

Higgs boson decays and the type II seesaw model

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Arhrib *et al*

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and

JHEP 1204 (2012) 136, arXiv:1112.5453 [hep-ph]

Prologue

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H I G G S

do not think...PETER

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think rather...

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' H ' Into Gamma Gamma Study

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Outline

The model

Introductory motivations

EWSB

Higgs spectrum, couplings,...

Higgs production and decays

$\gamma\gamma$ branching ratios

Ratio of branching ratios

Precision observables

Ratio of branching ratios

Outlook

Introductory motivations

are there hints for physics beyond the Standard Model?

- ▶ Naturalness or hierarchy problems are often overstated
- ▶ Dark matter!
- ▶ Neutrino masses? No and Yes

No: *simply add a ν_R and a standard Yukawa coupling* →
Dirac mass + perhaps a Majorana mass

- mysterious... SM **singlet** only gravitationally coupled !?
- more elegant (but not necessary!), ν_R charged under some GUT group... e.g. spinorial rep. of $SO(10)$

→ seesaw mechanisms

In this talk we will have in mind the type II seesaw →
neutrinos masses without an extra ν_R

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

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 $SU(3)_c \times SU(2)_L \times U(1)_Y$.

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

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

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

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

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

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 $v \equiv \sqrt{v_d^2 + 2v_t^2} = 246\text{GeV}$

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

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

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Electroweak symmetry breaking

→ 10 scalar states: 7 massive physical Higgses, $h^0, H^0, A^0, H^\pm, H^{\pm\pm}$ and 3 Goldstone bosons

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

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→ three mixing angles α, β, β' .

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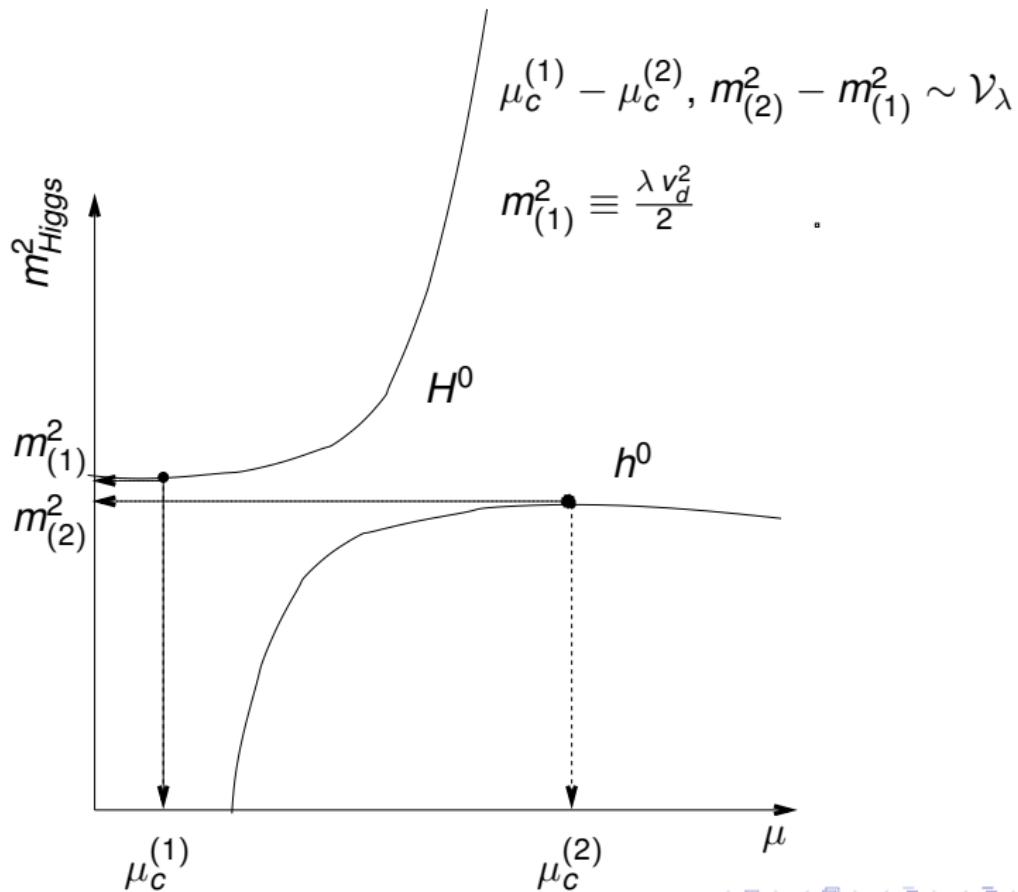
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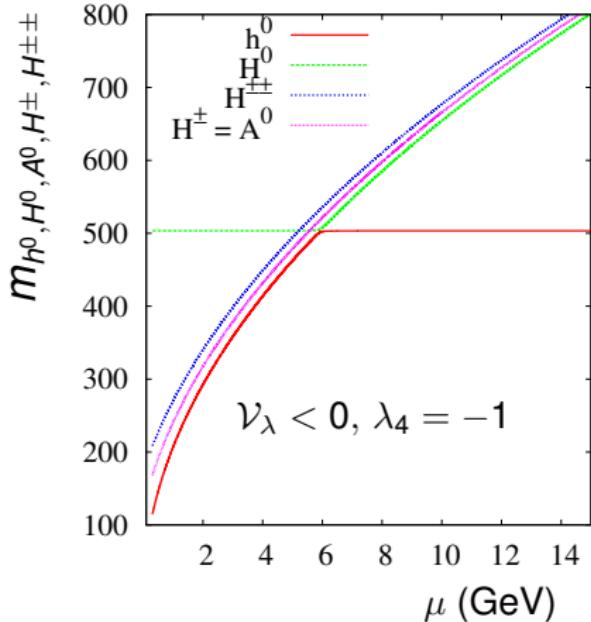
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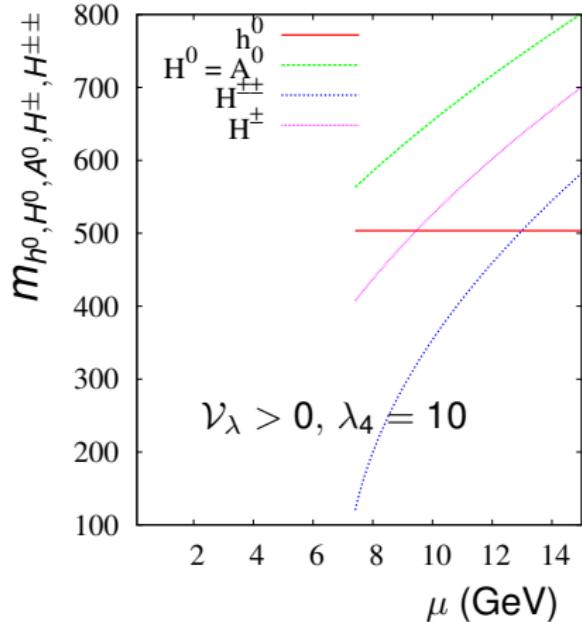
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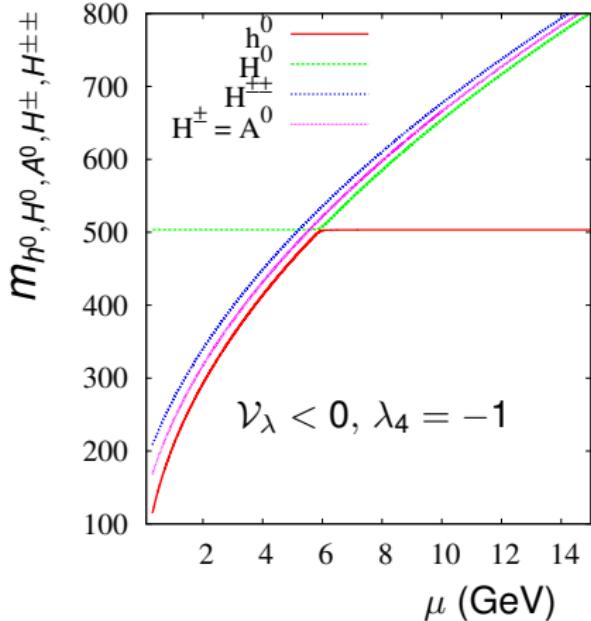
various mass hierarchies



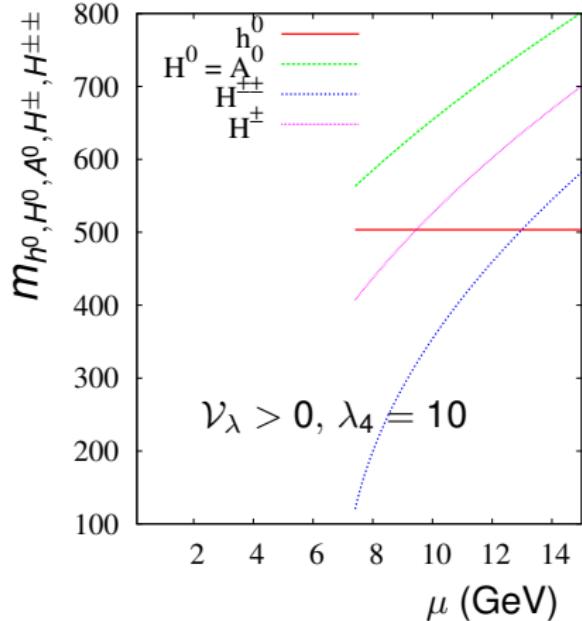
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h^0 or H^0 ?

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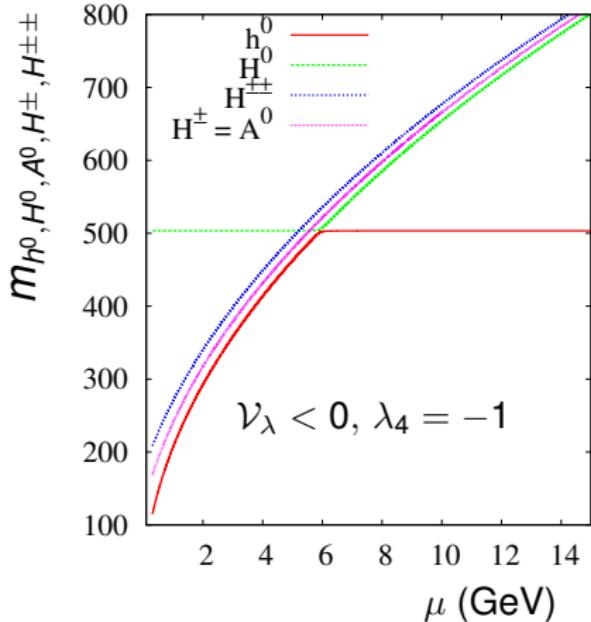
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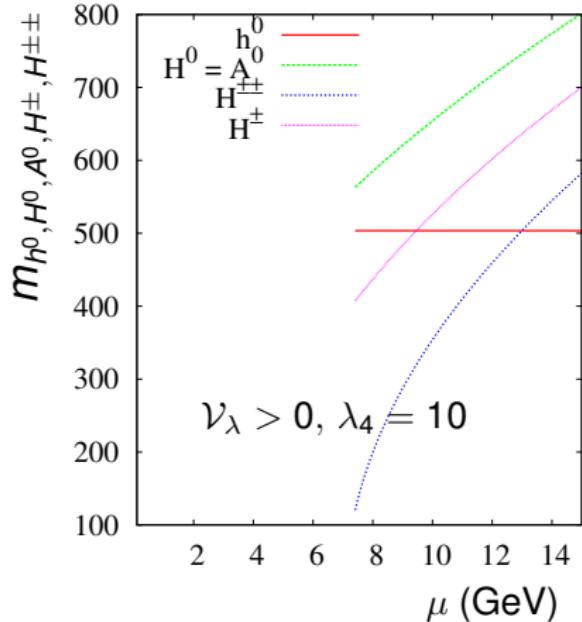
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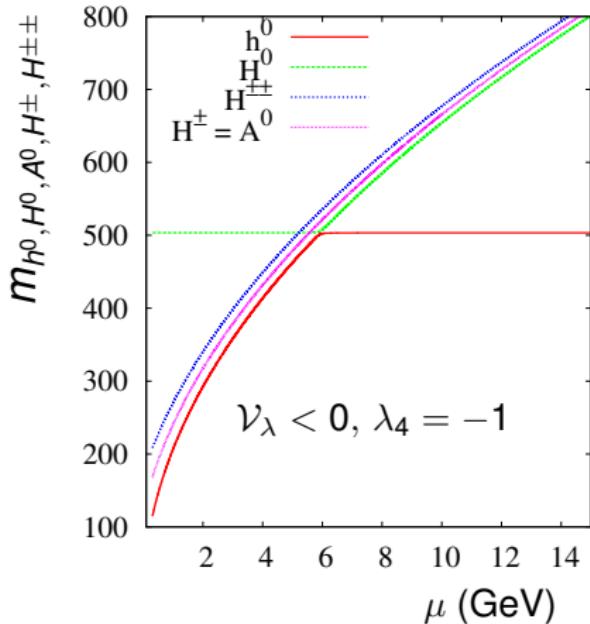
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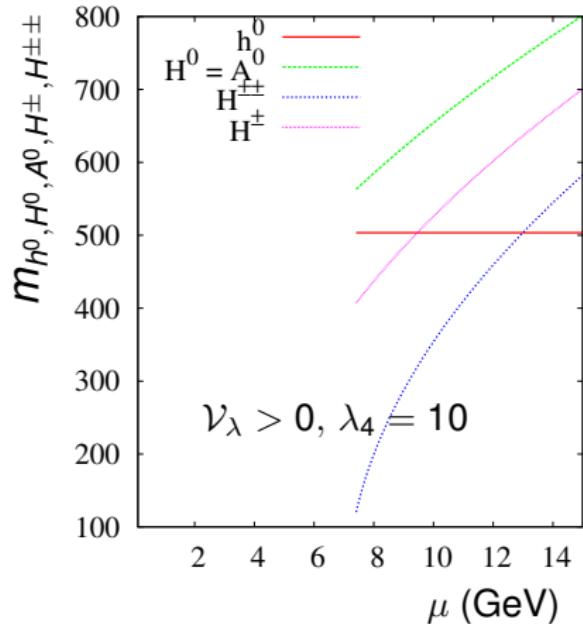
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Higgs production and decays

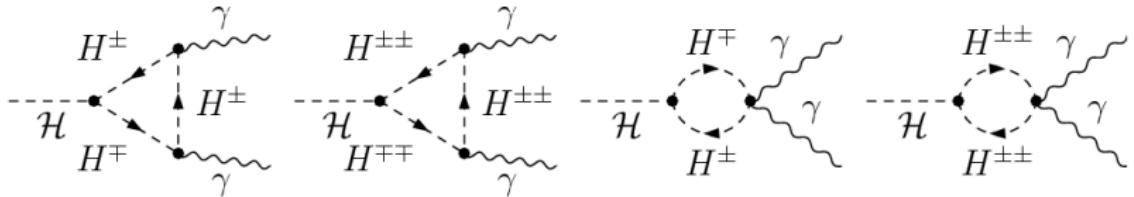
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$$\Gamma(\mathcal{H} \rightarrow \gamma\gamma) = \frac{G_F \alpha^2 M_{\mathcal{H}}^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 \tilde{g}_{\mathcal{H}ff} A_{1/2}^{\mathcal{H}}(\tau_f) + \tilde{g}_{\mathcal{H}WW} A_1^{\mathcal{H}}(\tau_W) \right. \\ \left. + \tilde{g}_{\mathcal{H}H^\pm H^\mp} A_0^{\mathcal{H}}(\tau_{H^\pm}) + 4\tilde{g}_{\mathcal{H}H^\pm\pm H^{\mp\mp}} A_0^{\mathcal{H}}(\tau_{H^\pm\pm}) \right|^2$$



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

$$g_{\mathcal{H}H^{++}H^{--}} \approx -\bar{\epsilon} \lambda_1 v_d$$

$$\bar{\epsilon} = 1$$

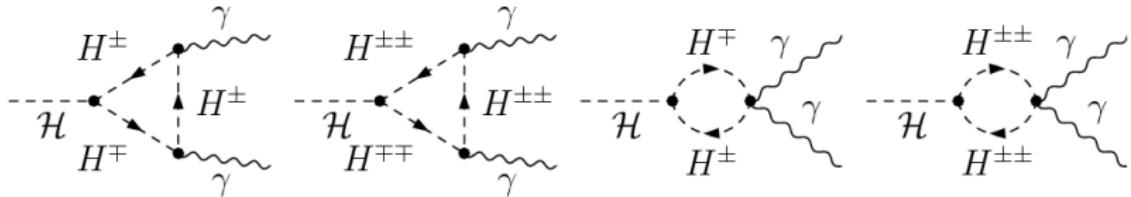
or

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

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

H.I.G.S

$$\Gamma(\mathcal{H} \rightarrow \gamma\gamma) = \frac{G_F \alpha^2 M_{\mathcal{H}}^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 \tilde{g}_{\mathcal{H}ff} A_{1/2}^{\mathcal{H}}(\tau_f) + \tilde{g}_{\mathcal{H}WW} A_1^{\mathcal{H}}(\tau_W) \right. \\ \left. + \tilde{g}_{\mathcal{H}H^\pm H^\mp} A_0^{\mathcal{H}}(\tau_{H^\pm}) + 4\tilde{g}_{\mathcal{H}H^\pm\pm H^{\mp\mp}} A_0^{\mathcal{H}}(\tau_{H^\pm\pm}) \right|^2$$



$$\tilde{g}_{\mathcal{H}H^{++}H^{--}} = -\frac{s_w}{e} \frac{m_w}{m_{H^{\pm\pm}}^2} g_{\mathcal{H}H^{++}H^{--}}, \quad \tilde{g}_{\mathcal{H}H^+H^-} = -\frac{s_w}{e} \frac{m_w}{m_{H^\pm}^2} g_{\mathcal{H}H^+H^-}$$

$$g_{\mathcal{H}H^{++}H^{--}} \approx -\bar{\epsilon} \lambda_1 v_d$$

$$\bar{\epsilon} = 1$$

or

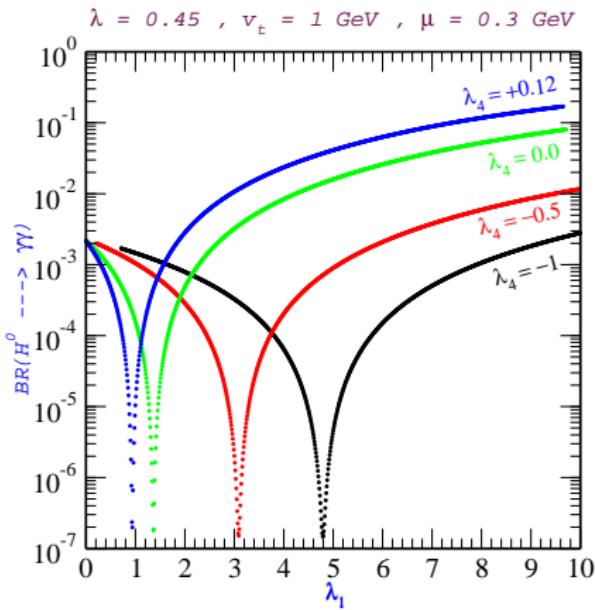
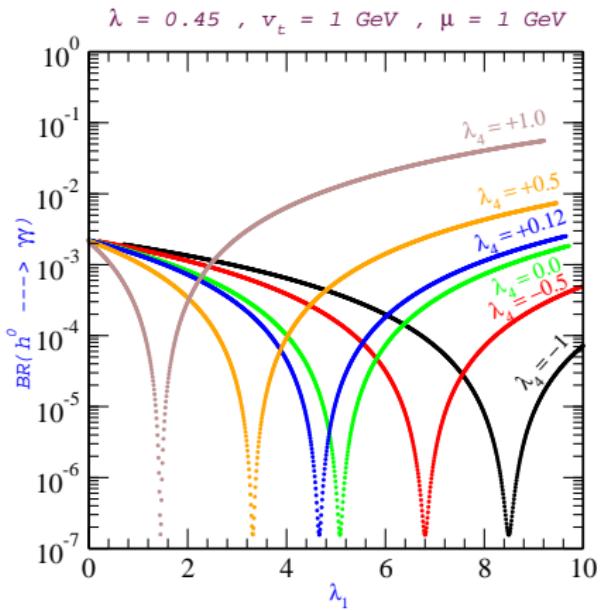
$$g_{\mathcal{H}H^+H^-} \approx -\bar{\epsilon} (\lambda_1 + \frac{\lambda_4}{2}) v_d$$

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

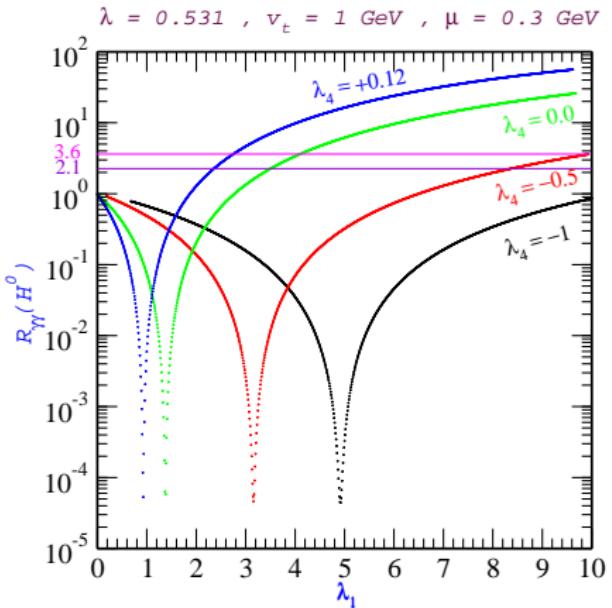
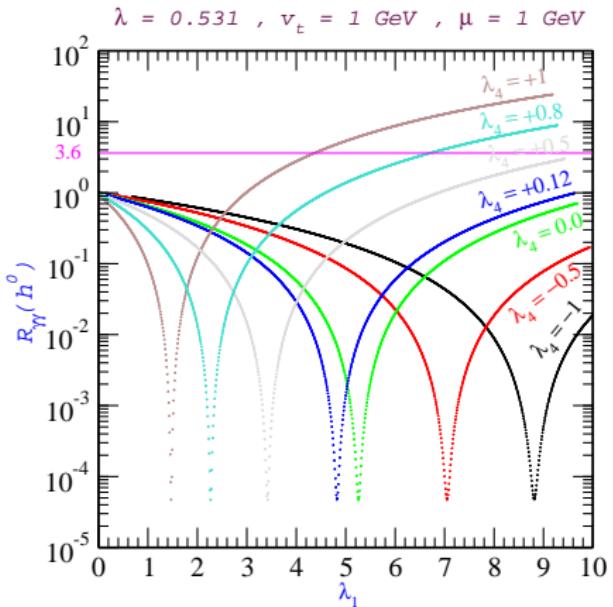
relative Higgs couplings

\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	$-s_\alpha/c_{\beta'}$	$-s_\alpha/c_{\beta'}$	$-e(s_\alpha v_d - 2c_\alpha v_t)/(2s_W m_W)$

$\gamma\gamma$ branching ratios



Ratio of branching ratios



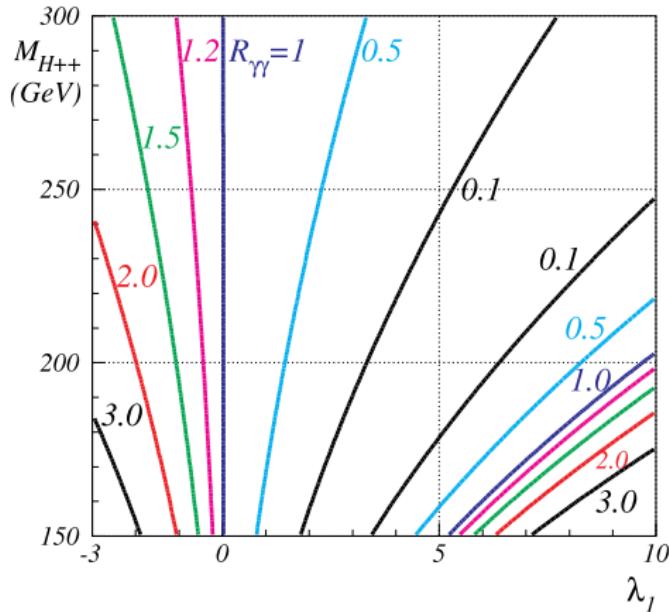
$$R_{\gamma\gamma}(\mathcal{H}) = \frac{(\Gamma(\mathcal{H} \rightarrow gg) \times \text{Br}(\mathcal{H} \rightarrow \gamma\gamma))^{DTHM}}{(\Gamma(\mathcal{H} \rightarrow gg) \times \text{Br}(\mathcal{H} \rightarrow \gamma\gamma))^{SM}}$$

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

$M_{H^{++}} > 110 \text{ GeV}$

$M_{H^+} > 90 \text{ GeV}$

Ratio of branching ratios



Akeroyd, Moretti, arXiv:1206.0535

Combined dynamical constraints

BFB and unitarity

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

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

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

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

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

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

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

Combined dynamical constraints

BFB and unitarity

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

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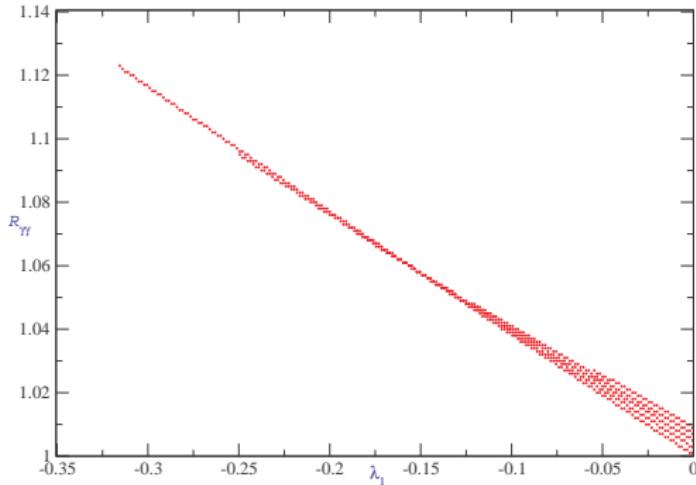
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Combined dynamical constraints



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

Precision observables

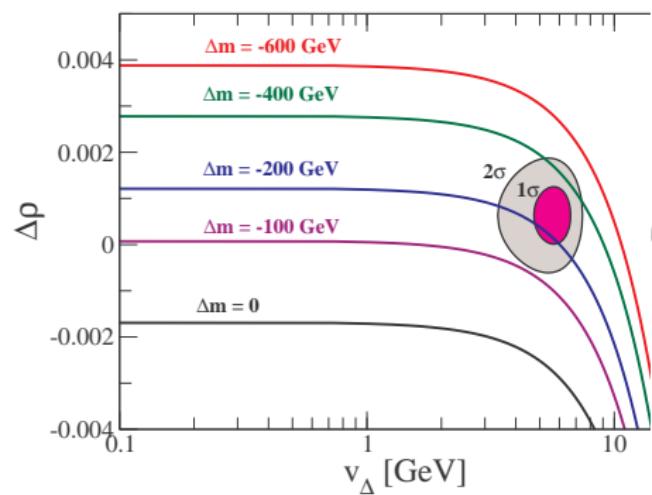
Kanemura, Yagyu, arXiv:1201.6287

$$m_{h^0} > m_{H^+} > m_{H^{++}}$$

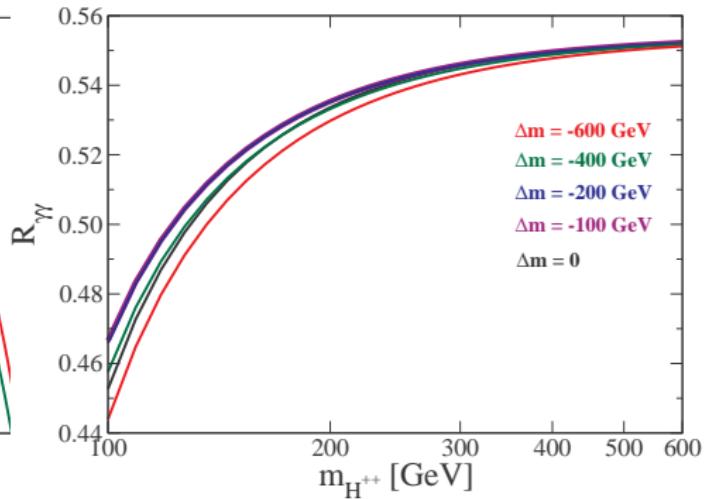
→ h^0 as SM-like disfavored!

Precision observables

Case I: $m_{H^{++}} = 150 \text{ GeV}$, $m_h = 125 \text{ GeV}$, $\tan\alpha$



Case I: $m_h = 125 \text{ GeV}$, $v_\Delta = 5 \text{ GeV}$, $\tan\alpha = 0$



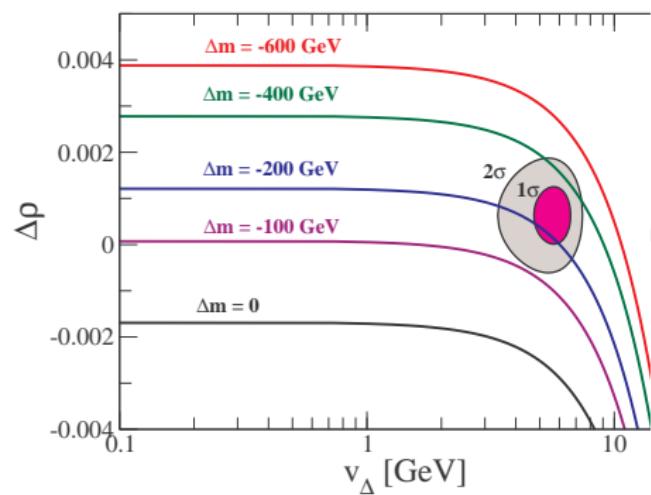
Kanemura, Yagyu, arXiv:1201.6287

$m_{h^0} > m_{H^+} > m_{H^{++}}$

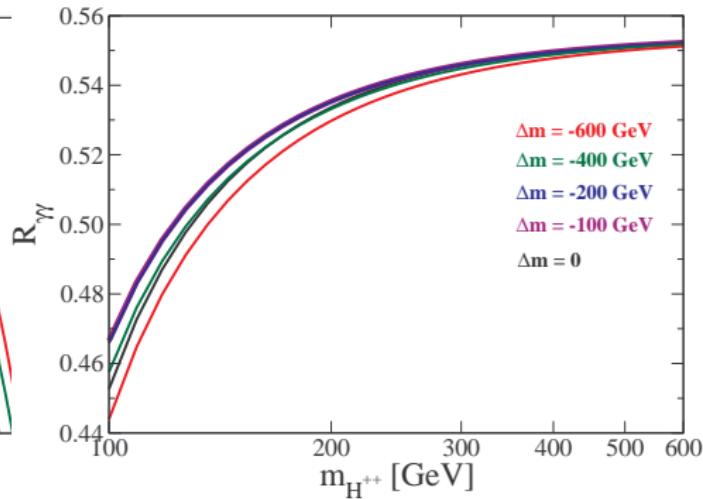
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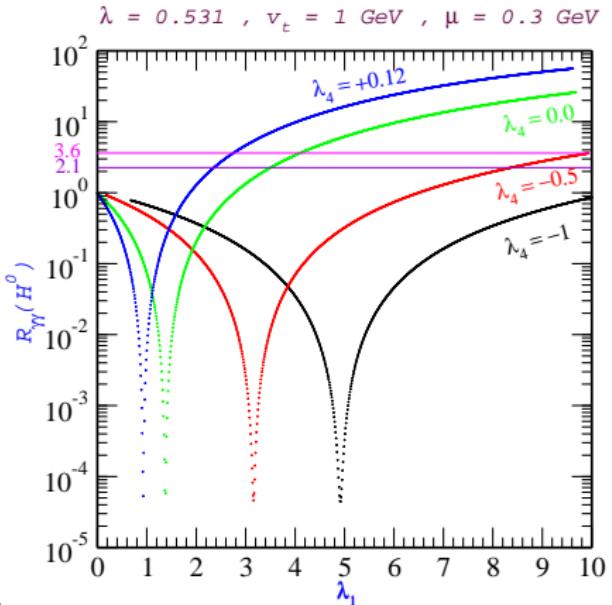
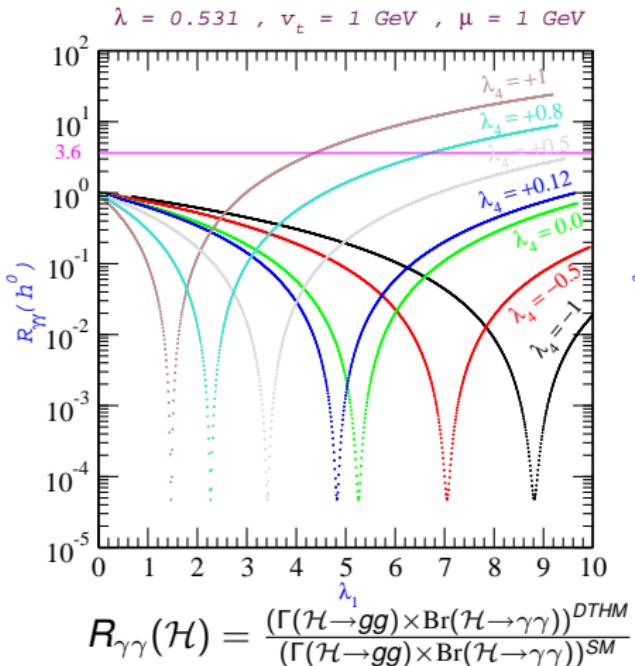


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→ H^0 as SM-like!

→ very small μ , good news(?) → h^0 Dark Matter-like !!

Outlook

- ▶ effects in the full set of precision observables (M_W , Γ_Z , $R_{Z,b,c}$, Asymmetries, etc.), not just S,T,U...
- ▶ a more realistic study with LHC data for all neutral Higgs channels → constraints on H^{++} , H^+ , (SFitter ?)
- ▶ a better understanding of the effective potential of the model, (loop improved dynamical constraints, non-physical minima, etc.)
- ▶ can the model have a viable dark matter candidate, (very small μ) ?

BACKUP

Dynamical constraints

- ▶ tree-level unitarity constraints from scalar and gauge boson scattering
- ▶ conditions for a bounded from below potential
- ▶ absence of charge breaking minima?
- ▶ metastable gauge symmetric vacuum?
- ▶ tachyonless states
- ▶ spontaneous CP violation?

Higgs spectrum ?

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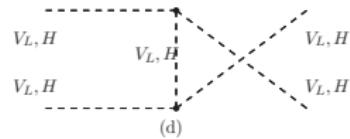
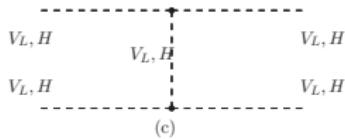
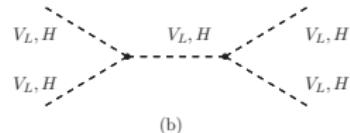
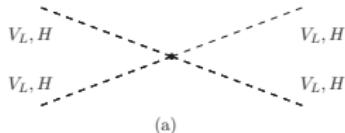
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Higgs spectrum ?

Dynamical constraints

Tree-level unitarity:

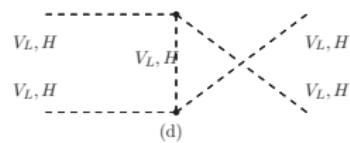
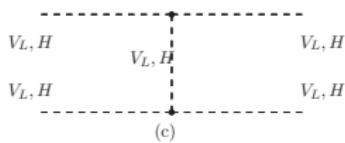
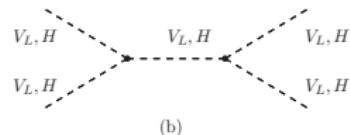
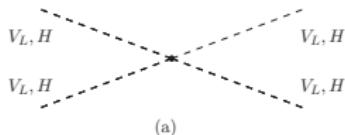


a 27×27 S matrix composed of 5 submatrices $\mathcal{M}_1(6 \times 6)$, $\mathcal{M}_2(7 \times 7)$, $\mathcal{M}_3(2 \times 2)$, $\mathcal{M}_4(8 \times 8)$, and $\mathcal{M}_5(4 \times 4)$

partial wave analyses $\rightarrow |a_0| \leq 1$

Dynamical constraints

Tree-level unitarity:

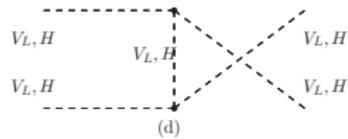
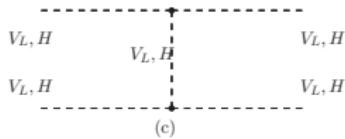
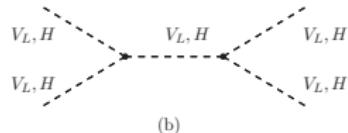
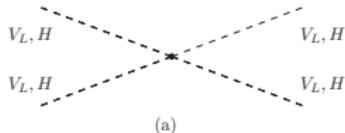


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Dynamical constraints

Tree-level unitarity:

$$|\lambda_1 + \lambda_4| \leq \kappa\pi \quad (1)$$

$$|\lambda_1| \leq \kappa\pi \quad (2)$$

$$|2\lambda_1 + 3\lambda_4| \leq 2\kappa\pi \quad (3)$$

$$|\lambda| \leq 2\kappa\pi \quad (4)$$

$$|\lambda_2| \leq \frac{\kappa}{2}\pi \quad (5)$$

$$|\lambda_2 + \lambda_3| \leq \frac{\kappa}{2}\pi \quad (6)$$

$$|\lambda + 4\lambda_2 + 8\lambda_3 \pm \sqrt{(\lambda - 4\lambda_2 - 8\lambda_3)^2 + 16\lambda_4^2}| \leq 4\kappa\pi \quad (7)$$

$$|3\lambda + 16\lambda_2 + 12\lambda_3 \pm \sqrt{(3\lambda - 16\lambda_2 - 12\lambda_3)^2 + 24(2\lambda_1 + \lambda_4)^2}| \leq 4\kappa\pi \quad (8)$$

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Dynamical constraints

Tree-level Boundedness From Below:

- ▶ Keep only the quartic operators

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

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Dynamical constraints

Tree-level Boundedness From Below:

In the literature one finds only very partial answers;

e.g. field space directions where only the electrically neutral components are non vanishing

$$V_0^{(4)} = \frac{\lambda}{4} |\phi^0|^4 + (\lambda_2 + \lambda_3) |\delta^0|^4 + (\lambda_1 + \lambda_4) |\phi^0|^2 |\delta^0|^2$$

lead to the sufficient and necessary conditions

$$\lambda > 0$$

$$\lambda_2 + \lambda_3 > 0$$

$$\lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2 + \lambda_3)} > 0$$

→ it becomes more complicated in other directions!

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Dynamical constraints

e.g. of a 3-field direction $(\phi^+, \delta^0, \delta^{++})$:

$$\begin{aligned} V^{(4)} = & (\lambda_2 + \lambda_3) |\delta^0|^4 + 2\lambda_2 |\delta^0|^2 |\delta^{++}|^2 + (\lambda_2 + \lambda_3) |\delta^{++}|^4 \\ & + \lambda_1 |\delta^0|^2 |\phi^+|^2 + (\lambda_1 + \lambda_4) |\delta^{++}|^2 |\phi^+|^2 + \frac{\lambda}{4} |\phi^+|^4 \end{aligned}$$

$$\begin{aligned} \lambda > 0 \wedge \lambda_2 + \lambda_3 > 0 \wedge \sqrt{\lambda(\lambda_2 + \lambda_3)} + \lambda_1 > 0 \wedge \\ \left(\left(\frac{(\lambda_2 + \lambda_3)(\lambda\lambda_2^2 + \lambda_1^2(\lambda_3 - \lambda_2) + 2\lambda_1\lambda_3\lambda_4 + \lambda_4^2(\lambda_2 + \lambda_3))}{\lambda_2(\lambda_1 + \lambda_4)} \right) < 0 \wedge \right. \\ \left. \left((\lambda_3(2\lambda_2 + \lambda_3) > 0 \wedge \lambda_1 + \lambda_4 > 0 \wedge \lambda_2 < 0) \vee (\lambda_2 > 0 \wedge \lambda(\lambda_2 + \lambda_3) > (\lambda_1 + \lambda_4)^2 \right. \right. \\ \left. \left. \wedge \lambda_1 + \lambda_4 < 0 \right) \right) \vee (\lambda_2 > 0 \wedge \lambda_1 + \lambda_4 > 0) \vee \left(\lambda(\lambda_2 + \lambda_3) > (\lambda_1 + \lambda_4)^2 \wedge \lambda_3(2\lambda_2 + \lambda_3) > 0 \right. \\ \left. \wedge \sqrt{-\lambda_3(2\lambda_2 + \lambda_3)((\lambda_1 + \lambda_4)^2 - \lambda(\lambda_2 + \lambda_3))} + \lambda_1\lambda_3 > \lambda_2\lambda_4 \right) \end{aligned}$$

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$$\begin{aligned} V^{(4)} = & (\lambda_2 + \lambda_3) |\delta^0|^4 + 2\lambda_2 |\delta^0|^2 |\delta^{++}|^2 + (\lambda_2 + \lambda_3) |\delta^{++}|^4 \\ & + \lambda_1 |\delta^0|^2 |\phi^+|^2 + (\lambda_1 + \lambda_4) |\delta^{++}|^2 |\phi^+|^2 + \frac{\lambda}{4} |\phi^+|^4 \end{aligned}$$

$$\begin{aligned} \lambda > 0 \wedge \lambda_2 + \lambda_3 > 0 \wedge \sqrt{\lambda(\lambda_2 + \lambda_3)} + \lambda_1 > 0 \wedge \\ \left(\left(\frac{(\lambda_2 + \lambda_3)(\lambda\lambda_2^2 + \lambda_1^2(\lambda_3 - \lambda_2) + 2\lambda_1\lambda_3\lambda_4 + \lambda_4^2(\lambda_2 + \lambda_3))}{\lambda_2(\lambda_1 + \lambda_4)} \right) < 0 \wedge \right. \\ \left. \left((\lambda_3(2\lambda_2 + \lambda_3) > 0 \wedge \lambda_1 + \lambda_4 > 0 \wedge \lambda_2 < 0) \vee (\lambda_2 > 0 \wedge \lambda(\lambda_2 + \lambda_3) > (\lambda_1 + \lambda_4)^2 \right. \right. \\ \left. \left. \wedge \lambda_1 + \lambda_4 < 0 \right) \right) \vee (\lambda_2 > 0 \wedge \lambda_1 + \lambda_4 > 0) \vee \left(\lambda(\lambda_2 + \lambda_3) > (\lambda_1 + \lambda_4)^2 \wedge \lambda_3(2\lambda_2 + \lambda_3) > 0 \right. \\ \left. \wedge \sqrt{-\lambda_3(2\lambda_2 + \lambda_3)((\lambda_1 + \lambda_4)^2 - \lambda(\lambda_2 + \lambda_3))} + \lambda_1\lambda_3 > \lambda_2\lambda_4 \right) \end{aligned}$$

Dynamical constraints

e.g. of a 3-field direction $(\phi^+, \delta^0, \delta^{++})$:

$$\begin{aligned} V^{(4)} = & (\lambda_2 + \lambda_3) |\delta^0|^4 + 2\lambda_2 |\delta^0|^2 |\delta^{++}|^2 + (\lambda_2 + \lambda_3) |\delta^{++}|^4 \\ & + \lambda_1 |\delta^0|^2 |\phi^+|^2 + (\lambda_1 + \lambda_4) |\delta^{++}|^2 |\phi^+|^2 + \frac{\lambda}{4} |\phi^+|^4 \end{aligned}$$

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there are 10 such 3-field directions

(up to gauge transformations) with as many different conditions

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Dynamical constraints

Tree-level Boundedness From Below: The most general solution

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

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

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

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

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Dynamical constraints

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

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

$$\lambda \geq 0 \tag{11}$$

$$\lambda_2 + \lambda_3 \geq 0 \tag{12}$$

$$\lambda_2 + \frac{\lambda_3}{2} \geq 0 \tag{13}$$

$$\lambda_1 + \sqrt{\lambda(\lambda_2 + \lambda_3)} \geq 0 \tag{14}$$

$$\lambda_1 + \sqrt{\lambda(\lambda_2 + \frac{\lambda_3}{2})} \geq 0 \tag{15}$$

$$\lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2 + \lambda_3)} \geq 0 \tag{16}$$

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Dynamical constraints

combining all constraints →

$$0 \leq \lambda \leq \frac{2}{3}\kappa\pi$$

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

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

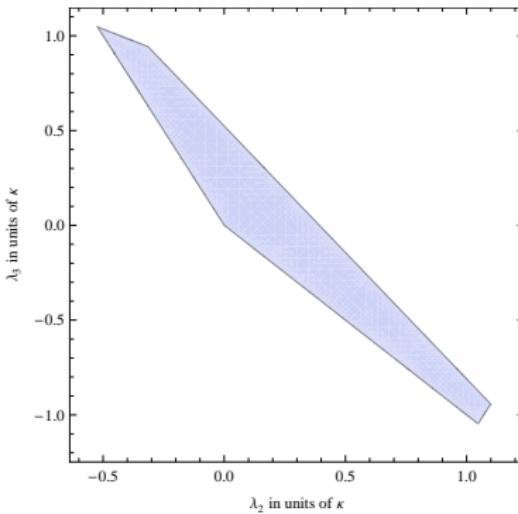
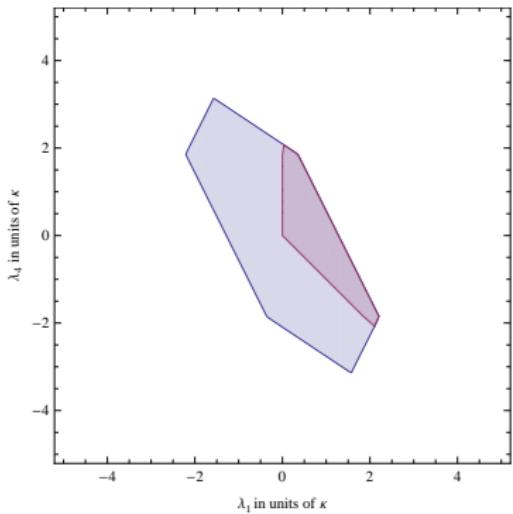
$$4\lambda_2 + 3\lambda_3 \leq \frac{\kappa}{2}\pi$$

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

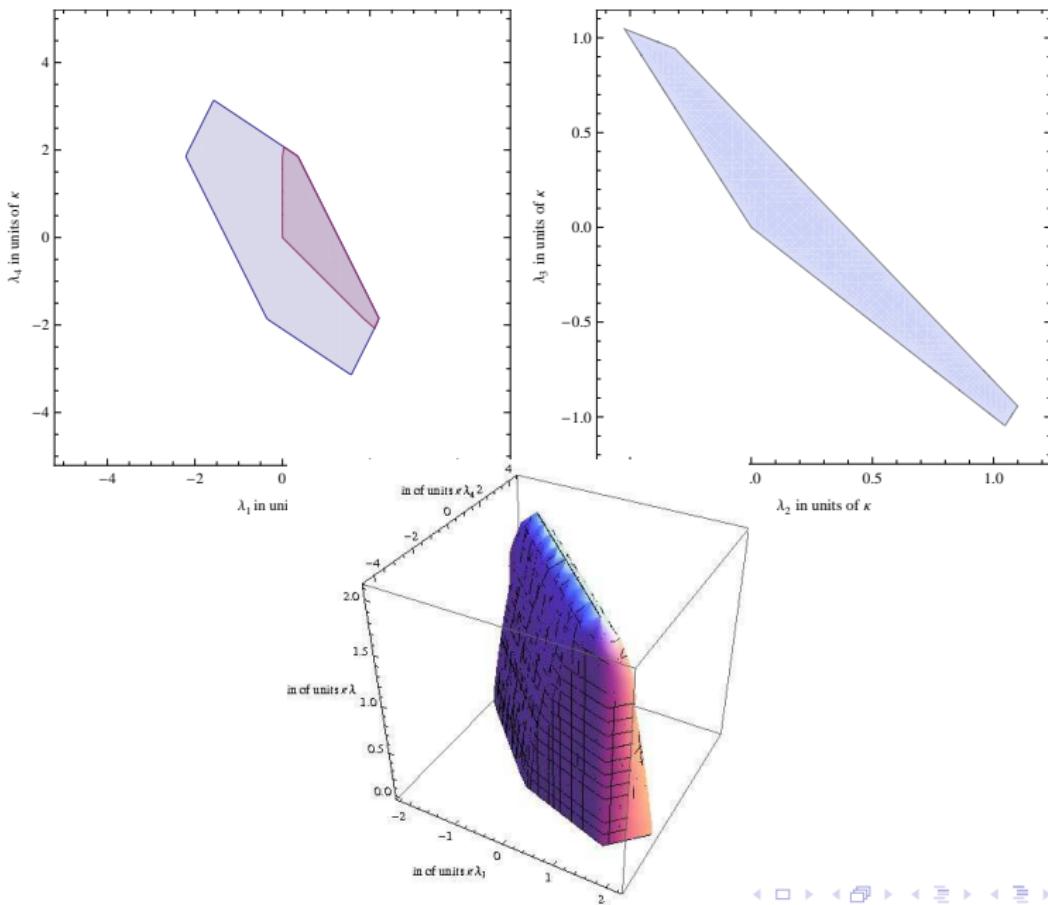
$$|\lambda_4| \leq \min \sqrt{(\lambda \pm 2\kappa\pi)(\lambda_2 + 2\lambda_3 \pm \frac{\kappa}{2}\pi)}$$

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

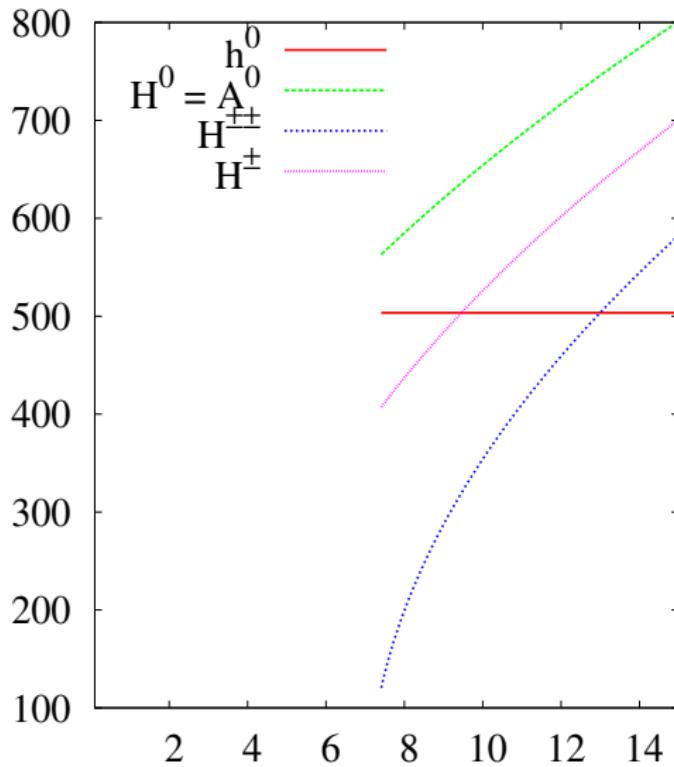
Dynamical constraints



Dynamical constraints



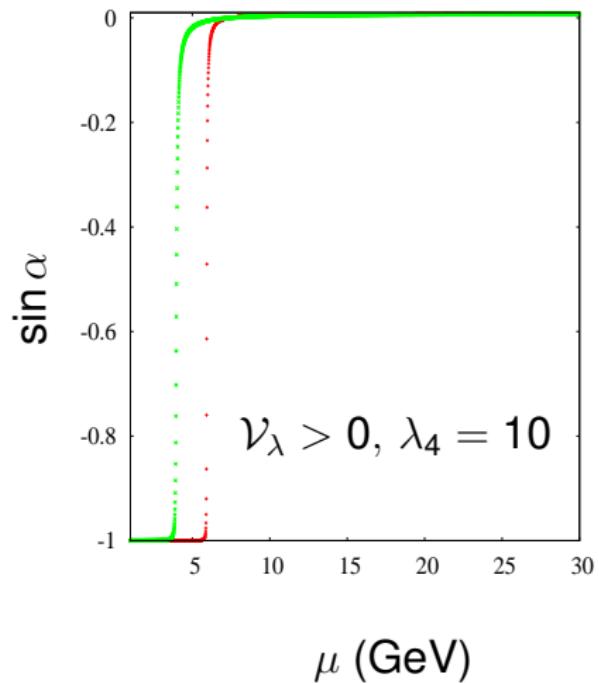
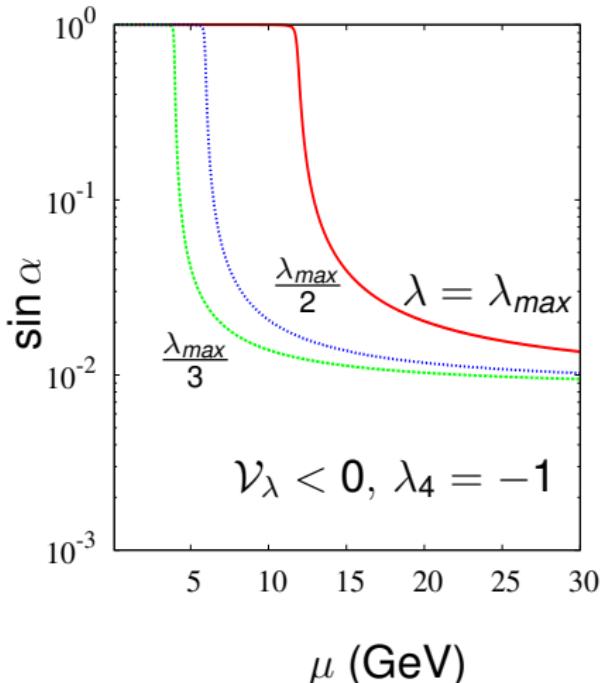
phenomenological implications



$$v_\lambda > 0, \lambda_4 = 10$$

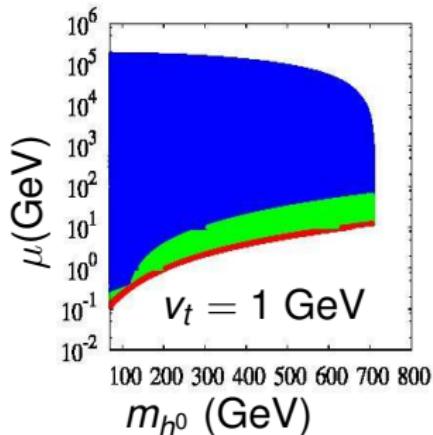
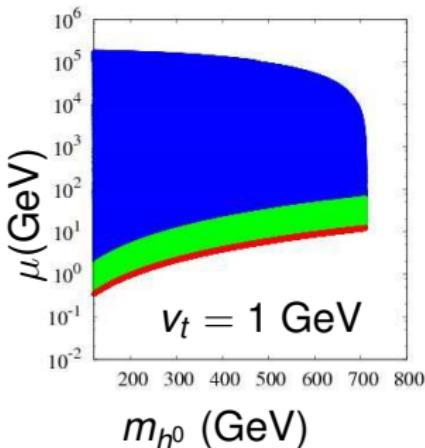
phenomenological implications

$$h^0 = \cos \alpha h + \sin \alpha \xi^0 \quad , \quad H^0 = -\sin \alpha h + \cos \alpha \xi^0$$



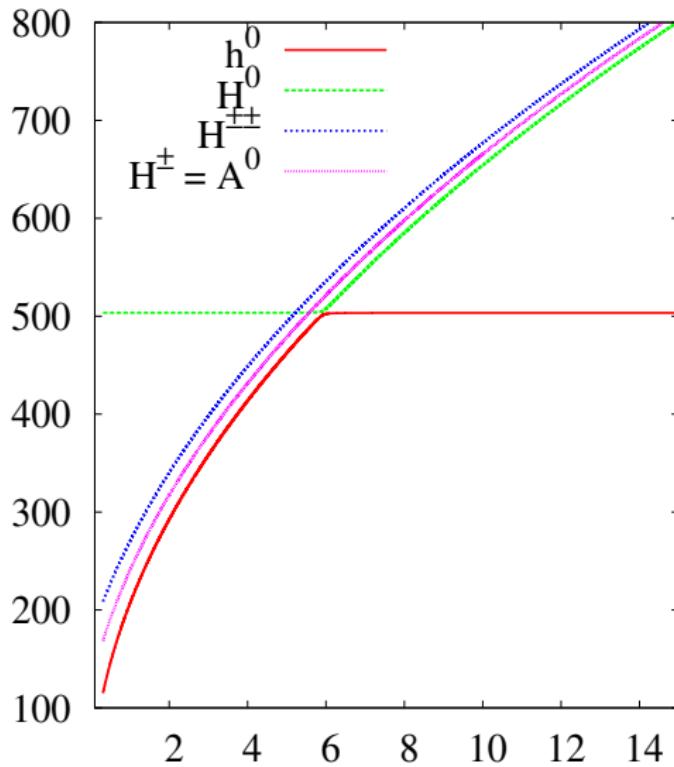
$$\nu_t = 1 \text{ GeV}, \lambda_{max} = 16\pi/3, \lambda_2 = \lambda_3 = 0.1, \lambda_1 = 0.5$$

phenomenological implications



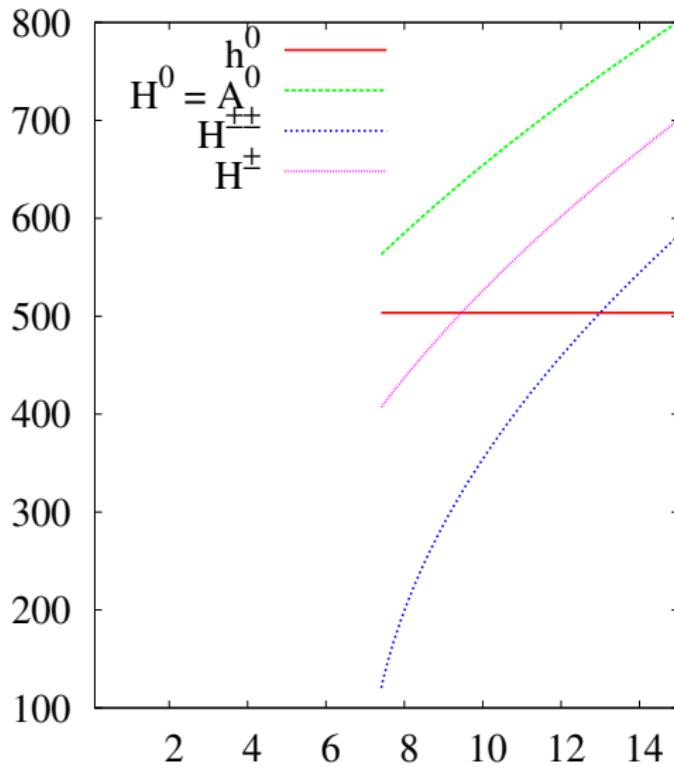
$$10^{-1} \leq |\sin \alpha| \leq 1 \text{ (red)}, \quad 10^{-2} \leq |\sin \alpha| \leq 10^{-1} \text{ (green)}, \quad 10^{-3} \leq |\sin \alpha| \leq 10^{-2} \text{ (blue)}$$

phenomenological implications



$$\mathcal{V}_\lambda < 0, \lambda_4 = -1$$

phenomenological implications



$$v_\lambda > 0, \lambda_4 = 10$$

Preliminary conclusions

- ▶ an $SU(2)$ triplet Higgs extension of the SM could be motivated by small neutrino masses
- ▶ the doublet-triplet Higgs sector has by itself a very rich structure and phenomenology
- ▶ a very good handle on theoretical constraints (in contrast with two-Higgs doublet models for instance)
- ▶ theoretical lower (upper) bounds in the CP-even sector
- ▶ high μ regimes, all non-SM Higgses decouple quickly
- ▶ low μ regimes, the SM-like Higgs is the heaviest (H_0)!
 h^0 decouples quickly; not necessarily the lightest Higgs!
distinctive $H^{\pm\pm}$ phenomenology ?
- ▶ exclusions from existing bounds? precision tests?
model-dependence?