Higgs weights 125 GeV! Now what?

1) Is the Higgs standard? (http://arxiv.org/abs/1203.4254)
2) Higgs and SUSY (http://arxiv.org/abs/1108.6077)
3) Will the SM vacuum decay? (http://arxiv.org/abs/1112.3022)

Alessandro Strumia

Talk at CERN and IFAE, updated to April 12, 2012

Legal disclaimer

I assume that the hint for a 125 GeV Higgs is a 125 GeV Higgs
rather than a statistical fluctuation or a superluminal cable

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By not abandoning the room you accept the above assumption.

Thank you

Is the Higgs standard?

with P.P. Giardino, K. Kannike, M. Raidal

Observables

$m_h = 125\,$GeV is a lucky mass for LHC; several BR

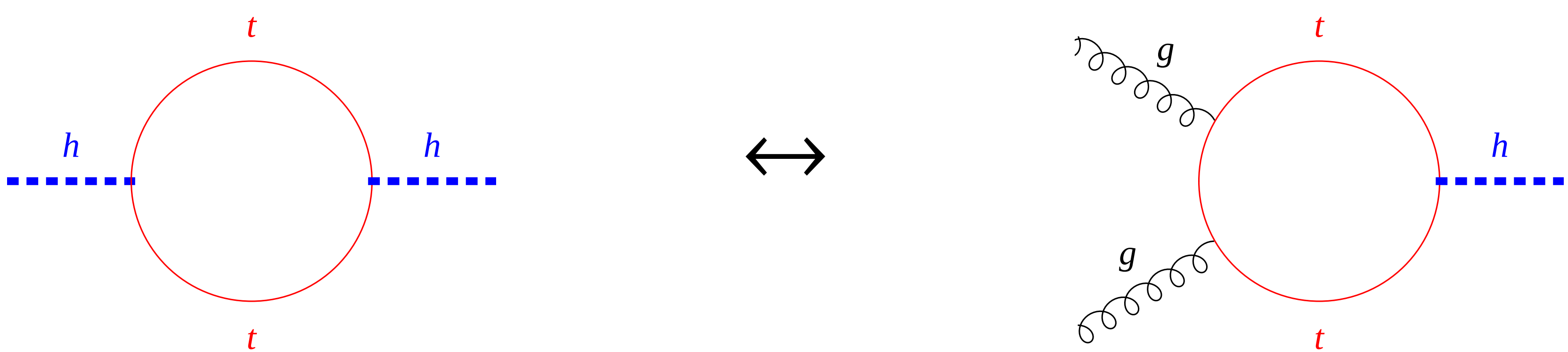
$$\begin{array}{lll} \text{BR}(h \to b\bar{b}) = 58\%, & \text{BR}(h \to WW^*) = 21.6\%, & \text{BR}(h \to \tau^+\tau^-) = 6.4\%, \\ \text{BR}(h \to ZZ^*) = 2.7\%, & \text{BR}(h \to gg) = 8.5\%, & \text{BR}(h \to \gamma\gamma) = 0.22\% \end{array}$$

and production mechanisms

$$\begin{array}{ll} \sigma(pp \to h) = (15.3 \pm 2.6)\,\text{pb}, & \sigma(pp \to jjh) = 1.2\,\text{pb}, \\ \sigma(pp \to Wh) = 0.57\,\text{pb}, & \sigma(pp \to Zh) = 0.32\,\text{pb}, \end{array}$$

allow to disentangle Higgs couplings and test Higgs properties.

Naturalness suggests that light stops or other new physics affect the Higgs



Fermiophobic searches

CMS looked for $pp \to jj\gamma\gamma$ measuring, at $m_h \approx 125\,\text{GeV}$:

$$[0.033\sigma(pp \to h) + \sigma(pp \to jjh)] \times \text{BR}(h \to \gamma\gamma) = \text{SM} \times (3.3 \pm 1.1)$$

ATLAS looked for $pp \to \gamma\gamma$ with $p_{T\gamma\gamma} > 40\,\text{GeV}$ measuring

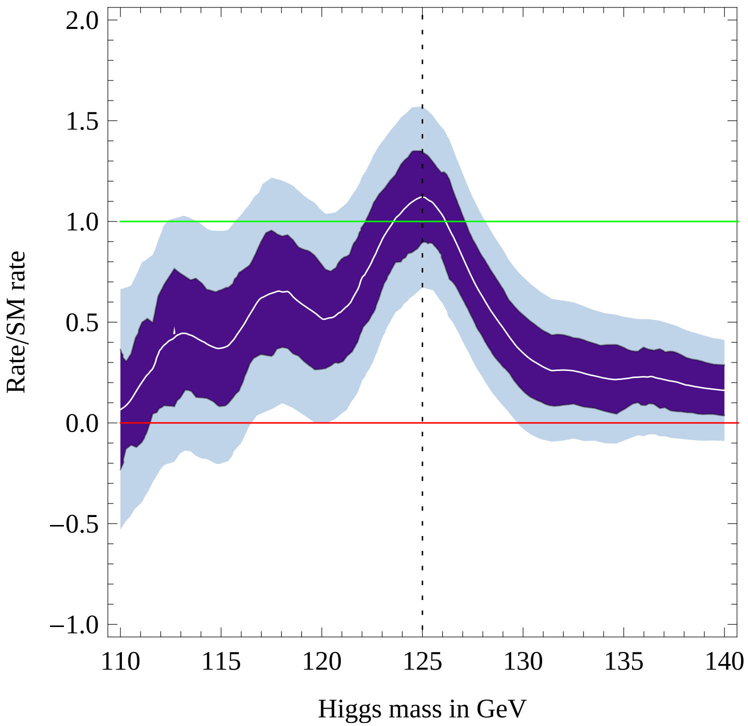
$$[0.3\sigma(pp \to h) + \sigma(pp \to Wh, Zh, jjh)] \times \text{BR}(h \to \gamma\gamma) = \text{SM} \times (3.3 \pm 1.1)$$

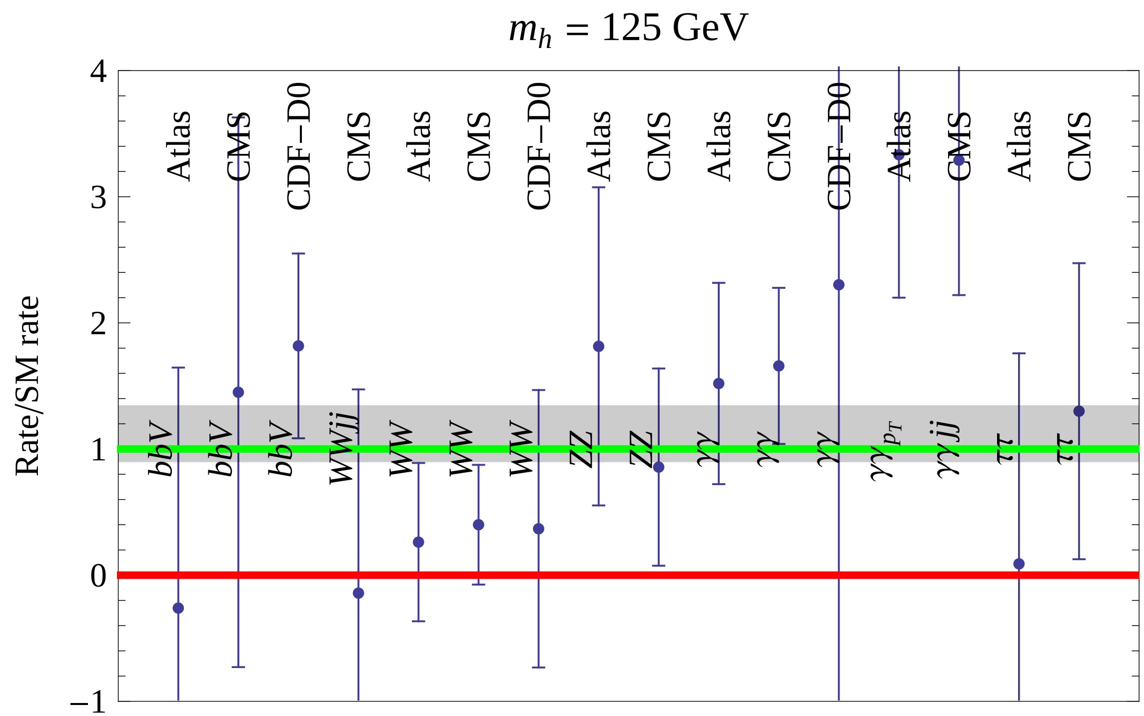
For data I would like this format. So far we have to approximately deduce:

$$\mu \approx R^{95\%}_{\text{observed}} - R^{95\%}_{\text{expected}}, \qquad \sigma = \frac{R^{95\%}_{\text{expected}}}{2},$$

and get weights of production channels by asking or doing MC simulations.

Higgs data: CMS, ATLAS, CDF, D0

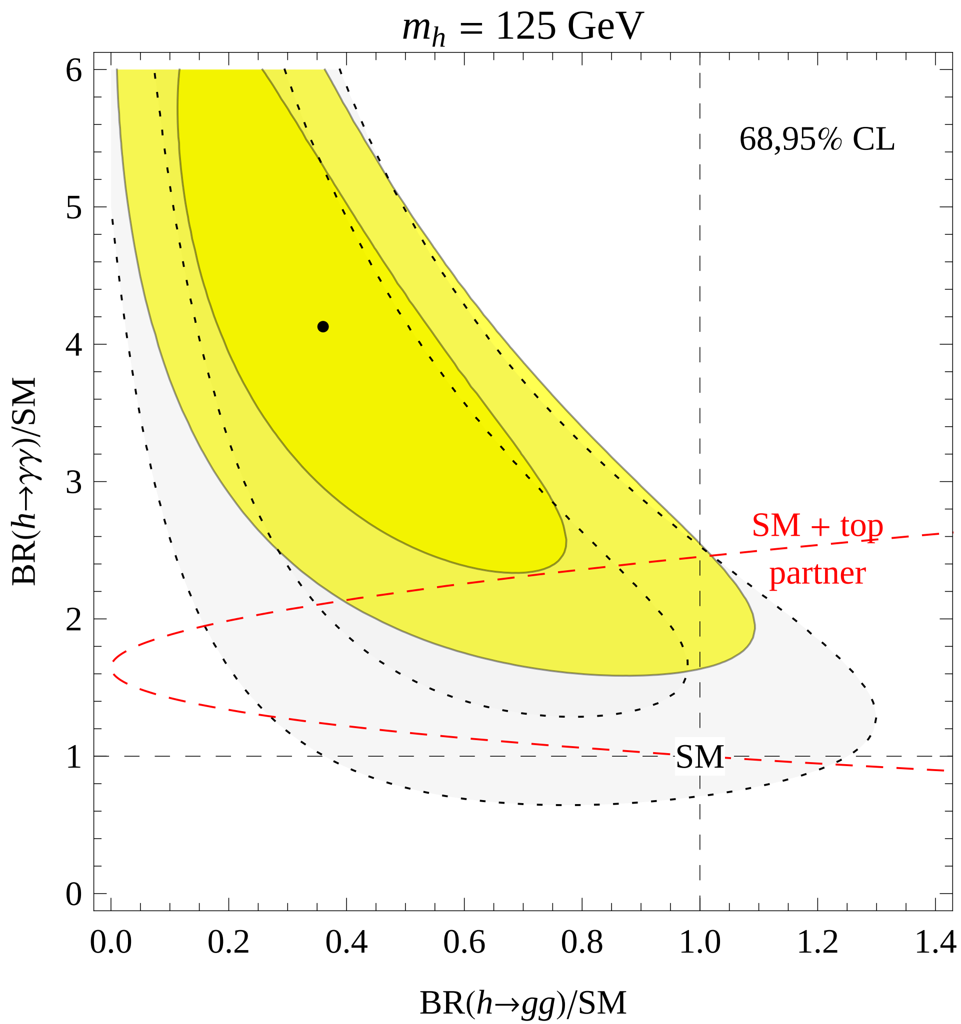




SM fit is good: $\chi^2 \approx 17$ (15 dof), the average rate is 1.1 ± 0.2, and

$$\frac{\text{observed rate}}{\text{SM rate}} = \begin{cases} 2.1 \pm 0.5 & \text{photons} \\ 0.5 \pm 0.3 & \text{vectors: } W \text{ and } Z \\ 1.3 \pm 0.5 & \text{fermions: } b \text{ and } \tau \end{cases} .$$

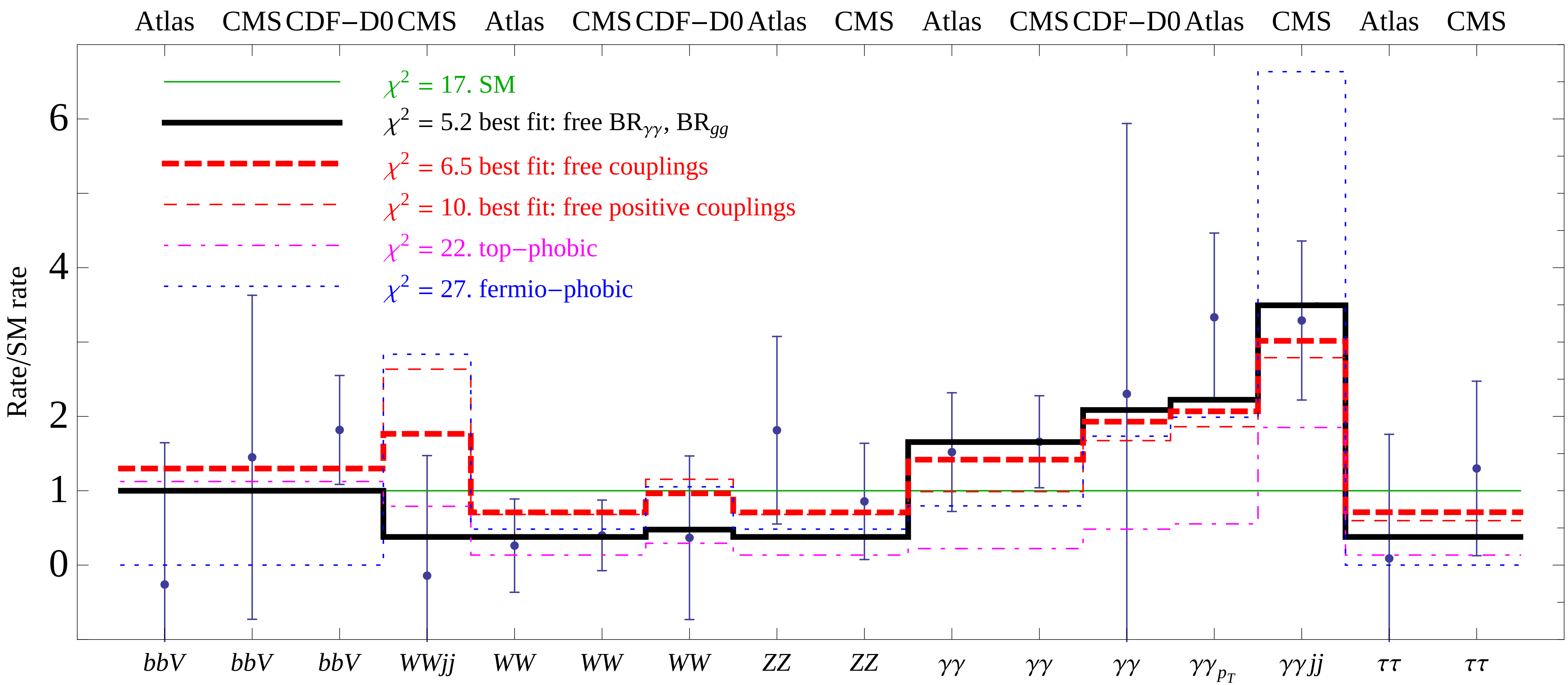
Non-standard BR for loop processes



Best fit $\chi^2 \approx 6$ (13 dof) away from SM and at

$$\frac{\text{BR}(h \leftrightarrow gg)}{\text{BR}(h \to gg)_{\text{SM}}} \approx 0.3, \qquad \frac{\text{BR}(h \to \gamma\gamma)}{\text{BR}(h \to \gamma\gamma)_{\text{SM}}} \approx 4,$$

Non standard best fits

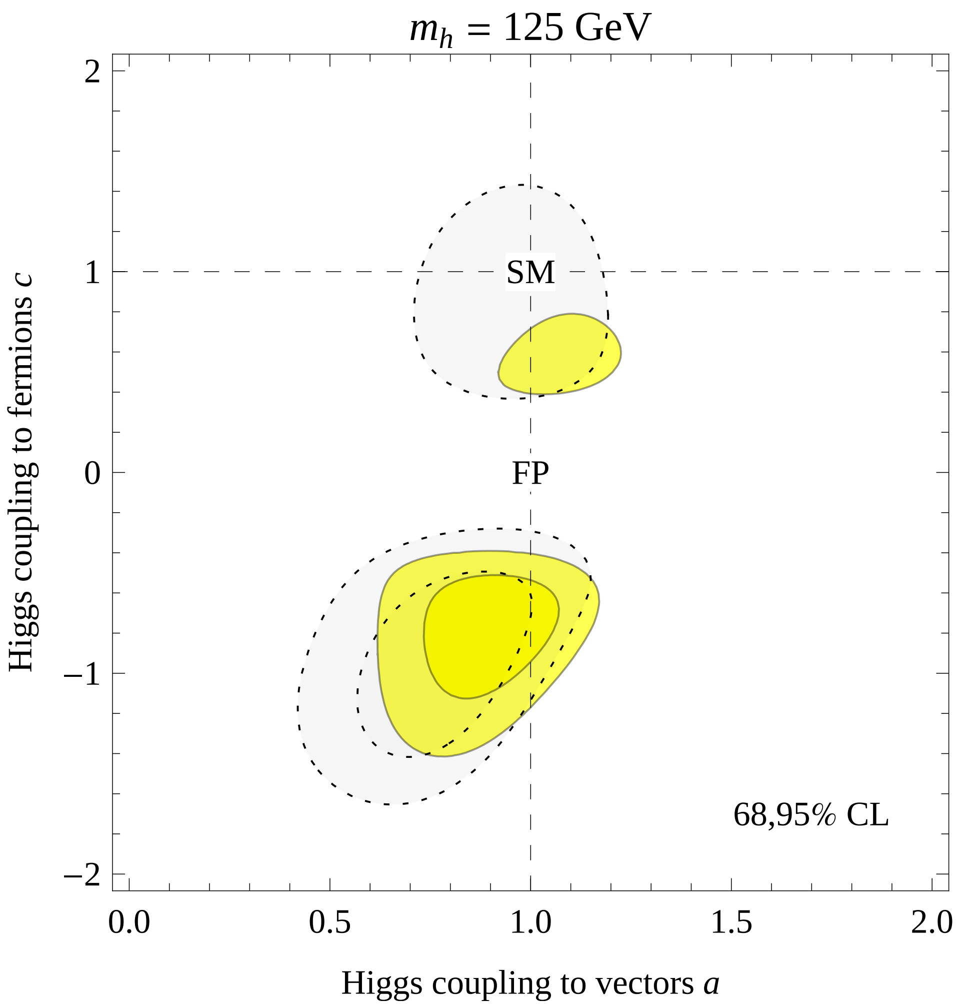


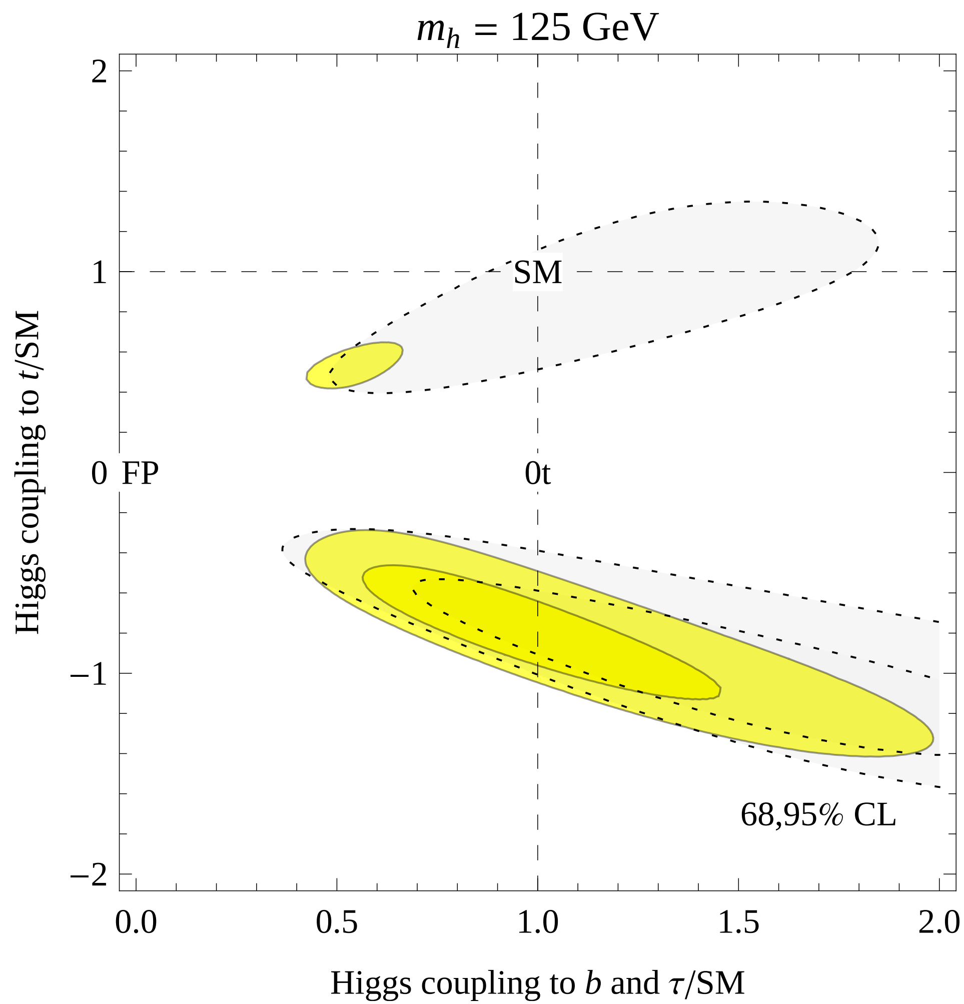
SM χ^2 is good. BSM fit is better. Maybe too good.

Fermiophobia not much worse than SM

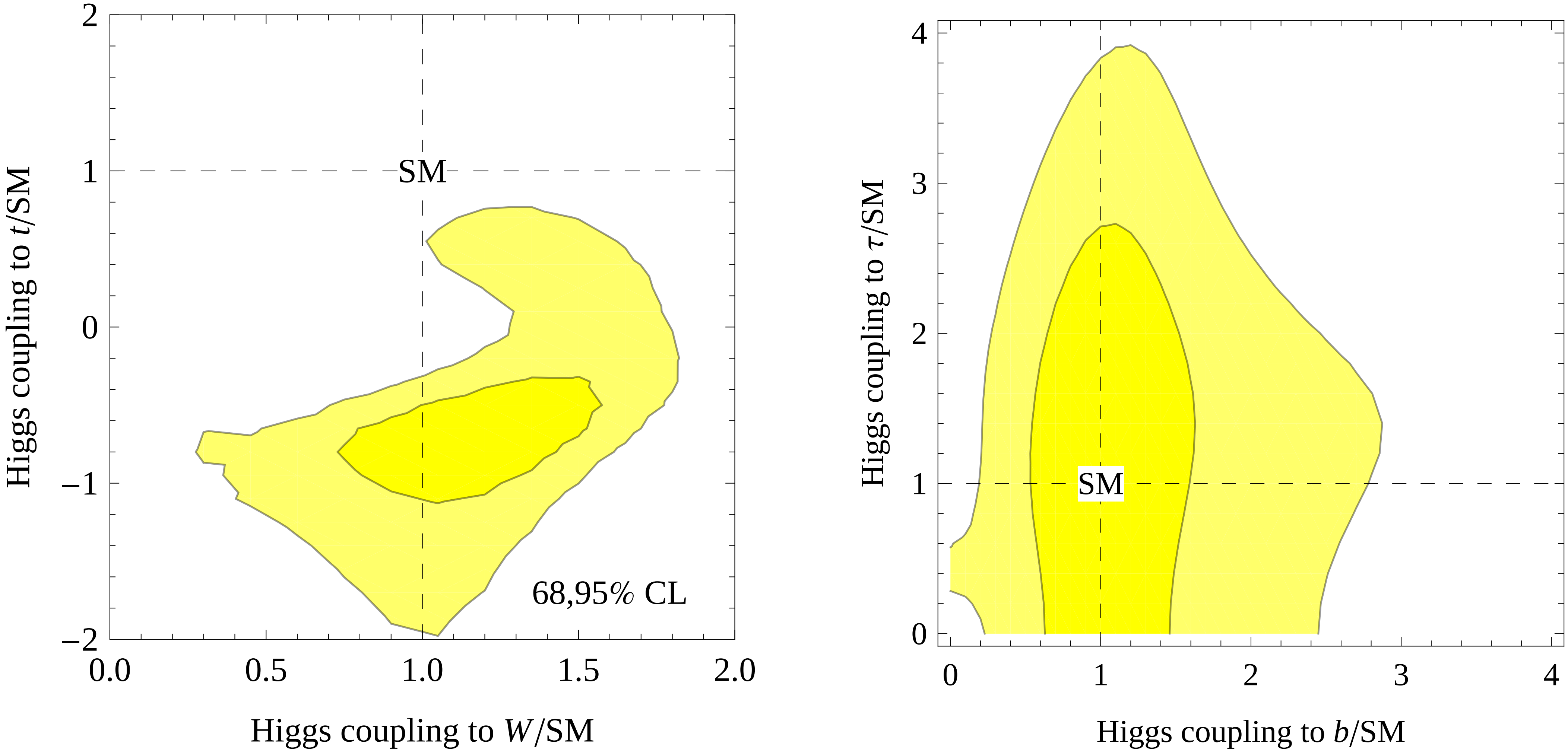
Fits to Higgs couplings: dysfermiophilia

Latest fermiophobic analyses prefer enhanced $h \to \gamma\gamma$ obtained for $y_t \approx -y_t^{\rm SM}$.





Global fit

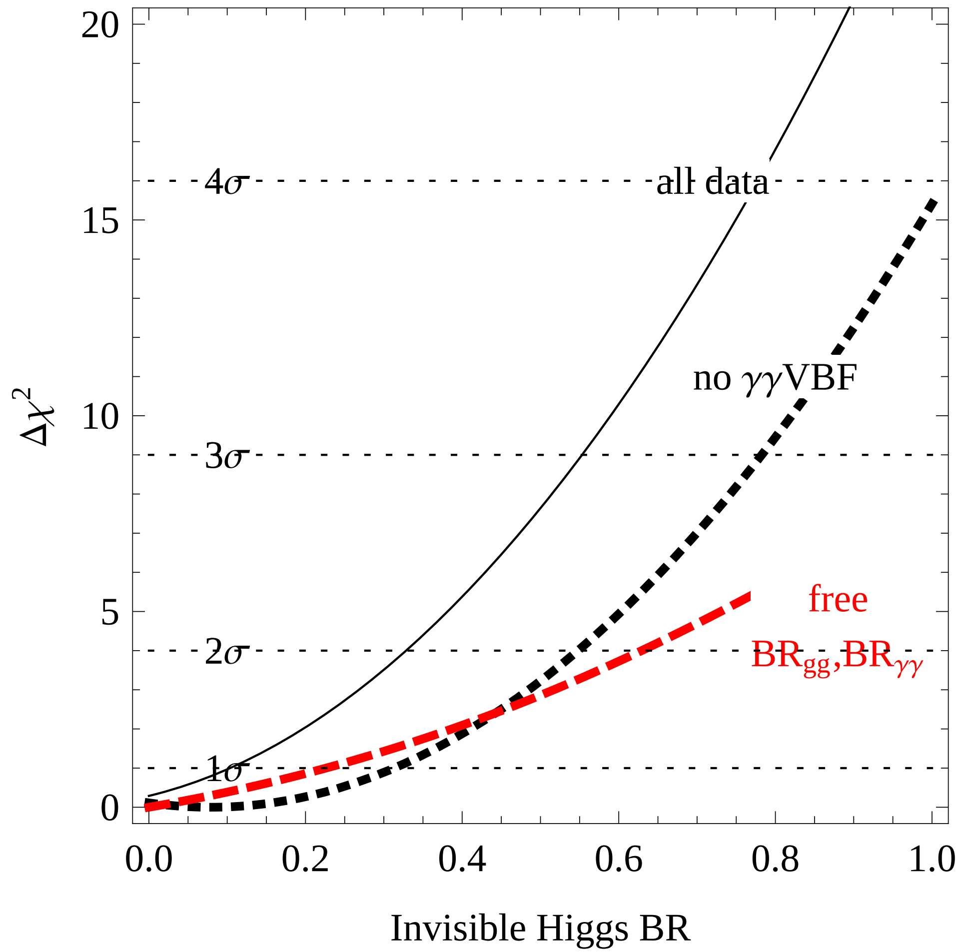


E.g. in the MSSM:

$$\frac{y_t}{\mathrm{SM}} = 1 + \frac{m_t^2}{4}\left[\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_1}^2} - \frac{(A_t - \mu/\tan\beta)^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_1}^2}\right] \qquad \frac{g_{hW}}{\mathrm{SM}} = \frac{g_{hZ}}{\mathrm{SM}} = \cos(\alpha - \beta)$$

Fit to the Higgs invisible width

$\mathrm{BR_{inv}} = 0 \pm 25\%$ depending on the fit



Data can test and disfavor an invisible width because $\Gamma(gg \to h) = \Gamma(h \to gg)$.

Higgs and SUSY

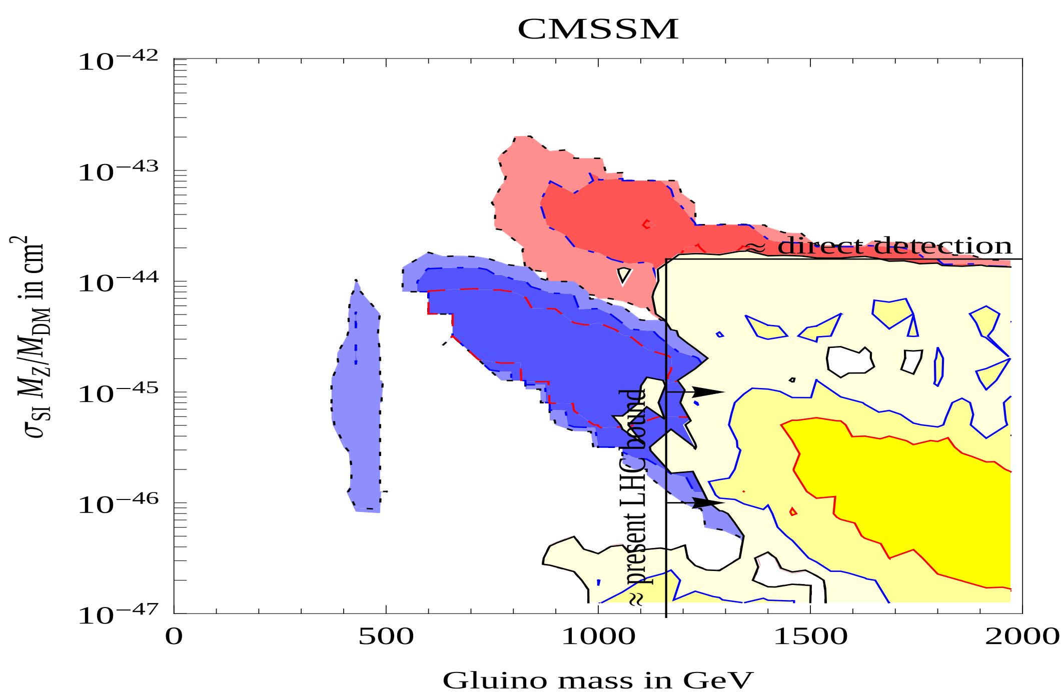
with G. Giudice

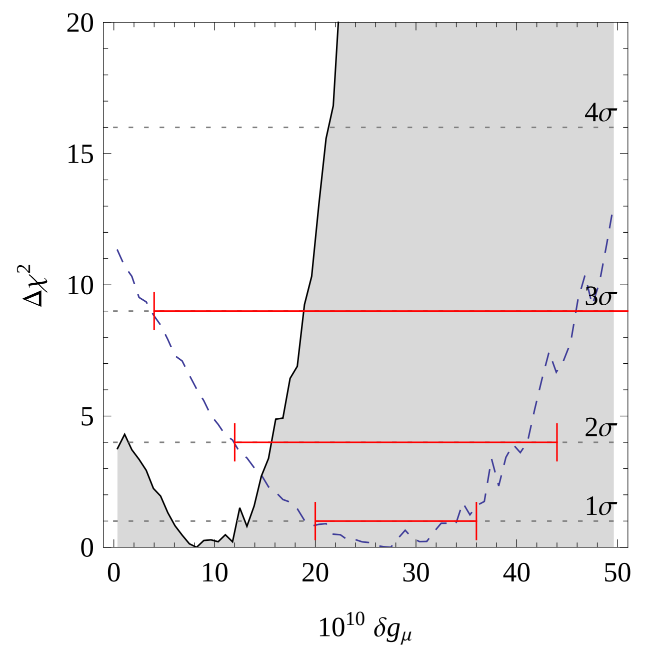
125 GeV is in no man's land

SM is stable up to the Planck scale for $m_h \gtrsim 130$ GeV but can go down to 115

MSSM with weak scale SUSY likes $m_h \lesssim 120$ GeV but can go up to 130

...but quasi-maximal stop mixing is needed (or NMSSM...)
...but best fit CMSSM regions are getting excluded (or LHC-phobic SUSY...)
...but the naturalness motivation for weak scale SUSY is mostly gone (light $\tilde{t}$?)





(global CMSSM fit of all latest data but m_h: we are no longer fitting anything)

Predicting $m_h(m_{\text{SUSY}}, \tan\beta)$

Time to consider $m_{\text{SUSY}} \gg M_Z$ (SUSY... GUT... string) and consider:

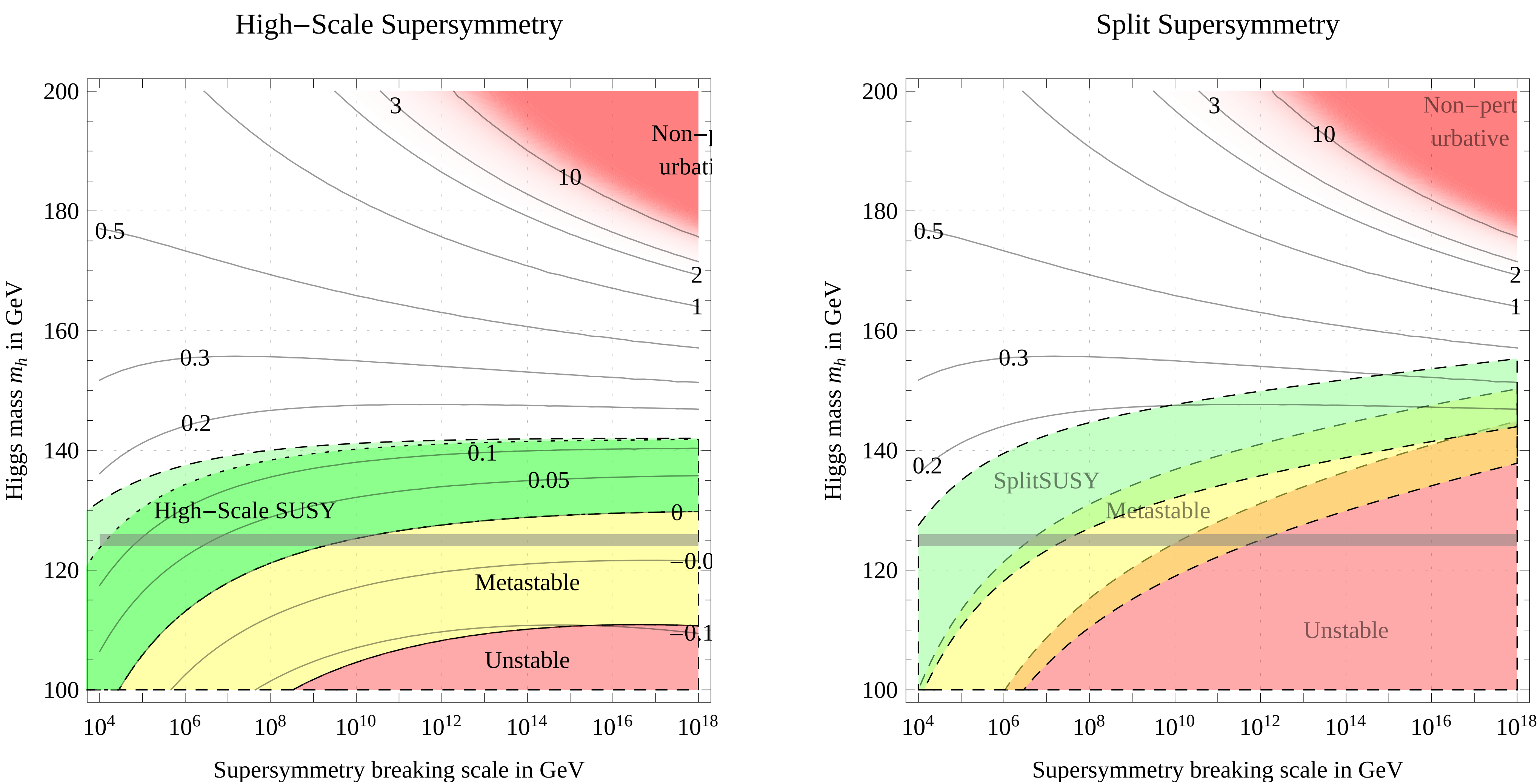
- **Split-SUSY** (SUSY scalars at m_{SUSY} and SUSY fermions around M_Z). Gives good unification and maybe makes theoretical sense.

- **High-Scale-SUSY** (all sparticles at m_{SUSY}) aka "Super-Split-SUSY".

Such a nice joke that its authors forgot to notice that there is one prediction

$$\lambda(m_{\text{SUSY}}) = \frac{1}{4}\left[g_2^2(m_{\text{SUSY}}) + \frac{3}{5}g_1^2(m_{\text{SUSY}})\right]\cos^2 2\beta + \text{loops}$$

$\lambda(m_h, m_{\mathsf{SUSY}})$



Light green: with maximal stop mixing, which is not possible in Split-SUSY.

Full NLO computation

The total result does not depend on the regularization scheme:

One loop thresholds at the weak scale

+

One loop thresholds at the SUSY scale

+

2 loop Split-SUSY RGE between M_Z and m_{SUSY}

$$\begin{aligned}\beta_2(g_t) \;=\;& -12g_t^5 + g_t\Big[g_b^2\Big(\frac{5\tilde g_{1\mathrm{d}}^2}{8} + \frac{5\tilde g_{1\mathrm{u}}^2}{8} + \frac{15\tilde g_{2\mathrm{d}}^2}{8} + \frac{15\tilde g_{2\mathrm{u}}^2}{8} + \frac{5g_\tau^2}{4} + \frac{7g_1^2}{80} + \frac{99g_2^2}{16} + 4g_3^2\Big) + \\ & + g_1^2\Big(\frac{3\tilde g_{1\mathrm{d}}^2}{16} + \frac{3\tilde g_{1\mathrm{u}}^2}{16} + \frac{9\tilde g_{2\mathrm{d}}^2}{16} + \frac{9\tilde g_{2\mathrm{u}}^2}{16} - \frac{9g_2^2}{20} + \frac{19g_3^2}{15}\Big) - 3\tilde g_{1\mathrm{d}}\tilde g_{1\mathrm{u}}\tilde g_{2\mathrm{d}}\tilde g_{2\mathrm{u}} + \\ & + g_2^2\Big(\frac{15\tilde g_{1\mathrm{d}}^2}{16} + \frac{15\tilde g_{1\mathrm{u}}^2}{16} + \frac{165\tilde g_{2\mathrm{d}}^2}{16} + \frac{165\tilde g_{2\mathrm{u}}^2}{16} + 9g_3^2\Big) - \frac{5}{4}\tilde g_{1\mathrm{d}}^2\tilde g_{1\mathrm{u}}^2 - \frac{9}{8}\tilde g_{1\mathrm{d}}^2\tilde g_{2\mathrm{d}}^2 - \frac{9\tilde g_{1\mathrm{d}}^4}{16} + \\ & - \frac{9}{8}\tilde g_{1\mathrm{u}}^2\tilde g_{2\mathrm{u}}^2 - \frac{9\tilde g_{1\mathrm{u}}^4}{16} - \frac{3}{4}\tilde g_{2\mathrm{d}}^2\tilde g_{2\mathrm{u}}^2 - \frac{45\tilde g_{2\mathrm{d}}^4}{16} - \frac{45\tilde g_{2\mathrm{u}}^4}{16} - \frac{g_b^4}{4} - \frac{9g_\tau^4}{4} + \\ & + \Big(\frac{15g_1^2}{8} + \frac{15g_2^2}{8}\Big)g_\tau^2 + \frac{1303g_1^4}{600} - \frac{15g_2^4}{4} - \frac{284g_3^4}{3} + \frac{3\lambda^2}{2}\Big] + \\ & + g_t^3\Big(-\frac{9\tilde g_{1\mathrm{d}}^2}{8} - \frac{9\tilde g_{1\mathrm{u}}^2}{8} - \frac{27\tilde g_{2\mathrm{d}}^2}{8} - \frac{27\tilde g_{2\mathrm{u}}^2}{8} - \frac{11g_b^2}{4} - \frac{9g_\tau^2}{4} + \frac{393g_1^2}{80} + \frac{225g_2^2}{16} + 36g_3^2 - 6\lambda\Big)\end{aligned}$$

pages and pages and pages of RGE in SplitSusy

Uncertain uncertainties at high energy

$m_{\text{SUSY}} \gg M_Z$ allows to get analytic expressions for everything, but one loop thresholds at the SUSY scale depend on unknown heavy sparticle masses:

$$(4\pi)^2 \delta\lambda(m_{\text{SUSY}}) = -\frac{9}{100} g_1^4 - \frac{3}{10} g_1^2 g_2^2 - \left(\frac{3}{4} - \frac{\cos^2 2\beta}{6}\right) g_2^4 + \\ +3 g_t^2 [g_t^2 + \frac{1}{10}(5 g_2^2 - g_1^2) \cos 2\beta] \ln \frac{m_Q^2}{m_{\text{SUSY}}^2} + \cdots + \cdots$$

In non-minimal SUSY models one can even have tree level corrections, positive or negative. E.g. in the NMSSM $\lambda_N N H_u H_d + M N^2/2$

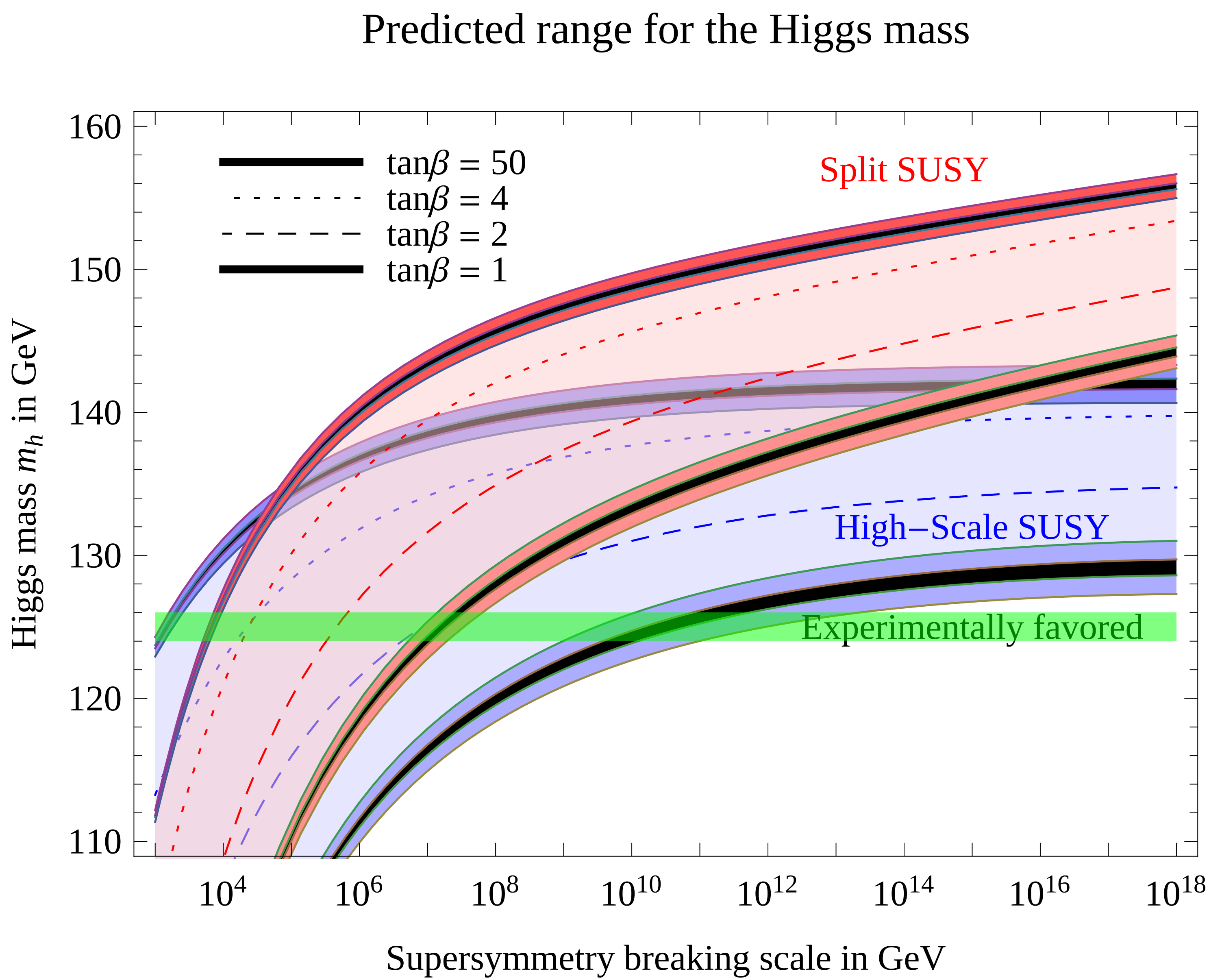
$$\delta\lambda = \lambda_N^2 \sin^2 2\beta \frac{(B-2A)M + m^2 - A^2}{2(M^2 + m^2 + BM)}$$

Or neutrino Yukawa couplings in see-saw models.

For example, the theory of everything could be $N=1$ SUSY with E_6 unification broken at the Planck scale by three fundamentals 27_i. The Higgs is one slepton that remains light due to anthropic selection. The Yukawa couplings come from:

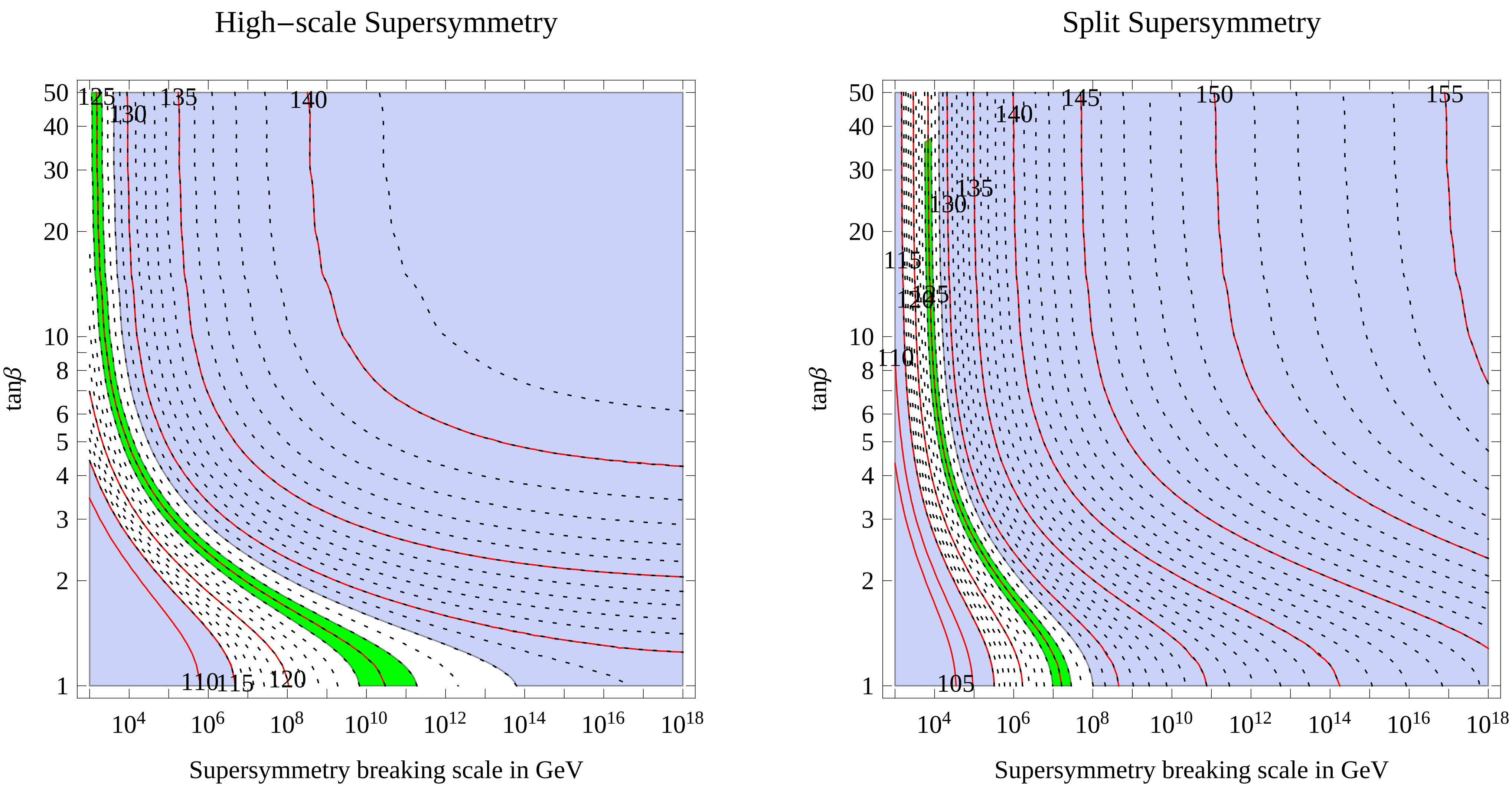
$$\mathscr{W} = \lambda_{ijk} 27_i 27_j 27_k$$

Effect of SM uncertainties



Thickness is $\pm 1\sigma$ on α_3 and on M_t. SUSY thresholds give more uncertainties.

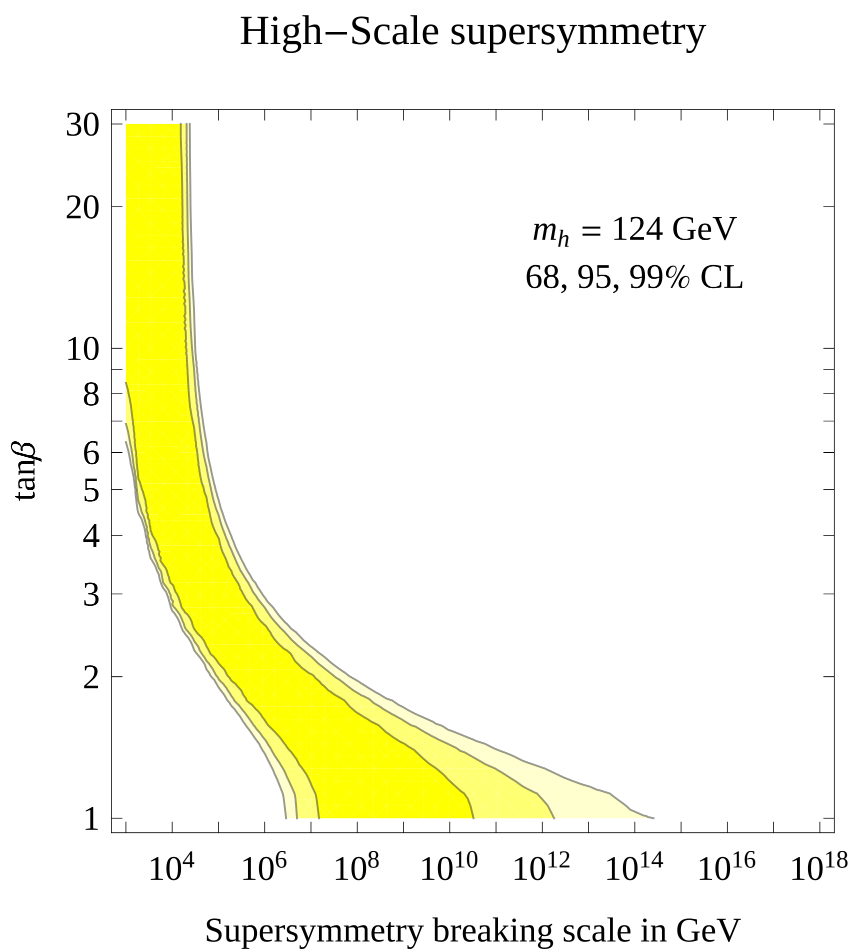
"Central values" for m_{SUSY} and $\tan\beta$

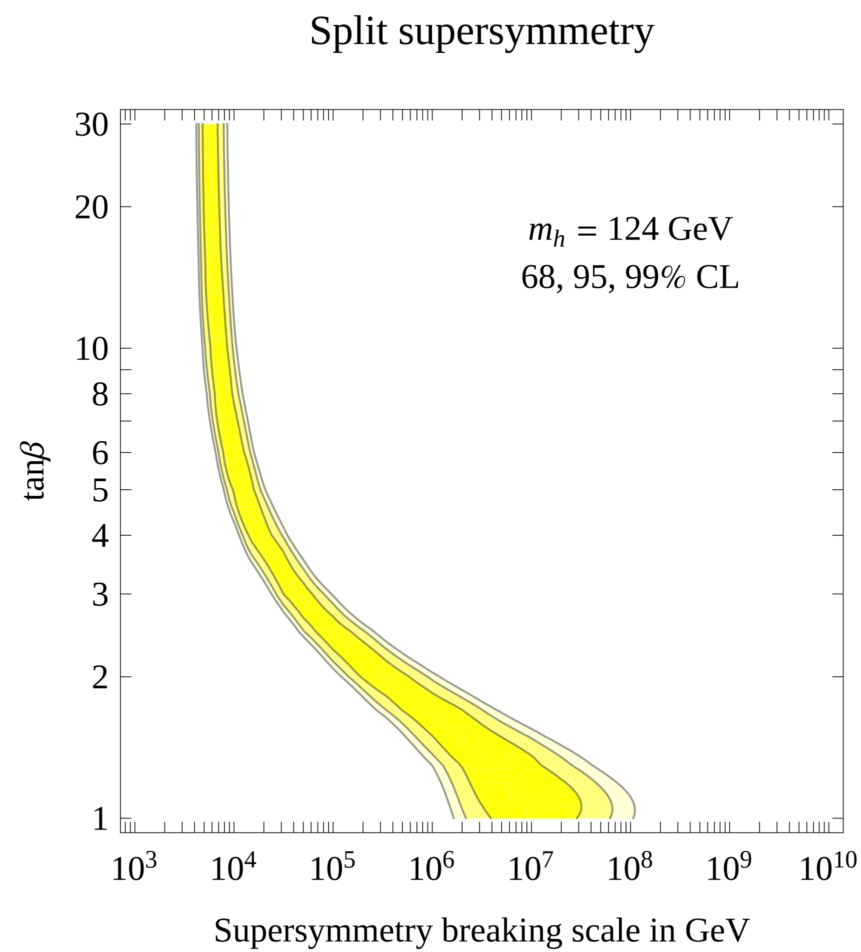


(Assuming degenerate heavy spectrum at m_{SUSY})

(Split-SUSY assumes $M_1 = m_t$, $M_2 = \mu$, unified gauginos)

Implications for m_{SUSY} and $\tan\beta$





$m_{\mathrm{SUSY}} \approx M_Z$ and maximal stop mixing and large $\tan\beta$?

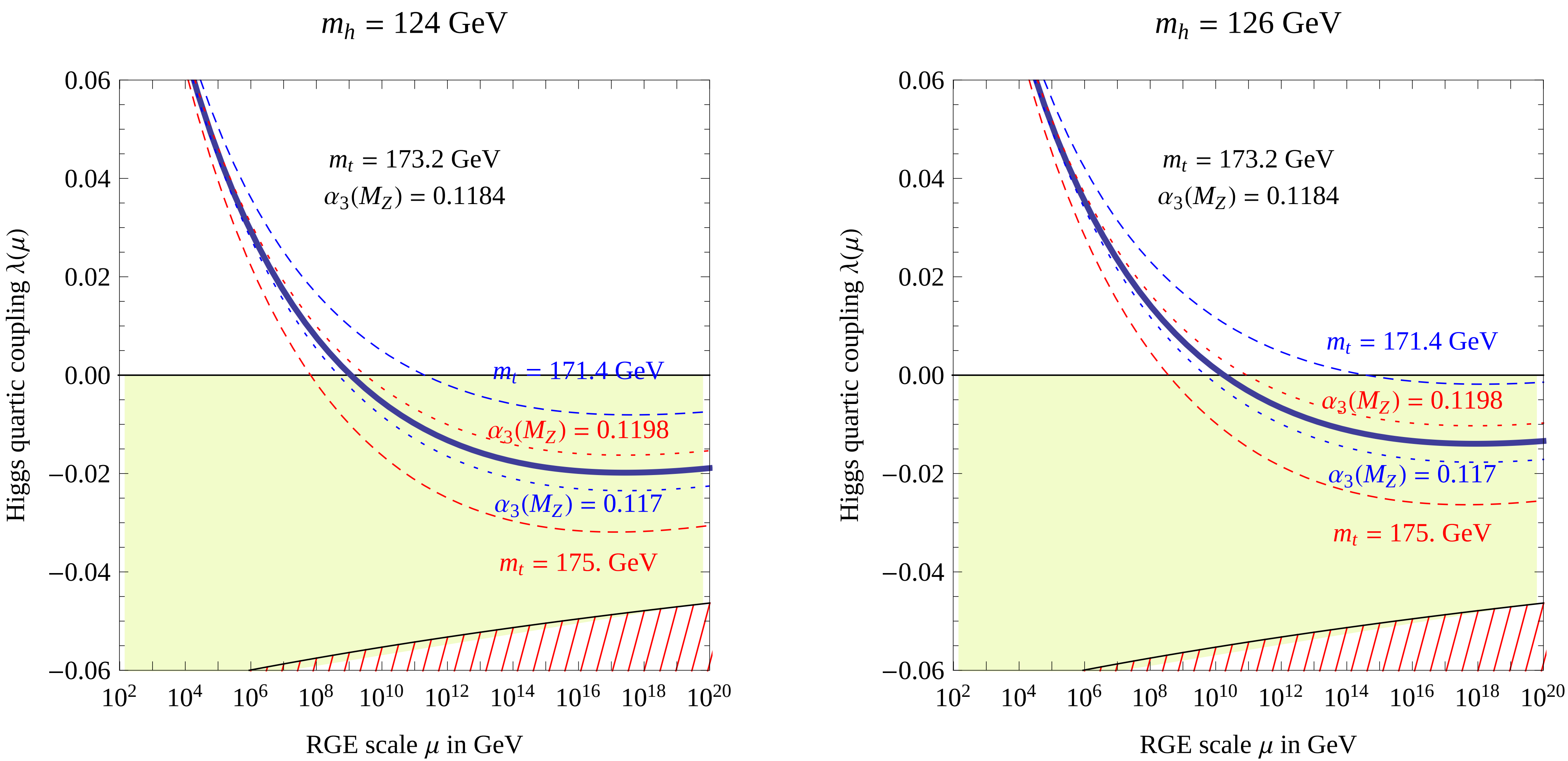
$m_{\mathrm{SUSY}} \approx (4\pi)^2 M_Z$ and moderate $\tan\beta$? Maybe $M_2 \approx 3\,\mathrm{TeV}$ and $M_3 =$?

$m_{\mathrm{SUSY}} \approx M_{\mathrm{Pl}}$ and $\tan\beta = 1$? Disfavored, unless extra couplings come in

Vacuum meta-stability

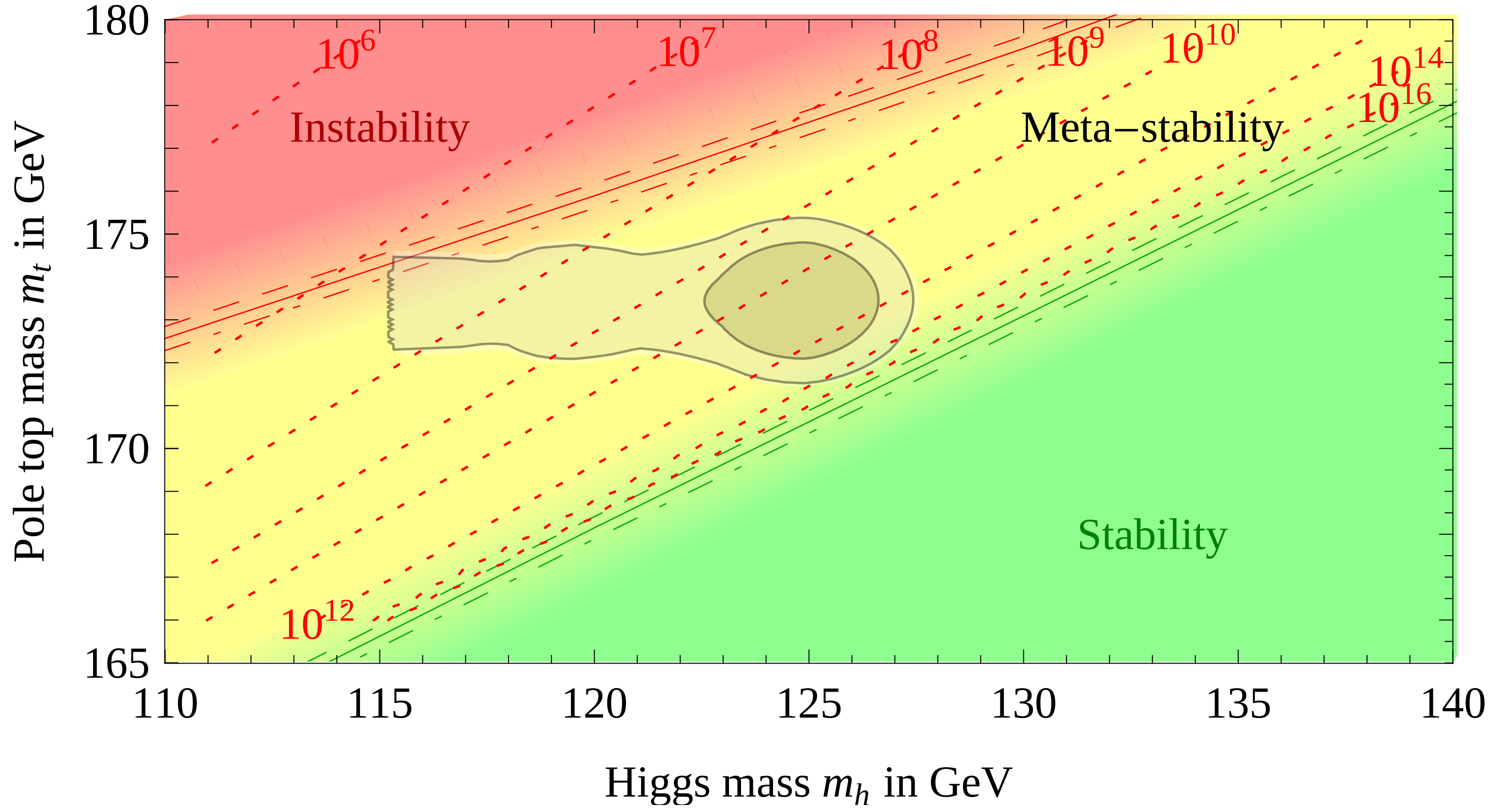
with J.E. Miró, J.R. Espinosa, G. Giudice, G. Isidori, A. Riotto

RGE running makes $\lambda < 0$



CAUTION: ± 3 GeV theory uncertainty .

Instability, meta-stability and stability



$$m_h > 130\,\text{GeV} + 1.8\,\text{GeV}\left(\frac{M_t - 173.2\,\text{GeV}}{0.9\,\text{GeV}}\right) - 0.5\,\text{GeV}\left(\frac{\alpha_3(M_Z) - 0.1184}{0.0007}\right) \pm 3\ \text{GeV}$$

$$\tau \sim 10^{100}\,\text{yr}$$

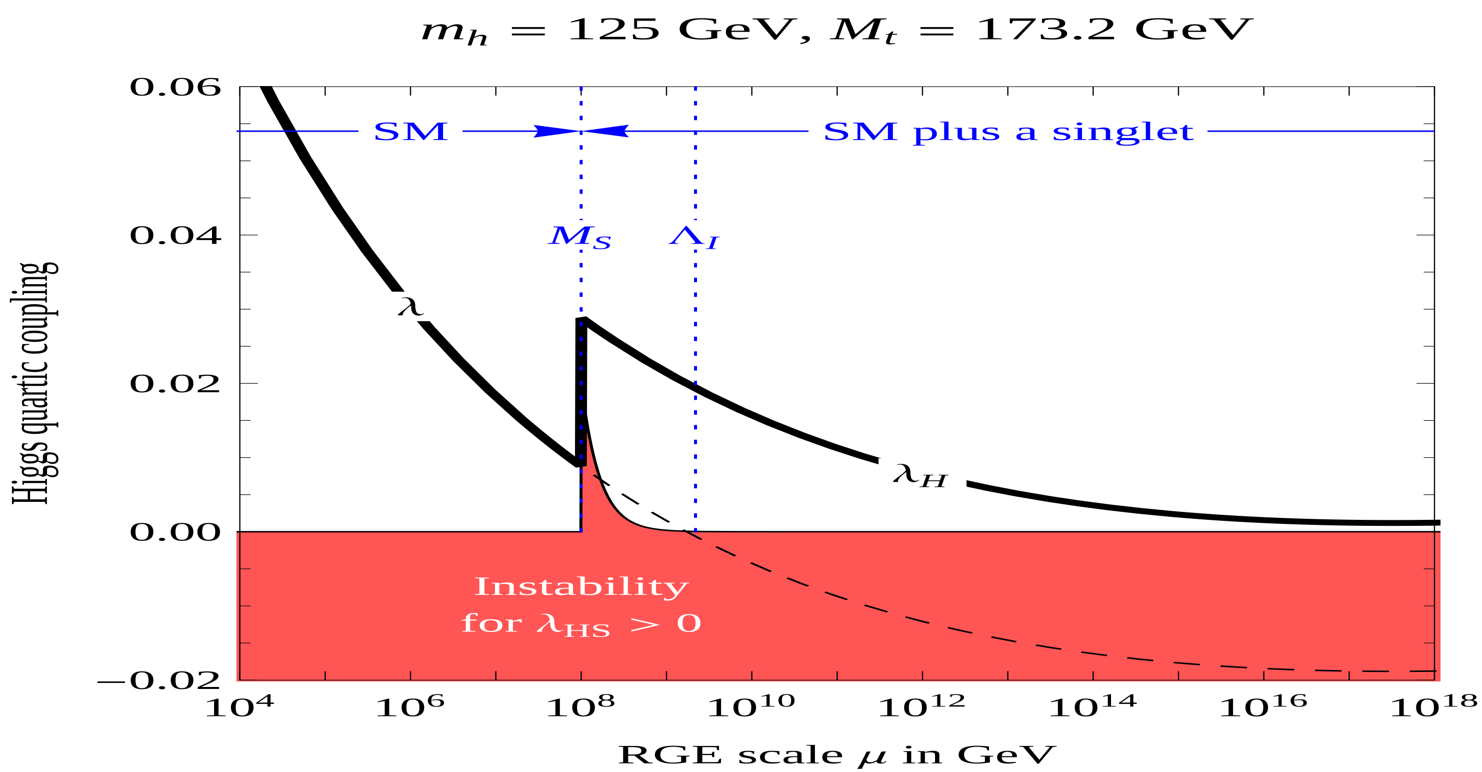
Tree level stabilization

Add a singlet S with a vev (possibly the axion):

$$V = \lambda_H \left(H^\dagger H - v^2\right)^2 + \lambda_S \left(S^\dagger S - w^2\right)^2 + 2\lambda_{HS} \left(H^\dagger H - v^2\right)\left(S^\dagger S - w^2\right)$$

Integrating out S at tree level gives a threshold correction that stabilizes V:

$$\lambda_{\text{low energy}} = \lambda_H - \frac{\lambda_{HS}^2}{\lambda_S}$$



(with J. Elias-Miro, J.R. Espinosa, G. Giudice, H.M. Lee)

The fate of the Universe

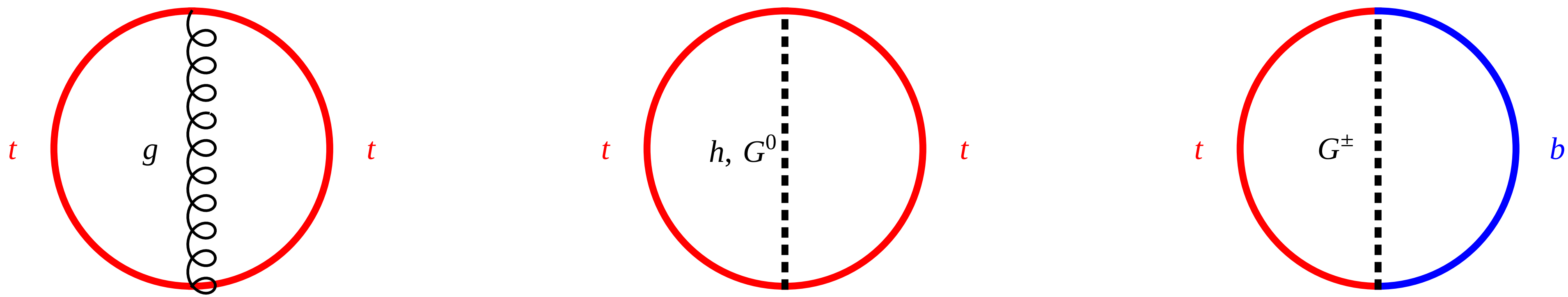
Does $m_h \approx 126\,\mathrm{GeV}$ correspond to $\lambda(M_{\rm Pl}) = 0$ within the SM?

(This would be the main message bla bla quantum gravity bla bla)

It is so close that so far the answer is

BOH

NNLO computation needed to reduce the theory uncertainty. The answer is...



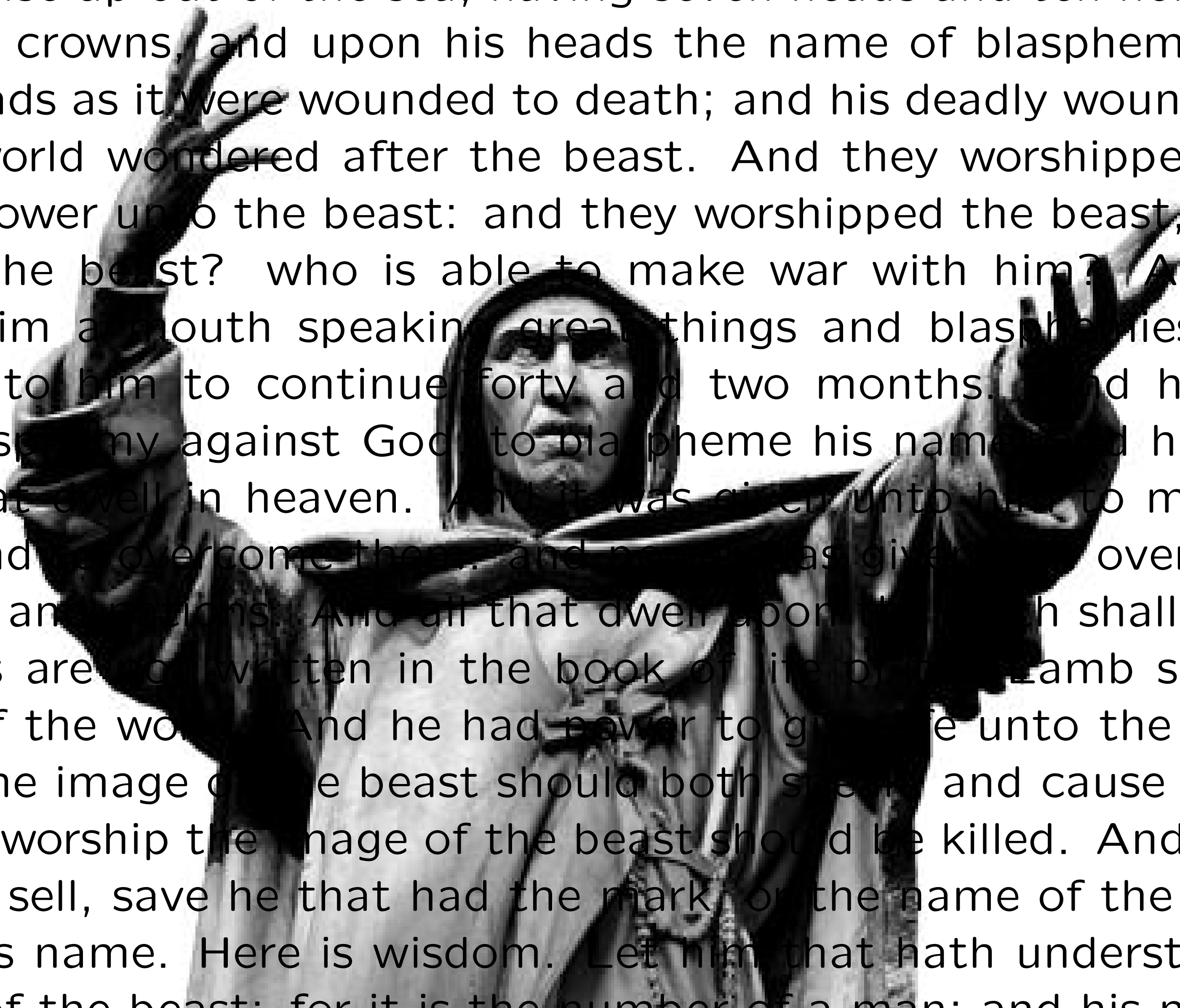
$$\delta m_h^2(\bar\mu = m_t)|_{\rm NNLO} = 0\frac{y_t^4 g_3^2 v^2}{(4\pi)^4} - 2(6+\pi^2)\frac{y_t^6 v^2}{(4\pi)^4} + \mathcal{O}(\lambda, g_1, g_2)$$

which means...

NO

[with Degrassi, Espinoza, Isidori, Giudice, Miró, to appear. Please don't scoop us]

Monuments in Ferrara



And a beast rise up out of the sea, having seven heads and ten horns, and upon his horns ten crowns, and upon his heads the name of blasphemy. And I saw one of his heads as it were wounded to death; and his deadly wound was healed: and all the world wondered after the beast. And they worshipped the dragon which gave power unto the beast: and they worshipped the beast, saying, Who is like unto the beast? who is able to make war with him? And there was given unto him a mouth speaking great things and blasphemies; and power was given unto him to continue forty and two months. And he opened his mouth in blasphemy against God, to blaspheme his name, and his tabernacle, and them that dwell in heaven. And it was given unto him to make war with the saints, and to overcome them: and power was given him over all kindreds, and tongues, and nations. And all that dwell upon the earth shall worship him, whose names are not written in the book of life of the Lamb slain from the foundation of the world. And he had power to give life unto the image of the beast, that the image of the beast should both speak, and cause that as many as would not worship the image of the beast should be killed. And that no man might buy or sell, save he that had the mark, or the name of the beast, or the number of his name. Here is wisdom. Let him that hath understanding count the number of the beast: for it is the number of a man; and his number is 126

Conclusions

- SM Higgs gives a good fit to data.
  Reduced $gg \to h$ and enhanced $h \to \gamma\gamma$ improves the fit.
  Too good: is this just over-fitting fluctuations?

- SUSY: at the weak scale, or one loop above, or much above.

- $m_h \approx 125\,\mathrm{GeV}$ corresponds to $\lambda = 0$ at the Planck scale? Almost, but NO.
  λ gets slightly negative and the SM vacuum is meta-stable.

Implications for European Strategy for Particle Physics:

The Higgs could be the last particle. Carpe diem.