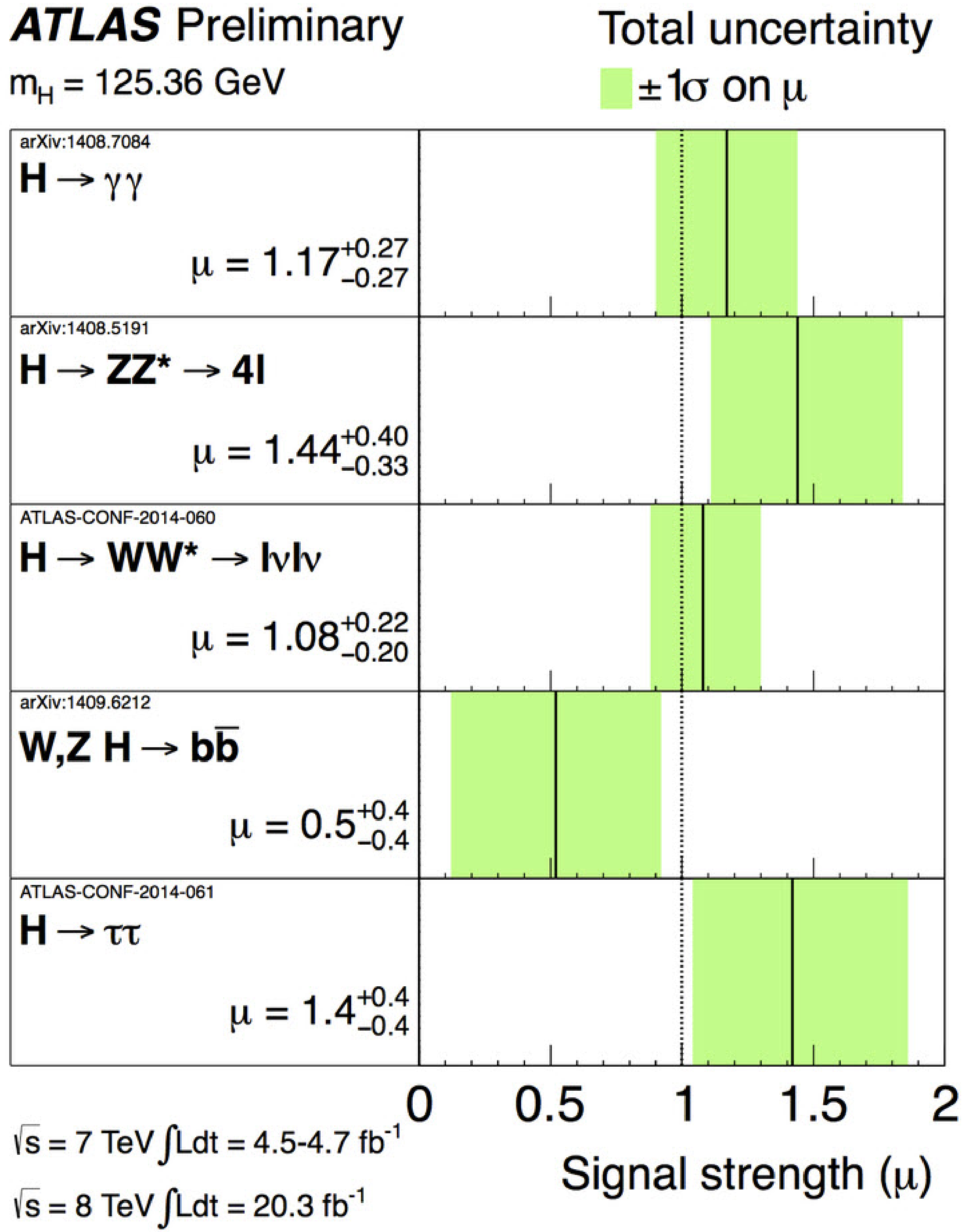


Values of the best-fit σ/σ_{SM} for the combination (solid vertical line) and for subcombinations by predominant decay mode and additional tags targeting a particular production mechanism. The vertical band shows the overall σ/σ_{SM} uncertainty. The σ/σ_{SM} ratio denotes the production cross section times the relevant branching fractions, relative to the SM expectation. The horizontal bars indicate the ±1 standard deviation uncertainties in the best-fit σ/σ_{SM} values for the individual modes; they include both statistical and systematic uncertainties. Taken from arXiv:1412.8662 (December, 2014).

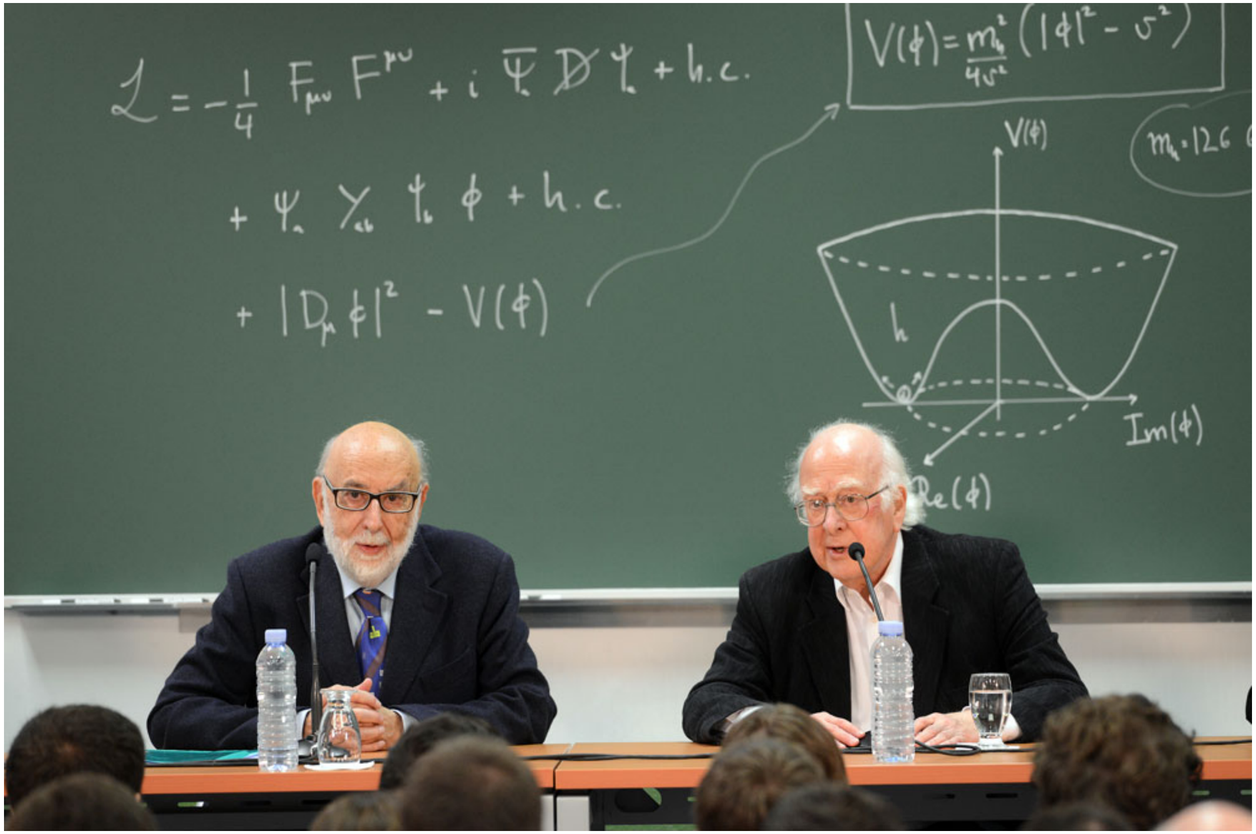


Values of the best-fit σ/σ_{SM} for the combination (solid vertical line) and for subcombinations by predominant decay mode. The vertical band shows the overall σ/σ_{SM} uncertainty. The σ/σ_{SM} ratio denotes the production cross section times the relevant branching fractions, relative to the SM expectation. The horizontal bars indicate the ±1 standard deviation uncertainties in the best-fit σ/σ_{SM} values for the individual modes; they include both statistical and systematic uncertainties. Taken from arXiv:1412.8662 (December, 2014).

ATLAS evidence for a SM-like Higgs boson (from a CERN seminar October 7, 2014)



Winners of the 2013 Nobel Prize in Physics

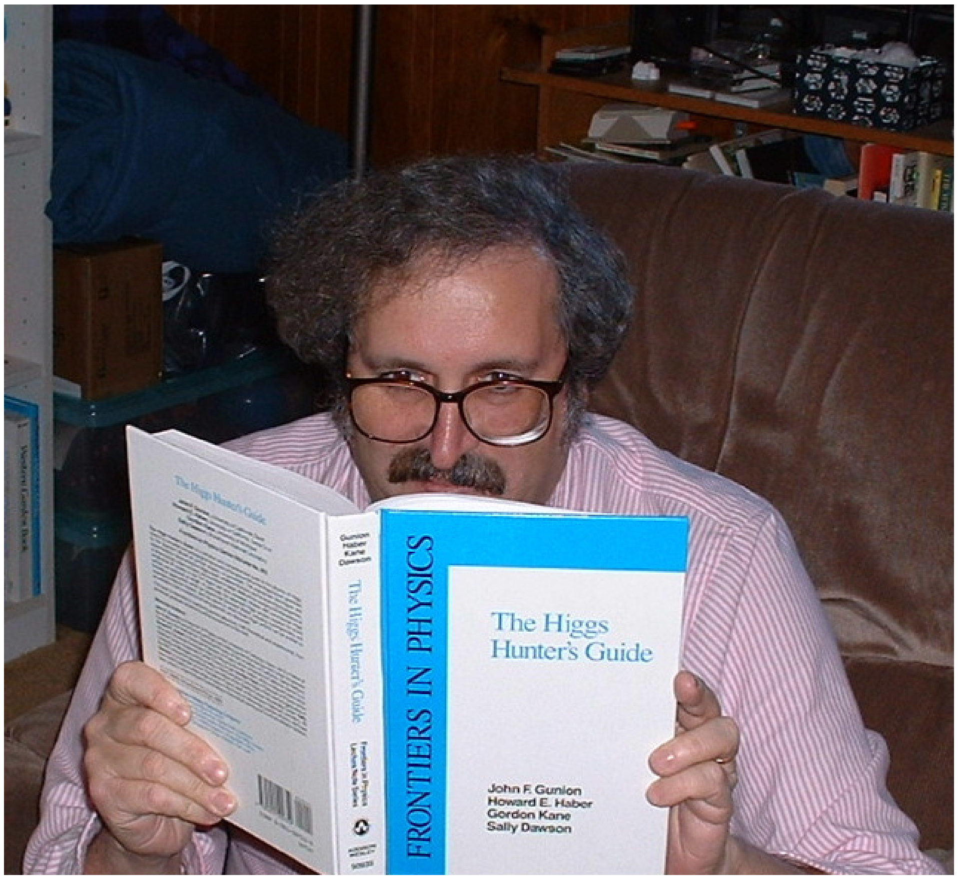


François Englert

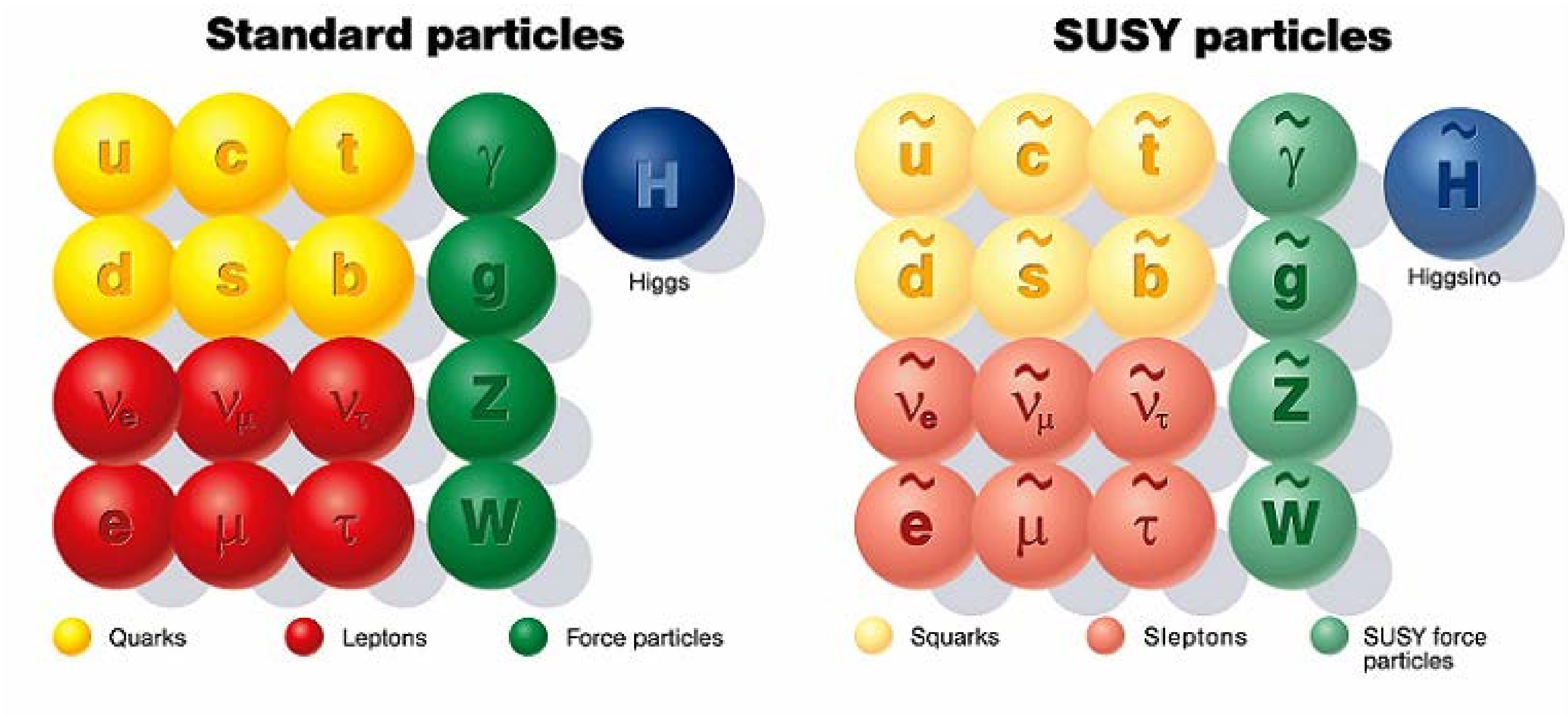
and

Peter Higgs

Research program 1: theory and phenomenology of Higgs bosons



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

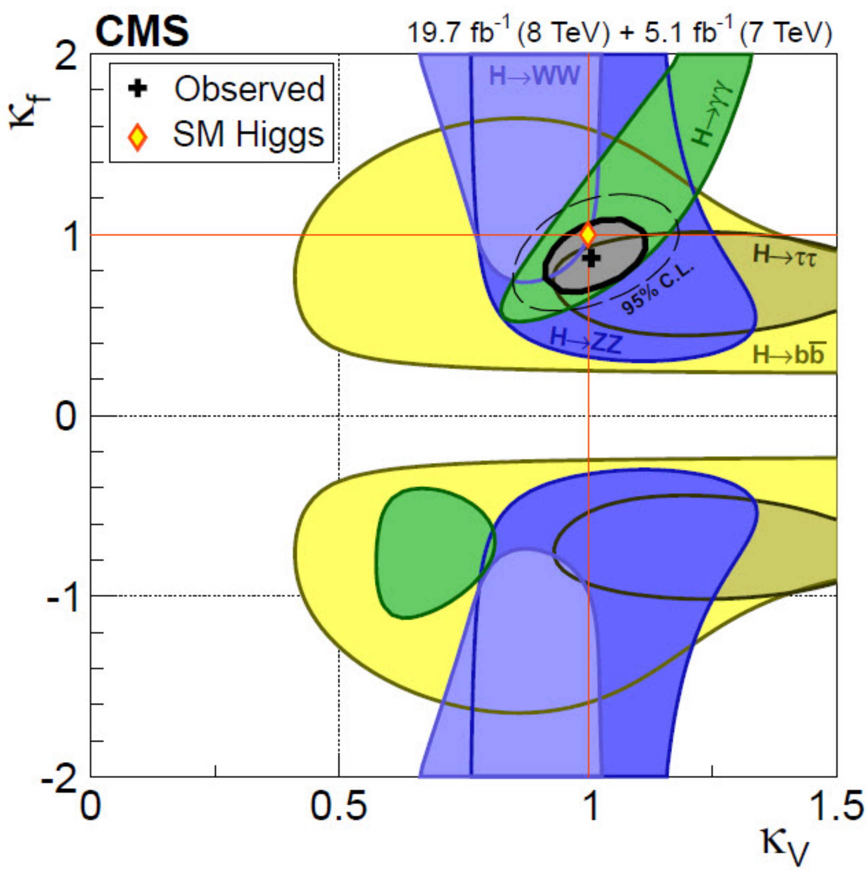


For a review, see H.E. Haber, *Supersymmetry Theory*, in the 2013 partial update for the 2014 edition of the *Review of Particle Physics*, to be published by the Particle Data Group [http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-1-theory.pdf].

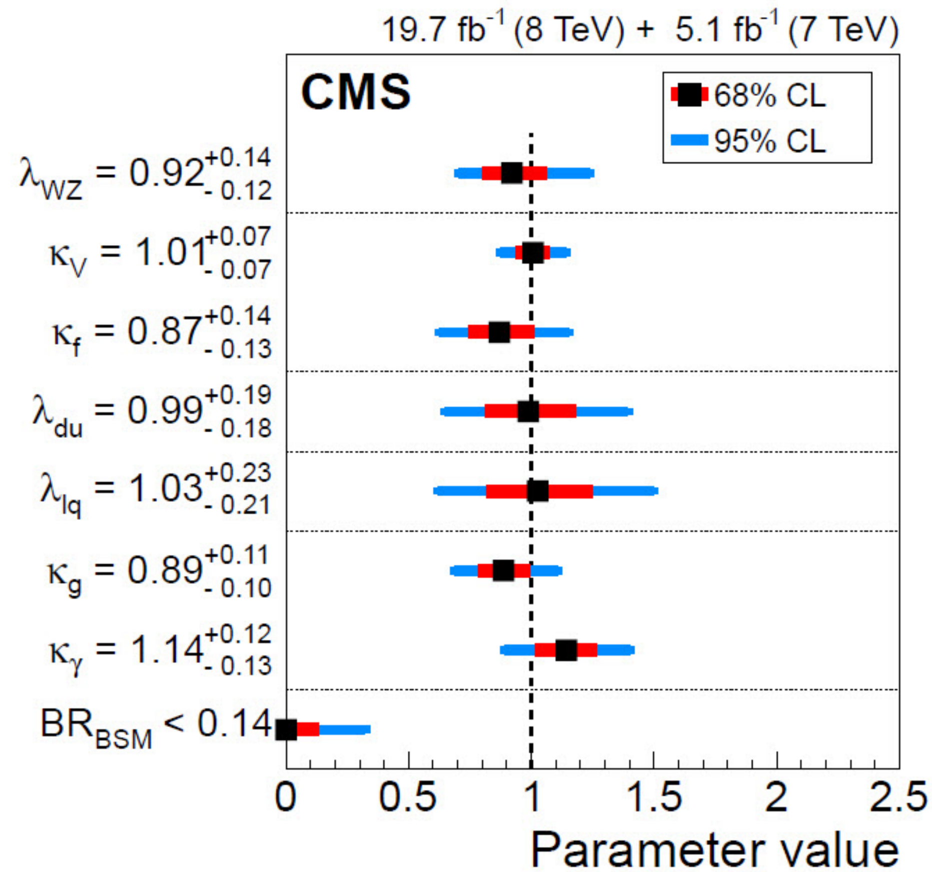
Research program 3: explorations of the Terascale at present and future colliders (LHC and ILC)

- 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)

CMS search for deviations from SM-Higgs couplings



2D test statistics q(κ_V, κ_F) scan for individual channels (colored swaths) and for the overall combination (thick curve). The cross indicates the global best-fit values. The dashed contour bounds the 95% CL region for the combination. The yellow diamond shows the SM point (κ_V, κ_f) = (1, 1). Two quadrants corresponding to (κ_V, κ_f) = (+,+) and (+,−) are physically distinct. Taken from arXiv:1412.8662 (December, 2014).



Summary plot of likelihood scan results for the different parameters of interest in benchmark models separated by dotted lines. The BR_{BSM} value at the bottom is obtained for the model with three parameters (κ_g, κ_γ, BR_{BSM}). The inner bars represent the 68% CL confidence intervals while the outer bars represent the 95% CL confidence intervals. Taken from arXiv:1412.8662 (December, 2014).

Implications of a SM-like Higgs boson

Typically, none of the scalar states of the 2HDM 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 ($M \gg m_h$). 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 and Thomas 2013, Haber 2013)

In the Higgs basis $\{H_1\,, H_2\}$, the vavuum expectation value $v = 246$ GeV resides completely in the neutral component of one of the Higgs doublets, H_1. In the limit where the mixing between H_1 and H_2 in the mass matrix goes to zero, one of the neutral mass eigenstates aligns with ${\rm Re}(H_1^0 - v)$. This state h is nearly indistinguishable from the SM Higgs boson. This limit can be attained even if all Higgs scalar masses are of the same order of magnitude.

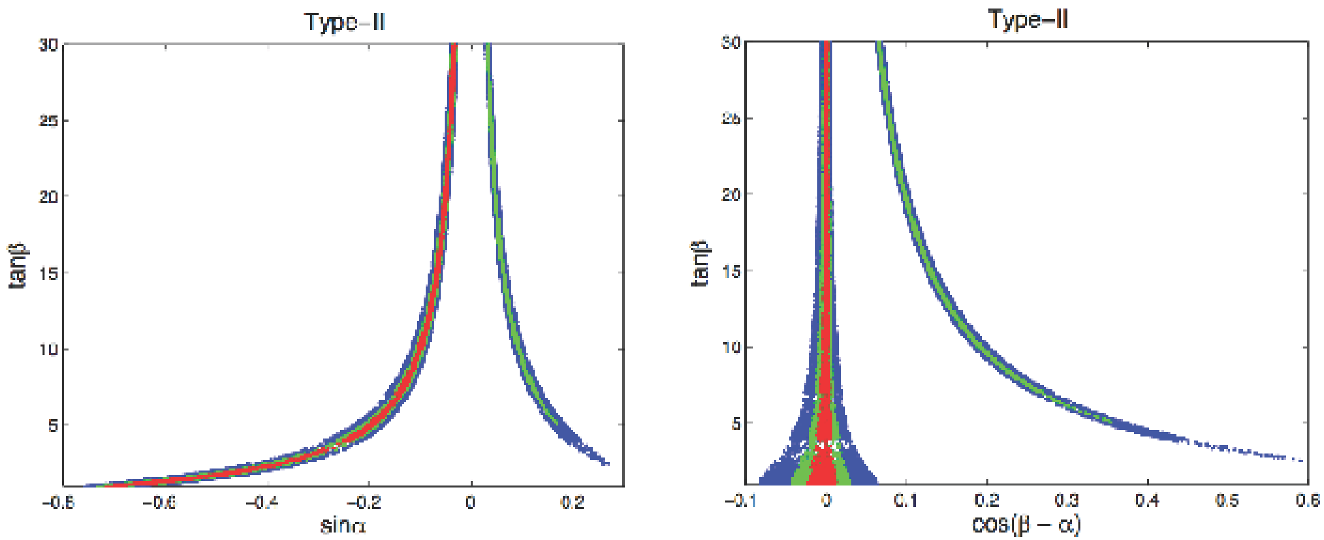
Is it possible that the Higgs coupling to bottom quarks and tau leptons have the expected magnitude but the opposite sign to their predicted SM values?

In collaboration with P. Ferreira, J.F. Gunion and R. Santos, we have scanned the 2HDM parameter space, imposing theoretical constraints, direct LHC experimental constraints, and indirect constraints (from precision electroweak fits, B physics observables, and R_b). The latter requires that $m_{H^\pm} \gtrsim 340$ GeV in the Type-II 2HDM.

Given a final state f resulting from Higgs decay, we define

$$\mu_f^h(\mathrm{LHC}) = \frac{\sigma^{\mathrm{2HDM}}(pp \to h)\, BR^{\mathrm{2HDM}}(h \to f)}{\sigma^{\mathrm{SM}}(pp \to h_{\mathrm{SM}})\, BR(h_{\mathrm{SM}} \to f)}\,.$$

Our baseline will be to require that the $\mu_f^h(\mathrm{LHC})$ for final states $f = WW$, ZZ, $b\bar{b}$, $\gamma\gamma$ and $\tau^+\tau^-$ are each consistent with unity within 20% (blue), which is a rough approximation to the precision of current data. We will then examine the consequences of requiring that all the $\mu_f^h(\mathrm{LHC})$ be within 10% (green) or 5% (red) of the SM prediction.



The main effects of the wrong-sign $h\overline{D}D$ coupling is to modify the hgg and $h\gamma\gamma$ loop amplitudes due to the interference of the b-quark loop with the t-quark loop (and the W loop in the case of $h \to \gamma\gamma$). In addition, the possibility of a contributing non-decoupling charged Higgs contribution can reduce the partial width of $h \to \gamma\gamma$ by as much as 10%.

The absence of a red region for $\sin\alpha > 0$ (the wrong-sign $h\overline{D}D$ Yukawa regime) demonstrates that a precision in the Higgs data at the 5% level is sufficient to rule out this possibility.

Taken from P.M. Ferreira, J.F. Gunion, H.E. Haber and R. Santos, *Probing wrong-sign Yukawa couplings at the LHC and a future linear collider* Phys. Rev. **D89**, 115003 (2014).

Is alignment without decoupling in the MSSM viable?

Analysis strategy:

- Make use of model-independent CMS search for $H, A \to \tau^+\tau^-$ in the regime $m_A > 200$ GeV. Both gg fusion and $b\bar{b}$ fusion production mechanisms are considered. CMS also considers specific MSSM Higgs scenarios. Recent ATLAS results are similar to those of CMS (although CMS limits are presently the most constraining).

- Analyze various benchmark MSSM Higgs scenarios and deduce limits on $\tan\beta$ as a function of m_A.

- Compare resulting limits to the constraints imposed by the properties of the observed Higgs boson with $m_h \simeq 125$ GeV.

- Extrapolate to future LHC runs. Determine what is needed to rule out alignment without decoupling in the MSSM.

MSSM Higgs scenarios[‡]

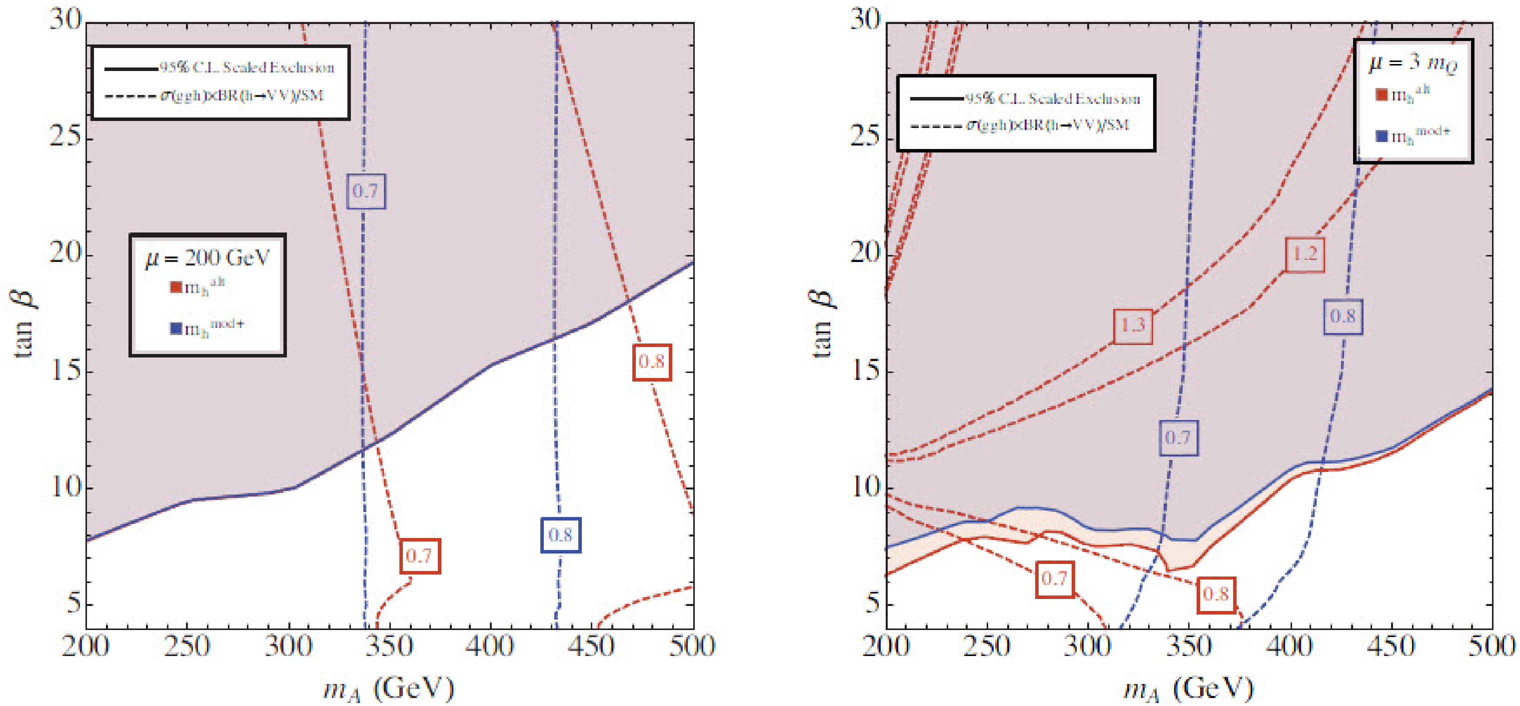
	$\mathrm{m}_h^{\mathrm{mod}+}$	$\mathrm{m}_h^{\mathrm{alt}}$
A_t/m_Q	1.5	2.45
$M_2 = 2\ M_1$	200 GeV	200 GeV
M_3	1.5 TeV	1.5 TeV
$m_{\tilde{\ell}} = m_{\tilde{q}}$	m_Q	m_Q
$A_\ell = A_q$	A_t	A_t
μ	free	free

The $m_h^{\rm alt}$ scenario (for large μ) has been chosen to exhibit a region of the MSSM parameter space where the alignment limit is approximately realized.

For $m_Q = 1$ TeV, $m_h = 125.5 \pm 3$ GeV for $\tan\beta > 6$ and $m_A > 200$ GeV. Here, we regard the ± 3 GeV as the theoretical error in the determination of m_h. Thus, for $\tan\beta < 6$, we increase m_Q such that m_h falls in the desired mass range for all $m_A > 200$ GeV.

[‡]Additional benchmark scenarios can be found in M. Carena, S. Heinemeyer, O. Stål, C.E.M. Wagner and G. Weiglein, "MSSM Higgs Boson Searches at the LHC: Benchmark Scenarios after the Discovery of a Higgs-like Particle," Eur. Phys. J. **C73**, 2552 (2013).

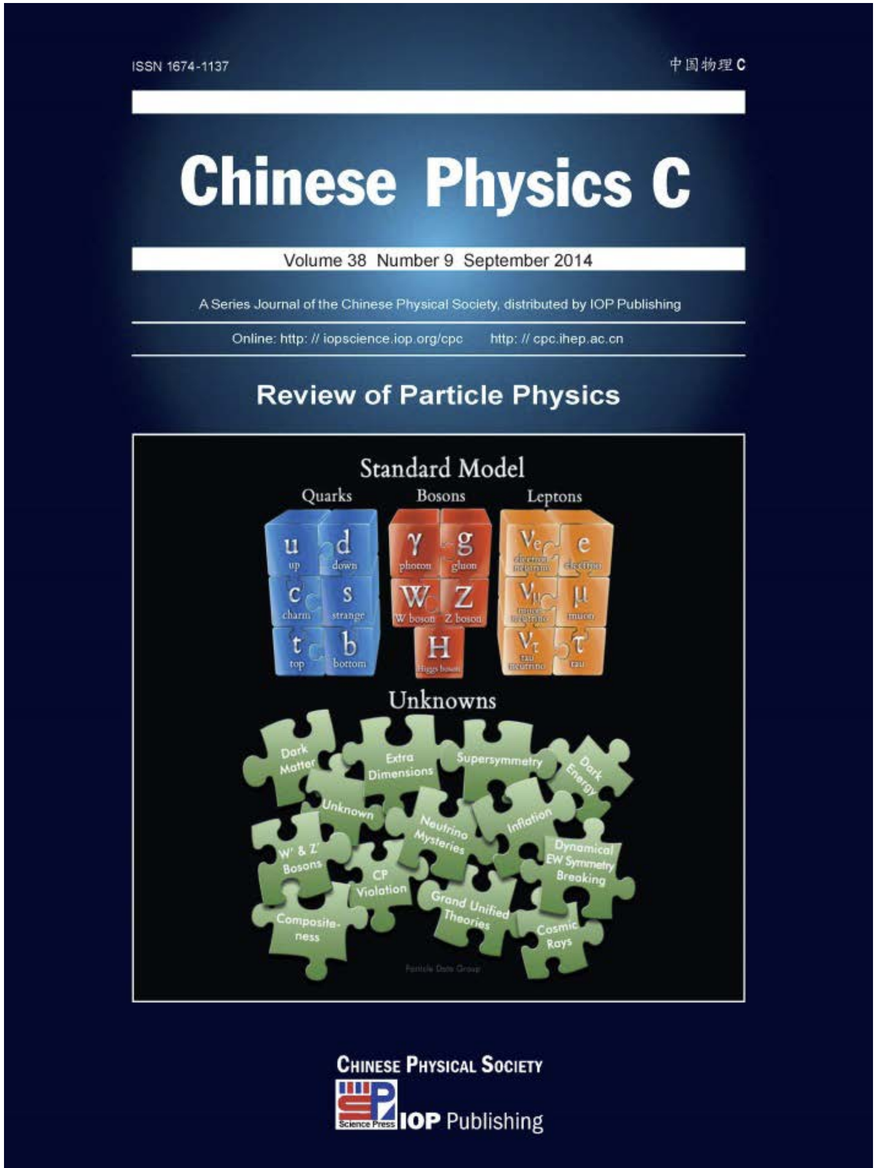
Complementarity of the H , A search and the h data



The alignment limit is most pronounced at large μ in the $m_h^{\rm alt}$ scenario. Taking values of μ much larger than $3M_Q$ would result in color and charge violating vacua, which suggests that alignment for $\tan\beta$ values below 10 is not viable in the MSSM.

M. Carena, H.E. Haber, I. Low, N.R. Shah and C. E.M. Wagner, *Complementarity Between Non-Standard Higgs Searches and Precision Higgs Measurements in the MSSM*, arXiv:1410.4969 [hep-ph], Physical Review **D91** (2015) in press.

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 Translated from ZETF 61 1721.	L.M. Barkov, I.I. Gurevich, M.S. Zolotorev	(KIAE+)
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	
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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

My recent Ph.D. students and their thesis projects

Douglas Pahel (2005): CP-Violating Effects in W and Z Boson Pair Production at the
the ILC in the Minimal Supersymmetric Standard Model

John Mason (2008): Hard supersymmetry-breaking "wrong-Higgs" couplings of
the MSSM

Deva O'Neil (2009): Phenomenology of the Basis-Independent CP-Violating
Two-Higgs Doublet Model

Where are they now?

D. Pahel – working in industry
J. Mason – following a three-year post doctoral research associate in particle
theory at Harvard University, John accepted a position as an
assistant professor of physics at Western State College of Colorado
D. O'Neil – assistant professor of physics at Bridgewater College (in Virginia)

My current Ph.D. students and their projects

Laura Fava: Precision measurements of couplings at the LHC and tests of theories of UED (universal extra dimensions).

Eddie Santos: Renormalization group running in the general CP-violating two-Higgs doublet model; predictions for Higgs-mediated flavor changing neutral current processes.

I am also working with:

Laurel Stephenson Haskins: Puzzle in the relation between the quark anomalous dimension and the mass anomalous dimension in supersymmetric non-abelian gauge theory.

Project with Laura Fava: study the potential for precision coupling measurements in the minimal Universal Extra Dimensions (mUED) model. Look for events with like-sign dileptons, associated hadronic jets and missing transverse energy.

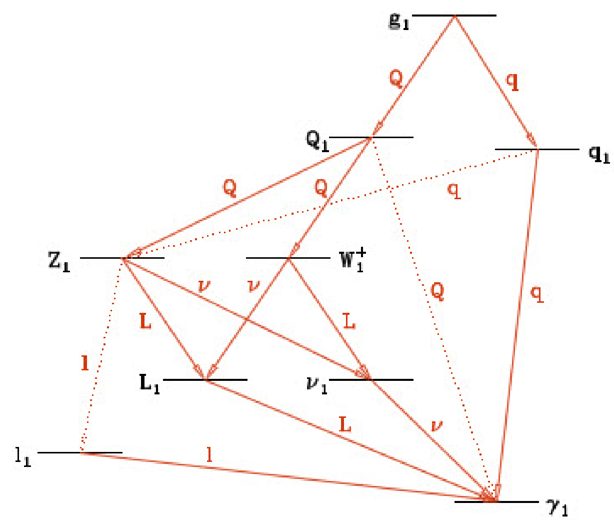


FIG. 2: The n=1 KK decay chain. Solid lines represent the dominant transitions (BRs ≥ %). From Ref. [7].

We draw the reader's attention to one particular feature of the model. In mUED, the couplings are independent of n. Because the SM fields are the $n = 0$ modes, the mUED couplings are the same as those of the SM, for example:

$$g_{sm}(qqg) = g_{sm}(Q_1 Q_1 g) = g_{ued}(q\, Q_1 g_1). \tag{3}$$

We may use this feature in conjuction with other predictions from the theory to determine to within what precision mUED couplings can be measured at the LHC. The goal of this analysis is to estimate this precision for the mUED strong coupling g_{ued} for the range 800 GeV $\leq R^{-1} \leq$ 1200 GeV at $\Lambda R = 20$, and a special case of $R^{-1} = 800$ GeV at $\Lambda R = 5$, energies which will be accessible to the LHC during the 14 TeV run.

Preliminary results

S=number of signal events observed

c= ratio of the strong UED coupling to the QCD coupling

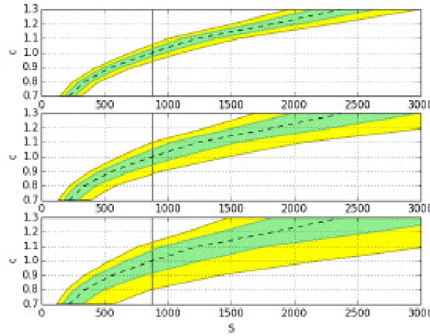
R= compactification radius of the extra dimension

Λ=cutoff energy scale of the mUED model

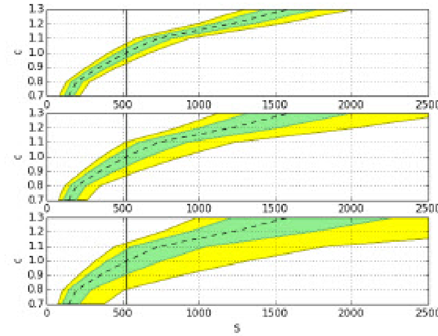
Brazil plots:

green—68% CL

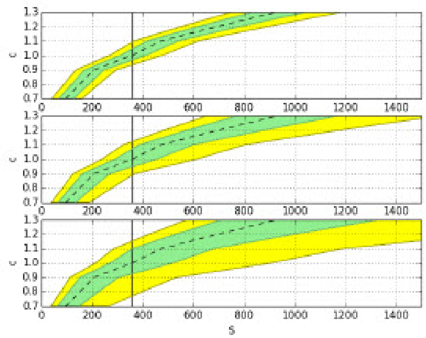
yellow—95% CL



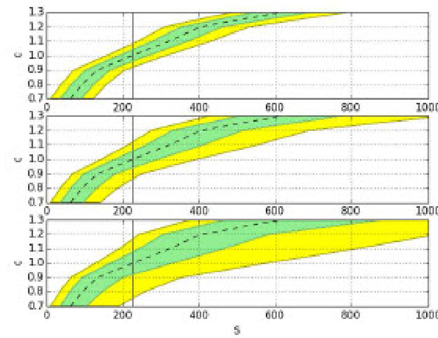
(a) $R^{-1} = 800$ GeV, $\Lambda R = 20$



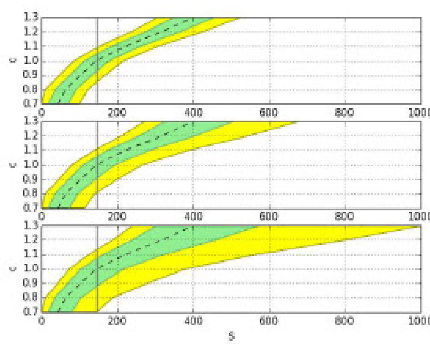
(b) $R^{-1} = 900$ GeV, $\Lambda R = 20$



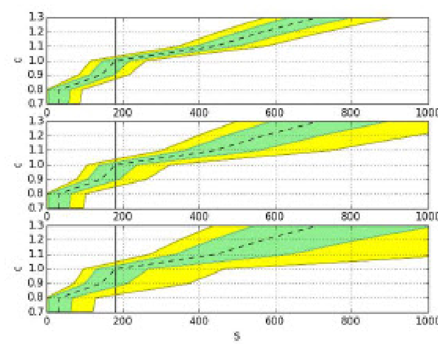
(c) $R^{-1} = 1000$ GeV, $\Lambda R = 20$



(d) $R^{-1} = 1100$ GeV, $\Lambda R = 20$



(e) $R^{-1} = 1200$ GeV, $\Lambda R = 20$



(f) $R^{-1} = 800$ GeV, $\Lambda R = 5$

FIG. 4: c vs. S for R^{-1} = (a) 800 GeV, (b) 900 GeV, (c) 1000 GeV, (d) 1100 GeV, and (e) 1200 GeV with $\Lambda R = 20$, and for (f) $R^{-1} = 800$ GeV with $\Lambda R = 5$. The assumed integrated luminosity is 100 fb^{-1} at $\sqrt{s} = 14$ TeV. In each plot, the vertical line denotes the number of signal events for $c = 1$.

Implication of the Higgs data for the stability of the vacuum

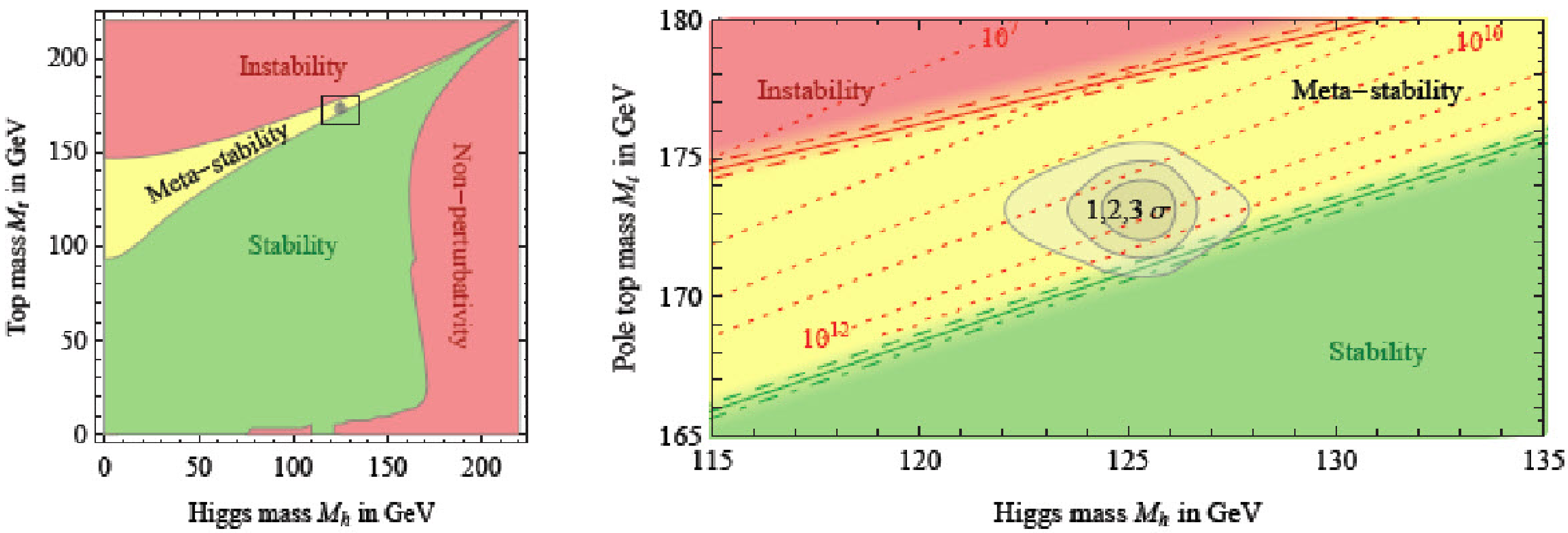


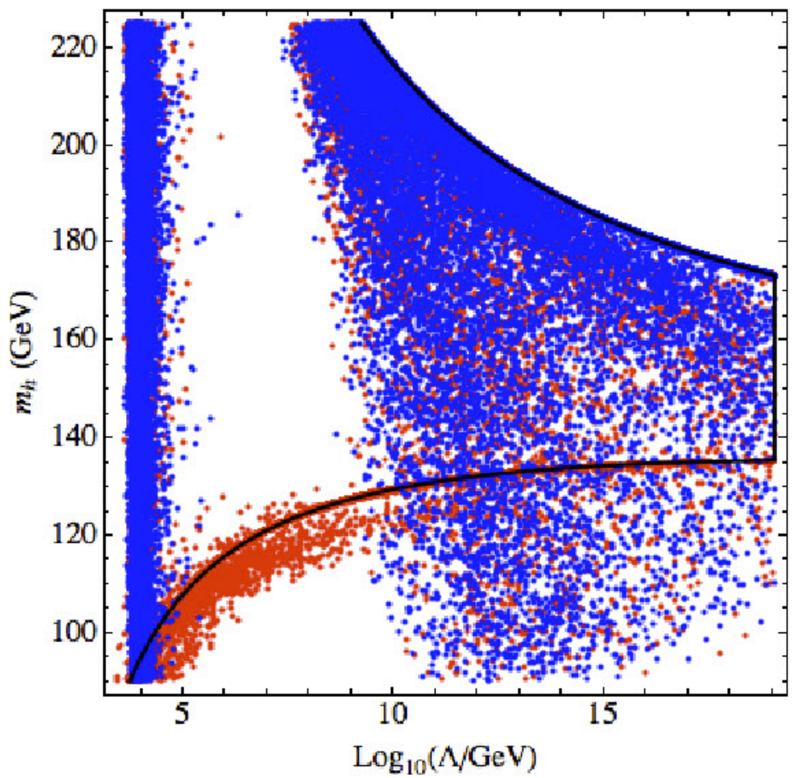
Figure 5: *Regions of absolute stability, meta-stability and instability of the SM vacuum in the M_t–M_h plane.* **Right**: *Zoom in the region of the preferred experimental range of M_h and M_t (the gray areas denote the allowed region at 1, 2, and 3σ). The three boundaries lines correspond to $\alpha_s(M_Z)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

Taken from G. Degrassi et al., arXiv:1205.6497

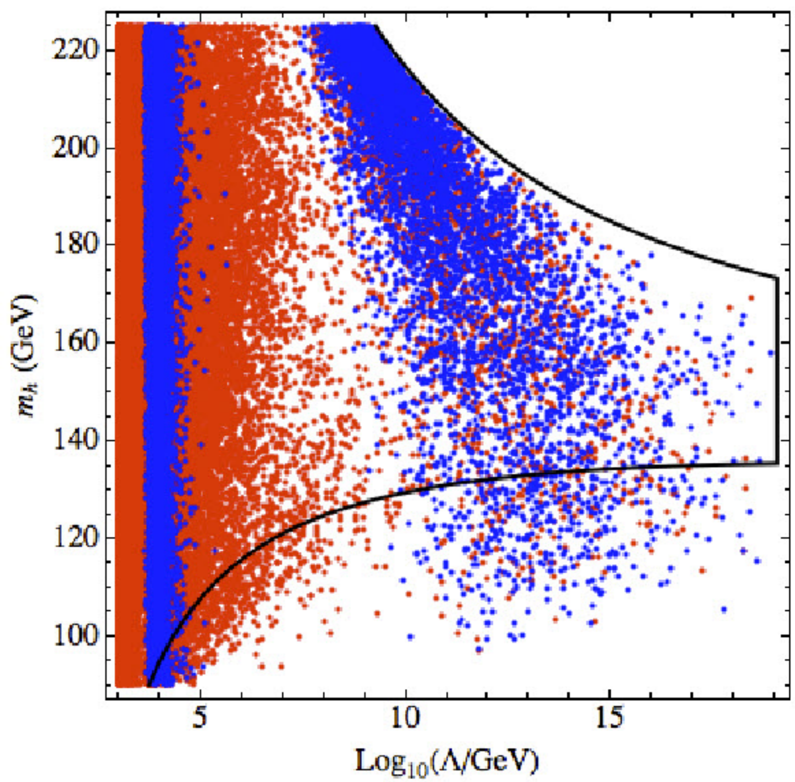
Project with Eddie Santos: Investigate whether stability up to the Planck scale is possible in the two-Higgs-doublet model (2HDM)

A partial scan over 2HDM parameter space

α=0



α=0.8



red—stability bound blue—Landau pole