Brout-Englert-Higgs doublet decay as the origin of the baryon asymmetry

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based on

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Introduction

- **Leptogenesis** is probably the most motivated explanation for the baryon asymmetry of the Universe
- based on nothing but the **seesaw** Lagrangian:

$$\mathcal{L} \supset -\frac{1}{2} m_{N_\alpha} \overline{N}^c_\alpha N_\alpha - Y_{N_{\alpha i}} \widetilde{H}^\dagger \bar{N}_\alpha L_i + h.c.$$

- straightforward with $m_N > 10^8 - 10^9\,\mathrm{GeV}$
  [Davidson, Ibarra, 2002; Hambye, Lin, Notari, Papucci, Strumia, 2004]
- To have it at **lower scales** (more testable), either:
  - quasi-degenerate N [Pilaftsis, 1997; Pilaftsis, Underwood, 2003; Asaka, Shaposhnikov, 2005; Garbrecht, Herranen, 2011; Garny, Kartavtsev, Hohenegger, 2011; Dev, Millington, Pilaftsis, Teresi, 2014, 2015; . . .]
  - 3 N and cancellation of large Yukawa couplings (tuning? symmetries?) [Akhmedov, Rubakov, Smirnov, 1998; Drewes, Garbrecht, 2012]

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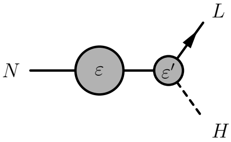
Low-scale resonant leptogenesis

- CP violation in $N \leftrightarrow LH$ decay



$$\epsilon_1 \;=\; \frac{\mathrm{Im}[(Y_N Y_N^\dagger)_{12}^2]}{(Y_N Y_N^\dagger)_{11}(Y_N Y_N^\dagger)_{22}} \;\times\; \frac{2\,\Delta m_N\,\Gamma_2}{4\,\Delta m_N^2 + \Gamma_2^2}$$

- thermal corrections to the masses: $m_i(T)^2 \simeq M_i^2(v(T)) + c_i\,T^2$
  - $c_H \sim g^2, g'^2, y_t^2 \; > \; c_L$
  - $c_N \sim y_N^2 \; \to \; 0$
- at T large enough $H \to NL$ **decay opens**

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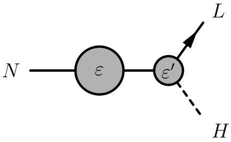

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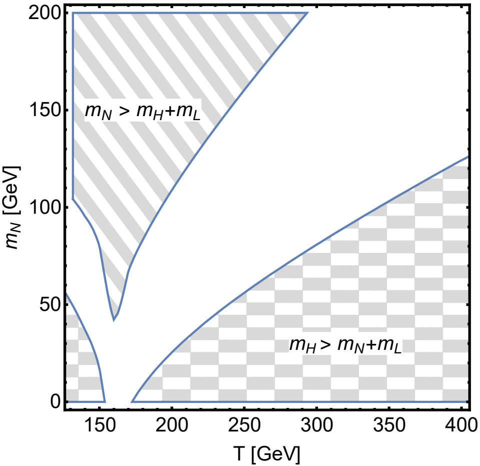
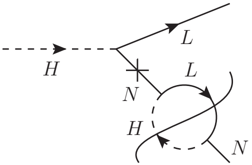
Parameter space for the decay processes



Thermal CP violation in $H \leftrightarrow NL$



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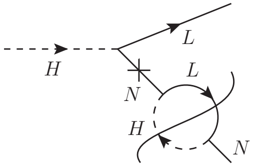

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CP asymmetry for successful leptogenesis - thermal N

- Sakharov condition: **decay product** (N) out of equilibrium, not decaying particle (H)
- for $m_N < T_{\rm sph}$, the lighter m_N, **the more N stays at equilibrium** at $T > T_{\rm sph}$
- $\tilde{m} \equiv v^2 (Y_N Y_N^\dagger)_{11} / m_N$
  natural seesaw: $\tilde{m} \approx 50\,\mathrm{meV}$
- due to $\Delta m_N(T)$ vs Δm_N^0:
  $\epsilon_{CP} \lesssim \frac{4}{\pi} \frac{50\, m_N^2}{f\, T_{sph}^2}$ (blue line)
- absolute **bound** for N initially at **equilibrium**: $m_N \gtrsim 2\,\mathrm{GeV}$

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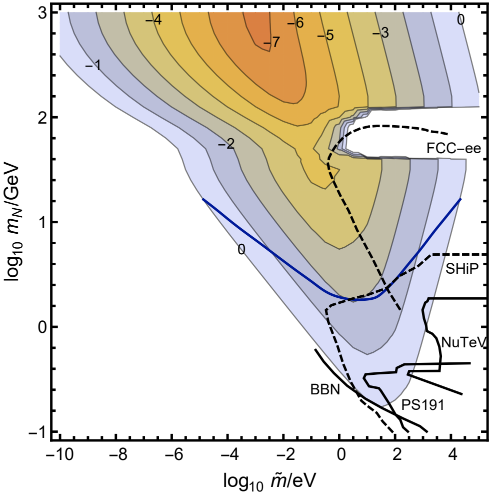

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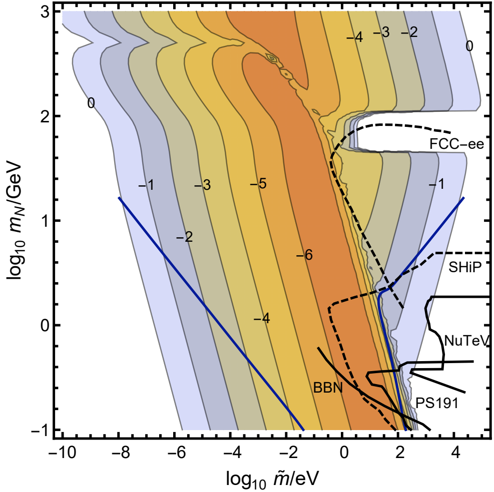
CP asymmetry for successful leptogenesis - initially no N



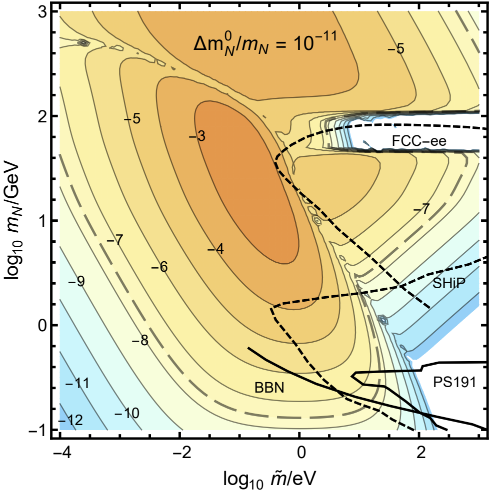
- the **less N thermalizes**, the smaller is n_N, the **larger** is

$$\epsilon_{CP} \frac{\gamma_D}{n_N^{\text{eq}}} |n_N^{\text{eq}} - n_N| \sim dn_N/dz$$

$H \to NL$ but no $NL \to H$

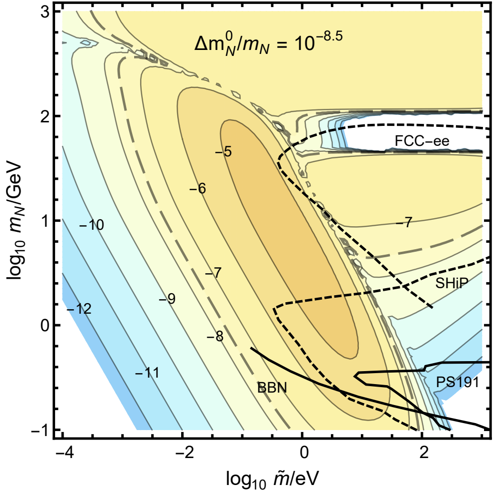
- asymmetry mostly produced at $T \sim T_{\text{sph}}$

Lepton asymmetry for $\Delta m_N / m_N = 10^{-11}$



- $f = \mathrm{CP}\, phase = 1$, $\Gamma_1/\Gamma_2 = m_{\mathrm{sol}}/m_{\mathrm{atm}}$
- **unflavoured** total **L violation** at $\mathcal{O}(Y_N^4)$, goes as m_N^2/T_{sph}^2

Lepton asymmetry for $\Delta m_N/m_N = 10^{-8.5}$



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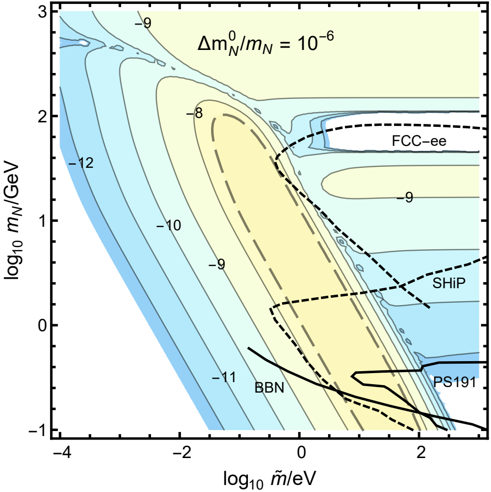

- $f = \mathrm{CP}\,phase = 1$, $\Gamma_1/\Gamma_2 = m_{\rm sol}/m_{\rm atm}$
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Comparison with ARS mechanism(s)

In the ARS mechanism: [Akhmedov, Rubakov, Smirnov, 1998; Asaka, Shaposhnikov, 2005; . . .]

- initially no N
- total L **conserved** at $\mathcal{O}(Y_N^4)$
- purely **flavoured** asymmetries at $\mathcal{O}(Y_N^4)$ which go as $T^2/(\Delta m_N^2)$
- L asymmetry at $\mathcal{O}(Y_N^6)$
- in the “linear” regime needs $T_{\text{in}} > T_{\text{osc}} \gg T_{\text{sph}}$ (according to Δm_N)

With 3 RH neutrinos: [Akhmedov, Rubakov, Smirnov, 1998; Drewes, Garbrecht, 2012; Hernández, Kekic, López-Pavón, Racker, Rius, 2015]

- it can work with $\Delta m_N \sim m_N \sim \text{GeV}$ if
  - very large Y_N for 2 active flavours $\Longrightarrow$ large flavoured asymmetries at $T_{\text{osc}} \sim 10^6\,\text{GeV}$
  - very small Y_N for 3$^{\text{rd}}$ flavour $\Longrightarrow$ no washout
  - no tuning in Δm_N, tuning in $\tilde{m} \sim 10^5 \Delta m_{\text{sol}}$

With 2 RH neutrinos: [Asaka, Shaposhnikov, 2005; Canetti, Drewes, Frossard, Shaposhnikov, 2013; . . .]

- it works up to $\Delta m_N/m_N \lesssim 10^{-3}$, allowing for some tuning of Y_N
- for $\Delta m_N/m_N = 10^{-11}$, $\tilde{m} \approx m_{\text{atm}}$, all $\text{CP phases} = 1$:
  H-decay$/$*ARS* ≈ 7 for $m_N = 2\,\text{GeV}$, *H-decay*$/$*ARS* ≈ 12 for $m_N = 10\,\text{GeV}$

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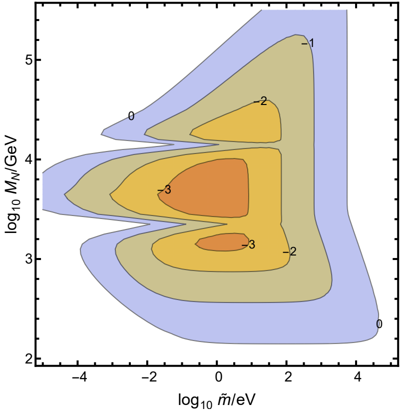
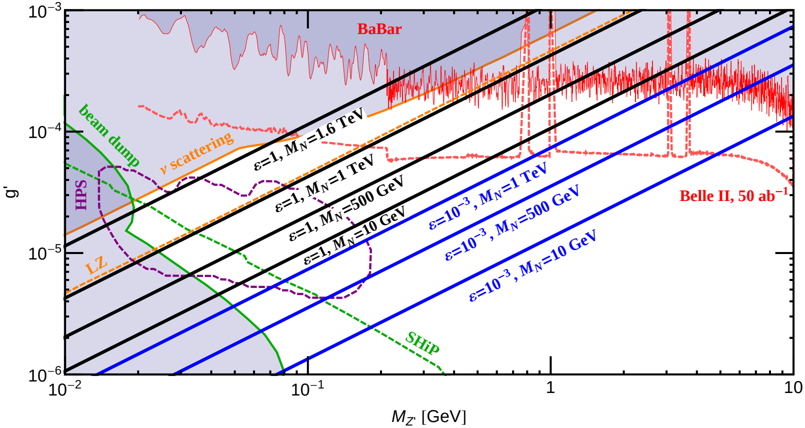
Low-scale leptogenesis with a Z'

- Consider a $U(1)_{B-L}$ model $\implies$ Z', N, S
- Leptogenesis from N-decay and H-decay [J. Heeck and DT, arXiv:1609.03594]
- For $M_Z' = 5\,\text{TeV}$, $M_S = 3\,\text{TeV}$, $g' = 0.2$:



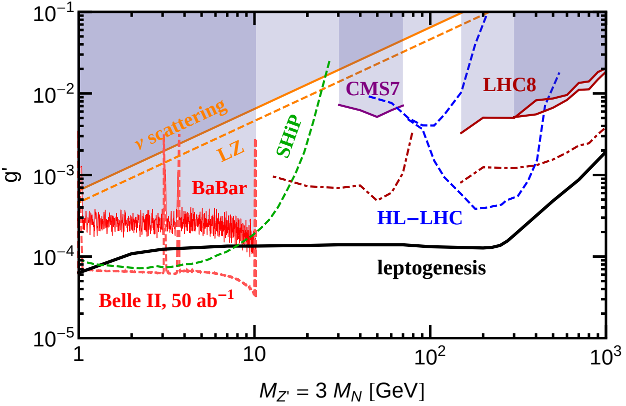
Leptogenesis and light Z'

- for fixed $M_{Z'}$, g' successful leptogenesis provides falsifiable bounds on M_N



Leptogenesis and heavy Z'

- For $M'_Z > 2M_N$ improved discovery prospects of Z' and N: $SM \to Z' + X \to NN + Y$
- For leptogenesis: $NN \to Z \to SM$ equilibrates N efficiently



Conclusions

- for $m_N < \mathcal{O}(100\,\mathrm{GeV})$, standard seesaw model, novel mechanism: **leptogenesis via Brout-Englert-Higgs decay** $H \leftrightarrow NL$

  [T. Hambye and DT, PRL 117 (2016) 091801]
- key points:
  - CP violation from **thermal** effects, zero at $T = 0$
  - Sakharov condition: **decay product** out-of-equilibrium, not the decaying particle
  - for initially **no** N: it **boosts** the asymmetry (contrary to high-scale)
- it occurs at $T \sim T_{\mathrm{sph}}$
- for N initially at **equilibrium**: $m_N > 2\,\mathrm{GeV}$
- **testable** at SHiP, FCC-ee, ILC, . . .
- tuning comparable to ARS mechanism(s), less than TeV-scale
- current uncertainties (= future work)
  - put together H-decay and ARS leptogenesis (which dominates when?)
  - include thermally-enhanced processes, $\mathcal{O}(\text{few})$ corrections to the rates [Besak, Bodeker, 2012; Ghisoiu, Laine, 2014; . . .]
  - more careful treatment of the washout for large Y_N (testable regime)
- applied to Z' models (rich phenomenology): [J. Heeck and DT, arXiv:1609.03594]