International Meeting on High Energy Physics (IMHEP)

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Venue: Institute of Physics, Bhubaneswar

Neutrino mass models at LHC

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Neutrinos are massive

Neutrino oscillation data

Flavor eigenstate ≠ Mass eigenstate

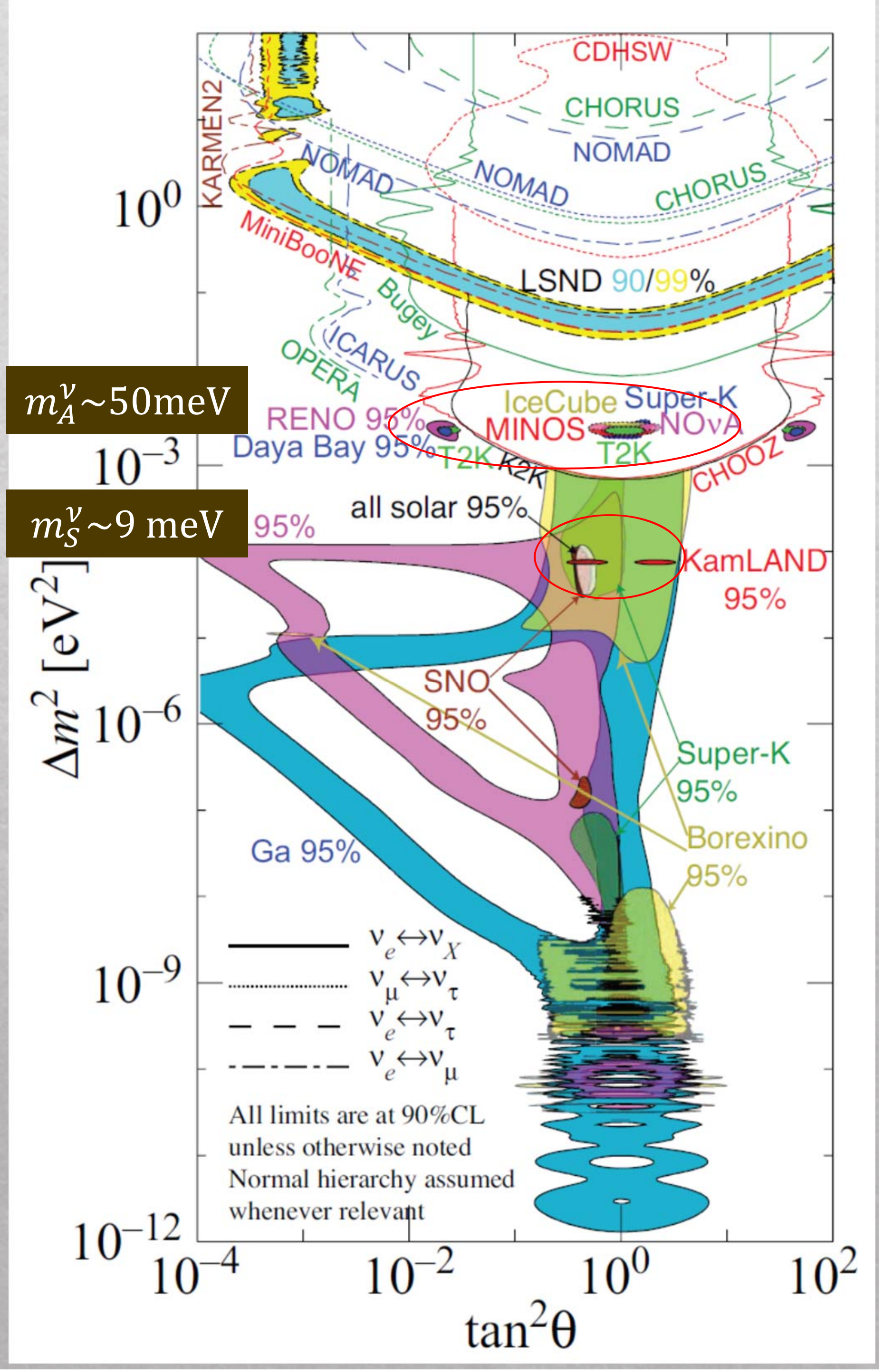
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}$$

θ_{23} (Atm. 1998) θ_{13} (Reactor 2012)

$$\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha} & 0 & 0 \\ 0 & e^{i\beta} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

θ_{12} (Sun 2002)



How neutrinos get massive?

- SM is required to be extended:

  $L \sim H \quad (H^c = \epsilon H^*) \rightarrow LH^c$ is a SM-singlet

- Add a singlet fermion (RHN) → Dirac mass

$$y_\nu^D LH^c\nu^c + h.c. \rightarrow \mathrm{m}_\nu \nu\nu^c + h.c. \rightarrow \mathrm{y}_\nu^\mathrm{D} = \frac{\mathrm{m}_\nu}{\langle H^0 \rangle} \sim 10^{-12}$$

- Add a D=5 (seesaw) operator → Majorana mass

$$\frac{1}{2M} LH^cLH^c + h.c. \rightarrow \frac{m_\nu}{2} \nu\nu + h.c. \quad \rightarrow m_\nu = \frac{\langle H^0 \rangle^2}{M}$$

Neutrino mass models

- Renormalizable models to get the seesaw operator (or the tiny Dirac Yukawa), realized at tree-level or loop-level.
- It involves new particles: fermions and/or bosons which could come with an extended gauge sector.
- The new particles affects the Higgs properties (Higgs stability, exotic decay).
- They may be around TeV → LHC signatures

In this talk, we consider

Type I/III seesaw with new singlet/triplet fermions;
Extended gauge group: U(1), Left-Right;
Type II seesaw with additional Higgs triplet.

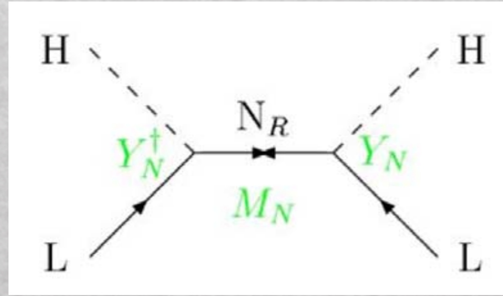
Type I seesaw

- Add a SM-singlet Majorana fermion (RH neutrino)

$$-\mathcal{L} = Y_N L H^c N + \frac{M_N}{2} NN + h.c.$$

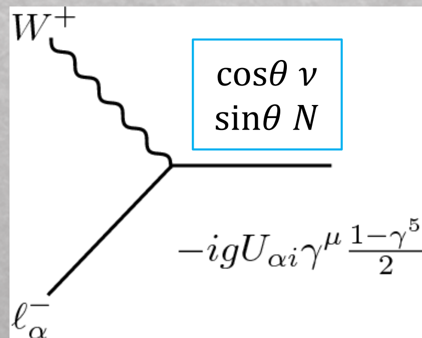
$$\begin{bmatrix} 0 & m_D \\ m_D & M_N \end{bmatrix}$$

$$m_D = Y_N \langle H^0 \rangle \Rightarrow m_\nu = m_D M_N^{-1} m_D^T$$



- $\nu - N$ mixing

$$\theta \approx \frac{m_D}{M_N} \sim \sqrt{\frac{m_\nu}{M_N}} \lesssim 10^{-6} \sqrt{\frac{100\text{GeV}}{M_N}}$$



Probing $\nu - N$ mixing

- θ can be large for specific textures of m_D & M_N while making $m_\nu = \theta M_N \theta^T$ is small.
- Inverse seesaw has naturally large θ

$$-\mathcal{L} = YLH^cN + MNN' + \frac{1}{2}\mu N'N' \;\rightarrow m_\nu = m_D M^{-1} \mu M^{-1} m_D^T$$

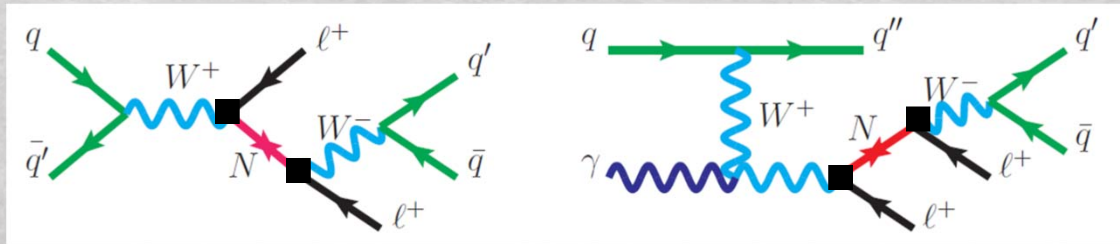
$$\Rightarrow \theta_{lN} \sim \frac{m_D}{M} \sim \sqrt{\frac{m_\nu}{\mu}} \lesssim 10^{-2}\sqrt{\frac{\text{keV}}{\mu}}$$

- EWPD limit: Aguila et.al., '08

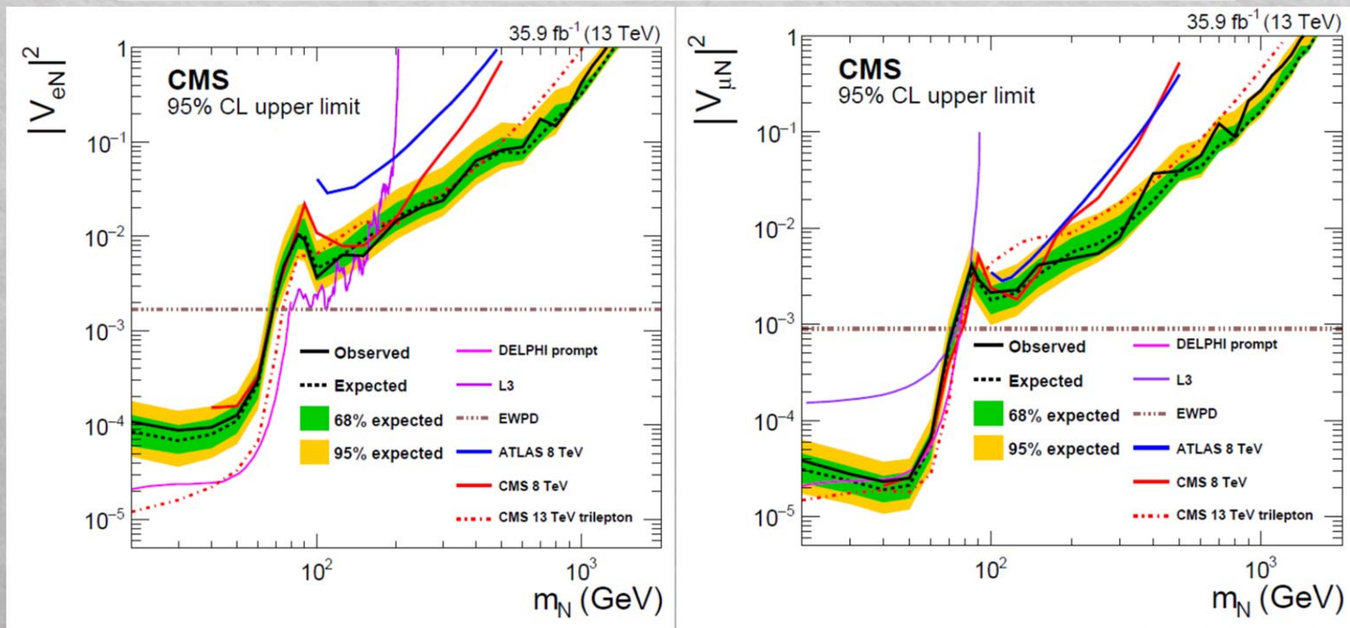
$$\theta_{e,\mu,\tau} < (0.055, 0.057, 0.079)$$

SSD + ≥ 1j

CMS 1806.10905

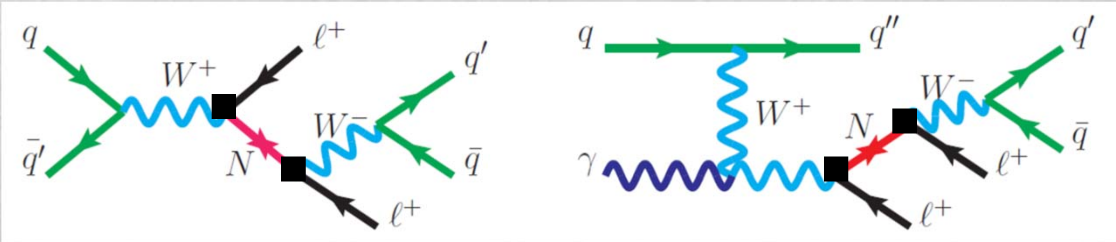


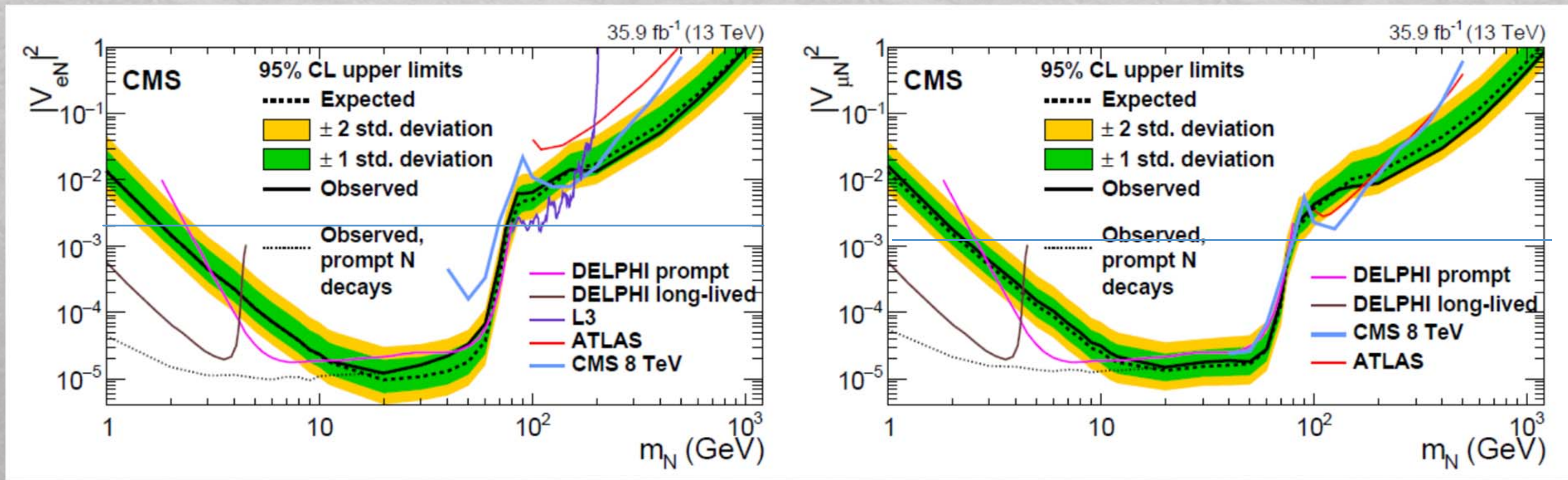
*) No SSD for
Inverse Seesaw



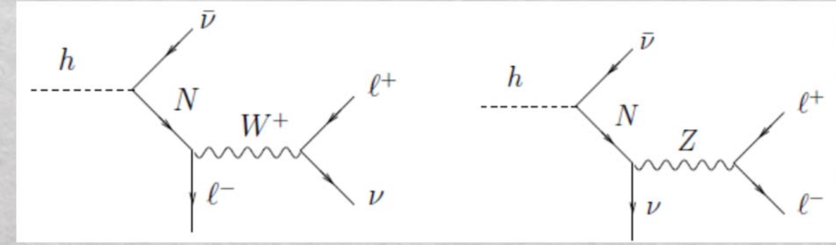
Trilepton+MET

CMS 1802.02965

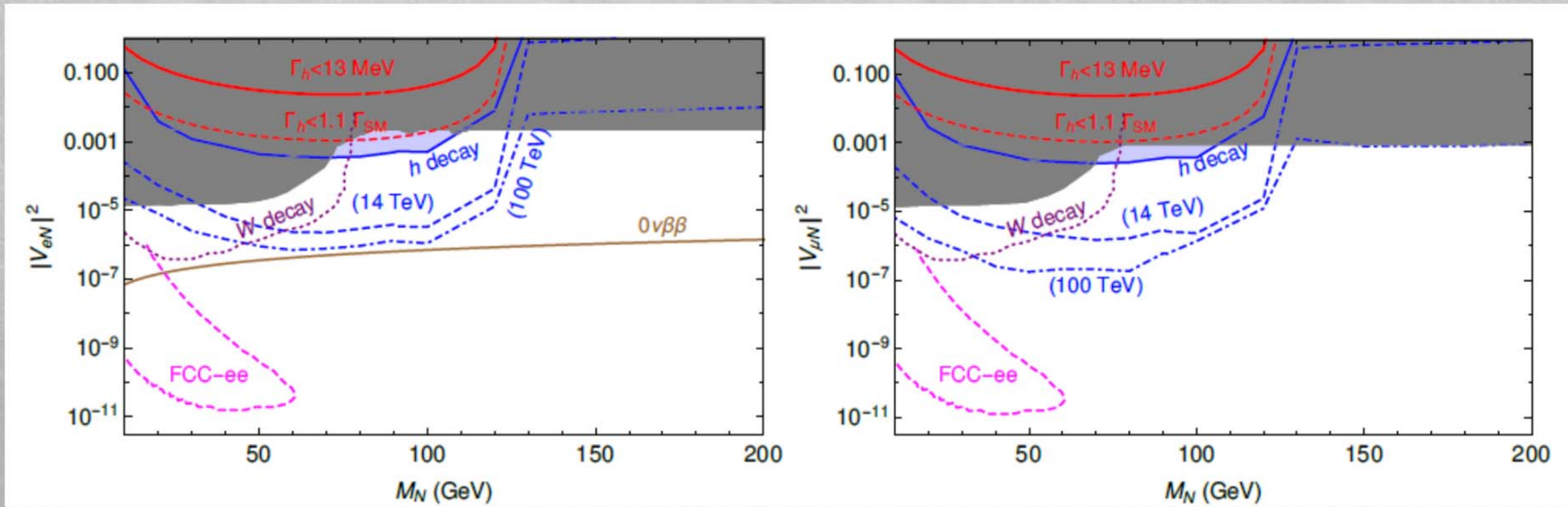




Higgs decay to N

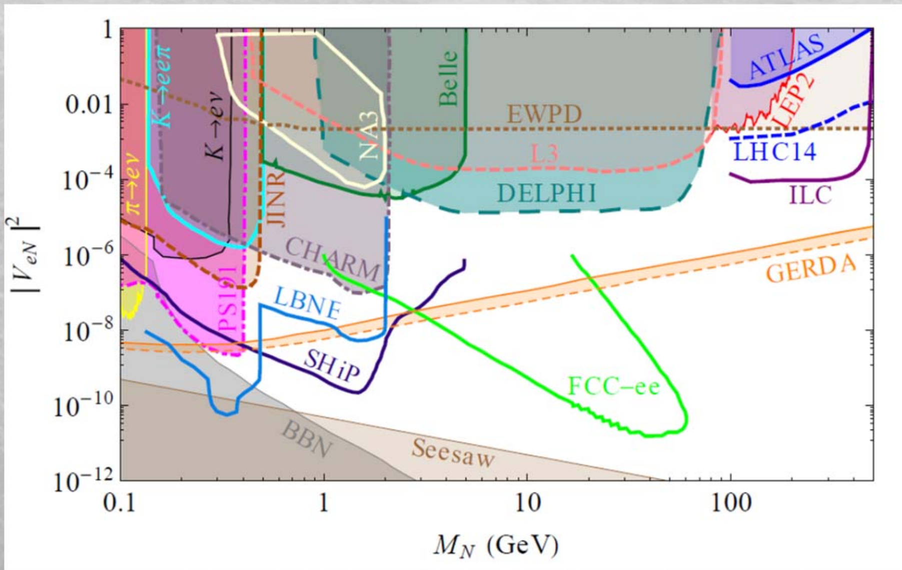


Dev et.al., 1207.2756
Cely et.al., 1208.3654
Bandyopadhyay et.al., 1209.4803

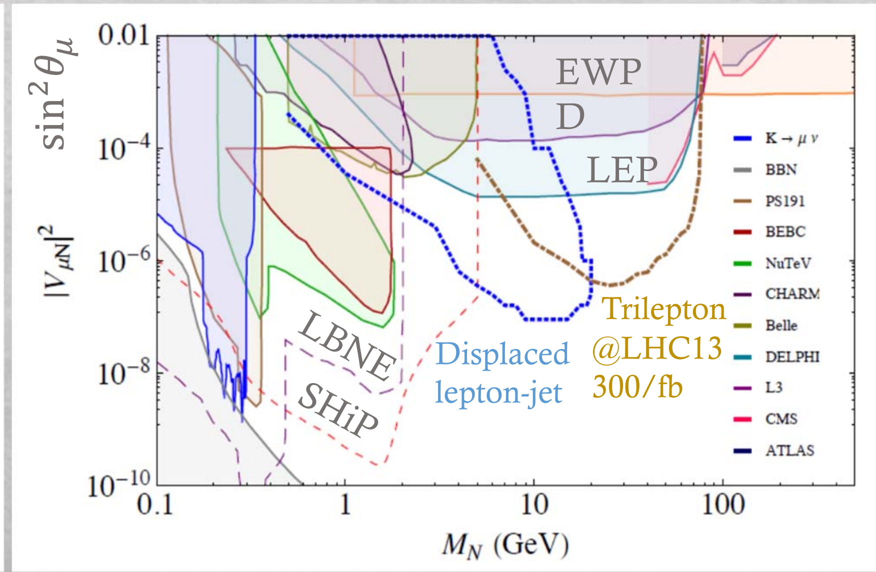


Das, Dev, Kim, 1704.00880

General search for *N*



Deppisch, et.al. 1502. 06541

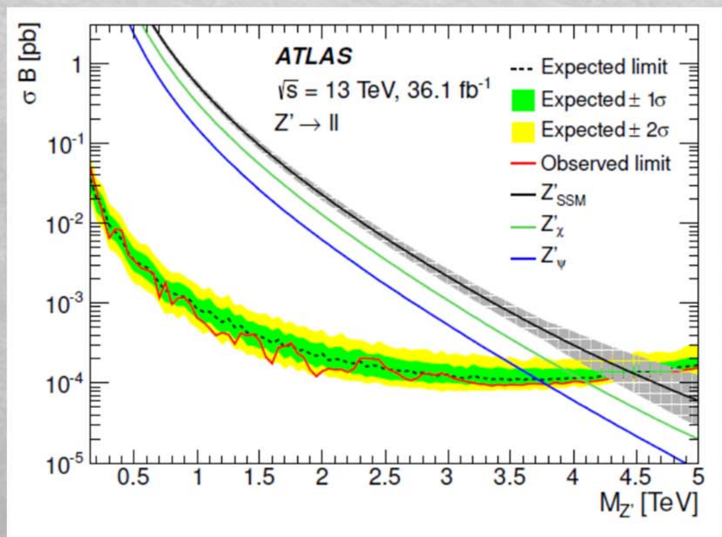


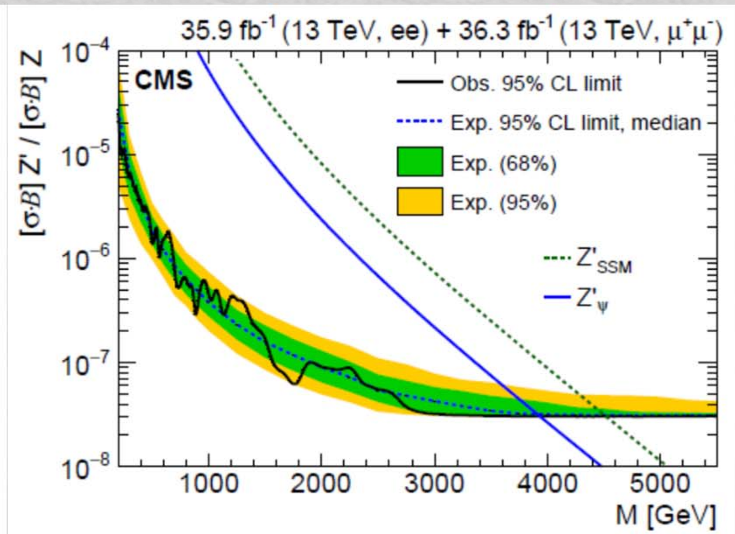
Izaguirre, Shuve 1504.02470

N with a new gauge symmetry

$U(1)'$

- Additional U(1) from GUT – searches for dilepton resonance



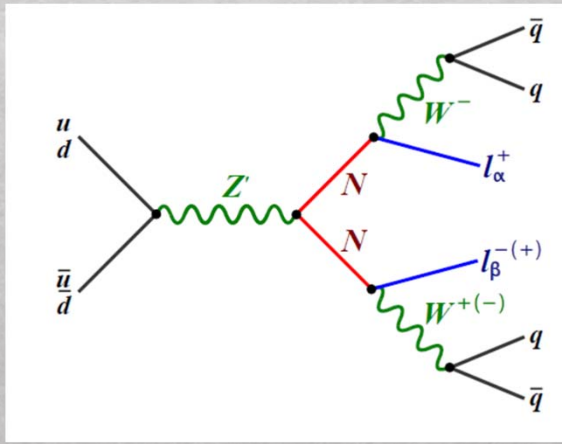


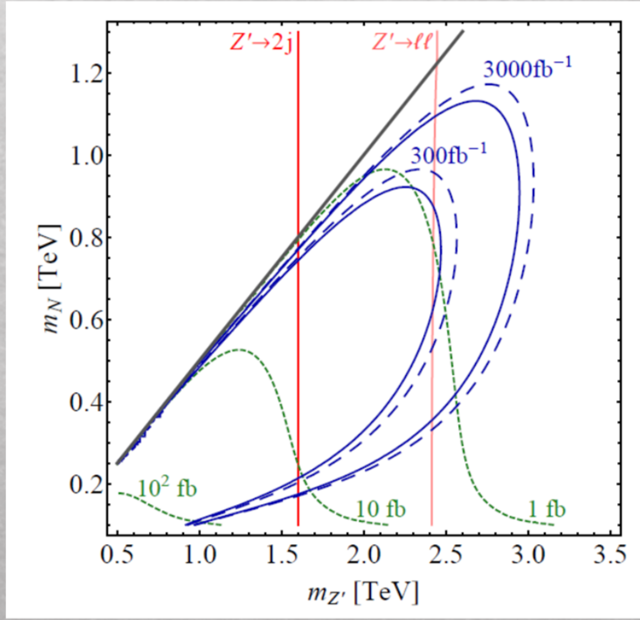
ATLAS 1707.02424

CMS 1803.06292

$N_{e,\mu}$ from Z$'$

- Anomaly free condition for $U(1)'$ requiring N (e.g. $B - L$).
- Gauge production of a pair of N decaying to $lW, \nu Z, \nu h$.





Deppisch, Desai, Valle, 1308.6789

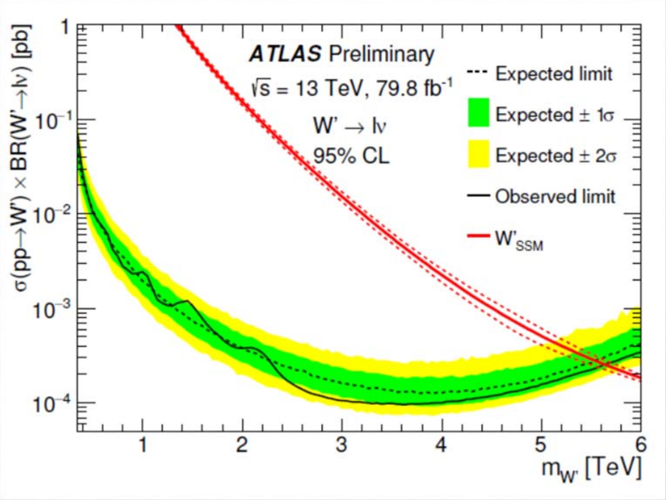
$SU(2)_R$

- SM after L-R breaking:

$$\begin{pmatrix}\nu\\ e\end{pmatrix}\updownarrow W_L \quad e^c \quad \nu^c \quad \Leftarrow \begin{pmatrix}\nu\\ e\end{pmatrix}\updownarrow W_L \begin{pmatrix}\nu^c\\ e^c\end{pmatrix}\updownarrow W_R$$

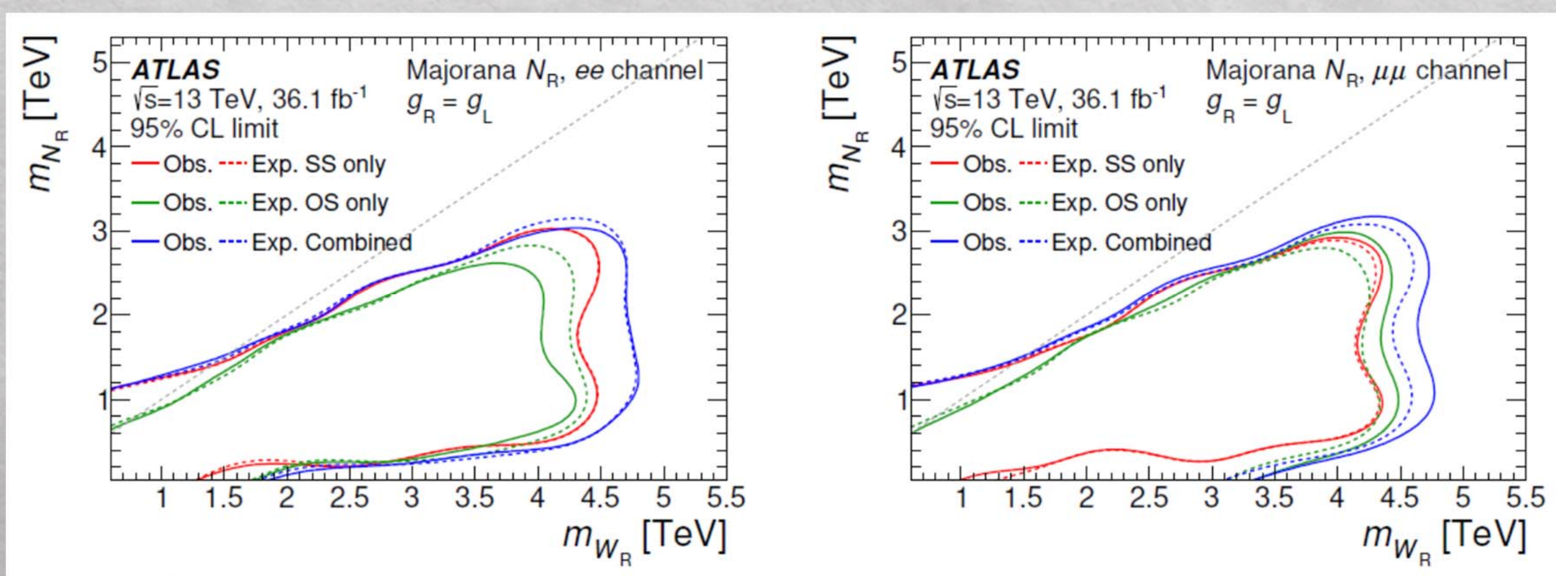
- $pp \to W' \to l\nu$

ATLAS-CONF-2018-017



$N_{e,\mu}$ from W_R

- Gauge production of N associated with e/μ
- Separate OS & SS analysis ATLAS 1809.11105

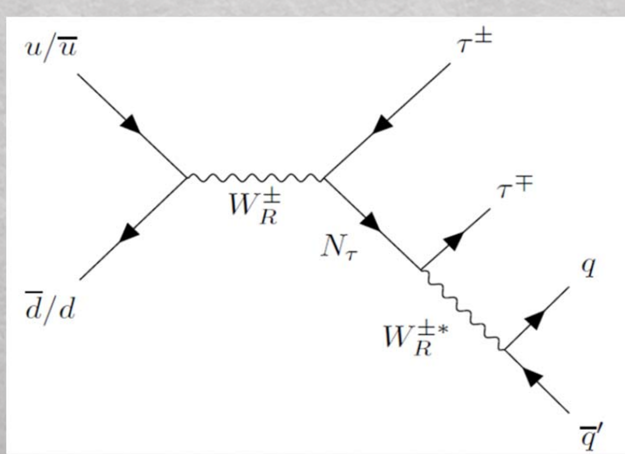


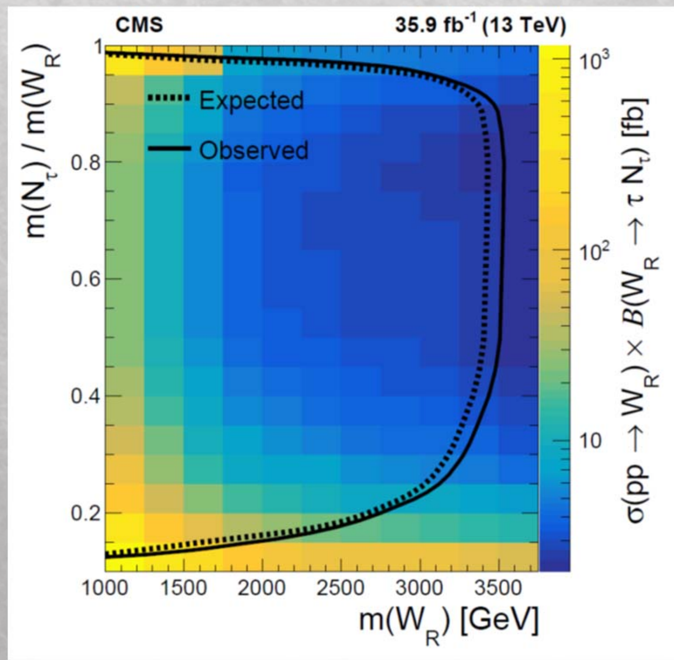
cf) CMS 1803.11116

N_τ from W_R

- Gauge production of N associated with τ

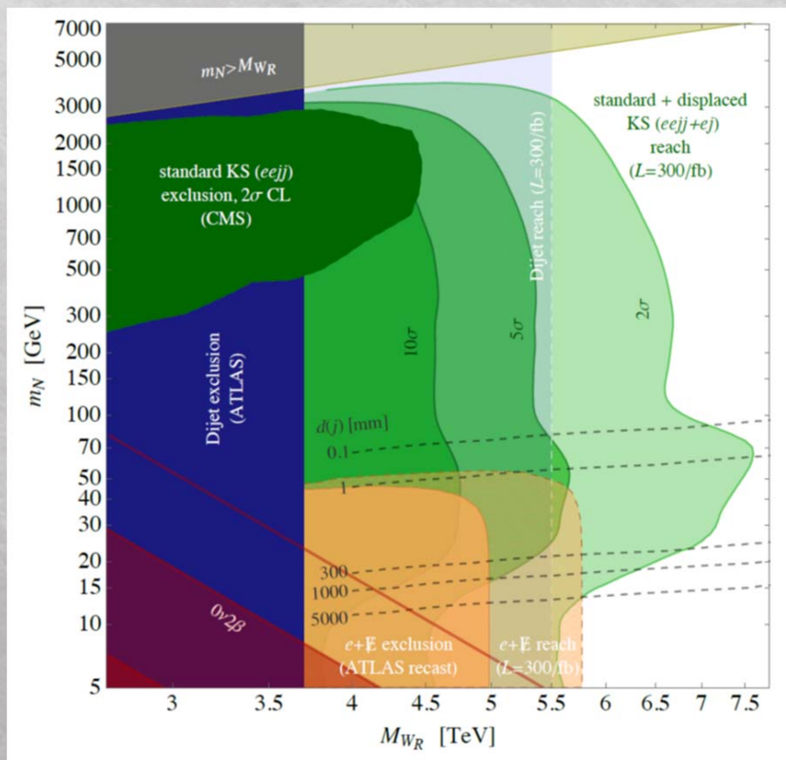
CMS 1811.00806





Future prospect for $N - W_R$

Nemevsek, Nesti, Popara, 1801.05813



Seesaw with SM-charged particles

Type III seesaw

- LH^c can form a triplet of $SU(2)_L$
- Introduce a (Majorana) triplet fermion $\Sigma_{Y=0} = (\Sigma^+, \Sigma^0, \Sigma^-)$

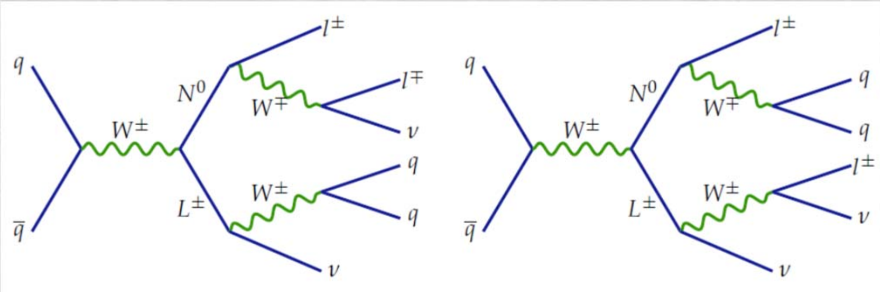
$$-\mathcal{L} = Y_\Sigma \mathrm{LH^c} \Sigma + \frac{M_\Sigma}{2} \Sigma\Sigma + h.c.$$

$$\rightarrow m_D = Y_\Sigma \langle H^0 \rangle \, ; \, m_\nu \approx m_D M_\Sigma^{-1} m_D^T$$

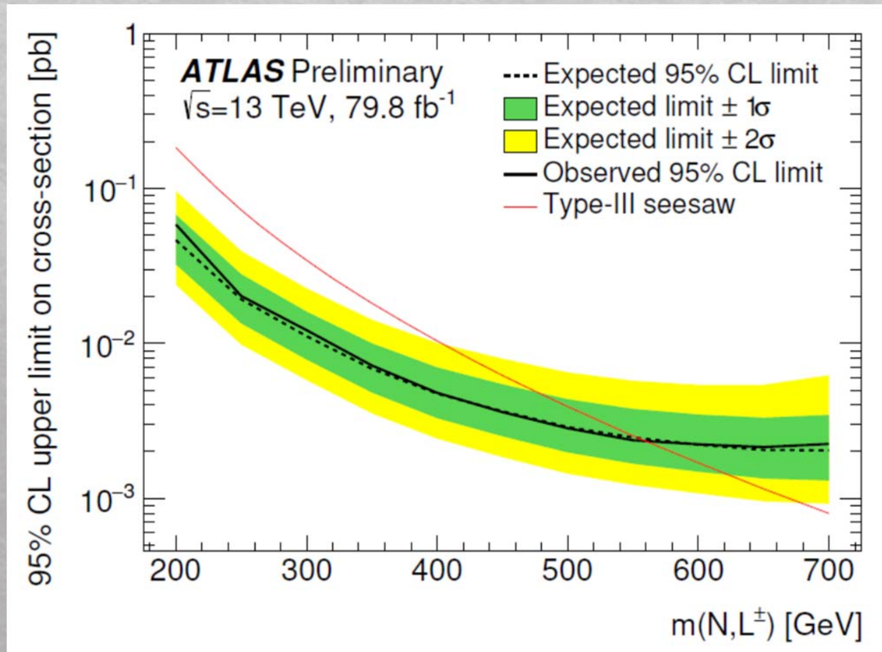
- Σ^0 is a RHN accompanied by the gauge partners $\Sigma^\pm$
- LHC signature of $\Sigma^0 - \Sigma^\pm$ associated production

Franceschini, et.al, '08

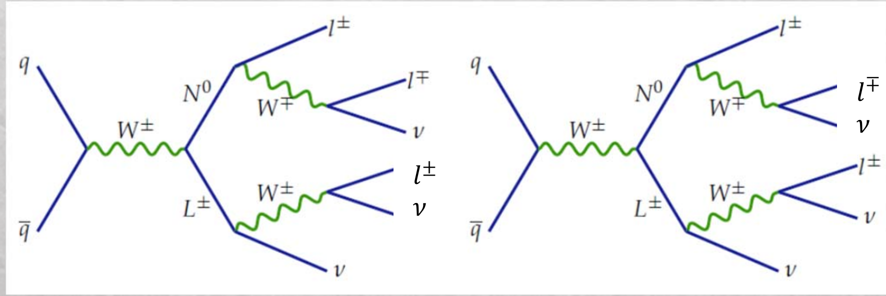
2l+2j+MET



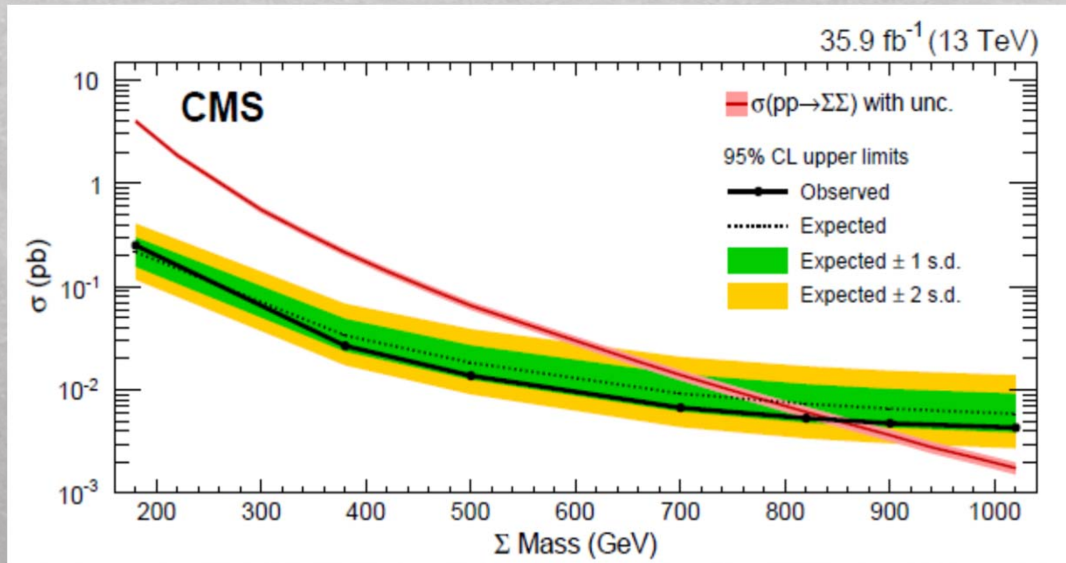
ATLAS-CONF-2018-020



Multi-lepton searches



CMS 1708.07962

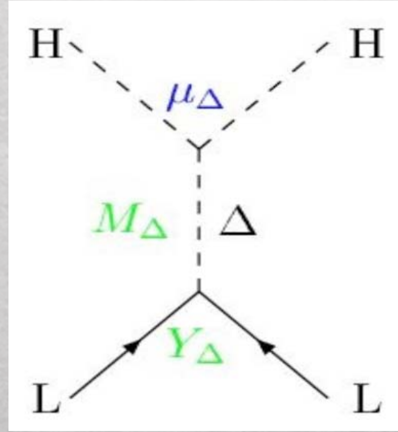


Type II Seesaw

- Add a triplet Higgs boson: $\Delta_{Y=1} = (\Delta^{++}, \Delta^{+}, \Delta^{0})$

$$-\mathcal{L} = Y_\Delta \mathrm{LL}\Delta + \mu_\Delta HH\Delta + \frac{M_\Delta^2}{2}|\Delta|^2 + h.c.$$

$$\to m_\nu = Y_\Delta \langle \Delta^0 \rangle = Y_\Delta \frac{\mu_\Delta \langle H^0 \rangle^2}{M_\Delta^2}$$

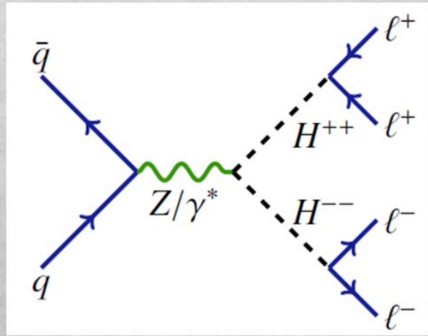


- Rho-parameter bound on the triplet VEV:

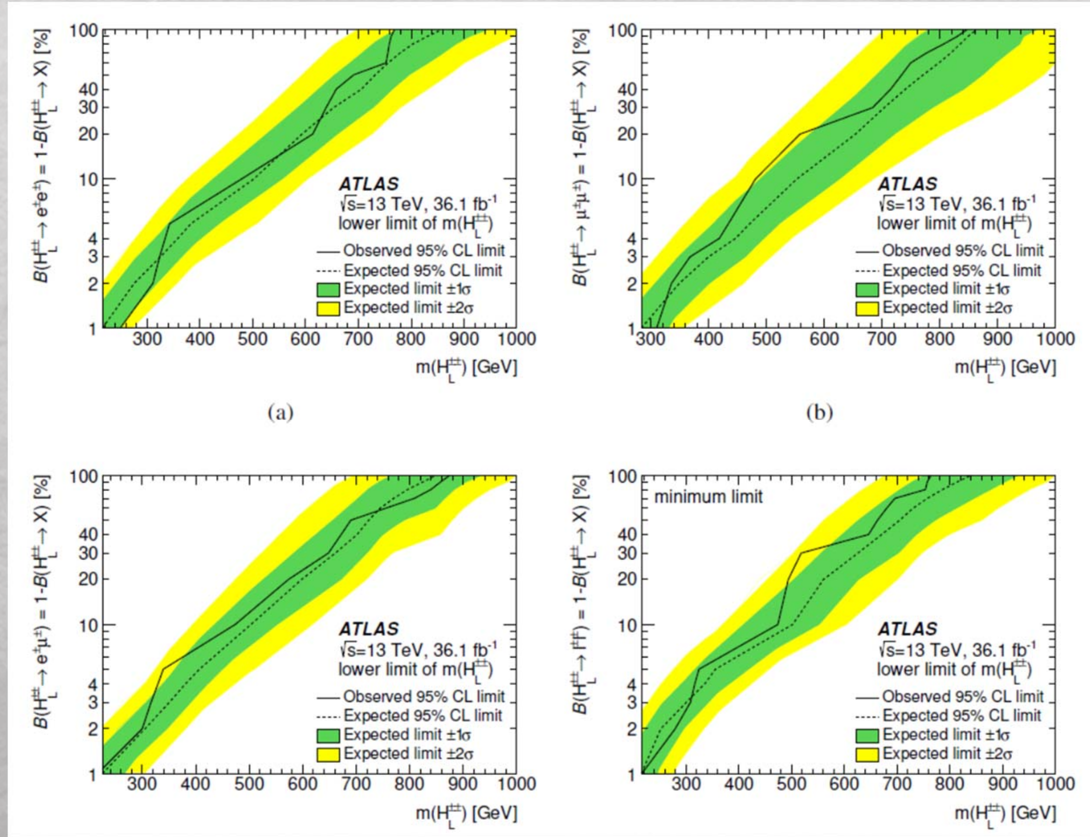
$$\rho \equiv \frac{m_W^2}{c_W^2 m_Z^2} = \frac{1 + 2\, v_\Delta^2/v_\Phi^2}{1 + 4\, v_\Delta^2/v_\Phi^2} \Rightarrow v_\Delta < 3 \text{ GeV at } 3\sigma$$

- Peculiar signals from a doubly charged boson to measure neutrino mass hierarchy: $\mathrm{Br}\left(\Delta^{++} \to l_i^+ l_j^+\right) \propto \left|m_{ij}^\nu\right|^2$ EJC, Lee, Park, '03

SSD resonance searches



ATLAS 1710.09748



*)

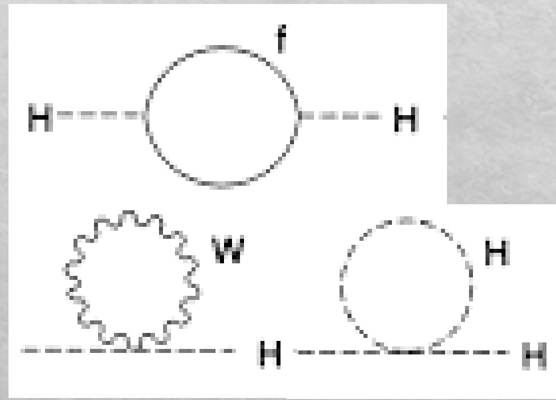
Br (%)	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
NH	0.62	5.11	0.51	26.8	35.6	31.4
IH1	47.1	1.27	1.35	11.7	23.7	14.9

Higgs property in Seesaw

Natural Higgs mass

- Higgs, a fundamental scalar, suffers from the hierarchy problem

$$\begin{aligned}\delta m_h^2 &= (-1)^F \frac{\lambda}{8\pi^2}\int^{\Lambda}\frac{d^4p}{p^2-m^2} \\ &= \frac{3}{8\pi^2 v^2}(4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2)\Lambda^2 \\ &= m_h^2\left(\frac{\Lambda}{500\mathrm{GeV}}\right)^2\end{aligned}$$

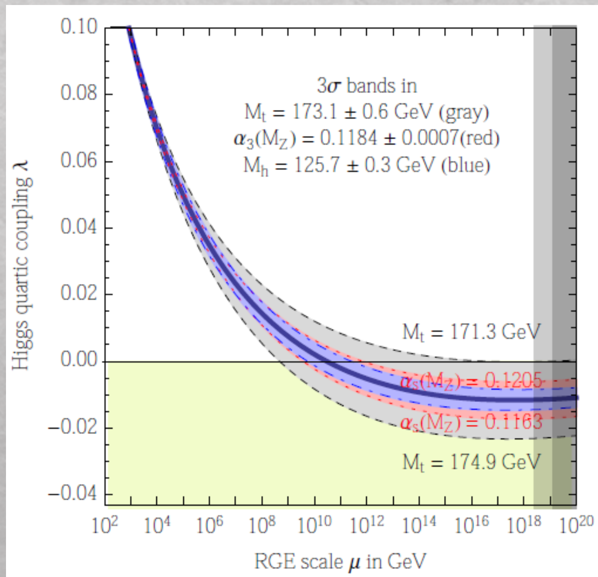


- Renormalizable away (e.g. DR).
- Still, Λ can be a physical scale of a UV theory.

Higgs vacuum stability

- Higgs quartic coupling turns to negative due to large top-Yukawa → makes the Higgs vacuum unstable.

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



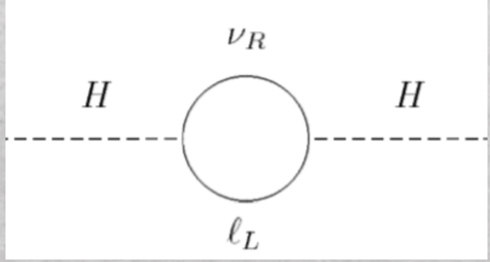
New physics below ~10^{10}GeV?

Degrassi, et.al., 1307.3536

Seesaw & Higgs mass

- Type I: Neutrino Yukawa contribution

$$\delta m_h^2 = 4\frac{Y_N^2}{16\pi^2}M^2\left(\ln\frac{M^2}{M_{pl}^2} - 1\right)$$



Vissani, '97

Farina, Pappadopulo, Strumia, 1303.7244

$$\delta m_h^2 \lesssim m_h^2\,\delta$$

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

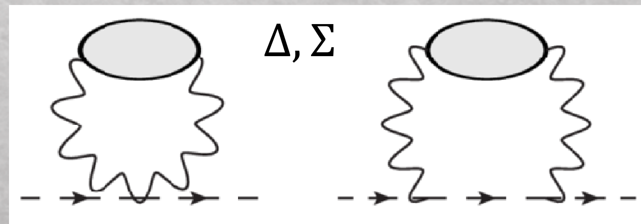
*) Supersymmetry removes such a concern.

Seesaw & Higgs mass

- Type II: gauge two-loop correction

$$\delta m_h^2 = -6\frac{6g_2^4 + 3g_Y^4}{(4\pi)^4}M^2\left(\frac{3}{2}\ln^2\frac{M^2}{M_{pl}^2} + 2\ln\frac{M^2}{M_{pl}^2} + \frac{7}{2}\right)$$

$$\boxed{M \lesssim\ 200\ GeV\quad \sqrt{\delta}}$$



- Type III: gauge two-loop correction

$$\delta m_h^2 = \frac{g_2^4}{(4\pi)^4}M^2\left(36\ln\frac{M^2}{M_{pl}^2} - 6\right)$$

$$\boxed{M \lesssim 940\ GeV\quad \sqrt{\delta}}$$

Higgs stability in Type II

- An extra Higgs triplet → additional terms in scalar potential change the vacuum stability condition and the running behavior (generic with any new boson field).

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

- Most general Higgs potential terms:

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

Higgs stability in Type II

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

- Are they valid up to a high scale, e.g., the Planck scale?

Higgs stability in Type II

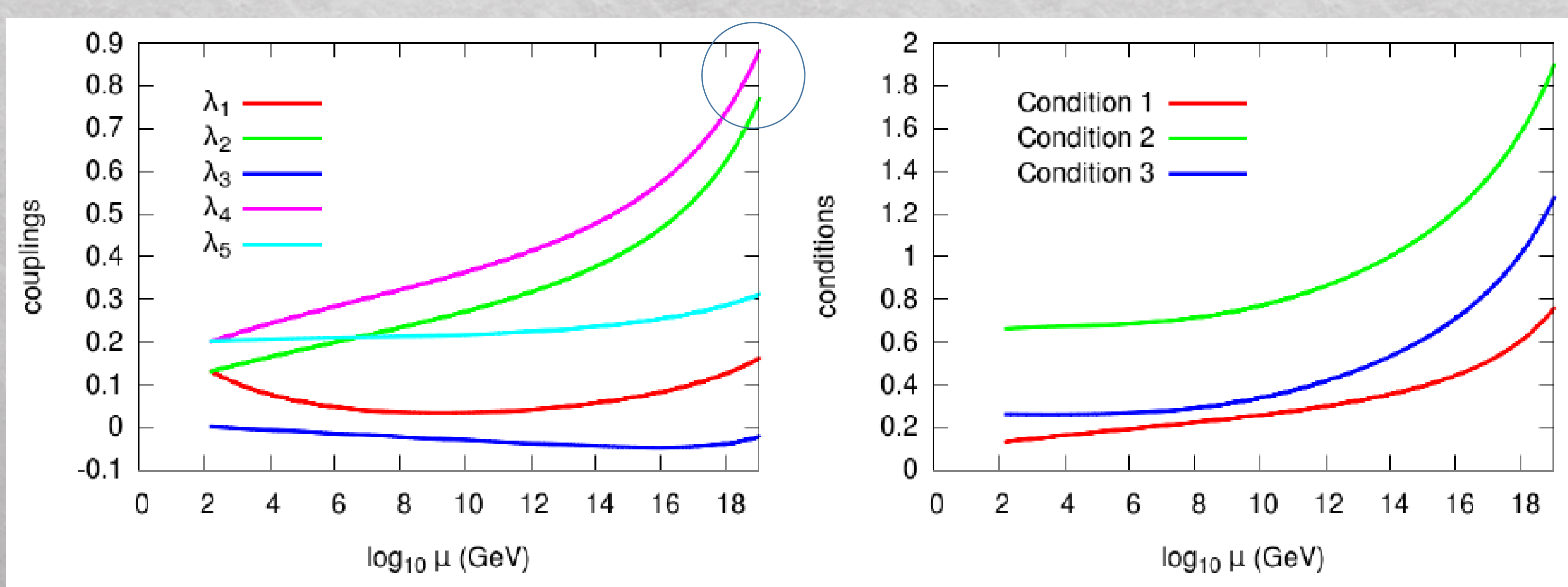
- One-loop RGE:

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

Chao, Zhang, 0611323
Schmidt, 07053841

Higgs stability in Type II

- Running of the couplings and vacuum stability conditions

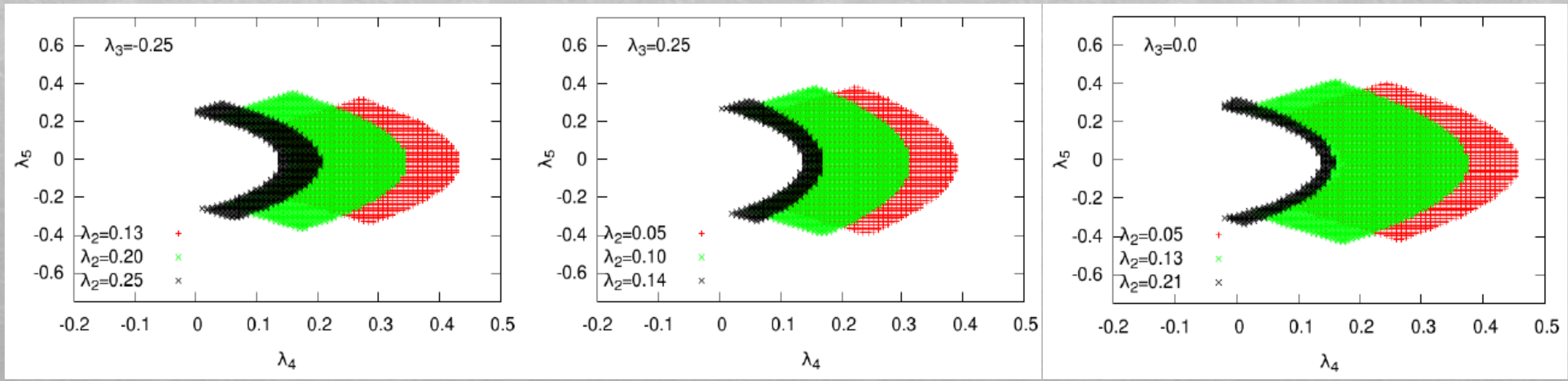


EJC, Lee, Sharma, 1209.1303

Higgs stability in Type II

- Allowed ranges of the couplings from Higgs stability depending on the cut-off scale:

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



EJC, Lee, Sharma, 1209.1303

Neutral boson oscillation in Type II

Boson mass spectrum

- Mass splitting between triplet components:

$$M_{H^{++}}^2 = M^2 + 2\,\frac{\lambda_4 - \lambda_5}{g^2}\,M_W^2$$

$$M_{H^{+}}^2 = M_{H^{++}}^2 + 2\,\frac{\lambda_5}{g^2}\,M_W^2$$

$$M_{H^0,A^0}^2 = M_{H^{+}}^2 + 2\,\frac{\lambda_5}{g^2}\,M_W^2$$

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

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

$*$) H^{++} is the lightest for $\lambda_5 > 0$

- Mass splitting between neutral scalars:

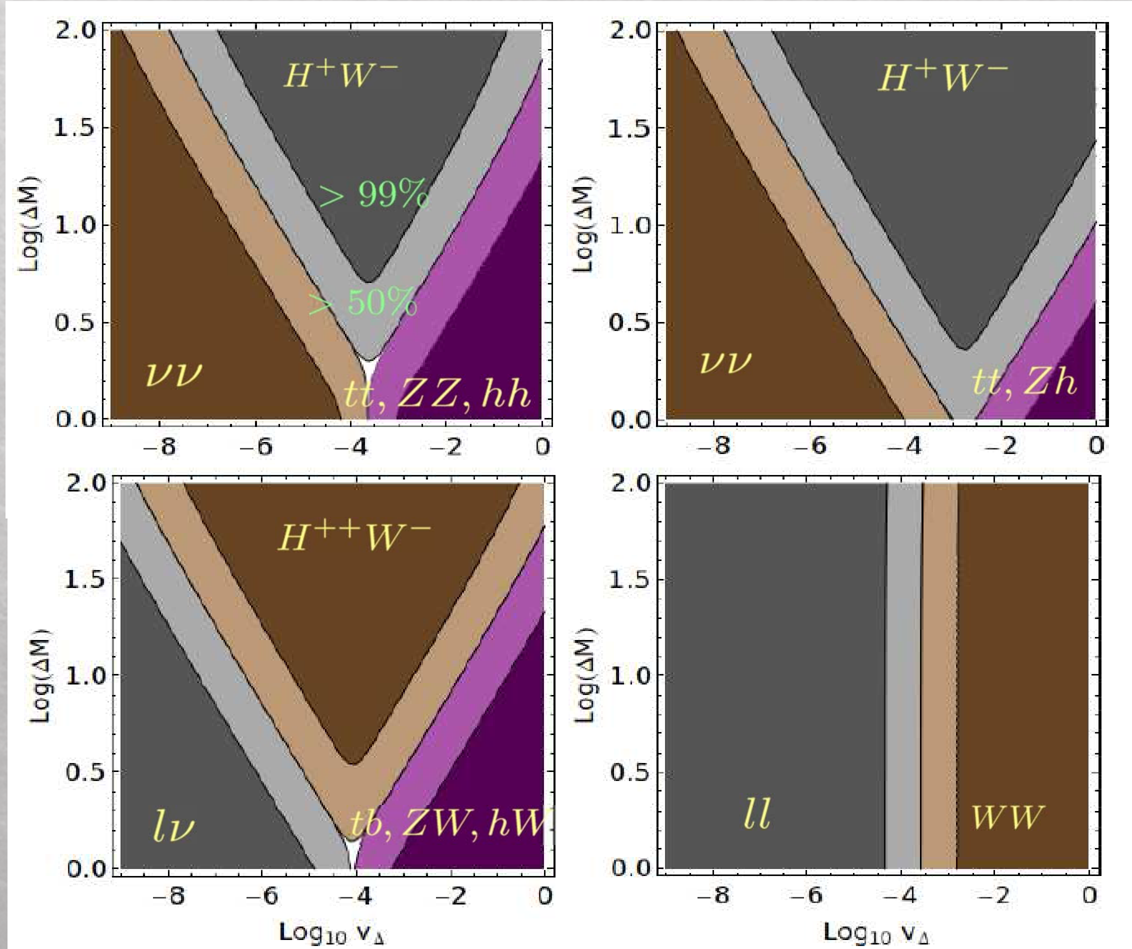
$$\mathcal{L}_{\not\Delta} = \frac{1}{\sqrt{2}}\mu\Phi^T i\tau_2\Delta^\dagger\Phi + h.c.$$

$$\Rightarrow -\mu v_\Phi h^0 H^0$$

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

Triplet decays

H^0 A^0 H$^+$ H^{++}



$*)\ m_\nu = Y_\Delta\, v_\Delta$

$\Delta - \bar{\Delta}$ mixing

EJC, Sharma, 1304.5059

- Triplet (lepton) number is conserved in the production

$$pp \to \Delta\bar{\Delta}$$

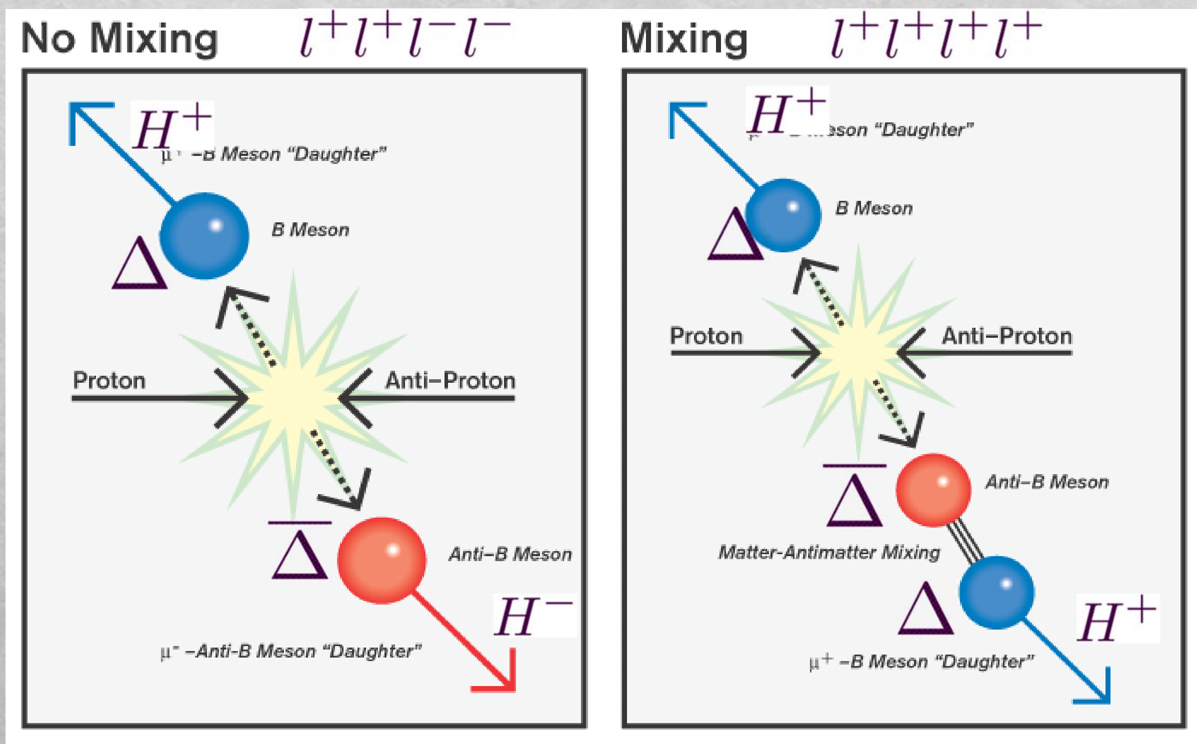
- Triplet number breaking (L=1) by doublet-triplet mixing:

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

- It induces the Δ–$\bar{\Delta}$ mixing (L=2): $\Delta^0 \leftrightarrow \bar{\Delta}^0$
- A tiny mass splitting between H & A (L=2) may be comparable their decay rate → observable oscillation:

$$x_{HA} \equiv \frac{\delta M_{HA}}{\tau_{H/A}} \sim 1$$

$\Delta - \bar{\Delta}$ oscillation



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: initial production×oscillation probability×gauge decays×leptonic decay

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

Same-Sign Tetra-Leptons

- Conditions for observable SS4L:

i) H^{++} is the lightest and ΔM large enough to allow $\Delta^0 \to H^+ W^- \to H^{++} 2W^-$.

ii) Sizable $\sigma \cdot BR(H^{++} \to l^+ l^+)$: larger Yukawa (smaller v_Δ) preferred.

iii) Large oscillation parameter, $x \gtrsim 1$, prefers smaller ΔM

$$x_{HA} = \frac{\delta M_{HA}}{\Gamma_{H/A}}$$

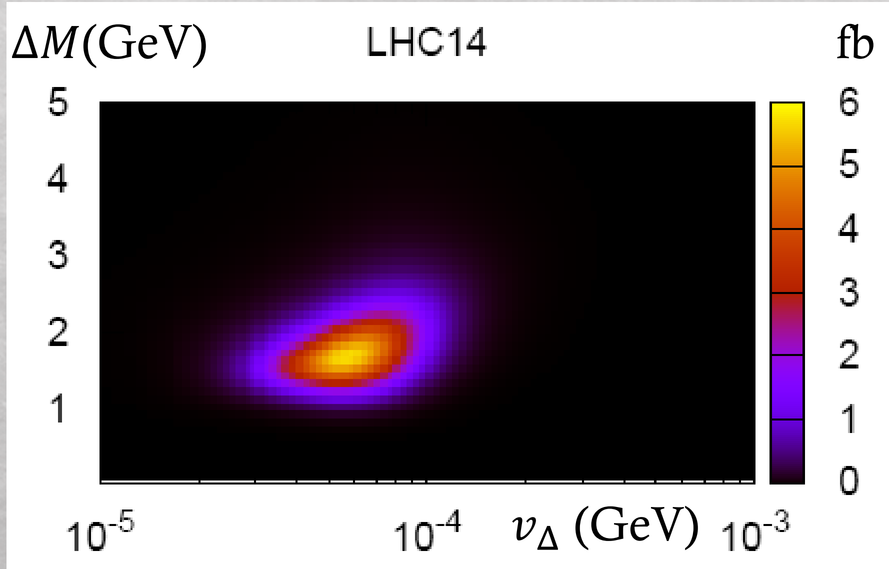
$$\delta M_{HA} \sim 2 \frac{v_\Delta^2}{v_\Phi^2} M_{H^0}$$

$$\Gamma_{H^0/A^0} \sim \frac{G_F^2 \Delta M^5}{\pi^3}$$

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

Same-Sign Tetra-Leptons

- SS4L production including the oscillation factor:



EJC, Sharma, 1304.5059

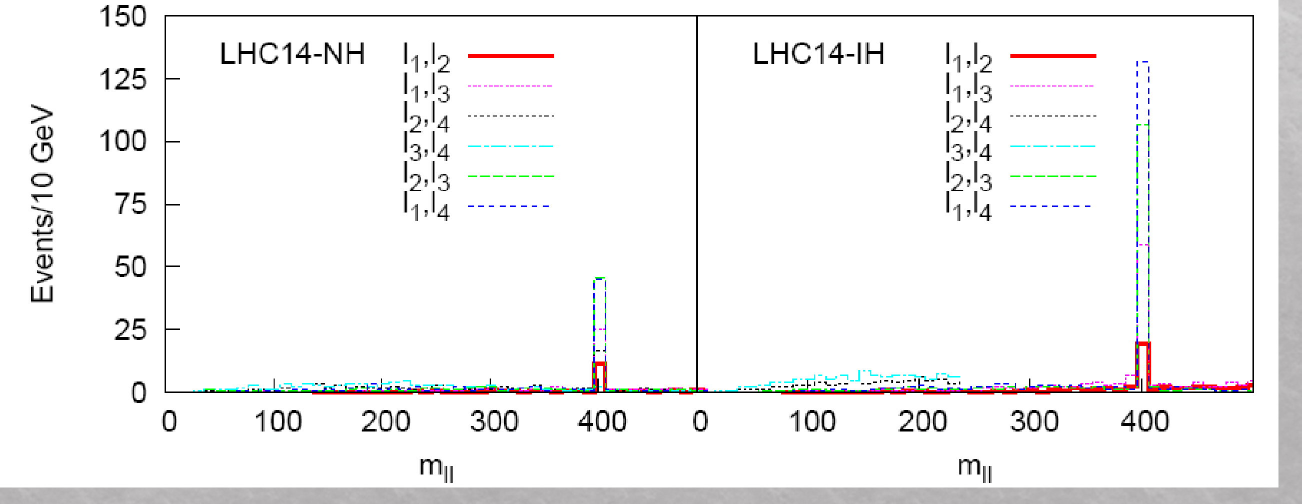
$M_{H^{\pm\pm}} = 400\text{GeV}$

- Benchmark point: v_Δ=7x10^{-5} GeV, ΔM=1.5 GeV.

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

100/fb	Pre-selection	Selection
$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC14-NH)	110	94
$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC14-IH)	240	210

No background; Lepton selection cuts only



Conclusion

- Neutrinos are a window to new physics beyond SM.
- Conventional seesaw models explains nicely the origin of neutrino mass, and could be associated with extra gauge symmetry.
- Their TeV scale option is being tested at LHC through same-sign di-lepton and multi-lepton signatures.
- In particular, Type II seesaw predicts novel phenomenon of triplet boson oscillation leading to same-sign tetra-leptons.
- Even lower energy options are also being investigated actively.

backup

Neutrino mass in Type II

- Neutrino mass matrix tested at colliders: EJC, Lee, Park, 0304069

$$\Delta^{++} \xrightarrow{f_{\alpha\beta}} l_\alpha^+ l_\beta^+$$

- Assuming vanishing CP phases and $v_\Delta < 10^{-4}$ GeV

NH IH1

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

Br (%)	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

*) Needs to be updated

Triplet decays

- Two mass hierarchies: $$M_{H^{++}} < M_{H^+} < M_{H^0/A^0} \quad \text{if} \quad \lambda_5 > 0$$ $$M_{H^{++}} > M_{H^+} > M_{H^0/A^0} \quad \text{if} \quad \lambda_5 < 0$$
- Gauge decay for non-zero ΔM:

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

- Dilepton decays through $f_{\alpha\beta}$:

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

- Di-quark/boson decays through doublet-triplet mixing with v_Δ/v_Φ:

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

$\Delta - \overline{\Delta}$ oscillation

- Initial $\Delta = H^0 + i\, A^0$ 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 $\overline{\Delta}$ is

$$\chi_\pm \equiv \frac{\int_0^\infty dt |g_\pm(t)|^2}{\int_0^\infty dt |g_+(t)|^2 + \int_0^\infty dt |g_-(t)|^2} = \boxed{\begin{cases} \frac{2+x^2}{2(1+x^2)} \\ \frac{x^2}{2(1+x^2)} \end{cases}}$$

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