Flavorful Leptogenesis

Bhupal Dev

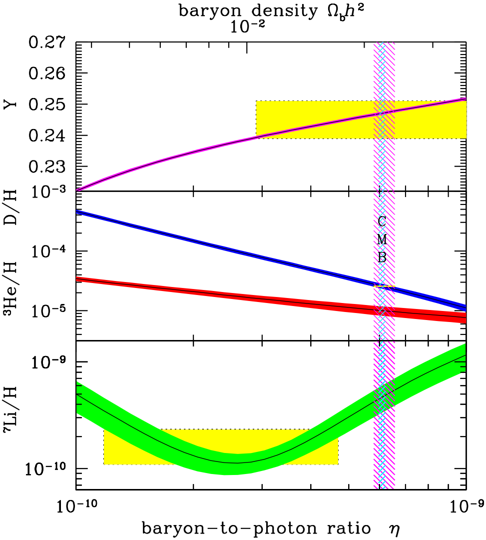
Washington University in St. Louis

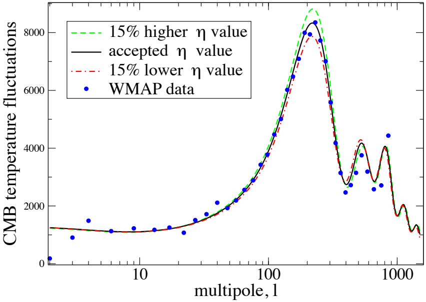
HEP2018: 7th International Conference on High Energy Physics in the LHC Era

Universidad Técnica Federico Santa María, Valparaiso, Chile

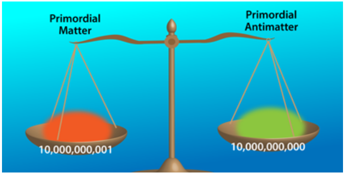
January 12, 2018

Matter-Antimatter Asymmetry





[Particle Data Group '17]



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

One number $\Longrightarrow$ BSM Physics

Baryogenesis

- Dynamical generation of baryon asymmetry.
- **Basic ingredients:** [Sakharov (JETP Lett. '67)]
  B violation, C & CP violation, departure from thermal equilibrium
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  - CKM CP violation is too small (by $\sim$ 10 orders of magnitude).
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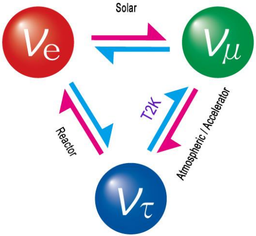
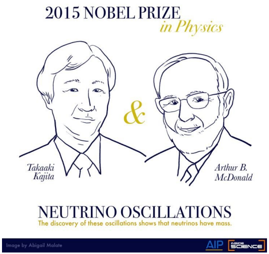
Requires New Physics!

- Many interesting ideas out there. [For review, see e.g. J. Cline, hep-ph/0609145]

This talk is on Low-scale leptogenesis

Connection to Neutrino Mass





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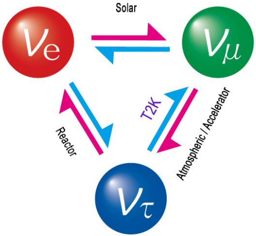
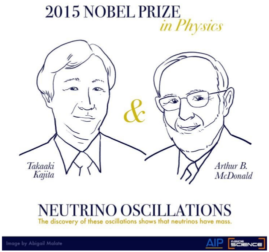
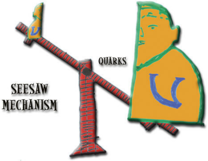
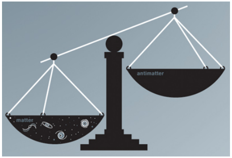




Seesaw Mechanism: a common link between neutrino mass and baryon asymmetry.





[Fukugita, Yanagida (Phys. Lett. B '86)]

Seesaw Mechanism

- Add SM-singlet heavy Majorana neutrinos. [Minkowski (PLB '77); Mohapatra, Senjanović (PRL '80); Yanagida '79; Gell-Mann, Ramond, Slansky '79; Glashow '80]
- In flavor basis $\{\nu^c, N\}$, (type-I) seesaw mass matrix

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D \\ M_D^\mathsf{T} & M_N \end{pmatrix}$$

- For $||M_D M_N^{-1}|| \ll 1$, $\boxed{M_\nu^{\rm light} \simeq -M_D M_N^{-1} M_D^\mathsf{T}}$.

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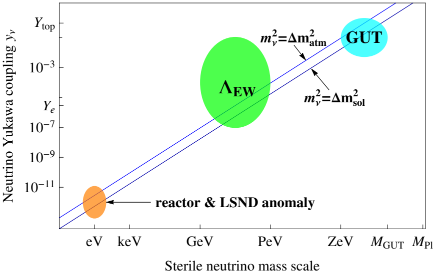
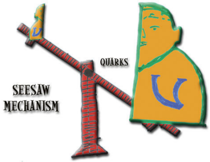
- In traditional $SO(10)$ GUT, $M_N \sim 10^{14}$ GeV for $\mathcal{O}(1)$ Dirac Yukawa couplings.
- But in a bottom-up approach, allowed to be anywhere (down to eV-scale).





Leptogenesis

[Fukugita, Yanagida (Phys. Lett. B '86)]

A cosmological consequence of the seesaw mechanism.

Naturally satisfies all 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 $\Gamma_N \lesssim H$.

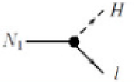
An experimentally testable scenario.

Leptogenesis for Pedestrians

[Buchmüller, Di Bari, Plümacher '05]

$\boxed{\text{Three basic steps:}}$

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



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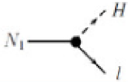
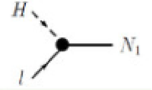


2. Partial washout of the asymmetry due to inverse decay (and scatterings):



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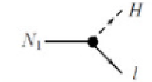

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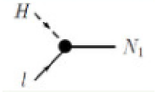
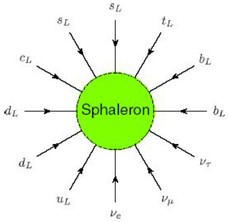


3. Conversion of the left-over L asymmetry to B asymmetry at $T > T_{\text{sph}}$.



Boltzmann Equations

[Buchmüller, Di Bari, Plümacher '02]

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

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

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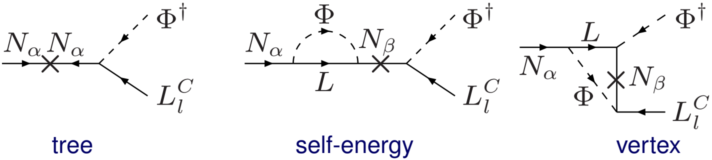
- Final baryon asymmetry:

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

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

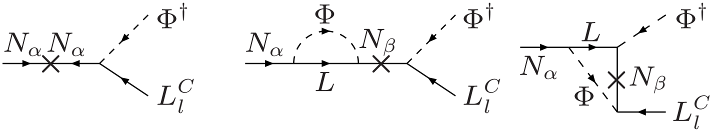
$$\kappa(z) = \int_{z_i}^{z} dz' \frac{D}{D+S} \frac{dN_N}{dz'} \, e^{-\int_{z'}^{z} dz'' W(z'')}$$

CP Asymmetry



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

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]

$$\begin{aligned}
\widehat{\mathbf{h}}_{l\alpha} &= \widehat{h}_{l\alpha} - i \sum_{\beta,\gamma} |\epsilon_{\alpha\beta\gamma}| \widehat{h}_{l\beta} \\
&\times \frac{m_\alpha (m_\alpha A_{\alpha\beta} + m_\beta A_{\beta\alpha}) - i R_{\alpha\gamma} [m_\alpha A_{\gamma\beta} (m_\alpha A_{\alpha\gamma} + m_\gamma A_{\gamma\alpha}) + m_\beta A_{\beta\gamma} (m_\alpha A_{\gamma\alpha} + m_\gamma A_{\alpha\gamma})]}{m_\alpha^2 - m_\beta^2 + 2 i m_\alpha^2 A_{\beta\beta} + 2 i \mathrm{Im}(R_{\alpha\gamma}) [m_\alpha^2 |A_{\beta\gamma}|^2 + m_\beta m_\gamma \mathrm{Re}(A_{\beta\gamma}^2)]},
\end{aligned}$$

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

Testability of Leptogenesis

$\boxed{\text{Three regions of interest:}}$

- High scale: $m_N \gg \mathrm{TeV}$.
  Can be falsified with an LNV signal at the LHC.
  [Deppisch, Harz, Hirsch (PRL '14); Talk by Frank Deppisch]

- Collider-friendly scale: $100\ \mathrm{GeV} \lesssim m_N \lesssim \text{few TeV}$.
  Can be tested in collider and/or low-energy ($0\nu\beta\beta$, LFV) searches.
  [Pilaftsis, Underwood (PRD '05); Deppisch, Pilaftsis (PRD '11); BD, Millington, Pilaftsis, Teresi (NPB '14)]

- Low-scale: $1\ \mathrm{GeV} \lesssim m_N \lesssim 5\ \mathrm{GeV}$.
  Can be tested at the intensity frontier: SHiP, DUNE or B-factories (LHCb, Belle-II).
  [Alekhin *et al.* '15]

For more details, see

Dedicated review volume on Leptogenesis (to appear in Int. J. Mod. Phys. A)

1. P. S. B. Dev, P. Di Bari, B. Garbrecht, S. Lavignac, P. Millington and D. Teresi, "Flavor effects in leptogenesis," arXiv:1711.02861 [hep-ph].
2. M. Drewes *et al.*, "ARS Leptogenesis," arXiv:1711.02862 [hep-ph].
3. P. S. B. Dev, M. Garny, J. Klaric, P. Millington and D. Teresi, "Resonant enhancement in leptogenesis," arXiv:1711.02863 [hep-ph].
4. S. Biondini *et al.*, "Status of rates and rate equations for thermal leptogenesis," arXiv:1711.02864 [hep-ph].
5. E. J. Chun *et al.*, "Probing Leptogenesis," arXiv:1711.02865 [hep-ph].
6. C. Hagedorn, R. N. Mohapatra, E. Molinaro, C. C. Nishi and S. T. Petcov, "CP Violation in the Lepton Sector and Implications for Leptogenesis," arXiv:1711.02866 [hep-ph].

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

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

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

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

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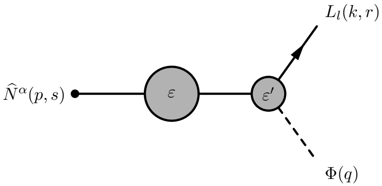
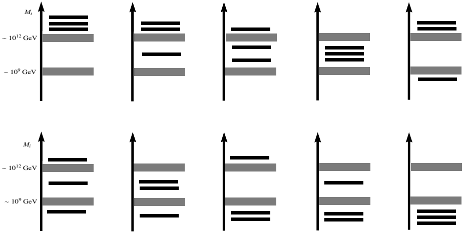
- Experimentally inaccessible!
- Also leads to a lower limit on the reheating temperature $T_{\rm rh} \gtrsim 10^9$ GeV.
- In supergravity models, need $T_{\rm rh} \lesssim 10^6 - 10^9$ GeV to avoid the gravitino problem.
  [Khlopov, Linde '84; Ellis, Kim, Nanopoulos '84; Cyburt, Ellis, Fields, Olive '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



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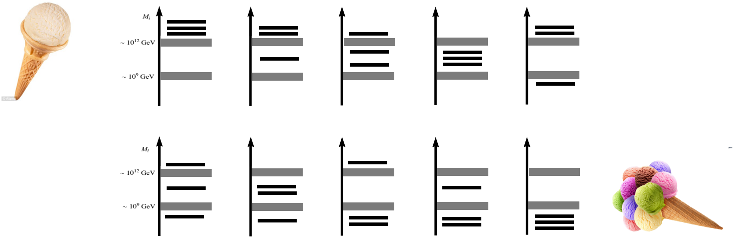

- Flavor effects important at low scale [Abada, Davidson, Ibarra, Josse-Michaux, Losada, Riotto '06; Nardi, Nir, Roulet, Racker '06; De Simone, Riotto '06; Blanchet, Di Bari, Jones, Marzola '12; BD, Millington, Pilaftsis, Teresi '14]
- Two sources of flavor effects:
  - Heavy neutrino Yukawa couplings h_l^{α} [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]

Master Equation for Transport Phenomena

[BD, Millington, Pilaftsis, Teresi (Nucl. Phys. B '14)]

- In quantum statistical mechanics,

$$\boldsymbol{n}^X(t) \;\equiv\; \langle \check{\boldsymbol{n}}^X(\tilde{t};\tilde{t}_i)\rangle_t \;=\; \mathrm{Tr}\left\{\rho(\tilde{t};\tilde{t}_i)\;\check{\boldsymbol{n}}^X(\tilde{t};\tilde{t}_i)\right\} \;.$$

- Differentiate w.r.t. the macroscopic time $t = \tilde{t} - \tilde{t}_i$:

$$\frac{\mathrm{d}\boldsymbol{n}^X(t)}{\mathrm{d}t} \;=\; \mathrm{Tr}\left\{\rho(\tilde{t};\tilde{t}_i)\,\frac{\mathrm{d}\check{\boldsymbol{n}}^X(\tilde{t};\tilde{t}_i)}{\mathrm{d}\tilde{t}}\right\} \;+\; \mathrm{Tr}\left\{\frac{\mathrm{d}\rho(\tilde{t};\tilde{t}_i)}{\mathrm{d}\tilde{t}}\,\check{\boldsymbol{n}}^X(\tilde{t};\tilde{t}_i)\right\} \;\equiv\; \mathcal{I}_1 \;+\; \mathcal{I}_2 . \;.$$

- Use the Heisenberg EoM for $\mathcal{I}_1$ and Liouville-von Neumann equation for $\mathcal{I}_2$.

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- Use the Heisenberg EoM for $\mathcal{I}_1$ and Liouville-von Neumann equation for $\mathcal{I}_2$.
- Markovian master equation for the number density matrix:

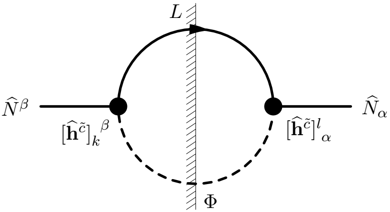
$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{n}^X(\mathbf{k},t) \;\simeq\; i\langle\,[H_0^X,\;\check{\boldsymbol{n}}^X(\mathbf{k},t)]\,\rangle_t - \frac{1}{2}\int_{-\infty}^{+\infty}\mathrm{d}t'\;\langle\,[H_{\mathrm{int}}(t'),\;[H_{\mathrm{int}}(t),\;\check{\boldsymbol{n}}^X(\mathbf{k},t)]]\,\rangle_t\;.$$

(Oscillation) (Mixing)

- Generalization of the density matrix formalism. [Sigl, Raffelt '93]

Collision Rates for Decay and Inverse Decay

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



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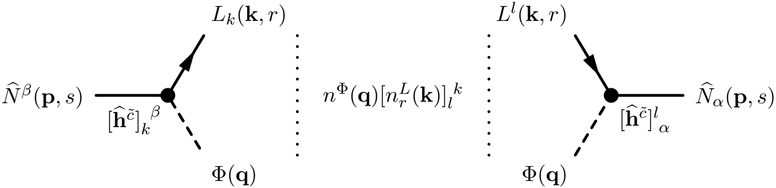

Collision Rates for 2 $\leftrightarrow$ 2 Scattering

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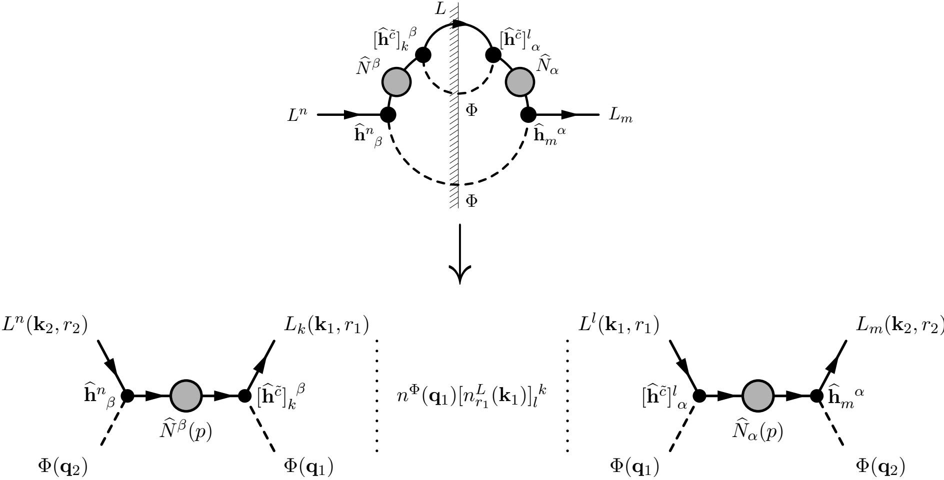
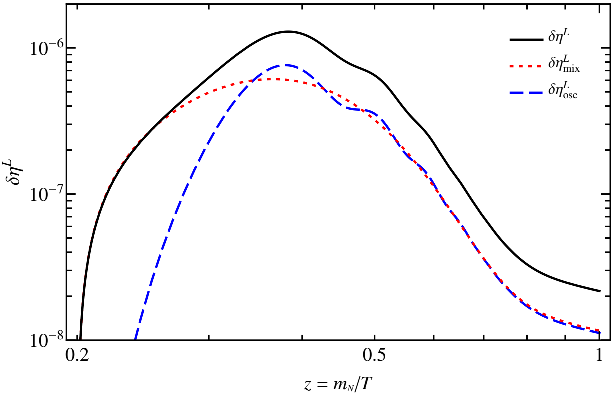
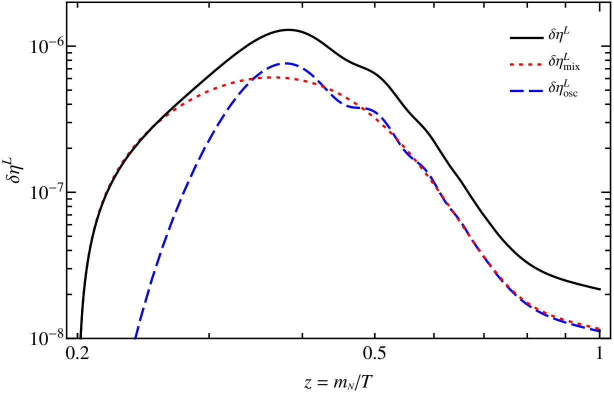


Key Result



$\delta\eta^L$
$\delta\eta^L_{\rm mix}$
$\delta\eta^L_{\rm osc}$
10^{-6}
10^{-7}
10^{-8}
0.2
0.5
1
$\delta\eta^L$
$z = m_N/T$

Key Result

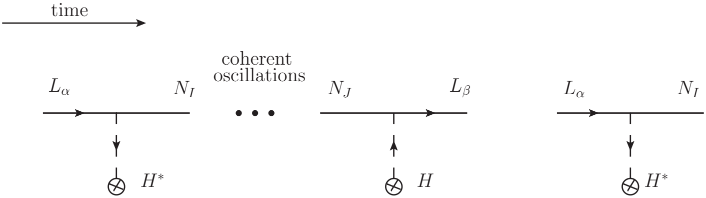


$$\delta\eta^L_{\rm mix} \simeq \frac{g_N}{2}\,\frac{3}{2{\rm K}z}\sum_{\alpha\neq\beta}\frac{\Im\big(\widehat{h}^\dagger\widehat{h}\big)^2_{\alpha\beta}}{(\widehat{h}^\dagger\widehat{h})_{\alpha\alpha}(\widehat{h}^\dagger\widehat{h})_{\beta\beta}}\;\frac{\big(M^2_{N,\,\alpha}-M^2_{N,\,\beta}\big)M_N\widehat{\Gamma}^{(0)}_{\beta\beta}}{\big(M^2_{N,\,\alpha}-M^2_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

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

ARS Mechanism

[Akhmedov, Rubakov, Smirnov (Phys. Rev. Lett. ’98); Alekhin, BD *et al.* (Rep. Prog. Phys. ’16)]



$Y_{\Delta L_1} = 0$

$Y_{\Delta L_2}, Y_{\Delta L_3} = 0$

$\sum_\alpha Y_{\Delta L_\alpha} = 0$

$Y_{\Delta L_1} > 0$

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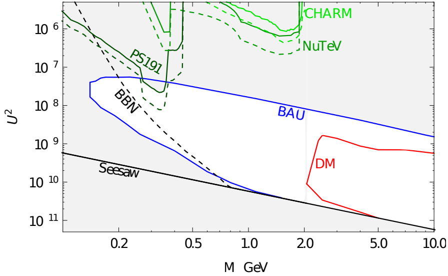
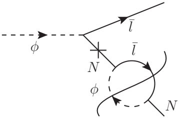
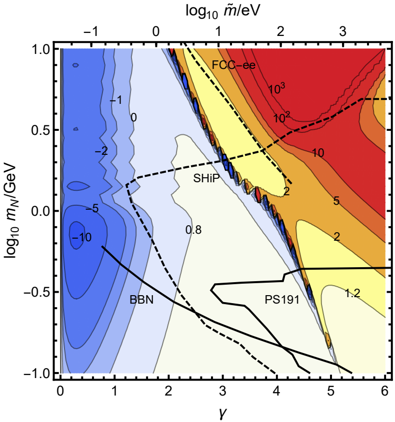


Higgs Decay Leptogenesis

[Hambye, Teresi (Phys. Rev. Lett. '16)]





Testable Models

- Need $m_N \lesssim \mathcal{O}(\mathrm{TeV})$.
- Naive type-I seesaw requires mixing with light neutrinos to be $\lesssim 10^{-5}$.
- Collider signal suppressed in the minimal set-up (SM+RH neutrinos).
- Two ways out:
  - Construct a TeV seesaw model with large mixing (special textures of m_D and m_N).
  - Go beyond the minimal SM seesaw (e.g. $U(1)_{B-L}$, Left-Right).
- Observable low-energy signatures (LFV, $0\nu\beta\beta$) possible in any case.
- Complementarity between high-energy and high-intensity frontiers.
- Leptogenesis brings in additional powerful constraints in each case.
- Can be used to test/falsify leptogenesis.

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 $m_{\rm lightest} = 0$, 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 $0\nu\beta\beta$:

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

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

$$\begin{array}{lr} 0.0019\,{\rm eV} \lesssim m_{\beta\beta} \lesssim 0.0040\,{\rm eV} & \text{(NO)} \\ 0.016\,{\rm eV} \lesssim m_{\beta\beta} \lesssim 0.048\,{\rm eV} & \text{(IO)}. \end{array}$$

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

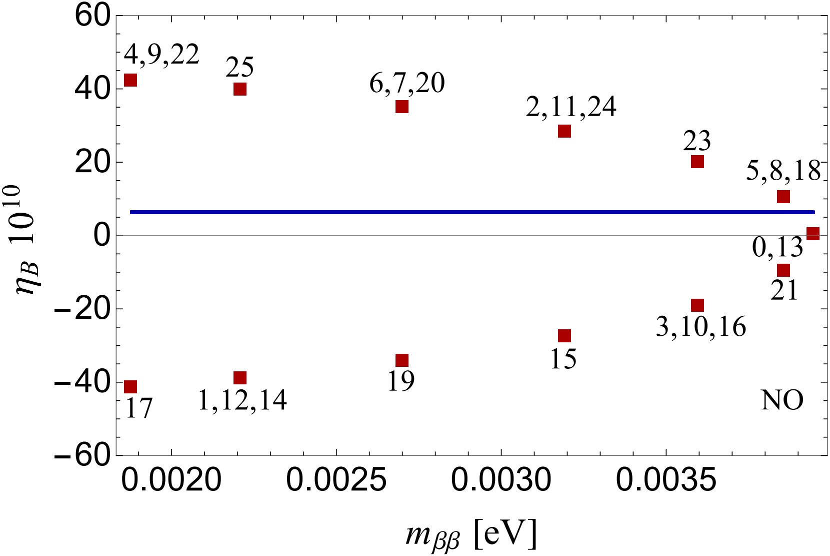
$$\varepsilon_{i\alpha} \approx \sum_{j\neq i} \mathrm{Im}\left(\hat{Y}^{\star}_{D,\alpha i}\,\hat{Y}_{D,\alpha j}\right)\,\mathrm{Re}\left(\left(\hat{Y}_D^{\dagger}\,\hat{Y}_D\right)_{ij}\right)\,F_{ij}$$

- 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

$$\varepsilon_{1\alpha} \approx \frac{y_2\,y_3}{9}\,(-2\,y_2^2 + y_3^2\,(1-\cos 2\,\theta_R))\,\sin 3\,\phi_s\,\sin\theta_R\,\sin\theta_{L,\alpha}\,F_{12} \quad (\mathrm{NO})$$
$$\varepsilon_{1\alpha} \approx \frac{y_1\,y_2}{9}\,(-2\,y_2^2 + y_1^2\,(1+\cos 2\,\theta_R))\,\sin 3\,\phi_s\,\cos\theta_R\,\cos\theta_{L,\alpha}\,F_{12} \quad (\mathrm{IO})$$

  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}.

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



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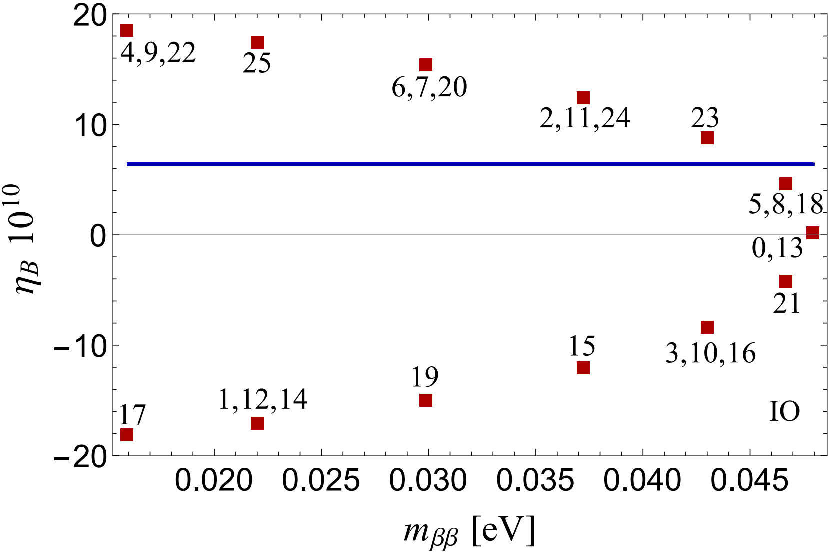
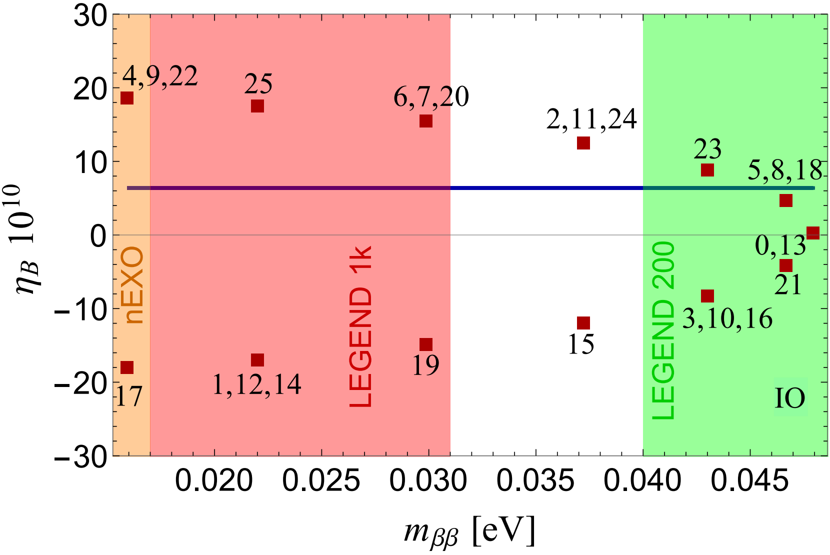


Correlation between BAU and $0\nu\beta\beta$

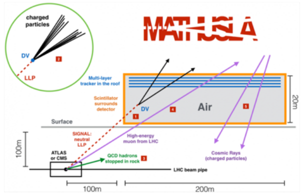


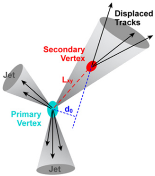
Decay Length

- 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.





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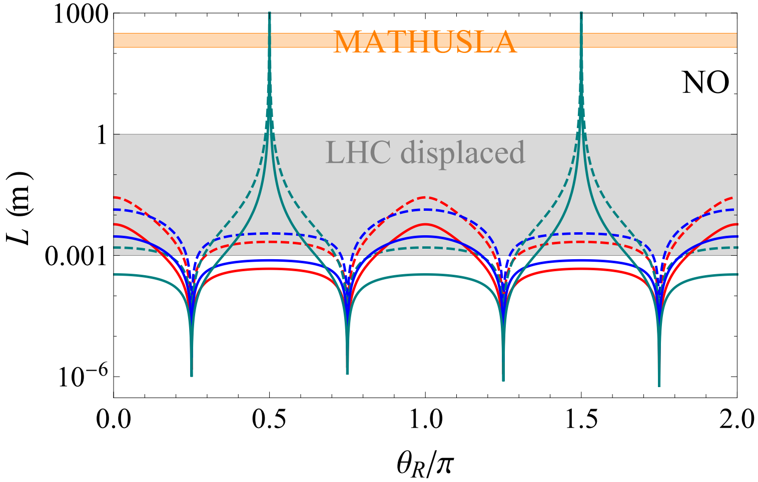

N_1 (red), N_2 (blue), N_3 (green).
M_N=150 GeV (dashed), 250 GeV (solid).

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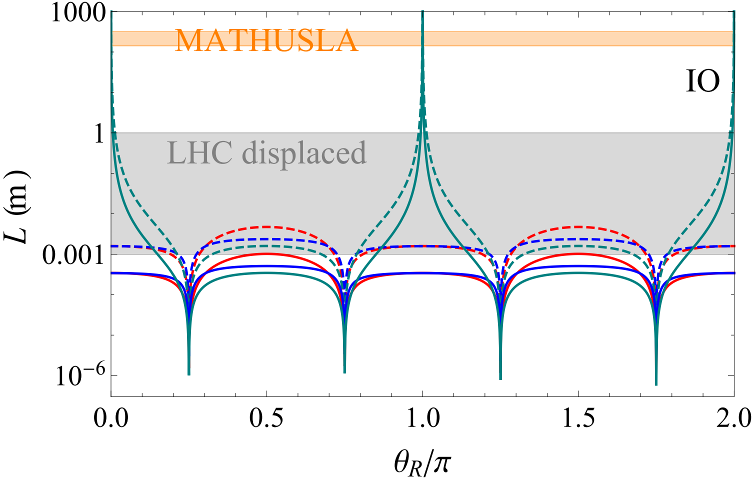

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Collider Signal

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

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

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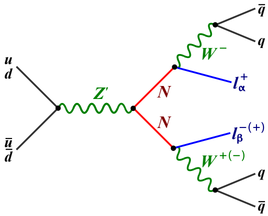
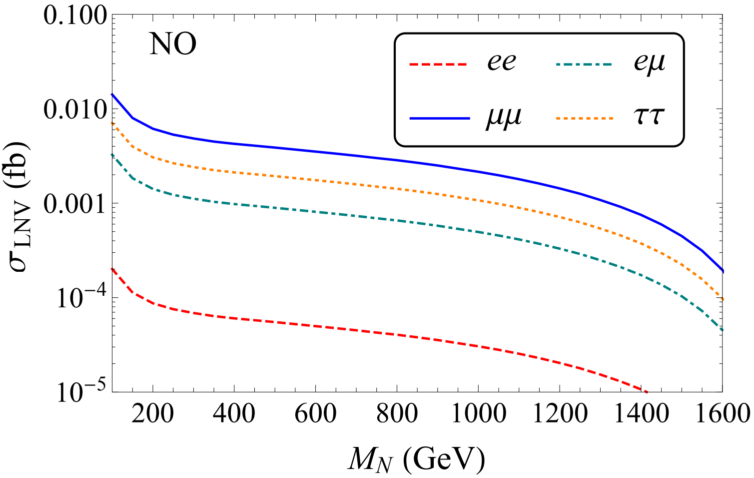
- Need to go beyond the minimal type-I seesaw to realize a sizable LNV signal.
- We consider a minimal $U(1)_{B-L}$ extension.
- Production cross section is no longer Yukawa-suppressed, while the decay is, giving rise to displaced vertex. [Deppisch, Desai, Valle '13]





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

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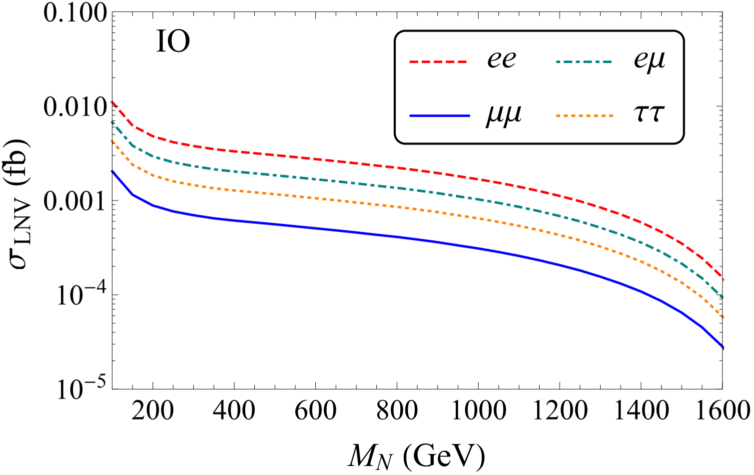

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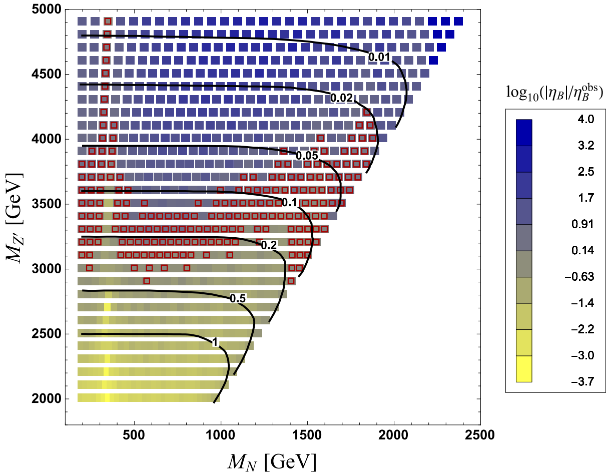
Bound on Z' Mass

- Z' interactions induce additional dilution effects, e.g. $NN \to Z' \to jj$.
- Successful leptogenesis requires a lower bound on $M_{Z'}$. [Blanchet, Chacko, Granor, Mohapatra '09; Heeck, Teresi '17; BD, Hagedorn, Molinaro (in prep)]



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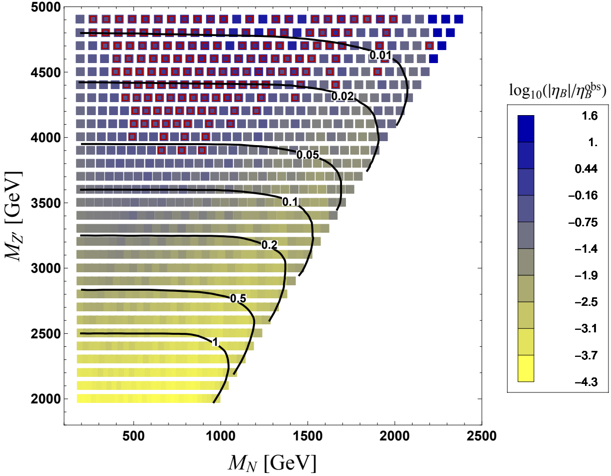

Conclusion

- 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.

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