Baryogenesis and Leptogenesis

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Matter-Antimatter Asymmetry

### Big-Bang nucleosynthesis

**Figure 24.1:** The primordial abundances of $^4$He, D, $^3$He, and $^7$Li as predicted by the standard model of Big-Bang nucleosynthesis — the band shows the 95% CL range. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN $^4$He concordance range (both at 95% CL).

Predictions and thus in the key reaction cross sections. For example, it has been suggested that $d(\text{p},\gamma)^3\text{He}$ measurements may suffer from systematic errors and be inferior to...
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.
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  - $B$ violation, $C$ & $CP$ violation, departure from thermal equilibrium
- Necessary but not sufficient.

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.
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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; ...]

Other ideas:

- 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, ...
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- **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; ...]
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  - **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. 
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This talk: **Low-scale leptogenesis**
Non-zero neutrino mass
At least two of the neutrinos are massive and hence they mix with each other.

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

\[ Ve \leftrightarrow V_\mu \]

Solar

Reactor

Atmospheric/Accelerator

\[ V_\tau \]
**Seesaw Mechanism:** a common link between neutrino mass and baryon asymmetry.

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

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

For \( \| M_D M_N^{-1} \| \ll 1 \),

\[
\mathcal{M}_\nu^{\text{light}} \simeq -M_D M_N^{-1} M_D^T.
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For \( \| M_D M_N^{-1} \| \ll 1 \), \( M_{\nu^{\text{light}}} \approx - M_D M_N^{-1} M_D^T \).

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).

---

**Diagram:**

- Reactor & LSND anomaly
- \( \Lambda_{\text{EW}} \)
- GUT
- \( m_\nu = \Delta m_{\text{atm}}^2 \)
- \( m_\nu = \Delta m_{\text{sol}}^2 \)
- Neutrino Yukawa coupling \( y_\nu \)
- Neutrino Yukawa coupling \( y_e \)
- Neutrino Yukawa coupling \( y_{\text{top}} \)
- Neutrino mass scale
- \( M_{\text{GUT}} \)
- \( M_{\pi} \)
Leptogenesis

**A cosmological consequence of the seesaw mechanism.**

Naturally satisfies all **Sakharov conditions**.

- $L$ violation due to the Majorana nature of heavy RH neutrinos.
- $\bar{L} \rightarrow \bar{B}$ 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
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~ 3000 citations

Year

Times cited


Neutrino oscillation discovered
Leptogenesis for Pedestrians

[Buchm"uller, Di Bari, Pl"umacher '05]

Three basic steps:

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

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

   \[ \begin{array}{c}
   N_1 \\
   \downarrow \\
   l
   \end{array} \quad \begin{array}{c}
   H \\
   \uparrow
   \end{array} \]

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

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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 $T > T_{\text{sph}}$. 
Boltzmann Equations

[Buchmüller, Di Bari, Plüümacher '02]

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

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

[Buchmüller, Di Bari, Plümacher '02]

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

- Final baryon asymmetry:
  \[
  \eta_{\Delta B} = d \cdot \varepsilon \cdot \kappa_f
  \]

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

- \(\kappa_f \equiv \kappa(z_f)\) is the final efficiency factor, where
  \[
  \kappa(Z) = \int_{z_i}^{Z} dz' \frac{D}{D + S} \frac{dN_N}{dz'} \int_{z_i}^{z''} dz'' W(z'')
  \]
\[ \varepsilon_{l\alpha} = \frac{\Gamma(N_\alpha \rightarrow L_\ell \Phi) - \Gamma(N_\alpha \rightarrow L_\ell^C \Phi^c)}{\sum_k [\Gamma(N_\alpha \rightarrow L_k \Phi) + \Gamma(N_\alpha \rightarrow L_k^C \Phi^c)]} \equiv \frac{\hat{h}_{l\alpha}^2 - |\hat{h}_{l\alpha}^c|^2}{(\hat{h}^*\hat{h})_{\alpha\alpha} + (\hat{h}^c\hat{h}^c)_{\alpha\alpha}} \]
Importance of self-energy effects

\[\text{Importance of heavy-neutrino width effects:} \quad \Gamma_{N_{\alpha}} \quad \text{[A.P., PRD56 (1997) 5431; A.P. and T. Underwood, NPB692 (2004) 303].}\]

Warsaw, 22–27 June 2014 Flavour Covariance in Leptogenesis A. Pilaftsis

\[\varepsilon_{l_{\alpha}} = \frac{\Gamma(N_{\alpha} \rightarrow L_{l}\Phi) - \Gamma(N_{\alpha} \rightarrow L_{l}^{c}\Phi^{c})}{\sum_{k} \left[\Gamma(N_{\alpha} \rightarrow L_{k}\Phi) + \Gamma(N_{\alpha} \rightarrow L_{k}^{c}\Phi^{c})\right]} \equiv \frac{|\hat{h}_{l_{\alpha}}|^{2} - |\hat{h}_{l_{\alpha}}^{c}|^{2}}{(\hat{h}^{\dagger}\hat{h})_{\alpha\alpha} + (\hat{h}^{c\dagger}\hat{h}^{c})_{\alpha\alpha}}\]

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

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

\[\times \frac{m_{\alpha}(m_{\alpha}A_{\alpha\beta} + m_{\beta}A_{\beta\alpha}) - iR_{\alpha\gamma}[m_{\alpha}A_{\gamma\beta}(m_{\alpha}A_{\alpha\gamma} + m_{\gamma}A_{\gamma\alpha}) + m_{\beta}A_{\beta\gamma}(m_{\alpha}A_{\gamma\alpha} + m_{\gamma}A_{\alpha\gamma})] + m_{\beta}A_{\beta\gamma}(m_{\alpha}A_{\gamma\alpha} + m_{\gamma}A_{\alpha\gamma})}{m_{\alpha}^{2} - m_{\beta}^{2} + 2im_{\alpha}^{2}A_{\beta\beta} + 2iIm(R_{\alpha\gamma})[m_{\alpha}^{2}|A_{\beta\gamma}|^{2} + m_{\beta}m_{\gamma}Re(A_{\beta\gamma}^{2})]}\]

\[R_{\alpha\beta} = \frac{m_{\alpha}^{2}}{m_{\alpha}^{2} - m_{\beta}^{2} + 2im_{\alpha}^{2}A_{\beta\beta}} ; \quad A_{\alpha\beta}(h) = \frac{1}{16\pi} \sum_{l} \hat{h}_{l_{\alpha}} \hat{h}_{l_{\beta}}^{*} .\]
Three regions of interest:

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

- **Collider-friendly scale:** $100 \text{ GeV} \lesssim m_N \lesssim \text{few TeV}$.
  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:** $1 \text{ GeV} \lesssim m_N \lesssim 5 \text{ GeV}$.
  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)


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

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

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

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

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- Experimentally inaccessible!
- Also leads to a lower limit on the reheating temperature $T_{\text{rh}} \gtrsim 10^9$ GeV.
- In supergravity models, need $T_{\text{rh}} \lesssim 10^6 - 10^9$ 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]
Dominant self-energy effects on the \( CP \)-asymmetry (\( \varepsilon \)-type) \cite{Flanz, Paschos, Sarkar '95; Covi, Roulet, Vissani '96].

Resonantly enhanced, even up to order 1, when \( \Delta m_N \sim \Gamma_N/2 \ll m_{N_1,2} \).
\cite{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.
\cite{Pilaftsis, Underwood '05; Deppisch, Pilaftsis '10; BD, Millington, Pilaftsis, Teresi '14]

A testable scenario at both Energy and Intensity Frontiers.
Figure 1: The ten different three RH neutrino mass patterns requiring 10 different sets of Boltzmann equations for the calculation of the asymmetry [17].

Component, escapes the washout from a lighter RH neutrino species [6]. Second, parts of the flavour asymmetries (phantom terms) produced in the one or two flavour regimes do not contribute to the total asymmetry at the production but can contribute to the final asymmetry [18].

Therefore, it is necessary to extend the density matrix formalism beyond the traditional N1-dominated scenario [6, 11, 19] and account for heavy neutrino flavours in order to calculate the final asymmetry for an arbitrary choice of the RH neutrino masses. This is the main objective of this paper. At the same time we want to show how Boltzmann equations can be recovered from the density matrix equations for the hierarchical RH neutrino mass patterns shown in Fig. 1 allowing an explicit analytic calculation of the final asymmetry. In this way we will confirm and extend results that were obtained within simplified assumptions that are in retrospect oversimplified. For illustrative purposes, we will proceed in a modular way, first discussing the specific effects in isolation within simplified cases and then discussing the most general case that includes all effects. The paper is organised in the following way.

In Section 2 we discuss the derivation of the kinetic equations for the N1-dominated scenario in the absence of heavy neutrino flavours. This is useful both to show the extension from classical Boltzmann to density matrix equations and to highlight some implications of the unitary assumption. For illustrative purposes, we will proceed in a modular way, first discussing the specific effects in isolation within simplified cases and then discussing the most general case that includes all effects. The paper is organised in the following way.

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 $h_\alpha l$ [Pilaftsis '04; Endoh, Morozumi, Xiong '04]
- Charged lepton Yukawa couplings $y_k l$ [Barbieri, Creminelli, Strumia, Tetradis '00]

Three distinct physical phenomena:

- Mixing
- Oscillation
- Decoherence.

Captured consistently in the Boltzmann approach by the fully flavor-covariant formalism [BD, Millington, Pilaftsis, Teresi '14; '15]
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In quantum statistical mechanics,

\[
\rho^{X}(t) \equiv \langle \hat{n}^{X}(\tilde{t}; \tilde{t}_i) \rangle_t = \text{Tr} \left\{ \rho(\tilde{t}; \tilde{t}_i) \, \hat{n}^{X}(\tilde{t}; \tilde{t}_i) \right\}.
\]

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

\[
\frac{dn^{X}(t)}{dt} = \text{Tr} \left\{ \rho(\tilde{t}; \tilde{t}_i) \frac{d\hat{n}^{X}(\tilde{t}; \tilde{t}_i)}{d\tilde{t}} \right\} + \text{Tr} \left\{ \frac{d\rho(\tilde{t}; \tilde{t}_i)}{d\tilde{t}} \, \hat{n}^{X}(\tilde{t}; \tilde{t}_i) \right\} \equiv \mathcal{I}_1 + \mathcal{I}_2.
\]

Use the Heisenberg EoM for \( \mathcal{I}_1 \) and Liouville-von Neumann equation for \( \mathcal{I}_2 \).
In quantum statistical mechanics,

\[ n^X(t) \equiv \langle \hat{n}^X(\tilde{t}; \tilde{t}_i) \rangle_t = \text{Tr} \left\{ \rho(\tilde{t}; \tilde{t}_i) \hat{n}^X(\tilde{t}; \tilde{t}_i) \right\} . \]

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

\[ \frac{dn^X(t)}{dt} = \text{Tr} \left\{ \rho(\tilde{t}; \tilde{t}_i) \frac{d\hat{n}^X(\tilde{t}; \tilde{t}_i)}{d\tilde{t}} \right\} + \text{Tr} \left\{ \frac{d\rho(\tilde{t}; \tilde{t}_i)}{d\tilde{t}} \hat{n}^X(\tilde{t}; \tilde{t}_i) \right\} = I_1 + I_2 . \]

Use the Heisenberg EoM for \( I_1 \) and Liouville-von Neumann equation for \( I_2 \).

**Markovian master equation** for the number density matrix:

\[ \frac{d}{dt} n^X(k, t) \simeq i \langle [H^X_0, \hat{n}^X(k, t)] \rangle_t - \frac{1}{2} \int_{-\infty}^{+\infty} dt' \langle [H_{\text{int}}(t'), [H_{\text{int}}(t), \hat{n}^X(k, t)]] \rangle_t . \]

(Oscillation) \hspace{5cm} (Mixing)

**Generalization of the density matrix formalism.** [Sigl, Raffelt '93]
Collision Rates for Decay and Inverse Decay

\[ n^\Phi [n^L]^k_l \gamma(L\Phi \rightarrow N)]_k^l_{\alpha} \rightarrow \text{rank-4 tensor} \]
Collision Rates for 2 ↔ 2 Scattering

\[ n^\Phi \left[ n^L \right]_k^l \left[ \gamma(L\Phi \to L\Phi) \right]_k^l \to \text{rank-4 tensor} \]
Combination "÷L₁ = "÷L₂ + "÷L₃ yields a factor of 2 enhancement compared to the isolated contributions for weakly-resonant RL.

δη⁰ ≃ g²N² K² z ∑ α̸=β ℑ(∫h†∫h)²αβ(∫h†∫h)²αα(∫h†∫h)²ββ(M²N,α − M²N,β)MNΓ(0)ββ(∫h†∫h)²αβ(M²N,α − M²N,β)² + (MNΓ(0)αα + MNΓ(0)ββ)² ℑ[∫h†∫h]²αβ(∫h†∫h)²αα(∫h†∫h)²ββ(M²N,α − M²N,β)².
The key result presented in the image is the combination of factors for weakly-resonant RL, yielding a factor of 2 enhancement compared to the isolated contributions.

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

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

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

\[
\begin{align*}
L_\alpha & \rightarrow N_I & \text{coherent oscillations} & N_J & \rightarrow L_\beta \\
\downarrow H^* & & & \downarrow H & \downarrow H^*
\end{align*}
\]

\[
\begin{align*}
Y_{\Delta L_1} &= 0 \\
Y_{\Delta L_2}, Y_{\Delta L_3} &= 0 \\
\sum_{\alpha} Y_{\Delta L_\alpha} &= 0
\end{align*}
\]

\[
\begin{align*}
Y_{\Delta L_1} &> 0 \\
Y_{\Delta L_2}, Y_{\Delta L_3} &< 0 \\
\sum_{\alpha} Y_{\Delta L_\alpha} &= 0
\end{align*}
\]

\[
\begin{align*}
Y_{\Delta L_1} &> 0 \\
Y_{\Delta L_2}, Y_{\Delta L_3} &< 0 \\
\sum_{\alpha} Y_{\Delta L_\alpha} &\neq 0
\end{align*}
\]
Accessible in $B$-decay

\[ \text{FIG. 1: Feynman diagram for} \]

\[ \text{baryogenesis} \]

\[ \text{LHCb} \]

\[ 1000 \ 2000 \ 3000 \ 4000 \ 5000 \]

\[ 10^{-9} \]

\[ 10^{-7} \]

\[ 10^{-5} \]

\[ 0.001 \]

\[ 10^{-3} \]

\[ M_2 \ \text{[MeV]} \]

\[ \text{past experiments} \]

\[ \text{BELLE} \]

\[ \text{LHCb} \]

\[ \text{Canetti, Drewes, Garbrecht (PRD '14)} \]
Higgs Decay Leptogenesis

The overall structure is similar to those, with the main novelty given by the presence of a dominant L-violating part. This dominance occurs generically for Yukawa couplings large enough, even for larger mass of later times due to this factor, resulting in a dominant asymmetry obtained. The observed value, whereas the LNV washout part, which is suppressed by an extra factor, will wash out less the asymmetry in the total lepton number asymmetry, whereas the LNV washout part, which is suppressed by an extra factor, will wash out less the asymmetry in the total lepton number.

The ARS phenomenon dominates. Instead, for small values of the imaginary part of the propagators in the loop of Fig. 7, Naively, one would not expect any CP-violation. However, this argument holds true only at zero temperature. On the left panel we show the region of successful ARS production. Instead, as argued recently (with the LNV one typically dominating for small mass splitting as in Fig. 8), as therefor neglected, because the corresponding rates have a form factor.

In the light gray region the final state is out of equilibrium, this process can therefore produce an asymmetry. While this possibility to generate an asymmetry has been confirmed in the Ra
des, this process can provide the energy required to put on shell the propagators in the loop of Fig. 7. Naively, one would not expect any CP-violation in this decay: in order to be kinematically accessible, this decay requires a SM lepton that do involve a Majorana mass insertion and violate CP-violation in this decay. Instead, as argued recently (with the LNV one typically dominating for small mass splitting as in Fig. 8), as therefor neglected, because the corresponding rates have a form factor.

To study the relative importance of the two phenomena beyond the linear weak-violation in this decay: in order to be kinematically accessible, this decay requires CP-violating rates accounting for the CP violation in the decays details, see [64].

In the right panel, we plot the ratio of the full LNC + LNV result to the LNC ARS one. In the resonant regime line. In the right panel, we plot the ratio of the full LNC + LNV result to the LNC ARS one. In the resonant regime line. In the right panel, we plot the ratio of the full LNC + LNV result to the LNC ARS one.

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To study the relative importance of the two phenomena beyond the linear weak-violation in this decay: in order to be kinematically accessible, this decay requires CP-violating rates accounting for the CP violation in the decays details, see [64].
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.
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 $X(s)(\tau)$ in the representation $\tau$ and depends on the integer parameter $s$, $0 \leq s \leq n - 1$. [Hagedorn, Meroni, Molinaro '14]
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CP symmetry is given by the transformation $X(s)(r)$ in the representation $r$ and depends on the integer parameter $s$, $0 \leq s \leq n - 1$. [Hagedorn, Meroni, Molinaro '14]

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)]

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

$$Y_D = \Omega(s)(\mathbf{3}) \, R_{13}(\theta_L) \begin{pmatrix} y_1 & 0 & 0 \\ 0 & y_2 & 0 \\ 0 & 0 & y_3 \end{pmatrix} \, R_{13}(-\theta_R) \, \Omega(s)(\mathbf{3}')^\dagger.$$
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\[
Z^\dagger(3) Y_D Z(3^\prime) = Y_D \quad \text{and} \quad X^\star(3) Y_D X(3^\prime) = Y_D^\star.
\]

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

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

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

\[
M_R = M_N \begin{pmatrix}
    1 & 0 & 0 \\
    0 & 0 & 1 \\
    0 & 1 & 0
\end{pmatrix}
\]
Correlation between BAU and $0^{\nu}\beta\beta$

[BD, Hagedorn, Molinaro (in prep)]
Correlation between BAU and $0\nu\beta\beta$

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Correlation between BAU and $0^{\nu}\beta\beta$
$L (\text{m})$

$\theta_R/\pi$

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

$L (m)$

$\theta_R/\pi$

$N_1$ (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)]
Finding Mass Hierarchy at the LHC

\[ \sigma_{\text{LNV}} (\text{fb}) \]

\[ M_N (\text{GeV}) \]

[BD, Hagedorn, Molinaro (in prep)]
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).
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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 $3\sigma$ of current global-fit results).
- Light neutrino masses given by the type-I seesaw:

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

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

$\text{IO}$:

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

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

\[
\begin{align*}
\text{NO} : & \quad y_1 = 0, \quad y_2 = \pm \frac{\sqrt{M_N} \sqrt{\Delta m_{\text{sol}}^2}}{v}, \quad y_3 = \pm \frac{\sqrt{M_N} \sqrt{\Delta m_{\text{atm}}^2}}{v} \\
\text{IO} : & \quad y_3 = 0, \quad y_2 = \pm \frac{\sqrt{M_N} \sqrt{|\Delta m_{\text{atm}}^2|}}{v}, \quad y_1 = \pm \frac{\sqrt{M_N} \sqrt{(|\Delta m_{\text{atm}}^2| - \Delta m_{\text{sol}}^2)}}{|\cos 2\theta_R|} v
\end{align*}
\]

- Only free parameters: \( M_N \) and \( \theta_R \).
Dirac phase is trivial: $\delta = 0$.

For $m_{\text{lightest}} = 0$, only one Majorana phase $\alpha$, which depends on the chosen CP transformation:

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

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

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

$$0.0019 \text{ eV} \lesssim m_{\beta\beta} \lesssim 0.0040 \text{ eV} \quad \text{(NO)}$$
$$0.016 \text{ eV} \lesssim m_{\beta\beta} \lesssim 0.048 \text{ eV} \quad \text{(IO)}.$$
At leading order, three degenerate RH neutrinos.
Higher-order corrections can break the residual symmetries, giving rise to a quasi-degenerate spectrum:

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

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

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

\( F_{ij} \) are related to the regulator in RL and are proportional to the mass splitting of \( N_i \).
We find \( \varepsilon_{3\alpha} = 0 \) and

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

with \( \theta_{L,\alpha} = \theta_L + \rho_\alpha \frac{4\pi}{3} \) and \( \rho_e = 0, \rho_\mu = 1, \rho_\tau = -1. \)
\( \varepsilon_{2\alpha} \) are the negative of \( \varepsilon_{1\alpha} \) with \( F_{12} \) being replaced by \( F_{21} \).
For RH Majorana neutrinos, $\Gamma_{\alpha} = M_{\alpha} (\hat{Y}_D^\dagger \hat{Y}_D)_{\alpha\alpha}/(8\pi)$. We get

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

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

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

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

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

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

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

In addition, $N_{1,2}$ can have displaced vertex signals at the LHC.
Need an efficient production mechanism.

In our scenario, $y_i \lesssim 10^{-6}$ suppresses the Drell-Yan production

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

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

Even if one assumes large Yukawa, the LNV signal will be generally suppressed by the quasi-degeneracy of the RH neutrinos [Kersten, Smirnov '07; Ibarra, Molinaro, Petcov '10; BD '15].

Need to go beyond the minimal type-I seesaw to realize a sizable LNV signal.
Collider Signal

- Need an efficient production mechanism.
- In our scenario, \( y_i \lesssim 10^{-6} \) suppresses the Drell-Yan production
  \[
  pp \rightarrow W^{(*)} \rightarrow N_i \ell \alpha ,
  \]
  and its variants. [Han, Zhang '06; del Aguila, Aguilar-Saavedra, Pittau '07; BD, Pilaftsis, Yang '14; Han, Ruiz, Alva '14; Deppisch, BD, Pilaftsis '15; Das, Okada '15]
- Even if one assumes large Yukawa, the LNV signal will be generally suppressed by the quasi-degeneracy of the RH neutrinos [Kersten, Smirnov '07; Ibarra, Molinaro, Petcov '10; BD '15].
- Need to go beyond the minimal type-I seesaw to realize a sizable LNV signal.
- 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]