Georg's Fest

BSM (SUSY) Higgs Physics and Gravitational Waves

Marcela Carena and Carlos Wagner, November 13, 2025

Coming Back to Hamburg

We did our Ph.D. at DESY !

We arrived in September 1987, left in July 1989

Probably one of the fastest Ph.D.'s in any subject in any German University !
It was so fast, that we did not need to pass the German language exam.
Look at it : No laptops, no desktops, no e-mails, no smart phones !

We came back to Germany, to the MPI, in 1991, before moving to CERN in 1993.
Through the years, many friends in Germany

Georg among the closest ones

Of course, we all changed a little bit...

Eventually, Georg became one of our most frequent collaborators

Many proceedings, of course, but several relevant articles :
Predominant subject : Higgs in SUSY

Author

Carlos E.M. Wagner	238
Marcela S. Carena	140
Sven Heinemeyer	33
Georg Ralf Weiglein	29
Nausheen R. Shah	25
Tao Han	20
Timothy M.P. Tait	18
Howard E. Haber	16
John Richard Ellis	16

?

Marcela S. Carena	240
Carlos E.M. Wagner	140
Georg Ralf Weiglein	34
Sven Heinemeyer	33
Howard E. Haber	27
John Richard Ellis	25
Nausheen R. Shah	24
Tao Han	20
Michael Spira	15

Marcela and Georg were members of the PDG

Review of Particle Physics
#1

Particle Data Group • M. Tanabashi (Nagoya U. and KMI, Nagoya) et al. (Aug 17, 2018)

Published in: *Phys.Rev.D* 98 (2018) 3, 030001

links DOI cite claim reference search 9,396 citations

Review of Particle Physics
#2

Particle Data Group • C. Patrignani (Bologna U. and INFN, Bologna) et al. (Oct 3, 2016)

Published in: *Chin.Phys.C* 40 (2016) 10, 100001

pdf links DOI cite claim reference search 7,202 citations

Review of Particle Physics
#3

Particle Data Group • K.A. Olive (Minnesota U.) et al. (2014)

Published in: *Chin.Phys.C* 38 (2014) 090001

links DOI cite claim reference search 9,400 citations

Review of Particle Physics (RPP)
#4

Particle Data Group • J. Beringer (LBL, Berkeley) et al. (2012)

Published in: *Phys.Rev.D* 86 (2012) 010001

DOI cite claim reference search 9,255 citations

We continue working regularly, and meeting periodically

This is at Herbi's Fest : Where is Marcela ?

Our First Work, on Higgs at LEP2,
after Georg and Sven produced the first two loop diagrammatic calculation of the MSSM Higgs Mass,
competing with our effective potential calculations.

These were exciting times, and the four of us were either at CERN or DESY

CERN-TH/99-374
DESY 99-186
hep-ph/9912223

Suggestions for Improved Benchmark Scenarios for Higgs-Boson Searches at LEP2*

M. Carena[1†], S. Heinemeyer[2], C.E.M. Wagner[1‡] and G. Weiglein[1]

[1] *Theoretical Physics Division, CERN, CH-1211 Geneva 23, Switzerland*

[2] *DESY Theorie, Notkestr. 85, 22603 Hamburg, Germany*

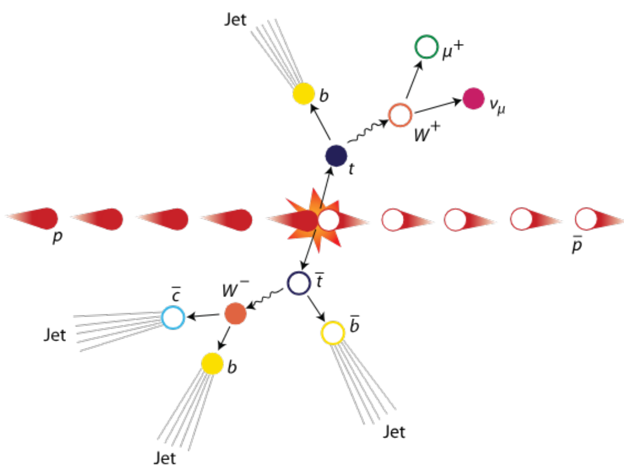
Abstract

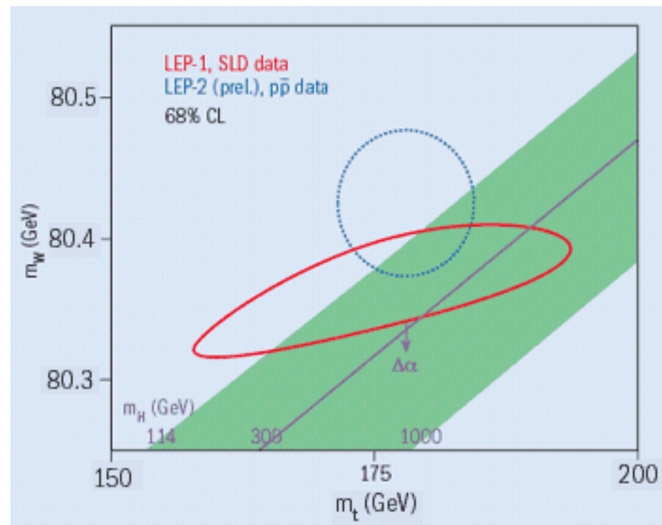
We suggest new benchmark scenarios for the Higgs-boson search at LEP2. Keeping m_t and $M_{\rm SUSY}$ fixed, we improve on the definition of the maximal mixing benchmark scenario defining precisely the values of all MSSM parameters such that the new $m_h^{\rm max}$ benchmark scenario yields the parameters which maximize the value of m_h for a given $\tan\beta$. The corresponding scenario with vanishing mixing in the scalar top sector is also considered. We propose a further benchmark scenario with a relatively large value of $|\mu|$, a moderate value of $M_{\rm SUSY}$, and moderate mixing parameters in the scalar top sector. While the latter scenario yields m_h values that in principle allow to access the complete M_A–$\tan\beta$-plane at LEP2, on the other hand it contains parameter regions where the Higgs-boson detection can be difficult, because of a suppression of the branching ratio of its decay into bottom quarks.

December 1999

What was the situation then ?

In 1995, the top quark was discovered at the Tevatron collider at Fermilab in Illinois through the collisions of protons with antiprotons. The top mass range was anticipated by the consistency of the electroweak theory with experiment at the quantum level





Amazing Feature : Mathematical consistency predicts the existence of a particle and also its mass !
Actually, the gauge symmetries are broken in the absence of a top quark

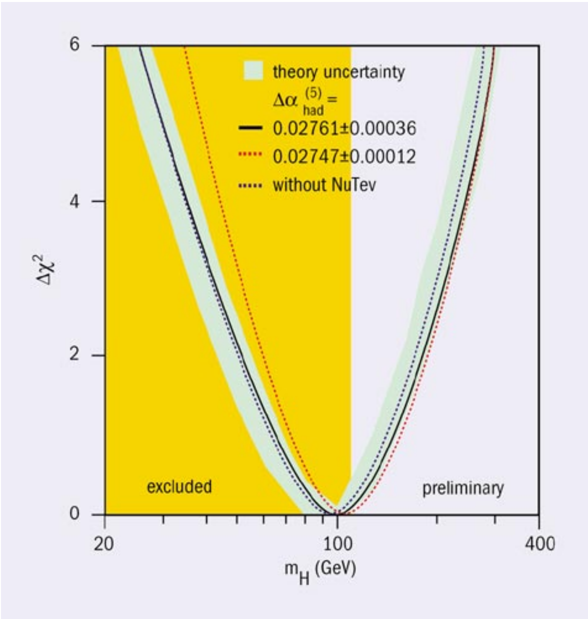
Top quark mass knowledge

Once the top was discovered, the fermion content was "complete" although new generations could be present. The consistency of the theory with experiment at the quantum level, however, suggested no such particles.

There was still no experimental evidence of the Higgs boson, but we knew of a logarithmic dependence of the electroweak observables on the Higgs mass, [in the case of the top quark it was quadratic]

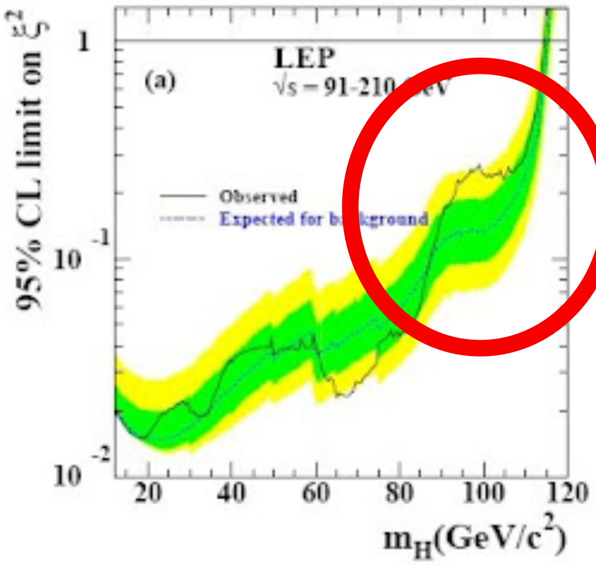
Very refined experimental techniques at the electron positron colliders (LEP at CERN and SLC at SLAC) suggested a certain preferred range for the Higgs mass !

The Higgs was simultaneously search for at LEP, in associated Z—Higgs production at a center of mass up to 209 GeV. No signal was found.



Situation in year 2000

ξ^2 : Ratio of bounded production coupling squared to the Standard Model expected value



Seeds of the 95 GeV Higgs

Lightest SM-like Higgs mass strongly depends on:

* CP-odd Higgs mass m_A * tan beta $\frac{v_u}{v_d}$ * the top quark mass

* the stop masses and mixing

$$\mathbf{M}^2_{\tilde{t}} = \begin{pmatrix} \mathbf{m}^2_Q + \mathbf{m}^2_t + \mathbf{D}_L & \mathbf{m}_t \mathbf{X}_t \\ \mathbf{m}_t \mathbf{X}_t & \mathbf{m}^2_U + \mathbf{m}^2_t + \mathbf{D}_R \end{pmatrix}$$

M_h depends logarithmically on the averaged stop mass scale M_{SUSY} and has a quadratic and quartic dep. on the stop mixing parameter X_t. [and on sbottom/stau sectors for large tan beta]

For moderate to large values of tan beta and large non-standard Higgs masses

$$\boxed{m_h^2 \cong M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]}$$

$$t = \log(M_{SUSY}^2 / m_t^2) \qquad \tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{SUSY}^2}\right)$$

$\underline{X_t = A_t - \mu/\tan\beta} \rightarrow$ LR stop mixing

Carena, Espinosa, Quiros, C.W.'95,96

Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

APPROXIMATING THE RADIATIVELY CORRECTED HIGGS MASS IN THE MINIMAL SUPERSYMMETRIC MODEL

Howard E. Haber,[1] Ralf Hempfling[2] and André H. Hoang[3]

[1] *CERN, TH-Division, CH-1211 Geneva 23, Switzerland*

and

Santa Cruz Institute for Particle Physics
University of California, Santa Cruz, CA 95064 USA

[2] *Max-Planck-Institut für Physik, Werner-Heisenberg-Institut,*
Föhringer Ring 6, D-80805 Munich, Germany

[3] *Institut für Theoretische Teilchenphysik, Universität Karlsruhe,*
Kaiserstrasse 12, D-76128 Karlsruhe, Germany

Abstract

To obtain the most accurate predictions for the Higgs masses in the minimal supersymmetric model (MSSM), one should compute the full set of one-loop radiative corrections, resum the large logarithms to all orders, and add the dominant two-loop effects. A complete computation following this procedure yields a complex set of formulae which must be analyzed numerically. We discuss a very simple approximation scheme which includes the most important terms from each of the three components mentioned above. We estimate that the Higgs masses computed using our scheme lie within 2 GeV of their theoretically predicted values over a very large fraction of MSSM parameter space.

$$
\begin{aligned}
m_h^2 = m_h^{2,\rm tree} &+ \frac{3}{2}\frac{G_F\sqrt{2}}{\pi^2}\overline{m}_t^4\left\{-\ln\left(\frac{\overline{m}_t^2}{\overline{M}_S^2}\right)+\frac{\overline{X}_t^2}{\overline{M}_S^2}\left(1-\frac{1}{12}\frac{\overline{X}_t^2}{\overline{M}_S^2}\right)\right\}\\
&- 3\frac{G_F\sqrt{2}}{\pi^2}\frac{\alpha_s}{\pi}\overline{m}_t^4\left\{\ln^2\left(\frac{\overline{m}_t^2}{\overline{M}_S^2}\right)+\left[\frac{2}{3}-2\frac{\overline{X}_t^2}{\overline{M}_S^2}\left(1-\frac{1}{12}\frac{\overline{X}_t^2}{\overline{M}_S^2}\right)\right]\ln\left(\frac{\overline{m}_t^2}{\overline{M}_S^2}\right)\right\}
\end{aligned}
$$

There were intriguing features in Georg's two loop computation, mostly induced by the on-shell renormalization. We clarified them in this article. Excellent agreement of the strong coupling corrections after gluino threshold corrections were included, and proper leading logs were taken into account.

hep–ph/0001002

Reconciling the Two-Loop Diagrammatic and Effective Field Theory Computations of the Mass of the Lightest $\mathcal{CP}$-even Higgs Boson in the MSSM

M. Carena [§,†], **H.E. Haber** [♯], **S. Heinemeyer** [‡],

W. Hollik [¶], **C.E.M. Wagner** [†,∗,♮] **and G. Weiglein** [†]

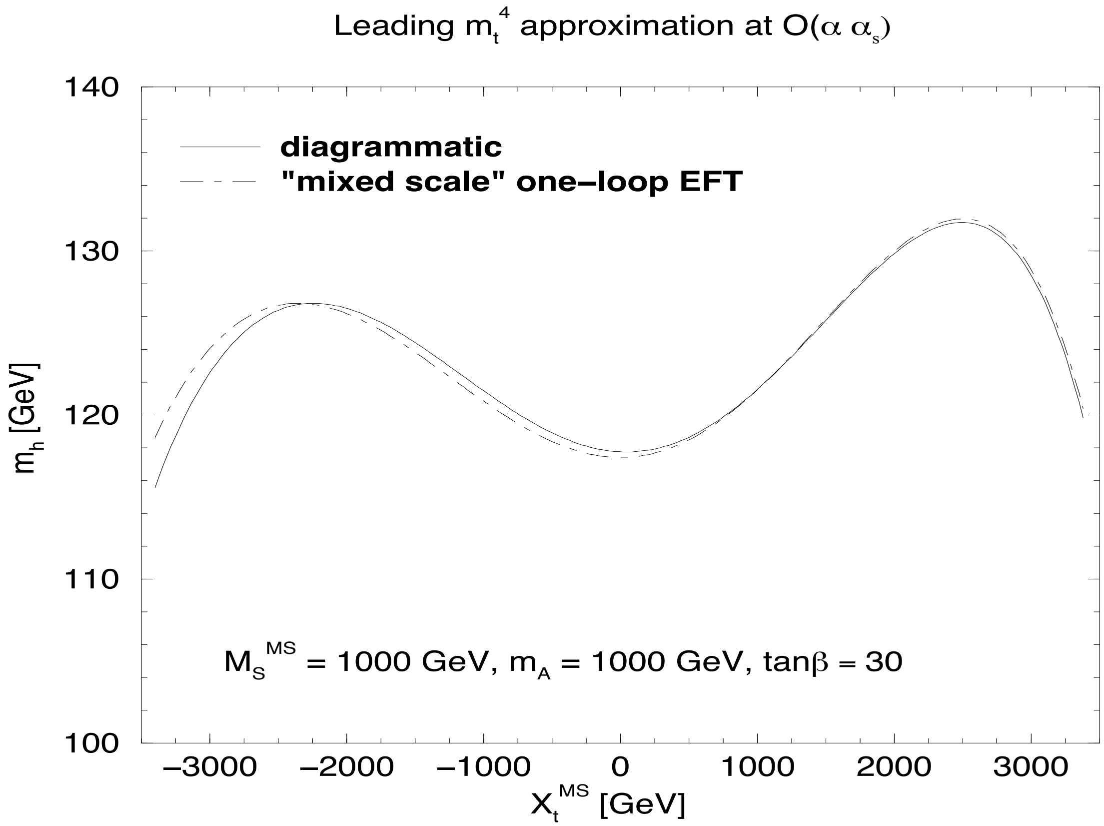
[§] FERMILAB, Batavia, IL 60510-0500 USA
[†] CERN, TH Division, CH–1211 Geneva 23, Switzerland
[♯] Santa Cruz Inst. for Part. Phys., Univ. of California, Santa Cruz, CA 95064 USA
[‡] DESY Theorie, Notkestrasse 85, 22603 Hamburg, Germany
[¶] Institut für Theoretische Physik, Univ. of Karlsruhe, 76128 Karlsruhe, Germany
[∗] High Energy Physics Division, Argonne National Lab., Argonne, IL 60439 USA
[♮] Enrico Fermi Institute, Univ. of Chicago, 5640 Ellis, Chicago, IL 60637 USA

Abstract

The mass of the lightest $\mathcal{CP}$-even Higgs boson of the minimal supersymmetric extension of the Standard Model (MSSM) has previously been computed including $\mathcal{O}(\alpha\alpha_s)$ two-loop contributions by an on-shell diagrammatic method, while approximate analytic results have also been obtained via renormalization-group-improved effective potential and effective field theory techniques. Initial comparisons of the corresponding two-loop results revealed an apparent discrepancy between terms that depend logarithmically on the supersymmetry-breaking scale, and different dependences of the non-logarithmic terms on the squark mixing parameter, X_t. In this paper, we determine the origin of these differences as a consequence of different renormalization schemes in which both calculations are performed. By re-expressing the on-shell result in terms of $\overline{\rm MS}$ parameters, the logarithmic two-loop contributions obtained by the different approaches are shown to coincide. The remaining difference, arising from genuine non-logarithmic two-loop contributions, is identified, and its effect on the maximal value of the lightest $\mathcal{CP}$-even Higgs boson mass is discussed. Finally, we show that in a simple analytic approximation to the Higgs mass, the leading two-loop radiative corrections can be absorbed to a large extent into an effective one-loop expression by evaluating the running top quark mass at appropriately chosen energy scales.

$$\overline{m}_t(M_S) = \overline{m}_t \left[1 + \frac{\alpha_s}{\pi} \ln\left(\frac{m_t^2}{M_S^2}\right) + \frac{\alpha_s}{3\pi}\frac{X_t}{M_S} \right] ,$$

$$\overline{M}_S^2 = M_S^{2,\mathrm{OS}} - \frac{8}{3}\frac{\alpha_s}{\pi} M_S^2 ,$$
$$\overline{X}_t = X_t^{\mathrm{OS}} \frac{M_t}{\overline{m}_t(M_S)} + \frac{8}{3}\frac{\alpha_s}{\pi} M_S .$$



In the meantime, while waiting for further Higgs searches at colliders, we worked together in exotic scenarios

Do electroweak precision data and Higgs-mass constraints rule out a scalar bottom quark with mass of $\mathcal{O}(5\ \text{GeV})$?

M. Carena[1], S. Heinemeyer[2], C.E.M. Wagner[3] and G. Weiglein[4]
[1] *Fermilab, Box 500, Batavia, IL 60510-0500, USA*
[2] *HET, Physics Department, Brookhaven Natl. Lab., Upton, NY 11973, USA*
[3] *High Energy Division, Argonne National Laboratory, Argonne, IL 60439, USA and the Enrico Fermi Institute, Univ. of Chicago, 5640 Ellis, Chicago, IL 60637, USA*
[4] *Theoretical Physics Division, CERN, CH-1211 Geneva 23, Switzerland*

We study the implications of a scalar bottom quark, with a mass of $\mathcal{O}(5\ \text{GeV})$, within the MSSM. Light sbottoms may naturally appear for large $\tan\beta$ and, depending on the decay modes, may have escaped experimental detection. We show that a light sbottom cannot be ruled out by electroweak precision data and the bound on the lightest $\mathcal{CP}$-even Higgs-boson mass. We infer that a light $\tilde{b}$ scenario requires a relatively light scalar top quark whose mass is typically about the top-quark mass. In this scenario the lightest Higgs boson decays predominantly into $\tilde{b}$ pairs and obeys the mass bound $m_h \lesssim 123$ GeV.

arXiv:hep-ph/0008023v2 5 May 2001

New light particles, with masses of the order of the weak scale, are an essential ingredient in any scenario beyond the standard model (SM) that leads to an explanation of the large hierarchy between the Planck mass and the weak scale. Although no clear evidence of such a particle has been reported so far, searches for new particles are usually performed under model-dependent assumptions and hence the quoted bounds may not be valid if these assumptions are relaxed. In particular, we shall investigate whether a light scalar bottom quark, $\tilde{b}$, with mass close to the bottom-quark mass, m_b, is consistent with present experimental data [1]. A light $\tilde{b}$ is most naturally obtained within supersymmetric theories [2] for large values of $\tan\beta$, as required in minimal SO(10) scenarios [3]. Supersymmetric theories have received much attention in the last years since they provide an elegant way to break the electroweak symmetry and to stabilize the huge hierarchy between the GUT and the Fermi scales; they also allow for a consistent ing the semileptonic decay of the $\tilde{b}$, $\tilde{b} \to c\, l\, +$ missing energy, if its branching ratio is small, for instance of about the bottom quark one, the exclusion bound derived by the CLEO collaboration does not apply [5]. If, on the other hand, the light $\tilde{b}$ decays into a light quark and missing energy, due to its small mass and the small mass splitting between the $\tilde{b}$ and its decay products, it cannot be detected through missing energy searches in e^+e^- or hadron colliders [1]. If, instead, the $\tilde{b}$ decays fully hadronically with no missing energy, it will remain undetected due to its small contribution to the hadronic cross section at hadron and lepton colliders. Finally, the presence of a light $\tilde{b}$ will slightly affect the extrapolated value of the electromagnetic and strong gauge couplings, α_{em} and α_s, at the scale M_Z: the variation induced on $\alpha_{em}(M_Z)$ is smaller than the difference between the two most commonly used values of $\alpha_{em}(M_Z)$ [6]. The variations of both α_{em} and $\alpha_s(M_Z)$ are smaller than the present error on the respective coupling [1].

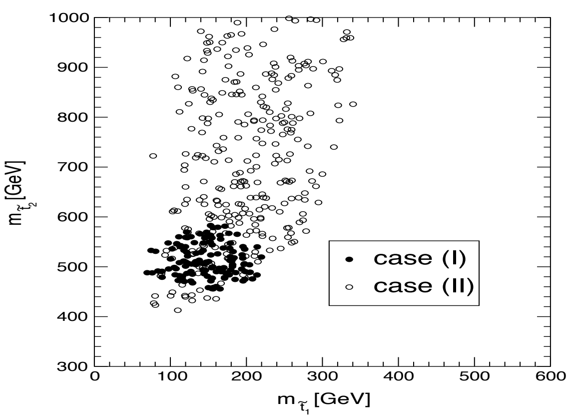
IS HINCHLIFFE'S RULE TRUE?

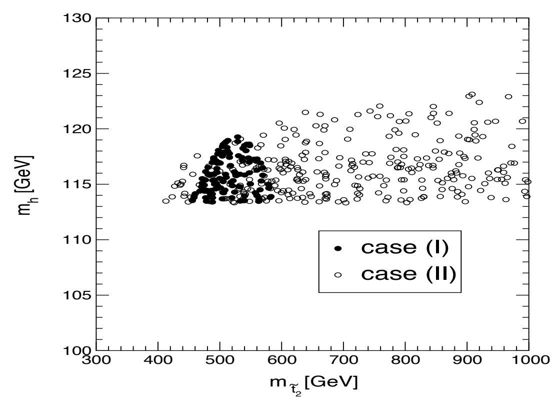
Boris Peon

Abstract

Hinchliffe has asserted that whenever the title of a paper is a question with a yes/no answer, the answer is always no. This paper demonstrates that Hinchliffe's assertion is false, but only if it is true.

Predicted stop and Higgs masses





But we soon went back to Higgs Searches

Suggestions for Benchmark Scenarios for MSSM Higgs Boson Searches at Hadron Colliders*

M. Carena[1†], S. Heinemeyer[2‡], C.E.M. Wagner[3,4§] and G. Weiglein[5¶]

[1] Theoretical Physics. Dept., Fermilab National Accelerator Lab., Batavia, IL 60510-0500, USA

[2] HET, Physics Dept., Brookhaven Natl. Lab., Upton, NY 11973, USA

[3] HEP Division, Argonne Natl. Lab., 9700 Cass Ave., Argonne, IL 60439, USA

[4] Enrico Fermi Institute, Univ. of Chicago, 5640 Ellis Ave., Chicago, IL 60637, USA

[5] Institute for Particle Physics Phenomenology, University of Durham, Durham DH1 3LR, UK

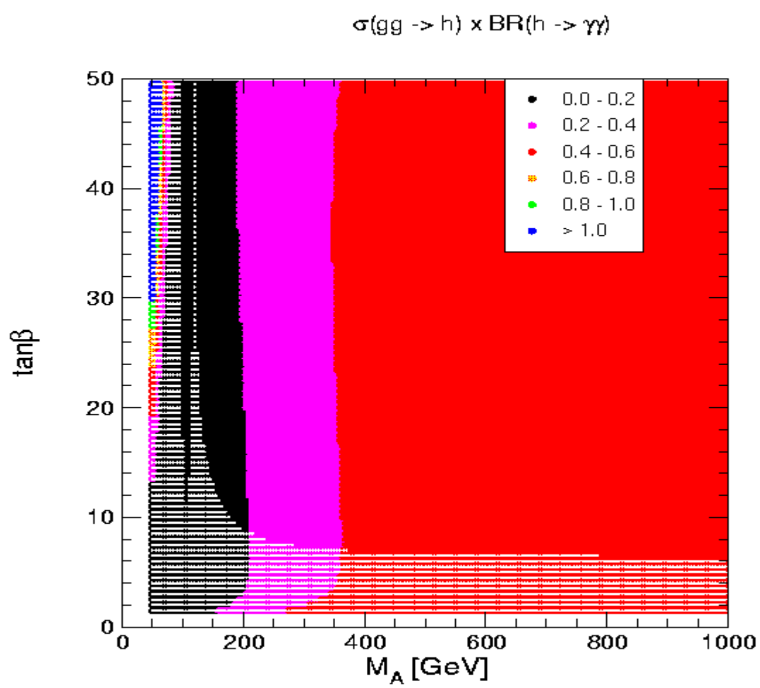
arXiv:hep-ph/0202167v1 16 Feb 2002

Abstract

The Higgs boson search has shifted from LEP2 to the Tevatron and will subsequently move to the LHC. Due to the different initial states, the Higgs production and decay channels relevant for Higgs boson searches were different at LEP2 to what they are at hadron colliders. We suggest new benchmark scenarios for the MSSM Higgs boson search at hadron colliders that exemplify the phenomenology of different parts of the MSSM parameter space. Besides the $m_h^{\max}$ scenario and the no-mixing scenario used in the LEP2 Higgs boson searches, we propose two new scenarios. In one the main production channel at the LHC, $gg \to h$, is suppressed. In the other, important Higgs decay channels at the Tevatron and at the LHC, $h \to b\bar{b}$ and $h \to \tau^+\tau^-$, are suppressed. All scenarios evade the LEP2 constraints for nearly the whole M_A–$\tan\beta$-plane.

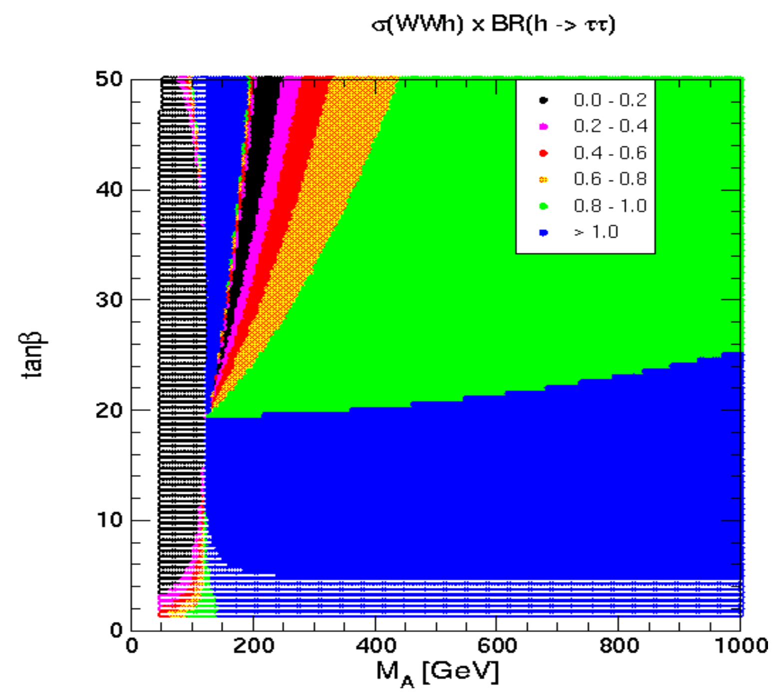
Higgs Properties are not fixed by type II scenario

SUSY Higgs sector is not precisely type II and SUSY particles affect Higgs physics



SUSY corrections to the gluon coupling

arXiv:0202167



Effects of coupling to the wrong Higgs

The competition of the Tevatron and the LHC was on, with the last one having much better chances

MSSM Higgs Boson Searches at the Tevatron and the LHC: Impact of Different Benchmark Scenarios

M. Carena[1*], S. Heinemeyer[2†], C.E.M. Wagner[3,4‡] and G. Weiglein[5§]

[1] Theoretical Physics Dept., Fermilab, Batavia, IL 60510-0500, USA

[2] CERN TH Division, Dept. of Physics, CH-1211 Geneva 23, Switzerland

[3] HEP Division, Argonne Natl. Lab., 9700 Cass Ave., Argonne, IL 60439, USA

[4] Enrico Fermi Institute, Univ. of Chicago, 5640 Ellis Ave., Chicago, IL 60637, USA

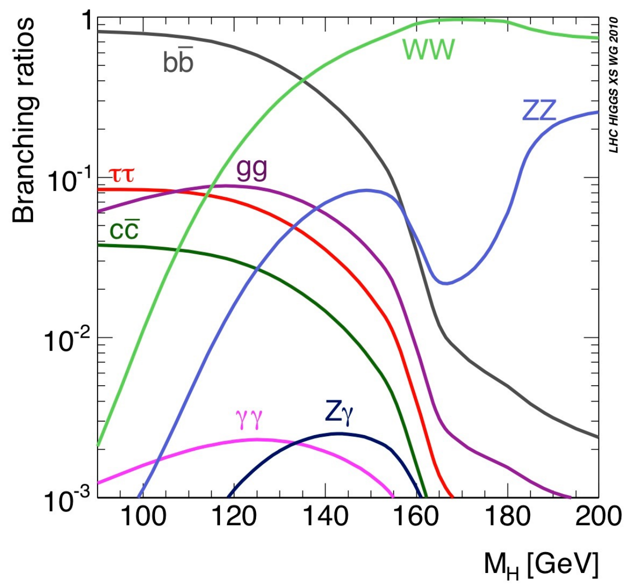
[5] IPPP, University of Durham, Durham DH1 3LE, UK

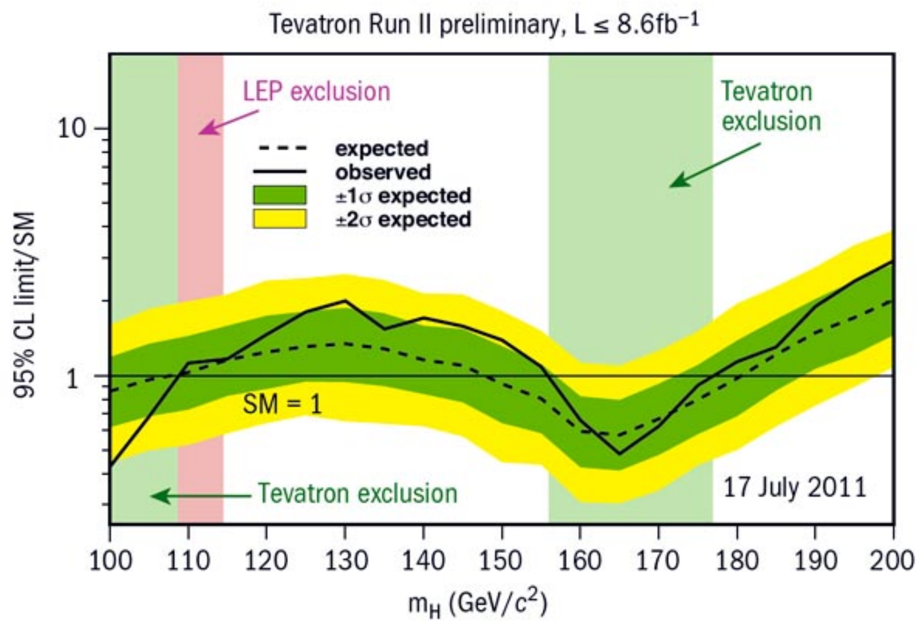
Abstract

The Higgs boson search has shifted from LEP2 to the Tevatron and will subsequently move to the LHC. The current limits from the Tevatron and the prospective sensitivities at the LHC are often interpreted in specific MSSM scenarios. For heavy Higgs boson production and subsequent decay into $b\bar{b}$ or $\tau^+\tau^-$, the present Tevatron data allow to set limits in the M_A–$\tan\beta$ plane for small M_A and large $\tan\beta$ values. Similar channels have been explored for the LHC, where the discovery reach extends to higher values of M_A and smaller $\tan\beta$. Searches for MSSM charged Higgs bosons, produced in top decays or in association with top quarks, have also been investigated at the Tevatron and the LHC. We analyze the current Tevatron limits and prospective LHC sensitivities. We discuss how robust they are with respect to variations of the other MSSM parameters and possible improvements of the theoretical predictions for Higgs boson production and decay. It is shown that the inclusion of supersymmetric radiative corrections to the production cross sections and decay widths leads to important modifications of the present limits on the MSSM parameter space. The impact on the region where only the lightest MSSM Higgs boson can be detected at the LHC is also analyzed. We propose to extend the existing benchmark scenarios by including additional values of the higgsino mass parameter μ. This affects only slightly the search channels for a SM-like Higgs boson, while having a major impact on the searches for non-standard MSSM Higgs bosons.

Searches at Hadron Colliders

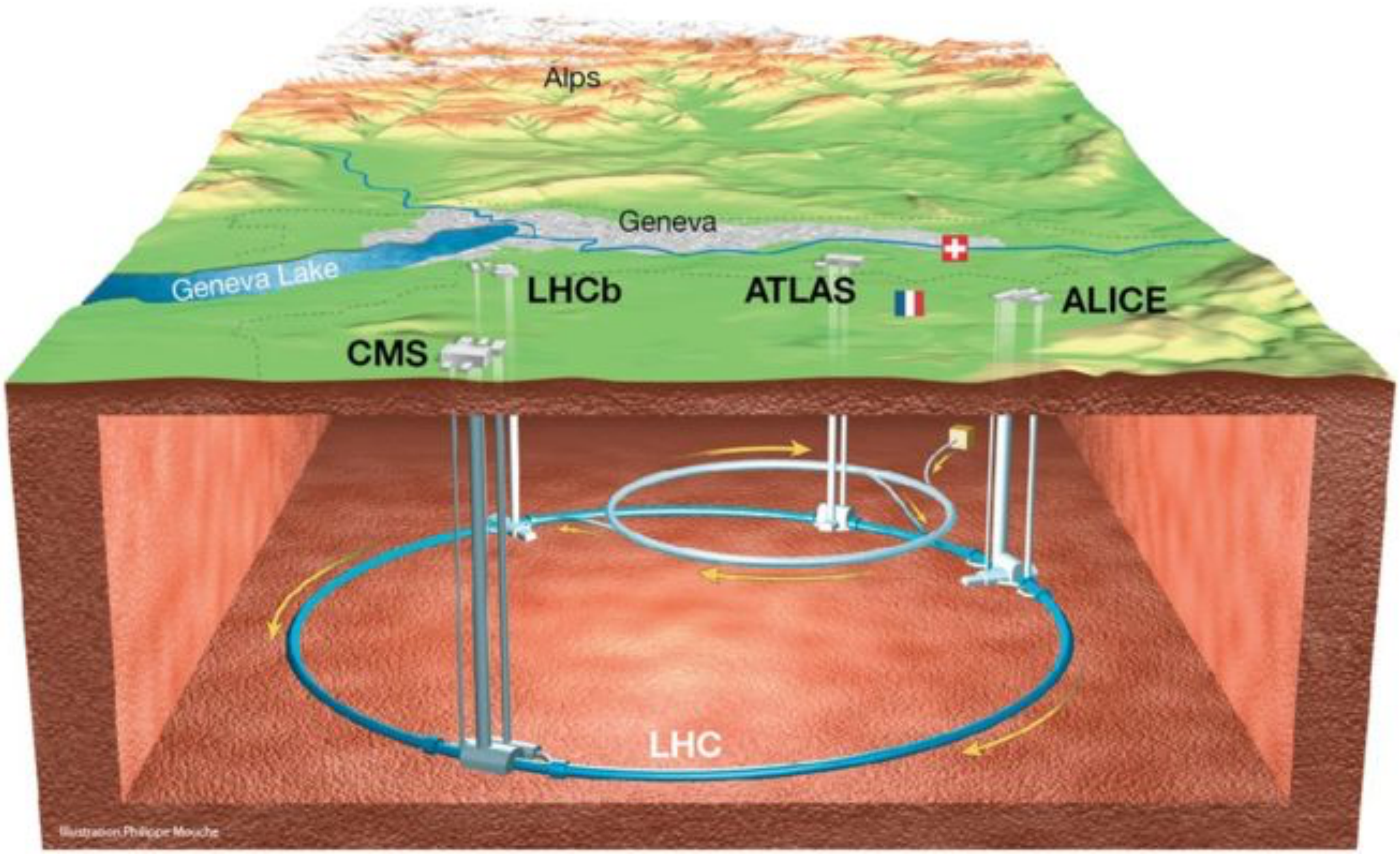
The Tevatron, where the top quark was discovered could look for the Higgs provided it decayed into weak bosons. Nothing was found. Smalll excess for masses around 125 GeV.





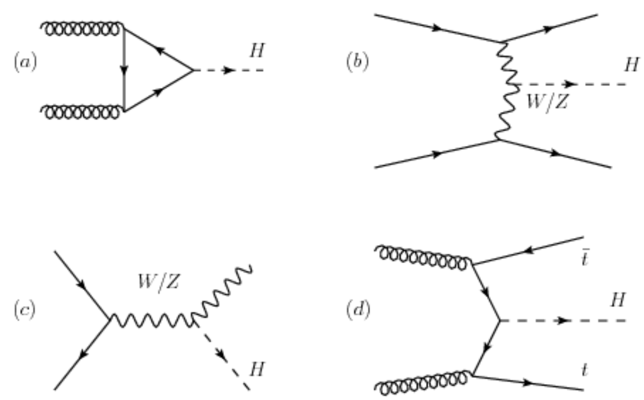
Testing Higgs' hypothesis : Looking for the Higgs boson

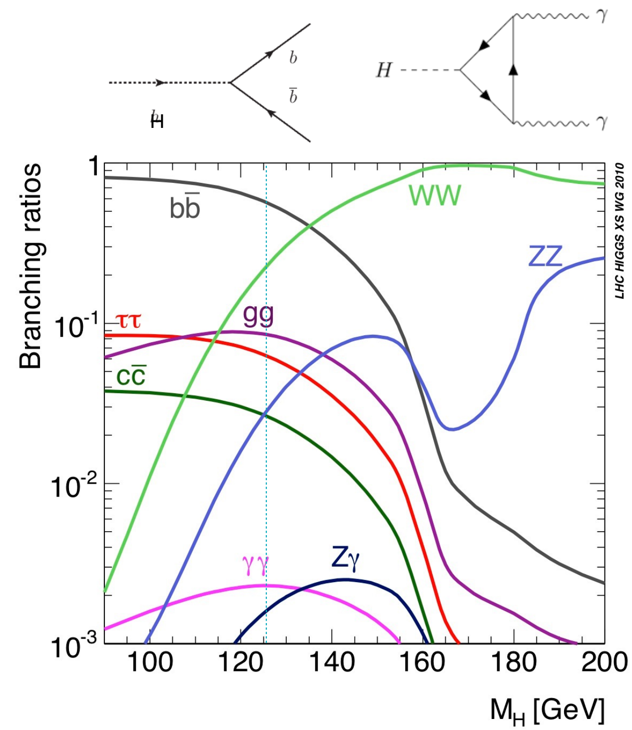
The Large Hadron (proton against proton) Collider (LHC)



We collide two protons (quarks and gluons) at high energies :

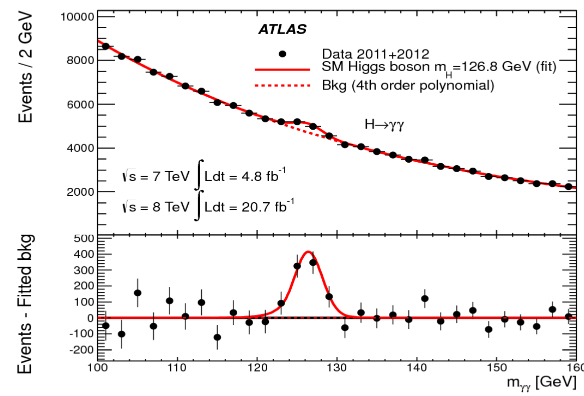
LHC Higgs Production Channels and Decay Branching Ratios





A Higgs with a mass of about 125 GeV allows to study many decay channels

The Higgs Discovery in July 2012 has established the Standard Model (SM) as the proper low energy theory describing all known particle interactions



Still, the Higgs could have properties different from the Standard Model one, and we defined scenarios that emphasize these distinguishing properties

MSSM Higgs Boson Searches at the LHC:

Benchmark Scenarios after the Discovery of a Higgs-like Particle

M. Carena[1,2], S. Heinemeyer[3], O. Stål[4], C.E.M. Wagner[2,5] and G. Weiglein[6*]

[1] Theoretical Physics Department, Fermilab, Batavia, IL 60510-0500, USA

[2] Enrico Fermi Institute and Kavli Institute for Cosmological Physics
Department of Physics, the University of Chicago, 5640 Ellis Ave., Chicago, IL 60637, USA

[3] Instituto de Física de Cantabria (CSIC-UC), E–39005 Santander, Spain

[4] The Oskar Klein Centre, Department of Physics
Stockholm University, SE-106 91 Stockholm, Sweden

[5] HEP Division, Argonne Natl. Lab., 9700 Cass Ave., Argonne, IL 60439, USA

[6] DESY, Notkestraße 85, D–22607 Hamburg, Germany

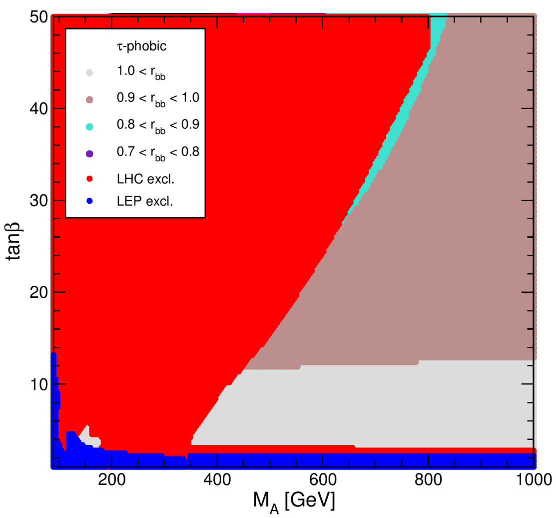
Abstract

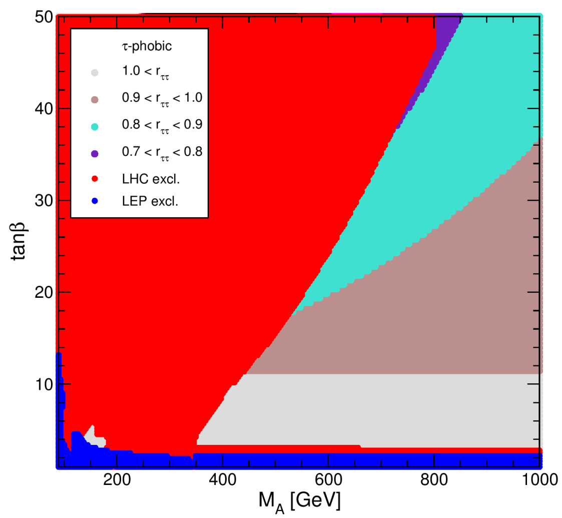
A Higgs-like particle with a mass of about 125.5 GeV has been discovered at the LHC. Within the current experimental uncertainties, this new state is compatible with both the predictions for the Standard Model (SM) Higgs boson and with the Higgs sector in the Minimal Supersymmetric Standard Model (MSSM). We propose new low-energy MSSM benchmark scenarios that, over a wide parameter range, are compatible with the mass and production rates of the observed signal. These scenarios also exhibit interesting phenomenology for the MSSM Higgs sector. We propose a slightly updated version of the well-known $m_h^{\rm max}$ scenario, and a modified scenario ($m_h^{\rm mod}$), where the light $\mathcal{CP}$-even Higgs boson can be interpreted as the LHC signal in large parts of the M_A–$\tan\beta$ plane. Furthermore, we define a *light stop scenario* that leads to a suppression of the lightest $\mathcal{CP}$-even Higgs gluon fusion rate, and a *light stau scenario* with an enhanced decay rate of $h \to \gamma\gamma$ at large $\tan\beta$. We also suggest a *τ-phobic Higgs scenario* in which the lightest Higgs can have suppressed couplings to down-type fermions. We propose to supplement the specified value of the μ parameter in some of these scenarios with additional values of both signs. This has a significant impact on the interpretation of searches for the non SM-like MSSM Higgs bosons. We also discuss the sensitivity of the searches to heavy Higgs decays into light charginos and neutralinos, and to decays of the form $H \to hh$. Finally, in addition to all the other scenarios where the lightest $\mathcal{CP}$-even Higgs is interpreted as the LHC signal, we propose a *low-M_H* scenario, where instead the *heavy* $\mathcal{CP}$-even Higgs boson corresponds to the new state around 125.5 GeV.

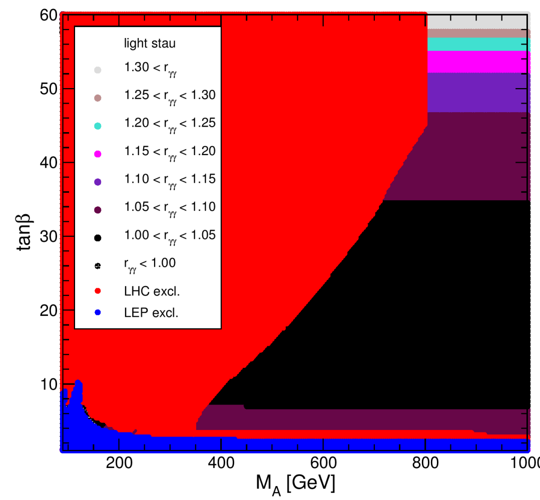
Higgs to diphotons seemed to be enhanced !

Carena, Gori, Shah, C.W. arXiv:1112.3336

Scenarios were adapted to the new reality







The decay rate into taus and bottoms was still uncertain

arXiv:1302.7033

Light staus could enhanced the decay rate into photons

The more we knew about the Higgs, the more subtle the differences were

MSSM Higgs Boson Searches at the LHC: Benchmark Scenarios for Run 2 and Beyond

Emanuele Bagnaschi[a], Henning Bahl[b], Elina Fuchs[c], Thomas Hahn[b],
Sven Heinemeyer[d,e,f], Stefan Liebler[g], Shruti Patel[g,h], Pietro Slavich[i],
Tim Stefaniak[j], Carlos E.M. Wagner[k,l,m] and Georg Weiglein[j]

[a] *Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland*
[b] *Max-Planck Institut für Physik, D-80805 München, Germany*
[c] *Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 76100, Israel*
[d] *Instituto de Física de Cantabria (CSIC-UC), E-39005 Santander, Spain*
[e] *Instituto de Física Teórica, (UAM/CSIC), Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain*
[f] *Campus of International Excellence UAM+CSIC, Cantoblanco, E-28049, Madrid, Spain*
[g] *Institute for Theoretical Physics (ITP), Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany*
[h] *Institute for Nuclear Physics (IKP), Karlsruhe Institute of Technology, D-76344 Karlsruhe, Germany*
[i] *Sorbonne Université, CNRS, Laboratoire de Physique Théorique et Hautes Énergies, LPTHE, F-75005 Paris, France*
[j] *DESY, Notkestraße 85, D-22607 Hamburg, Germany*
[k] *High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*
[l] *Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[m] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA*

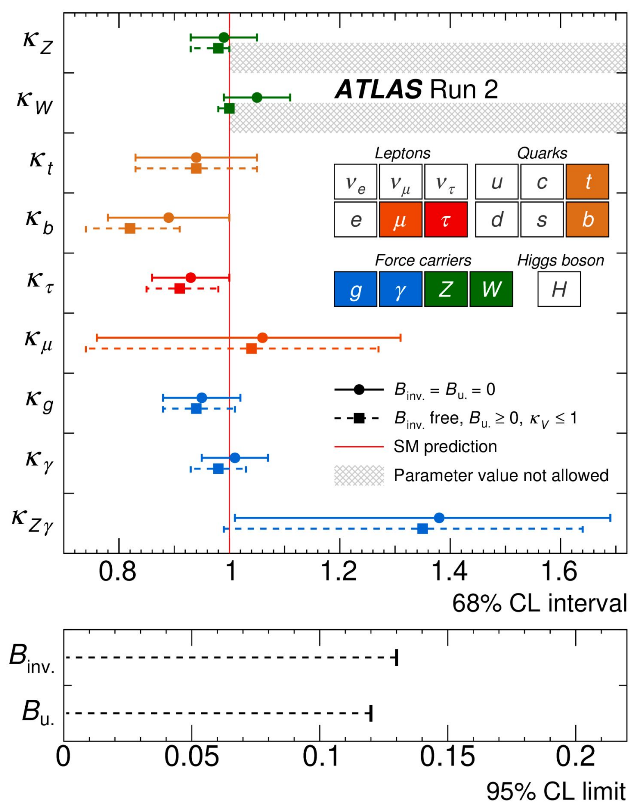
arXiv:1808.07542v2 [hep-ph] 17 Jul 2019

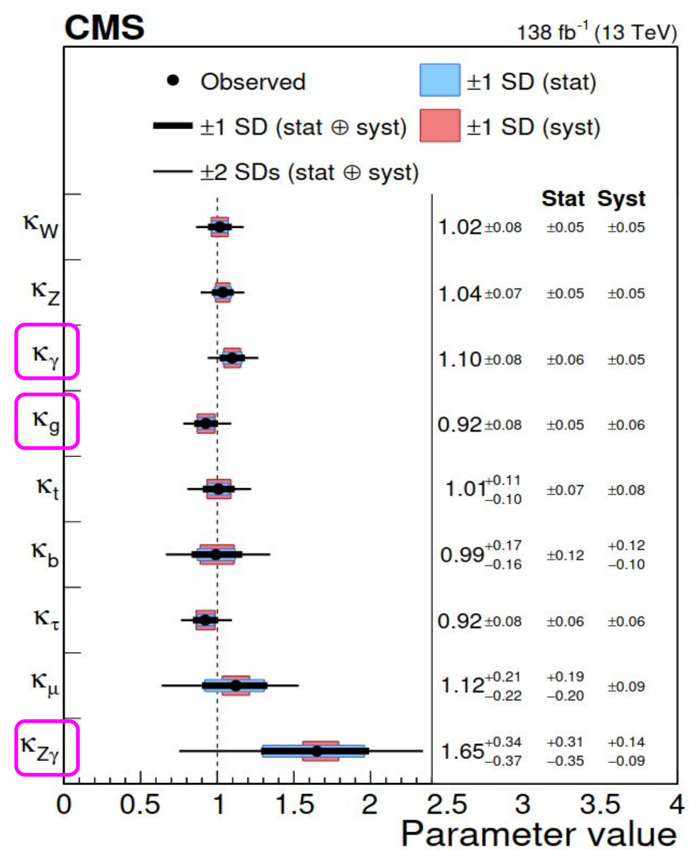
Abstract

We propose six new benchmark scenarios for Higgs boson searches in the Minimal Supersymmetric Standard Model. Our calculations follow the recommendations of the LHC Higgs Cross Section Working Group, and benefit from recent developments in the predictions for the Higgs-boson masses and mixing. All of the proposed scenarios are compatible with the most recent results from Run 2 of the LHC. In particular, they feature a scalar with mass and couplings compatible with those of the observed Higgs boson, and a significant portion of their parameter space is allowed by the limits from the searches for SUSY particles and additional Higgs bosons. We define a scenario where all SUSY particles are relatively heavy, and two scenarios with light colorless SUSY particles (charginos, neutralinos and, in one case, staus). In addition, we present two scenarios featuring alignment without decoupling, realized with either the lighter or the heavier scalar being SM-like, and a scenario with $\mathcal{CP}$ violation.

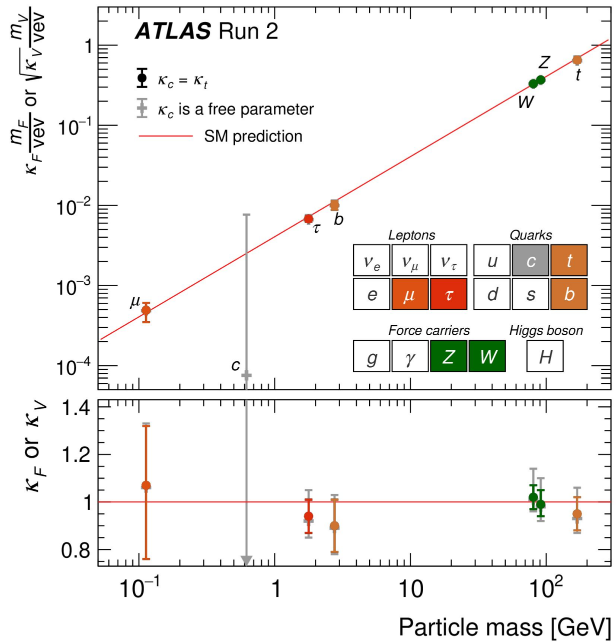
ATLAS and CMS Fit to Higgs Couplings

Departure from SM predictions of the order of few tens of percent allowed at this point.

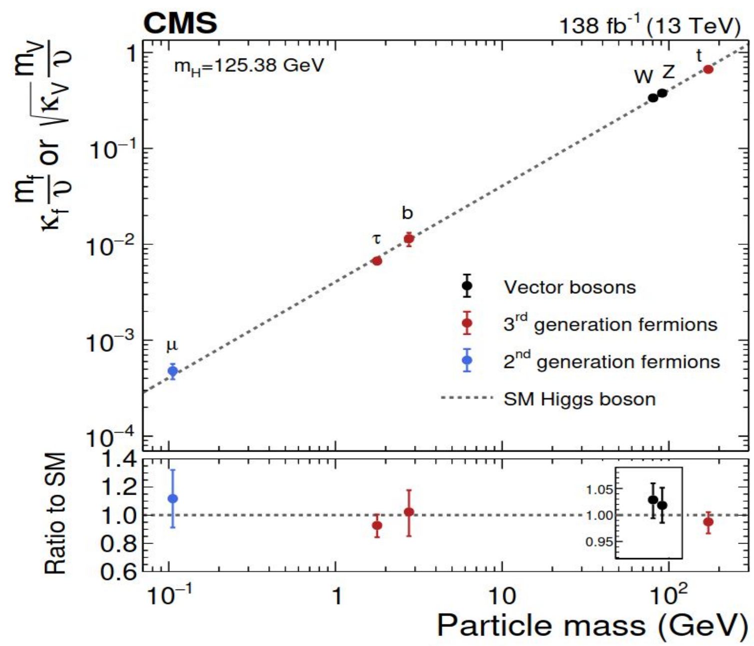




Correlation between masses and couplings consistent with the Standard Model expectations



H couplings vs particle mass

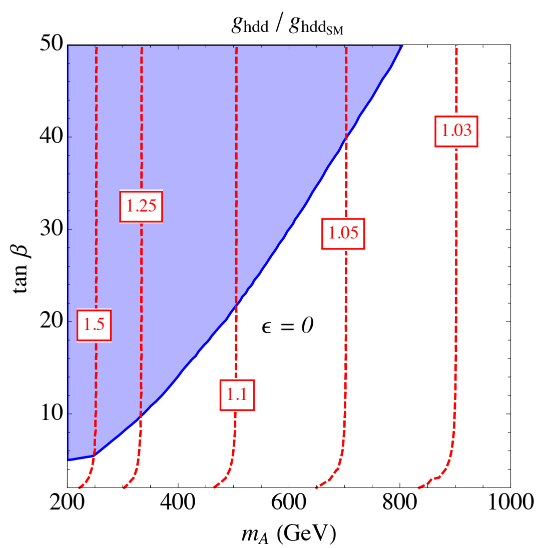


Down Couplings in the MSSM for low values of μ

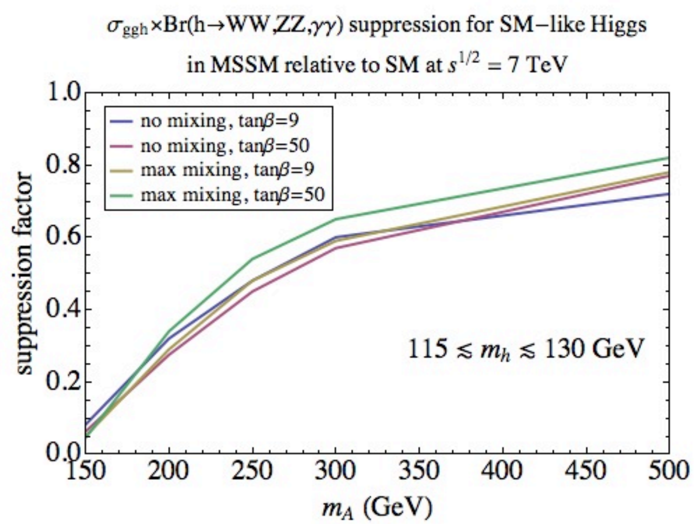
- Higgs Decay into bottom quarks is the dominant one
- A modification of the bottom quark coupling affects all other decays

$$t_\beta \, c_{\beta-\alpha} \simeq \frac{-1}{m_H^2 - m_h^2}\left[m_h^2 + m_Z^2 + \frac{3m_t^4}{4\pi^2 v^2 M_S^2}\left\{A_t \mu t_\beta \left(1 - \frac{A_t^2}{6M_S^2}\right) - \mu^2\left(1 - \frac{A_t^2}{2M_S^2}\right)\right\}\right]$$

Carena, Haber, Low, Shah, C.W. '14



Carena, Low, Shah, C.W.'13



Enhancement of bottom quark and tau couplings independent of $\tan\beta$

Carena, Haber, Low, Shah, C.W.'14

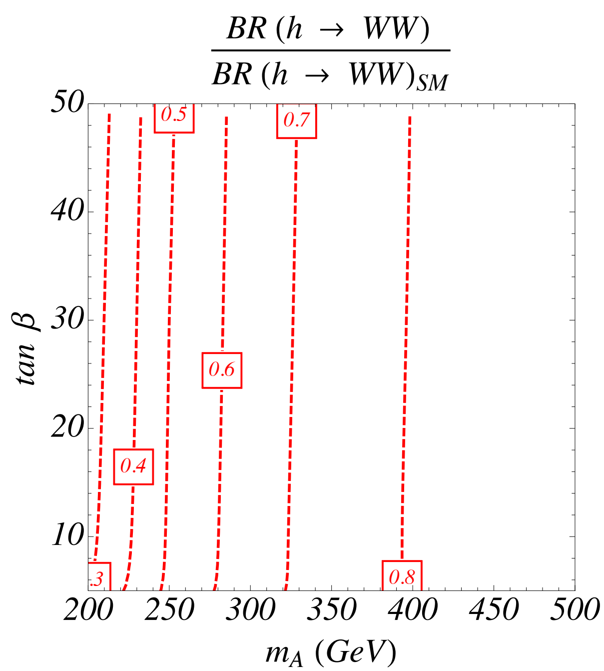
M. Carena, I. Low, N. Shah, C.W.'13

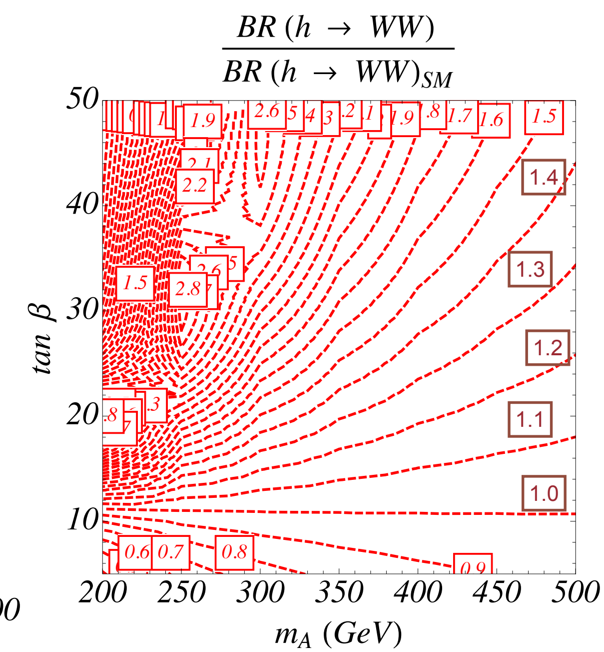
Higgs Decay into Gauge Bosons

Mostly determined by the change of width

Small μ

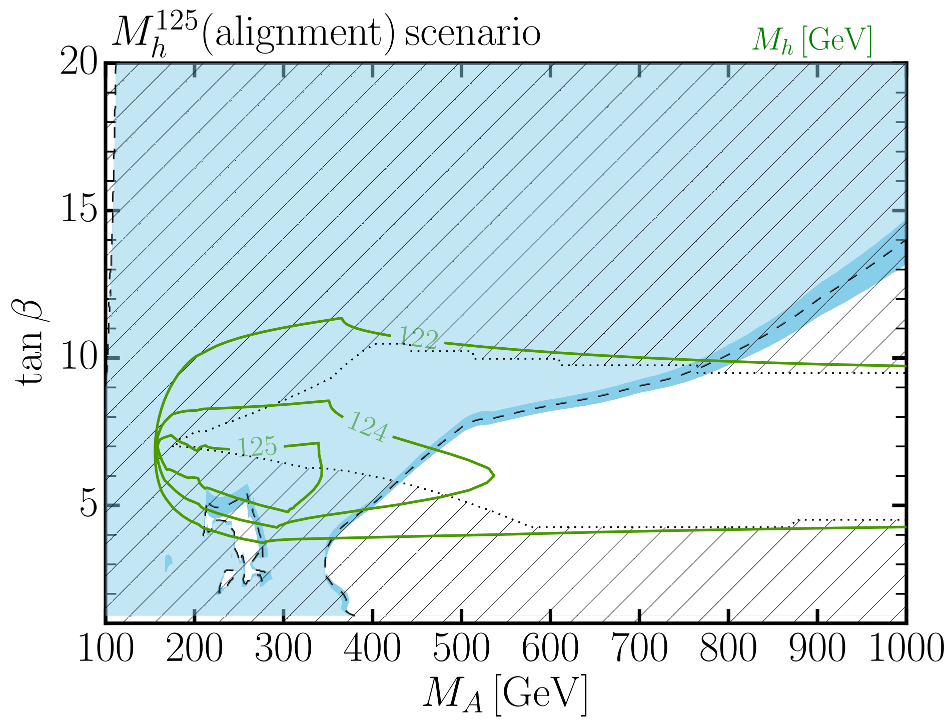
$\mu/M_{\rm SUSY} = 2, \quad A_t/M_{\rm SUSY} \simeq 3$





CP-odd Higgs masses of order 200 GeV and tanβ = 10 OK in the alignment case

Our benchmarks included now Alignment



arXiv:1808.07542

$$\cos(\beta - \alpha) = 0$$

This happens when the quartic couplings are such that the mixing between the SM-like Higgs and the non-standard Higgs vanish

After all relevant corrections were included, we joined a big effort to define the final Higgs mass predictions

Higgs-mass predictions in the MSSM and beyond

P. Slavich[a] and S. Heinemeyer[b,c,d] (eds.),

E. Bagnaschi[e], H. Bahl[f], M. Goodsell[a], H.E. Haber[g], T. Hahn[h], R. Harlander[i], W. Hollik[h], G. Lee[j,k,l], M. Mühlleitner[m], S. Paßehr[i], H. Rzehak[n], D. Stöckinger[o], A. Voigt[p], C.E.M. Wagner[q,r,s] and G. Weiglein[f],

B.C. Allanach[t], T. Biekötter[f], S. Borowka[u ‡], J. Braathen[f], M. Carena[r,s,v], T.N. Dao[w], G. Degrassi[x], F. Domingo[y], P. Drechsel[f ‡], U. Ellwanger[z], M. Gabelmann[m], R. Gröber[aa], J. Klappert[i], T. Kwasnitza[o], D. Meuser[f], L. Mihaila[bb ‡], N. Murphy[cc ‡], K. Nickel[y ‡], W. Porod[dd], E.A. Reyes Rojas[ee], I. Sobolev[f] and F. Staub[m ‡]

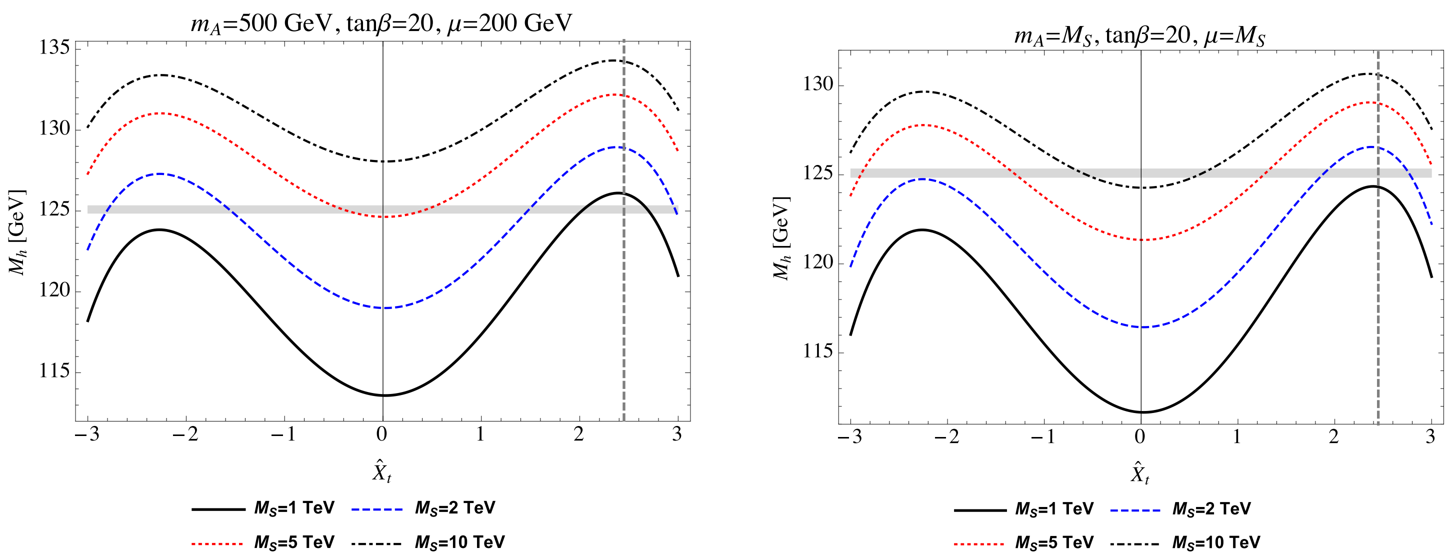
Predictions for the Higgs masses are a distinctive feature of supersymmetric extensions of the Standard Model, where they play a crucial role in constraining the parameter space. The discovery of a Higgs boson and the remarkably precise measurement of its mass at the LHC have spurred new efforts aimed at improving the accuracy of the theoretical predictions for the Higgs masses in supersymmetric models. The *"Precision SUSY Higgs Mass Calculation Initiative"* (KUTS) was launched in 2014 to provide a forum for discussions between the different groups involved in these efforts. This report aims to present a comprehensive overview of the current status of Higgs-mass calculations in supersymmetric models, to document the many advances that were achieved in recent years and were discussed during the KUTS meetings, and to outline the prospects for future improvements in these calculations.

MSSM Guidance:
Stop Masses above about 1 TeV lead to the right Higgs Masss

P. Slavich, S. Heinemeyer et al, arXiv:2012.15629

P. Draper, G. Lee, C.W.'13, Bagnaschi et al' 14, Vega and Villadoro '14, Bahl et al'17

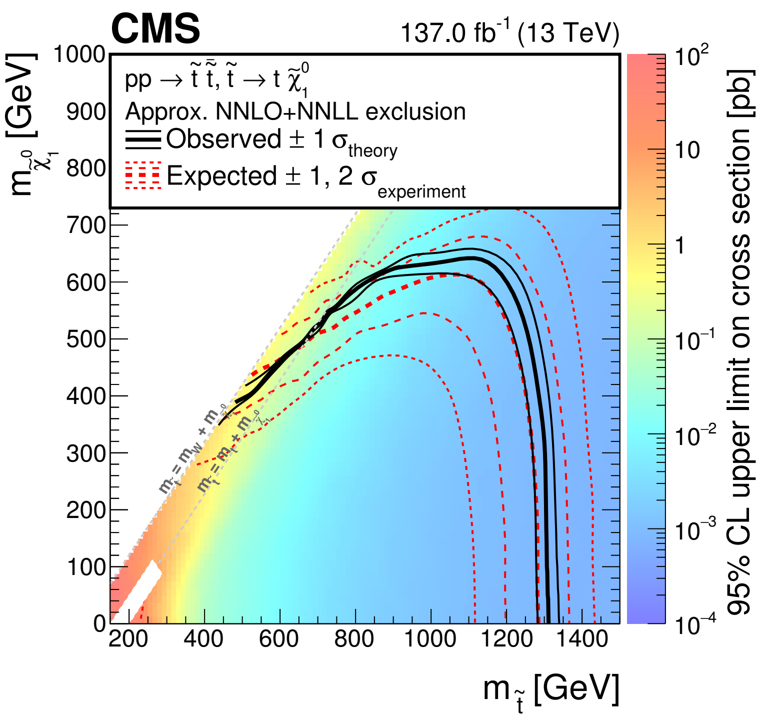
G. Lee, C.W. arXiv:1508.00576

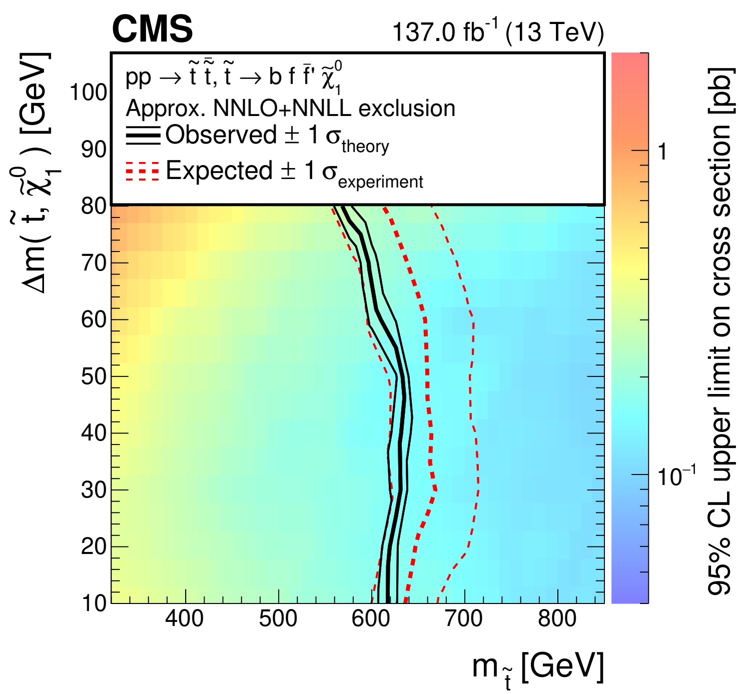


Necessary stop masses increase for lower values of tanβ, larger values of μ smaller values of the CP-odd Higgs mass or lower stop mixing values.

Lighter stops demand large splittings between left- and right-handed stop masses

Stop Searches



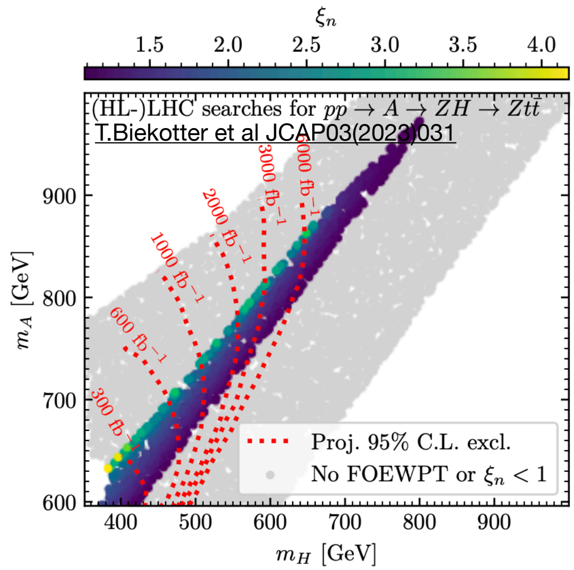


Combining all searches, in the simplest decay scenarios, it is hard to avoid the constraints of 700 GeV for sbottoms and 600 GeV for stops. Islands in one search are covered by other searches.

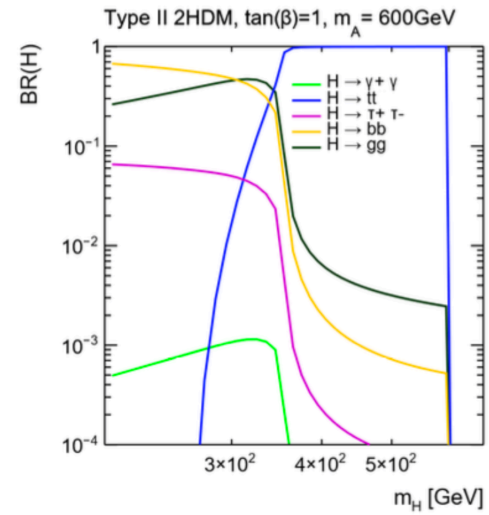
We are starting to explore the mass region suggested by the Higgs mass determination !

Two Higgs Doublets : Extra Heavy Physical state, a CP-odd (A), a CP-even (H) and a charged Higgs Boson

Phase Transition in 2HDM



$$\xi = \frac{v}{T}$$

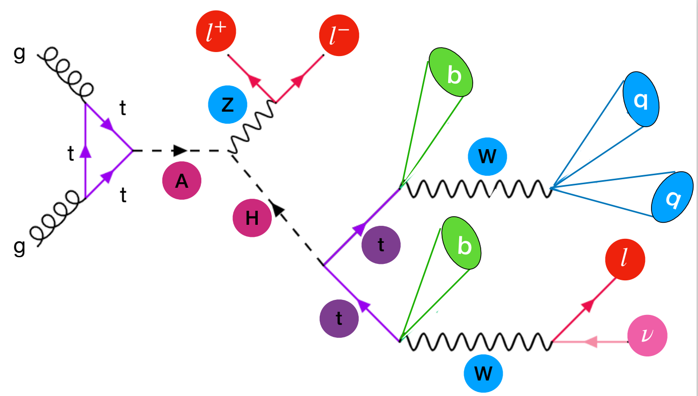


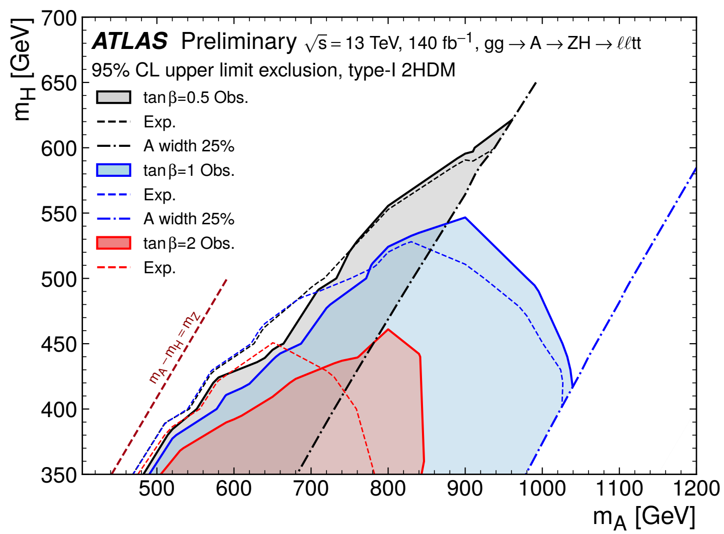
- “Smoking-gun” collider signature for FOEWPT in 2HDM
- Type-II 2HDM constraints pushes $m_H \geq 2m_t$ in parameter region featuring FOEWPT

Baseler, Krause, Muhlleitner, Wittbrodt, Wlotzka ’16
Basler, Muhlleitner, Wittbrodt ‘18

- BRs for H → bb and H → $\tau\tau$ become small
- H → tt much more promising

Searches at the LHC





(a) $\ell^+\ell^- t\bar{t}$, type-I

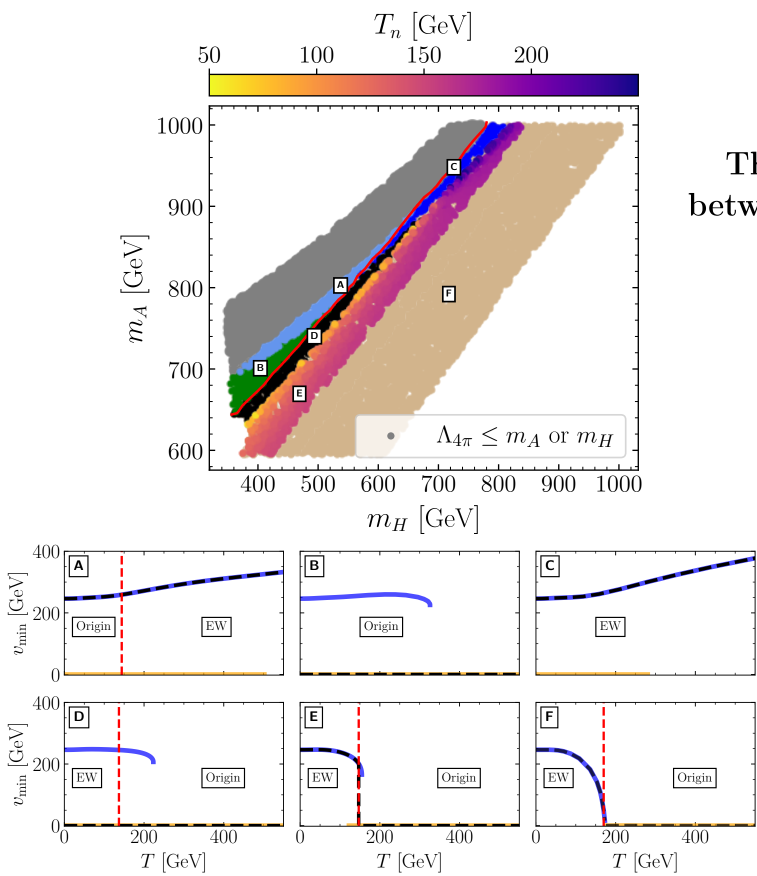
Excess at ATLAS in region consistent with a FOPT

$$(m_A, n_H) = (650, 450) GeV$$

Not confirmed by CMS

ATLAS-CONF-2023-034

Georg and collaborators reanalyzed this scenario



The trap in the early Universe: impact on the interplay between gravitational waves and LHC physics in the 2HDM

Thomas Biekötter[1§], Sven Heinemeyer[2¶], José Miguel No[2,3‖],
María Olalla Olea-Romacho[1**] and Georg Weiglein[1,4††]

arXiv:2208.14466

The non-restoration results are induced by features of the Arnold Espinosa resummation scheme.

Searches at the LHC

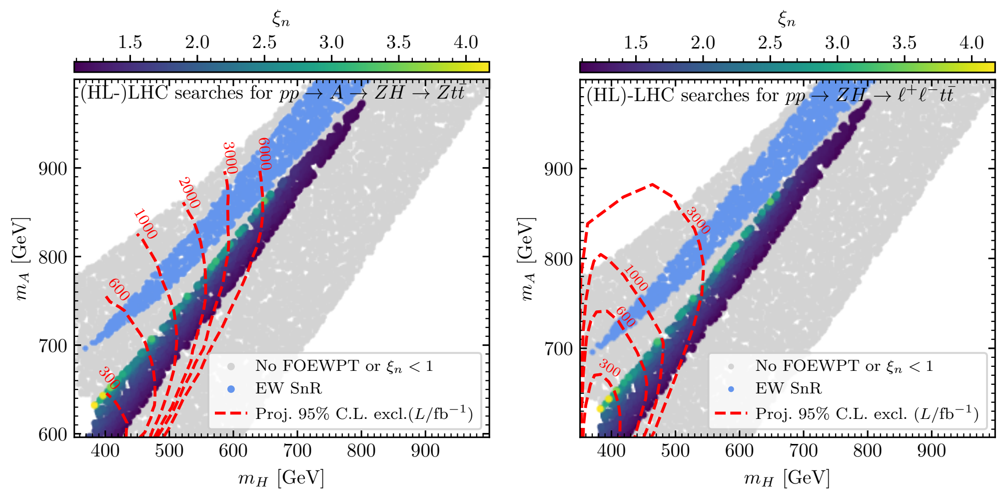


Figure 7: Projected exclusion regions in the (m_H, m_A) plane with $\tan\beta = 3$ and $m_{H^\pm} = m_A$ and for integrated luminosities of $300, 600, 1000, 3000$ fb^{-1}, expected to be collected in future runs of the LHC. The displayed limits are derived from rescaled CMS (left) and ATLAS (right) expected limits for the $\ell^+\ell^- t\bar{t}$ final state. The color bar indicates the strength of the phase transition. The blue points indicate the parameter region that features electroweak symmetry non-restoration at high temperatures (see Ref. [24] for more details).

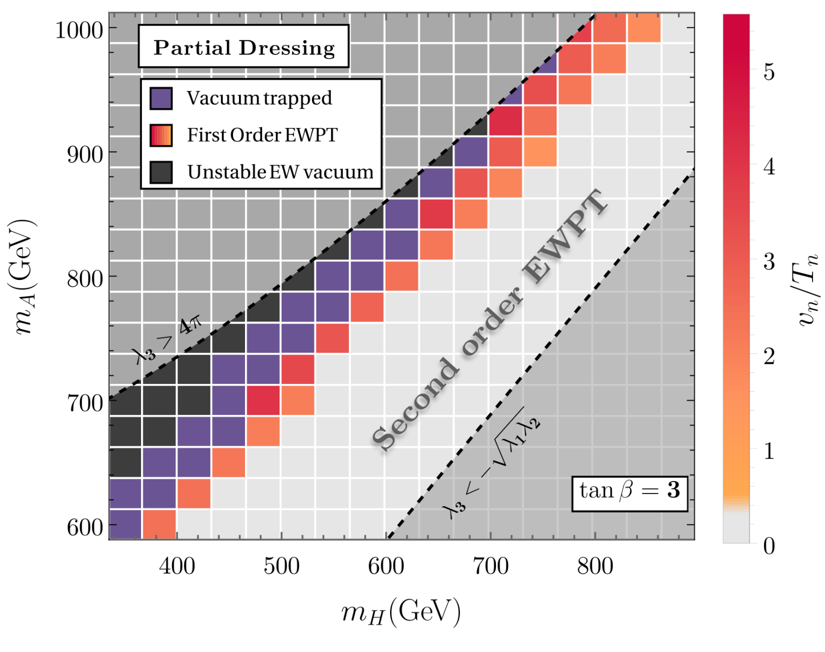
First shot of the smoking gun: probing the electroweak phase transition in the 2HDM with novel searches for $A \to ZH$ in $\ell^+\ell^- t\bar{t}$ and $\nu\nu b\bar{b}$ final states

Thomas Biekötter[1*], Sven Heinemeyer[2†], Jose Miguel No[2,3‡], Kateryna Radchenko[4§], María Olalla Olea Romacho[5¶] and Georg Weiglein[4,6‖]

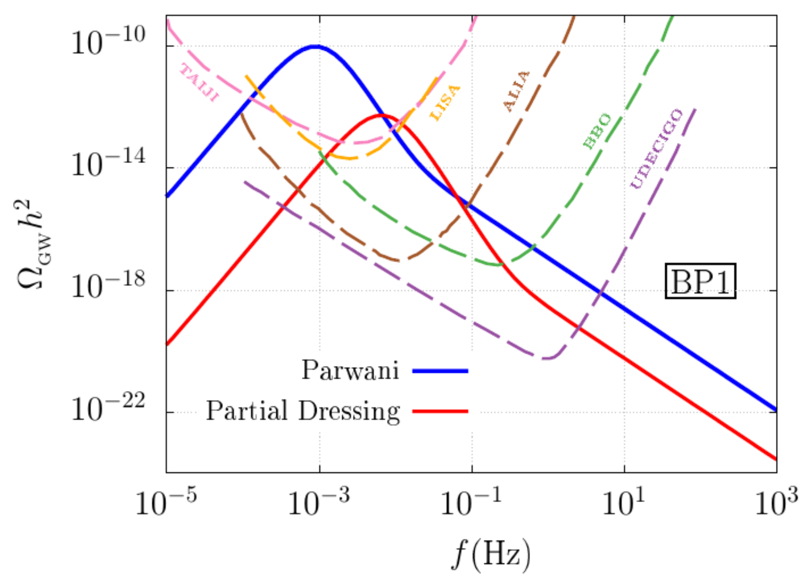
arXiv:2309.17431

Alternative computation of EWPT using Partial Dressing resummation scheme

No symmetry non-restoration found in this case. Overall Features found by Georg and collaborators confirmed.

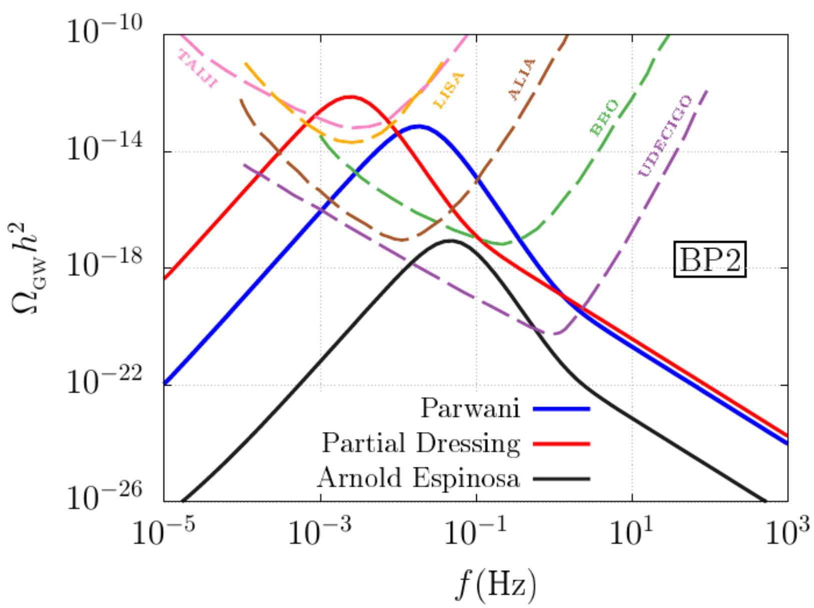


Gravitational wave production affected by effective potential calculations. Results shown in NR parameters in AE resummation



P. Bittar, S. Roy, C.W. , arXiv:2504.02024, JHEP

Alternative Region of Parameters

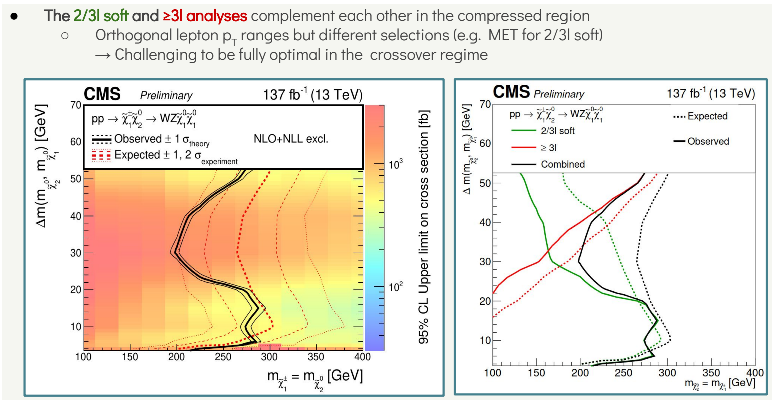


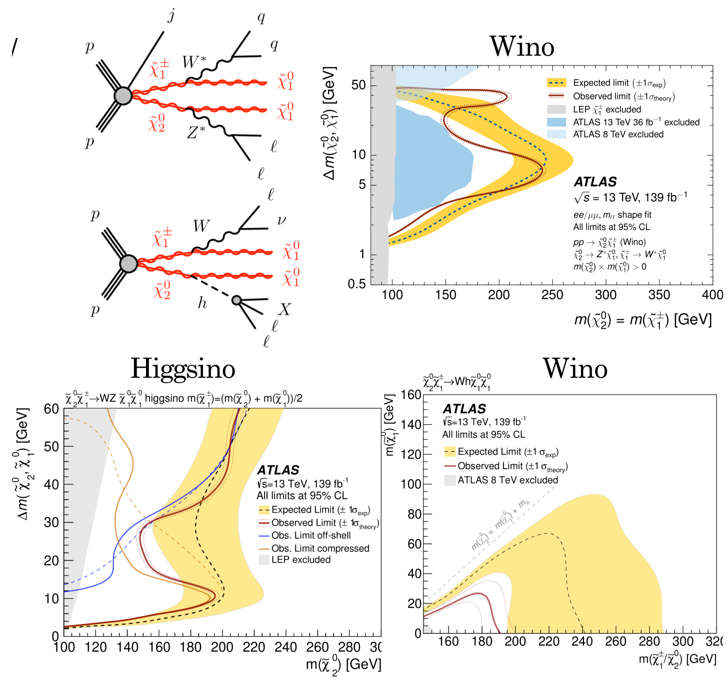
P. Bittar, S. Roy, C.W. , arXiv:2504.02024, JHEP

Conclusions

- We celebrate Georg's sixtieth birthday
- He has been a great friend and collaborator for the last 30 years
- Thanks Georg for making our scientific career more productive and enjoyable !
- Looking forward for the next 30 years :)

There may be surprises at the LHC





Excesses in regions consistent with co-annihilating Dark Matter

First weak evidences of SUSY electroweakino sector ?

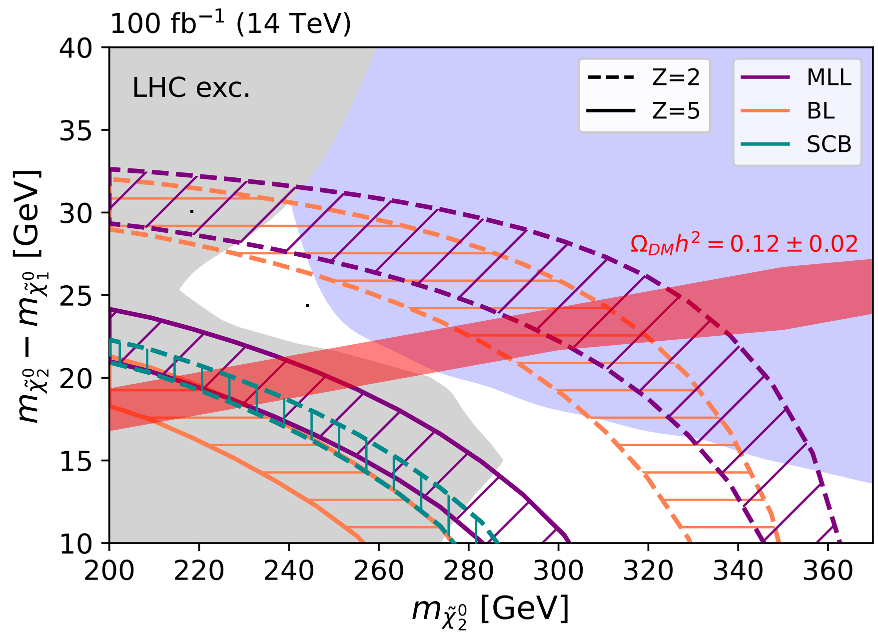
Eagerly waiting for Run3 results :)

Manimala Chakraborti, Sven Heinemeyer, Ipsita Saha, arXiv:2403.14759

Results of the ML Analysis

Arganda, Carena, De Los Rios, Perez, Rocha, Sanda Seoane, C.W., arXiv:2410.13799
see also Arganda, De Los Rios, Perez, Sanda Seoane, C.W. , arXiv:2509.15121

Manimala Chakraborti, Sven Heinemeyer, Ipsita Saha, arXiv:2403.14759



Results are optimistic, ignoring probable systematic errors.
One can probe currently allowed parameter space, although discovery will demand higher luminosities.