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, updated to March 28, 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

While this is believed to be a correct information, nobody makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of the information. Reference herein to any specific experiment does not necessarily constitute or imply its endorsement, recommendation, or favoring.

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

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

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

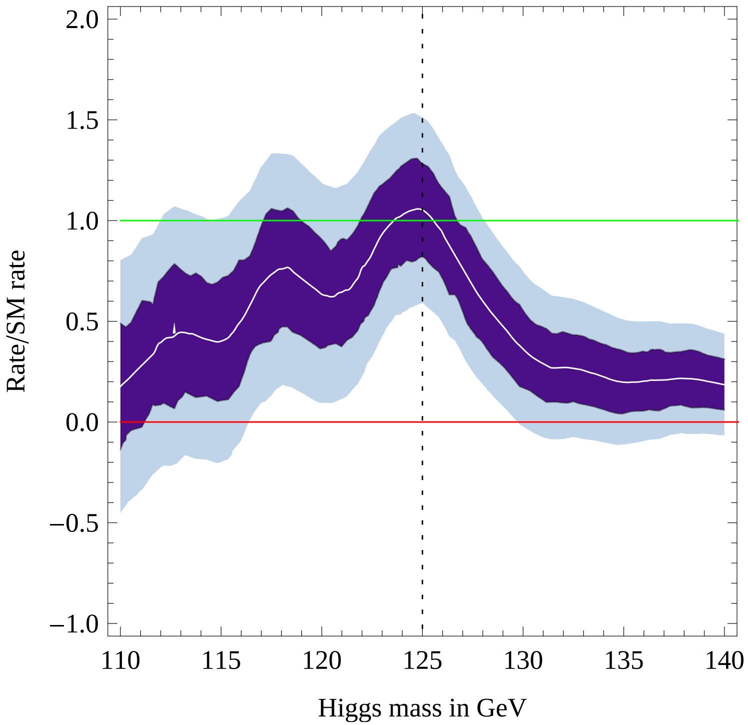
and production mechanisms

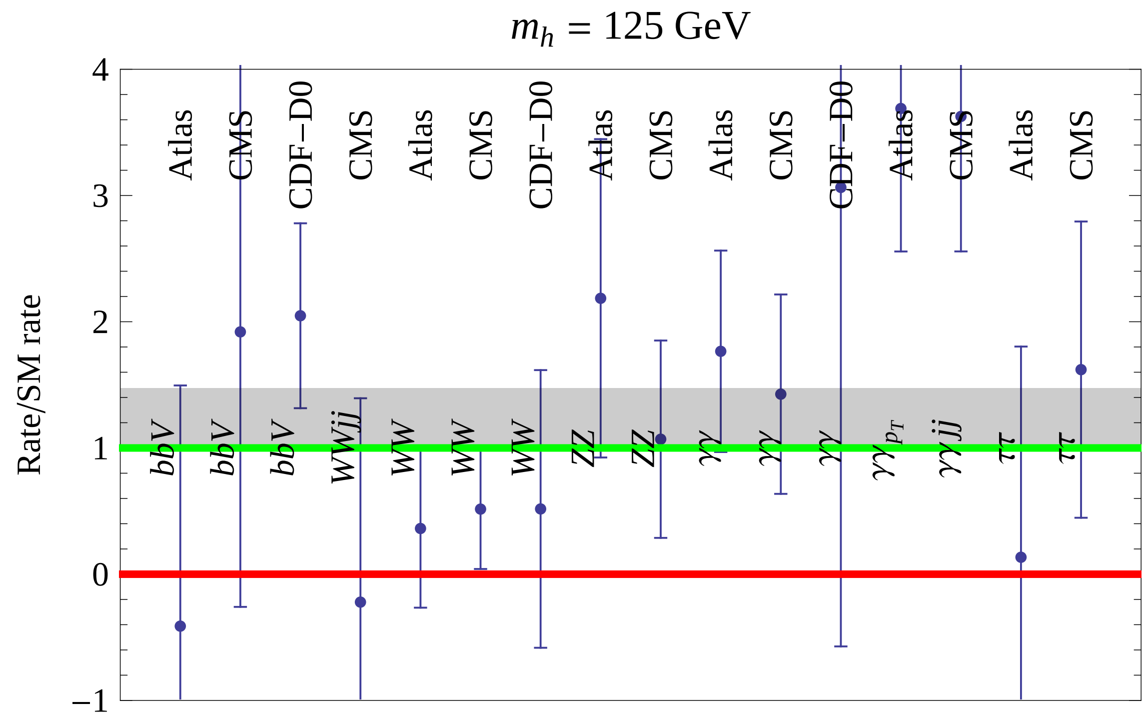
$$\begin{array}{ll} \sigma(pp \to h) = (15.3 \pm 2.6)\,\text{pb}, & \sigma(pp \to jjh) = 1.2\,\text{pb}, \\ \sigma(pp \to Wh) = 0.57\,\text{pb}, & \sigma(pp \to Zh) = 0.32\,\text{pb}, \end{array}$$

allow to disentangle Higgs couplings and test Higgs properties.

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

Higgs data: CMS, ATLAS, CDF, D0





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

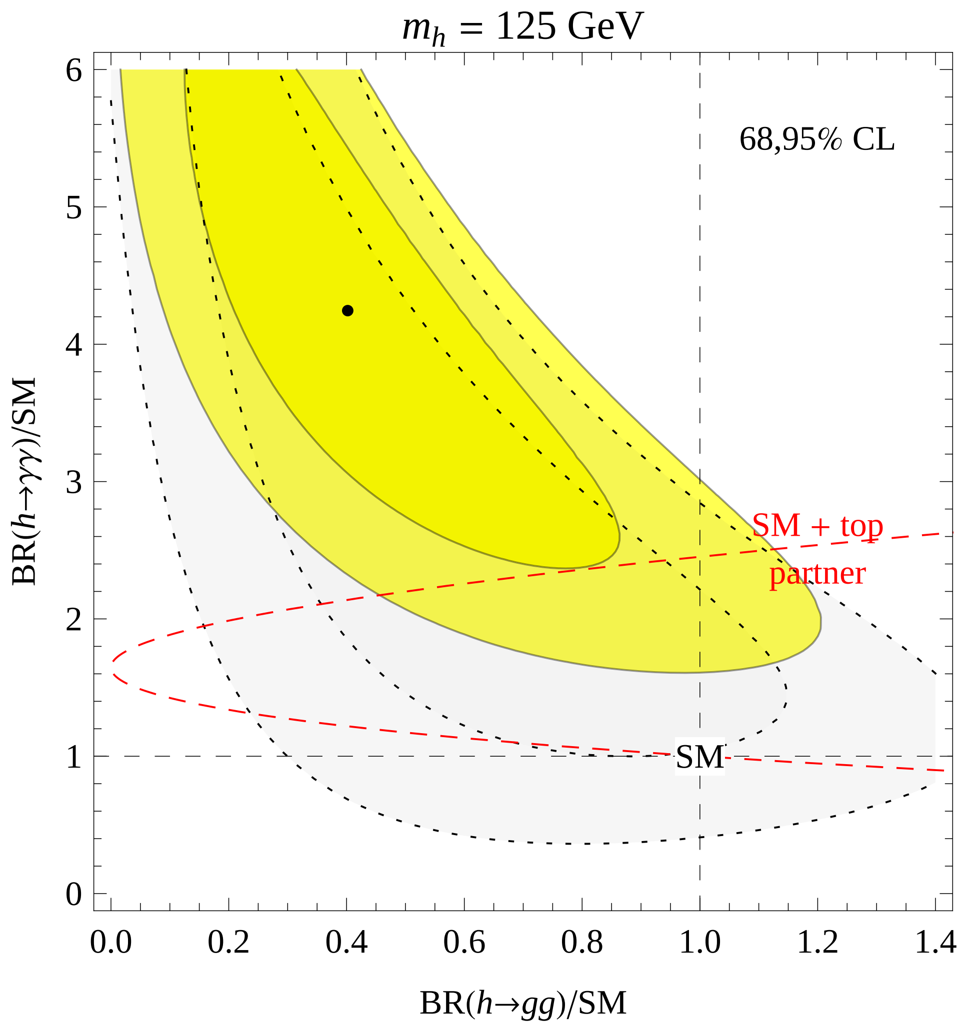
$$[0.3\sigma(pp \to h) + \sigma(pp \to Wh, Zh, jjh)] \times \text{BR}(h \to \gamma\gamma) = \text{SM} \times (3.3 \pm 1.1)$$

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.

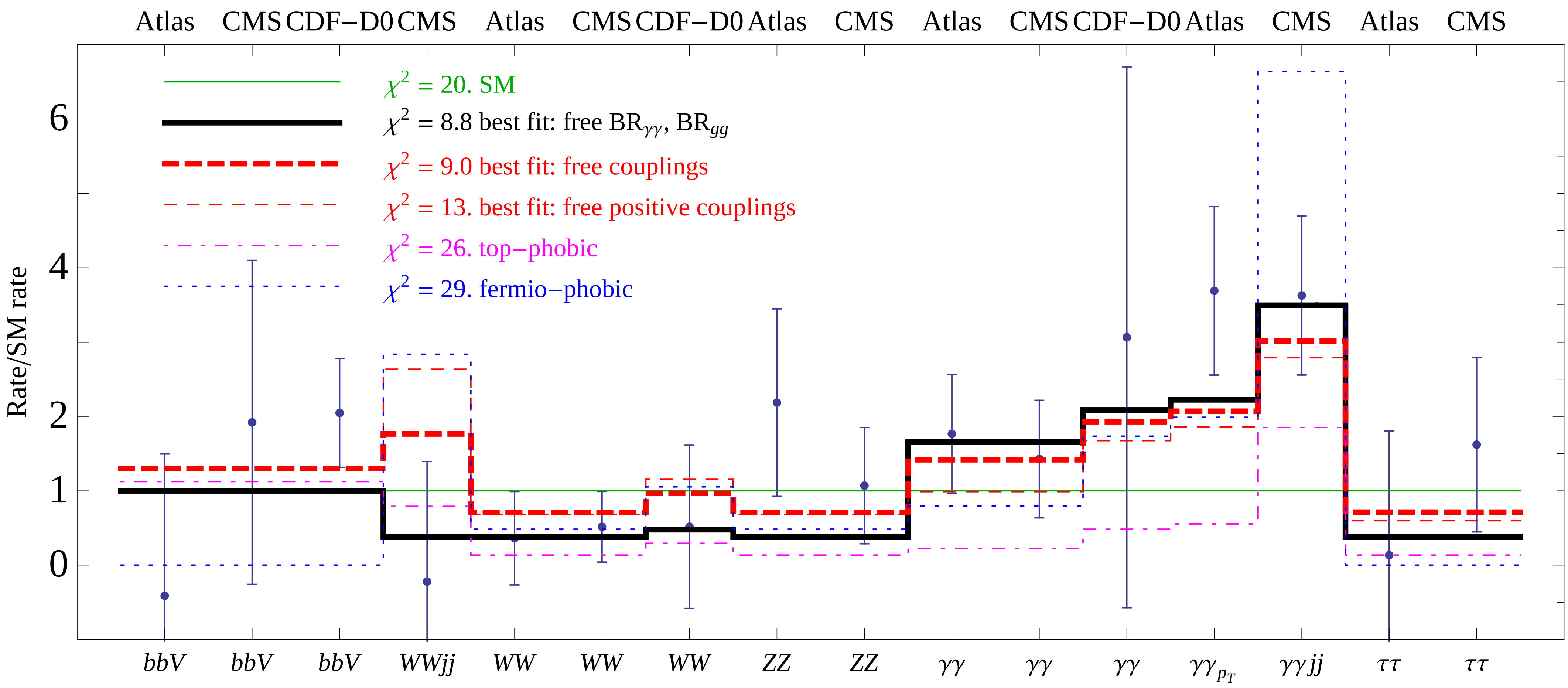
Non-standard BR for loop processes



Best fit $\chi^2 \approx 5.5$ (13 dof) away from SM and at

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

Non standard best fits

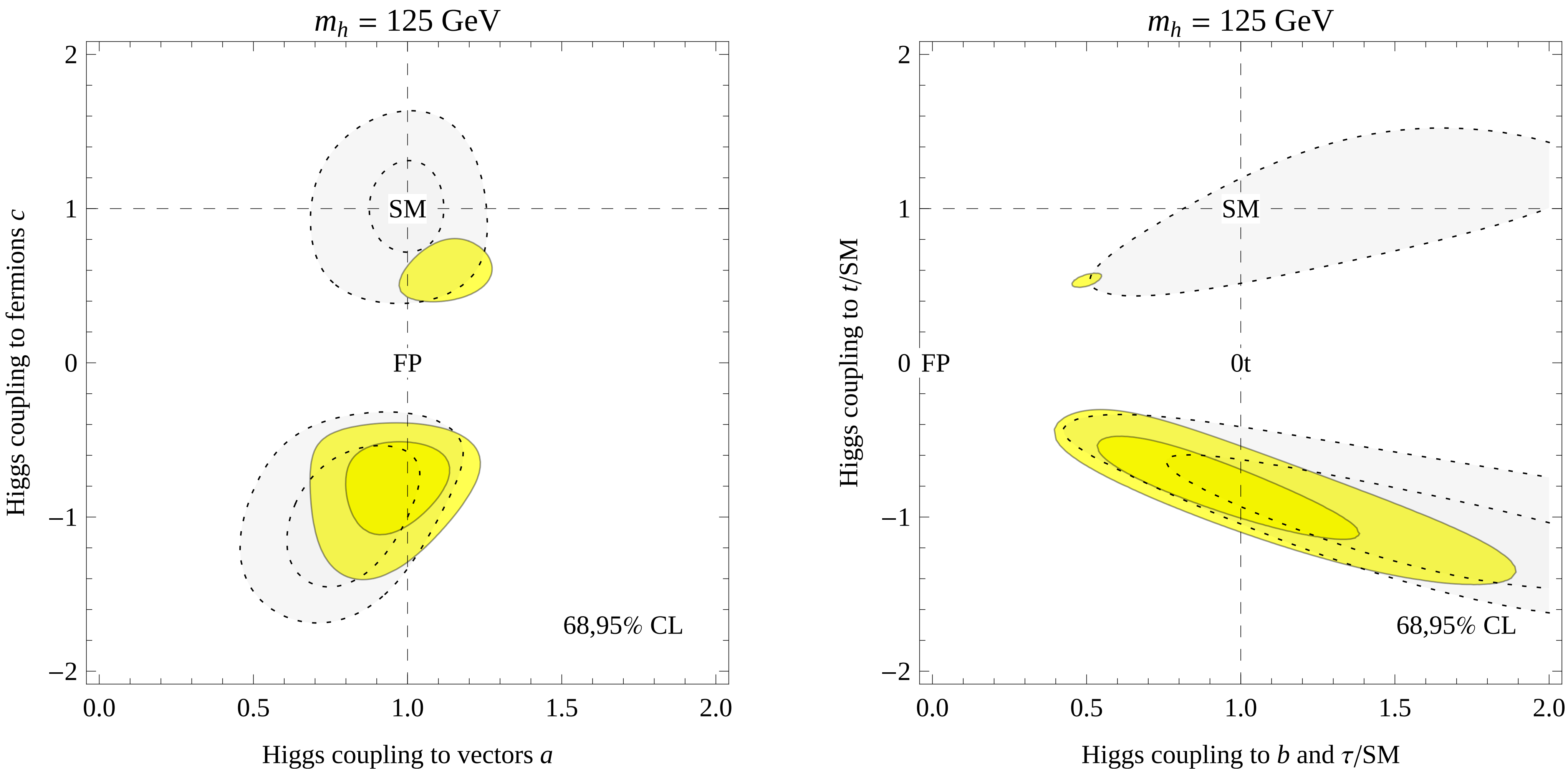


SM χ^2 is good. BSM fit is better. Maybe too good.

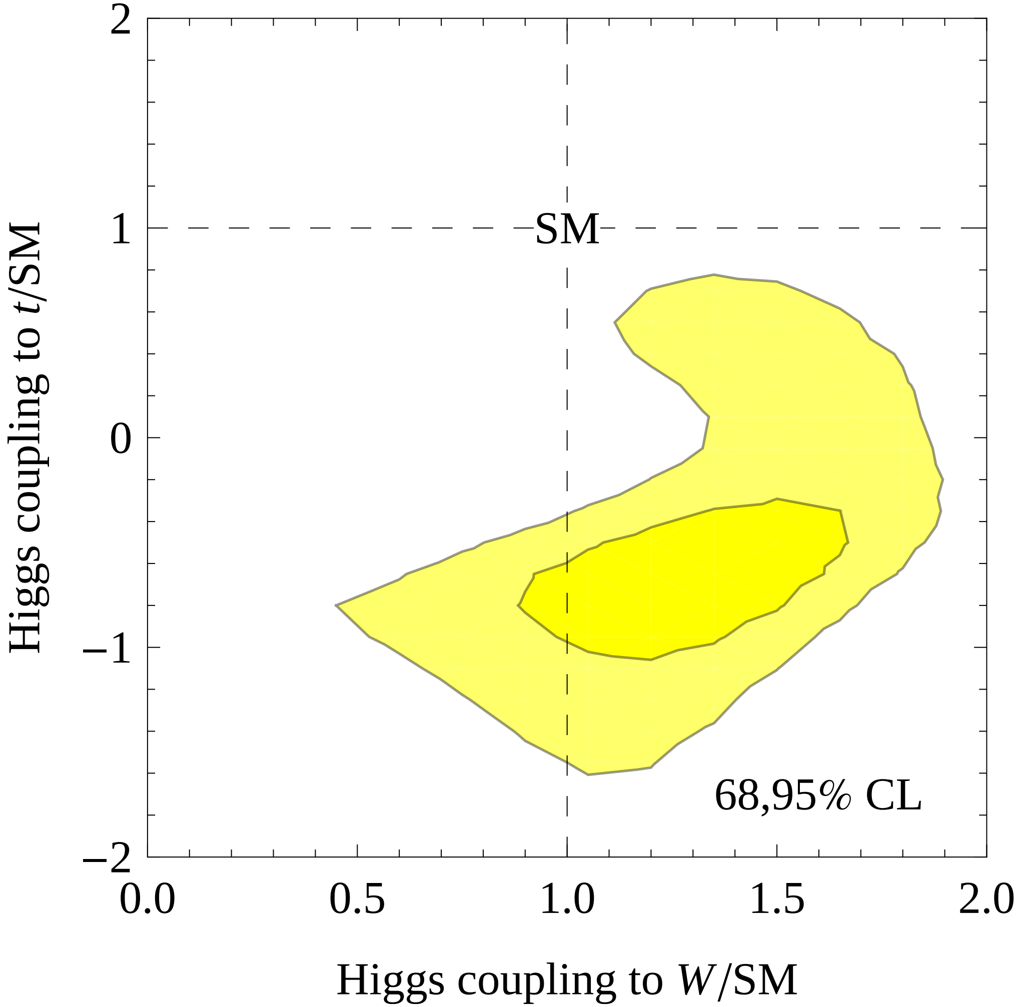
Fermiophobia not much worse than SM

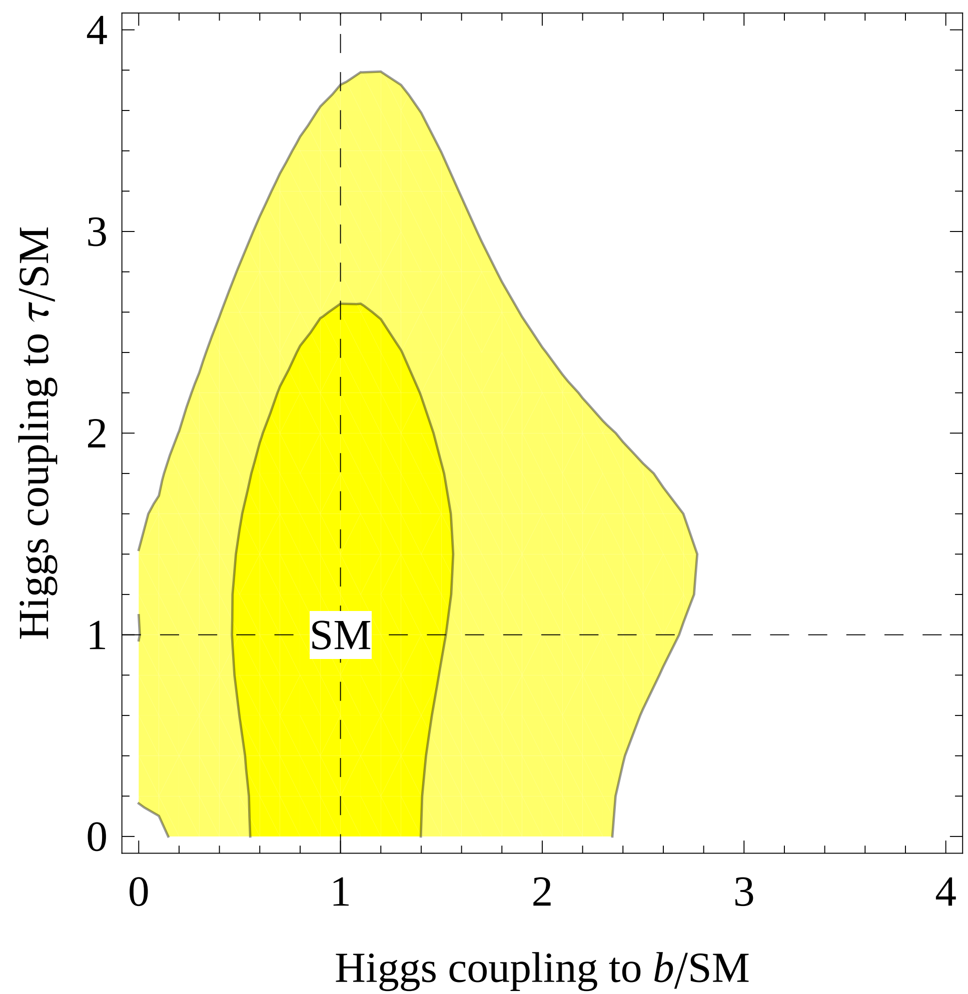
Fits to Higgs couplings: dysfermiophilia

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



Global fit



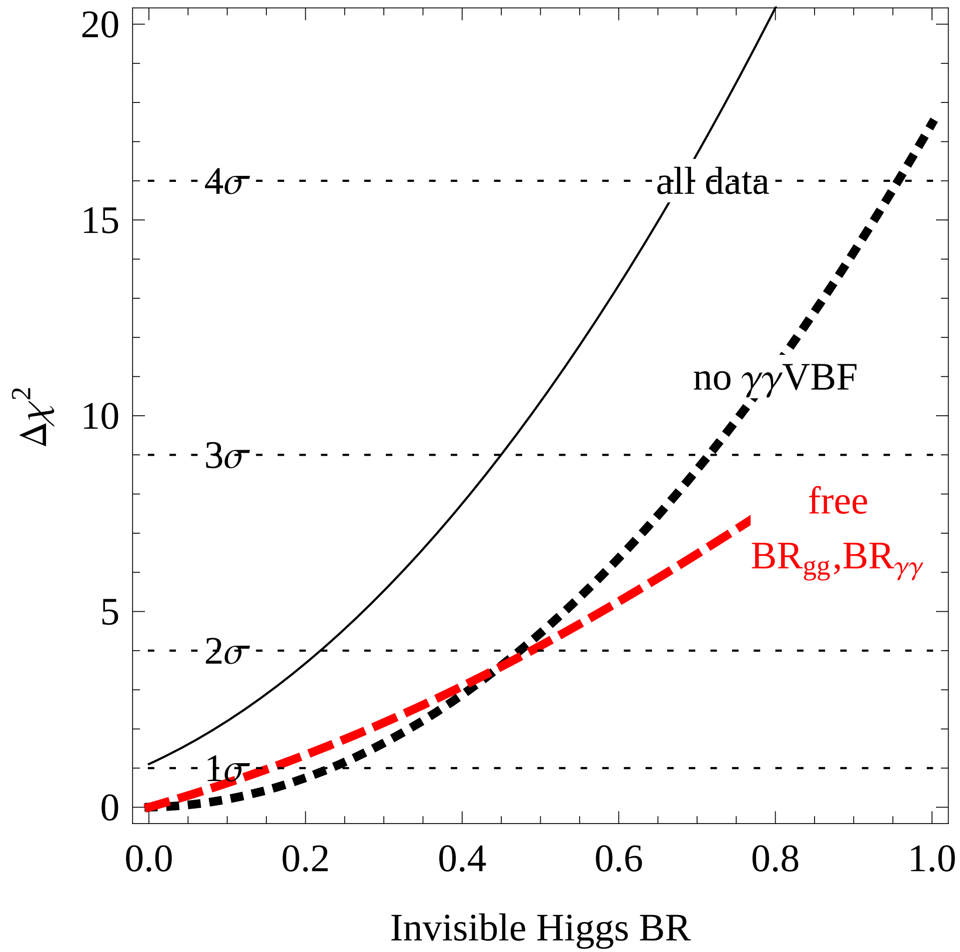


E.g. in the MSSM:

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

Fit to the Higgs invisible width

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



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

Higgs and SUSY

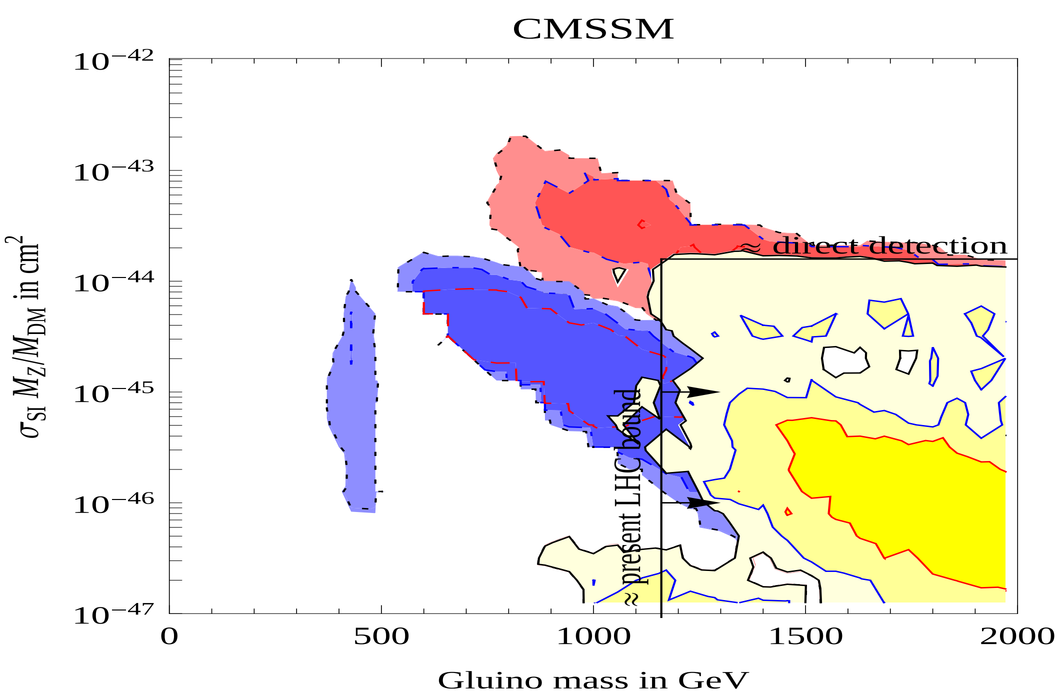
with G. Giudice

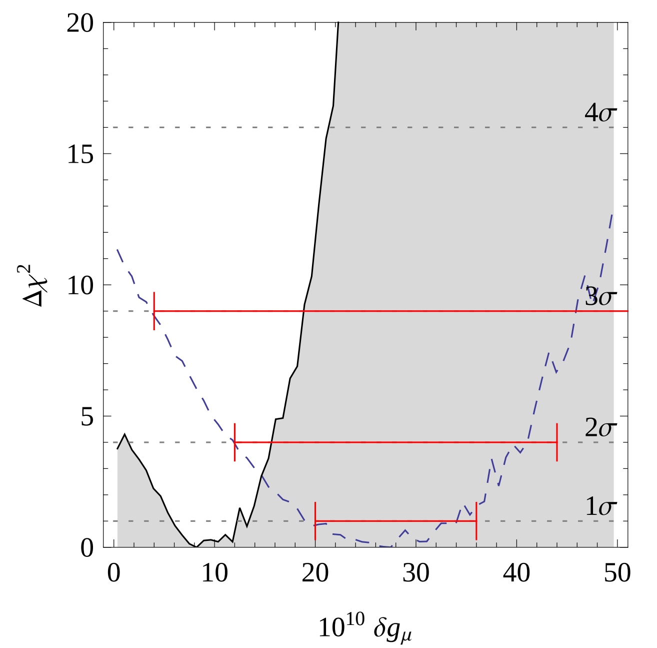
125 GeV is in no man's land

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:

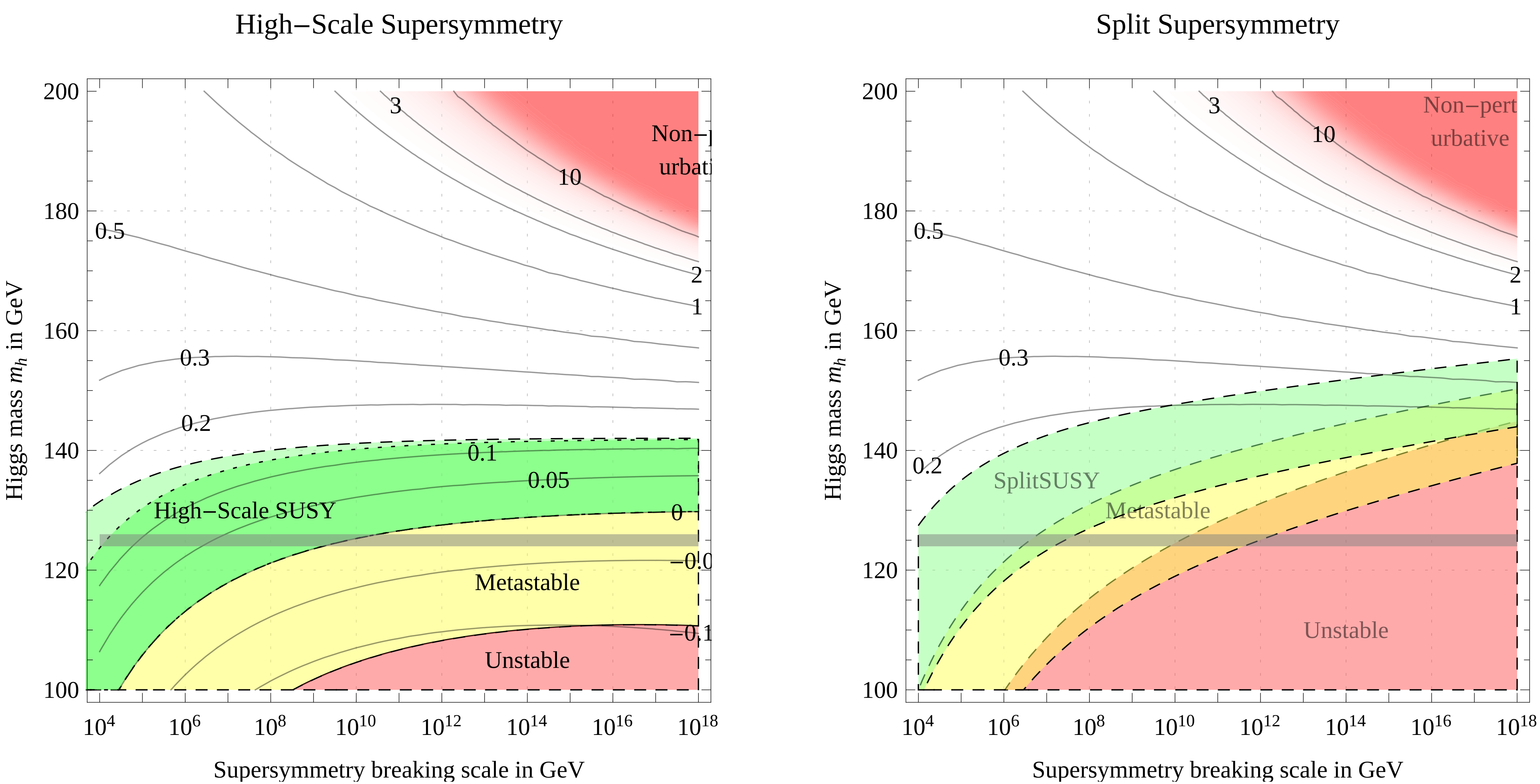
- **Split-SUSY** (SUSY scalars at m_{SUSY} and SUSY fermions around M_Z). Gives good unification and maybe makes theoretical sense.

- **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 $m_{\rm SUSY}$

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

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:

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

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

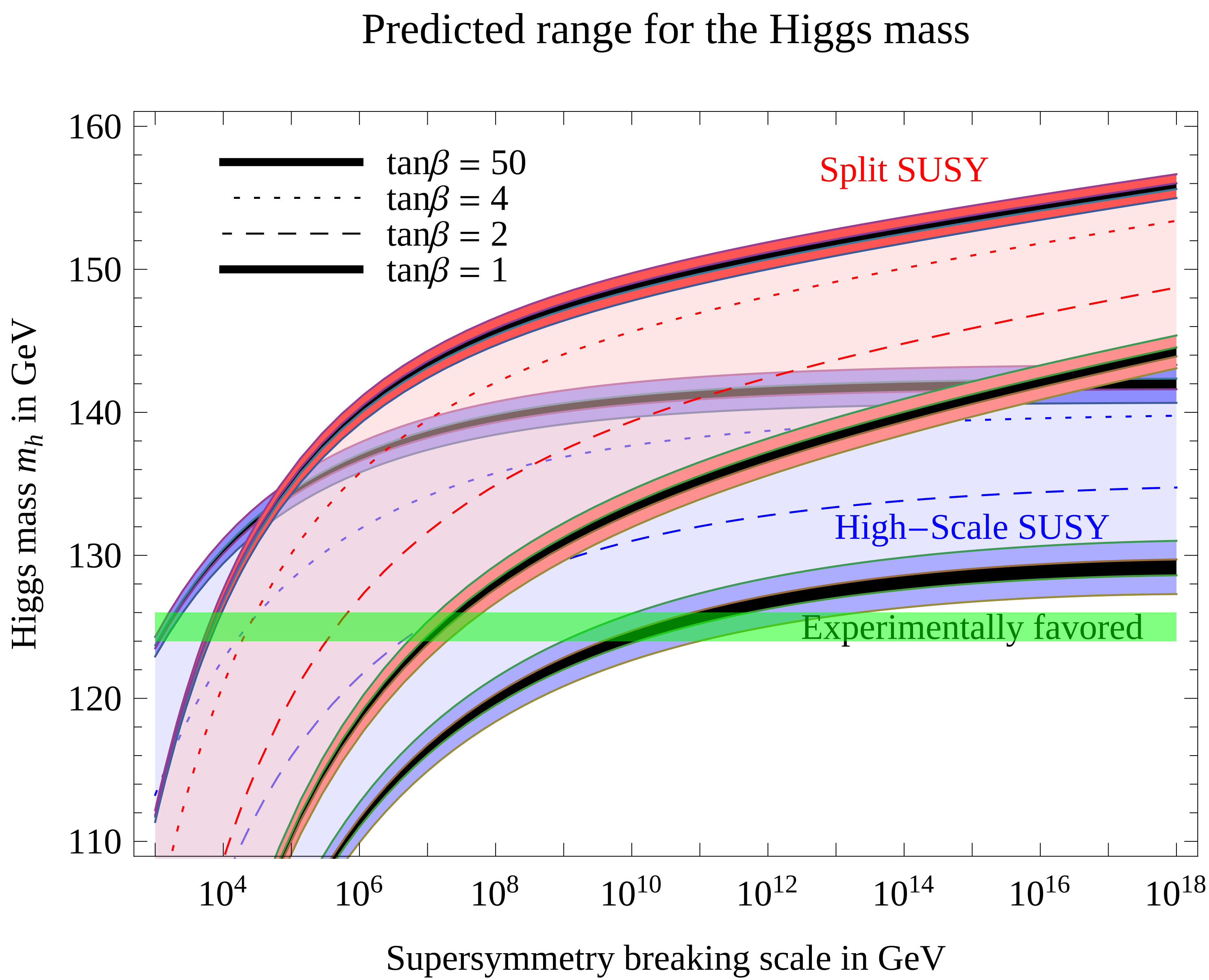
$$\delta\lambda = \lambda_N^2 \sin^2 2\beta \frac{(B-2A)M + m^2 - A^2}{2(M^2 + m^2 + BM)}$$

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:

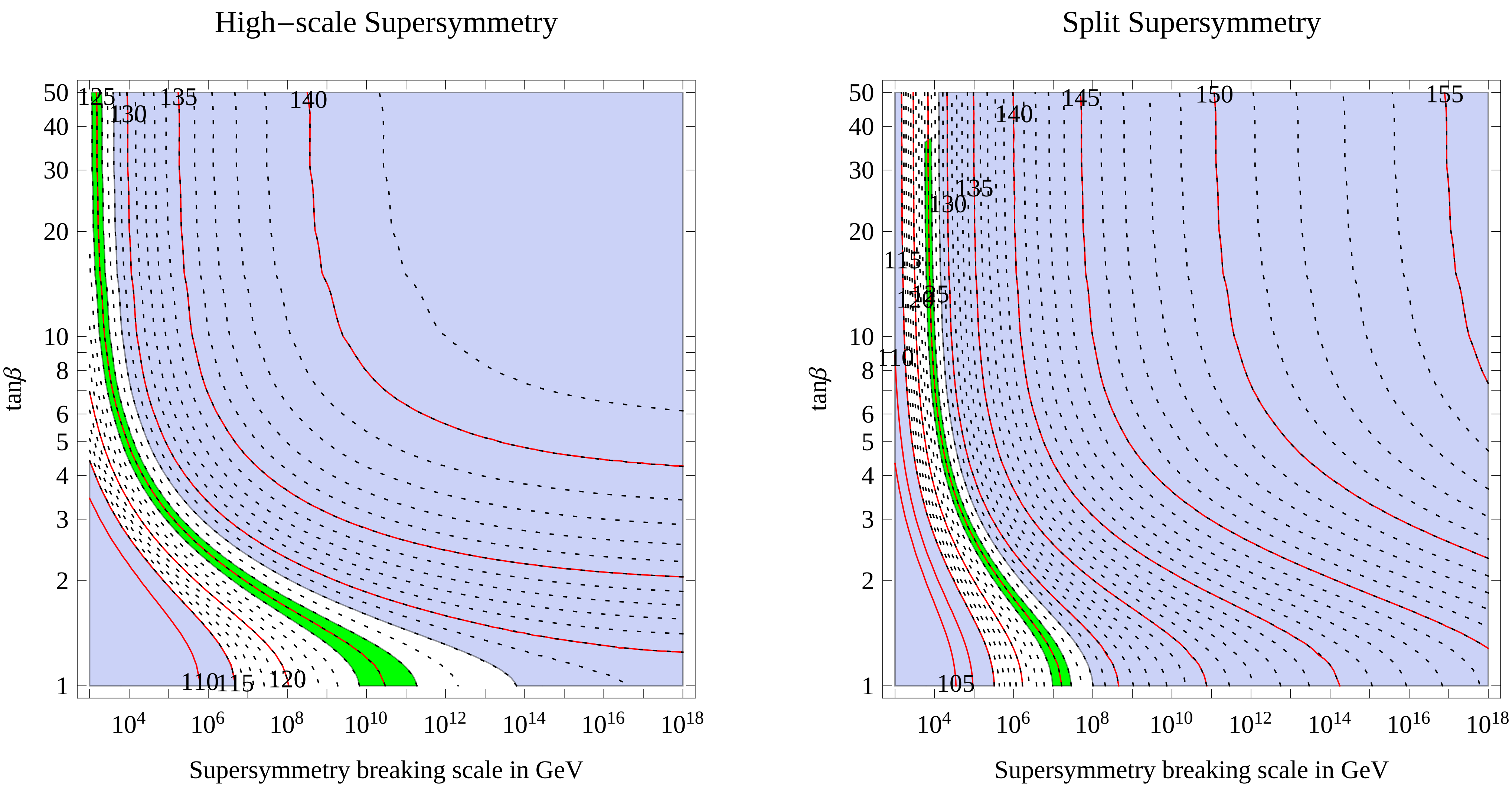
$$\mathscr{W} = \lambda_{ijk} 27_i 27_j 27_k$$

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 $\tan\beta$

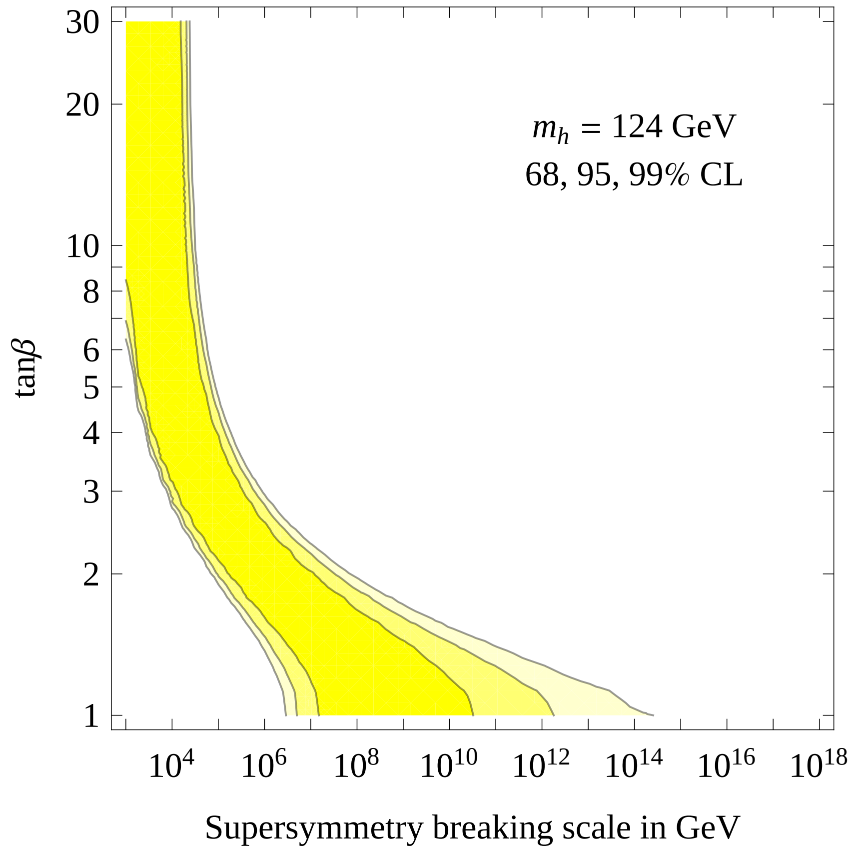


(Assuming degenerate heavy spectrum at m_{SUSY})

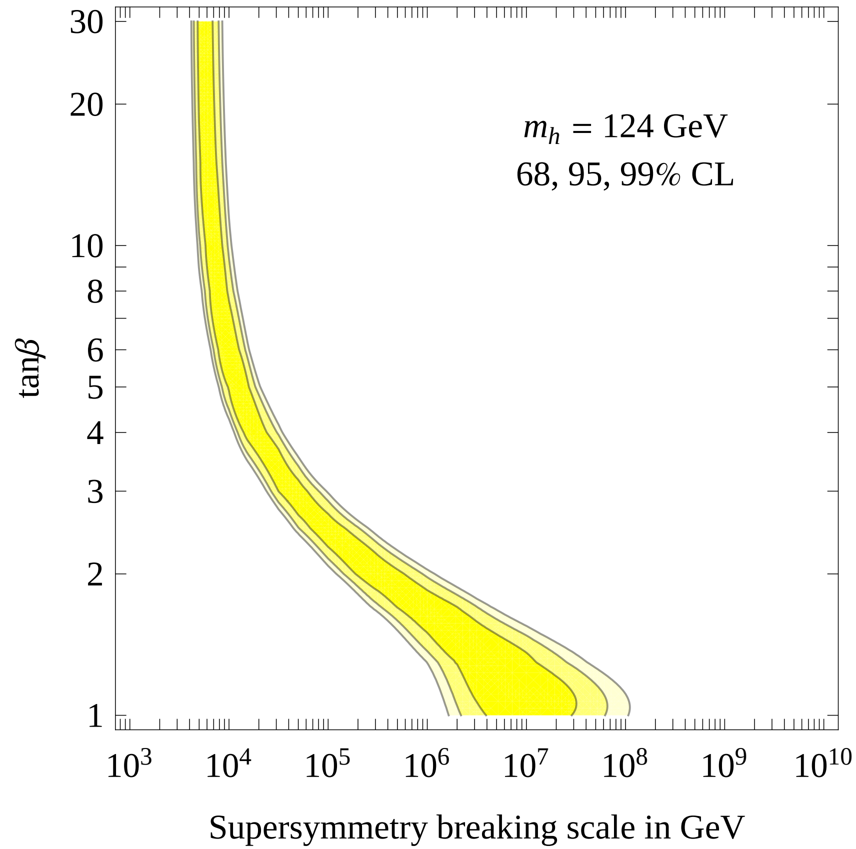
(Split-SUSY assumes $M_1 = m_t$, $M_2 = \mu$, unified gauginos)

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

High−Scale supersymmetry



Split supersymmetry



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

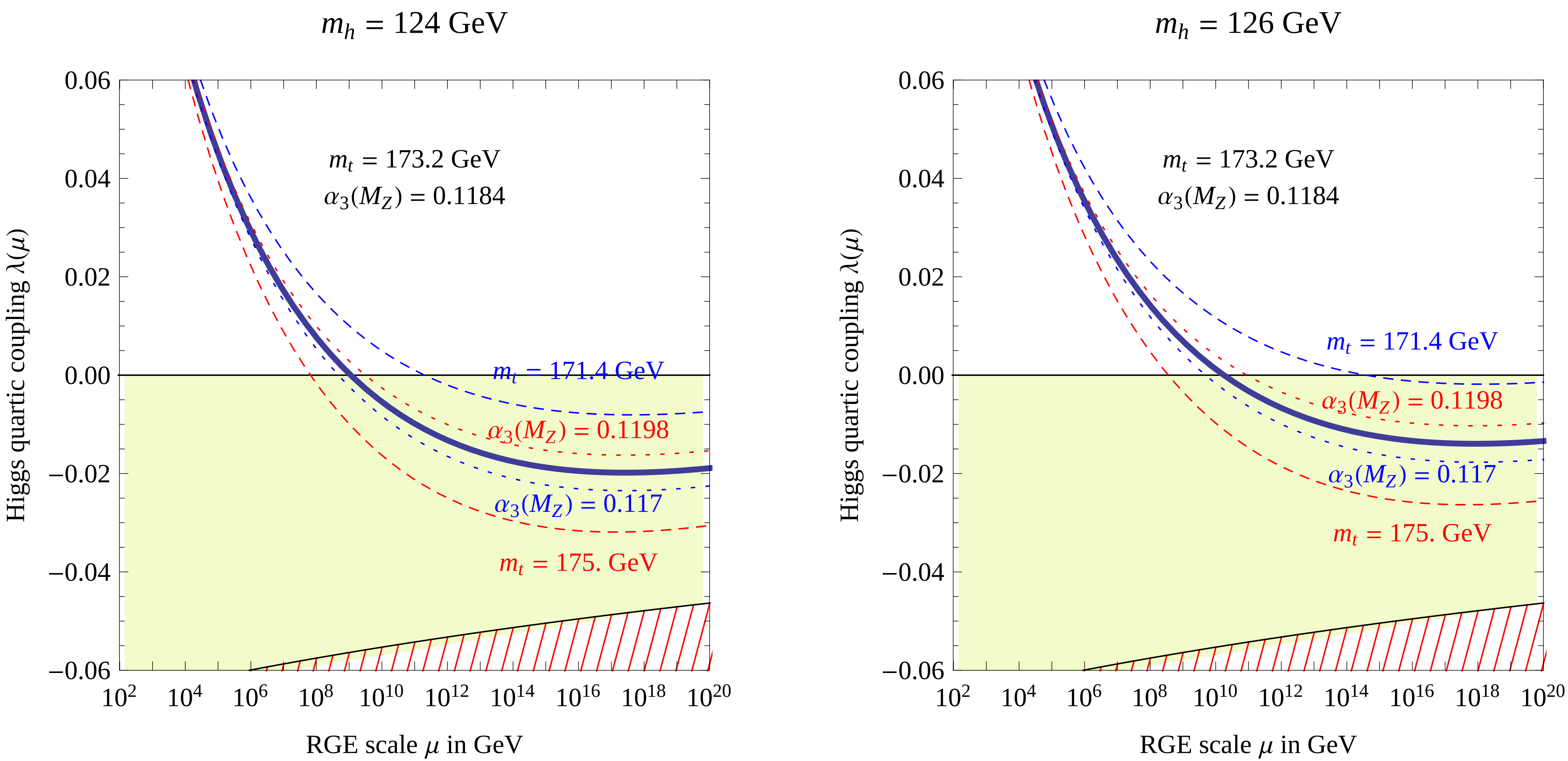
$m_{\mathsf{SUSY}} \approx (4\pi)^2 M_Z$ and moderate $\tan\beta$? Maybe $M_2 \approx 3\,\mathrm{TeV}$ and $M_3 = ?$

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

Vacuum meta-stability

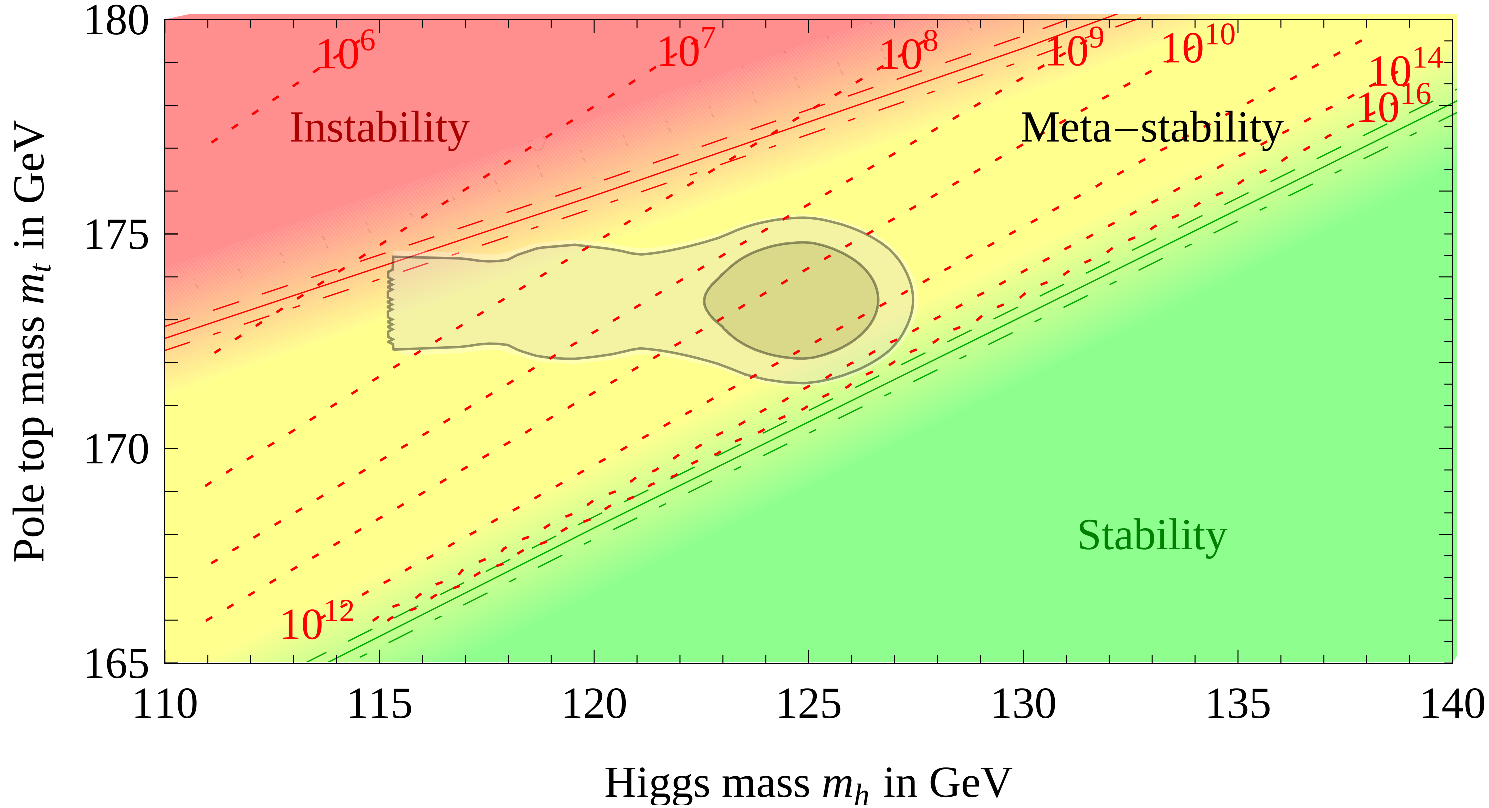
with J.E. Miró, J.R. Espinosa, G. Giudice, G. Isidori, A. Riotto

RGE running makes $\lambda < 0$



CAUTION: ± 3 GeV theory uncertainty .

Instability, meta-stability and stability



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

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

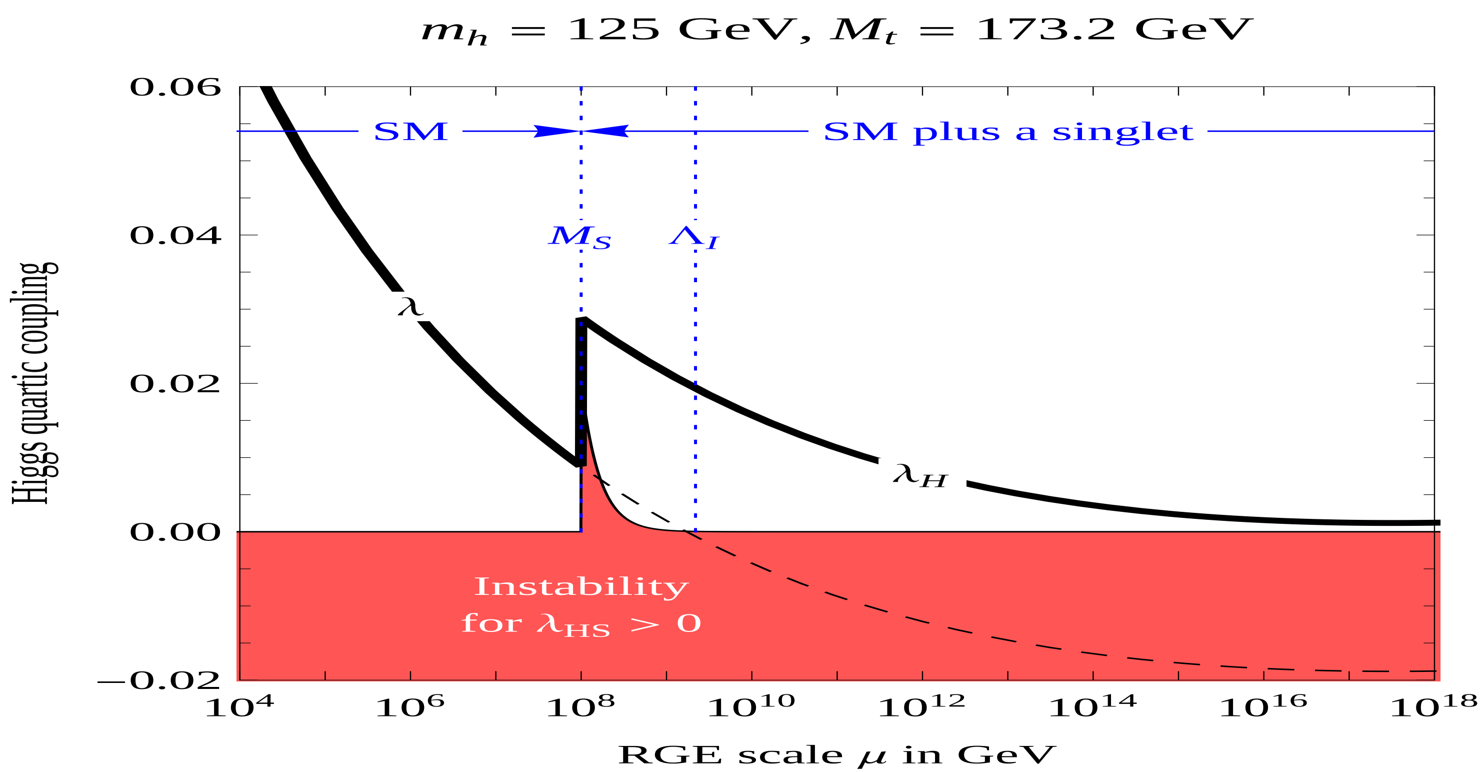
Tree level stabilization

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 $\lambda(M_{\mathrm{Pl}}) = 0$ 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...

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

which means...

NO

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

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.

- $m_h \approx 125\,\text{GeV}$ 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.