Research on the Theory of the Terascale

Howard Haber

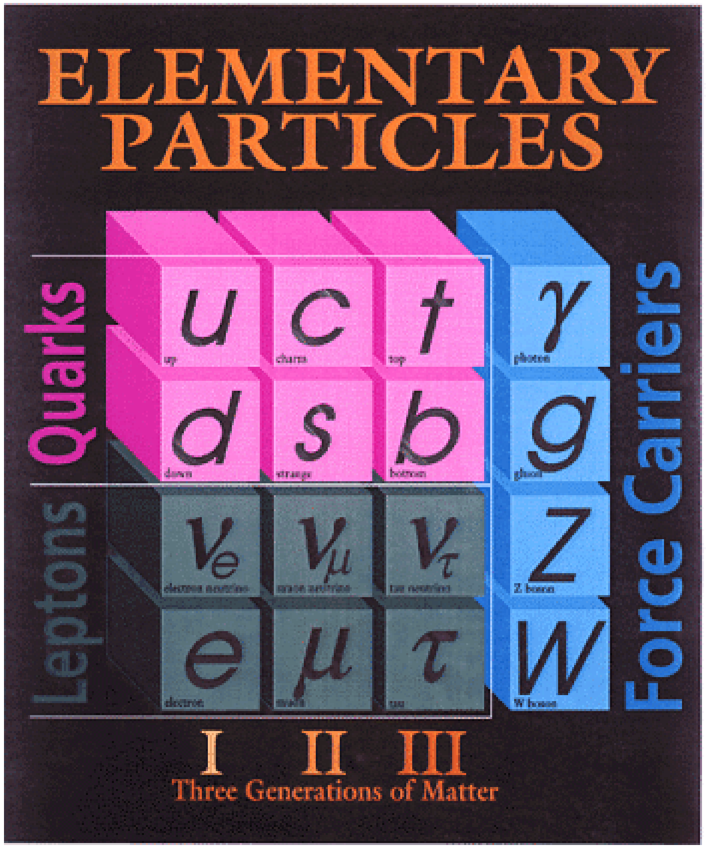
SCIPP Theory

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 of Particle Physics

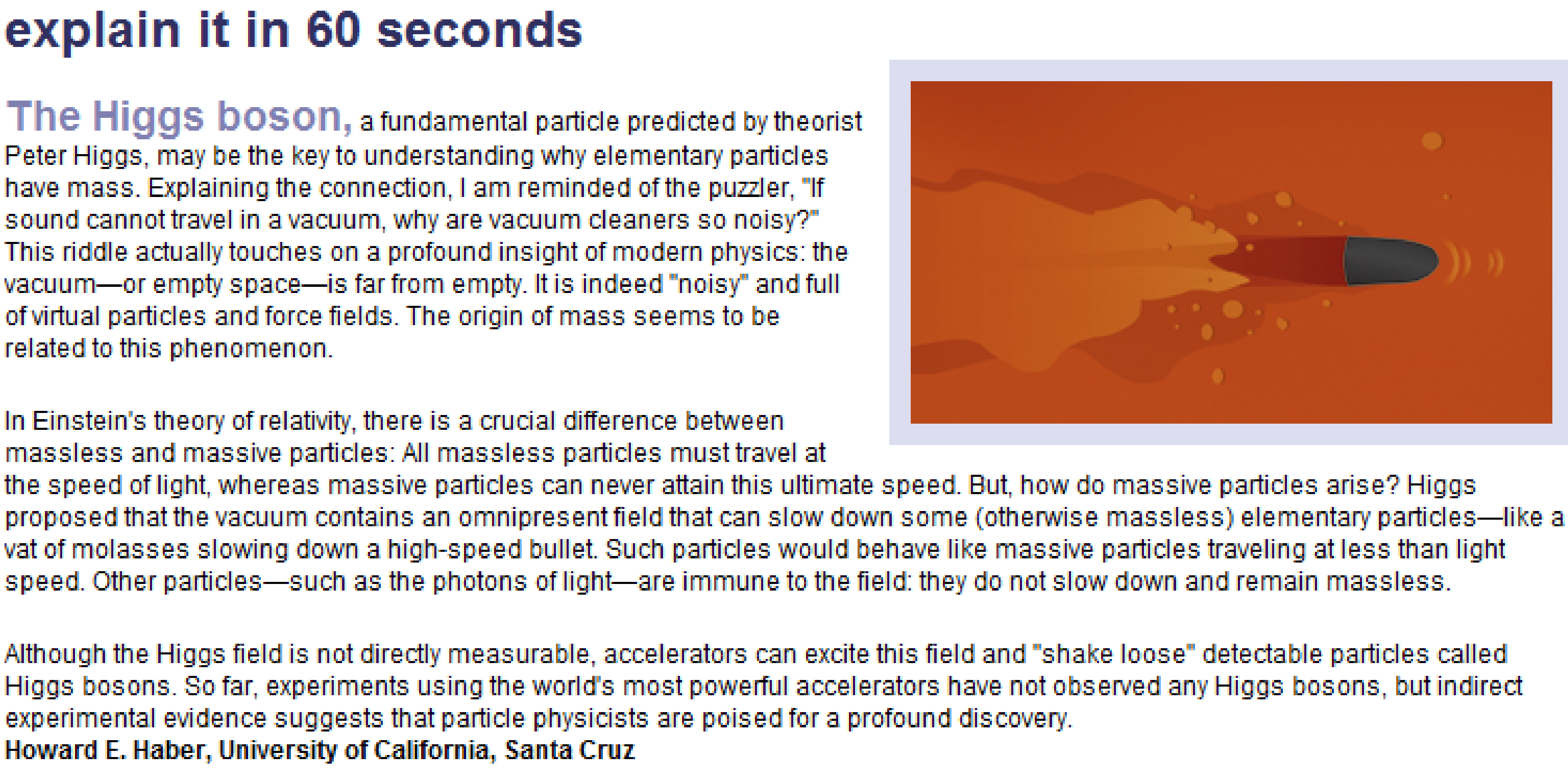


The elementary particles consists of three generations of spin-1/2 quarks and leptons and the gauge bosons of SU(3)xSU(2)xU(1).

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.

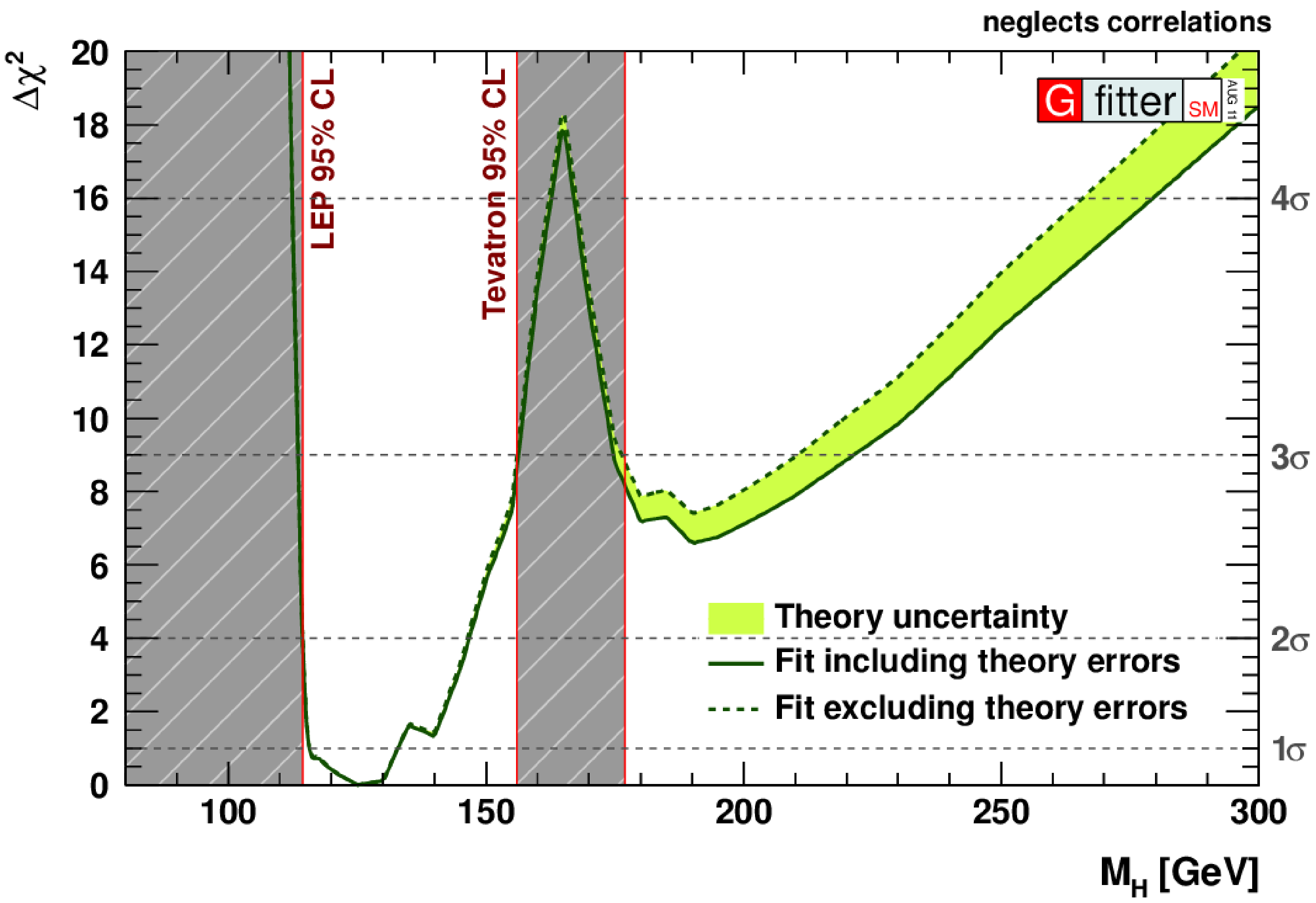
In Einstein's theory of relativity, there is a crucial difference between massless and massive particles: All massless particles must travel at the speed of light, whereas massive particles can never attain this ultimate speed. But, how do massive particles arise? Higgs proposed that the vacuum contains 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

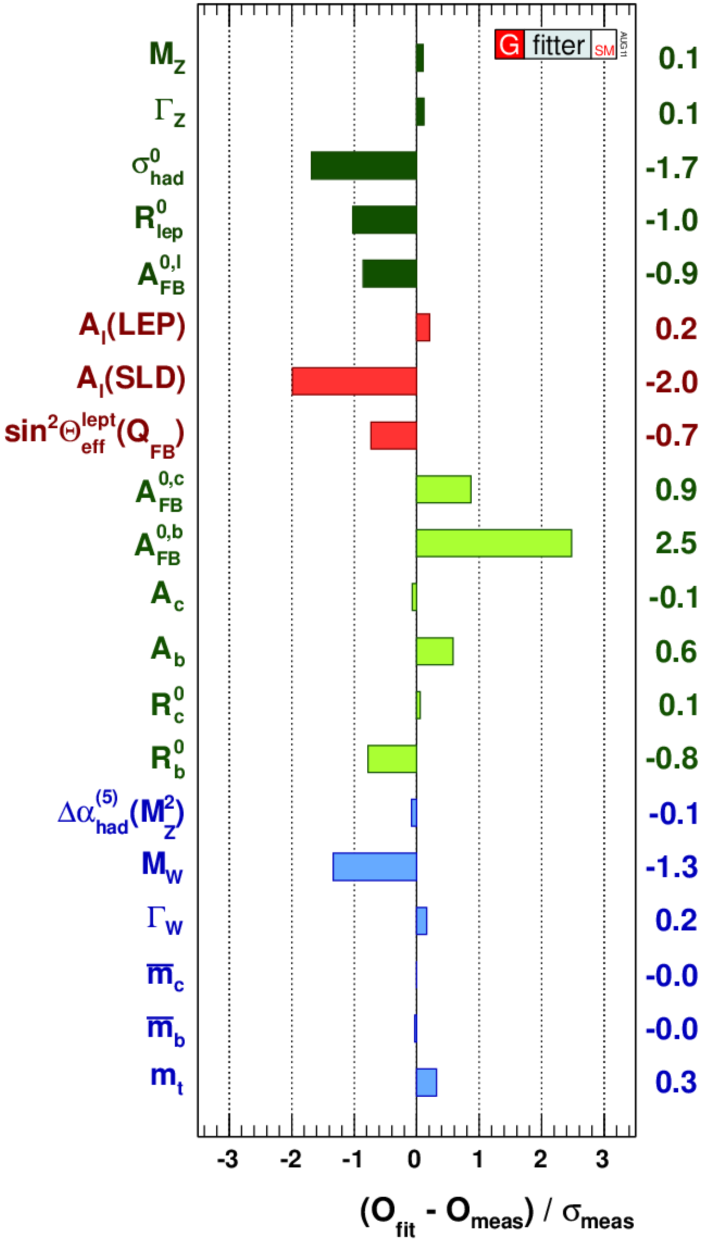
From Symmetry Magazine, volume 3, issue 6, August 2006

Where is the Higgs boson?

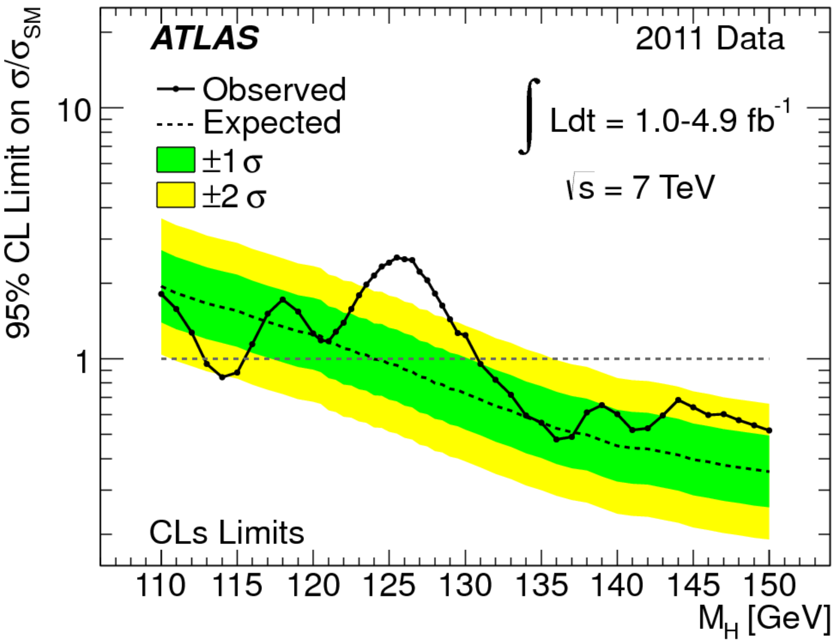


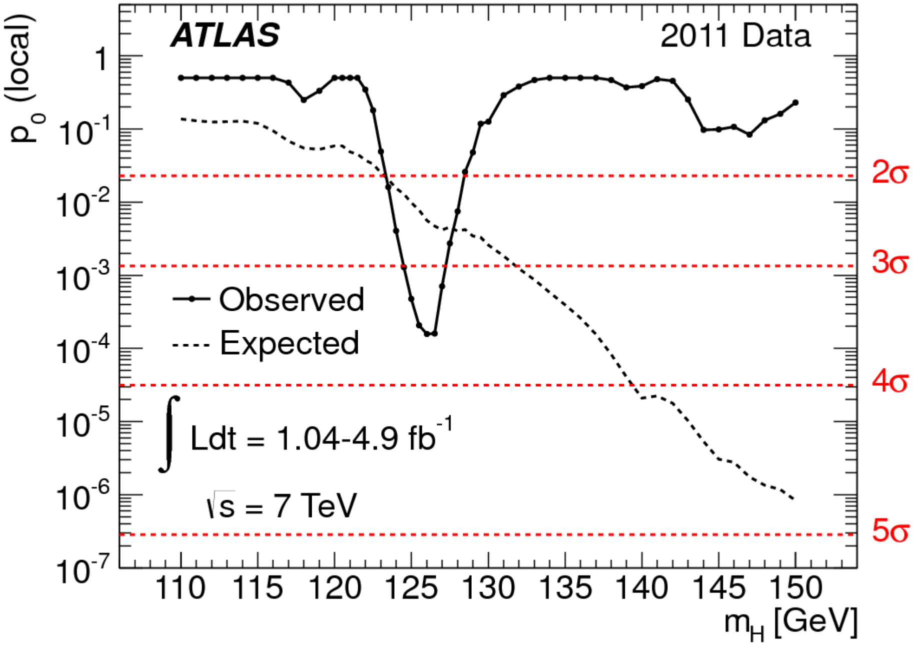
G fitter figures taken from http://gfitter.desy.de/

How good are the Standard Model predictions for physical observables?



Hints for the Higgs boson in the 2011 LHC data





ATLAS 2011 Higgs data: see ATLAS Collaboration, arXiv:1202.1415 [hep-ex].

CMS 2011 Higgs data: see CMS Collaboration, arXiv:1202.1416 [hep-ex].

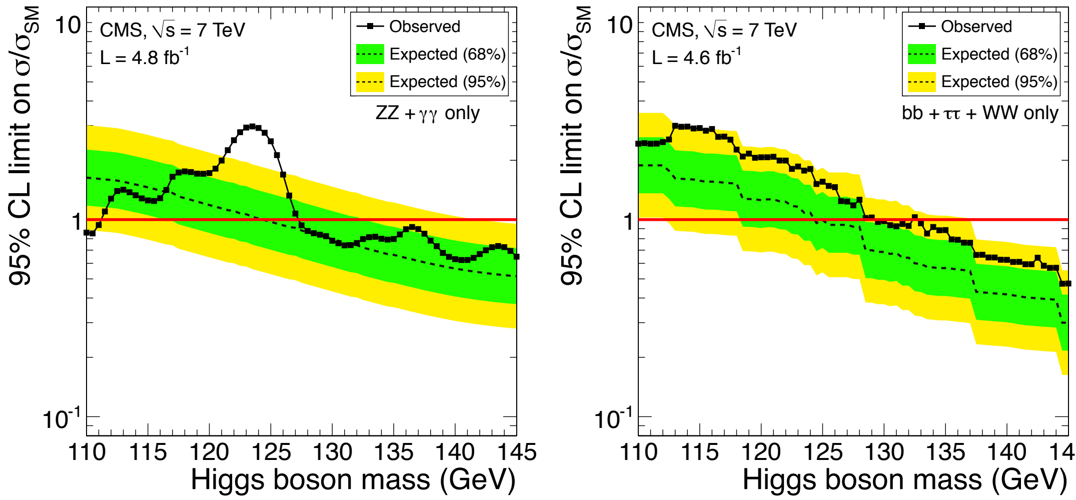


Figure 5: The 95% CL upper limits on the signal strength parameter $\mu = \sigma/\sigma_{\mathrm{SM}}$ for the SM Higgs boson hypothesis as a function of m_{H}, separately for the combination of the ZZ + $\gamma\gamma$ (left) and bb + $\tau\tau$ + WW (right) searches. The observed values as a function of mass are shown by the solid line. The dashed line indicates the expected median of results for the background-only hypothesis, while the green (dark) and yellow (light) bands indicate the ranges that are expected to contain 68% and 95% of all observed excursions from the median, respectively.

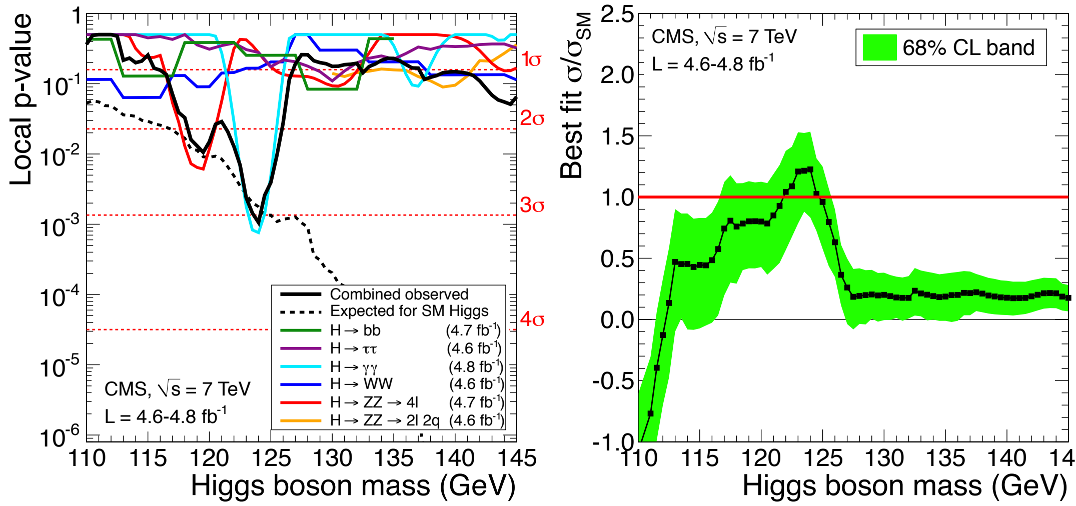
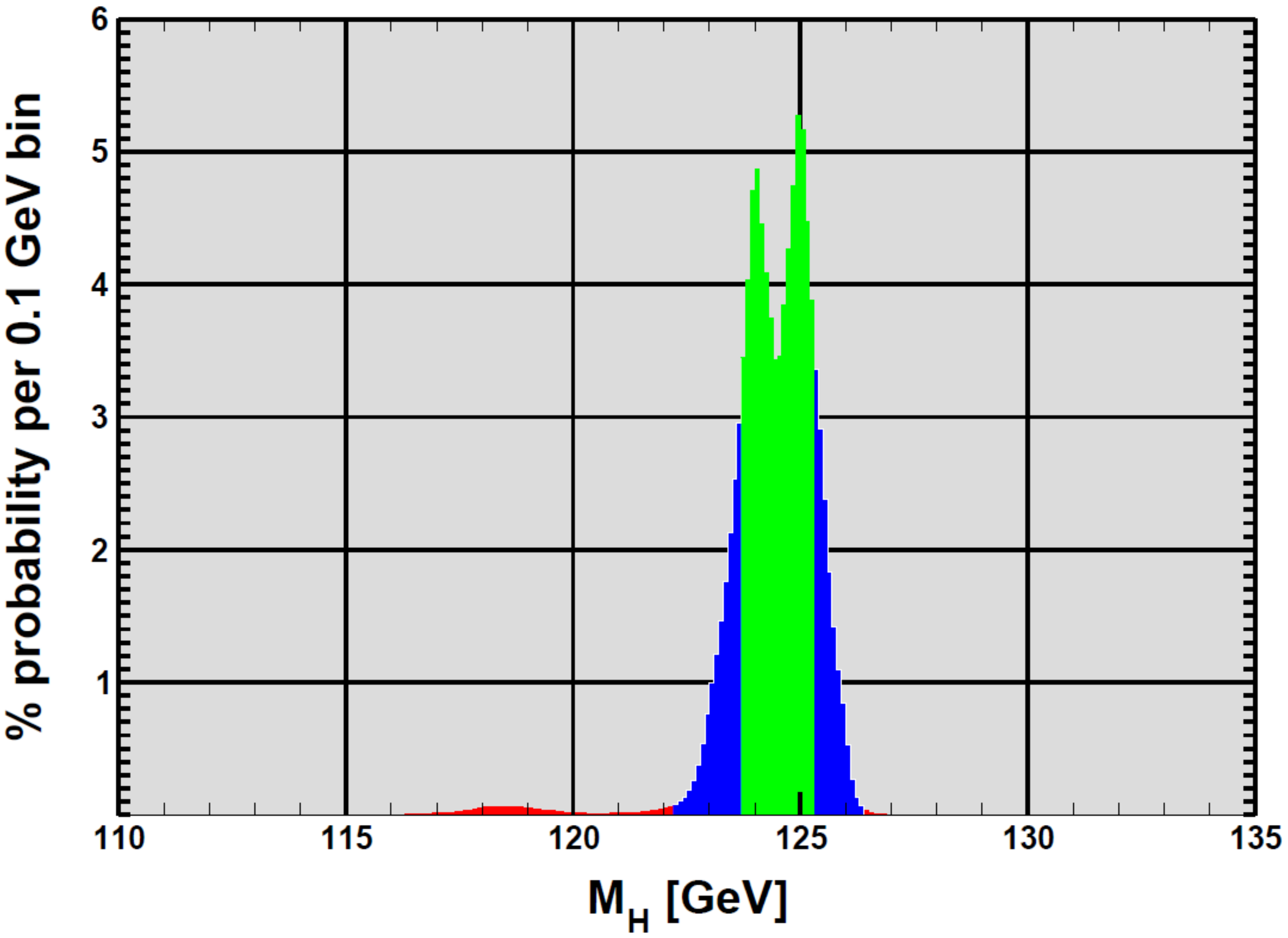


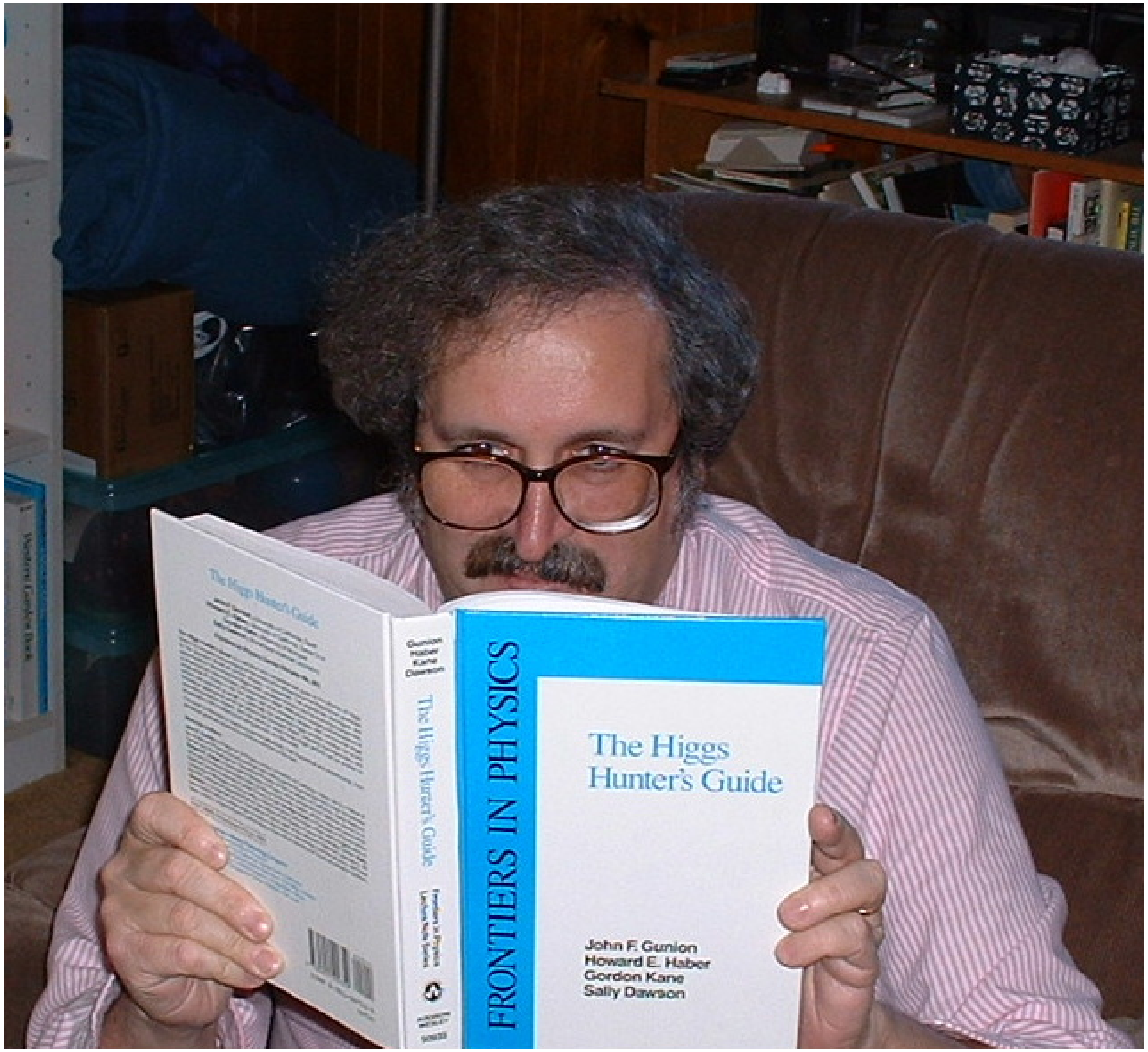
Figure 6: The observed local p-value p_0 (left) and best-fit $\hat{\mu} = \sigma/\sigma_{\mathrm{SM}}$ (right) as a function of the SM Higgs boson mass in the range 110–145 GeV. The global significance of the observed maximum excess (minimum local p-value) in this mass range is about 2.1σ, estimated using pseudo-experiments. The dashed line on the left plot shows the expected local p-values $p_0(m_{\mathrm{H}})$, should a Higgs boson with a mass m_{H} exist. The band in the right plot corresponds to the $\pm 1\sigma$ uncertainties on the $\hat{\mu}$ values.

Combining the 2011 LHC data with precision electroweak constraints

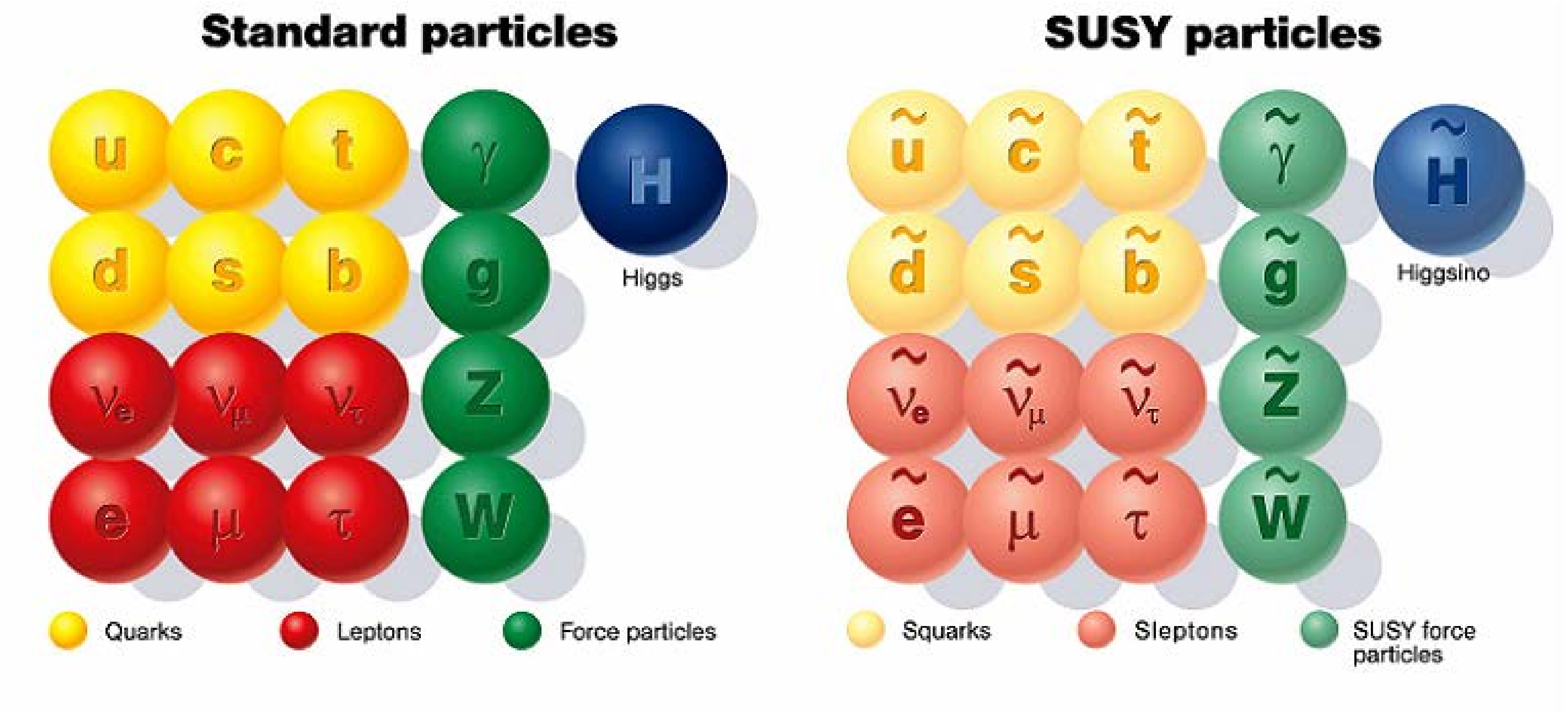


The normalized probability distribution of M_H in the low mass region based on all data. Shown in green (blue) is the 68% (98.2%) CL highest probability density region. Taken from Jens Erler, arXiv:1201.0695 [hep-ph].

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*, The 2010 Review of Particle Physics, from the Particle Data Group, http://pdg.lbl.gov (the 2012 update will be available soon).

Research program 3: explorations of the Terascale at 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)

Simulation of a precision measurements of SUSY coupling relations at a high-intensity LHC using the monojet signal

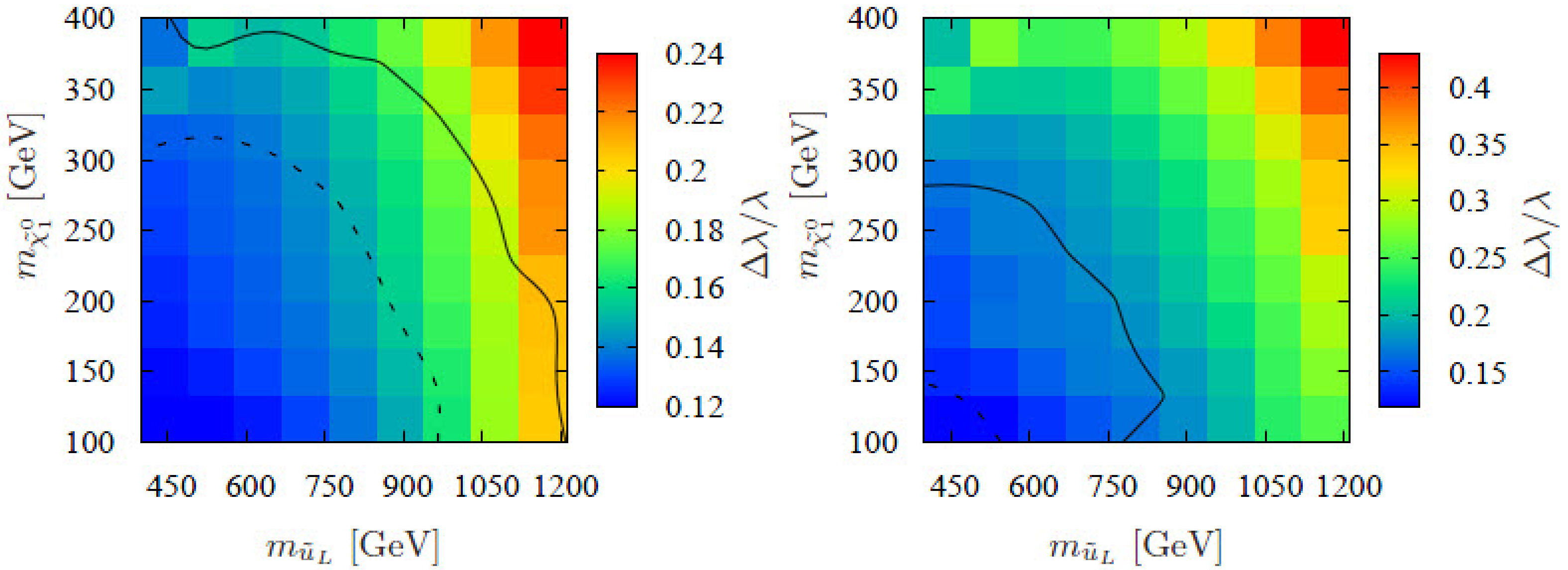
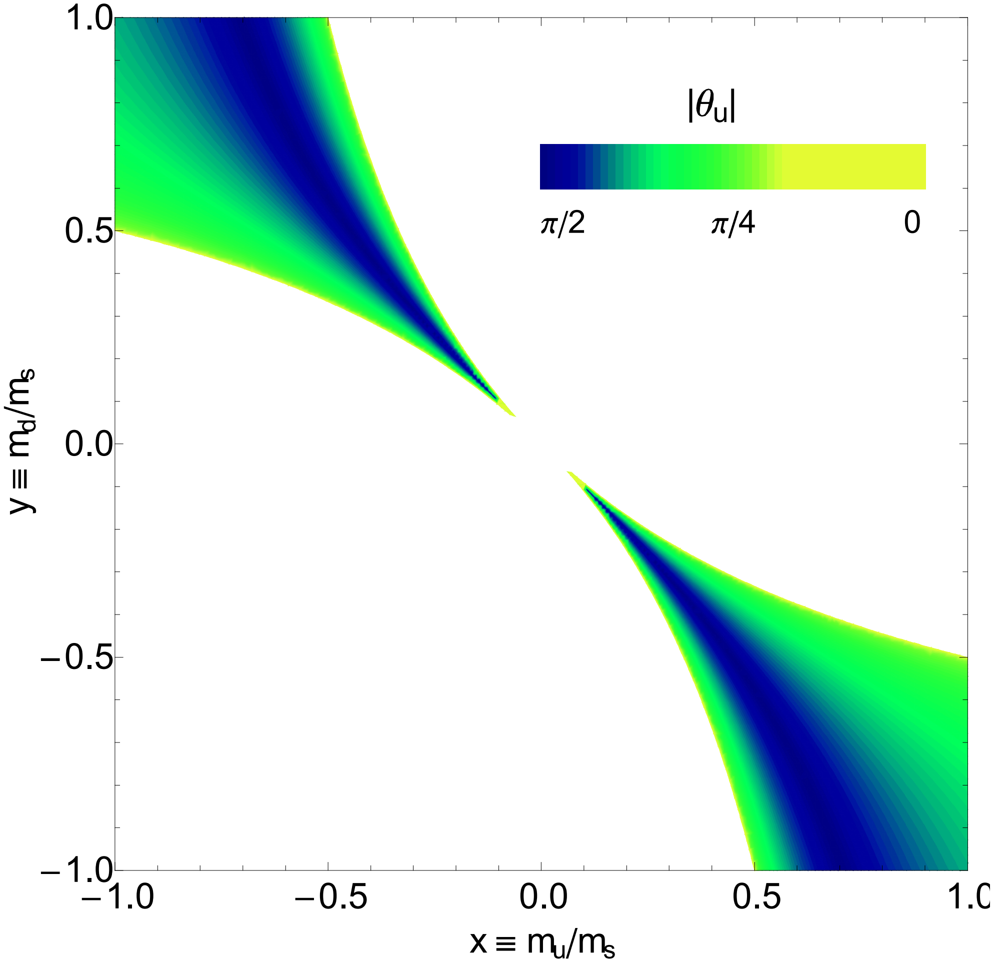


Figure 9: Fractional precision to which the $\tilde\chi_1^0\tilde q_L q$ coupling λ can be reconstructed as function of the squark and $\tilde\chi_1^0$ mass. The left (right) figure employs our optimistic (conservative) estimate for the SM background uncertainties. The solid and dashed black lines correspond to $S/\sqrt{B}$ ($S/\sqrt{7B}$) of 5σ and 10σ, respectively.

Taken from B.C. Allanach, S. Grab and H.E. Haber, JHEP 1101, 138 (2011)

A group-theoretic condition for spontaneous CP violation



Regions of the parameter space where spontaneous CP violation occurs. A point in this parameter space corresponds to (x, y) ≡ (mu/ms, md/ms). The size of the phase θ_u is shown, with maximum values depicted in dark (blue), and minimum values in light (yellow). In these regions, θ_d also acquires a nonzero value. The value of θ_d at the point (x, y) is equal to the value of θ_u at the point (y,x). Taken from H.E. Haber and Z. Surujon, arXiv:1201.1730 [hep-ph].

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?

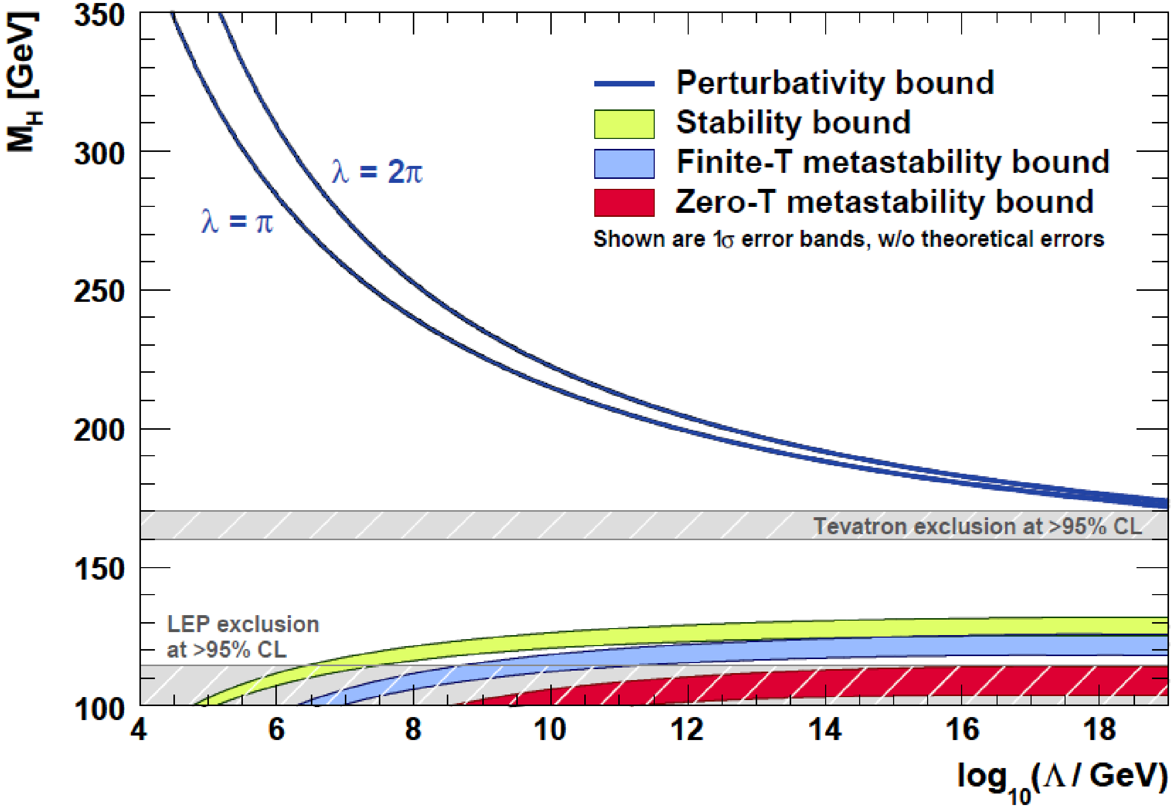
D. Pahel – working in industry
J. Mason – following a three-year post doctoral research associate in particle theory at Harvard University, John accepted a position as an assistant professor of physics at Western State College of Colorado
D. O'Neil – assistant professor of physics at Bridgewater College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

My current Ph.D. students and their projects

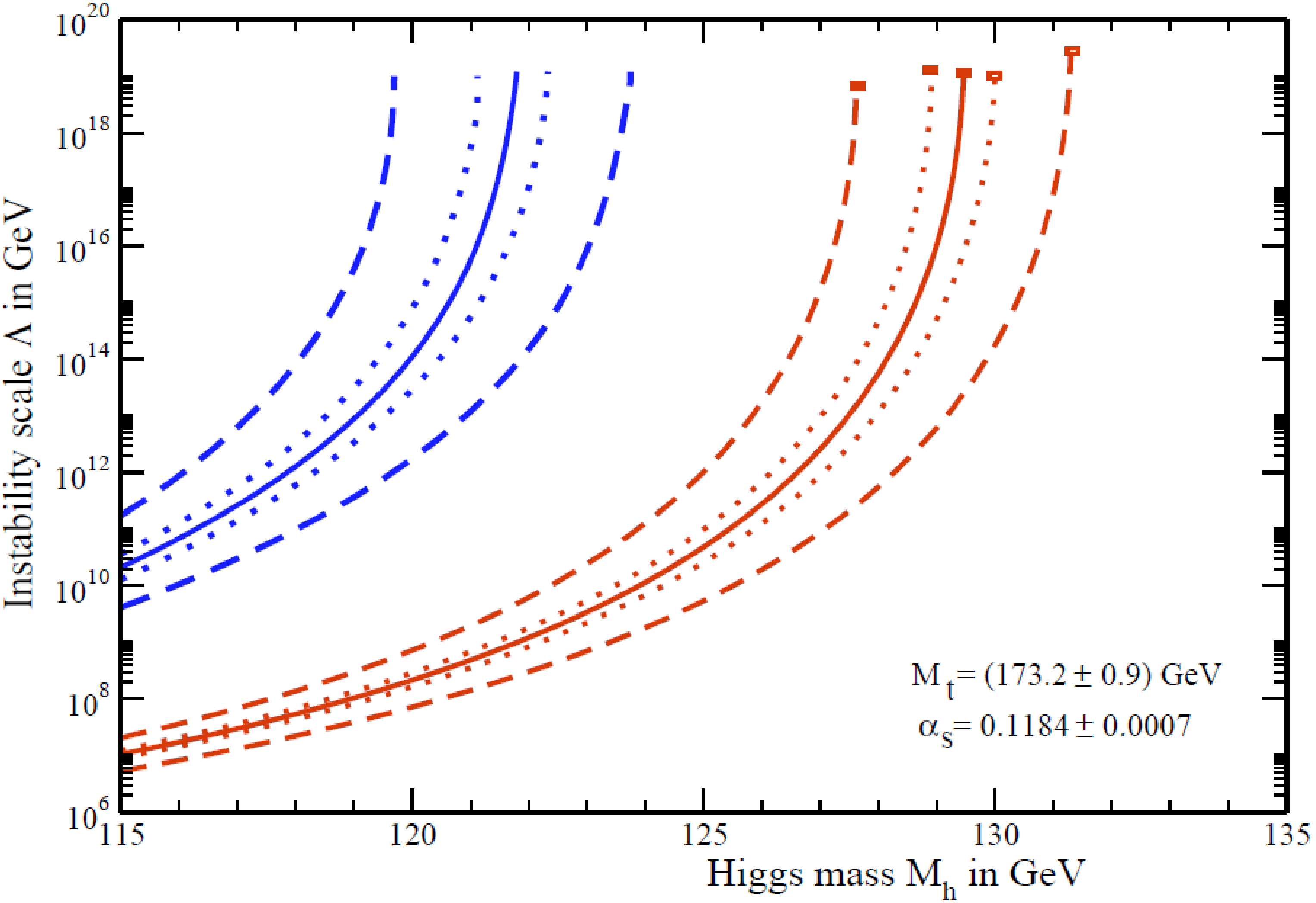
Laura Daniel: Precision measurements of couplings at the LHC and tests of UED (universal extra dimensions) theories

Eddie Santos: Renormalization group running in the general CP-violating two-Higgs doublet model; predictions for a lower limit on the energy scale at which new physics must enter

How to deduce the energy scale Λ at which new physics enters



The scale Λ at which the two-loop RGEs drive the quartic SM Higgs coupling non-perturbative, and the scale Λ at which the RGEs create an instability in the electroweak vacuum ($\lambda<0$). The width of the bands indicates the errors induced by the uncertainties in m_t and α_s (added quadratically). The perturbativity upper bound is given for $\lambda=\pi$ (lower blue line) and for $\lambda=2\pi$ (upper blue line). Their difference indicates the size of the uncertainty in this bound. The absolute vacuum stability bound is displayed by the green band, while the less restrictive finite-temperature and zero-temperature metastability bounds are blue and red, respectively. The theoretical uncertainties in these bounds have been ignored. The grey hatched areas indicate the LEP and Tevatron exclusion domains. Taken from J. Ellis, J.R. Espinosa, G.F. Giudice, A. Hoecker and A. Riotto, Phys. Lett. B **679**, 369 (2009).



The scale Λ at which the SM Higgs potential becomes negative as a function of the Higgs mass for the central value of m_t and α_s (plain red) , as well as for ±2σ variations of m_t (dashed red) and α_s (dotted red). The blue lines on the left are the metastability bounds (plain blue: central values m_t and α_s ; dashed blue for ±2σ variations of m_t). The theoretical error in the determination of the instability scale is not shown. Taken from J. Elias-Miro, J.R. Espinosa, G. F. Giudice, G. Isidori, A. Riotto and A. Strumia, arXiv:1112.3022 [hep-ph].