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Higgs and Neutrinos

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Outline

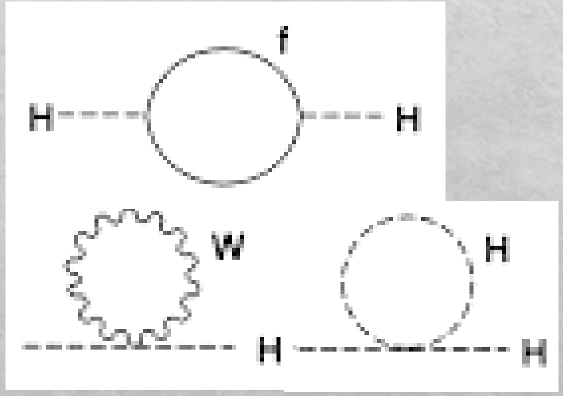
- Standard Higgs suffers from the problems with quadratic divergence and vacuum stability.
- It may be an indication for New Physics around TeV scale.
- Is it related to the origin of neutrino mass?
- Higgs may give us some hints.
- Neutrino-related signatures of Higgs can/should be looked at the LHC.

Elementary Higgs properties

Natural Higgs mass

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

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

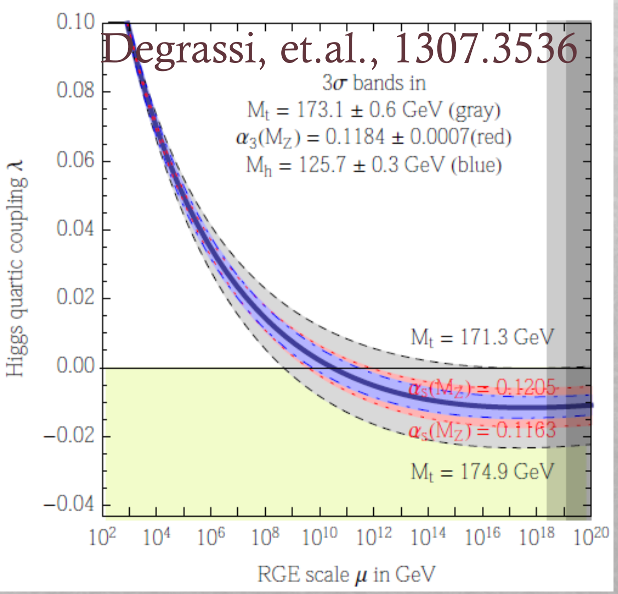


- Renormalizable away (e.g. DR).
- Still, Λ can be a physical scale of a UV theory.

Higgs vacuum stability

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

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



New physics below ~10^{10}GeV?

New physics scale

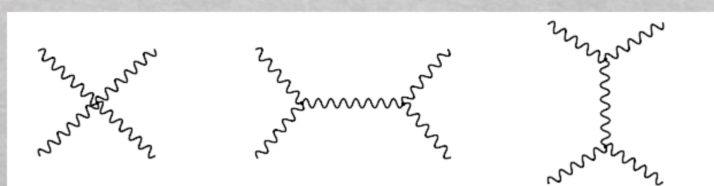
- Non-tolerable quadratic divergence: $\Lambda \lesssim 1\,TeV$.
- New physics changing the Higgs property, e.g.,

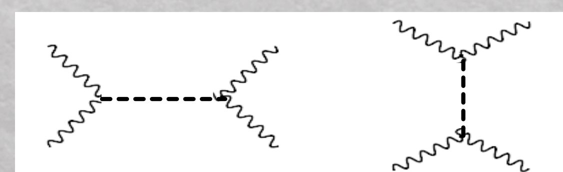
$$\mathcal{L} = \left(m_W^2 W^\mu W_\mu + \frac{1}{2}\, m_Z^2 Z^\mu Z_\mu\right)\left(1 + 2a\frac{h}{v}\right)$$

*) $a = 1$ in SM & MSSM

*) $a \approx 1 - \frac{2v^2}{f^2}$ in CH

Perturbative unitarity bound



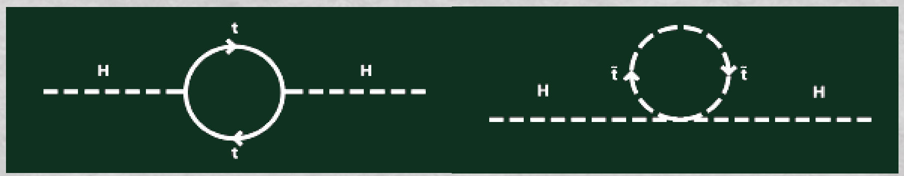


$$a_0(W_l W_L \to W_L W_L) = \frac{1}{32\pi}\left(\frac{s}{v^2}(1-a^2) - 4\frac{m_h^2}{v^2}\right) + \cdots$$

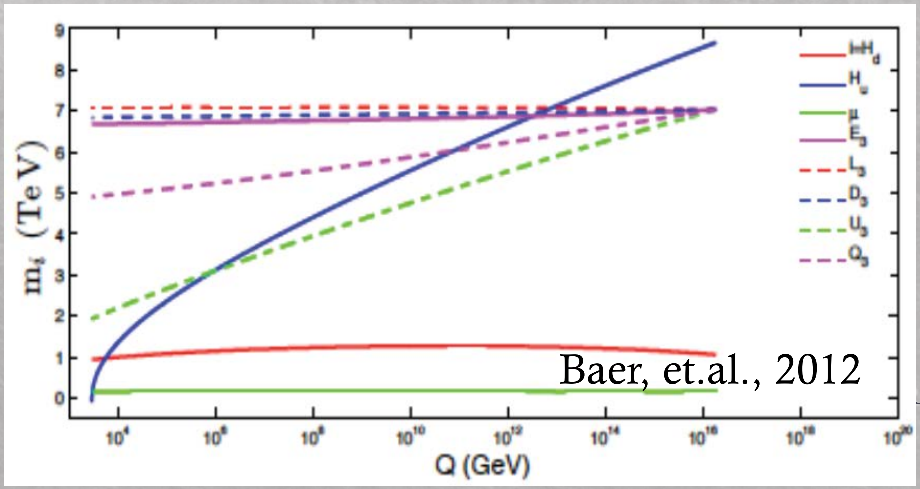
$$\Rightarrow \Lambda\sqrt{1-a^2}, m_h \lesssim 1\,TeV$$

Supersymmetric Higgs

- Quadratic divergences cancel out by opposite contribution from super-partners:



- SUSYS breaking, $m_{\tilde{f}} \gg m_f$, induces $\delta m_h^2 \sim \frac{y^2}{16\pi^2} m_{\tilde{f}}^2$ and thus naturalness requires $m_{\tilde{f}} \lesssim 1\, TeV$.
- Radiative EWSB: Large top-Yukawa drives a Higgs mass-squared to negative!



Supersymmetric Higgs

- Higgs potential in SUSY:

$$V_H = (m^2_{H_u} + \mu^2)|H_u|^2 + (m^2_{H_d} + \mu^2)|H_d|^2 + (B\mu H_u H_d + h.c.) + V_D$$

$$V_D = \frac{1}{8}(g_2^2 + g_1^2)\left[|H_u|^2 - |H_d|^2\right]^2$$

- Minimization condition: less fine-tuned for SUSY parameters close to M_Z:

$$\frac{M_Z^2}{2} = \frac{m^2_{H_d} - m^2_{H_u}\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

$$\frac{2B\mu}{\sin 2\beta} = m^2_{H_u} + m^2_{H_d} + \mu^2$$

- Higgs quartic coupling from the gauge D-term → too light Higgs:

$$\lambda = \frac{1}{8}(g^2 + g_1^2) \approx 0.07 \Rightarrow m_h^2 \approx \frac{1}{2}\,(125\ GeV)^2$$

Supersymmetric Higgs

- Top-stop loop to save the Higgs:

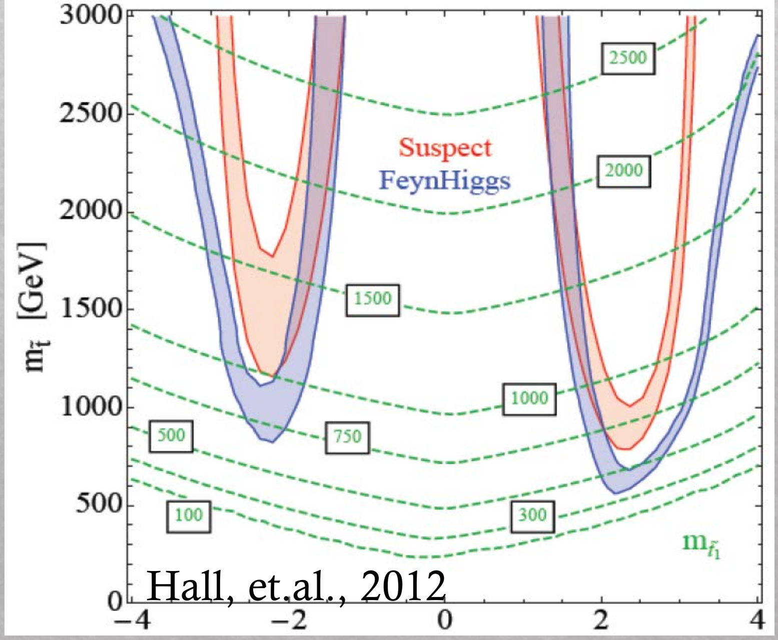
$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3y_t^2 m_t^2}{4\pi^2}\left[\ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{1}{12}\frac{X_t^2}{m_{\tilde{t}}^2}\right)\right]$$

- Higgs prefers multi-TeV stop mass or maximal stop left-right mixing:

$$X_t = A_t + \mu \cot\beta \approx \sqrt{6}\, m_{\tilde{t}}$$

- Heavy sfermions consistent with the LHC search, but conflict with natural EWSB:

$$M_Z^2 \sim m_{H_{u,d}}^2 \sim \mu^2$$



New Physics for Neutrinos

Neutrino mass operator

- Neutrino requires a trivial extension of SM:

$$L \sim H \quad (H^c = \epsilon H^*) \text{ and thus } LH^c \text{ is a SM singlet}$$

- Add a singlet fermion → Dirac mass

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

- Add a D=5 operator → Majorana mass

$$\frac{1}{2M} LH^c LH^c + h.c. \to \frac{m_\nu}{2} \nu\nu + h.c. \to M = \frac{\langle H^0 \rangle^2}{m_\nu} \sim 10^{14} GeV$$

- Looking for the origin of the smallness (y_ν^D) or largeness (M).

Majorana Seesaw

- Type I with RH neutrino: N

$$-\mathcal{L} = Y_N L H^c N + \frac{M_N}{2} NN + h.c. \to m_\nu = Y_N \; M_N^{-1} Y_N^T \langle H^0 \rangle^2$$

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

$$-\mathcal{L} = Y_\Delta \mathrm{LL}\Delta + \mu_\Delta HH\Delta + \frac{M_\Delta^2}{2} |\Delta|^2 + h.c. \to m_\nu = Y_N \langle \Delta^0 \rangle = Y_N \frac{\mu_\Delta \langle H^0 \rangle^2}{M_\Delta^2}$$

- Type III with triplet fermion: $\Sigma_{Y=0} = (\Sigma^{+}, \Sigma^{0}, \Sigma^{-})$

$$-\mathcal{L} = Y_\Sigma \mathrm{LH^c}\Sigma + \frac{M_\Sigma}{2} \Sigma\Sigma + h.c. \to m_\nu = Y_\Sigma \; M_\Sigma^{-1} Y_\Sigma^T \langle H^0 \rangle^2$$

Inverse Seesaw

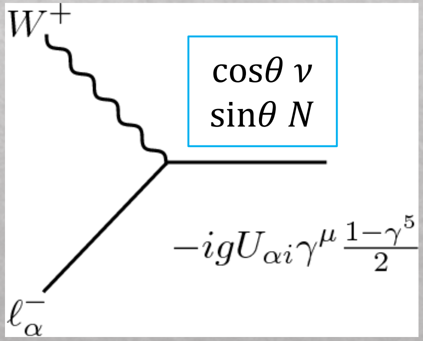
- A large neutrino Yukawa with a tiny B-L breaking mass:

$$-\mathcal{L} = YLH^cN + MNN' + \frac{1}{2}\mu N'N' \quad \rightarrow m_\nu = YM^{-1}\mu M^{-1}Y^T\langle H^0\rangle^2$$

- Generally large $\nu - N$ mixing : $\sin\theta = \dfrac{m_D}{\sqrt{m_D^2 + M^2}}$ $\quad m_D = Y\langle H^0\rangle$

EWPD limit: $\sin\theta_{e,\mu,\tau} < (0.055, 0.057, 0.079)$

Aguila et.al., 0803.4008 $\quad y_{e,\mu,\tau} \approx \sin\theta_{e,\mu,\tau}\dfrac{M}{174GeV}$



- Additional large Yukawas make worse quadratic divergence and Higgs stability.

Dirac Seesaw

- Type I : $\frac{yy'}{M} LH^c S \nu^c$ $\quad \mathrm{y}_\nu^{\mathrm{D}} = yy' \langle S \rangle / M$

Murayama, Pierce 2002

$$yL\Psi_D^c S + y' H^c \Psi_D \nu^c + \mu H H^c S + M \Psi_D \Psi_D^c$$

Requies a (discrete) symmetry to forbid the $LH^c\nu^c$ term

- Type II : $\frac{yy'}{M} LH\Delta \nu^c$ $\quad \mathrm{y}_\nu^{\mathrm{D}} = yy' \langle \Delta^0 \rangle / M$

*) Low-energy signatures?

$$yL\Psi_D \Delta + y' H \Psi_D^c \nu^c + \mu H H \Delta + M \Psi_D \Psi_D^c$$

- Type III : $\frac{yy'}{M} LH^c \Sigma \nu^c$ $\quad \mathrm{y}_\nu^{\mathrm{D}} = yy' \langle \Sigma^0 \rangle / M$

$$yLH^c \Psi_T + y' \Psi_T^c \Sigma \nu^c + \mu H H^c \Sigma + M \Psi_T \Psi_T^c$$

Neutrinos affecting Higgs

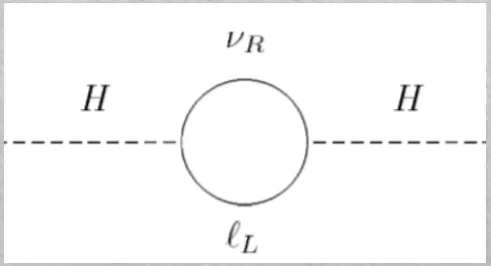
Majorana Seesaw & Higgs mass

- Heavy seesaw particles coupling to Higgs contribute to radiative Higgs mass.

*) Not applicable to SUSY Seesaw

- Type I:

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



Vissani, 9709409

Farina, Pappadopulo, Strumia, 1303.7244

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

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

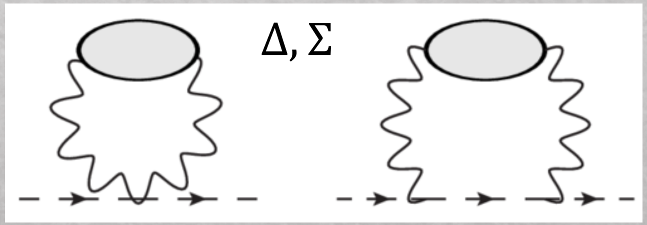
*) Viable low-scale leptogenesis?

Majorana 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

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

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

Dirac seesaw & Higgs mass

- Higgs couples to heavy doublet or triplet fermions, which can induce again problematic Higgs mass correction.
- Yukawa effect, e.g., in Type I

$$\lambda L \Psi_D^c S + \lambda' H^c \Psi_D \nu^c + \mu H H^c S + M \Psi_D \Psi_D^c \Rightarrow m_\nu = \frac{\lambda \lambda' v_S v_H}{2M}$$

$$\Rightarrow \delta m_h^2 \sim 4 \frac{\lambda'^2}{16\pi^2} M^2$$

*) without rigor

$$\lambda = a\lambda', v_S = b v_H \Rightarrow M \lesssim m_h \left(ab\delta \frac{16\pi^2 m_h}{m_\nu} \right)^{\frac{1}{3}} \approx 0.7\ 10^7 GeV \sqrt[3]{ab\delta}$$

- Leading gauge effect: $\delta m_h^2 \sim 9 \frac{g_2^4}{(4\pi)^4} M^2 \Rightarrow M \lesssim TeV\ \sqrt{\delta}$

*) Heavy leptons at TeV with $\lambda\lambda' \sim 10^{-12}$..

Inverse seesaw & Higgs mass

- Larger Yukawa is more dangerous:

$$-\mathcal{L} = yLH^cN + MNN' + \frac{1}{2}\mu N'N' \quad \rightarrow m_\nu = yM^{-1}\mu M^{-1}y^T\langle H^0\rangle^2$$

$$\delta m_h^2 \sim 4\frac{y^2}{16\pi^2}M^2 < m_h^2\,\delta \qquad y_{e,\mu,\tau} \approx \sin\theta_{e,\mu,\tau}\frac{M}{174GeV}$$

$$\Rightarrow M < 1.7TeV\frac{\sqrt[4]{\delta}}{\sqrt{\sin\theta/0.05}}$$

Seesaw & Higgs stability

- Type I/III with either small neutrino Yukawa or $M > 10^{10} GeV$

→ same as in SM.

- Type II with an extra Higgs triplet → doublet & triplet mixing terms in scalar potential change the running behavior (generic with any new boson field):

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

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

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

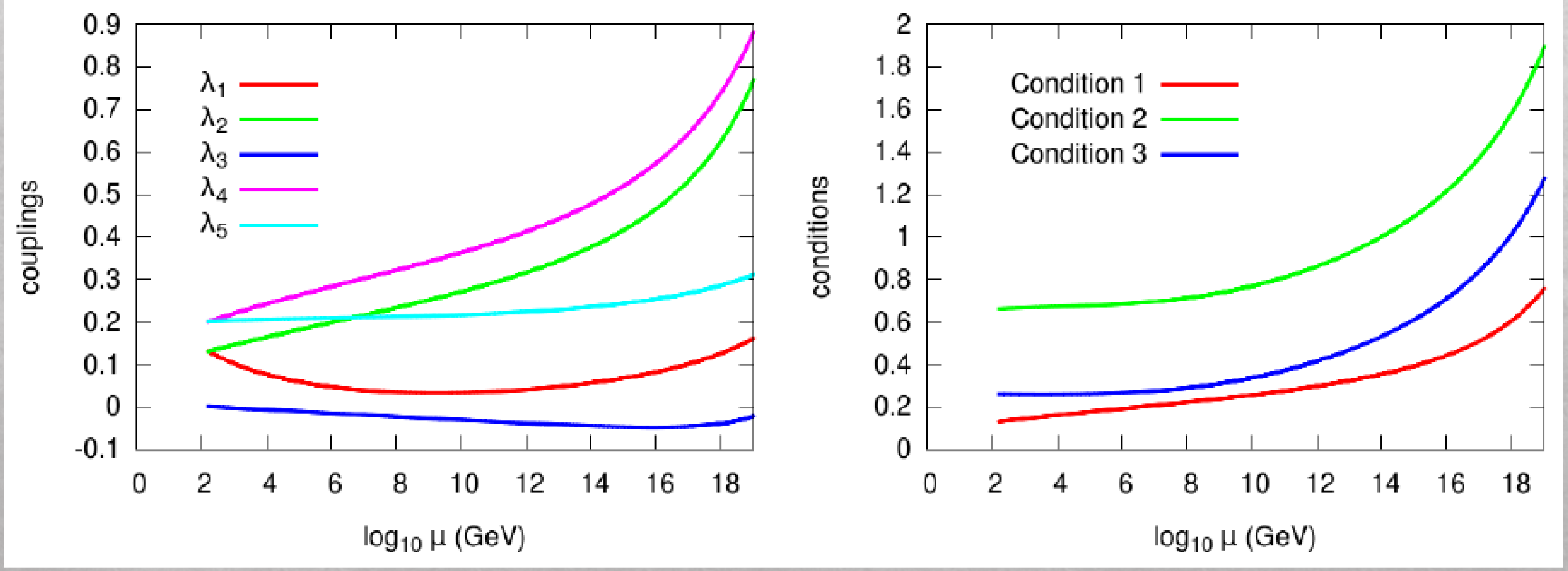
- One-loop RGE:

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

Chao, Zhang, 0611323
Schmidt, 07053841

Higgs stability in Type II

- Running of the couplings and vacuum stability conditions

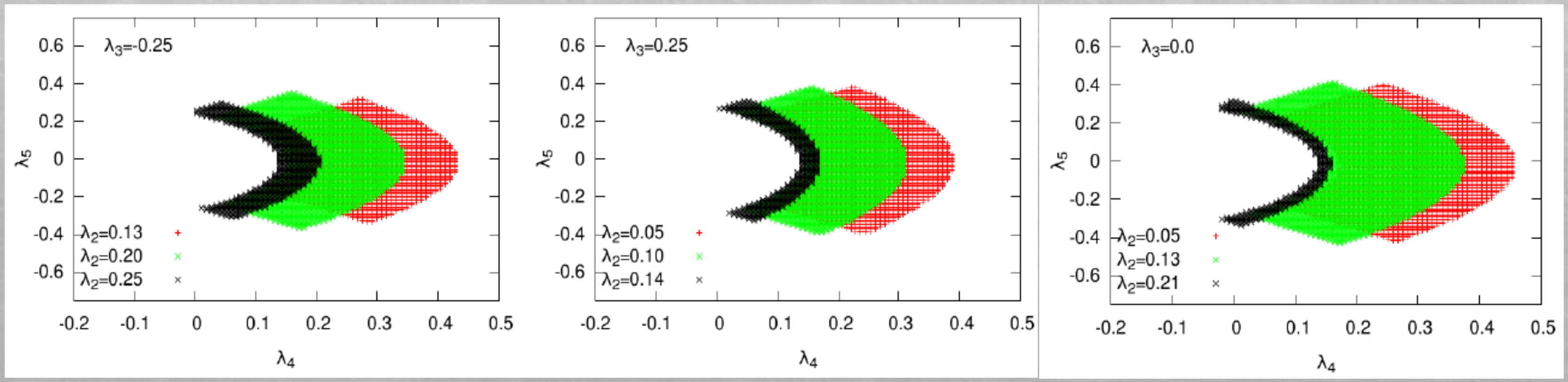


EJC, Lee, Sharma, 1209.1303

Higgs stability in Type II

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

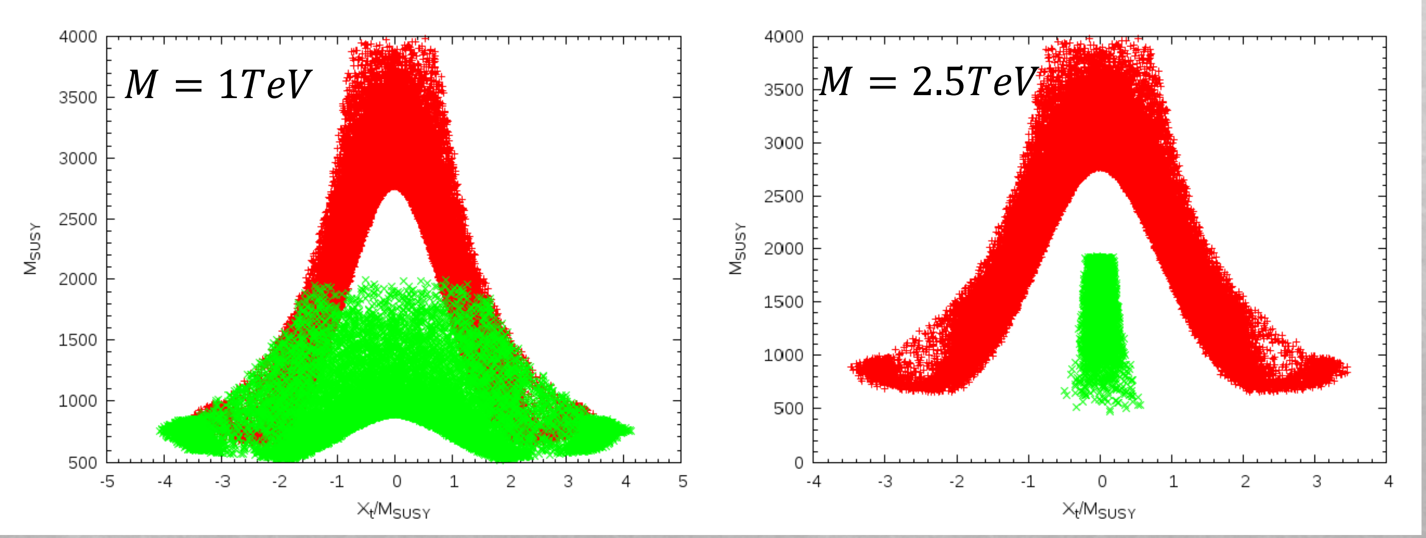
	10^5 GeV	10^{10} GeV	10^{19} GeV
λ_2	$(0, 1)$	$(0, 0.5)$	$(0, 0.25)$
λ_3	$(-2.0, 2.4)$	$(-1.0, 1.25)$	$(-0.55, 0.62)$
λ_4	$(-0.5, 1.7)$	$(-0.1, 0.9)$	$(0, 0.5)$
λ_5	$(-1.5, 1.5)$	$(-0.7, 0.7)$	$(-0.4, 0.4)$



EJC, Lee, Sharma, 1209.1303

Inverse seesaw & SUSY Higgs

- A large neutrino Yukawa with new heavy sleptons → additional contribution to Higgs mass correction



Inverse seesaw contribution in PMSSM for $m_s < 3TeV, y < 1.$

EJC, Mummidi, Vempati, 1405.5478

Higgs signatures from neutrino

Can Higgs be seen from seesaw?

- Type I: Heavy RHN decays through Y_N and $\theta_{\nu N} \sim Y_N v/M$.

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

- RHN could be associated with an extra Z', e.g, from $U(1)_{B-L}$.

$$pp \to Z' \to NN \to (lW, \nu Z, \nu h)(lW, \nu Z, \nu h)$$

Majorana nature → SSD signature of $l^{\pm}l^{\pm}W^{\mp}W^{\mp}$
Displaced vertices for small Yukawa
RHN mass reconstruction: M_{ljj}
Higgs signature: $l^{\pm}W^{\mp}\nu h$

Need to be checked if …

- LHC limit: $m_{Z'} \gtrsim 4TeV$ Atlas-Conf-2017-028

General search for N

- N production: $pp \to W^* \to l_1 N \to l_1 l_2 W;\ l_1 \nu Z;\ l_1 \nu h$

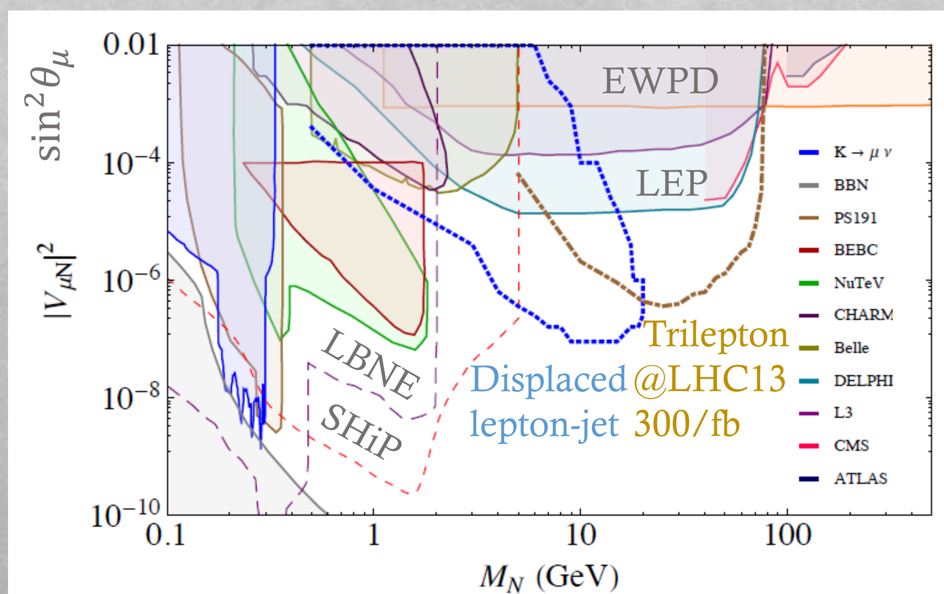
*) only OSD for inverse seesaw

- Exotic Higgs decay:

$$h \to \nu N \to \nu l_1 W \to \nu l_1 l_2$$

$$\to \nu \nu Z \to \nu \nu l^+ l^-$$

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



Deppisch, et.al. 1502. 06541
Izaguirre, Shuve 1504.02470

Can Higgs be seen from seesaw?

- Type II: $\Delta^{++} \to l_1^+ l_2^+$ (SSD)

  $\Delta^0(H^0, A^0) \to hh, hZ$ (?)

- LHC limit: $m_{\Delta^{++}} \gtrsim 500\ GeV$ (NH), $700\ GeV$ (IH) ATLAS 1710.09748

- Type III: $\Sigma^\pm \to l^\pm h, l^\pm Z, \nu W^\pm;\ \ \Sigma^0 \to \nu h, \nu Z, l^\pm W^\mp$ Francheschini et.al. 0805.1613

  $pp \to \Sigma^\pm \Sigma^0 \to l_1^\pm h\ l_2^\pm W^\mp$ (DV)

  $pp \to \Sigma^+ \Sigma^- \to l_1^\pm h\ l_2^\mp Z$

  Bandyopadhyay, EJC 1007.2281

  Bandyopadhyay et.al. 1112.3080

  Mass reconstruction: M_{lbb} & M_{bb}

- LHC limit: $m_\Sigma > 840$ GeV CMS 1708.07962 multi-lepton searches assuming $B_e = B_\mu = B_\tau$

Triplet Higgs in Type II

Neutrino mass in Type II

- Neutrino mass from neutrino Yukawa and small triplet VEV:

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

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

- Rho-parameter bound on the triplet VEV:

$$\rho \equiv \frac{m_W^2}{m_Z^2\, c_W^2} = \frac{\sum_i [T(i)(T(i)+1) - T_3(i)^2]|v_i|^2}{2\sum_i T_3(i)^2 |v_i|^2} = 1.00037 \pm 0.00023$$

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

- Neutrino mass matrix tested at colliders: $\Delta^{++} \xrightarrow{f_{\alpha\beta}} l_\alpha^+ l_\beta^+$

EJC, Lee, Park, 0304069

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

$$M^\nu = \begin{pmatrix} 0.00403 & 0.00816 & 0.00259 \\ 0.00816 & 0.0264 & 0.0215 \\ 0.00259 & 0.0215 & 0.0286 \end{pmatrix}$$

IH1

$$\begin{pmatrix} 0.0479 & -0.00557 & -0.00573 \\ -0.00557 & 0.0239 & -0.0240 \\ -0.00573 & -0.0240 & 0.02693 \end{pmatrix}$$

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

Scalar mass spectrum

- Mass splitting between triplet components:

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

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

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

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

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

- Mass splitting between neutral scalars:

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

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

Triplet decays

- Two mass hierarchies: $M_{H^{++}} < M_{H^+} < M_{H^0/A^0}$ if $\lambda_5 > 0$

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

- 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:

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

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

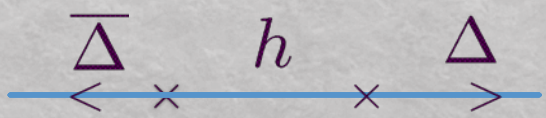
- Triplet (lepton) number is conserved in the production

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

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

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

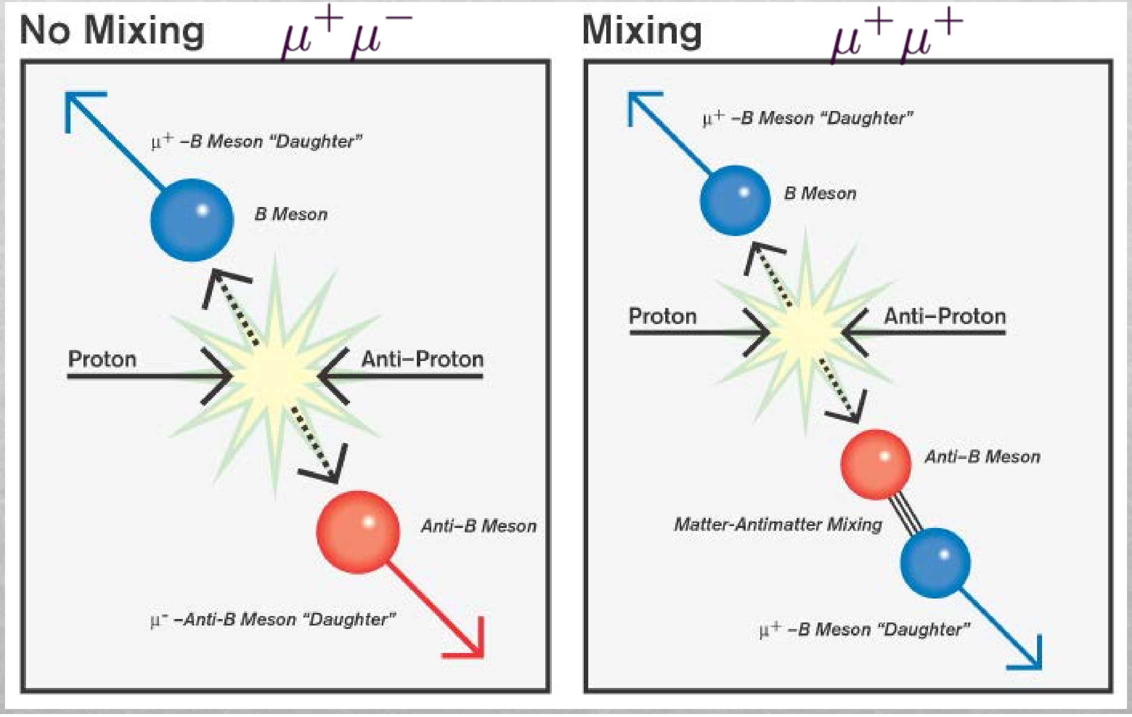
- It can lead to Δ–$\bar{\Delta}$ mixing (L=2):

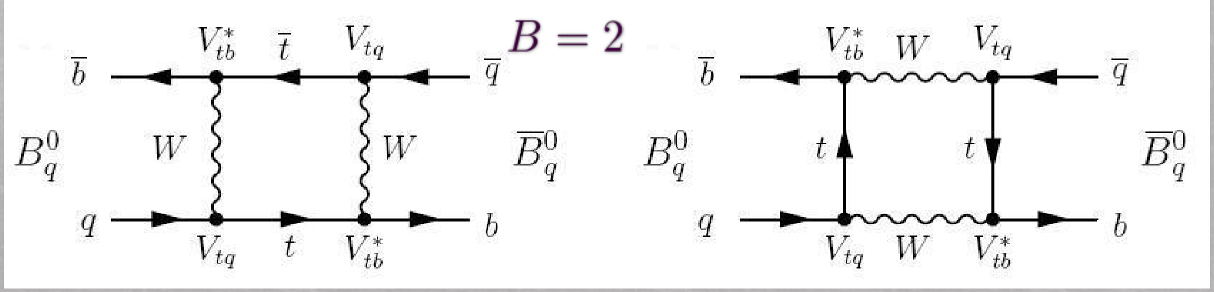


- Note a tiny mass splitting between H & A (L=2):

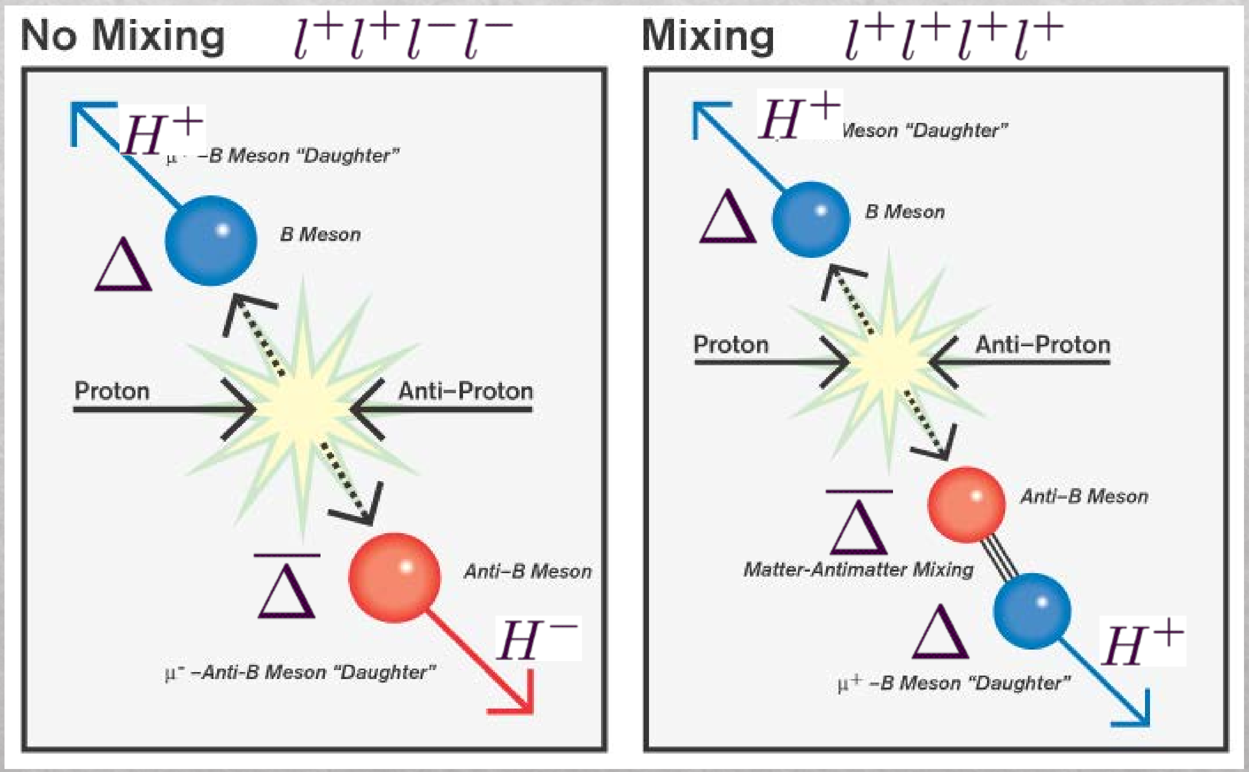
$$\boxed{\delta M_{HA} \approx 2M_{H^0}\frac{v_\Delta^2}{v_0^2}\frac{M_{H^0}^2}{M_{H^0}^2 - m_{h^0}^2}}$$

$B - \bar{B}$ mixing





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



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

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

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

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

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

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

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

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

- Conditions for observable SS4L:

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

  ii) Sizable $\sigma \cdot BR(H^{++} \rightarrow l^+ l^+)$: larger $f_{\alpha\beta}$ (smaller v_Δ) preferred.

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

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

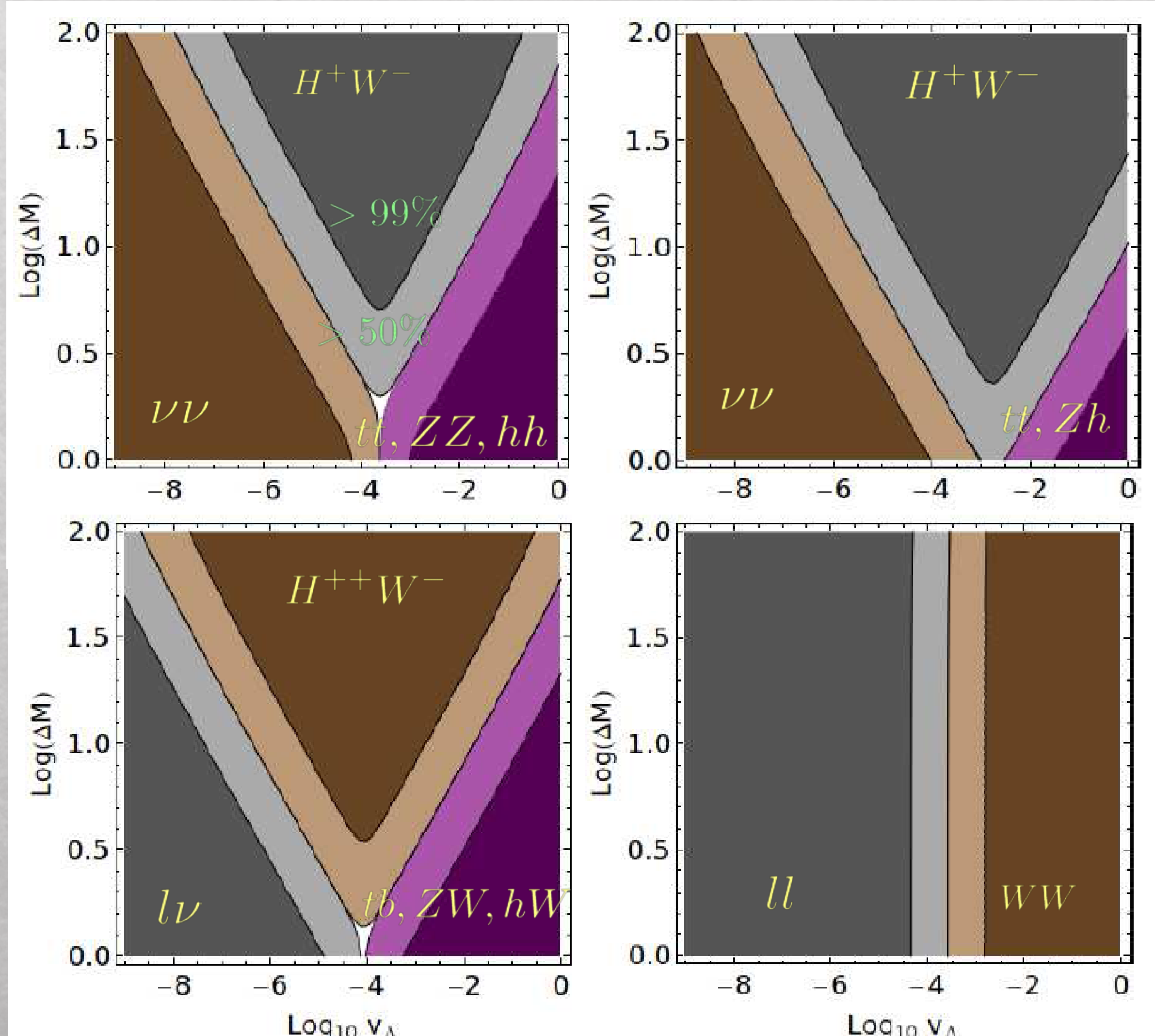
$$\delta M_{HA} \sim 2 \frac{v_\Delta^2}{v_\Phi^2} M_{H^0}$$

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

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

H^0

A^0



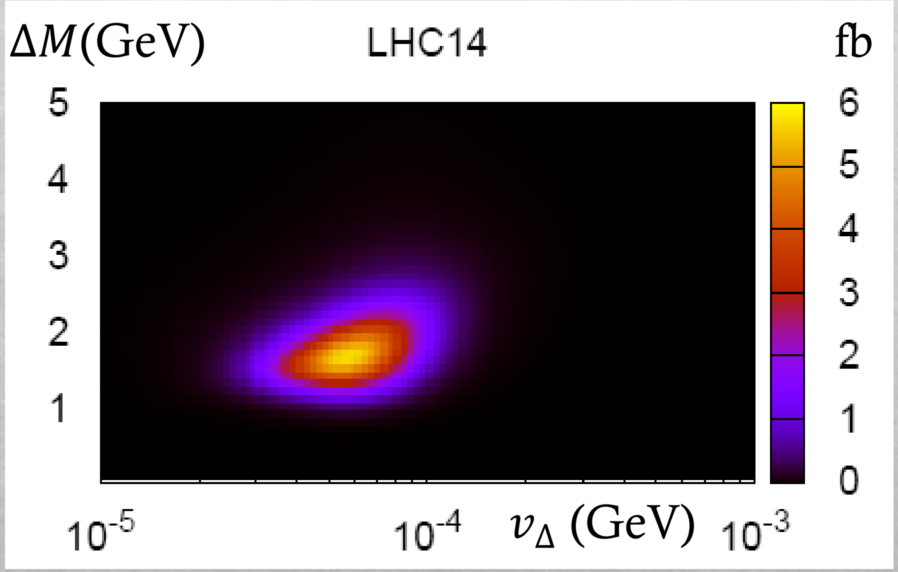
H^+

H^{++}

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

Same-Sign Tetra-Leptons

- SS4L production including the oscillation factor:



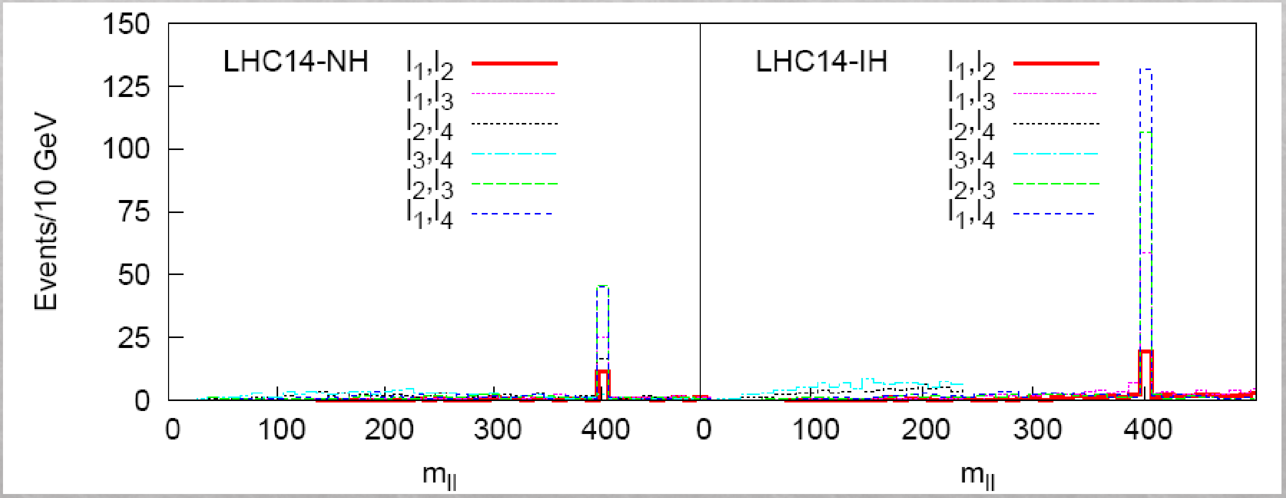
$M_{H^{\pm\pm}} = 400\text{GeV}$

- 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



More issues

- Lepto-/baryo-genesis
- Flavour physics: LFV signatures
- Muon g-2
- SHiPology: new physics at sub-GeV
- Dark matter