Higgs-electroweak precision, vacuum stability and perturbativity

Pankaj Sharma

Korea Institute for Advanced Study

KIAS Pheno Workshop

Based on : arxiv:1209.1303

In Collaboration with : Prof. Eung Jin Chun and Dr. Hyun Min Lee

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PLAN

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- **Vacuum Stabilty and perturbativity.**

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Introduction

A 125 GeV Higgs has been discovered at the LHC.

However the Higgs sector is still unknown.

Minimal or non-minimal?

We already have various BSM phenomenon.

- Neutrino Oscillations
  $\Rightarrow$ confirms tiny neutrino mass
- Dark Matter $\Rightarrow \Omega_{DM}h^2 \sim 0.11$
- Matter-antimatter asymmetry

To understand these, we need to go beyond the SM.

From Standard Model to New Physcis

- One major motivations for new physics smallness of neutrino masses
- Origin can be attributed to a new particle coupling to the lepton doublets of the SM.
- The type II seesaw mechanism introduces a Higgs triplet whose VEV generates the neutrino masses and mixing.
- The Higgs sector of the type II seesaw contains four more bosons, H^{++}, H^{+} and H^0/A^0, in addition to the SM Higgs boson, h.
- Higgs triplet couplings can change drastically the stability of the SM electroweak vacuum
  $\Rightarrow$ Hence are quite constrained.

Type II seesaw Lagrangian

- One triplet scalar Δ with hypercharge $Y = 1$ is included.

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}.$$

- The leptonic part of the Lagrangian required to generate neutrino masses is

$$\mathcal{L}_Y = f_{\alpha\beta} L_\alpha^T C i\tau_2 \Delta L_\beta + \text{H.c.}$$

- When the neutral component acquires vev, the neutrino gets mass.

- So, we get $M_\nu = f_{\alpha\beta} v_\Delta$ by leptonic number violating interaction.

Scalar Potential of type II seesaw

The scalar potential is

$$
\begin{aligned}
V(\Phi,\Delta) &= m^2\Phi^\dagger\Phi + \lambda_1(\Phi^\dagger\Phi)^2 + M^2\mathrm{Tr}(\Delta^\dagger\Delta) \\
&+ \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Det}(\Delta^\dagger\Delta) + \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) \\
&+ \lambda_5(\Phi^\dagger\tau_i\Phi)\mathrm{Tr}(\Delta^\dagger\tau_i\Delta) + \left[\frac{1}{\sqrt{2}}\mu(\Phi^T i\tau_2\Delta\Phi) + \mathrm{H.c.}\right].
\end{aligned}
$$

- Upon EWSB with $\langle\Phi^0\rangle = v_0/\sqrt{2}$,
- the μ term gives rise to the vev of the triplet $\langle\Delta^0\rangle = v_\Delta/\sqrt{2}$
- μ term violates lepton number by two units
- It also protects from the existence of majoron.
- small μ can be viewed as a soft breaking term for lepton number.

Particle content in type II seesaw

- Upon EWSB, there are seven physical massive scalar eigenstates denoted by $H^{\pm,\pm}$, $H^{\pm}$, H^0, A^0, h^0.

- Under the condition that $|\xi| \ll 1$ where $\xi \equiv v_\Delta / v_0$, the first five states are mainly from the triplet scalar and the last from the doublet scalar.

- For the neutral pseudoscalar and charged scalar parts,

$$\phi_I^0 = G^0 - 2\xi A^0 \,, \qquad \phi^+ = G^+ + \sqrt{2}\xi H^+$$
$$\Delta_I^0 = A^0 + 2\xi G^0 \,, \qquad \Delta^+ = H^+ - \sqrt{2}\xi G^+$$

- for the neutral scalar part,

$$\phi_R^0 = h^0 - a\xi \, H^0 \,,$$
$$\Delta_R^0 = H^0 + a\xi \, h^0$$

- For $v_\Delta << v$, the mixing between doublet and triplet is very small.

Masses of scalars

The masses of the Higgs bosons are

- $M^2_{H^{\pm\pm}} = M^2 + 2\frac{\lambda_4 - \lambda_5}{g^2} M^2_W$
- $M^2_{H^{\pm}} = M^2_{H^{\pm\pm}} + 2\frac{\lambda_5}{g^2} M^2_W$
- $M^2_{H^0, A^0} = M^2_{H^{\pm}} + 2\frac{\lambda_5}{g^2} M^2_W$.

The sign of the coupling $\lambda_5 \Rightarrow$ Two mass hierarchies:

- $M_{H^{\pm\pm}} > M_{H^{\pm}} > M_{H^0/A^0}$ for $\lambda_5 < 0$;
- $M_{H^{\pm\pm}} < M_{H^{\pm}} < M_{H^0/A^0}$ for $\lambda_5 > 0$.

Constraints on H^{++} mass

- LEP bound on H^{++} mass is order of 80 GeV.
- Tevatron excluded $m_{H^{++}}$ upto 150 GeV.
- Recently, CMS also performed with 4.9 fb^{-1} luminosity a search for doubly charged Higgs decaying to a pair of leptons,

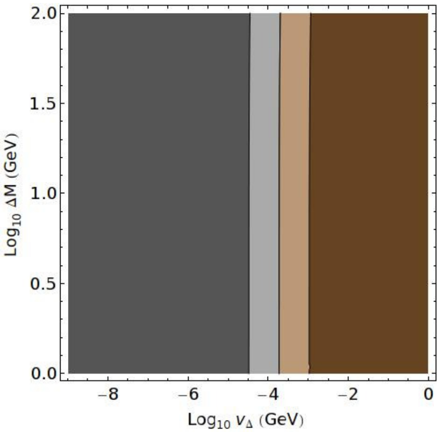
$H^{++}H^{--} \to \ell^+\ell^+\ell^-\ell^-$ and $H^{++}H^{-} \to \ell^+\ell^+\ell^-\nu$

Benchmark point	Combined 95% CL limit [GeVns]	95% CL limit for pair production only [GeVns]
$\mathcal{B}(H^{++} \to e^+e^+) = 100\%$	444	382
$\mathcal{B}(H^{++} \to e^+\mu^+) = 100\%$	453	391
$\mathcal{B}(H^{++} \to e^+\tau^+) = 100\%$	373	293
$\mathcal{B}(H^{++} \to \mu^+\mu^+) = 100\%$	459	395
$\mathcal{B}(H^{++} \to \mu^+\tau^+) = 100\%$	375	300
$\mathcal{B}(H^{++} \to \tau^+\tau^+) = 100\%$	204	169
BP1	383	333
BP2	408	359
BP3	403	355
BP4	400	353

Constraints on H^{++} mass

When H^{++} is the lightest.

P.S., E.J. Chun, JHEP 1208 (2012) 162



Gray region : $H^{++} \to \ell^+ \ell^+$
Brown region : $H^{++} \to W^+ W^+$

Constraints on H^{++} mass

When H^{++} is the heaviest.

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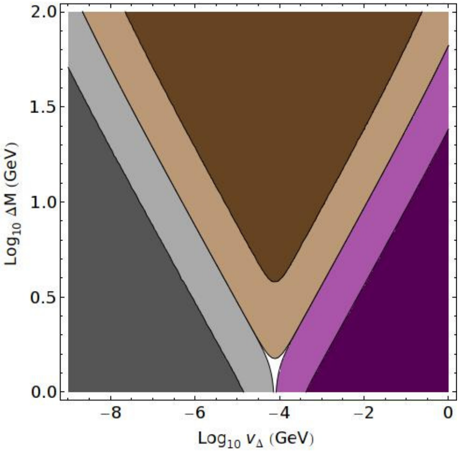


Gray region : $H^{++} \to \ell^+\ell^+$
Brown region : $H^{++} \to W^+W^+$
Purple region : $H^{++} \to$ rest

Vacuum stability and perturbativity conditions

The vacuum stability conditions on the scalar couplings λ_i are as follows:
Arhrib, Benbrik et al PRD 84, 095005 (2010)

- $\lambda_1 > 0,$
- $\lambda_2 > 0,$
- $\lambda_2 + \frac{1}{2}\lambda_3 > 0$
- $\lambda_4 \pm \lambda_5 + 2\sqrt{\lambda_1\lambda_2} > 0,$
- $\lambda_4 \pm \lambda_5 + 2\sqrt{\lambda_1(\lambda_2 + \frac{1}{2}\lambda_3)} > 0.$

Apart from these conditions, we will put the perturbativity condition:

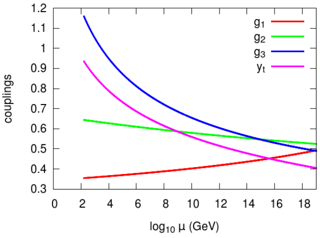
$$|\lambda_i| \leq \sqrt{4\pi}$$

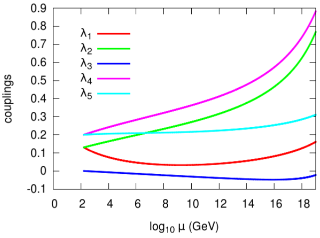
RG evolution of couplings

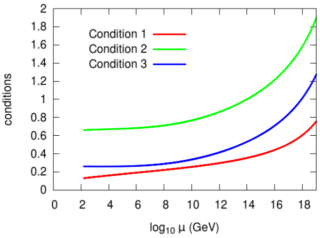
The one-loop RG equations relevant for our analysis are as below:
Schimidt, PRD 76, 073010 (2007)

$$
\begin{aligned}
16\pi^2\frac{d\lambda_1}{dt} &= 24\lambda_1^2+\lambda_1(-9g_2^2-3g'^2+12y_t^2)+\frac{3}{4}g_2^4+\frac{3}{8}(g'^2+g_2^2)^2\\
&- 6y_t^4+3\lambda_4^2+2\lambda_5^2\\
16\pi^2\frac{d\lambda_2}{dt} &= \lambda_2(-12g'^2-24g_2^2)+6g'^4+9g_2^4+12g'^2g_2^2+28\lambda_2^2\\
&+ 8\lambda_2\lambda_3+4\lambda_3^2+2\lambda_4^2+2\lambda_5^2\\
16\pi^2\frac{d\lambda_3}{dt} &= \lambda_3(-12g'^2-24g_2^2)+6g_2^4-24g'^2g_2^2+6\lambda_3^2\\
&+ 24\lambda_2\lambda_3-4\lambda_5^2\\
16\pi^2\frac{d\lambda_4}{dt} &= \lambda_4(-\frac{15}{2}g'^2-\frac{33}{2}g_2^2)+\frac{9}{5}g'^4+6g_2^4+\lambda_4(12\lambda_1\\
&+ 16\lambda_2+4\lambda_3+4\lambda_4+6y_t^2)+8\lambda_5^2\\
16\pi^2\frac{d\lambda_5}{dt} &= \lambda_4(-\frac{15}{2}g'^2-\frac{33}{2}g_2^2)+6g'^2g_2^2+\lambda_5(4\lambda_1+4\lambda_2\\
&- 4\lambda_3+8\lambda_4+6y_t^2),
\end{aligned}
$$

RG evolution of couplings and vacuum stability conditions







Updated EWPD Observables

- We use the most recent fit results for the allowed regions of the S, T and U

Espinosa et al, arXiv:1207.1717 [hep-ph]

$$\begin{aligned} S_{\text{best fit}} &= 0.00\,, & \sigma_S &= 0.10\,, \\ T_{\text{best fit}} &= 0.02\,, & \sigma_T &= 0.11\,, \\ U_{\text{best fit}} &= 0.03\,, & \sigma_U &= 0.09\,, \end{aligned}$$

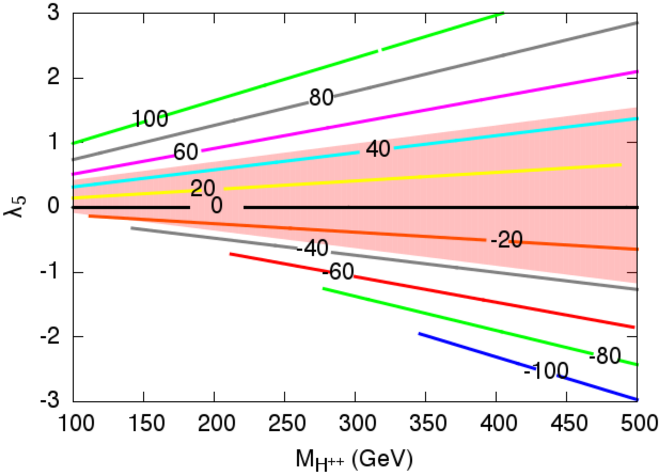
- The correlation coefficients are given by

$$\rho_{ST} = 0.89, \quad \rho_{SU} = -0.55, \quad \rho_{TU} = -0.80$$

- The contour allowed by the EWPD at a given confidence level CL is then determined by

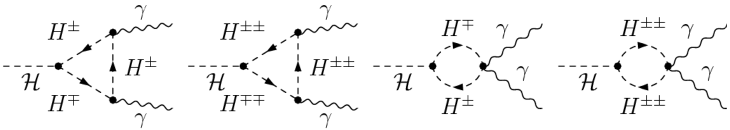
$$\begin{pmatrix} \Delta S \\ \Delta T \\ \Delta U \end{pmatrix}^T \begin{pmatrix} \sigma_S\sigma_S & \sigma_S\sigma_T\rho_{ST} & \sigma_S\sigma_U\rho_{SU} \\ \sigma_S\sigma_T\rho_{ST} & \sigma_T\sigma_T & \sigma_T\sigma_U\rho_{TU} \\ \sigma_U\sigma_S\rho_{US} & \sigma_U\sigma_T\rho_{TU} & \sigma_U\sigma_U \end{pmatrix}^{-1} \begin{pmatrix} \Delta S \\ \Delta T \\ \Delta U \end{pmatrix} = -2\ln(1-CL)\,.$$

EWPD Observables



- EWPD allows mass splittings $\lesssim$ 40 GeV

Higgs-to-dipoton in type II seesaw



- $H \to \gamma\gamma$ decays occurs at 1-loop level through
  - SM gauge bosons
  - the SM fermions
  - the new charged states
- Summing up all the contributions, one gets the following Higgs-to-diphoton rate

$$\Gamma(h \to \gamma\gamma) = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \Big| \sum_f N_c Q_f^2 \, g_{ff}^h A_{1/2}^h(x_f) + g_{WW}^h A_1^h(x_W) + g_{H^+H^-}^h A_0^h(x_{H^+}) + 4 g_{H^{++}H^{--}}^h A_0^h(x_{H^{++}}) \Big|^2$$

Higgs couplings

- The Higgs triplet couplings are
  - $g^h_{H^+H^+} = \frac{\lambda_4}{2} \frac{v_0^2}{M^2_{H+}}$,
  - $g^h_{H^{++}H^{++}} = \frac{\lambda_4 - \lambda_5}{2} \frac{v_0^2}{M^2_{H^{++}}}$,.
- SM contribution amounts to about -6.5 in the amplitude,
  $\Rightarrow$ Thus, negative values of λ_4 and $\lambda_4 - \lambda_5$ make a constructive interference to enhance the diphoton rate.
- Vacuum stability condition strongly disfavors negative λ_4 and $\lambda_4 - \lambda_5$
  $\Rightarrow$Thus, allows more parameter region leading to a destructive interference to reduce the diphoton rate.

Higgs-to-diphoton

We define $R_{\gamma\gamma} = \Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)|_{SM}$

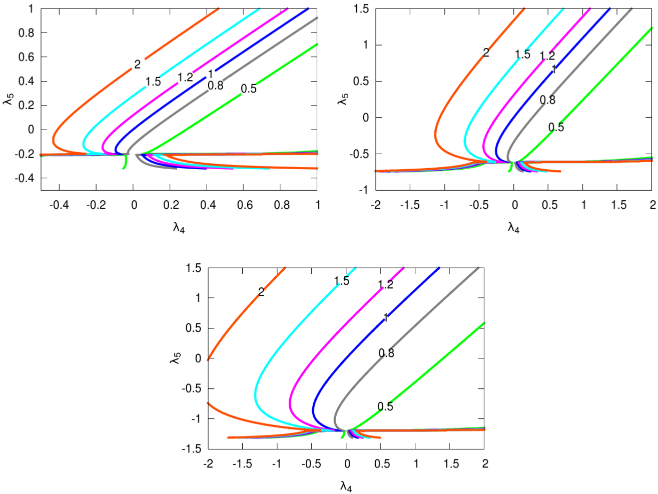


Figure: $R_{\gamma\gamma}$ contours in the λ_4–λ_5 plane.

Allowed ranges of scalar couplings

	10^5 GeV	10^{10} GeV	10^{19} GeV
λ_2	$(0, 1)$	$(0, 0.5)$	$(0, 0.25)$
λ_3	$(-2.0, 2.4)$	$(-1.0, 1.25)$	$(-0.55, 0.62)$
λ_4	$(-0.5, 1.7)$	$(-0.1, 0.9)$	$(0, 0.5)$
λ_5	$(-1.5, 1.5)$	$(-0.7, 0.7)$	$(-0.4, 0.4)$

- EWPD puts stringent constraints on λ_5 couplings.
- The EWPD allow the following ranges of λ_5

$$\lambda_5 = (-0.1, 0.4), \quad (-0.2, 0.6), \quad (-0.35, 0.7)$$

for $M_{H^{++}} = 100$, 150, and 200 GeV, respectively.

Results for cut-off scale 10^5 GeV

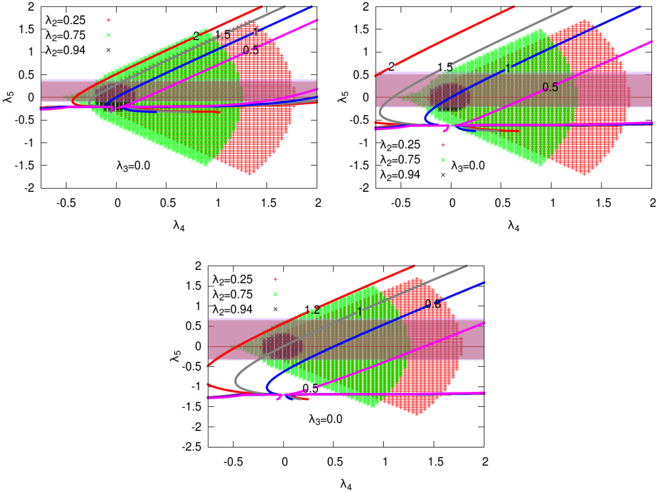


Figure: Allowed parameter space in the λ_4–λ_5 plane with different values of λ_2 and λ_3 for the doubly charged Higgs mass, $M_{H^{++}} = 100$ GeV (left), 150 GeV (middle) and 200 GeV (right).

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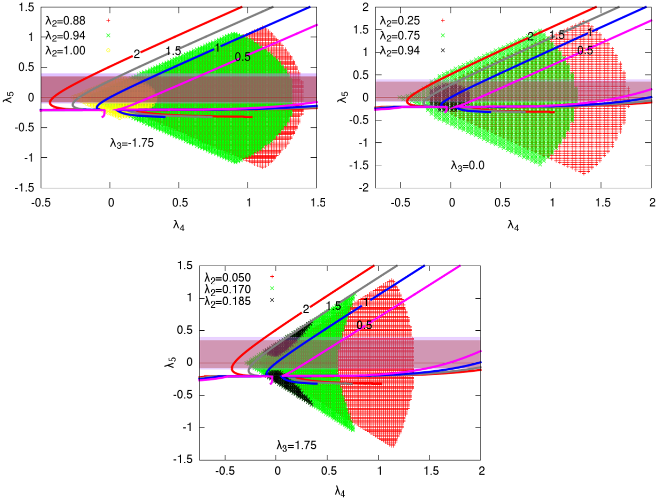
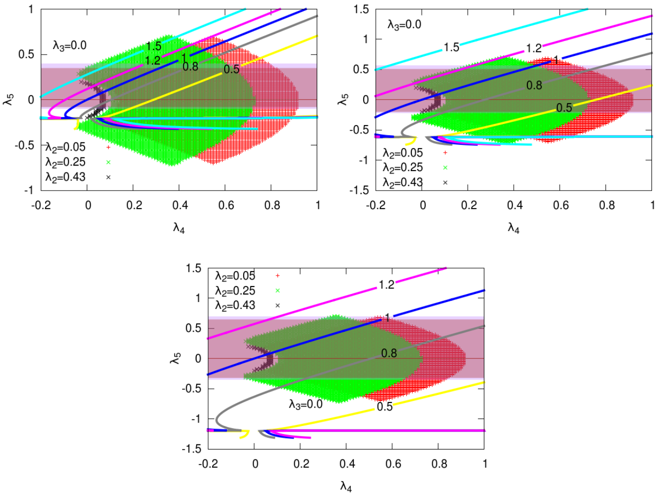


Figure: Allowed parameter space in the λ_4–λ_5 plane with different values of λ_2 and λ_3 for the doubly charged Higgs mass, $M_{H^{++}} = 100$ GeV.

Results for cut-off scale 10^{10} GeV



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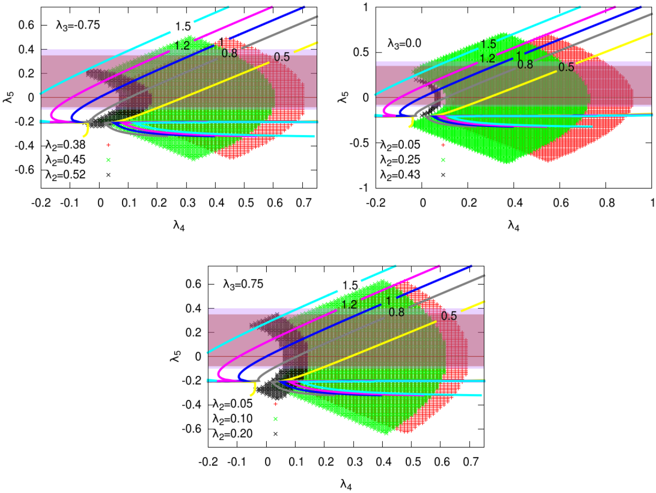

Figure: Allowed parameter space in the λ_4–λ_5 plane with different values of λ_2 and λ_3 for the doubly charged Higgs mass, $M_{H^{++}} = 100$ GeV.

Results for cut-off scale 10^{19} GeV

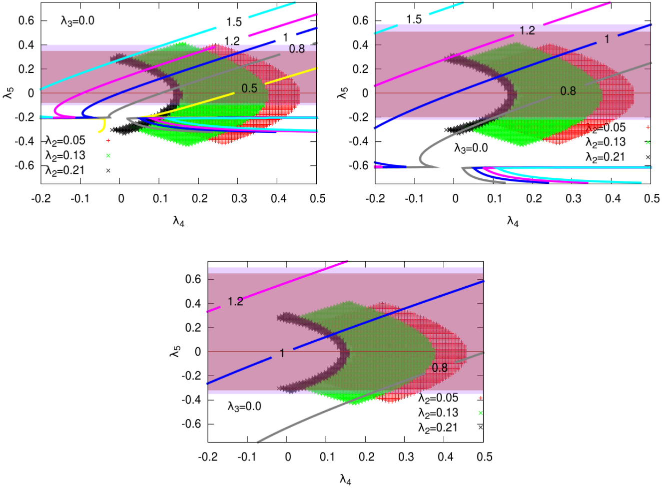

Figure: Allowed parameter space in the λ_4–λ_5 plane with different values of λ_2 and λ_3 for the doubly charged Higgs mass, $M_{H^{++}} = 100$ GeV (left), 150 GeV (middle) and 200 GeV (right).

Results for cut-off scale 10^{19} GeV

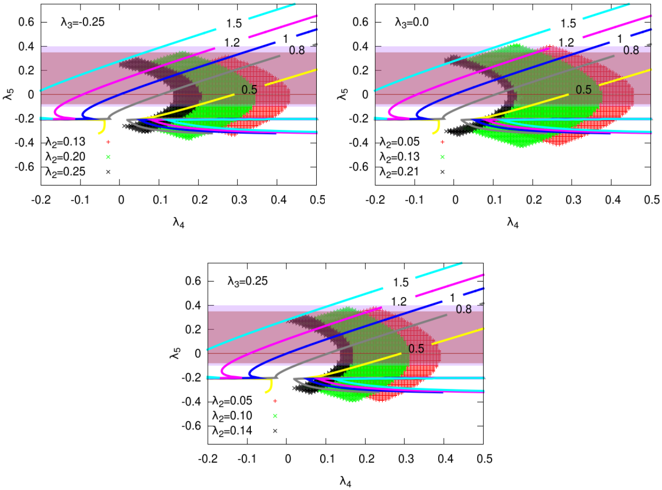

Figure: Allowed parameter space in the λ_4–λ_5 plane with different values of λ_2 and λ_3 for the doubly charged Higgs mass, $M_{H^{++}} = 100$ GeV.

Conclusions

- Neutrino mass genertaion may require a new particle.
- Higgs triplet may be one candidate.
- We study parameter space in the scalar couplings allowed by the vacuum stability, perturbativity and EWPD.
- We then study the possible deviation in Higgs-to-diphoton decay within the allowed parameter space
- We find that about 100%-50% enhancement is possible within a restricted range of parameter space.

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THANKS

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