Workshop on High Energy Physics and Phenomenology
WHEPP13
December 12-21, 2013 Blue Lily Beach Resort Puri, Odisha, India

Neutrino – Theory Status

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

Eung Jin Chun

Outline

- Neutrino mass operators and observables
- Neutrino and New Physics
- Neutrino and Higgs
- Neutrino and DM/BAU
- Neutrino and LHC

Neutrino mass operators & observables

Neutrino mass operators

- SM allows simple extensions for neutrino mass operators:

$$L \approx H_d \; (\approx \epsilon H_u^\dagger)$$

- Dirac operator – renormalizable, $U(1)_L$ conserving.

$$\mathcal{L}_D = y_{ij}^D L_i H_u N_j \;\Rightarrow\; m_{ij}^D = y_{ij}^D v_H/\sqrt{2}$$

- Majorana operator – effective, $U(1)_L$ violating.

$$\mathcal{L}_M = \frac{y_{ij}^M}{M_X}(L_i H_u)(L_j H_u)/(L_i L_j)(H_u H_u)$$

Weinberg 1979

$$\Rightarrow\; m_{ij}^M = y_{ij}^M \frac{v_H^2}{M_X}$$

- No reason to forbid them → observed!

Neutrino parameters

- Three masses, three angles, 1+2 phases:

$$\begin{aligned} |\nu_e\rangle &= U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle \\ |\nu_\mu\rangle &= U_{\mu 1}|\nu_1\rangle + U_{\mu 2}|\nu_2\rangle + U_{\mu 3}|\nu_3\rangle \\ |\nu_\tau\rangle &= U_{\tau 1}|\nu_1\rangle + U_{\tau 2}|\nu_2\rangle + U_{\tau 3}|\nu_3\rangle \end{aligned}$$

$$m_1 \qquad m_2 \qquad m_3$$

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

atmoshperic reactor solar Majorana

$$\Delta m^2_{atm} = |m_3^2 - m_1^2| \qquad \Delta m^2_{sol} = m_2 - m_1^2$$

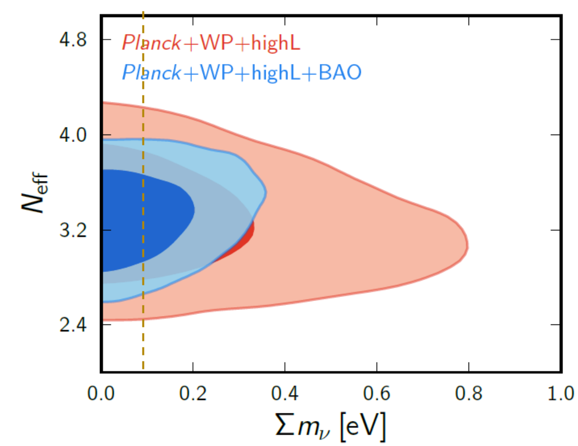
- Two Δm^2 + three angles measured precisely by oscillation experiments.

Measurements: present & future

Talks by Cheubey & Agarwala

Parameter	best-fit ($\pm 1\sigma$)	3σ	
$\Delta m^2_{\odot}$ [10^{-5} eV ^{2}]	$7.58^{+0.22}_{-0.26}$	6.99 – 8.18	2002
$\lvert\Delta m^2_A\rvert$ [10^{-3} eV ^{2}]	$2.35^{+0.12}_{-0.09}$	2.06 – 2.67	1998
$\sin^2\theta_{12}$	$0.306\ (0.312)^{+0.018}_{-0.015}$	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)	2012
$\sin^2\theta_{13}$ [142]	0.0251 ± 0.0034	0.015 – 0.036	

- Mass hierarchy: $m_3 > m_1$ or $m_1 > m_3$?
- CP violation?
- Majorana m_{ee}?
- Sum[m_i] from cosmology?

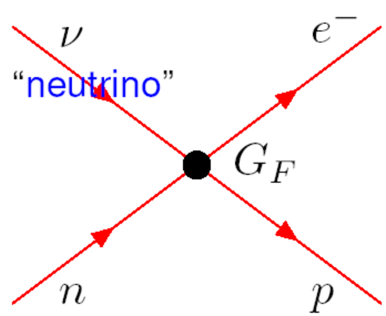


Neutrino & New Physics

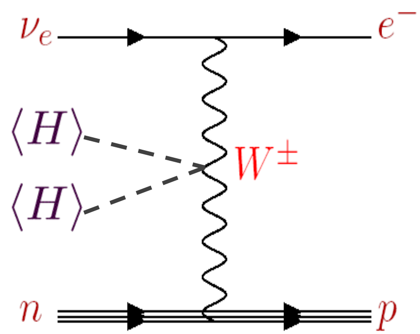
UV theory of neutrino mass operators

- From Fermi to EBH.

1933



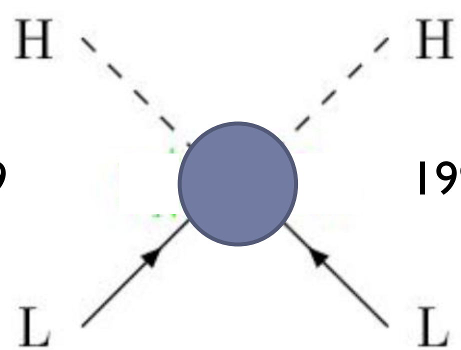
$$G_F = \frac{1}{\sqrt{2}v^2}$$



2012

- From Weinberg to …

1979



1998

?

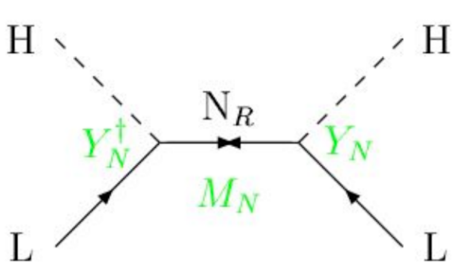
Dirac seesaw:
$y^D \sim v/M_X \sim 10^{-13}$
Dick, et.al., 9907462
EJC, Roy, 0803.1720

Majorana seesaw:
Arbitrary Yukawa with
M_X=keV-10^{15} GeV

Three Majorana Seesaws

Fermion Singlet (Type I)	Scalar Triplet (Type II)	Fermion Triplet (Type III)

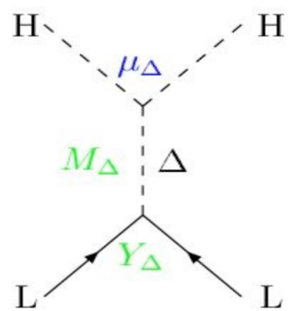
Fermion Singlet (Type I)



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

Y(N) =0

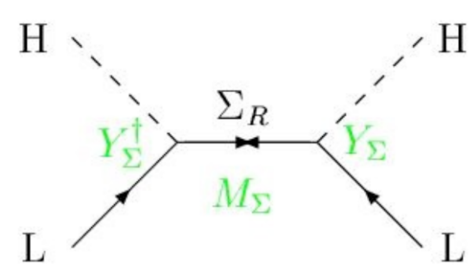
Scalar Triplet (Type II)



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

Y(Δ) =1

Fermion Triplet (Type III)



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

Y(Σ) =0

Type I/II in a gauge model

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

  $SU(2)_R$ breaking v_R giving heavy masses to N & W_R

- $U(1)'$: $c_1\, U(1)_\chi + c_2\, U(1)_\psi + c_3\, U(1)_Y$

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

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

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

$$\mathcal{L}_\nu = y_\nu HLN + \frac{1}{2} y_N SNN + h.c.$$

$$m_\nu = y_\nu \frac{v_H^2}{M_N} y_\nu^T$$

U(1)′ models

Erler, et.al., 1103.2659

Q'	q	$\bar{u}$	e^+	$\bar{d}$	l	$\bar{\nu}$	$\overline{D}$	L	D	$\overline{L}$	S
$2\,Q_R$	0	−1	+1	+1	0	−1	0	−1	0	1	0
$2\,Q_{\not d}$	0	+1	−1	0	+1	0	−1	0	0	−1	1
$2\,Q_I$	0	0	0	−1	−1	+1	1	1	0	0	−1
$2\sqrt{3}\,Q_{L_1}$	+1	0	+2	0	−1	+2	0	−1	−2	−1	2
$2\sqrt{3}\,Q_{R_1}$	0	−1	+1	−1	−2	+1	2	1	0	1	−2
$2\sqrt{3}\,Q_{\not p}$	0	−1	+1	+2	+1	−2	−1	−2	0	1	1
$2\sqrt{3}\,Q_{\not n}$	0	+2	−2	−1	+1	+1	−1	1	0	−2	1
$2\sqrt{6}\,Q_{B-L}$	+1	−1	+3	−1	−3	+3	2	0	−2	0	0
$2\sqrt{6}\,Q_{ALR}$	+1	−1	+3	+2	0	0	−1	−3	−2	0	3
$2\sqrt{6}\,Q_{\not L}$	+1	+2	0	−1	0	+3	−1	0	−2	−3	3
$2\sqrt{6}\,Q_\psi$	+1	+1	+1	+1	+1	+1	−2	−2	−2	−2	4
$2\sqrt{10}\,Q_\chi$	−1	−1	−1	+3	+3	−5	−2	−2	2	2	0
$2\sqrt{10}\,Q_N$	+1	+1	+1	+2	+2	0	−3	−3	−2	−2	5
$2\sqrt{15}\,Q_\eta$	+2	+2	+2	−1	−1	+5	−1	−1	−4	−4	5
$2\sqrt{15}\,Q_Y$	+1	−4	+6	+2	−3	0	2	−3	−2	3	0
$4\sqrt{15}\,Q_S$	−1	−1	−1	+8	+8	−10	−7	−7	2	2	5

$S H_u H_d$

if $Q'(S) \neq 0$

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:

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

- A peculiar signature of SS2L resonance from the doubly charged boson if f ~> v_Δ/v_Φ : $\Delta^{++} \xrightarrow{f_{\alpha\beta}} l_\alpha^+ l_\beta^+$

  → Determine the neutrino mass hierarchy at colliders!

EJC, Lee, Park, 0304069

Type II Yukawa after θ_{13}

- Neutrino oscillation data (assuming vanishing CP phases) determines the coupling f = M^ν/v_Δ:

NH IH

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

- Br(Δ^{++}) for di-lepton channels (100% for $v_\Delta < 10^{-4}$ 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

Q) Revisit the CP phase effect?

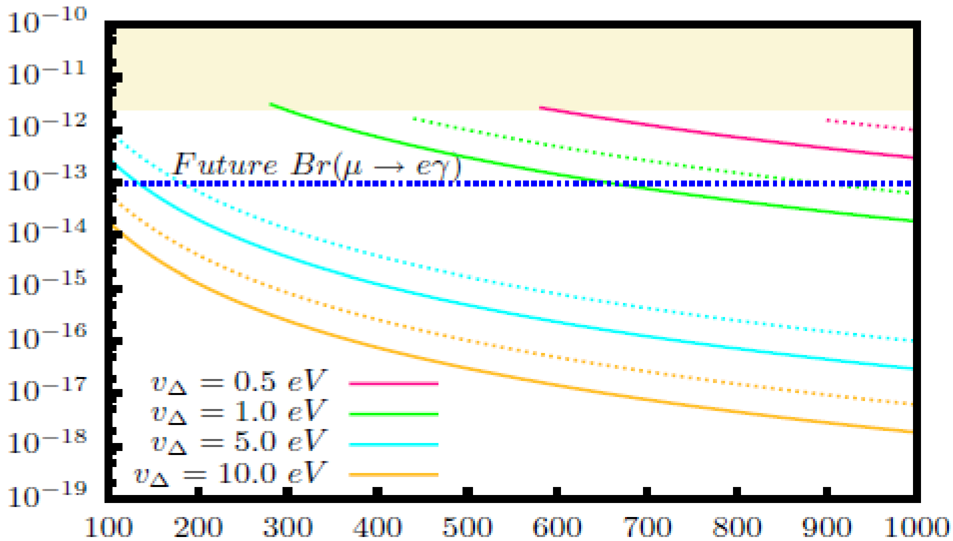
LFV after θ_{13}

Chakrabortty, Gosh, Redejohann, 1204.1000

- Correlations of LFV procedures in type II.

$$\mathrm{Br}(\mu \to e\gamma) = \frac{27\alpha}{256\pi G_F^2 M_{H^{\pm\pm}}^4} \frac{|(m_\nu m_\nu^\dagger)_{e\mu}|^2}{v_\Delta^4} \mathrm{Br}(\mu \to e\bar{\nu}\nu)$$

$$\mathrm{Br}(\mu \to 3e) = \frac{1}{16 G_F^2 M_{H^{\pm\pm}}^4} \frac{|(m_\nu)_{\mu e}|^2 |(m_\nu)_{ee}|^2}{v_\Delta^4} \mathrm{Br}(\mu \to e\bar{\nu}\nu)$$



$$m_{ee} m_{e\mu}^* < 0.025$$

$$(mm^\dagger)_{e\mu} < 1$$

EJC, Lee, Park, 0304069

Type III Seesaw

- SM + fermion triplets with Y=0:

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

- Additional Dirac & Majorana masses for leptons:

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

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

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

- l-Σ^-/ν-Σ^0 mixing

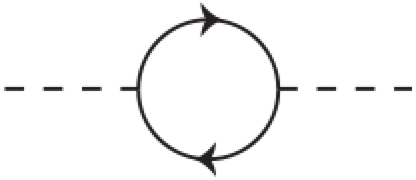
  → L-Σ gauge vertices $\propto g\, m_D/M \sim 10^{-6}$

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

Neutrino & Higgs

Natural Higgs mass?

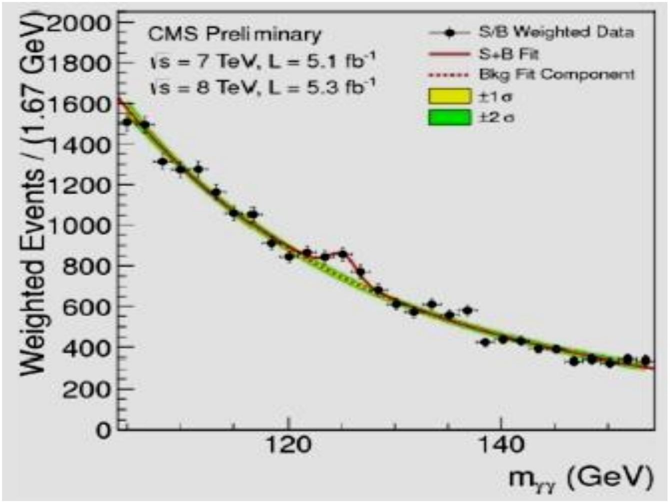
- 125 GeV Higgs at LHC questions the usual argument for NP through the hierarchy problem:



$$\delta m_h^2 = (-1)^F \frac{\lambda}{8\pi^2}\int^\Lambda \frac{d^4p}{p^2 - m^2}$$

$$= \frac{3}{8\pi^2 v^2}(4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2)\Lambda^2$$

$$= m_h^2 \left(\frac{\Lambda}{500\text{GeV}}\right)^2$$



- Λ can be a physical mass scale of a UV theory, *i.e.*, $\Lambda = M_X$.
- Naturalness with Higgs coupling to seesaw particles.

Low-scale seesaw natural?

- Seesaw particle contribution to Higgs mass:

$$\delta m_h^2 \lesssim m_h^2 \times \Delta$$

Farina, Pappadopulo, Strumia, 1303.7244

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

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

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

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

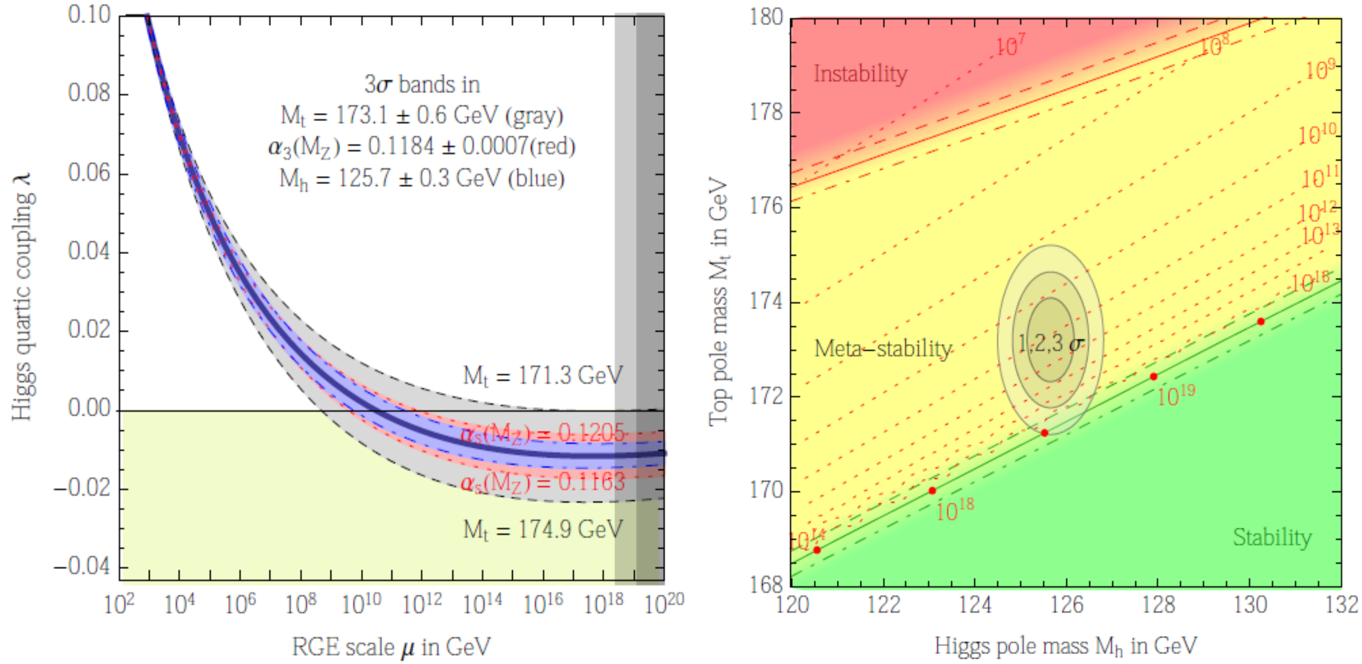
- Type III: $$\delta m^2 = \frac{g_2^4}{(4\pi)^4} M^2 (36 \ln \frac{M^2}{\bar\mu^2} - 6)$$

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

Higgs instability

- Higgs quartic turns to negative due to large y_t:

$$32\pi^2\frac{d\lambda_H}{dt} = 24\lambda_H^2-(3g_Y^2+9g^2-24y_t^2)\lambda_H+\frac{3}{8}g_Y^4+\frac{3}{4}g_Y^2g^2+\frac{9}{8}g^4-24y_t^4+\cdots$$



Degrassi, et.al., 1307.3536

Higgs instability in type II

- Higgs potential of type II – coupling of doublet and triplet:

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

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

Higgs instability in type II

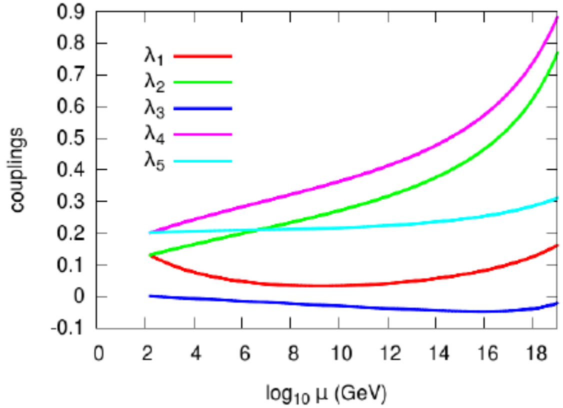
- 1-loop RGE in type II:

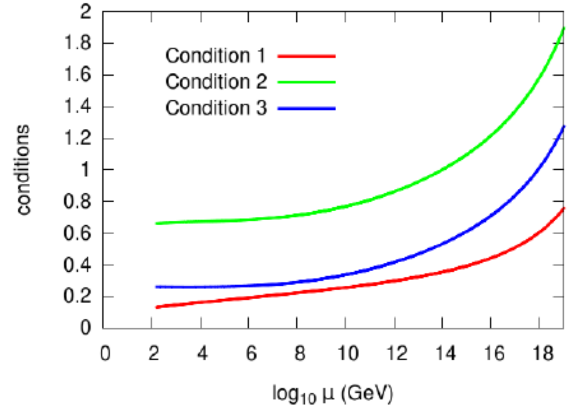
Chao, Zhang, 0611323
Schmidt, 07053841

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

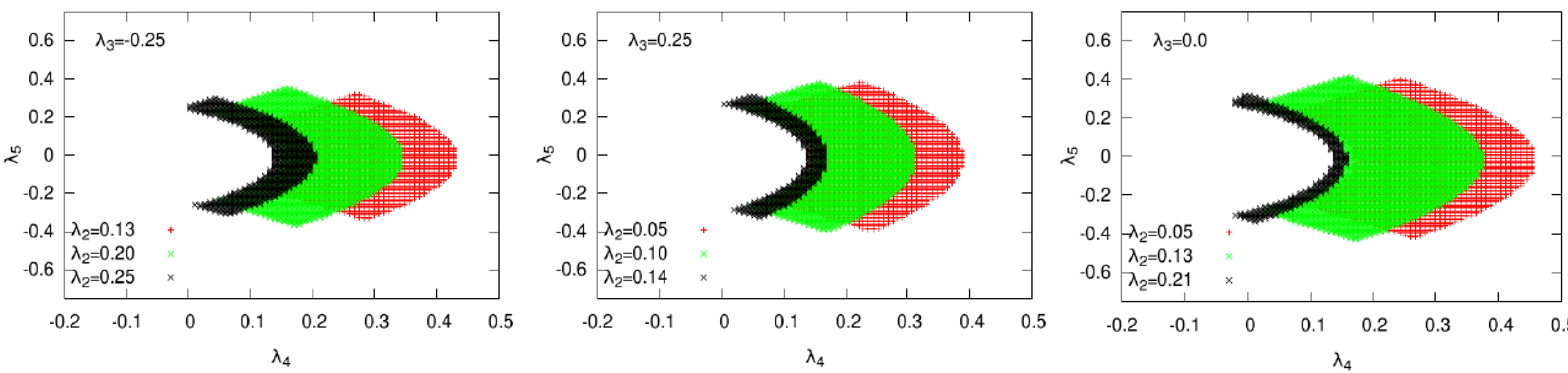
Higgs stability & perturvativity in type II

EJC, Lee, Sharma, 1209.1303





	10^{19} GeV
λ_2	$(0, 0.25)$
λ_3	$(-0.55, 0.62)$
λ_4	$(0, 0.5)$
λ_5	$(-0.4, 0.4)$

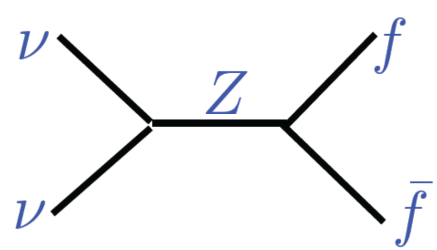


Neutrino & DM/BAU

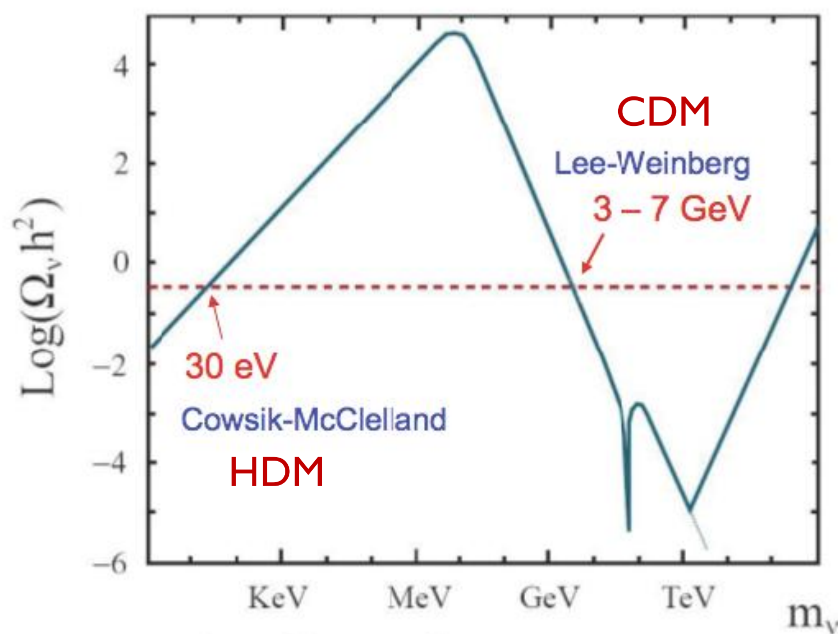
Neutrino as DM

- The standard weak interaction can generate a right amount of CDM for a10 GeV neutrino – WIMP.

Lee-Weinberg, 1977



$$\langle \sigma_w v \rangle \sim \frac{\alpha_w^2 m_{\nu_H}^2}{m_Z^4} \sim \frac{10^{-9}}{\mathrm{GeV}^2}$$



Neutrino-DM connection?

Leptogenesis I

Type I/III seesaw :

$$\mathcal{L} = yLH_2N + \tfrac{1}{2}MNN \qquad M^{\nu}_{ij} = y_{ik}y_{jk}\frac{\langle H_2\rangle^2}{M_k}$$

L asymmetry from N decay: CP phase in Y_ν.

$$\epsilon_1 = \frac{\Gamma(N_1\to LH_2)-\Gamma(N_1\to\bar{L}\bar{H}_2)}{\Gamma(N_1\to LH_2)+\Gamma(N_1\to\bar{L}\bar{H}_2)} = \frac{3}{8\pi}\frac{\sum_i \mathrm{Im}\left([(yy^\dagger)_{1i}]^2\right)}{(yy^\dagger)_{11}}\frac{M_1}{M_i}$$

$$\epsilon_1 \le \frac{M_1 m_{\nu_3}}{\langle H_2\rangle^2} \simeq 2\times 10^{-7}\left(\frac{M_1}{10^9\ \mathrm{GeV}}\right)\left(\frac{m_{\nu_3}}{0.05\ \mathrm{eV}}\right)$$

Davidson-Ibarra

L asymmetry converted to B asymmetry by Γ_{sp}

$$Y_B \equiv c_{sp}\frac{n_L - n_{\bar{L}}}{s} = c_{sp}\frac{n_N^{eq}}{s}\epsilon\eta \approx 0.1\frac{1}{g_*}\epsilon_1\eta \sim 10^{-10}$$

$g_* \sim 100$, $\eta<1$, $\varepsilon>10^{-7}$

M > 10^9 GeV

nb) $m_\nu, \epsilon \propto y^2$

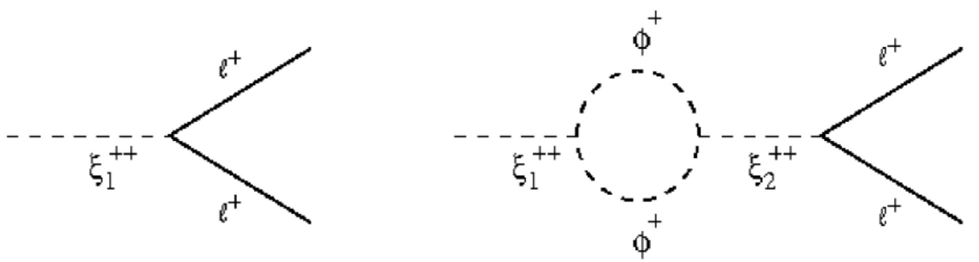
Leptogenesis II

Type II seesaw : $\mathcal{L} = f_{ij} L_i L_j \Delta + \mu H H \Delta + h.c.$

$$M^\nu_{ij} = f_{ij} v_\Delta = f_{ij} \mu \frac{v_H^2}{M_\Delta^2}$$

L asymmetry from $\Delta_{1,2}$ decay: CPV from mixing:

Ma-Sarkar



$$\delta_i \simeq \frac{Im\left[\mu_1 \mu_2^* \sum_{k,l} f_{1kl} f_{2kl}^*\right]}{8\pi^2 (M_1^2 - M_2^2)} \left[\frac{M_i}{\Gamma_i}\right]$$

$\Gamma \sim f^2 + \mu^2/M^2$

Davidson-Ibarra bound persists.

Efficiency

Efficiency η and K factor:

$$K \equiv \frac{\Gamma_D}{H(T{=}M)}$$

K >> 1 → η <<1 (strong wash-out regime) :

inverse-decay ($n_{eq}\Gamma_D$) decouples at T<M;
Boltzmann suppression.

K ∼ 1 → η ∼1 : out-of-equilibrium decay.

K << 1 → η <<1 (weak wash-out regime) :

weak neutrino Yukawa interaction;
inefficient thermalization of N.

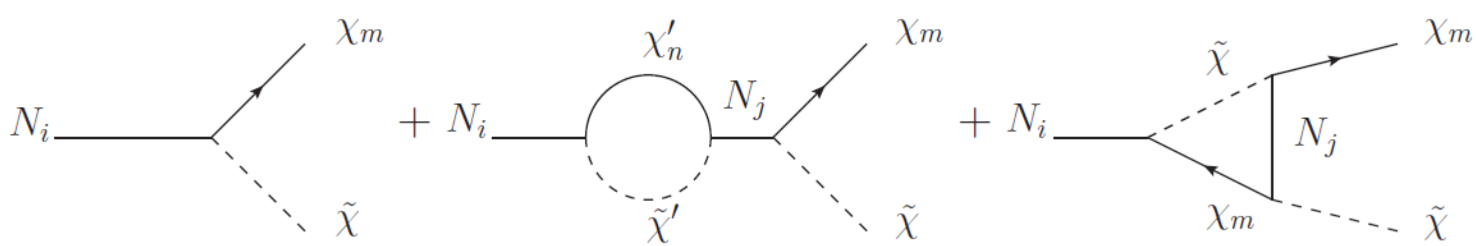
Gauge interaction reduces the efficiency.

TeV Leptogenesis

- Difficult to realize a low scale leptogenesis through CP asymmetry from neutrino Yukawas in type I (with U(1)′), II, III seesaw (K>>1 due to tiny $H \sim T^2/M_P$, and large gauge interaction).
- A common exercise: add new states unrelated neutrino mass generation in type I.

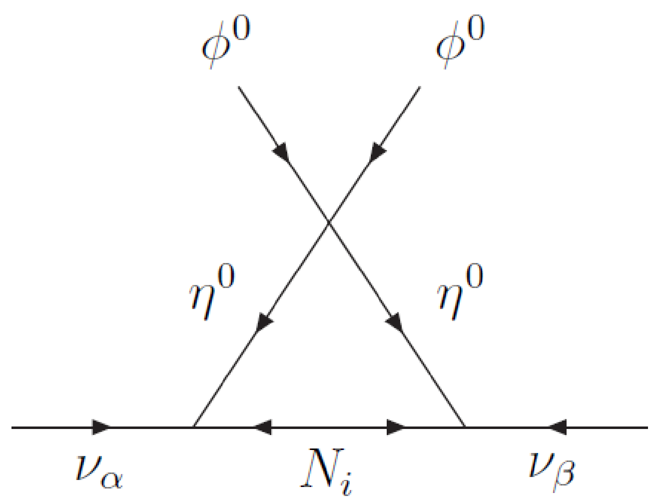
Fong, et.al., 1305.6312

$$-\mathcal{L}_{\tilde{\psi}} = \eta_{mi}\bar{\psi}_{Lm}N_i\,\tilde{\psi} + \sum_{\psi'\,\psi''} y_{mn}\bar{\psi}'_{Lm}\psi''_{Rn}\,\tilde{\psi} \;+\; \mathrm{h.c.}$$



Radiative seesaw and inert doublet DM

- Inert doublet for neutrinos: $y_\nu L H' N$. Ma, 0605180
- One-loop neutrino mass with $\lambda_5 (H^\dagger H')^2$.
- DM=H'_R lighter than H'_I : correct thermal density + direct detection bound.
- Leptogenesis for $M_1 > 10^7$ GeV.



Sub-GeV scenario

Canetti, Drewes, Shaposhnikov, 1204.3902

- No Higgs hierarchy problem.
- Seesaw/DM/BAU from sterile neutrinos.
- BAU from GeV $N_{2,3}$ through CP violating oscillations of sterile neutrinos ($Y_L = -Y_{Ls} \sim 10^{-10}$) at $T > T_{sph}$ if $\Delta M / M \sim 10^{-4\sim-6}$.

$$\hat{H} = V(t) + U \frac{\hat{M}^2}{2k(t)} U^\dagger$$

Akhmedov, Rubakov, Smirnov, 9810255

- keV N_1 DM production through MSW conversion in thermal plasma if $Y_L > 8\times10^{-6}$ at $T \sim 100$ MeV.

Shi, Fuller, 9810076

$$V_x = \frac{\delta m^2}{2E} \sin 2\theta, \quad V_y = 0, \quad V_z = -\frac{\delta m^2}{2E} \cos 2\theta + V_\alpha^L + V_\alpha^T$$

$$V_\alpha^L \approx 0.35 G_F T^3 \Big[L_0 + 2L_{\nu_\alpha} + \sum_{\beta\neq\alpha} L_{\nu_\beta}\Big]$$

Q) Consistent M_ν & $0\nu2\beta$?

Asymmetric Dark Matter

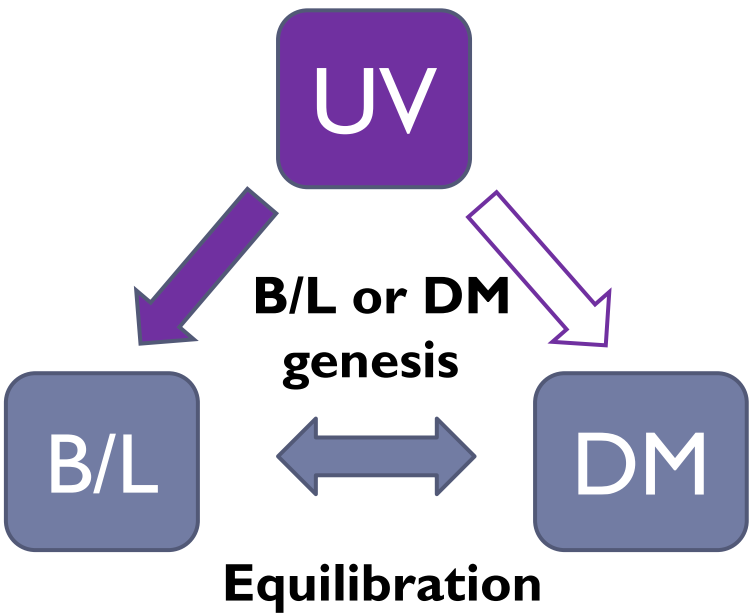
- $\Omega_{DM}/\Omega_B = 5$: coincidence?
- Postulate the same origin for matter-antimatter asymmetry & dark matter population.

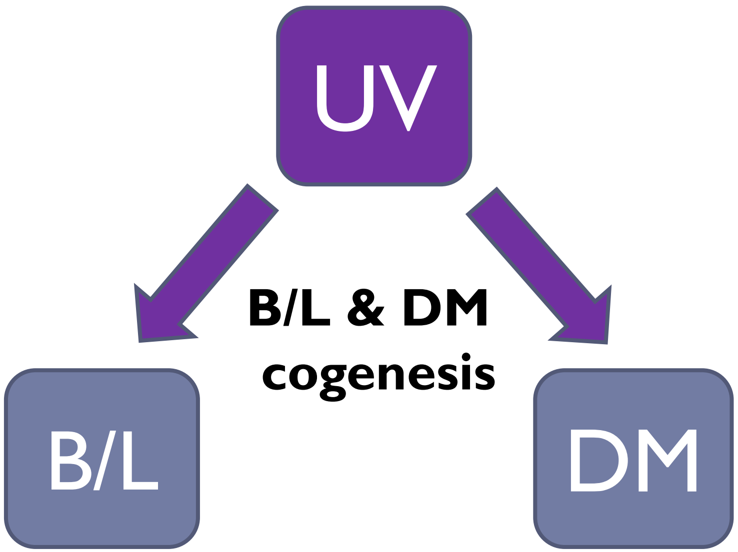
$$\Omega_{DM}/\Omega_B = m_{DM}Y_{DM}/m_B Y_B$$

i) $Y_{DM} \sim Y_B$, $m_{DM} \sim 5$ GeV for COGENT/DAMA

ii) $Y_{DM} \sim 0.05 Y_B$, $m_{DM} \sim 100$ GeV for usual WIMP

Scenarios


UV
B/L or DM
genesis
B/L
DM
Equilibration


UV
B/L & DM
cogenesis
B/L
DM

Techni-Baryon Asymmetry

- Consider a GUT group containing both the baryon sector and the techni-baryon sector.
- Asymmetries in both sectors can be assumed to arise from a heavy GUT particle decay: $Y_B = Y_{TB}$.

$$\rho_B = Y_B\, m_B, \quad \rho_{TB} = Y_{TB}\, m_{TB} = \rho_{DM}$$

$$\Omega_{DM}/\Omega_B = m_{TB}/m_B = 5 \text{ if } \Lambda_{TB}/\Lambda_B = 5$$

Nussinov, PLB, 1985

Equilibration of B-L & DM

Kaplan, et.al., 0911.4117

- Assume an initial B-L (or DM) asymmetry
- Add an interaction which equilibrate the dark matter asymmetry and the initial B-L asymmetry
- A conserved quanturm number: B-L+DM/2

  e.g., L H ←→ X X

Equilibration interaction

$$W = \frac{1}{M} L H_u X X + m_X X X^c$$

Interaction rate > Expansion rate

$$\Gamma \sim \frac{T^3}{8\pi M^2} > H \sim \frac{3T^2}{M_P}$$

Chemical equilibrium relation

$$X = -\frac{11}{79}(B-L), \;\; B = 0.3(B-L)$$

$$\frac{\Omega_{DM}}{\Omega_B} = \frac{m_X X}{m_B B} \Rightarrow m_X = 12\text{GeV}$$

Equilibration of B-L & DM

- Require the suppression of the symmetric component. → Annihilation rate much lager than the standard value for the thermal freeze-out relic density.

Assume a "strong" interaction:

$$W = \lambda_X S X X^c + \lambda_H S H_u H_d + \lambda_S S^3$$

$$X\bar{X} \leftrightarrow H_u H_d$$

$$\Omega_{X+\bar{X}} h^2 \approx 0.1 \frac{3\times 10^{-9}\mathrm{GeV}^{-2}}{\langle \sigma_A v\rangle}$$

Type I seesaw & EWDM asymmetry

- A simple model relating the origins of tiny neutrino masses, the baryon asymmetry and the DM density.
- Realize asymmetric EWDM with sub-TeV mass.
- Naturally suppressed symmetric density. $\Omega_{\rm SDM} h^2 \sim 0.1 \left(\frac{2{\rm TeV}}{m_{DM}} \right)^2$
- Copious production at the LHC.
- Clean singals of disappearing charged tracks & stable charged tracks.

An, et.al., 0911.4463
EJC, 1009.0983
Falkowski, et.al., 1101.4936
Haba, et.al., 1101.5679
EJC, 1102.3455

A simple Model

- Introduce a vector-like $SU(2)_L$ multiplet:

EJC, 1102.3455

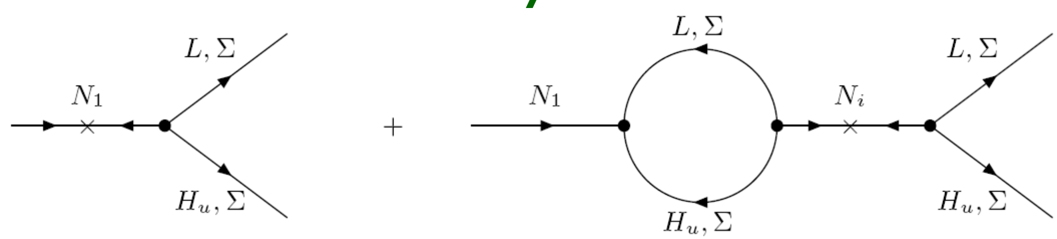
$$\Sigma, \Sigma^c \text{ with } Y = 0 \text{ and } T = 1, 2, 3, \cdots$$

$$W = y_i N_i L H_u + \frac{1}{2} h_i N_i \Sigma\Sigma + m_\Sigma \Sigma\Sigma^c + \frac{1}{2} M_i N_i N_i$$

- "Extended B-L" broken by M:

superfields	L	N	Σ	Σ^c	M
$B-L$	-1	1	$-\frac{1}{2}$	$\frac{1}{2}$	-2

- Asymmetries from N decay:



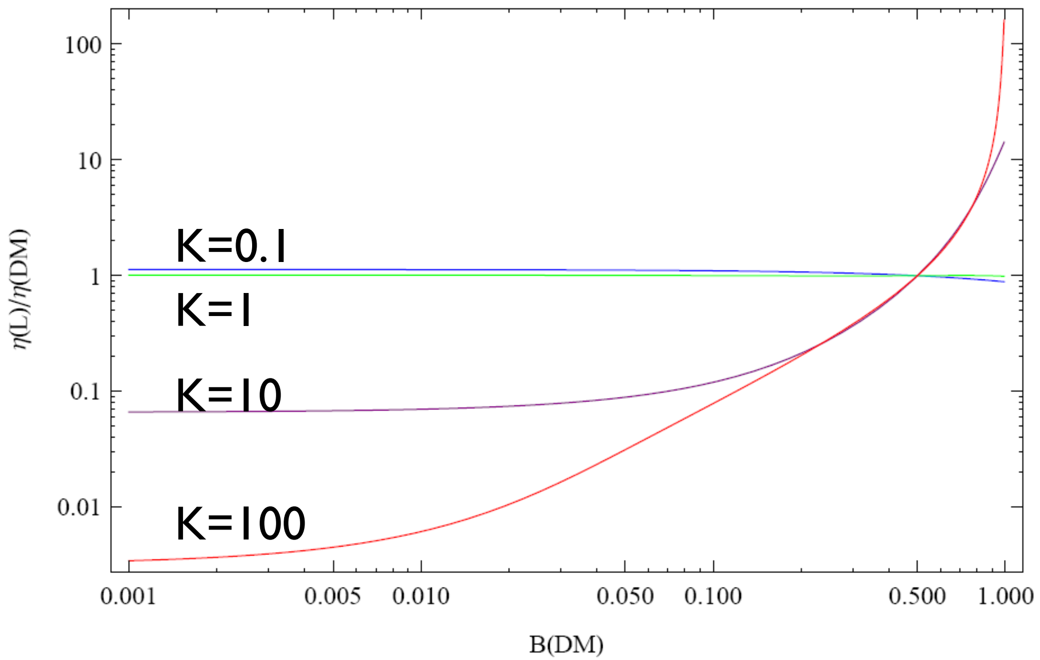
$$\varepsilon_L \approx \frac{1}{4\pi} \frac{\sum_i \mathrm{Im}[y_i y_1^* (y_i y_1^* + h_i h_1^*)]}{|y_1|^2 + \frac{3}{4}|h_1|^2} \frac{M_1}{M_i},$$

$$\varepsilon_{DM} \approx \frac{2}{4\pi} \frac{\sum_i \mathrm{Im}[h_i h_1^* (y_i y_1^* + h_i h_1^*)]}{|y_1|^2 + \frac{3}{4}|h_1|^2} \frac{M_1}{M_i},$$

$\Rightarrow$

$$Y_{L,DM} = \frac{315\zeta(3)}{4\pi^4 g_*} \varepsilon_{L,DM}\, \eta_{L,DM}$$

L/DM efficiency ratio



$$K = \frac{\Gamma_{N_1}}{H(T = M_{N_1})} \sim \frac{\tilde{m}_\nu}{10^{-3}\,\mathrm{eV}}$$

$$\frac{\varepsilon_{\rm DM}}{\varepsilon_{\rm L}} \approx 10^{-2}\,\frac{\eta_{\rm L}}{\eta_{\rm DM}}\,\frac{200\ \mathrm{GeV}}{m_{\rm DM}}$$

$$\frac{\Omega_{DM}}{\Omega_B} = \frac{m_{DM} Y_{DM}}{m_B Y_B} \approx \frac{31}{10}\,\frac{\varepsilon_{DM}}{\varepsilon_L}\,\frac{\eta_{DM}}{\eta_L}\,\frac{m_{DM}}{1\,\mathrm{GeV}}$$

Mass spectra of DM multiplets (T=1)

- Fermion: $(\Sigma^{\pm}\Sigma^{0})$

  Scalar: $(\tilde{\Sigma}^{\pm}_{1,2}, \tilde{\Sigma}^{0}_{1,2})$

- Mass specturm: $m_{\tilde{\Sigma}^0_1} > m_{\tilde{\Sigma}^\pm_1} > m_{\Sigma^\pm} > m_{\Sigma^0}$

D-term splitting ~ 1GeV

EW loop splitting ~ 0.1GeV

LHC Signatures

- Effective interaction below M:

$$\mathcal{L}_{eff} = \xi \nu \Sigma^{\pm} \tilde{\Sigma}^{\mp} \Leftarrow W_{eff} = \frac{yh}{2M} L H_u \Sigma\Sigma$$

$$\xi = \frac{yh\langle H_u^0 \rangle}{2M} \sim \frac{m_\nu}{\langle H_u^0 \rangle} \sim 10^{-12} \text{ for } m_\nu = 0.1\text{eV}$$

- Two kinds of long-lived charged particle tracks:

$$\tilde{\Sigma}^{\pm} \to \nu \Sigma^{\pm} \qquad \Sigma^{\pm} \to \pi^{\pm} \Sigma^0$$

$$\Gamma_{\tilde{\Sigma}^{\pm}} = \frac{\xi^2}{8\pi} m_{\tilde{\Sigma}^{\pm}} \qquad \Gamma_{\Sigma^{\pm}} = \frac{T(T+1)}{\pi} G_F^2 V_{ud}^2 \Delta m^3 f_\pi^3 \sqrt{1 - \frac{m_{\pi^{\pm}}^2}{\Delta m^2}}$$

$$\tau_{\tilde{\Sigma}^{\pm}} \sim 10^{-2}\text{sec} \qquad \tau_{\tilde{\Sigma}^{\pm}} \approx 106\text{cm}$$

Stable charged track — Disappearing charged tracks

- Multiply charged tracks for T=3,2:

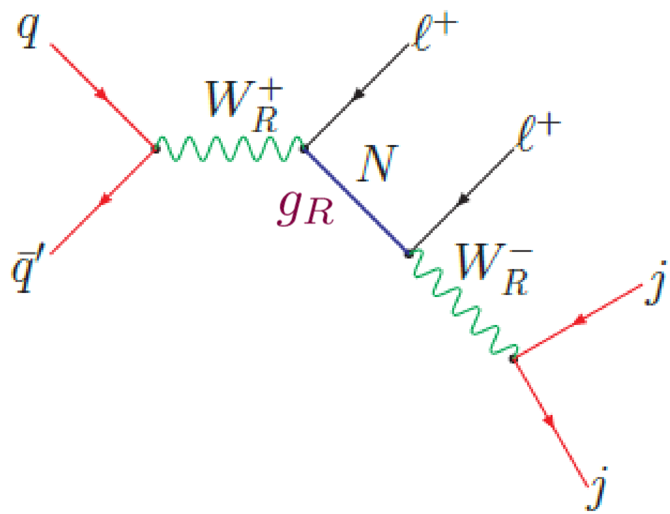
$$\tilde{\Sigma}^{\pm\pm\pm}, \; \tilde{\Sigma}^{\pm\pm} \qquad \Sigma^{\pm\pm\pm} \xrightarrow{\text{35cm}} \pi^{\pm} \Sigma^{\pm\pm} \xrightarrow{\text{18cm}} \pi^{\pm} \Sigma^{\pm}$$

Neutrino & LHC

LR & U(1)′ at LHC

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

Keung, Senjanovic, 1983



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

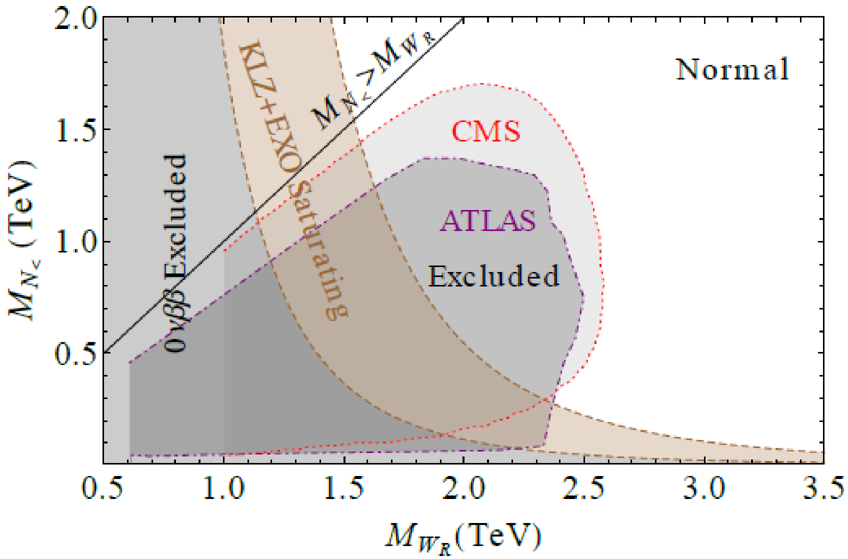
$$\theta_{\nu N} \sim \sqrt{\frac{m_\nu}{M_N}}$$

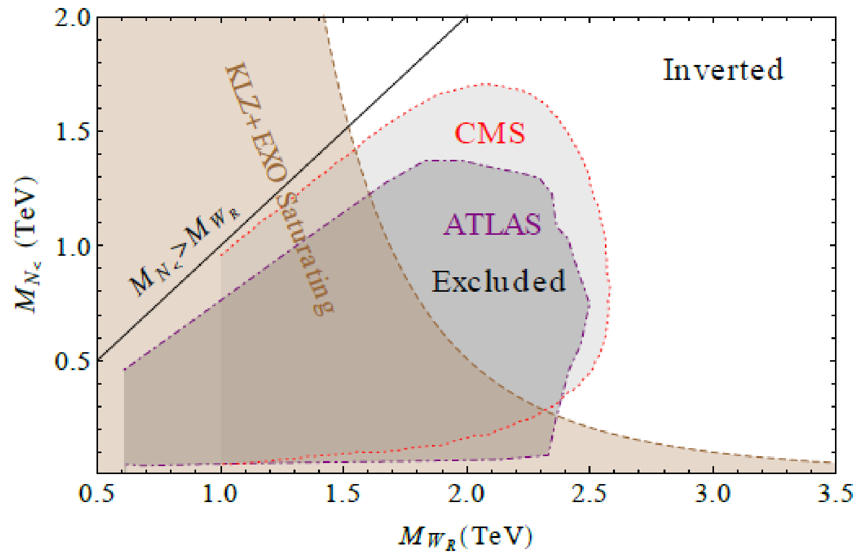
LR

U(1)′

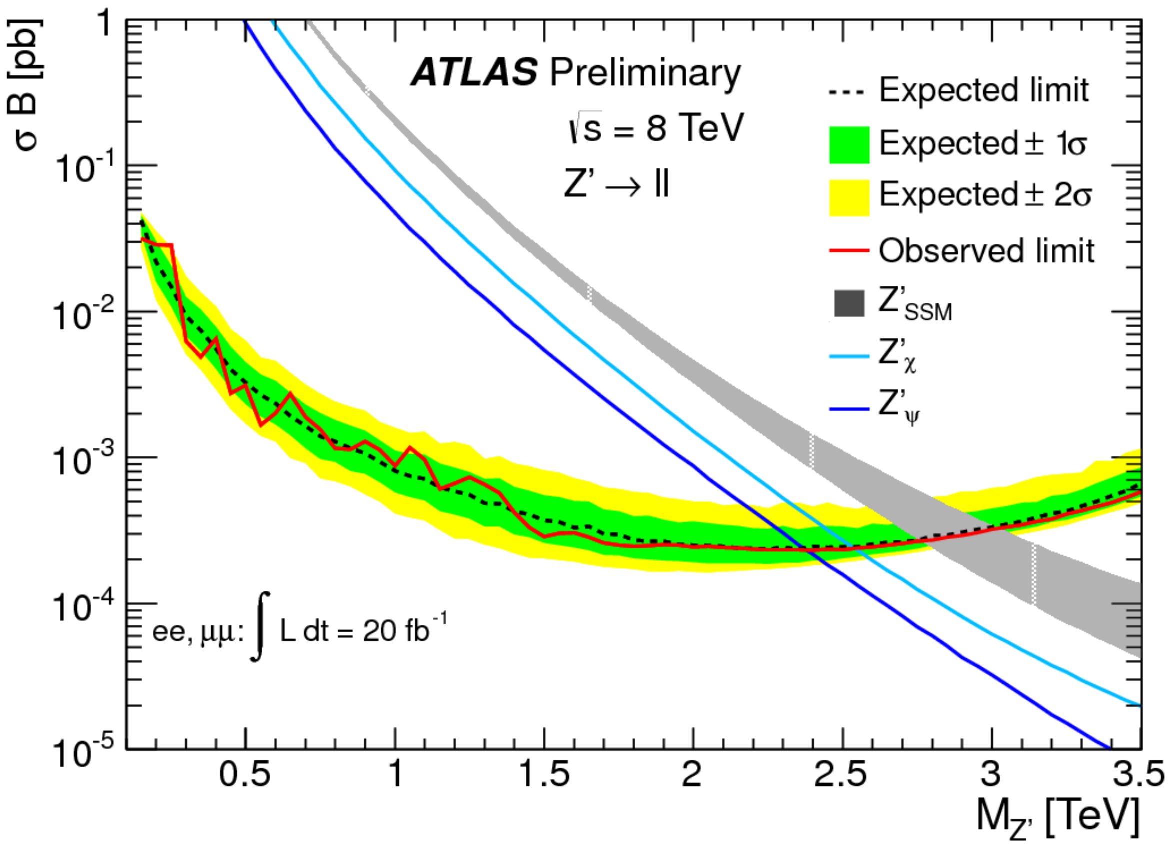
LHC+$0\nu2\beta$ search of LR model

Bhupal Dev, et.al., 1305.0056
Type II dominance



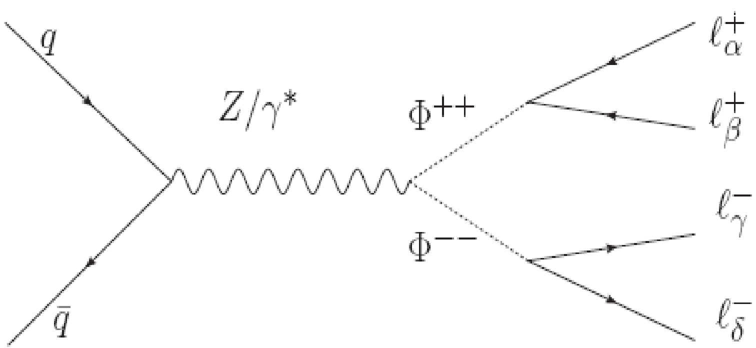


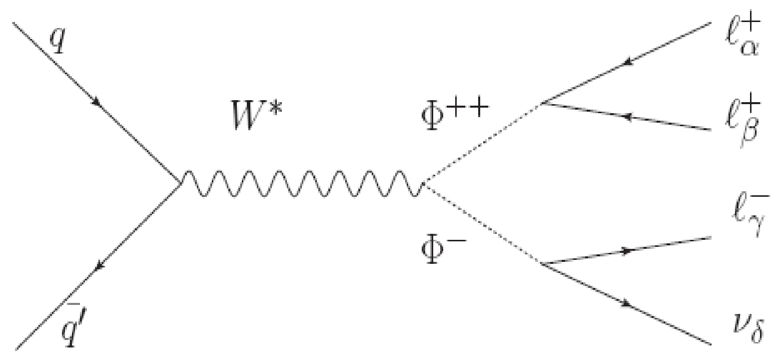
Z' search


ATLAS Preliminary
√s = 8 TeV
Z' → ll
Expected limit
Expected ± 1σ
Expected ± 2σ
Observed limit
Z'SSM
Z'χ
Z'ψ
ee, μμ: ∫ L dt = 20 fb-1
σ B [pb]
MZ' [TeV]
1
10-1
10-2
10-3
10-4
10-5
0.5
1
1.5
2
2.5
3
3.5

Multi-lepton signals in type II

- 4l (2xSS2L) from H^{++} H^{--} pair production.
- 3l from H^{++} H^{-} associated production if ΔM ~0.
- CMS looks for 4l or 3l events.
- ATLAS looks for SS2L resonances.





CMS search

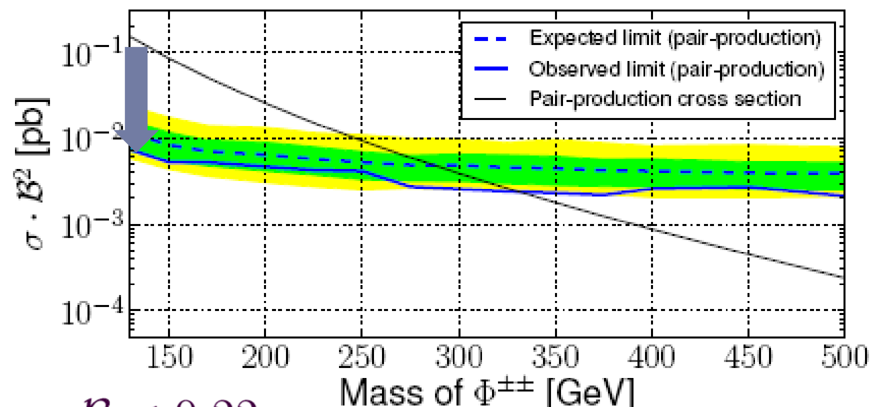
CMS, 1207.2666

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

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



$\mathcal{B} < 0.22$

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

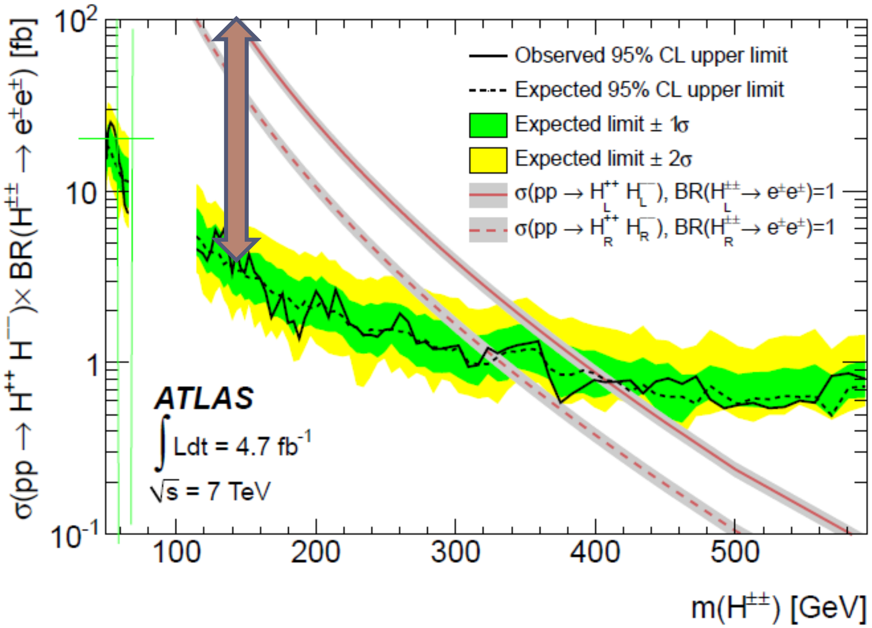
ATLAS search

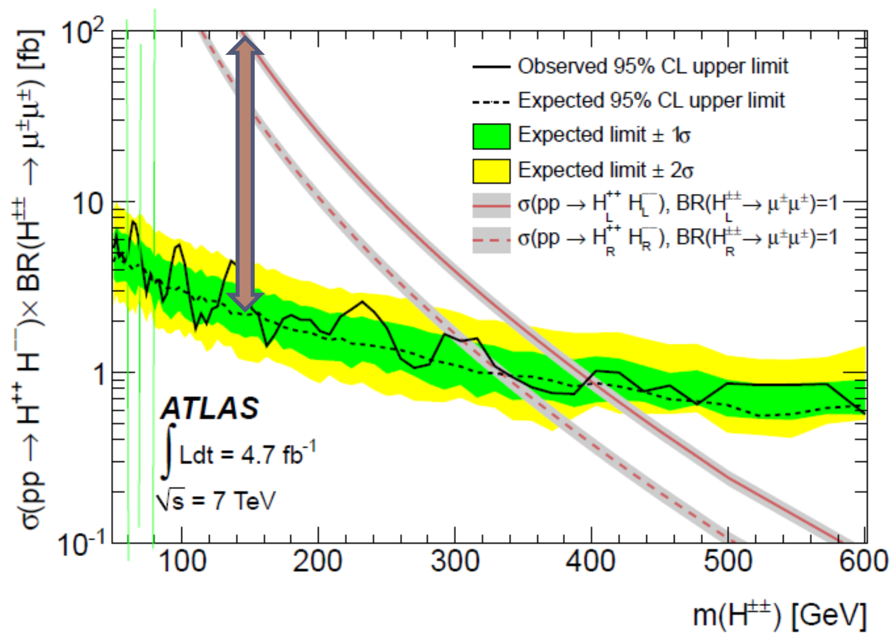
ATLAS, 1210.5070

$\mathrm{BR}(H_L^{\pm\pm} \to \ell^\pm \ell'^\pm)$	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

$\mathrm{NH}: \mathrm{BR}(\mu\mu) \approx 27\%$

$\mathrm{IH}: \mathrm{BR}(ee) \approx 47\%$

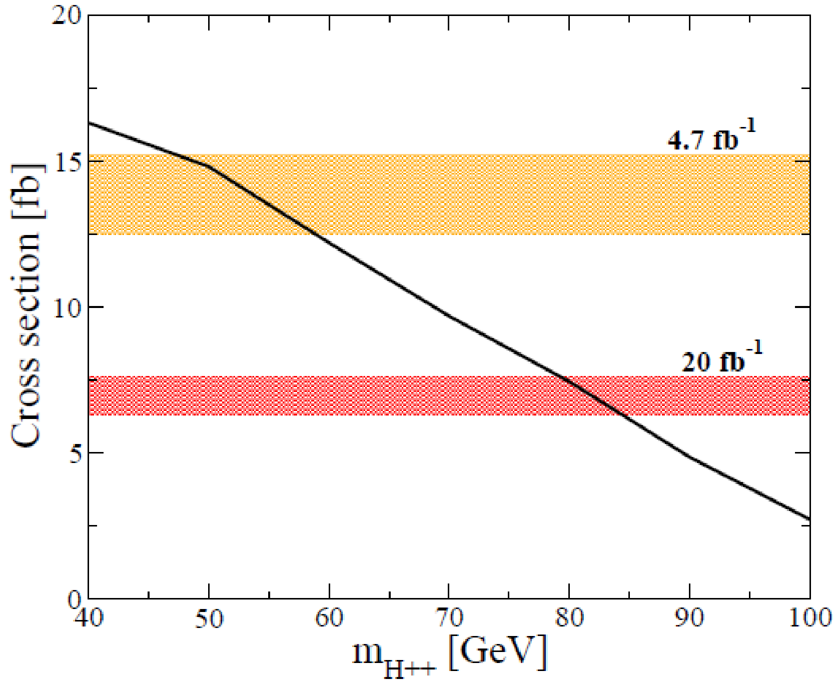




$H^{++} \to W^{+} W^{+}$ search

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

Kanemura, Yagyu, Yokoya, 1305.2383



Q) LEP limit from multi-jet final states?

Type III Seesaw

- SM + fermion triplets with Y=0:

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

- Additional Dirac & Majorana masses for leptons:

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

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

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

- l-Σ^-/ν-Σ^0 mixing

  → L-Σ gauge vertices $\propto g\, m_D/M \sim 10^{-6}$

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

LHC signatures

- Σ decay: $\Sigma^{\pm} \to l^{\pm}h, l^{\pm}Z, \nu W^{\pm}$

  $$\Sigma^0 \to \nu h, \nu Z, l^{\pm}W^{\mp}$$

Franceschini, et.al. 0805.1613

- Σ production: $pp \to \Sigma^+\Sigma^-,\ \Sigma^{\pm}\Sigma^0$
- Four lepton final states at ATLAS

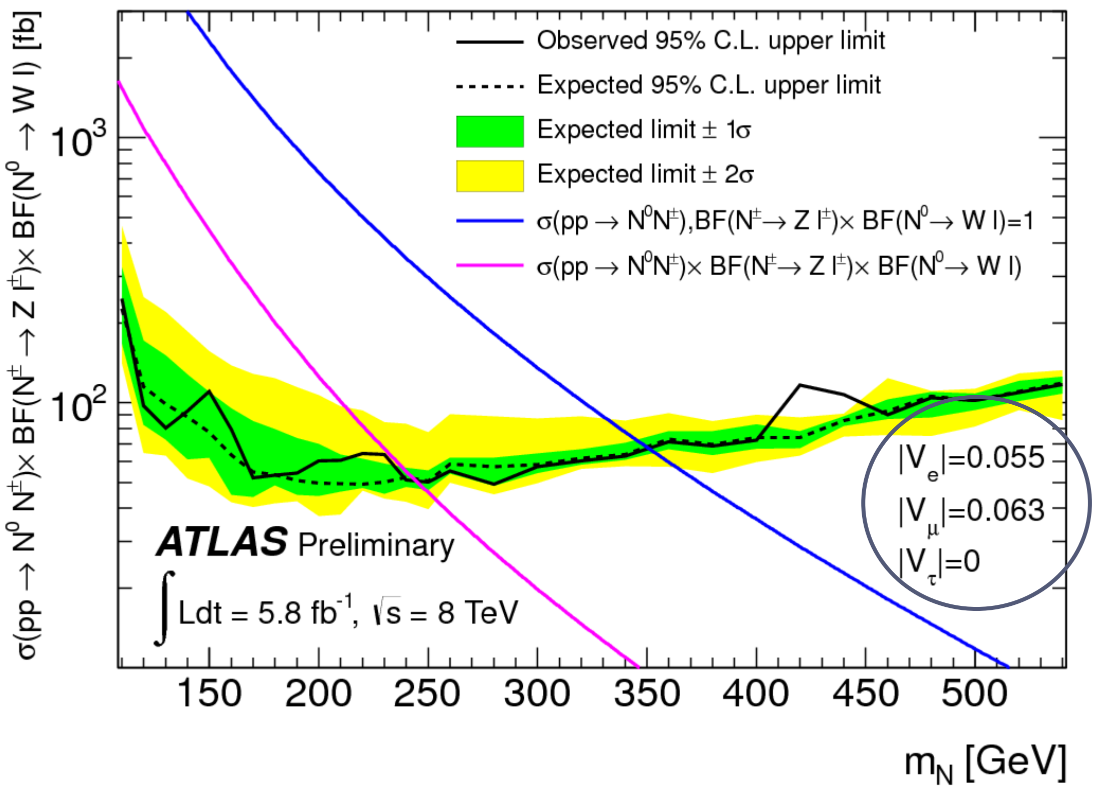
  $$pp \to \Sigma^{\pm}\Sigma^0 \to l^{\pm}Z(l\bar{l})l^{\pm}W^{\mp}(jj')$$

- Higgs production associated with charged leptons:

  $$pp \to \Sigma^{\pm}\Sigma^0 \to l^{\pm}l^{\pm}hW^{\mp}$$

Bandyopadhyay, Choi, EJC, Kang, 1112.3080

ATLAS search



Conclusion

- Great achievements from oscillation observation during past 15 years.
- Further Quest for the nature of neutrino mass: Dirac/Majorana, absolute scale, hierarchy & CPV.
- Neutrino-DM/BAU connection: leptogenesis+ADM.
- Majorana mass models at TeV scale?
- LHC signatures of type I, II, III seesaws: SS2L, displacement, associated Higgs production.
- LHC13/14 continues to probe the neutrino signals.
- More for peculiar type II: SS2L resonance, SS4L, Higgs-to-diphoton.

Neutrino & LHC – More on Type II

- Same-sign tetra-leptons. EJC & Sharma, 1206.6278

  Triplet-antitriplet oscillation

- Higgs boson Phenomenology. EJC, Lee & Sharma, 1209.1303

  EWPD

  Perturbativity & vacuum stability

  Higgs-to-diphoton rate

- General study in (v_Δ, ΔM). EJC & Sharma, 1309.6888

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:

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

- A peculiar signature of SS2L resonance from the doubly charged boson if f ~> v_Δ/v_Φ : $\Delta^{++} \xrightarrow{f_{\alpha\beta}} l_\alpha^+ l_\beta^+$

  → Determine the neutrino mass hierarchy at colliders!

EJC, Lee, Park, 0304069

Type II Yukawa after θ_{13}

- Neutrino oscillation data (assuming vanishing CP phases) determines the coupling f = M^ν/v_Δ:

NH IH

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

- Br(Δ^{++}) for di-lepton channels (100% for $v_\Delta < 10^{-4}$ 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

Q) Revisit the CP phase effect at LHC?

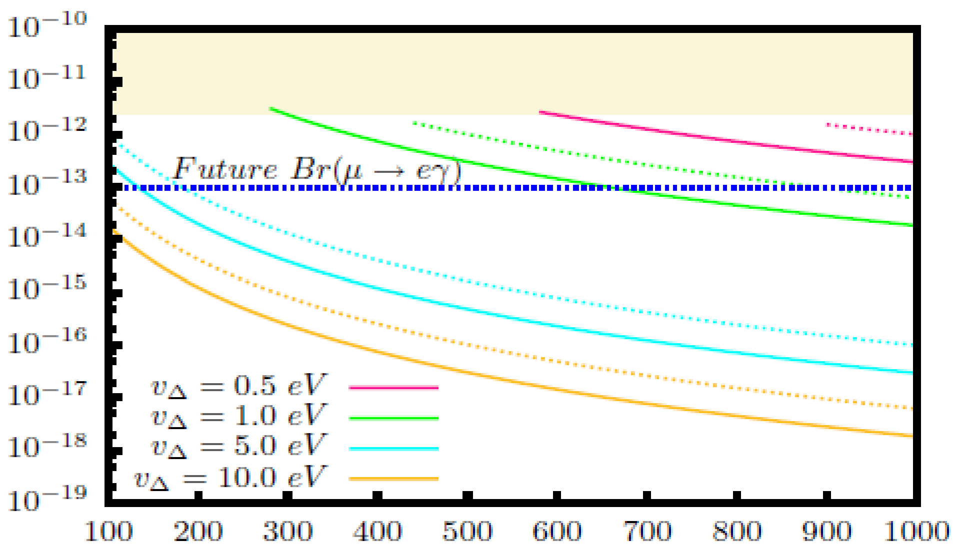
LFV after θ_{13}

Charkrabortti, Gosh, Redejohann, 1204.1000

- Correlations of LFV procedures in type II.

$$\mathrm{Br}(\mu \to e\gamma) = \frac{27\alpha}{256\pi G_F^2 M_{H^{\pm\pm}}^4} \frac{|(m_\nu m_\nu^\dagger)_{e\mu}|^2}{v_\Delta^4} \mathrm{Br}(\mu \to e\bar{\nu}\nu)$$

$$\mathrm{Br}(\mu \to 3e) = \frac{1}{16 G_F^2 M_{H^{\pm\pm}}^4} \frac{|(m_\nu)_{\mu e}|^2 |(m_\nu)_{ee}|^2}{v_\Delta^4} \mathrm{Br}(\mu \to e\bar{\nu}\nu)$$



$$m_{ee} m_{e\mu}^* < 0.025$$
$$(m m^\dagger)_{e\mu} < 1$$

EJC, Lee, Park, 0304069

Type II 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

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

Doublet-triplet 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: $\xi << 0.01$.
- (note) ρ parameter constraint:

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

Triplet scalar spectrum

- Mass gap among triplet components:

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

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

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

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

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

- 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 ΔM (λ_5):

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

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

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

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

- Di-quark/di-boson decays through ξ:

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

Δ-$\bar{\Delta}$ Oscillation

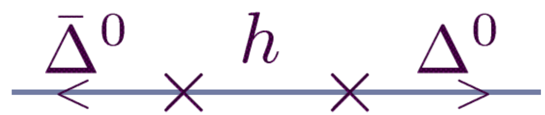
EJC & Sharma, 1206.6278

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

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

- Triplet number breaking by doublet-triplet mixing:

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



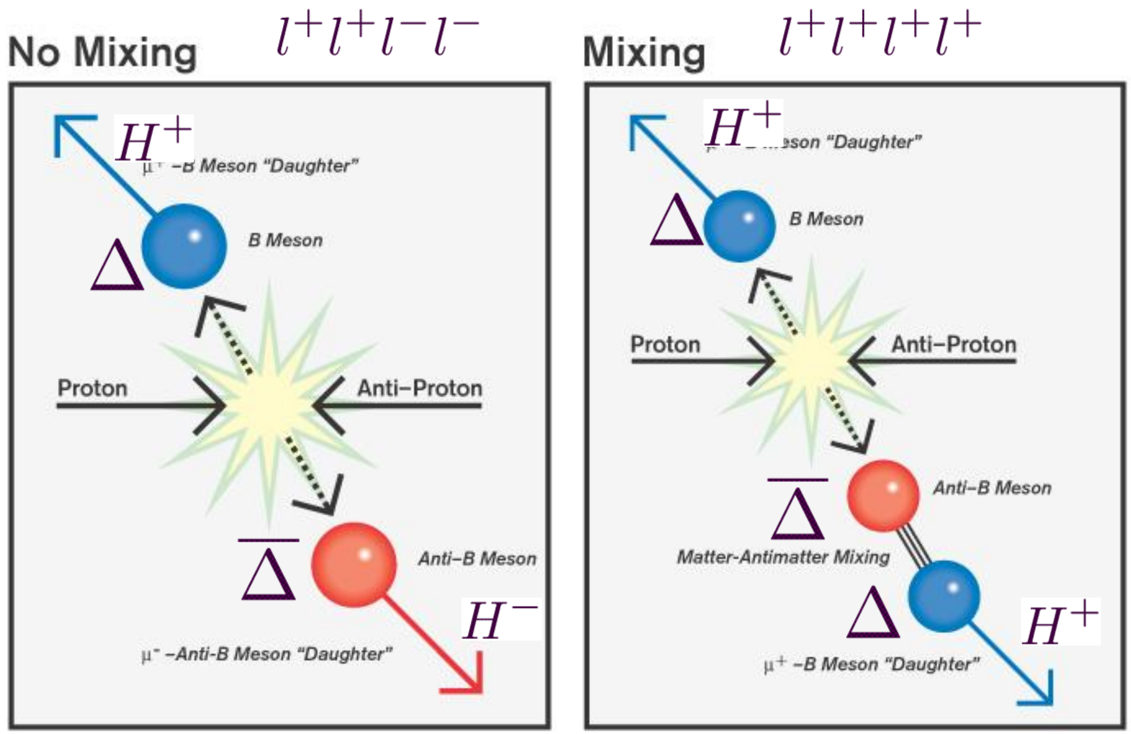
- It induces a tiny mass splitting between H⁰ & A⁰ :

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

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

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

Δ-$\overline{\Delta}$ Oscillation



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

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

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

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

Same-Sign Tetra-Leptons

- Lepton number violating processes:

$$pp \to \Delta^0 \bar{\Delta}^0 \Rightarrow \Delta^0 \Delta^0 \to H^+ H^+ 2W^- \to H^{++} H^{++} 4W^-$$
$$\Delta^+ \bar{\Delta}^0 \Rightarrow \Delta^+ \Delta^0 \to H^{++} H^+ 2W^- \to H^{++} H^{++} 3W^-$$

- 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.

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

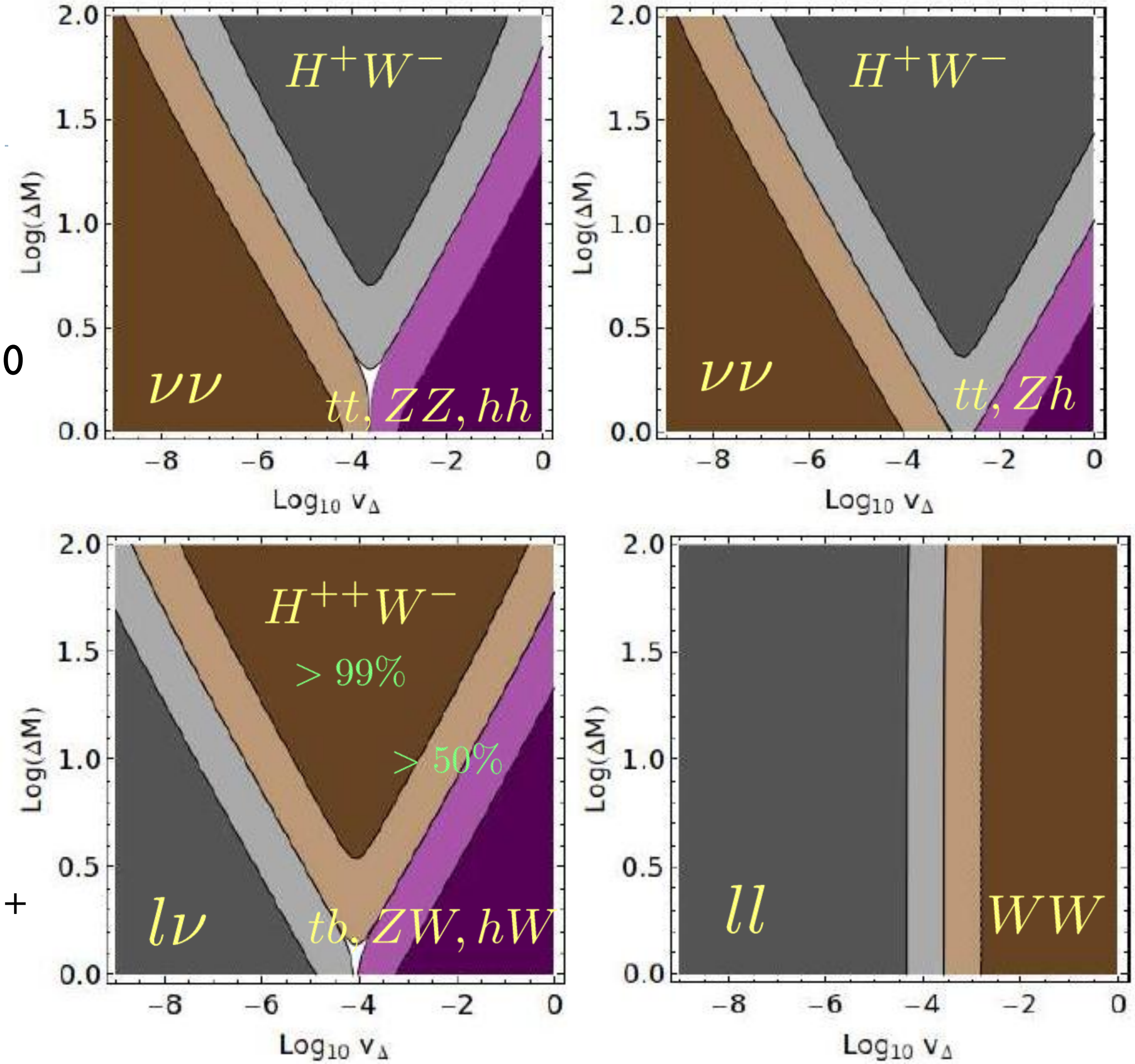
$$v_\Delta \sim 10^{-4}\text{GeV}, \quad \Delta M \sim 2\text{GeV} \quad \Rightarrow \delta M_{HA} \sim \Gamma_{H^0/A^0} \sim 10^{-11}\text{GeV}$$

Triplet decay channels

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

H^0

A^0

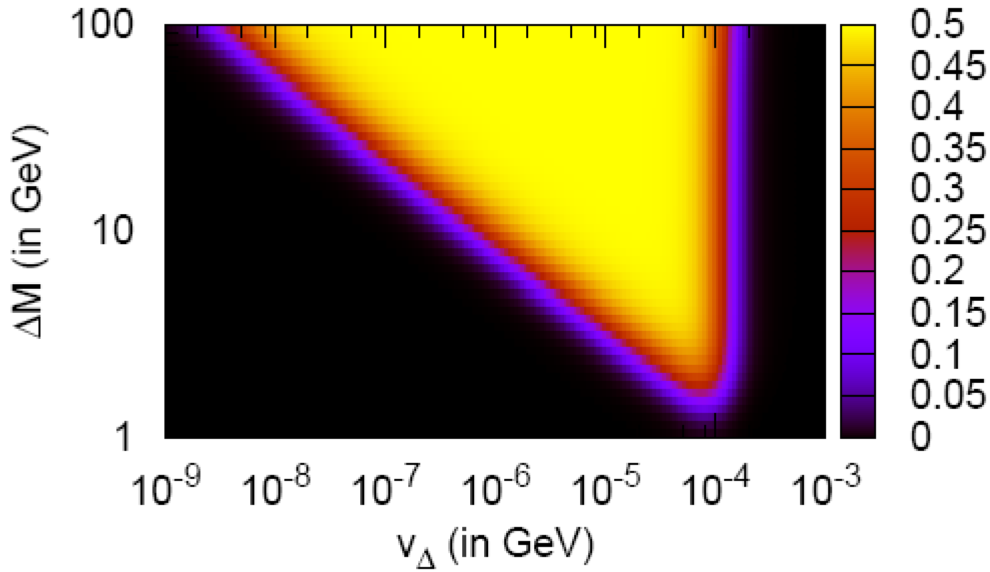


H^+

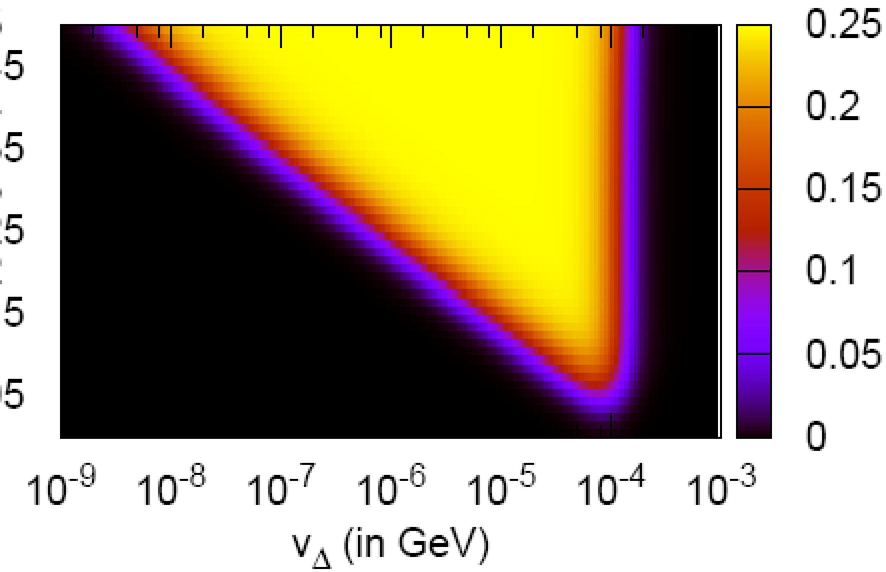
H^{++}

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

Maximizing the branching fraction



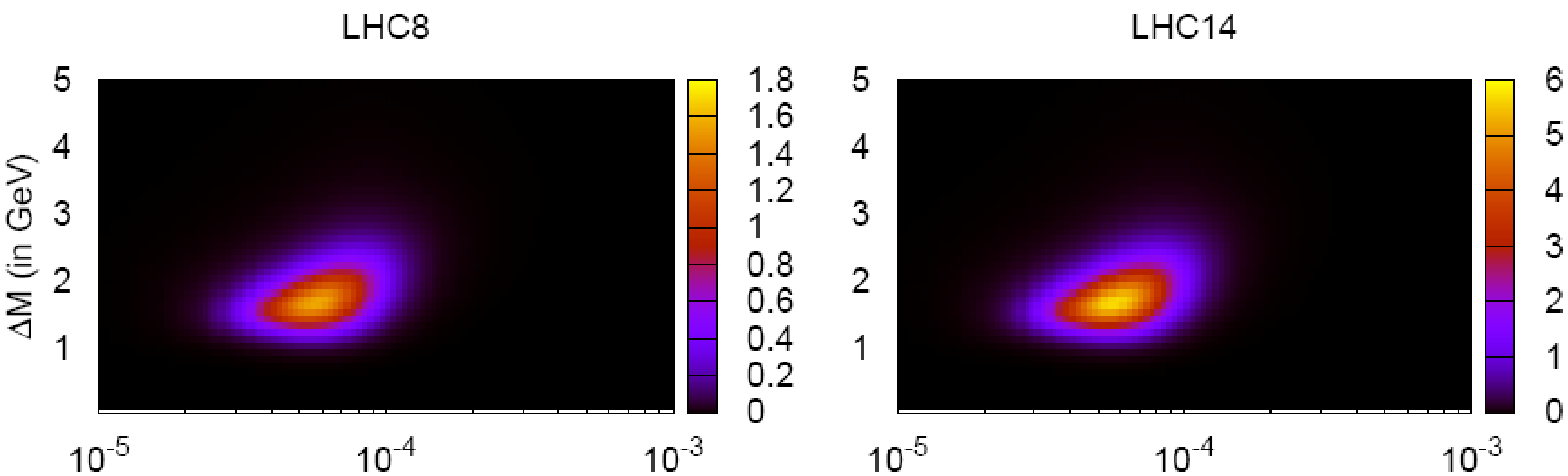
for $4l + 3W^*$



for $4l + 4W^*$

SS4L cross-section

- SS4L production including the oscillation factor:



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

- Benchmark point:

v_Δ=7x10^{-5} GeV, ΔM=1.5 GeV.

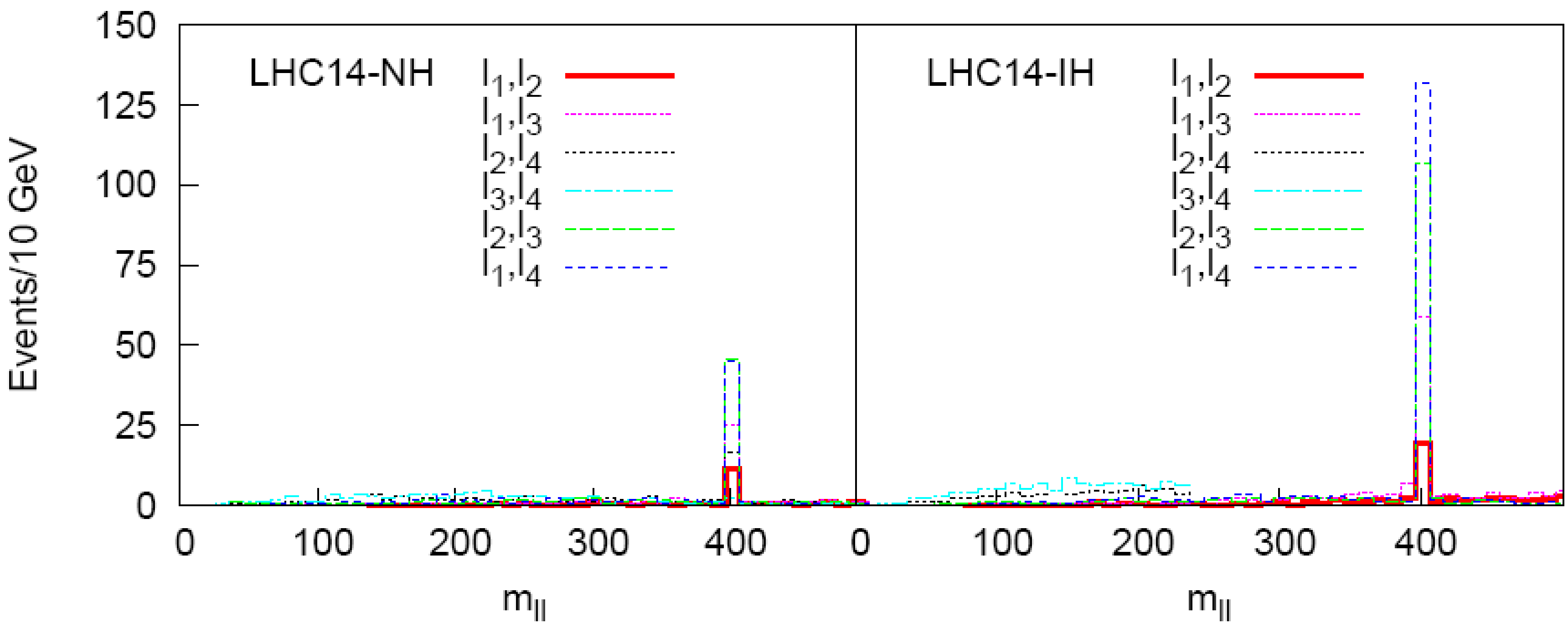
Event numbers

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

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

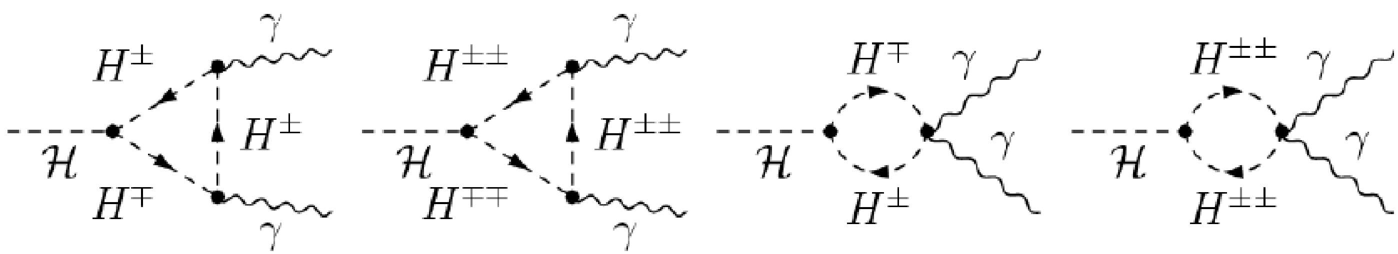
Mass reconstruction



Higgs-to-diphoton

EJC, Lee & Sharma, 1209.1303

- 1-loop process sensitive to New Physics.
- Its precision data to constrain 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

EWPD

- Triplet contribution to S, T & U:

Lavoura, Li, 9309262

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

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

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

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

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

EWPD

- Most recent STU fit:

Baak, et.al., 1209.2716

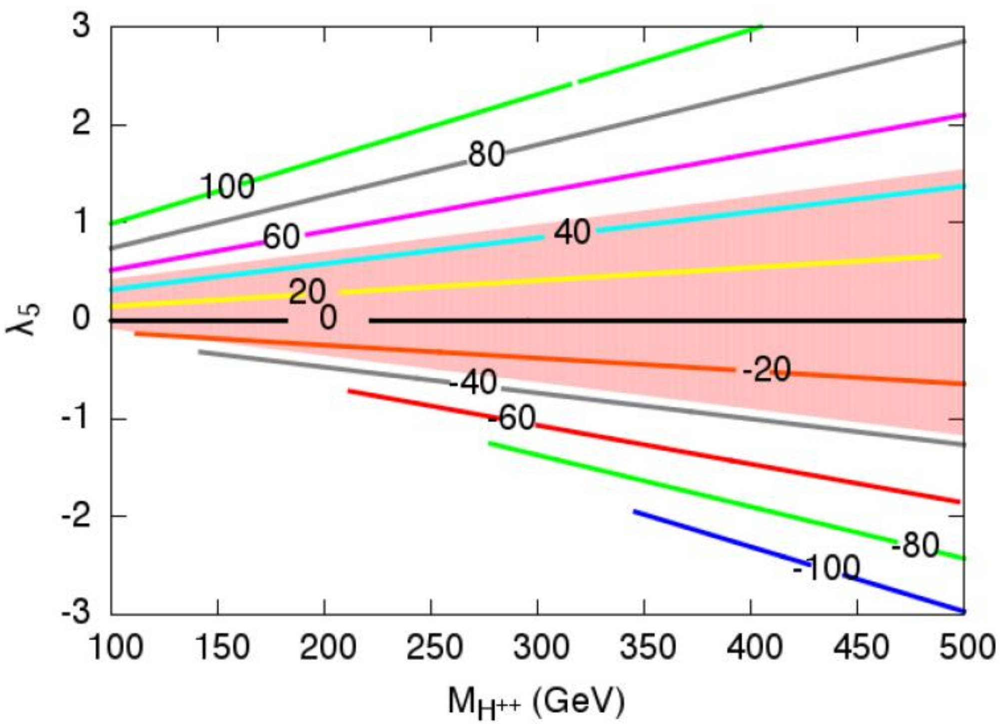
$$S_{\text{best fit}} = 0.03\,, \quad \sigma_S = 0.10$$
$$T_{\text{best fit}} = 0.05\,, \quad \sigma_T = 0.12$$
$$U_{\text{best fit}} = 0.03\,, \quad \sigma_U = 0.10$$

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

- 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

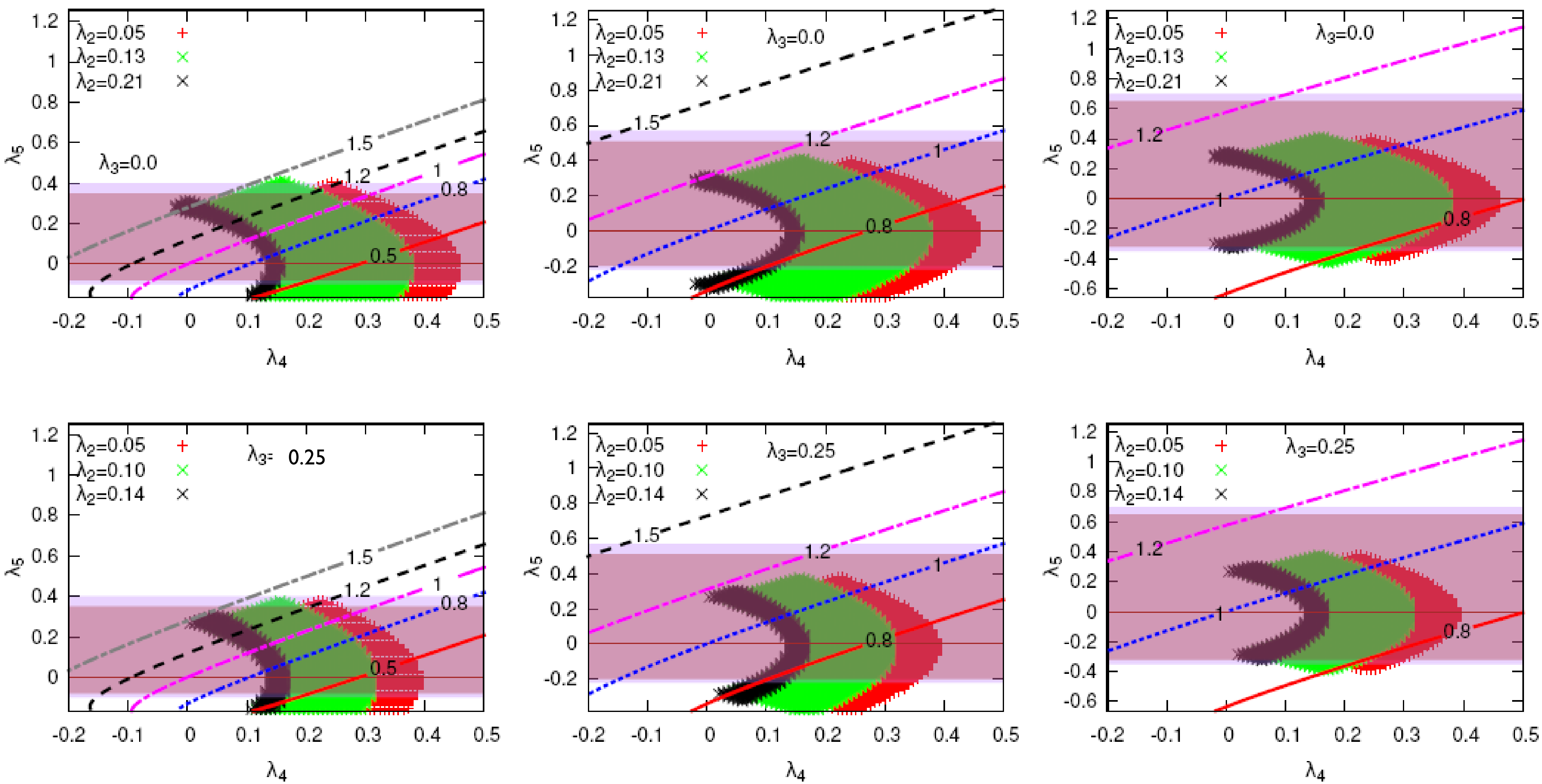


$|\Delta M| < 40$ GeV

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

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

Combined results for 10^{19} GeV

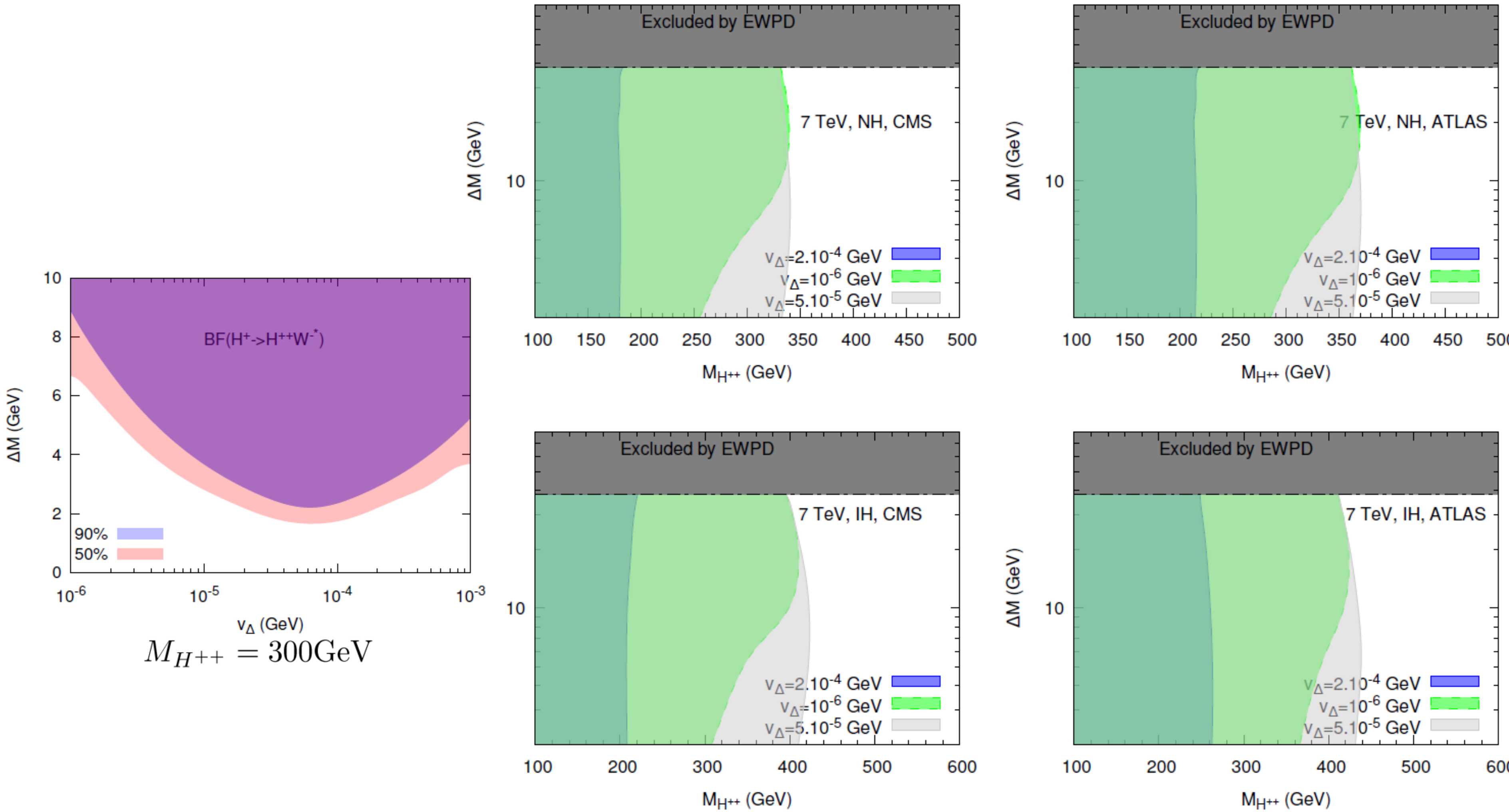


$m_{H^{++}} = 100\text{GeV}$ $m_{H^{++}} = 150\text{GeV}$ $m_{H^{++}} = 200\text{GeV}$

General v_Δ -ΔM study

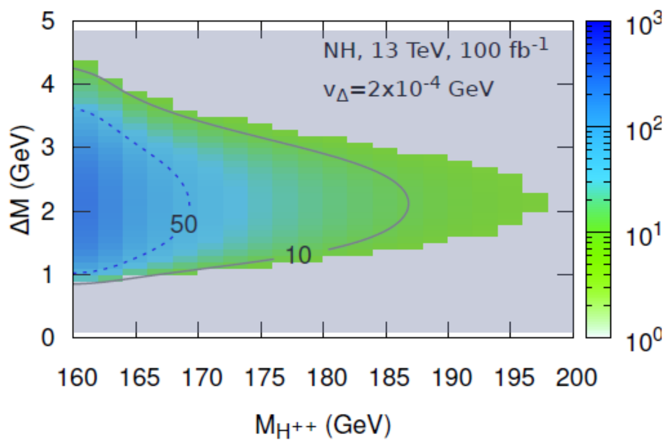
Melfo, et.al., 1108.4416

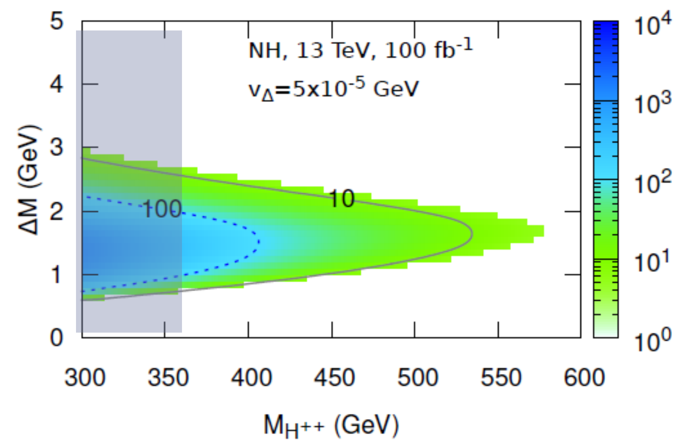
EJC & Sharma, 1309.6888

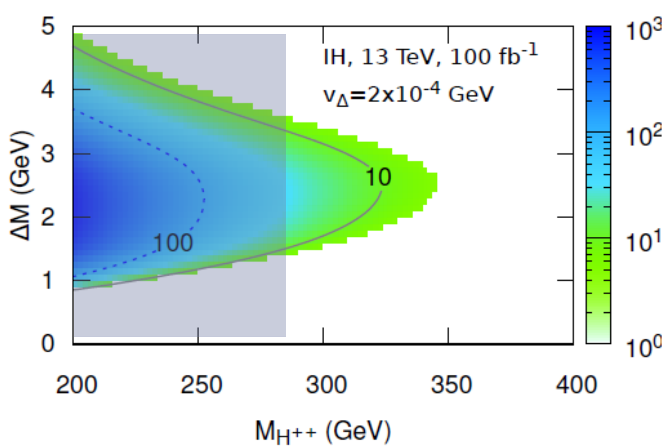


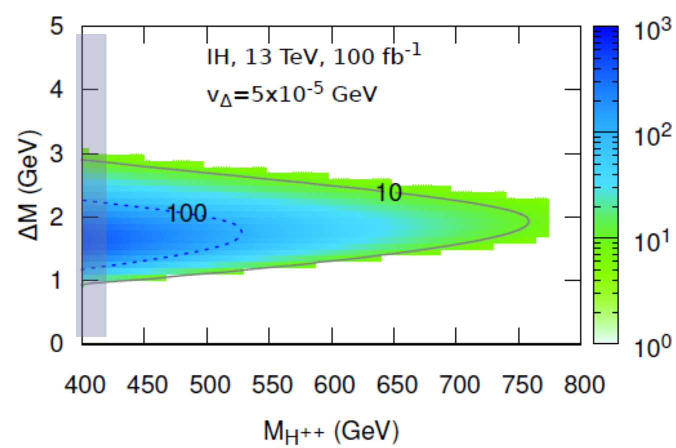
$M_{H^{++}} = 300\text{GeV}$

SS4L at LHC13





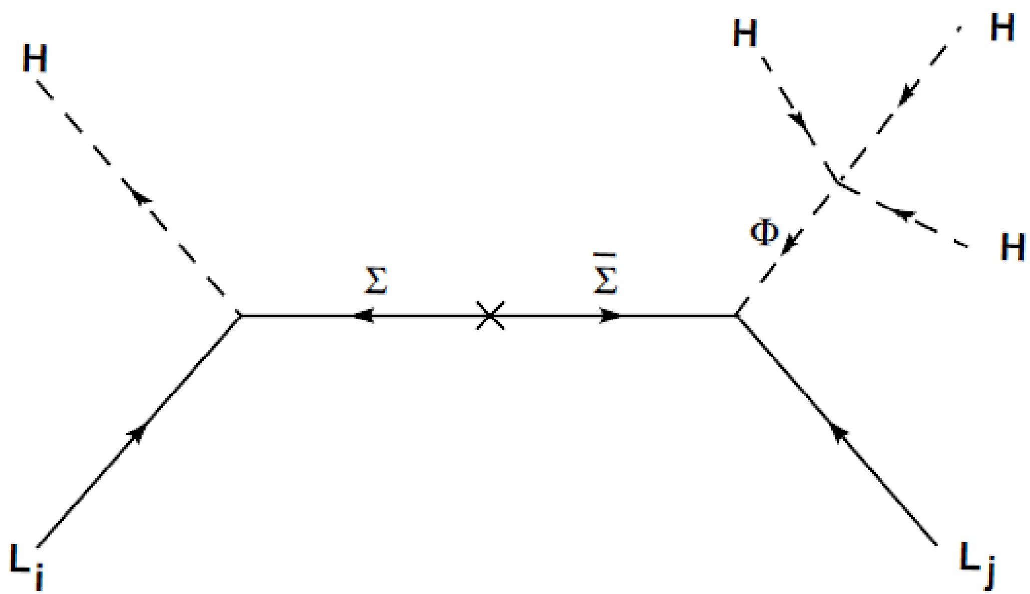




UV theories of D>5 operators?

- 4-plet Model: (Φ^{+++}, Φ^{++}, Φ^{+},Φ^{0}).
- $\Phi^{+++} \rightarrow l^+ l^+ W^+$,$W^+ W^+ W^+$

Babu, et.al., 0905.2710
Bambhaniya, et.al.,1305.2795



Q) SS5L study?

Conclusion

- Great achievements from oscillation observation during past 15 years.
- Further Quest for the nature of neutrino mass: Dirac/Majorana, absolute scale, hierarchy & CPV.
- Neutrino-DM/BAU connection: leptogenesis+ADM.
- Majorana mass models at TeV scale?
- LHC signatures of type I, II, III seesaws: SS2L, displacement, associated Higgs production.
- LHC13/14 continues to probe the neutrino signals.
- More for peculiar type II: SS2L resonance, SS4L, Higgs-to-diphoton.

Thank you