Parameter space for testable leptogenesis

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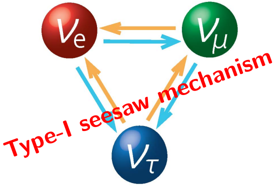
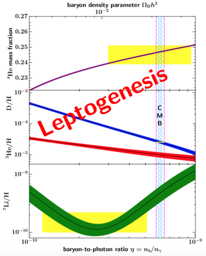
based on work in collaboration with M. Drewes and J. Klarić
[arXiv:2106.16226]

57th Rencontres de Moriond: EW session
March 20, 2023

Right-handed neutrinos (RHN)

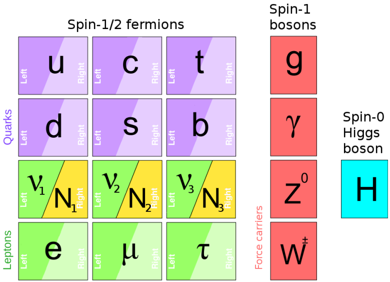


Neutrino masses



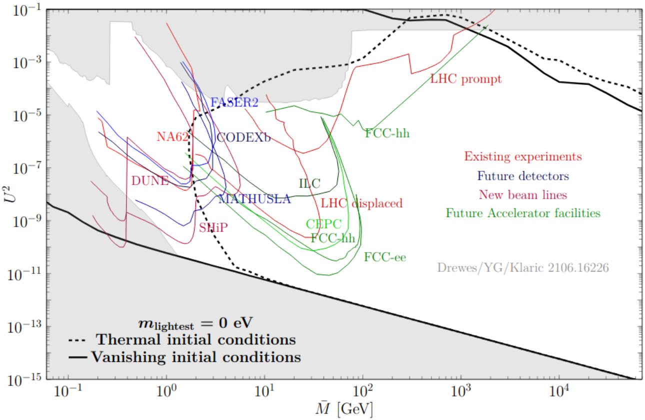
[Particle Data Group]

Baryon asymmetry



- Minimal scenario: 2 RHN generations (neutrino masses)
- In this work: 3 RHN generations (LRSM, flavour symmetries,...)
- Focus on low scale models: RHN mass at MeV-TeV scale
[see talk by J. Klarić]

Leptogenesis parameter space ($m_{\text{lightest}} = 0$ eV)



- Experiments will cut deep into $n = 3$ parameter space.
- Most optimistic case: Produce thousands of displaced vertices at HL-LHC. Testability !
- Thermal initial conditions within reach of *e.g.* NA62.

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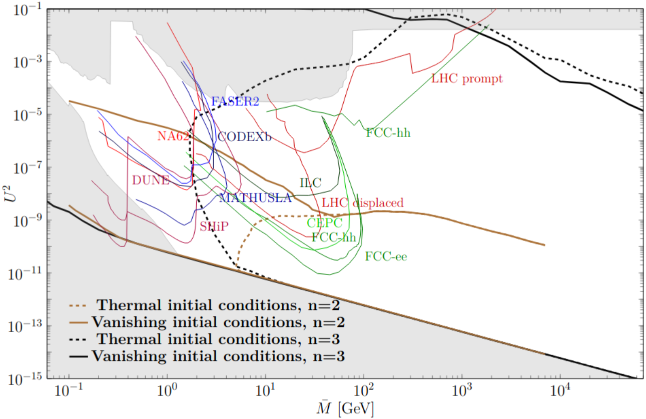

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- Most optimistic case: Observe thousands of displaced vertices at HL-LHC. Testability !
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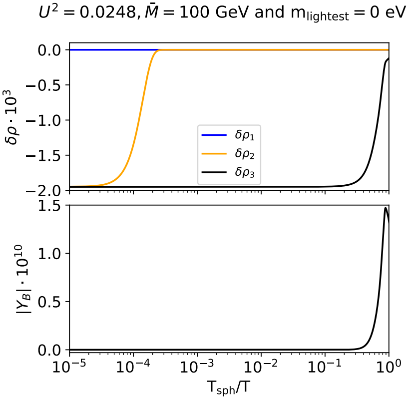
How can we understand the parameter space ?



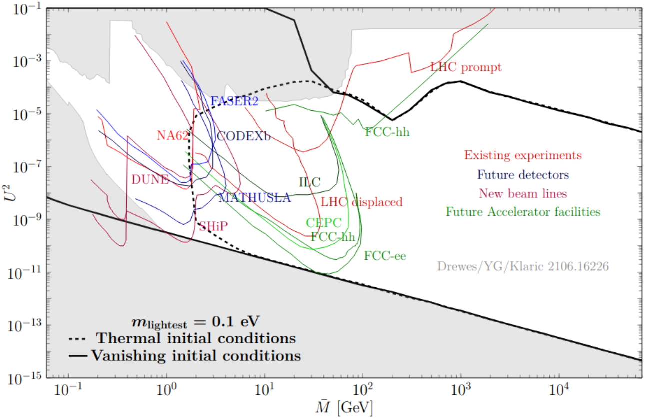
- Large mixing angles allow late equilibration of one RHN $U_i^2 \ll 1$.

  $\hookrightarrow$ Late BAU production, less time for washout.

- For thermal initial conditions, resonant and flavour effects partly compensate for $\frac{M^2}{T^2}$ suppression.

- At large $\bar{M}$, parameter space for thermal I.C. is larger because asymmetry produced during freeze-in and freeze-out have opposite signs.

Leptogenesis parameter space ($m_{\text{lightest}} = 0.1$ eV)



- Parameter space slightly smaller for $m_{\text{lightest}} = 0.1$ eV.
  $\hookrightarrow$ Weaker Yukawa hierarchy: $F = \frac{i}{v} U_\nu \sqrt{m_\nu^{diag}} \mathrm{R} \sqrt{M_M}$.
- Dip at $\bar{M} \sim 100$ GeV due to transition between freeze-in and freeze-out regime.

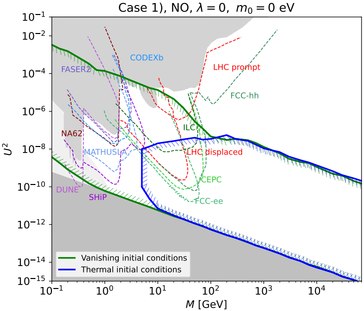
Take-home

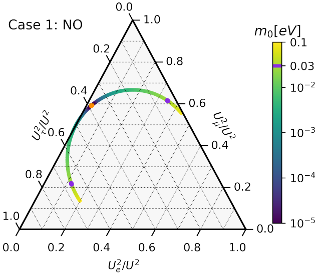
- Parameter space much larger for models with 3 RHN due to late equilibration of the additional RHN.
- Testability prospects largely improved: can hope to test RHN as solution to neutrinos masses and baryon asymmetry problem !
- Leptogenesis with thermal initial conditions work as low as $\mathcal{O}(1)$ GeV, within reach of current experiments !
- Smaller parameter space for non-zero m_{lightest} but remains large.

Thanks for your attention !

Backup slides

Parameter space in presence of flavour symmetries

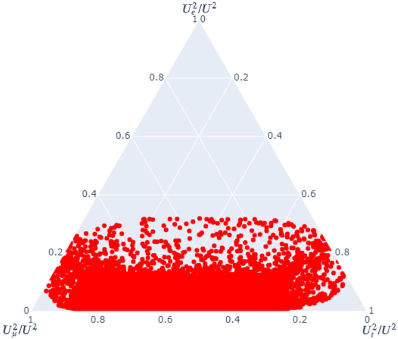




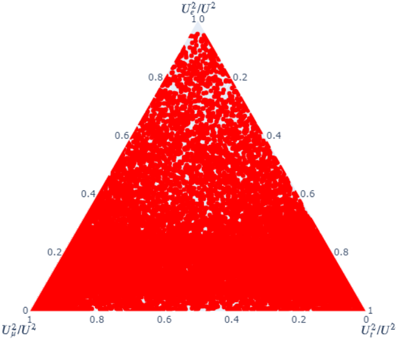
[Drewes/YG/Hagedorn/Klarič, 23xx.xxxx]

Enhanced predictivity in presence of flavour symmetries (*e.g.* $\Delta(6n^2)$)

Flavour branching ratios



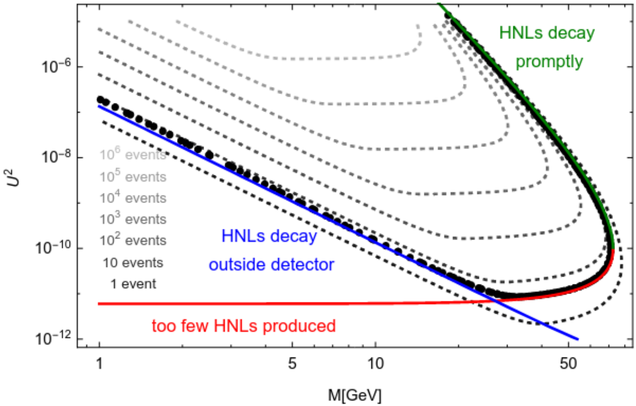
$m_{\text{lightest}} = 0$ eV



$m_{\text{lightest}} = 0.1$ eV

[Drewes/YG/Klarić 23xx.xxxx]

Expected number of events at FCC-ee



Expected number of events for

$U_e^2 : U_\mu^2 : U_\tau^2 = 0 : 1 : 0, N_Z = 2.5 \cdot 10^{12}, l_0 = 400\mu\mathrm{m}, \mathrm{d_{cyl}} = 10\mathrm{m}, \mathrm{l_{cyl}} = 8.6\mathrm{m}.$

[Drewes, 2210.17110]

Quantum kinetic equations

$$i\frac{\mathrm{d}\rho}{\mathrm{d}t} = [\mathbf{H}, \delta\rho] - \frac{i}{2}\{\Gamma, \delta\rho\} - i \sum_{a\in\{e,\mu,\tau\}} \tilde{\Gamma}_a \frac{\mu_a}{T} f_F(1-f_F),$$

$$i\frac{\mathrm{d}\bar{\rho}}{\mathrm{d}t} = -[\mathbf{H}, \delta\bar{\rho}] - \frac{i}{2}\{\Gamma, \delta\bar{\rho}\} + i \sum_{a\in\{e,\mu,\tau\}} \tilde{\Gamma}_a \frac{\mu_a}{T} f_F(1-f_F),$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{n}_{\Delta_a} = -\frac{2i\mu_a}{T}\int \frac{\mathrm{d}^3\vec{k}}{(2\pi)^3}\mathrm{Tr}[\Gamma_a] f_F(1-f_F) + i\int \frac{\mathrm{d}^3\vec{k}}{(2\pi)^3}\mathrm{Tr}[\tilde{\Gamma}_a(\delta\bar{\rho} - \delta\rho)].$$

Density matrix/**Matter-antimatter asymmetry**
Effective Hamiltonian/**Interaction rates**

- Momentum-averaged rates from Klaric/Shaposhnikov/Timiryasov [2103.165451]
- Cover a mass range from 50 MeV to 70 TeV.

B-$\bar{\text{L}}$ approximate symmetry

Naive seesaw bound

$$U_i^2 \sim \frac{\sqrt{\Delta m^2_{atm} + m^2_{light}}}{M} \lesssim 10^{-10}\frac{\text{GeV}}{M_i}$$

B-$\bar{\text{L}}$ approximate symmetry

Majorana mass

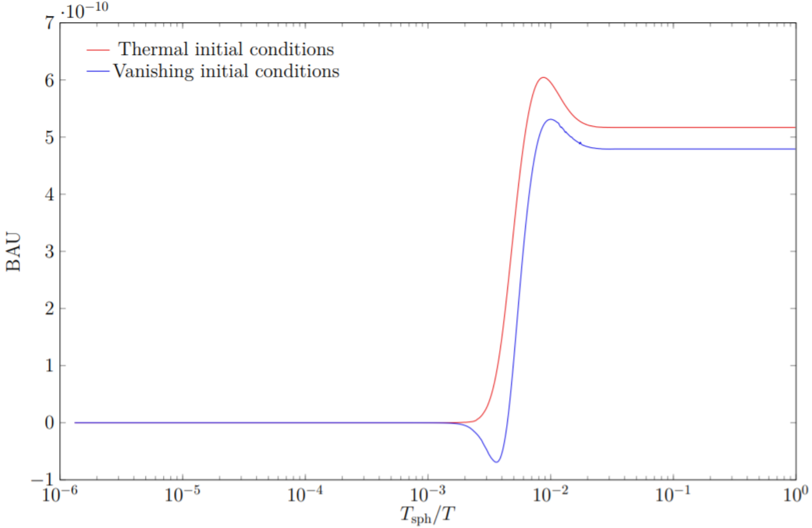
$$\bar{M} \cdot \begin{pmatrix} 1-\mu & 0 & 0 \\ 0 & 1+\mu & 0 \\ 0 & 0 & \mu' \end{pmatrix}$$

Yukawa coupling

$$\begin{pmatrix} f_e(1+\epsilon_e) & if_e(1-\epsilon_e) & f_e\epsilon'_e \\ f_\mu(1+\epsilon_\mu) & if_\mu(1-\epsilon_\mu) & f_\mu\epsilon'_\mu \\ f_\tau(1+\epsilon_\tau) & if_\tau(1-\epsilon_\tau) & f_\tau\epsilon'_\tau \end{pmatrix}$$

Smallness of light neutrino masses from the smallness of the symmetry breaking parameters $\mu, \epsilon, \epsilon' \ll 1$.

Thermal vs vanishing initial conditions



- Asymmetries generated during freeze-in and freeze-out have opposite signs.

Seesaw parameter space

Consistency with ν-oscillation data induced by Casas-Ibarra parametrisation

$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{diag}} \mathbf{R} \sqrt{M_M}$$

n=2	**n=3**
2 CP-violating phases	**3 CP-violating phases**
3 PMNS angles (fixed)	**3 PMNS angles** (fixed)
2 light neutrino masses (fixed)	**3 light neutrino masses** (2 fixed)
1 complex Euler angle	**3 complex Euler angles**
2 Majorana masses	**3 Majorana masses**
6 free parameters	13 free parameters