

# Low-scale leptogenesis via extended scalar sectors

Tommi Alanne



NonMinimalHiggs

Helsinki

May 28, 2019

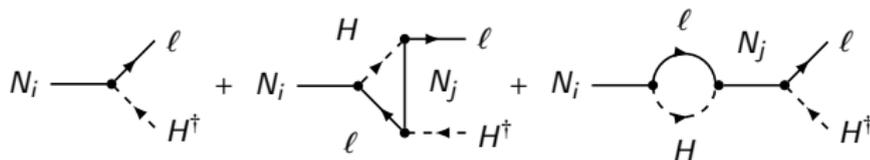
## Introductory notes

- Leptogenesis is an attractive alternative to generate BAU
- Connects generation of BAU at high energies to low-energy  $\nu$  oscillations
  - ▶ Type-I seesaw requires at least 2 RHNs,  $N_i$
  - ▶  $CP$ -violating out-of-equilibrium decays of the RHNs generate lepton asymmetry
  - ▶ EW sphalerons convert it to baryon asymmetry
- In standard scenario  $CP$  violation suppressed by tiny active- $\nu$  masses  
⇒ strong lower bound on RHN masses
  - ▶ Large radiative corrections to the Higgs mass  
[Vissani \(1997\) \[hep-ph/9709409\]](#)

# The Davidson–Ibarra bound

Davidson & Ibarra (2002) [hep-ph/0202239]

- The CP violation parameterised by 
$$\epsilon_i \equiv \frac{\Gamma(N_i \rightarrow LH) - \Gamma(N_i \rightarrow \overline{LH})}{\Gamma(N_i \rightarrow LH) + \Gamma(N_i \rightarrow \overline{LH})}$$
- Arises from interference between tree-level and loop diagrams:



- For hierarchical RHN masses,  $M_1 \ll M_2$ ,  $|\epsilon_1| \lesssim \frac{3M_1(m_3 - m_1)}{8\pi v^2}$
- For thermally produced RHNs,  $10^{-3}\epsilon_1 \gtrsim \eta_{B-L} \approx 10^{-10}$   
 $\Rightarrow$  A lower bound  $M_1 \gtrsim 10^9$  GeV
- Ways out:
  - ▶ resonant leptogenesis [Pilaftsis \(1997\) \[hep-ph/9707235\]](#),  
[Pilaftsis & Underwood \(2003\) \[hep-ph/0309342\]](#)
  - ▶ RHN oscillations [Akhmedov, Rubakov, Smirnov \(1998\) \[hep-ph/9803255\]](#)

## Degenerate case: Resonant leptogenesis

- Relative mass difference  $\delta \equiv (M_2 - M_1)/M_1$
- Resonant leptogenesis possible, if

$$\delta \simeq 0.8 \times 10^{-7} \left( \frac{f(m_\nu, \Omega)}{f_{\max}} \right) \left( \frac{M_1}{10^4 \text{ GeV}} \right)$$

- ▶  $f$  contains light  $\nu$  masses and mixings  
Pascoli, Petcov, Riotto (2006) [hep-ph/0611338 & hep-ph/0609125]  
Di Bari, Ludl, Palomares-Ruiz (2016) [1606.06238]

- For  $M_1 \simeq 1 \text{ TeV}$ ,  $\delta \lesssim 10^{-9}$

# Setup

- Extra source of CP violation from the singlet scalar coupling to RHNs  
Le Dall & Ritz (2014) [1408.2498]

- Minimal scenario: a real singlet scalar

$$-\mathcal{L} \supset \left[ h_{\alpha i} \ell_{\alpha} N_i H + \frac{1}{2} (\delta_{ij} M_j + \alpha_{ij} S) N_i N_j + \text{h.c.} \right] + V(H, S)$$

- ▶ Requirements:

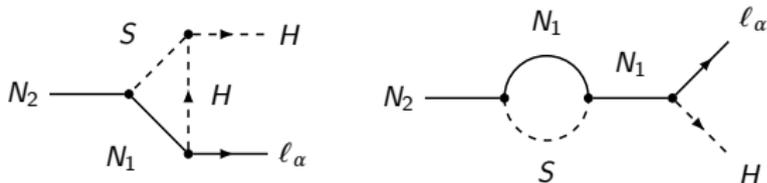
- ★ Need non-diagonal Yukawa matrix  $\alpha \Rightarrow M_j \neq 0$
- ★  $V(H, S) \supset \mu S |H|^2$

- Easily extendable to more complicated scalar sectors

- ▶ Connect RHNs to radiative EWSB in a pseudo-Goldstone Higgs scenario  
TA, Meroni, Tuominen (2017) [1706.10128]

## Extra CP asymmetry

- Additional contributions from via the singlet couplings



- For  $M_2 \gg M_1$ , one obtains

$$\varepsilon_2^V \approx -\frac{|\mu \alpha_{21}|}{8\pi M_2} \sqrt{\frac{M_1}{M_2}} \left(1 - \frac{m_S^2}{M_2^2}\right), \quad \varepsilon_2^S \approx \frac{|\alpha_{21} \alpha_{11}|}{16\pi} \sqrt{\frac{M_1}{M_2}} \left(1 - \frac{m_S^2}{M_2^2}\right)^2$$

- $\varepsilon_1$  not affected because  $N_1 \rightarrow N_2 S$  not kinematically allowed
- Extra CP violation vs. washout
  - In the standard case the  $CP$  & washout by inverse decays controlled by same combination Yukawa couplings
  - Here enhanced  $CP$  is not washed out due to additional  $N_2 \rightarrow N_1 S$  decays

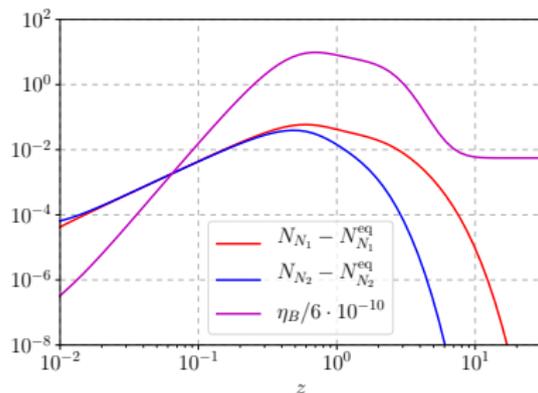
# Boltzmann equations

- With dominant washout terms  $\left( \Delta_{N_i}(z) \equiv \frac{N_{N_i}(z)}{N_{N_i}^{\text{eq}}(z)} - 1, \quad \Delta_{N_i N_j} \equiv \frac{N_{N_i} N_{N_j}}{N_{N_i}^{\text{eq}} N_{N_j}^{\text{eq}}} - 1 \right)$

$$\frac{dN_{N_2}}{dz} = -(D_2 + D_{21})\Delta_{N_2} + D_{21}\Delta_{N_1} - \Delta_{N_1 N_2} S_{N_1 N_2 \rightarrow HH} - \Delta_{N_2 N_2} S_{N_2 N_2 \rightarrow HH}$$

$$\frac{dN_{N_1}}{dz} = -(D_1 + D_{21})\Delta_{N_1} + D_{21}\Delta_{N_2} - \Delta_{N_1 N_2} S_{N_1 N_2 \rightarrow HH} - \Delta_{N_1 N_1} S_{N_1 N_1 \rightarrow HH},$$

$$\frac{dN_{B-L}}{dz} = -\sum_{i=1}^2 \varepsilon_i D_i \Delta_i - W N_{B-L}$$



$D_i : N_i \rightarrow L H$

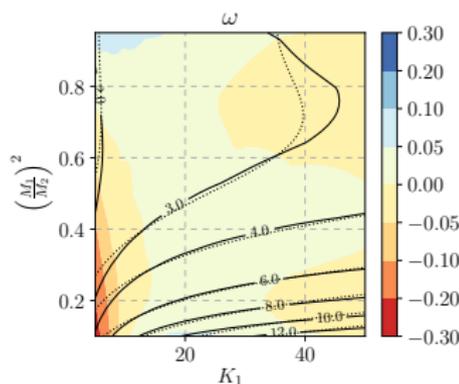
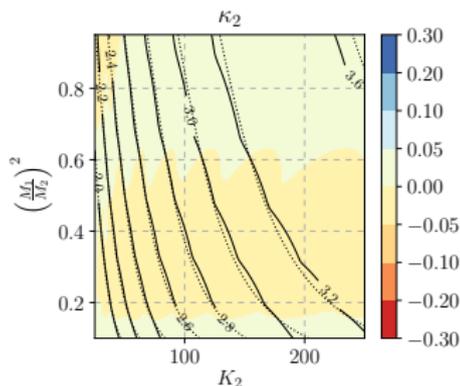
$D_{21} : N_2 \rightarrow S N_1$

## Semianalytic fit

- Goal: efficient exploration of the viable parameter space
- Neglecting scattering terms  
 $\eta_B \simeq 0.01 \kappa_2(K_2, r) \varepsilon_2 \times e^{-\omega(K_1, r)}$ ,  $r = (M_1/M_2)^2$ ,  $K_i \gtrsim 8$   
Buchmuller, Di Bari, Plumacher (2004) [hep-ph/0401240]
- Semianalytic fit beyond strongly hierarchical masses  
(cf. Blanchet, Di Bari (2006) [hep-ph/0603107])

$$\kappa_2(K_2, r) = \frac{2}{z_B(K_2)} \frac{K_2^{0.44} r^{-0.2}}{0.3 K_2 + 1.6 r^{2.6}},$$

$$\omega(K_1, r) = \frac{3\pi}{8} \left[ -K_1^{0.5} (1.4 r^2 - 2.1 r + 0.8) \ln(r) + 1.2 K_1^{0.2} \right]$$



# Washout due to scatterings

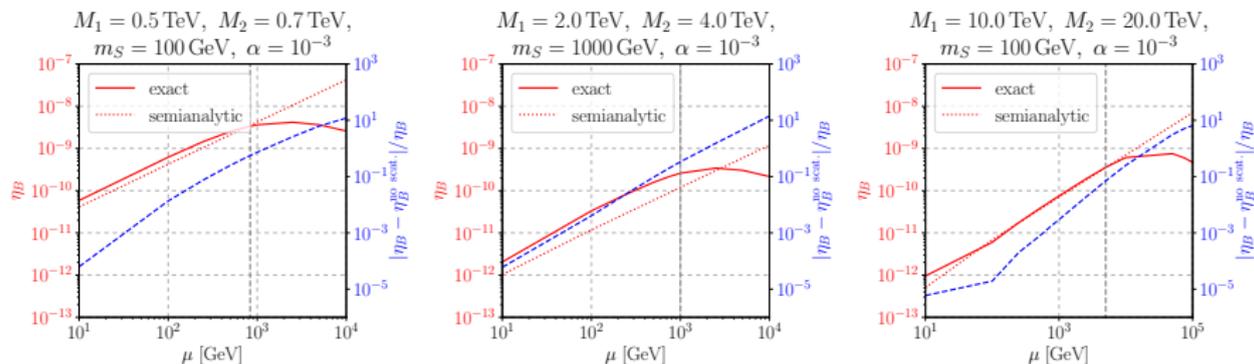
- Scatterings to di-Higgs wash out the asymmetry if the trilinear  $SH^\dagger H$  coupling is large

$$\sigma_{N_i N_j \rightarrow HH} = \frac{|\alpha\alpha^\dagger|_{ji}^2 \mu^2}{8\pi} \frac{s - (M_i + M_j)^2}{(s - m_S^2)^2 \sqrt{\delta_{M_i, M_j}}}$$

- Comparison of the semi-analytical estimate and the exact result with scattering terms  $\Rightarrow$  upper bound for  $\mu$  for which the fit is valid

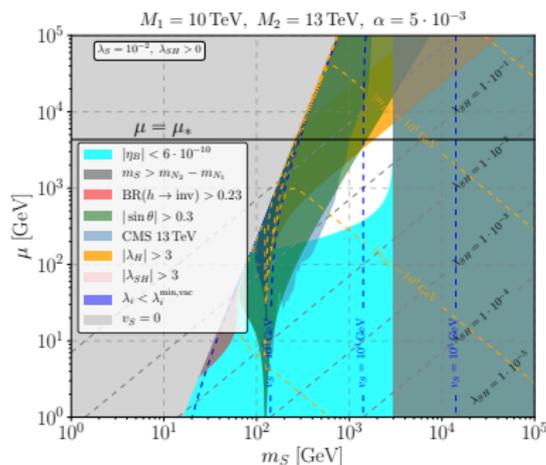
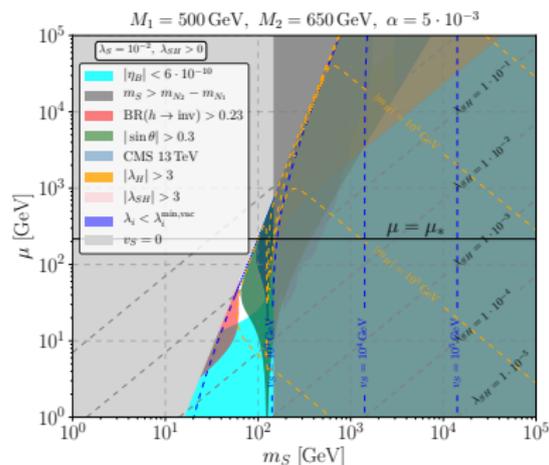
$$\mu < \mu_* \simeq M_1 \times \left( \frac{0.5}{\delta_M} \right) \left( \frac{10^{-3}}{\alpha} \right), \quad \delta_M \equiv \frac{M_2 - M_1}{M_1},$$

- Above the validity the washout larger  $\Rightarrow$  smaller baryon asymmetry



# Viable parameter space for low-scale leptogenesis

- Closer look at  $Z_2$ -symmetric scalar potential with a real singlet scalar
  - Impose constraints from LHC + perturbative unitarity & vacuum stability
- Viable region for  $m_{N_1} \gtrsim 500$  GeV



## Conclusions and Outlook

- Extended scalar sectors allow for intriguing *testable* scenarios for neutrino mass generation & leptogenesis
  - ▶ Dynamical mass for RHN's via a singlet scalar
  - ▶ Couplings between scalar and the RHN's can provide extra CP violation to circumvent the Davidson–Ibarra bound
  - ▶ Sub-TeV RHNs viable without the need for extremely degenerate RHNs
- Easily generalisable to more complicated scalar extensions
  - ▶ e.g. connect RHNs to radiative EWSB with pseudo-Goldstone Higgs  
TA, Meroni, Tuominen (2017) [[1706.10128](#)]
- Flavour effects need to be included to precisely determine the viable regions of the parameter space

Thank you!