Higgs weights 125 GeV!
Now what?

1) Is Higgs standard?	**(**http://arxiv.org/abs/1203.4254**)**
2) SM vacuum (in)stability	**(**http://arxiv.org/abs/1205.6497**)**
3) Higgs & SUSY	**(**http://arxiv.org/abs/1108.6077**)**

Alessandro Strumia

Talk at CERN, IFAE, Princeton and Planck2012

updated to May 31, 2012

Mobilitas
ESF programm
Euroopa Liit
Euroopa Sotsiaalfond
Eesti tuleviku heaks

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.

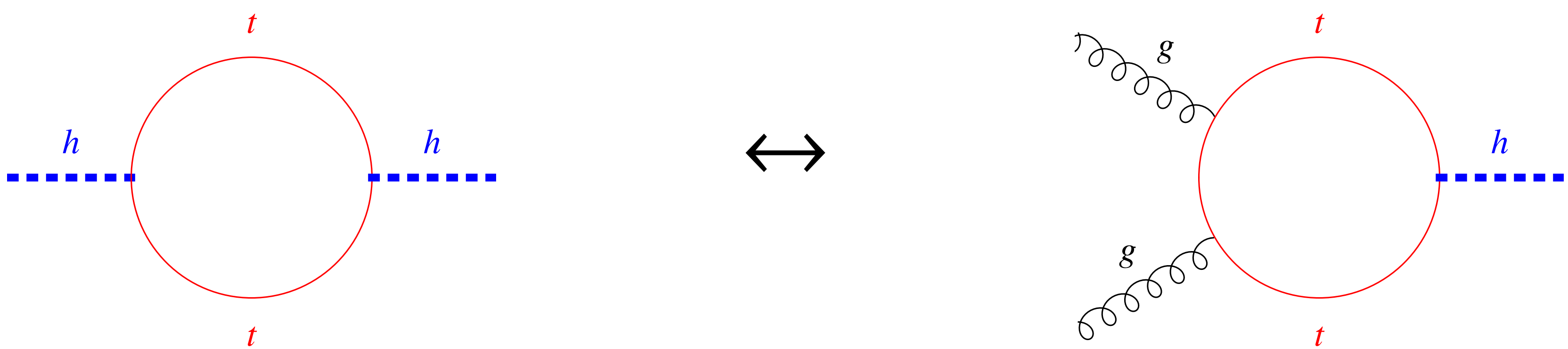
Thank you

Is the Higgs standard?

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

Motivation

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



Testing the Higgs is a way to test naturalness

Observables

$m_h = 125\,\text{GeV}$ is a favorable 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.

Fit needed: e.g. changing the higgs/bottom coupling also changes all BR.

Fermiophobic searches

We included all data after Moriond2012. In particular these ones are unsafe:

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

$$[(0.03 \pm 0.02)\sigma(pp \to h) + \sigma(pp \to jjh)] \times \text{BR}(h \to \gamma\gamma) = \text{SM} \times (3.3 \pm 1.1)$$

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

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

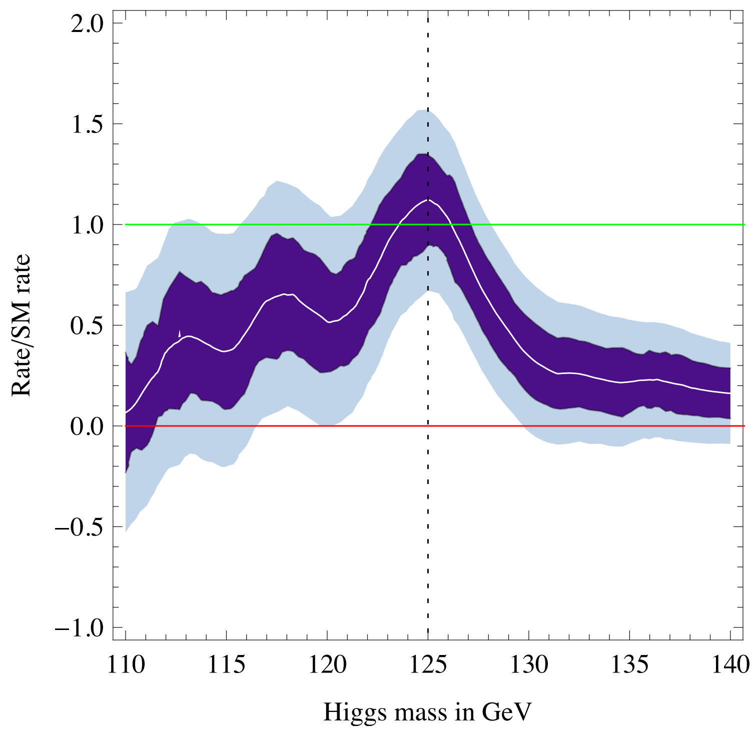
This format would be perfect for future data releases. So far we have to get weights of production channels by asking or doing MC simulations and...

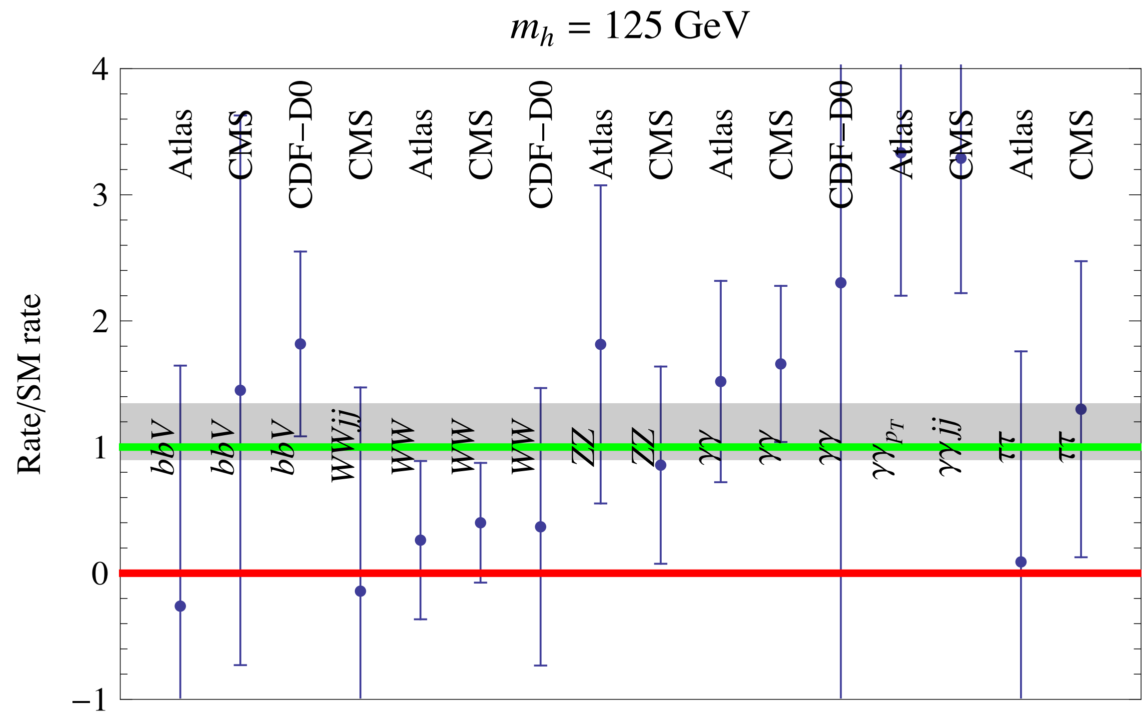
Data

Likelihoods not released due to peculiar politics of particle physics. We use:

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

Higgs data: CMS, ATLAS, CDF, D0



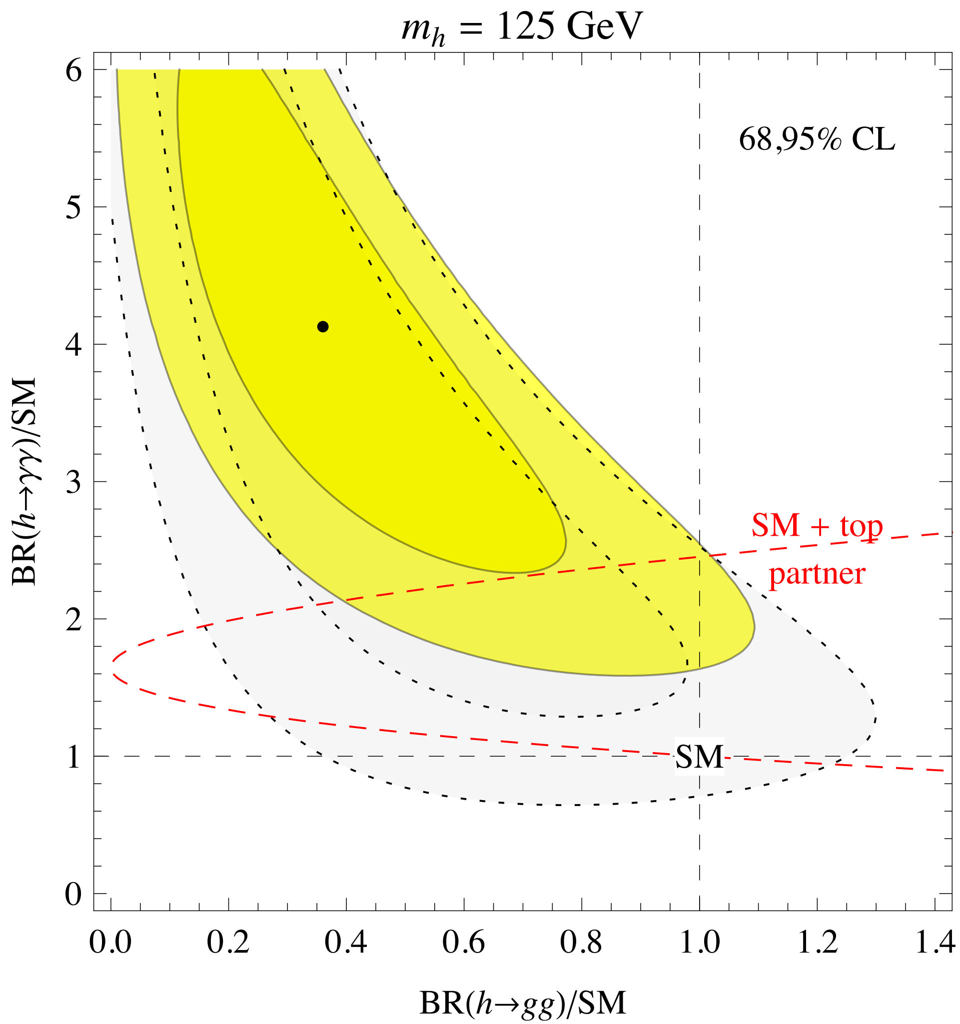


SM fit is good: $\chi^2 \approx 17$ (15 dof), the average rate is 1.1 ± 0.2, and

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

New 2012 data will reduce errors by a factor of ~ 2

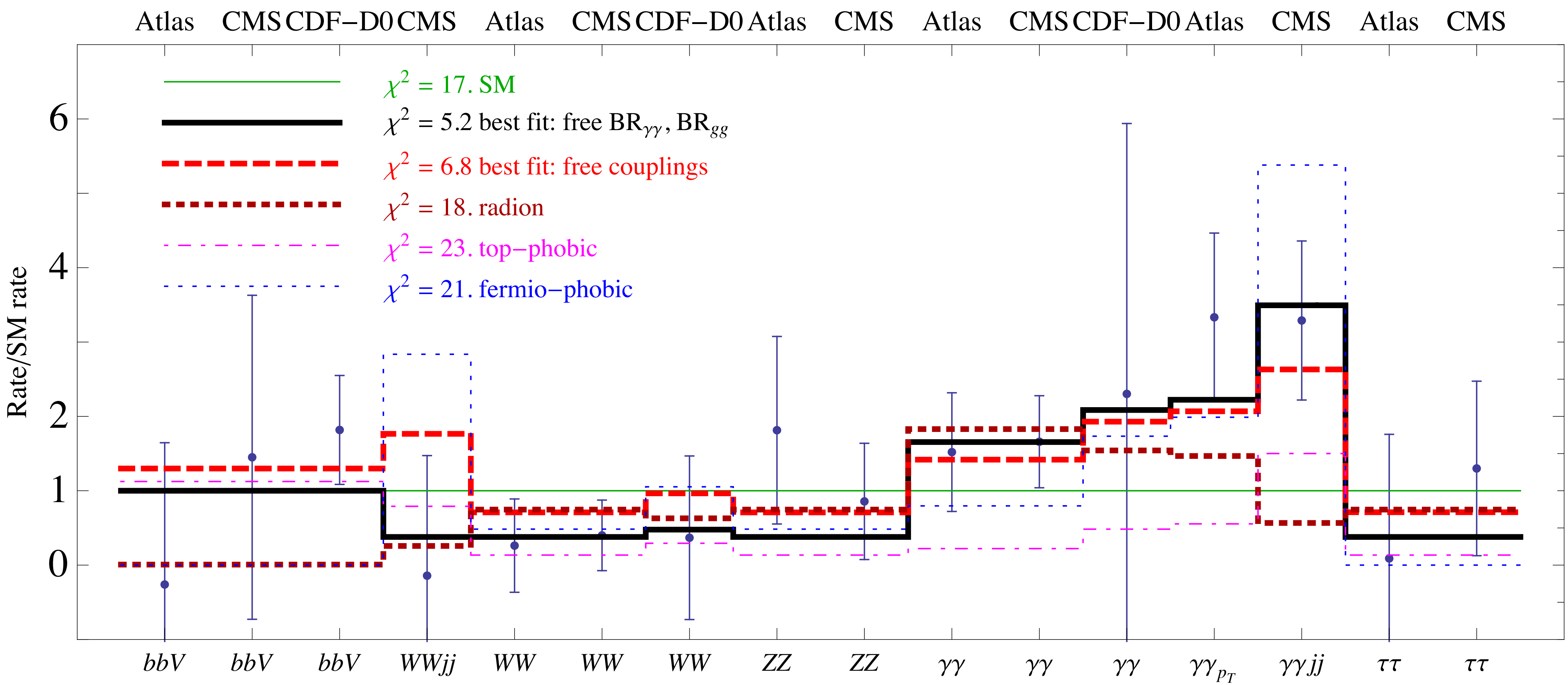
Non-standard BR for loop processes



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

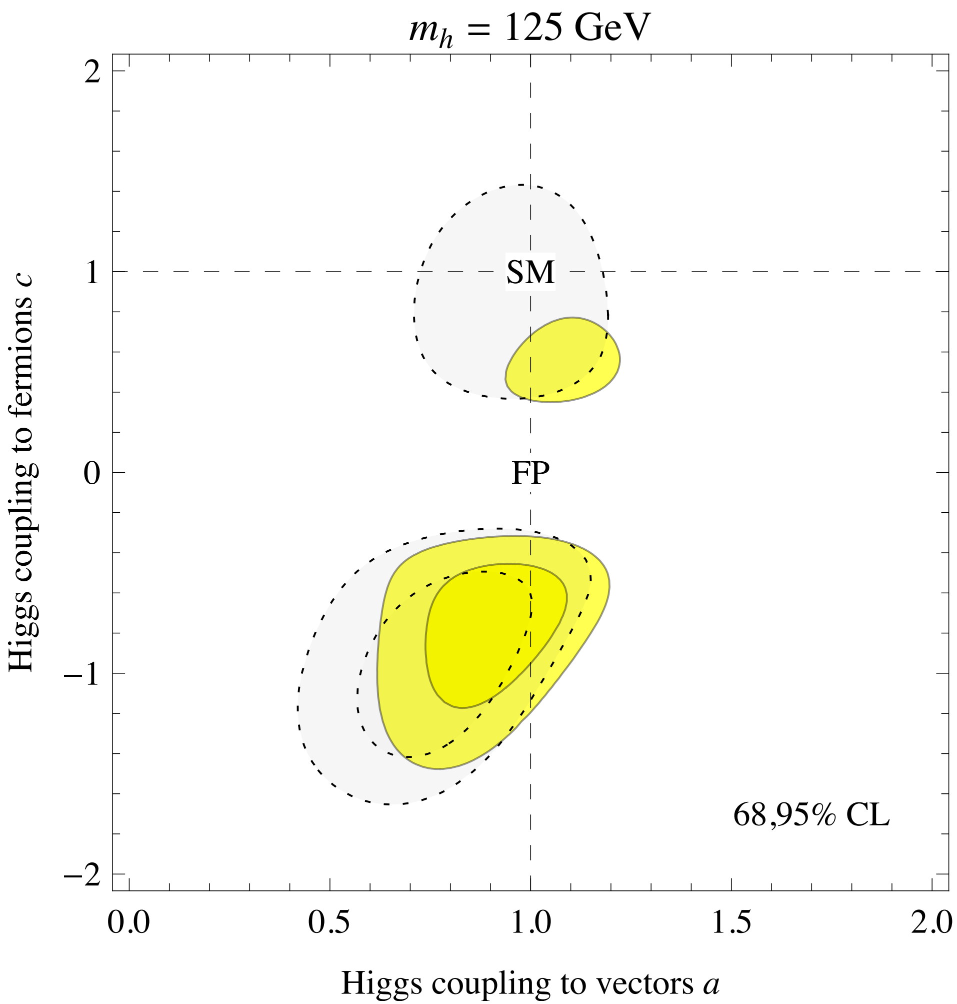


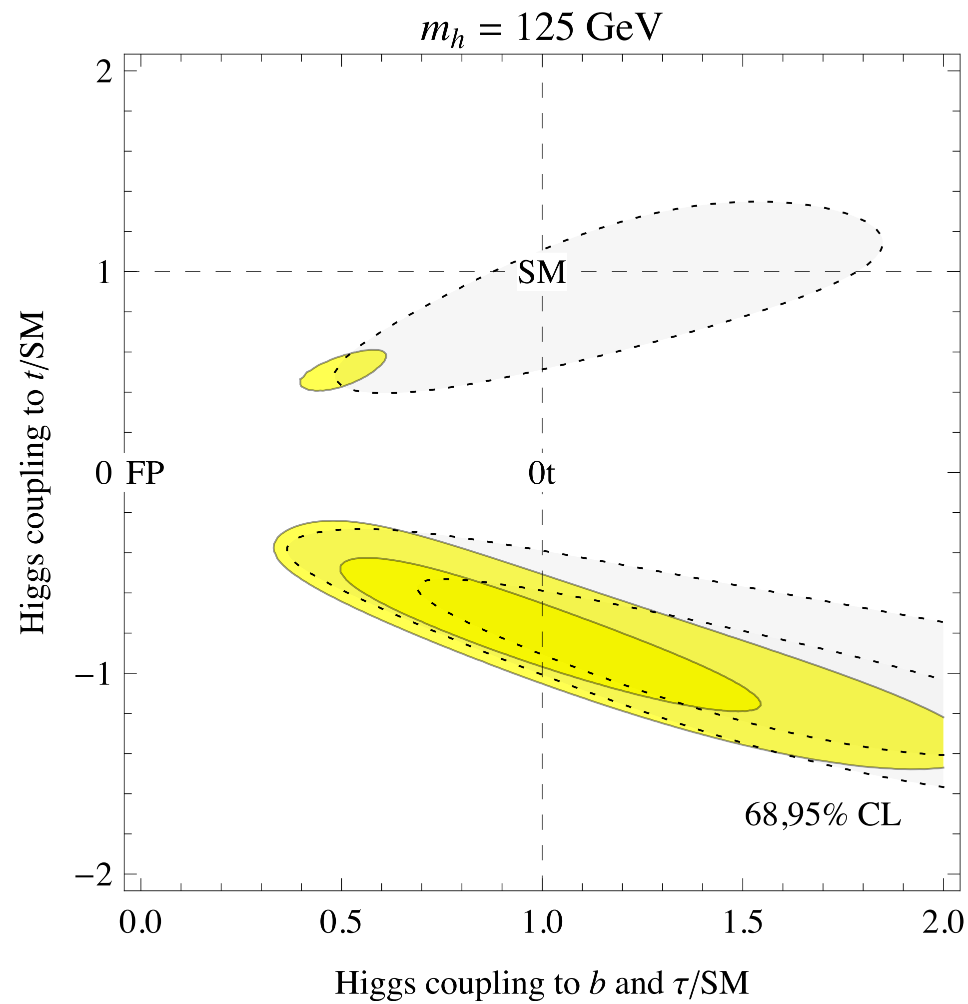
SM χ^2 is good. BSM fit is better. Maybe too good.

Fermiophobia not much worse than SM

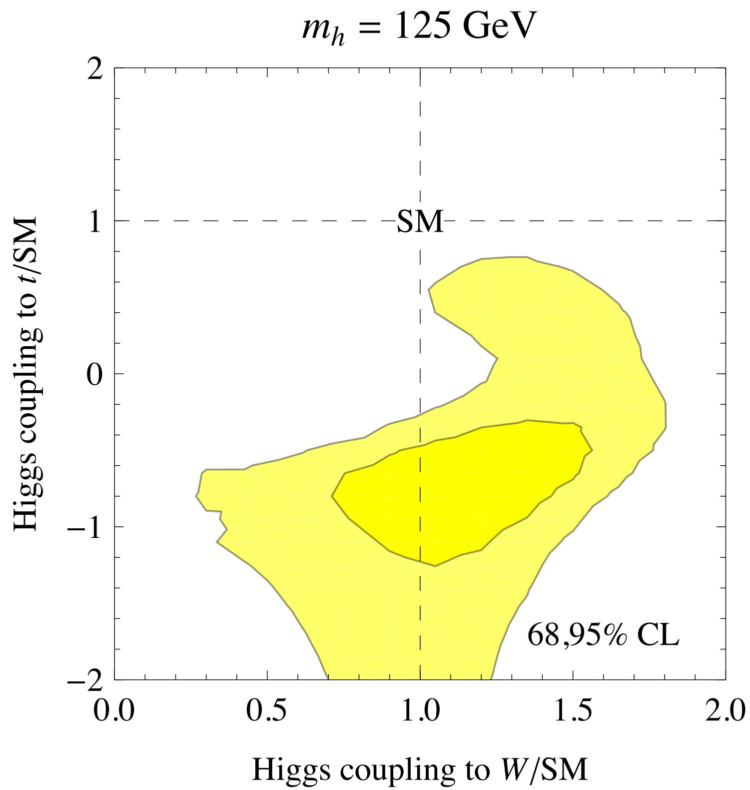
Fits to Higgs couplings: dysfermiophilia

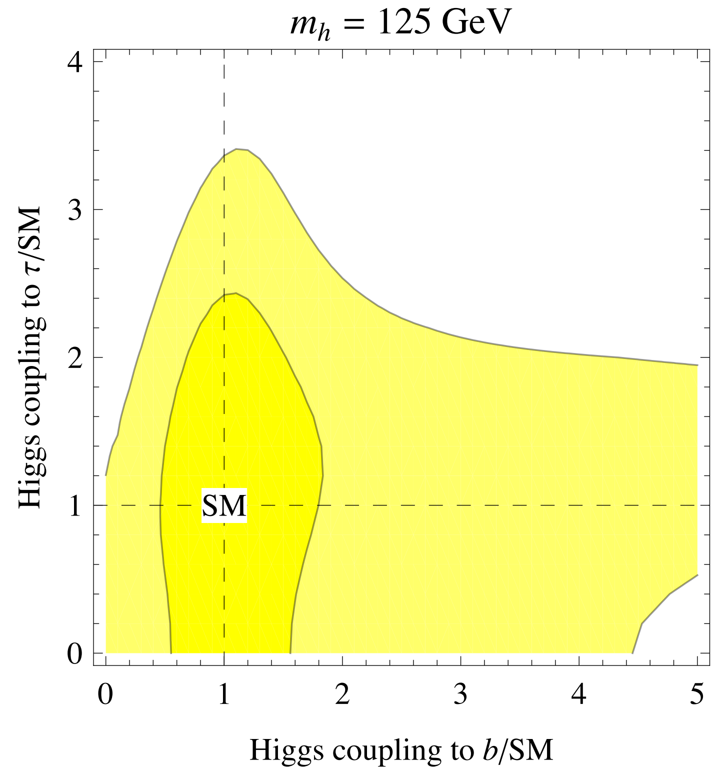
Latest fermiophobic analyses prefer enhanced $h \to \gamma\gamma$ obtained for $y_t \approx -y_t^{\text{SM}}$.





Global fit





E.g. in the MSSM at tree level

$$\frac{g_{hW}}{\mathrm{SM}} = \frac{g_{hZ}}{\mathrm{SM}} = \sin(\beta-\alpha), \qquad \frac{y_b}{\mathrm{SM}} = \frac{y_\tau}{\mathrm{SM}} = -\frac{\sin\alpha}{\cos\beta}, \qquad \frac{y_t}{\mathrm{SM}} = \frac{\cos\alpha}{\sin\beta},$$

and at loop level

$$\frac{y_t}{\mathrm{SM}} = 1 + \frac{m_t^2}{4}\left[\frac{1}{m_{\tilde t_1}^2} + \frac{1}{m_{\tilde t_1}^2} - \frac{(A_t - \mu/\tan\beta)^2}{m_{\tilde t_1}^2 m_{\tilde t_1}^2}\right]$$

Fitting the Higgs invisible width

A referee believes that this cannot be done:

> "Only ratios of couplings can be fitted. I do not see how the authors can rectify their paper without a complete change of analysis strategy. Consequently, a new revised version will be unacceptable as well".

Let's see...

Fitting the Higgs invisible width

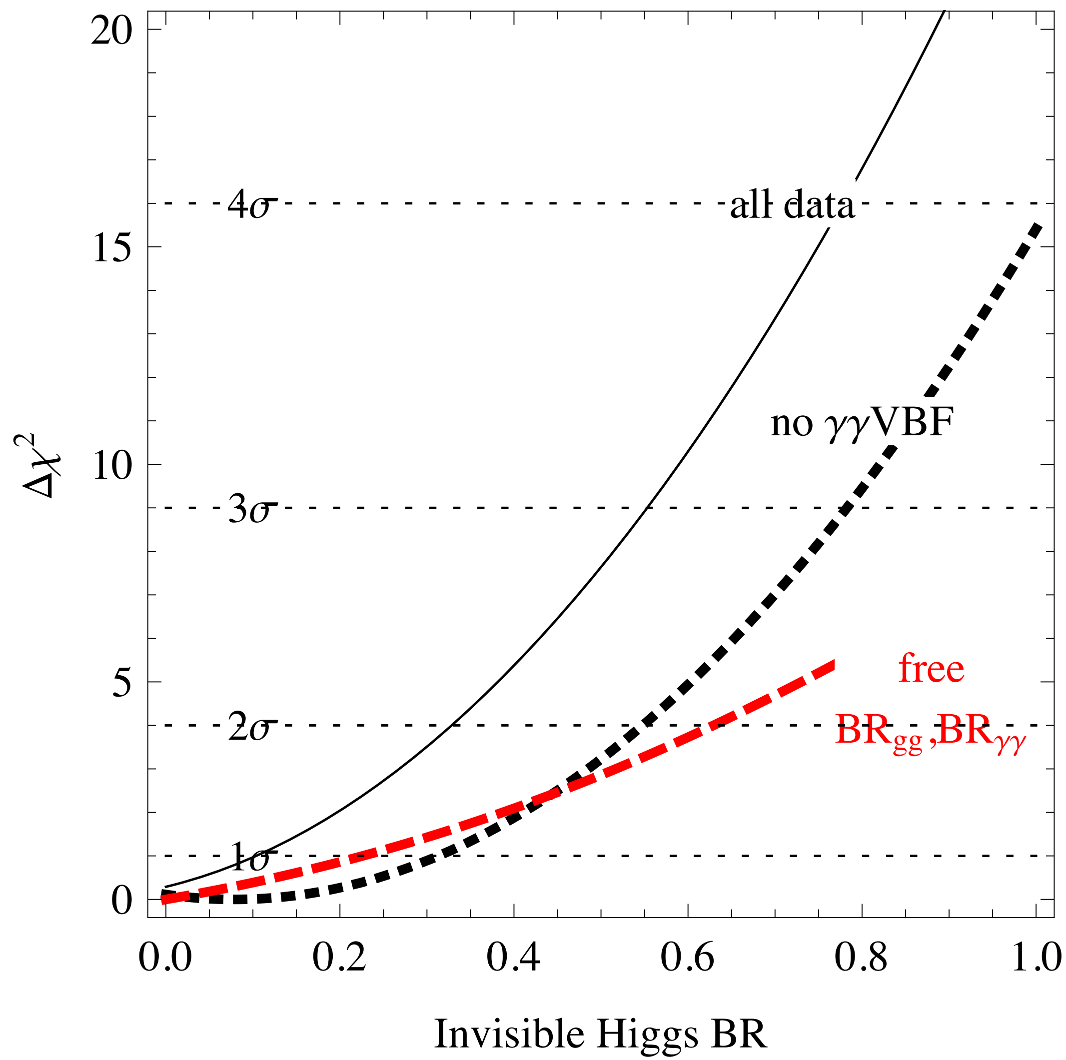
Data can test and disfavor an invisible width because $gg \to h$ and $h \to gg$ are related as well known since Breit-Wigner

$$\sigma(gg \to h) \overset{\Gamma \ll m}{\simeq} \frac{\pi^2}{8m_h}\Gamma(h \to gg)\delta(s - m_h^2)$$

Result:

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

Commonsense: BR_{inv} cannot be too large, otherwise we would not see the Higgs.



Higgs or radion?

A 'radion' particle φ coupled to the trace of $T_{\mu\nu}$ can mimic the Higgs:

$$\frac{\varphi}{\Lambda}T^{\mu}_{\mu} = \frac{\varphi}{\Lambda}\left(\sum_f m_f \bar{f} f - M_Z^2 Z_\mu^2 - 2M_W^2 W_\mu^2 + A\right)$$

At tree level, it like a Higgs with all couplings rescaled by $R = \sqrt{2}v/\Lambda$.

The difference arises at quantum level because scale invariance is anomalous:

$$A = -7\frac{\alpha_3}{8\pi}G^a_{\mu\nu}G^a_{\mu\nu} + \frac{11}{3}\frac{\alpha_{\rm em}}{8\pi}F_{\mu\nu}F_{\mu\nu}$$

So $\varphi \leftrightarrow gg$ is strongly enhanced and $\varphi \to \gamma\gamma$ changed.

Fit almost as good as the SM Higgs, best at $R = 0.28 \pm 0.03$ (i.e. $\Lambda \approx 870$ GeV).

From the EW scale
to the Planck scale

With Degrassi, di Vita, Miró, Espinosa, Giudice, Isidori and the SM

M_h =125 GeV. And now?

RGE running can make λ negative or non-perturbative

For the measured masses both λ and its β-function vanish around $M_{\rm Pl}$!!?

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

NNLO corrections are like a ± 3 GeV uncertainty in m_h: compute them!

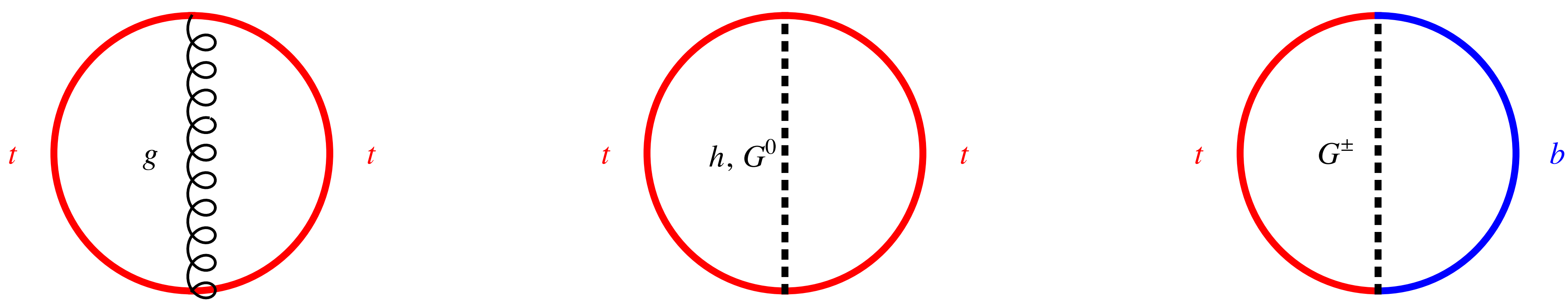
NNLO

3loop RGE + 2 loop potential + 2 loop matching at the weak scale

$\lambda \leftrightarrow M_h$ at NNLO is the main effect, because g_3 and y_t get big at low E:

$$M_h^2 = \left(\lambda + \frac{y_t^4}{(4\pi)^2} + ?\frac{y_t^4}{(4\pi)^2}\frac{g_3^2 + y_t^2}{(4\pi)^2}\right) v^2$$

Leading terms in $M_h^2/4M_t^2$ can be obtained from the known 2 loop potential

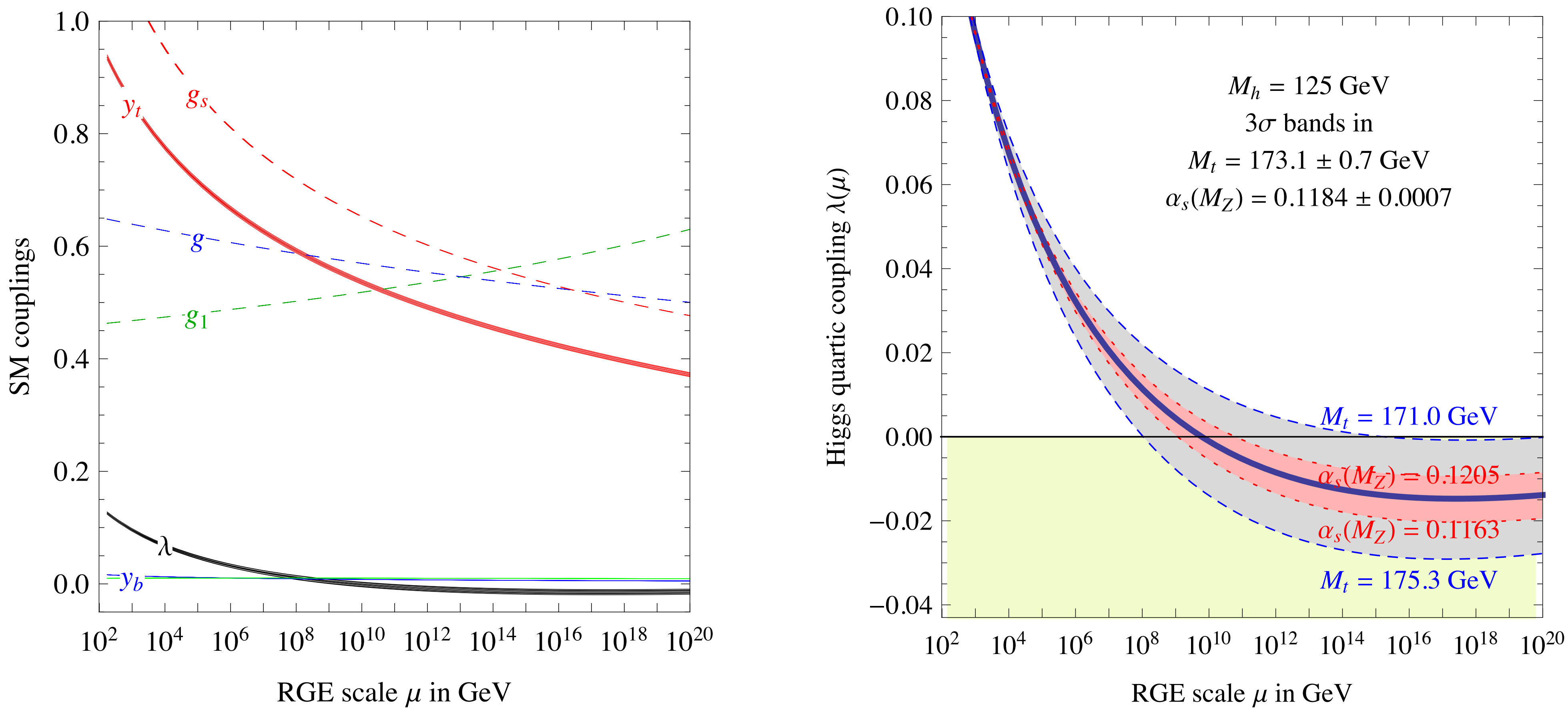


$$\delta m_h^2(\bar\mu = M_t)|_{\rm NNLO} = 0\frac{y_t^4 g_3^2 v^2}{(4\pi)^4} - 2(6+\pi^2)\frac{y_t^6 v^2}{(4\pi)^4} + \mathcal{O}(\lambda, g_1, g_2)$$

Status now: full g_3, y_t, λ at NNLO, g, g' at NLO: -1 GeV shift towards instability

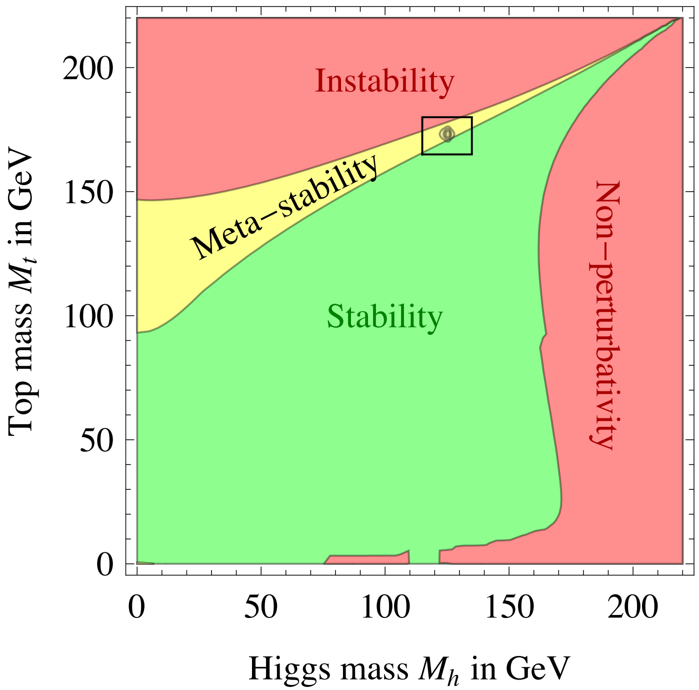
From the EW scale to the Planck scale

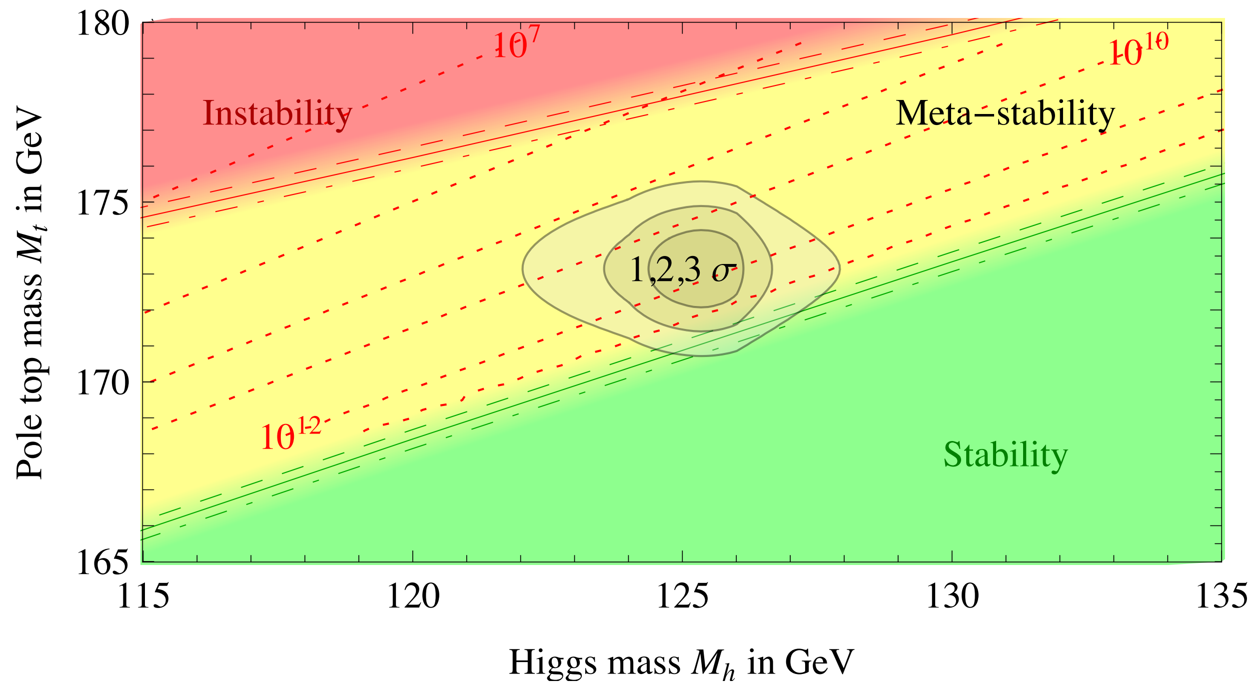
$$\lambda(M_t) = 0.12577 + 0.00205\left(\frac{M_h}{\text{GeV}} - 125\right) - 0.00004\left(\frac{M_t}{\text{GeV}} - 173.15\right) \pm 0.00140_{\text{th}}$$



$$\lambda(M_{\text{Pl}}) = -0.0144 + 0.0028\left(\frac{M_h}{\text{GeV}} - 125\right) \pm 0.0047_{M_t} \pm 0.0018_{\alpha_s} \pm 0.0028_{\text{th}}$$

The SM vacuum is metastable





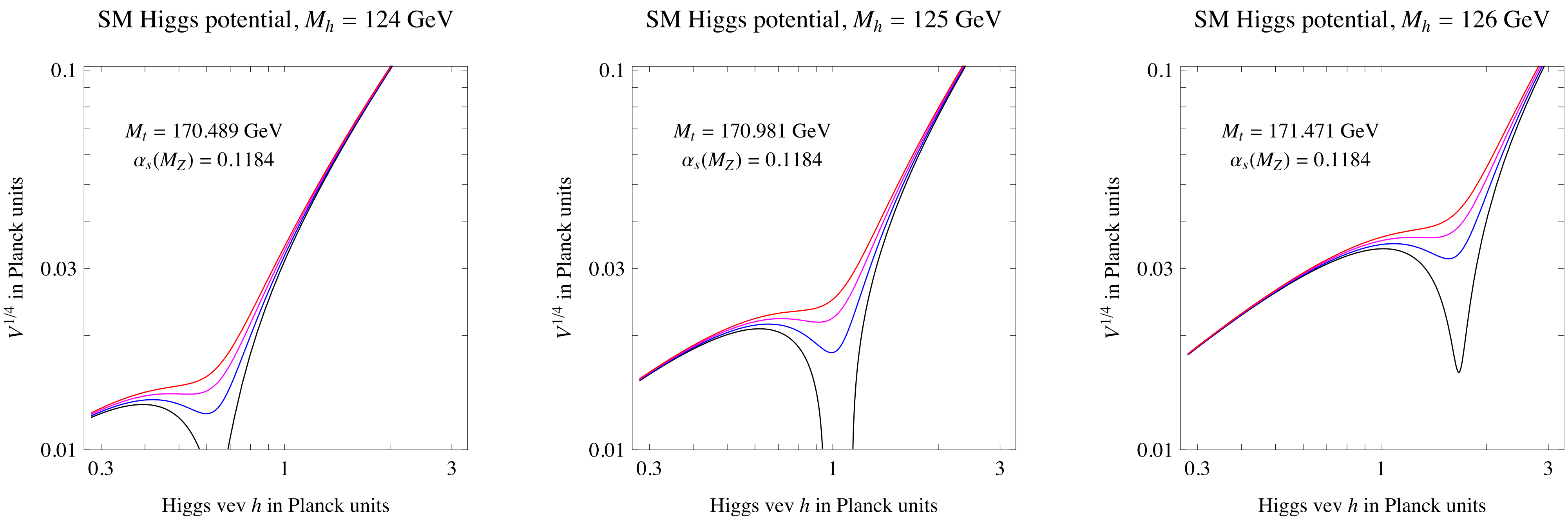
$$M_h\ [\text{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\text{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\text{th}}\ .$$

Vacuum stability is excluded at 2σ (98% C.L. one sided) for $M_h < 126\,\text{GeV}$.

The main uncertainty is M_t, which will **soon** be measured better.

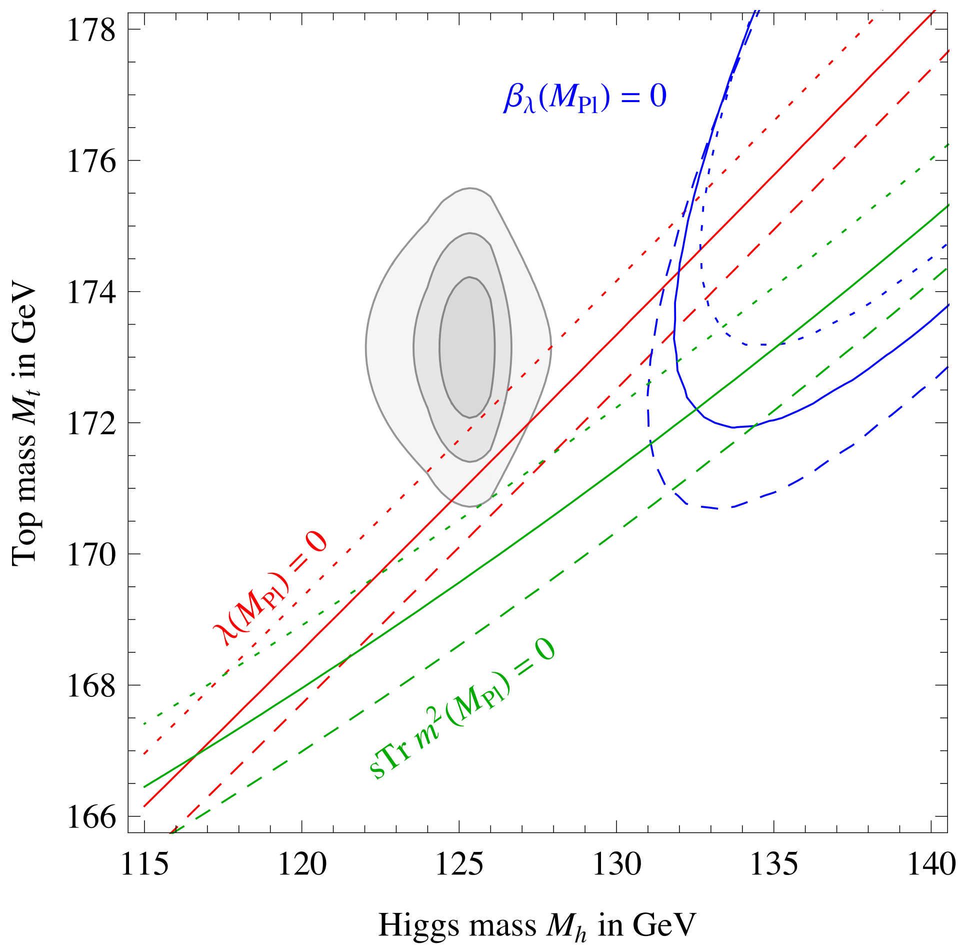
Implications: Higgs inflation?

A) Criticality allows inflation with a plateau or a second minimum. Needs adjustments. In practice it predicts $\lambda = \beta_\lambda = 0$ and so...



B) Inflation with a non-minimal coupling to gravity, $|H|^2R$. Maybe it allows inflation or maybe the theory is uncontrollable. In practice it predicts $\lambda > 0$.

Veltman throat at the Planck scale?



Excluded

Cut-off for $y_t^2\Lambda^2$ must be lower than for $g^2\Lambda^2$

Tree level stabilization

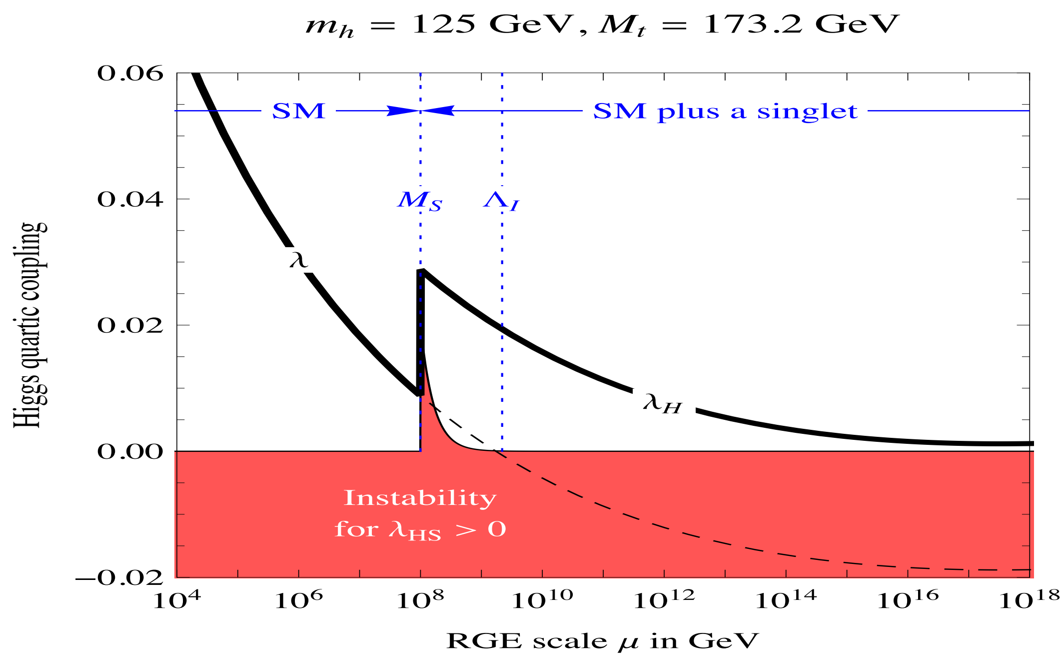
New physics can easily stabilize the SM potential. Lots of possibilities.

The simplest possibility is 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:

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



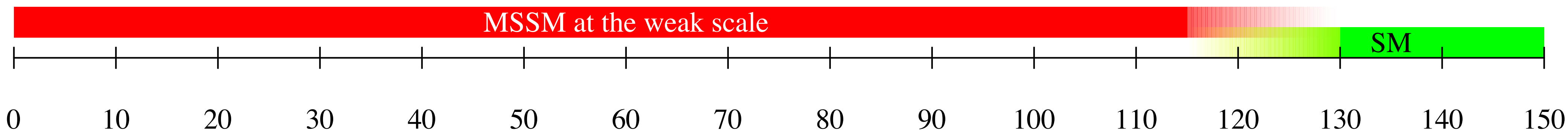
(with J. Elias-Miro, J.R. Espinosa, G. Giudice, H.M. Lee)

Higgs and SUSY

with G. Giudice

125 GeV is in no man's land

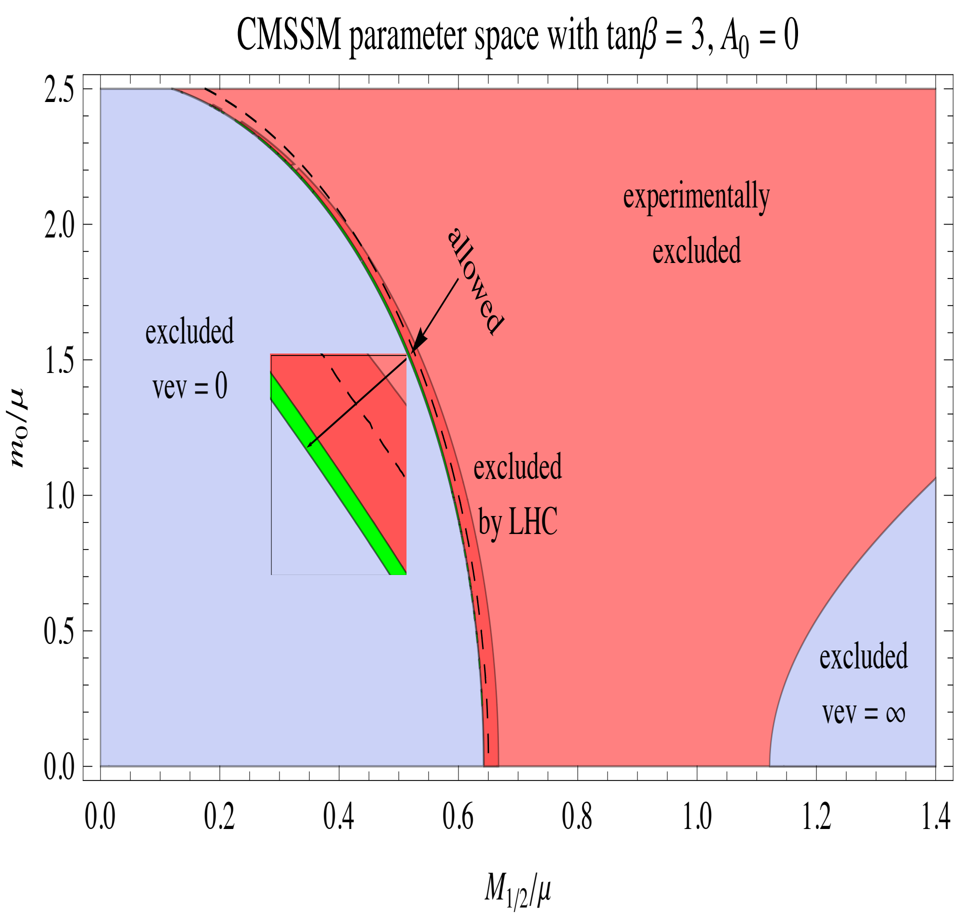
SM is stable up to the Planck scale for $m_h \gtrsim 130\,\text{GeV}$ but can go down to 115

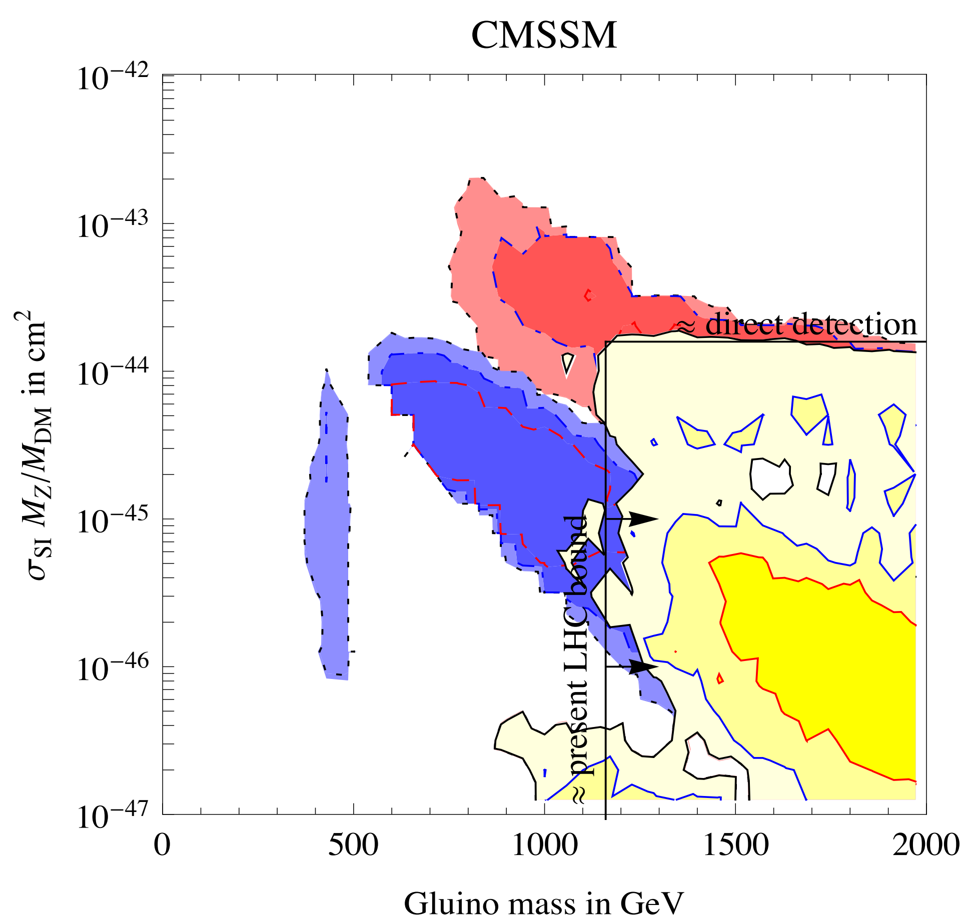


MSSM with weak scale SUSY likes $m_h \lesssim 120\,\text{GeV}$ but can go up to 130

SUSY is dead...

... $m_h \approx 125\,\text{GeV}$ needs quasi-maximal stop mixing or beyond-MSSM...
... naturalness of weak scale SUSY is mostly gone (KFT or light $\tilde{t}, \tilde{b}$?)
... $g-2$ regions are getting excluded in the CMSSM (or LHC-phobic SUSY...)





But SUSY is the king of BSM so...

...Long live SUSY!

Time to consider $m_{\rm SUSY} \gg M_Z$ and compute $m_h(m_{\rm SUSY}, \tan\beta)$:

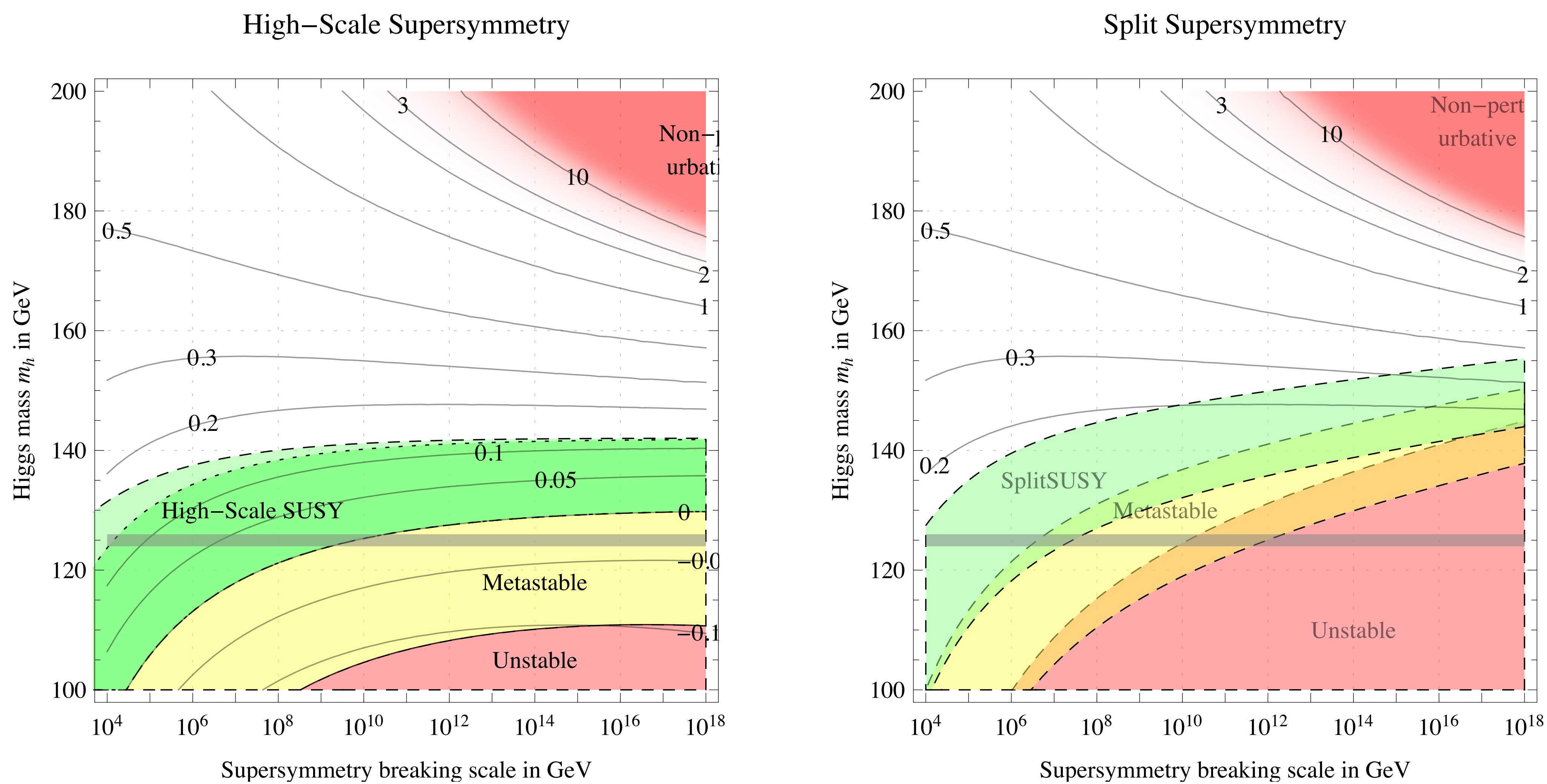
- **Split-SUSY** (SUSY scalars at $m_{\rm SUSY}$ and SUSY fermions around M_Z). Gives good unification and maybe makes theoretical sense.

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

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

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

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



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

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

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

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

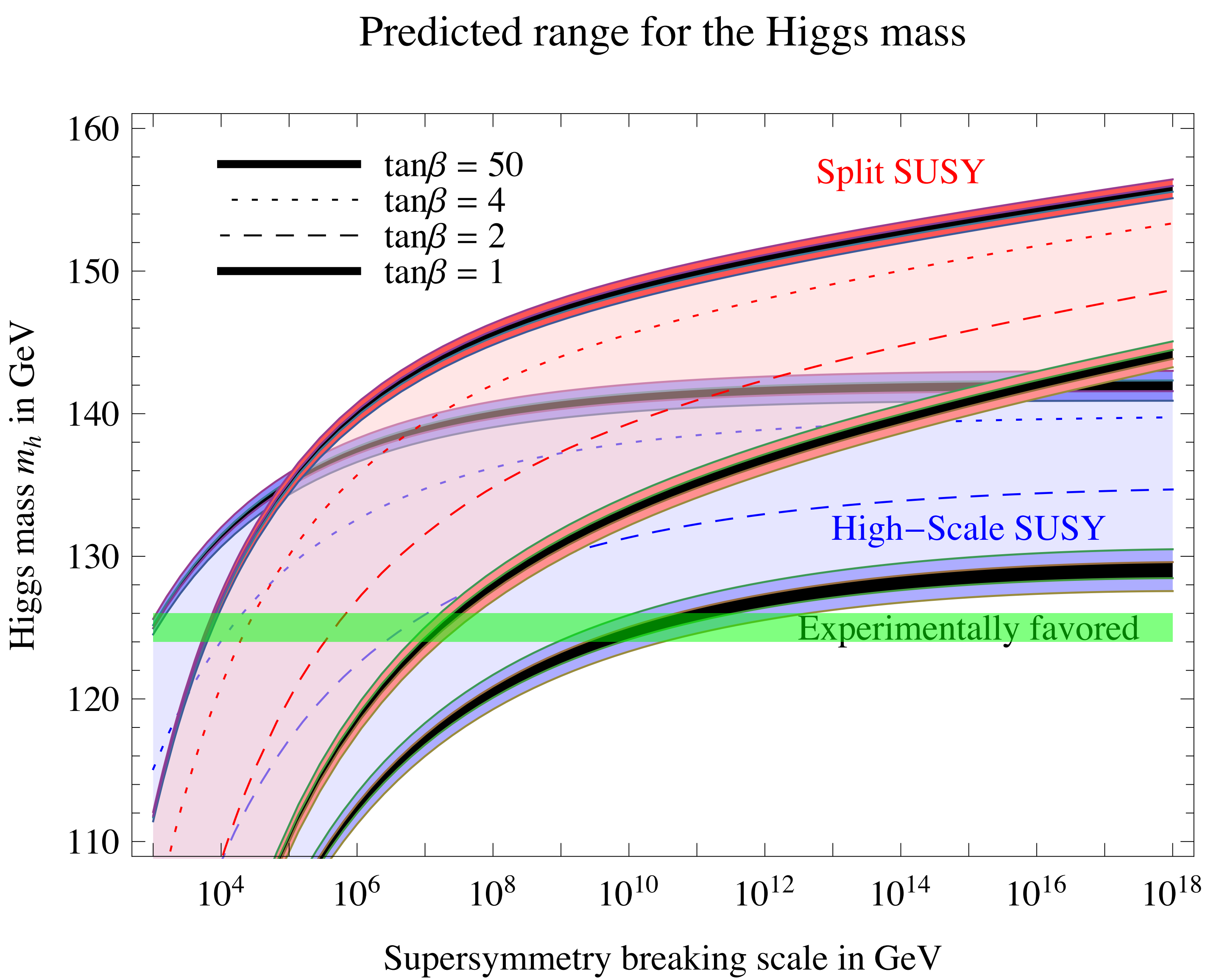
$$\delta\lambda = \lambda_N^2 \sin^2 2\beta \frac{(B-2A)M + m^2 - A^2}{2(M^2 + m^2 + BM)}$$

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 3 fundamentals 27_i. The Higgs is one slepton that remains light due to ant**pic. The Yukawa couplings come from:

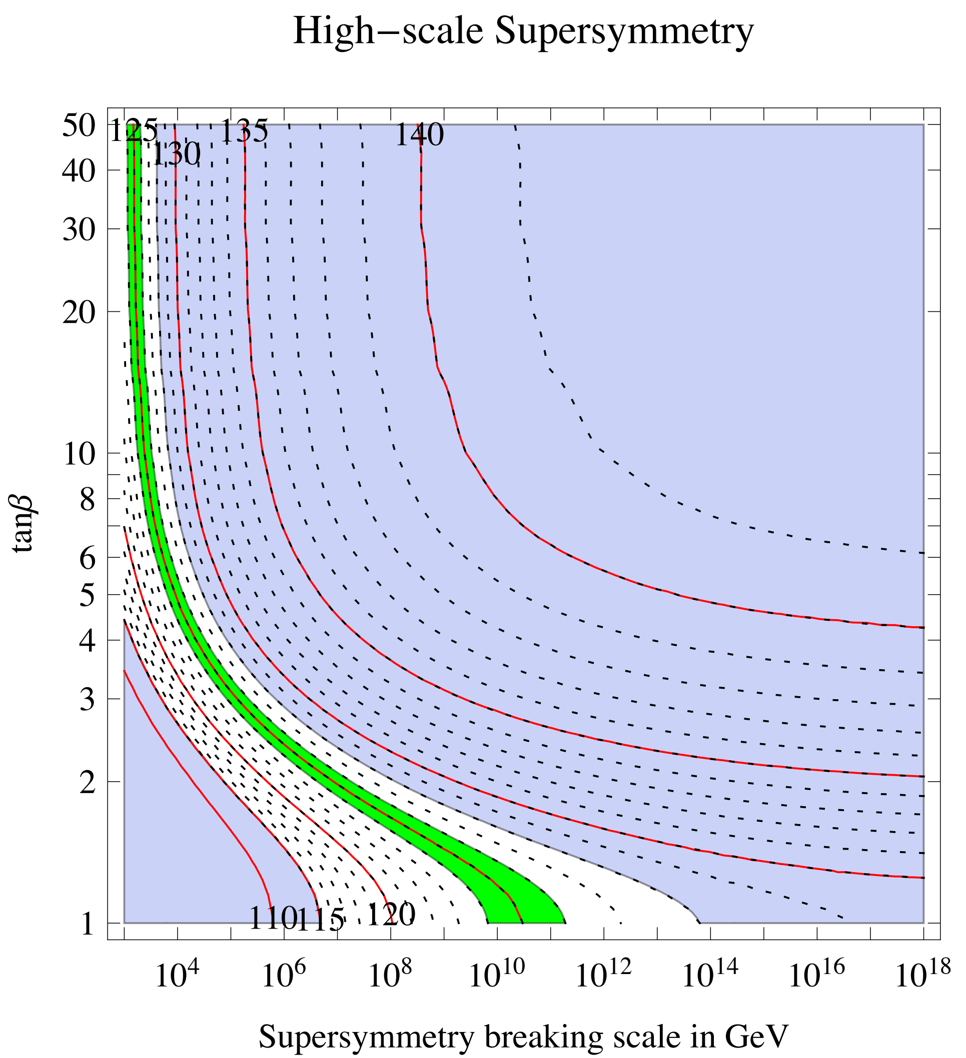
$$\mathscr{W} = \lambda_{ijk} 27_i 27_j 27_k$$

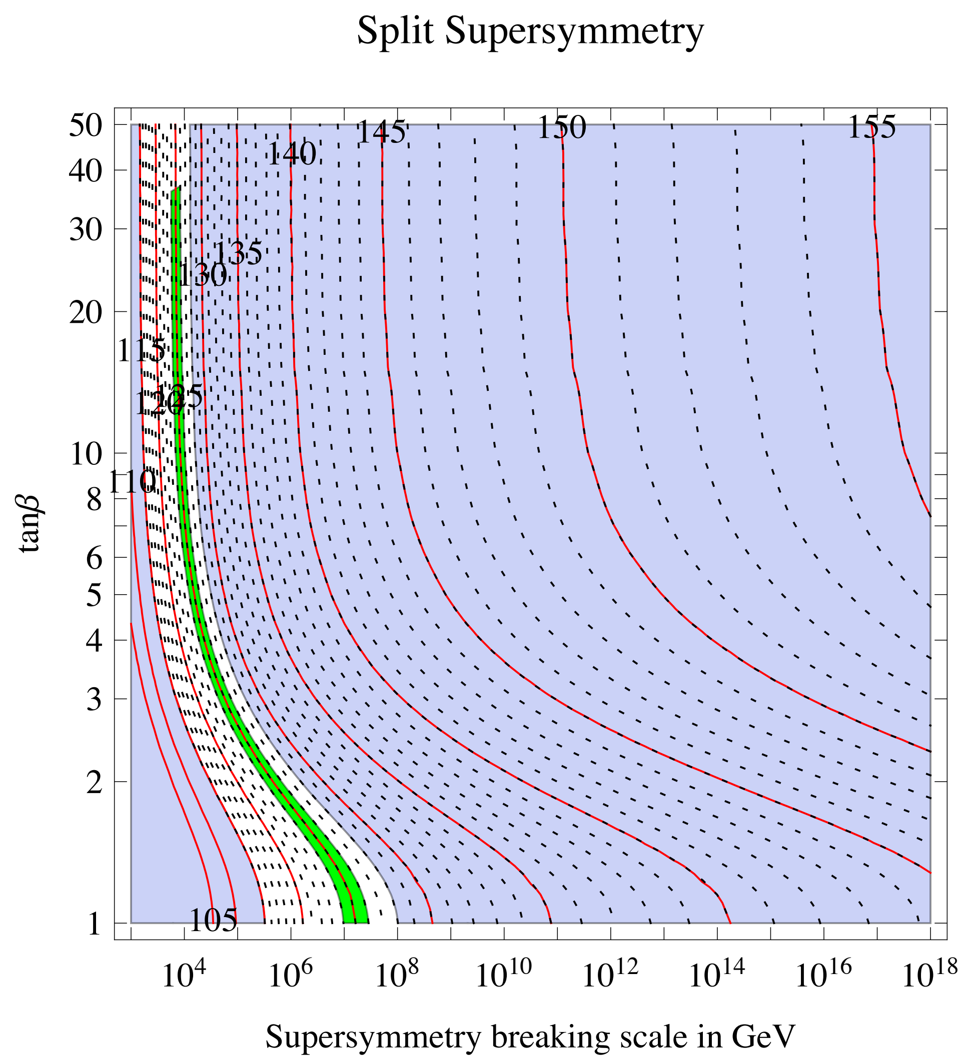
Effect of SM uncertainties



Thickness is $\pm 1\sigma$ on α_3 and on M_t. Theory error is now ± 1 GeV. Extra uncertainties coming from unknown SUSY thresholds are not in the figure.

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

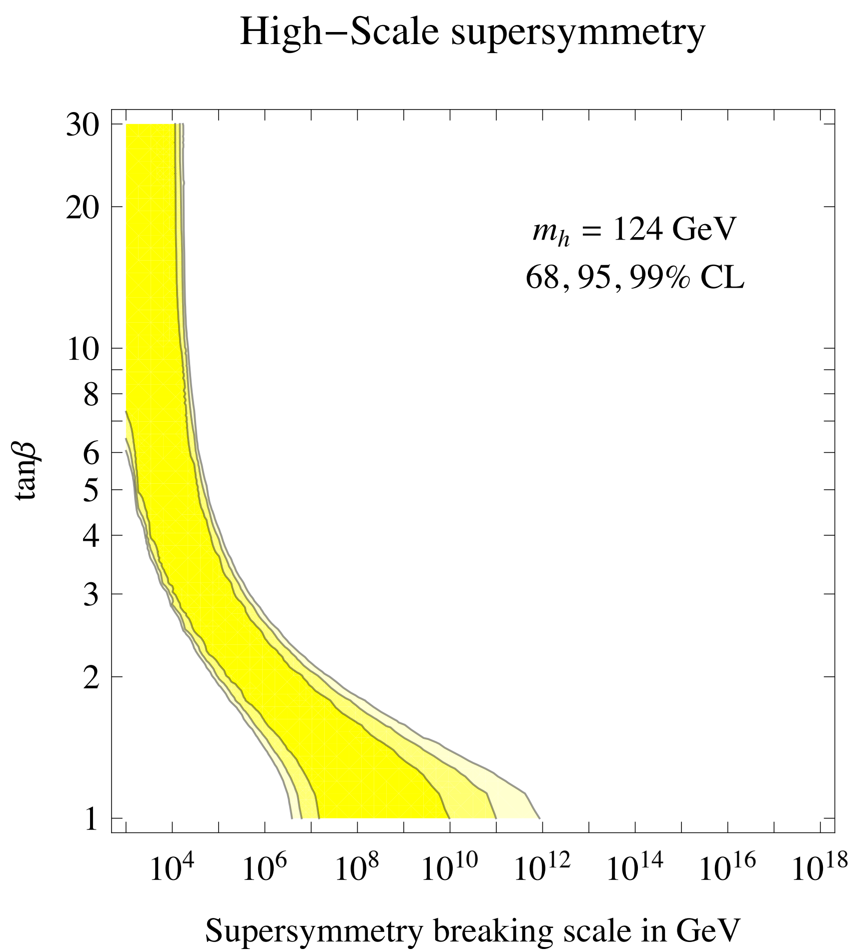


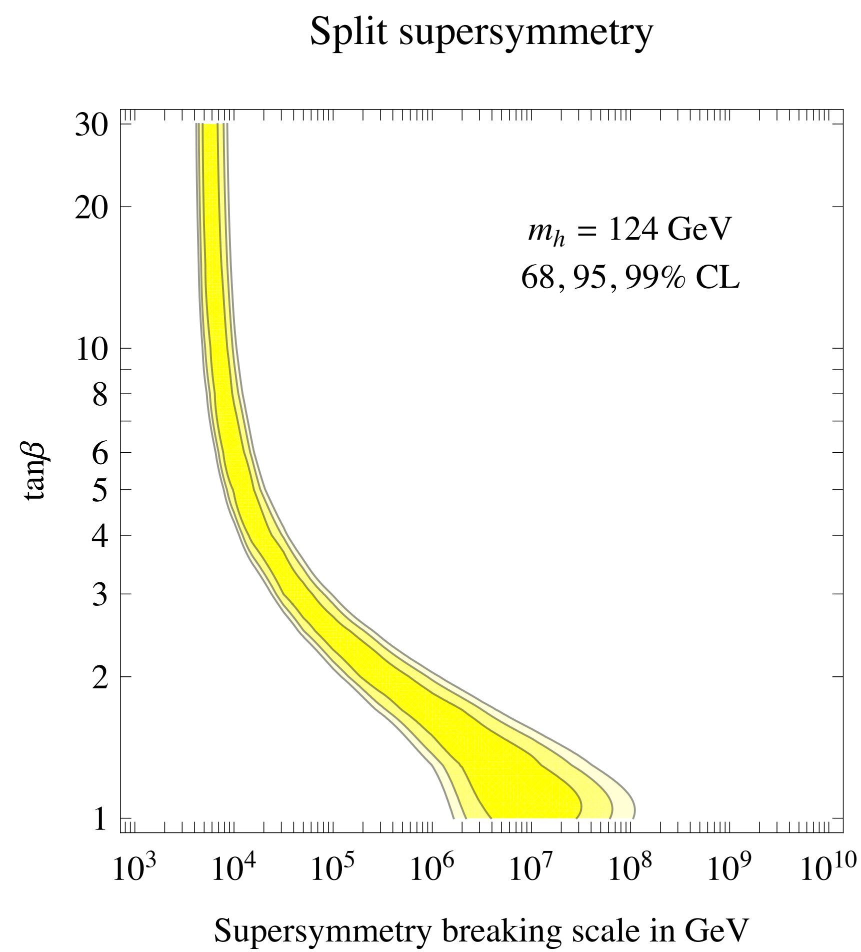


(Assuming degenerate heavy spectrum at m_{SUSY})

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

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





$m_{\mathsf{SUSY}} \approx M_Z$ 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

Conclusions

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

- $m_h \approx 125\,\text{GeV}$ means λ small and negative at the Planck scale (98% C.L.). $m^2 \approx 0$, $\lambda \approx 0$: Higgs potential is doubly critical. Accident or hint?

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

It could be the last particle. Carpe diem.