LHC Phenomenology of Type II Seesaw

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Thank you for invitation!

Outline

- Introduction to type II seesaw

  Triplet boson spectrum and decay channels

EJC, Lee, Park, 0304069

- LHC search

  Doubly charged boson production and decay

  CMS result

- Same-sign tetra-leptons

  Triplet-antitriplet oscillation

EJC & Sharma, 1206.6278

- EBH boson Phenomenology

  EWPD

  Perturbativity & vacuum stability

  Diphoton rate

EJC, Lee & Sharma, 1209.1303

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)" :

Type II Seesaw

- 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):

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

- Triplet VEV generates neutrino mass matrix:

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

$$m^\nu_{\alpha\beta} = f_{\alpha\beta} v_\Delta \;\Rightarrow\; f_{\alpha\beta}\frac{v_\Delta}{v_\Phi} \sim 10^{-12}$$

- Collider can tell the neutrino mass pattern:
  Measure $\mathrm{BR}(\Delta^{++} \xrightarrow{f_{\alpha\beta}} l^+_\alpha l^+_\beta)$!

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

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

Scalar mixing

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

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

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

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

- We will work in the limit of $\xi << 0.01$.
- (note) ρ parameter constraint:

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

Scalar spectrum

- Mass gap among triplet components:

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

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

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

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

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

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

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

Triplet boson decay channels

- Two mass hierarchies:

EJC, Lee, Park, 0304069

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

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

- Gauge decays if ΔM (λ_5) large enough:

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

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

⇐ $\Delta M(\lambda_5)$

Triplet decay channels

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

$$H^{++} \to l_\alpha^+ l_\beta^+$$

$$H^+ \to l_\alpha^+ \nu_\beta \qquad \Longleftarrow \quad f_{\alpha\beta}$$

$$H^0/A^0 \to \nu_\alpha \nu_\beta$$

$$\boxed{\begin{aligned} f\xi &\sim 10^{-12} \\ \Rightarrow f \sim \xi &\sim 10^{-6} \end{aligned}}$$

- Di-quark/di-boson decays through ξ:

$$H^{++} \to W^+ W^+$$

$$\begin{aligned} H^+ &\to t\bar{b} \\ &\to ZW, hW \end{aligned} \qquad \Longleftarrow \quad \xi \equiv v_\Delta / v_\Phi$$

$$\begin{aligned} H^0/A^0 &\to t\bar{t},\ b\bar{b} \\ &\to ZZ, hh/Zh \end{aligned}$$

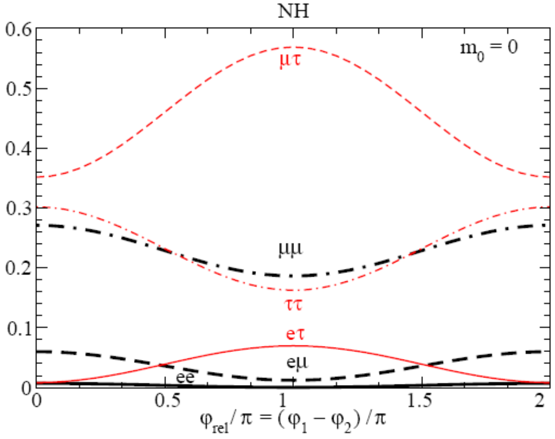
Best search channel: SSD from H^{++}

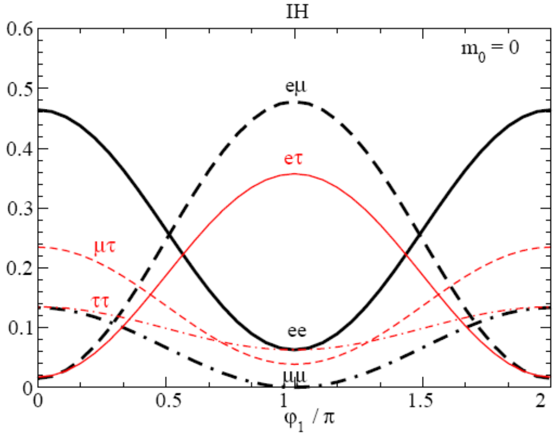
- Measure BR($H^{++} \rightarrow l^+ l^+$) to determine the neutrino mass pattern: e.g.) NH vs. IH

EJC, Lee, Park, 0304069
Garagoya, Schwetz, 0712.1453
Kadastik, Raidal, Lebane, 0712.3912
Akeroyd, Aoki, Sugiyama, 0712.4019
Perez, et.al., 0805.3536

$$\begin{aligned}
&\mathrm{BR}(ee):\mathrm{BR}(e\mu):\mathrm{BR}(\mu\mu) = \\
&4r\sin^4\theta_{12} : r\sin^2 2\theta_{12} : 1 \ (\mathrm{NH}); \\
&4 : \tfrac{r^2}{4}\sin^2 2\theta_{12} : 1 \ (\mathrm{IH1}); \\
&4 : 4\tan^2 2\theta_{12} : 1 \ (\mathrm{IH2})
\end{aligned}$$

$$r \equiv \frac{\Delta m^2_{\mathrm{sol}}}{\Delta m^2_{\mathrm{atm}}} \sim 0.03$$





Lepton Yukawas of the Triplet

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

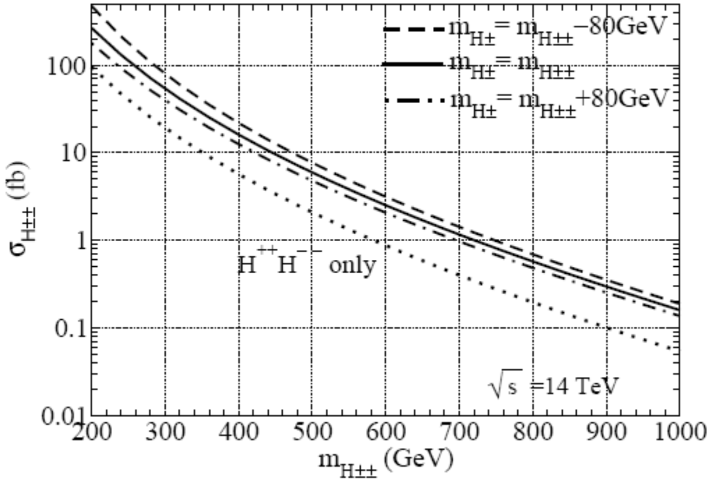
NH IH

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

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

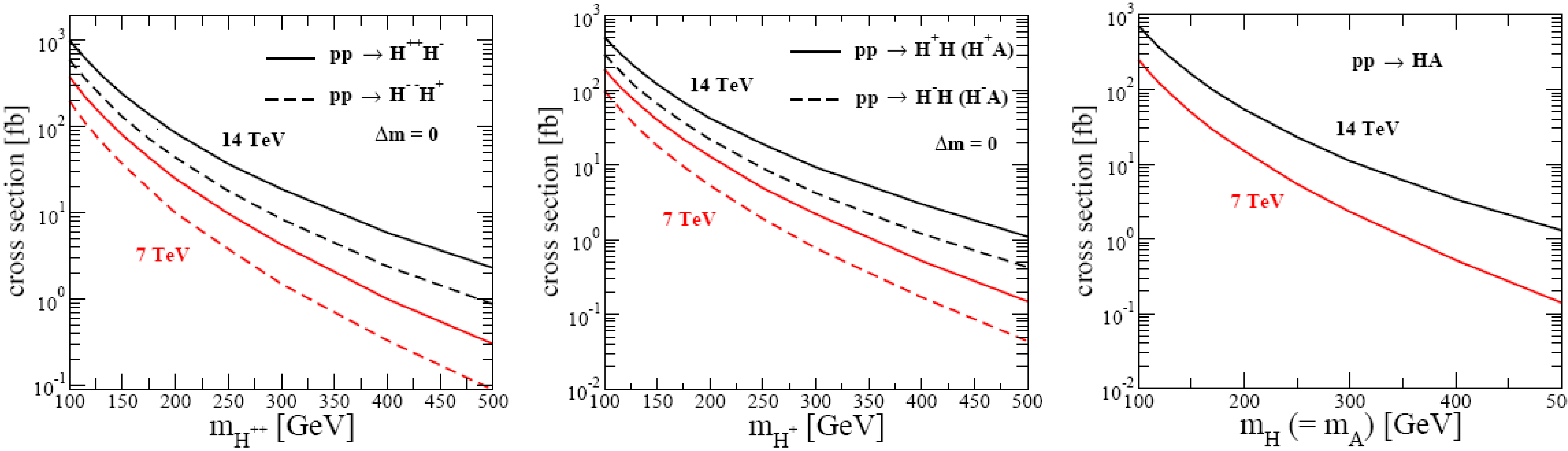
Br (%)	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
NH	0.62	5.11	0.51	26.8	35.6	31.4
IH1	47.1	1.27	1.35	11.7	23.7	14.9

Production at LHC



Akeroyd, Aoki, 0506176

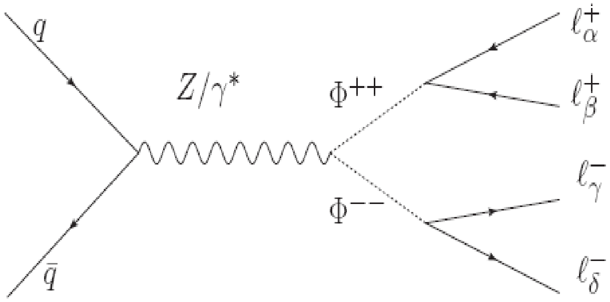
Aoki, Kanemura, Yagyu, 1110.4625

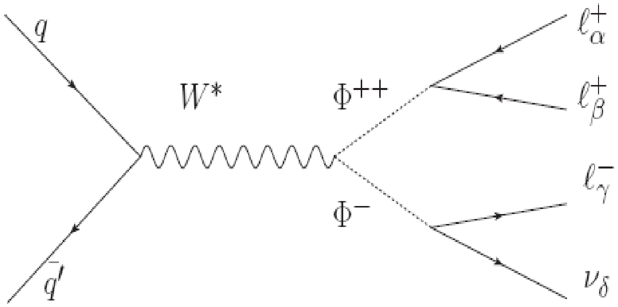


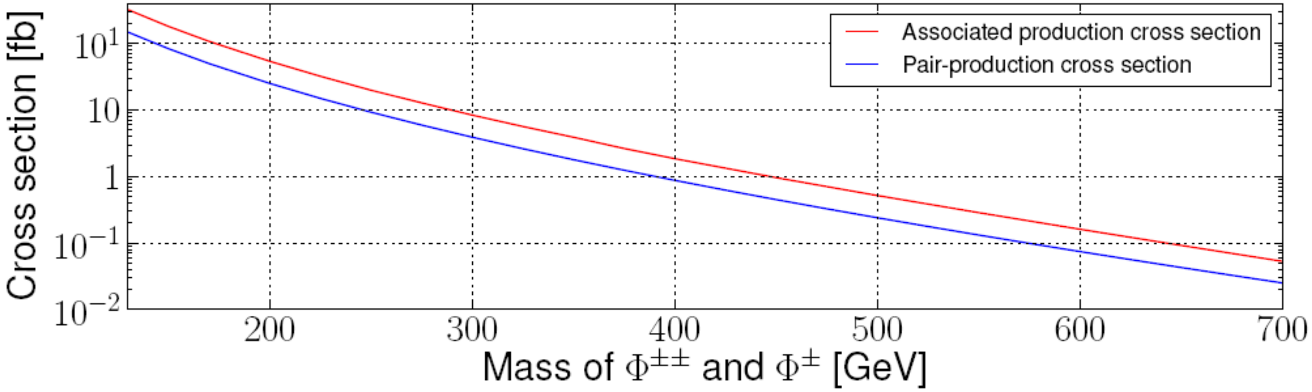
LHC search

CMS, 1207.2666
ATLAS, 1210.5070

- CMS looks for $pp \to H^{++} H^{-} \to l^{+} l^{+} l^{-} \nu$
  & $pp \to H^{++} H^{--} \to l^{+} l^{+} l^{-} l^{-}$.
- Assumption of 100% leptonic decay & $\Delta M=0$.

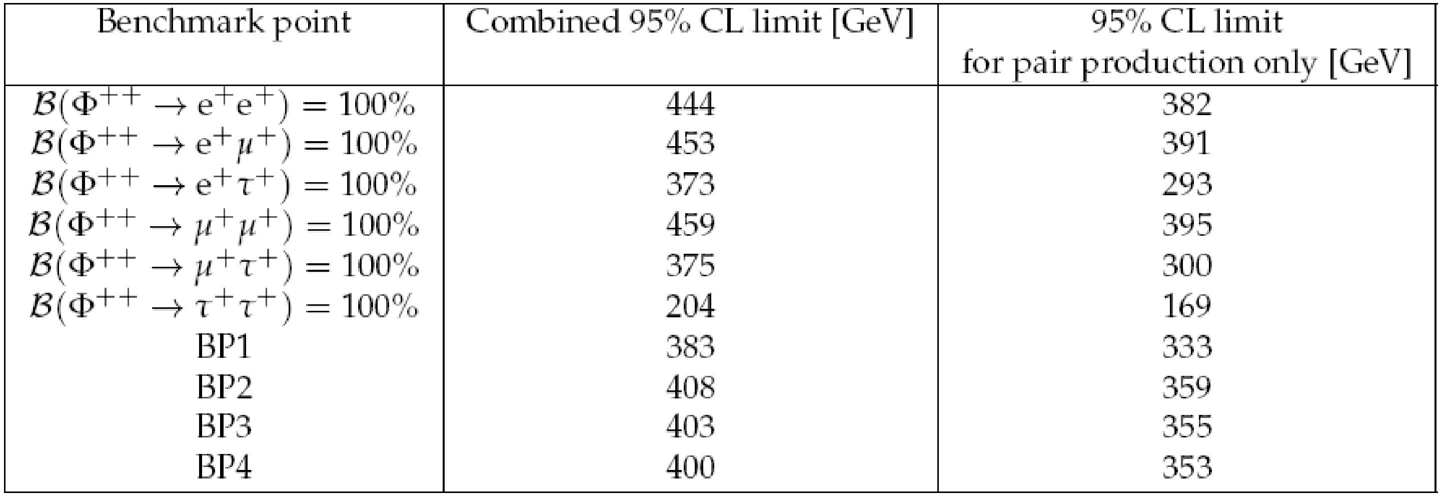




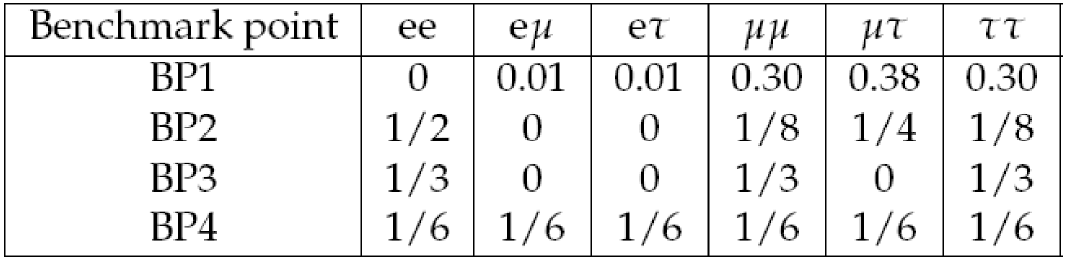


LHC7 limit

- $H^{++} H^{-} \rightarrow l^{+} l^{+} l^{-} \nu$ & $H^{++} H^{--} \rightarrow l^{+} l^{+} l^{-} l^{-}$

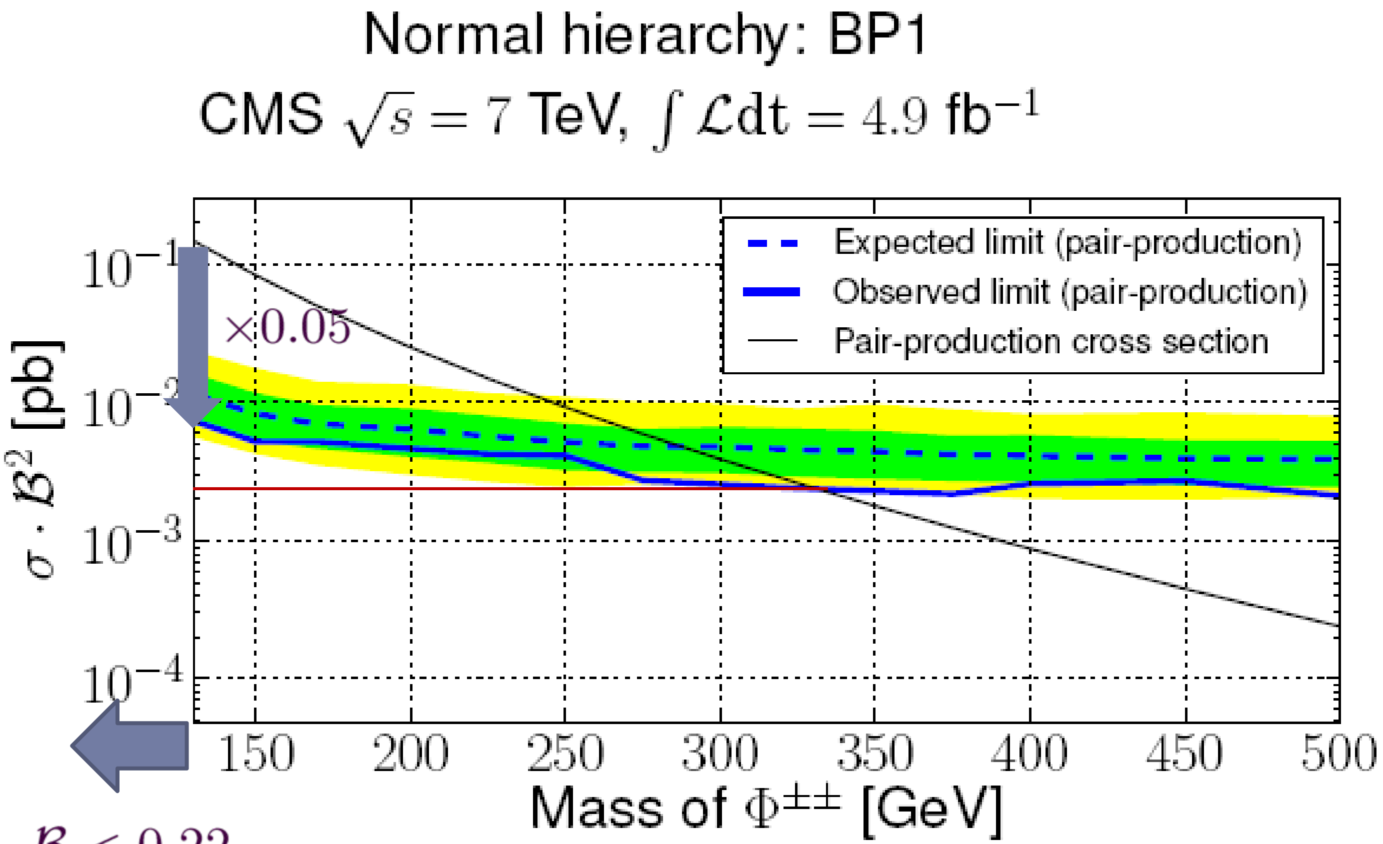


Benchmark point	Combined 95% CL limit [GeV]	95% CL limit for pair production only [GeV]
$\mathcal{B}(\Phi^{++} \rightarrow e^{+}e^{+}) = 100\%$	444	382
$\mathcal{B}(\Phi^{++} \rightarrow e^{+}\mu^{+}) = 100\%$	453	391
$\mathcal{B}(\Phi^{++} \rightarrow e^{+}\tau^{+}) = 100\%$	373	293
$\mathcal{B}(\Phi^{++}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



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

LHC7 limit



Normal hierarchy: BP1

CMS $\sqrt{s} = 7$ TeV, $\int \mathcal{L}dt = 4.9$ fb^{-1}

$\mathcal{B} < 0.22$

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

Search for other channels?

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

  $H^{++} \rightarrow W^+W^+$; $H^+ \rightarrow W^+Z$, tb ; $H^0/A^0 \rightarrow ZZ$, hh/Zh, tt
- Missing triplet if $\lambda_5<0$ and f >> ξ :

  $H^{++} \rightarrow H^+ W^* \rightarrow H^0/A^0 W^* W^* \rightarrow \nu\nu W^* W^*$.
- **No mass limit yet** in these two cases.

Triplet–antitriplet mixing

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

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

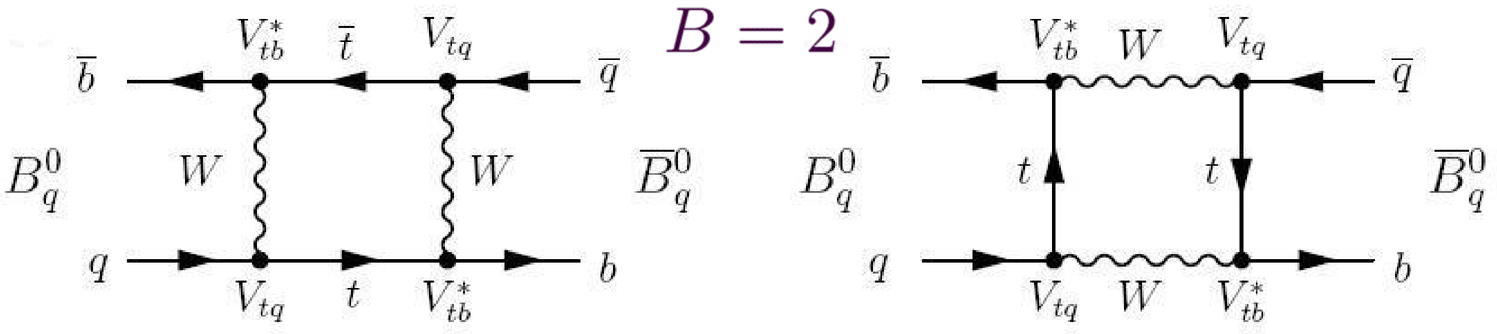
- Triplet number breaking by doublet-triplet mixing:

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

- It induces a tiny mass splitting:

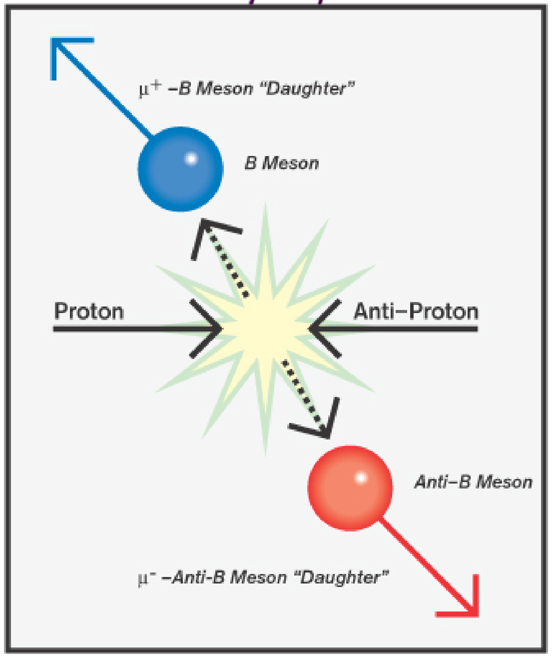
$$\mathcal{L}_{\not{\Delta}} = -\mu v_\Phi h^0 H^0 \Rightarrow \boxed{\delta M_{HA} \approx 2M_{H^0}\frac{v_\Delta^2}{v_0^2}\frac{M_{H^0}^2}{M_{H^0}^2 - m_{h^0}^2}}$$

B-B̄ Mixing

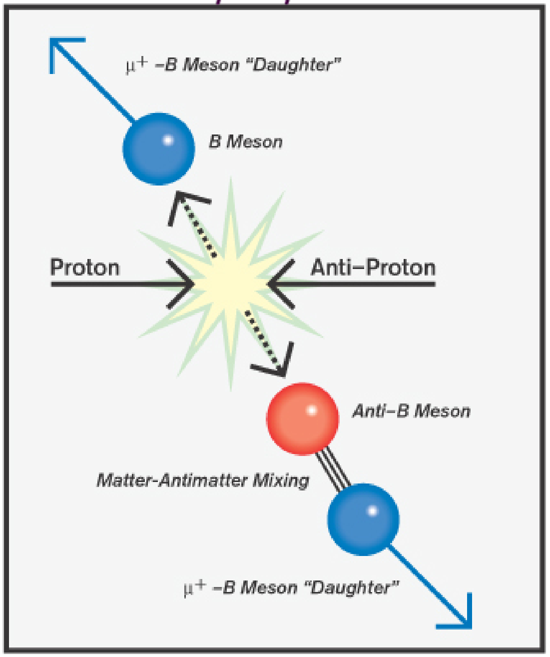


$B = 2$

No Mixing $\mu^+\mu^-$



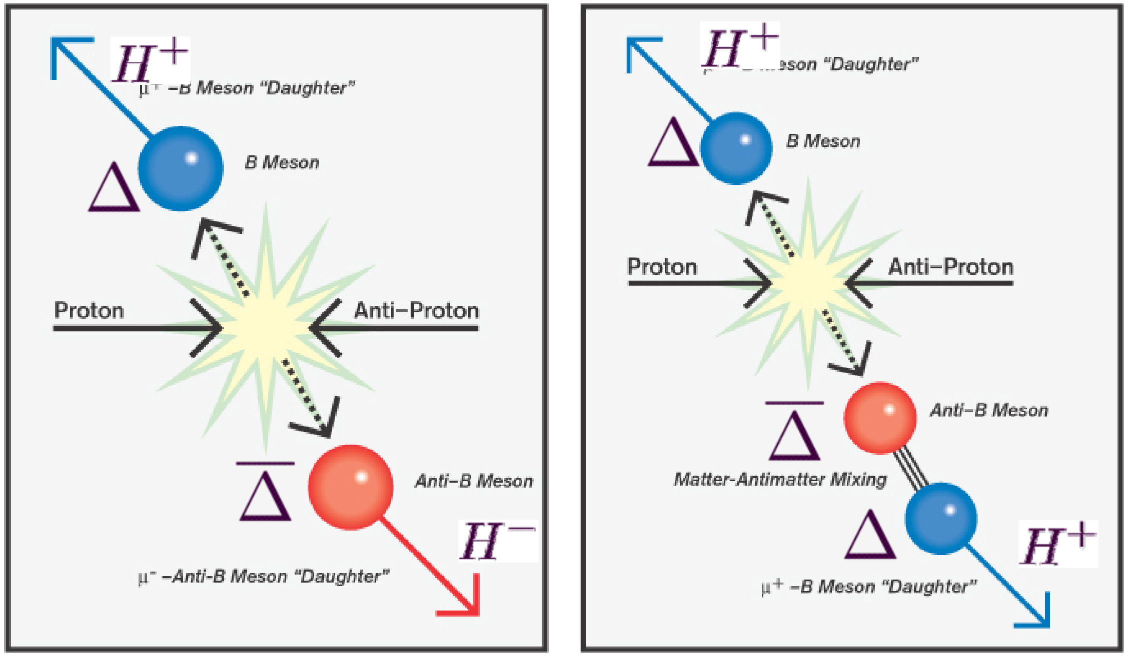
Mixing $\mu^+\mu^+$



Δ-$\bar{\Delta}$ Mixing

No Mixing $l^+l^+l^-l^-$

Mixing $l^+l^+l^+l^+$



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

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

$$\boxed{\chi_\pm = \begin{cases} \frac{2+x^2}{2(1+x^2)} \\ \frac{x^2}{2(1+x^2)} \end{cases}}$$

$$\boxed{x \equiv \frac{\delta M}{\Gamma} = \frac{\tau_{dec}}{\tau_{osc}}}$$

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

- Is this observable?

  i) H^{++} is the lightest and $f_{\alpha\beta} > \xi$.

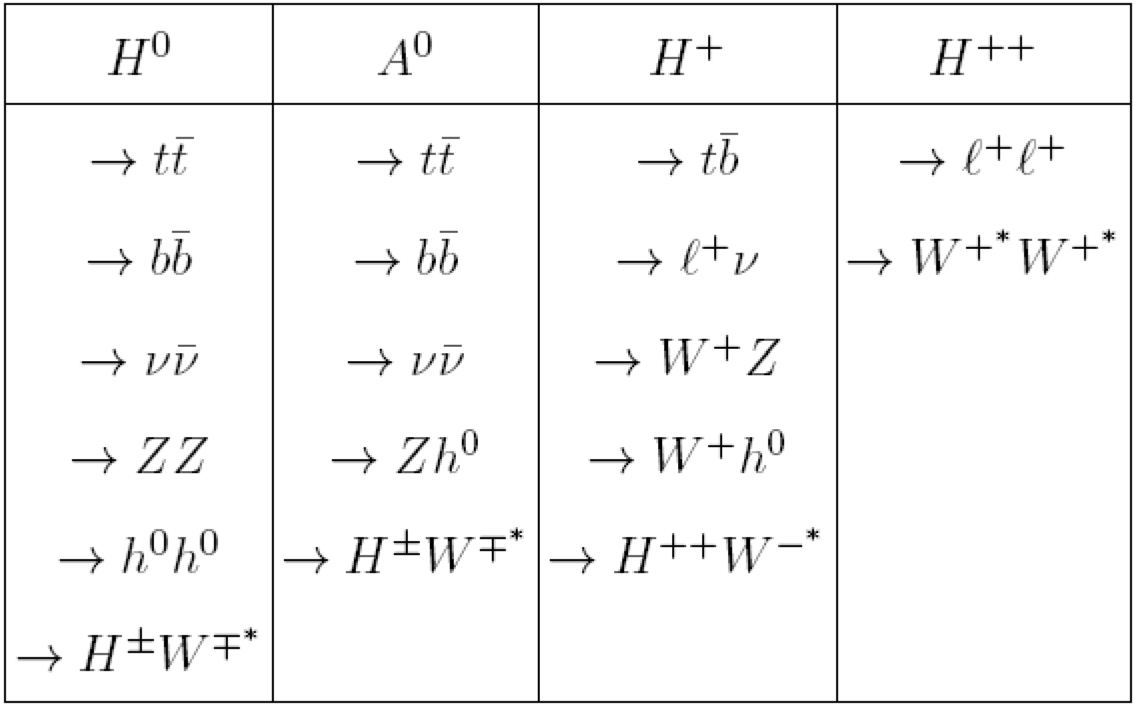
  ii) ΔM sufficiently large to allow $\Delta^0 \to H^+ W^- \to H^{++} 2W^-$.

  iii) Sizable oscillation parameter: x~1.

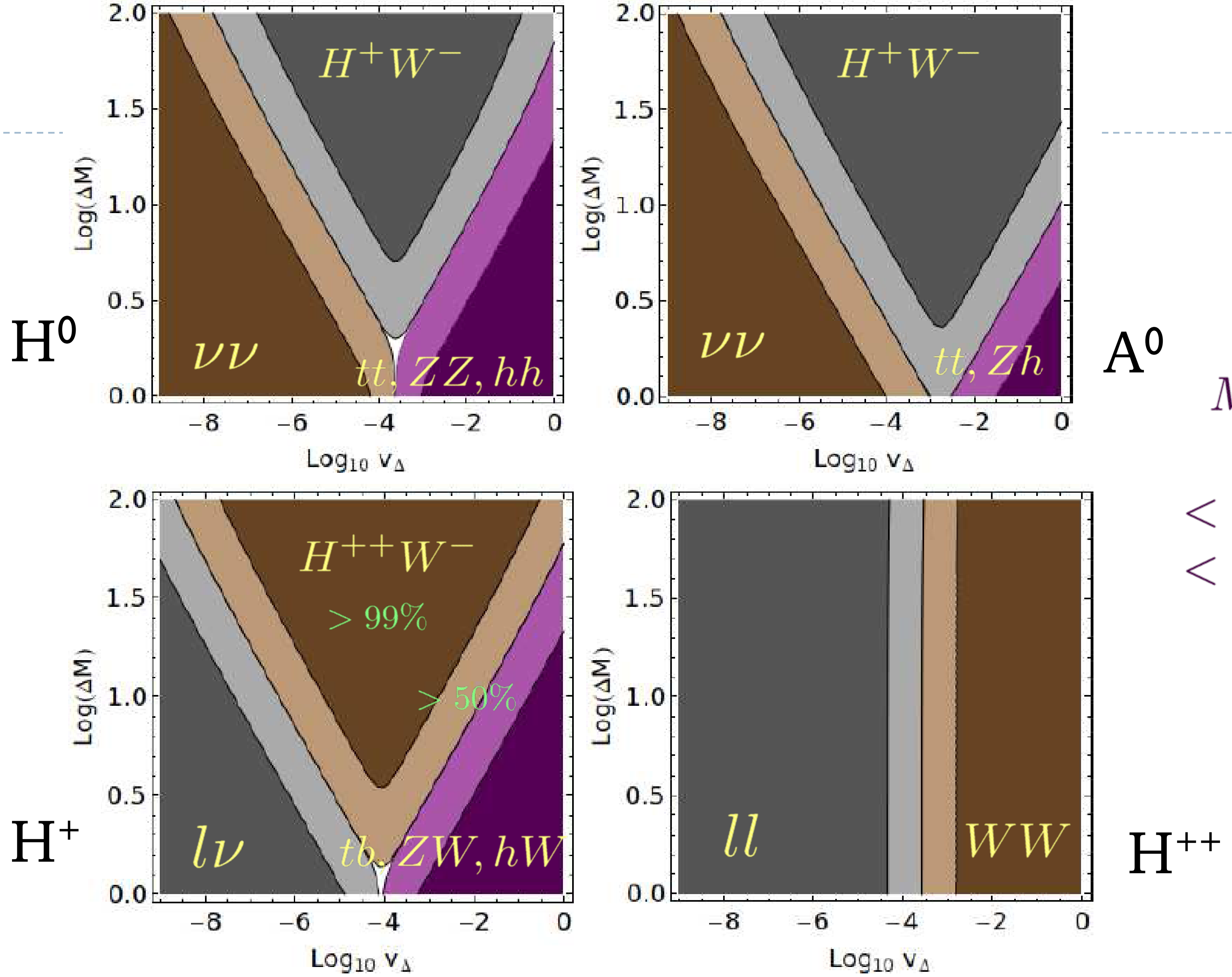
$$\delta M_{HA} \sim 2 \frac{v_\Delta^2}{v_\Phi^2} M_{H^0} \qquad \Gamma_{H^0/A^0} \sim \frac{G_F^2 \Delta M^5}{\pi^3}$$

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

Triplet decay channels

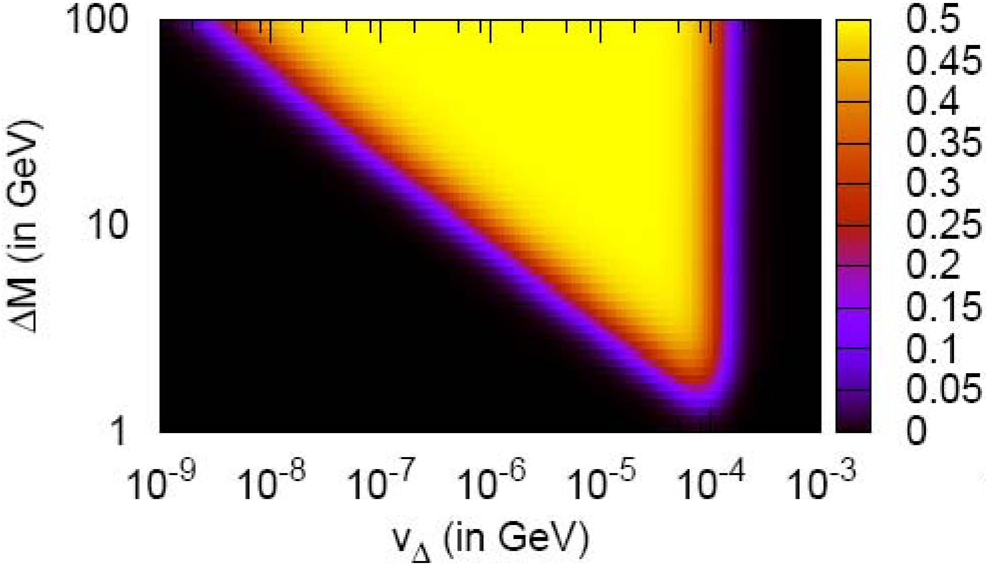


H^0	A^0	H^+	H^{++}
$\to t\bar{t}$	$\to t\bar{t}$	$\to t\bar{b}$	$\to \ell^+\ell^+$
$\to b\bar{b}$	$\to b\bar{b}$	$\to \ell^+\nu$	$\to W^{+^*}W^{+^*}$
$\to \nu\bar{\nu}$	$\to \nu\bar{\nu}$	$\to W^+Z$	
$\to ZZ$	$\to Zh^0$	$\to W^+h^0$	
$\to h^0h^0$	$\to H^\pm W^{\mp^*}$	$\to H^{++}W^{-^*}$	
$\to H^\pm W^{\mp^*}$			

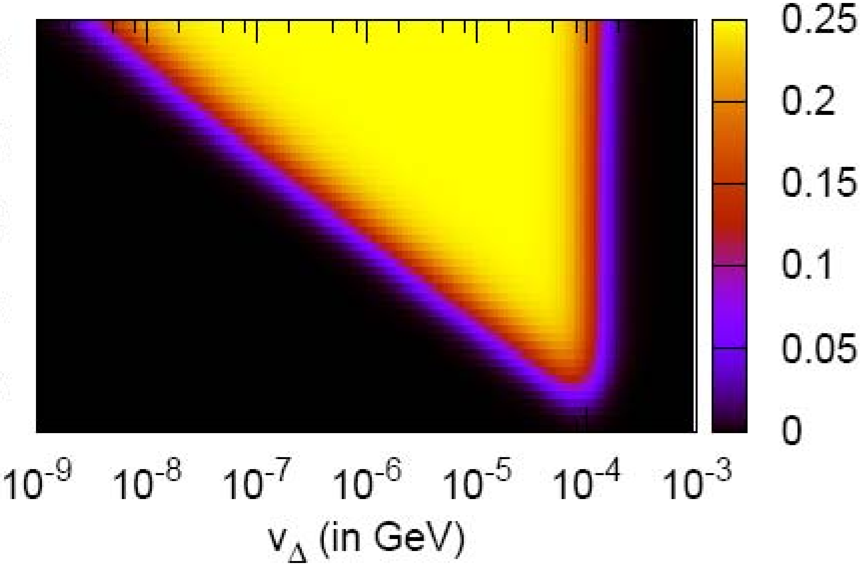


$M_{H^{++}} =$
300GeV
$< M_{H^+}$
$< M_{H^0/A^0}$

Maximizing the branching fraction



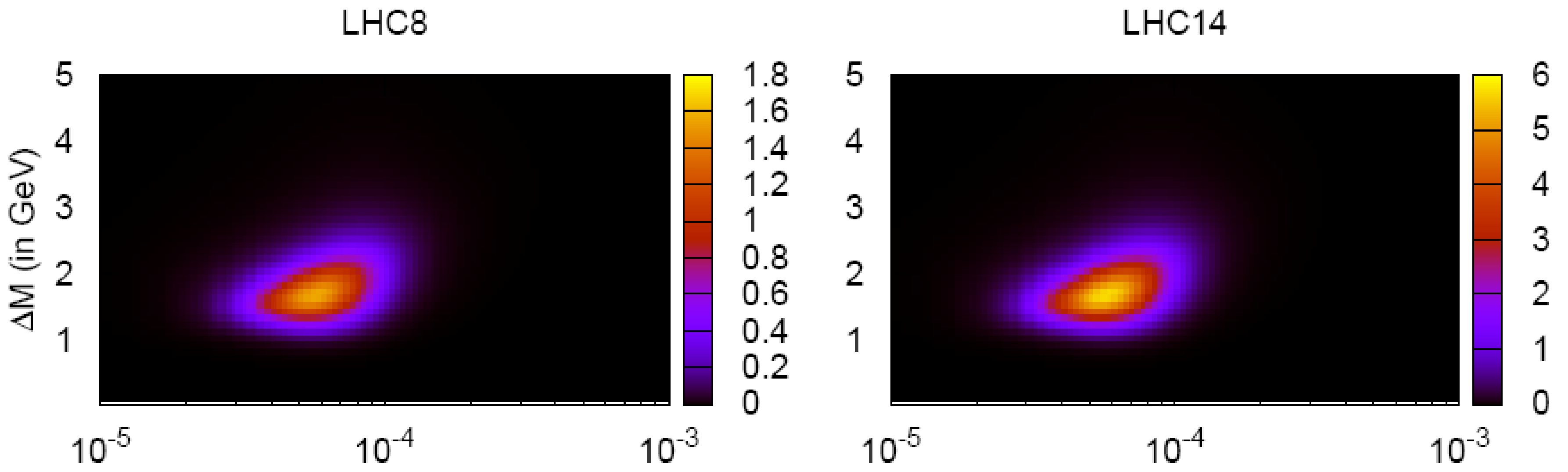
for $4l + 3W^*$



for $4l + 4W^*$

SS4L cross-section

- SS4L production including the oscillation factor:

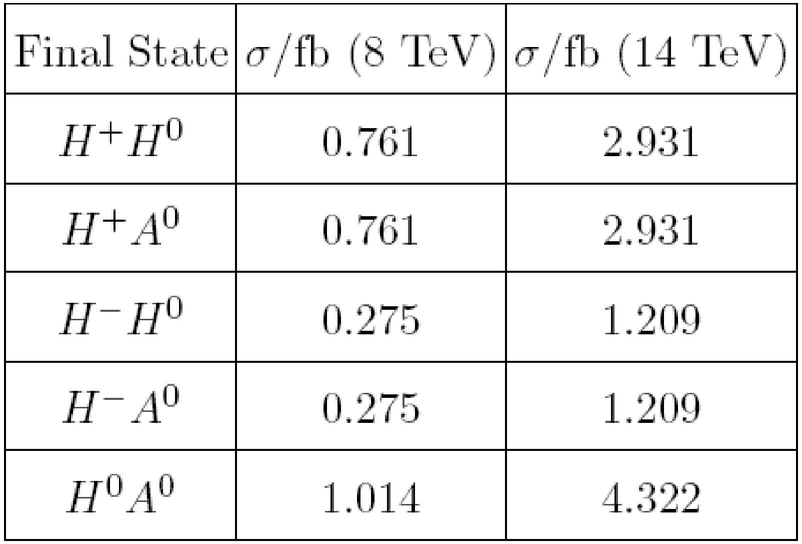


$$M_{H^{\pm\pm}} = 400\text{GeV}$$

- Benchmark point:

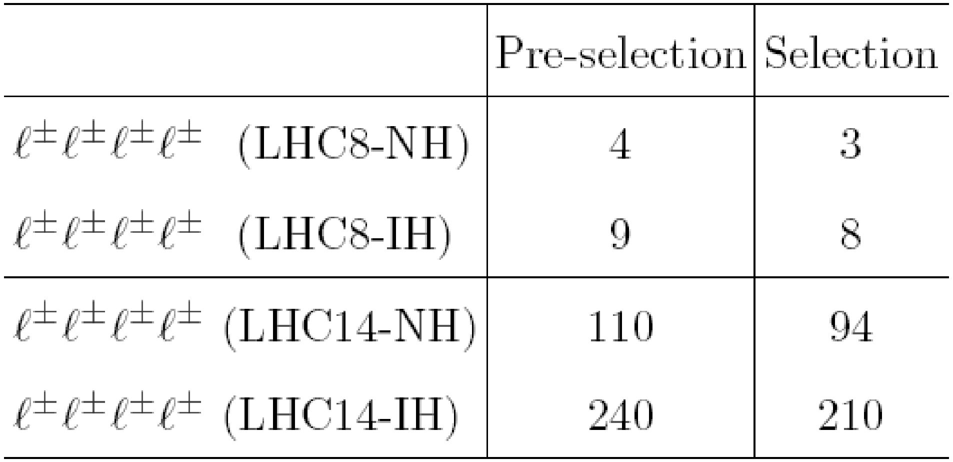
  $v_\Delta = 7\text{x}10^{-5}$ GeV, ΔM=1.5 GeV.

Event numbers



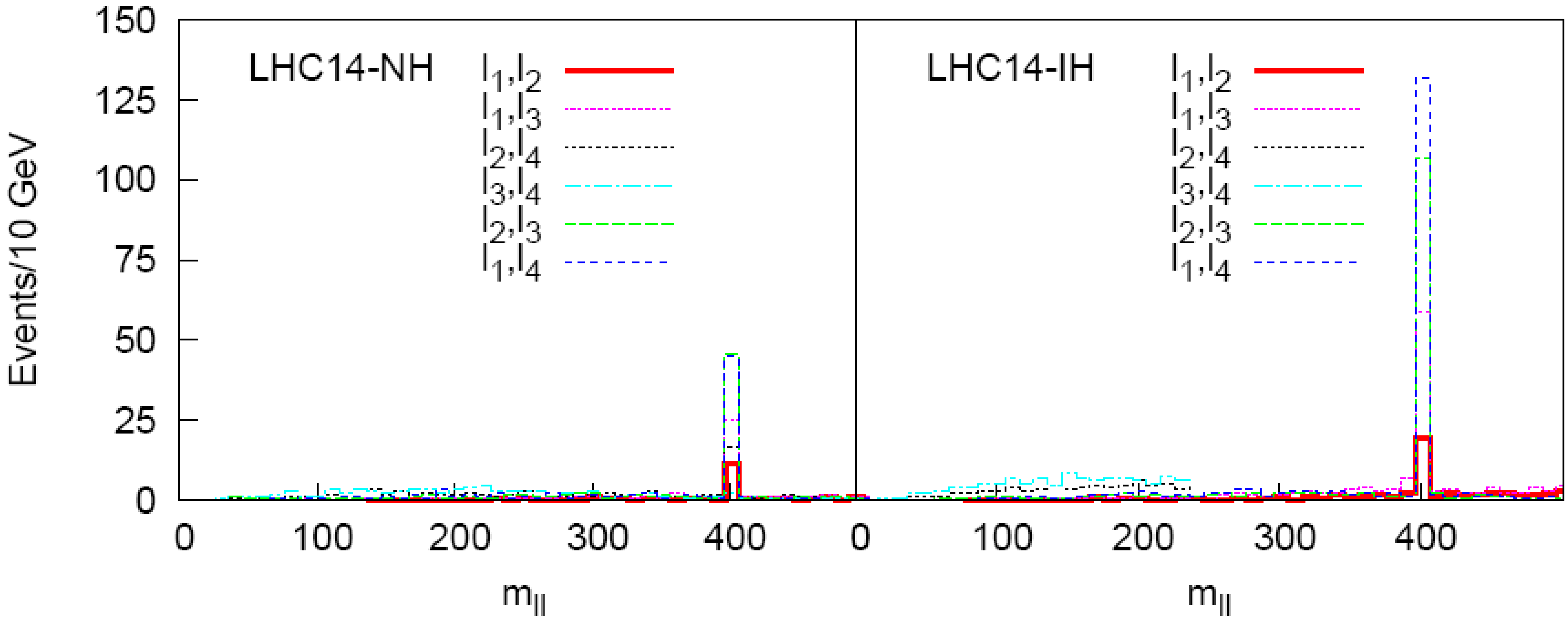
Final State	σ/fb (8 TeV)	σ/fb (14 TeV)
H^+H^0	0.761	2.931
H^+A^0	0.761	2.931
H^-H^0	0.275	1.209
H^-A^0	0.275	1.209
H^0A^0	1.014	4.322

No background
Lepton selection cuts only



		Pre-selection	Selection
$15fb^{-1}$	$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC8-NH)	4	3
	$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC8-IH)	9	8
$100fb^{-1}$	$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC14-NH)	110	94
	$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC14-IH)	240	210

Mass reconstruction

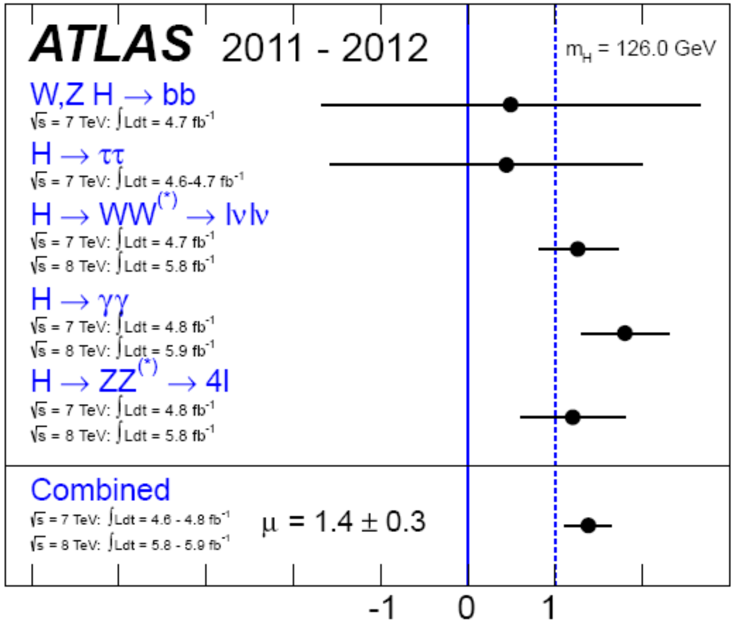


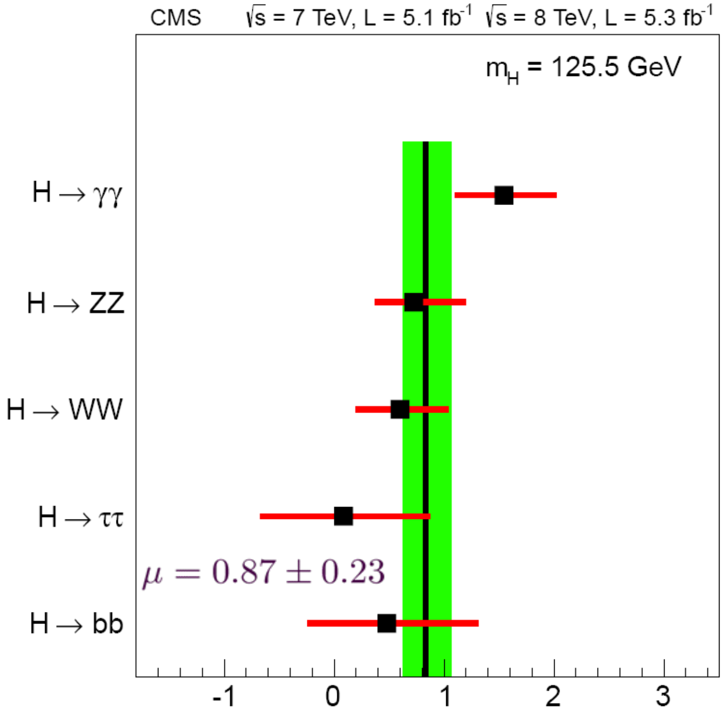
Conclusion I

- Type II seesaw may show a novel signature of same-sign tetra-leptons due to the mixing between two neutral (triplet) bosons.
- LHC14 with 100/bf could see more than 10 such signals for the triplet Higgs boson lighter than 600-700 GeV.
- The tiny VEV and mass gaps of the triplet may be measured through the oscillation phenomena.

SM boson-to-diphoton

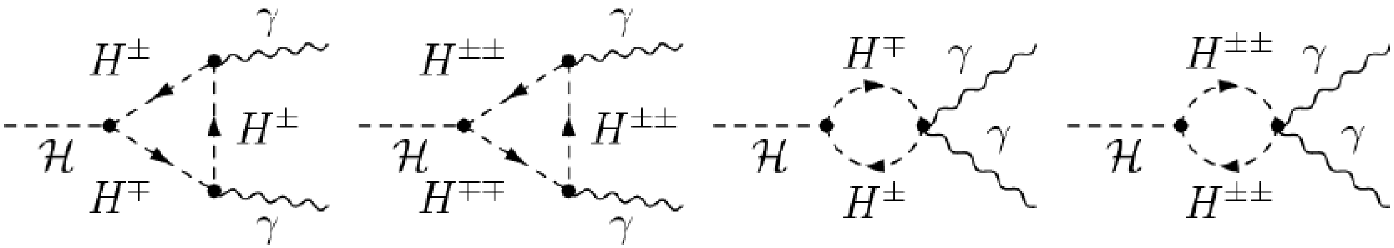
- 1-loop process – sensitive to New Physics.
- A large deviation in the current data.
- Its precision data is important to constrain NP.





SM boson-to-diphoton

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



$$\Gamma(h \to \gamma\gamma) = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \Bigg| \sum_f N_c Q_f^2\, g^h_{ff} A^h_{1/2}(x_f) + g^h_{WW} A^h_1(x_W)$$

$$+ g^h_{H^+H^-} A^h_0(x_{H^+}) + 4 g^h_{H^{++}H^{--}} A^h_0(x_{H^{++}}) \Bigg|^2$$

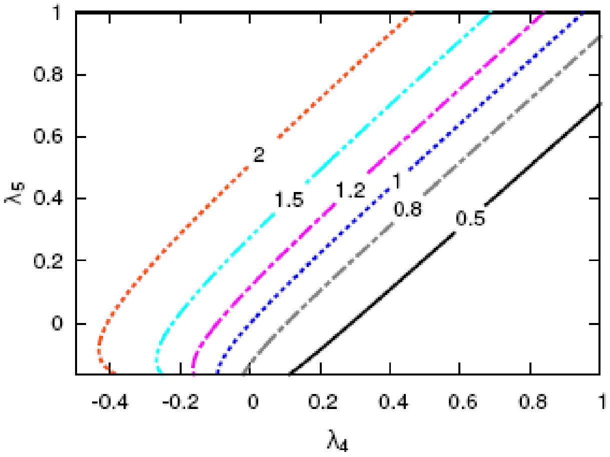
- $g^h_{H^+H^+} = \frac{\lambda_4}{2} \frac{v_0^2}{M^2_{H^+}},$
- $g^h_{H^{++}H^{++}} = \frac{\lambda_4 - \lambda_5}{2} \frac{v_0^2}{M^2_{H^{++}}},$

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

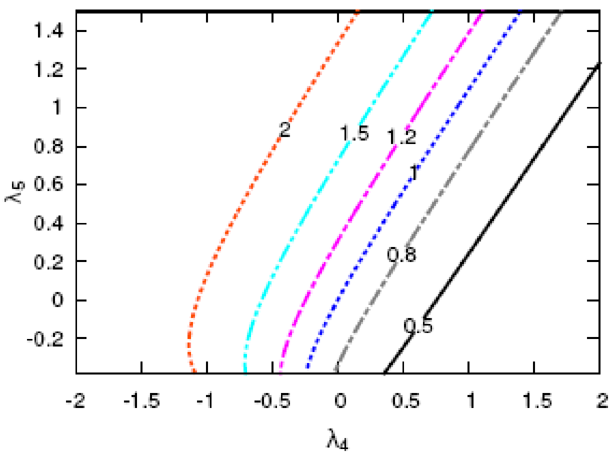
SM boson-to-diphoton

- 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.

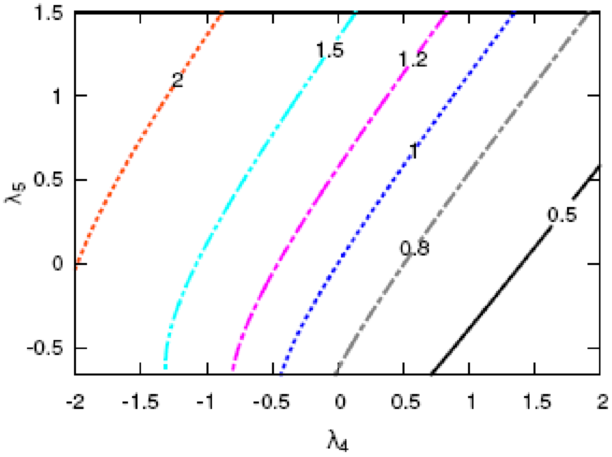
$$R_{\gamma\gamma} = \Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\rm SM}$$



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



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



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

Vacuum stability & perturbativity

- Scalar 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 boson 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

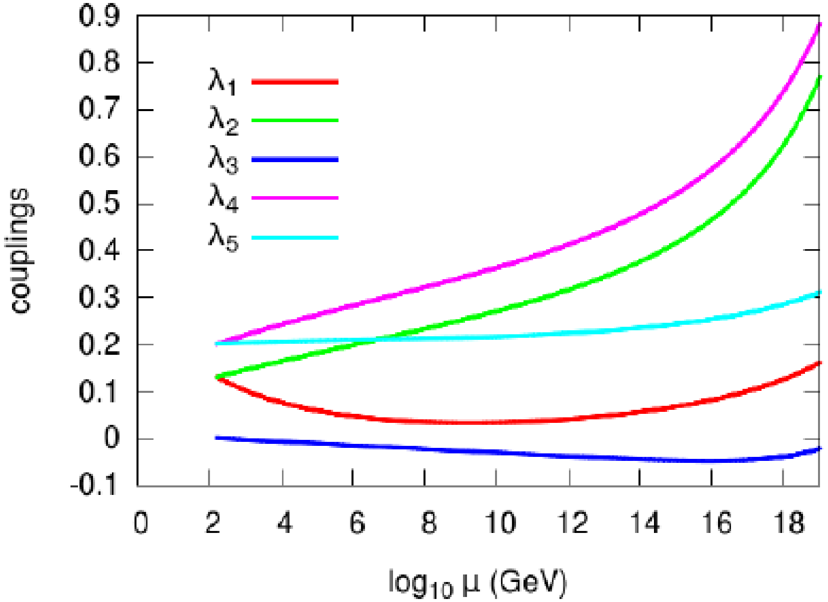
- Use 1-loop RGE:

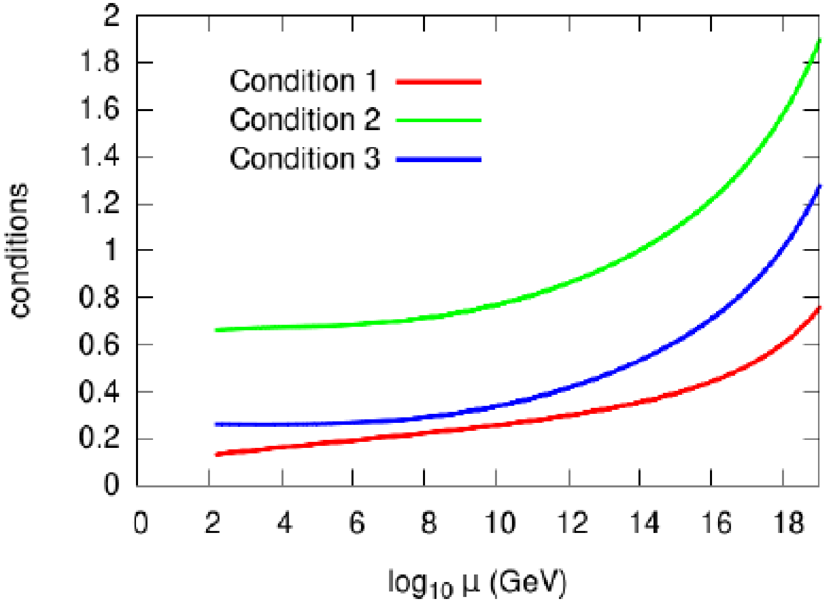
Chao, Zhang, 0611323
Schmidt, 07053841

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

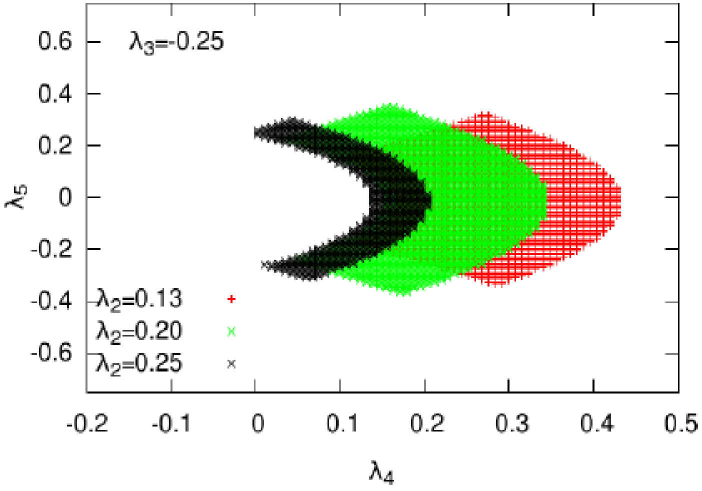
RGE running

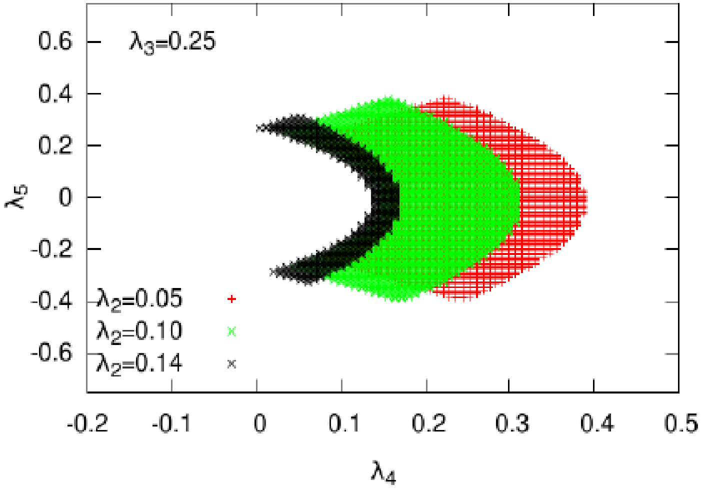
- An example

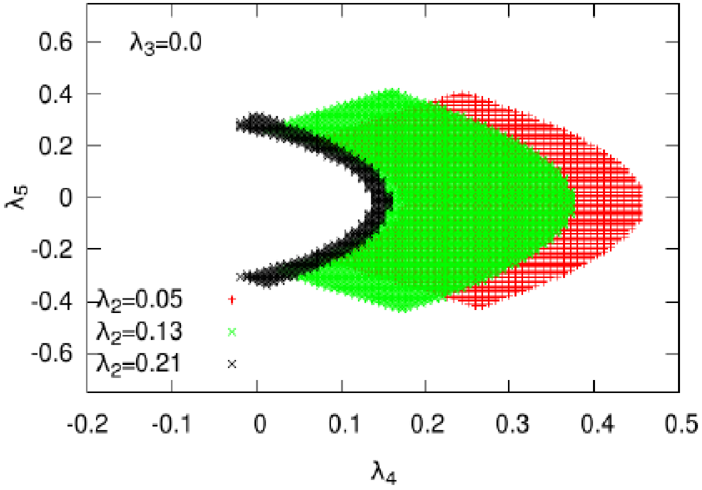




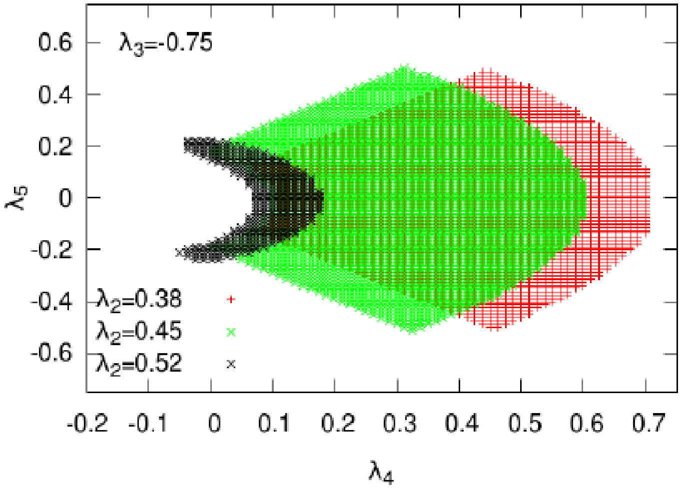
Cut-off scale 10^{19} GeV

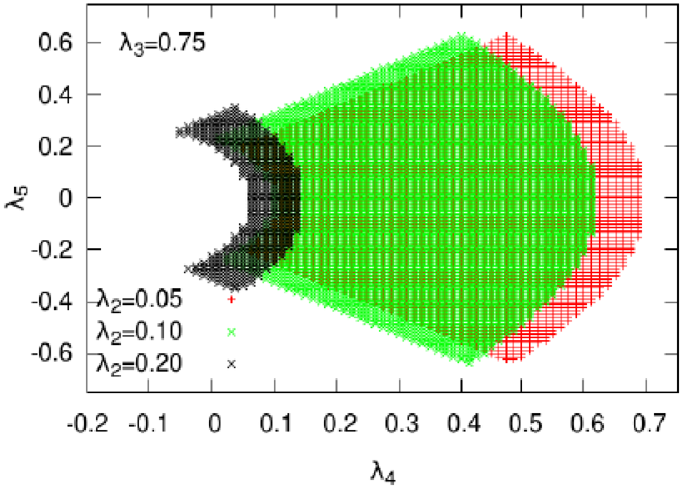


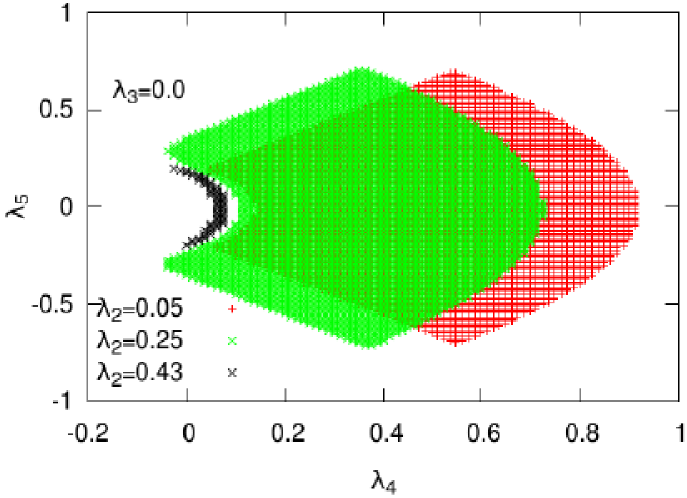




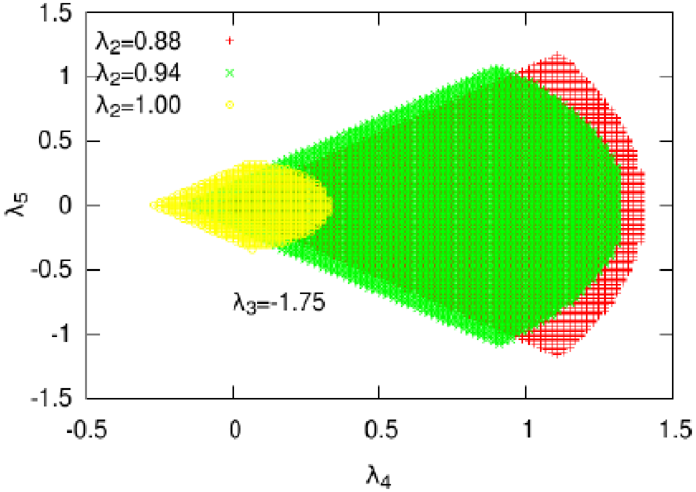
Cut-off scale 10^{10} GeV

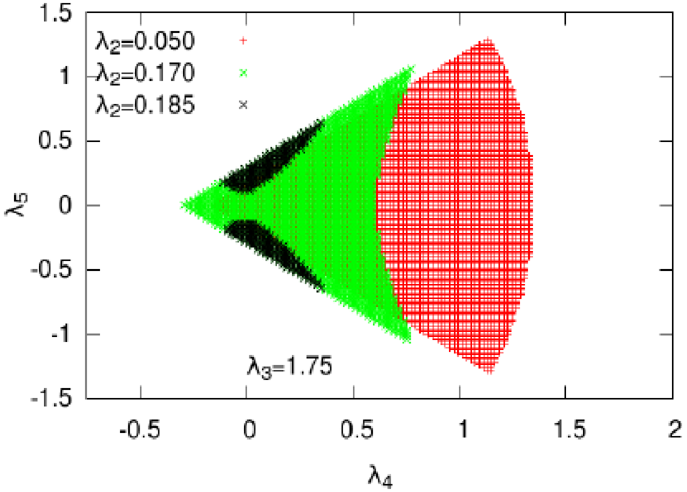


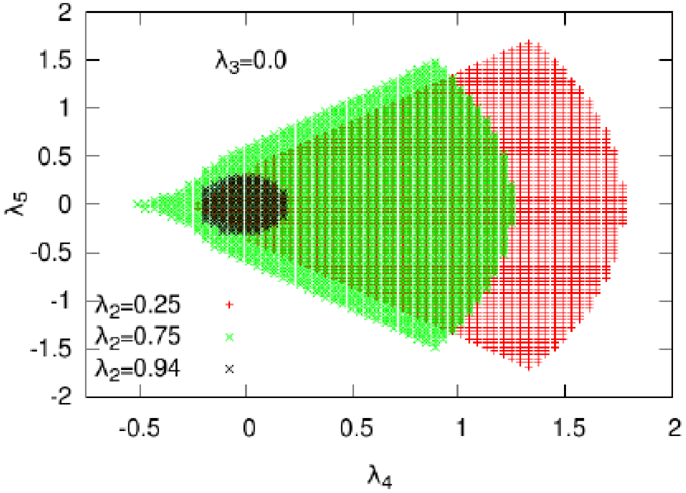




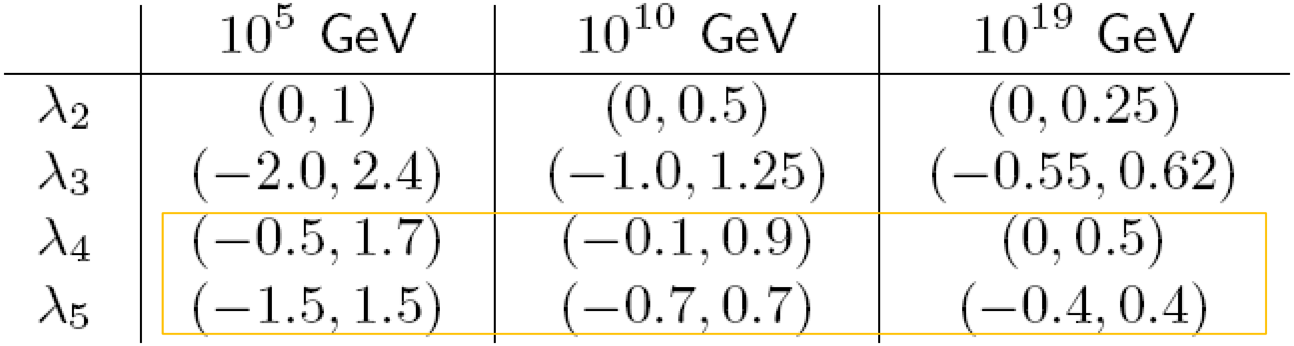
Cut-off scale 10^5 GeV







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

EWPD

- Triplet contribution to S, T & U:

Lavoura, Li, 9309262

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

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

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

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

- Tree-level contribution is neglected (μ→0).

EWPD

- Most recent STU fit:

Baak, et.al., 1209.2716

$$S_{\text{best fit}} = 0.03\,, \quad \sigma_S = 0.10$$
$$T_{\text{best fit}} = 0.05\,, \quad \sigma_T = 0.12$$
$$U_{\text{best fit}} = 0.03\,, \quad \sigma_U = 0.10$$

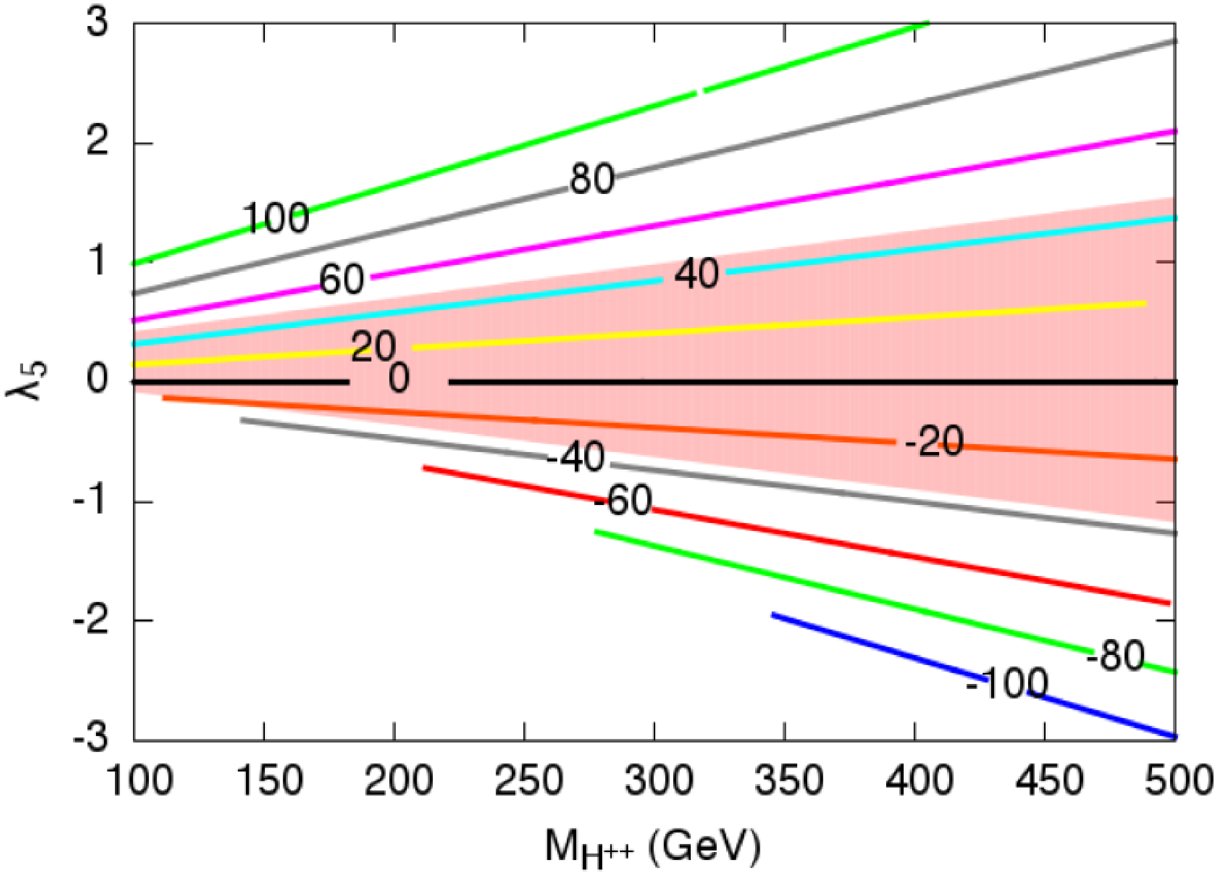
$$\rho_{ST} = 0.89, \quad \rho_{SU} = -0.54, \quad \rho_{TU} = -0.83$$

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

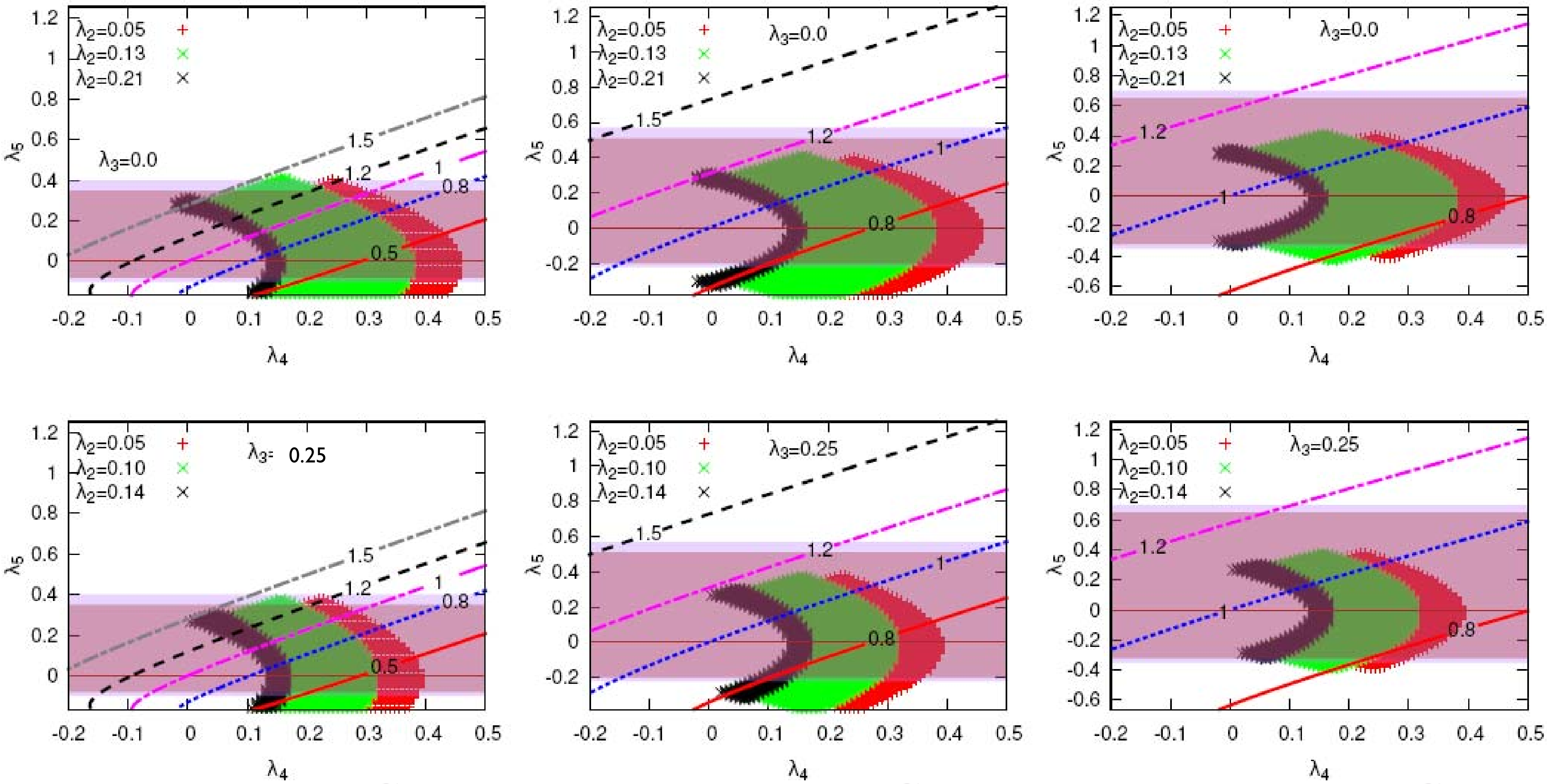
Constrained λ_5

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

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

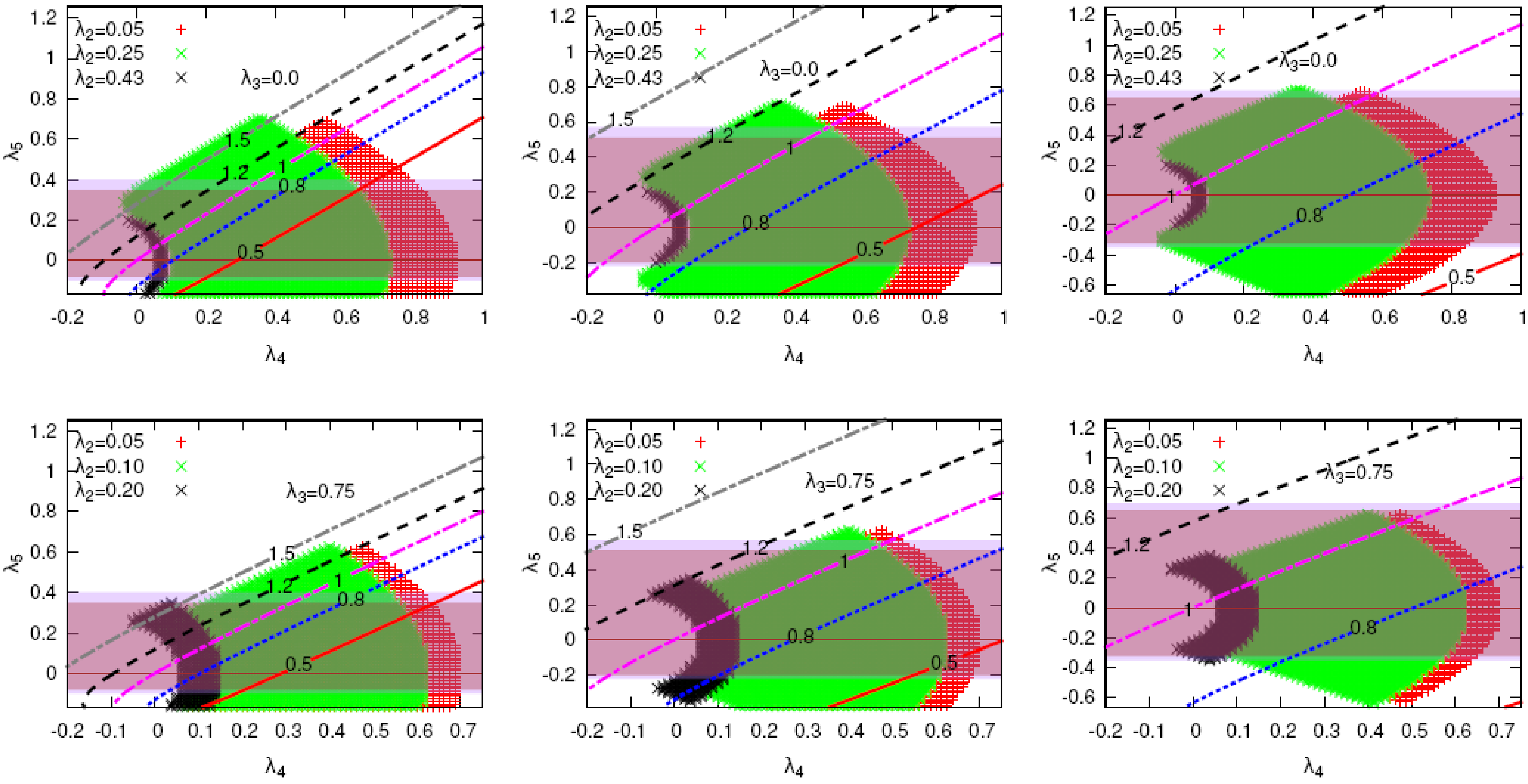
$$M_{H^{++}} = 100,\ 150,\ \text{and}\ 200\ \text{GeV},$$

Combined results for 10^{19} GeV

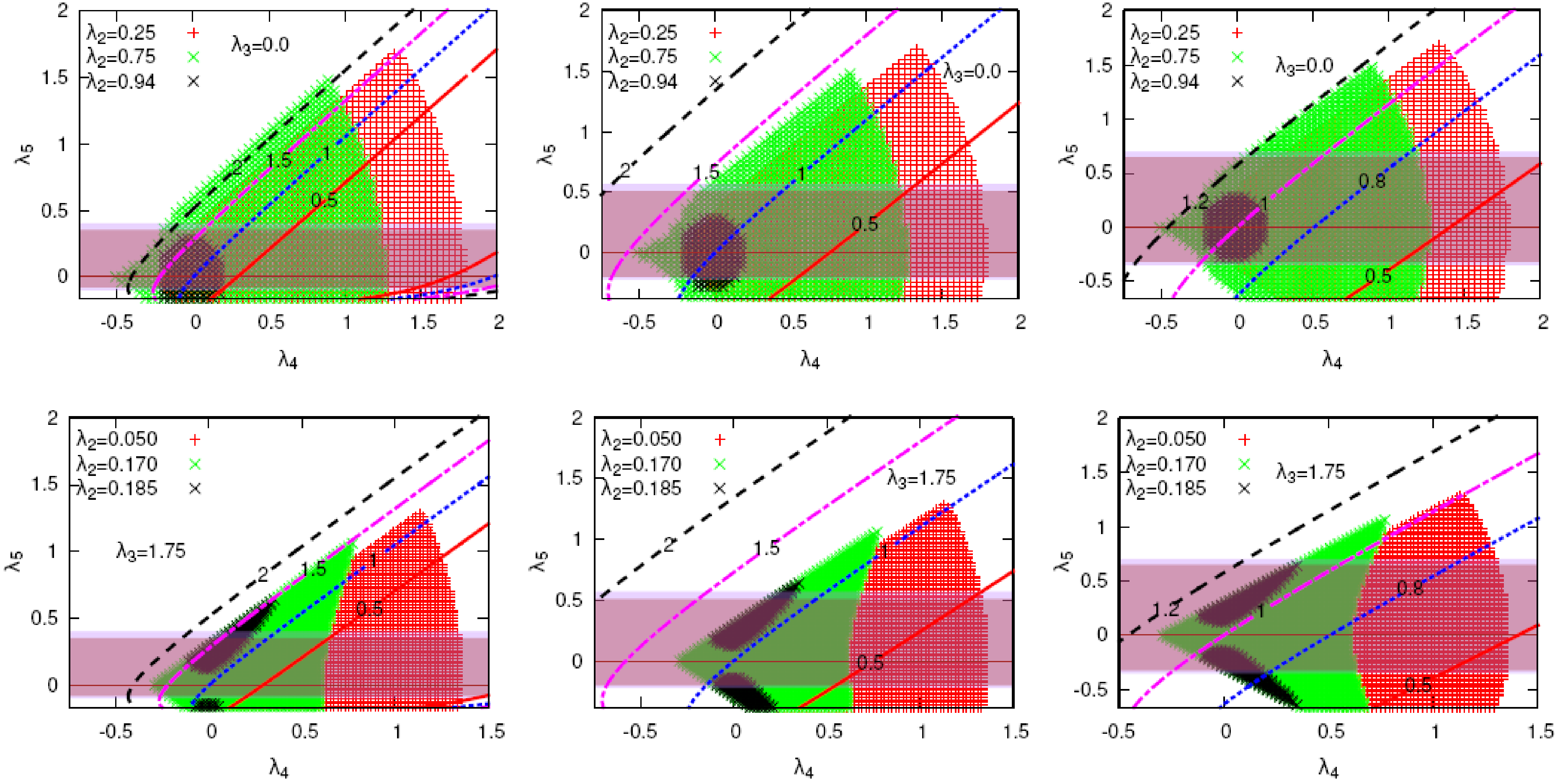


$m_{H^{++}} = 100\text{GeV}$ $m_{H^{++}} = 150\text{GeV}$ $m_{H^{++}} = 200\text{GeV}$

Combined results for 10^{10} GeV



Combined results for 10^5 GeV



Conclusion II

- EWPD constrains tightly the triplet mass splitting:

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

Thank you