SEESAW, DARK MATTER AND LEPTOGENESIS AT THE TEV SCALE

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Standard Model and New Physics

❖ Standard Model: very successful theory of high energy phenomena

❖ Physics beyond the Standard Model must be advocated to solve three main experimental facts:

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❖ Physics beyond the Standard Model must be advocated to solve three main experimental facts:

1. Data on neutrino oscillation experiments: tiny mass and flavour mixing

2. Baryon asymmetry of the Universe: measurement from BBN and CMB

3. Indirect gravitational observations of Dark Matter: non-baryonic, neutral and stable

$\Omega_{\rm DM} h^2 = 0.1199 \pm 0.0027$ $\quad$ $\Omega_{\rm B} h^2 = 0.02205 \pm 0.00028$ $\quad$ PLANCK 2013

Standard Model and New Physics

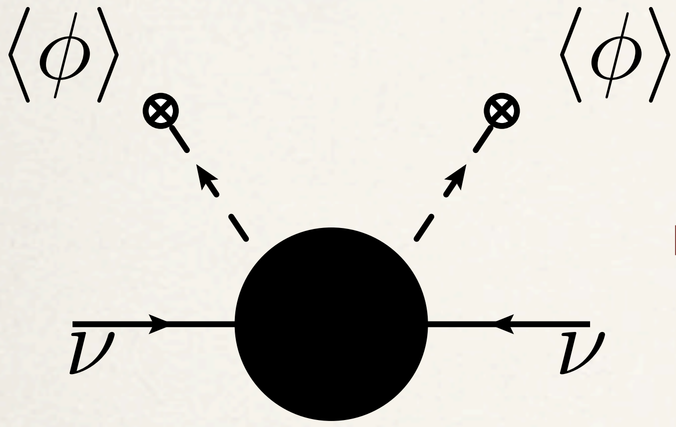
New Physics at the TeV scale: scenario testable in collider and experiments at high intensity frontier

- Seesaw mechanism of neutrino mass generation:
  - additional U(1) (global) symmetry
  - extended Higgs sector (singlet majoron scenario)
- Scalar dark matter

Backup Slides

- Thermal leptogenesis: link between baryon asymmetry, dark matter and neutrino masses

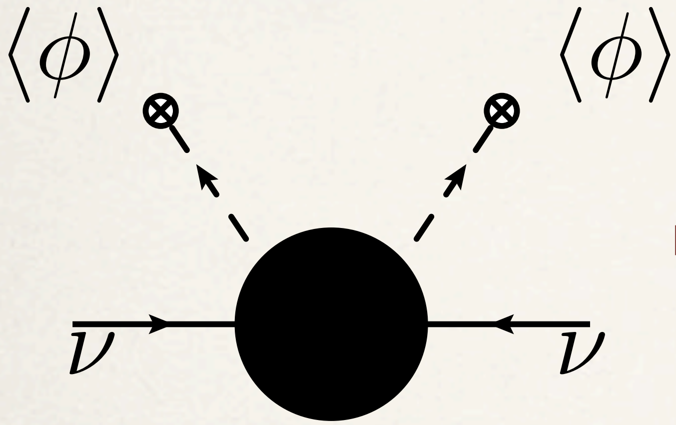
Seesaw Mechanism



$$\frac{c_{\ell\ell'}}{\Lambda}\left(\overline{L^c_\ell}\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L_{\ell'}\right)$$

Weinberg, PRD 22 (1980), 1694

Seesaw Mechanism



$$\frac{c_{\ell\ell'}}{\Lambda}\left(\overline{L^c_\ell}\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L_{\ell'}\right)$$

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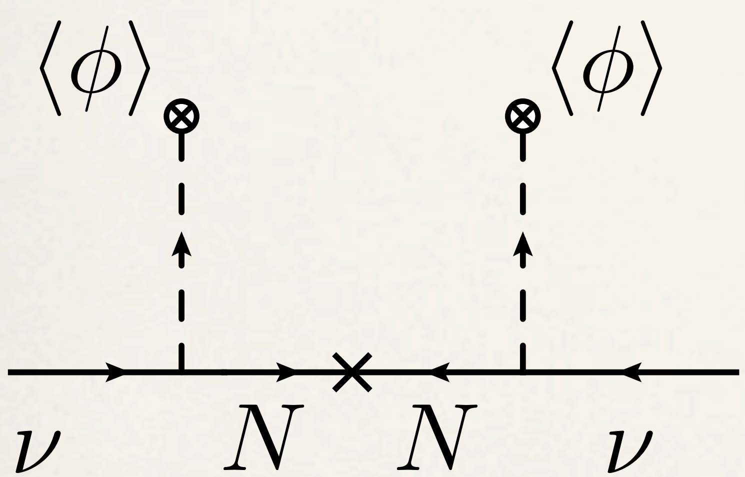
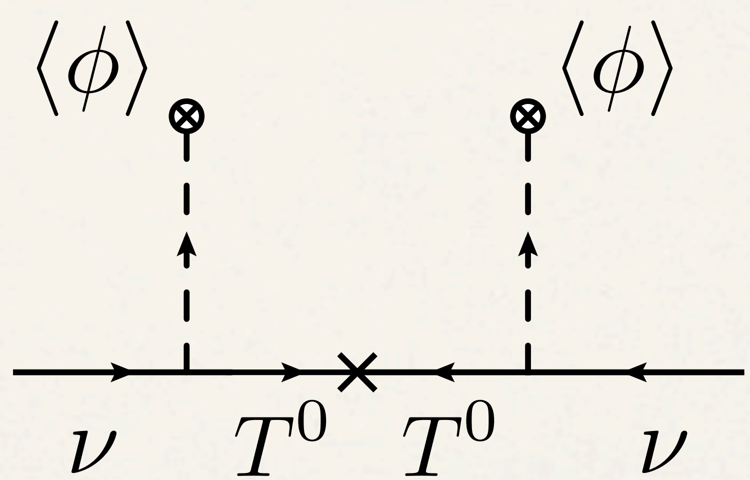
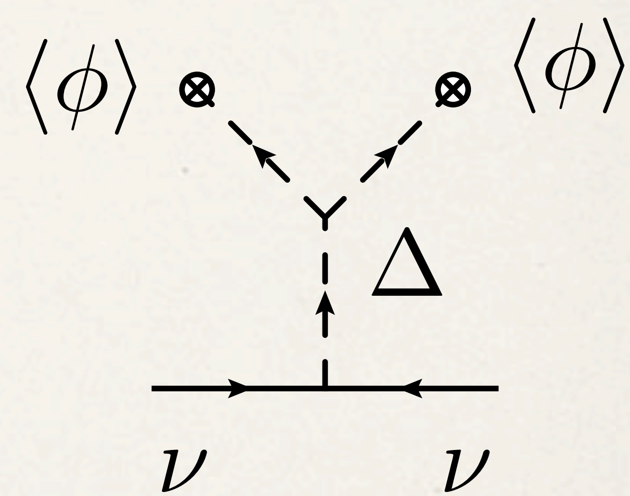
three possible realizations at tree-level



type I



type III



type II

Type I Seesaw Scenario

Minkowski, PLB 67 (1977) 421;
Gell-Mann, Ramond, Slansky, 1979;
Yanagida, 1979;
Mohapatra, Senjanovic, PRL 44 (1980) 912

with at least two Majorana fermion singlets:

$$\begin{aligned} \mathcal{L}_{\mathrm{Y}}(x) &= \lambda_{i\ell}\,\overline{N_i}(x)\,H^\dagger(x)\,L_\ell(x) + h_\ell\,H^c(x)\,\overline{\ell_R}(x)\,L_\ell(x) + \mathrm{h.c.} \\ \mathcal{L}_{\mathrm{M}}^{\mathrm{N}}(x) &= -\frac{1}{2}\,M_i\,\overline{N_i}(x)\,N_i(x)\,, \qquad i \geq 2 \end{aligned}$$

$$m_\nu = v^2 \lambda^T\,M^{-1}\,\lambda = U^*_{\mathrm{PMNS}}\,Diag(m_1, m_2, m_3)\,U^\dagger_{\mathrm{PMNS}}$$

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$$\mathcal{L}_{\mathrm{M}}^{\mathrm{N}}(x) = -\frac{1}{2}\,M_i\,\overline{N_i}(x)\,N_i(x)\,, \qquad i \geq 2$$

$$m_\nu = v^2 \lambda^T\, M^{-1}\,\lambda = U^*_{\mathrm{PMNS}}\, Diag(m_1, m_2, m_3)\, U^\dagger_{\mathrm{PMNS}}$$

naively...

$|\lambda| \sim 1$ and $m_\nu \sim 10^{-2}$ eV $\Longrightarrow$ $M \sim 10^{14}$ GeV **not testable!**

$m_\nu \sim 10^{-2}$ eV and $M \sim 1$ TeV $\Longrightarrow$ $|\lambda| \sim 10^{-6}$ **not testable!**

Type I Seesaw Scenario

is it possible to have seesaw models at TeV scale consistent with light neutrino masses and sizable Yukawa couplings ?

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Mohapatra, '86
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Pilaftsis, Underwood, 2005
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→ **Lepton number softly broken: pseudo-Dirac fermions**

inverse/linear seesaw scenarios

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→ **Lepton number softly broken: pseudo-Dirac fermions**

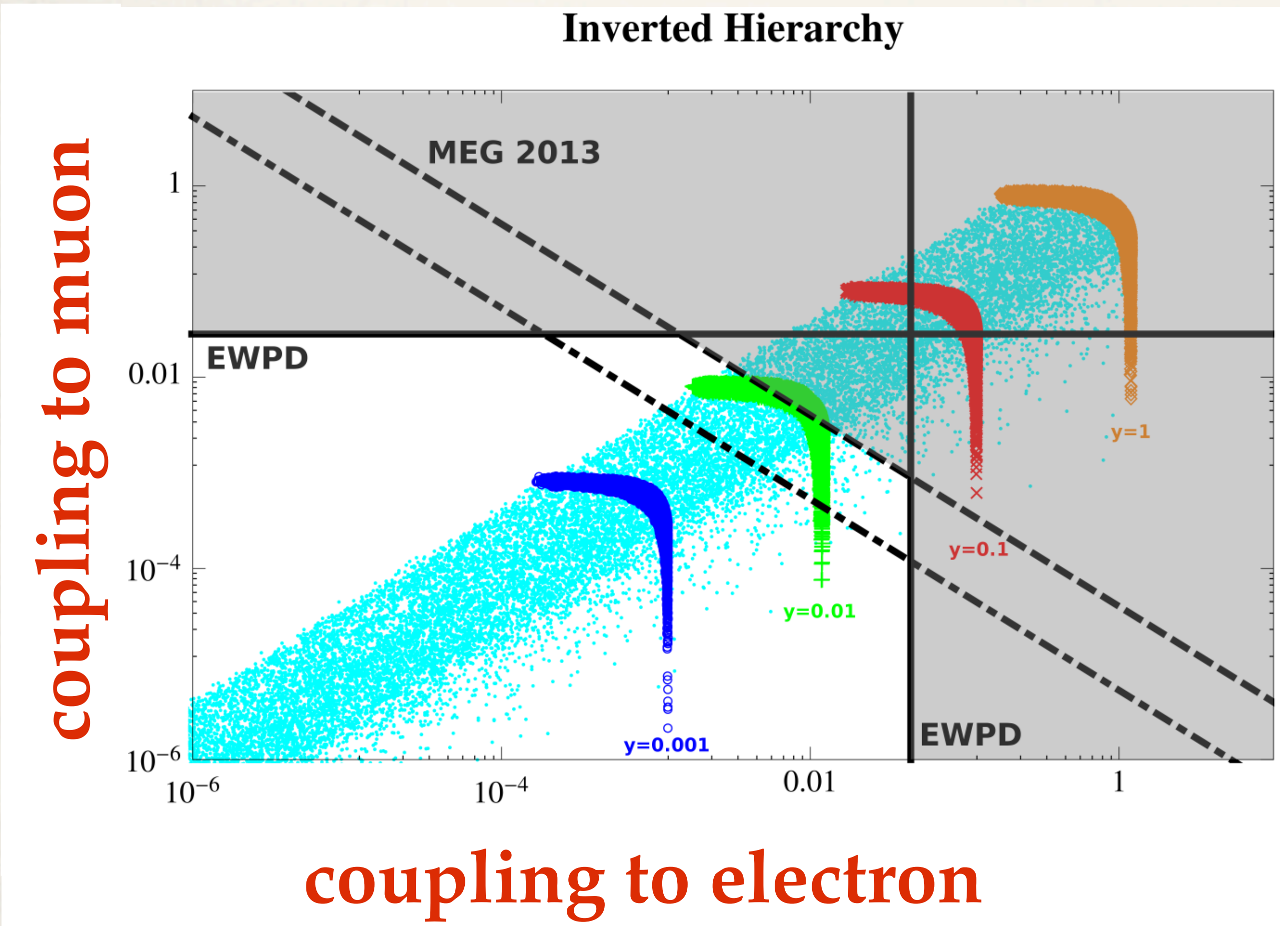
inverse/linear seesaw scenarios

measurable low and high energy observables:

- charged lepton radiative decays
- deviations from EW precision observables
- production at colliders of heavy Majorana fermions

Type I Seesaw Scenario

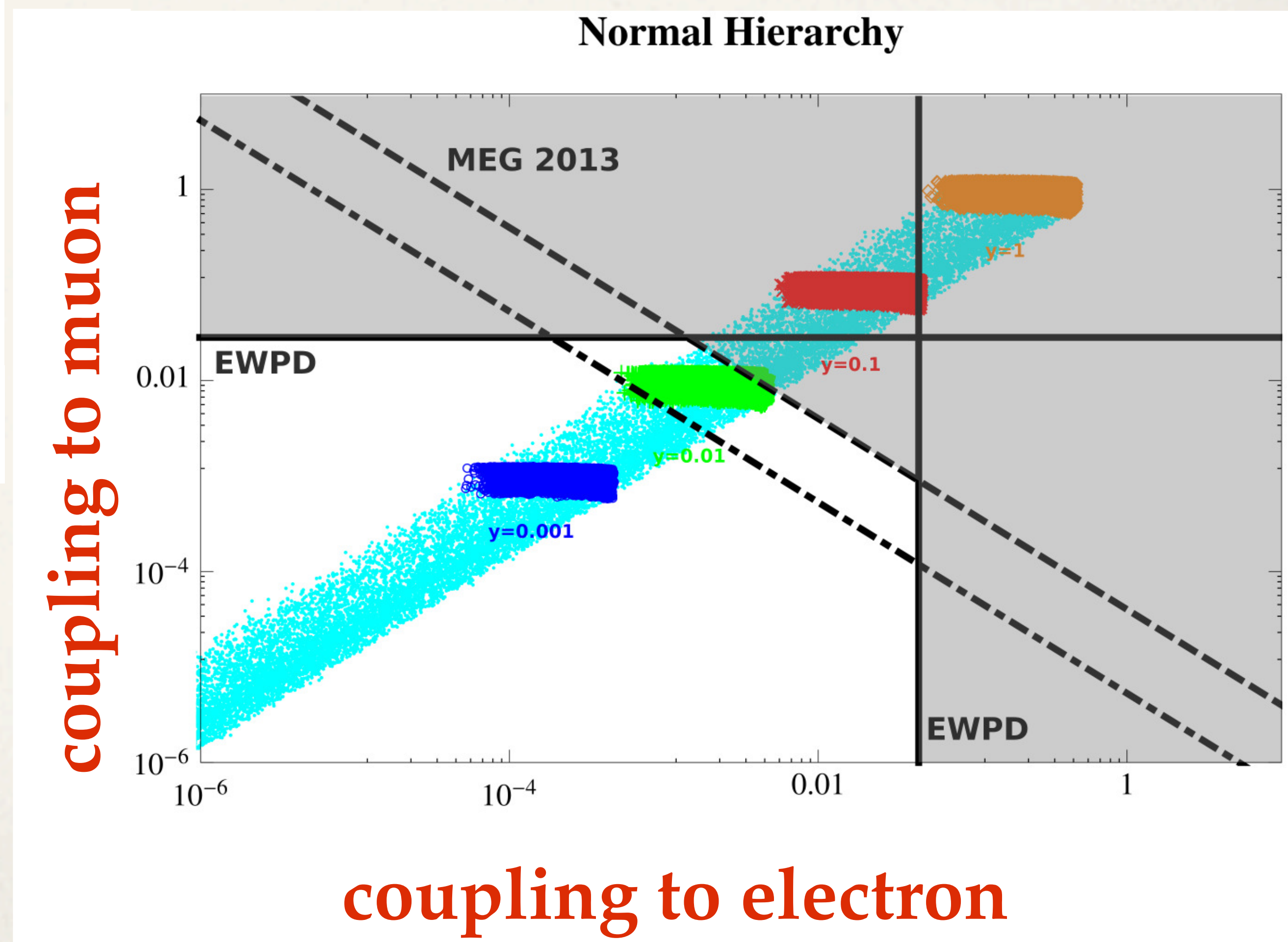
couplings of heavy Majorana fermions to charged leptons



$$y \lesssim 0.04$$

Ibarra, EM, Petcov, 2011
Dinh, Ibarra, EM, Petcov, 2012

$$M_1 = 100 \text{ GeV}$$



SEESAW SCENARIOS WITH A GLOBAL $U(1)_{L'}$

add 3 **RH neutrinos**

	H_1	Q_i	u_{Ri}	d_{Ri}	L_α	$e_{R\alpha}$	N_1	N_2	N_3
$U(1)_{L'}$	0	0	0	0	1	1	1	-1	0

conserved lepton number L′:

$$-\mathcal{L} \supset y_1^i\, \overline{N}_1\, \tilde{H}_1\, L_i \,+\, M\, \overline{N}_1\, N_2^C \,+\, \text{h.c.}$$

$$\hookrightarrow m_D^i \overline{N}_1 \nu_{iL} + M \overline{N}_1 N_2^C + \text{h.c.}$$

$$\begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M & 0 \end{pmatrix}$$

$$m_\nu = 0$$

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softly broken lepton number L′:

$$-\mathcal{L} \supset y_1^i \, \overline{N}_1 \, \tilde{H}_1 \, L_i + M \, \overline{N}_1 \, N_2^C + \text{h.c.} + \frac{1}{2} \mu \, \overline{N}_2^C \, N_2$$

$$\begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M & \mu \end{pmatrix}$$

$$m_\nu = \mu \, \frac{m_D m_D^T}{M^2} \neq 0$$

INVERSE SEESAW

Mohapatra, Valle, '89

μ small lepton number violating term

light Majorana neutrino masses can be generated while keeping m_D sizable and $M \sim 1$ TeV

Interesting Phenomenology:

Branco, Grimus, Lavoura, '89;
Shaposhnikov, 2006;
Kersten, Smirnov, 2007;
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SEESAW SCENARIOS WITH A GLOBAL $U(1)_{L'}$

add 3 **RH neutrinos** + 1 scalar **doublet** H_2 + 1 scalar **singlet** H_3

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INVERSE SEESAW

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renormalizable UV completion

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$U(1)_{L'}$	0	0	0	0	1	1	1	-1	0	-2	2

TOP - DOWN APPROACH:

EM, Josse-Michaux, PRD 84 (2011)
EM, Josse-Michaux, PRD 87 (2013)

perturbating the zeros entries by adding new scalar representations:

$$-\mathcal{L} \supset M\,\overline{N}_D N_D + \left(y_1^i\,\overline{N}_D\,\widetilde{H}_1^\dagger\,L_i + y_2^j\,\overline{N}_D^c\,\widetilde{H}_2^\dagger\,L_j + \frac{\alpha}{\sqrt{2}}\,H_3\,\overline{N}_D\,N_D^c + \text{h.c.}\right)$$

$$P_R N_D \equiv N_1\,, \qquad P_L N_D \equiv N_2^c$$

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$$P_R N_D \equiv N_1\,, \qquad P_L N_D \equiv N_2^c$$

$$-\mathcal{L}_{\text{eff}} \supset -\frac{y_1^i y_2^j + y_1^j y_2^i}{2M}\left(\overline{L}_j^c\,\widetilde{H}_2^*\right)\left(\widetilde{H}_1^\dagger\,L_i\right) + \frac{y_1^i y_1^j \alpha^*}{\sqrt{2}M^2}\left(\overline{L}_j^c\,\widetilde{H}_1^*\right)\left(\widetilde{H}_1^\dagger\,L_i\right) H_3^* + \frac{y_2^i y_2^j \alpha}{\sqrt{2}M^2}\left(\overline{L}_j^c\,\widetilde{H}_2^*\right)\left(\widetilde{H}_2^\dagger\,L_i\right) H_3 + \text{h.c.}$$

SEESAW SCENARIOS WITH A GLOBAL $U(1)_{L'}$

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	H_1	Q_i	u_{Ri}	d_{Ri}	L_α	$e_{R\alpha}$	N_1	N_2	N_3	H_2	H_3
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EWSB

$$\begin{pmatrix} 0 & m_D & \bullet \\ m_D^T & \bullet & M \\ \bullet & M & \bullet \end{pmatrix}$$

$$(m_\nu)_{ij} = -\left(y_1^i\,y_2^j + y_2^i\,y_1^j - y_1^i\,y_1^j\,\alpha^*\,\frac{v_1\,v_3}{v_2\,M} - y_2^i\,y_2^j\,\alpha\,\frac{v_2\,v_3}{v_1\,M}\right)\frac{v_1\,v_2}{2\,M}$$

SEESAW SCENARIOS WITH A GLOBAL $U(1)_{L'}$

add 3 **RH neutrinos** + 1 scalar **doublet** H_2 + 1 scalar **singlet** H_3

	H_1	Q_i	u_{Ri}	d_{Ri}	L_α	$e_{R\alpha}$	N_1	N_2	N_3	H_2	H_3
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perturbating the zeros entries by adding new scalar representations:

$$m_\nu^\pm \simeq \frac{1}{M}\left(\sqrt{\bar{y}_1^2\,\bar{y}_2^2 - \frac{\alpha\, v_3}{M}\,(\bar{y}_1^2+\bar{y}_2^2)\,\mathrm{Re}(\bar{y}_{12})} \pm \sqrt{|\bar{y}_{12}|^2 - \frac{\alpha\, v_3}{M}\,(\bar{y}_1^2+\bar{y}_2^2)\,\mathrm{Re}(\bar{y}_{12})}\right)$$

$$\simeq \frac{1}{M}\,(\,\bar{y}_1\,\bar{y}_2 \pm |\bar{y}_{12}\,|)\times\left(1 \mp \frac{\alpha\, v_3}{2M}\,\frac{(\bar{y}_1^2+\bar{y}_2^2)\,\mathrm{Re}(\bar{y}_{12})}{\bar{y}_1\,\bar{y}_2\,|\bar{y}_{12}|}\right)\,, \quad \bar{y}_i \equiv |\mathbf{y}_i| v_i \quad y_{12} \equiv \mathbf{y_1}\cdot\mathbf{y_2}\, v_1 v_2$$

$$|\mathbf{y_1}\times\mathbf{y_2}|\; v_1\, v_2/M \cong (\Delta m^2_\odot\,|\Delta m^2_{\mathrm{A}}|)^{1/4}$$

$$|\mathbf{y_1}||\mathbf{y_2}| \approx 10^{-8}\,(M/1\ \mathrm{TeV})\,(10\ \mathrm{MeV}/v_2)$$

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0	0	0	0	1	1	1	-1	0	-2	2

$$
\begin{aligned}
\mathcal{V}_{\rm SB} \;=\; & -\mu_1^2\, H_1^\dagger\, H_1 + \lambda_1\, (H_1^\dagger\, H_1)^2 - \mu_2^2\, H_2^\dagger\, H_2 + \lambda_2\, (H_2^\dagger\, H_2)^2 - \mu_3^2\, H_3^* H_3 + \lambda_3\, (H_3^* H_3)^2 \\
+ \; & \kappa_{12}\, H_1^\dagger\, H_1 H_2^\dagger\, H_2 + \kappa_{12}'\, H_1^\dagger\, H_2 H_2^\dagger\, H_1 + \kappa_{13}\, H_1^\dagger\, H_1 H_3^* H_3 + \kappa_{23}\, H_2^\dagger\, H_2 H_3^* H_3 \\
- \; & \frac{\mu'}{\sqrt{2}} \left(H_1^\dagger\, H_2 H_3 + H_2^\dagger\, H_1 H_3^* \right)
\end{aligned}
$$

$$\langle H_i \rangle = \frac{v_i}{\sqrt{2}}$$

$$SU(2)_W \times U(1)_Y \times [U(1)_{L'}] \to U(1)_{em} \times \mathbf{Z}_2$$

SEESAW SCENARIOS WITH A GLOBAL U(1)$_{L'}$

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0	0	0	0	1	1	1	-1	0	-2	2

$$\begin{aligned}\mathcal{V}_{\rm SB} \;=\; & -\mu_1^2 H_1^\dagger H_1 + \lambda_1 (H_1^\dagger H_1)^2 - \mu_2^2 H_2^\dagger H_2 + \lambda_2 (H_2^\dagger H_2)^2 - \mu_3^2 H_3^* H_3 + \lambda_3 (H_3^* H_3)^2 \\ + \; & \kappa_{12} H_1^\dagger H_1 H_2^\dagger H_2 + \kappa'_{12} H_1^\dagger H_2 H_2^\dagger H_1 + \kappa_{13} H_1^\dagger H_1 H_3^* H_3 + \kappa_{23} H_2^\dagger H_2 H_3^* H_3 \\ - \; & \frac{\mu'}{\sqrt{2}} \left(H_1^\dagger H_2 H_3 + H_2^\dagger H_1 H_3^* \right)\end{aligned}$$

$$\langle H_i \rangle = \frac{v_i}{\sqrt{2}}$$

$$SU(2)_W \times U(1)_Y \times [U(1)_{L'}] \to U(1)_{em} \times \mathbf{Z}_2$$

$\mu' \ll 1$ GeV $\;\rightarrow\;$ $v_2 \approx \dfrac{v_1\, v_3\, \mu'}{v_1^2\, \tilde{\kappa}_{12} + v_3^2\, \kappa_{23} - 2\,\mu_2^2} \ll v_{1,3}$

$\mu' \to 0$ $\;\rightarrow\;$ symmetry of the Lagrangian enlarged by a global U(1)

SCALAR SPECTRUM

2 doublets + 1 singlet Brout-Englert-Higgs fields

3 CP even neutral scalars: h^0 H^0 **LEP2, Tevatron, LHC constraints**

h_A

A^0 } **~ degenerate and fermiophobic**

2 CP odd neutral scalars:

J **Goldstone boson: Majoron**

1 charged scalar: $H^{\pm}$ **LEP2 constraints:** $m_{H^{\pm}} \gtrsim 80\,\mathrm{GeV}$

If $U(1)_{L'}$ is explicitly broken then the Majoron is a massive long-lived particle: viable dark matter candidate

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Coupling Majoron-SM fermions:

$$-\mathcal{L} \supset i\, g_{\mathcal{J}ee}\, \bar{e}\gamma_5\, e\, J$$

cooling rate of white dwarf: $|g_{\mathcal{J}ee}| \lesssim 10^{-12}$

$$g_{\mathcal{J}ee} \simeq \frac{m_e}{v}\frac{v_2^2}{v_1\, v_3} \quad \Rightarrow \quad v_2 \lesssim 0.2\ \mathrm{GeV}\ \sqrt{v_3/v}$$

SCALAR SPECTRUM

$$H^\pm \sim H_2^\pm,\; h_A \sim \sqrt{2}\,\mathrm{Re}(H_2^0),\; J \sim \sqrt{2}\,\mathrm{Im}(H_3) \text{ and } A_0 \sim \sqrt{2}\,\mathrm{Im}(H_2^0)$$

$$v_2 \lesssim 10\,\mathrm{MeV} \qquad \begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = R(-\theta) \begin{pmatrix} \sqrt{2}\,\mathrm{Re}(H_1^0) \\ \sqrt{2}\,\mathrm{Re}(H_3) \end{pmatrix}$$

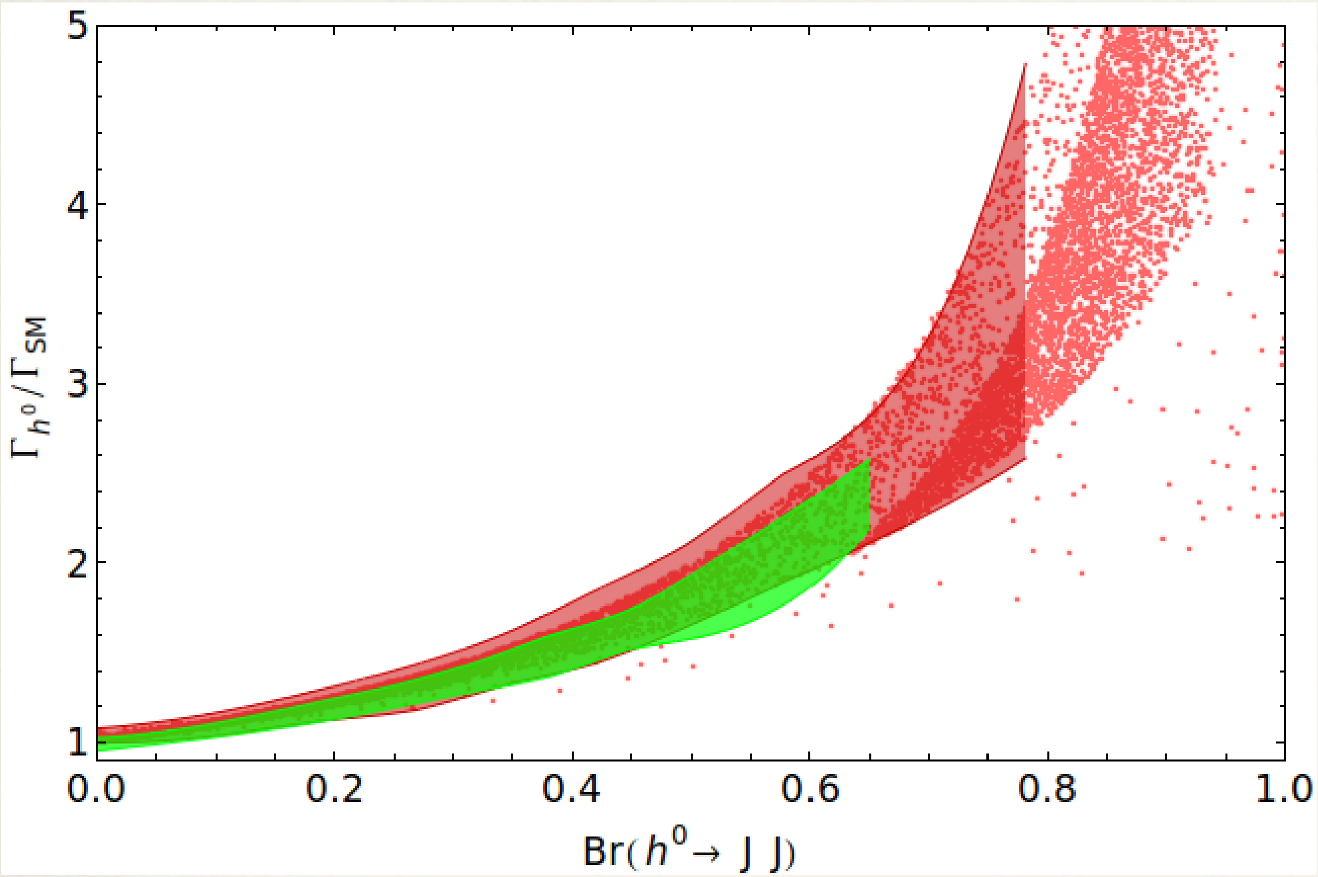
production and detection of the new scalars:

- h_A, A^0 and $H^\pm$ couple to the SM sector through gauge interactions
- h^0 and H^0 couple also to SM fermions:

$$\mu_i(H) \equiv \frac{\sigma(pp \to h^0/H^0)_i \times \mathrm{Br}(h^0/H^0 \to i)}{\sigma(pp \to h)_i^{\mathrm{SM}} \times \mathrm{Br}(h \to i)^{\mathrm{SM}}}$$

$$\frac{\sigma(pp \to h^0)_i}{\sigma(pp \to h)_i^{\mathrm{SM}}} = \cos^2(\theta)\,, \qquad \frac{\sigma(pp \to H^0)_i}{\sigma(pp \to h)_i^{\mathrm{SM}}} = \sin^2(\theta)$$

SCALAR SPECTRUM



$$\Gamma(h^0)_{\rm tot} \simeq \cos(\theta)^2\,\Gamma(h)^{\rm SM}_{\rm tot} + \Gamma(h^0 \to {\rm inv})$$
$$\Gamma(h^0 \to {\rm inv}) \simeq \Gamma(h^0 \to JJ)$$

SM Higgs boson

$M_{h^0} \simeq 125\ {\rm GeV}$

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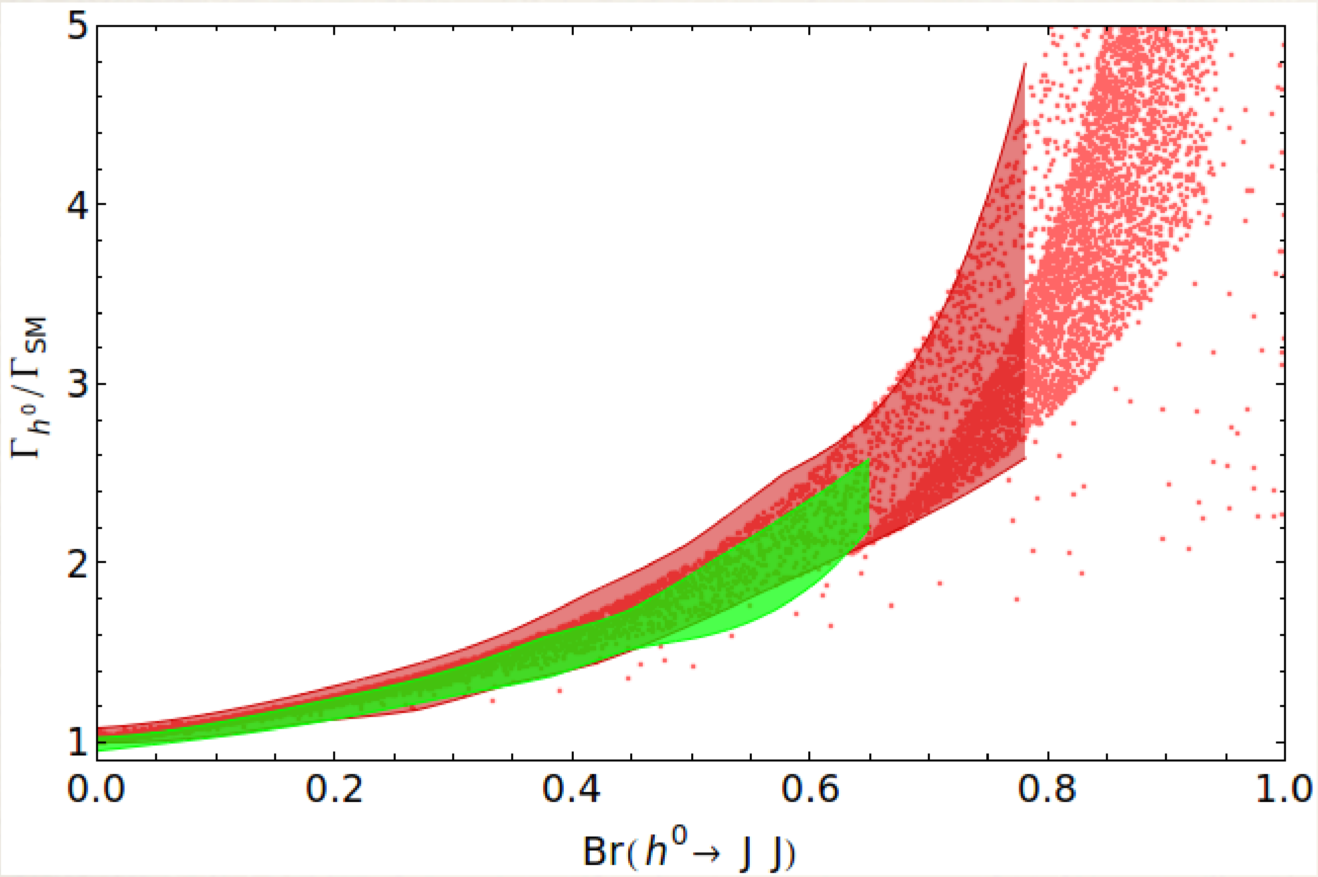

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$$\Gamma(h^0 \to {\rm inv}) \simeq \Gamma(h^0 \to JJ)$$

ATLAS: $R_{\gamma\gamma} = 1.65 \pm 0.24^{+0.25}_{-0.18}$

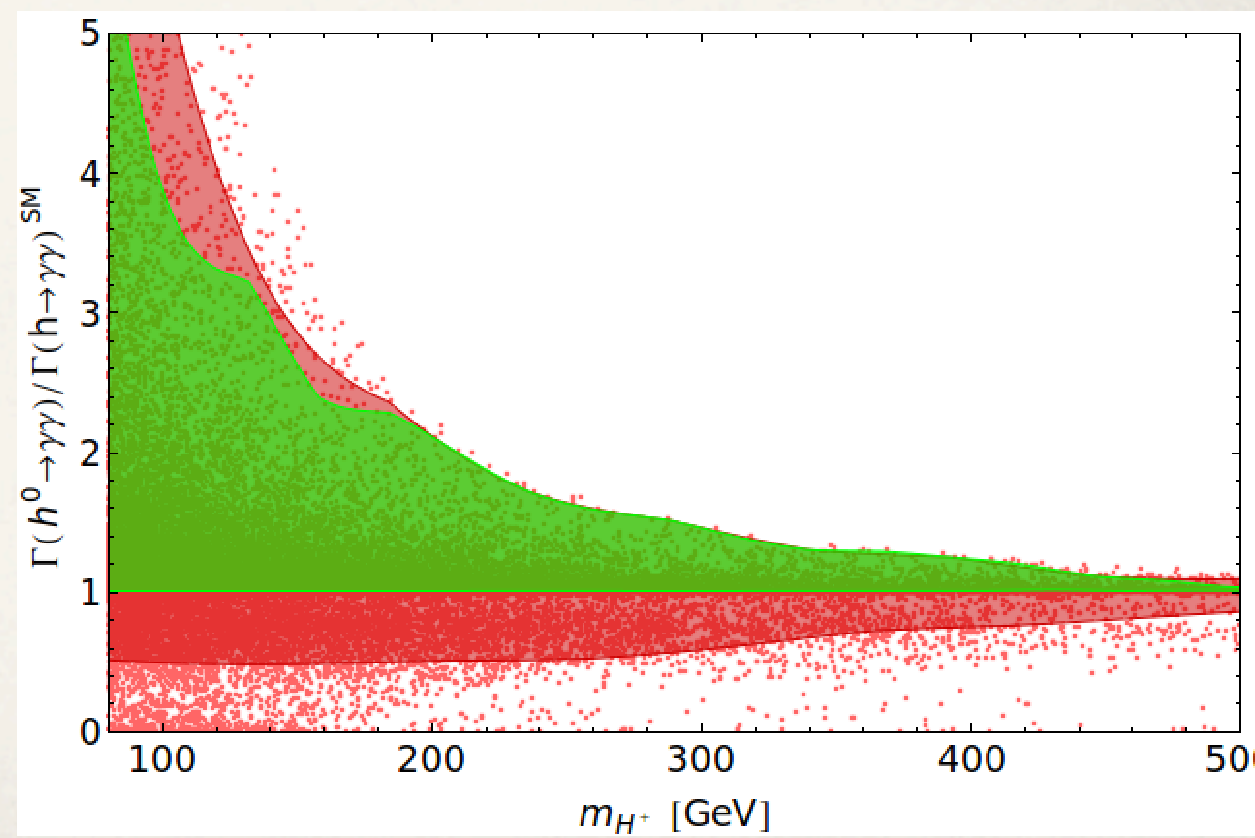
CMS: $R_{\gamma\gamma} = 0.79^{+0.28}_{-0.26}$

SM Higgs boson

$M_{h^0} \simeq 125$ GeV

$$\Gamma(h^0 \to \gamma\gamma) = \frac{G_\mu\,\alpha^2\,m^3_{h^0}}{128\sqrt{2}\pi^3}\left|\sum_f N_c\,Q_f^2\,\lambda^{h^0}_{ff}\,A_{1/2}\left(\frac{m^2_{h^0}}{4\,m_f^2}\right) + \lambda^{h^0}_{WW}A_1\left(\frac{m^2_{h^0}}{4\,m_W^2}\right)\right.$$
$$\left. - \frac{v^2}{2\,m^2_{H^+}}\lambda^{h^0}_{H^+\,H^-}\,A_0\left(\frac{m^2_{h^0}}{4\,m^2_{H^\pm}}\right)\right|^2$$

$$\lambda^{h^0}_{H^+\,H^-} \simeq -\left(\kappa_{12}\,\cos(\theta) + \kappa_{23}\sin(\theta)\,v_3/v_1\right)$$



Summary

UV - completion of Inverse/Linear Seesaw with a U(1) symmetry

add 2 RH neutrinos + 1 scalar doublet H_2 + 1 scalar singlet H_3

all new Physics at the TeV scale

Gain: 2 massive light Majorana neutrinos

reach phenomenology to be tested at LHC and intensity frontier experiments

Summary

UV - completion of Inverse/Linear Seesaw with a U(1) symmetry

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reach phenomenology to be tested at LHC and intensity frontier experiments

add 1 complex scalar singlet S with $L'(S) = 1$

Gain: 2 massive light Majorana neutrinos

+

viable dark matter

+

successful leptogenesis

Backup Slides

SCALAR SECTOR

	H_1	Q_i	u_{Ri}	d_{Ri}	L_α	$e_{R\alpha}$	N_1	N_2	N_3	H_2	H_3	S
$U(1)_{L'}$	0	0	0	0	1	1	1	-1	0	-2	2	1

$$\mathcal{V}_{\rm SC} \equiv \mathcal{V}_{\rm SB} + \mathcal{V}_{\rm DM}$$

$$\begin{aligned}
\mathcal{V}_{\rm SB} &= -\mu_1^2 H_1^\dagger H_1 + \lambda_1 (H_1^\dagger H_1)^2 - \mu_2^2 H_2^\dagger H_2 + \lambda_2 (H_2^\dagger H_2)^2 - \mu_3^2 H_3^* H_3 + \lambda_3 (H_3^* H_3)^2 \\
&+ \kappa_{12} H_1^\dagger H_1 H_2^\dagger H_2 + \kappa'_{12} H_1^\dagger H_2 H_2^\dagger H_1 + \kappa_{13} H_1^\dagger H_1 H_3^* H_3 + \kappa_{23} H_2^\dagger H_2 H_3^* H_3 \\
&- \frac{\mu'}{\sqrt{2}} \left(H_1^\dagger H_2 H_3 + H_2^\dagger H_1 H_3^* \right) \\
\mathcal{V}_{\rm DM} &= \mu_S^2 S^* S + \lambda_S (S^* S)^2 + \mathcal{F}_1 H_1^\dagger H_1 S^* S + \mathcal{F}_2 H_2^\dagger H_2 S^* S + \mathcal{F}_3 H_3^* H_3 S^* S \\
&+ h S^2 H_1^\dagger H_2 + h^* S^{*2} H_2^\dagger H_1 - \frac{\mu''}{\sqrt{2}} (S^2 H_3^* + S^{*2} H_3)
\end{aligned}$$

$$\langle H_i \rangle = \frac{v_i}{\sqrt{2}} \quad \text{and} \quad \langle S \rangle = 0$$

$$SU(2)_W \times U(1)_Y \times [U(1)_{L'}] \to U(1)_{em} \times \mathbf{Z}_2$$

the lightest component of S is stable

TYPE I SEESAW SCENARIO AND LEPTOGENESIS

Thermal Leptogenesis: N_i produced by thermal scatterings after inflation

M. Fukugita, T. Yanagida, Phys. Lett. B 174 (1986) 45

$$\mathcal{L} \supset \left(\lambda_{1\ell}\,\overline{N_1}\,H^\dagger\,L_\ell + \text{h.c.}\right) - \frac{1}{2}\,M_1\,\overline{N_1}\,N_1{}^C$$

L-violating couplings

Majorana neutrino

N_1

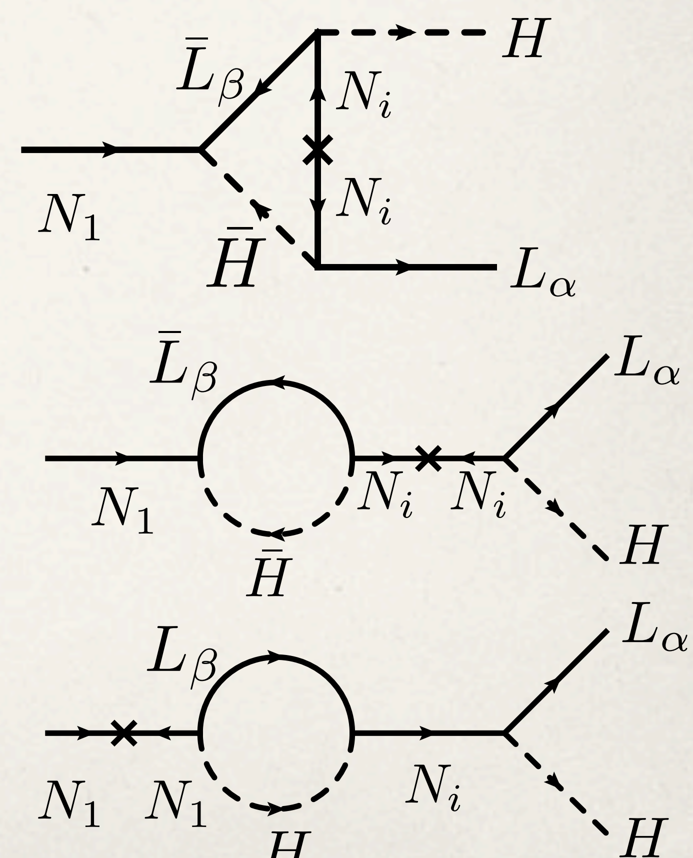
CP violation in decays

ΔL ⟷ sphalerons ⟷ ΔB

lepton asymmetry

baryon asymmetry

$$M_1 \ll M_{2,3}$$



VARIATIONS OF LEPTOGENESIS

Typical Dirac leptogenesis/neutrinogenesis scenario:

Φ

VARIATIONS OF LEPTOGENESIS

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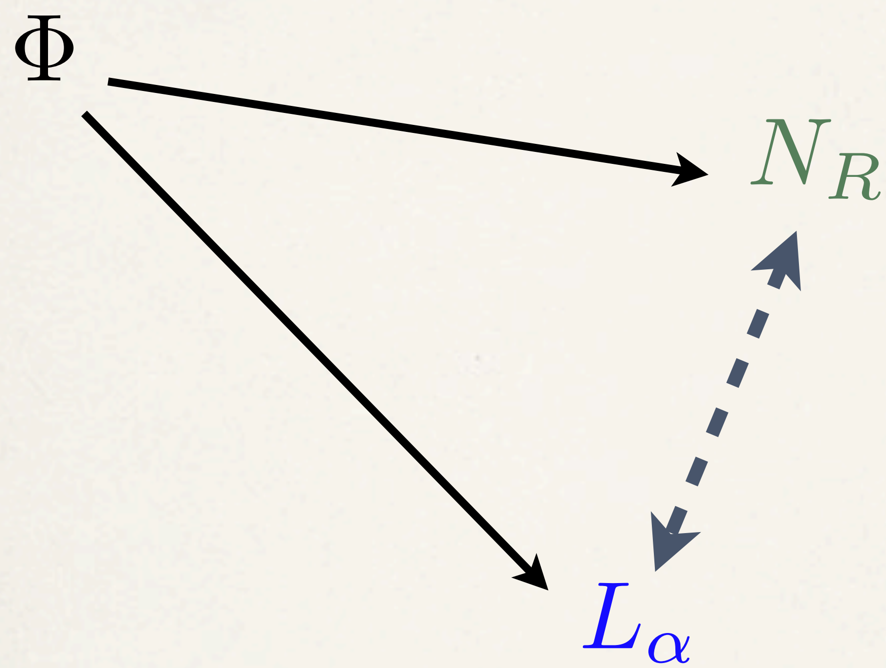

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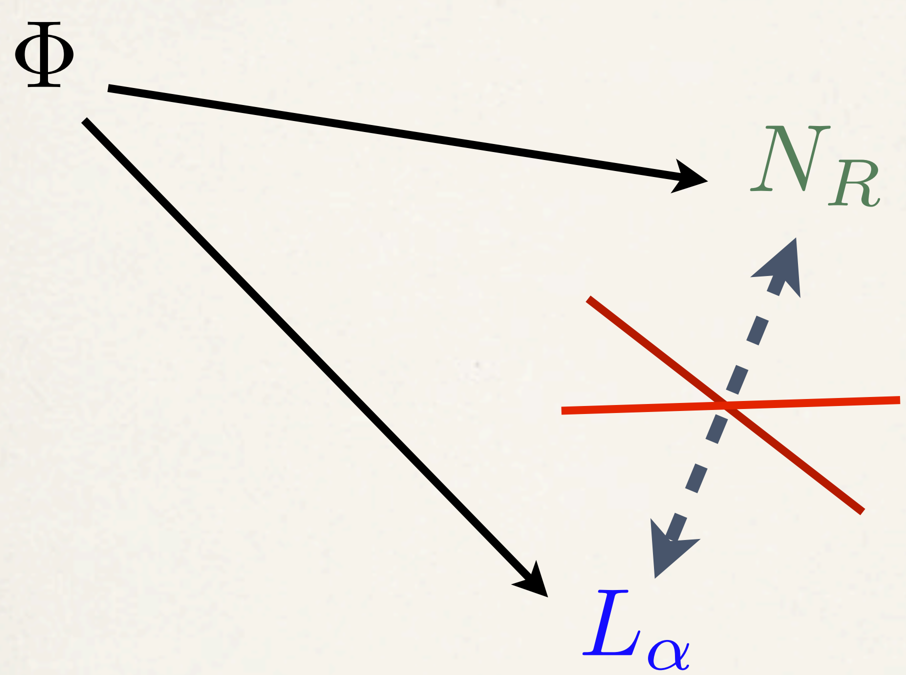

$$n_B = n_L \propto n_{N_R}$$

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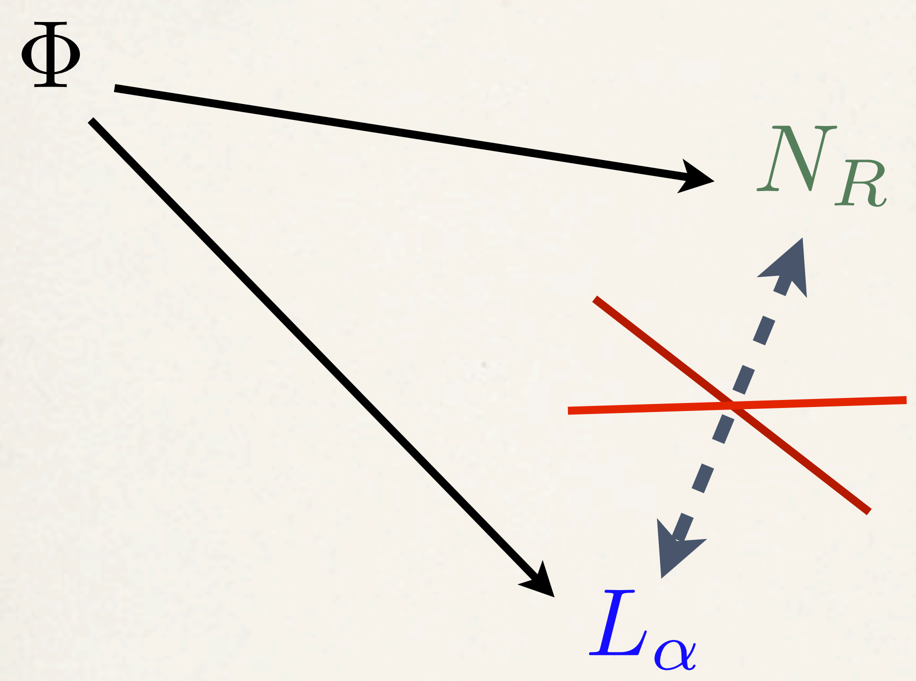

Dick, Lindner, Ratz, Wight, 2000
Murayama, Pierce, 2002
Pei-Hong Gu, Hong-Jan He, 2007
Pei-Hong Gu, Sarkar, 2008
Sahu, Sarkar, 2008
Gonzalez-Garcia, Racker, Rius, 2009
EM, Josse-Michaux, 2011
Davidson, Elmer, 2012
Kohri, Mazumdar, Sahu, Stephens, 2009
Feng, Mazumdar, Nath, 2013
....

$$n_B = n_L \propto n_{N_R}$$

- The asymmetry stored in the left-handed leptons is equal but opposite to that stored in the other fields

- The left-handed asymmetry is partially converted into a net baryon number if no equilibration between the lepton doublets and the other fields occurs before the decoupling of the sphalerons

- Interplay between LR-equilibration and sphaleron washout determines the final amount of the baryon asymmetry

SEESAW SCENARIOS WITH A GLOBAL $U(1)_{L'}$

$$-\mathcal{L}_{\rm int} \supset \mu_S^2\, S^* S + \frac{1}{2} M_3\, \overline{N}_3\, N_3^c + \left(g\, S\, \overline{N}_D\, N_3 - \frac{\mu''}{\sqrt{2}} S^2 H_3^* + \frac{\alpha}{\sqrt{2}}\, H_3\, \overline{N}_D\, N_D^c + \text{h.c.} \right)$$

$$+ M\, \overline{N}_D N_D + \left(y_1^i\, \overline{N}_D\, \widetilde{H}_1^\dagger\, L_i + y_2^j\, \overline{N}_D^c\, \widetilde{H}_2^\dagger\, L_j + \text{h.c.} \right)$$

EM, Josse-Michaux, PRD 84 (2011)

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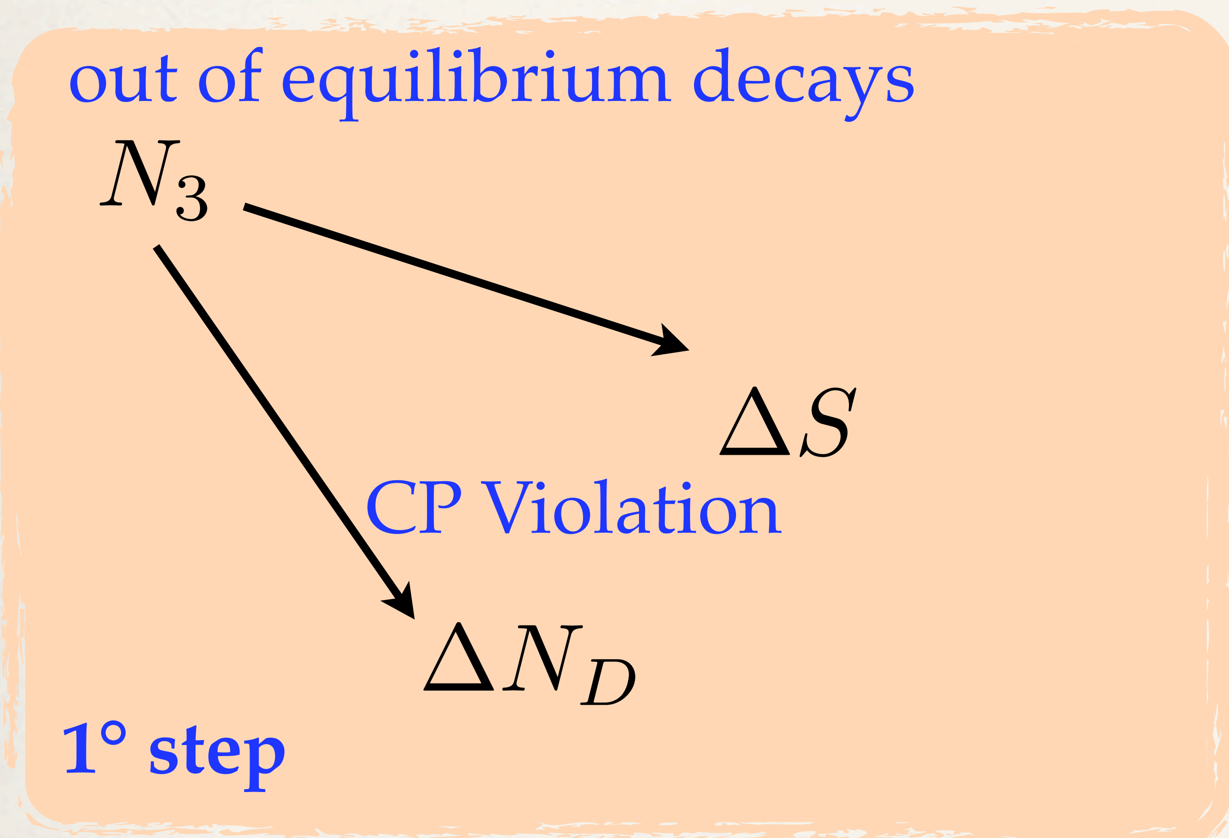

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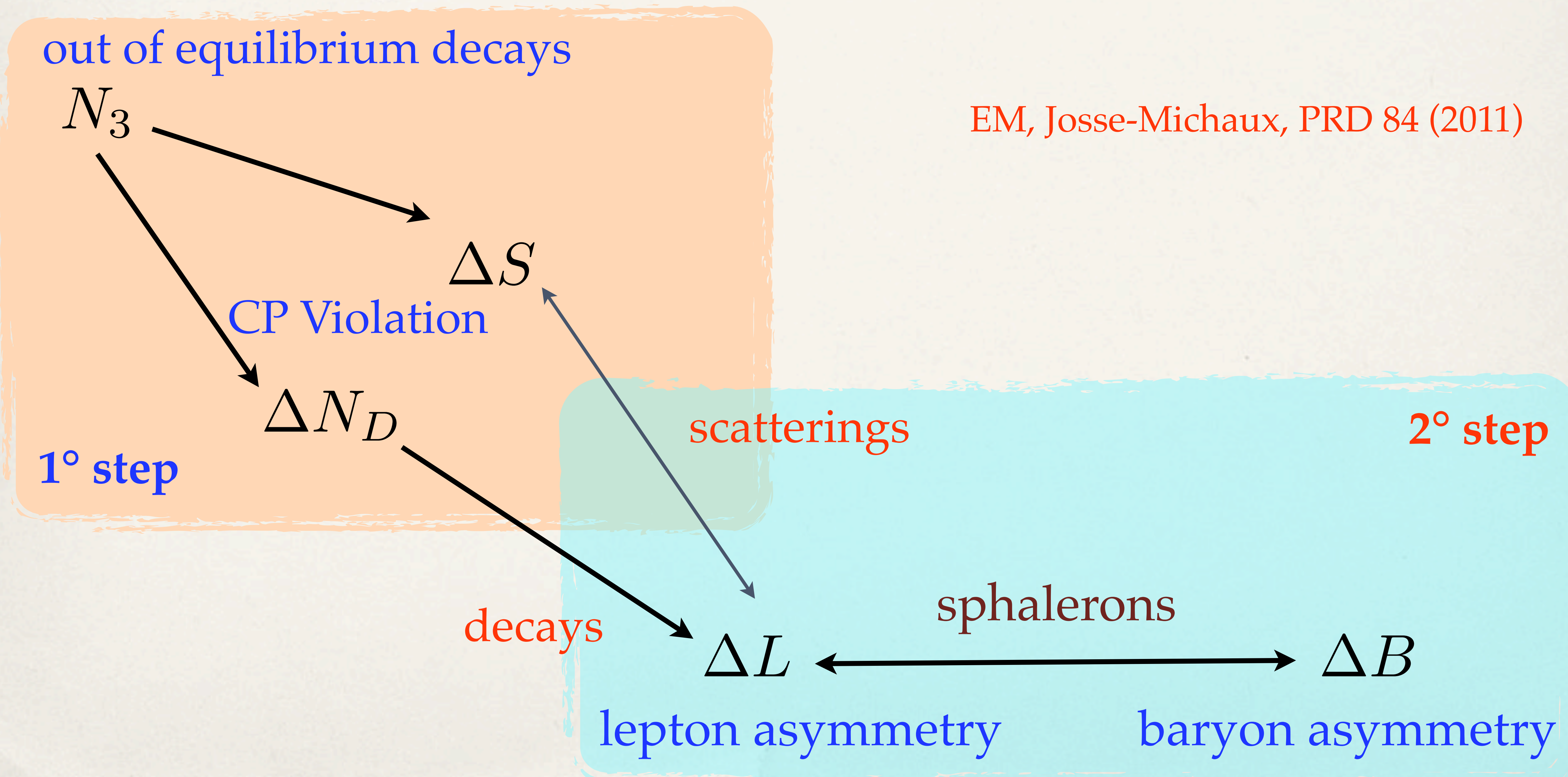

SEESAW SCENARIOS WITH A GLOBAL $U(1)_{L'}$

2-Step Leptogenesis

scatterings: $\mathcal{O}(\alpha^2)$, $\mathcal{O}(\alpha^2\mu''^2)$, $\mathcal{O}(g^2)$, $\mathcal{O}(g^2\,\alpha^2)$, $\mathcal{O}(y_{1,2}^2)$, $\mathcal{O}(g^2\,y_{1,2}^2)$ and $\mathcal{O}(g^4)$

1° step

decays/inverse decays

$[\,N_3 \leftrightarrow N_D\,\overline{S}\,]$

$\Delta N_D = 2$ scatterings

$[\,N_D\,N_D \leftrightarrow S\,S\,]$ $[\,N_D\,\overline{S} \leftrightarrow \overline{N}_D\,S\,]$

scatterings on N_3: CP violation included

$[\,N_3\,N_D \leftrightarrow \overline{S}\,H_3\,]$ $[\,N_3\,S \leftrightarrow \overline{N}_D\,H_3\,]$ $[\,N_D\,S \leftrightarrow N_3\,H_3\,]$

$$\frac{\Gamma_{N_3}}{H(M_3)} \simeq 2\left(\frac{g}{10^{-6}}\right)^2\left(\frac{50\mathrm{TeV}}{M_3}\right)$$

2° step

decays/inverse decays

$[\,N_D \leftrightarrow L\,H_1\,]$ $[\,N_D \leftrightarrow \overline{L}\,\overline{H}_2\,]$

scatterings on N_3

$[\,N_3\,S \leftrightarrow L\,H_1\,]$ $[\,N_3\,S \leftrightarrow \overline{L}\,\overline{H}_2\,]$

scatterings on top-quarks

$[\,N_D\,\overline{L} \leftrightarrow \bar{t}\,Q_3\,]$ $[\,N_D\,t\,(\overline{Q}_3) \leftrightarrow L\,Q_3\,(\bar{t})\,]$

scatterings with gauge bosons

$$\frac{\gamma^t_{N_D}}{n^{eq}_{N_D}\,H(M)} \gtrsim 1 \quad\Longrightarrow\quad |y_1| \gtrsim 10^{-5}\times\sqrt{\frac{M}{10\,\mathrm{TeV}}}$$

SEESAW SCENARIOS WITH A GLOBAL $U(1)_{L'}$

2-Step Leptogenesis

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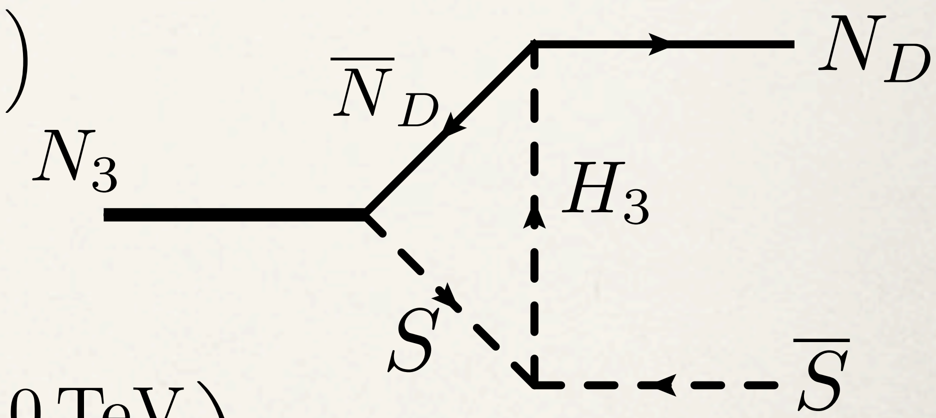
$$+ M\, \overline{N}_D N_D + \left(y_1^i\, \overline{N}_D\, \widetilde{H}_1^\dagger\, L_i + y_2^j\, \overline{N}_D^c\, \widetilde{H}_2^\dagger\, L_j + \text{h.c.} \right)$$



CP asymmetry in N_3 decays:

$$\epsilon_{CP} \simeq -\frac{\text{Im}(\alpha)}{16\pi}\, \frac{\mu''}{M_3} \simeq -2 \times 10^{-6} \left(\frac{\mu''}{1\,\text{GeV}} \right) \left(\frac{10\,\text{TeV}}{M_3} \right) \text{Im}(\alpha)$$

N_D asymmetry @ 1° step:

$$Y_{\Delta N_D}^{1st} \propto \epsilon_{CP}\, \eta_1(g)$$

L asymmetry @ 2° step:

$$Y_{\Delta L}^{2nd} \propto Y_{\Delta N_D}^{1st}\, \eta_2(y_1, y_2)$$

Final baryon asymmetry:

$$Y_{\Delta B} \propto \epsilon_{CP}\, \eta_1(g)\, \eta_2(y_1, y_2)$$