Baryogenesis and Neutrino Mass
A Common Link and Experimental Signatures

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$\eta_{\Delta B} \equiv \frac{n_B - n_{\bar{B}}}{n_{\gamma}} \simeq 6.1 \times 10^{-10}$

One number $\rightarrow$ BSM Physics
Baryogenesis

- Dynamical generation of baryon asymmetry.
- **Basic ingredients:** [Sakharov ’67]
  - $B$ violation, $C$ & $CP$ violation, departure from thermal equilibrium
- Necessary but not sufficient.

The Standard Model has all the basic ingredients, but $\text{CKM CP}$ violation is too small (by $\sim 10$ orders of magnitude).

Observed Higgs boson mass is too large for a strong first-order phase transition. Requires New Physics!
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- CKM $CP$ violation is too small (by $\sim 10$ orders of magnitude).
- Observed Higgs boson mass is too large for a strong first-order phase transition.

**Requires New Physics!**
Many ideas, some of which can be realized down to the (sub)TeV scale, e.g.:

- **EW baryogenesis** [Kuzmin, Rubakov, Shaposhnikov '87; Cohen, Kaplan, Nelson '90; Carena, Quiros, Wagner '96; Cirigliano, Lee, Tulin '11; Morrissey, Ramsey-Musolf '12; ...]
- **(Low-scale) Leptogenesis** [Fukugita, Yanagida '86; Akhmedov, Rubakov, Smirnov '98; Pilaftsis, Underwood '03; Fong, Gonzalez-Garcia, Nardi, Peinado '13; BD, Millington, Pilaftsis, Teresi '14; ...]
- **Cogenesis** [Kaplan '92; Farrar, Zaharijas '06; Kitano, Murayama, Ratz '08; Kaplan, Luty, Zurek '09; Berezhiani '16; Bernal, Fong, Fonseca '16; ...]
- **WIMPy baryogenesis** [Cui, Randall, Shuve '11; Cui, Sundrum '12; Racker, Rius '14; ...]
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- **Cogeneration** [Kaplan '92; Farrar, Zaharijas '06; Kitano, Murayama, Ratz '08; Kaplan, Luty, Zurek '09; Berezhiani '16; Bernal, Fong, Fonseca '16; ...]
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Can also go below the EW scale, independent of sphalerons, e.g.

- **Post-sphaleron baryogenesis** [Babu, Mohapatra, Nasri '07; Babu, BD, Mohapatra '08]
- **Dexiogenesis** [BD, Mohapatra '15; Davoudiasl, Zhang '15]
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Testable effects: collider signatures, gravitational waves, electric dipole moment, $0\nu\beta\beta$, lepton flavor violation, $n - \bar{n}$ oscillation, ...
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Leptogenesis

A cosmological consequence of the seesaw mechanism.

- Provides a common link between neutrino mass and baryon asymmetry.
- Naturally satisfies the Sakharov conditions.
  - $L$ violation due to the Majorana nature of heavy RH neutrinos.
  - $\mathcal{L} \rightarrow \mathcal{B}$ through sphaleron interactions.
  - New source of CP violation in the leptonic sector (through complex Dirac Yukawa couplings and/or PMNS CP phases).
  - Departure from thermal equilibrium when $\Gamma_N \ll H$. 

[Fukugita, Yanagida ’86]
Popularity of Leptogenesis
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\[ \sim 3000 \text{ citations} \]

Neutrino oscillation discovered
Three basic steps:

1. Generation of $L$ asymmetry by heavy Majorana neutrino decay:

$$ N_1 \rightarrow H \ell $$

2. Partial washout of the asymmetry due to inverse decay (and scatterings):

$$ H \rightarrow N_1 \ell $$

3. Conversion of the left-over $L$ asymmetry to $B$ asymmetry at $T > T_{sph}$.

$$ \text{Sphaleron} $$
Boltzmann Equations

[Buchmüller, Di Bari, Plümacher ’02]

\[
\frac{dN_N}{dz} = -(D + S)(N_N - N_N^{eq}),
\]

\[
\frac{dN_{\Delta L}}{dz} = \varepsilon D(N_N - N_N^{eq}) - N_{\Delta L} W,
\]

(where \(z = m_{N_1}/T\) and \(D, S, W = \Gamma_{D,S,W}/Hz\) for decay, scattering and washout rates.)

- Final baryon asymmetry:

\[
\eta_{\Delta B} = d \cdot \varepsilon \cdot \kappa_f
\]

- \(d \simeq \frac{28}{51} \frac{1}{27} \simeq 0.02\) (\(\mathcal{L} \to \mathcal{B}\) conversion at \(T_c\) + entropy dilution from \(T_c\) to recombination epoch).

- \(\kappa_f \equiv \kappa(z_f)\) is the final efficiency factor, where

\[
\kappa(z) = \int_{z_i}^{z} dz' \frac{D}{D + S} \frac{dN_N}{dz'} \ e^{-\int_{z'}^{z_f} dz'' W(z'')}
\]
Importance of self-energy effects  

\[ |\Gamma(N_\alpha \rightarrow L_l \Phi) - \Gamma(N_\alpha \rightarrow L_c L_c^\dagger)| \leq |\frac{\epsilon_l \alpha}{\sum_k [\Gamma(N_\alpha \rightarrow L_k \Phi) + \Gamma(N_\alpha \rightarrow L_c L_c^\dagger)]}| \]

\[ \equiv \frac{|\hat{h}_{l \alpha}|^2 - |\hat{h}_{l \alpha}^c|^2}{(\hat{h}^* \hat{h})_{\alpha \alpha} + (\hat{h}_{\alpha}^c \hat{h}_{\alpha}^c)_{\alpha \alpha}} \]

with the one-loop resummed Yukawa couplings  

\[ \hat{h}_{l \alpha} = \hat{h}_{l \alpha} - i \sum_{\beta, \gamma} |\epsilon_{\alpha \beta \gamma}| \hat{h}_{l \beta} \]

\[ \times \frac{m_\alpha (m_\alpha A_{\alpha \beta} + m_\beta A_{\beta \alpha}) - i R_{\alpha \gamma} [m_\alpha A_{\gamma \alpha} (m_\alpha A_{\alpha \gamma} + m_\gamma A_{\gamma \alpha}) + m_\beta A_{\beta \gamma} (m_\alpha A_{\gamma \alpha} + m_\gamma A_{\alpha \gamma})]}{m_\alpha^2 - m_\beta^2 + 2i m_\alpha^2 A_{\alpha \beta} + 2i \text{Im}(R_{\alpha \gamma}) [m_\alpha^2 A_{\beta \gamma}^2 + m_\beta m_\gamma \text{Re}(A_{\beta \gamma}^2)]} \]

\[ R_{\alpha \beta} = \frac{2m_\beta}{m_\alpha^2 - m_\beta^2 + 2i m_\alpha^2 A_{\alpha \beta}} \quad ; \quad A_{\alpha \beta}(\hat{h}) = \frac{1}{16\pi} \sum_l \hat{h}_{l \alpha} \hat{h}_{l \beta}^* . \]
Vanilla Leptogenesis

- Hierarchical heavy neutrino spectrum \( (m_{N_1} \ll m_{N_2} < m_{N_3}) \).
- Both vertex correction and self-energy diagrams are relevant.
- For type-I seesaw, the maximal CP asymmetry is given by

\[
\varepsilon_{1}\text{max} = \frac{3}{16 \pi} \frac{m_{N_1}}{v^2} \sqrt{\Delta m^2_{\text{atm}}}
\]

- Lower bound on \( m_{N_1} \): [Davidson, Ibarra '02; Buchmüller, Di Bari, Plümacher '02]

\[
m_{N_1} > 6.4 \times 10^8 \text{ GeV} \left( \frac{\eta_B}{6 \times 10^{-10}} \right) \left( \frac{0.05 \text{ eV}}{\sqrt{\Delta m^2_{\text{atm}}}} \right)^{\kappa_f^{-1}}
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\]

**Experimentally inaccessible!**
Also leads to a lower limit on the reheating temperature \( T_{\text{rh}} \gtrsim 10^9 \text{ GeV}. \)
In supergravity models, need \( T_{\text{rh}} \lesssim 10^6 - 10^9 \text{ GeV} \) to avoid the gravitino problem.
[Khlopov, Linde '84; Ellis, Kim, Nanopoulos '84; Cyburt, Ellis, Fields, Olive '02; Kawasaki, Kohri, Moroi, Yotsuyanagi '08]
Also in conflict with the Higgs naturalness bound \( m_N \lesssim 10^7 \text{ GeV}. \) [Vissani '97; Clarke, Foot, Volkas '15; Bambhaniya, BD, Goswami, Khan, Rodejohann '16]
Dominant self-energy effects on the $CP$-asymmetry ($\varepsilon$-type) [Flanz, Paschos, Sarkar ’95; Covi, Roulet, Vissani ’96].

Resonantly enhanced, even up to order 1, when $\Delta m_N \sim \Gamma_N/2 \ll m_{N_1,2}$.

[Flanz, Paschos, Sarkar ’95; Pilaftsis, Underwood ’03]

The quasi-degeneracy can be naturally motivated as due to approximate breaking of some symmetry in the leptonic sector.

Heavy neutrino mass scale can be as low as the EW scale.

[Flanz, Paschos, Sarkar ’95; Pilaftsis, Underwood ’03; Deppisch, Pilaftsis ’10; BD, Millington, Pilaftsis, Teresi ’14]

A testable scenario at both Energy and Intensity Frontiers.
Flavor effects important at low scale [Abada, Davidson, Ibarra, Josse-Michaux, Losada, Riotto '06; Nardi, Nir, Roulet, Racker '06; De Simone, Riotto '06; Blanchet, Di Bari, Jones, Marzola '12; BD, Millington, Pilaftsis, Teresi '14]

Two sources of flavor effects:
- Heavy neutrino Yukawa couplings $h_{i}^{\alpha}$ [Pilaftsis '04; Endoh, Morozumi, Xiong '04]
- Charged lepton Yukawa couplings $y_{j}^{k}$ [Barbieri, Creminelli, Strumia, Tetrasis '00]

Three distinct physical phenomena: mixing, oscillation and decoherence.

Captured consistently in the Boltzmann approach by the fully flavor-covariant formalism. [BD, Millington, Pilaftsis, Teresi '14; '15]
Collision Rates for Decay and Inverse Decay

\[ n^\Phi [n^L]_l^k [\gamma(L\Phi \rightarrow N)]_k^l \beta \rightarrow \text{rank-4 tensor} \]
Collision Rates for $2 \leftrightarrow 2$ Scattering

\[ n^\Phi [n^L]^k_l [\gamma(L\Phi \rightarrow L\Phi)]^l_m \rightarrow \text{rank-4 tensor} \]
The diagram illustrates the key result for the system described in the text. The figure shows the contributions of mixing and oscillations to the overall factor, with a factor of 2 enhancement compared to the isolated contributions for weakly-resonant RL.

Mathematically, the results are given by:

\[
\delta \eta^L_{\text{mix}} \approx \frac{g_N}{2} \frac{3}{2Kz} \sum_{\alpha \neq \beta} \frac{\Im \left( \hat{h}^\dagger \hat{h} \right)_{\alpha\beta}}{\left( \hat{h}^\dagger \hat{h} \right)_{\alpha\alpha} \left( \hat{h}^\dagger \hat{h} \right)_{\beta\beta}} \left( \frac{M_N^2 - M_N^2}{M_N^2} \right) M_N \hat{\Gamma}(0)_{\beta\beta}
\]

\[
\delta \eta^L_{\text{osc}} \approx \frac{g_N}{2} \frac{3}{2Kz} \sum_{\alpha \neq \beta} \frac{\Im \left( \hat{h}^\dagger \hat{h} \right)_{\alpha\beta}}{\left( \hat{h}^\dagger \hat{h} \right)_{\alpha\alpha} \left( \hat{h}^\dagger \hat{h} \right)_{\beta\beta}} \left( \frac{M_N^2 - M_N^2}{M_N^2} \right) M_N \left( \hat{\Gamma}(0)_{\alpha\alpha} + \hat{\Gamma}(0)_{\beta\beta} \right)
\]

Where \( \delta \eta^L \) represents the overall enhancement factor, \( M_N \) is the mass, \( \hat{\Gamma}(0) \) is the zero-frequency decay rate, and \( \hat{h} \) is the field operator.
Based on residual leptonic flavor $G_f = \Delta(3n^2)$ or $\Delta(6n^2)$ (with $n$ even, $3 \nmid n$, $4 \nmid n$) and CP symmetries. [Luhn, Nasri, Ramond '07; Escobar, Luhn '08; Feruglio, Hagedorn, Ziegler '12]

CP symmetry is given by the transformation $X(s)(r)$ in the representation $r$ and depends on the integer parameter $s$, $0 \leq s \leq n - 1$. [Hagedorn, Meroni, Molinaro '14]
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Dirac neutrino Yukawa matrix must be invariant under $Z_2$ and CP, i.e. under the generator $Z$ of $Z_2$ and $X(s)$. [BD, Hagedorn, Molinaro (in prep)]

$$Z^\dagger(3) Y_D Z(3') = Y_D \quad \text{and} \quad X^*(3) Y_D X(3') = Y_D^* .$$

$$Y_D = \Omega(s)(3) R_{13}(\theta_L) \begin{pmatrix} y_1 & 0 & 0 \\ 0 & y_2 & 0 \\ 0 & 0 & y_3 \end{pmatrix} R_{13}(-\theta_R) \Omega(s)(3')^\dagger .$$

The unitary matrices $\Omega(s)(r)$ are determined by the CP transformation $X(s)(r)$.

Form of the RH neutrino mass matrix invariant under flavor and CP symmetries:

$$M_R = M_N \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$
Six real parameters: $y_i, \theta_{L,R}, M_N$.

$\theta_L \approx 0.18(2.96)$ gives $\sin^2 \theta_{23} \approx 0.605(0.395)$, $\sin^2 \theta_{12} \approx 0.341$ and $\sin^2 \theta_{13} \approx 0.0219$ (within $3\sigma$ of current global-fit results).

Light neutrino masses given by the type-I seesaw:

$$M_{\nu}^2 = \frac{\nu^2}{M_N} \left\{ \begin{pmatrix} y_1^2 \cos 2\theta_R & 0 & y_1 y_3 \sin 2\theta_R \\ 0 & y_2^2 & 0 \\ y_1 y_3 \sin 2\theta_R & 0 & -y_3^2 \cos 2\theta_R \end{pmatrix} \begin{pmatrix} y_1^2 \cos 2\theta_R & 0 & y_1 y_3 \sin 2\theta_R \\ 0 & y_2^2 & 0 \\ y_1 y_3 \sin 2\theta_R & 0 & y_3^2 \cos 2\theta_R \end{pmatrix} \right\}$$

(s even),

(s odd).
Fixing Model Parameters

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\[
M^2_\nu = \frac{v^2}{M_N} \begin{cases} 
\begin{pmatrix}
    y_1^2 \cos 2\theta_R & 0 & y_1 y_3 \sin 2\theta_R \\
    0 & y_2^2 & 0 \\
    y_1 y_3 \sin 2\theta_R & 0 & -y_3^2 \cos 2\theta_R \\
   -y_1^2 \cos 2\theta_R & 0 & -y_1 y_3 \sin 2\theta_R \\
    0 & y_2^2 & 0 \\
   -y_1 y_3 \sin 2\theta_R & 0 & y_3^2 \cos 2\theta_R 
\end{pmatrix} & (s \text{ even}), \\
\begin{pmatrix}
   -y_1^2 \cos 2\theta_R & 0 & -y_1 y_3 \sin 2\theta_R \\
    0 & y_2^2 & 0 \\
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   -y_1^2 \cos 2\theta_R & 0 & y_3^2 \cos 2\theta_R 
\end{pmatrix} & (s \text{ odd}).
\end{cases}
\]

- For \( y_1 = 0 \) (\( y_3 = 0 \)), we get strong normal (inverted) ordering, with \( m_{\text{lightest}} = 0 \).

\[
\text{NO: } y_1 = 0, \quad y_2 = \pm \sqrt{\frac{M_N \sqrt{\Delta m^2_{\text{sol}}}}{v}}, \quad y_3 = \pm \sqrt{\frac{M_N \sqrt{\Delta m^2_{\text{atm}}}}{\cos 2\theta_R v}}
\]

\[
\text{IO: } y_3 = 0, \quad y_2 = \pm \sqrt{\frac{M_N \sqrt{|\Delta m^2_{\text{atm}}|}}{v}}, \quad y_1 = \pm \sqrt{\frac{M_N \sqrt{|\Delta m^2_{\text{atm}}| - \Delta m^2_{\text{sol}}}}{|\cos 2\theta_R| v}}
\]

- Only free parameters: \( M_N \) and \( \theta_R \).
Low Energy CP Phases and $0\nu\beta\beta$

- Dirac phase is trivial: $\delta = 0$.
- For $m_{\text{lightest}} = 0$, only one Majorana phase $\alpha$, which depends on the chosen CP transformation:
  \[
  \sin \alpha = (-1)^{k+r+s} \sin 6 \phi_s \quad \text{and} \quad \cos \alpha = (-1)^{k+r+s+1} \cos 6 \phi_s \quad \text{with} \quad \phi_s = \frac{\pi S}{\eta},
  \]
  where $k = 0$ ($k = 1$) for $\cos 2 \theta_R > 0$ ($\cos 2 \theta_R < 0$) and $r = 0$ ($r = 1$) for NO (IO).
- Restricts the light neutrino contribution to $0\nu\beta\beta$:
  \[
  m_{\beta\beta} \approx \frac{1}{3} \left\{ \begin{array}{ll}
  \sqrt{\Delta m^2_{\text{sol}}} + 2 (-1)^{s+k+1} \sin^2 \theta_L e^{6i\phi_s} \sqrt{\Delta m^2_{\text{atm}}} & \text{(NO)}
  \end{array} \right.
  \]
  \[
  \left| 1 + 2 (-1)^{s+k} e^{6i\phi_s} \cos^2 \theta_L \right| \sqrt{\Delta m^2_{\text{atm}}} & \text{(IO)}
  \right.
  \]
- For $n = 26$, $\theta_L \approx 0.18$ and best-fit values of $\Delta m^2_{\text{sol}}$ and $\Delta m^2_{\text{atm}}$, we get
  \[
  0.0019 \text{eV} \lesssim m_{\beta\beta} \lesssim 0.0040 \text{eV} \quad \text{(NO)}
  \]
  \[
  0.016 \text{eV} \lesssim m_{\beta\beta} \lesssim 0.048 \text{eV} \quad \text{(IO)}
  \]
At leading order, three degenerate RH neutrinos. Higher-order corrections can break the residual symmetries, giving rise to a quasi-degenerate spectrum:

\[ M_1 = M_N (1 + 2 \kappa) \quad \text{and} \quad M_2 = M_3 = M_N (1 - \kappa). \]

CP asymmetries in the decays of \( N_i \) are given by

\[ \varepsilon_{i\alpha} \approx \sum_{j \neq i} \text{Im} \left( \hat{Y}_{D,\alpha i}^{*} \hat{Y}_{D,\alpha j} \right) \text{Re} \left( \left( \hat{Y}_{D}^{\dagger} \hat{Y}_{D} \right)_{ij} \right) F_{ij} \]

\( F_{ij} \) are related to the regulator in RL and are proportional to the mass splitting of \( N_i \).

We find \( \varepsilon_{3\alpha} = 0 \) and

\[ \varepsilon_{1\alpha} \approx \frac{y_2 y_3}{9} \left( -2 y_2^2 + y_3^2 (1 - \cos 2 \theta_R) \right) \sin 3 \phi_s \sin \theta_R \sin \theta_{L,\alpha} F_{12} \quad (\text{NO}) \]

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with \( \theta_{L,\alpha} = \theta_L + \rho_\alpha \frac{4\pi}{3} \) and \( \rho_e = 0, \rho_\mu = 1, \rho_\tau = -1 \).

\( \varepsilon_{2\alpha} \) are the negative of \( \varepsilon_{1\alpha} \) with \( F_{12} \) being replaced by \( F_{21} \).
Correlation between BAU and $0\nu\beta\beta$
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Correlation between BAU and $0^{\nu}\beta\beta$
For RH Majorana neutrinos, $\Gamma_\alpha = M_\alpha (\hat{Y}_D^\dagger \hat{Y}_D)_{\alpha\alpha} / (8\pi)$. We get

$$\Gamma_1 \approx \frac{M_N}{24\pi} \left( 2y_1^2 \cos^2 \theta_R + y_2^2 + 2y_3^2 \sin^2 \theta_R \right),$$

$$\Gamma_2 \approx \frac{M_N}{24\pi} \left( y_1^2 \cos^2 \theta_R + 2y_2^2 + y_3^2 \sin^2 \theta_R \right),$$

$$\Gamma_3 \approx \frac{M_N}{8\pi} \left( y_1^2 \sin^2 \theta_R + y_3^2 \cos^2 \theta_R \right).$$

For $y_1 = 0$ (NO), $\Gamma_3 = 0$ for $\theta_R = (2j + 1)\pi/2$ with integer $j$.

For $y_3 = 0$ (IO), $\Gamma_3 = 0$ for $j\pi$ with integer $j$.

In either case, $N_3$ is an ultra long-lived particle.

Suitable for MATHUSLA (MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles) [Coccaro, Curtin, Lubatti, Russell, Shelton '16; Chou, Curtin, Lubati '16]

In addition, $N_{1,2}$ can have displaced vertex signals at the LHC.
$L \text{ (m)}$

$\theta_R/\pi$

$N_1$ (red), $N_2$ (blue), $N_3$ (green).

$M_N=150$ GeV (dashed), 250 GeV (solid).
Decay Length

\[ \frac{\theta_R}{\pi} \]

\[ L (m) \]

\[ 10^{-6} \quad 0.001 \quad 1 \quad 1000 \]

\[ 0.0 \quad 0.5 \quad 1.0 \quad 1.5 \quad 2.0 \]

\[ N_1 \text{ (red), } N_2 \text{ (blue), } N_3 \text{ (green).} \]

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Collider Signal

- Need an efficient production mechanism.
- In our scenario, $y_i \lesssim 10^{-6}$ suppresses the Drell-Yan production

$$pp \rightarrow W(*) \rightarrow N_i \ell_\alpha,$$

and its variants. [Han, Zhang '06; del Aguila, Aguilar-Saavedra, Pittau '07; BD, Pilaftsis, Yang '14; Han, Ruiz, Alva '14; Deppisch, BD, Pilaftsis '15; Das, Okada '15]

- Even if one assumes large Yukawa, the LNV signal will be generally suppressed by the quasi-degeneracy of the RH neutrinos [Kersten, Smirnov '07; Ibarra, Molinaro, Petcov '10; BD '15].
- Need to go beyond the minimal type-I seesaw to realize a sizable LNV signal.
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- Need an efficient production mechanism.
- In our scenario, $y_i \lesssim 10^{-6}$ suppresses the Drell-Yan production
  $$pp \rightarrow W^{(*)} \rightarrow N_i \ell_\alpha,$$
  and its variants. [Han, Zhang '06; del Aguila, Aguilar-Saavedra, Pittau '07; BD, Pilaftsis, Yang '14; Han, Ruiz, Alva '14; Deppisch, BD, Pilaftsis '15; Das, Okada '15]
- Even if one assumes large Yukawa, the LNV signal will be generally suppressed by the quasi-degeneracy of the RH neutrinos [Kersten, Smirnov '07; Ibarra, Molinaro, Petcov '10; BD '15].
- Need to go beyond the minimal type-I seesaw to realize a sizable LNV signal.
- We consider a minimal $U(1)_{B-L}$ extension.
- Production cross section is no longer Yukawa-suppressed, while the decay is, giving rise to displaced vertex. [Deppisch, Desai, Valle '13]
At $\sqrt{s} = 14$ TeV LHC and for $M_{Z'} = 3.5$ TeV.
At $\sqrt{s} = 14$ TeV LHC and for $M_{Z'} = 3.5$ TeV.
Falsifying Leptogenesis at the LHC

- An observation of LNV signal at a given energy scale will falsify leptogenesis above that scale. [Deppisch, Harz, Hirsch ’14]
- Due to the large dilution/washout effects induced by related process.
- In specific models, can make this argument more concrete and falsify leptogenesis at all scales.
- In the $Z'$ case, leptogenesis constraints put a lower bound on $M_{Z'}$. [Blanchet, Chacko, Granor, Mohapatra ’09; BD, Hagedorn, Molinaro (in prep)]
Leptogenesis provides an attractive link between neutrino mass and observed baryon asymmetry of the universe.

Resonant Leptogenesis provides a way to test this idea in laboratory experiments.

Flavor effects play a crucial role in the calculation of lepton asymmetry.

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Approximate analytic solutions are available for a quick pheno analysis.
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Backup Slides
A Minimal Model of RL

- Resonant $\ell$-genesis (RL$\ell$). [Pilaftsis (PRL '04); Deppisch, Pilaftsis '10]
- Minimal model: $O(N)$-symmetric heavy neutrino sector at a high scale $\mu_X$.
- Small mass splitting at low scale from RG effects.

\[ M_N = m_N 1 + \Delta M_{N}^{\text{RG}}, \text{ with } \Delta M_{N}^{\text{RG}} = -\frac{m_N}{8\pi^2} \ln \left( \frac{\mu_X}{m_N} \right) \text{Re} \left[ h^\dagger(\mu_X) h(\mu_X) \right]. \]

- An example of RL$\tau$ with $U(1)_{L_e+L_\mu} \times U(1)_{L_\tau}$ flavor symmetry:

\[
\begin{pmatrix}
0 & ae^{-i\pi/4} & ae^{i\pi/4} \\
0 & be^{-i\pi/4} & be^{i\pi/4} \\
0 & 0 & 0
\end{pmatrix} + \delta h,
\]

\[
\delta h = \begin{pmatrix}
\epsilon_e & 0 & 0 \\
\epsilon_\mu & 0 & 0 \\
\epsilon_\tau & \kappa_1 e^{-i(\pi/4-\gamma_1)} & \kappa_2 e^{i(\pi/4-\gamma_2)}
\end{pmatrix},
\]
A Next-to-minimal $RL_\ell$ Model

[BD, Millington, Pilaftsis, Teresi '15]

- Asymmetry vanishes at $\mathcal{O}(h^4)$ in minimal $RL_\ell$.
- Add an additional flavor-breaking $\Delta M_N$:

\[
M_N = m_N 1 + \Delta M_N + \Delta M_N^{\text{RG}}, \quad \text{with} \quad \Delta M_N = \begin{pmatrix}
\Delta M_1 & 0 & 0 \\
0 & \Delta M_2/2 & 0 \\
0 & 0 & -\Delta M_2/2
\end{pmatrix},
\]

\[
h = \begin{pmatrix}
0 & a e^{-i\pi/4} & a e^{i\pi/4} \\
0 & b e^{-i\pi/4} & b e^{i\pi/4} \\
0 & c e^{-i\pi/4} & c e^{i\pi/4}
\end{pmatrix} + \begin{pmatrix}
\epsilon_e & 0 & 0 \\
\epsilon_\mu & 0 & 0 \\
\epsilon_\tau & 0 & 0
\end{pmatrix}.
\]

- Light neutrino mass constraint:

\[
M_\nu \simeq -\frac{v^2}{2} h M_N^{-1} h^T \simeq \frac{v^2}{2m_N} \begin{pmatrix}
\frac{\Delta m_N}{m_N} a^2 - \epsilon_e^2 & \frac{\Delta m_N}{m_N} ab - \epsilon_e \epsilon_\mu & -\epsilon_e \epsilon_\tau \\
\frac{\Delta m_N}{m_N} ab - \epsilon_e \epsilon_\mu & \frac{\Delta m_N}{m_N} b^2 - \epsilon_\mu^2 & -\epsilon_\mu \epsilon_\tau \\
-\epsilon_e \epsilon_\tau & -\epsilon_\mu \epsilon_\tau & -\epsilon_\tau^2
\end{pmatrix},
\]

where

\[
\Delta m_N \equiv 2 [\Delta M_N]_{23} + i \left( [\Delta M_N]_{33} - [\Delta M_N]_{22} \right) = -i \Delta M_2.
\]
## Benchmark Points

<table>
<thead>
<tr>
<th>Parameters</th>
<th>BP1</th>
<th>BP2</th>
<th>BP3</th>
<th>Current Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_N$</td>
<td>120 GeV</td>
<td>400 GeV</td>
<td>5 TeV</td>
<td></td>
</tr>
<tr>
<td>$c$</td>
<td>$2 \times 10^{-6}$</td>
<td>$2 \times 10^{-7}$</td>
<td>$2 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>$\Delta M_1/m_N$</td>
<td>$-5 \times 10^{-6}$</td>
<td>$-3 \times 10^{-5}$</td>
<td>$-4 \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>$\Delta M_2/m_N$</td>
<td>$(1.59 - 0.47 i) \times 10^{-8}$</td>
<td>$(1.21 + 0.10 i) \times 10^{-9}$</td>
<td>$(1.46 + 0.11 i) \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$a$</td>
<td>$(5.54 - 7.41 i) \times 10^{-4}$</td>
<td>$(4.93 - 2.32 i) \times 10^{-3}$</td>
<td>$(4.67 - 4.33 i) \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>$b$</td>
<td>$(0.89 - 1.19 i) \times 10^{-3}$</td>
<td>$(8.04 - 3.79 i) \times 10^{-3}$</td>
<td>$(7.53 - 6.97 i) \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>$\epsilon_e$</td>
<td>$3.31 i \times 10^{-8}$</td>
<td>$5.73 i \times 10^{-8}$</td>
<td>$2.14 i \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>$\epsilon_\mu$</td>
<td>$2.33 i \times 10^{-7}$</td>
<td>$4.30 i \times 10^{-7}$</td>
<td>$1.50 i \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>$\epsilon_\tau$</td>
<td>$3.50 i \times 10^{-7}$</td>
<td>$6.39 i \times 10^{-7}$</td>
<td>$2.26 i \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>Observables</td>
<td>BP1</td>
<td>BP2</td>
<td>BP3</td>
<td>Current Limit</td>
</tr>
<tr>
<td>BR($\mu \rightarrow e\gamma$)</td>
<td>$4.5 \times 10^{-15}$</td>
<td>$1.9 \times 10^{-13}$</td>
<td>$2.3 \times 10^{-17}$</td>
<td>$&lt; 4.2 \times 10^{-13}$</td>
</tr>
<tr>
<td>BR($\tau \rightarrow \mu\gamma$)</td>
<td>$1.2 \times 10^{-17}$</td>
<td>$1.6 \times 10^{-18}$</td>
<td>$8.1 \times 10^{-22}$</td>
<td>$&lt; 4.4 \times 10^{-8}$</td>
</tr>
<tr>
<td>BR($\tau \rightarrow e\gamma$)</td>
<td>$4.6 \times 10^{-18}$</td>
<td>$5.9 \times 10^{-19}$</td>
<td>$3.1 \times 10^{-22}$</td>
<td>$&lt; 3.3 \times 10^{-8}$</td>
</tr>
<tr>
<td>BR($\mu \rightarrow 3e$)</td>
<td>$1.5 \times 10^{-16}$</td>
<td>$9.3 \times 10^{-15}$</td>
<td>$4.9 \times 10^{-18}$</td>
<td>$&lt; 1.0 \times 10^{-12}$</td>
</tr>
<tr>
<td>$R_{\mu \rightarrow e}^{T_i}$</td>
<td>$2.4 \times 10^{-14}$</td>
<td>$2.9 \times 10^{-13}$</td>
<td>$2.3 \times 10^{-20}$</td>
<td>$&lt; 6.1 \times 10^{-13}$</td>
</tr>
<tr>
<td>$R_{\mu \rightarrow e}^{Au}$</td>
<td>$3.1 \times 10^{-14}$</td>
<td>$3.2 \times 10^{-13}$</td>
<td>$5.0 \times 10^{-18}$</td>
<td>$&lt; 7.0 \times 10^{-13}$</td>
</tr>
<tr>
<td>$R_{\mu \rightarrow e}^{Pb}$</td>
<td>$2.3 \times 10^{-14}$</td>
<td>$2.2 \times 10^{-13}$</td>
<td>$4.3 \times 10^{-18}$</td>
<td>$&lt; 4.6 \times 10^{-11}$</td>
</tr>
<tr>
<td>$\Omega_{e\mu}$</td>
<td>$5.8 \times 10^{-6}$</td>
<td>$1.8 \times 10^{-5}$</td>
<td>$1.6 \times 10^{-7}$</td>
<td>$&lt; 7.0 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
Falsifying (High-scale) Leptogenesis at the LHC

[Deppisch, Harz, Hirsch (PRL '14)]
Falsifying (Low-scale) Leptogenesis?

- One example: **Left-Right Symmetric Model**. [Pati, Salam '74; Mohapatra, Pati '75; Senjanović, Mohapatra 75]
- **Common lore:** $M_{W_R} > 18$ TeV for leptogenesis. [Frere, Hambye, Vertongen '09]
- Mainly due to additional $\Delta L = 1$ washout effects induced by $W_R$.

- True only with generic $Y_N \lesssim 10^{-11/2}$.
- Somewhat weaker in a class of low-scale LRSM with larger $Y_N$.
  [BD, Lee, Mohapatra '13]
- A lower limit of $M_{W_R} \gtrsim 10$ TeV.
- **A Discovery of $M_{W_R}$ at the LHC rules out leptogenesis in LRSM.**
  [BD, Lee, Mohapatra '14, '15; Dhuria, Hati, Rangarajan, Sarkar '15]