Baryogenesis and Neutrino Mass

A Common Link and Experimental Signatures

Bhupal Dev

Washington University in St. Louis

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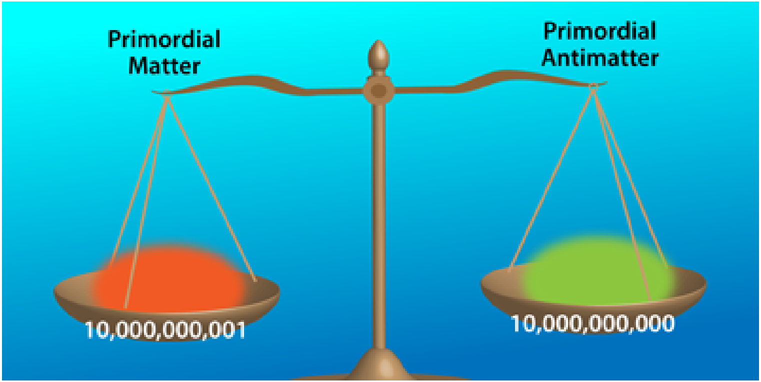
Matter-Antimatter Asymmetry



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

One number $\longrightarrow$ 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.

$+$

$\neq$

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$\neq$

- The Standard Model has all the basic ingredients, but
  - 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!

Testable Baryogenesis

- 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; ...]
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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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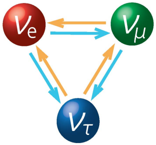
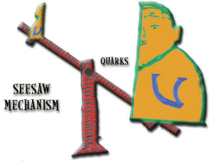
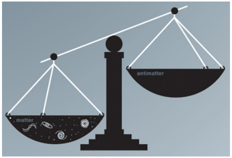
This talk: Low-scale leptogenesis

Leptogenesis

[Fukugita, Yanagida '86]



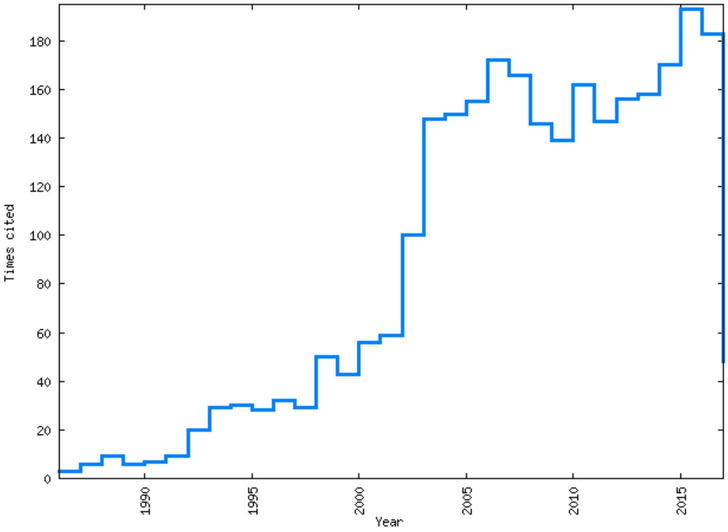




A cosmological consequence of the seesaw mechanism.

- 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.
  - $\not{L} \to \not{B}$ 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 $\Gamma_N \lesssim H$.

Popularity of Leptogenesis



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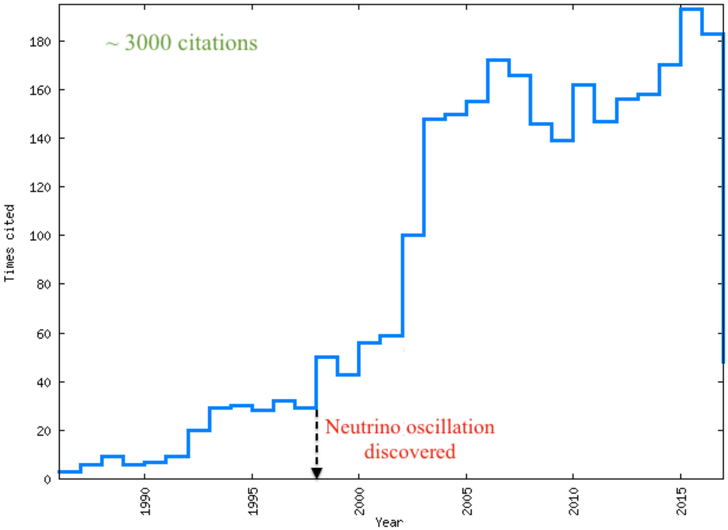
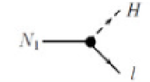


Leptogenesis for Pedestrians

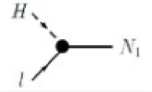
[Buchmüller, Di Bari, Plümacher ’05]

Three basic steps:

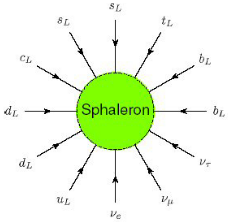
1. Generation of L asymmetry by heavy Majorana neutrino decay:



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



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



Boltzmann Equations

[Buchmüller, Di Bari, Plümacher '02]

$$\begin{aligned} \frac{dN_N}{dz} &= -(D+S)(N_N - N_N^{\rm eq}), \\ \frac{dN_{\Delta L}}{dz} &= \varepsilon D(N_N - N_N^{\rm eq}) - N_{\Delta L} W, \end{aligned}$$

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

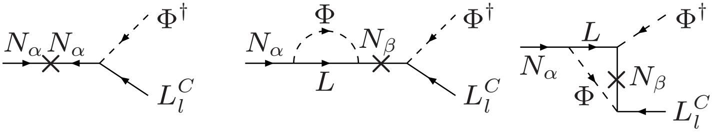
- FInal baryon asymmetry:

$$\eta_{\Delta B} = d \cdot \varepsilon \cdot \kappa_f$$

- $d \simeq \frac{28}{51}\frac{1}{27} \simeq 0.02$ ($\not{L} \to \not{B}$ conversion at T_c + entropy dilution from T_c to recombination epoch).
- $\kappa_f \equiv \kappa(z_f)$ is the final efficiency factor, where

$$\kappa(z) = \int_{z_i}^{z} dz' \frac{D}{D+S} \frac{dN_N}{dz'} \, e^{-\int_{z'}^{z} dz'' W(z'')}$$

CP Asymmetry



tree | self-energy | vertex

$$\varepsilon_{l\alpha} = \frac{\Gamma(N_\alpha \to L_l \Phi) - \Gamma(N_\alpha \to L_l^c \Phi^c)}{\sum_k \left[\Gamma(N_\alpha \to L_k \Phi) + \Gamma(N_\alpha \to L_k^c \Phi^c)\right]} \equiv \frac{|\widehat{\mathbf{h}}_{l\alpha}|^2 - |\widehat{\mathbf{h}}^c_{l\alpha}|^2}{(\widehat{\mathbf{h}}^\dagger \widehat{\mathbf{h}})_{\alpha\alpha} + (\widehat{\mathbf{h}}^{c\dagger} \widehat{\mathbf{h}}^c)_{\alpha\alpha}}$$

with the one-loop resummed Yukawa couplings [Pilaftsis, Underwood '03]

$$\widehat{\mathbf{h}}_{l\alpha} = \widehat{h}_{l\alpha} - i \sum_{\beta,\gamma} |\epsilon_{\alpha\beta\gamma}| \widehat{h}_{l\beta}$$

$$\times \frac{m_\alpha(m_\alpha A_{\alpha\beta} + m_\beta A_{\beta\alpha}) - iR_{\alpha\gamma}[m_\alpha A_{\gamma\beta}(m_\alpha A_{\alpha\gamma} + m_\gamma A_{\gamma\alpha}) + m_\beta A_{\beta\gamma}(m_\alpha A_{\gamma\alpha} + m_\gamma A_{\alpha\gamma})]}{m_\alpha^2 - m_\beta^2 + 2im_\alpha^2 A_{\beta\beta} + 2i\mathrm{Im}(R_{\alpha\gamma})[m_\alpha^2 |A_{\beta\gamma}|^2 + m_\beta m_\gamma \mathrm{Re}(A_{\beta\gamma}^2)]} ,$$

$$R_{\alpha\beta} = \frac{m_\alpha^2}{m_\alpha^2 - m_\beta^2 + 2im_\alpha^2 A_{\beta\beta}} ; \qquad A_{\alpha\beta}(\widehat{h}) = \frac{1}{16\pi} \sum_l \widehat{h}_{l\alpha} \widehat{h}^*_{l\beta} .$$

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

$$\varepsilon_1^{\rm max} = \frac{3}{16\pi}\frac{m_{N_1}}{v^2}\sqrt{\Delta m^2_{\rm atm}}$$

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

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

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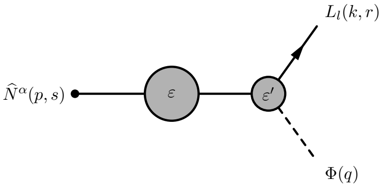
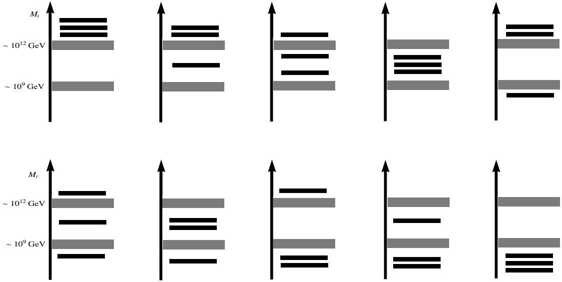
- Experimentally inaccessible!
- Also leads to a lower limit on the reheating temperature $T_{\rm rh} \gtrsim 10^9$ GeV.
- In supergravity models, need $T_{\rm rh} \lesssim 10^6 - 10^9$ GeV to avoid the gravitino problem.
  [Khlopov, Linde '84; Ellis, Kim, Nanopoulos '84; Cyburt, Ellis, Fields, Olive '02; Kawasaki, Kohri, Moroi, Yotsuyanagi '08]
- Also in conflict with the Higgs naturalness bound $m_N \lesssim 10^7$ GeV. [Vissani '97; Clarke, Foot, Volkas '15; Bambhaniya, BD, Goswami, Khan, Rodejohann '16]

Resonant Leptogenesis



- Dominant self-energy effects on the *CP*-asymmetry (ε-type) [Flanz, Paschos, Sarkar '95; Covi, Roulet, Vissani '96].
- Resonantly enhanced, even up to order 1, when $\Delta m_N \sim \Gamma_N/2 \ll m_{N_{1,2}}$. [Pilaftsis '97; 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. [Pilaftsis, Underwood '05; Deppisch, Pilaftsis '10; BD, Millington, Pilaftsis, Teresi '14]
- A testable scenario at both Energy and Intensity Frontiers.

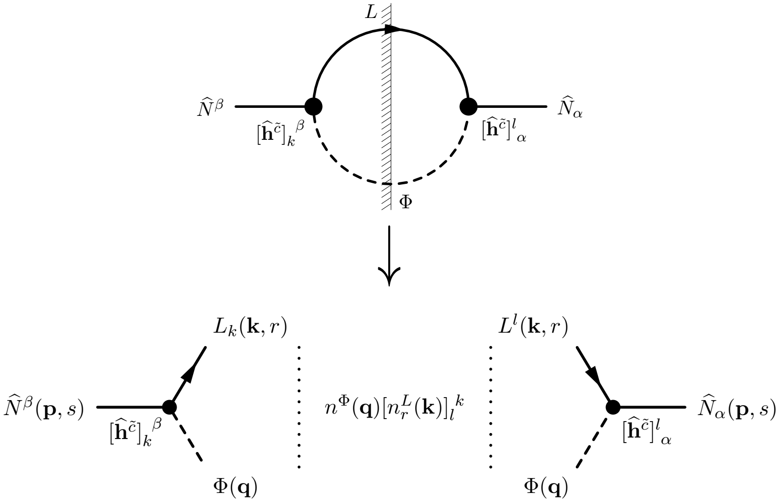
Flavordynamics



- 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 $h_l^{\ \alpha}$ [Pilaftsis '04; Endoh, Morozumi, Xiong '04]
  - Charged lepton Yukawa couplings $y_l^{\ k}$ [Barbieri, Creminelli, Strumia, Tetradis '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]

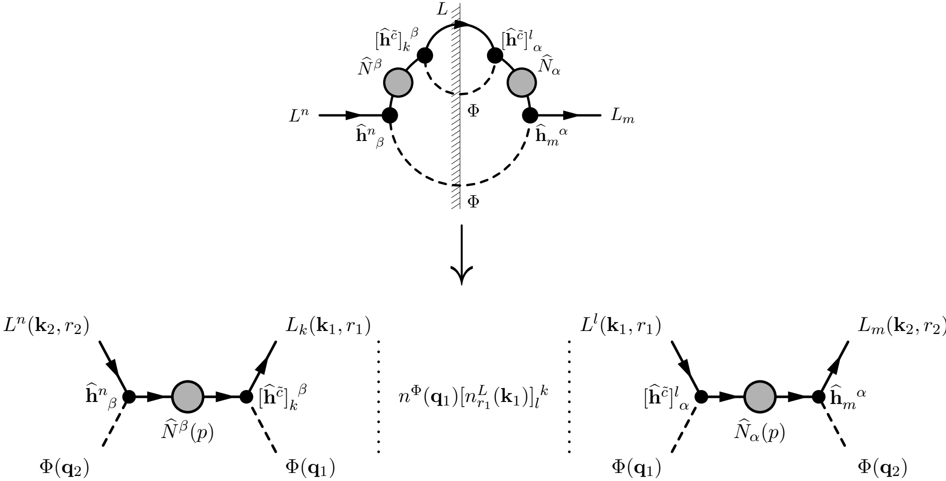
Collision Rates for Decay and Inverse Decay

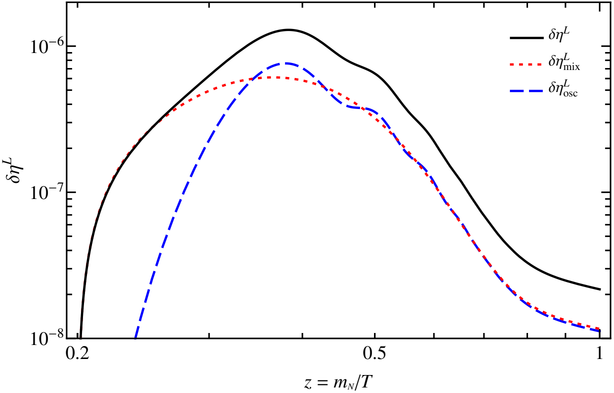
$$\boxed{n^{\Phi}\ [n^{L}]_{l}{}^{k}\ [\gamma(L\Phi \to N)]_{k}{}^{l}{}_{\alpha}{}^{\beta}} \longrightarrow \text{rank-4 tensor}$$



Collision Rates for 2 $\leftrightarrow$ 2 Scattering

$$\boxed{n^{\Phi}\ [n^{L}]_{l}^{\ k}\ [\gamma(L\Phi \to L\Phi)]_{k\ m}^{\ l\ \ n}} \longrightarrow \text{rank-4 tensor}$$





$$\delta\eta^L_{\rm mix} \simeq \frac{g_N}{2}\,\frac{3}{2{\rm K}z}\sum_{\alpha\neq\beta}\frac{\Im\big(\widehat{h}^\dagger\widehat{h}\big)^2_{\alpha\beta}}{\big(\widehat{h}^\dagger\widehat{h}\big)_{\alpha\alpha}\big(\widehat{h}^\dagger\widehat{h}\big)_{\beta\beta}}\;\frac{\big(M^2_{N,\,\alpha}-M^2_{N,\,\beta}\big)M_N\widehat{\Gamma}^{(0)}_{\beta\beta}}{\big(M^2_{N,\,\alpha}-M^2_{N,\,\beta}\big)^2+\big(M_N\widehat{\Gamma}^{(0)}_{\beta\beta}\big)^2}\,,$$

$$\delta\eta^L_{\rm osc} \simeq \frac{g_N}{2}\,\frac{3}{2{\rm K}z}\sum_{\alpha\neq\beta}\frac{\Im\big(\widehat{h}^\dagger\widehat{h}\big)^2_{\alpha\beta}}{\big(\widehat{h}^\dagger\widehat{h}\big)_{\alpha\alpha}\big(\widehat{h}^\dagger\widehat{h}\big)_{\beta\beta}}\;\frac{\big(M^2_{N,\,\alpha}-M^2_{N,\,\beta}\big)M_N\big(\widehat{\Gamma}^{(0)}_{\alpha\alpha}+\widehat{\Gamma}^{(0)}_{\beta\beta}\big)}{\big(M^2_{N,\,\alpha}-M^2_{N,\,\beta}\big)^2+M^2_N(\widehat{\Gamma}^{(0)}_{\alpha\alpha}+\widehat{\Gamma}^{(0)}_{\beta\beta})^2\,\frac{\Im[(\widehat{h}^\dagger\widehat{h})_{\alpha\beta}]^2}{(\widehat{h}^\dagger\widehat{h})_{\alpha\alpha}(\widehat{h}^\dagger\widehat{h})_{\beta}}}$$

A Predictive RL Model

- 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, Zieglar '12]
- CP symmetry is given by the transformation $X(s)(\mathrm{r})$ 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)]

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

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

- The unitary matrices $\Omega(s)(\mathrm{r})$ are determined by the CP transformation $X(s)(\mathrm{r})$.
- Form of the RH neutrino mass matrix invariant under flavor and CP symmetries:

$$M_R = M_N \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

Fixing Model Parameters

- 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 3σ of current global-fit results).
- Light neutrino masses given by the type-I seesaw:

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

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

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

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

- Only free parameters: M_N and θ_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 α, which depends on the chosen CP transformation:

$$\sin\alpha = (-1)^{k+r+s}\,\sin 6\,\phi_s \quad \text{and} \quad \cos\alpha = (-1)^{k+r+s+1}\,\cos 6\,\phi_s \;\; \text{with } \phi_s = \frac{\pi\, s}{n}\,,$$

  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 $0\nu\beta\beta$:

$$m_{\beta\beta} \approx \frac{1}{3}\begin{cases} \left|\sqrt{\Delta m^2_{\text{sol}}} + 2\,(-1)^{s+k+1}\,\sin^2\theta_L\, e^{6\,i\,\phi_s}\sqrt{\Delta m^2_{\text{atm}}}\right| & \text{(NO)}. \\ \left|1 + 2\,(-1)^{s+k}\,e^{6\,i\,\phi_s}\cos^2\theta_L\right|\sqrt{\left|\Delta m^2_{\text{atm}}\right|} & \text{(IO)}\,. \end{cases}$$

- For $n = 26$, $\theta_L \approx 0.18$ and best-fit values of Δm^2_{sol} and Δm^2_{atm}, we get

$$0.0019\,\text{eV} \lesssim m_{\beta\beta} \lesssim 0.0040\,\text{eV} \qquad \text{(NO)}$$
$$0.016\,\text{eV} \lesssim m_{\beta\beta} \lesssim 0.048\,\text{eV} \qquad \text{(IO)}.$$

High Energy CP Phases and Leptogenesis

- At leading order, three degenerate RH neutrinos.
- Higher-order corrections can break the residual symmetries, giving rise to a quasi-degenerate spectrum:

$$M_1 = M_N\,(1+2\,\kappa) \;\text{ and }\; M_2 = M_3 = M_N\,(1-\kappa)\,.$$

- CP asymmetries in the decays of N_i are given by

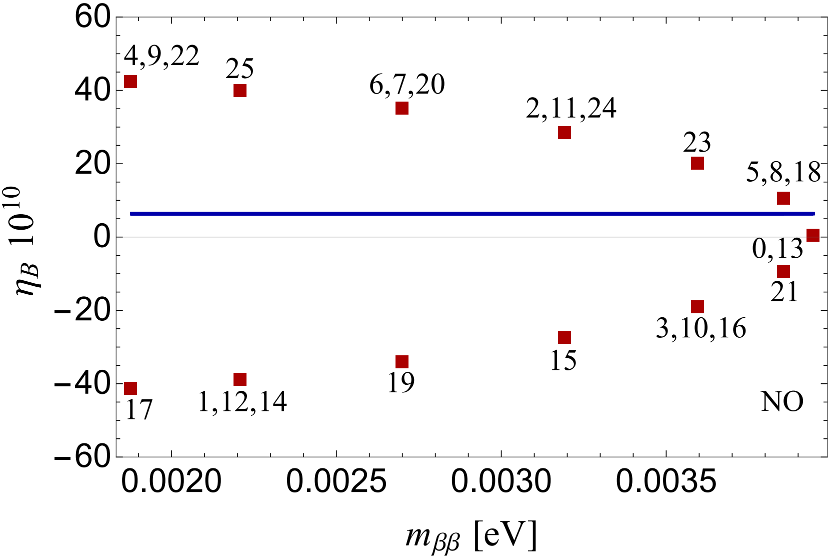
$$\varepsilon_{i\alpha} \approx \sum_{j\neq i} \mathrm{Im}\left(\hat{Y}^{\star}_{D,\alpha i}\,\hat{Y}_{D,\alpha j}\right)\,\mathrm{Re}\left(\left(\hat{Y}^{\dagger}_{D}\,\hat{Y}_{D}\right)_{ij}\right)\,F_{ij}$$

- 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

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

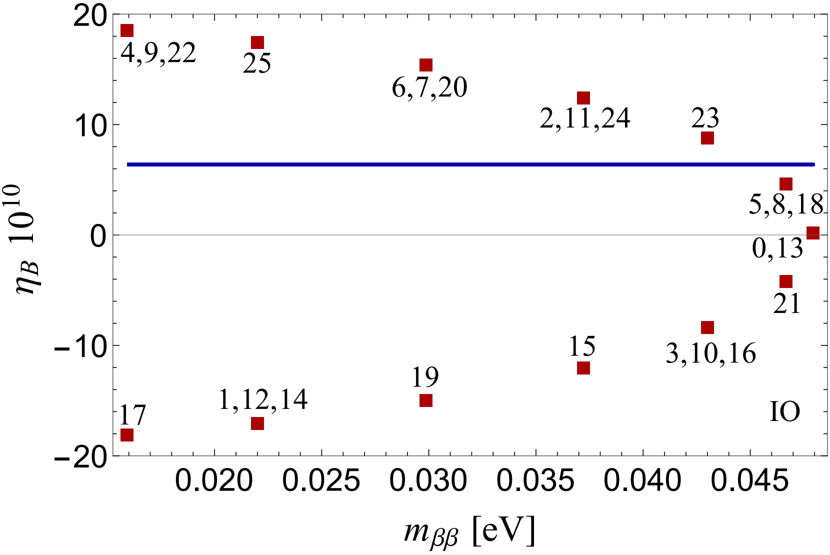
$$\varepsilon_{1\alpha} \approx \frac{y_1\,y_2}{9}\left(-2\,y_2^2 + y_1^2\,(1+\cos 2\,\theta_R)\right)\sin 3\,\phi_s\,\cos\theta_R\,\cos\theta_{L,\alpha}\,F_{12} \quad (\mathrm{IO})$$

  with $\theta_{L,\alpha} = \theta_L + \rho_\alpha\,4\pi/3$ and $\rho_e = 0$, $\rho_\mu = 1$, $\rho_\tau = -1$.
- $\varepsilon_{2\alpha}$ are the negative of $\epsilon_{1\alpha}$ with F_{12} being replaced by F_{21}.

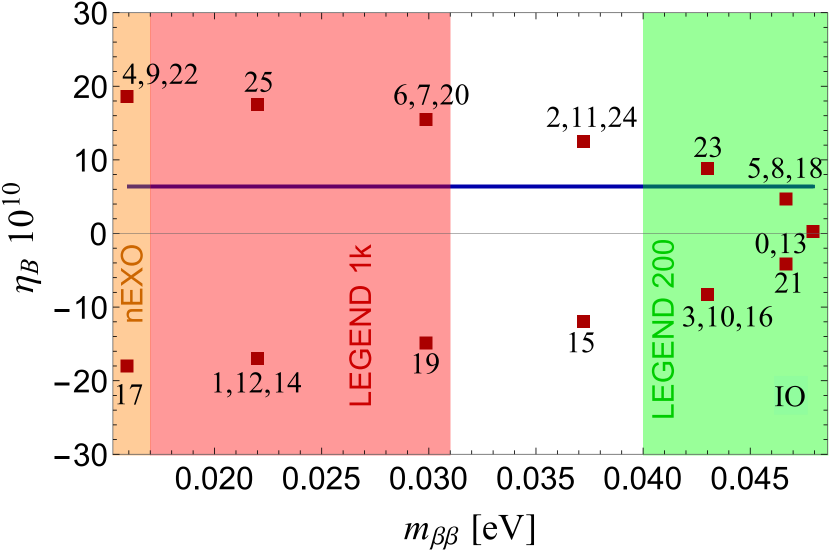


60
40
20
0
−20
−40
−60
$\eta_B\ 10^{10}$
4,9,22
25
6,7,20
2,11,24
23
5,8,18
0,13
21
3,10,16
15
19
1,12,14
17
NO
0.0020
0.0025
0.0030
0.0035
$m_{\beta\beta}$ [eV]

Correlation between BAU and $0\nu\beta\beta$



Correlation between BAU and $0\nu\beta\beta$

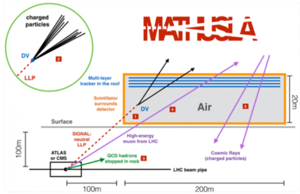


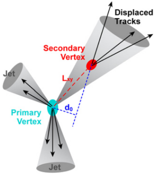
Decay Length

- For RH Majorana neutrinos, $\Gamma_\alpha = M_\alpha\,(\hat{Y}_D^\dagger\,\hat{Y}_D)_{\alpha\alpha}/(8\,\pi)$. We get

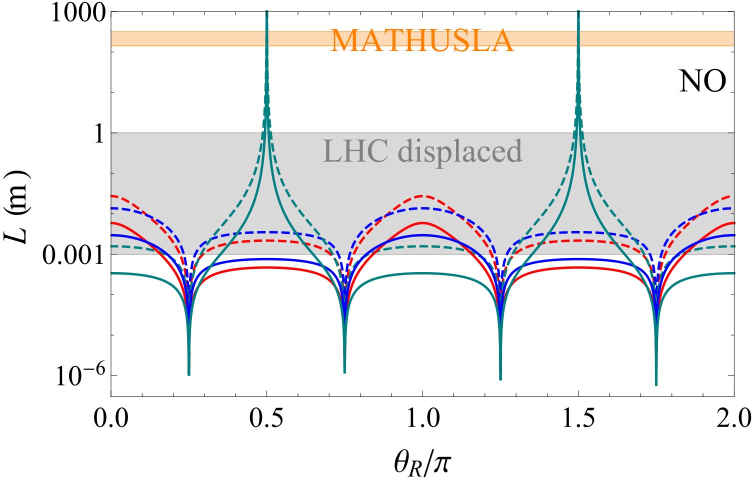
$$\begin{aligned}
\Gamma_1 &\approx \frac{M_N}{24\,\pi}\left(2\,y_1^2\,\cos^2\theta_R + y_2^2 + 2\,y_3^2\,\sin^2\theta_R\right)\,,\\
\Gamma_2 &\approx \frac{M_N}{24\,\pi}\left(y_1^2\,\cos^2\theta_R + 2\,y_2^2 + y_3^2\,\sin^2\theta_R\right)\,,\\
\Gamma_3 &\approx \frac{M_N}{8\,\pi}\left(y_1^2\,\sin^2\theta_R + y_3^2\,\cos^2\theta_R\right)\,.
\end{aligned}$$

- 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.



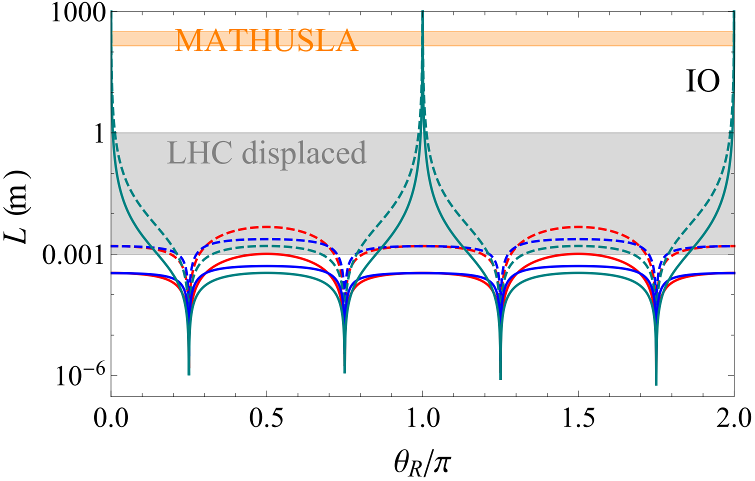


Decay Length



N_1 (red), N_2 (blue), N_3 (green).
M_N=150 GeV (dashed), 250 GeV (solid).

Decay Length



N_1 (red), N_2 (blue), N_3 (green).
M_N=150 GeV (dashed), 250 GeV (solid).

Collider Signal

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

$$pp \to W^{(*)} \to N_i \ell_\alpha \, ,$$

  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].
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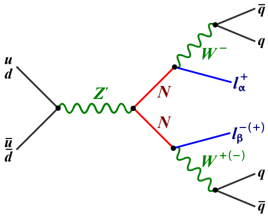
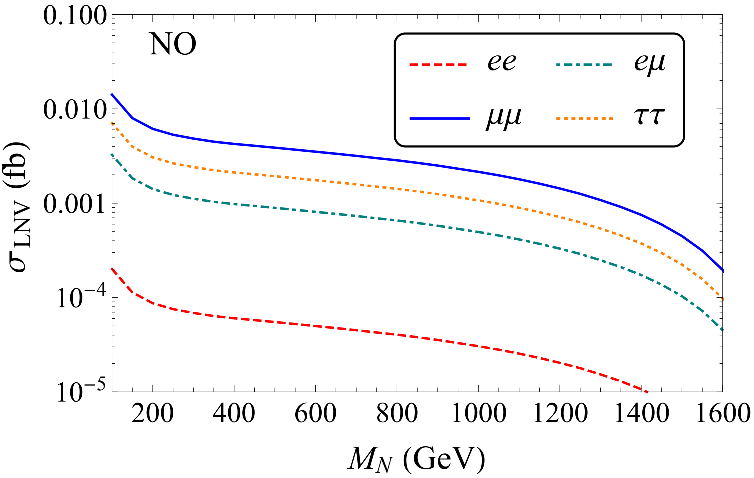
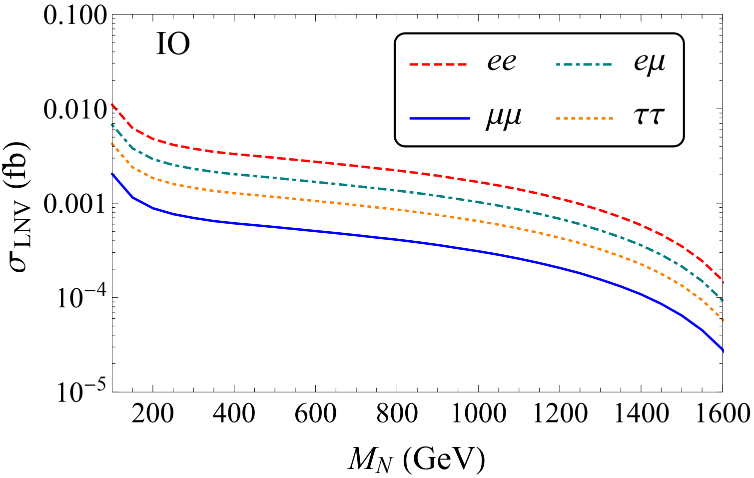
- Need to go beyond the minimal type-I seesaw to realize a sizable LNV signal.
- We consider a minimal $U(1)_{B-L}$ extension.
- Production cross section is no longer Yukawa-suppressed, while the decay is, giving rise to displaced vertex. [Deppisch, Desai, Valle '13]



Collider Signal



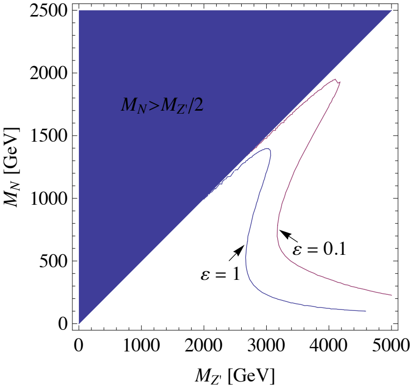
At $\sqrt{s} = 14$ TeV LHC and for $M_{Z'} = 3.5$ TeV.



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)]



Conclusion

- 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.
- Developed a fully flavor-covariant formalism to consistently capture all flavor effects in the semi-classical Boltzmann approach.
- Approximate analytic solutions are available for a quick pheno analysis.

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- Presented a predictive RL model based on residual flavor and CP symmetries.
- Correlation between BAU and $0\nu\beta\beta$.
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Backup Slides

A Minimal Model of RL

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

$$\boldsymbol{M}_N = m_N \mathbf{1} + \boldsymbol{\Delta M}_N^{\mathrm{RG}}, \quad \text{with} \quad \boldsymbol{\Delta M}_N^{\mathrm{RG}} = -\frac{m_N}{8\pi^2} \ln\left(\frac{\mu_X}{m_N}\right) \mathrm{Re}\left[\boldsymbol{h}^\dagger(\mu_X)\boldsymbol{h}(\mu_X)\right] .$$

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

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

$$\boldsymbol{\delta h} = \begin{pmatrix} \epsilon_e & 0 & 0 \\ \epsilon_\mu & 0 & 0 \\ \epsilon_\tau & \kappa_1 e^{-i(\pi/4-\gamma_1)} & \kappa_2 e^{i(\pi/4-\gamma_2)} \end{pmatrix},$$

A Next-to-minimal RL_ℓ Model

[BD, Millington, Pilaftsis, Teresi '15]

- Asymmetry vanishes at $\mathcal{O}(h^4)$ in minimal RL_ℓ.
- Add an additional flavor-breaking $\boldsymbol{\Delta M}_N$:

$$\boldsymbol{M}_N \;=\; m_N\mathbf{1} \;+\; \boldsymbol{\Delta M}_N \;+\; \boldsymbol{\Delta M}_N^{\rm RG}\,, \quad \text{with } \boldsymbol{\Delta M}_N \;=\; \begin{pmatrix} \Delta M_1 & 0 & 0 \\ 0 & \Delta M_2/2 & 0 \\ 0 & 0 & -\Delta M_2/2 \end{pmatrix}\,,$$

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

- Light neutrino mass constraint:

$$\boldsymbol{M}_\nu \;\simeq\; -\frac{v^2}{2}\boldsymbol{h}\boldsymbol{M}_N^{-1}\boldsymbol{h}^{\mathsf{T}} \;\simeq\; \frac{v^2}{2m_N}\begin{pmatrix} \frac{\Delta m_N}{m_N}a^2 - \epsilon_e^2 & \frac{\Delta m_N}{m_N}ab - \epsilon_e\epsilon_\mu & -\epsilon_e\epsilon_\tau \\ \frac{\Delta m_N}{m_N}ab - \epsilon_e\epsilon_\mu & \frac{\Delta m_N}{m_N}b^2 - \epsilon_\mu^2 & -\epsilon_\mu\epsilon_\tau \\ -\epsilon_e\epsilon_\tau & -\epsilon_\mu\epsilon_\tau & -\epsilon_\tau^2 \end{pmatrix},$$

where

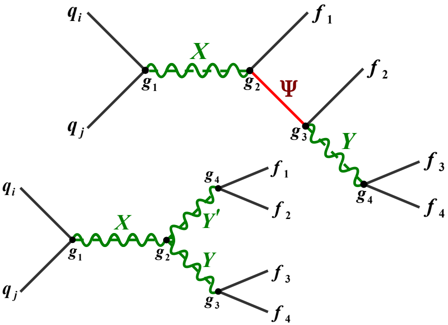
$$\Delta m_N \equiv 2\,[\Delta M_N]_{23} + i\left([\Delta M_N]_{33} - [\Delta M_N]_{22}\right) \;=\; -\,i\,\Delta M_2\,.$$

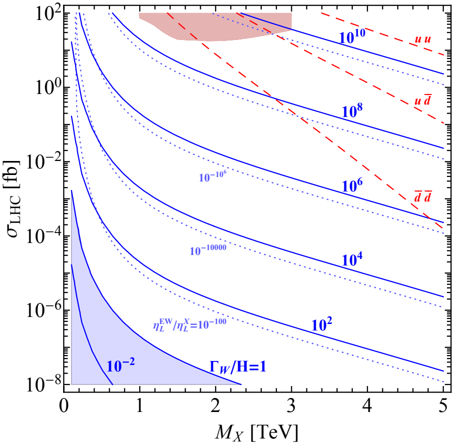
Benchmark Points

Parameters	BP1	BP2	BP3
m_N	120 GeV	400 GeV	5 TeV
c	2×10^{-6}	2×10^{-7}	2×10^{-6}
$\Delta M_1/m_N$	-5×10^{-6}	-3×10^{-5}	-4×10^{-5}
$\Delta M_2/m_N$	$(-1.59 - 0.47\,i) \times 10^{-8}$	$(-1.21 + 0.10\,i) \times 10^{-9}$	$(-1.46 + 0.11\,i) \times 10^{-8}$
a	$(5.54 - 7.41\,i) \times 10^{-4}$	$(4.93 - 2.32\,i) \times 10^{-3}$	$(4.67 - 4.33\,i) \times 10^{-3}$
b	$(0.89 - 1.19\,i) \times 10^{-3}$	$(8.04 - 3.79\,i) \times 10^{-3}$	$(7.53 - 6.97\,i) \times 10^{-3}$
ϵ_e	$3.31\,i \times 10^{-8}$	$5.73\,i \times 10^{-8}$	$2.14\,i \times 10^{-7}$
ϵ_μ	$2.33\,i \times 10^{-7}$	$4.30\,i \times 10^{-7}$	$1.50\,i \times 10^{-6}$
ϵ_τ	$3.50\,i \times 10^{-7}$	$6.39\,i \times 10^{-7}$	$2.26\,i \times 10^{-6}$

Observables	BP1	BP2	BP3	Current Limit
$\mathrm{BR}(\mu \to e\gamma)$	4.5×10^{-15}	1.9×10^{-13}	2.3×10^{-17}	$< 4.2 \times 10^{-13}$
$\mathrm{BR}(\tau \to \mu\gamma)$	1.2×10^{-17}	1.6×10^{-18}	8.1×10^{-22}	$< 4.4 \times 10^{-8}$
$\mathrm{BR}(\tau \to e\gamma)$	4.6×10^{-18}	5.9×10^{-19}	3.1×10^{-22}	$< 3.3 \times 10^{-8}$
$\mathrm{BR}(\mu \to 3e)$	1.5×10^{-16}	9.3×10^{-15}	4.9×10^{-18}	$< 1.0 \times 10^{-12}$
$\mathrm{R}^{\mathrm{Ti}}_{\mu\to e}$	2.4×10^{-14}	2.9×10^{-13}	2.3×10^{-20}	$< 6.1 \times 10^{-13}$
$\mathrm{R}^{\mathrm{Au}}_{\mu\to e}$	3.1×10^{-14}	3.2×10^{-13}	5.0×10^{-18}	$< 7.0 \times 10^{-13}$
$\mathrm{R}^{\mathrm{Pb}}_{\mu\to e}$	2.3×10^{-14}	2.2×10^{-13}	4.3×10^{-18}	$< 4.6 \times 10^{-11}$
$\lvert\Omega\rvert_{e\mu}$	5.8×10^{-6}	1.8×10^{-5}	1.6×10^{-7}	$< 7.0 \times 10^{-5}$

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]