Same-Sign Tetra-Leptons from Type II Seesaw

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

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Outline

- Introduction to type II seesaw — EJC, Lee, Park, 0304069

  Triplet boson spectrum and decay channels

  CMS/ATLAS search

- Constraints from — EJC, Lee & Sharma, 1209.1303

  EWPD, Perturbativity/vacuum stability,

  & Higgs-to-Diphoton rate

- Triplet-antitriplet oscillation & — EJC & Sharma, 1206.6278, 1309.6888

  Same-sign tetra-leptons

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 is discovered.
- What about neutrino masses? Maybe due to

  "SU(2) triplet boson (Y=1)" :

  Type II Seesaw

  Magg and Wetterich, '80
  Cheng and Li, '80
  Schechter and Valle, '80
  Lazarides, Shafi and Wetterich, '81
  Mohapatra and Senjanovic, '81

- Peculiar prediction of a doubly charged boson:

$$\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$$

- Main search channel: $\Delta^{++} \rightarrow l^{+}\, l^{+}$

Type II Seesaw

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

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

- Triplet VEV generates neutrino mass matrix:

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

$$\Rightarrow\ v_\Delta = \mu \frac{v_\Phi^2}{M_\Delta^2} \ \Rightarrow\ m^\nu_{\alpha\beta} = f_{\alpha\beta} v_\Delta$$

- Two free parameters related by neutrino mass:

$$f_{\alpha\beta}\frac{v_\Delta}{v_\Phi} \sim 10^{-12}$$

- Collider probes neutrino mass pattern by measuring

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

EJC, Lee, Park, 0304069

Scalar sector

- Scalar 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

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

Scalar sector

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

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

$$a = 2 + (4\lambda_1 - \lambda_4 - \lambda_5) v_\Phi^2 / (M_{H^0}^2 - m_{h^0}^2)$$

- ρ parameter constraint:

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

- We will work in the limit of $\xi << 0.03$.

Scalar spectrum

- Mass splitting among triplet components:

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

$$\Delta M = M_{H^+} - M_{H^{++}}$$

$$\boxed{\Delta M \approx \frac{\lambda_5}{g^2}\frac{M^2_W}{M} < M_W}$$

- Tiny mass splitting between H^0 & A^0 due to L violation:

$$\mathcal{L}_{\not{\Delta}} = \frac{1}{\sqrt{2}}\mu \Phi^T i\tau_2 \Delta^\dagger \Phi + h.c. \Rightarrow -\mu v_\Phi h^0 H^0$$

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

$$\boxed{\delta M_{HA} \approx 2 M_{H^0} \frac{v_\Delta^2}{v_0^2} \frac{M^2_{H^0}}{M^2_{H^0} - m^2_{h^0}} \ll \Delta M}$$

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):

$$H^0/A^0 \to H^\pm W^* \to H^{\pm\pm} W^* W^*$$
$$H^{++} \to H^\pm W^* \to H^0/A^0\, W^* W^*$$
$$\Longleftarrow \; \Delta M(\lambda_5)$$

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

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

- Di-quark/di-boson decays through ξ:

$$H^{++} \to W^+ W^+;\ H^+ \to t\bar{b}; \qquad H^0/A^0 \to t\bar{t},\ b\bar{b}$$
$$\to ZW, hW \qquad \to ZZ, hh/Zh$$
$$\Longleftarrow \; \xi \equiv \frac{v_\Delta}{v_\Phi}$$

Lepton Yukawas of the Triplet

- The neutrino mass matrix (assuming vanishing CP phases) determines the coupling $f = M^{\nu}/v_{\Delta}$ for given v_{Δ} :

NH IH

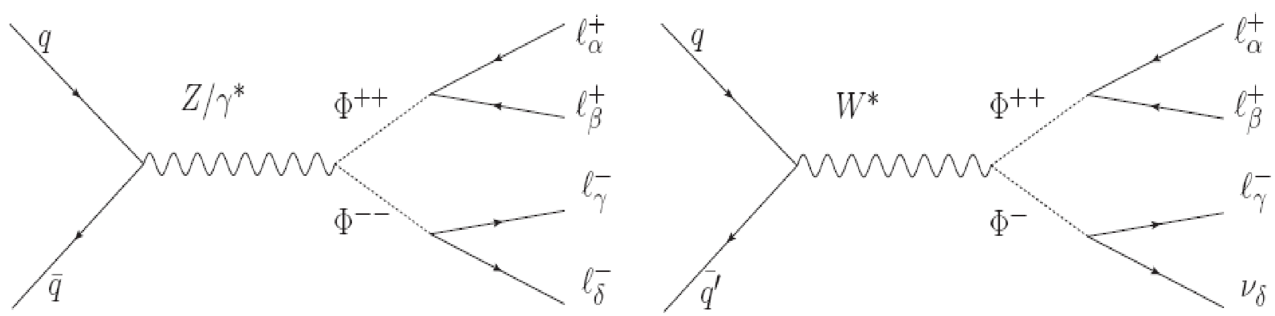
$$M^{\nu} = \begin{pmatrix} 0.00403 & 0.00816 & 0.00259 \\ 0.00816 & 0.0264 & 0.0215 \\ 0.00259 & 0.0215 & 0.0286 \end{pmatrix} \quad \begin{pmatrix} 0.0479 & -0.00557 & -0.00573 \\ -0.00557 & 0.0239 & -0.0240 \\ -0.00573 & -0.0240 & 0.02693 \end{pmatrix}$$

- Assuming 100% BF for di-lepton channels ($v_{\Delta} < 10^{-4}$ GeV)

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

LHC search

- CMS looks for three or four lepton signals from
  pp→H^{++} H^{-} → l^{+} l^{+} l^{-} ν & pp → H^{++} H^{--} → l^{+} l^{+} l^{-} l^{-} .
- ATLAS looks for same-sign di-letons from pp → H^{++} H^{--} → l^{+} l^{+} l^{-} l^{-}
- Assuming 100% leptonic decays & ΔM=0.

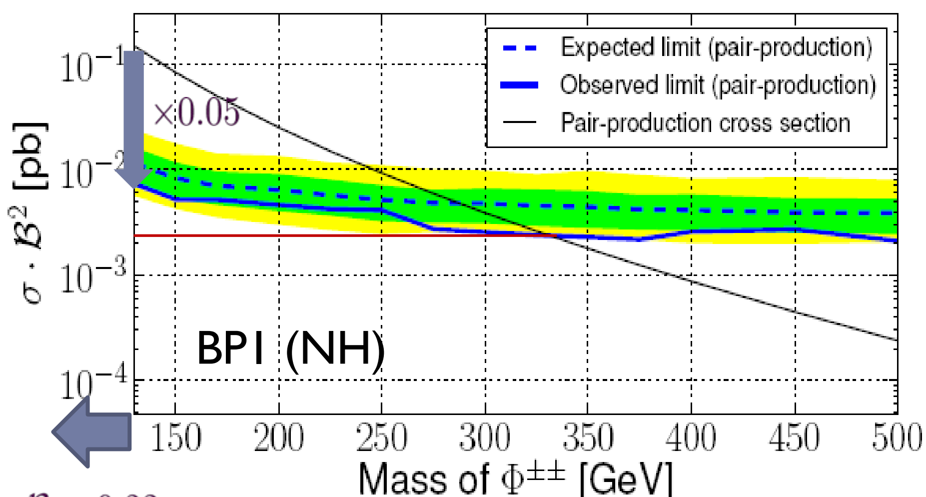


LHC7 limit

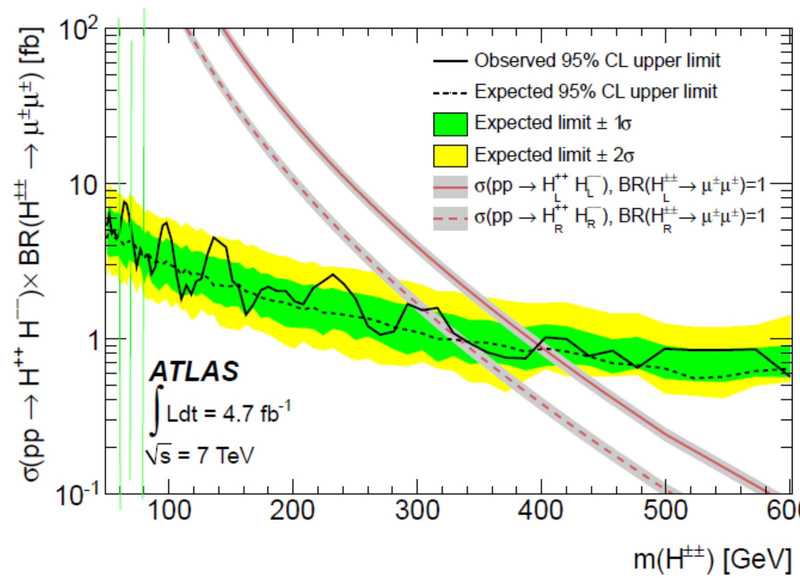
CMS, 1207.2666
ATLAS, 1210.5070

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

$\mathrm{BR}(H_L^{\pm\pm} \to \ell^\pm \ell'^\pm)$	95% CL lower limit on $m(H_L^{\pm\pm})$ [GeV]					
	$e^\pm e^\pm$		$\mu^\pm\mu^\pm$		$e^\pm\mu^\pm$	
	exp.	obs.	exp.	obs.	exp.	obs.
100%	407	409	401	398	392	375
33%	318	317	317	290	279	276
22%	274	258	282	282	250	253
11%	228	212	234	216	206	190



$\mathcal{B} < 0.22$
$M_{H^{++}} < 100\mathrm{GeV}$



Vacuum stability & perturbativity

- Relevant scalar potential terms:

$$\begin{aligned} V(\Phi,\Delta) = m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) \\ + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2[\mathrm{Tr}(\Delta^\dagger\Delta)]^2 + 2\lambda_3\mathrm{Det}(\Delta^\dagger\Delta) \\ + \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5(\Phi^\dagger\tau_i\Phi)\mathrm{Tr}(\Delta^\dagger\tau_i\Delta) \end{aligned}$$

- Demand the absolute vacuum stability condition:
  - $\lambda_1 > 0,$
  - $\lambda_2 > 0,$
  - $\lambda_2 + \frac{1}{2}\lambda_3 > 0$
  - $\lambda_4 \pm \lambda_5 + 2\sqrt{\lambda_1\lambda_2} > 0,$
  - $\lambda_4 \pm \lambda_5 + 2\sqrt{\lambda_1(\lambda_2 + \frac{1}{2}\lambda_3)} > 0.$

Arhrib, et.al., 1105.1925

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

Vacuum stability & perturbativity

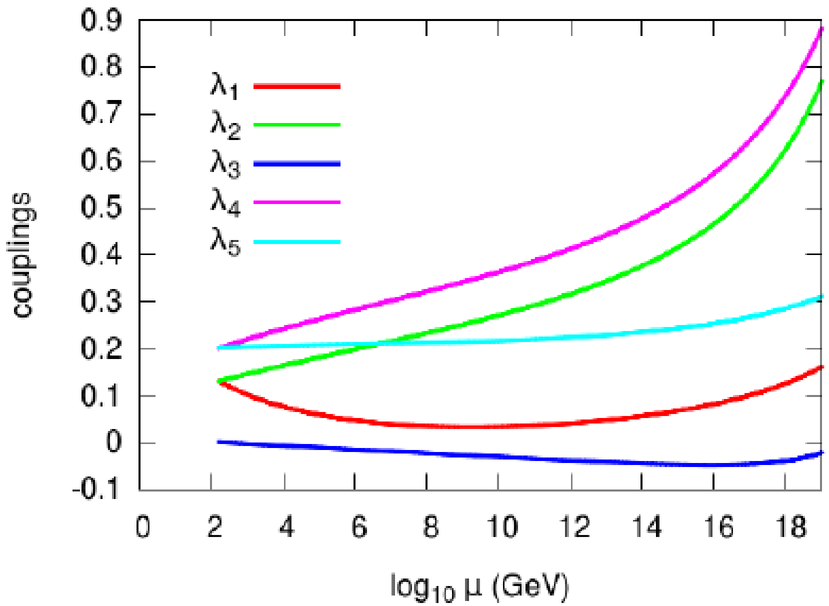
- Use 1-loop RGE:

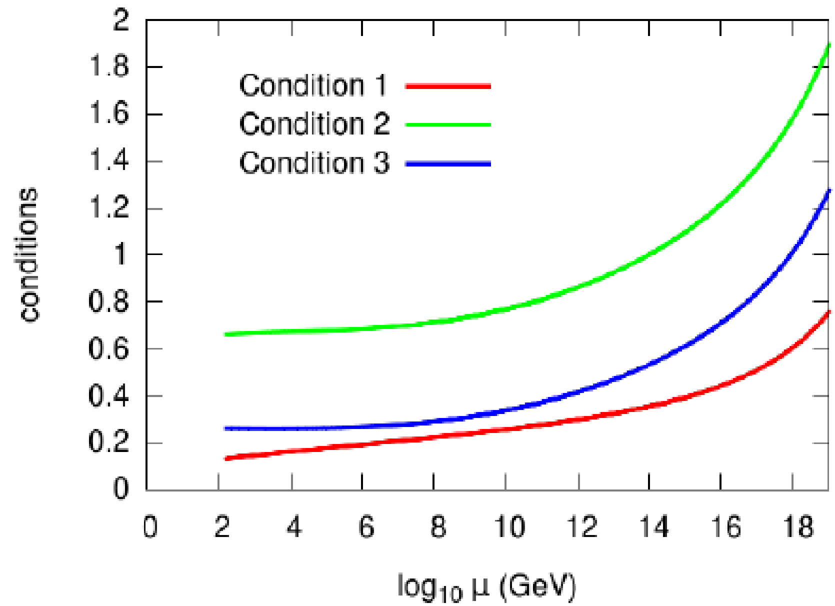
Chao, Zhang, 0611323
Schmidt, 07053841

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

RGE running

- An example





EWPD

- Triplet contribution to S, T & U: Lavoura, Li, 9309262

$$S = -\frac{1}{3\pi}\ln\frac{m_{+1}^2}{m_{-1}^2} - \frac{2}{\pi}\sum_{T_3=-1}^{+1}(T_3 - Qs_W^2)^2\,\xi\left(\frac{m_{T_3}^2}{m_Z^2}, \frac{m_{T_3}^2}{m_Z^2}\right)$$

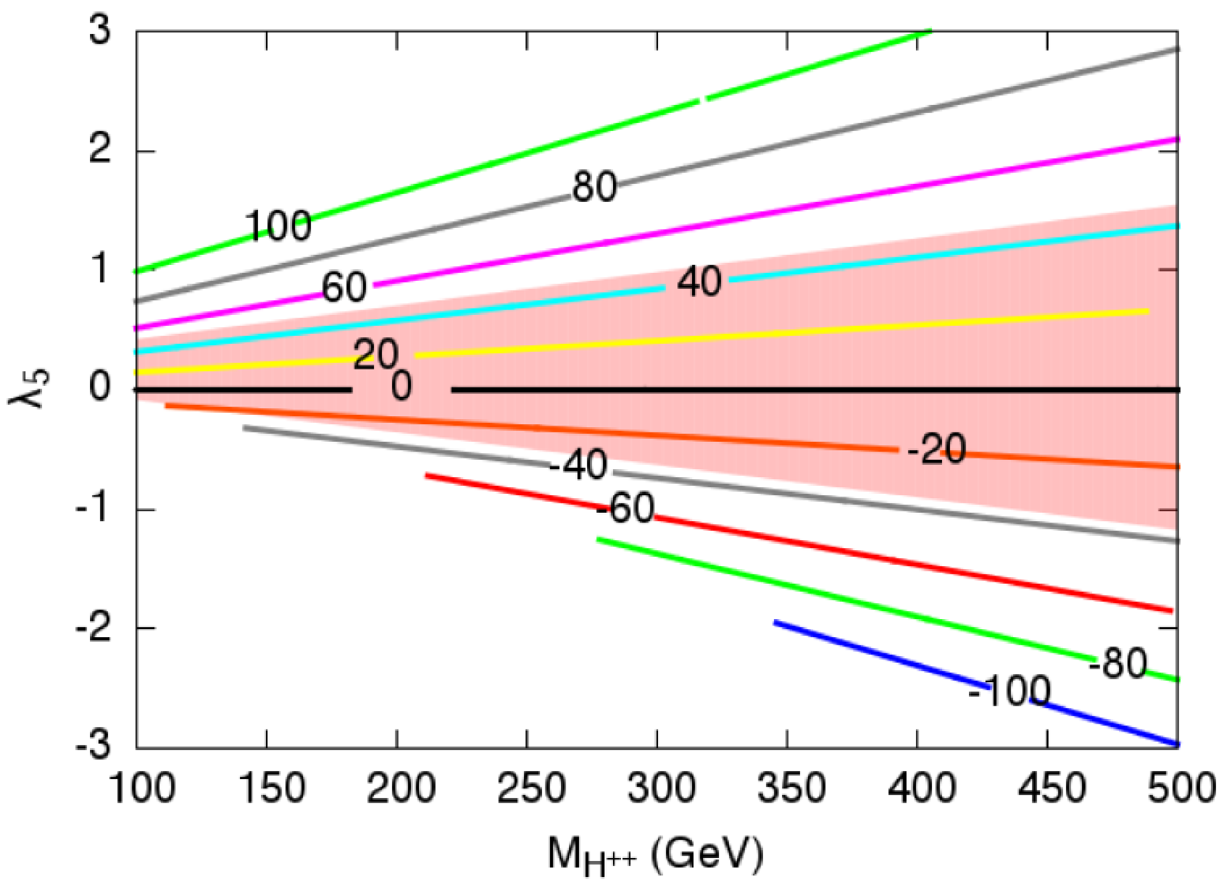
$$T = \frac{1}{16\pi c_W^2 s_W^2}\sum_{T_3=-1}^{+1}(2 - T_3(T_3-1))\,\eta\left(\frac{m_{T_3}^2}{m_Z^2}, \frac{m_{T_3-1}^2}{m_Z^2}\right)$$

$$U = \frac{1}{6\pi}\ln\frac{m_0^4}{m_{+1}^2 m_{-1}^2} + \frac{1}{\pi}\sum_{T_3=-1}^{+1}\left[2(T_3 - Qs_W^2)^2\,\xi\left(\frac{m_{T_3}^2}{m_Z^2}, \frac{m_{T_3}^2}{m_Z^2}\right) - (2 - T_3(T_3-1))\,\xi\left(\frac{m_{T_3}^2}{m_W^2}, \frac{m_{T_3}^2}{m_W^2}\right)\right]$$

$$m_{+1,0,-1} = M_{H^{++},H^{+},H^{0}}$$

- Strong constraint on mass splitting.

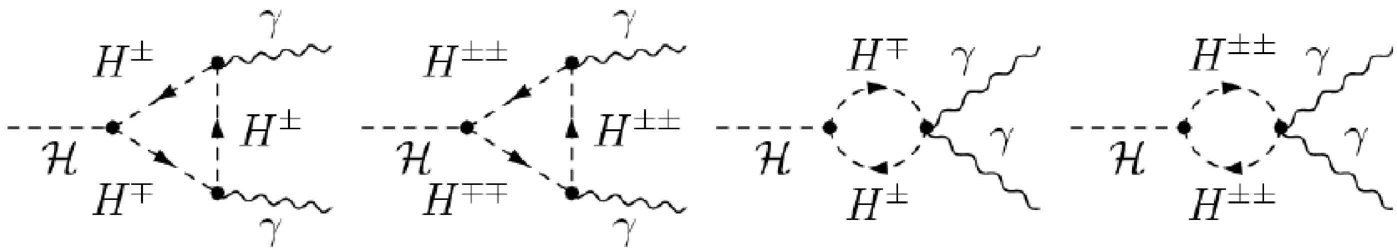
EWPD



$$|\Delta M| < 40 \text{ GeV} \quad (\xi << 10^{-2})$$

Higgs-to-diphoton

- H^{++} & H^{+} contribution sizable for low mass ≲ 200 GeV



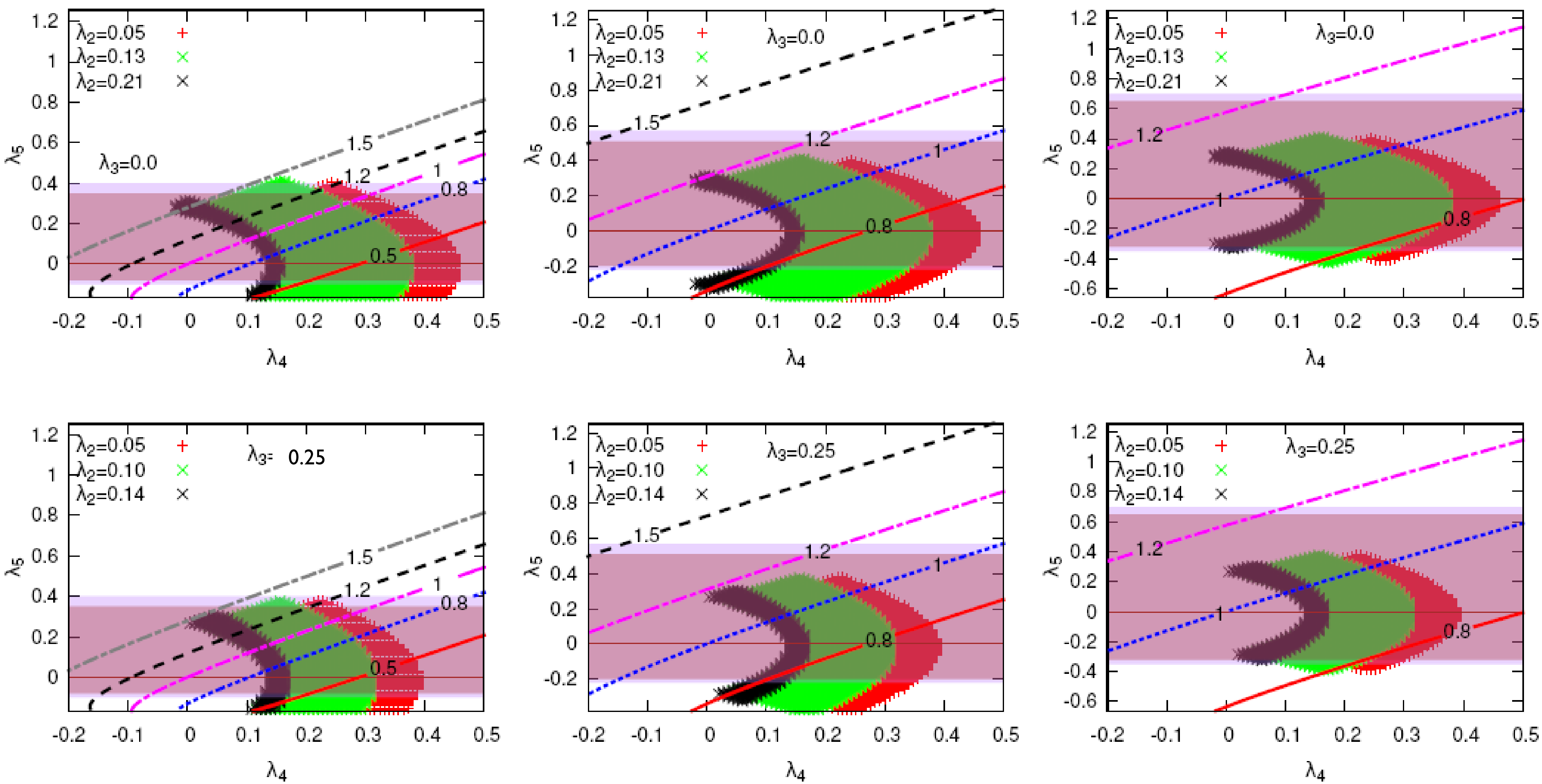
$$\Gamma(h \to \gamma\gamma) = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \Big| \sum_f N_c Q_f^2 \, g_{ff}^h A_{1/2}^h(x_f) + g_{WW}^h A_1^h(x_W)$$

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

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

Arhrib, et.al., 1112.5453
Kanemura, Yagyu, 1201.6287
Akeryod, Moretti, 1206.0535
Melfo, et.al., 1108.4416

Combined results for cutoff 10^{19} GeV



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

Triplet–antitriplet mixing

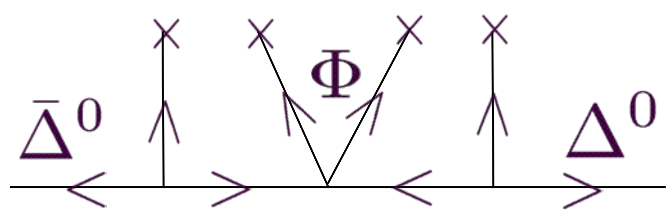
- Triplet (lepton) number is conserved in the production:

$$pp \longrightarrow \Delta\bar{\Delta}$$

- Triplet number breaking by doublet-triplet mixing:

$$\mathcal{L}_{\Delta\!\!\!/} = \frac{1}{\sqrt{2}}\mu\Phi^T i\tau_2\Delta^\dagger\Phi + h.c.$$

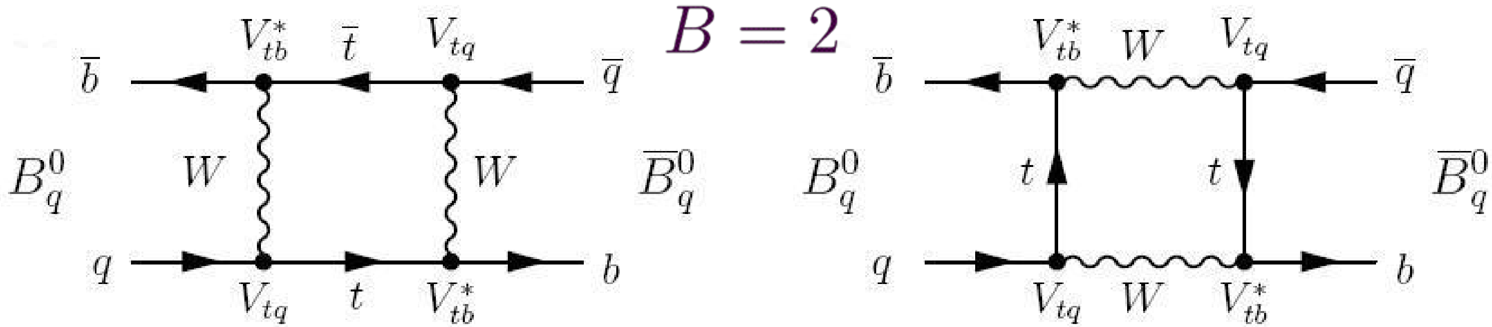
- Leading to $\Delta - \bar{\Delta}$ mixing (L=2):

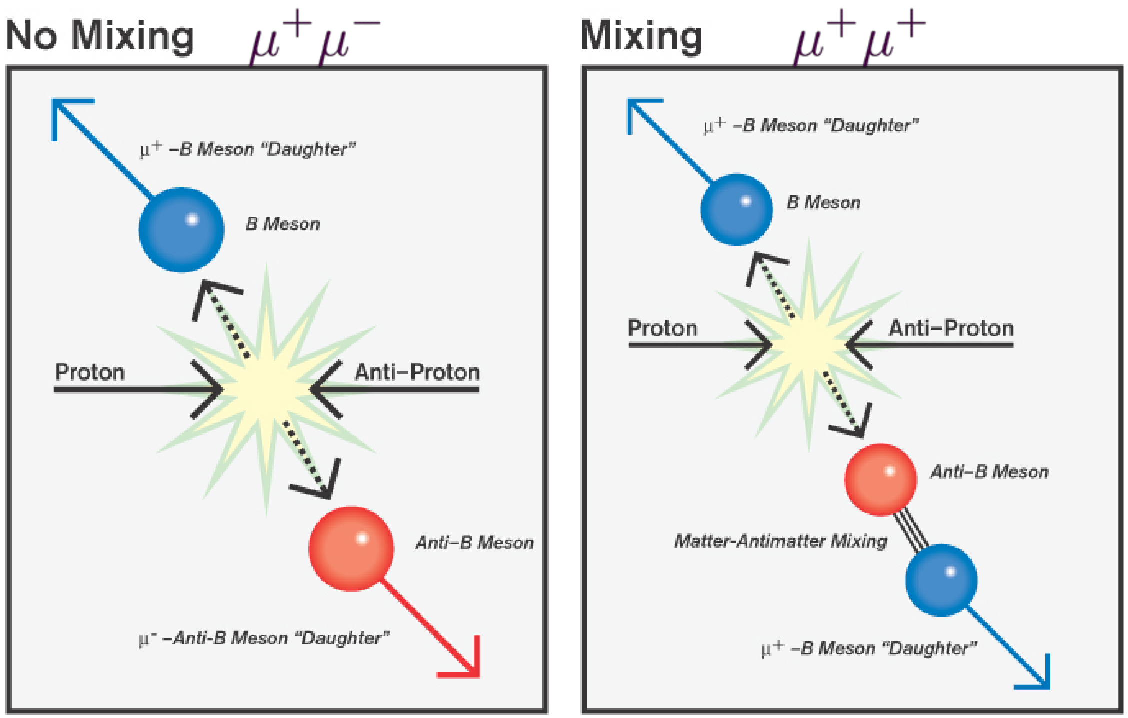


- Note a tiny mass splitting btw H/A (L=2):

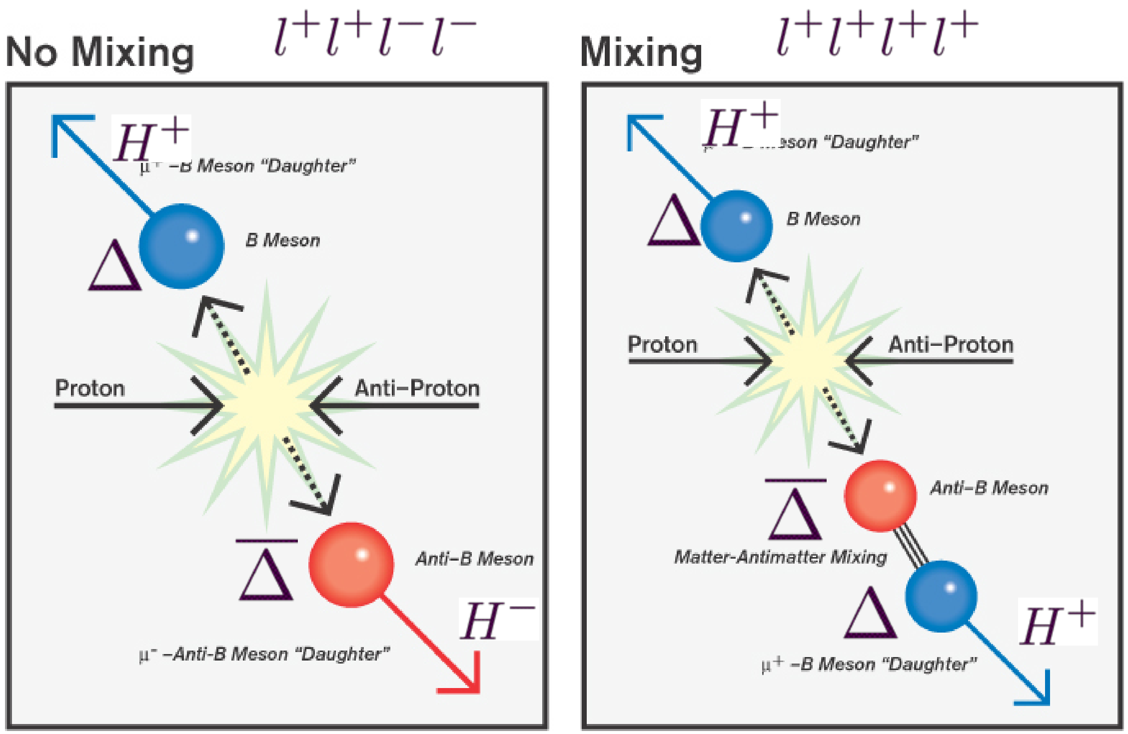
$$\mathcal{L}_{\Delta\!\!\!/} = -\mu v_\Phi h^0 H^0 \Rightarrow \boxed{\delta M_{HA} \approx 2M_{H^0}\frac{v_\Delta^2}{v_0^2}\frac{M_{H^0}^2}{M_{H^0}^2 - m_{h^0}^2}}$$

B-$\overline{\text{B}}$ Mixing





Δ-$\bar{\Delta}$ Mixing



Δ-$\overline{\Delta}$ Oscillation

- Initial Δ = H^0 + i A^0 evolves as

$$|\Delta(t)\rangle = g_+(t)|\Delta\rangle + g_-(t)|\overline{\Delta}\rangle \qquad [\Gamma = \Gamma_{H^0} = \Gamma_{A^0}]$$

$$g_\pm(t) = \frac{1}{2} e^{-\Gamma t/2} \left(e^{iM_{H^0} t} \pm e^{iM_{A^0} t} \right)$$

- Probabilities of Δ going to Δ or $\overline{\Delta}$ are

$$\chi_\pm \equiv \frac{\int_0^\infty dt |g_\pm(t)|^2}{\int_0^\infty dt |g_+(t)|^2 + \int_0^\infty dt |g_-(t)|^2}$$

$$\boxed{\chi_\pm = \begin{cases} \frac{2+x^2}{2(1+x^2)} \\ \frac{x^2}{2(1+x^2)} \end{cases}} \qquad \boxed{x \equiv \frac{\delta M}{\Gamma} = \frac{\tau_{dec}}{\tau_{osc}}}$$

Same-Sign Tetra-Leptons

- Lepton number violating processes:

$$
\begin{aligned}
pp \to \Delta^0\bar{\Delta}^0 \Rightarrow \Delta^0\Delta^0 \;&\to H^+H^+2W^- \;\to H^{++}H^{++}4W^- \\
\Delta^+\bar{\Delta}^0 \Rightarrow \Delta^+\Delta^0 &\to H^{++}H^+2W^- \to H^{++}H^{++}3W^-
\end{aligned}
$$

- Production cross-section:

$$
\begin{aligned}
\sigma\left(4\ell^\pm + 3W^{\mp^*}\right) &= \sigma\left(pp \to H^\pm H^0 + H^\pm A^0\right)\left[\frac{x_{HA}^2}{1+x_{HA}^2}\right]\mathrm{BF}(H^0/A^0 \to H^\pm W^{\mp^*}) \\
&\times \left[\mathrm{BF}(H^\pm \to H^{\pm\pm}W^{\mp^*})\right]^2\left[\mathrm{BF}(H^{\pm\pm} \to \ell^\pm\ell^\pm)\right]^2; \\
\sigma\left(4\ell^\pm + 4W^{\mp^*}\right) &= \sigma\left(pp \to H^0 A^0\right)\left[\frac{2+x_{HA}^2}{1+x_{HA}^2}\frac{x_{HA}^2}{1+x_{HA}^2}\right]\mathrm{BF}(H^0 \to H^\pm W^{\mp^*})\mathrm{BF}(A^0 \to H^\pm W^{\mp^*}) \\
&\times \left[\mathrm{BF}(H^\pm \to H^{\pm\pm}W^{\mp^*})\right]^2\left[\mathrm{BF}(H^{\pm\pm} \to \ell^\pm\ell^\pm)\right]^2.
\end{aligned}
$$

Same-Sign Tetra-Leptons

- Conditions for observable SS4L:

  i) H^{++} is the lightest and sizable σ·BR($H^{++} \rightarrow l^+ l^+$): larger f (smaller v_Δ) preferred.

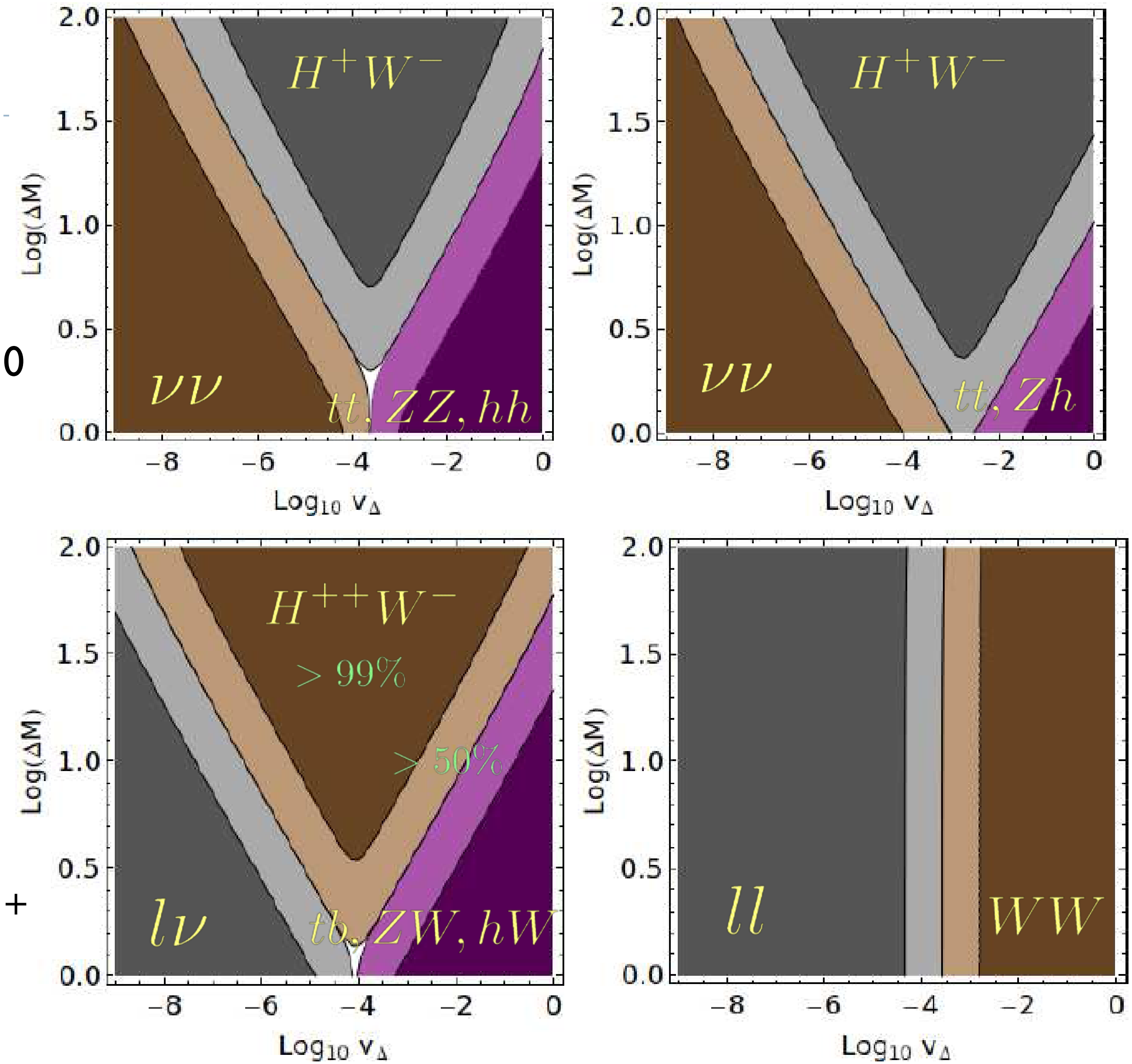
  ii) ΔM large enough to allow $\Delta^0 \rightarrow H^+ W^- \rightarrow H^{++} 2W^-$.

  iii) Sizable oscillation parameter: x ~ 1 prefers smaller ΔM

$$\delta M_{HA} \sim 2\frac{v_\Delta^2}{v_\Phi^2} M_{H^0} \qquad \Gamma_{H^0/A^0} \sim \frac{G_F^2 \Delta M^5}{\pi^3}$$

$$\boxed{v_\Delta \sim 10^{-4}\mathrm{GeV}, \quad \Delta M \sim 2\mathrm{GeV} \quad \Rightarrow \delta M_{HA} \sim \Gamma_{H^0/A^0} \sim 10^{-11}\mathrm{GeV}}$$

H^0 A^0

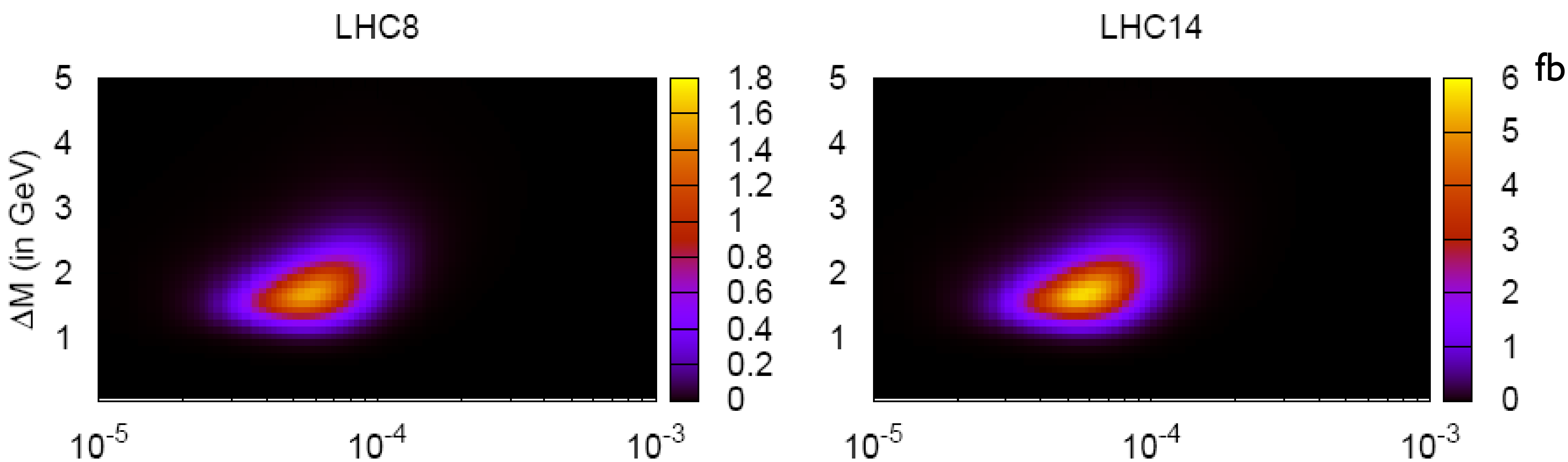


H$^+$ H^{++}

$M_{H^{++}} =$ 300GeV $< M_{H^+} < M_{H^0/A^0}$

SS4L cross-section

- SS4L production including the oscillation factor:



$$M_{H^{\pm\pm}} = 400\text{GeV}$$

- Benchmark point:

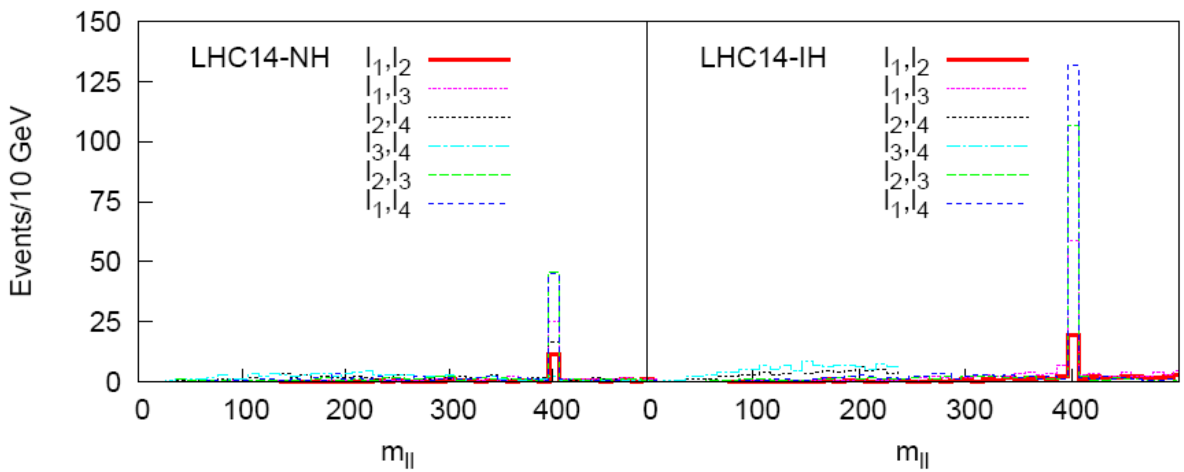
  v_Δ=7x10^{-5} GeV, ΔM=1.5 GeV.

Event numbers

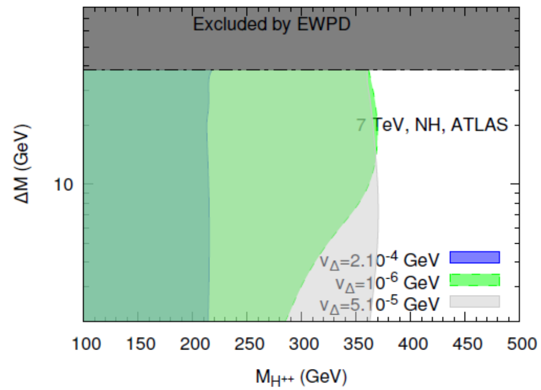
Final State	σ/fb (8 TeV)	σ/fb (14 TeV)
H^+H^0	0.761	2.931
H^+A^0	0.761	2.931
H^-H^0	0.275	1.209
H^-A^0	0.275	1.209
H^0A^0	1.014	4.322

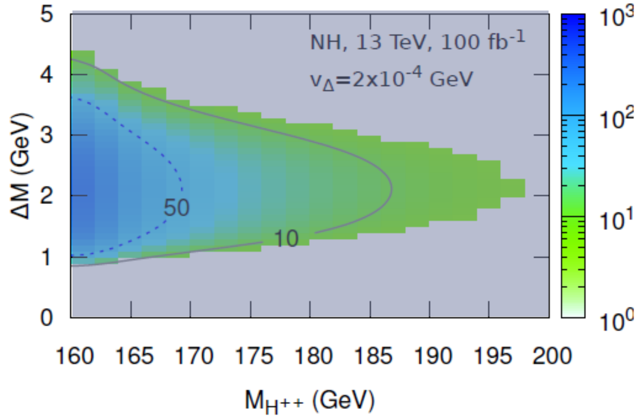
	Pre-selection	Selection	
$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC8-NH)	4	3	15/fb
$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC8-IH)	9	8	
$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC14-NH)	110	94	100/fb
$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC14-IH)	240	210	

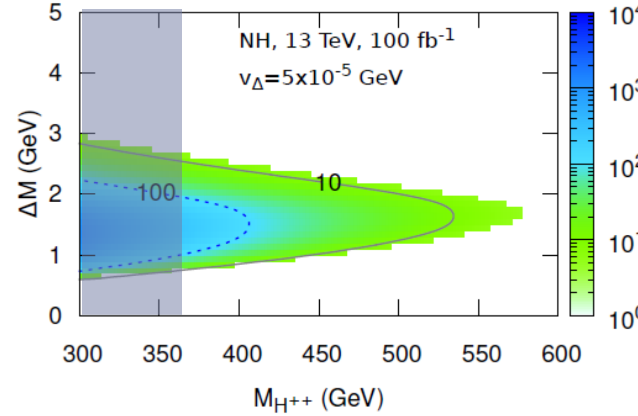
No background; Lepton selection cuts only

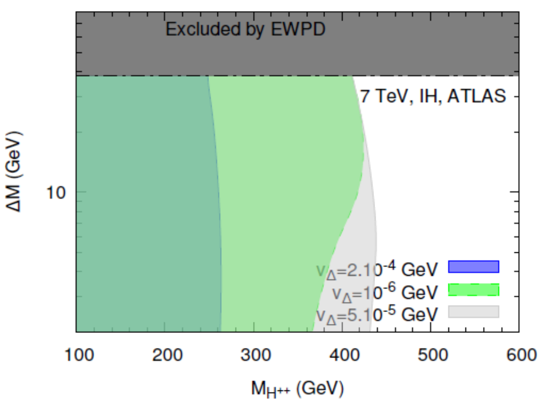


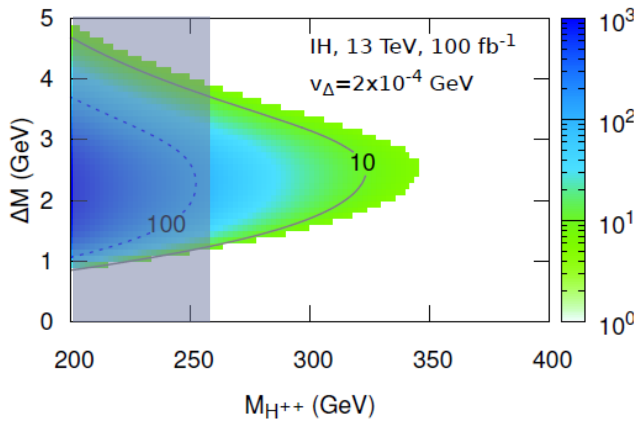
Extension to lower masses

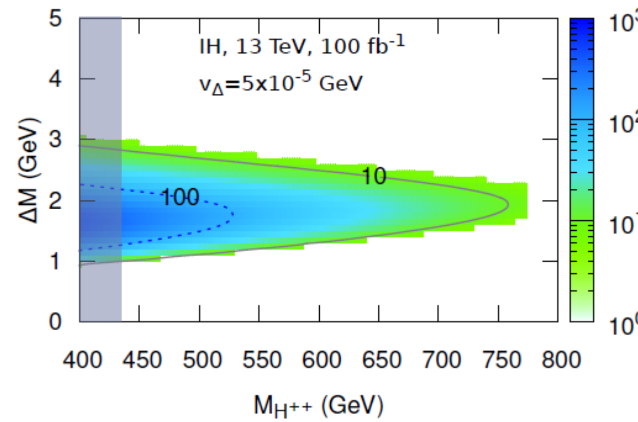












Conclusion

- A triplet boson may be responsible for the generation of neutrino masses through its VEV.
- Vacuum stability/perturbativity, EWPD, and Higgs-to-diphoton (for $m_{H^{++}}$ < 200 GeV) provide strong constraints on the scalar potential couplings requiring, e.g., $|\Delta M|$ < 40 GeV.
- Although limited, there could appear triplet-antitriplet oscillation in the neutral component leading to a novel signature of same-sign tetra-leptons .
- Its observation confirms the existence of a tiny triplet VEV and thus the type II seesaw mechanism at work.