Baryogenesis and Leptogenesis

Bhupal Dev

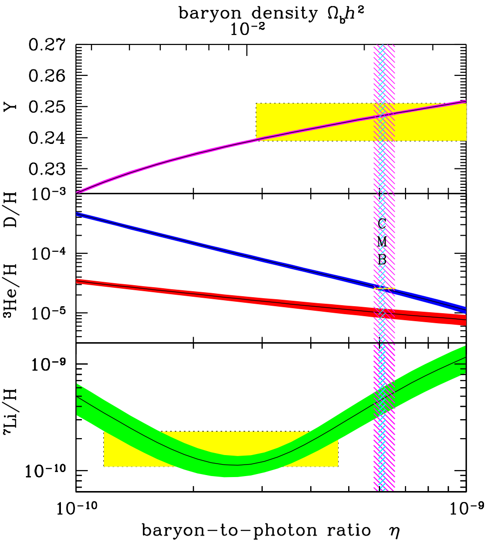
Washington University in St. Louis

16th Conference on Flavor Physics & CP Violation (FPCP 2018)

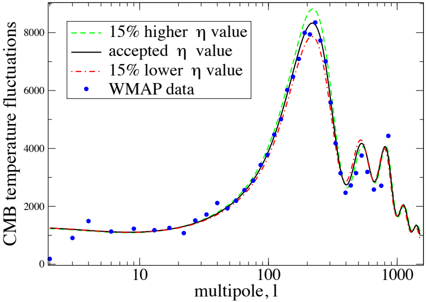
UoH and IITH, Hyderabad, India

July 17, 2018

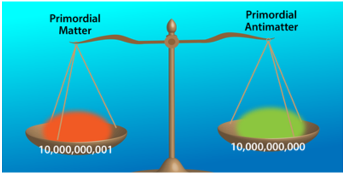
Matter-Antimatter Asymmetry



[Particle Data Group '17]



[J. Cline '06]



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

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

Baryogenesis

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

$+$

$\neq$

Baryogenesis

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

$+$

$\neq$

- 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!

Baryogenesis

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

$+$


$\neq$


- 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!

  - New sources of *CP* violation.
  - A departure from equilibrium (in addition to EWPT) or modify the EWPT itself.

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; ...]

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; ...]
  - Leptogenesis [Fukugita, Yanagida '86; Akhmedov, Rubakov, Smirnov '98; Pilaftsis, Underwood '03; Ma, Sahu, Sarkar '06; Deppisch, Pilaftsis '10; Fong, Gonzalez-Garcia, Nardi, Peinado '13; BD, Millington, Pilaftsis, Teresi '14; Aristizabal Sierra, Tortola, Valle, Vicente '14; ...]

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; ...]
  - Leptogenesis [Fukugita, Yanagida '86; Akhmedov, Rubakov, Smirnov '98; Pilaftsis, Underwood '03; Ma, Sahu, Sarkar '06; Deppisch, Pilaftsis '10; Fong, Gonzalez-Garcia, Nardi, Peinado '13; BD, Millington, Pilaftsis, Teresi '14; Aristizabal Sierra, Tortola, Valle, Vicente '14; ...]
  - Cogenesis [Kaplan '92; Farrar, Zaharijas '06; Sahu, Sarkar '07; Kitano, Murayama, Ratz '08; Kaplan, Luty, Zurek '09; Berezhiani '16; Bernal, Fong, Fonseca '16; Narendra, Patra, Sahu, Shil '18; ...]
  - WIMPy baryogenesis [Cui, Randall, Shuve '11; Cui, Sundrum '12; Racker, Rius '14; Dasgupta, Hati, Patra, Sarkar '16; ...]

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; ...]
  - Leptogenesis [Fukugita, Yanagida '86; Akhmedov, Rubakov, Smirnov '98; Pilaftsis, Underwood '03; Ma, Sahu, Sarkar '06; Deppisch, Pilaftsis '10; Fong, Gonzalez-Garcia, Nardi, Peinado '13; BD, Millington, Pilaftsis, Teresi '14; Aristizabal Sierra, Tortola, Valle, Vicente '14; ...]
  - Cogenesis [Kaplan '92; Farrar, Zaharijas '06; Sahu, Sarkar '07; Kitano, Murayama, Ratz '08; Kaplan, Luty, Zurek '09; Berezhiani '16; Bernal, Fong, Fonseca '16; Narendra, Patra, Sahu, Shil '18; ...]
  - WIMPy baryogenesis [Cui, Randall, Shuve '11; Cui, Sundrum '12; Racker, Rius '14; Dasgupta, Hati, Patra, Sarkar '16; ...]
- 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]

Testable Baryogenesis

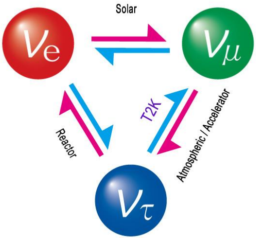
- Many ideas, some of which can be realized down to the (sub)TeV scale, e.g.
  - EW baryogenesis [Kuzmin, Rubakov, Shaposhnikov '87; Cohen, Kaplan, Nelson '90; Carena, Quiros, Wagner '96; Cirigliano, Lee, Tulin '11; Morrissey, Ramsey-Musolf '12; ...]
  - Leptogenesis [Fukugita, Yanagida '86; Akhmedov, Rubakov, Smirnov '98; Pilaftsis, Underwood '03; Ma, Sahu, Sarkar '06; Deppisch, Pilaftsis '10; Fong, Gonzalez-Garcia, Nardi, Peinado '13; BD, Millington, Pilaftsis, Teresi '14; Aristizabal Sierra, Tortola, Valle, Vicente '14; ...]
  - Cogenesis [Kaplan '92; Farrar, Zaharijas '06; Sahu, Sarkar '07; Kitano, Murayama, Ratz '08; Kaplan, Luty, Zurek '09; Berezhiani '16; Bernal, Fong, Fonseca '16; Narendra, Patra, Sahu, Shil '18; ...]
  - WIMPy baryogenesis [Cui, Randall, Shuve '11; Cui, Sundrum '12; Racker, Rius '14; Dasgupta, Hati, Patra, Sarkar '16; ...]
- 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]
- Testable effects: collider signatures, gravitational waves, electric dipole moment, $0\nu\beta\beta$, lepton flavor violation, $n - \bar{n}$ oscillation, ...

Testable Baryogenesis

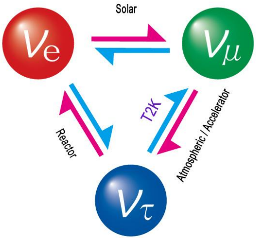
- Many ideas, some of which can be realized down to the (sub)TeV scale, e.g.
  - EW baryogenesis [Kuzmin, Rubakov, Shaposhnikov '87; Cohen, Kaplan, Nelson '90; Carena, Quiros, Wagner '96; Cirigliano, Lee, Tulin '11; Morrissey, Ramsey-Musolf '12; ...]
  - Leptogenesis [Fukugita, Yanagida '86; Akhmedov, Rubakov, Smirnov '98; Pilaftsis, Underwood '03; Ma, Sahu, Sarkar '06; Deppisch, Pilaftsis '10; Fong, Gonzalez-Garcia, Nardi, Peinado '13; BD, Millington, Pilaftsis, Teresi '14; Aristizabal Sierra, Tortola, Valle, Vicente '14; ...]
  - Cogenesis [Kaplan '92; Farrar, Zaharijas '06; Sahu, Sarkar '07; Kitano, Murayama, Ratz '08; Kaplan, Luty, Zurek '09; Berezhiani '16; Bernal, Fong, Fonseca '16; Narendra, Patra, Sahu, Shil '18; ...]
  - WIMPy baryogenesis [Cui, Randall, Shuve '11; Cui, Sundrum '12; Racker, Rius '14; Dasgupta, Hati, Patra, Sarkar '16; ...]
- 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]
- Testable effects: collider signatures, gravitational waves, electric dipole moment, $0\nu\beta\beta$, lepton flavor violation, $n - \bar{n}$ oscillation, ...

This talk: Low-scale leptogenesis

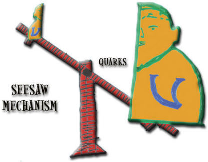
Connection to Neutrino Mass

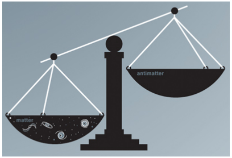


Connection to Neutrino Mass



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

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

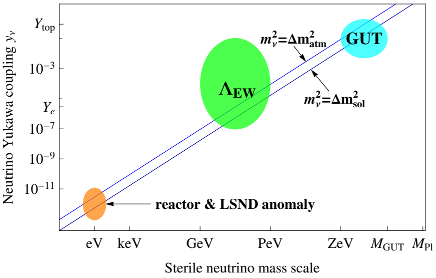
- For $||M_D M_N^{-1}|| \ll 1$, $\boxed{M_\nu^{\text{light}} \simeq -M_D M_N^{-1} M_D^\mathsf{T}}$.

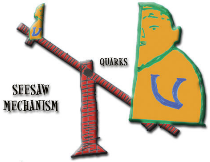
Seesaw Mechanism

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

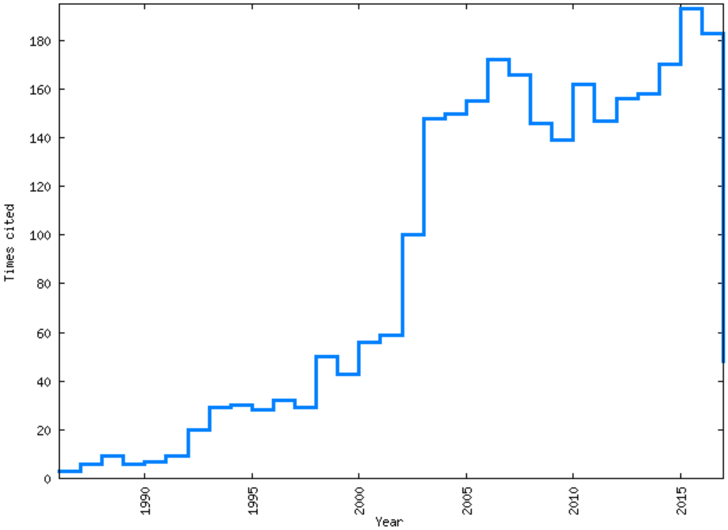
A cosmological consequence of the seesaw mechanism.

Naturally satisfies all Sakharov conditions.

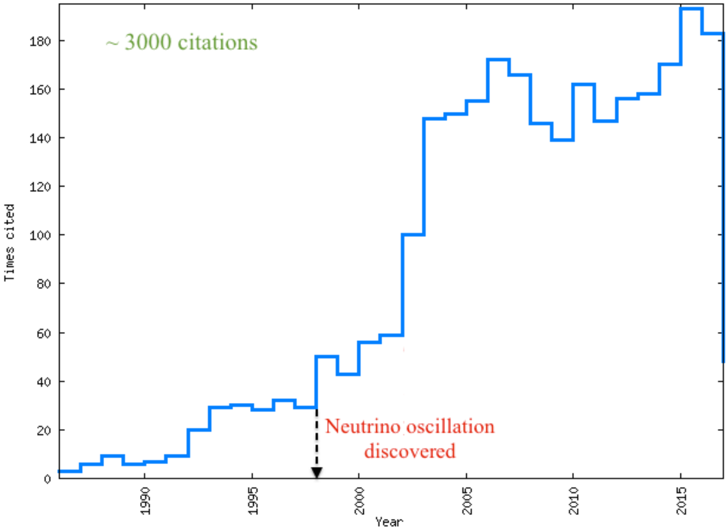
- L violation due to the Majorana nature of heavy RH neutrinos.
- $\not{L} \to \not{B}$ through sphaleron interactions.
- New source of CP violation in the leptonic sector (through complex Dirac Yukawa couplings and/or PMNS CP phases).
- Departure from thermal equilibrium when $\Gamma_N \lesssim H$.

An experimentally testable scenario.

Popularity of Leptogenesis



Popularity of Leptogenesis

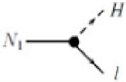


Leptogenesis for Pedestrians

[Buchmüller, Di Bari, Plümacher ’05]

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

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

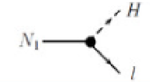


Leptogenesis for Pedestrians

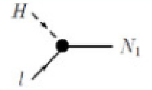
[Buchmüller, Di Bari, Plümacher ’05]

Three basic steps:

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



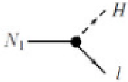
2. Partial washout of the asymmetry due to inverse decay (and scatterings):



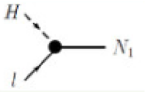
[Buchmüller, Di Bari, Plümacher '05]

Three basic steps:

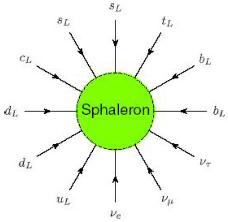
1. Generation of L asymmetry by heavy Majorana neutrino decay:



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]

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

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

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.)

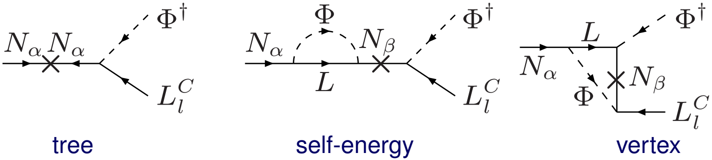
- Final baryon asymmetry:

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

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

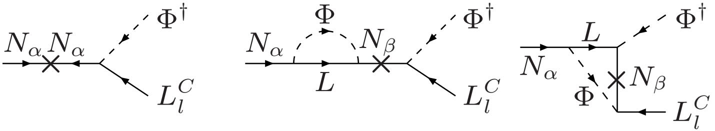
$$\kappa(z) = \int_{z_i}^{z} dz' \frac{D}{D+S} \frac{dN_N}{dz'}\, e^{-\int_{z'}^{z} dz'' W(z'')}$$

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]

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

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

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)]

- 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).
  [Canetti, Drewes, Garbrecht (PRD '14); Alekhin *et al.* (RPP '15)]

For more details, see

Dedicated review volume on Leptogenesis (Int. J. Mod. Phys. A '18)

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

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

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

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

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

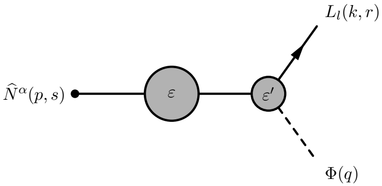
$$\varepsilon_1^{\rm max} = \frac{3}{16\pi}\frac{m_{N_1}}{v^2}\sqrt{\Delta m^2_{\rm atm}}$$

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

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

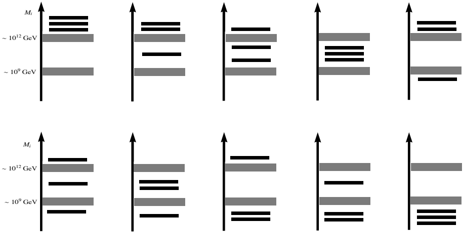
- Experimentally inaccessible!
- Also leads to a lower limit on the reheating temperature $T_{\rm rh} \gtrsim 10^9$ GeV.
- In supergravity models, need $T_{\rm rh} \lesssim 10^6 - 10^9$ GeV to avoid the gravitino problem.
  [Khlopov, Linde '84; Ellis, Kim, Nanopoulos '84; Cyburt, Ellis, Fields, Olive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

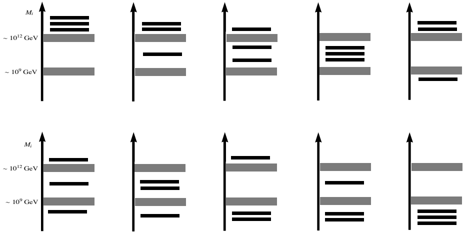


- Dominant self-energy effects on the *CP*-asymmetry (ε-type) [Flanz, Paschos, Sarkar '95; Covi, Roulet, Vissani '96].
- Resonantly enhanced, even up to order 1, when $\Delta m_N \sim \Gamma_N/2 \ll m_{N_{1,2}}$. [Pilaftsis '97; Pilaftsis, Underwood '03]
- The quasi-degeneracy can be naturally motivated 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



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^{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 $t = \tilde{t} - \tilde{t}_i$:

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

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

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 $t = \tilde{t} - \tilde{t}_i$:

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

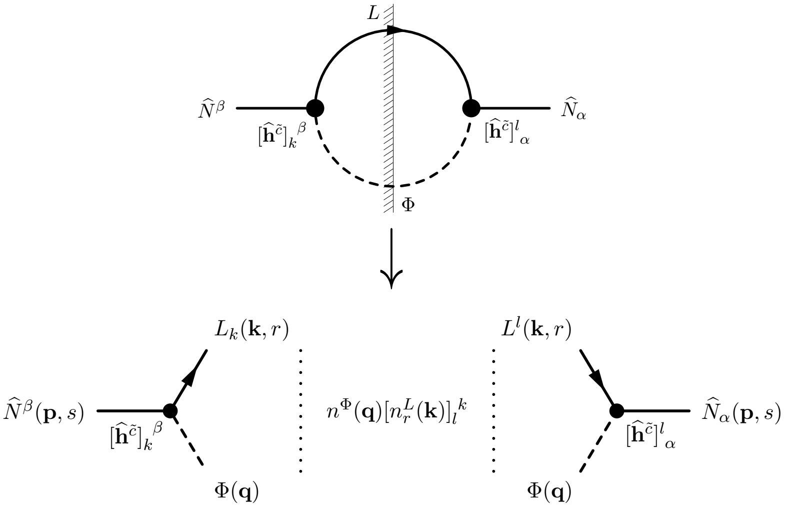
- Use the Heisenberg EoM for $\mathcal{I}_1$ and Liouville-von Neumann equation for $\mathcal{I}_2$.
- Markovian master equation for the number density matrix:

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

(Oscillation) (Mixing)

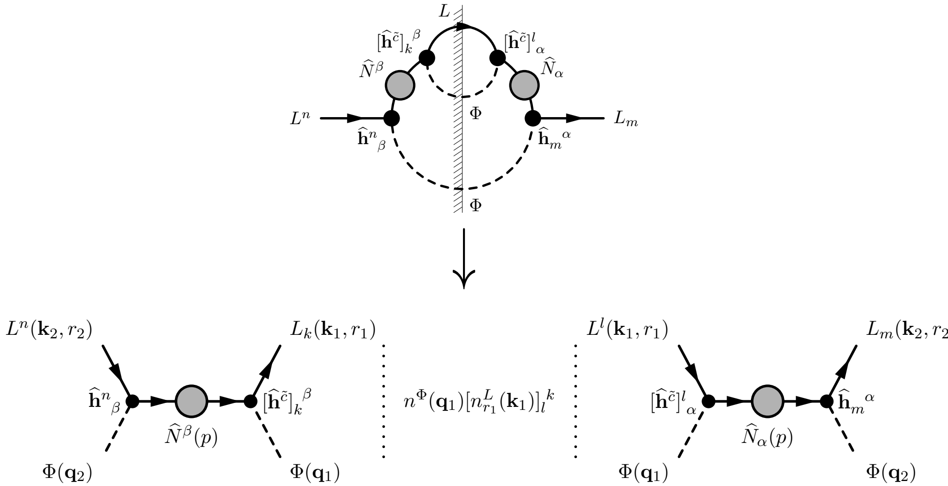
- Generalization of the density matrix formalism. [Sigl, Raffelt '93]

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

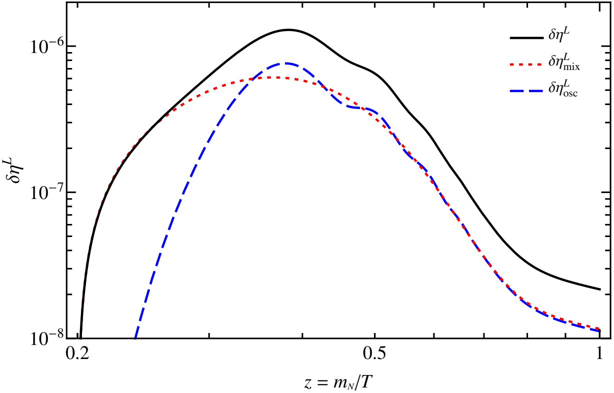


Collision Rates for $2 \leftrightarrow 2$ Scattering

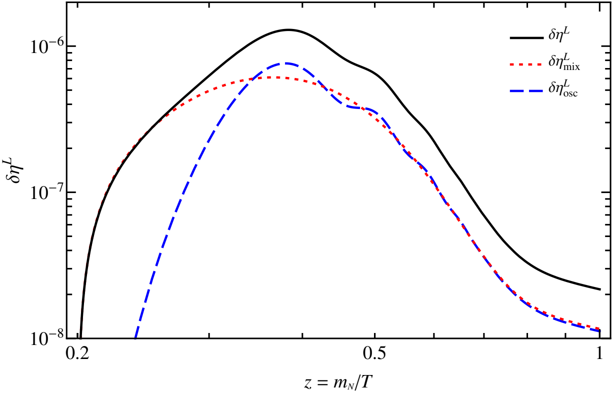
$$\boxed{n^{\Phi}\,[n^{L}]_{l}{}^{k}\,[\gamma(L\Phi \to L\Phi)]_{k}{}^{l}{}_{m}{}^{n}} \longrightarrow \text{rank-4 tensor}$$



Key Result



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

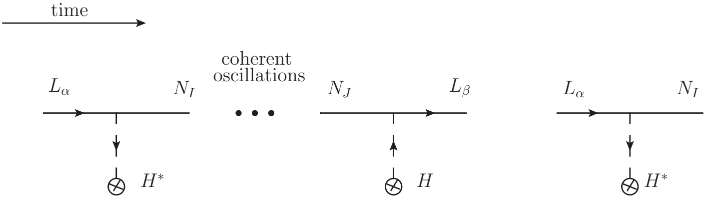


$$\delta\eta^L_{\rm mix} \simeq \frac{g_N}{2}\,\frac{3}{2\mathrm{K}z}\sum_{\alpha\neq\beta}\frac{\Im\left(\widehat{h}^\dagger\widehat{h}\right)^2_{\alpha\beta}}{(\widehat{h}^\dagger\widehat{h})_{\alpha\alpha}(\widehat{h}^\dagger\widehat{h})_{\beta\beta}}\;\frac{\left(M^2_{N,\,\alpha}-M^2_{N,\,\beta}\right)M_N\widehat{\Gamma}^{(0)}_{\beta\beta}}{\left(M^2_{N,\,\a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

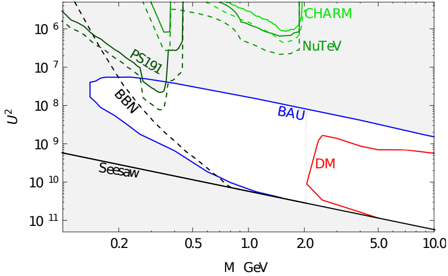
$$\delta\eta^L_{\rm osc} \simeq \frac{g_N}{2}\,\frac{3}{2\mathrm{K}z}\sum_{\alpha\neq\beta}\frac{\Im\left(\widehat{h}^\dagger\widehat{h}\right)^2_{\alpha\beta}}{(\widehat{h}^\dagger\widehat{h})_{\alpha\alpha}(\widehat{h}^\dagger\widehat{h})_{\beta\beta}}\;\frac{\left(M^2_{N,\,\alpha}-M^2_{N,\,\beta}\right)M_N\left(\widehat{\Gamma}^{(0)}_{\alpha\alpha}+\widehat{\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

ARS Mechanism

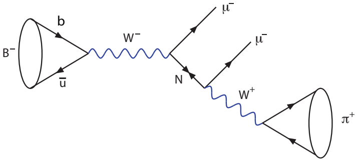
[Akhmedov, Rubakov, Smirnov (Phys. Rev. Lett. '98); Alekhin *et al.* (Rep. Prog. Phys. '16)]

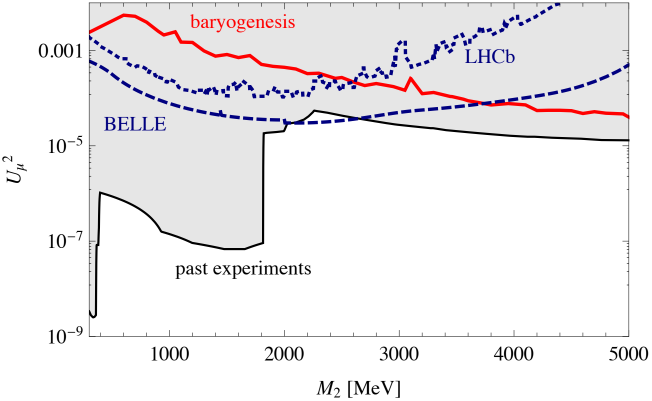


$Y_{\Delta L_1} = 0$	$Y_{\Delta L_1} > 0$	$Y_{\Delta L_1} > 0$
$Y_{\Delta L_2}, Y_{\Delta L_3} = 0$	$Y_{\Delta L_2}, Y_{\Delta L_3} < 0$	$Y_{\Delta L_2}, Y_{\Delta L_3} < 0$
$\sum_\alpha Y_{\Delta L_\alpha} = 0$	$\sum_\alpha Y_{\Delta L_\alpha} = 0$	$\sum_\alpha Y_{\Delta L_\alpha} \neq 0$



Accessible in B-decay

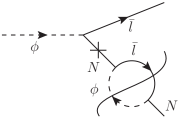


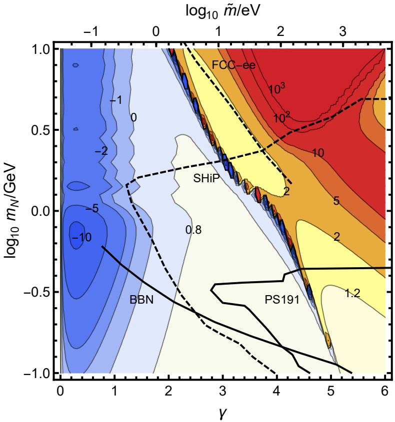


[Canetti, Drewes, Garbrecht (PRD '14)]

Higgs Decay Leptogenesis

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





Testable Models

- Need $m_N \lesssim \mathcal{O}(\text{TeV})$.
- 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]

- 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]
- 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)]

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

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

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]
- 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)]

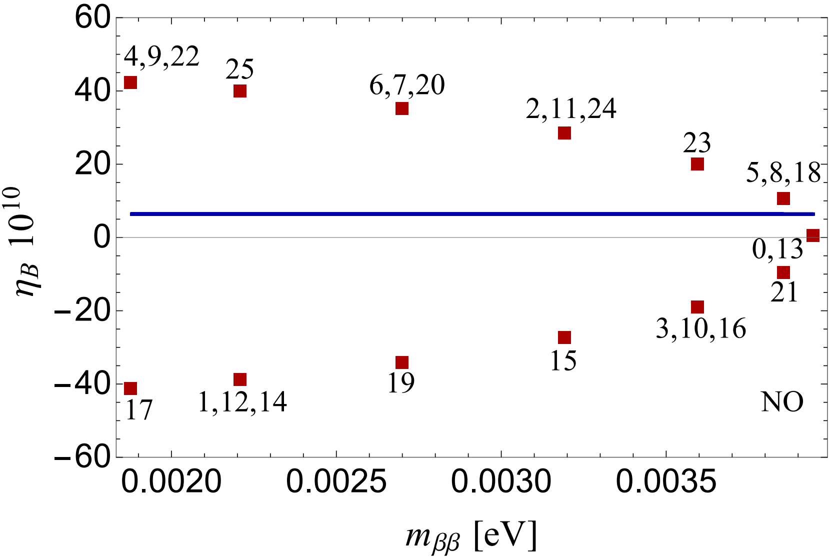
$$Z^\dagger(\mathbf{3})\, Y_D\, Z(\mathbf{3}') = Y_D \quad \text{and} \quad X^\star(\mathbf{3})\, Y_D\, X(\mathbf{3}') = Y_D^\star\ .$$

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

- 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:

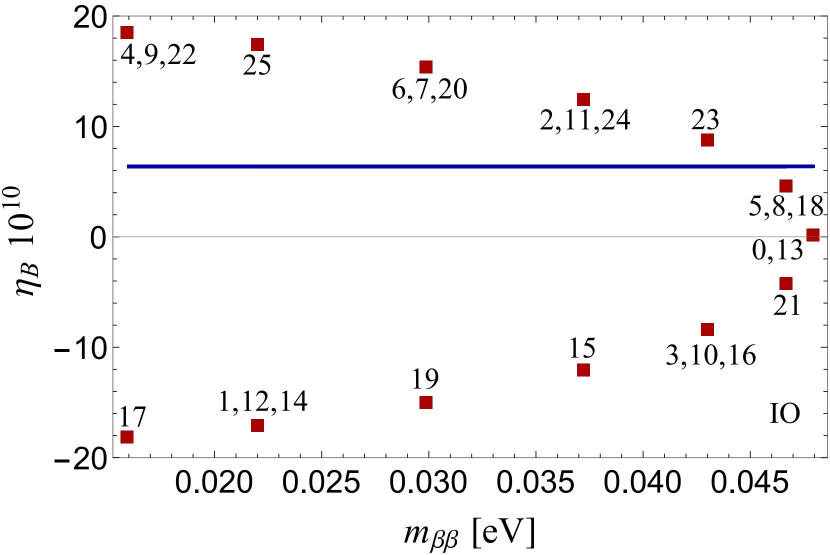
$$M_R = M_N \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

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



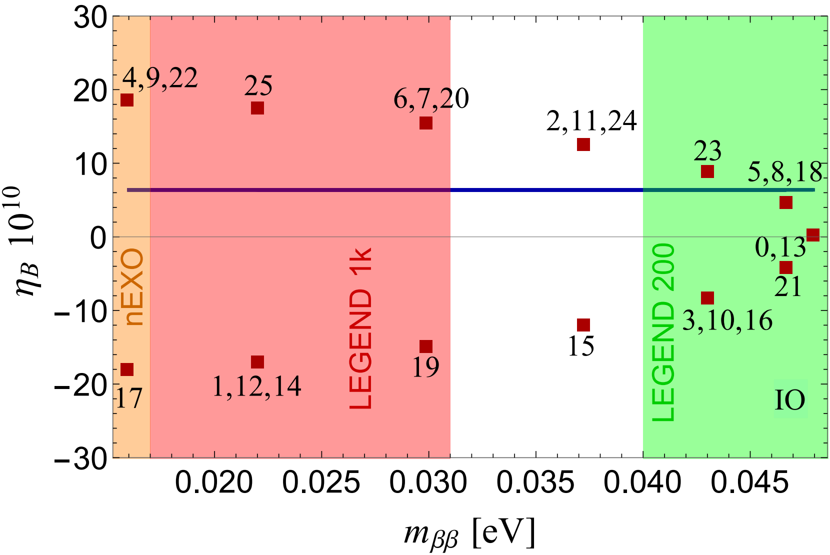
[BD, Hagedorn, Molinaro (in prep)]

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



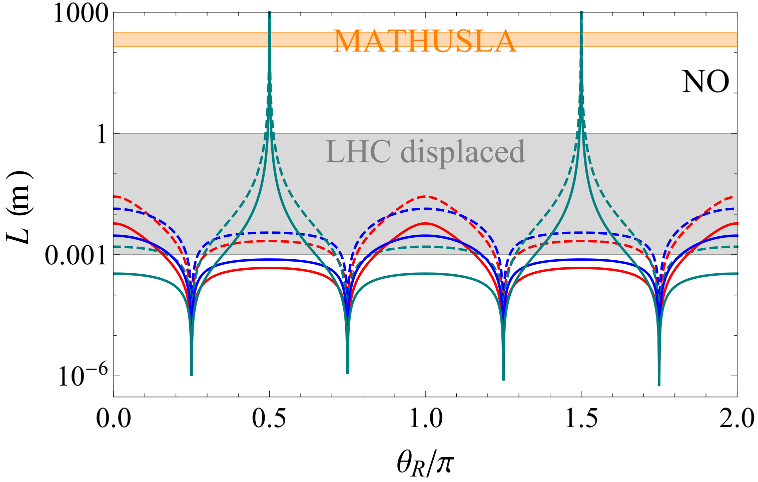
[BD, Hagedorn, Molinaro (in prep)]

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



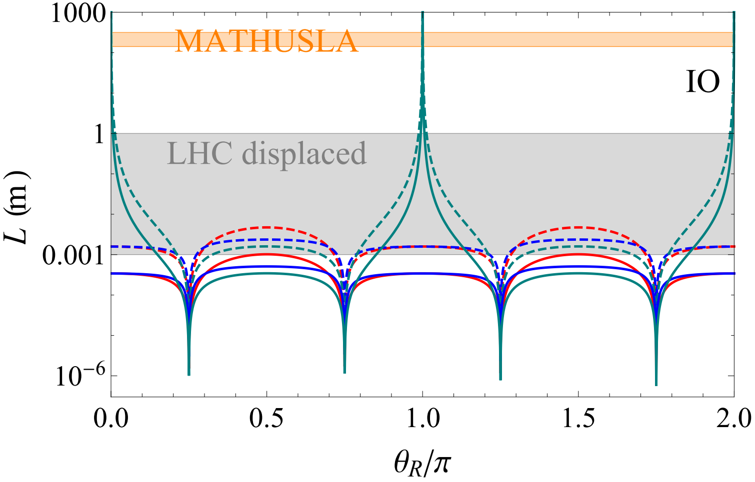
[BD, Hagedorn, Molinaro (in prep)]

Decay Length



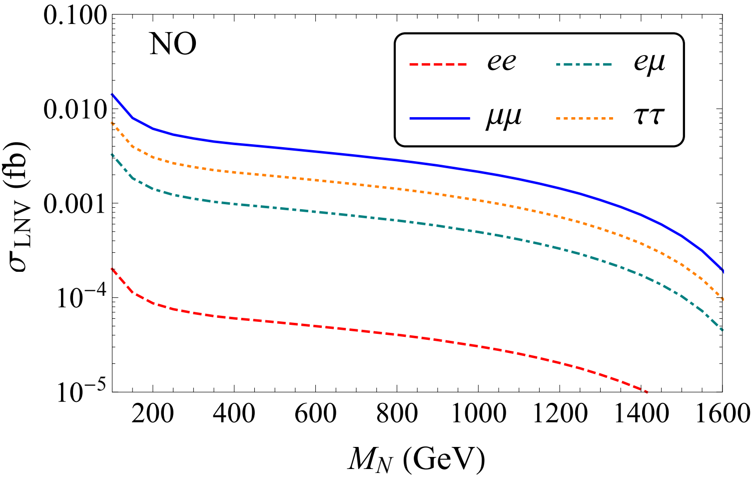
N_1 (red), N_2 (blue), N_3 (green).
M_N=150 GeV (dashed), 250 GeV (solid).

Decay Length

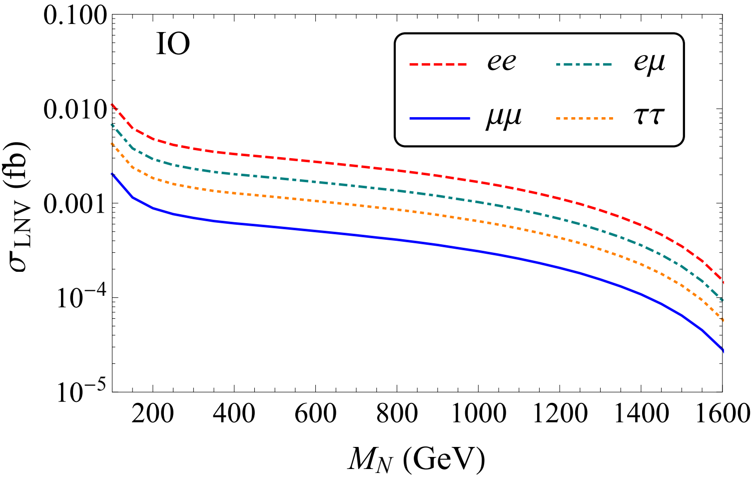


N_1 (red), N_2 (blue), N_3 (green).
M_N=150 GeV (dashed), 250 GeV (solid).

Finding Mass Hierarchy at the LHC



[BD, Hagedorn, Molinaro (in prep)]



[BD, Hagedorn, Molinaro (in prep)]

Conclusion

- Observed baryon asymmetry provides a strong evidence for BSM.
- Many interesting ideas for baryogenesis, some of which can be tested in laboratory experiments.
- Leptogenesis provides an attractive link between neutrino mass and observed baryon asymmetry.
- Can be realized at low scale: Resonant Leptogenesis/ARS.
- Flavor effects are important.

Conclusion

- Observed baryon asymmetry provides a strong evidence for BSM.
- Many interesting ideas for baryogenesis, some of which can be tested in laboratory experiments.
- Leptogenesis provides an attractive link between neutrino mass and observed baryon asymmetry.
- Can be realized at low scale: Resonant Leptogenesis/ARS.
- Flavor effects are important.

- Predictive models of leptogenesis based on residual flavor and CP symmetries.
- Correlation between BAU and $0\nu\beta\beta$.
- Correlation between BAU and LNV signals (involving displaced vertex) at the LHC.
- Can probe neutrino mass hierarchy (complementary to oscillation experiments).

Conclusion

- Observed baryon asymmetry provides a strong evidence for BSM.
- Many interesting ideas for baryogenesis, some of which can be tested in laboratory experiments.
- Leptogenesis provides an attractive link between neutrino mass and observed baryon asymmetry.
- Can be realized at low scale: Resonant Leptogenesis/ARS.
- Flavor effects are important.

- Predictive models of leptogenesis based on residual flavor and CP symmetries.
- Correlation between BAU and $0\nu\beta\beta$.
- Correlation between BAU and LNV signals (involving displaced vertex) at the LHC.
- Can probe neutrino mass hierarchy (complementary to oscillation experiments).

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:

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

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:

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

- 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

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

- 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

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

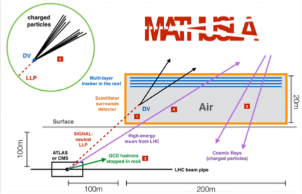
  with $\theta_{L,\alpha} = \theta_L + \rho_\alpha\,4\pi/3$ and $\rho_e = 0$, $\rho_\mu = 1$, $\rho_\tau = -1$.
- $\varepsilon_{2\alpha}$ are the negative of $\epsilon_{1\alpha}$ with F_{12} being replaced by F_{21}.

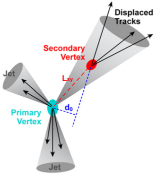
Decay Length

- 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.





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].
- Need to go beyond the minimal type-I seesaw to realize a sizable LNV 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].
- 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]