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Higgs at Seesaw Type II

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Introduction

- An SU(2) doublet boson (Y=1/2) is responsible for the masses of quarks and charged leptons as well as for the electroweak symmetry breaking. July 4, 2012!
- What about neutrino masses? Maybe due to an "SU(2) triplet boson (Y=1)", $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$: Type II Seesaw
- Main search channel $\Delta^{++} \to l^{+} l^{+}$; and others…
- Study the properties of the SM 125 GeV Higgs.
- Consider EWPD, perturbativity and vacuum stability to constrain the type II seesaw sector, and analyze its impact on the Higgs-to-diphoton rate.

EJC, Lee, Sharma, 1209.11303

Type II Seesaw

- Introduce Higgs doublet (Y=1/2) & triplet (Y=1):

$$\Phi = (\Phi^+, \Phi^0) \qquad \Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

- Triplet VEV generates neutrino mass matrix:

$$\mathcal{L}_Y = f_{\alpha\beta}\, L^T_\alpha C i\tau_2 \Delta L_\beta + \frac{1}{\sqrt{2}}\mu\, \Phi^T i\tau_2 \Delta\Phi + h.c.$$

$$v_\Delta = \mu \frac{v_\Phi^2}{M_\Delta^2} \;\Rightarrow\; \mathbf{m}^\nu_{\alpha\beta} = \mathbf{f}_{\alpha\beta}\mathbf{v}_\Delta \;\Leftarrow\; f_{\alpha\beta}\frac{v_\Delta}{v_\Phi} \sim 10^{-12}$$

- ρ parameter constraint on $\xi = \mathbf{v}_\Delta / \mathbf{v}_\Phi$:

$$\rho = (1+2\xi^2)/(1+4\xi^2) \rightarrow \xi < 0.03$$

- We will work in the limit of $\xi << 0.01$, neglecting the tree-level $\Delta\rho$ contribution.

Higgs sector

- Higgs potential of type II seesaw:

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

- Five Higgs boson mass eigenstates:

$$
\begin{matrix} \Delta^{++}, \Delta^{+}, \Delta^{0} \\ \Phi^{+}, \Phi^{0} \end{matrix} \quad \Rightarrow \quad h^0, H^0, A^0, H^+, H^{++}
$$

- Doublet-triplet mixing controlled by ξ = v_Δ/v_Φ:

$$
\begin{aligned}
\phi_I^0 &= G^0 - 2\xi A^0 & \phi^+ &= G^+ + \sqrt{2}\xi H^+ & \phi_R^0 &= h^0 - a\xi H^0 \\
\Delta_I^0 &= A^0 + 2\xi G^0 & \Delta^+ &= H^+ - \sqrt{2}\xi G^+ & \Delta_R^0 &= H^0 + a\xi h^0
\end{aligned}
$$

Higgs spectrum

- Mass gap among triplet components: EJC, Lee, Park, 0304069

$$
\begin{aligned}
M^2_{H^{\pm\pm}} &= M^2 + 2\frac{\lambda_4 - \lambda_5}{g^2} M_W^2 \\
M^2_{H^{\pm}} &= M^2_{H^{\pm\pm}} + 2\frac{\lambda_5}{g^2} M_W^2 \\
M^2_{H^0, A^0} &= M^2_{H^{\pm}} + 2\frac{\lambda_5}{g^2} M_W^2 \,.
\end{aligned}
$$

$$
\Delta M^2 = 2\frac{\lambda_5}{g^2} M_W^2
$$

- Mass gap between H^0 & A^0:

$$
\mathcal{L}_{\Delta} = \frac{1}{\sqrt{2}} \mu \Phi^T i\tau_2 \Delta^\dagger \Phi + h.c. \Rightarrow -\mu v_\Phi h^0 H^0
$$

$$
v_\Delta = \frac{\mu v_\Phi^2}{\sqrt{2} M^2_{H^0}}
$$

$$
\delta M_{HA} \approx 2 M_{H^0} \frac{v_\Delta^2}{v_\Phi^2} \frac{M^2_{H^0}}{M^2_{H^0} - m^2_{h^0}}
$$

Higgs triplet decay channels

- Two mass hierarchies:

$$M_{H^{++}} < M_{H^+} < M_{H^0/A^0} \quad \text{if} \quad \lambda_5 > 0$$

$$M_{H^{++}} > M_{H^+} > M_{H^0/A^0} \quad \text{if} \quad \lambda_5 < 0$$

- Gauge decays for non-vanishing ΔM (λ_5):

$$H^0/A^0 \to H^\pm W^* \to H^{\pm\pm} W^* W^*$$

$$H^{++} \to H^\pm W^* \to H^0/A^0\, W^* W^*$$

$\Leftarrow \Delta M(\lambda_5)$

- Di-lepton (same-sign) decays through $f_{\alpha\beta}$:

$$H^{++} \to l^+_\alpha l^+_\beta;\ H^+ \to l^+_\alpha \nu_\beta;\ H^0/A^0 \to \nu_\alpha \nu_\beta$$

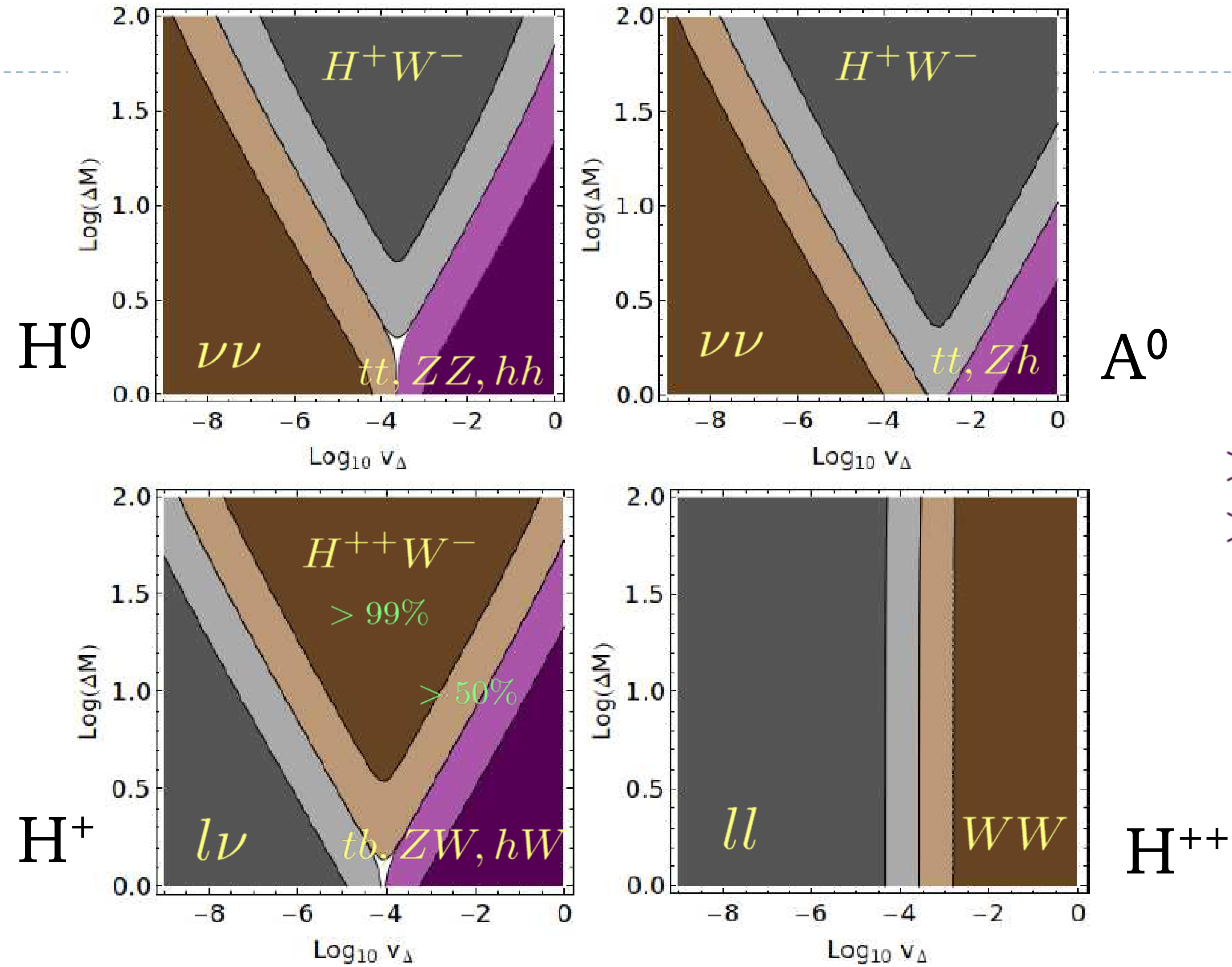
$\Leftarrow f_{\alpha\beta}$

- Di-quark/di-boson decays through ξ:

$$H^{++} \to W^+ W^+;\ H^+ \to t\bar{b}; \qquad H^0/A^0 \to t\bar{t},\ b\bar{b}$$

$$\to ZW, hW \qquad \to ZZ, hh/Zh$$

$\Leftarrow \xi \equiv \dfrac{v_\Delta}{v_\Phi}$



M_{H^0/A^0}
$> M_{H^+}$
$> M_{H^{++}}$

EJC, Sharma, 1206.6278

Collider search

- Only $H^{++}\ H^{--} \to l^+\ l^+\ l^-\ l^-$ so far.
- Neutrino mass pattern can be determined by measuring

$$BR(\Delta^{++} \xrightarrow{f_{\alpha\beta}} l^+_\alpha l^+_\beta)\,!$$

EJC, Lee, Park, 0304069

- Updated neutrino mass matrix after θ_{13} (no CP phase):

Br (%)	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
NH	0.62	5.11	0.51	26.8	35.6	31.4
IH1	47.1	1.27	1.35	11.7	23.7	14.9

EJC, Sharma, 1206.6278

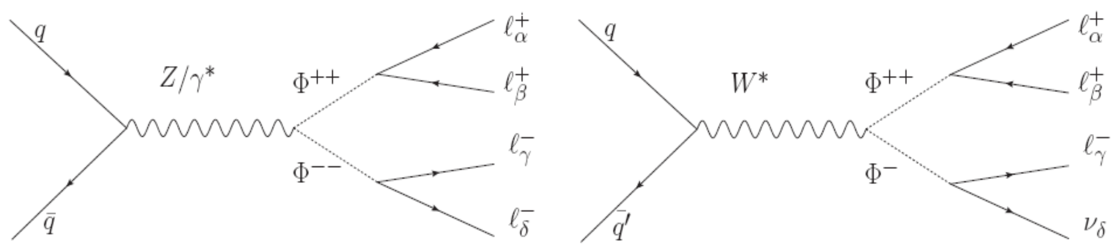
Benchmark point	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	1/2	0	0	1/8	1/4	1/8
BP3	1/3	0	0	1/3	0	1/3
BP4	1/6	1/6	1/6	1/6	1/6	1/6

CMS, 1207.2666

LHC7 limit

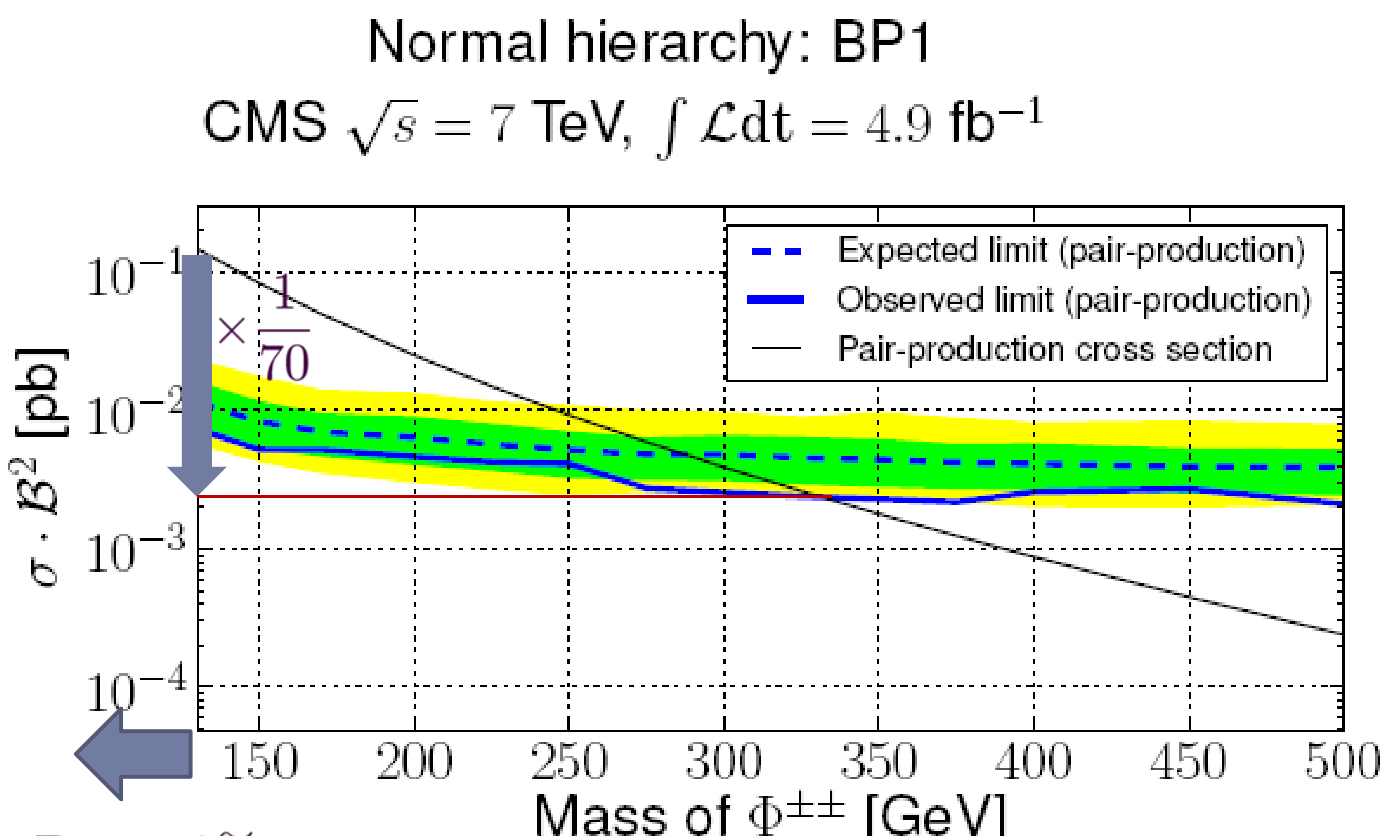
- CMS looks for pp→H^{++} H^{-} → l^+ l^+ l^- ν
  & pp → H^{++} H^{--} → l^+ l^+ l^- l^- .
- Assuming 100% leptonic decay & ΔM=0.

CMS, 1207.2666
ATLAS, 1210.5070



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

LHC7 limit



$\mathrm{Br} < 12\%$

$M_{H^{++}} < 100\mathrm{GeV}$

Search for other channels?

- If ξ > f, Br(ll) < 100% weakens the mass limit. Search for other channels may be necessary:

  $H^{++} \to W^+W^+$; $H^+ \to W^+Z$, tb ; $H^0/A^0 \to ZZ$, hh/Zh, tt
- Missing triplet if λ_5<0 and f >> ξ :

  $H^{++} \to H^+ W^* \to H^0/A^0 W^* W^* \to \nu\nu W^* W^*$.
- **No mass limit yet** in these two cases.
- We will take the doubly charged mass as low as 100 GeV.

EWPD

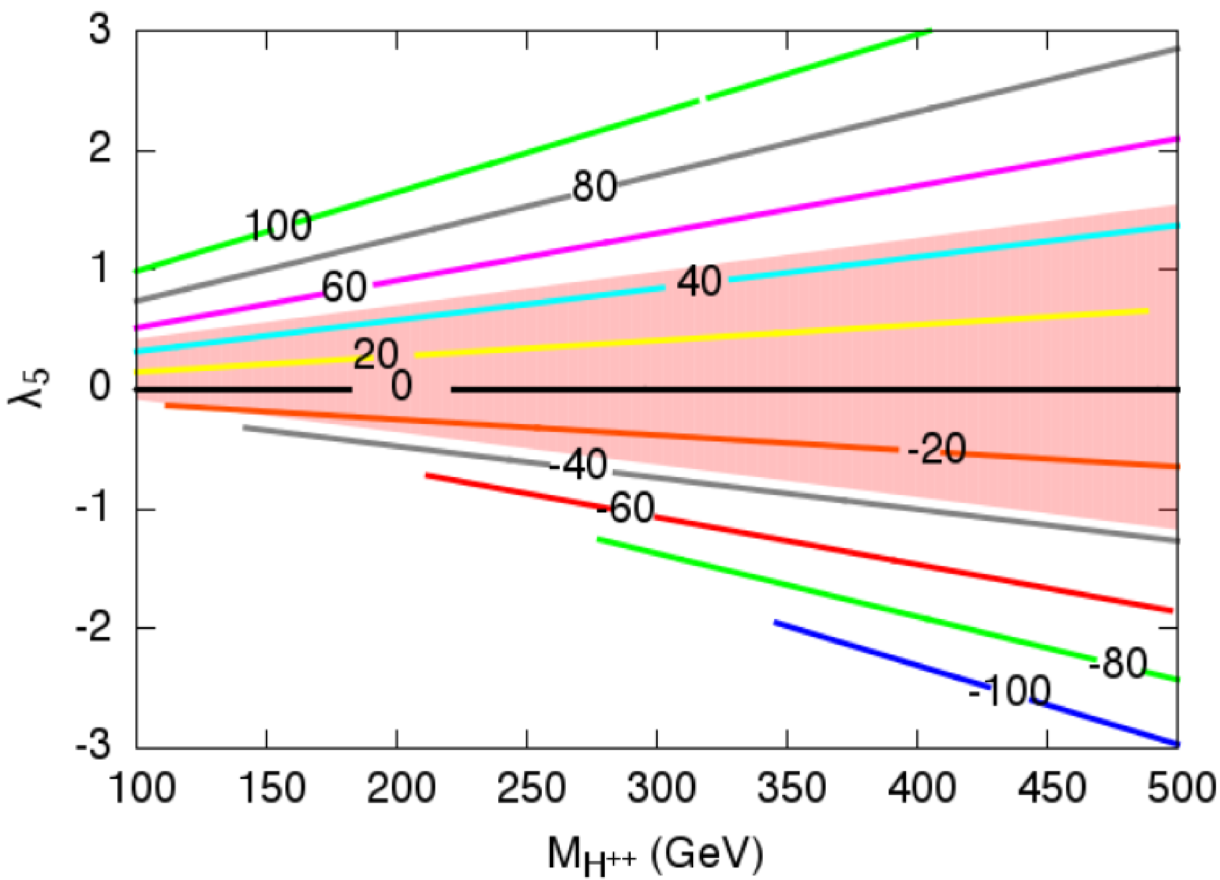
- Triplet contribution to S, T & U: Lavoura, Li, 9309262
- Most recent STU fit: Baak, et.al., 1209.2716

$$S_{\text{best fit}} = 0.03\,, \quad \sigma_S = 0.10$$
$$T_{\text{best fit}} = 0.05\,, \quad \sigma_T = 0.12$$
$$U_{\text{best fit}} = 0.03\,, \quad \sigma_U = 0.10$$
$$\rho_{ST} = 0.89, \quad \rho_{SU} = -0.54, \quad \rho_{TU} = -0.83$$

- It strongly constrains the mass splitting.

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

EWPD



3
2
1
0
-1
-2
-3
λ_5
100
150
200
250
300
350
400
450
500
$M_{H^{++}}$ (GeV)
100
80
60
40
20
0
-20
-40
-60
-80
-100

Constrained λ_5

- EWPD limit $|\Delta M|$ < ~40 GeV for $\xi \ll 10^{-2}$.
- Strong constraints on λ_5 for small triplet mass:

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

$$M_{H^{++}} = 100,\ 150,\ \text{and}\ 200\ \text{GeV}$$

Vacuum stability & perturbativity

- Higgs sector of type II seesaw:

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

- Vacuum stability of the SM Higgs changes due to its couplings to the Higgs triplet.
- Triplet self coupling (λ_2) tends to diverge rapidly.
- Strong constraints on $\lambda_{2,3,4,5}$.
- Take λ_1=0.13 and μ << v_Φ.

Vacuum stability & perturbativity

- Demand the absolute vacuum stability condition.

  Arhrib, et.al., 1105.1925

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

- Perturbativity: $|\lambda_i| \le \sqrt{4\pi}.$

Vacuum stability & perturbativity

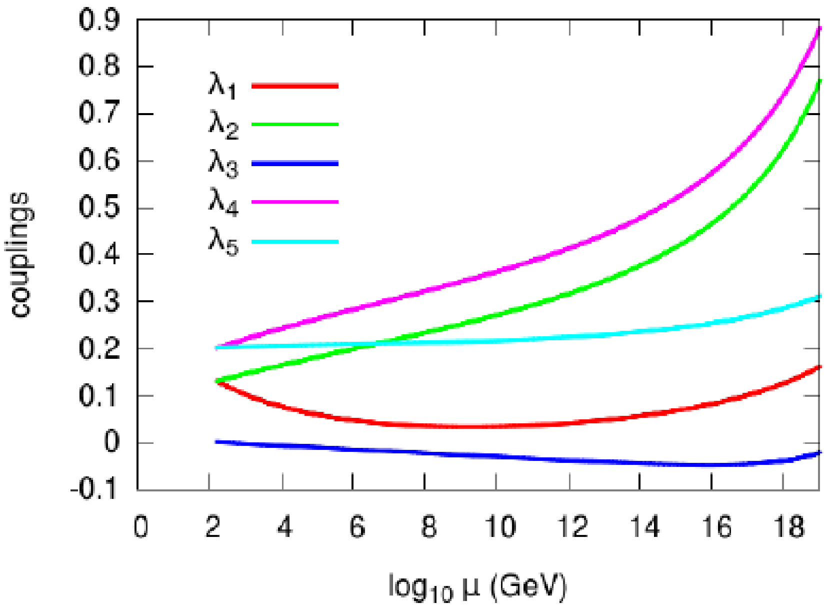
- Use 1-loop RGE:

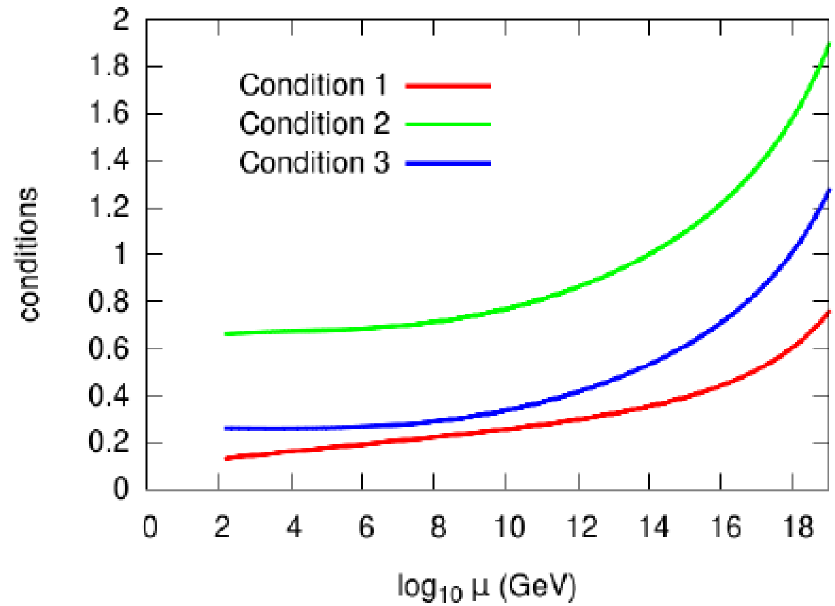
Chao, Zhang, 0611323
Schmidt, 07053841

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

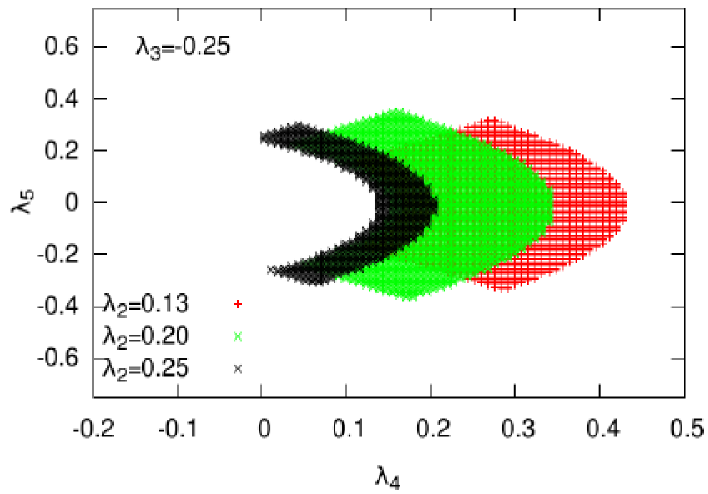
RGE running

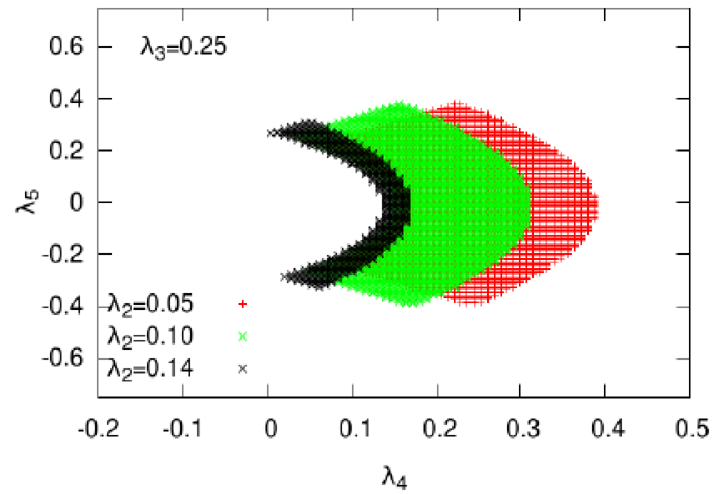
- An example

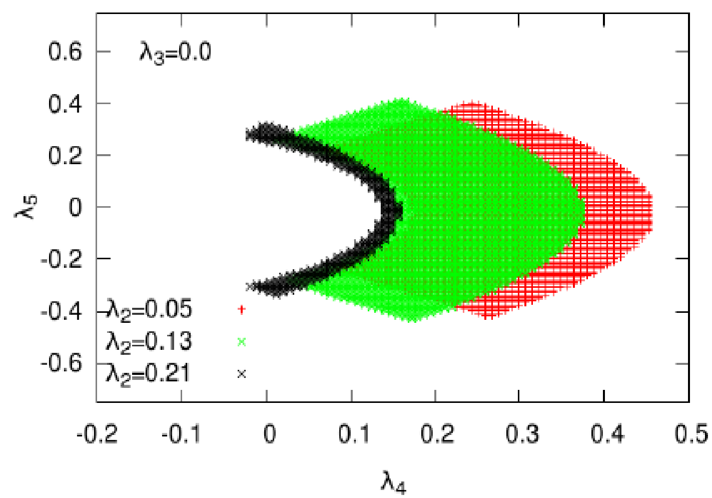




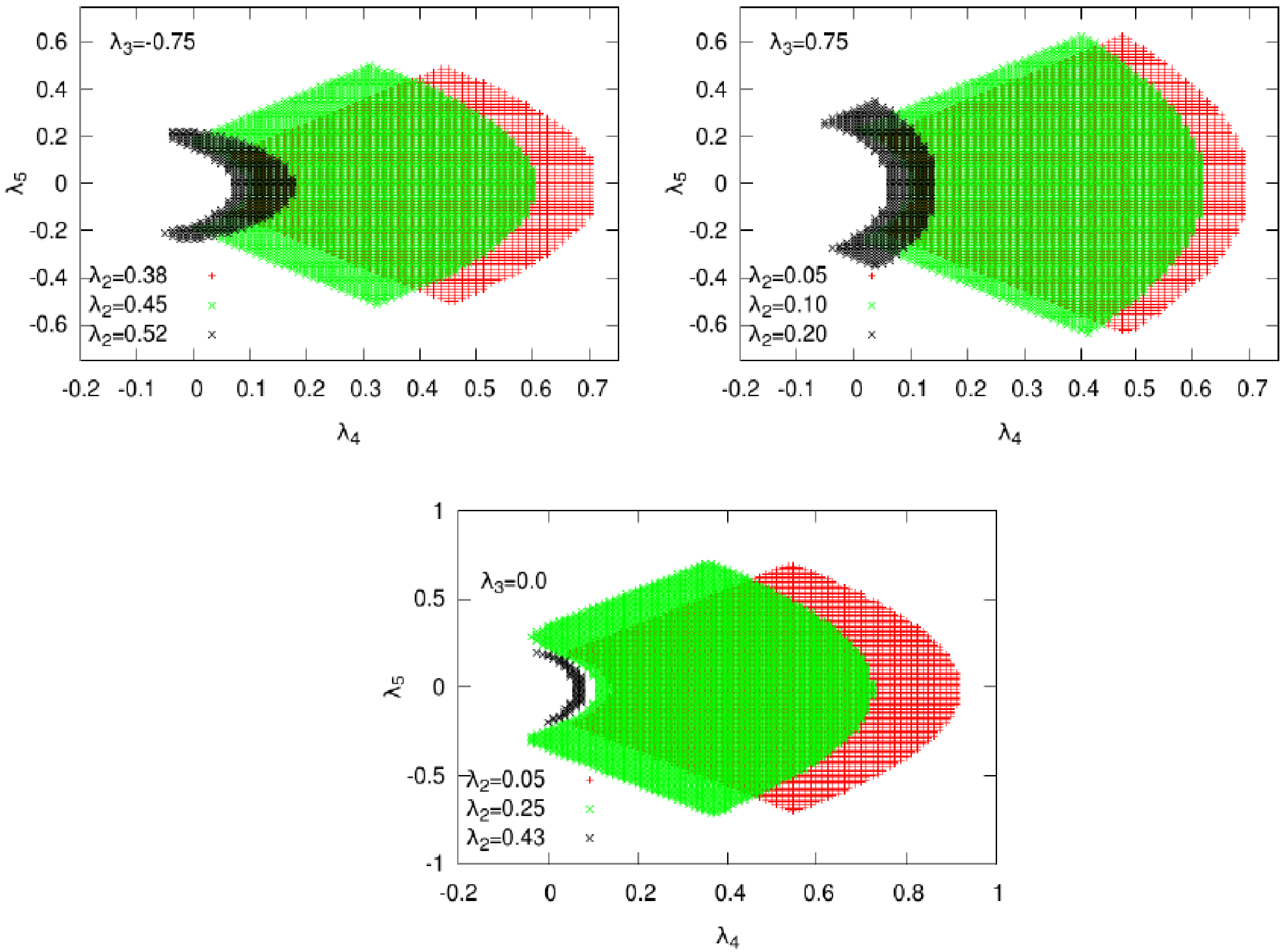
Cut-off scale 10^{19} GeV



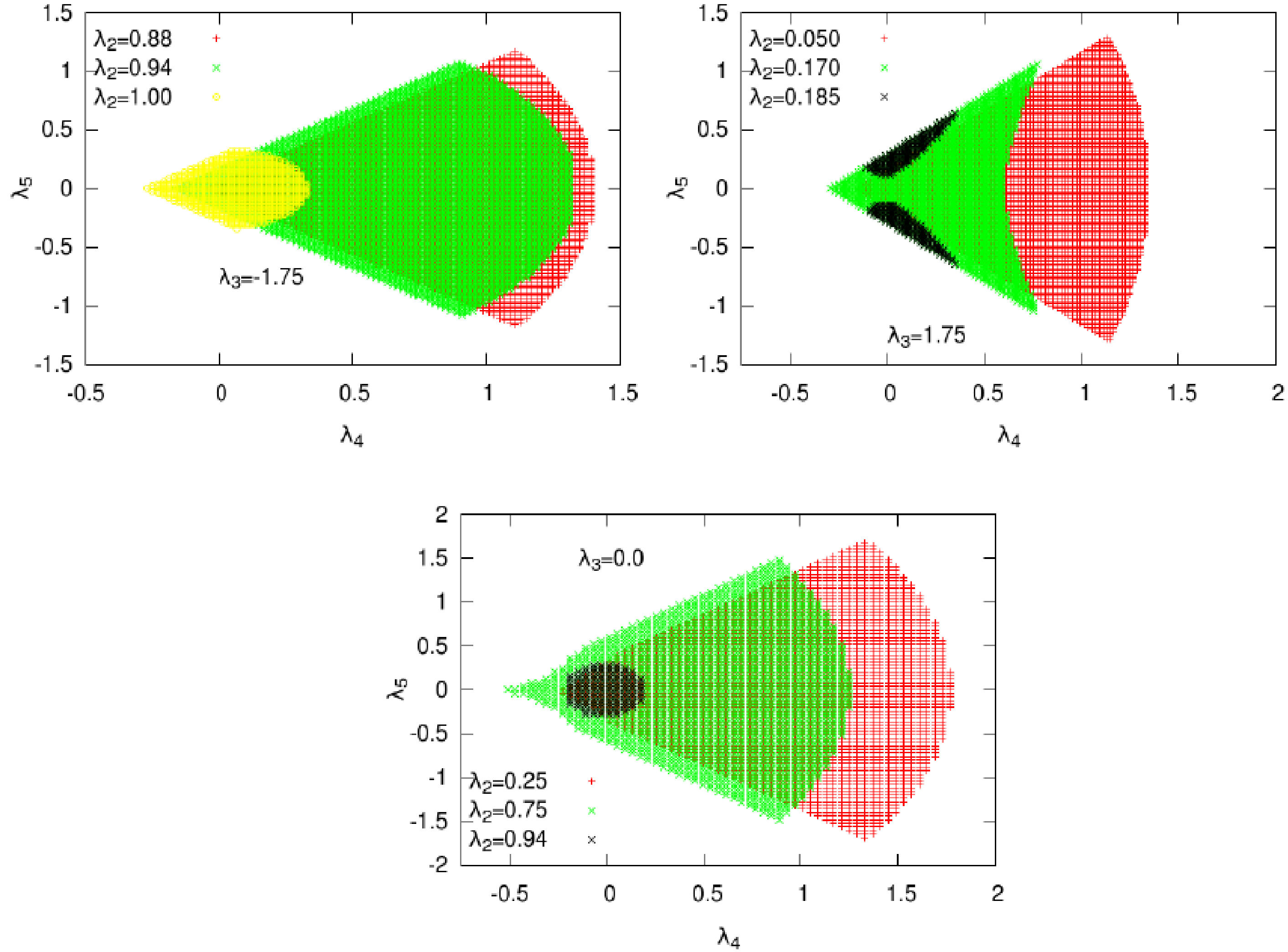




Cut-off scale 10^{10} GeV



Cut-off scale 10^5 GeV

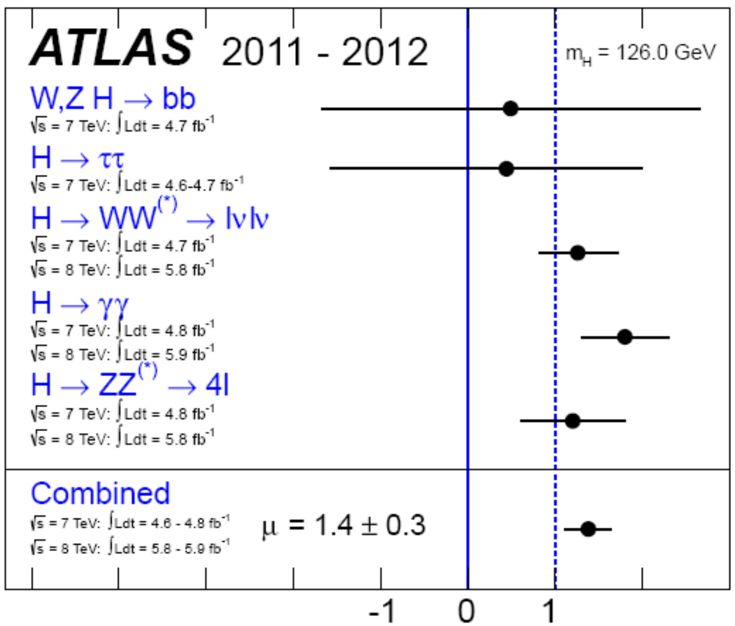


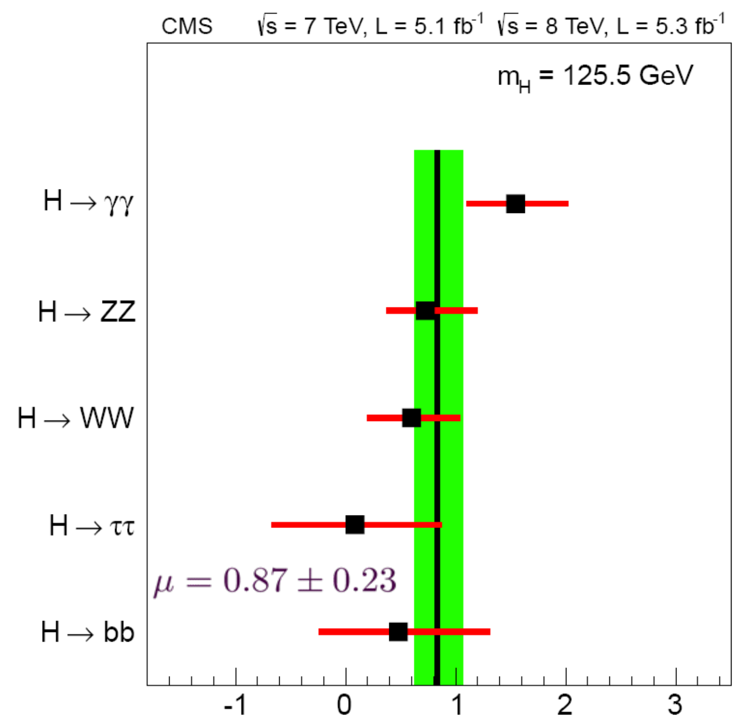
Allowed ranges

	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	$(-1.5, 1.5)$	$(-0.7, 0.7)$	$(-0.4, 0.4)$

Higgs-to-diphoton

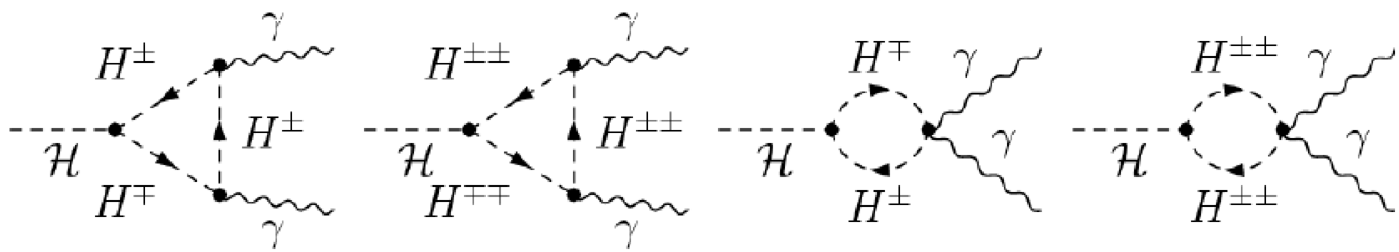
- 1-loop process – sensitive to New Physics.
- A large deviation in the current data.
- Its precision data is important to constrain NP.





Higgs-to-diphoton

- H^{++} & H^{+} contribution:



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

$$\left. + g_{H^+H^-}^h A_0^h(x_{H^+}) + 4 g_{H^{++}H^{--}}^h A_0^h(x_{H^{++}}) \right|^2$$

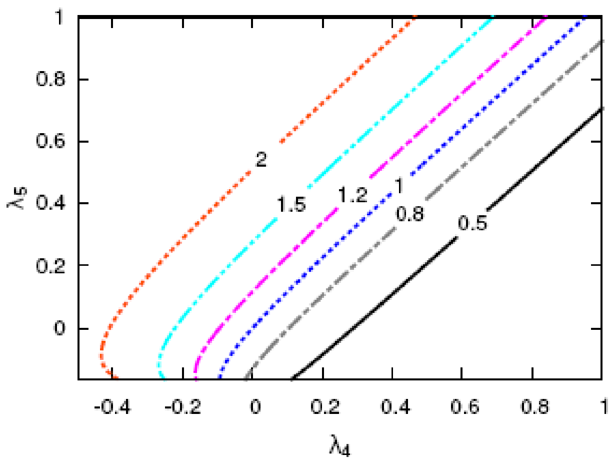
- $g_{H^+H^+}^h = \frac{\lambda_4}{2} \frac{v_0^2}{M_{H^+}^2}$,
- $g_{H^{++}H^{++}}^h = \frac{\lambda_4 - \lambda_5}{2} \frac{v_0^2}{M_{H^{++}}^2}$,

Arhrib, et.al., 1112.5453
Kanemura, Yagyu, 1201.6287
Akeryod, Moretti, 1206.0535

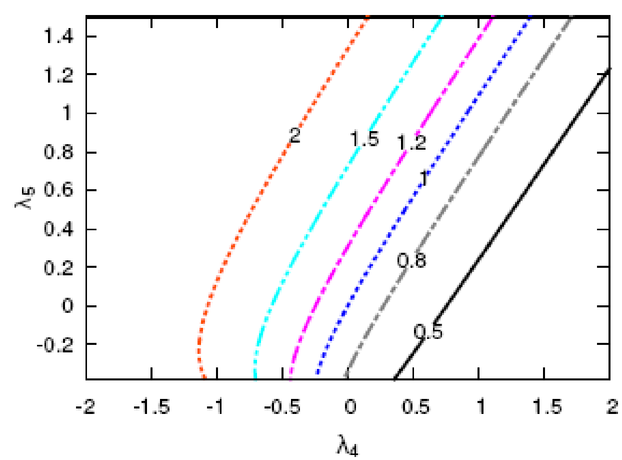
Higgs-to-diphoton

- Sizable H^{++}/H^{+} contribution if light enough (< 250 GeV).
- CMS limit does not apply if BR($H^{++} \to l^{+}l^{+}$) is not 100%.
- Calculate possible deviation by Higgs triplet combined with conditions from EWPD, vacuum stability and perturbativity.

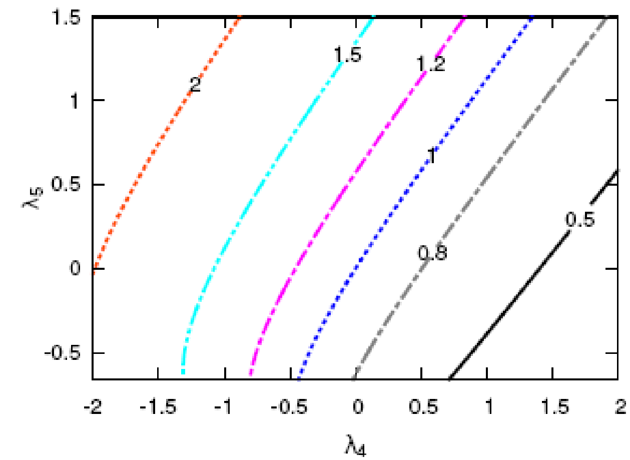
$R_{\gamma\gamma} = \Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\rm SM}$



$m_{H^{++}} = 100{\rm GeV}$

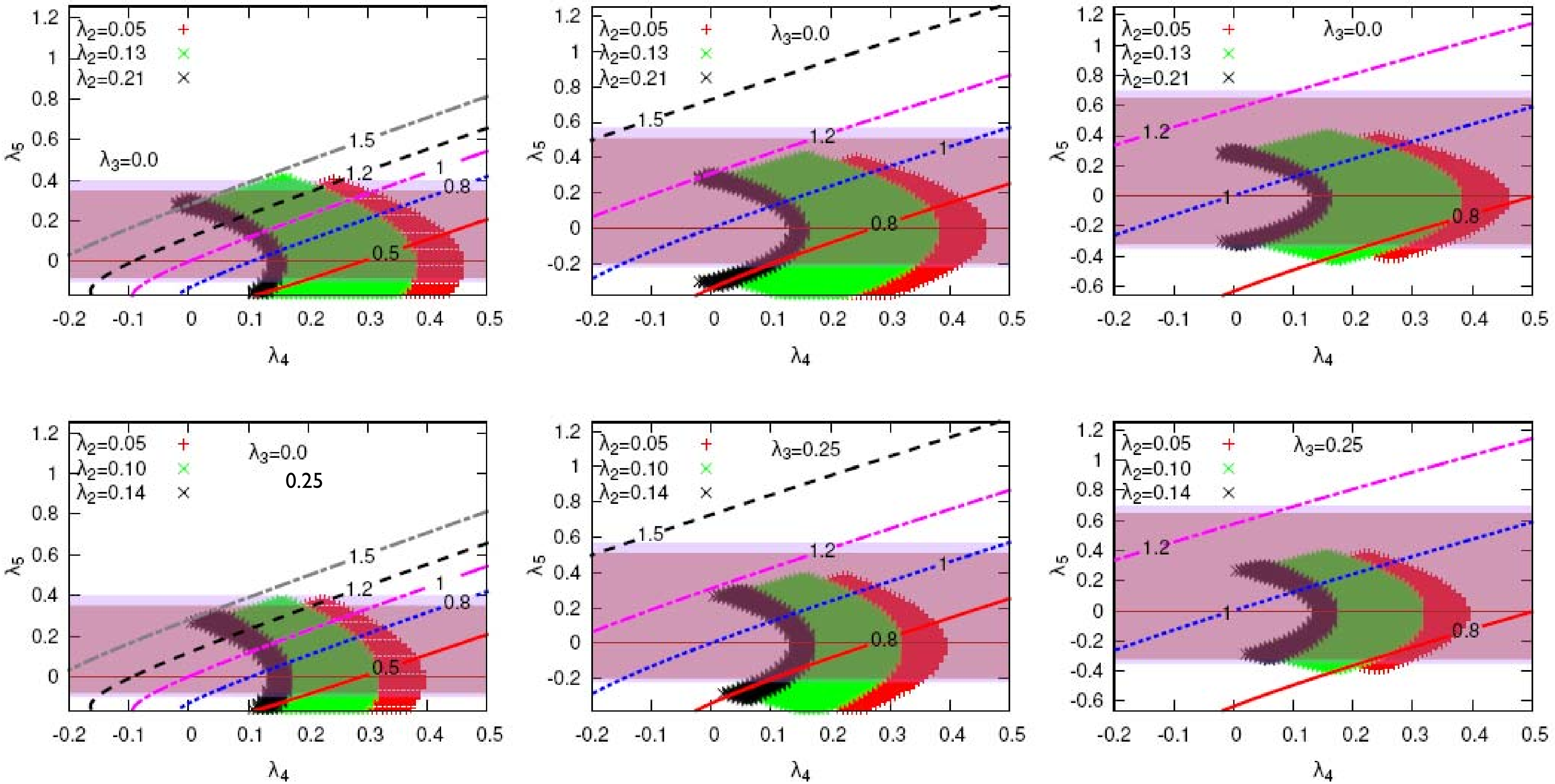


$m_{H^{++}} = 150{\rm GeV}$



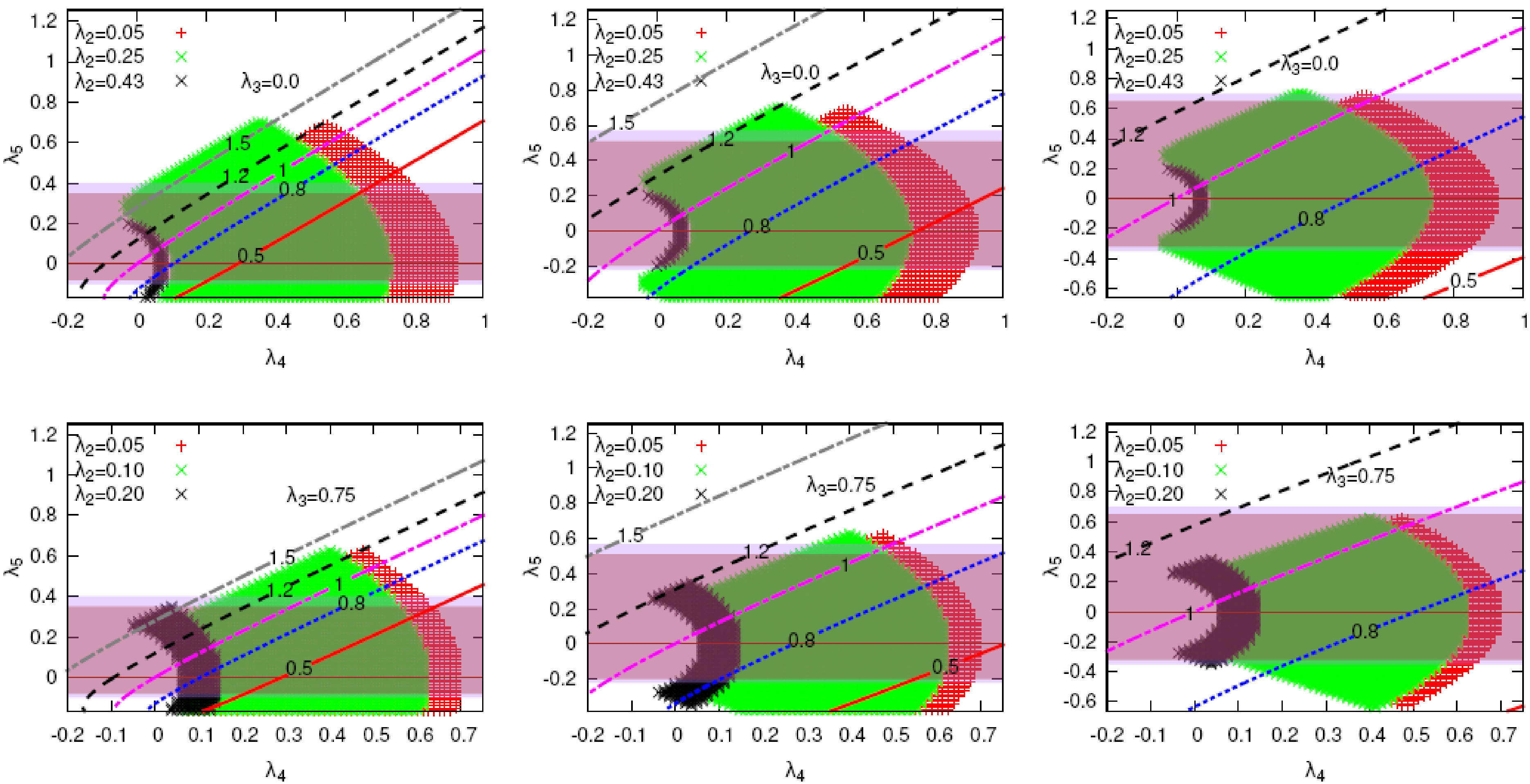
$m_{H^{++}} = 200{\rm GeV}$

Combined results for 10^{19} GeV

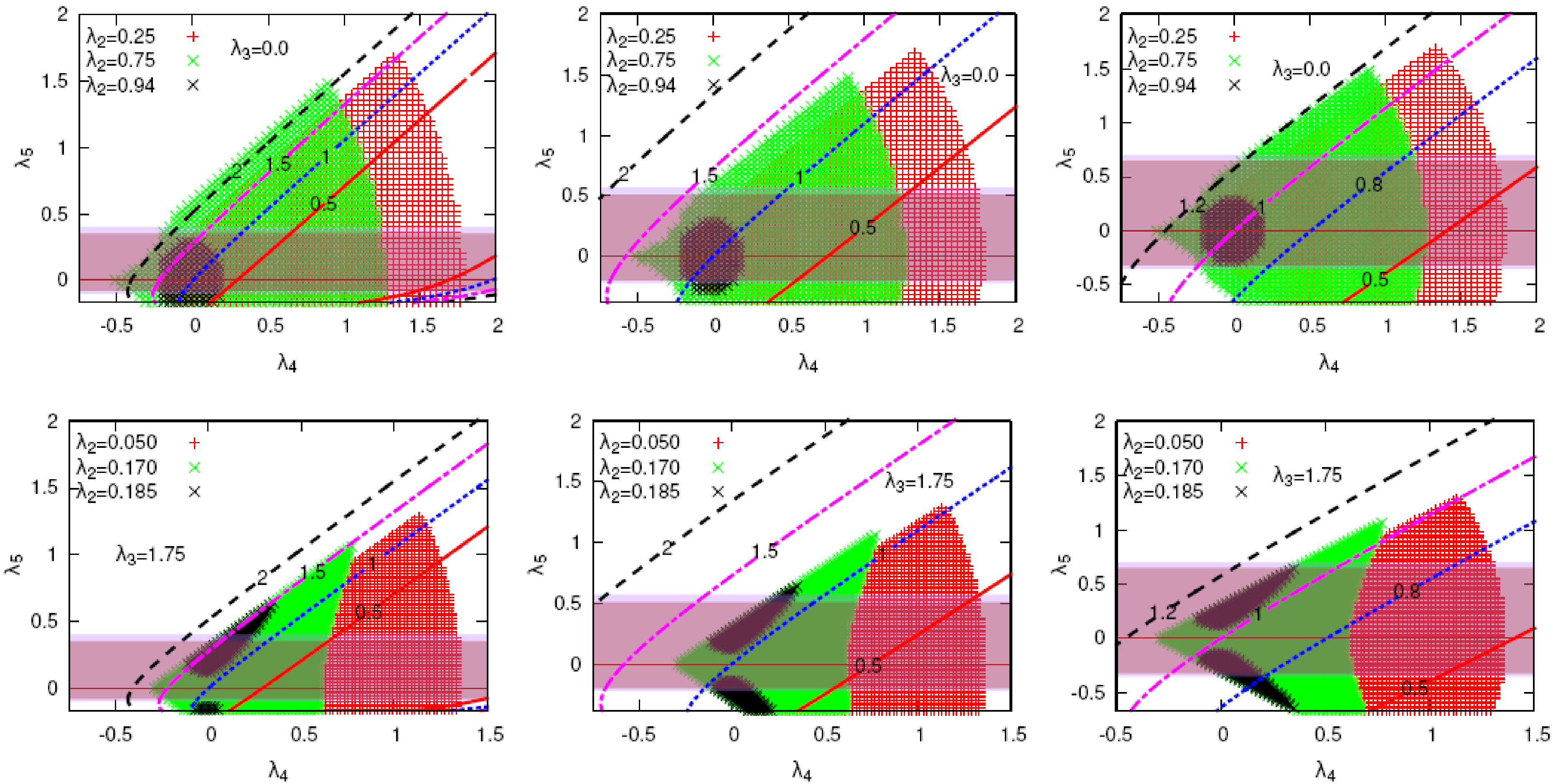


$m_{H^{++}} = 100\text{GeV}$ $m_{H^{++}} = 150\text{GeV}$ $m_{H^{++}} = 200\text{GeV}$

Combined results for 10^{10} GeV



Combined results for 10^5 GeV



Conclusion

- EWPD constrains tightly the triplet mass splitting:

  $|\Delta M| < 40$ GeV.
- Vacuum stability and perturbativity put strong bounds on the Higgs couplings, roughly $\lambda_i <\sim 1$.
- Higgs-to-diphoton rate can be enhanced up to 100% ~ 50% for the triplet mass 100 GeV depending on the cut-off scale.
- The Higgs precision data will severely constrain the Higgs triplet parameter space.

Thank you