Higgs weighs 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)
4) Maybe something more	(http://arxiv.org/abs/1204.5465)

Alessandro Strumia

Talk at CERN, IFAE, Princeton, Planck2012, Mass2012

still improving, updated to June 15, 2012

Slides on-line so photos not needed

Mobilitas
ESF programm

Euroopa Liit
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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.

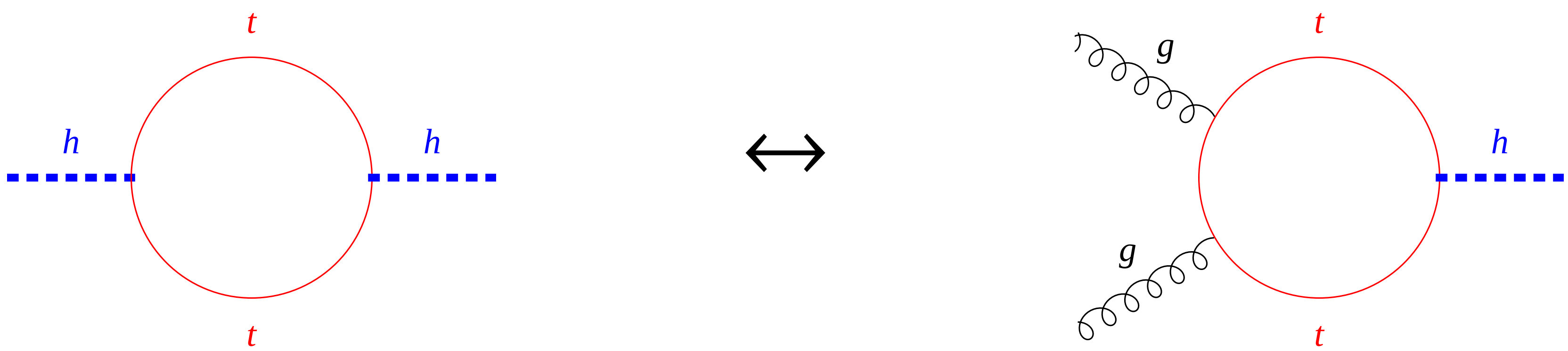
Thank you

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

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

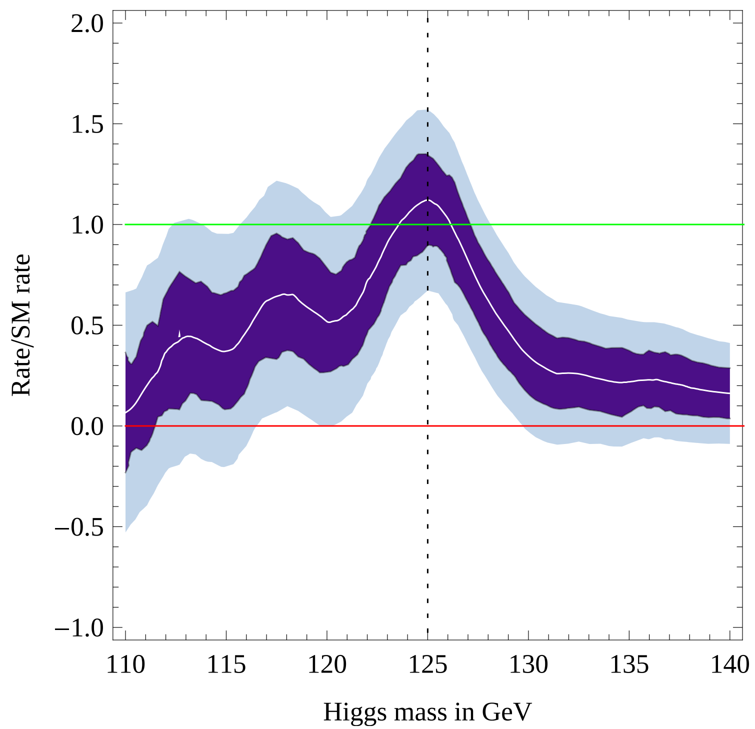
This format would be perfect for future data releases. So far we have to get weights of production channels by asking or doing MC simulations and...

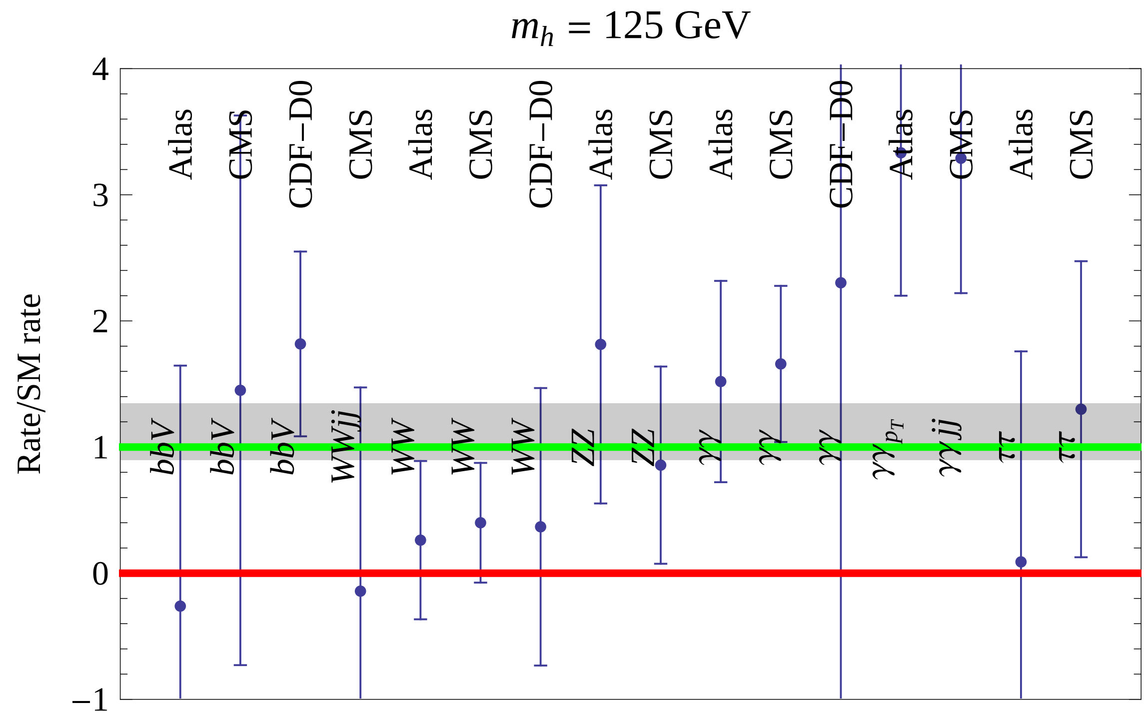
Data

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



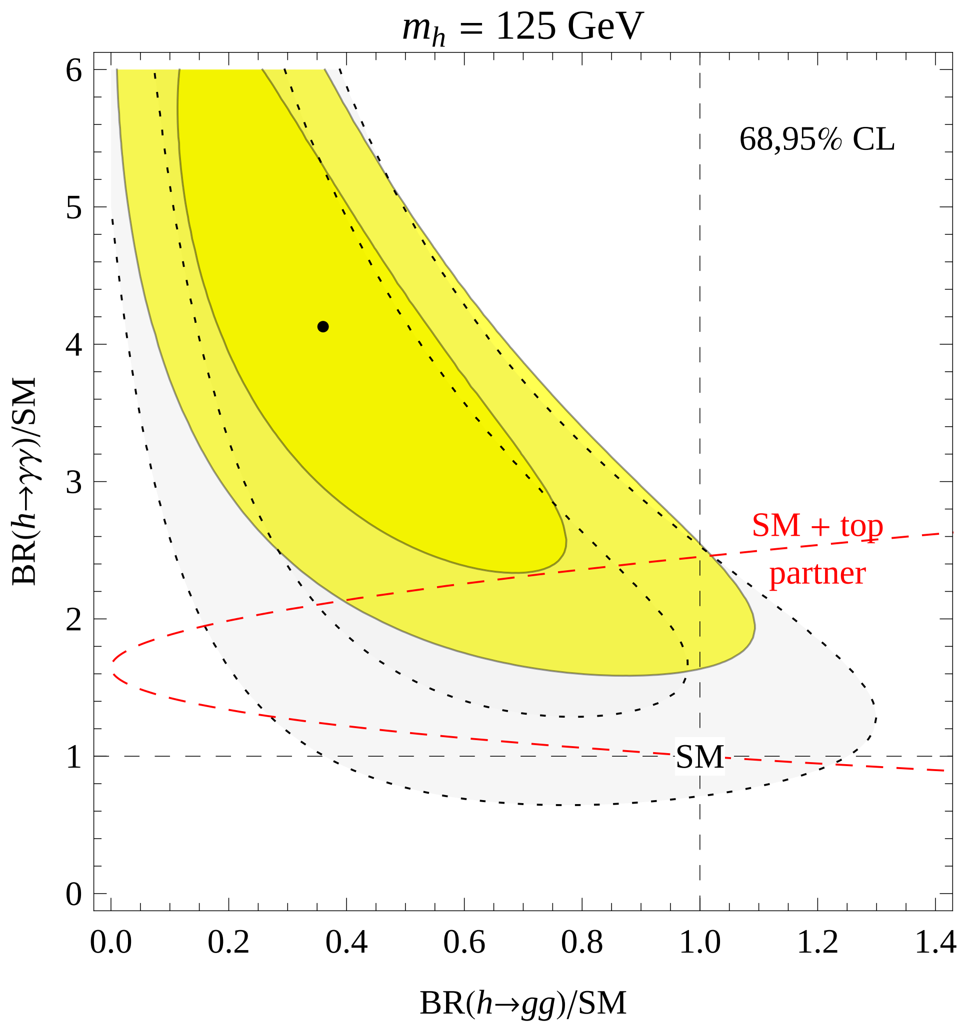


SM fit is good: $\chi^2 \approx 17$ (15 dof), the average rate is 1.1 ± 0.2, and

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

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

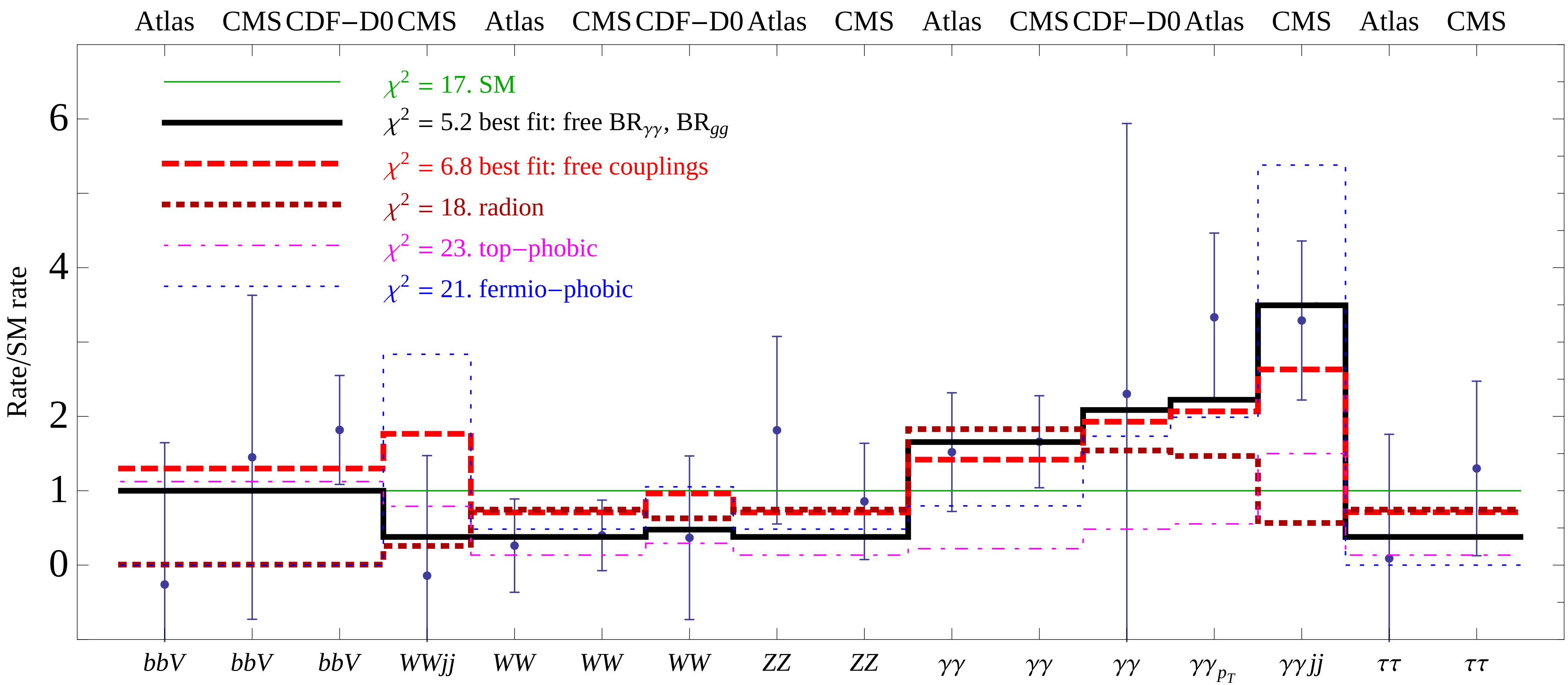
Non-standard BR for loop processes



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

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

Non standard best fits

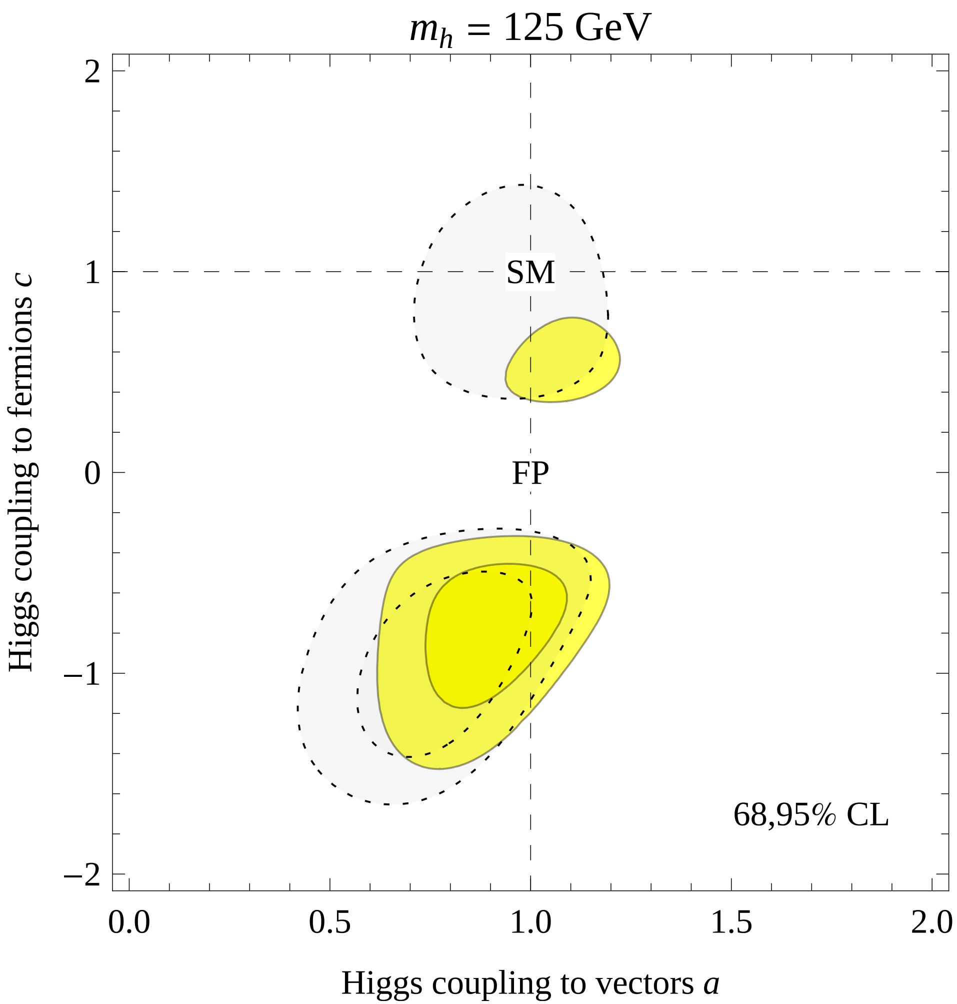


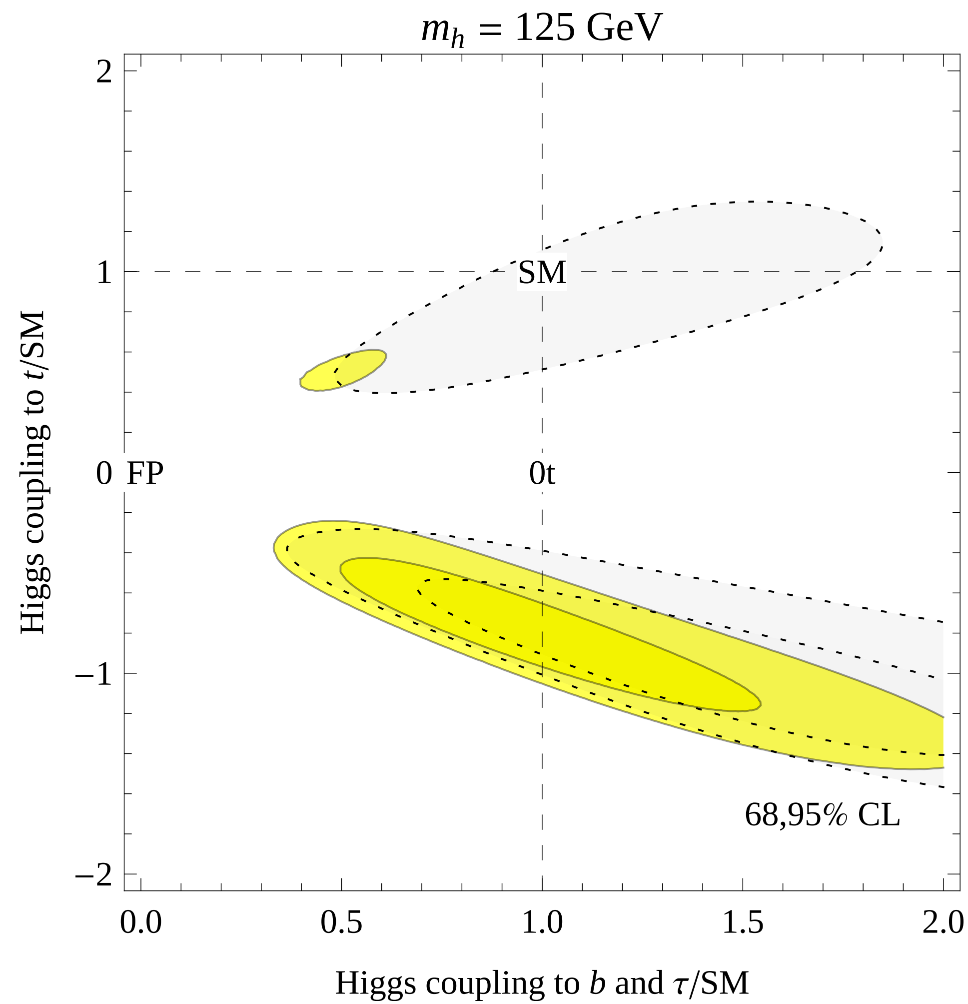
SM χ^2 is good. BSM fit is better. Maybe too good.

Fermiophobia not much worse than SM

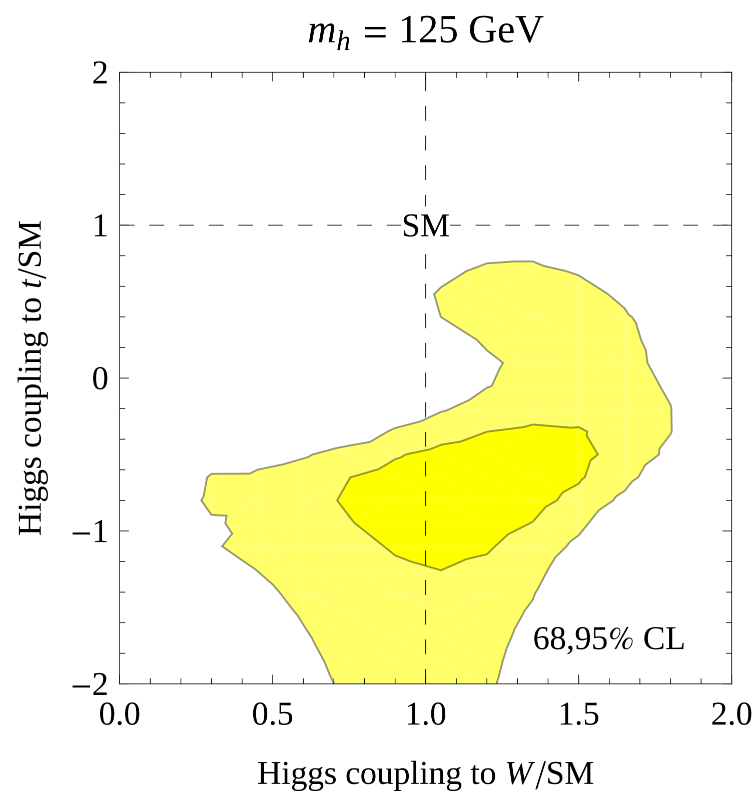
Fits to Higgs couplings: dysfermiophilia

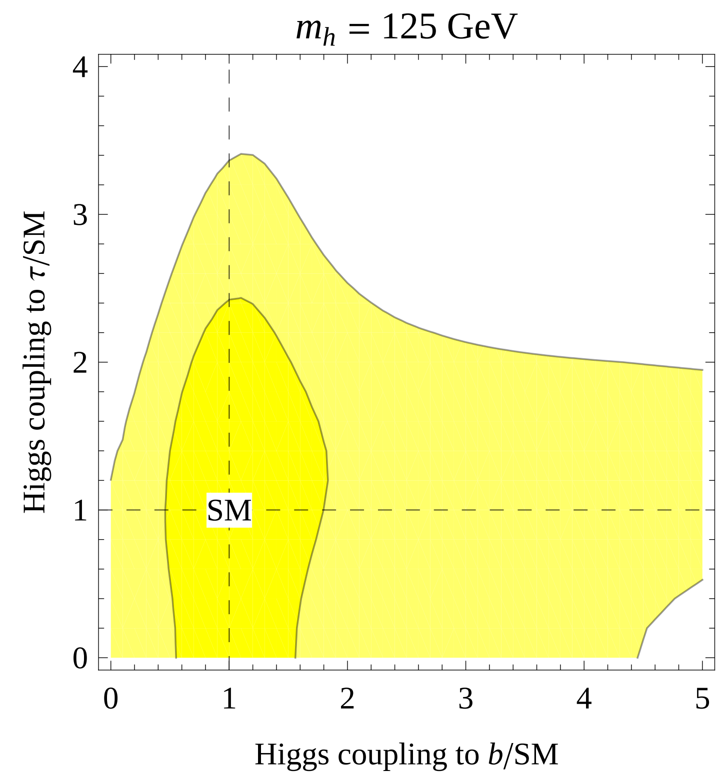
Latest fermiophobic analyses prefer enhanced $h \to \gamma\gamma$ obtained for $y_t \approx -y_t^{\mathsf{SM}}$.





Global fit





E.g. in the MSSM at tree level

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

and at loop level

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

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".

2nd referee says we can go on...

Fitting the Higgs invisible width

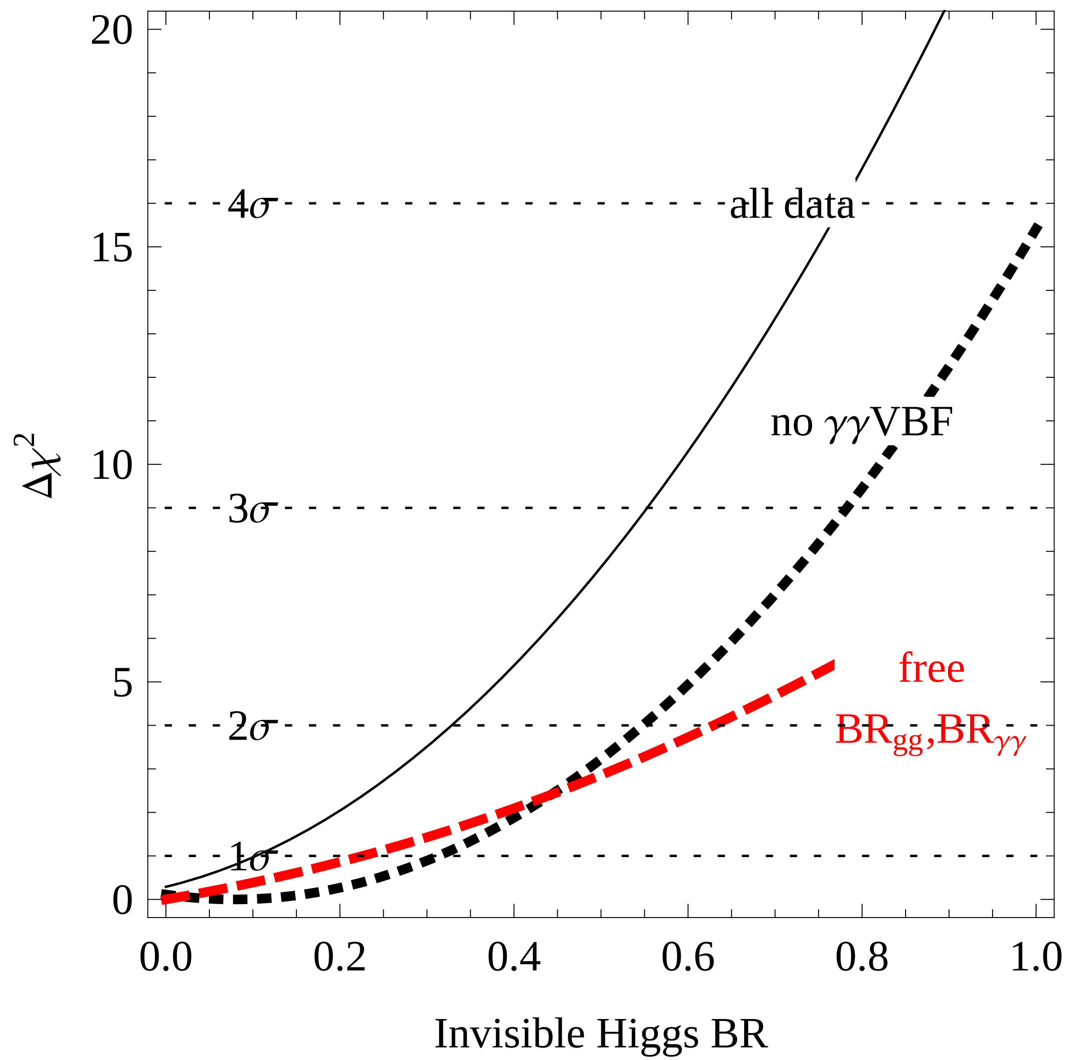
Data can test and disfavor an invisible width because $gg \to h$ and $h \to gg$ are related as well known since Breit-Wigner

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

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:

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

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

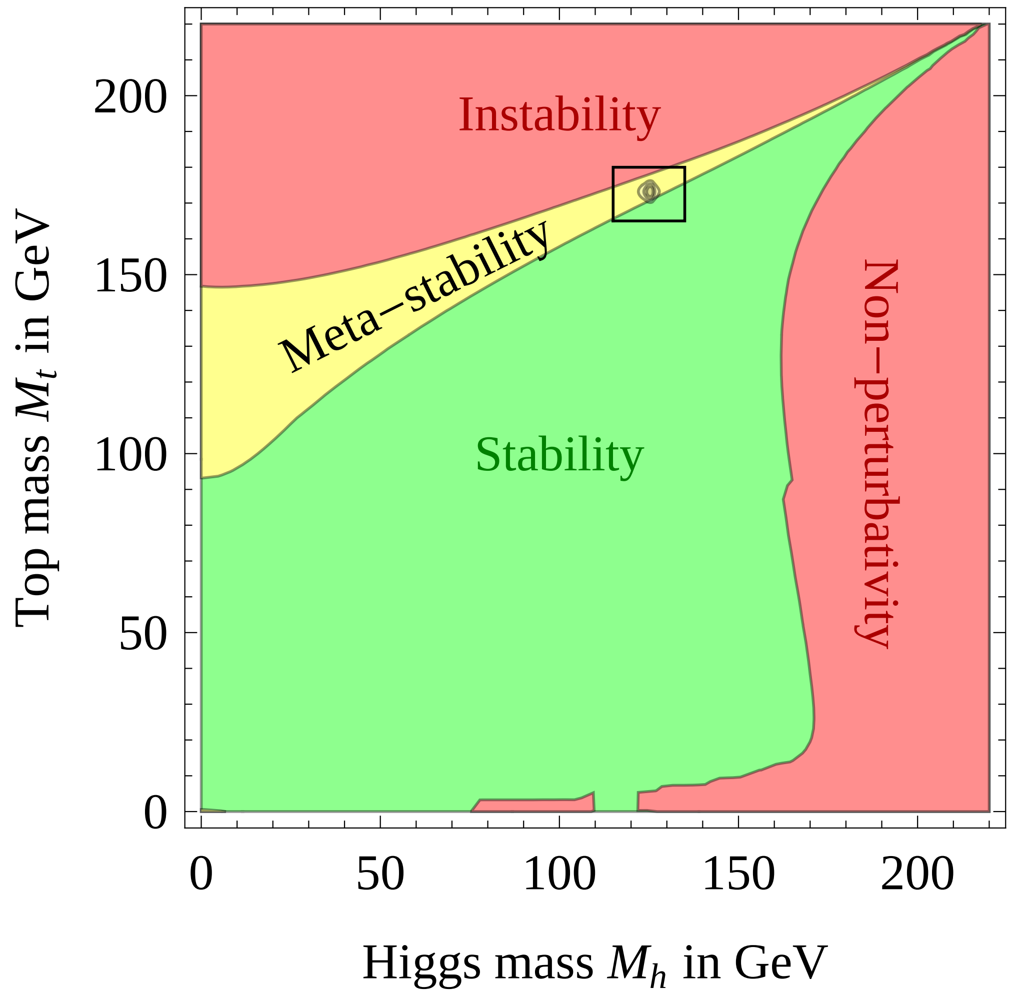
Fit almost as good as the SM Higgs, best at $R = 0.28 \pm 0.03$ (i.e. $\Lambda \approx 870$ GeV).

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_{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!

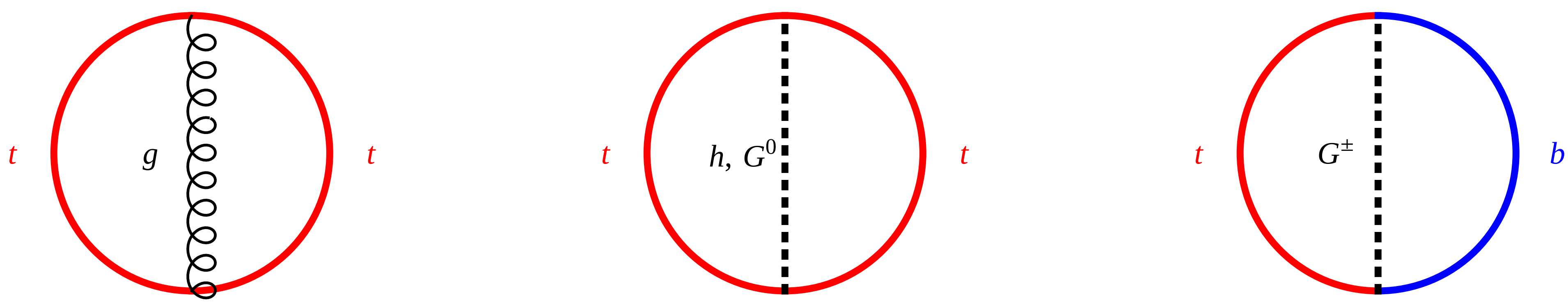
NNLO

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

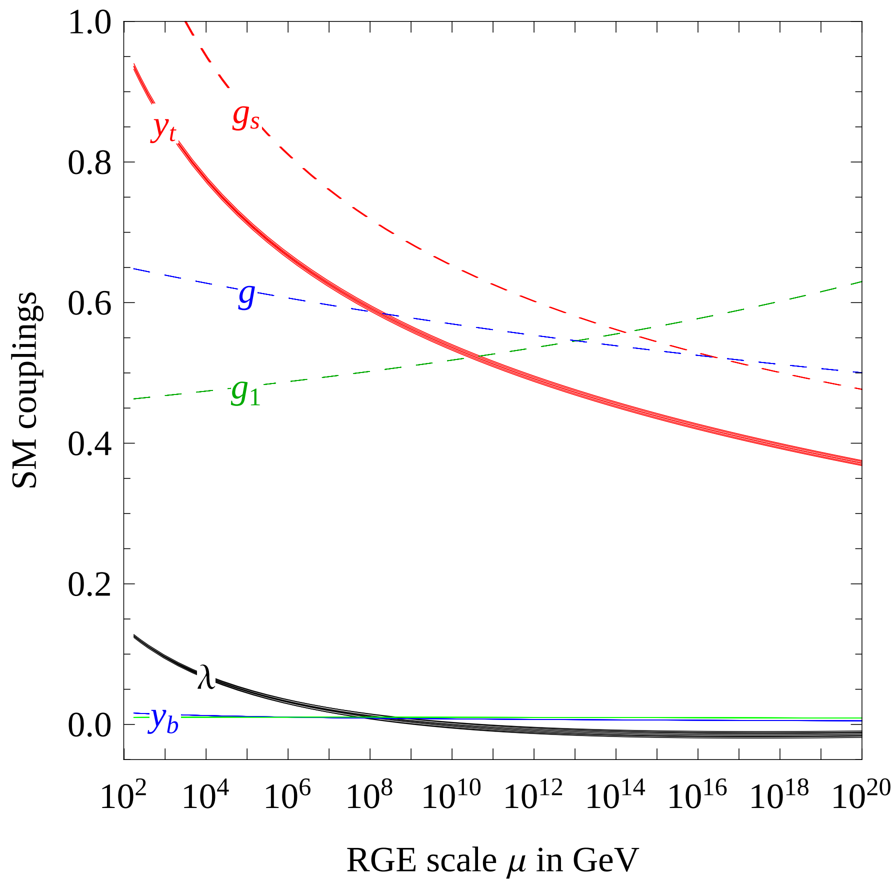


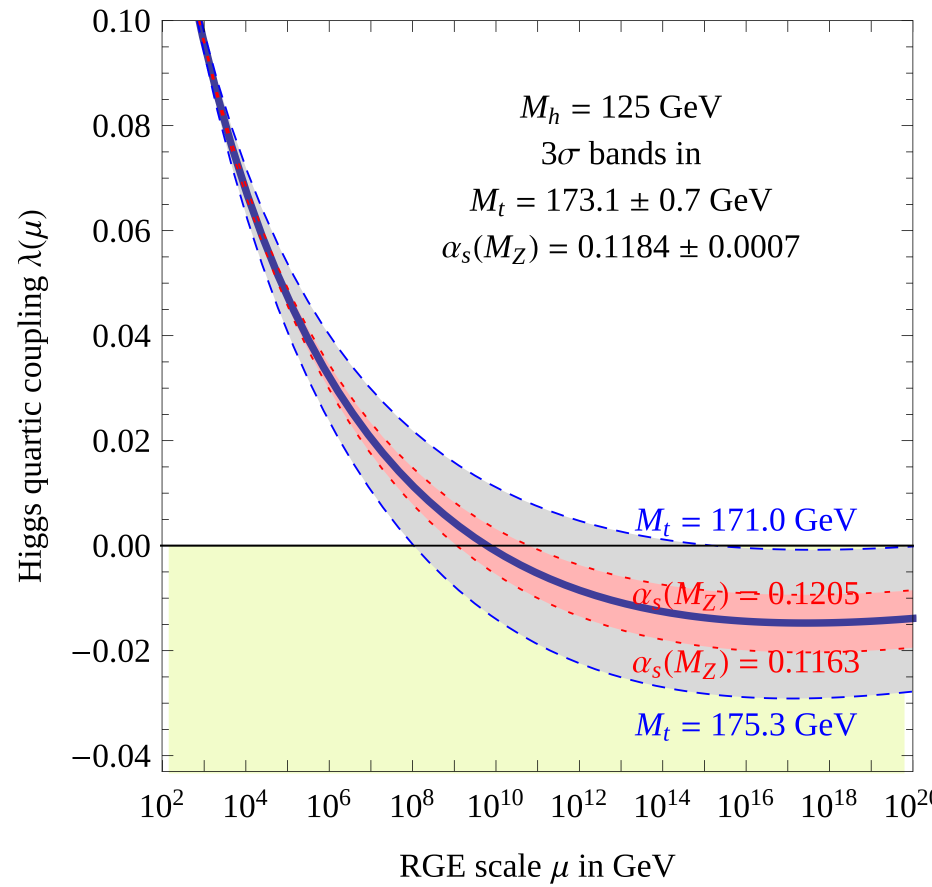
$$\delta m_h^2(\bar{\mu} = M_t)|_{\rm NNLO} = 0\frac{y_t^4 g_3^2 v^2}{(4\pi)^4} - 2(6+\pi^2)\frac{y_t^6 v^2}{(4\pi)^4} + \mathcal{O}(\lambda, g_1, g_2)$$

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

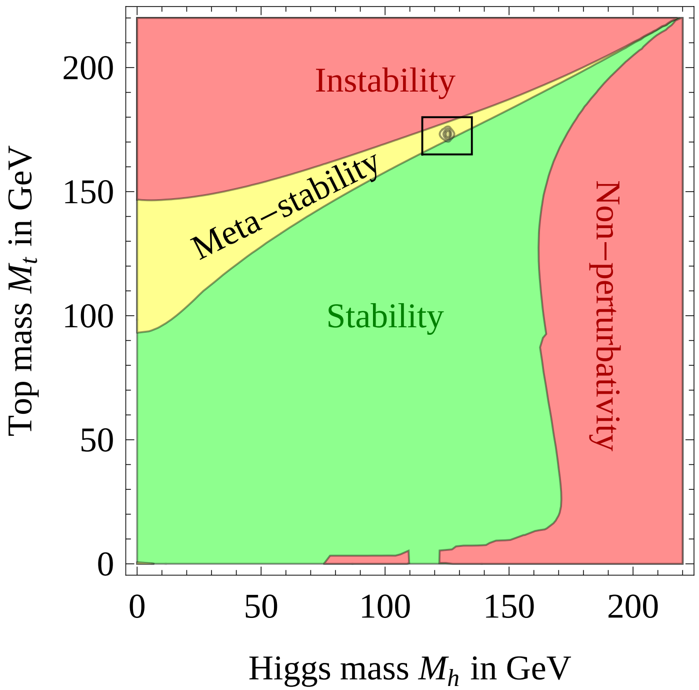
$$\lambda(M_t) = 0.12577 + 0.00205\left(\frac{M_h}{\mathrm{GeV}} - 125\right) - 0.00004\left(\frac{M_t}{\mathrm{GeV}} - 173.15\right) \pm 0.00140_{\mathrm{th}}$$

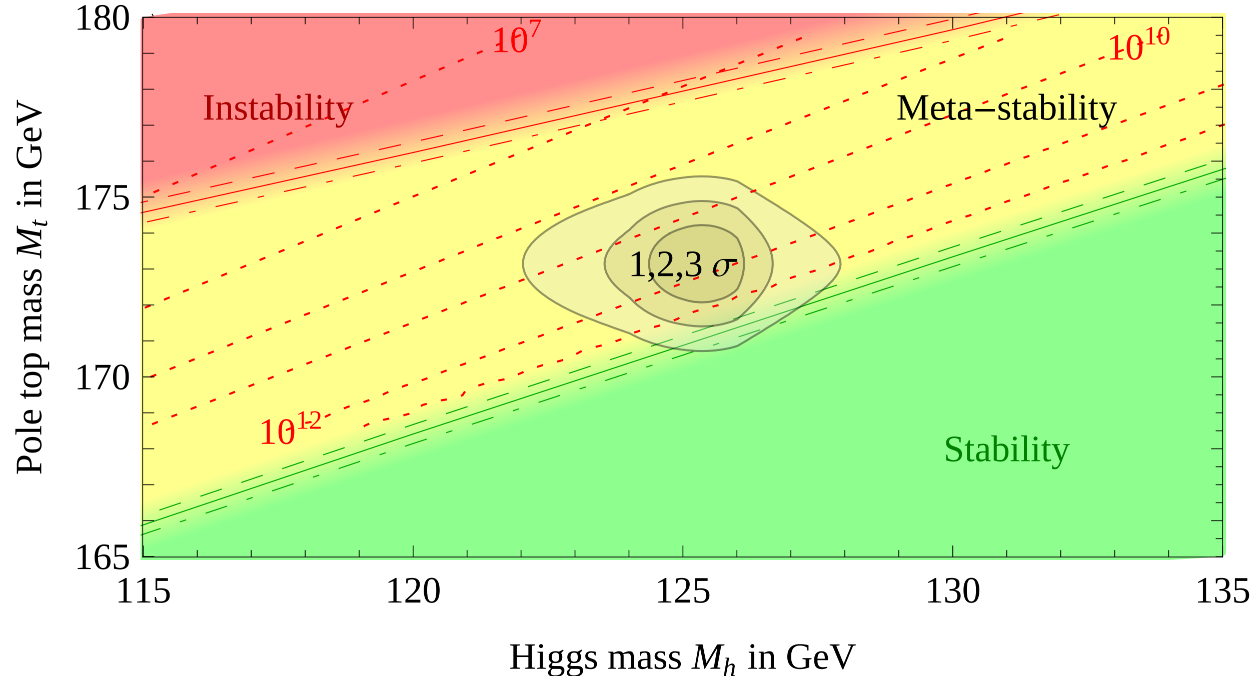




$$\lambda(M_{\mathrm{Pl}}) = -0.0144 + 0.0028\left(\frac{M_h}{\mathrm{GeV}} - 125\right) \pm 0.0047_{M_t} \pm 0.0018_{\alpha_s} \pm 0.0028_{\mathrm{th}}$$

The SM vacuum is metastable





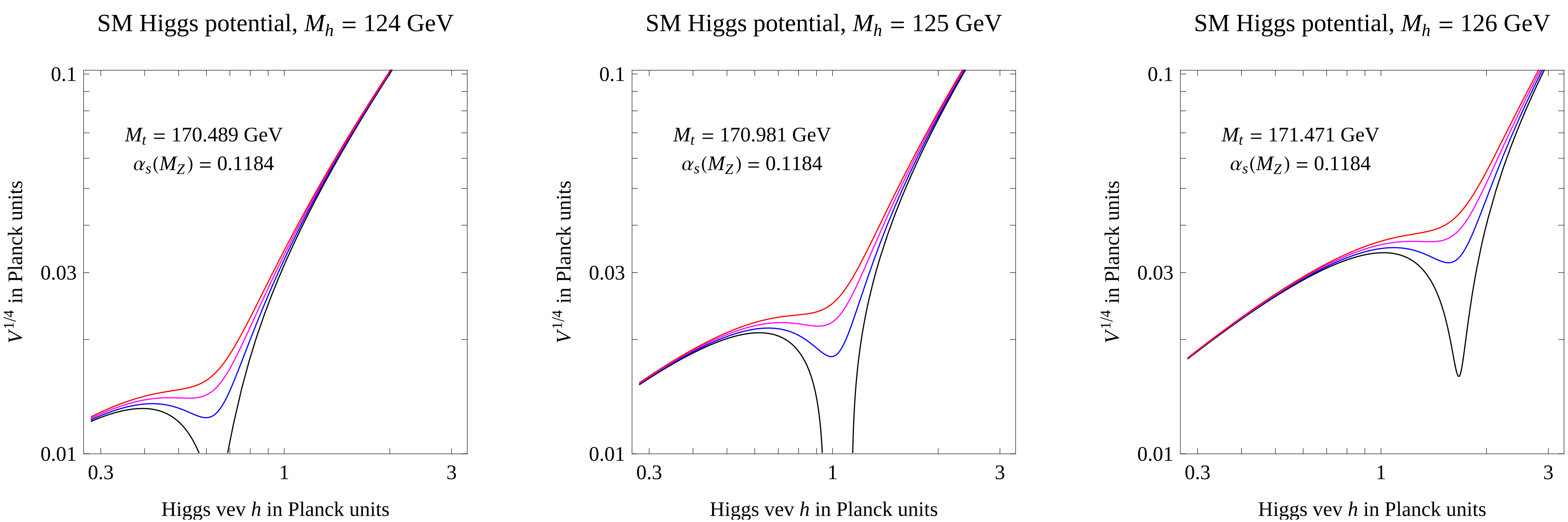
$$M_h\ [\text{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\text{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\text{th}}\ .$$

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.

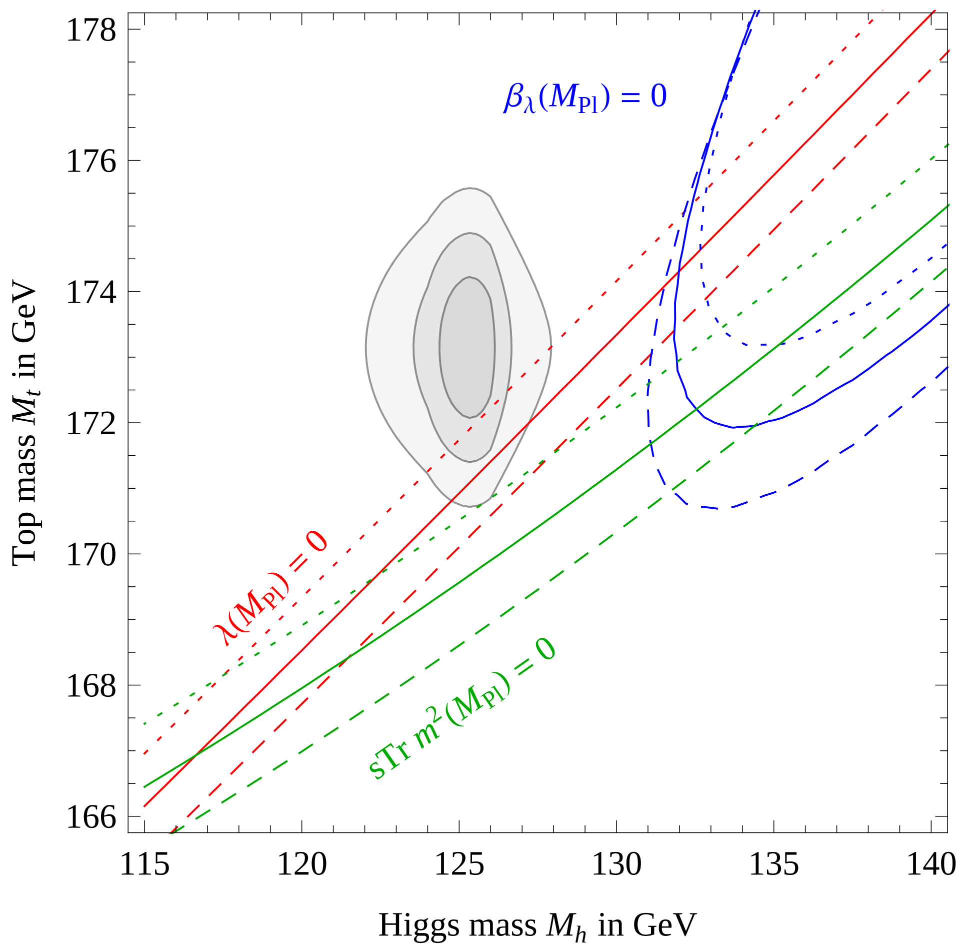
Implications: Higgs inflation?

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

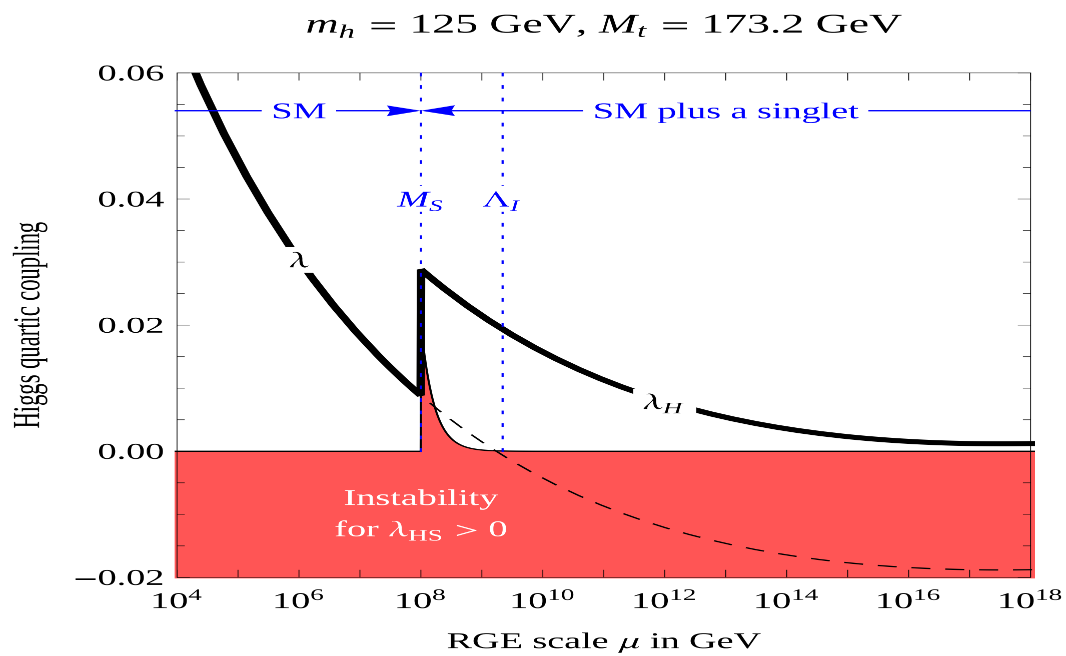
New physics can easily stabilize the SM potential. Lots of possibilities.

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:

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



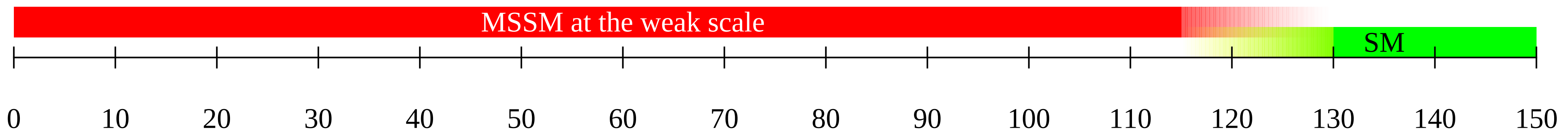
(with J. Elias-Miro, J.R. Espinosa, G. Giudice, H.M. Lee)

Higgs and SUSY

with G. Giudice

125 GeV is in no man's land

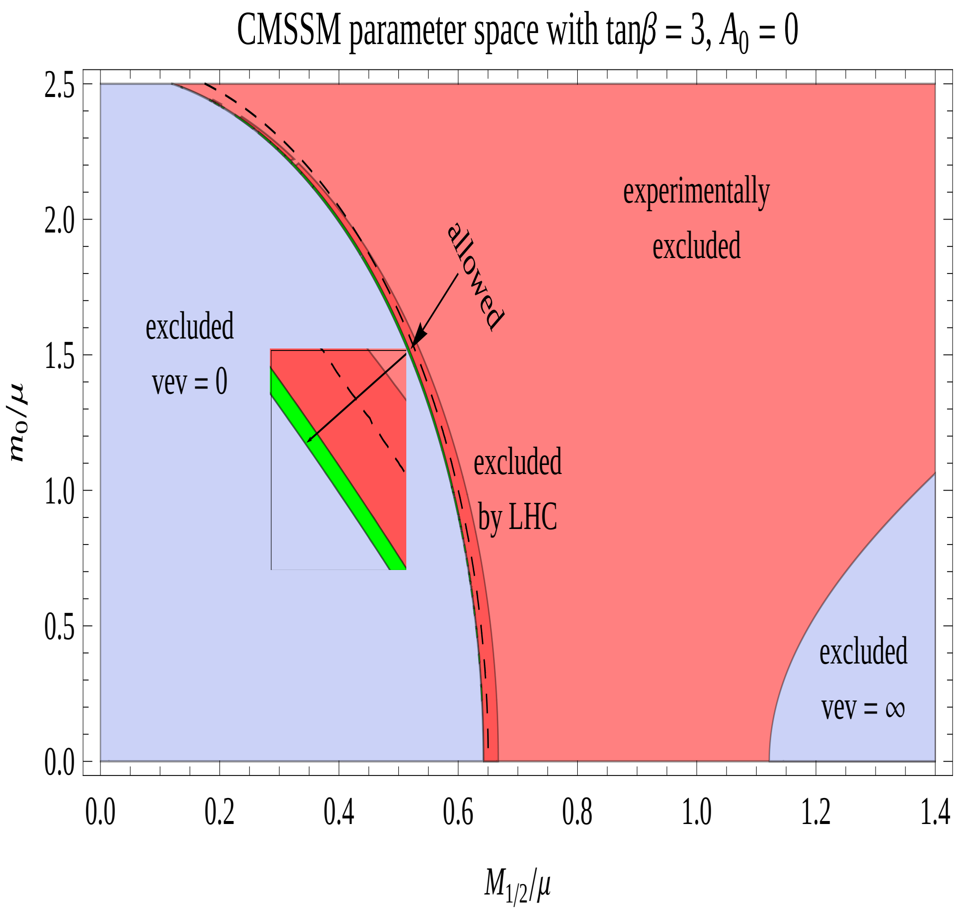
SM is stable up to the Planck scale for $m_h \gtrsim 130\,\text{GeV}$ but can go down to 115

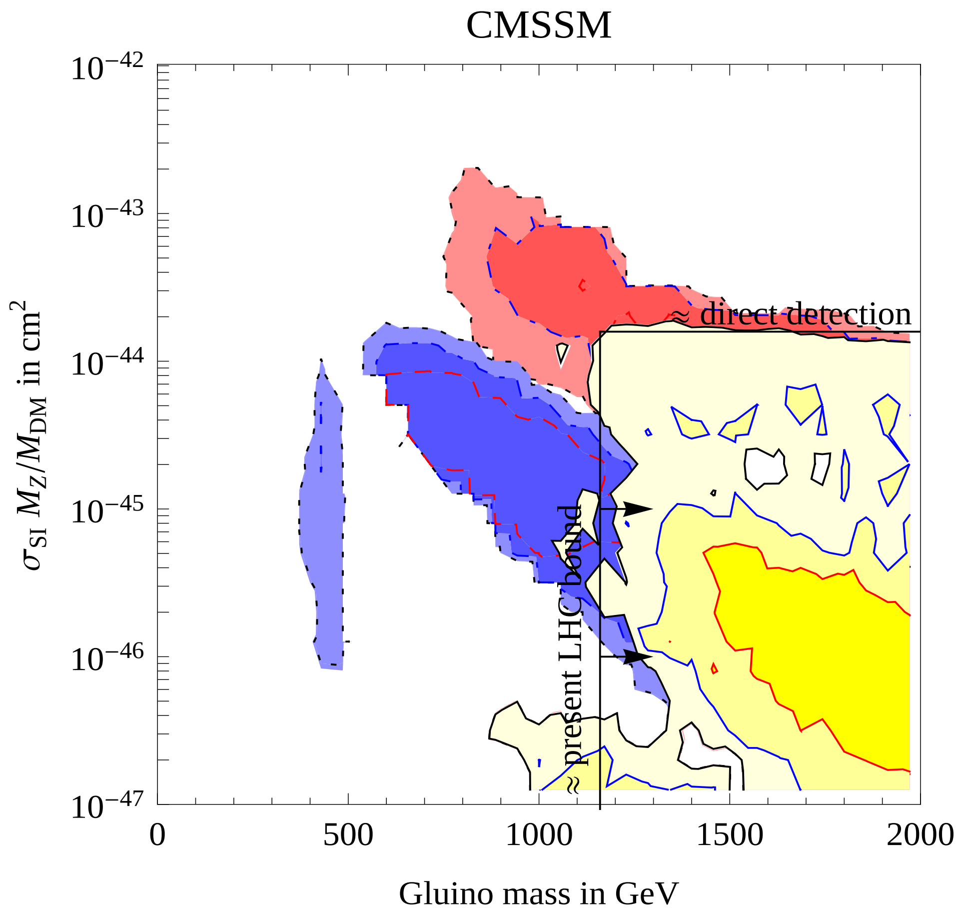


MSSM with weak scale SUSY likes $m_h \lesssim 120\,\text{GeV}$ but can go up to 130

SUSY is dead...

... $m_h \approx 125\,\mathrm{GeV}$ 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 $m_{\text{SUSY}} \gg M_Z$ and compute $m_h(m_{\text{SUSY}}, \tan\beta)$:

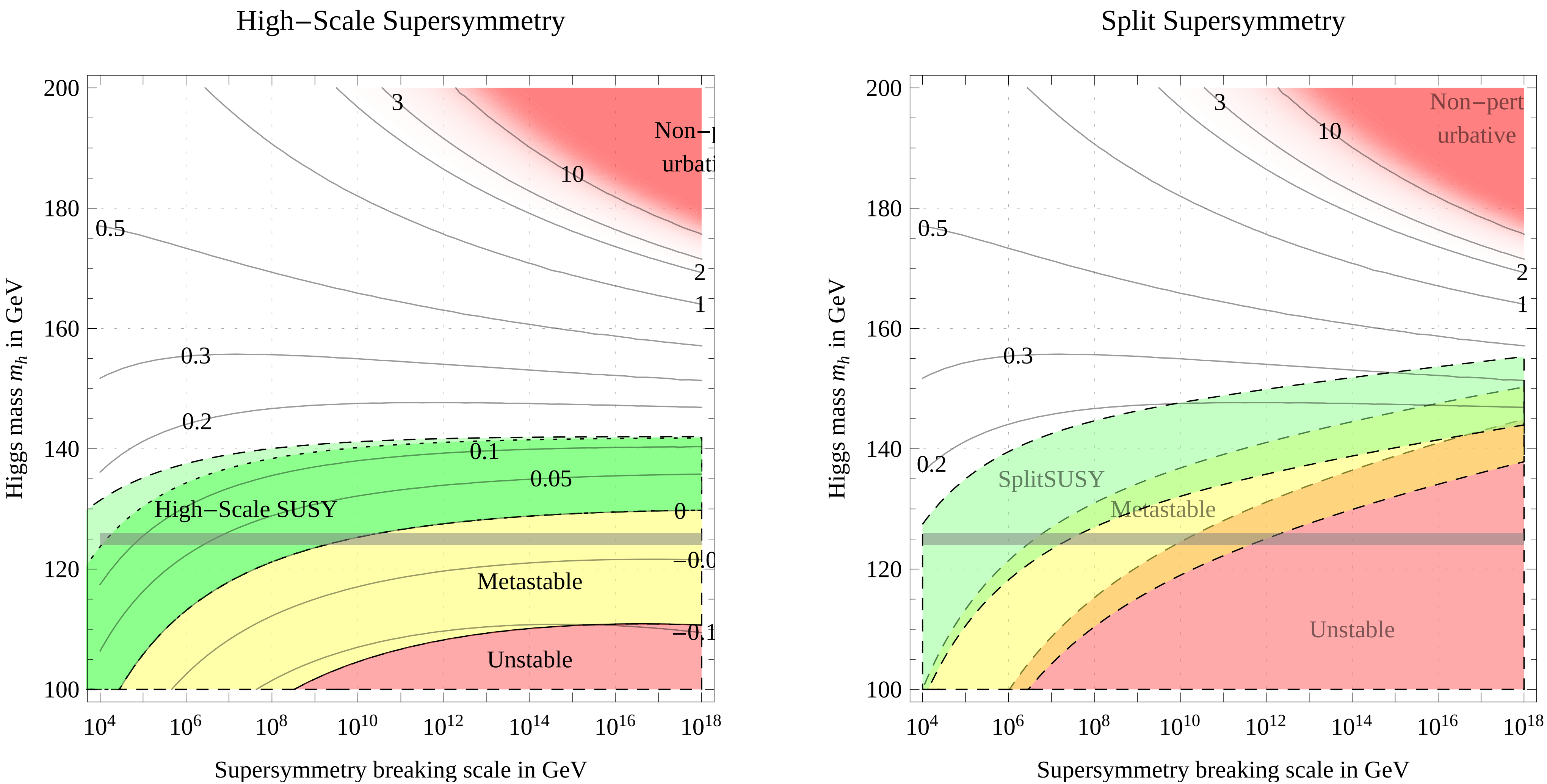
- **Split-SUSY** (SUSY scalars at m_{SUSY} and SUSY fermions around M_Z). Gives good unification and maybe makes theoretical sense.

- **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:

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

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

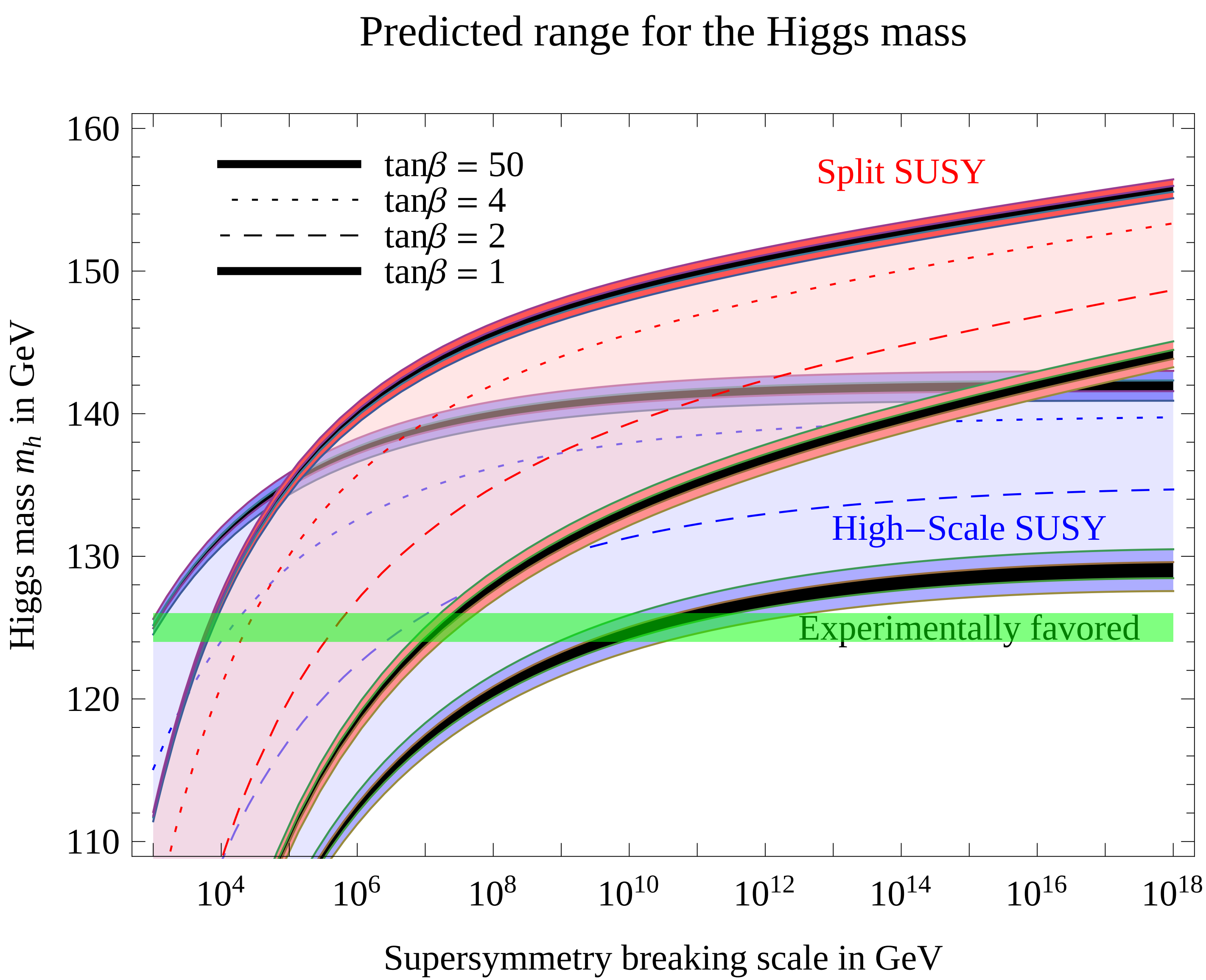
$$\delta\lambda = \lambda_N^2 \sin^2 2\beta \frac{(B-2A)M + m^2 - A^2}{2(M^2 + m^2 + BM)}$$

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:

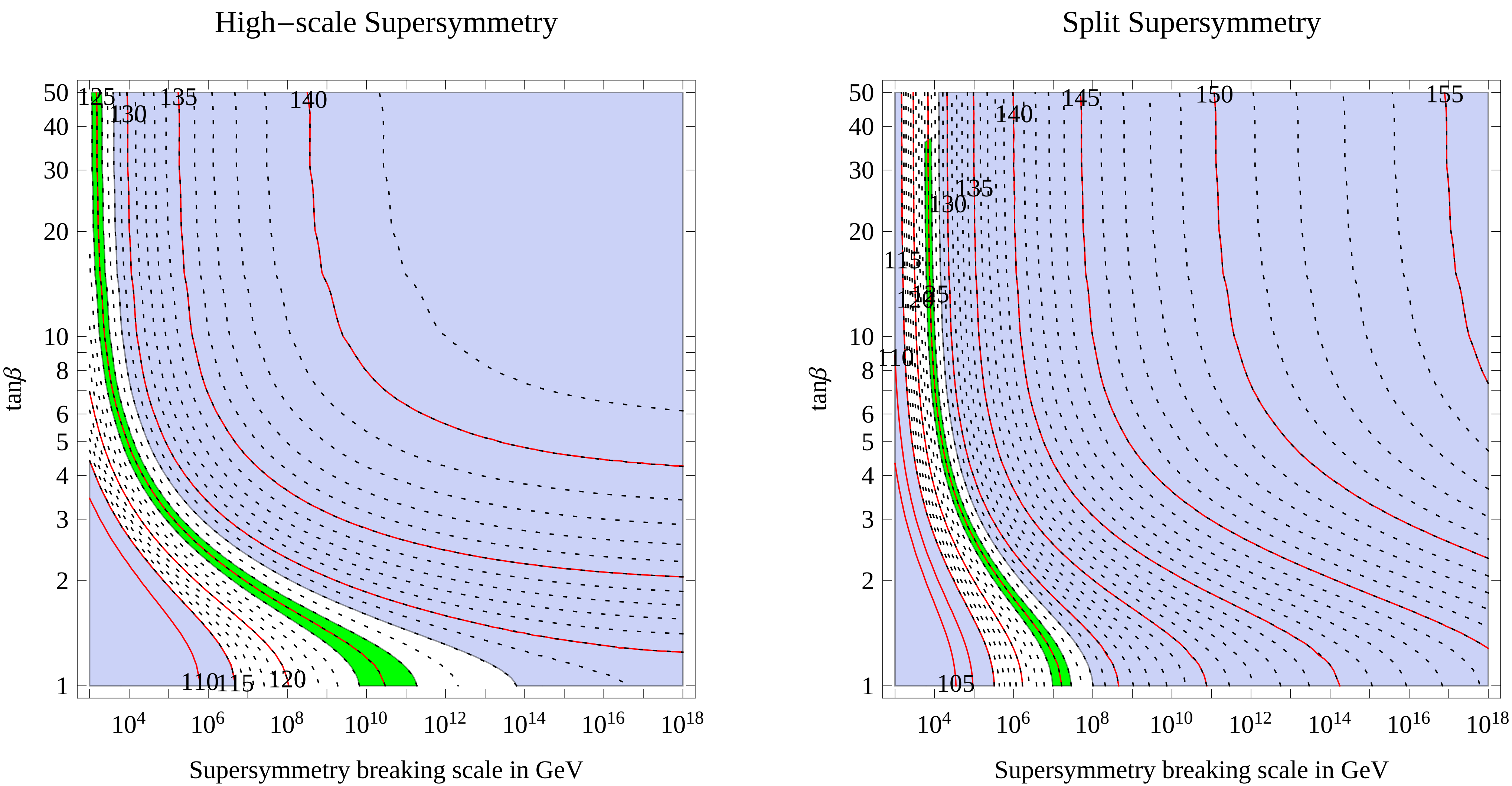
$$\mathscr{W} = \lambda_{ijk} 27_i 27_j 27_k$$

Effect of SM uncertainties



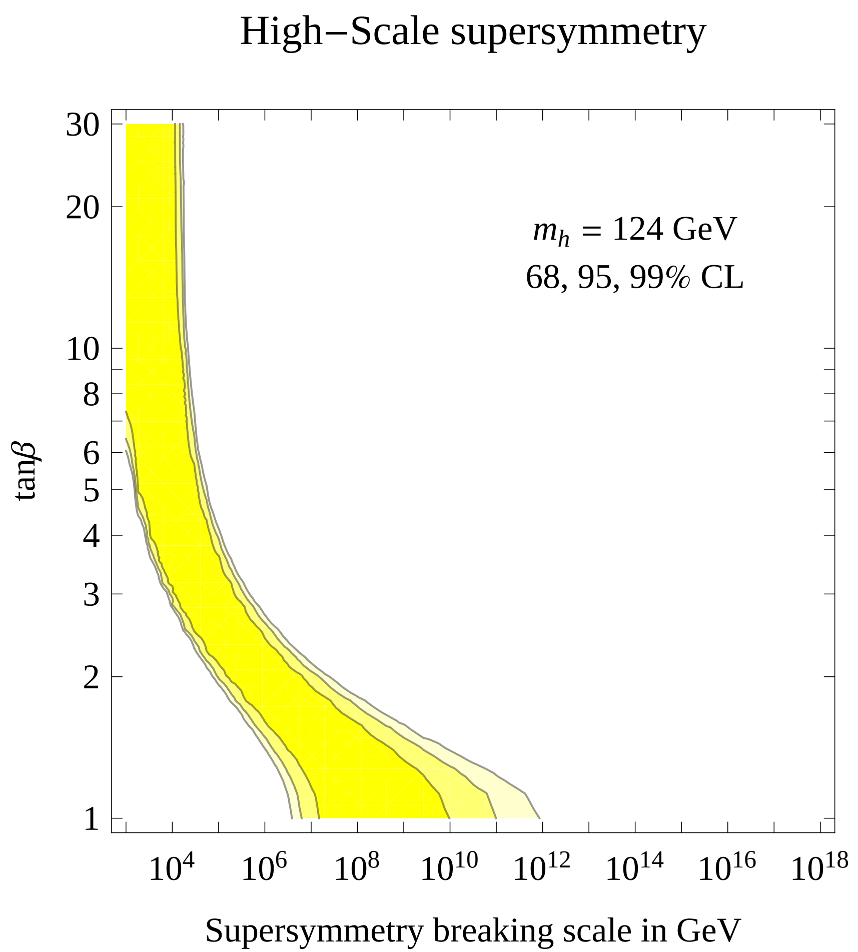
Thickness is $\pm 1\sigma$ on α_3 and on M_t. Theory error is now ± 1 GeV. Extra uncertainties coming from unknown SUSY thresholds are not in the figure.

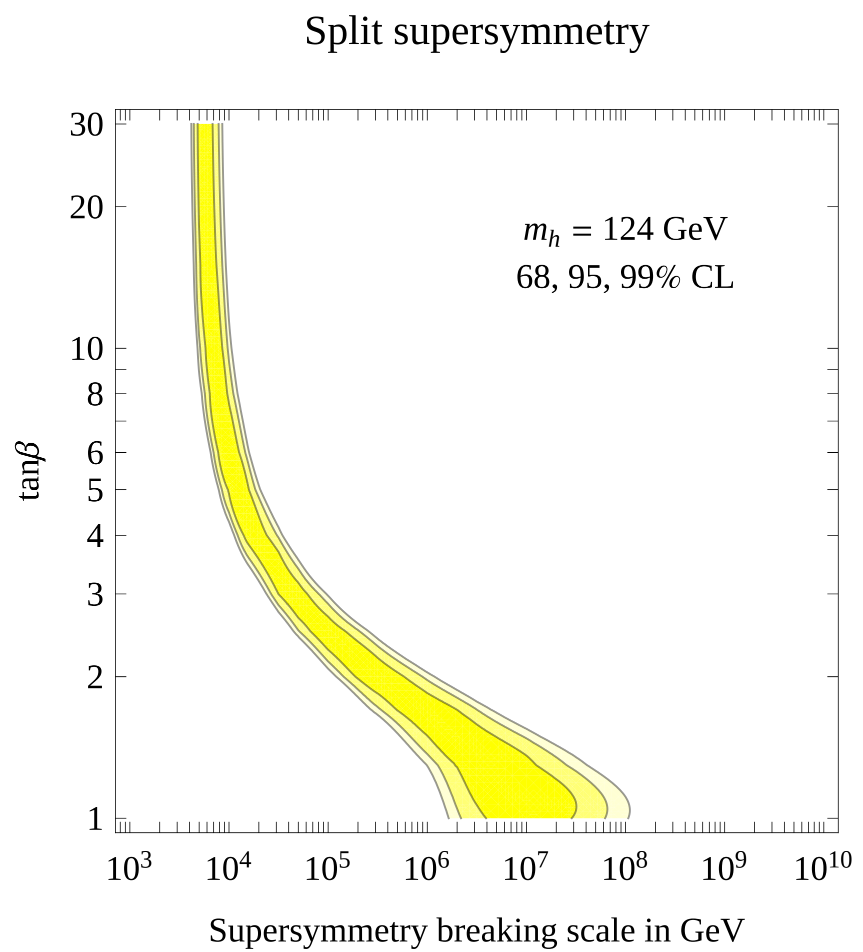
“Central values” for m_{SUSY} and $\tan\beta$



(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 $M_2 \approx 3$ 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.

What next?

Time to look outside the 'Higgs hierarchy ideology' lamppost

Split SUSY. Keep DM and unification and SUSY.

Higgs inflation. Does criticality of the Higgs potential allows inflation?

Minimal Dark Matter: DM is one SU(2) multiplet with only gauge couplings. Maybe a 5, which is accidentally stable like the proton: predict mass and $\sigma_{\rm SI}$.

$g-2$ **from fermions?** can be produced using only new fermions at the weak scale, assuming that m_μ comes from a see-saw. Predicts a non-standard $h \to \mu\mu$

Unificaxion: assume that axions give SM unification and predict its coupling.

g − 2 from fermions

Consider models 'charged see-saw models' like

$$\mathscr{L} = M_L \bar{L}' L' + M_E \bar{E}' E' + \lambda_L L' E H^* + \lambda_E L E' H^* + \bar{\lambda}_{LE} \bar{L}' \bar{E}' \; H + \text{h.c.}$$

where the muon mass comes out by integrating out heavy fermions L', E':

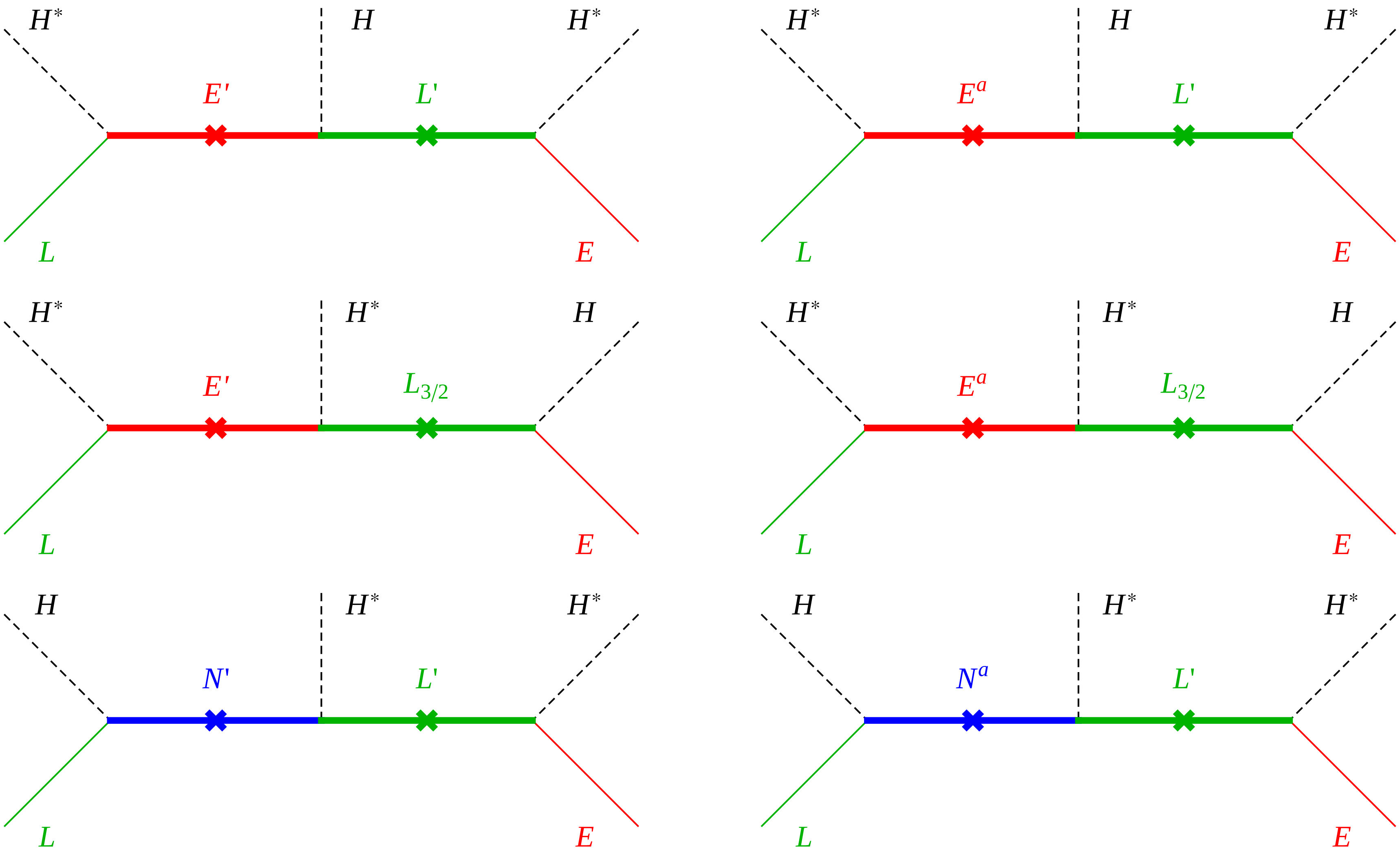
$$m_\mu = m_\mu^H + m_\mu^{HHH} = \lambda_\mu v + \frac{\lambda_L \bar{\lambda}_{LE} \lambda_E}{M_L M_E} v^3$$

Then

$$\Delta a_\mu \simeq c \frac{m_\mu m_\mu^{HHH}}{(4\pi v)^2} = 0.82 c \frac{m_\mu^{HHH}}{m_\mu} \times \Delta a_\mu^{\text{exp}},$$

where c is a model-dependent order-one number:

c	$-\frac{7}{2}$	$-\frac{15}{2}$	$-\frac{11}{2}$	-6	—	$-\frac{7}{2}$
see-saw	$L' \oplus E'$	$L' \oplus E^a$	$L_{3/2} \oplus E'$	$L_{3/2} \oplus E^a$	$L' \oplus N'$	$L' \oplus N_a$


H^*
H
H^*
E'
L'
L
E
H^*
H
H^*
E^a
L'
L
E
H^*
H^*
H
E'
$L_{3/2}$
L
E
H^*
H^*
H
E^a
$L_{3/2}$
L
E
H
H^*
H^*
N'
L'
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H
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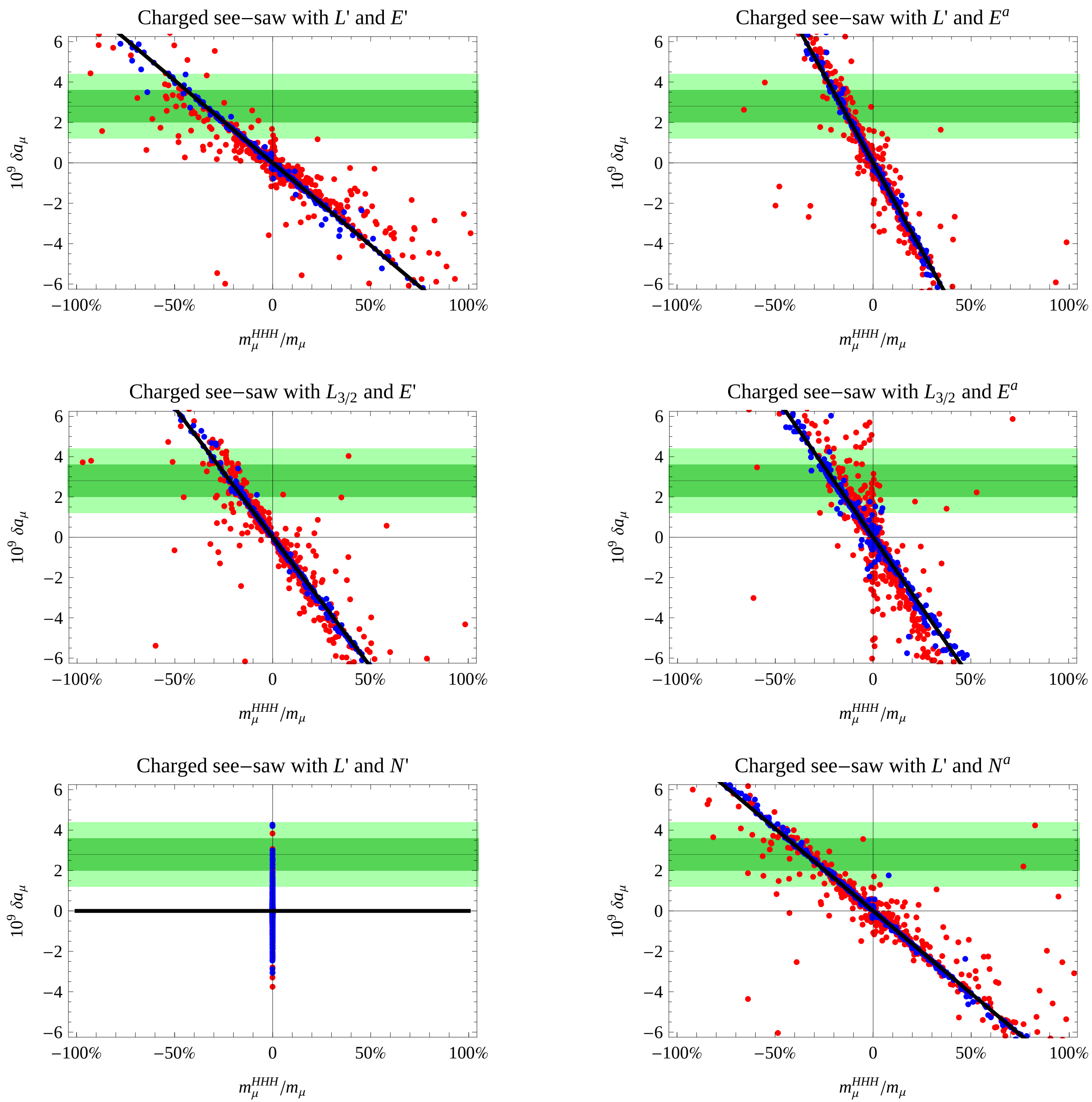
N^a
L'
L
E



Charged see−saw with L' and E'
Charged see−saw with L' and E^a
Charged see−saw with $L_{3/2}$ and E'
Charged see−saw with $L_{3/2}$ and E^a
Charged see−saw with L' and N'
Charged see−saw with L' and N^a
$10^9\ \delta a_\mu$
m_μ^{HHH}/m_μ
−100%
−50%
0
50%
100%
6
4
2
0
−2
−4
−6

Unificaxion

0) Abandon SUSY and naturalness of the weak scale
1) The QCD θ problem is non-ant***opic: axion
2) Realize axion with heavy fermions a la KSVZ
3) Assume that such fermions give unification
4) Predict axion couplings, test assuming axionic DM
(arXiv/1204.5465 with Giudice and Rattazzi)

SU(5) unification

New fermions at M_Ψ affect RGE running with their β-function coefficients Δb_i:

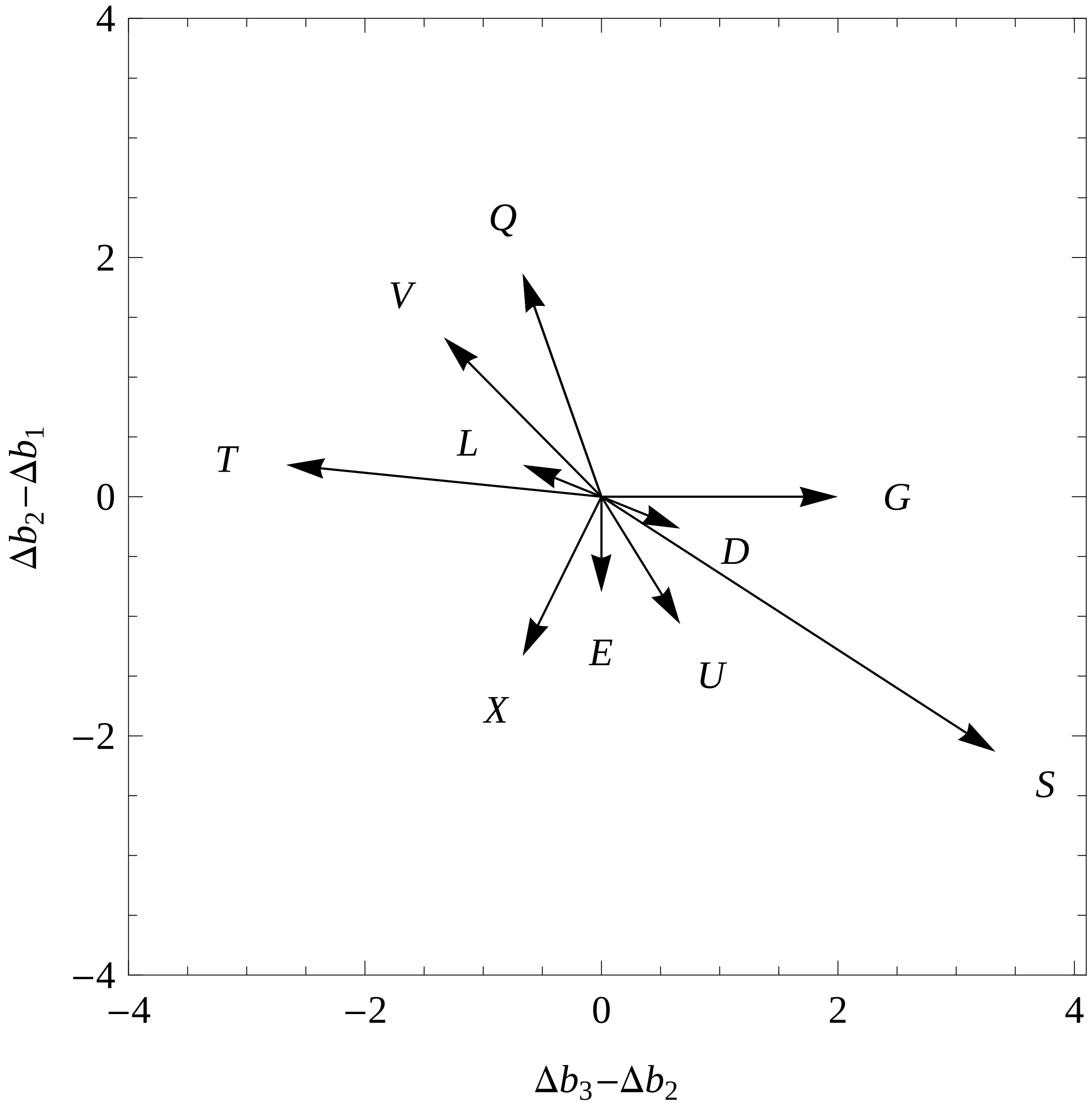
$$\frac{1}{\alpha_{\text{GUT}}} = \frac{1}{\alpha_i(M_Z)} - \frac{b_i^{\text{SM}}}{2\pi} \ln \frac{M_{\text{GUT}}}{M_Z} - \frac{\Delta b_i}{2\pi} \ln \frac{M_{\text{GUT}}}{M_\Psi}.$$

The simplest SU(5) fragments are:

SU(5)	SU(3) $\otimes$	SU(2) $\otimes$	U(1)	n_3	$\bar{n}_3$	n_2	z	name	Δb_3	Δb_2	Δb_1
$5 \oplus \bar{5}$	$\bar{3}$	1	$^1/_3$	0	1	0	0	D	2/3	0	4/15
$5 \oplus \bar{5}$	1	2	$^1/_2$	0	0	1	0	L	0	2/3	2/5
$10 \oplus \overline{10}$	$\bar{3}$	1	$-^2/_3$	0	1	0	1	U	2/3	0	16/15
$10 \oplus \overline{10}$	1	1	-1	0	0	0	1	E	0	0	4/5
$10 \oplus \overline{10}$	3	2	$^1/_6$	1	0	1	0	Q	4/3	2	2/15
$15 \oplus \overline{15}$	3	2	$^1/_6$	=	=	=	=	Q	=	=	=
$15 \oplus \overline{15}$	1	3	1	0	0	2	0	T	0	8/3	12/5
$15 \oplus \overline{15}$	6	1	$-^2/_3$	2	0	0	0	S	10/3	0	32/15
24	1	3	0	0	0	2	1	V	0	4/3	0
24	8	1	0	1	1	0	0	G	2	0	0
24	$\bar{3}$	2	$^5/_6$	0	1	1	0	X	4/3	2	10/3

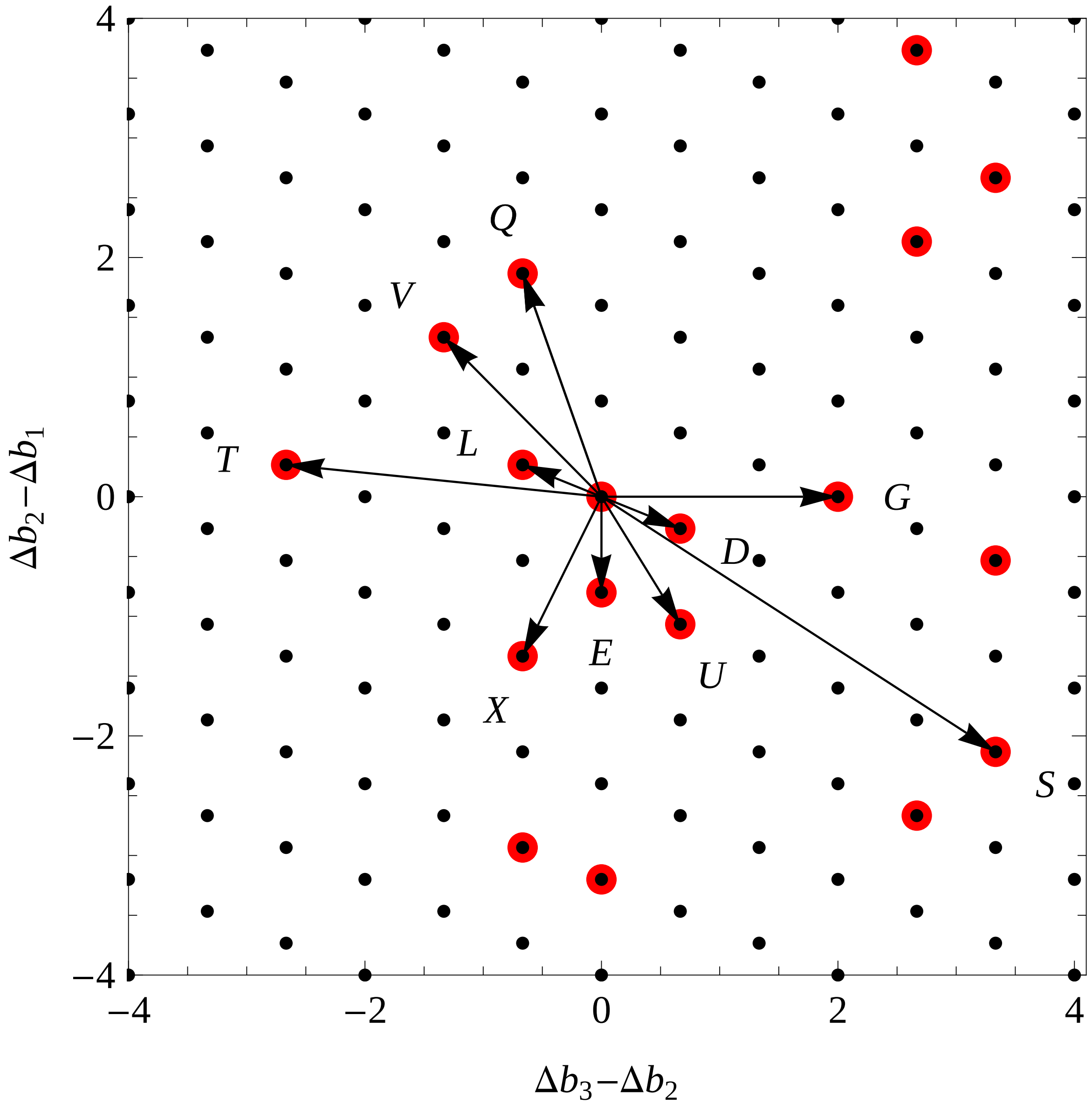
The SU(5) lattice

Apparently, the Δb_i arising from generic combinations of SU(5) fragments are a hopeless huge number of possibilities

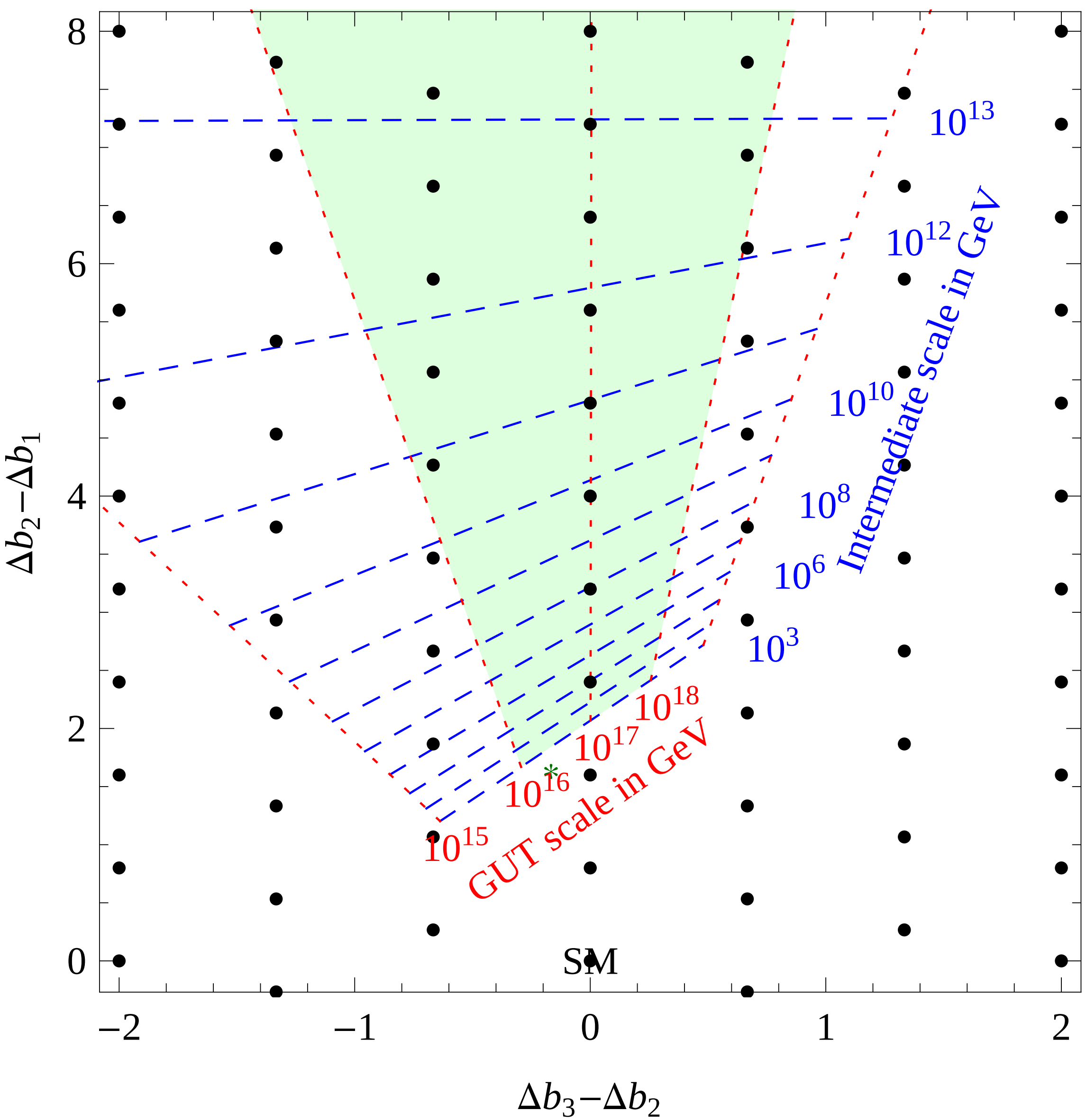


The SU(5) lattice

Actually, the Δb_i arising from generic combinations of SU(5) fragments form a sparse lattice generated by the simplest 5 and 10 rep.s



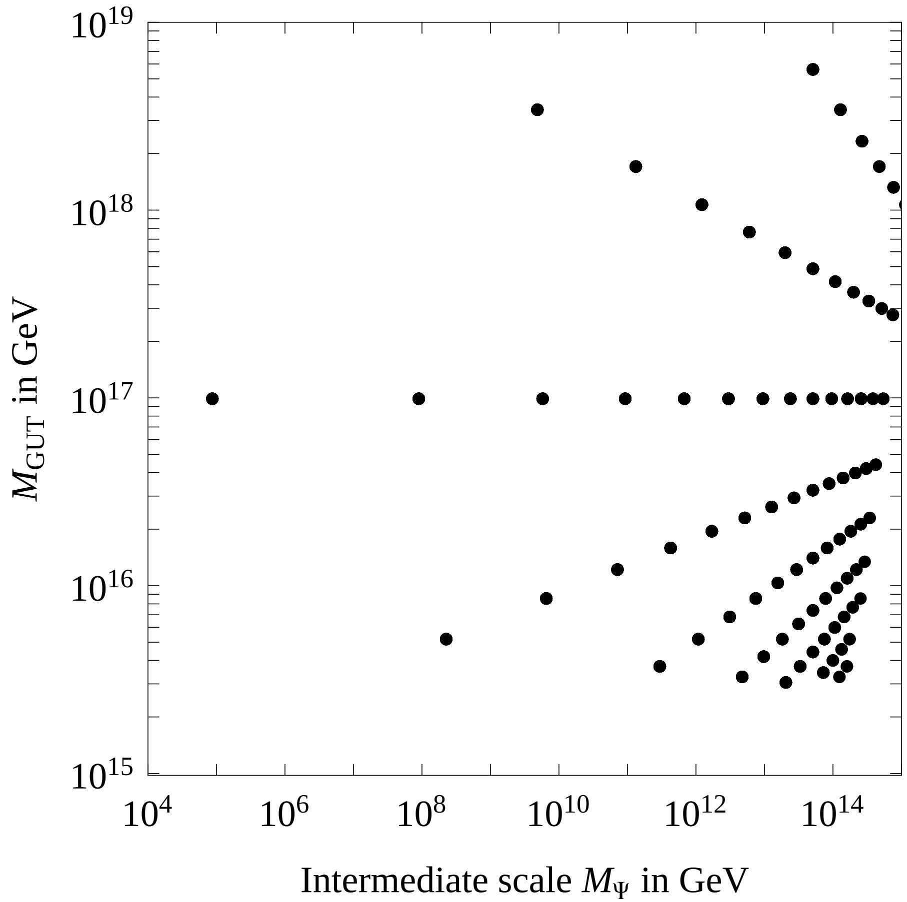
Gut GUT

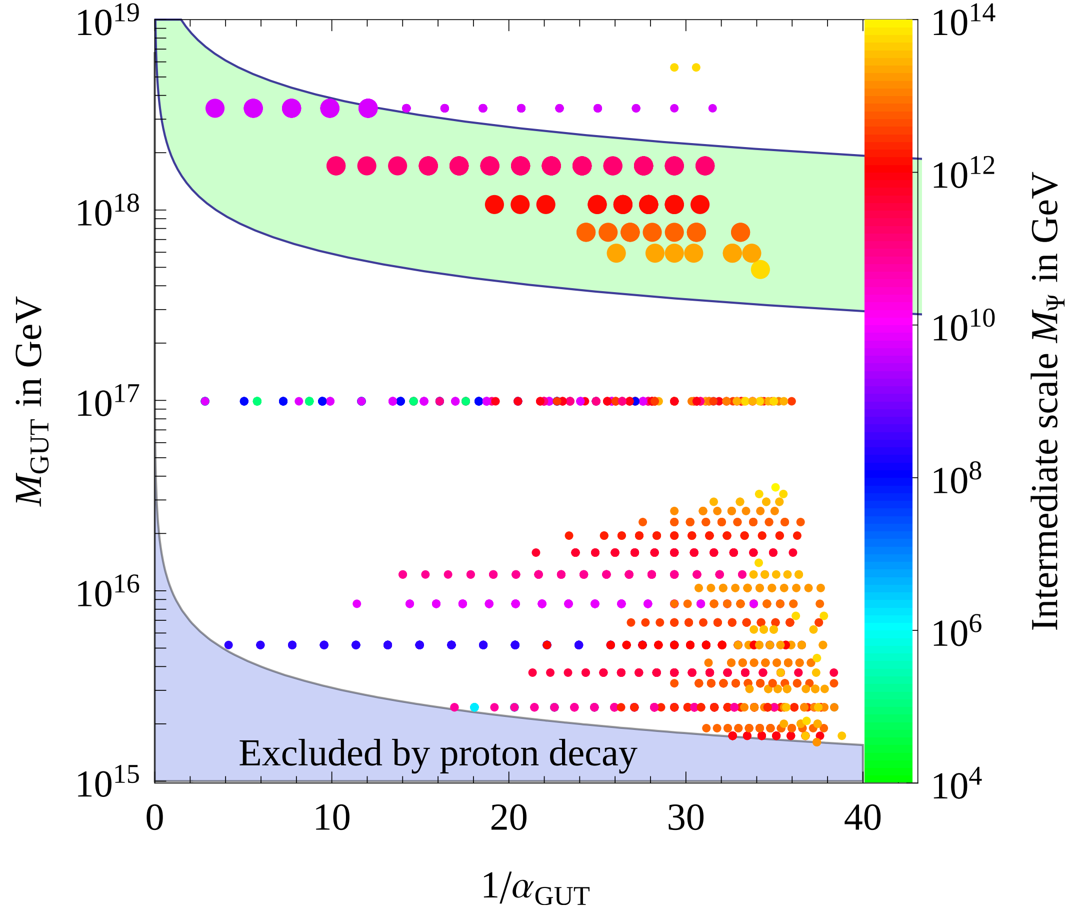


$\star$ ist ZUZY

GUT collection

Discrete set of values for the GUT scale and for the intermediate scale:

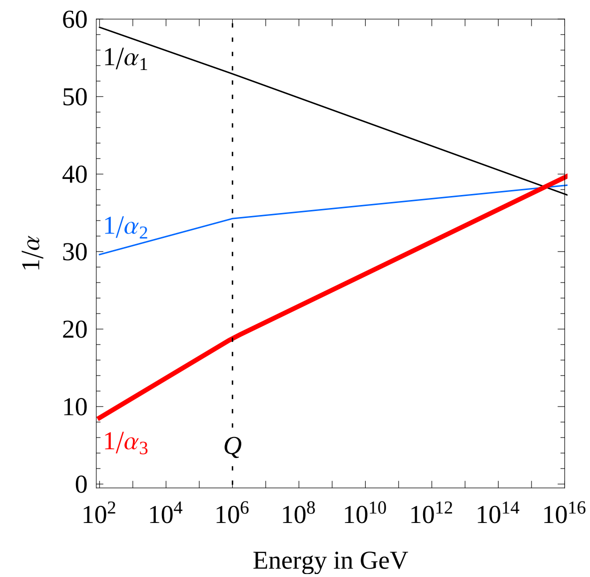




Green thick dots: favored by gauge/gravity unification $\alpha_{\mathrm{GUT}} = (1\ldots 43)(\frac{M_{\mathrm{GUT}}}{M_{\mathrm{Pl}}})^2$.

Simplest GUTs

heavy fermions	$\alpha_{\rm GUT}$	$M_{\rm GUT}$	M_Ψ	E/N
Q	$1/38$	2×10^{15} GeV	1×10^{6} GeV	$5/3$
$2Q$	$1/38$	2×10^{15} GeV	5×10^{10} GeV	$5/3$
$3Q$	$1/38$	2×10^{15} GeV	2×10^{12} GeV	$5/3$
$2Q\oplus D$	$1/36$	8×10^{15} GeV	6×10^{9} GeV	$22/15$
$2Q\oplus U$	$1/34$	5×10^{15} GeV	2×10^{8} GeV	$28/15$
$G\oplus 2V$	$1/38$	5×10^{15} GeV	2×10^{8} GeV	$4/3$
$Q\oplus G\oplus V$	$1/35$	9×10^{16} GeV	8×10^{7} GeV	$16/15$
$Q\oplus D\oplus L$	$1/36$	2×10^{15} GeV	1×10^{6} GeV	2



Proton decay could be around the corner: $M_{\rm GUT} > \sqrt{\dfrac{\alpha_{\rm GUT}}{1/24}}\; 2\times 10^{15}$ GeV

Axion basics

Assume a PQ symmetry that allows for $\lambda A\bar{\Psi}\Psi$

$$\Psi \to e^{i\gamma_5\alpha}\Psi, \qquad A \to e^{-2i\alpha}A,$$

with equal or comparable λ such that there is one intermediate scale $M \sim \lambda f_a$.

$* \qquad * \qquad *$

The “initial misalignment” mechanism gives a DM axion density

$$\Omega_a \approx 0.15 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6}\left(\frac{a_*}{f_a}\right)^2$$

Ω_{DM} reproduced for $f_a \sim 10^{12}\,\mathrm{GeV}$ unless the initial axion vev is $a_* \ll f_a$.

This favors $m_a \sim \mu\mathrm{eV} = 1/20\,\mathrm{cm}$

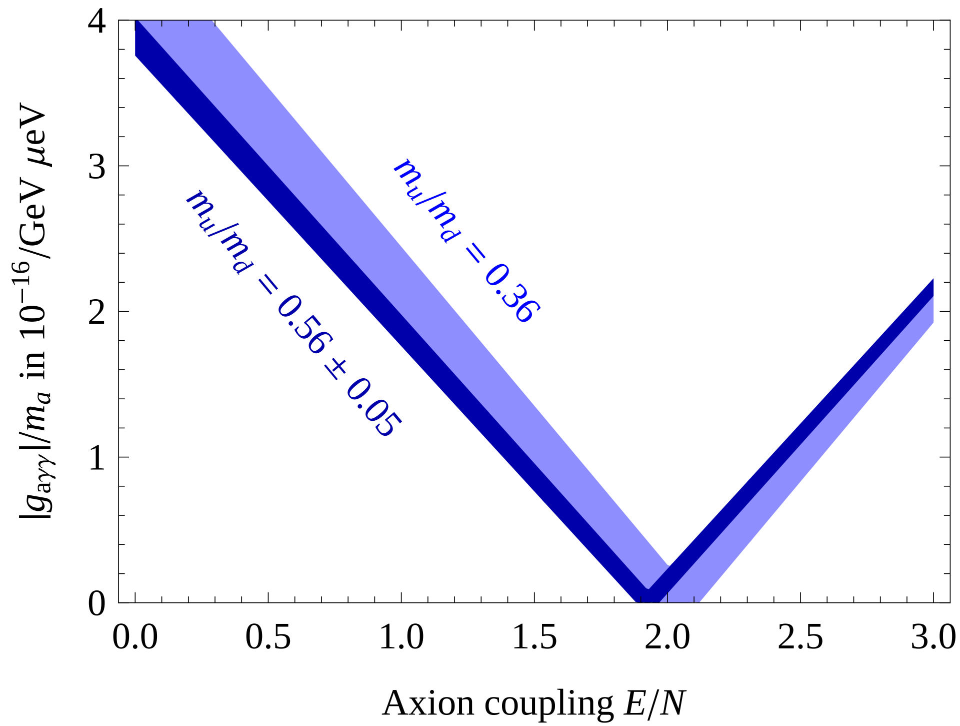
Axion coupling to photons: theory

The coupling $-g_{a\gamma\gamma}\frac{1}{4}aF_{\mu\nu}\tilde{F}_{\mu\nu}$ is predicted in terms of model coefficients E/N:

$$g_{a\gamma\gamma}=\frac{\alpha\ m_a}{2\pi f_\pi m_\pi}\sqrt{(1+\frac{m_d}{m_u})(1+\frac{m_u}{m_d})}\left[\frac{E}{N}-\frac{2}{3}\frac{4+m_u/m_d}{1+m_u/m_d}\right]\approx\frac{2.0\ (E/N-1.92)}{10^{16}\,\text{GeV}}\frac{m_a}{\mu\text{eV}}$$

$$E=\sum_\Psi q^2,\qquad T=\sum_\Psi T^2$$

Uncertainty band

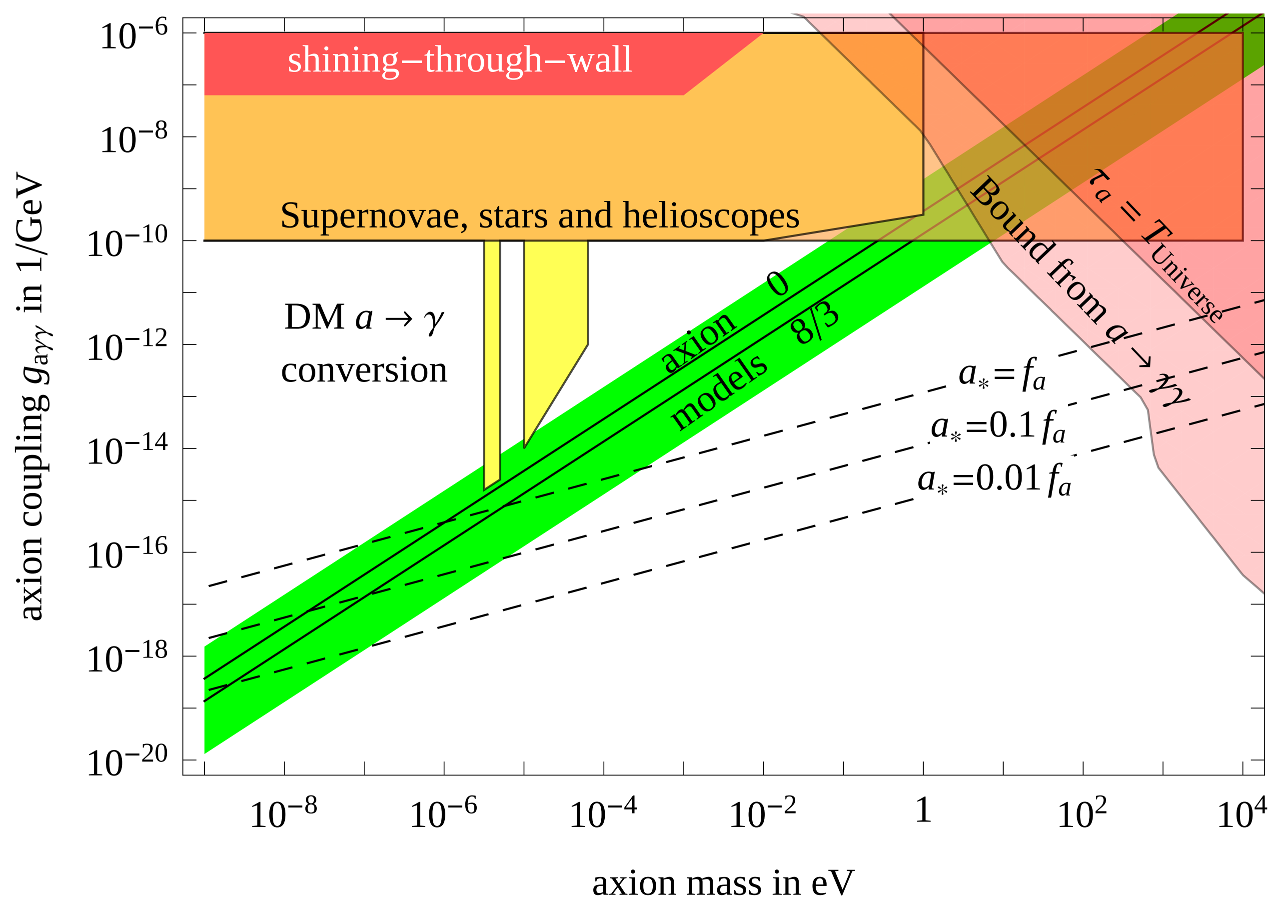


Axion coupling to photons: data

ADMX reached

$$|g_{a\gamma\gamma}| < \frac{6}{10^{16}\,\mathrm{GeV}} \frac{m_a}{\mu\mathrm{eV}} \sqrt{\frac{0.4\,\mathrm{GeV/cm}^3}{\rho_{\mathrm{DM}}}}$$

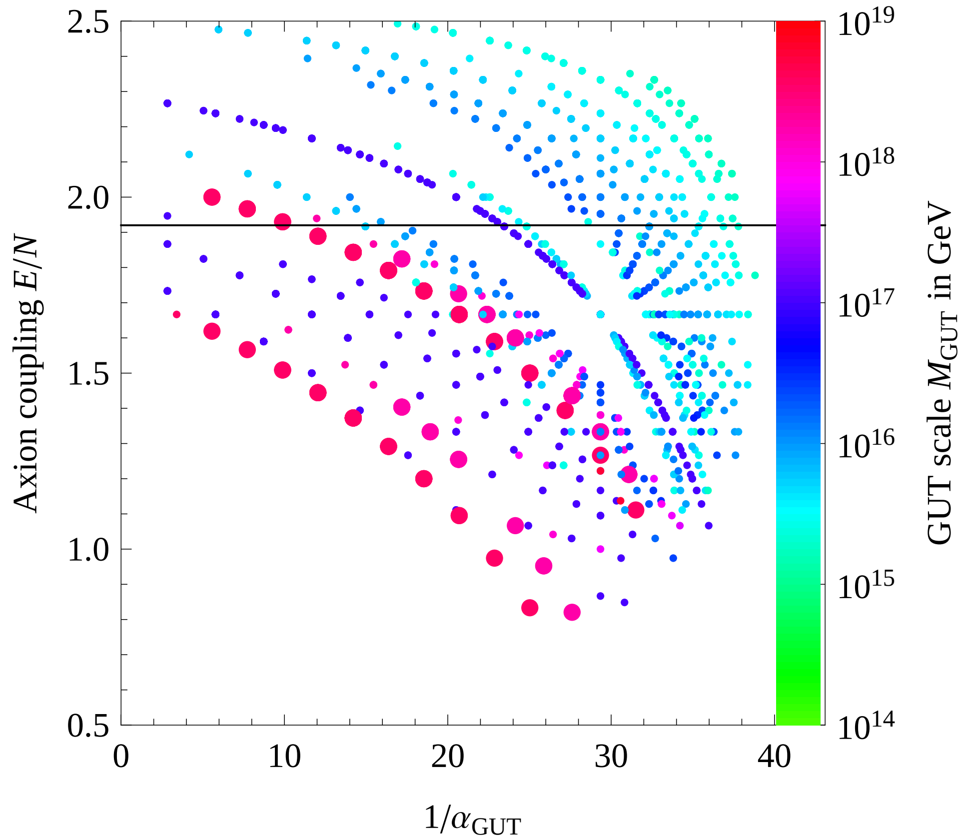
for m_a in the range $1.9 - 3.55\,\mu$eV

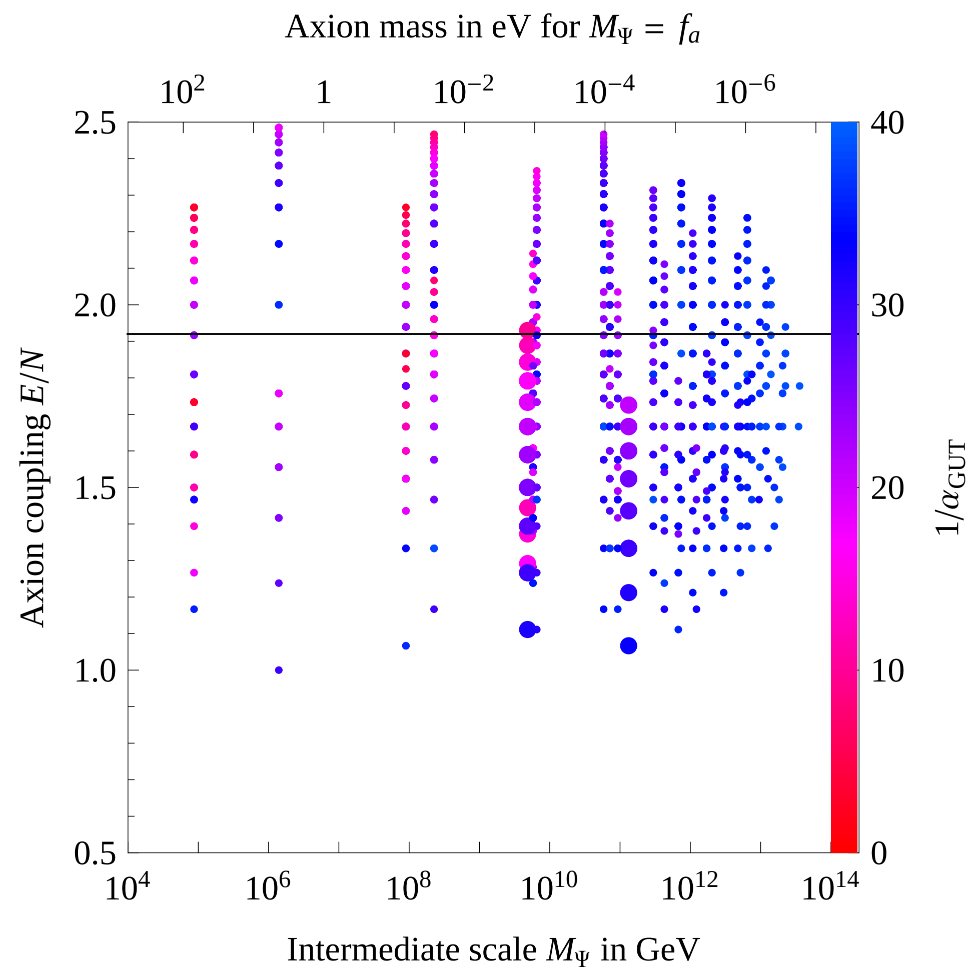


Unificaxion

Axion coupling predicted in terms of β-functions restricted by unification:

$$\frac{E}{N} \equiv \frac{\sum q^2}{\sum T^2} = \frac{\Delta b_2 + 5\Delta b_1/3}{\Delta b_3}$$





[Predict $1 < E/N < 2.5$] [$+\alpha_{\mathrm{GUT}} \sim 1$: $E/N > 1.6$] [+gauge/gravity: $E/N < 2$]