Higgsology in the type II seesaw model

G. Moultaka

Laboratoire Charles Coulomb (L2C)
CNRS & University of Montepllier II

GDRI-P2IM, Rabat, 17/12/2015

based on: Arhrib et al.,
Phys.Rev. D84 (2011) 095005
+
JHEP 1204 (2012) 136
+
arXiv:1411.5645 [hep-ph]

+ *work in progress*

→ Chabab et al. Phys.Rev. D90 (2014) 3

Outline

IFAC/Montpellier activities

- quick reminder of IFAC expertise:

  [Felix Brümmer, Michele Frigerio, Cyril Hugonie, Karsten Jedamzik Jean-Loïc Kneur, Julien Lavalle, G. M., Stephan Narison, Michel C. Peyranère]

  susy: MSSM, NMSSM (specific models, mSUGRA, GMSB, AMSB, RPV,... spectrum calc. authors, SuSpect2,3 (C++), NMSTools), model-building (supergravity...).

  non-susy BSM: composite Higgs ("SILH-like", GUT scenarios, heavy top-like states,...), extended Higgs sector (2HDM, Higgs triplets,...)

  astro/cosmo: dark matter (candidates, relic density, DD & ID constraints,...), early universe (non-thermal DM, BBN, primordial magnetic fields, ...)

  [QCD, strong interactions: sum rules, variational methods,...]

Introductory motivations

why is physics beyond the Standard Model needed?

- fine-tuning or hierarchy problems are often overstated:
  they may be relevant only if a BSM new scale is assumed,
  ...not the opposite!

Introductory motivations

why is physics beyond the Standard Model needed?

- Dark matter!
- Neutrino masses!
- • Unification électro-faible, forte et...gravitationnelle?
- • Origine de la brisure de la symétrie électro-faible?
  • “Naturalness" de la masse du scalaire de Higgs?
  • Problème de l’hierarchie des échelles de masses
- • Trivialité du secteur scalaire de Higgs?
- • Plusieurs paramètres libres (19)
- • Spectre de masse des particules “élémentaires”
- • nbre de familles, nbre de générations
- • Origine de la chiralité
- • Pourquoi $SU(3) \times SU(2) \times U(1)$?
- • CP forte
- • ...pas de candidats à la matière noire
- •...Le problème de la constante cosmologique
- ...

Introductory motivations

why is physics beyond the Standard Model needed?

- Neutrino masses? No and Yes

No: *simply add a ν_R and a standard Yukawa coupling*
$\rightarrow$ *Dirac mass* $+$ perhaps a Majorana mass
$\rightarrow$ mysterious... SM singlet only gravitationally coupled !?

Yes: $\rightarrow$ more elegant (but not necessary!), ν_R charged under some GUT group... e.g. spinorial rep. of $SO(10)$
$\rightarrow$ seesaw mechanisms
Here we concentrate on the type II seesaw $\rightarrow$ neutrinos masses without an extra ν_R [Konetschny, Kummer ('77), Cheng, Li ('80), Lazarides, Shafi, Wetterich ('81), Schechter, Valle ('80), Mohapatra, Senjanovic ('81)]

on-going collaboration Marrakech/Tanger/Montpellier since several years:
A. Arhrib, R. Benbrik, M. Chabab, G. Moultaka, M. C. Peyranère, L. Rahili, J. Ramadan.

$\rightarrow$ an extra motivation in retrospect:
why is the discovered 125 GeV scalar so much SM-like??

The model

The scalar sector consists of the standard Higgs weak doublet H and a colorless scalar field Δ transforming as a triplet under the $SU(2)_L$ gauge group with hypercharge $Y_\Delta = 2$:
$H \sim (1,2,1)$ and $\Delta \sim (1,3,2)$ under $SU(3)_c \times SU(2)_L \times U(1)_Y$.

$$Q = I_3 + \frac{Y}{2}$$

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix} \quad \text{and} \quad H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$\mathcal{L} = (D_\mu H)^\dagger (D^\mu H) + Tr(D_\mu \Delta)^\dagger (D^\mu \Delta) - V(H,\Delta) + \mathcal{L}_{Yukawa} + \ldots$$

$$\mathcal{L}_{Yukawa} \supset Y_\nu L^T C \otimes i\sigma_2 \Delta L$$

$$\begin{aligned} V(H,\Delta) = & -m_H^2 H^\dagger H + M_\Delta^2 Tr(\Delta^\dagger \Delta) + [\mu(H^T i\sigma_2 \Delta^\dagger H) + \text{h.c.}] \\ & + \frac{\lambda}{4}(H^\dagger H)^2 + \lambda_1 (H^\dagger H) Tr(\Delta^\dagger \Delta) \\ & + \lambda_2 (Tr \Delta^\dagger \Delta)^2 + \lambda_3 Tr(\Delta^\dagger \Delta)^2 + \lambda_4 H^\dagger \Delta \Delta^\dagger H \end{aligned}$$

Electroweak symmetry breaking

$$\langle \Delta \rangle = \begin{pmatrix} 0 & 0 \\ v_t/\sqrt{2} & 0 \end{pmatrix} \quad \text{and} \quad \langle H \rangle = \begin{pmatrix} 0 \\ v_d/\sqrt{2} \end{pmatrix}$$

one finds after minimization of the potential the following necessary conditions:

$$M_\Delta^2 = \frac{2\mu v_d^2 - \sqrt{2}(\lambda_1 + \lambda_4) v_d^2 v_t - 2\sqrt{2}(\lambda_2 + \lambda_3) v_t^3}{2\sqrt{2} v_t}$$

$$m_H^2 = \frac{\lambda v_d^2}{4} - \sqrt{2}\mu v_t + \frac{(\lambda_1 + \lambda_4)}{2} v_t^2$$

8 parameters $\longrightarrow$ 7 parameters with $v \equiv \sqrt{v_d^2 + 2v_t^2} = 246\text{GeV}$

$$M_Z^2 = \frac{(g^2 + g'^2)}{4}(v_d^2 + 4v_t^2) \qquad M_W^2 = \frac{g^2}{4}(v_d^2 + 2v_t^2)$$

Electroweak symmetry breaking

$$\langle\Delta\rangle = \begin{pmatrix} 0 & 0 \\ v_t/\sqrt{2} & 0 \end{pmatrix} \quad \text{and} \quad \langle H\rangle = \begin{pmatrix} 0 \\ v_d/\sqrt{2} \end{pmatrix}$$

one finds after minimization of the potential the following necessary conditions:

$$M_\Delta^2 = \frac{2\mu v_d^2 - \sqrt{2}(\lambda_1+\lambda_4)v_d^2 v_t - 2\sqrt{2}(\lambda_2+\lambda_3)v_t^3}{2\sqrt{2}v_t}$$

$$m_H^2 = \frac{\lambda v_d^2}{4} - \sqrt{2}\mu v_t + \frac{(\lambda_1+\lambda_4)}{2}v_t^2$$

8 parameters $\longrightarrow$ 7 parameters with $v \equiv \sqrt{v_d^2 + 2v_t^2} = 246\text{GeV}$

$$M_Z^2 = \frac{(g^2+g'^2)}{4}(v_d^2+4v_t^2) \qquad M_W^2 = \frac{g^2}{4}(v_d^2+2v_t^2)$$

$\rho = \frac{v_d^2+2v_t^2}{v_d^2+4v_t^2} < 1,$

Electroweak symmetry breaking

$$\langle \Delta \rangle = \begin{pmatrix} 0 & 0 \\ v_t/\sqrt{2} & 0 \end{pmatrix} \quad \text{and} \quad \langle H \rangle = \begin{pmatrix} 0 \\ v_d/\sqrt{2} \end{pmatrix}$$

one finds after minimization of the potential the following necessary conditions:

$$M_\Delta^2 = \frac{2\mu v_d^2 - \sqrt{2}(\lambda_1 + \lambda_4) v_d^2 v_t - 2\sqrt{2}(\lambda_2 + \lambda_3) v_t^3}{2\sqrt{2} v_t}$$

$$m_H^2 = \frac{\lambda v_d^2}{4} - \sqrt{2}\mu v_t + \frac{(\lambda_1 + \lambda_4)}{2} v_t^2$$

8 parameters $\longrightarrow$ 7 parameters with $v \equiv \sqrt{v_d^2 + 2v_t^2} = 246\text{GeV}$

$$M_Z^2 = \frac{(g^2 + g'^2)}{4}(v_d^2 + 4v_t^2) \qquad M_W^2 = \frac{g^2}{4}(v_d^2 + 2v_t^2)$$

$\rho = \frac{v_d^2 + 2v_t^2}{v_d^2 + 4v_t^2} < 1$, but $v_t \ll v_d \rightarrow$ neutrino masses.

Higgs spectrum, couplings,...

$\rightarrow$ 10 scalar states: 7 massive physical Higgses, $h^0, H^0, A^0, H^{\pm}, H^{\pm\pm}$
$+$ 3 Goldstone bosons and 3 mixing angles α, β, β'

Higgs spectrum, couplings,...

$\rightarrow$ 10 scalar states: 7 massive physical Higgses, $h^0, H^0, A^0, H^\pm, H^{\pm\pm}$
$+$ 3 Goldstone bosons and 3 mixing angles α, β, β'

$$h^0 = \cos\alpha\, h + \sin\alpha\, \xi^0, \quad H^0 = -\sin\alpha\, h + \cos\alpha\, \xi^0, \quad A^0 = -\sin\beta\, Z_1 + \cos\beta\, Z_2, \quad G^0 = \cos\beta\, Z_1 + \sin\beta\, Z_2$$

$$G^\pm = \cos\beta^{'}\, \phi^\pm + \sin\beta^{'}\, \delta^\pm \quad H^\pm = -\sin\beta^{'}\, \phi^\pm + \cos\beta^{'}\, \delta^\pm$$

Higgs spectrum, couplings,...

$\rightarrow$ 10 scalar states: 7 massive physical Higgses, $h^0, H^0, A^0, H^\pm, H^{\pm\pm}$
$+$ 3 Goldstone bosons and 3 mixing angles α, β, β'

$$h^0 = \cos\alpha\, h + \sin\alpha\, \xi^0, \quad H^0 = -\sin\alpha\, h + \cos\alpha\, \xi^0, \quad A^0 = -\sin\beta\, Z_1 + \cos\beta\, Z_2, \quad G^0 = \cos\beta\, Z_1 + \sin\beta\, Z_2$$

$$G^\pm = \cos\beta'\, \phi^\pm + \sin\beta'\, \delta^\pm \quad H^\pm = -\sin\beta'\, \phi^\pm + \cos\beta'\, \delta^\pm$$

$$m^2_{h^0, H^0} = \frac{1}{2}[A + C \mp \sqrt{(A-C)^2 + 4B^2}]$$

$$A = \frac{\lambda}{2} v_d^2 \quad , \quad B = v_d[-\sqrt{2}\mu + (\lambda_1 + \lambda_4)v_t] \quad , \quad C = \frac{\sqrt{2}\mu v_d^2 + 4(\lambda_2 + \lambda_3)v_t^3}{2v_t}$$

$$m^2_{H^{\pm\pm}} = \frac{\sqrt{2}\mu v_d^2 - \lambda_4 v_d^2 v_t - 2\lambda_3 v_t^3}{2v_t}$$

$$m^2_{H^\pm} = \frac{(v_d^2 + 2v_t^2)[2\sqrt{2}\mu - \lambda_4 v_t]}{4v_t}$$

$$m^2_A = \frac{\mu(v_d^2 + 4v_t^2)}{\sqrt{2}v_t}$$

Higgs spectrum, couplings,...

$\rightarrow$ 10 scalar states: 7 massive physical Higgses, $h^0, H^0, A^0, H^\pm, H^{\pm\pm}$
$+$ 3 Goldstone bosons and 3 mixing angles α, β, β'

$$h^0 = \cos\alpha\, h + \sin\alpha\, \xi^0, \quad H^0 = -\sin\alpha\, h + \cos\alpha\, \xi^0, \quad A^0 = -\sin\beta\, Z_1 + \cos\beta\, Z_2, \quad G^0 = \cos\beta\, Z_1 + \sin\beta\, Z_2$$

$$G^\pm = \cos\beta'\, \phi^\pm + \sin\beta'\, \delta^\pm \quad H^\pm = -\sin\beta'\, \phi^\pm + \cos\beta'\, \delta^\pm$$

$$m^2_{h^0, H^0} = \frac{1}{2}[A + C \mp \sqrt{(A-C)^2 + 4B^2}]$$

$$A = \frac{\lambda}{2} v_d^2 \quad , \quad B = v_d[-\sqrt{2}\mu + (\lambda_1 + \lambda_4) v_t] \quad , \quad C = \frac{\sqrt{2}\mu v_d^2 + 4(\lambda_2 + \lambda_3) v_t^3}{2 v_t}$$

$$m^2_{H^{\pm\pm}} = \frac{\sqrt{2}\mu v_d^2 - \lambda_4 v_d^2 v_t - 2\lambda_3 v_t^3}{2 v_t}$$

$$m^2_{H^\pm} = \frac{(v_d^2 + 2 v_t^2)[2\sqrt{2}\mu - \lambda_4 v_t]}{4 v_t}$$

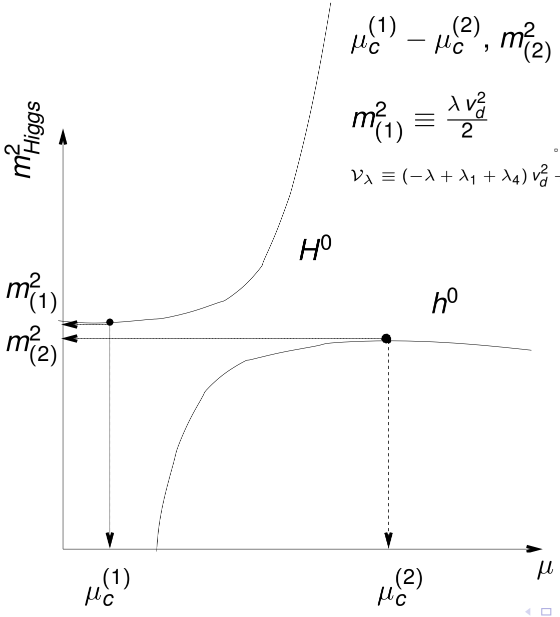
$$m_A^2 = \frac{\mu(v_d^2 + 4 v_t^2)}{\sqrt{2} v_t}$$ $\leftarrow$ would-be Majoron

Higgs spectrum, couplings,...

$$\mu_c^{(1)} - \mu_c^{(2)},\ m^2_{(2)} - m^2_{(1)} \sim \mathcal{V}_\lambda$$

$$m^2_{(1)} \equiv \frac{\lambda\, v_d^2}{2}$$

$$\mathcal{V}_\lambda \equiv (-\lambda + \lambda_1 + \lambda_4)\, v_d^2 + 4\,(\lambda_2 + \lambda_3)\, v_t^2 \quad (< 0)$$



Higgs spectrum, couplings,...

a comment:

- sometimes in the literature the EWSB equations are approximated as

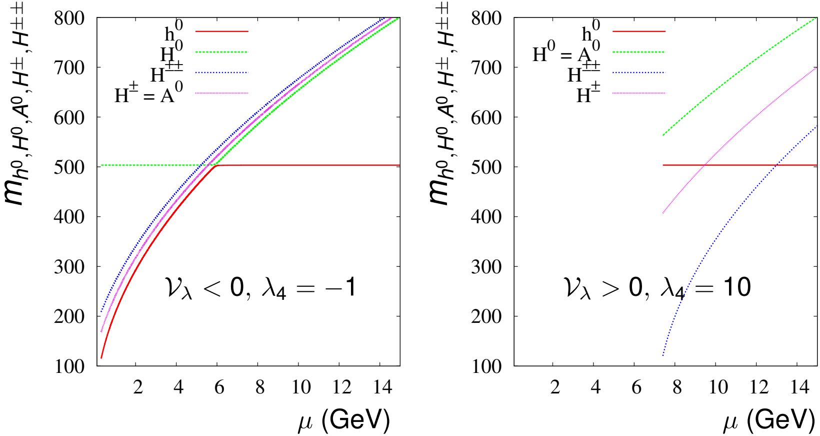
$$M_\Delta^2 = \frac{2\mu v_d^2 - \sqrt{2}(\lambda_1+\lambda_4)v_d^2 v_t - 2\sqrt{2}(\lambda_2+\lambda_3)v_t^3}{2\sqrt{2}v_t} \rightarrow M_\Delta^2 \simeq \frac{\mu v_d^2}{\sqrt{2}v_t} \quad (1)$$

$$m_H^2 = \frac{\lambda v_d^2}{4} - \sqrt{2}\mu v_t + \frac{(\lambda_1+\lambda_4)}{2}v_t^2 \rightarrow m_H^2 \simeq \frac{\lambda v_d^2}{4} \quad (2)$$

  while (2) is trivially OK, (1) assumes $\mu \gg v_t$.

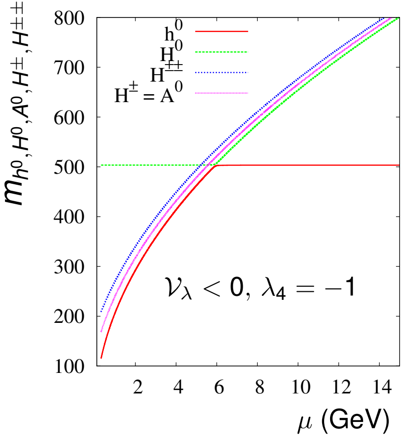
- $M_\Delta \sim \mu \sim M_{GUT}$ → seesaw → only SM-like h^0 at the LHC!
- $\mu \lesssim, \ll v_t$ more interesting

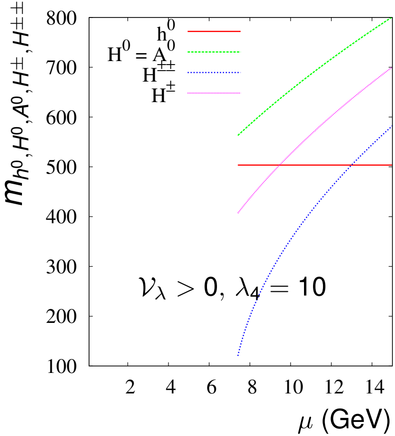
Higgs spectrum, couplings,...



$$\text{sign}[\mathcal{V}_\lambda] \sim \text{sign}[-\lambda + \lambda_1 + \lambda_4]$$

Higgs spectrum, couplings,...

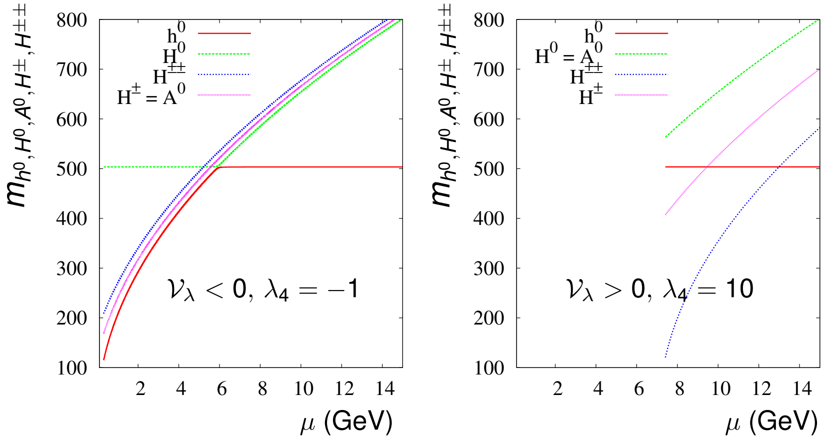




$$\text{sign}[\mathcal{V}_\lambda] \sim \text{sign}[-\lambda + \lambda_1 + \lambda_4]$$

various mass hierarchies

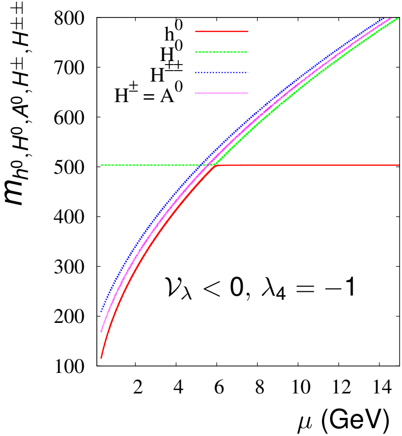
Higgs spectrum, couplings,...

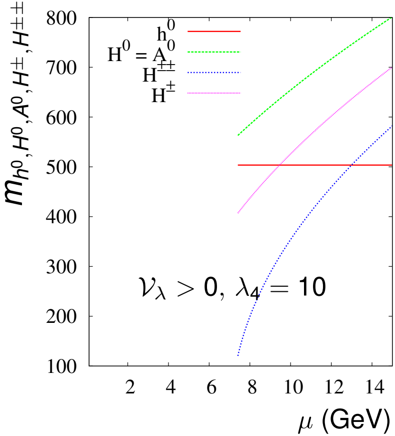


$\mathrm{sign}[\mathcal{V}_\lambda] \sim \mathrm{sign}[-\lambda + \lambda_1 + \lambda_4]$ two possible SM-like Higgs regimes!

various mass hierarchies

Higgs spectrum, couplings,...





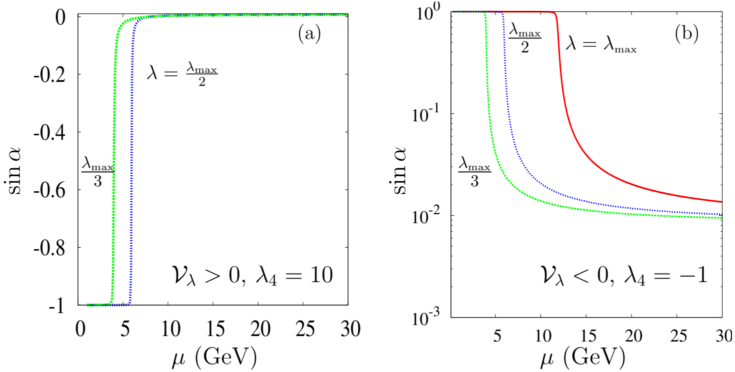
$\mathrm{sign}[\mathcal{V}_\lambda] \sim \mathrm{sign}[-\lambda + \lambda_1 + \lambda_4]$ two possible SM-like Higgs regimes!

various mass hierarchies h^0 or H^0 ?

Higgs spectrum, couplings,...

- lepton number conserving couplings of Higgs and Goldstone to fermions same as in the SM convoluted by cos's and sin's of the mixing angles α, β, β'
- $s_\beta = \frac{2v_t}{\sqrt{v_d^2+4v_t^2}}, s_{\beta'} = \frac{\sqrt{2}v_t}{\sqrt{v_d^2+2v_t^2}} \ll 1$
- $\sin\alpha$ essentially a step function of μ, $|\sin\alpha| \simeq 0 \text{ or } \simeq 1$

Higgs spectrum, couplings,...



$$\mathcal{V}_\lambda \equiv (-\lambda + \lambda_1 + \lambda_4)\, v_d^2 + 4\,(\lambda_2 + \lambda_3)\, v_t^2$$

$$h = \cos\alpha\; h^0 - \sin\alpha\; H^0$$

Higgs spectrum, couplings,...

- lepton number conserving couplings of Higgs and Goldstone to fermions same as in the SM convoluted by cos's and sin's of the mixing angles α, β, β'
- $s_\beta = \frac{2v_t}{\sqrt{v_d^2+4v_t^2}}, s_{\beta'} = \frac{\sqrt{2}v_t}{\sqrt{v_d^2+2v_t^2}} \ll 1$
- $\sin\alpha$ essentially a step function of μ, $|\sin\alpha| \simeq 0$ or $\simeq 1$
- there is a SM-like Higgs state
- $\rightarrow$ the new neutral scalars (almost) fermiophobic

Higgs spectrum, couplings,...

- lepton number conserving couplings of Higgs and Goldstone to fermions same as in the SM convoluted by cos's and sin's of the mixing angles α, β, β'
- $s_\beta = \frac{2v_t}{\sqrt{v_d^2+4v_t^2}}, s_{\beta'} = \frac{\sqrt{2}v_t}{\sqrt{v_d^2+2v_t^2}} \ll 1$
- $\sin\alpha$ essentially a step function of μ, $|\sin\alpha| \simeq 0$ or $\simeq 1$
- there is a SM-like Higgs state
- $\rightarrow$ the new neutral scalars (almost) fermiophobic
- gauge couplings of H^+, H^{++} with electric charges 1 and 2 !
- scalar sector couplings
- un-suppressed electroweak coupling of the new scalars to gauge bosons

Higgs production and decays

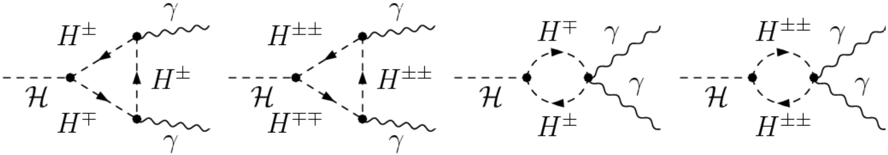
- all production channels gF/VBF/VH/ttH as well as all tree-level decay modes, essentially those of the SM [apart from a fine-tuned maximal $H^0 - h^0$ mixing region]

- deviations/constraints expected in $\gamma\gamma$ and $Z\gamma$ decay channels, due to H^+, H^{++} contributions

$\mathcal{H}$ Into GammaGamma Study

$$\Gamma(\mathcal{H}\to\gamma\gamma) = \frac{G_F\alpha^2 M_{\mathcal{H}}^3}{128\sqrt{2}\pi^3}\Big| \sum_f N_c Q_f^2 \tilde{g}_{\mathcal{H}ff} A_{1/2}^{\mathcal{H}}(\tau_f) + \tilde{g}_{\mathcal{H}WW} A_1^{\mathcal{H}}(\tau_W)$$

$$+\tilde{g}_{\mathcal{H}H^\pm H^\mp} A_0^{\mathcal{H}}(\tau_{H^\pm}) + 4\tilde{g}_{\mathcal{H}H^{\pm\pm}H^{\mp\mp}} A_0^{\mathcal{H}}(\tau_{H^{\pm\pm}}) \Big|^2$$



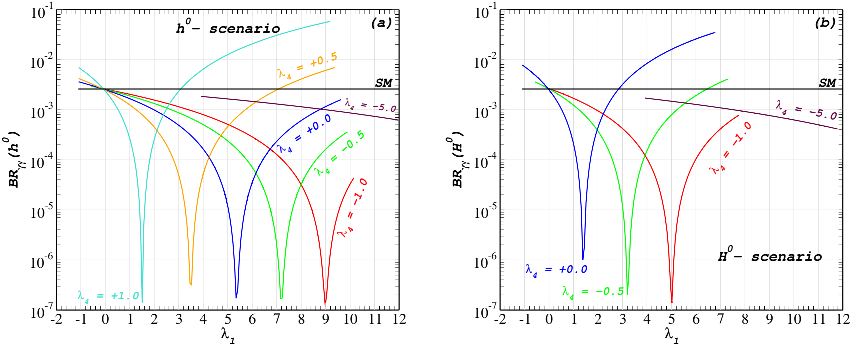
$$\tilde{g}_{\mathcal{H}H^{++}H^{--}} = -\frac{s_W}{e}\frac{m_W}{m^2_{H^{\pm\pm}}} g_{\mathcal{H}H^{++}H^{--}}, \quad \tilde{g}_{\mathcal{H}H^{+}H^{-}} = -\frac{s_W}{e}\frac{m_W}{m^2_{H^{\pm}}} g_{\mathcal{H}H^{+}H^{-}}$$

$g_{\mathcal{H}H^{++}H^{--}} \approx -\bar{\epsilon}\lambda_1 v_d$ $\quad\quad$ $g_{\mathcal{H}H^{+}H^{-}} \approx -\bar{\epsilon}(\lambda_1 + \frac{\lambda_4}{2}) v_d$

$\bar{\epsilon} = 1$ $\quad$ or $\quad$ $\bar{\epsilon} = \text{sign}[\sqrt{2}\mu - (\lambda_1+\lambda_4)v_t]$

relative Higgs couplings

$\mathcal{H}$	$\tilde{g}_{\mathcal{H}\bar{u}u}$	$\tilde{g}_{\mathcal{H}\bar{d}d}$	$\tilde{g}_{\mathcal{H}W^+W^-}$
h^0	$c_\alpha/c_{\beta'}$	$c_\alpha/c_{\beta'}$	$+e(c_\alpha v_d + 2s_\alpha v_t)/(2s_W m_W)$
H^0	$-s_\alpha/c_{\beta'}$	$-s_\alpha/c_{\beta'}$	$-e(s_\alpha v_d - 2c_\alpha v_t)/(2s_W m_W)$



$M_{\mathcal{H}} \simeq 125$ GeV

$M_{H^+}, M_{H^{++}} > 110$ GeV

$m_{H^0} \simeq m_{A^0} \approx 210$ GeV $\qquad$ $m_{h^0} \simeq m_{A^0} \approx 113$ GeV

light h^0, A^0

- $\frac{\mu}{v_t} \ll 1 \Rightarrow H^0$ SM-like & $m_{h^0} \simeq m_{A^0} < m_{H^0}$
- $g_{h^0 h^0 H^0} = g_{A^0 A^0 H^0} \simeq (\lambda_1 + \lambda_4) v_d$
- $|g_{Z h^0 A^0}| \approx |g_{ZZH^0}|^{SM}$

light h^0, A^0

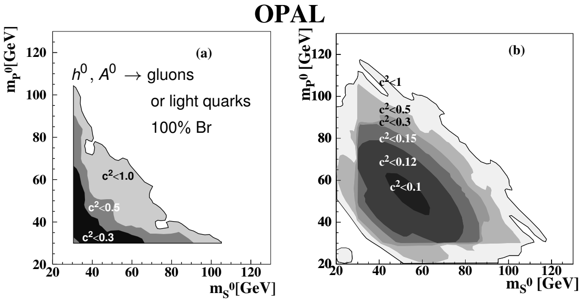
constraints to worry about:

- non-standard decay modes of the SM-like Higgs:
  - $\mathcal{H} \to h^0 h^{0(*)}, A^0 A^{0(*)}$
  - followed by $h^0, A^0 \to b\bar{b}, \nu\nu + \bar{\nu}\bar{\nu}, (gg, \tau\tau, \gamma\gamma)$, ...
- LEP2 direct search limits

  $e^+ e^- \to Z^* \to h^0 A^0$
- the Z boson width

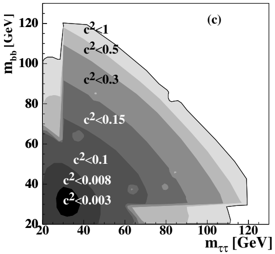
  $Z \to h^0 A^0$

light h^0, A^0



$h^0, A^0 \to b\bar{b}b\bar{b}$

100% Br



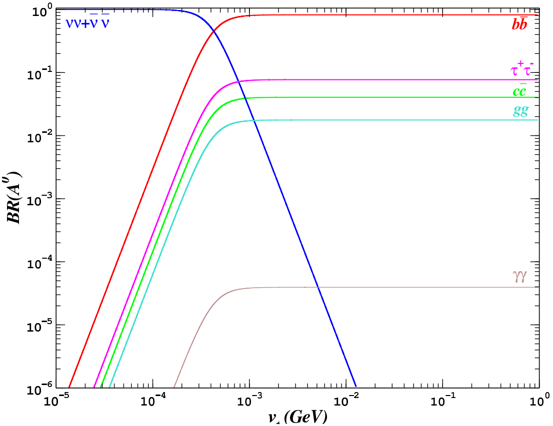
$$\sigma_{e^+e^- \to Z^* \to h^0 A^0} = (\ldots) c^2 \sigma^{SM}_{HZ}$$

$h^0, A^0 \to b\bar{b}\tau^+\tau^-$

or $b\bar{b}\tau^+\tau^-$

100% Br

light h^0, A^0



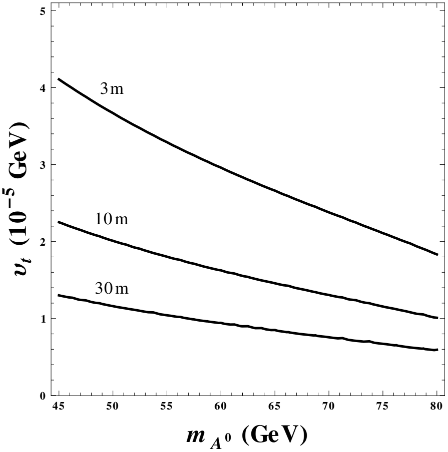
A^0: LNC decays, $4v_t^2/v_d^2$ suppression $\quad h^0$: $\times(\lambda_1+\lambda_4)^2/\lambda^2$

LNV decays, $2\sum m_\nu^2/v_t^2$ enhancement $\quad \times 1$

light h^0, A^0

LEP2 constraints can be evaded for sufficiently small v_t in two ways:

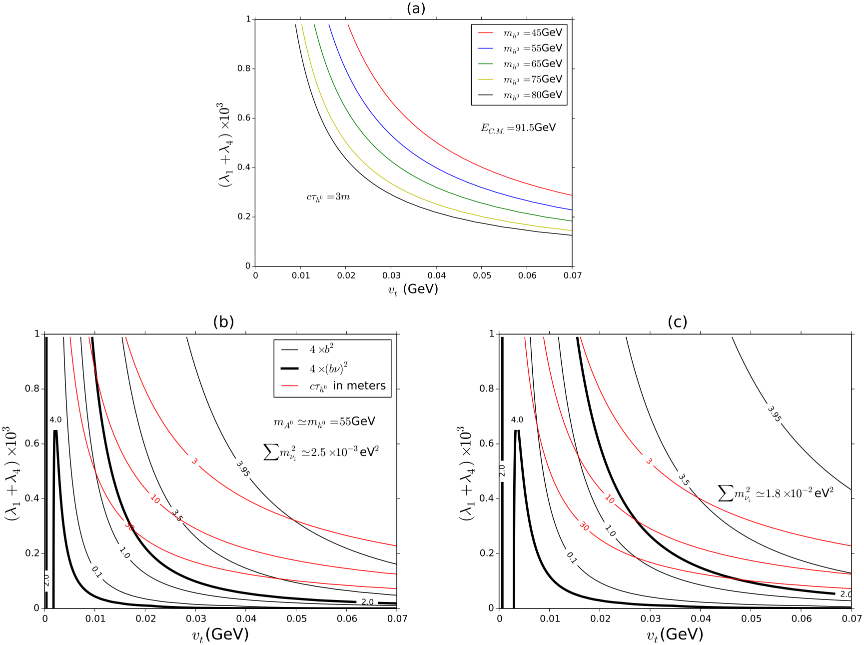
- branching ratios of decays in neutrinos become important or dominant
- lifetime of h^0 or A^0 becomes sufficiently long, decaying outside the detector



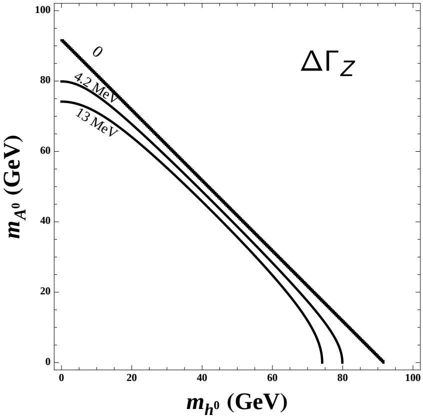
decay length $c\tau$

light h^0, A^0

$\Rightarrow$ LEP2 bounds evaded for $v_t \lesssim \mathcal{O}(10^{-3})$GeV


(a)
m_{h^0} =45GeV
m_{h^0} =55GeV
m_{h^0} =65GeV
m_{h^0} =75GeV
m_{h^0} =80GeV
$E_{C.M.}$ =91.5GeV
$c\tau_{h^0}$ =3m
$(\lambda_1+\lambda_4)\times 10^3$
v_t (GeV)
(b)
$4\times b^2$
$4\times (b\nu)^2$
$c\tau_{h^0}$ in meters
$m_{A^0}\simeq m_{h^0}$ =55GeV
$\sum m^2_{\nu_i}\simeq 2.5\times 10^{-3}$ eV^2
$(\lambda_1+\lambda_4)\times 10^3$
v_t(GeV)
(c)
$\sum m^2_{\nu_i}\simeq 1.8\times 10^{-2}$ eV^2
$(\lambda_1+\lambda_4)\times 10^3$
v_t(GeV)

light h^0, A^0



$\Gamma_Z = 2.4952 \pm 0.0023$ GeV (LEP)

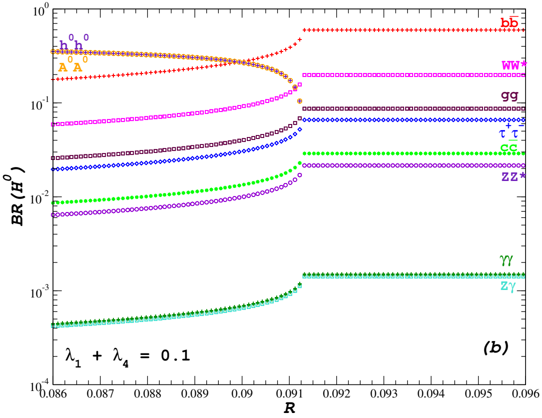
$\Gamma_Z^{SM} = 2.4961 \pm 0.0010$ (Th.)

$\Delta\Gamma_Z^{max} \simeq 4.2$MeV at the 95% C.L.

irreducible bound

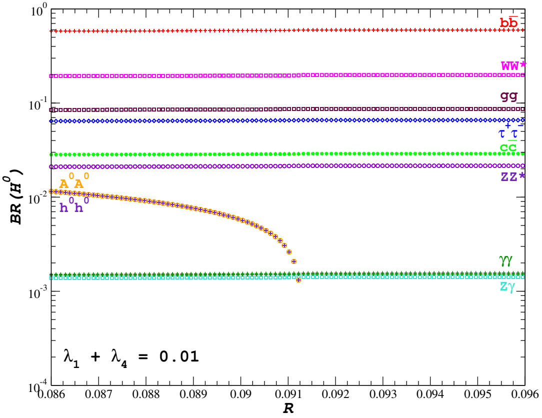
$\Rightarrow m_{h^0} \simeq m_{A^0} \gtrsim 44.3$GeV

light h^0, A^0



$$R \equiv \frac{\mu}{v_t}$$

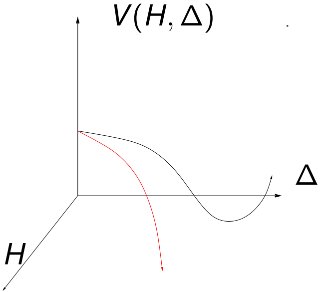
light h^0, A^0



$$R \equiv \frac{\mu}{v_t}$$

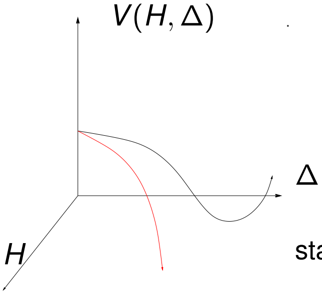
Dynamical constraints

Tree-level Boundedness From Below:



Dynamical constraints

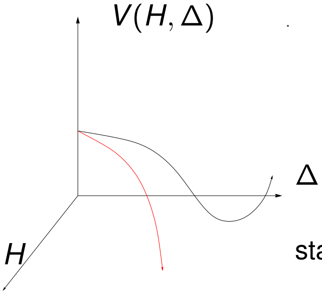
Tree-level Boundedness From Below:



stable vacuum $\leftrightarrow$ $V > V_{min}, \ \forall H, \Delta$

Dynamical constraints

Tree-level Boundedness From Below:

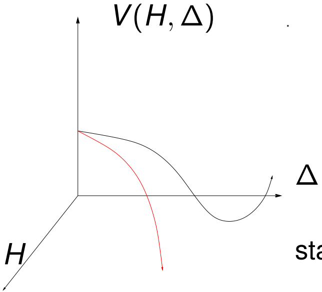


stable vacuum $\leftrightarrow V > V_{min},\ \forall H, \Delta$

keep only the quartic operators

Dynamical constraints

Tree-level Boundedness From Below:



stable vacuum $\leftrightarrow V > V_{min}, \ \forall H, \Delta$

keep only the quartic operators

$$V^{(4)}(H,\Delta) = \frac{\lambda}{4}(H^\dagger H)^2 + \lambda_1 (H^\dagger H) Tr(\Delta^\dagger \Delta) + \lambda_2 (Tr \Delta^\dagger \Delta)^2$$
$$+\lambda_3 Tr(\Delta^\dagger \Delta)^2 + \lambda_4 H^\dagger \Delta \Delta^\dagger H$$

Dynamical constraints

Tree-level Boundedness From Below: The most general solution

Tree-level Boundedness From Below: The most general solution

$$r \equiv \sqrt{H^\dagger H + Tr\Delta^\dagger\Delta}$$
$$H^\dagger H \equiv r^2 \cos^2\gamma$$
$$Tr(\Delta^\dagger\Delta) \equiv r^2 \sin^2\gamma$$
$$(H^\dagger\Delta\Delta^\dagger H)/(H^\dagger H Tr\Delta^\dagger\Delta) \equiv \xi$$
$$Tr(\Delta^\dagger\Delta)^2/(Tr\Delta^\dagger\Delta)^2 \equiv \zeta$$

Dynamical constraints

<u>*Tree-level Boundedness From Below:*</u> The most general solution

$$
\begin{aligned}
r &\equiv \sqrt{H^\dagger H + Tr\Delta^\dagger\Delta} \\
H^\dagger H &\equiv r^2 \cos^2\gamma \\
Tr(\Delta^\dagger\Delta) &\equiv r^2 \sin^2\gamma \\
(H^\dagger\Delta\Delta^\dagger H)/(H^\dagger H Tr\Delta^\dagger\Delta) &\equiv \xi \\
Tr(\Delta^\dagger\Delta)^2/(Tr\Delta^\dagger\Delta)^2 &\equiv \zeta
\end{aligned}
$$

$$0 \leq \xi \leq 1 \quad \text{and} \quad \frac{1}{2} \leq \zeta \leq 1$$

Dynamical constraints

Tree-level Boundedness From Below: The most general solution

$$
\begin{aligned}
r &\equiv \sqrt{H^\dagger H + Tr\Delta^\dagger\Delta} \\
H^\dagger H &\equiv r^2 \cos^2\gamma \\
Tr(\Delta^\dagger\Delta) &\equiv r^2 \sin^2\gamma \\
(H^\dagger\Delta\Delta^\dagger H)/(H^\dagger H Tr\Delta^\dagger\Delta) &\equiv \xi \\
Tr(\Delta^\dagger\Delta)^2/(Tr\Delta^\dagger\Delta)^2 &\equiv \zeta
\end{aligned}
$$

$$V^{(4)}(r, \tan\gamma, \xi, \zeta) = \frac{r^4}{4(1+\tan^2\gamma)^2}(\lambda + 4(\lambda_1 + \xi\lambda_4)\tan^2\gamma + 4(\lambda_2 + \zeta\lambda_3)\tan^4\gamma)$$

$$0 \leq \xi \leq 1 \quad \text{and} \quad \frac{1}{2} \leq \zeta \leq 1$$

Dynamical constraints

Tree-level Boundedness From Below: The most general solution

$$
\begin{aligned}
r &\equiv \sqrt{H^\dagger H + Tr\Delta^\dagger\Delta} \\
H^\dagger H &\equiv r^2\cos^2\gamma \\
Tr(\Delta^\dagger\Delta) &\equiv r^2\sin^2\gamma \\
(H^\dagger\Delta\Delta^\dagger H)/(H^\dagger H Tr\Delta^\dagger\Delta) &\equiv \xi \\
Tr(\Delta^\dagger\Delta)^2/(Tr\Delta^\dagger\Delta)^2 &\equiv \zeta
\end{aligned}
$$

$$
V^{(4)}(r,\tan\gamma,\xi,\zeta) = \frac{r^4}{4(1+\tan^2\gamma)^2}(\lambda + 4(\lambda_1+\xi\lambda_4)\tan^2\gamma + 4(\lambda_2+\zeta\lambda_3)\tan^4\gamma)
$$

$$
0 \leq \tan\gamma < +\infty
$$

$$
0 \leq \xi \leq 1 \quad \text{and} \quad \frac{1}{2} \leq \zeta \leq 1
$$

Dynamical constraints

$$\lambda > 0 \;\; \& \;\; \lambda_2 + \zeta\lambda_3 > 0 \;\; \& \;\; \lambda_1 + \xi\lambda_4 + \sqrt{\lambda(\lambda_2 + \zeta\lambda_3)} > 0,$$

$$\forall\zeta \in [\frac{1}{2}, 1], \forall\xi \in [0, 1]$$

Dynamical constraints

$$\lambda > 0 \;\; \& \;\; \lambda_2 + \zeta\lambda_3 > 0 \;\; \& \;\; \lambda_1 + \xi\lambda_4 + \sqrt{\lambda(\lambda_2 + \zeta\lambda_3)} > 0,$$

$$\forall\zeta \in [\frac{1}{2}, 1], \forall\xi \in [0, 1]$$

$$\lambda \geq 0 \;\; \& \;\; \lambda_2 + \lambda_3 \geq 0 \;\; \& \;\; \lambda_2 + \frac{\lambda_3}{2} \geq 0$$

$$\& \;\; \lambda_1 + \sqrt{\lambda(\lambda_2 + \lambda_3)} \geq 0 \;\; \& \;\; \lambda_1 + \sqrt{\lambda(\lambda_2 + \frac{\lambda_3}{2})} \geq 0$$

$$\& \;\; \lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2 + \lambda_3)} \geq 0 \;\; \& \;\; \lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2 + \frac{\lambda_3}{2})} \geq 0$$

Combined dynamical constraints

BFB and unitarity

Combined dynamical constraints

BFB and unitarity

$$0 \leq \lambda \leq \frac{2}{3}\kappa\pi \ \ \& \ \ \lambda_2 + \lambda_3 \geq 0 \ \ \& \ \ \lambda_2 + \frac{\lambda_3}{2} \geq 0 \ \ \&$$

$$\lambda_1 + \sqrt{\lambda(\lambda_2 + \lambda_3)} \geq 0 \ \ \& \ \ \lambda_1 + \sqrt{\lambda(\lambda_2 + \frac{\lambda_3}{2})} \geq 0 \ \ \&$$

$$\lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2 + \lambda_3)} \geq 0 \ \ \& \ \ \lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2 + \frac{\lambda_3}{2})} \geq 0 \ \ \&$$

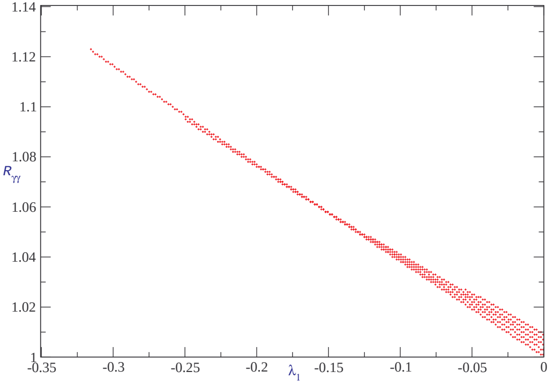
$$\lambda_2 + 2\lambda_3 \leq \frac{\kappa}{2}\pi \ \ \& \ \ 4\lambda_2 + 3\lambda_3 \leq \frac{\kappa}{2}\pi \ \ \&$$

$$\lambda_2 - 2\lambda_3 - \sqrt{(\lambda_2 - \frac{\kappa}{2}\pi)(9\lambda_2 - \frac{5}{2}\kappa\pi)} \leq \frac{\kappa}{2}\pi \ \ \&$$

$$|\lambda_4| \leq \min \sqrt{(\lambda \pm 2\kappa\pi)(\lambda_2 + 2\lambda_3 \pm \frac{\kappa}{2}\pi)} \ \ \&$$

$$|2\lambda_1 + \lambda_4| \leq \sqrt{2(\lambda - \frac{2}{3}\kappa\pi)(4\lambda_2 + 3\lambda_3 - \frac{\kappa}{2}\pi)}$$

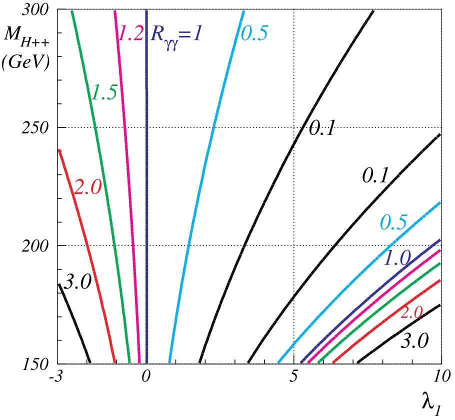
Combined dynamical constraints



$$\lambda = 0.52, \lambda_3 = 2\lambda_2 = 0.2, v_t = 1 \text{ GeV}$$

$\Rightarrow$ exact full 5D hyper-volume: $\lambda_1 < -1, -0.5 \rightarrow$ 3permil, 3%

Ratio of branching ratios



Akeroyd, Moretti, arXiv:1206.0535

Outlook

- the new Higgs states difficult to exclude for v_t very small
- radiative corrections: effects in the full set of precision observables ($\Delta\rho$, M_W, Γ_Z, $R_{Z,b,c}$, Asymmetries, etc.), not just S,T,U...
- a better understanding of the effective potential of the model, (loop improved dynamical constraints, non-physical minima, etc.)
- no dark matter candidate! extensions ?
- a more complete study with coming LHC data for the (quasi triplet) neutral Higgs and improved limits on H^{++}, H^{+}.
- ongoing (Arhrib, Capdequi, G.M.), improved BFB and extension to two triplets...
- ongoing (Chabab, Capdequi, Rahili), quadratic div. structures...