Lepton Number Violation and Leptogenesis

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[1a] BD, P. Millington, A. Pilaftsis and D. Teresi, Nucl. Phys. B **886**, 569 (2014).
[1b] BD, P. Millington, A. Pilaftsis and D. Teresi, arXiv:1504.07640 [hep-ph].
[2] BD, P. Millington, A. Pilaftsis and D. Teresi, Nucl. Phys. B **891**, 128 (2015).

[3a] BD, C. H. Lee and R. N. Mohapatra, Phys. Rev. D **90**, 095012 (2014).
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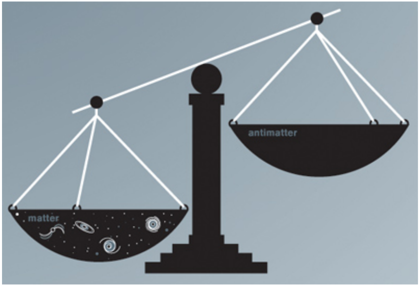
Outline

- Motivation
- Low-scale Leptogenesis
- Flavor Effects
- Phenomenology
- Conclusions and Outlook

Matter-Antimatter Asymmetry



$$\eta_{\Delta B} \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = \left(6.105^{+0.086}_{-0.081}\right) \times 10^{-10} \qquad \text{[Planck (2015)]}$$

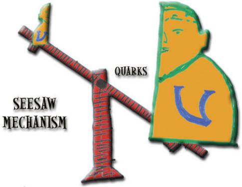
- **Baryogenesis**: Dynamical generation of baryon asymmetry.
- **Sakharov conditions:** Need B violation, C and CP violation, departure from thermal equilibrium. [Sakharov '67]
- **Requires some New Physics beyond the Standard Model**.

Leptogenesis

[Fukugita, Yanagida '86] (talk by M. Garny)

- Introduce at least two SM-singlet heavy Majorana neutrinos (N_α).
  - L violation due to the Majorana nature.
  - New source of $\not{C}\not{P}$ violation through complex Yukawa couplings.
  - Departure from equilibrium due to N decay in an expanding Universe.
  - L asymmetry partially converted to B asymmetry through $(B+L)$-violating sphaleron effects. [Kuzmin, Rubakov, Shaposhnikov '85]

- Heavy neutrinos can also explain the observed non-zero neutrino masses and mixing: **Seesaw mechanism.** [Minkowski '77; Mohapatra, Senjanović '79; Yanagida '79; Gell-Mann, Ramond, Slansky '79; Glashow '79; Schechter and Valle '80]
- **Leptogenesis is a cosmological consequence of the seesaw mechanism.**



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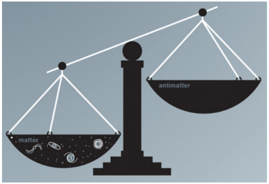
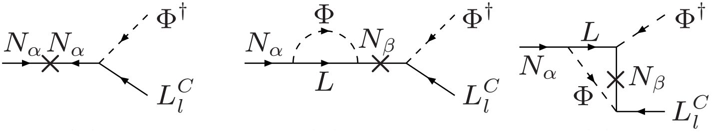
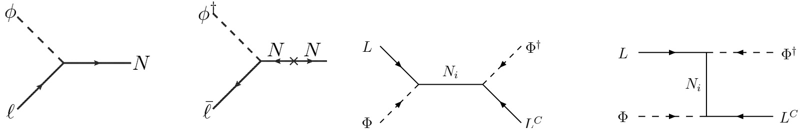


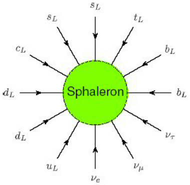
1. Generation of lepton asymmetry by decay of a heavy Majorana neutrino.



2. Partial washout of the asymmetry due to inverse decays and scatterings.



3. Conversion of the residual lepton asymmetry to baryon asymmetry.



Problems with 'Vanilla' Leptogenesis

- For a hierarchical heavy neutrino spectrum ($m_{N_1} \ll m_{N_2}$), **lower** bound on m_{N_1}:
  [Davidson, Ibarra '02; Buchmüller, Di Bari, Plümacher '02]

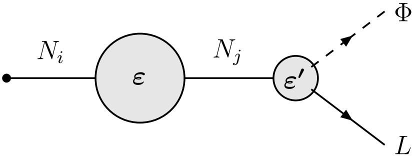
$$m_{N_1} \gtrsim 6.4 \times 10^8 \text{ GeV} \left(\frac{\eta_{\Delta B}}{6 \times 10^{-10}} \right) \left(\frac{0.05 \text{ eV}}{\sqrt{\Delta m^2_{\text{atm}}}} \right)$$

- Experimentally inaccessible mass range!

- Also leads to a potetial tension with the gravitino overproduction bound on the reheat temperature: $T_{\text{rh}} \lesssim 10^6 - 10^9$ GeV [Khlopov, Linde '84; Ellis, Kim, Nanopoulos '84; ...; Kawasaki, Kohri, Moroi, Yotsuyanagi '08]

- An attractive solution: Resonant Leptogenesis. [Pilaftsis, Underwood '03]

Resonant Leptogenesis



- For quasi-degenerate heavy Majorana neutrinos, self-energy effects on the leptonic CP-asymmetry (ε-type) become dominant.

  [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]
- 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]

- Provides a potentially testable scenario of leptogenesis, with implications at both Energy and Intensity Frontiers. [Deppisch, BD, Pilaftsis '15; BD '15]

Flavordynamics of Leptogenesis

- Flavor effects could be important for the time-evolution of lepton asymmetry.
- In the minimal scenario, two potential sources of flavor effects due to
  - Heavy neutrino Yukawa couplings h_l^{α} [Pilaftsis '05; Blanchet, Di Bari, Jones, Marzola '11]

    Note: Can also generate lepton asymmetry from heavy neutrino oscillations [Akhmedov, Rubakov, Smirnov '98; Asaka, Shaposhnikov '05] (talk by T. Asaka)
  - Charged lepton Yukawa couplings y_l^{k} [Barbieri, Creminelli, Strumia, Tetradis '00; Abada, Davidson, Ibarra, Josse-Michaux, Losada, Riotto '06; Nardi, Nir, Roulet, Racker '06; Blanchet, Di Bari '07]
- Need a *fully* flavor-covariant formalism to consistently capture all flavor effects, including the interplay between them.

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Flavour covariant transport equations:
An application to resonant leptogenesis

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Flavor-covariant Master Equation

- In the semi-classical Boltzmann approach, promote the number densities (numbers) to matrices in flavor space: 'density matrix' formalism [Sigl, Raffelt '93]

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

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

$$\frac{\mathrm{d}\boldsymbol{n}^X(t)}{\mathrm{d}t} \;=\; \mathrm{Tr}\left[\rho(\tilde{t};\tilde{t}_i)\,\underbrace{\frac{\mathrm{d}\check{\boldsymbol{n}}^X(\tilde{t};\tilde{t}_i)}{\mathrm{d}\tilde{t}}}_{i[H_0^X,\check{\boldsymbol{n}}^X]}\right] + \mathrm{Tr}\left[\underbrace{\frac{\mathrm{d}\rho(\tilde{t};\tilde{t}_i)}{\mathrm{d}\tilde{t}}}_{-\,i\,[H_{\mathrm{int}}(\tilde{t};\tilde{t}_i),\;\rho(\tilde{t};\tilde{t}_i)]}\;\check{\boldsymbol{n}}^X(\tilde{t};\tilde{t}_i)\right]$$

(Heisenberg) (Liouville-von Neumann)

- In the Markovian limit,

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

(oscillation terms) (collision terms)

Application to Resonant Leptogenesis

- For charged-lepton and heavy-neutrino matrix number densities,

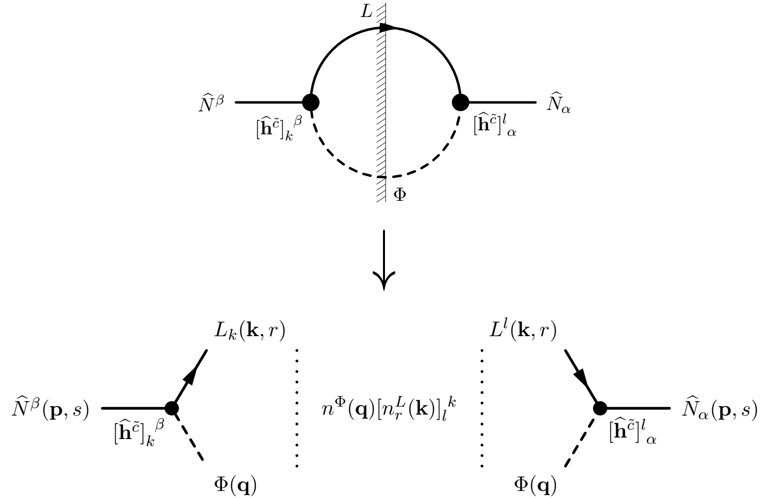
$$\frac{\mathrm{d}}{\mathrm{d}t}\,[n^L_{s_1s_2}(\mathbf{p},t)]_l^{\ m} \;=\; -\,i\,\Big[E_L(\mathbf{p}),\; n^L_{s_1s_2}(\mathbf{p},t)\Big]_l^{\ m} \;+\; [C^L_{s_1s_2}(\mathbf{p},t)]_l^{\ m}$$
$$\frac{\mathrm{d}}{\mathrm{d}t}\,[n^N_{r_1r_2}(\mathbf{k},t)]_\alpha^{\ \beta} \;=\; -i\,\Big[E_N(\mathbf{k}),\; n^N_{r_1r_2}(\mathbf{k},t)\Big]_\alpha^{\ \beta} + [C^N_{r_1r_2}(\mathbf{k},t)]_\alpha^{\ \beta} + G_{\alpha\lambda}[\overline{C}^N_{r_2r_1}(\mathbf{k},t)]_\mu^{\ \lambda}G^{\mu\beta}$$

- Collision terms are of the form

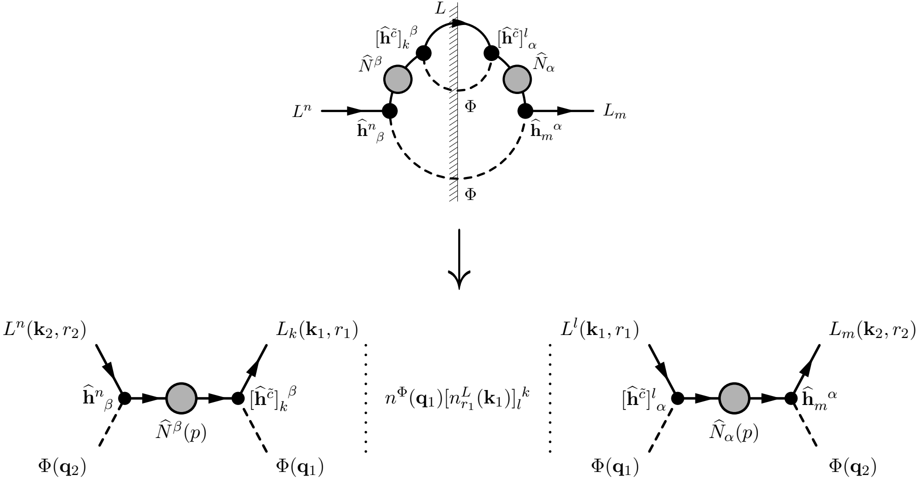
$$[C^L_{s_1s_2}(\mathbf{p},t)]_l^{\ m} \;\supset\; -\frac{1}{2}\,[\mathcal{F}_{s_1s\,r_1r_2}(\mathbf{p},\mathbf{q},\mathbf{k},t)]_l^{\ n}{}_\alpha^{\ \beta}\;[\Gamma_{s\,s_2r_2r_1}(\mathbf{p},\mathbf{q},\mathbf{k})]_n^{\ m}{}_\beta^{\ \alpha},$$

- Statistical tensor $\boldsymbol{\mathcal{F}} \;=\; n^\Phi\,\boldsymbol{n}^L \otimes \big(\mathbf{1} - \boldsymbol{n}^N\big) \;-\; \big(1 + n^\Phi\big)\,\big(\mathbf{1} - \boldsymbol{n}^L\big) \otimes \boldsymbol{n}^N$.
- Absorptive rate tensor $\boldsymbol{\Gamma}$: rank-4 object describing heavy neutrino decays and inverse decays.

Collision Rates for Decay and Inverse Decay



$$[C^N]_{\alpha}{}^{\beta} \;\propto\; n^{\Phi}\; [n^L]_{l}{}^{k}\; [\gamma(L\Phi \to N)]_{k}{}^{l}{}_{\alpha}{}^{\beta}$$



$$[C^L]_m{}^n \;\propto\; n^\Phi \; [n^L]_l{}^k \; [\gamma(L\Phi \to L\Phi)]_{k\,m}^{\;l\;\;n}$$

Final Rate Equations

$$\frac{H_N\, n^\gamma}{z}\,\frac{\mathrm{d}[\underline{\eta}^N]_\alpha{}^\beta}{\mathrm{d}z} = -\,i\,\frac{n^\gamma}{2}\left[\mathcal{E}_N,\,\delta\eta^N\right]_\alpha{}^\beta + \left[\widetilde{\mathrm{Re}}(\gamma^N_{L\Phi})\right]_\alpha{}^\beta - \frac{1}{2\,\eta^N_{\mathrm{eq}}}\left\{\underline{\eta}^N,\,\widetilde{\mathrm{Re}}(\gamma^N_{L\Phi})\right\}_\alpha{}^\beta$$

$$\frac{H_N\, n^\gamma}{z}\,\frac{\mathrm{d}[\delta\eta^N]_\alpha{}^\beta}{\mathrm{d}z} = -\,2\,i\,n^\gamma\left[\mathcal{E}_N,\,\underline{\eta}^N\right]_\alpha{}^\beta + 2\,i\left[\widetilde{\mathrm{Im}}(\delta\gamma^N_{L\Phi})\right]_\alpha{}^\beta - \frac{i}{\eta^N_{\mathrm{eq}}}\left\{\underline{\eta}^N,\,\widetilde{\mathrm{Im}}(\delta\gamma^N_{L\Phi})\right\}_\alpha{}^\beta - \frac{1}{2\,\eta^N_{\mathrm{eq}}}\left\{\delta\eta^N,\,\widetilde{\mathrm{Re}}(\gamma^N_{L\Phi})\right\}_\alpha{}^\beta$$

$$\frac{H_N\, n^\gamma}{z}\,\frac{\mathrm{d}[\delta\eta^L]_l{}^m}{\mathrm{d}z} = -\,[\delta\gamma^N_{L\Phi}]_l{}^m + \frac{[\underline{\eta}^N]_\beta{}^\alpha}{\eta^N_{\mathrm{eq}}}\,[\delta\gamma^N_{L\Phi}]_l{}^m{}_\alpha{}^\beta + \frac{[\delta\eta^N]_\beta{}^\alpha}{2\,\eta^N_{\mathrm{eq}}}\,[\gamma^N_{L\Phi}]_l{}^m{}_\alpha{}^\beta - \frac{1}{3}\left\{\delta\eta^L,\,\gamma^{L\Phi}_{L^{\tilde c}\Phi^{\tilde c}} + \gamma^{L\Phi}_{L\Phi}\right\}_l{}^m - \frac{2}{3}\,[\delta\eta^L]_k{}^n\left([\gamma^{L\Phi}_{L^{\tilde c}\Phi^{\tilde c}}]_n{}^k{}_l{}^m - [\gamma^{L\Phi}_{L\Phi}]_n{}^k{}_l{}^m\right) - \frac{2}{3}\left\{\delta\eta^L,\,\gamma_{\mathrm{dec}}\right\}_l{}^m + [\delta\gamma^{\mathrm{back}}_{\mathrm{dec}}]_l{}^m$$

Final Rate Equations: Mixing

$$\frac{H_N\, n^\gamma}{z}\,\frac{\mathrm{d}[\underline{\eta}^N]_\alpha{}^\beta}{\mathrm{d}z} = -\,i\,\frac{n^\gamma}{2}\left[\mathcal{E}_N,\,\delta\eta^N\right]_\alpha^{\ \beta} + \boxed{\left[\widetilde{\mathrm{Re}}(\gamma^N_{L\Phi})\right]_\alpha^{\ \beta} - \frac{1}{2\,\eta^N_{\mathrm{eq}}}\left\{\underline{\eta}^N,\,\widetilde{\mathrm{Re}}(\gamma^N_{L\Phi})\right\}_\alpha^{\ \beta}}$$

$$\frac{H_N\, n^\gamma}{z}\,\frac{\mathrm{d}[\delta\eta^N]_\alpha{}^\beta}{\mathrm{d}z} = -\,2\,i\,n^\gamma\left[\mathcal{E}_N,\,\underline{\eta}^N\right]_\alpha^{\ \beta} + 2\,i\left[\widetilde{\mathrm{Im}}(\delta\gamma^N_{L\Phi})\right]_\alpha^{\ \beta} - \frac{i}{\eta^N_{\mathrm{eq}}}\left\{\underline{\eta}^N,\,\widetilde{\mathrm{Im}}(\delta\gamma^N_{L\Phi})\right\}_\alpha^{\ \beta}$$
$$-\ \frac{1}{2\,\eta^N_{\mathrm{eq}}}\left\{\delta\eta^N,\,\widetilde{\mathrm{Re}}(\gamma^N_{L\Phi})\right\}_\alpha^{\ \beta}$$

$$\frac{H_N\, n^\gamma}{z}\,\frac{\mathrm{d}[\delta\eta^L]_l{}^m}{\mathrm{d}z} = \boxed{-\,[\delta\gamma^N_{L\Phi}]_l^{\ m} + \frac{[\underline{\eta}^N]_\beta{}^\alpha}{\eta^N_{\mathrm{eq}}}\,[\delta\gamma^N_{L\Phi}]_l{}^m{}_\alpha{}^\beta} + \frac{[\delta\eta^N]_\beta{}^\alpha}{2\,\eta^N_{\mathrm{eq}}}\,[\gamma^N_{L\Phi}]_l{}^m{}_\alpha{}^\beta$$
$$-\ \frac{1}{3}\left\{\delta\eta^L,\,\gamma^{L\Phi}_{L^{\tilde c}\Phi^{\tilde c}} + \gamma^{L\Phi}_{L\Phi}\right\}_l^{\ m} - \frac{2}{3}\,[\delta\eta^L]_k^{\ n}\left([\gamma^{L\Phi}_{L^{\tilde c}\Phi^{\tilde c}}]_n{}^k{}_l{}^m - [\gamma^{L\Phi}_{L\Phi}]_n{}^k{}_l{}^m\right)$$
$$-\ \frac{2}{3}\left\{\delta\eta^L,\,\gamma_{\mathrm{dec}}\right\}_l^{\ m} + [\delta\gamma^{\mathrm{back}}_{\mathrm{dec}}]_l^{\ m}$$

Final Rate Equations: Oscillation

$$\frac{H_N\, n^\gamma}{z}\,\frac{\mathrm{d}[\underline{\eta}^N]_\alpha^{\ \beta}}{\mathrm{d}z} = \boxed{-\,i\,\frac{n^\gamma}{2}\Big[\mathcal{E}_N,\ \delta\eta^N\Big]_\alpha^{\ \beta}} + \Big[\widetilde{\mathrm{Re}}(\gamma^N_{L\Phi})\Big]_\alpha^{\ \beta} - \frac{1}{2\,\eta^N_{\mathrm{eq}}}\Big\{\underline{\eta}^N,\ \widetilde{\mathrm{Re}}(\gamma^N_{L\Phi})\Big\}_\alpha^{\ \beta}$$

$$\frac{H_N\, n^\gamma}{z}\,\frac{\mathrm{d}[\delta\eta^N]_\alpha^{\ \beta}}{\mathrm{d}z} = \boxed{-\,2\,i\,n^\gamma\Big[\mathcal{E}_N,\ \underline{\eta}^N\Big]_\alpha^{\ \beta}} + 2\,i\Big[\widetilde{\mathrm{Im}}(\delta\gamma^N_{L\Phi})\Big]_\alpha^{\ \beta} - \frac{i}{\eta^N_{\mathrm{eq}}}\Big\{\underline{\eta}^N,\ \widetilde{\mathrm{Im}}(\delta\gamma^N_{L\Phi})\Big\}_\alpha^{\ \beta} - \frac{1}{2\,\eta^N_{\mathrm{eq}}}\Big\{\delta\eta^N,\ \widetilde{\mathrm{Re}}(\gamma^N_{L\Phi})\Big\}_\alpha^{\ \beta}$$

$$\frac{H_N\, n^\gamma}{z}\,\frac{\mathrm{d}[\delta\eta^L]_l^{\ m}}{\mathrm{d}z} = -\,[\delta\gamma^N_{L\Phi}]_l^{\ m} + \frac{[\underline{\eta}^N]_\beta^{\ \alpha}}{\eta^N_{\mathrm{eq}}}[\delta\gamma^N_{L\Phi}]_l^{\ m}{}_\alpha^{\ \beta} + \boxed{\frac{[\delta\eta^N]_\beta^{\ \alpha}}{2\,\eta^N_{\mathrm{eq}}}[\gamma^N_{L\Phi}]_l^{\ m}{}_\alpha^{\ \beta}} - \frac{1}{3}\Big\{\delta\eta^L,\ \gamma^{L\Phi}_{L^{\tilde c}\Phi^{\tilde c}} + \gamma^{L\Phi}_{L\Phi}\Big\}_l^{\ m} - \frac{2}{3}[\delta\eta^L]_k^{\ n}\Big([\gamma^{L\Phi}_{L^{\tilde c}\Phi^{\tilde c}}]_n^{\ k}{}_l^{\ m} - [\gamma^{L\Phi}_{L\Phi}]_n^{\ k}{}_l^{\ m}\Big) - \frac{2}{3}\Big\{\delta\eta^L,\ \gamma_{\mathrm{dec}}\Big\}_l^{\ m} + [\delta\gamma^{\mathrm{back}}_{\mathrm{dec}}]_l^{\ m}$$

Final Rate Equations: Charged Lepton Decoherence

$$\frac{H_N\, n^\gamma}{z}\,\frac{d[\underline{\eta}^N]_\alpha{}^\beta}{dz} = -\,i\,\frac{n^\gamma}{2}\Big[\mathcal{E}_N,\,\delta\eta^N\Big]_\alpha{}^\beta + \Big[\widetilde{\mathrm{Re}}(\gamma^N_{L\Phi})\Big]_\alpha{}^\beta - \frac{1}{2\,\eta^N_{\mathrm{eq}}}\Big\{\underline{\eta}^N,\,\widetilde{\mathrm{Re}}(\gamma^N_{L\Phi})\Big\}_\alpha{}^\beta$$

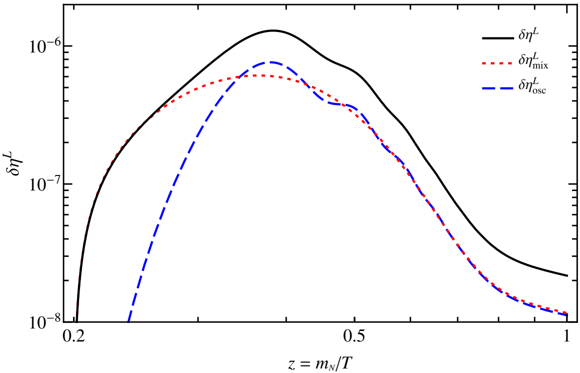
$$\frac{H_N\, n^\gamma}{z}\,\frac{d[\delta\eta^N]_\alpha{}^\beta}{dz} = -\,2\,i\,n^\gamma\Big[\mathcal{E}_N,\,\underline{\eta}^N\Big]_\alpha{}^\beta + 2\,i\,\Big[\widetilde{\mathrm{Im}}(\delta\gamma^N_{L\Phi})\Big]_\alpha{}^\beta - \frac{i}{\eta^N_{\mathrm{eq}}}\Big\{\underline{\eta}^N,\,\widetilde{\mathrm{Im}}(\delta\gamma^N_{L\Phi})\Big\}_\alpha{}^\beta$$
$$-\,\frac{1}{2\,\eta^N_{\mathrm{eq}}}\Big\{\delta\eta^N,\,\widetilde{\mathrm{Re}}(\gamma^N_{L\Phi})\Big\}_\alpha{}^\beta$$

$$\frac{H_N\, n^\gamma}{z}\,\frac{d[\delta\eta^L]_l{}^m}{dz} = -\,[\delta\gamma^N_{L\Phi}]_l{}^m + \frac{[\underline{\eta}^N]_\beta{}^\alpha}{\eta^N_{\mathrm{eq}}}\,[\delta\gamma^N_{L\Phi}]_l{}^m{}_\alpha{}^\beta + \frac{[\delta\eta^N]_\beta{}^\alpha}{2\,\eta^N_{\mathrm{eq}}}\,[\gamma^N_{L\Phi}]_l{}^m{}_\alpha{}^\beta$$
$$-\,\frac{1}{3}\Big\{\delta\eta^L,\,\gamma^{L\Phi}_{L^{\tilde c}\Phi^{\tilde c}} + \gamma^{L\Phi}_{L\Phi}\Big\}_l{}^m - \frac{2}{3}\,[\delta\eta^L]_k{}^n\Big([\gamma^{L\Phi}_{L^{\tilde c}\Phi^{\tilde c}}]_n{}^k{}_l{}^m - [\gamma^{L\Phi}_{L\Phi}]_n{}^k{}_l{}^m\Big)$$

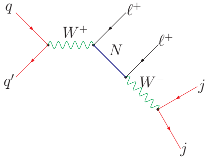
$$\boxed{-\,\frac{2}{3}\Big\{\delta\eta^L,\,\gamma_{\mathrm{dec}}\Big\}_l{}^m + [\delta\gamma^{\mathrm{back}}_{\mathrm{dec}}]_l{}^m}$$

A Unified Framework

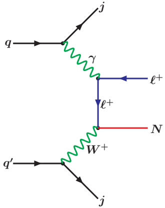
- Our flavor-covariant formalism provides a unified framework to consistently decribe all pertinent flavor effects: mixing, oscillation and decoherence.
- Mixing and Oscillation are *distinct* physical phenomena, analogous to neutral meson systems.
- Confirmed in a more rigorous 'first principles' approach using Kadanoff-Baym formalism. [BD, Millington, Pilaftsis, Teresi '14]

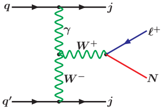


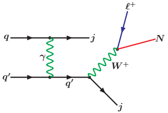
- Same sign dilepton plus two jets with no missing E_T. [Keung, Senjanovic '83]

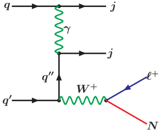


- Collinear enhancement effects could improve the LHC sensitivity by up to a factor of 10. [BD, Pilaftsis, Yang '14; Das, BD, Okada '14] (see talk by U. K. Yang)







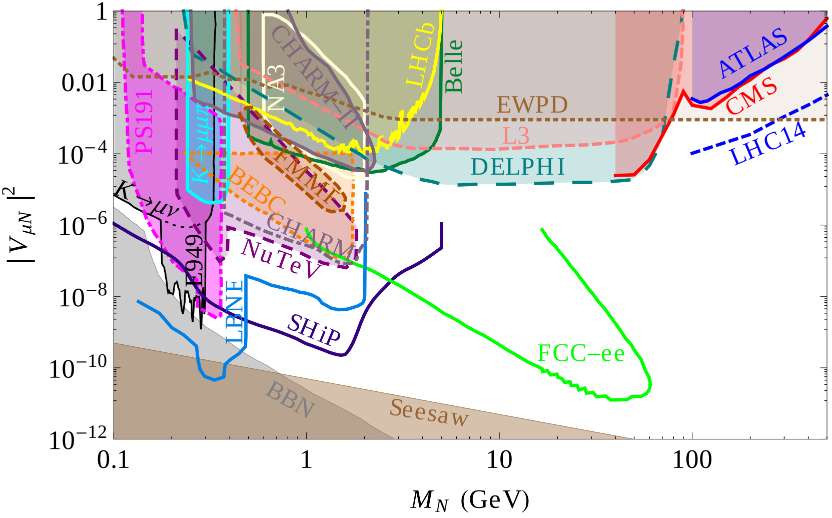


Testing Leptogenesis at Intensity Frontier

Low-energy observables	Benchmark Point in a Mminimal RL$_\tau$ Model	Experimental Limit
BR($\mu \to e\gamma$)	1.9×10^{-13}	$< 5.7 \times 10^{-13}$
BR($\tau \to \mu\gamma$)	1.6×10^{-18}	$< 4.4 \times 10^{-8}$
BR($\tau \to e\gamma$)	5.9×10^{-19}	$< 3.3 \times 10^{-8}$
BR($\mu \to 3e$)	9.3×10^{-15}	$< 1.0 \times 10^{-12}$
$\text{R}^{\text{Ti}}_{\mu\to e}$	2.9×10^{-13}	$< 6.1 \times 10^{-13}$
$\text{R}^{\text{Au}}_{\mu\to e}$	3.2×10^{-13}	$< 7.0 \times 10^{-13}$
$\text{R}^{\text{Pb}}_{\mu\to e}$	2.2×10^{-13}	$< 4.6 \times 10^{-11}$
$\|\Omega\|_{e\mu}$	1.8×10^{-5}	$< 7.0 \times 10^{-5}$
$\langle m \rangle$ [eV]	3.8×10^{-3}	$<$ (0.11–0.25)

[BD, Millington, Pilaftsis, Teresi '14]

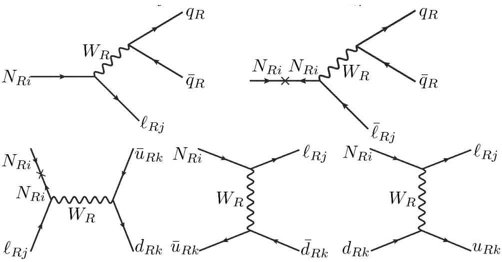
Testing Leptogenesis at Intensity Frontier



[Deppisch, BD, Pilaftsis '15]

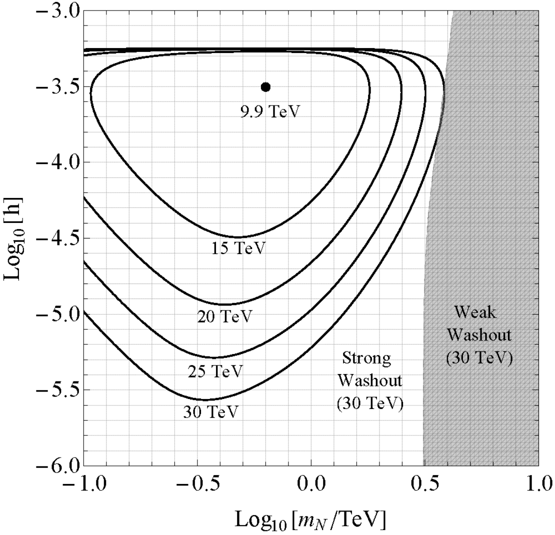
Falsifying Leptogenesis

- Observation of LNV could falsify leptogenesis (barring exceptions).
  [Deppisch, Harz, Hirsch '14] (talks by M. Hirsch and J. Harz)
- A concrete example: TeV-scale Leptogenesis in Left-Right Seesaw
- Large washout effects due to gauge scattering.



- In minimal LRSM, $M_{W_R} > 18$ TeV for successful leptogenesis. [Frere, Hambye, Vertongen '09]
- In a class of TeV-scale LRSM with large M_D elements [BD, Lee, Mohapatra '14], including flavor effects could lower the leptogenesis bound to $M_{W_R} \gtrsim 10$ TeV.
  [BD, Lee, Mohapatra '14, '15]

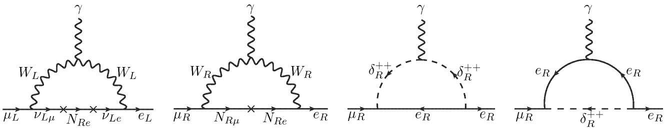
Lower Bound on M_{W_R} from Leptogenesis



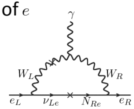
[BD, Lee, Mohapatra '15]

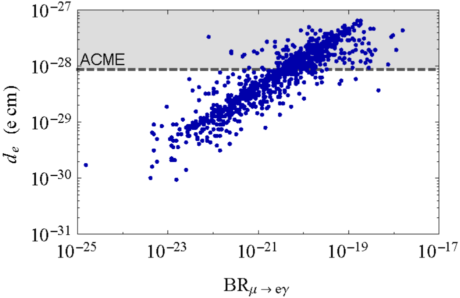
Correlation with LFV Observables

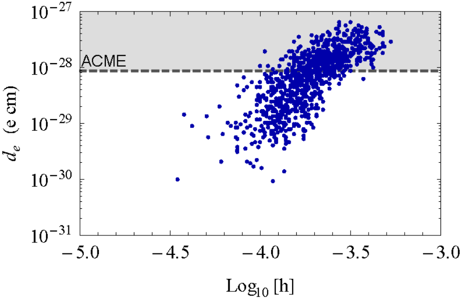
$\mu \to e\gamma$



EDM of e





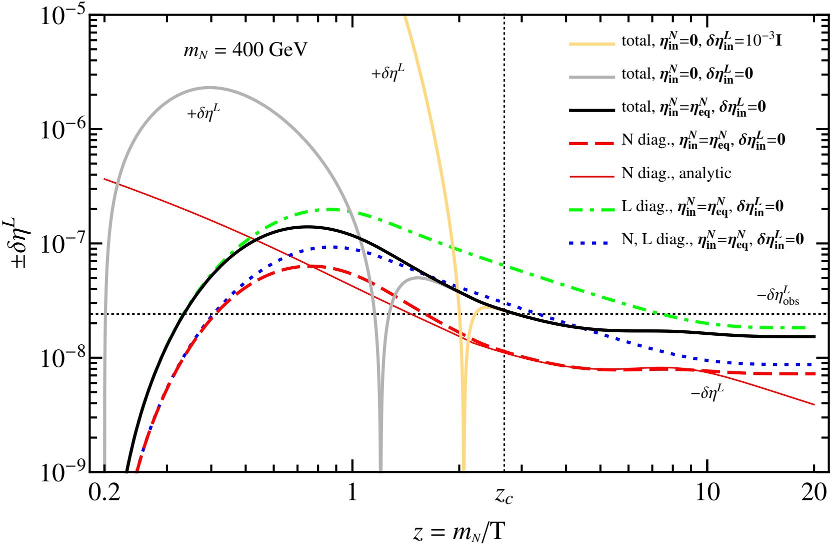


[BD, Lee, Mohapatra '15]

Conclusions and Outlook

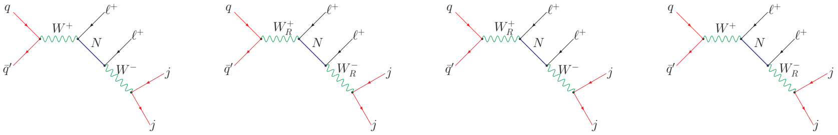
- Leptogenesis provides an attractive link between two seemingly disparate pieces of evidence for BSM physics, namely, neutrino mass and baryon asymmetry.
- Resonant Leptogenesis provides a way to test this idea in laboratory experiments.
- Flavor effects play a crucial role in the calculation of the lepton asymmetry.
- We have developed a *fully* flavor-covariant formalism, which provides a complete and unified description of Resonant Leptogenesis.
- TeV-scale leptogenesis has potential testable effects at both Energy and Intensity frontiers.
- Could be falsified at the LHC and other low-energy experiments.
- Other possible low-scale baryogenesis mechanisms?
- **NEW:** A Simple Model for TeV-scale $\not{B}$ and $\not{L}$ and Resonant Baryogenesis
  [BD and R. N. Mohapatra, arXiv:1504.07196 [hep-ph]]

A Numerical Example

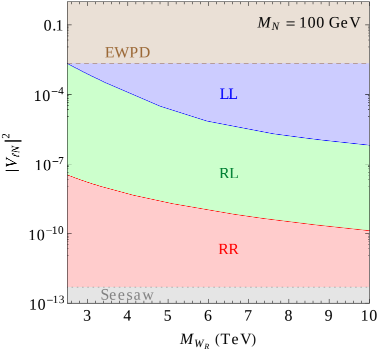


[BD, P. Millington, A. Pilaftsis and D. Teresi, arXiv:1504.07640 [hep-ph]]

Testing L-R Leptogenesis at Energy Frontier

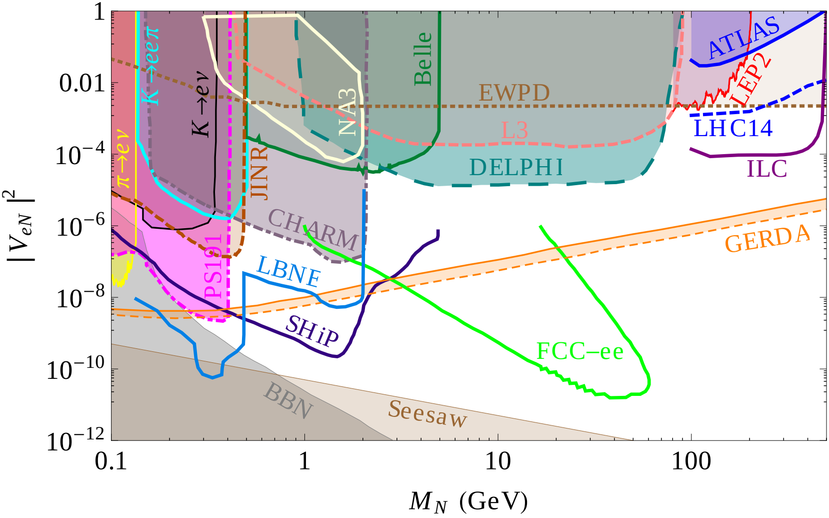


(a) LL (b) RR (c) RL (d) LR



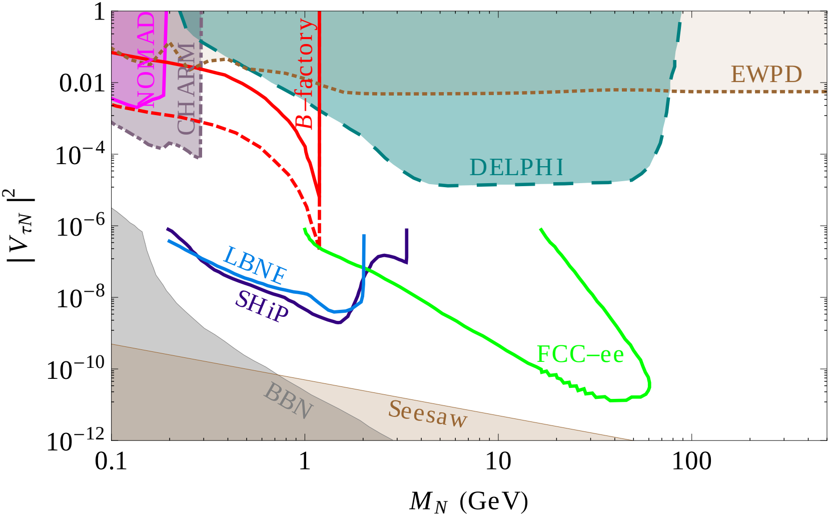
[Chen, BD, Mohapatra '13]

Heavy Neutrino Searches: Current Status and Future Prospects



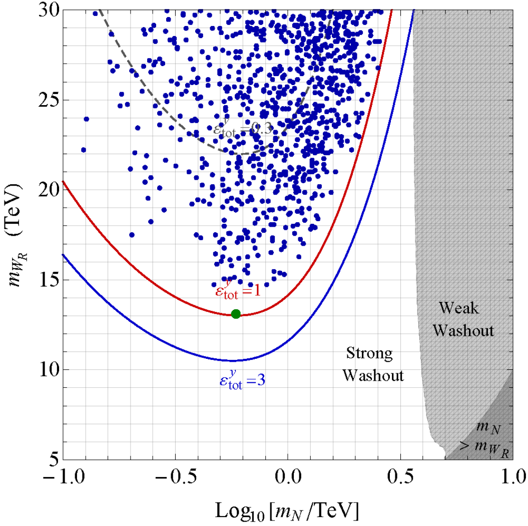
[Deppisch, BD, Pilaftsis '15]

Heavy Neutrino Searches: Current Status and Future Prospects



[Deppisch, BD, Pilaftsis '15]

Lower Bound on M_{W_R} from Leptogenesis



[BD, Lee, Mohapatra '15]