Higgs boson implications for natural and unnatural theories

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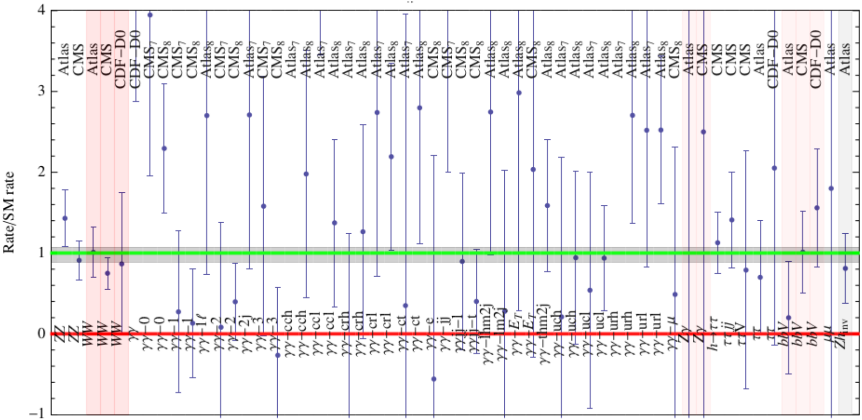
The observed Higgs looks Standard Model

$m_h \simeq 125.7$ GeV and

Giardino et al. 1303.3570



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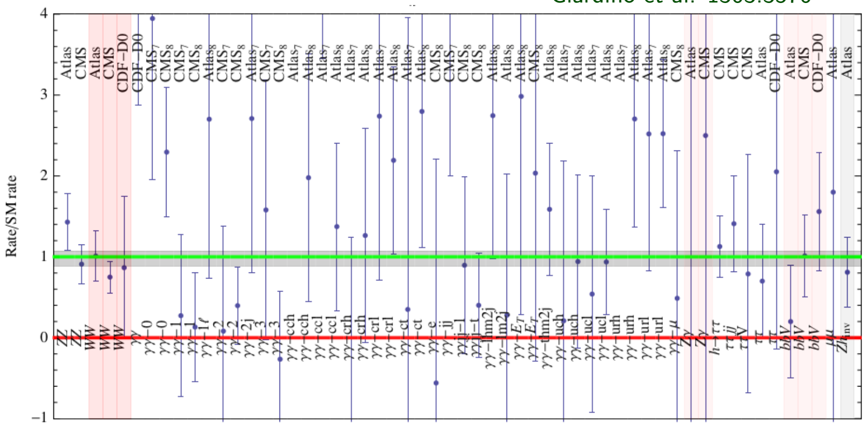

What can we learn about higher energy scales?

Where is New Physics?

Hierarchy problem: $m_h \approx \Lambda$ [Λ = highest scale h couples to]

How to deal with it?

$\rightarrow$ The Fermi scale is natural [$\Rightarrow$ NP at scale $\Lambda \lesssim$ TeV]

$\rightarrow$ Multiverse: Fermi scale anthropic, near-critical, ..

$\rightarrow$ Third way(s)

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Outline

I Higgs boson and the SM up to higher energies
Buttazzo, Degrassi, Giardino, Giudice, Salvio, S, Strumia arXiv:1307.3536

II Higgs boson and the NMSSM
Barbieri, Buttazzo, Kannike, S, Tesi arXiv:1304.3670,1307.4937

Extrapolating the SM to higher energies

$$V(h) = -m^2 h^2 + \frac{\lambda}{4} h^4$$

$$M_h^2 = 2\lambda v^2, \quad v^2 = \frac{1}{\sqrt{2}\, G_\mu}$$

Before LHC:

$\rightarrow$ $M_h \lesssim 175$ GeV or λ non-perturbative before $M_{\rm Pl}$

$\rightarrow$ $M_h \gtrsim 110$ GeV or our vacuum is unstable   Cabibbo et al. 1979,..

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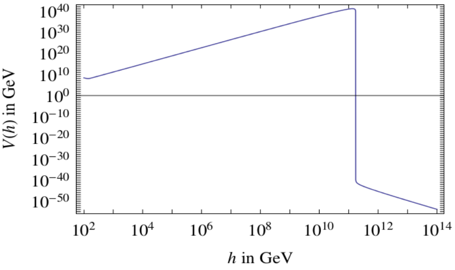
Vacuum decays via quantum tunneling to the true minimum!



Prob density of decay: $\dfrac{dP}{dVdt} = \Lambda_B^4 e^{-S}$

$S = \frac{8\pi^2}{3} \frac{1}{|\lambda(\mu{=}\Lambda_B)|}$ = action of the classical field that interpolates the vacua

Coleman 1977, Callan Coleman 1977,..

Exponential sensitivity to λ & $\lambda \lesssim 0 \Rightarrow$ precise computation needed!

$\overline{\mathrm{MS}}$ parameters in terms of physical ones: G_μ, $\alpha_s(M_Z)$, M_t, M_h, M_Z, M_W

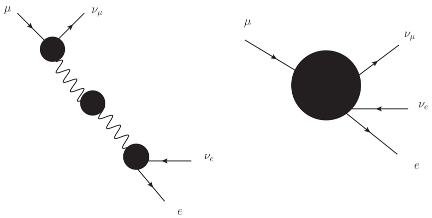
$$\lambda(\mu) = \frac{G_\mu}{\sqrt{2}} M_h^2 - \delta^{(1)}\lambda - \delta^{(2)}\lambda + \Delta_\lambda \qquad G_\mu = \frac{1}{\sqrt{2} v_0^2}(1 + \Delta r_0)$$

$$v_{\mathrm{OS}}^2 = \frac{1}{\sqrt{2}\, G_\mu} \equiv \text{minimum of } V_{\mathrm{eff}}(h)$$

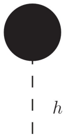
$$\delta^{(2)}\lambda = -\frac{G_\mu}{\sqrt{2}} M_h^2 \left\{ \Delta r_0^{(2)} + \frac{1}{M_h^2}\left[\frac{T^{(2)}}{v_{\mathrm{OS}}} + \delta^{(2)} M_h^2\right] - \Delta r_0^{(1)} \left(\Delta r_0^{(1)} + \frac{1}{M_h^2}\left[\frac{3}{2}\frac{T^{(1)}}{v_{\mathrm{OS}}} + \delta^{(1)} M_h^2\right]\right)\right\}$$

$\delta^{(2)} M_h^2$

$\Delta r_0^{(2)}$

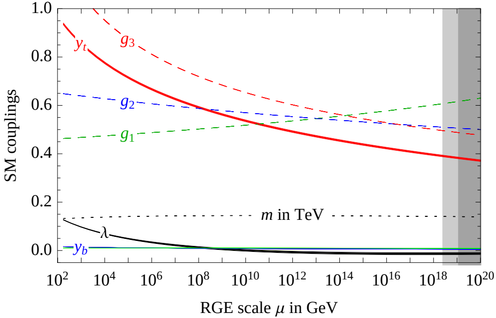


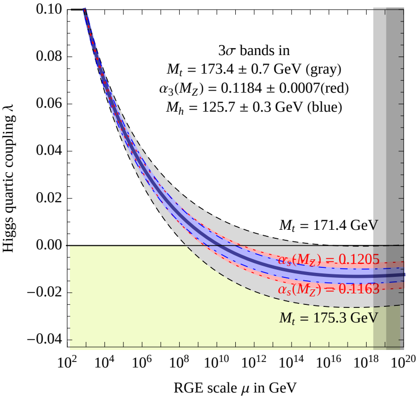
$T^{(2)}$



Most accurate computation to date (full 2-loop)

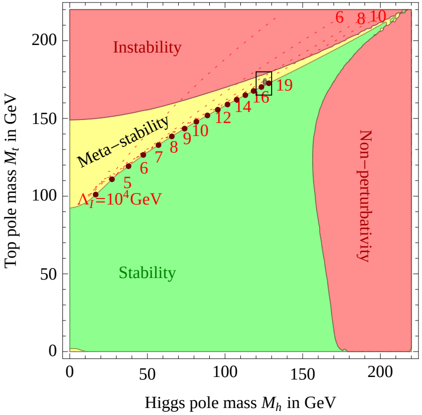
$\overline{\rm MS}$ parameters in terms of physical ones: G_μ, $\alpha_s(M_Z)$, M_t, M_h, M_Z, M_W

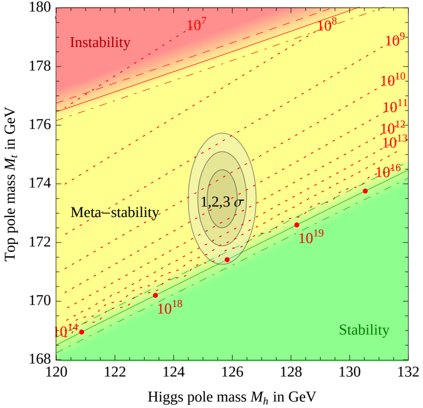




$$\frac{d\lambda}{d\ln\bar{\mu}^2} = \frac{1}{(4\pi)^2}\left[\lambda\left(+12\lambda + 6y_t^2 + .. - \frac{9g_2^2}{2} - \frac{9g_1^2}{10}\right) - 3y_t^4 - .. + \frac{9g_2^4}{16} + \frac{27g_1^4}{400} + \frac{9g_2^2g_1^2}{40}\right]$$

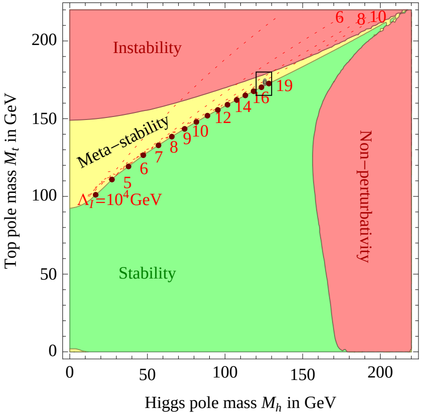
Metastability of the SM vacuum

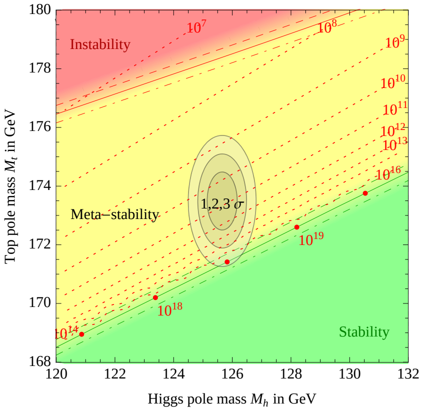




Red dotted: Instability scale Λ_I in GeV.

Error on boundaries: α_s and theory





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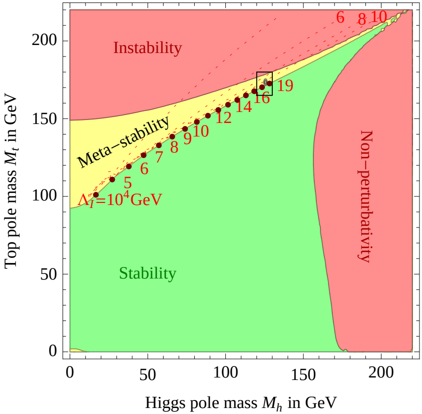
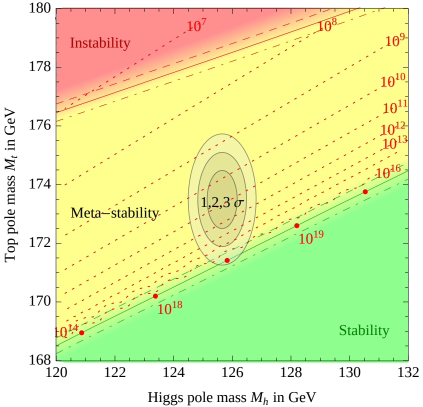
Error on boundaries: α_s and theory

$$M_h > 129.6\text{GeV} + 2.0(M_t - 173.35\text{GeV}) - 0.5\text{GeV}\frac{\alpha_3(M_Z) - 0.1184}{0.0007} \pm 0.3\text{ GeV}$$



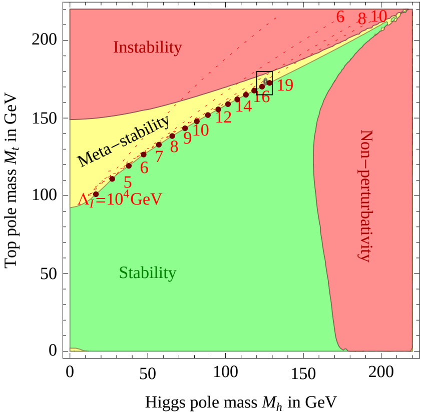


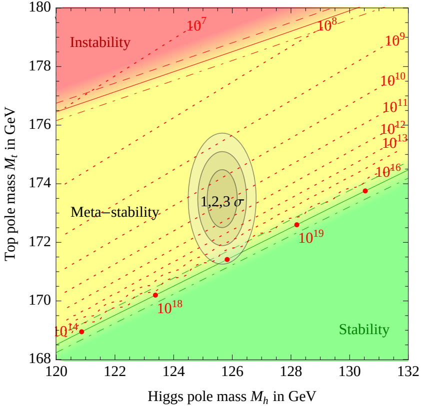
Red dotted: Instability scale Λ_I in GeV.

Error on boundaries: α_s and theory

$$M_h > 129.9\text{GeV} + 2.0(M_t - 173.35\text{GeV}) - 0.5\text{GeV}\frac{\alpha_3(M_Z) - 0.1184}{0.0007} \pm 1\text{ GeV}$$

Metastability of the SM vacuum





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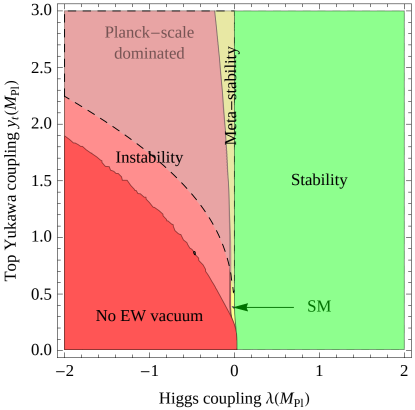
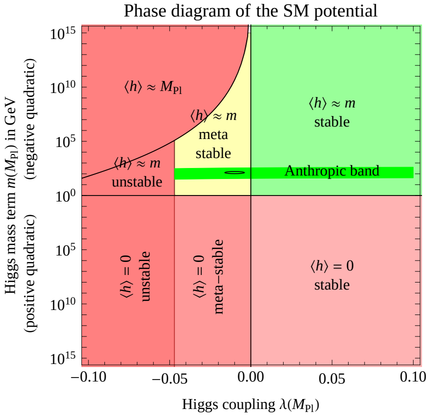
$$M_t < (171.36 \pm 0.15 \pm 0.25_{\alpha_3} \pm 0.17_{M_h})\text{GeV} \quad \text{vs} \quad \boxed{\Delta M_t = \pm 0.7_{exp} \pm 0.3_{th}\text{GeV}}$$

In terms of Planck scale parameters





Legenda: No EW vacuum: $\lambda|_{\text{EW scale}} < 0$, Planck-scale dominated: $\Lambda_I > M_{\text{Planck}}$

Anthropic band Agrawal et al. 9707389

λ and y_t are near-critical: accident or deeper meaning?

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How to deal with it?

$\rightarrow$ The Fermi scale is natural [$\Rightarrow$ NP at scale $\Lambda \lesssim$ TeV]

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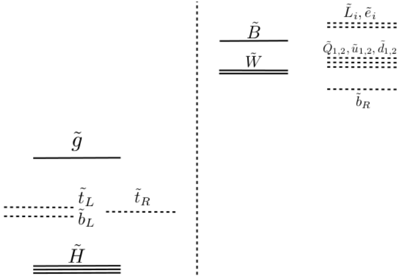
Barbieri, Buttazzo, Kannike, S, Tesi arXiv:1304.3670,1307.4937

$$m_Z^2 = -2(m_{H_u}^2 + |\mu|^2)$$

$$\delta m_{H_u}^2 \simeq -\frac{3}{4\pi^2} y_t^2 m_{\tilde{t}}^2 \left(1 + a^2/2\right) \log \frac{\Lambda}{m_{\tilde{t}}}$$

$$\delta m_{\tilde{t}}^2 = \frac{8\alpha_s}{3\pi} M_3^2 \log \frac{\Lambda}{M_3}$$



Natural Supersymmetry [Dimopoulos Giudice '95, Cohen Kaplan Nelson '96]

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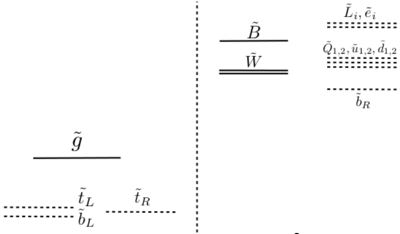
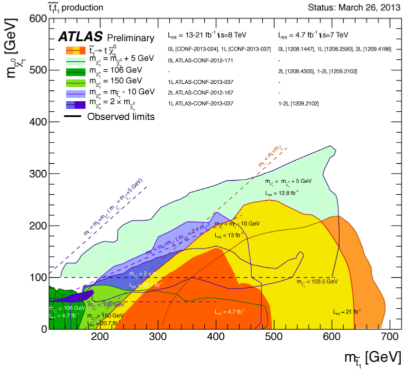
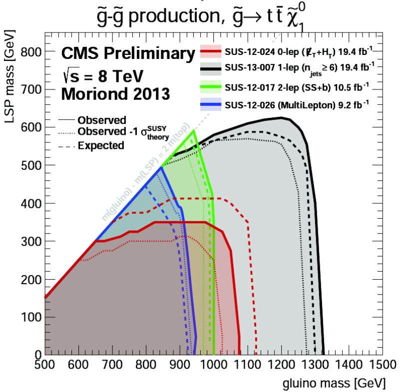






Naturalness and m_h in the MSSM

$$m_h^2 \leq m_Z^2 \cos^2 2\beta + \Delta_t^2$$

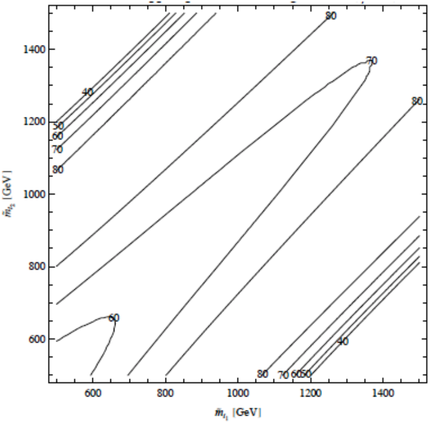
$$m_h \simeq 126 \text{ GeV} \;\Rightarrow\; \Delta_t \gtrsim 85 \text{ GeV}$$

$$\Downarrow$$

→ stops above a TeV!

→ fine tuning worse than 1%!

Isolines of Δ_t [$\tan\beta = 4$, max mixing]



Naturalness and m_h in the NMSSM

NMSSM Add singlet S $\quad \Delta W = \lambda S H_u H_d + f(S)$

$\rightarrow$ $m_h^2 \leq m_Z^2 c_{2\beta}^2 + \Delta_t^2 + \lambda^2 v^2 s_{2\beta}^2 \Rightarrow$ Lighter stops allowed!

$\rightarrow$ Better fine tuning for $\lambda \gtrsim 1$! ...,Hall Pinner Ruderman 1112.2703

Naturalness and m_h in the NMSSM

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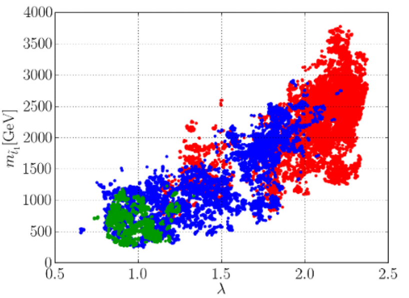
A specific Example: The scale invariant NMSSM $\left[f(S) = \kappa/3\ S^3\right]$

Gherghetta et al. 1212.5243



$$\mathrm{FT}_v \equiv \max_i \left| \frac{d \log v^2}{d \log \xi_i} \right|$$

$$\frac{dv^2}{dm_{H_u}^2} \simeq \frac{\kappa}{\lambda^3} \frac{1}{t_{2\beta}} \quad \left[\simeq -2\frac{v^2}{m_Z^2} \text{ in MSSM}\right]$$

all points: FT in v better than 5%

green: combined FT better than 5%

$(\Lambda_{\mathrm{MESS}} = 20$ TeV$)$

The Higgs sector

(CP-even scalars)

→ How Higgs measurements affect parameter space

→ Where to look for the other Higgses

→ Sketch of a model for $\lambda \gtrsim 1$

Physical parameters
(no specific NMSSM, no scatter plots..)

$$\mathcal{H}_{\rm ph} \equiv \begin{pmatrix} h_3 \\ h_1 \\ h_2 \end{pmatrix} = R^T \begin{pmatrix} H \\ h \\ S \end{pmatrix}, \quad R = R^{12}_{\delta} R^{23}_{\gamma} R^{13}_{\sigma}$$

$$m_{h_1} = 125.7 \text{ GeV}$$

$$\mathcal{M}^2 = \begin{pmatrix} \widetilde{\mathcal{M}}^2(m^2_{H^\pm}, \lambda, t_\beta, \Delta_t) & & \\ vM_1 & vM_2 & M_3^2 \end{pmatrix} = R^T \mathrm{diag}(m^2_{h_3}, m^2_{h_1}, m^2_{h_2}) R$$

Analytical relations!

$$\delta,\ \gamma,\ \sigma\left(m_{h_2},\ m_{h_3},\quad m_{H^\pm},\ \lambda,\ t_\beta,\ \Delta_t\right)$$

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Analytical relations!

$$\delta,\ \gamma,\ \sigma\left(m_{h_2},\ m_{h_3},\quad m_{H^\pm},\ \lambda,\ t_\beta,\ \Delta_t\right)$$

$$s^2_\gamma = \frac{\det \widetilde{\mathcal{M}}^2 + m^2_{h_1}(m^2_{h_1} - \mathrm{tr}\,\widetilde{\mathcal{M}}^2)}{(m^2_{h_1} - m^2_{h_2})(m^2_{h_1} - m^2_{h_3})} \qquad s^2_\sigma = \frac{m^2_{h_2} - m^2_{h_1}}{m^2_{h_2} - m^2_{h_3}} \frac{\det \widetilde{\mathcal{M}}^2 + m^2_{h_3}(m^2_{h_3} - \mathrm{tr}\,\widetilde{\mathcal{M}}^2)}{\det \widetilde{\mathcal{M}}^2 - m^2_{h_2} m^2_{h_3} + m^2_{h_1}(m^2_{h_2} + m^2_{h_3} - \mathrm{tr}\,\widetilde{\mathcal{M}}^2)}$$

$$\begin{aligned} s_{2\delta} = \Big[& 2 s_\sigma c_\sigma s_\gamma \left(m^2_{h_3} - m^2_{h_2}\right)\left(2\widetilde{\mathcal{M}}^2_{11} - m^2_{h_1} c^2_\gamma - m^2_{h_2}(s^2_\gamma + s^2_\sigma c^2_\gamma) - m^2_{h_3}(c^2_\sigma + s^2_\gamma s^2_\sigma)\right) \\ & + 2\widetilde{\mathcal{M}}^2_{12}\left(m^2_{h_3}\left(c^2_\sigma - s^2_\gamma s^2_\sigma\right) + m^2_{h_2}\left(s^2_\sigma - s^2_\gamma c^2_\sigma\right) - m^2_{h_1} c^2_\gamma\right)\Big] \\ & \times \Big[\left(m^2_{h_3} - m^2_{h_2} s^2_\gamma - m^2_{h_1} c^2_\gamma\right)^2 + \left(m^2_{h_2} - m^2_{h_3}\right)^2 c^4_\gamma s^4_\sigma \\ & + 2\left(m^2_{h_2} - m^2_{h_3}\right)\left(m^2_{h_3} + m^2_{h_2} s^2_\gamma - m^2_{h_1}\left(1 + s^2_\gamma\right)\right) c^2_\gamma s^2_\sigma\Big]^{-1} \end{aligned}$$

Physical parameters

(no specific NMSSM, no scatter plots..)

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Analytical relations! $\delta,\ \gamma,\ \sigma\big(m_{h_2},\ m_{h_3},\quad m_{H^\pm},\ \lambda,\ t_\beta,\ \Delta_t\big)$

Two limiting cases

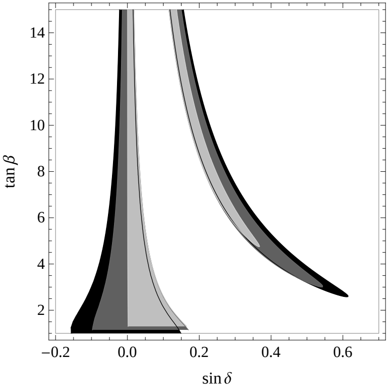
H decoupled: $m_{h_3} \gg m_{h_{1,2}}$ and $\sigma, \delta \to 0$ free par.s: $m_{h_2}, t_\beta, \Delta_t, \lambda$

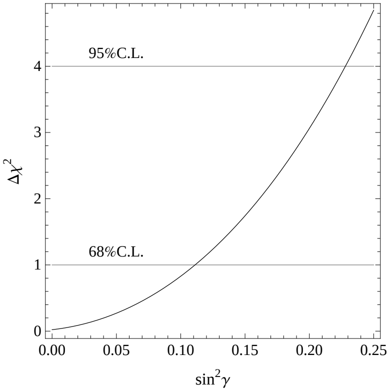
S decoupled: $m_{h_2} \gg m_{h_{1,3}}$ and $\sigma, \gamma \to 0$ free par.s: $m_{h_3}, t_\beta, \Delta_t$

$$\left[h_{\text{LHC}} = h_1 = c_\gamma(c_\delta h - s_\delta H) + s_\gamma S\right]$$

$$\frac{g_{h_1 tt}}{g^{\text{SM}}_{htt}} = c_\gamma\left(c_\delta + \frac{s_\delta}{\tan\beta}\right), \qquad \frac{g_{h_1 bb}}{g^{\text{SM}}_{hbb}} = c_\gamma(c_\delta - s_\delta \tan\beta), \qquad \frac{g_{h_1 VV}}{g^{\text{SM}}_{hVV}} = c_\gamma c_\delta$$

LHC8 status





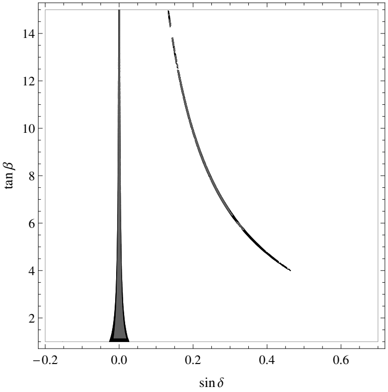
$s_\gamma^2 = 0,\ 0.15,\ 0.3$

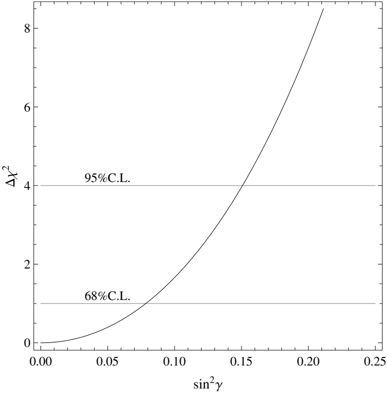
Higgs couplings and fit

$$\left[h_{\rm LHC} = h_1 = c_\gamma(c_\delta h - s_\delta H) + s_\gamma S\ \right]$$

$$\frac{g_{h_1 tt}}{g^{\rm SM}_{htt}} = c_\gamma\left(c_\delta + \frac{s_\delta}{\tan\beta}\right), \qquad \frac{g_{h_1 bb}}{g^{\rm SM}_{hbb}} = c_\gamma(c_\delta - s_\delta \tan\beta), \qquad \frac{g_{h_1 VV}}{g^{\rm SM}_{hVV}} = c_\gamma c_\delta$$

LHC14 projections (300 fb^{-1})

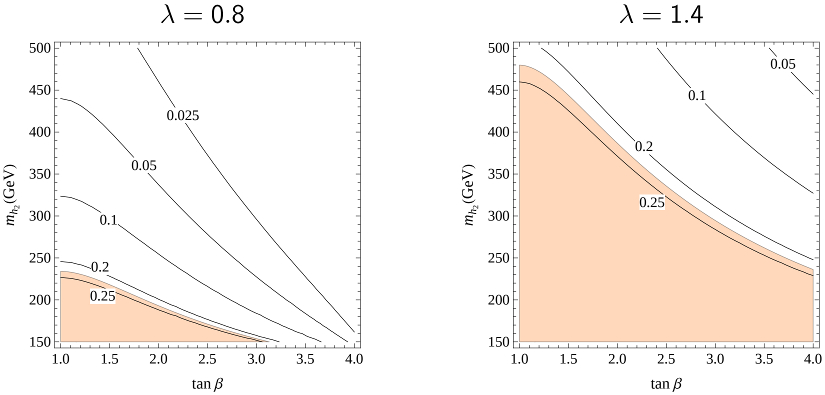




$s_\gamma^2 = 0,\ 0.15,\ 0.3$

$$\frac{g_{h_1 ff}}{g_{hff}^{SM}} = \frac{g_{h_1 VV}}{g_{hVV}^{SM}} = c_\gamma \qquad \frac{g_{h_2 ff}}{g_{hff}^{SM}} = \frac{g_{h_2 VV}}{g_{hVV}^{SM}} = -s_\gamma \qquad [\Delta_t = 75 \text{ GeV}]$$

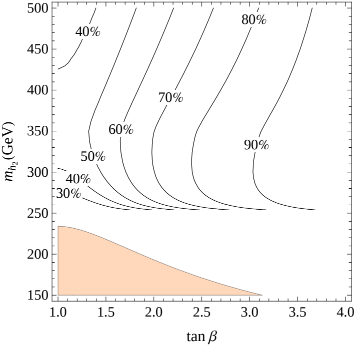
Isolines of $\sin^2\gamma = \dfrac{m_{hh}^2 - m_{h_1}^2}{m_{h_2}^2 - m_{h_1}^2}$



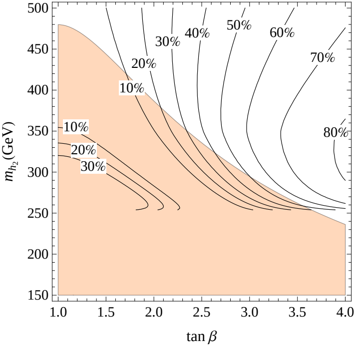
$m_{h_2} > 250$ GeV: $h_1 h_1$ dominant decay

$h_2 \to hh$

$\lambda = 0.8, v_s = 2v$



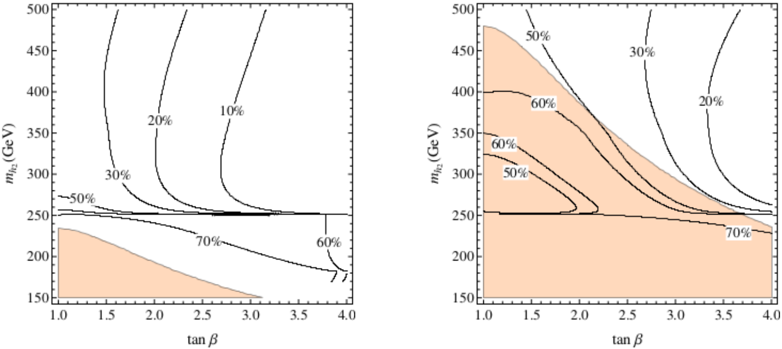
$\lambda = 1.4, v_s = v$



CMS and ATLAS: work in progress...

$m_{h_2} < 250$ GeV: signal strengths $= \; s_\gamma^2 \times$ Standard Model

$h_2 \to WW$



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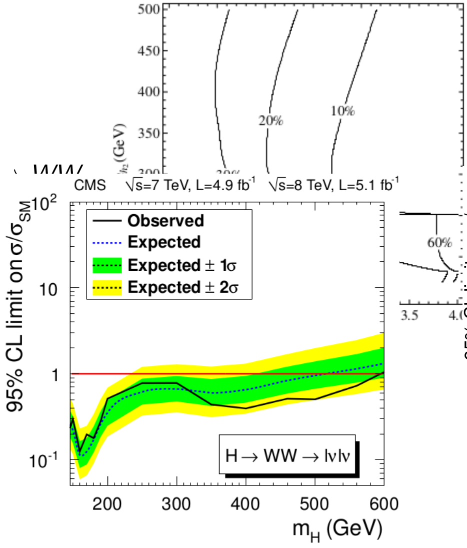
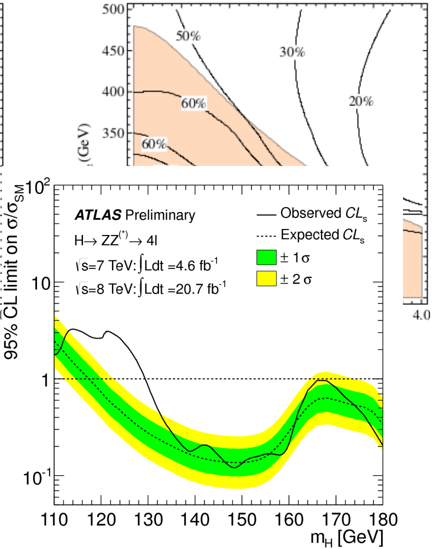
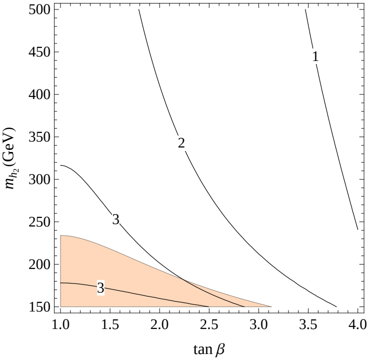


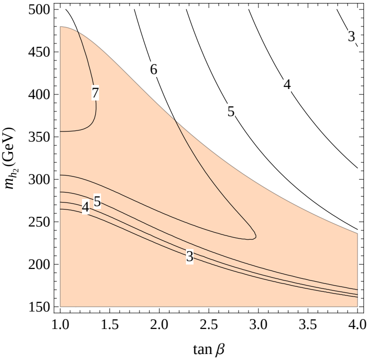


H dec - Trilinear Higgs self coupling g_{hhh}/g_{hhh}^{SM}

$\lambda = 0.8,\ v_s = 2v$



$\lambda = 1.4,\ v_s = v$



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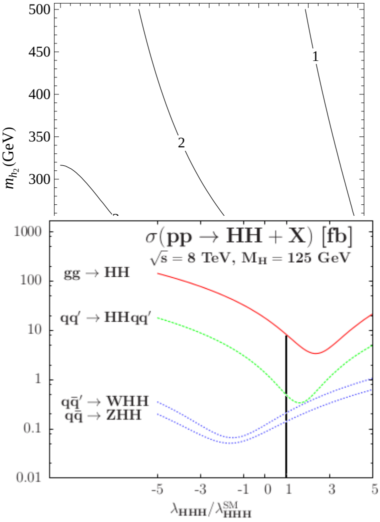
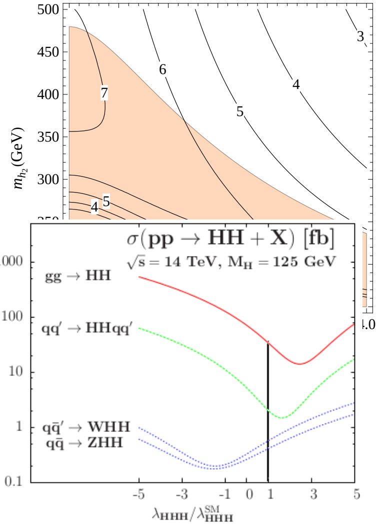




LHC? work in progress...

Baglio Djouadi Spira 1212.5581

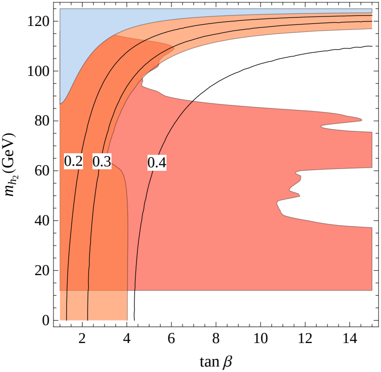
H dec - h_2 lighter than h_1

FIT: again LHC14 impact is mild $\quad (\lambda = 1.4$ wants $t_\beta > 10)$

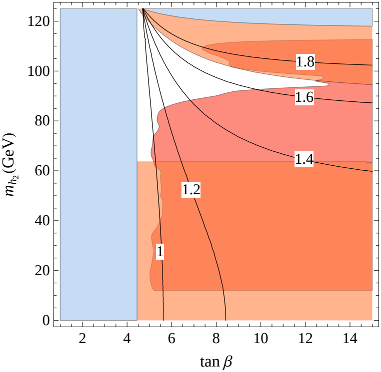
h_2 pheno: again signal $= s_\gamma^2 \times$ SM, direct searches not (yet) competitive

Trilinear Higgs coupling g_{hhh}/g_{hhh}^{SM}: $\qquad$ [Red: $h_2 \to b\bar{b}$ LEP exclusion]

$\lambda = 0.1, \Delta_t = 85$ GeV$, v_s = v$



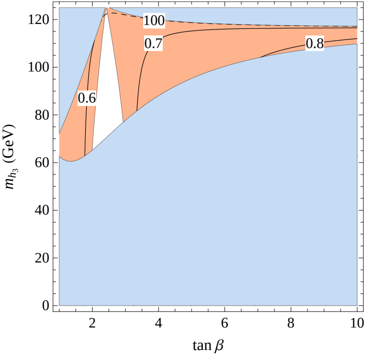
$\lambda = 0.8, \Delta_t = 75$ GeV$, v_s = v$

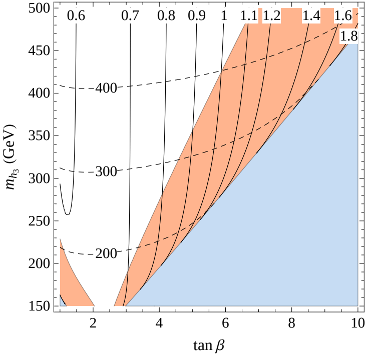


S decoupled case $[\gamma, \sigma = 0,$ free parameters: $m_{h_3}, t_\beta, \Delta_t]$

$$\frac{g_{h_3tt}}{g^{SM}_{htt}} = s_\delta - \frac{c_\delta}{t_\beta} \qquad \frac{g_{h_3bb}}{g^{SM}_{hbb}} = s_\delta + t_\beta c_\delta \qquad \frac{g_{h_3VV}}{g^{SM}_{hVV}} = s_\delta \qquad [\Delta_t = 75\text{ GeV}]$$

LHC8 fit status: dashed: $m_{H^\pm}$ cont: λ





Indirect bounds on $H^\pm$ from $B \to X_s\gamma$! $[\widetilde{\mathcal{M}}^2_{12}(t_\beta, \ldots) = 0 \to \delta = 0]$

h_3 pheno: more similar to MSSM, CMS and ATLAS are looking for it

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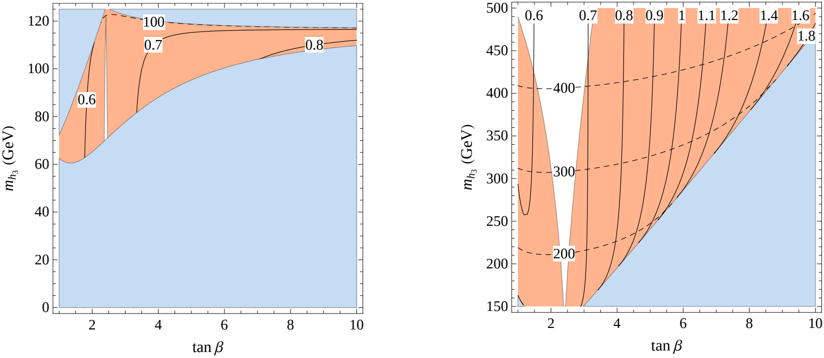
LHC14 fit projections (300 fb^{-1}): dashed: $m_{H^\pm}$ cont: λ



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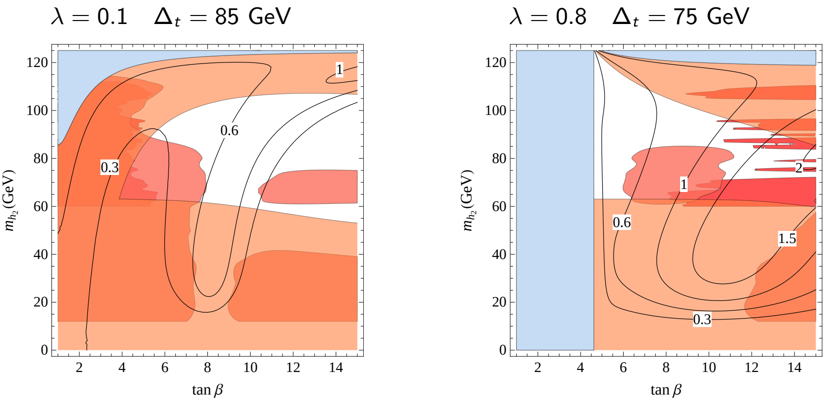
Fully mixed case and $h_2 \to \gamma\gamma$

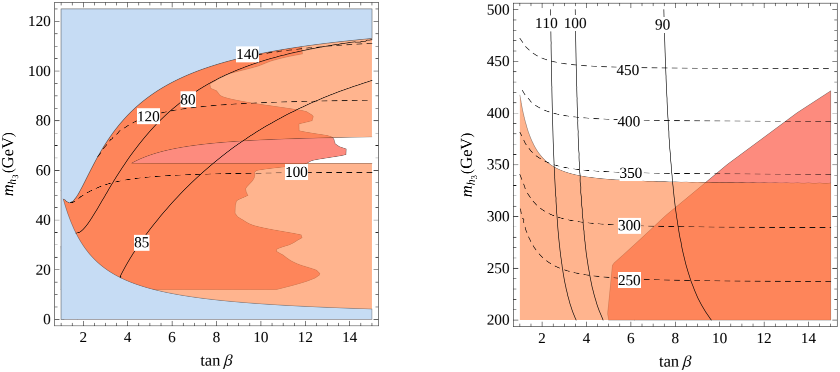
Signal strengths relative to the SM $[m_{h_3} = 500 \text{ GeV},\ s_\sigma^2 = 0.001,\ v_s = v]$



Red: LEP $h \to \bar{b}b$ Dark Red: LEP $h \to$hadrons

$h_2 > h_{\rm LHC}$: harder to have an enhancement [free parameters: m_{h_3}, t_β]

LHC8 fit status: $\Big[$dashed: $m_{H^\pm}$ cont: $\Delta_t\Big]$



LHC14 fit projections: above regions completely filled, up to $m_{h_3} \simeq 1$ TeV

$\left[\text{if } \dfrac{\mu A_t}{m_{\tilde{t}}^2} \text{ very large this conclusion could change}\right]$

Pheno summary

- Higgs couplings $\Rightarrow m_{h_3}(\text{MSSM}) \gtrsim 350$ GeV*

$\gtrsim 1$ TeV from LHC14!

$m_{h_{2,3}}(\text{NMSSM})$ can be much lighter!

*see also D'Agnolo Kuflik Zanetti 1212.1165
Gupta Montull Riva 1212.5240

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- Other effects? Large deviations in λ_{hhh} allowed in H-dec case

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The Higgs sector

(CP-even scalars)

$\rightarrow$ How Higgs measurements affect parameter space

$\rightarrow$ Where to look for the other Higgses

$\rightarrow$ Sketch of a model for $\lambda \gtrsim 1$

The Higgs sector

(CP-even scalars)

$\rightarrow$ Sketch of a model for $\lambda \gtrsim 1$

Living with a $\lambda \gtrsim 0.7$

$m_h \simeq 126$ GeV $+$ Naturalness $\Rightarrow$ λ(weak scale) $\gtrsim 0.8$

Hall Pinner Ruderman 1112.2703, ...

λ perturbative up to GUT scale $\Rightarrow$ λ(weak scale) $\lesssim 0.7$

Espinosa Quiros PLB 279 (1992), ...

Ways out

Add max number of families in $\bar{5} + 5$ of $SU(5)$ that do not spoil GUT

$\Rightarrow \lambda \lesssim 0.8$ Masip Munoz-Tapia Pomarol hep-ph/9801437,...

Promote (some of) S, H_u, H_d to composite objects

Harnik et al. hep-ph/0311349, ...

$\Rightarrow \lambda \lesssim 2$, not bigger otherwise strong sector at ~ 10 TeV (EWPT)

Sketch of a model for $\lambda \gtrsim 1$

- Field content: NMSSM + vector-like $F_u \sim 5$ and $F_d \sim \bar{5}$ of $SU(5)$

  $F_{u,d} \supset h_{u,d}$ with same quantum numbers of standard $H_{u,d}$.

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Growth of λ cured above $M_{u,d}, m_{u,d} \lesssim 1000$ TeV $\quad (\lambda \lesssim 1.5)$

Conclusions

Learning from the Higgs boson: unnatural (I) and natural (II) new physics

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Thank you for your attention!