THE HIGGS, VACUUM STABILITY, AND OTHER CONSTRAINTS

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at the PCTS, April 26, 2013

THIS TALK

First, I'm going to explain some constraints on new physics scenarios that try to significantly alter Higgs properties. The motivation for dwelling on this is diminished given recent CMS updates on diphoton.

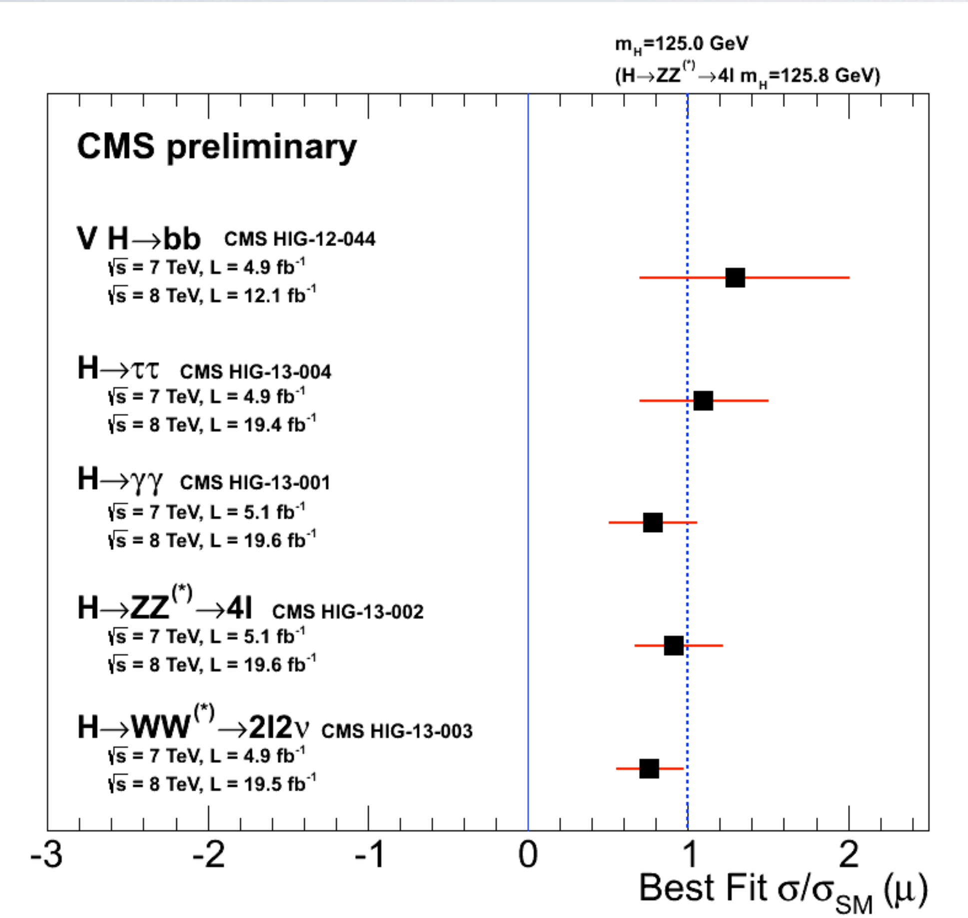
Then I'll talk a bit about Higgs vacuum stability in the Standard Model.

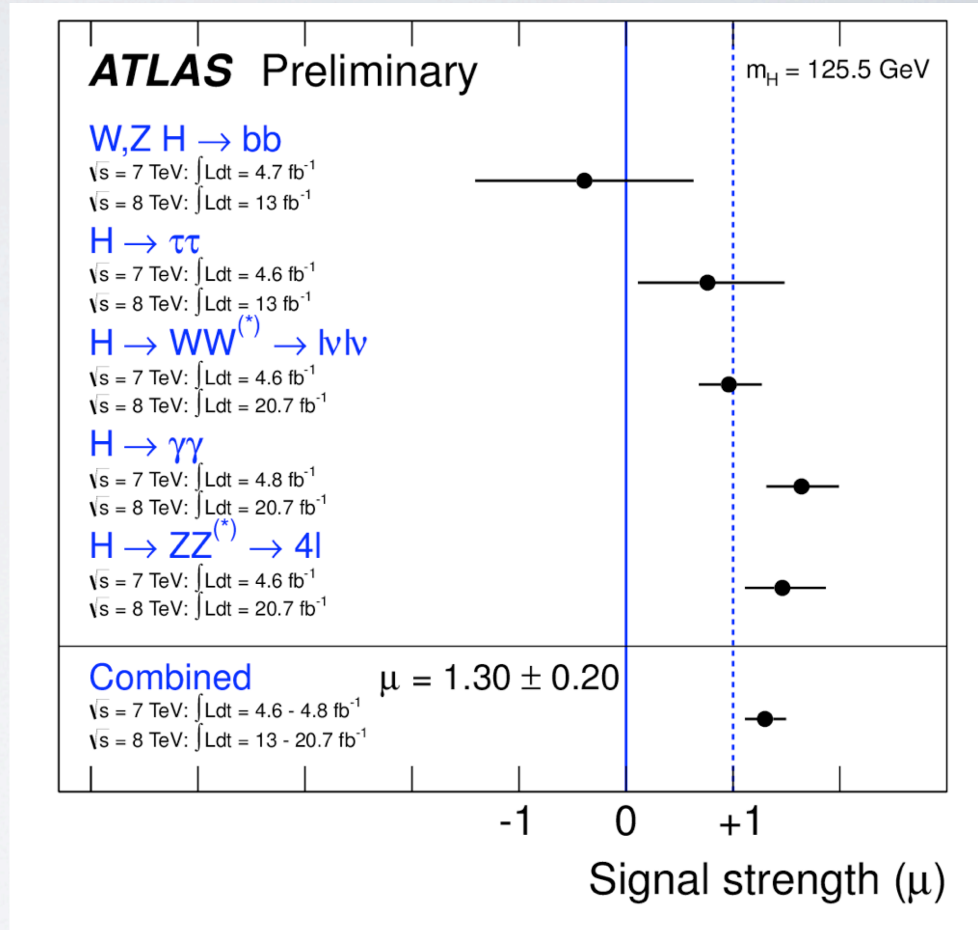
LHC: WHERE WE STAND

I looked over my slides from my PCTS talk almost exactly one year ago and still agree with what I said then:

- **No hint of strong dynamics**. Technicolor, composite Higgs, Randall-Sundrum all look even less plausible than they did pre-Higgs.
- Higgs mass puts **SUSY in an awkward spot**
- "Natural SUSY": the MSSM must be very tuned to fit a 125 GeV Higgs (despite many contrary claims in the literature in the last year). Models beyond the MSSM are typically awkward and/or complicated.
- **Semi-split SUSY**: solve most of the hierarchy problem, put scalars at ~10 to 1000 TeV. Increasingly plausible.
- Important to keep looking for small deviations from SM Higgs
- **Keep looking for naturalness signatures (stops, etc.), but bounds are already becoming very strong...**

HIGGS PROPERTIES





Looking increasingly Standard Model-like as more data comes in. Still room for 30 to 50% (*large*!) deviations!

HIGGS LOOP-LEVEL COUPLINGS

A lot of interest in this when both ATLAS and CMS showed a high diphoton rate. Recall: Higgs couplings to photons, gluons related to low-energy theorem.

Run from Λ down to μ with an intermediate threshold $\mu < M < \Lambda$ at which the beta function changes from b to $b + \Delta b$.

RG:

$$\frac{1}{g^2(\mu)} = \frac{1}{g^2(\Lambda)} + \frac{b}{8\pi^2} \log \frac{\Lambda}{\mu} + \frac{\Delta b}{8\pi^2} \log \frac{\Lambda}{M}$$

LOW-ENERGY THEOREM

Suppose the mass threshold is actually a function of space and time:

$$M \to M + \delta M(x)$$

Then we have a spatially varying gauge coupling:

$$\frac{1}{g^2(\mu, x)} = \frac{1}{g^2(\mu)} + \frac{\Delta b}{8\pi^2} \log \frac{M}{M(x)} = \frac{1}{g^2(\mu)} - \frac{\Delta b}{8\pi^2} \frac{\delta M(x)}{M}$$

In particular, if $M(x)$ depends on the Higgs, $M = M(h(x))$, then we extract an effective coupling:

$$\frac{\Delta b}{32\pi^2} h G^a_{\mu\nu} G^{a\mu\nu} \frac{\partial \log M(v)}{\partial v}$$

STOPS

Things to note:

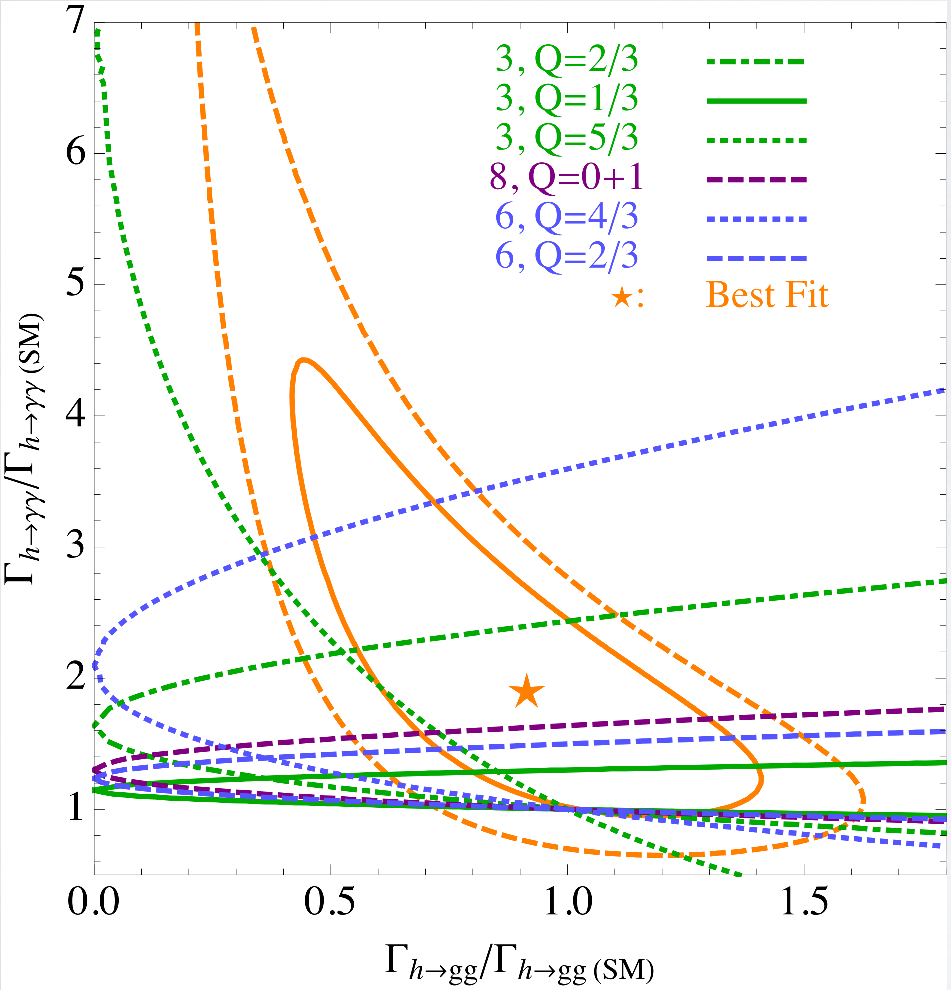
$$\frac{1}{2}\frac{\partial \log \det M_{\tilde{t}}^2}{\partial v} \sim y_t m_t \frac{\tilde{m}_Q^2 + \tilde{m}_u^2 - X_t^2 \sin^2\beta}{\tilde{m}_Q^2 \tilde{m}_u^2 - X_t^2 m_t^2 \sin^2\beta}$$

Small numerator factor (for heavy stops): decoupling

Minus sign: large mixing leads to opposite-sign couplings

Intuition: in the highly mixed case, larger VEV means more mixing, splitting light and heavy stops more. The light one contributes more, and is pushed lighter, so the overall sign reverses.

MODIFIED GLUON AND PHOTON COUPLINGS

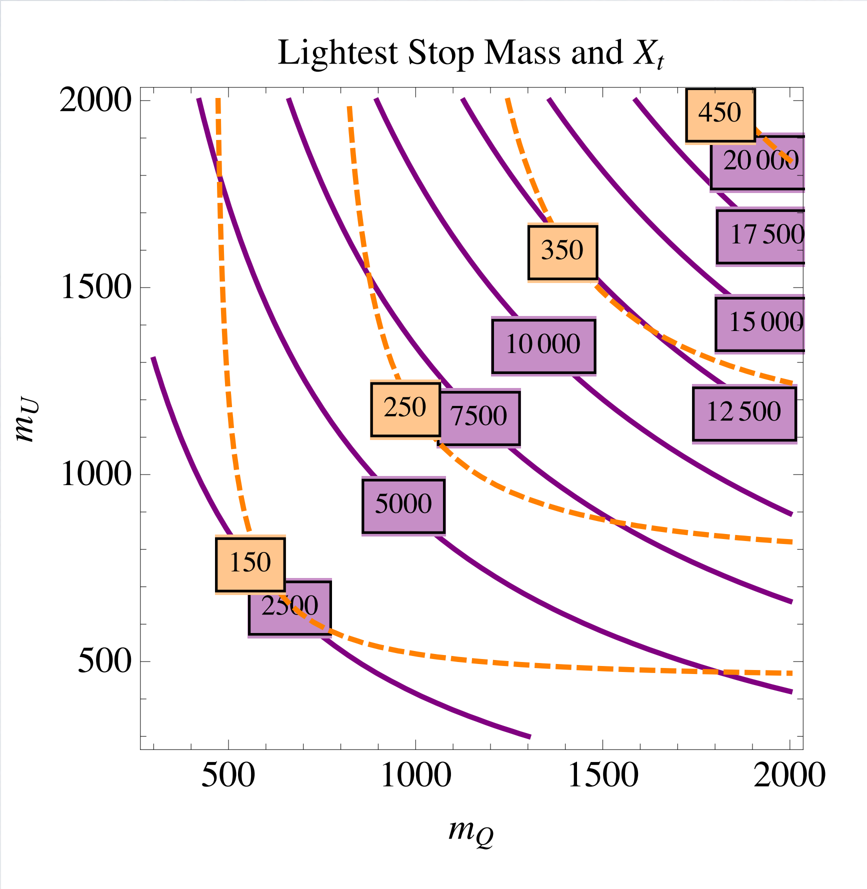


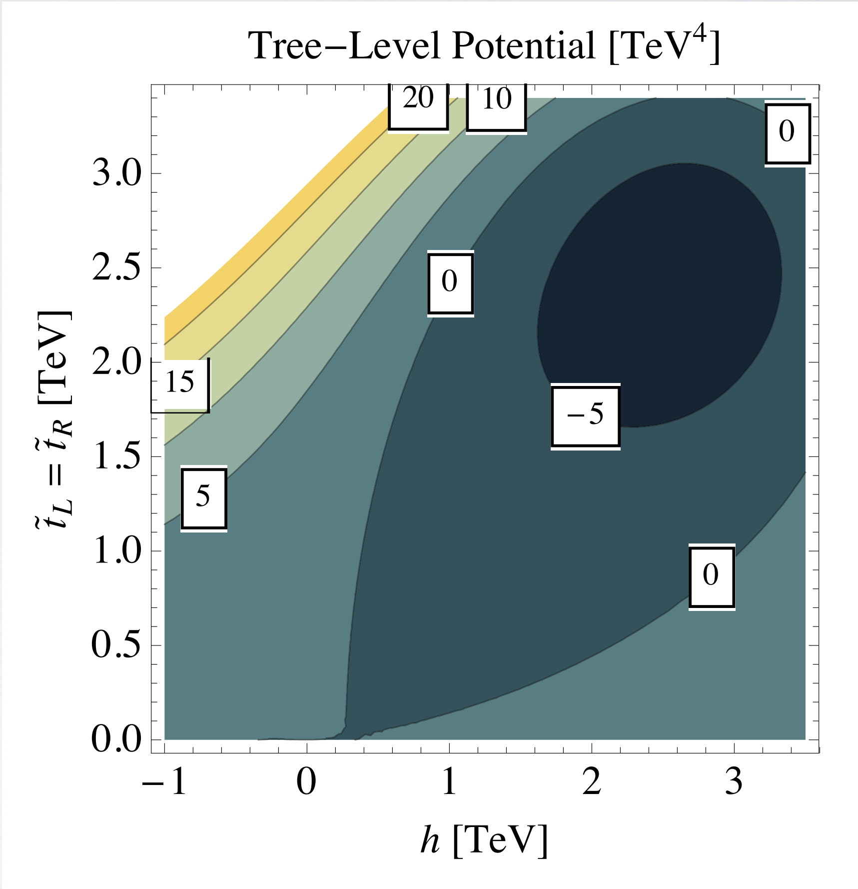
Many papers last year: new particles with color and charge running in loops can alter Higgs couplings to gluons and photons.

Opposite-sign gluon coupling helps?

MR, 1208.1765: No.

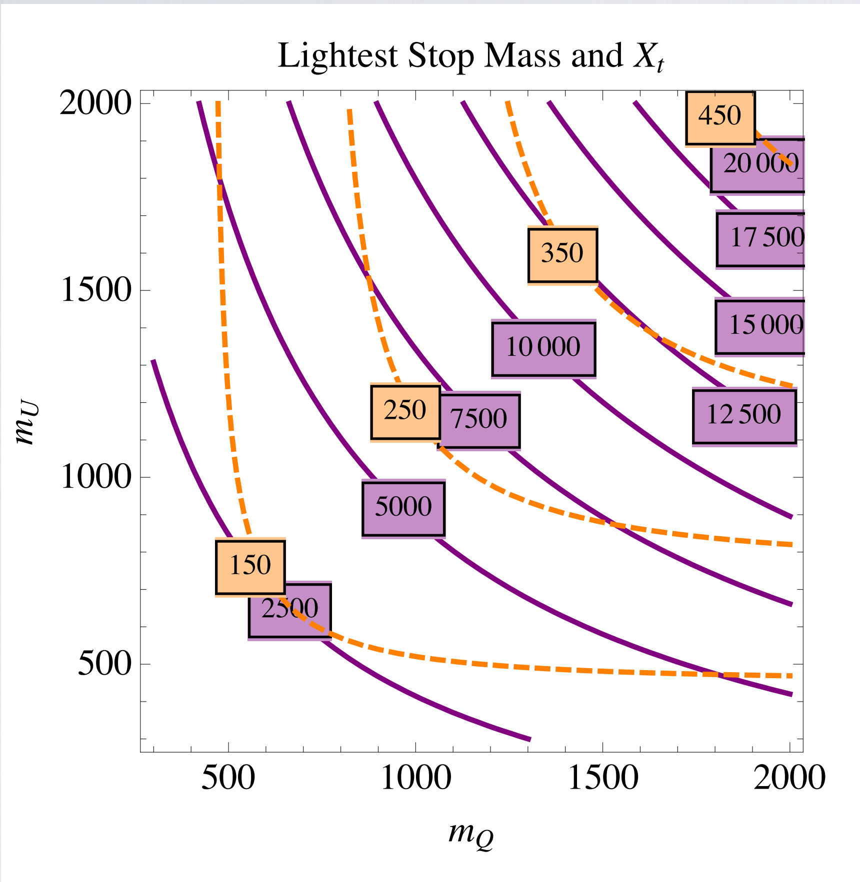
What it takes to get *hGG* coupling equal and opposite to its SM value:

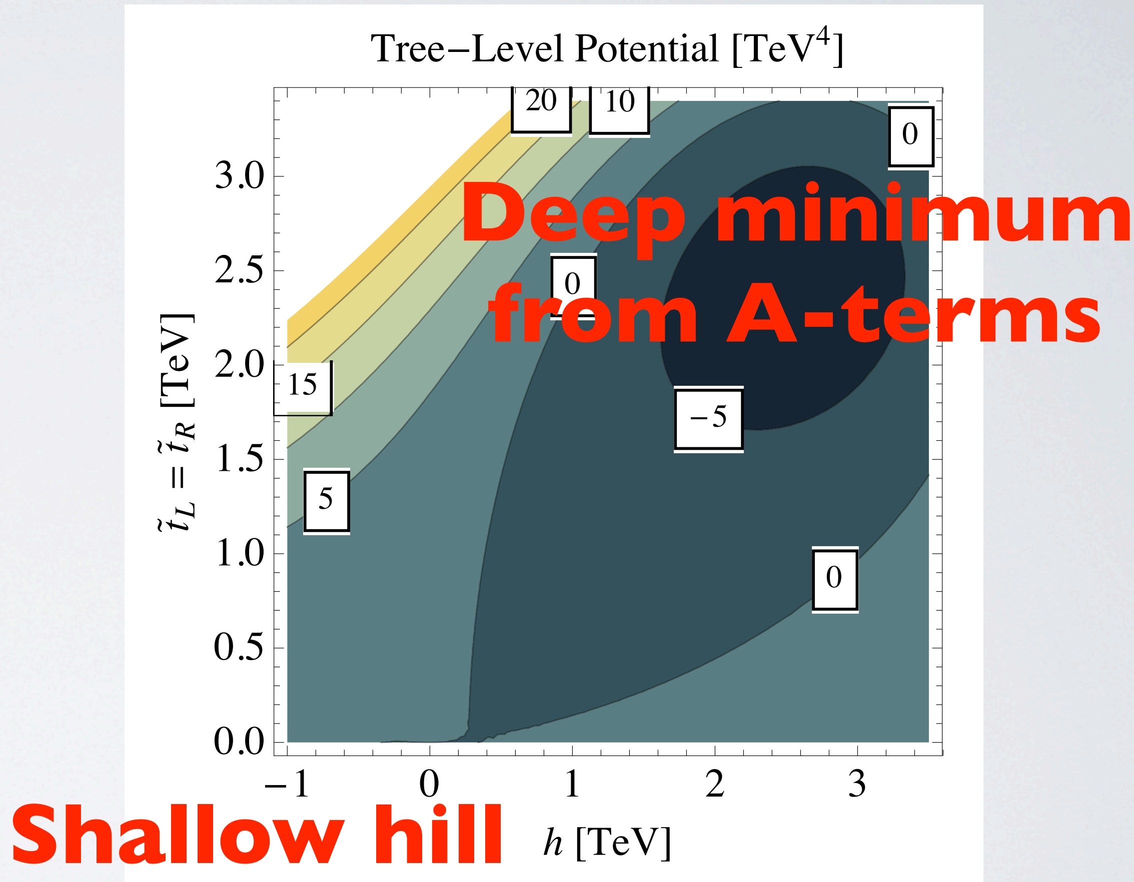




$$
\begin{aligned}
V(H,\tilde{Q}_3,\tilde{u}_3^c) \;=\;& m_H^2\,|H|^2 + m_Q^2\,\left|\tilde{Q}_3\right|^2 + m_U^2\,\left|\tilde{u}_3^c\right|^2 + y_t^2\left(\left|\tilde{Q}_3\tilde{u}_3^c\right|^2 + \left|H\tilde{Q}_3\right|^2 + \left|H\tilde{u}_3^c\right|^2\right) \\
&+\;\frac{1}{8}g'^2\left(|H|^2 + \frac{1}{3}\left|\tilde{Q}_3\right|^2 - \frac{4}{3}\left|\tilde{u}_3^c\right|^2\right)^2 + \frac{1}{8}g^2\left(|H|^2 - \left|\tilde{Q}_3\right|^2\right)^2 + \frac{4}{3}\left(\left|\tilde{Q}_3\right|^2 - \left|\tilde{u}_3^c\right|^2\right)^2 \\
&+\;\delta\lambda\,|H|^4 - y_t X_t H\tilde{Q}_3\tilde{u}_3^c - \left(y_t X_t H\tilde{Q}_3\tilde{u}_3^c\right)^*. \qquad (15)
\end{aligned}
$$

What it takes to get *hGG* coupling equal and opposite to its SM value:





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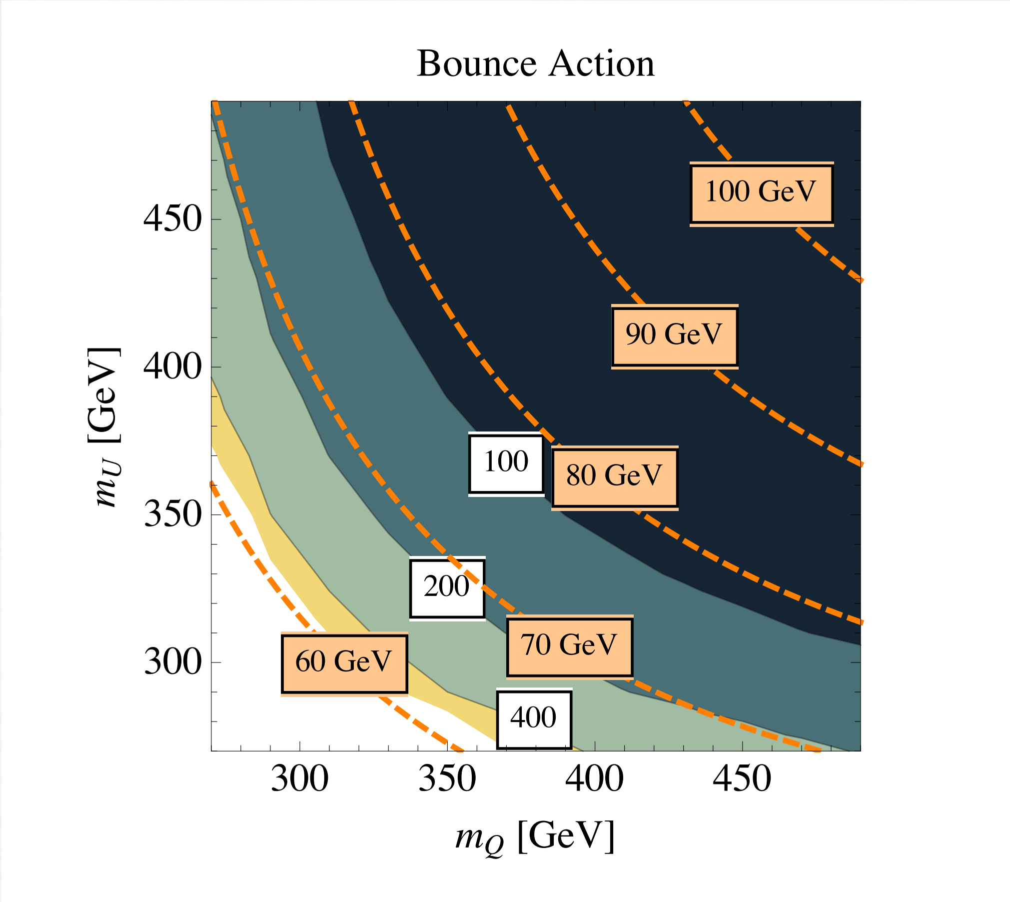
&+\; \frac{1}{8}g'^2\left(|H|^2 + \frac{1}{3}\left|\tilde{Q}_3\right|^2 - \frac{4}{3}\left|\tilde{u}_3^c\right|^2\right)^2 + \frac{1}{8}g^2\left(|H|^2 - \left|\tilde{Q}_3\right|^2\right)^2 + \frac{4}{3}\left(\left|\tilde{Q}_3\right|^2 - \left|\tilde{u}_3^c\right|^2\right)^2\\
&+\; \delta\lambda\,|H|^4 - y_t X_t H\tilde{Q}_3\tilde{u}_3^c - \left(y_t X_t H\tilde{Q}_3\tilde{u}_3^c\right)^*. \qquad (15)
\end{aligned}
$$

RAPID VACUUM DECAY

The large trilinear terms in this region lead to rapid vacuum decay (known already in 90s: Kusenko, Langacker, Segre, hep-ph/9602414).

Bounce action computed with CosmoTransitions code by Max Wainwright (UCSC student)

Excludes these scenarios



NEW SCALARS WITH QUARTICS

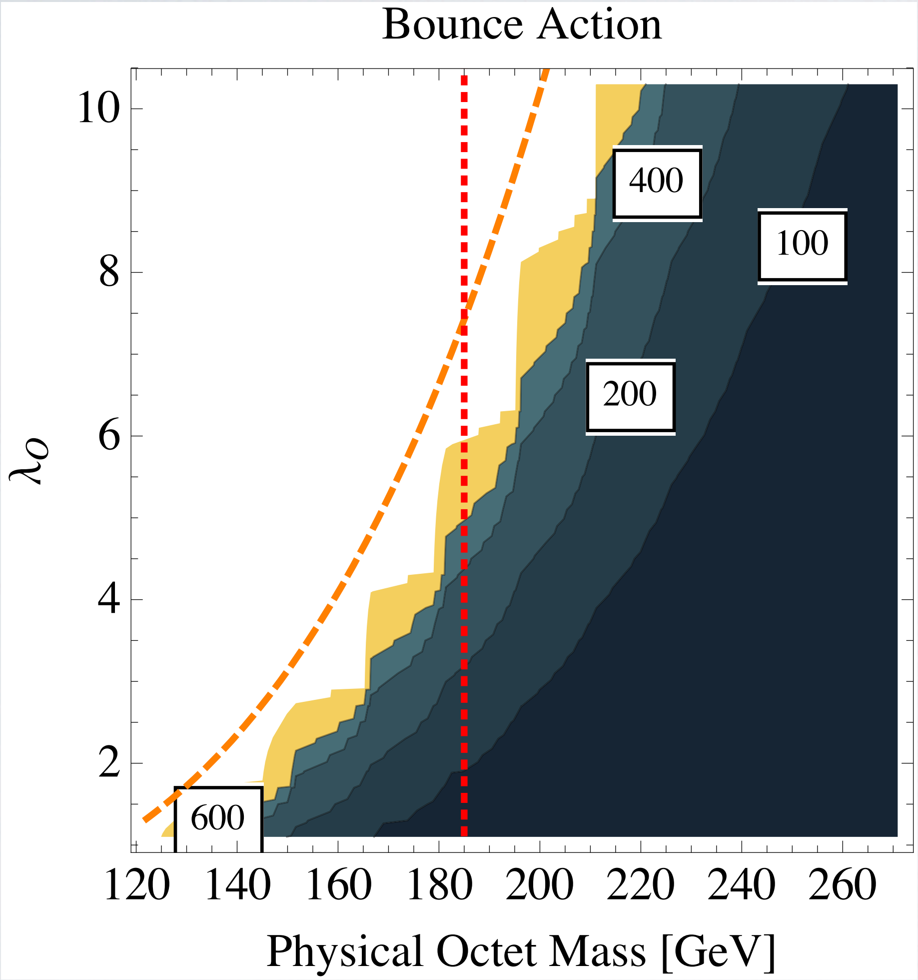
Another option, e.g. Manohar-Wise scalar octet O:

$$V = -\mu^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 + \left(m_O^2 - \lambda_{HO} H^\dagger H\right) O^\dagger O + \lambda_O \left(O^\dagger O\right)^2$$

Increasing Higgs diphoton means **large negative** HHOO quartic, requiring the O^4 quartic to be ***even larger*** to prevent a runaway negative potential.

Again, **tree-level vacuum stability problem.**

Collider bound



As you would expect, in all but a tiny sliver of the parameter space, having a potential that's unbounded from below leads to very quick vacuum decay.

Unbounded below

VACUUM STABILITY AND FERMIONS

Arkani-Hamed, Blum, D'Agnolo, Fan 1207.4482

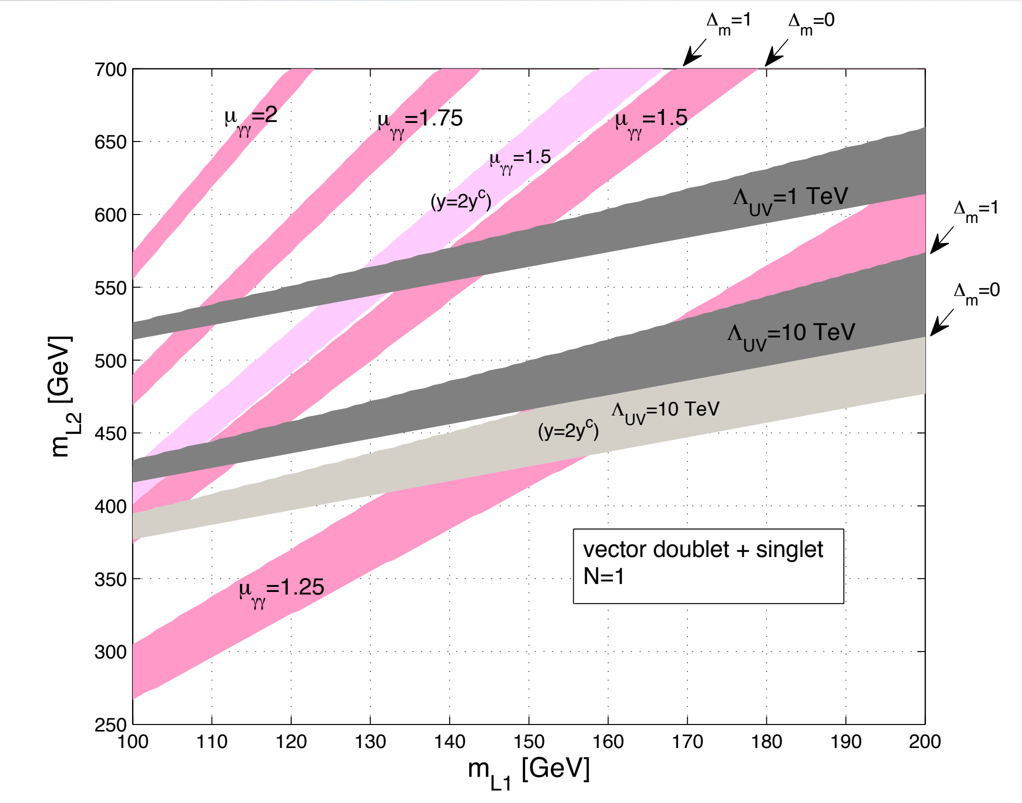
$$16\pi^2\frac{d\lambda}{dt} = \lambda\left(24\lambda - 9g_2^2 - \frac{9g_1^2}{5} + 12y_t^2 + 4\mathcal{N}\left(y_n^2 + y_n^{c2} + y^2 + y^{c2}\right)\right) - 2\mathcal{N}\left(y^4 + y^{c4} + y_n^4 + y_n^{c4}\right) - 6y_t^4$$
$$+\frac{3}{8}\left(2g_2^4 + \left(g_2^2 + \frac{3g_1^2}{5}\right)^2\right). \qquad \text{(A.1)}$$

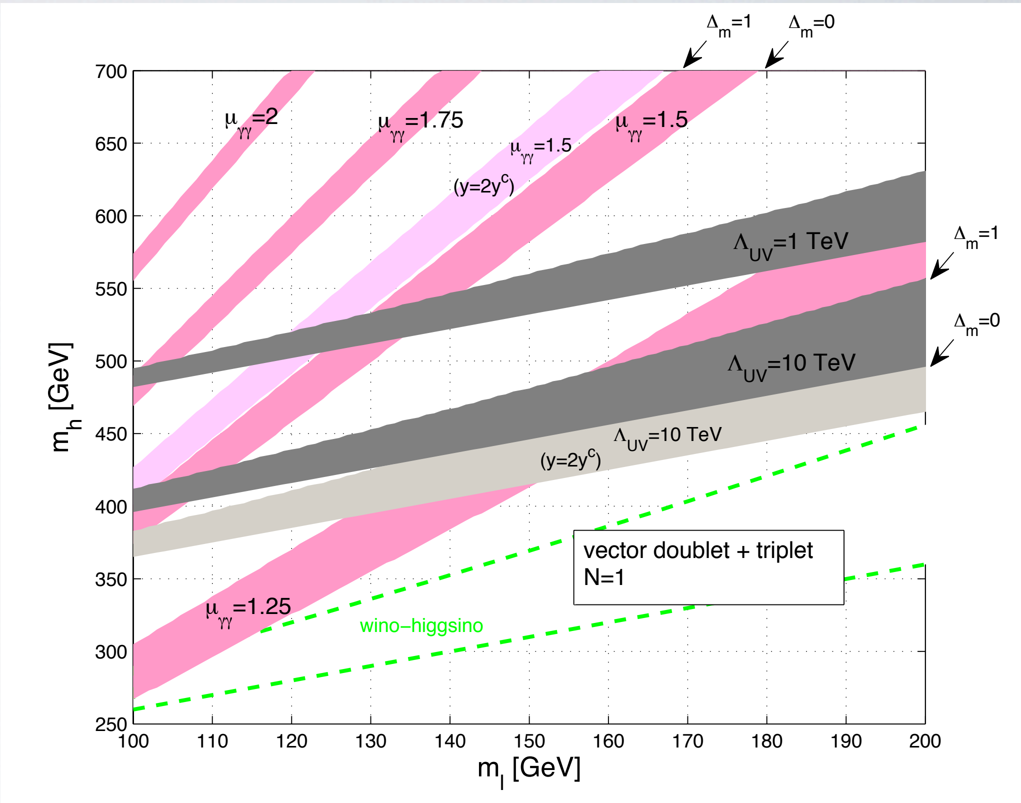
Yukawas from a mass matrix

$$\mathcal{L}_M = -\begin{pmatrix}\psi^{+Q} & \chi^{+Q}\end{pmatrix}\begin{pmatrix} m_\psi & \frac{yv}{\sqrt{2}} \\ \frac{y^c v}{\sqrt{2}} & m_\chi \end{pmatrix}\begin{pmatrix}\psi^{-Q} \\ \chi^{-Q}\end{pmatrix} + cc.$$

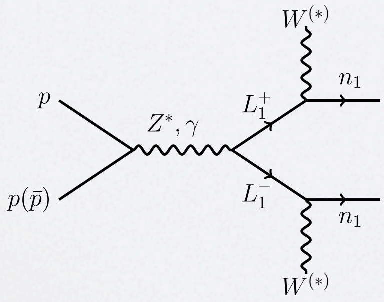
drive Higgs quartic negative fast (unless superpartners are nearby)

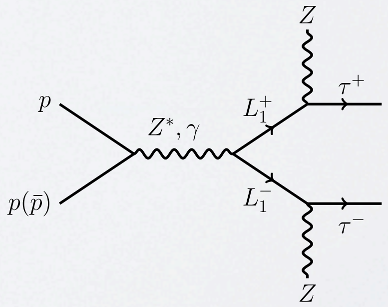
Significant fermion loop effects require very low cutoff:

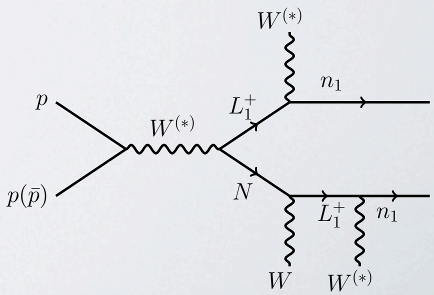




Viable region would be probed directly:







HIGGS AND CP

Operators modifying the Higgs to diphoton rate have CP-violating cousins:

$$\begin{aligned} \mathcal{O}_{hW} &= H^\dagger H W^a_{\mu\nu} W^{a\mu\nu}, & \mathcal{O}_{h\tilde{W}} &= H^\dagger H \tilde{W}^a_{\mu\nu} W^{a\mu\nu} \\ \mathcal{O}_{hB} &= H^\dagger H B_{\mu\nu} B^{\mu\nu}, & \mathcal{O}_{h\tilde{B}} &= H^\dagger H \tilde{B}_{\mu\nu} B^{\mu\nu} \\ \mathcal{O}_{WB} &= (H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}, & \mathcal{O}_{\tilde{W}B} &= (H^\dagger \sigma^a H) \tilde{W}^a_{\mu\nu} B^{\mu\nu} \end{aligned}$$

CP-violating phases in mass matrix of fermions running in the loop generate these operators and affect the rate:

$$\mu_{\gamma\gamma} = \left| 1 + \frac{1}{\mathcal{A}_{\rm SM}} \frac{2}{3} Q_\psi^2 \frac{\partial}{\partial \log v} \log\det \mathcal{M}^\dagger \mathcal{M} \right|^2 + \left| \frac{2}{\mathcal{A}_{\rm SM}} Q_\psi^2 \frac{\partial}{\partial \log v} \arg\det \mathcal{M} \right|^2$$

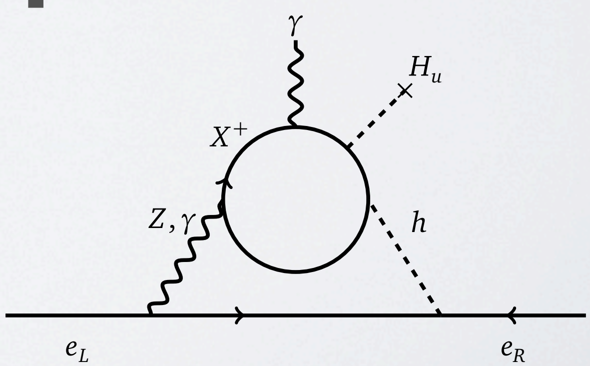
CP VIOLATION

Could try to probe this with CPV Higgs decays (Voloshin 1208.4303), but also: RGE mixes

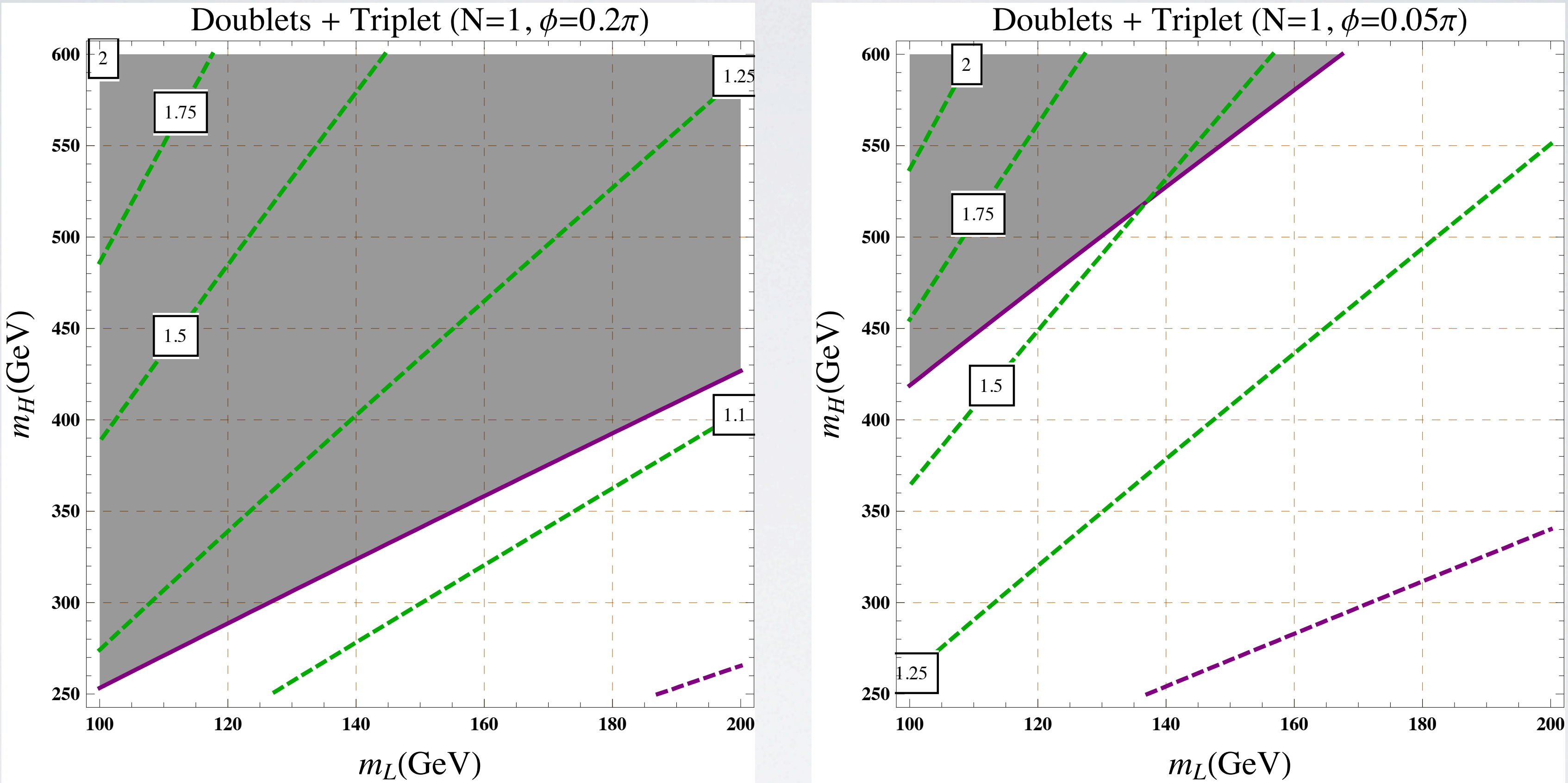
$$H^\dagger H F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \text{and} \quad LH\sigma_{\mu\nu}\bar{e}F^{\mu\nu}$$

Generically, new physics that alters Higgs decays **with fermions** will **produce a nonzero electron (or neutron) EDM. "Higgs CP problem"**

"Barr-Zee" type diagrams: may be familiar, e.g. split SUSY



Constraints from EDMs: green contours are Higgs to diphoton enhancement



Solid purple: $d_e/e = 1.05\ 10^{-27}$ cm;
dashed purple: $d_e/e = 10^{-28}$ cm

J. Fan and MR, 1301.2597

The ACME collaboration (DeMille/Doyle/Gabrielse) claims to be able to improve the EDM limit by an order of magnitude (or measure it). Latest news at colloquium on Monday (April 29) at Harvard?

"Particle Physics with Cold Molecules: The ACME Experiment"

John Doyle

Harvard Physics

Measurement of a non-zero electric dipole moment (EDM) of the electron within a few orders of magnitude of the current best limit[1] of |de|<1.05*10-27 e*cm would be an indication of CP violation beyond the Standard Model, probably an indication of SUSY and possibly indicating the T violation necessary for explaining the matter-antimatter asymmetry of the universe. The ACME Collaboration is searching for an electron EDM by performing a precision measurement of electron spin precession signals from cold thorium monoxide (ThO). I will discuss the current status of the experiment. Based on a data set acquired from 65 hours of running time, we have achieved a one-sigma statistical uncertainty in the value of de of 1*10-28 e*cm/√T, where T is the running time in days.

[1] JJ Hudson et al., "Improved measurement of the shape of the electron." Nature 473, 493 (2011)

MORAL

Loop-level corrections to Higgs properties are small in almost any well-behaved model. Still worth looking! But don't expect effects larger than ~20% without running into vacuum instabilities that are likely to kill or severely constrain the model.

Many reasonable people who thought about the diphoton excess concluded it would go away and, at CMS, it has.

MORAL

A more plausible scenario for modifying Higgs couplings is through an extended Higgs sector (e.g. 2HDM m_Z^2/m_A^2 effects in the MSSM). Not surprising: it's **tree-level**.

Then, expect correlated changes in diphoton and ZZ, WW.

Important to look for other Higgses as well!

STANDARD MODEL VACUUM STABILITY

Aside from neutrino masses and gravity modifying physics at high energies, and dark matter with no definite connection to the SM, we currently have **no compelling beyond Standard Model signals.**

This raises the question: does the SM Higgs potential give us any reason to suspect new physics at some scale?

VACUUM STABILITY IN THE SM

The Higgs quartic coupling runs according to:

$$\beta(\lambda) \approx \frac{1}{8\pi^2}\left(12\lambda^2 + 6\lambda y_t^2 - 3y_t^4\right)$$

The top Yukawa has:

$$\beta(y_t) = \frac{1}{8\pi^2}\left(\frac{9}{4}y_t^3 - 4y_t g_s^2\right)$$

Experimentally, we now know $\lambda \approx 0.13,\; y_t \approx 1.$

So, the leading effect is that the Higgs quartic decreases at high scales due to the top Yukawa, and top Yukawa decreases due to the strong gauge coupling.

SHAPE OF THE HIGGS POTENTIAL

To good accuracy, the running quartic $\lambda(\mu)$ describes the behavior of the potential at large field values *H*:

$$V(H) \approx \lambda(|H|)\,|H|^4 \quad \text{at} \quad |H| \gg v.$$

This is due to the RG improvement of the Coleman-Weinberg potential, which involves $\log \frac{|H|^2}{\mu^2}$ terms.

The leading μ dependence cancels between logs in the Coleman-Weinberg potential and the logs in the running couplings.

TUNNELING

There is a simple approximation for the bounce action of the tunneling solution (Isidori, Ridolfi, Strumia [IRS] hep-ph/0104016):

$$H = \frac{1}{\sqrt{2}} h(r), r^2 = x_\mu x^\mu$$

where

$$\frac{d^2 h}{dr^2} + \frac{3}{r}\frac{dh}{dr} + V'(h) = 0$$

solution with $h = v$ at infinity and $h'(0) = 0$:

$$h(r) = \sqrt{\frac{2}{|\lambda|}} \frac{2R}{r^2 + R^2}, \quad S_0 = \frac{8\pi^2}{3\,|\lambda|}$$

Here λ is taken ***fixed and negative***.

TUNNELING

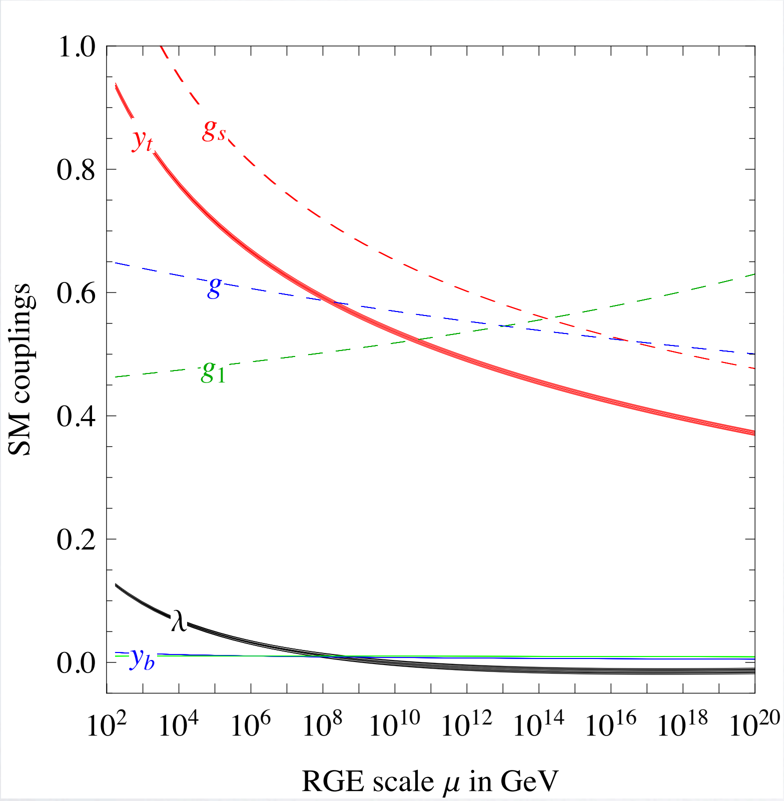
Our toy solution has an arbitrary size modulus *R*, and it's unclear what scale to evaluate the quartic at. IRS do a one-loop calculation including the functional determinant to pin them down. Should take: $R \sim 1/\mu$ with μ near the scale where the potential goes unstable.

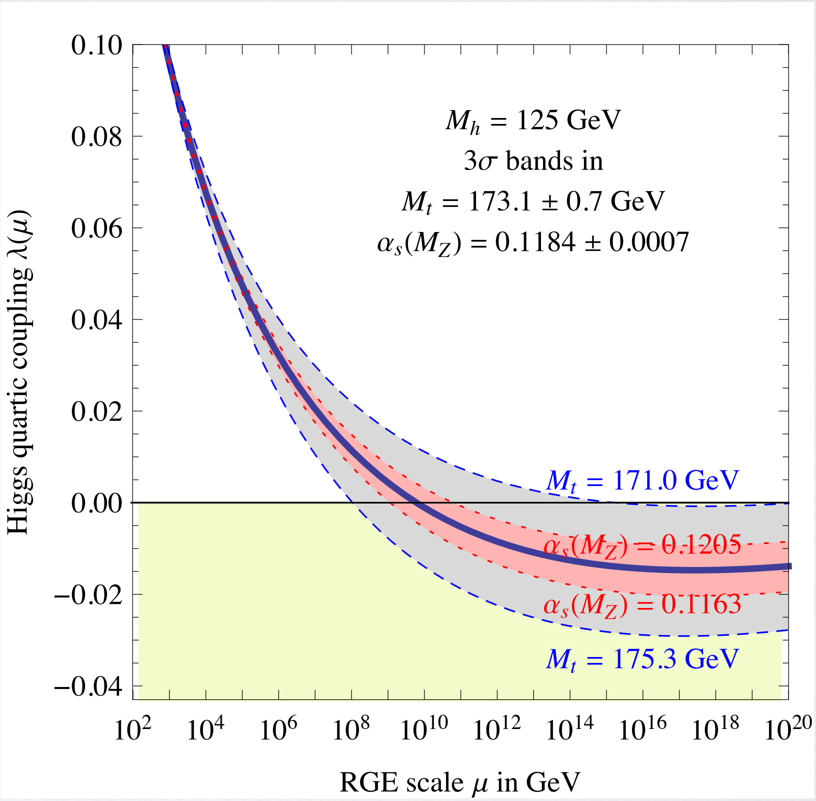
Scale of the instability:

$$\lambda\left(\Lambda_{UV}\right) = \frac{2\pi^2}{3\log\left(\frac{H}{\Lambda_{UV}}\right)} = -0.065\left(1 - 0.02\log_{10}\left(\frac{\Lambda_{UV}}{100\ \mathrm{GeV}}\right)\right)$$

RUNNING QUARTIC

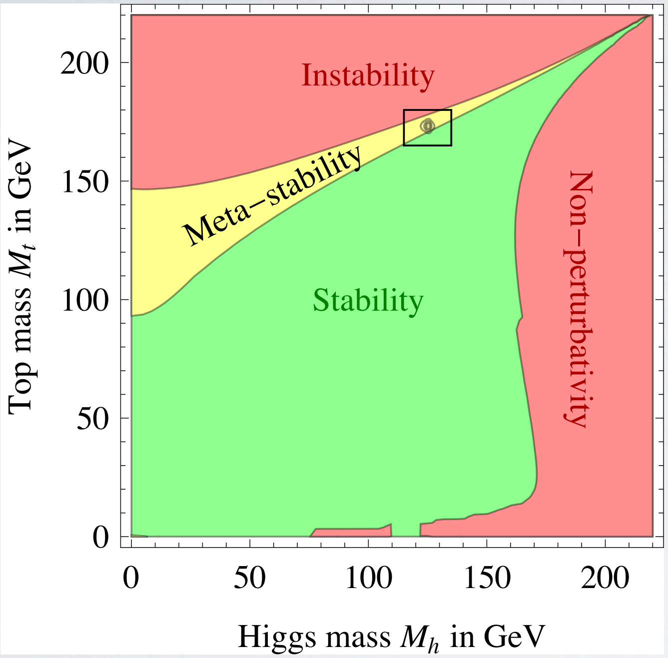
Recently: 1205.6497 by Degrassi, Di Vita, Elias-Miró, Espinosa, Giudice, Isidori, Strumia. NNLO.

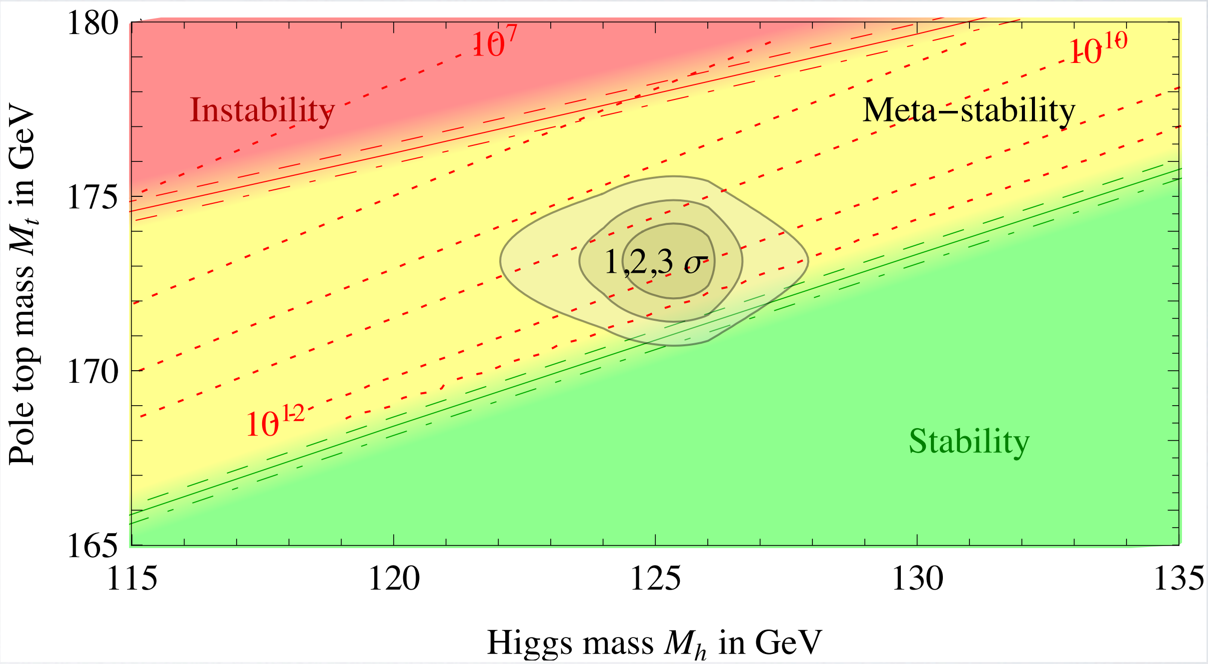




Metastable potential, instability near the intermediate scale.

VACUUM INSTABILITY

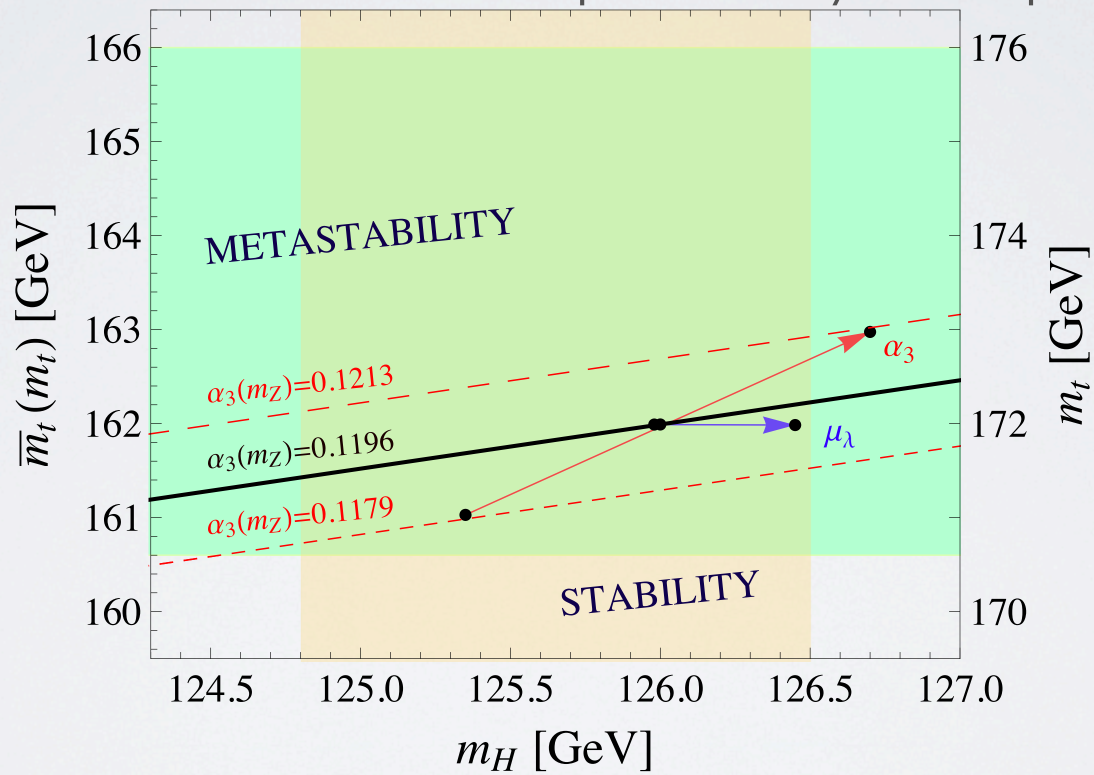




Degrassi et al. find that the measured values fall in a region where the quartic runs negative, but the lifetime is long enough that it could be our universe (metastable region).

ANOTHER VIEW

1209.0393 by Isabella Masina: emphasizes uncertainty in top mass (is what's measured precisely the pole mass?)



Becomes important to reduce uncertainties in the top sector in order to make a definite claim.

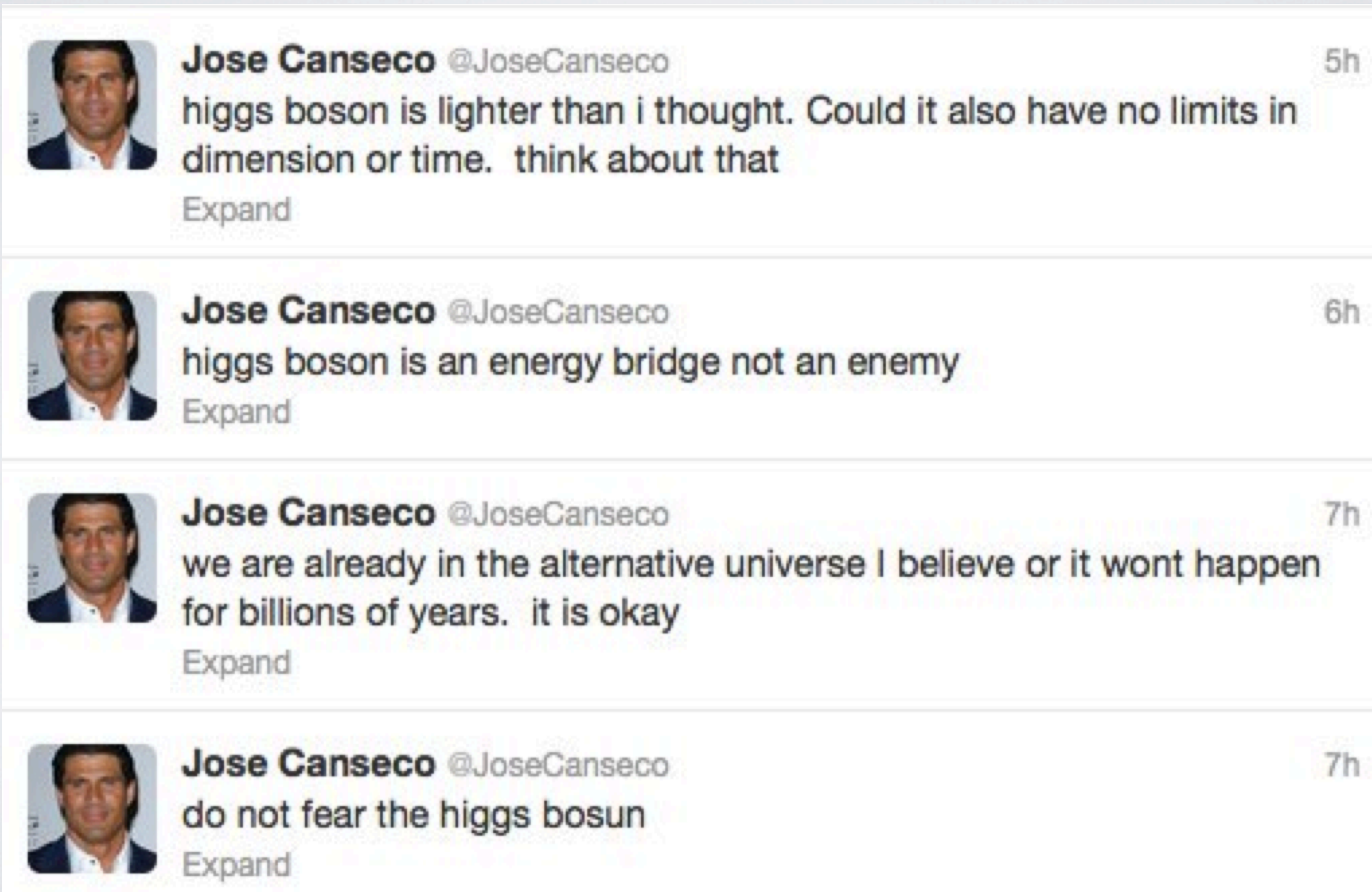
WHAT DOES IT MEAN?

- **Bad news for supersplit supersymmetry.**
MSSM boundary conditions at a high scale lead to larger Higgs masses, ~ 140 GeV.

- Some are using it as propaganda for "asymptotic safety," an idea that seems to me to be obviously inconsistent with black hole physics & semiclassical GR.

- *Many* others are adopting a (related?) view that quadratic divergences are not real. But quadratic sensitivity to large mass scales ***is*** physical, the SM is not UV complete, and gravity is real, so I can't make sense of this viewpoint.

WHAT DOES IT MEAN? INSIGHTS FROM TWITTER


Jose Canseco @JoseCanseco 5h
higgs boson is lighter than i thought. Could it also have no limits in dimension or time. think about that
Expand

Jose Canseco @JoseCanseco 6h
higgs boson is an energy bridge not an enemy
Expand

Jose Canseco @JoseCanseco 7h
we are already in the alternative universe I believe or it wont happen for billions of years. it is okay
Expand

Jose Canseco @JoseCanseco 7h
do not fear the higgs bosun
Expand

CONCLUSIONS

- Vacuum instabilities plague most attempts to significantly modify the loop-level Higgs couplings to photons and to gluons. Tree-level alterations (mixing) typically safer.

- If large loop corrections observed, possible "Higgs CP problem."

- Standard Model: probably metastable, with quartic running negative at intermediate scale. Lots of room for unknown new physics to modify the story.

- I'm skeptical of any deep meaning attached to small lambda at high scale.