

# Summer Institute 2013 17-23 August 2013, Jirisan National Park, Korea

## 19th International Summer Institute on Phenomenology of Elementary Particles and Cosmology

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### Invited Lecturers:

- Nima Arkani-Hamed
- Ki Young Choi
- Ian Low
- Tatsuya Nakada
- Riccardo Rattazzi

# Neutrinos

## Eung Jin Chun



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# What to talk about?

- Neutrinos from the sky and reactors  
Observation of oscillations → masses and mixing
- Neutrinos for the future  
Origin of neutrino mass?  
Dirac/Majorana, hierarchy, absolute mass scale
- Neutrinos at LHC  
New particles for neutrino mass

# Neutrino oscillation

Neutrino masses and mixing → oscillations

three masses :

$$\Delta m_{atm}^2 = |m_3^2 - m_1^2|$$

$$\Delta m_{sol}^2 = m_2^2 - m_1^2$$

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

$$|\nu_\mu\rangle = U_{\mu 1}|\nu_1\rangle + U_{\mu 2}|\nu_2\rangle + U_{\mu 3}|\nu_3\rangle$$

$$|\nu_\tau\rangle = U_{\tau 1}|\nu_1\rangle + U_{\tau 2}|\nu_2\rangle + U_{\tau 3}|\nu_3\rangle$$

three angles

one + two phases

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\theta_{23}} & s_{\theta_{23}} \\ 0 & -s_{\theta_{23}} & c_{\theta_{23}} \end{pmatrix} \begin{pmatrix} c_{\theta_{13}} & 0 & s_{\theta_{13}} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{\theta_{13}} e^{-i\delta} & 0 & c_{\theta_{13}} \end{pmatrix} \begin{pmatrix} c_{\theta_{12}} & s_{\theta_{12}} & 0 \\ -s_{\theta_{12}} & c_{\theta_{12}} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & e^{i\phi_3} \end{pmatrix}$$

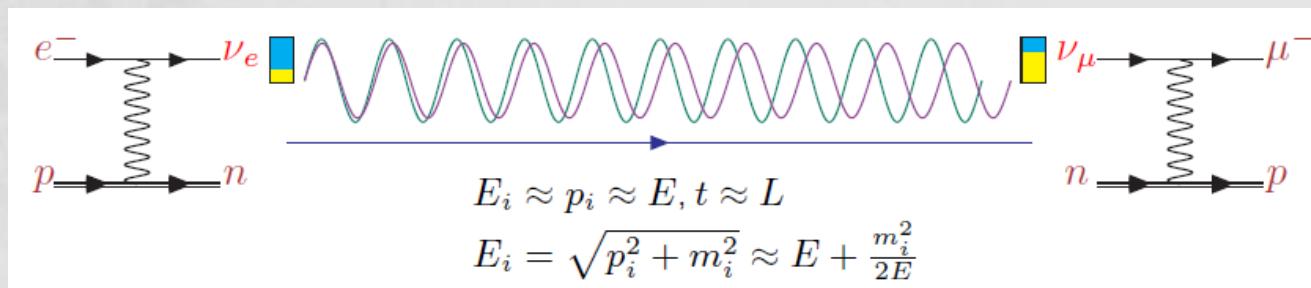
atmospheric

reactor

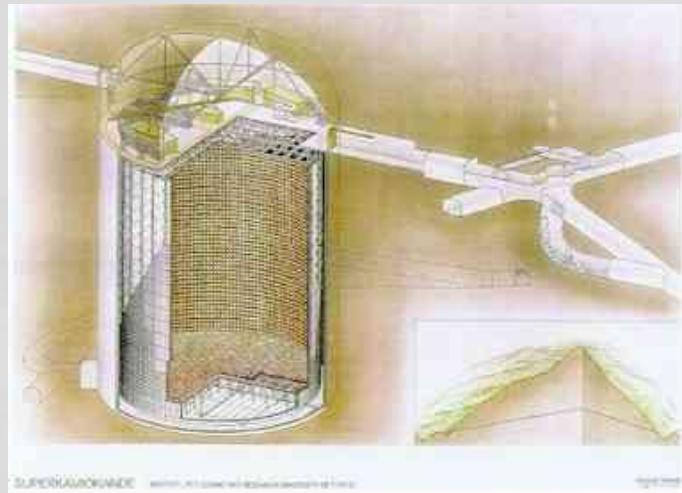
solar

Majorana

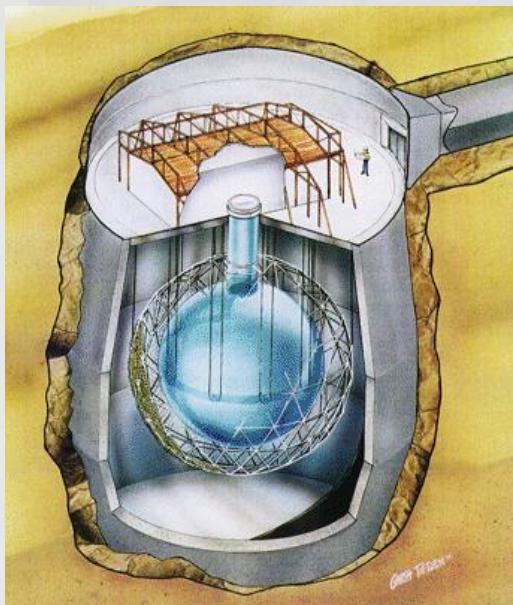
$$P_{e\mu} = \sin^2 2\theta \sin^2 \left( 1.27 \frac{\Delta m_{21}^2 (\text{eV}^2) L (\text{km})}{E (\text{GeV})} \right)$$



# Neutrinos kind to us



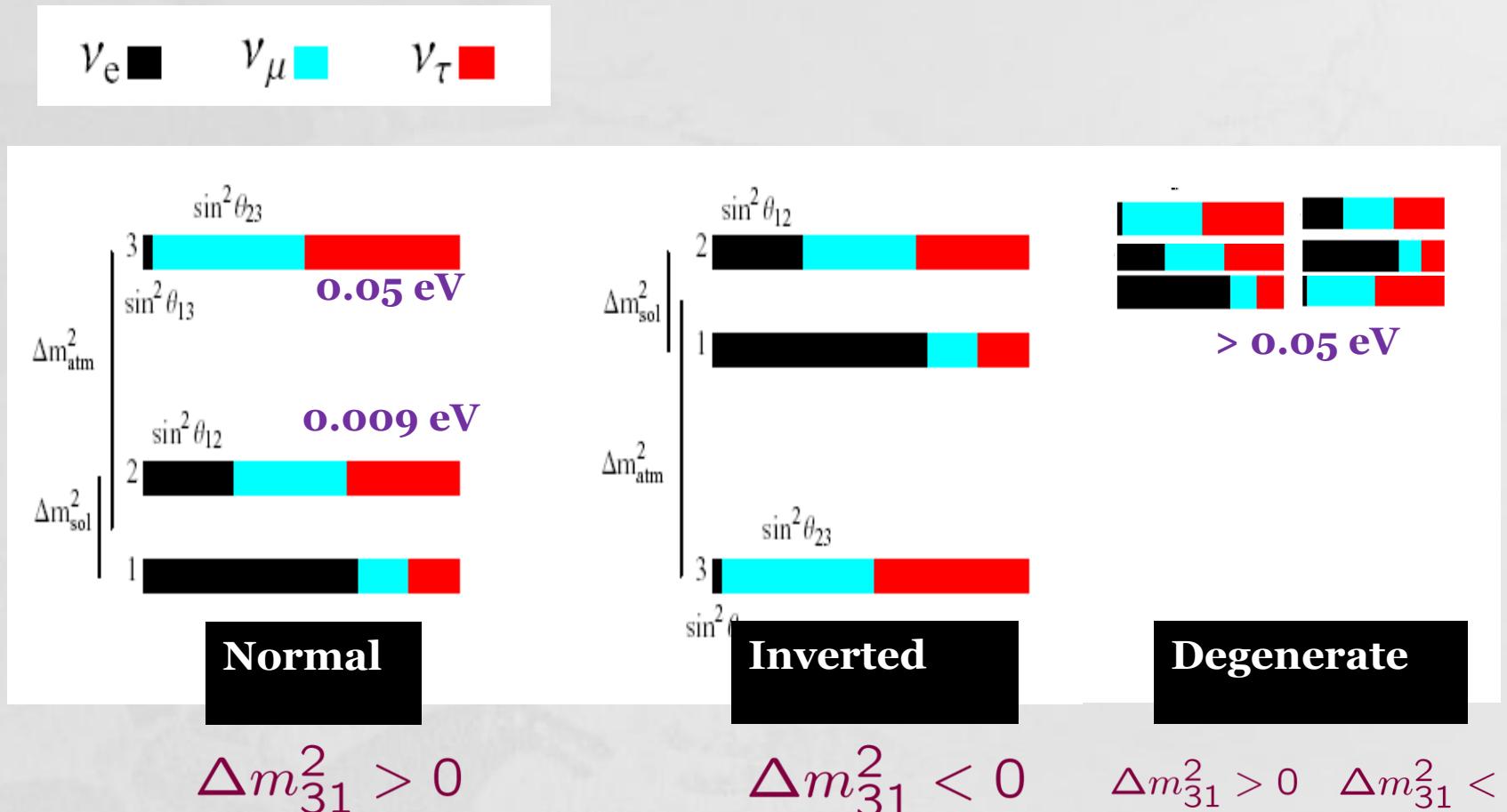
SUPERKAMIOKANDE: KAMIOKANDE-II RESEARCH GROUP, UNIVERSITY OF TOKYO



# Oscillation measurements

Parameter	best-fit ( $\pm 1\sigma$ )	$3\sigma$	
$\Delta m_{\odot}^2$ [10 $^{-5}$ eV $^2$ ]	$7.58^{+0.22}_{-0.26}$	6.99 – 8.18	$\Delta m_{21}^2$
$ \Delta m_A^2 $ [10 $^{-3}$ eV $^2$ ]	$2.35^{+0.12}_{-0.09}$	2.06 – 2.67	$ \Delta m_{31}^2 $
$\sin^2 \theta_{12}$	$0.306$ (0.312) $^{+0.018}_{-0.015}$	0.259 (0.265) – 0.359 (0.364)	
$\sin^2 \theta_{23}$	$0.42^{+0.08}_{-0.03}$	0.34 – 0.64	
$\sin^2 \theta_{13}$ [140]	$0.021$ (0.025) $^{+0.007}_{-0.008}$	0.001 (0.005) – 0.044 (0.050)	
$\sin^2 \theta_{13}$ [142]	$0.0251 \pm 0.0034$	0.015 – 0.036	

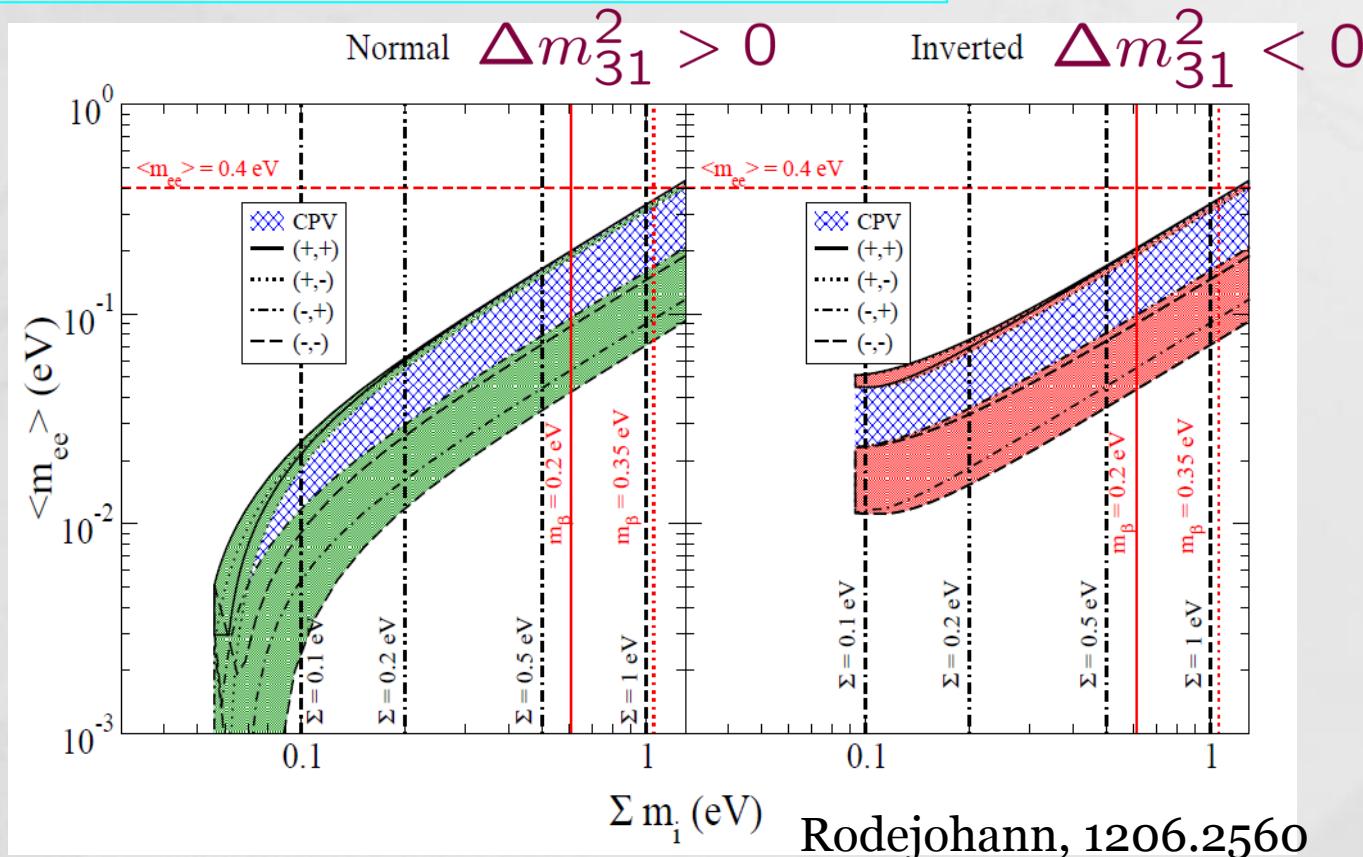
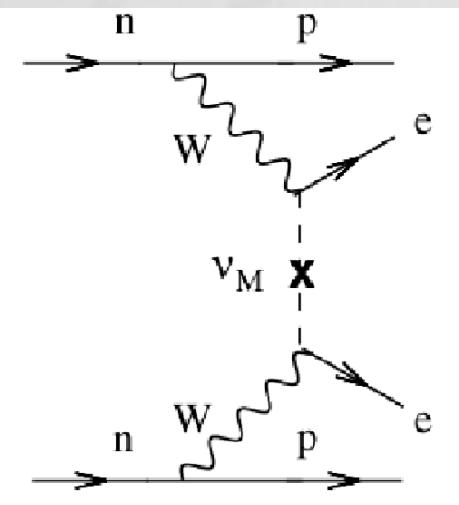
# Undetermined Mass hierarchy



# $\text{O}\nu\beta\beta$

- Direct measurement of Majorana mass

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right| = |c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$



# World competition

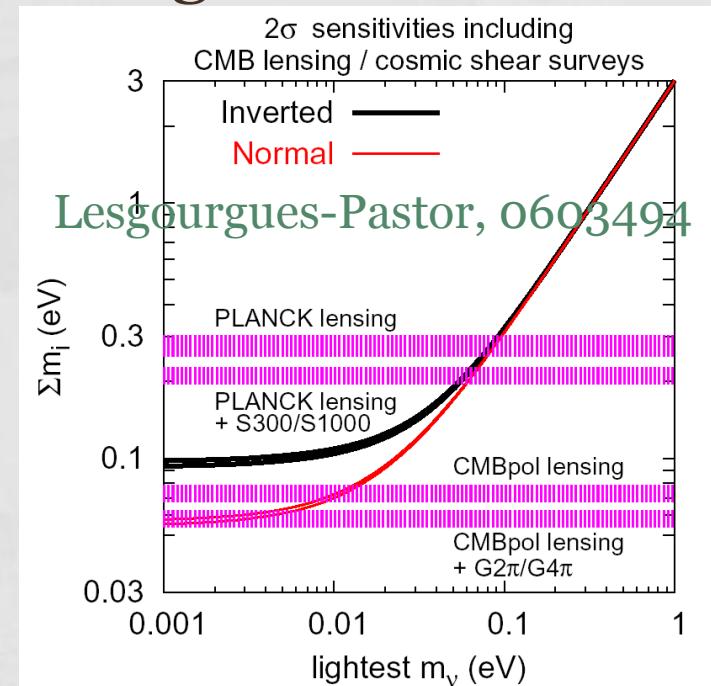
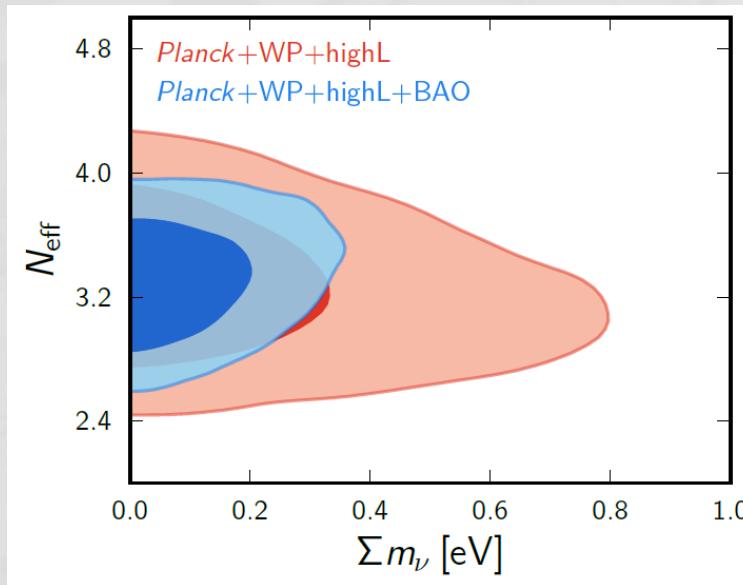
Experiment	Isotope	Mass [kg]	Sensitivity $T_{1/2}^{0\nu}$ [yrs]	Status	Start of data-taking	Sensitivity $\langle m_\nu \rangle$ [eV]
GERDA	$^{76}\text{Ge}$	18	$3 \times 10^{25}$	running	$\sim 2011$	0.17-0.42
		40	$2 \times 10^{26}$		$\sim 2012$	0.06-0.16
		1000	$6 \times 10^{27}$	R&D	$\sim 2015$	0.012-0.030
CUORE	$^{130}\text{Te}$	200	$6.5 \times 10^{26*}$	construction	$\sim 2013$	0.018-0.037
			$2.1 \times 10^{26**}$			0.03-0.066
MAJORANA	$^{76}\text{Ge}$	30-60	$(1 - 2) \times 10^{26}$	construction	$\sim 2013$	0.06-0.16
		1000	$6 \times 10^{27}$		$\sim 2015$	0.012-0.030
EXO	$^{136}\text{Xe}$	200	$6.4 \times 10^{25}$	running	$\sim 2011$	0.073-0.18
		1000	$8 \times 10^{26}$		$\sim 2015$	0.02-0.05
SuperNEMO	$^{82}\text{Se}$	100-200	$(1 - 2) \times 10^{26}$	R&D	$\sim 2013\text{-}15$	0.04-0.096
KamLAND-Zen	$^{136}\text{Xe}$	400	$4 \times 10^{26}$	running	$\sim 2011$	0.03-0.07
		1000	$10^{27}$		$\sim 2013\text{-}15$	0.02-0.046
SNO+	$^{150}\text{Nd}$	56	$4.5 \times 10^{24}$	construction	$\sim 2012$	0.15-0.32
		500	$3 \times 10^{25}$		$\sim 2015$	0.06-0.12

**AMoRE**     $\text{CaMoO}_4$     250     $3 \times 10^{26}$     R&D    ?    0.02-0.06  
 (TAUP 2011)

# Neutrino mass from Cosmology

$$0.056(0.095) \text{ eV} \lesssim \sum_i m_i \lesssim 6 \text{ eV}$$

- Neutrino dark matter (hot)  
 $\Omega_\nu = \sum m_\nu / 92.5 \text{ h}^2 \text{ eV} = \textbf{0.022}(\sum m_\nu / 1 \text{ eV})$
- Power spectrum of CMB & large scale structure



# Neutrinos toward New Physics

- Neutrino mass requires more than Higgs.
- Dirac with a (singlet) chiral state?

$$\mathcal{L}_\nu = y_\nu LHN + h.c.$$

$$m_\nu \sim 0.1\text{eV} \Rightarrow y_\nu \sim 10^{-12}$$

- Majorana with more physics beyond EW?

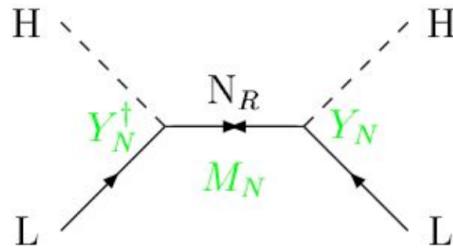
$$\mathcal{L}_W = \frac{\lambda}{M_X} LH LH + h.c.$$

$$M_X \sim \lambda \cdot 10^{15}\text{GeV}$$

- Who gives  $\mathcal{L}_W$ ? Where is  $M_X$ ?

# Three Seesaws

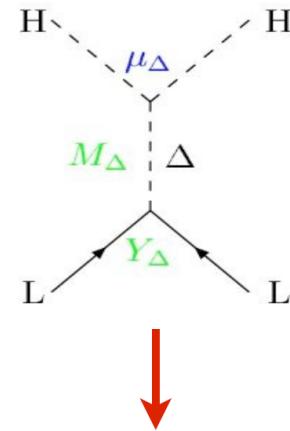
Fermion Singlet  
(Type I)



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

**Y(N) = 0**

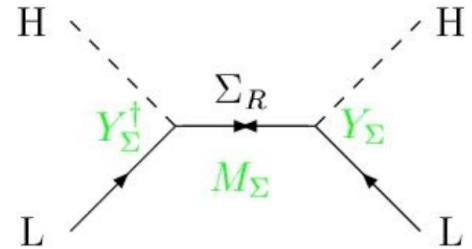
Scalar Triplet  
(Type II)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

**Y(Δ) = 1**

Fermion Triplet  
(Type III)



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

**Y(Σ) = 0**

# Neutrinos & Higgs

- Naturalness question with Higgs coupling to a heavy field.  
Farina, Pappadopulo, Strumia, 1303.7244

- Type I:  $\delta m^2 = \frac{4\lambda_N^2}{(4\pi)^2} M^2 \left( \ln \frac{M^2}{\bar{\mu}^2} - 1 \right)$   $\bar{\mu} \sim M_{\text{Pl}}$

$$M \lesssim m_h \left( \Delta \frac{16\pi^2 m_h}{m_\nu} \right)^{1/3} \approx 0.7 \cdot 10^7 \text{ GeV} \times \sqrt[3]{\Delta}$$

- Type II:  $\delta m^2 = -M^2 \frac{6g_2^4 + 3g_Y^4}{(4\pi)^4} \left( \frac{3}{2} \ln^2 \frac{M^2}{\bar{\mu}^2} + 2 \ln \frac{M^2}{\bar{\mu}^2} + \frac{7}{2} \right)$

$$M \lesssim 200 \text{ GeV} \times \sqrt{\Delta}$$

- Type III:  $\delta m^2 = \frac{g_2^4}{(4\pi)^4} M^2 \left( 36 \ln \frac{M^2}{\bar{\mu}^2} - 6 \right)$

$$M \lesssim 0.94 \text{ TeV} \times \sqrt{\Delta}$$

# Type I in a gauge model

- LR:  $W_L \begin{pmatrix} \nu \\ l \end{pmatrix} \begin{pmatrix} N \\ l^c \end{pmatrix} W_R$

SU(2)<sub>R</sub> breaking v<sub>R</sub> giving heavy masses to N & W<sub>R</sub>

- U(1)': c<sub>1</sub> U(1)<sub>χ</sub> + c<sub>2</sub> U(1)<sub>ψ</sub> + c<sub>3</sub> U(1)<sub>Y</sub>

$$E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi$$

$$27 \rightarrow 10 + \bar{5} + 1 + (5 + \bar{5}) + 1$$

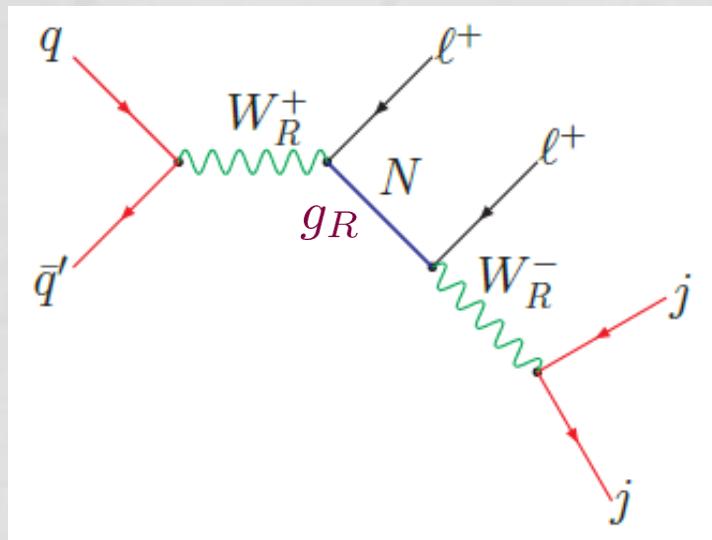
U(1)' breaking v' giving heavy masses to N & Z'

$$\mathcal{L}_\nu = y_\nu HLN + y_N SNN$$

# Type I at LHC

- Typical signatures: SS2L+jj probing  
Majorana nature of N.

Keung, Senjanovic, 1983



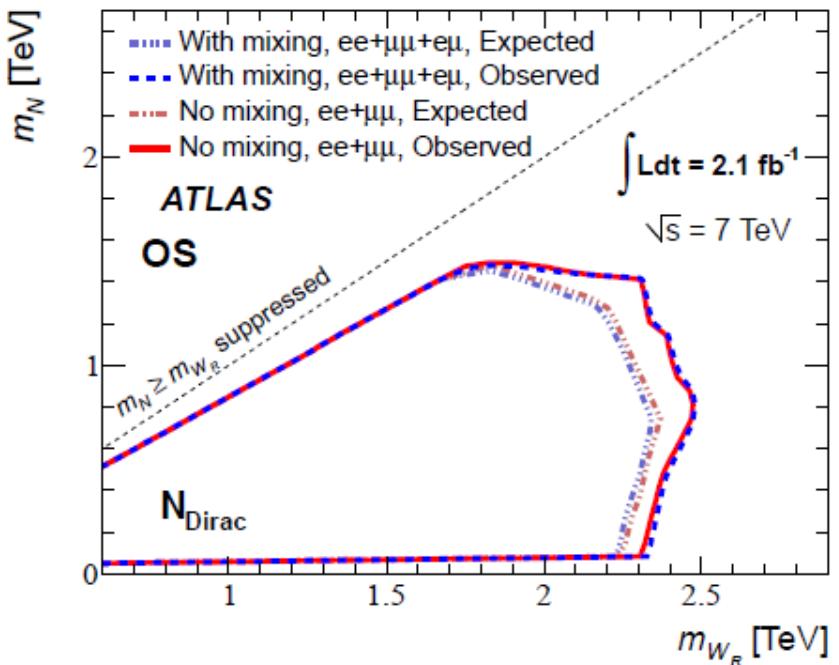
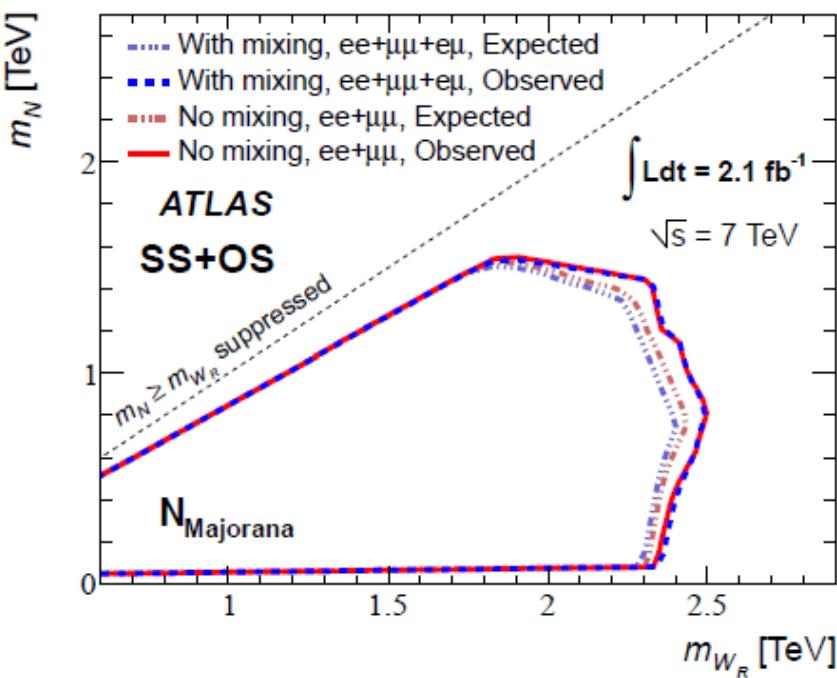
LR

$$q\bar{q} \rightarrow Z' \rightarrow NN \\ \rightarrow l^\pm l^\pm W^\mp W^\mp$$

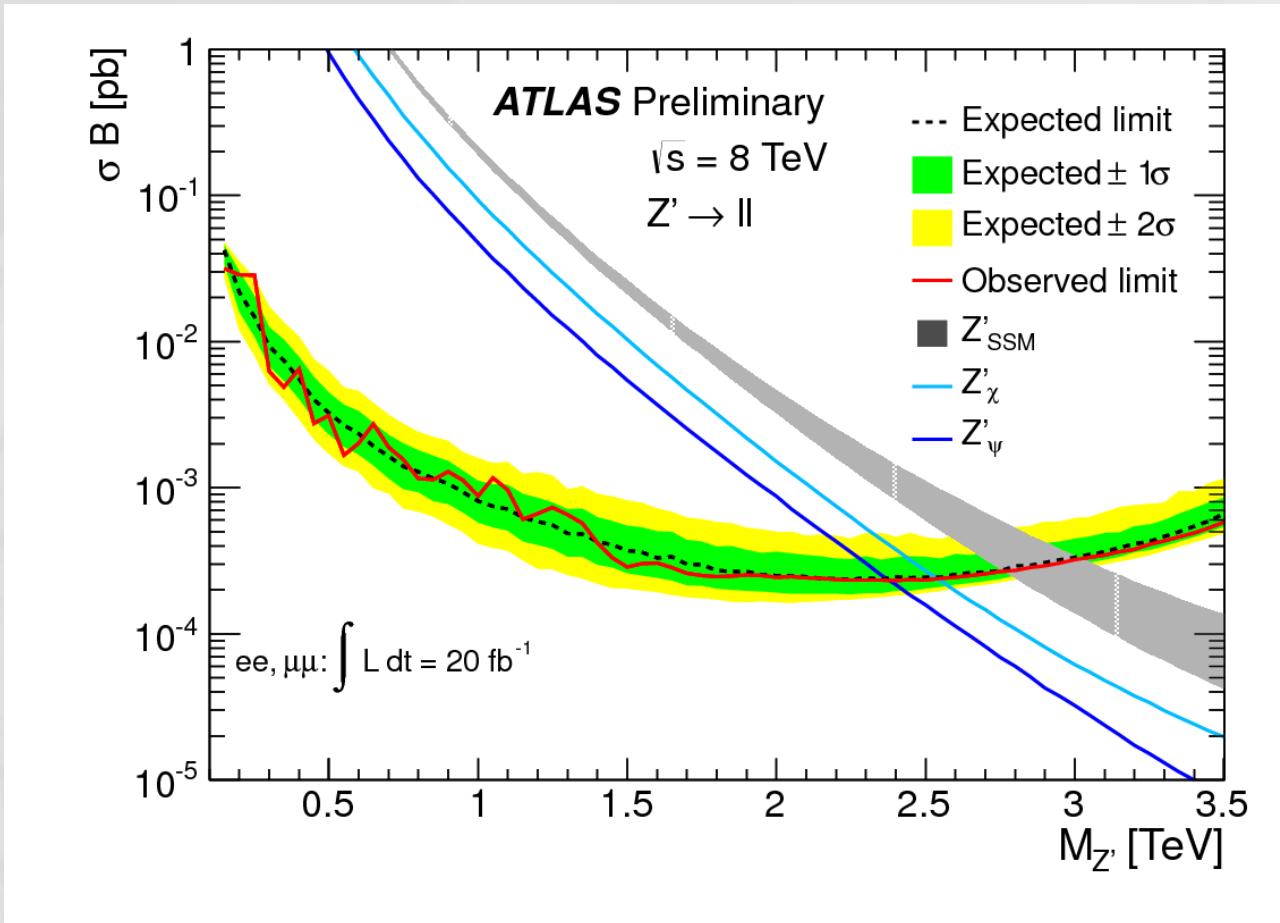
$$\theta_{\nu N} \sim \sqrt{\frac{m_\nu}{M_N}}$$

$U(1)'$

# N-W<sub>R</sub> Search

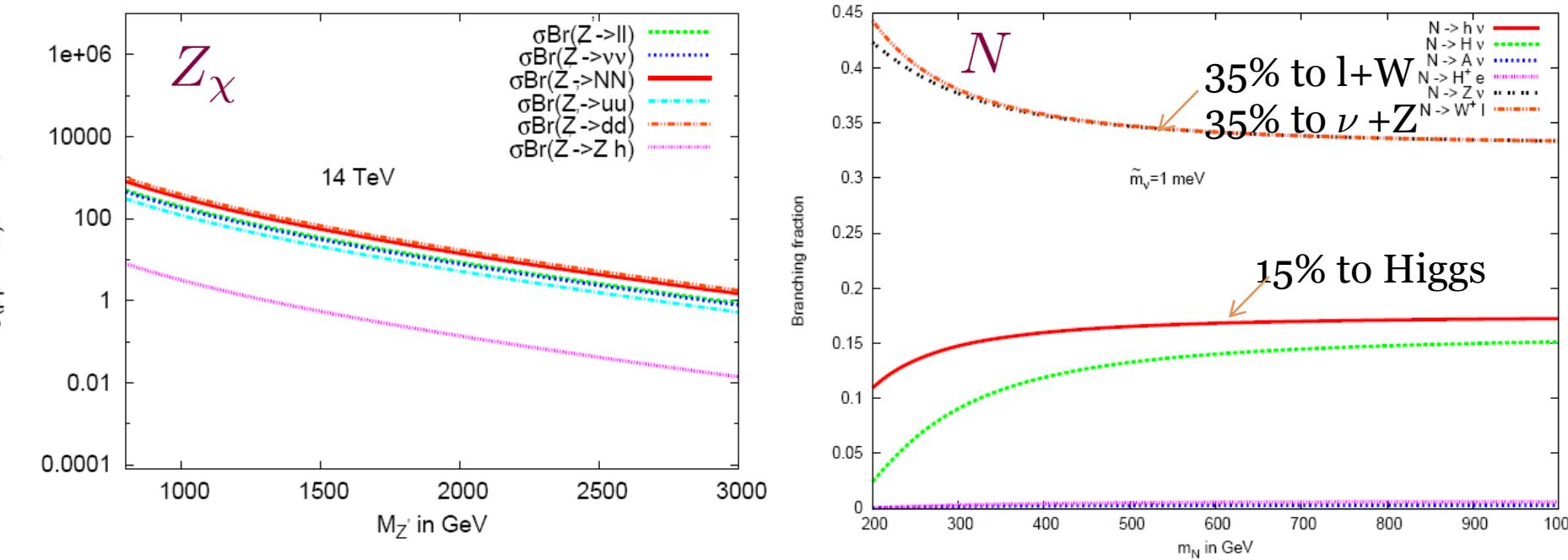


# $Z'$ search



# N-Z' search

Bandyopadhyay, EJC, Park, 1105.1652



Associated Higgs production: another handle to probe  $h \rightarrow bb$

# Type II Seesaw

- SM + a triplet boson ( $Y=1$ ):

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

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

- Triplet VEV generates neutrino mass matrix:  $m_{\alpha\beta}^\nu = f_{\alpha\beta} v_\Delta \Rightarrow f_{\alpha\beta} \frac{v_\Delta}{v_\Phi} \sim 10^{-12}$
- Collider can tell the neutrino mass pattern: Measure  $\text{BR}(\Delta^{++} \xrightarrow{f_{\alpha\beta}} l_\alpha^+ l_\beta^+)$ !

EJC, Lee, Park, 0304069

# Lepton Yukawa reconstruction

- Neutrino oscillation data (assuming vanishing CP phases) determines the coupling  $f = M^\nu/v_\Delta$ :

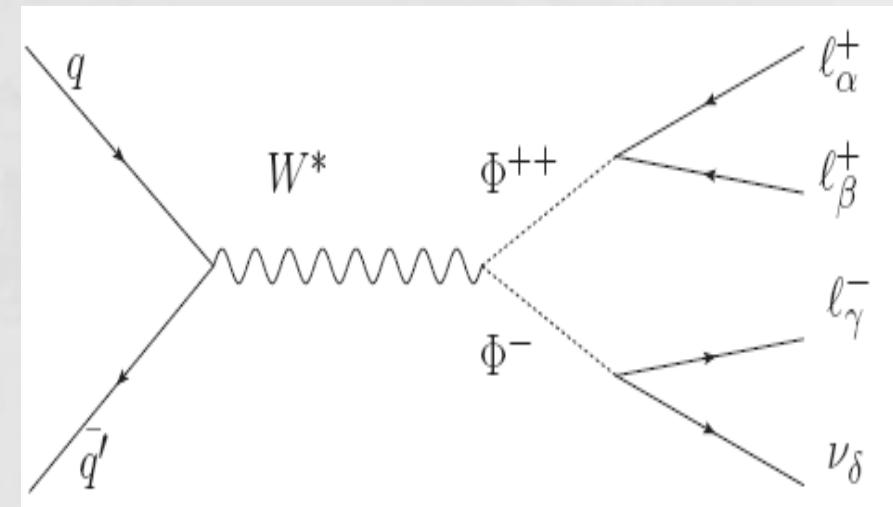
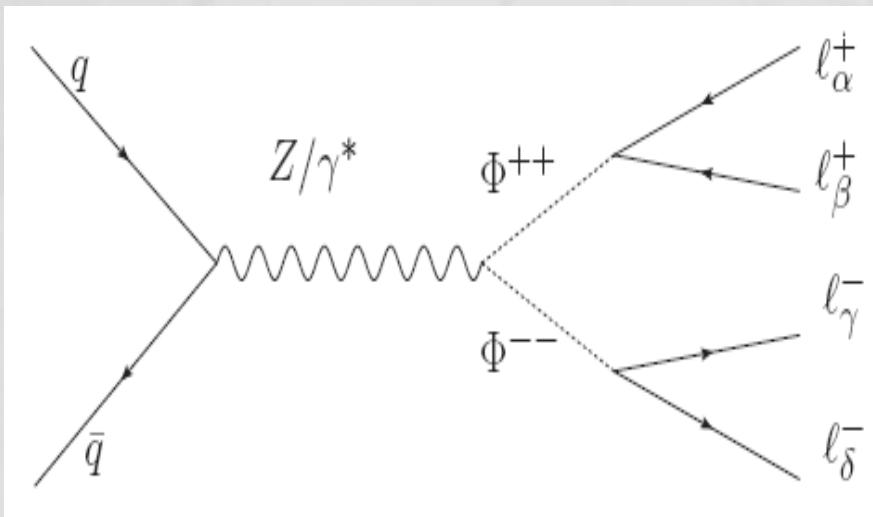
$$M^\nu = \begin{pmatrix} \text{NH} & & & \text{IH} & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \end{pmatrix}$$
$$M^\nu = \begin{pmatrix} 0.00403 & 0.00816 & 0.00259 \\ 0.00816 & 0.0264 & 0.0215 \\ 0.00259 & 0.0215 & 0.0286 \end{pmatrix} \begin{pmatrix} 0.0479 & -0.00557 & -0.00573 \\ -0.00557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

- 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

# Triplet signatures

- SS2L from  $H^{++} H^{--}$  pair production
- 3L from  $H^{++} H^-$  associated production



# CMS search

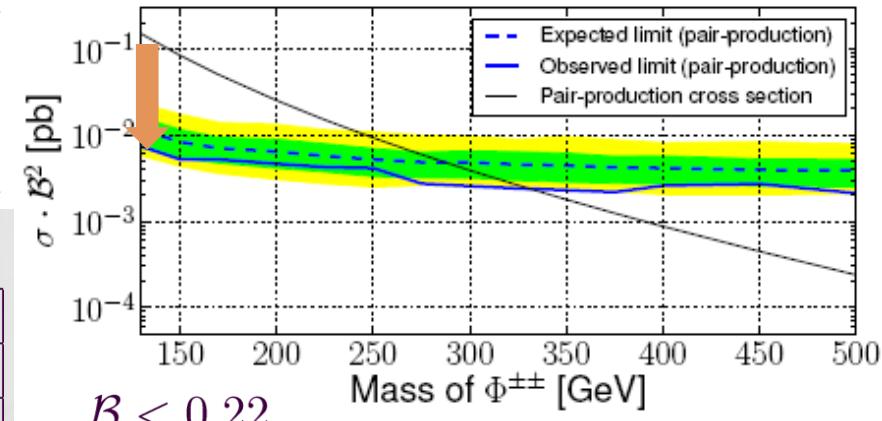
CMS, 1207.2666

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

Cf.)

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



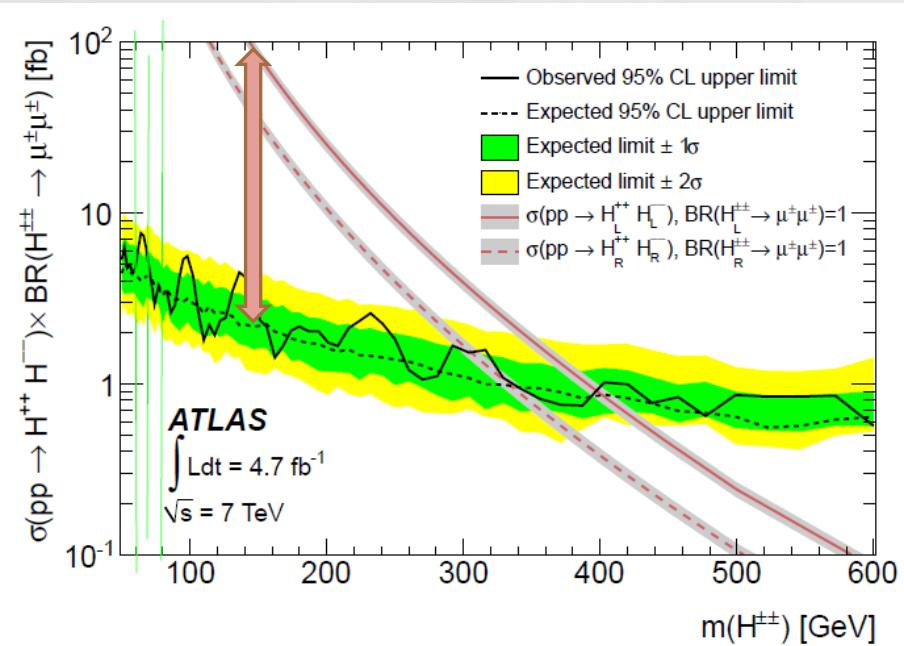
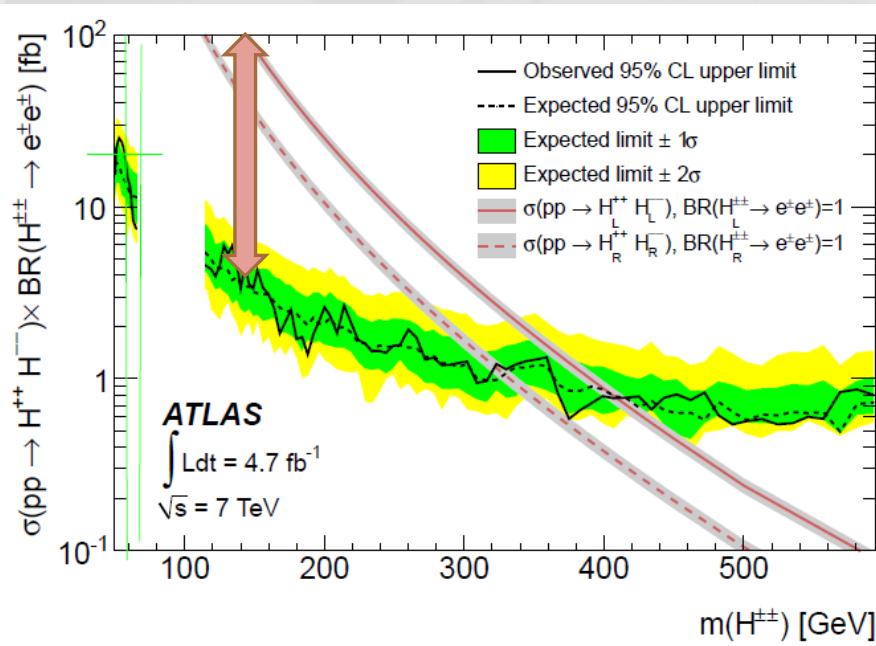
$\mathcal{B} < 0.22$   
 $M_{H^{++}} < 100\text{GeV}$

# ATLAS search

ATLAS, 1210.5070

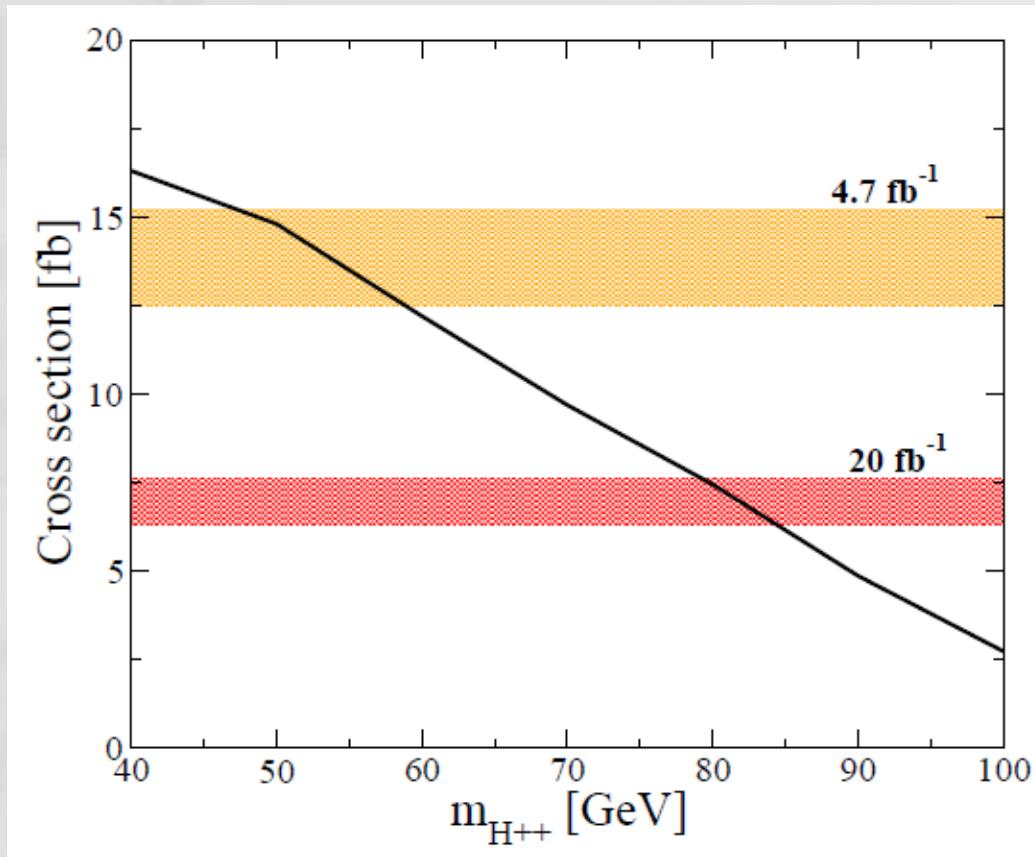
	$\text{BR}(H_L^{\pm\pm} \rightarrow \ell^\pm \ell'^\pm)$		95% CL lower limit on $m(H_L^{\pm\pm})$ [GeV]			
	$e^\pm e^\pm$		$\mu^\pm \mu^\pm$		$e^\pm \mu^\pm$	
	exp.	obs.	exp.	obs.	exp.	obs.
100%	407	409	401	398	392	375
33%	318	317	317	290	279	276
22%	274	258	282	282	250	253
11%	228	212	234	216	206	190

NH :  $\text{BR}(\mu\mu) \approx 27\%$   
IH :  $\text{BR}(ee) \approx 47\%$



# $H^{++} \rightarrow W^+ W^+$ search

- $H^{++} \rightarrow l^+ l^+ + X$  from ATLAS SS2L data:



Kanemura, Yagyu, Yokoya, 1305.2383

# Type III Seesaw

- SM + fermion triplets with Y=0:

$$\mathcal{L}_{\text{III}} = y_\nu L H_u \Sigma + \frac{1}{2} M \Sigma \Sigma \quad \Sigma = (\Sigma^+, \Sigma^0, \Sigma^-)$$

- Additional Dirac & Majorana masses for leptons:

$$\mathcal{L}_{\text{mass}} = m_D (l^- \Sigma^+ + \nu \Sigma^0) + M \Sigma^+ \Sigma^- + \frac{1}{2} M \Sigma^0 \Sigma^0$$

- Neutrino mass matrix by Seesaw ( $m_D \ll M$ ):

$$M_\nu = m_D \frac{1}{M} m_D^T$$

- $l$ - $\Sigma^-$ / $\nu$ - $\Sigma^0$  mixing

$\rightarrow L$ - $\Sigma$  gauge vertices  $\propto g m_D/M \sim 10^{-6}$

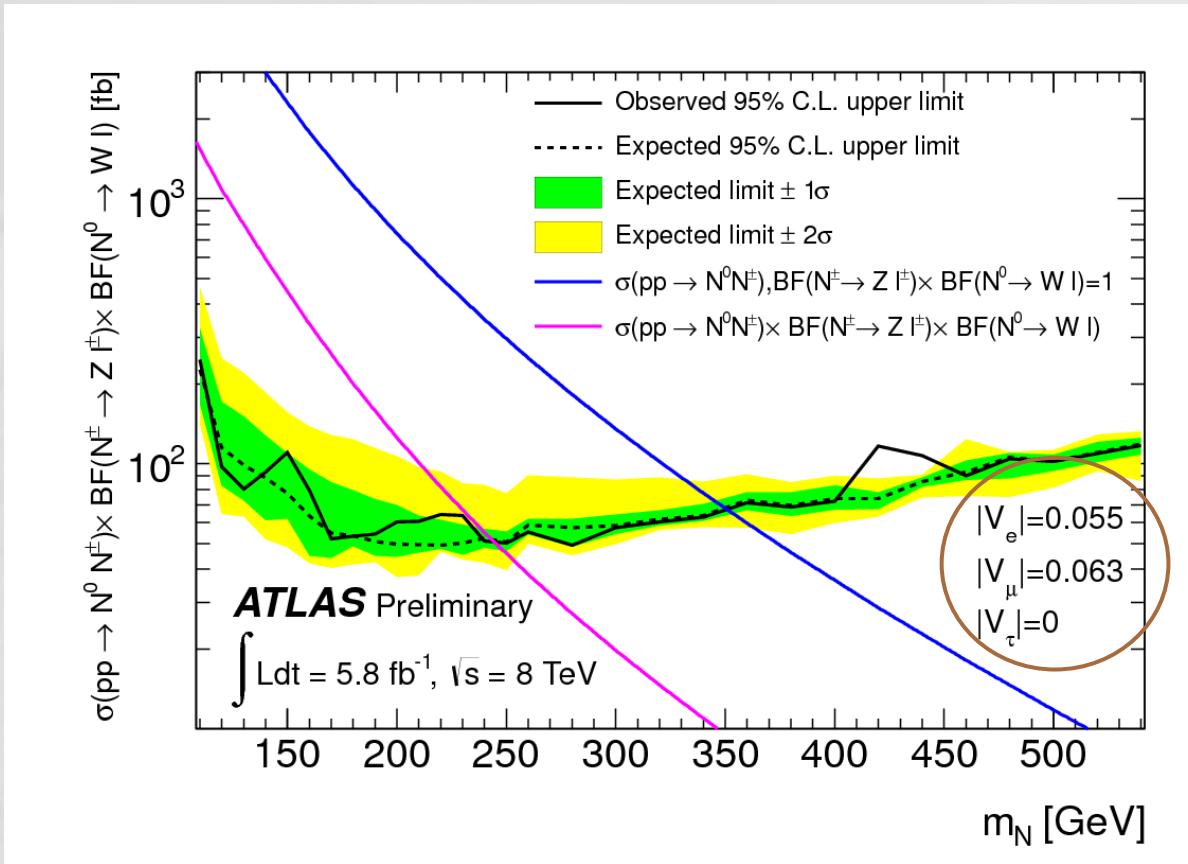
$$W^\pm l^\mp \Sigma^0, \quad W^\pm \nu \Sigma^\mp, \quad Z l^\pm \Sigma^\mp, \quad Z \nu \Sigma^0$$

# LHC signatures

- $\Sigma$  decay:  $\Sigma^\pm \rightarrow l^\pm h, l^\pm Z, \nu W^\pm$   
 $\Sigma^0 \rightarrow \nu h, \nu Z, l^\pm W^\mp$  Franceschini, et.al.  
0805.1613
- $\Sigma$  production:  $pp \rightarrow \Sigma^+ \Sigma^-, \Sigma^\pm \Sigma^0$
- Four lepton final states at ATLAS  
 $pp \rightarrow \Sigma^\pm \Sigma^0 \rightarrow l^\pm Z(l\bar{l})l^\pm W^\mp(jj')$
- Higgs production associated with charged leptons:  $pp \rightarrow \Sigma^\pm \Sigma^0 \rightarrow l^\pm l^\pm h W^\mp$

Bandyopadhyay, Choi, EJC, Kang, 1112.3080

# ATLAS search



# Search for $h \rightarrow bb$ in type III?

Production cross-sections (fb)		
$m_\Sigma$	250 GeV	400 GeV
$\Sigma^+ \Sigma^0$	439.1	73.8
$\Sigma^+ \Sigma^-$	320.0	50.0
$\Sigma^- \Sigma^0$	221.8	32.3

Decay modes	Branching ratios	
$m_\Sigma$	250 GeV	400 GeV
$\Sigma^0 \rightarrow h\nu$	0.17	0.22
$\Sigma^0 \rightarrow Z\nu$	0.27	0.26
$\Sigma^0 \rightarrow W^\pm l^\mp$	0.56	0.52
$\Sigma^\pm \rightarrow h l^\pm$	0.17	0.22
$\Sigma^\pm \rightarrow Z l^\pm$	0.27	0.26
$\Sigma^\pm \rightarrow W^\pm \nu$	0.55	0.52
$\Sigma^\pm \rightarrow \Sigma^0 \pi^\pm$	0.009	0.003

Bandyopadhyay, Choi, EJC, Kang, 1112.3080

# 2b + SSD

$8\sigma$  |  $2.2\sigma$

$5\sigma$  with  
 $6.7/\text{fb}$  |  $52/\text{fb}$

$10\sigma$  |  $3\sigma$

$\geq 2b - \text{jet} + \text{SSD}$							
Signal		Backgrounds					
BP1	BP2	$t\bar{t}$	$t\bar{t}b\bar{b}$	$t\bar{t}Z$	$t\bar{t}h$	$VV$	$t\bar{t}W$
127.38	29.09	24.0	7.5	41.6	29.0	0.0	41.4
$m_{b-b}$							
Signal		Backgrounds					
BP1	BP2	$t\bar{t}$	$t\bar{t}b\bar{b}$	$t\bar{t}Z$	$t\bar{t}h$	$VV$	$t\bar{t}W$
60.61	10.39	8.0	3.0	10.6	6.5	0.0	9.6
$m_{b-b-l}$							
Signal		Backgrounds					
		$t\bar{t}$	$t\bar{t}b\bar{b}$	$t\bar{t}Z$	$t\bar{t}h$	$VV$	$t\bar{t}W$
BP1	117.37	4.0	0.35	7.00	2.67	0.0	2.50
BP2	11.74	0.0	0.0	1.71	0.12	0.0	1.05

# More on Type II

- Same-sign tetra-leptons

Triplet-antitriplet oscillation

EJC & Sharma, 1206.6278

- Higgs boson Phenomenology

EWPD

Perturbativity & vacuum stability

Higgs-to-diphoton rate

EJC, Lee & Sharma, 1209.1303

# Type II scalar sector

- Scalar potential of type II seesaw

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

- Five boson mass eigenstates

$$\begin{array}{ccc}\Delta^{++}, \Delta^+, \Delta^0 & \xrightarrow{\hspace{1cm}} & h^0, H^0, A^0, H^+, H^{++} \\ \Phi^+, \Phi^0 & & \end{array}$$

# Scalar mixing

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

$$\phi_I^0 = G^0 - 2\xi A^0$$

$$\Delta_I^0 = A^0 + 2\xi G^0$$

$$\phi^+ = G^+ + \sqrt{2}\xi H^+$$

$$\Delta^+ = H^+ - \sqrt{2}\xi G^+$$

$$\phi_R^0 = h^0 - a\xi H^0$$

$$\Delta_R^0 = H^0 + a\xi h^0$$

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

- We will work in the limit:  $\xi \ll 0.01$ .
- (note)  $\rho$  parameter constraint:

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

# Scalar spectrum

- Mass gap among triplet components:

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



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

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

- Two mass hierarchies:

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

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

# Triplet decay channels

- Gauge decays for non-vanishing  $\Delta M (\lambda_5)$ :

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

$$\Delta M(\lambda_5)$$

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

$$H^{++} \rightarrow l_\alpha^+ l_\beta^+; \quad H^+ \rightarrow l_\alpha^+ \nu_\beta; \quad H^0/A^0 \rightarrow \nu_\alpha \nu_\beta$$

$$f_{\alpha\beta}$$

- Di-quark/di-boson decays through  $\xi$ :

$$H^{++} \rightarrow W^+ W^+; \quad H^+ \rightarrow t\bar{b}; \quad H^0/A^0 \rightarrow t\bar{t}, b\bar{b}$$
$$\rightarrow ZW, hW \quad \rightarrow ZZ, hh/Zh$$

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

$$(*) f\xi \sim 10^{-12}$$

# Triplet–antitriplet mixing

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



- Triplet number breaking by doublet-triplet mixing:

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



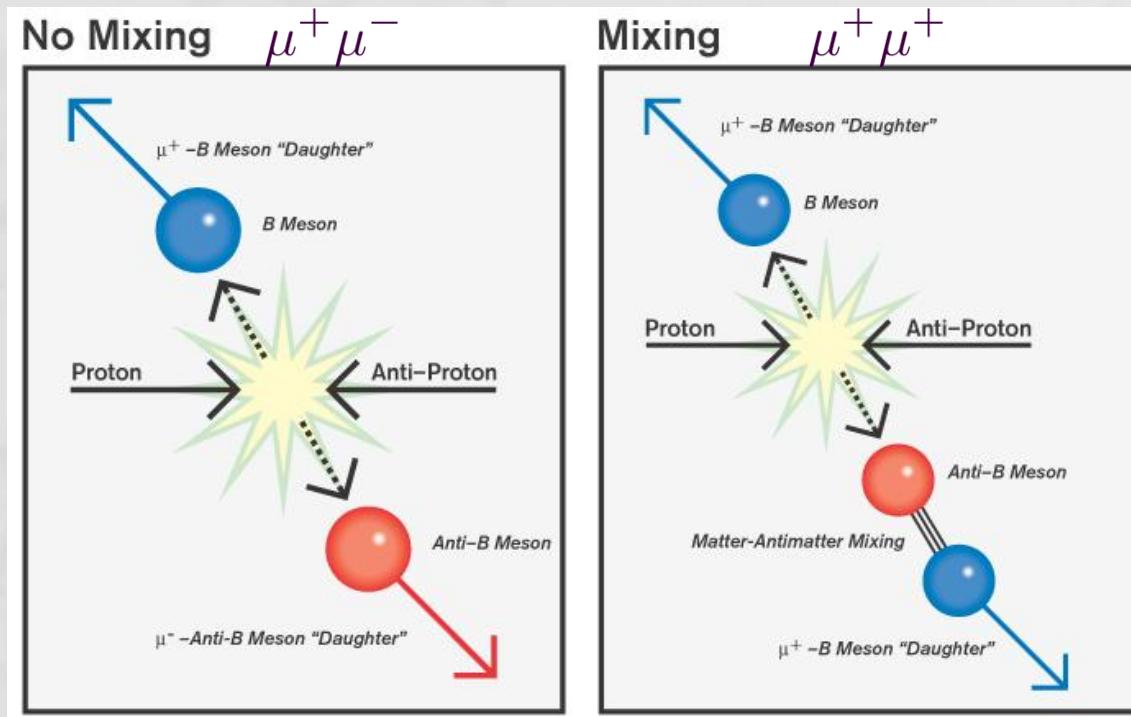
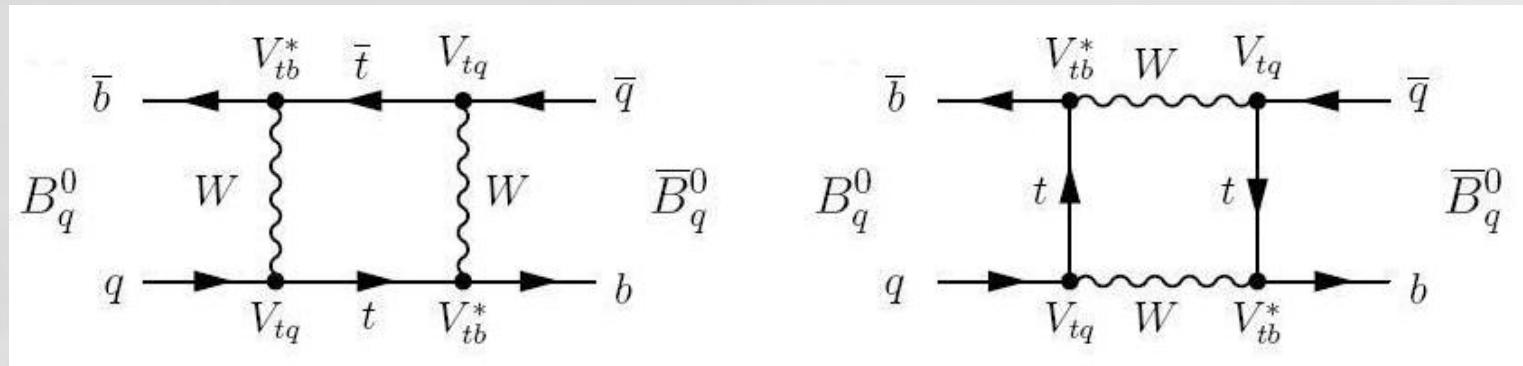
- It induces a tiny mass splitting between  $H^0$  &  $A^0$  :

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

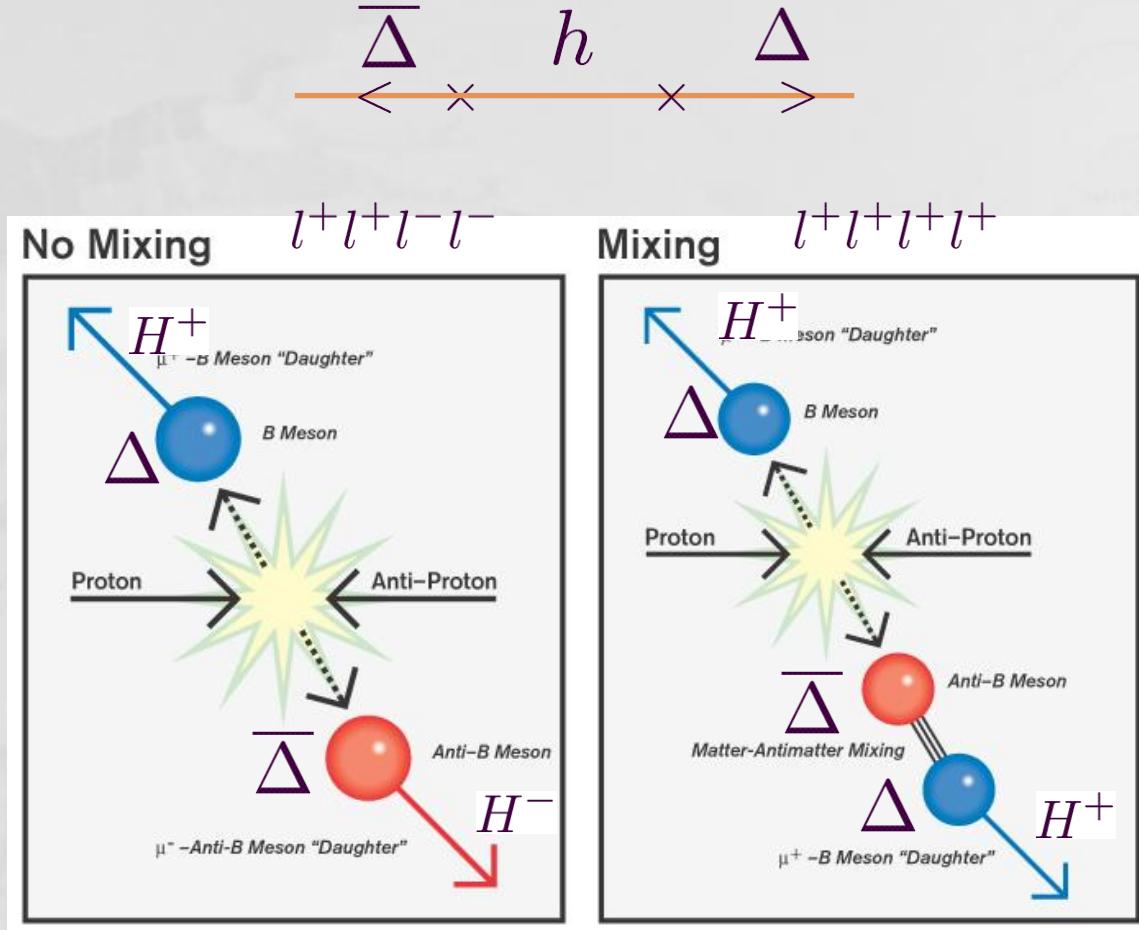
$$v_\Delta = \frac{\mu v_\Phi^2}{\sqrt{2} M_{H^0}^2}$$

$$\delta M_{HA} \approx 2M_{H^0} \frac{v_\Delta^2}{v_0^2} \frac{M_{H^0}^2}{M_{H^0}^2 - m_{h^0}^2}$$

# B- $\bar{B}$ Mixing



# $\Delta$ - $\bar{\Delta}$ Mixing



# $\Delta$ - $\bar{\Delta}$ Oscillation

- Initial  $\Delta = H^0 + i A^0$  evolves as

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

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

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

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

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

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

# Same-Sign Tetra-Leptons

- Lepton number violating processes:

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

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

# Same-Sign Tetra-Leptons

- Is this observable?

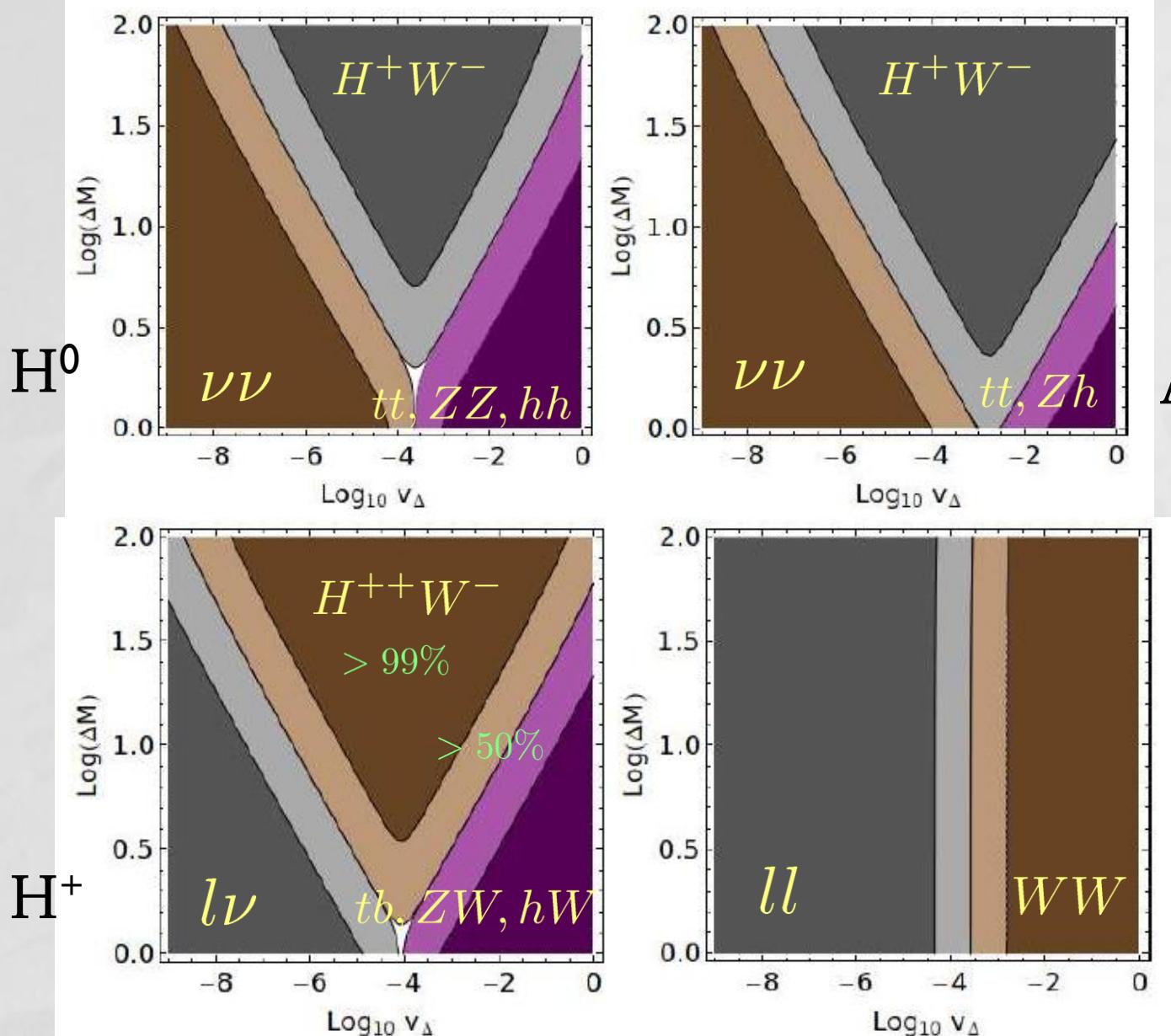
- i)  $H^{++}$  is the lightest and  $f_{\alpha\beta} > \xi$ .
- ii)  $\Delta M$  sufficiently large to allow  $\Delta^0 \rightarrow H^+ W^- \rightarrow H^{++} 2W^-$ .
- iii) Sizable oscillation parameter:  $x \sim 1$ .

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

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

# Triplet decay channels

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

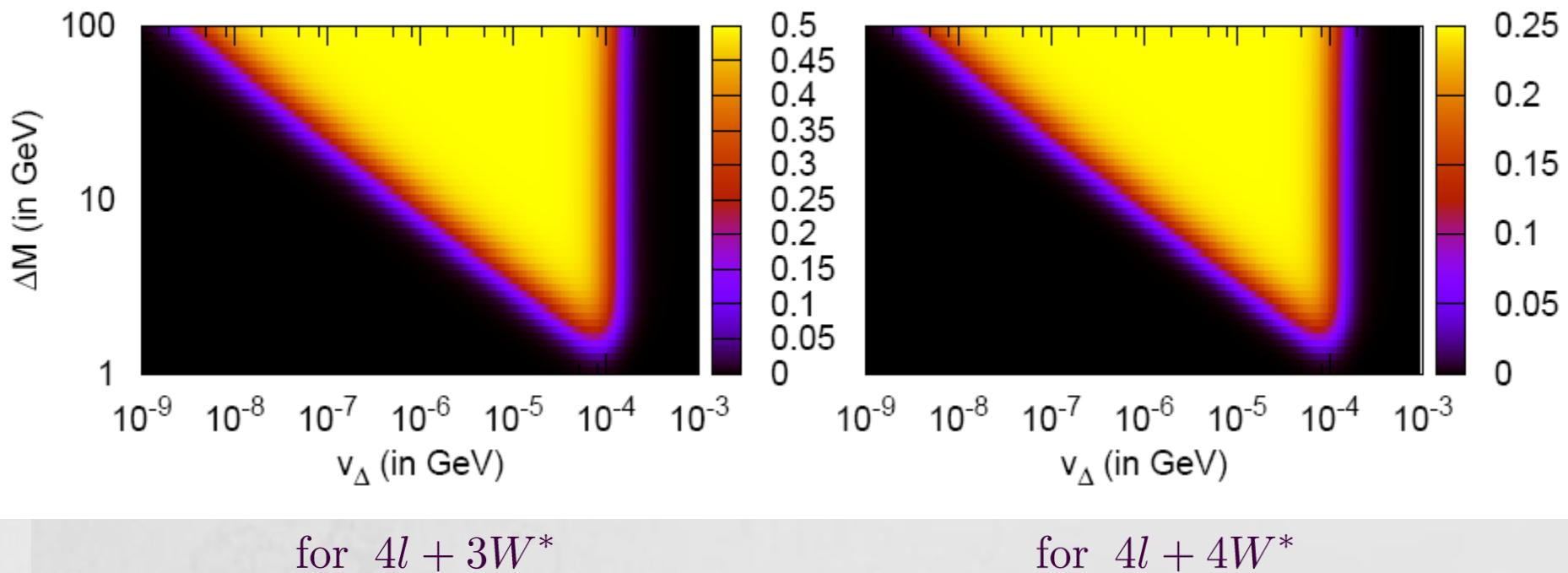


$$M_{H^{++}} = 300 \text{ GeV}$$

$$< M_{H^+}$$

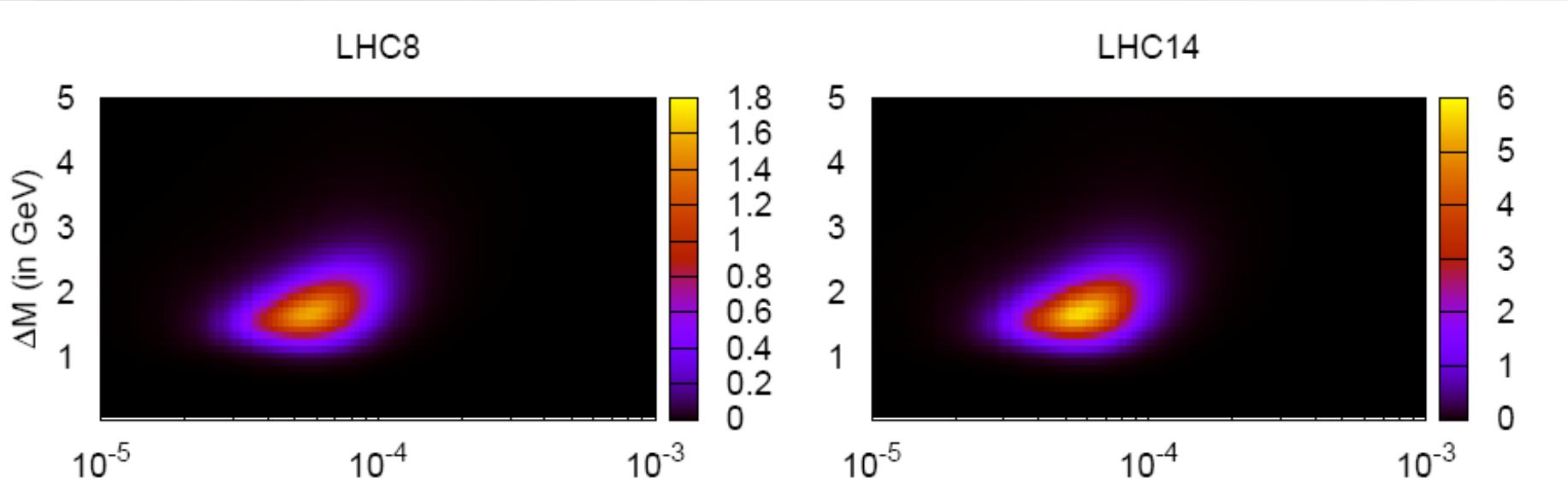
$$< M_{H^0/A^0}$$

# Maximizing the branching fraction



# SS4L cross-section

- SS4L production including the oscillation factor:



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

- Benchmark point:  
 $v_\Delta = 7 \times 10^{-5} \text{ GeV}, \Delta M = 1.5 \text{ GeV.}$

# Event numbers

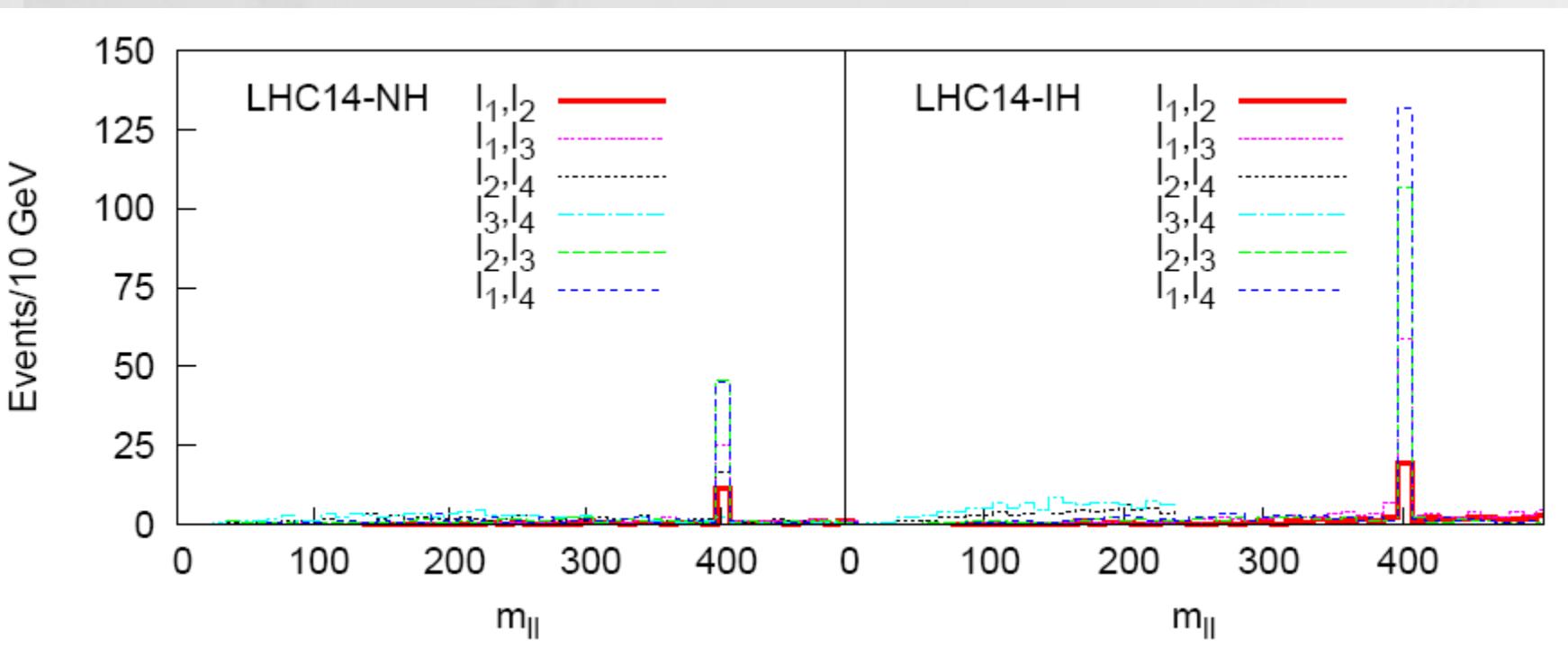
Final State	$\sigma/\text{fb}$ (8 TeV)	$\sigma/\text{fb}$ (14 TeV)
$H^+ H^0$	0.761	2.931
$H^+ A^0$	0.761	2.931
$H^- H^0$	0.275	1.209
$H^- A^0$	0.275	1.209
$H^0 A^0$	1.014	4.322

No background  
Lepton selection cuts only

$15\text{fb}^{-1}$   
 $100\text{fb}^{-1}$

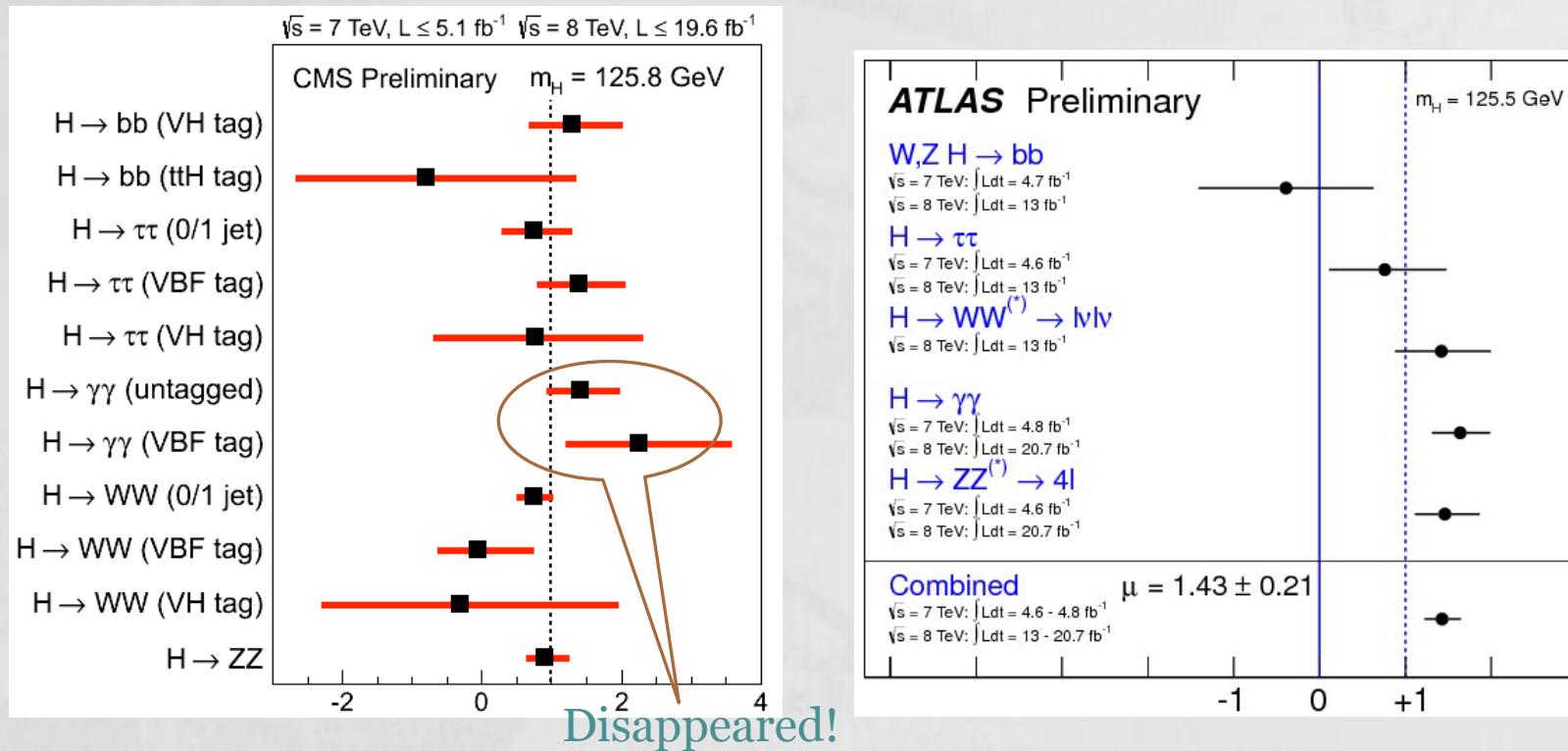
	Pre-selection	Selection
$\ell^\pm \ell^\pm \ell^\pm \ell^\pm$ (LHC8-NH)	4	3
$\ell^\pm \ell^\pm \ell^\pm \ell^\pm$ (LHC8-IH)	9	8
$\ell^\pm \ell^\pm \ell^\pm \ell^\pm$ (LHC14-NH)	110	94
$\ell^\pm \ell^\pm \ell^\pm \ell^\pm$ (LHC14-IH)	240	210

# Mass reconstruction



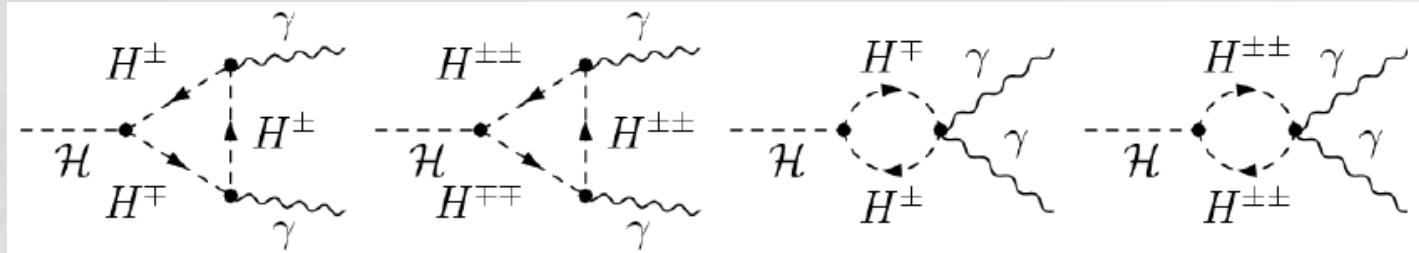
# Higgs-to-diphoton

- 1-loop process – sensitive to New Physics.
- Deviation from the SM prediction?
- Its precision data is important to constrain NP.



# Higgs-to-diphoton

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



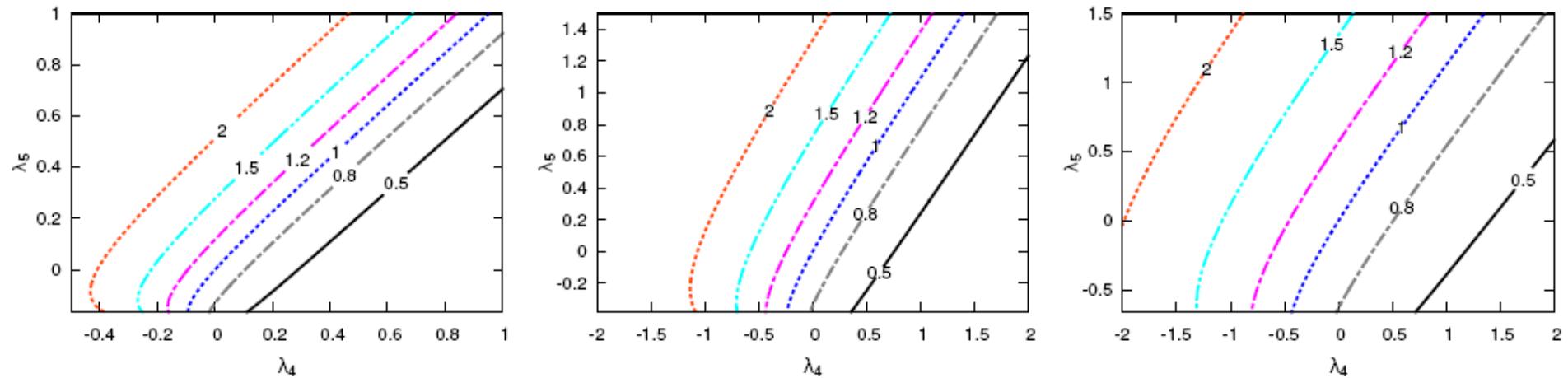
$$\begin{aligned} \Gamma(h \rightarrow \gamma\gamma) = & \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 g_{ff}^h A_{1/2}^h(x_f) + g_{WW}^h A_1^h(x_W) \right. \\ & \left. + g_{H+H+}^h A_0^h(x_{H+}) + 4g_{H++H+-}^h A_0^h(x_{H++}) \right|^2 \end{aligned}$$

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

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

# Higgs-to-diphoton

$$R_{\gamma\gamma} = \Gamma(h \rightarrow \gamma\gamma)/\Gamma(h \rightarrow \gamma\gamma)_{\text{SM}}$$



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

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

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

# Vacuum stability & perturbativity

- Scalar sector of type II seesaw:

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

- Vacuum stability of the SM boson changes due to its couplings to the Higgs triplet.
- Triplet self coupling ( $\lambda_2$ ) tends to diverge rapidly.
- Strong constraints on  $\lambda_{2,3,4,5}$ .
- Take  $\lambda_1=0.13$  and  $\mu \ll v_\Phi$ .

# 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

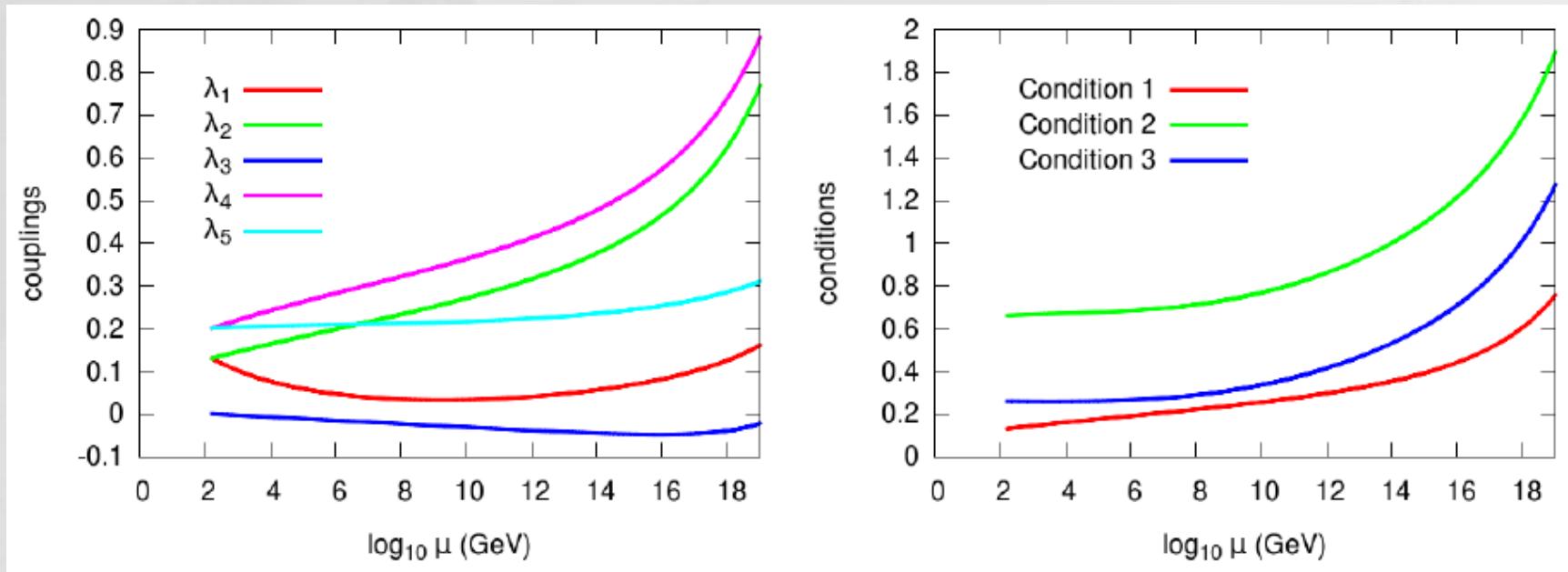
- Use 1-loop RGE:

Chao, Zhang, 0611323  
Schmidt, 07053841

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

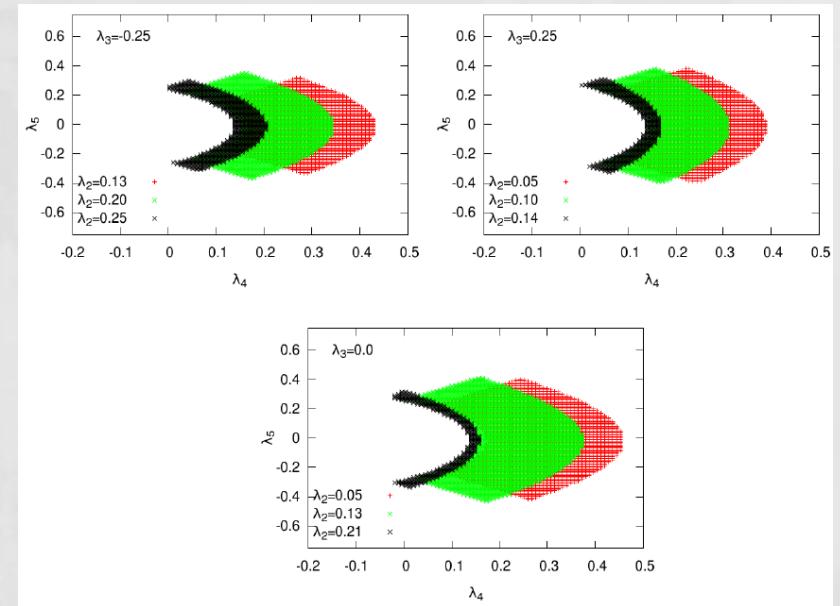
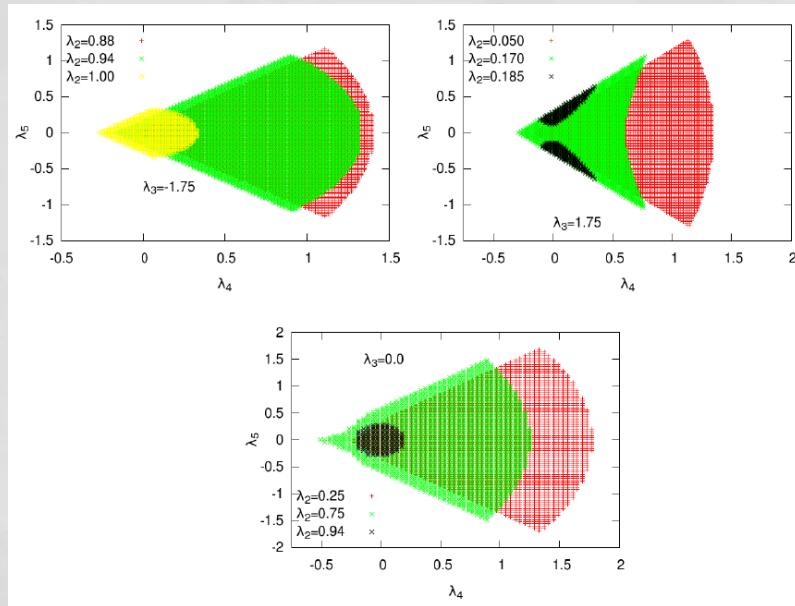
# RGE running

- An example



# Allowed ranges

	$10^5 \text{ GeV}$	$10^{10} \text{ GeV}$	$10^{19} \text{ GeV}$
$\lambda_2$	(0, 1)	(0, 0.5)	(0, 0.25)
$\lambda_3$	(-2.0, 2.4)	(-1.0, 1.25)	(-0.55, 0.62)
$\lambda_4$	(-0.5, 1.7)	(-0.1, 0.9)	(0, 0.5)
$\lambda_5$	(-1.5, 1.5)	(-0.7, 0.7)	(-0.4, 0.4)



# EWPD

- Triplet contribution to S, T & U:

Lavoura, Li, 9309262

$$S = -\frac{1}{3\pi} \ln \frac{m_{+1}^2}{m_{-1}^2} - \frac{2}{\pi} \sum_{T_3=-1}^{+1} (T_3 - Q s_W^2)^2 \xi \left( \frac{m_{T_3}^2}{m_Z^2}, \frac{m_{T_3}^2}{m_Z^2} \right)$$
$$T = \frac{1}{16\pi c_W^2 s_W^2} \sum_{T_3=-1}^{+1} (2 - T_3(T_3 - 1)) \eta \left( \frac{m_{T_3}^2}{m_Z^2}, \frac{m_{T_3-1}^2}{m_Z^2} \right)$$
$$U = \frac{1}{6\pi} \ln \frac{m_0^4}{m_{+1}^2 m_{-1}^2} + \frac{1}{\pi} \sum_{T_3=-1}^{+1} \left[ 2(T_3 - Q s_W^2)^2 \xi \left( \frac{m_{T_3}^2}{m_Z^2}, \frac{m_{T_3}^2}{m_Z^2} \right) \right.$$
$$\left. - (2 - T_3(T_3 - 1)) \xi \left( \frac{m_{T_3}^2}{m_W^2}, \frac{m_{T_3}^2}{m_W^2} \right) \right]$$
$$m_{+1,0,-1} = M_{H^{++}, H^+, H^0}$$

- Tree-level contribution is neglected ( $\mu \rightarrow 0$ ).

# EWPD

- Most recent STU fit:

Baak, et.al., 1209.2716

$$S_{\text{best fit}} = 0.03, \quad \sigma_S = 0.10$$

$$T_{\text{best fit}} = 0.05, \quad \sigma_T = 0.12$$

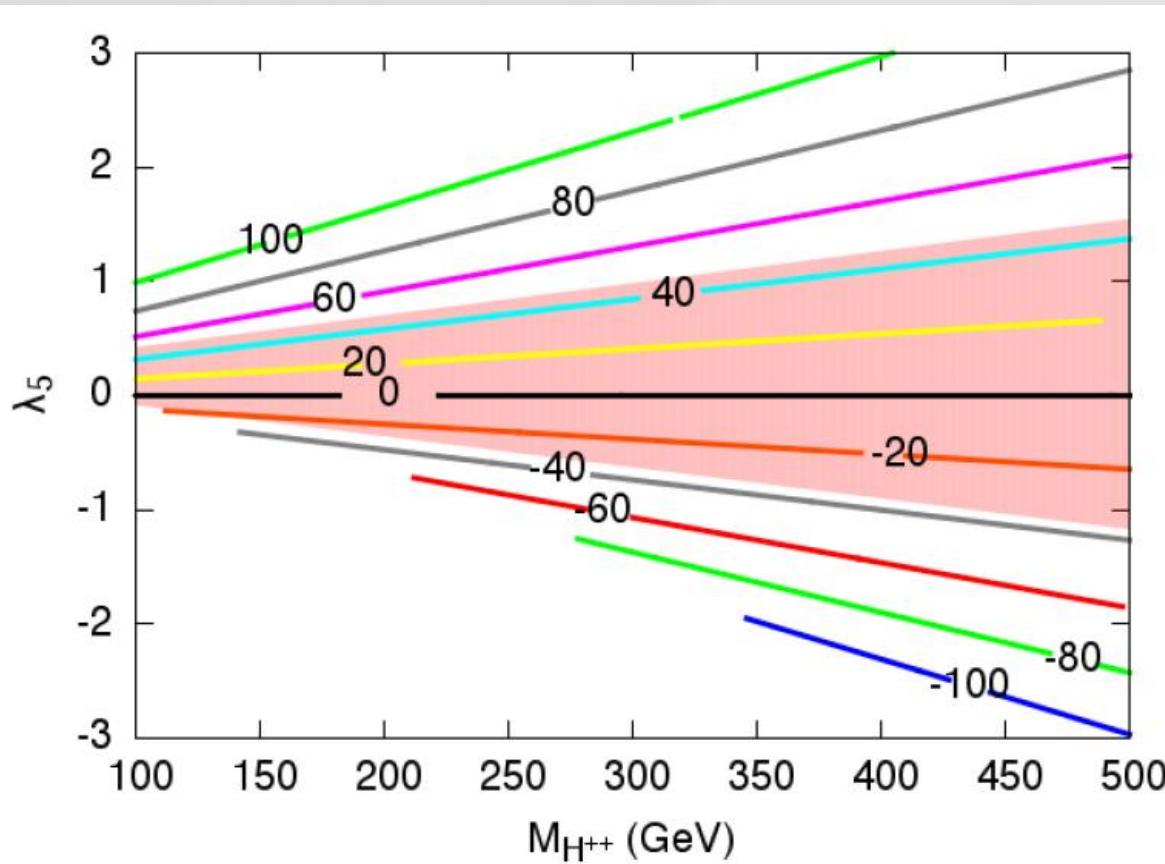
$$U_{\text{best fit}} = 0.03, \quad \sigma_U = 0.10$$

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

- 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

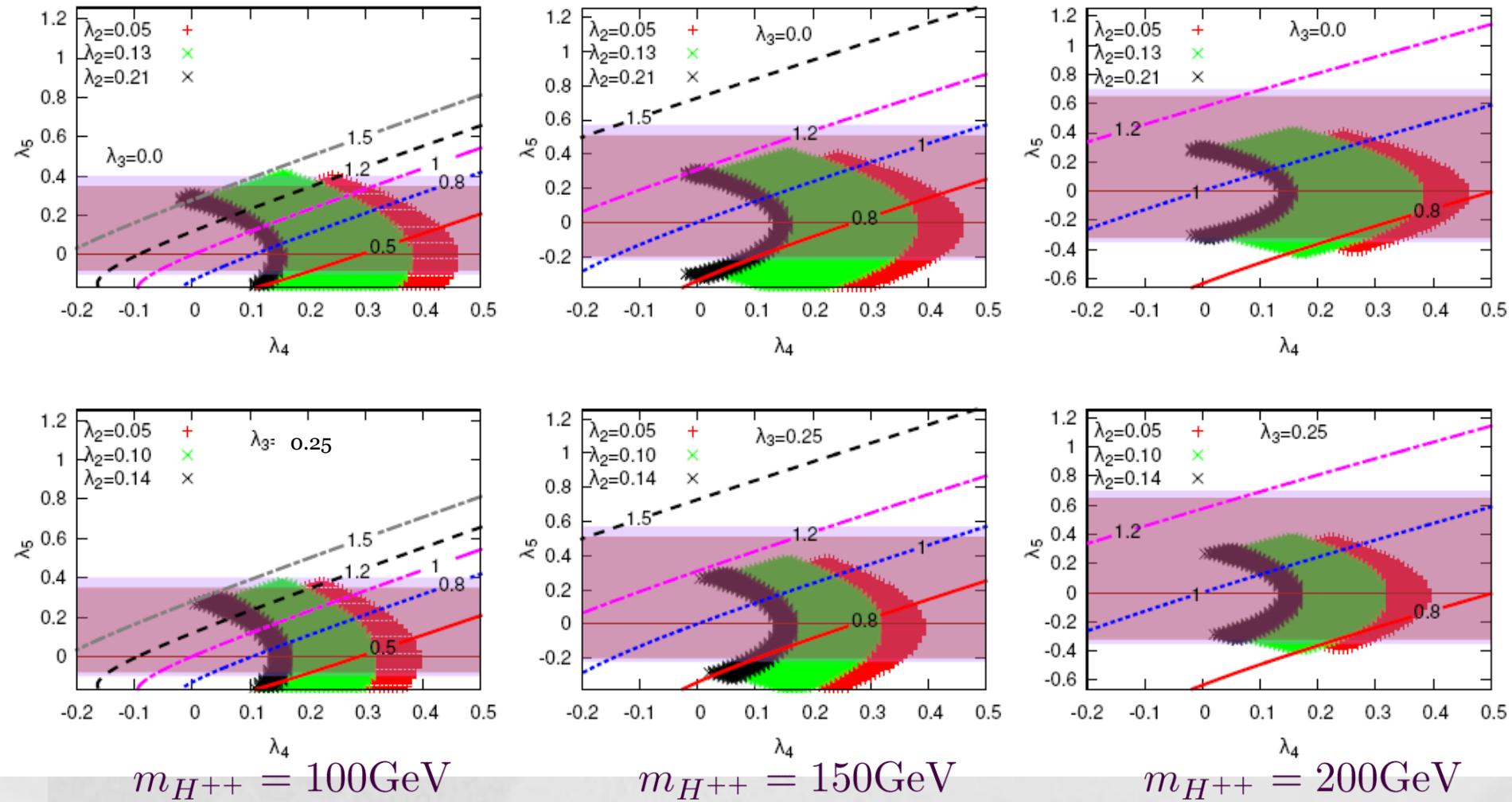


$|\Delta M| < 40 \text{ GeV}$

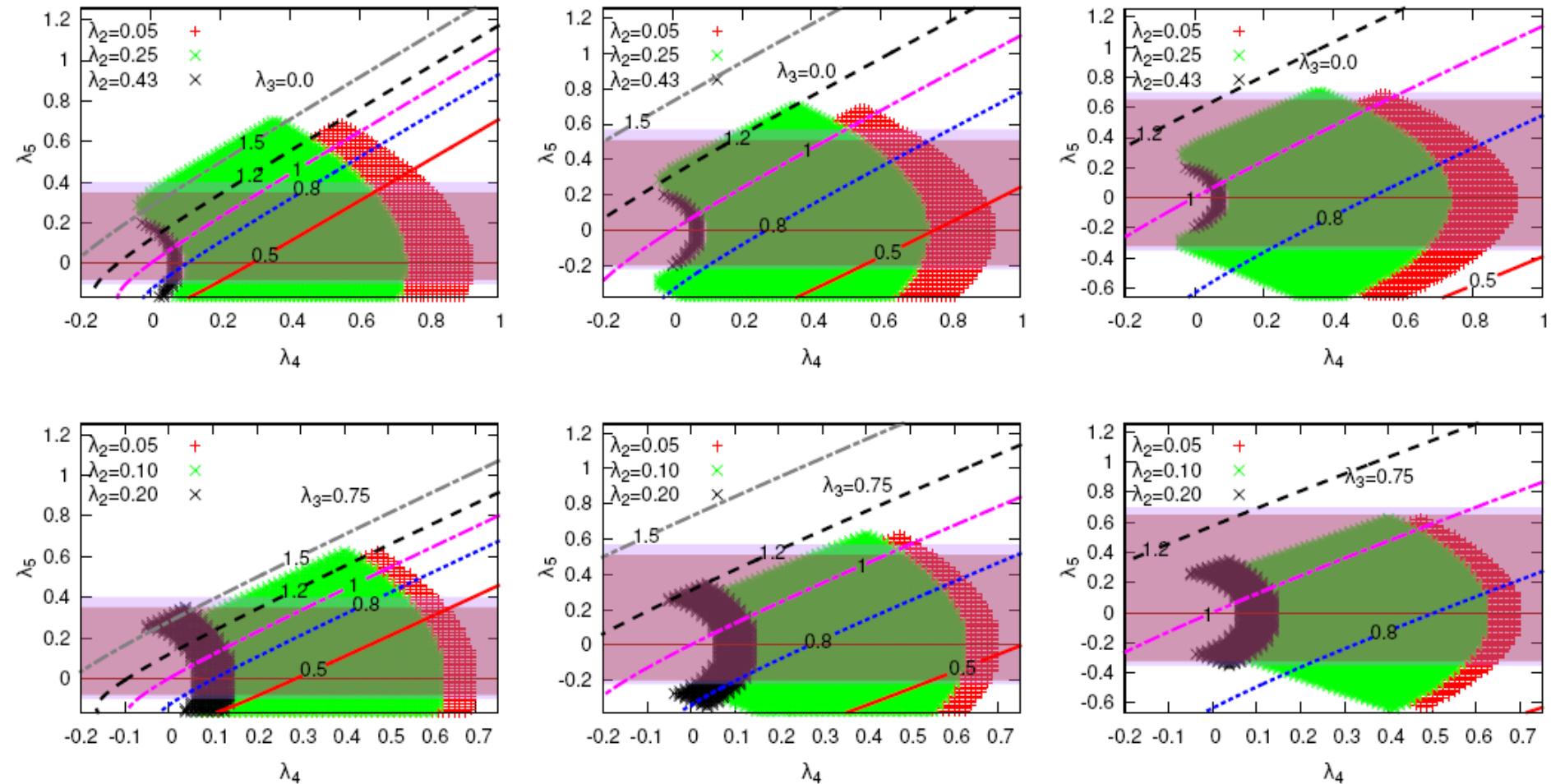
$$\lambda_5 = (-0.1, 0.4), \quad (-0.2, 0.6), \quad (-0.35, 0.7)$$

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

# Combined results for $10^{19}$ GeV



# Combined results for $10^{10}$ GeV

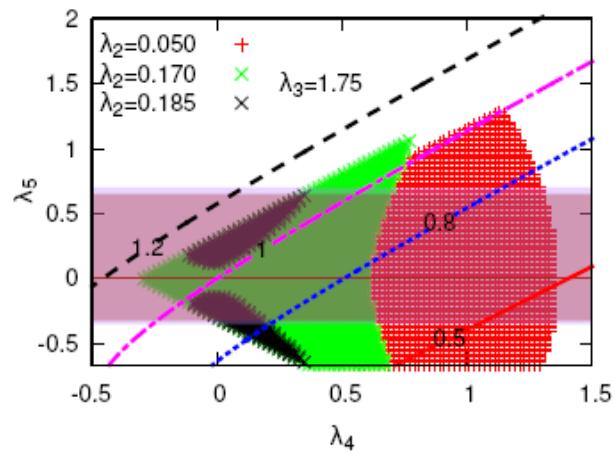
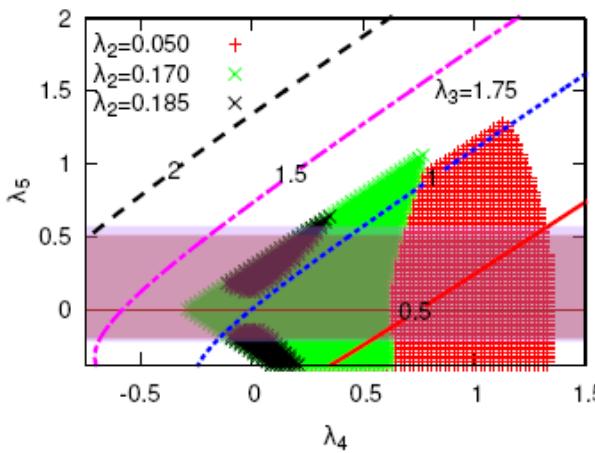
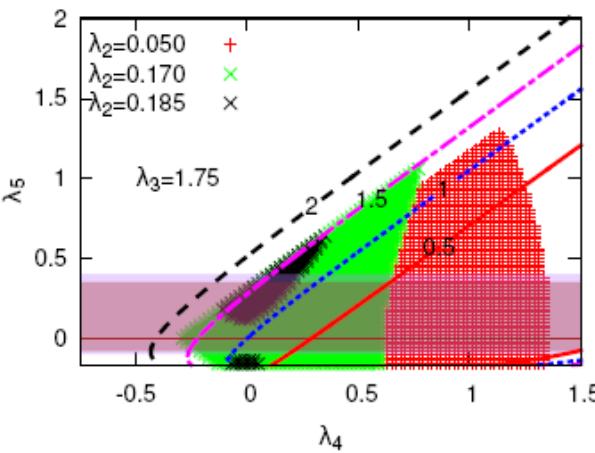
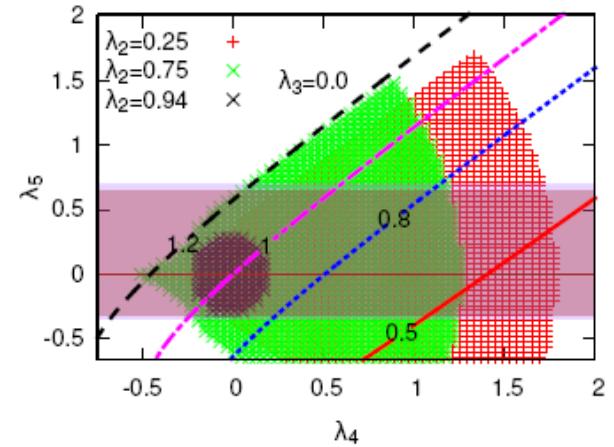
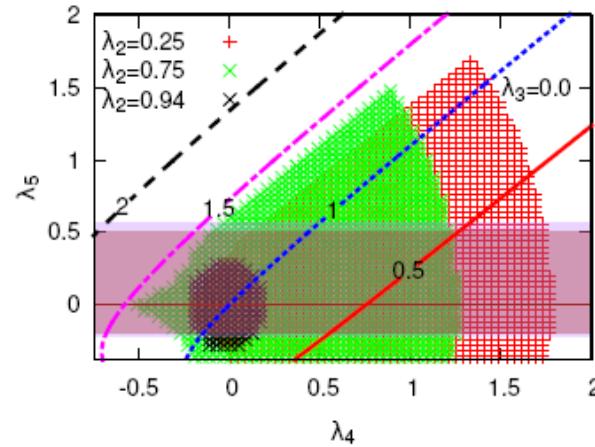
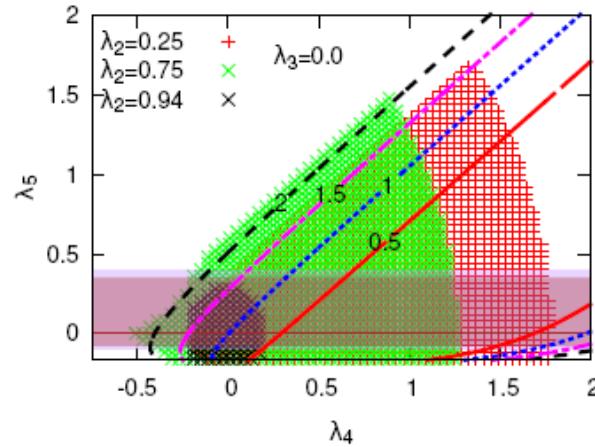


$m_{H^{++}} = 100\text{GeV}$

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

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

# Combined results for $10^5$ GeV



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

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

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

# Conclusion

- Great achievements from oscillation observation during past 15 years.
- Further Quest for the nature of neutrino mass: Dirac/Majorana, absolute scale, hierarchy
- Majorana mass models at TeV scale?
- LHC signatures of type I, II, III seesaws: SS2L, displacement, associated Higgs production.
- Peculiar type II: SS2L resonance, SS4L, Higgs-to-diphoton.

# Thank you