HPNP2013 Toyama International Workshop on Higgs as a Probe of New Physics 2013

February 13-16, 2013, University of Toyama, Japan

Higgs at Seesaw Type II

KIAS
Korea Institute for Advanced Study

Eung Jin Chun

EJC, Lee, Sharma, 1209.1303
EJC, Sharma, 1301.1407

Introduction

- An SU(2) doublet boson (Y=1/2) 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
- Clean signals $\Delta^{++} \rightarrow l^{+} l^{+}$ & more [see Sharma's poster]
- Implication to the Higgs-to-diphoton rate.
- Non-SUSY version constrained by EWPD, perturbativity and vacuum stability. EJC, Lee, Sharma, 1209.1303
- SUSY version with one light triplet and Higgs controlled by the D-term potential. EJC, Sharma, 1301.1407

Type II Seesaw (Non-SUSY)

- 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:

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

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

- ρ parameter constraint on $\xi = v_\Delta / v_\Phi$:

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

- 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 boson mass eigenstates:

$$
\Delta^{++},\Delta^{+},\Delta^{0} \quad \Phi^{+},\Phi^{0} \;\Rightarrow\; h^0, H^0, A^0, H^+, H^{++}
$$

- Doublet-triplet mixing controlled by $\xi = v_\Delta/v_\Phi$:

$$
\phi_I^0 = G^0 - 2\xi A^0 \qquad \phi^+ = G^+ + \sqrt{2}\xi H^+ \qquad \phi_R^0 = h^0 - a\xi H^0
$$

$$
\Delta_I^0 = A^0 + 2\xi G^0 \qquad \Delta^+ = H^+ - \sqrt{2}\xi G^+ \qquad \Delta_R^0 = H^0 + a\xi h^0
$$

Triplet boson spectrum

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

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

$$M^2_{H^{\pm}} = M^2_{H^{\pm\pm}} + 2\frac{\lambda_5}{g^2} M^2_W$$

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

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

- Mass gap between H^0 & A^0: [see Sharma's poster]

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

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

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

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:

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

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

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

Collider search

- Look for $H^{++} \to l^+ l^+$
- Neutrino mass pattern can be determined by measuring

$$\mathrm{BR}(H^{++} \xrightarrow{f_{\alpha\beta}} l_\alpha^+ l_\beta^+)\,!$$

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

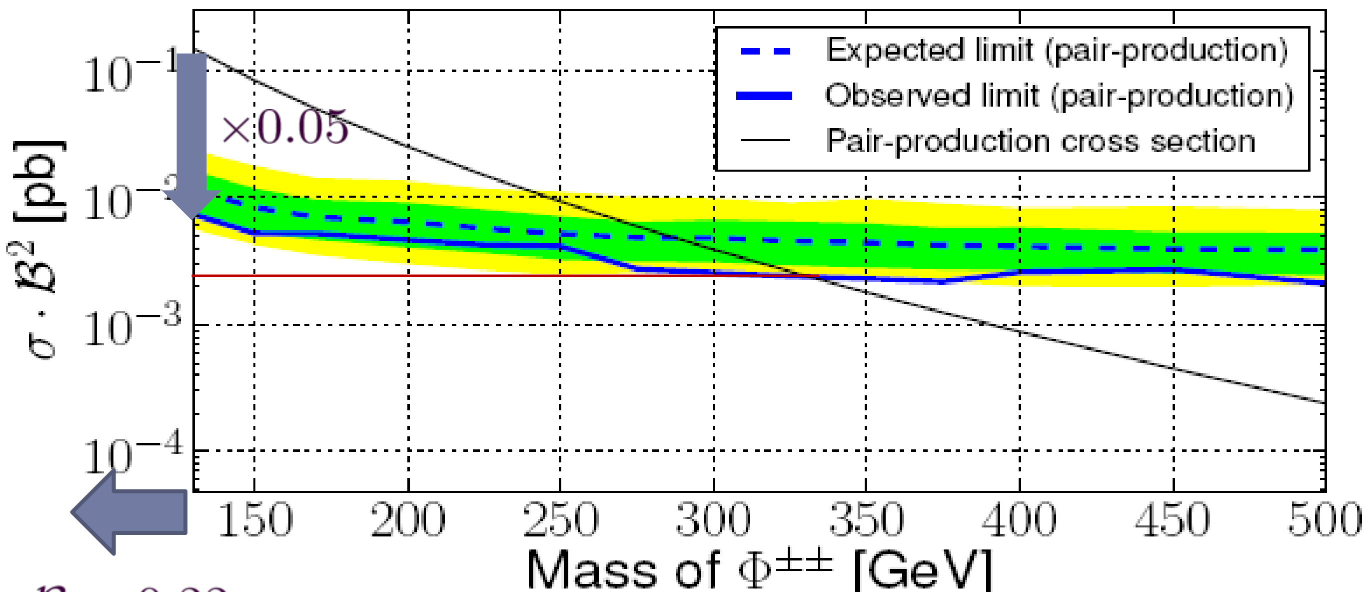
CMS, 1207.2666

CMS 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

BP1 (NH)

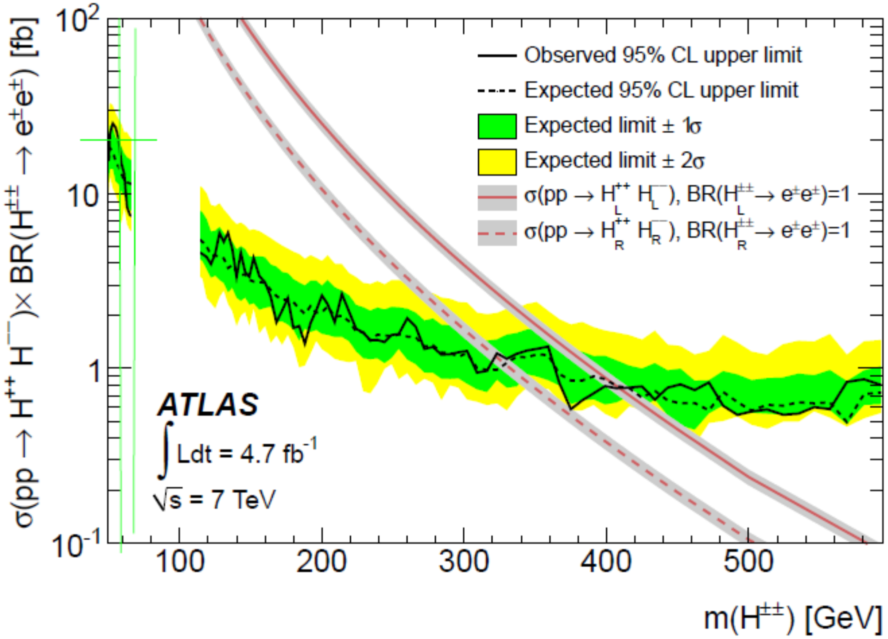


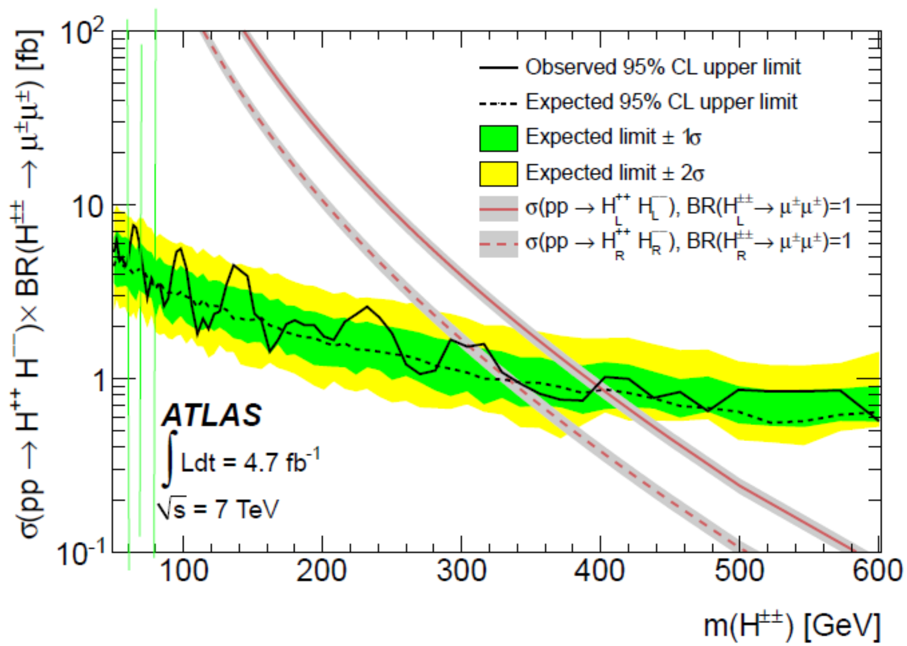
$\mathcal{B} < 0.22$

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

ATLAS limit

ATLAS, 1210.5070





- No mass limit for $Br(H^{++} \rightarrow l^+ l^+)$ small enough.

EWPD

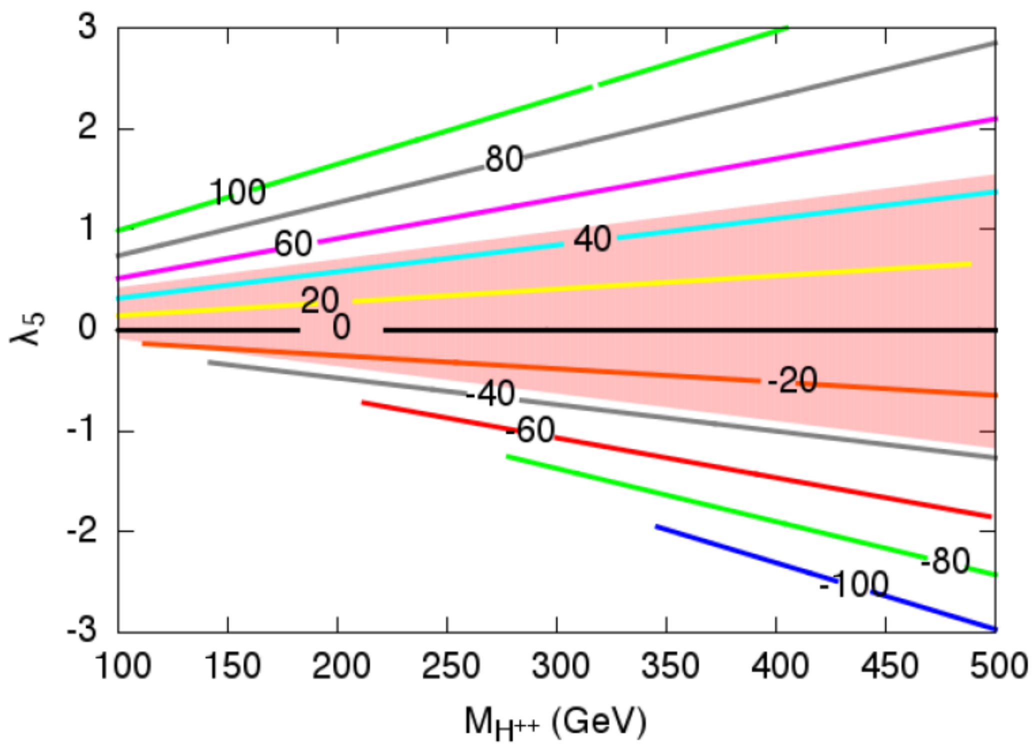
- Triplet contribution to S, T & U: Lavoura, Li, 9309262
- Most recent STU fit: Baak, et.al., 1209.2716

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

- It strongly constrains the mass splitting.

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

Constraint on ΔM (λ_5)



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

$$\lambda_5 = (-0.1, 0.4), \quad (-0.2, 0.6), \quad (-0.35, 0.7) \quad M_{H^{++}} = 100,\ 150,\ \text{and}\ 200\ \text{GeV},$$

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

Vacuum stability & perturbativity

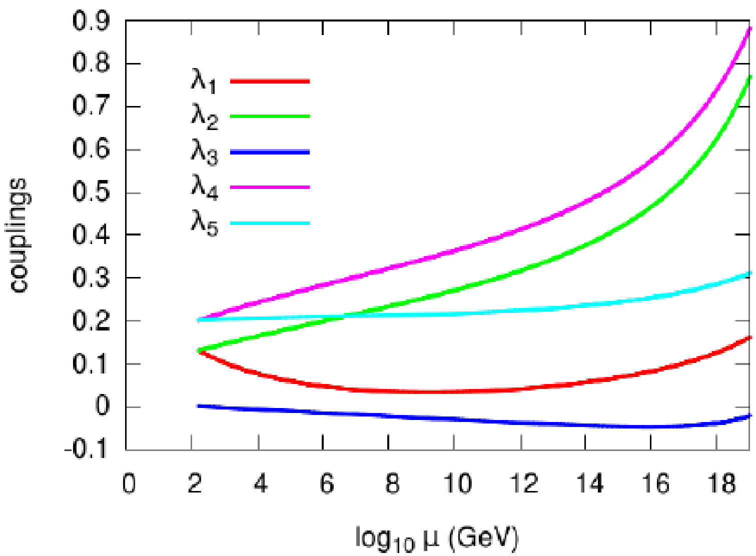
- Use 1-loop RGE:

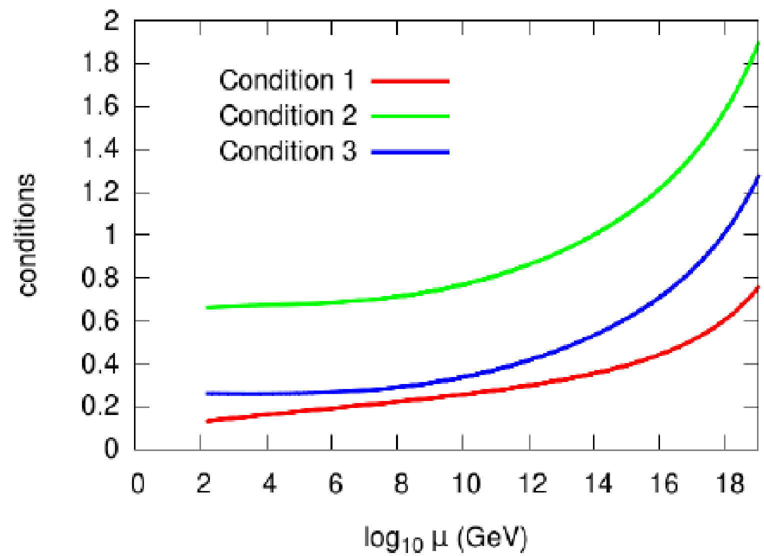
Chao, Zhang, 0611323
Schmidt, 07053841

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

Constraints on λ's

- RGE – an example:



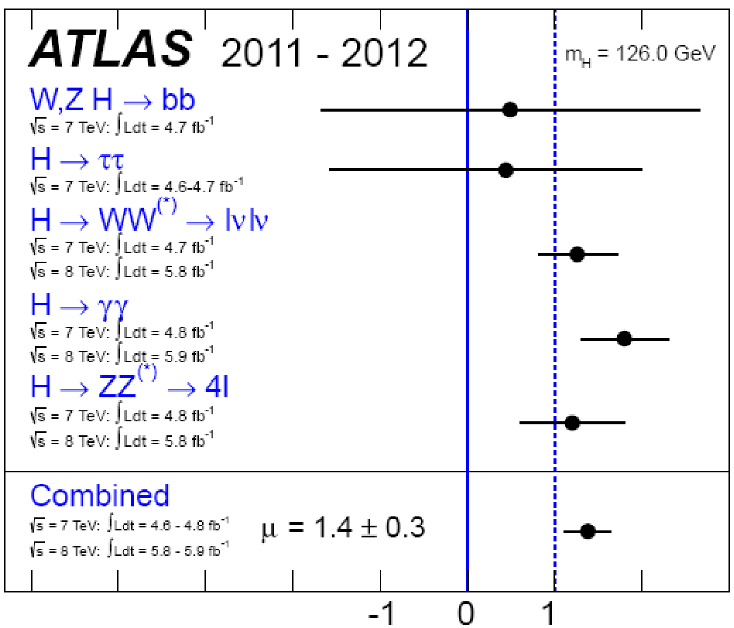


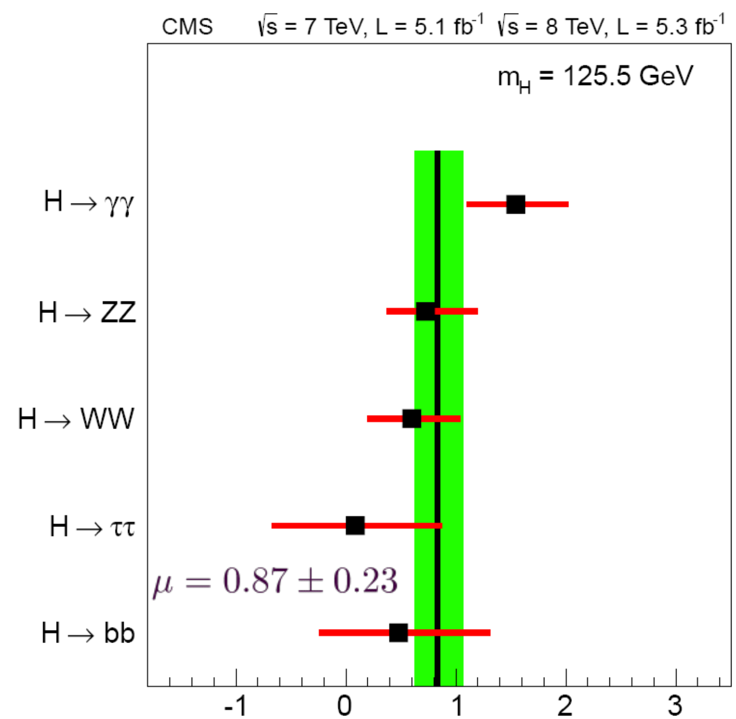
- Allowed ranges:

	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

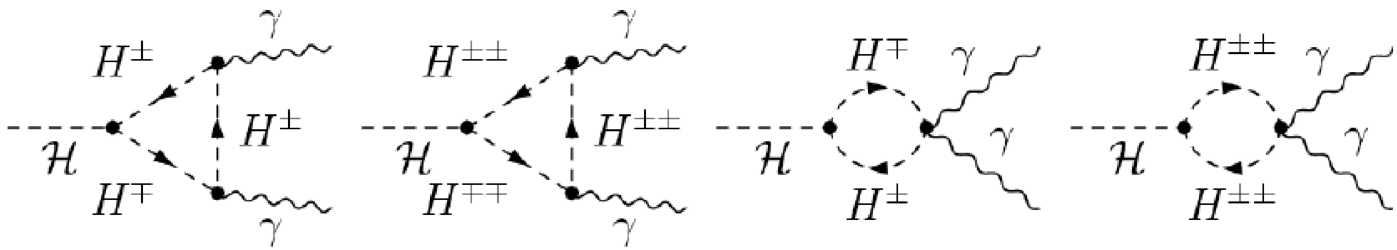
- 1-loop process – sensitive to New Physics.
- A large deviation in the current data.
- Its precision data is important to constrain NP.





Higgs-to-diphoton

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

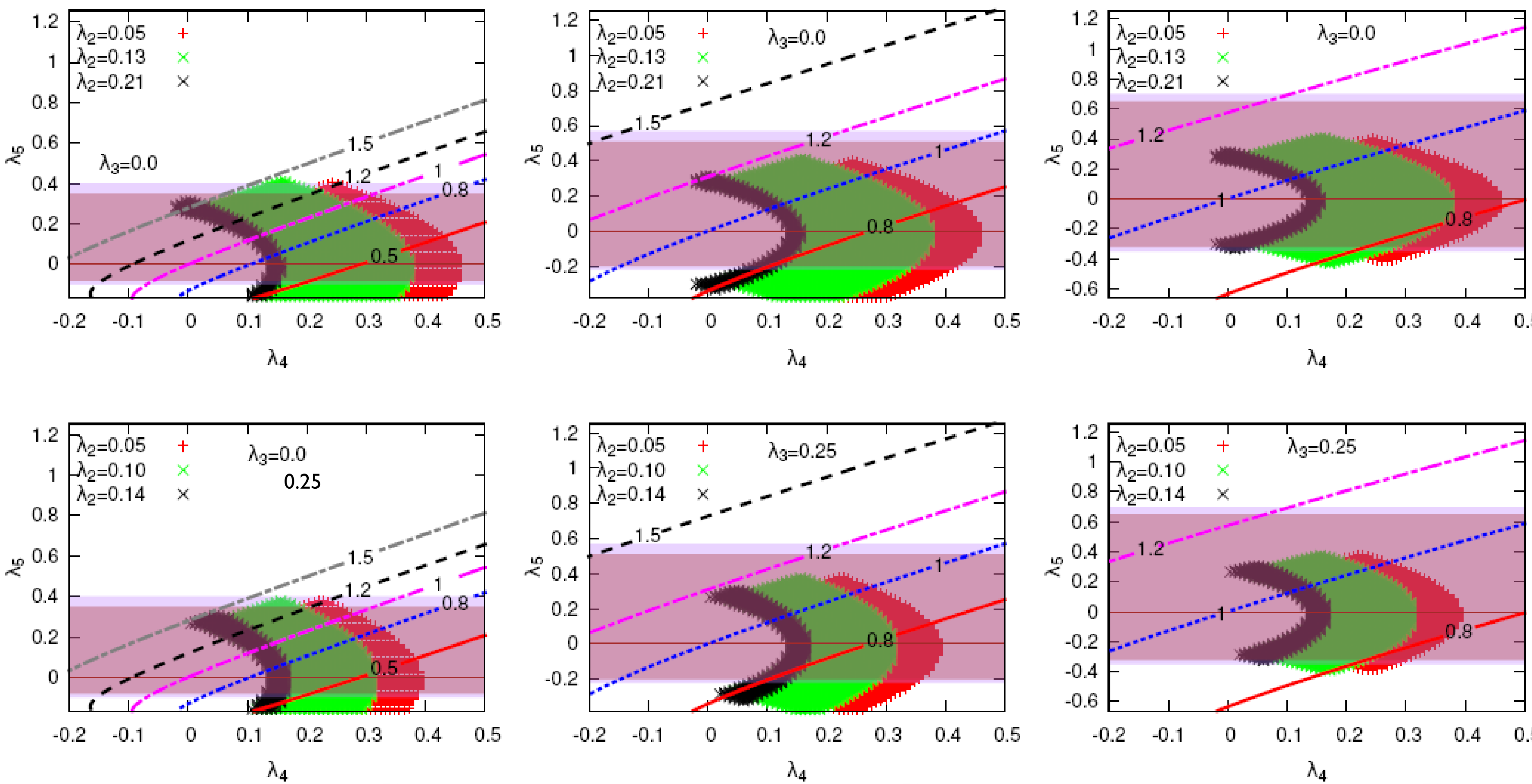


$$\Gamma(h \to \gamma\gamma) = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 \, g_{ff}^h A_{1/2}^h(x_f) + g_{WW}^h A_1^h(x_W) + g_{H^+H^-}^h A_0^h(x_{H^+}) + 4 g_{H^{++}H^{--}}^h A_0^h(x_{H^{++}}) \right|^2$$

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

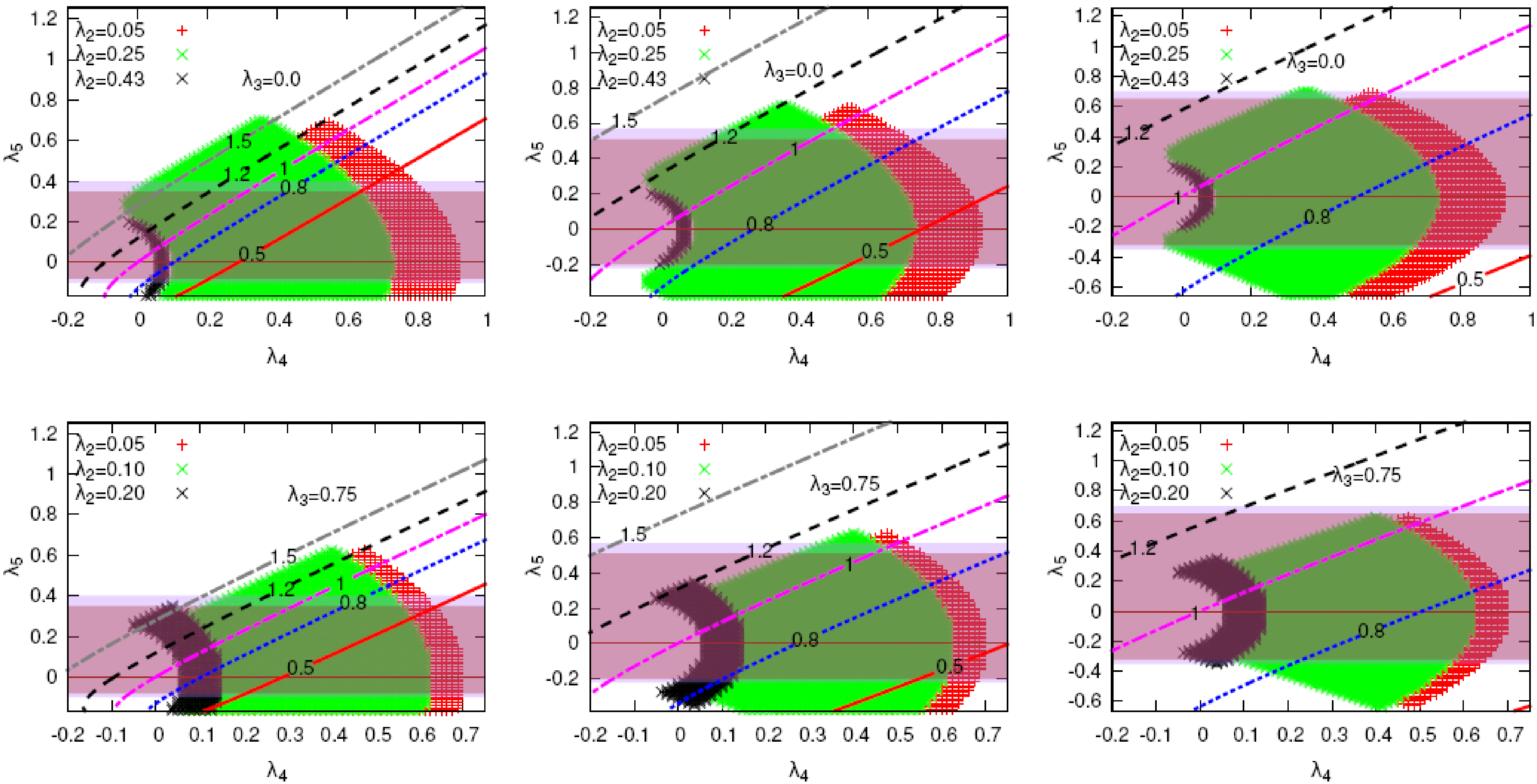
Arhrib, et.al., 1112.5453
Kanemura, Yagyu, 1201.6287
Akeryod, Moretti, 1206.0535
Chiang, Yagyu, 1207.1065

Combined results for 10^{19} GeV

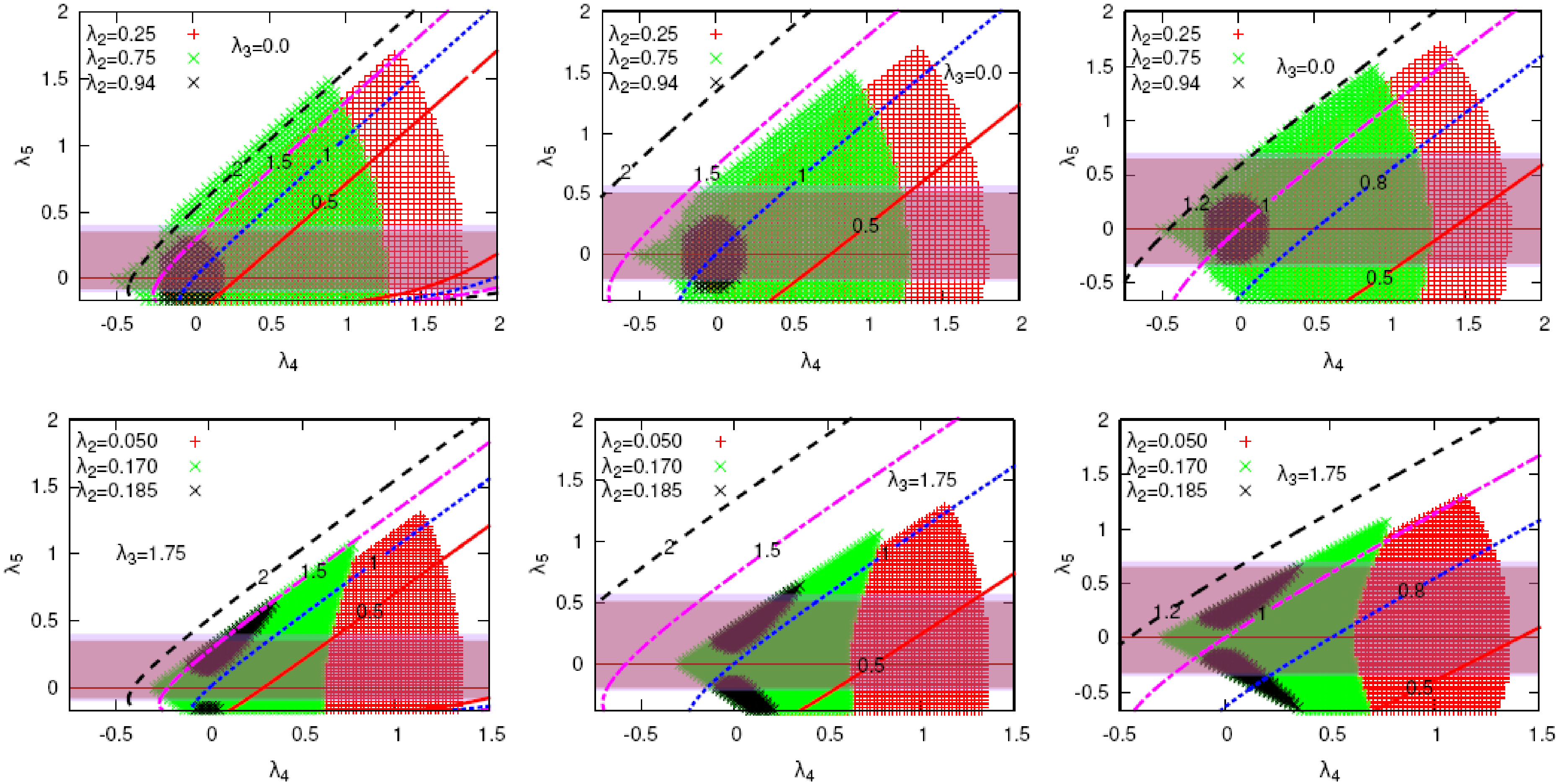


$m_{H^{++}} = 100\text{GeV}$ $m_{H^{++}} = 150\text{GeV}$ $m_{H^{++}} = 200\text{GeV}$

Combined results for 10^{10} GeV



Combined results for 10^5 GeV



Supersymmetric Type II Seesaw

- Needs a vector-like pair of triplets to write the gauge-invariant superpotential:

$$\mathbf{\Delta} = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}, \quad \bar{\mathbf{\Delta}} = \begin{pmatrix} \frac{\bar{\Delta}^-}{\sqrt{2}} & \bar{\Delta}^0 \\ \bar{\Delta}^{--} & -\frac{\bar{\Delta}^-}{\sqrt{2}} \end{pmatrix}$$

$$W = \frac{1}{2} f_{ij} L_i^T i\tau_2 \mathbf{\Delta} L_j + \frac{1}{2}\lambda_1 H_1^T i\tau_2 \mathbf{\Delta} H_1 - \frac{1}{2}\lambda_2 H_2^T i\tau_2 \bar{\mathbf{\Delta}} H_2 + \mu H_1^T i\tau_2 H_2 + M \mathrm{Tr}[\mathbf{\Delta}\bar{\mathbf{\Delta}}]$$

- D-term potential: mass splitting & Higgs-to-triplet coupling:

$$\begin{aligned} V_D &= \frac{g^2}{8}\left[|H_1^0|^2 - |H_2^0|^2 + 2|\Delta^{++}|^2 - 2|\Delta^0|^2 - 2|\bar{\Delta}^{--}|^2 + 2|\bar{\Delta}^0|^2\right]^2 \\ &+ \frac{g'^2}{8}\left[|H_1^0|^2 - |H_2^0|^2 - 2|\Delta^{++}|^2 - 2|\Delta^+|^2 - 2|\Delta^0|^2 + 2|\bar{\Delta}^{--}|^2 + 2|\bar{\Delta}^-|^2 + 2|\bar{\Delta}^0|^2\right]^2 \end{aligned}$$

Triplet boson spectrum

- Triplet mass matrix: $\begin{pmatrix} M^2_{\Delta^a} & B_M \\ B_M & M^2_{\Delta^{\bar{a}}} \end{pmatrix}$

$$M^2_{\Delta^a} \equiv M^2 + m^2_\Delta + d_a M_Z^2 c_{2\beta} + \frac{c_a}{4}\lambda_1^2 v_0^2 c_\beta^2,$$
$$M^2_{\Delta^{\bar{a}}} \equiv M^2 + m^2_\Delta - d_a M_Z^2 c_{2\beta} + \frac{c_a}{4}\lambda_2^2 v_0^2 s_\beta^2$$

$$(d_{++}, d_+, d_0) = (1 - 2s_W^2, -s_W^2, -1) \quad (c_{++}, c_+, c_0) = (0, 1, 2)$$

- Mass eigenvalues:

$$M^2_{\Delta^a_{1,2}} = \frac{1}{2}\left[2M^2 + m^2_\Delta + m^2_\Delta \mp \sqrt{(m^2_\Delta - m^2_\Delta + 2d_a M_Z^2 c_{2\beta})^2 + 4B_M^2}\right]$$

- Mass splitting among triplet components:

$$M^2_{\Delta^0_{1,2}} - M^2_{\Delta^+_{1,2}} = M^2_{\Delta^+_{1,2}} - M^2_{\Delta^{++}_{1,2}} = \mp(1 - s_W^2) c_{2\delta} c_{2\beta} M_Z^2$$

$$c_{2\delta} \equiv -\frac{m^2_\Delta - m^2_\Delta}{\sqrt{(m^2_\Delta - m^2_\Delta)^2 + 4B_M^2}}.$$

A light triplet boson & its couplings

- Mass hierarchy: $M_{\Delta_1} \ll M_{\Delta_2}$

$$M_{\Delta_1^{++}} < M_{\Delta_1^{+}} < M_{\Delta_1^{0}} \quad \text{if} \quad c_{2\delta} > 0$$

- Di-lepton/W coupling:

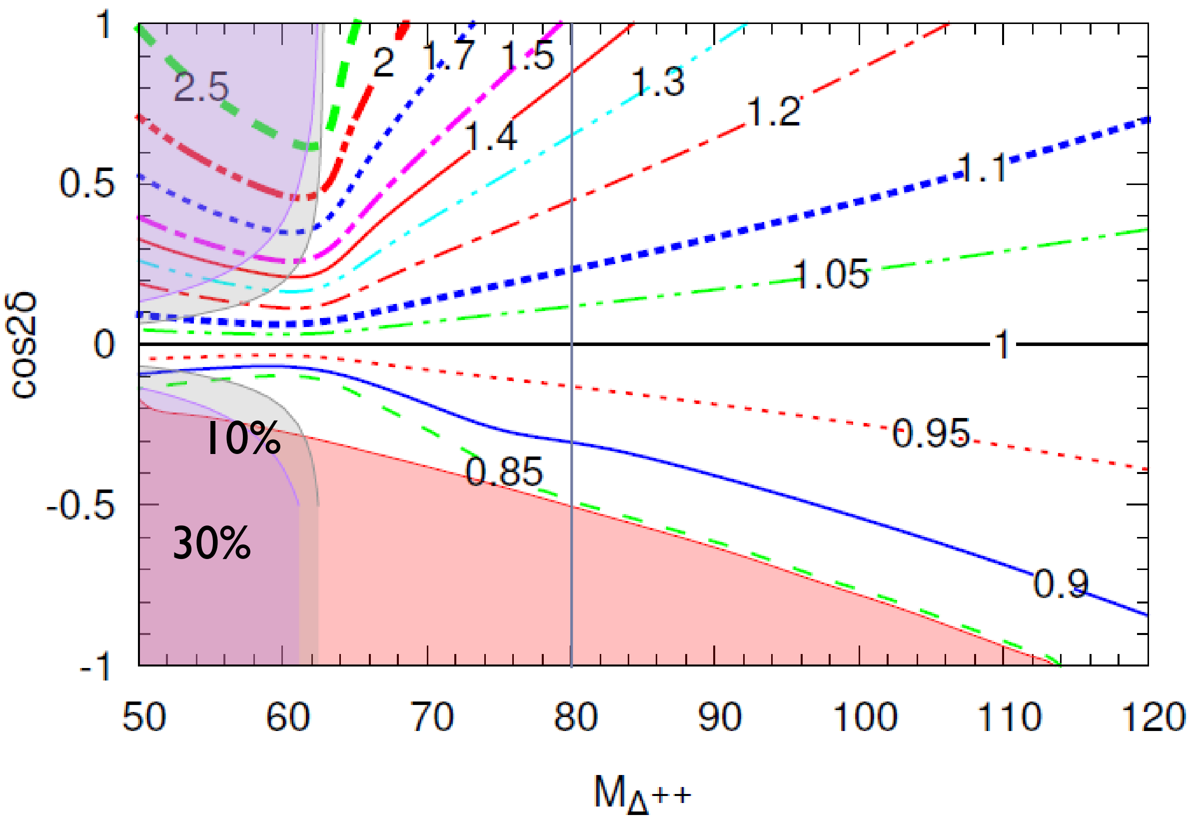
$$\mathcal{L} \;=\; \frac{1}{\sqrt{2}} \left[c_\delta f_{ij} \bar{l}_i^c P_L l_j + g\xi_1 M_W W^- W^- \right] \Delta_1^{++} + h.c.$$

- Higgs coupling:

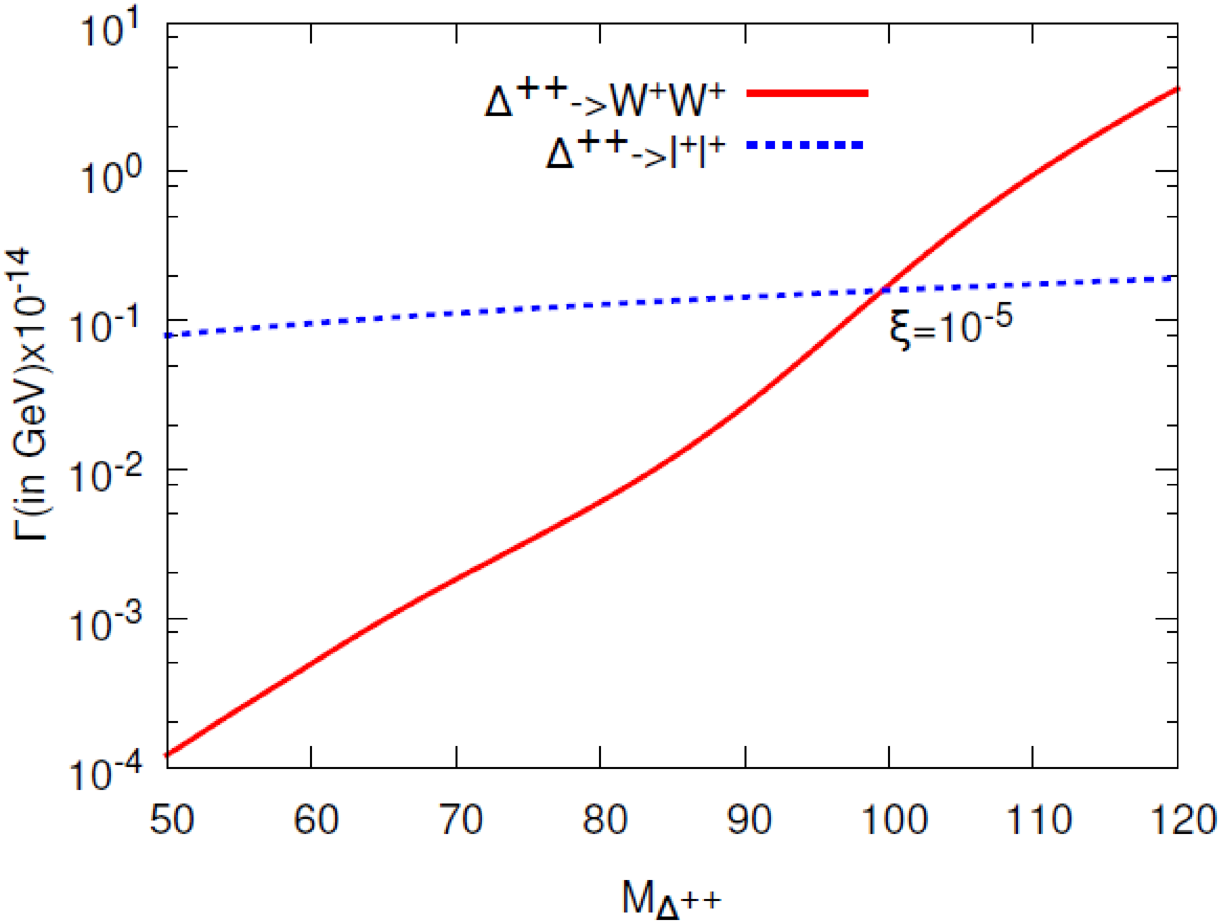
$$V_D = c_{2\beta} c_{2\delta} v_0 \, h \left[\frac{g^2 - g'^2}{2} (|\Delta_1^{++}|^2 - |\Delta_2^{++}|^2) - \frac{g'^2}{2} (|\Delta_1^{+}|^2 - |\Delta_2^{+}|^2) \right]$$

$$g^h_{\Delta^+\Delta^+} = -c_{2\delta} c_{2\beta} t_W^2 \frac{M_W^2}{m_h^2} \quad \text{and} \quad g^h_{\Delta^{++}\Delta^{++}} = c_{2\delta} c_{2\beta} (1 - t_W^2) \frac{M_W^2}{m_h^2}$$

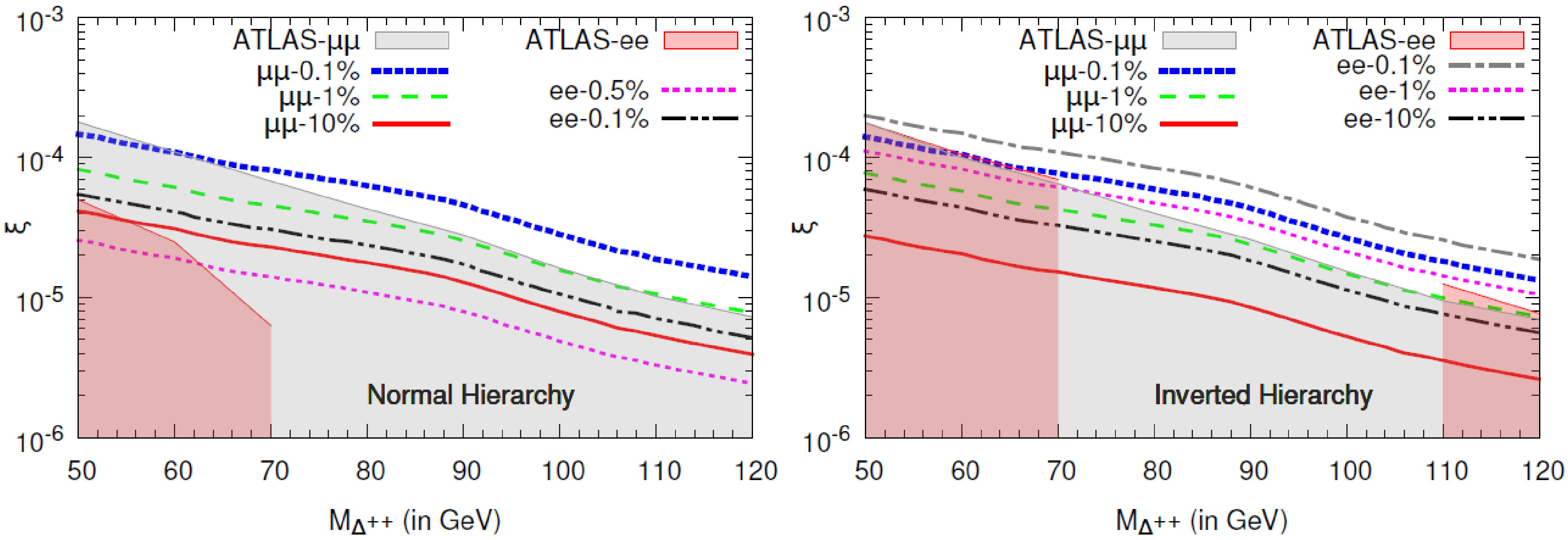
Higgs decay to di-photon & di-Δ



Light triplet decays to di-lepton/W

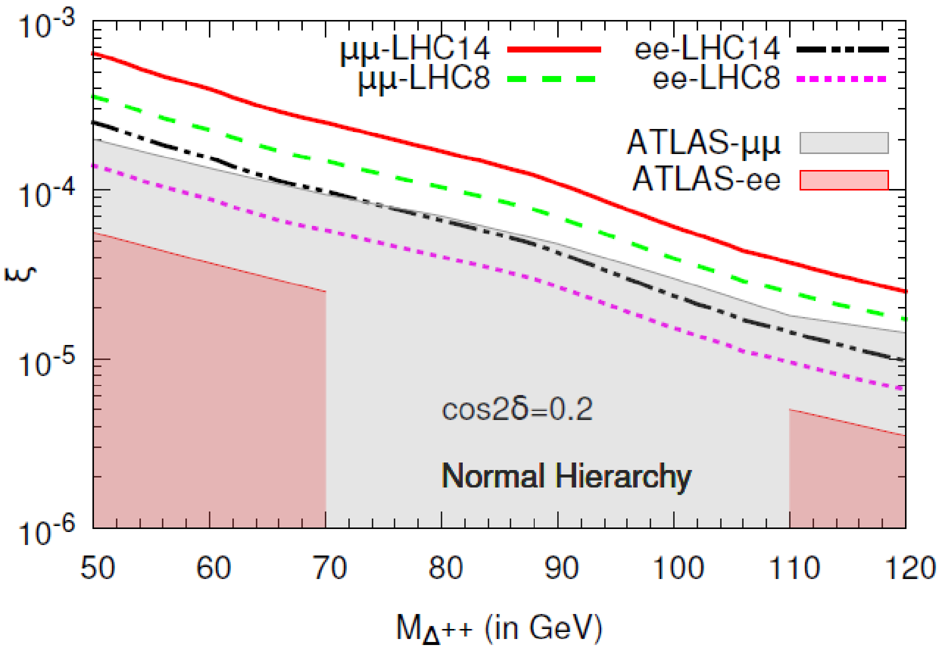


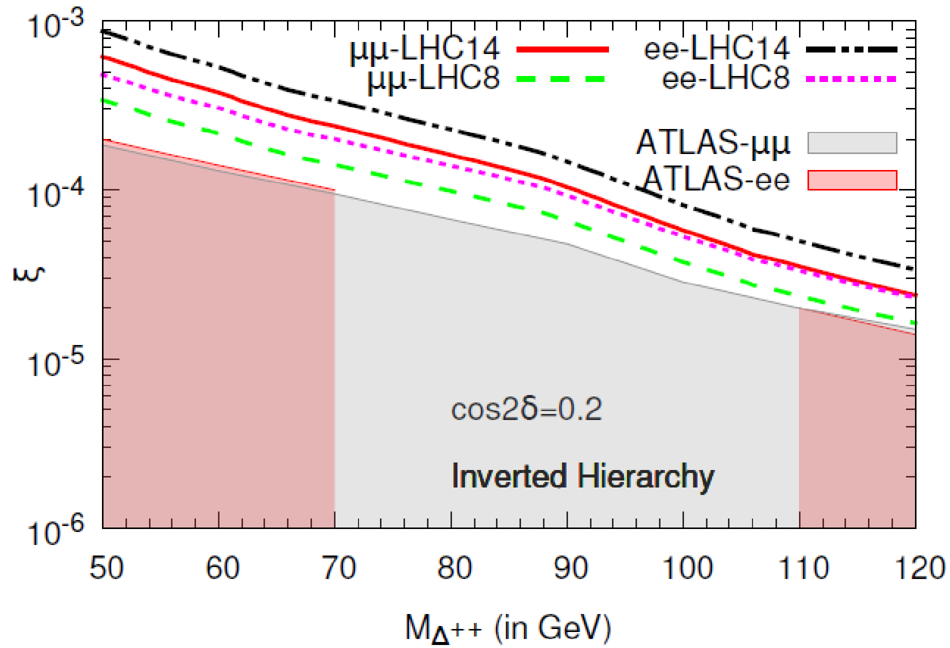
LHC7 limits for NH & IH



Future sensitivity

- Lines for σ x BF(ll) = 1fb:





Conclusion

- EWPD constrains tightly the triplet mass splitting:

  $$|\Delta M| < 40 \text{ GeV}.$$

- Vacuum stability and perturbativity put strong bounds on the Higgs couplings, roughly $\lambda_i \lesssim 1$.
- Higgs-to-diphoton rate can be enhanced up to 100% ~ 50% for the triplet mass 100 GeV depending on the cut-off scale.
- In SUSY, an enhanced diphoton rate implies the presence of a light triplet boson (<80 GeV).
- The Higgs precision data will severely constrain the Higgs-triplet parameter space.