Low-scale leptogenesis and varying relativistic degrees of freedom

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Workshop on the Standard Model and Beyond
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P. Candia da Silva, DK, T. McKelvey, A. Pilaftsis	arXiv:2206.08352[hep-ph]	JHEP **11**, 065 (2022)
DK, T. McKelvey, A. Pilaftsis	arXiv:2310.03703[hep-ph]	Phys.Rev.D 108 (2023) 5, 055038

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3. Leptogenesis
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Observations consistently show that there are more particles than antiparticles:

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- Baryon-number violation.
- C and CP violation.
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Direct evidence of CP violation!

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A popular scenario of baryon asymmerty production is *baryogenesis through leptogenesis*:

- CP and L violation from *new physics*.
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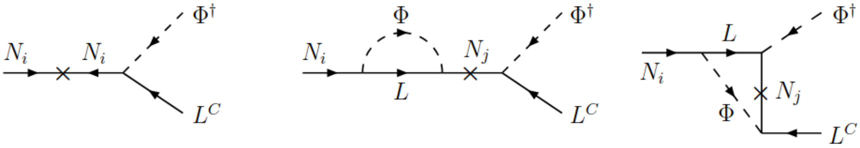
Violation of L-number terms are naturally connected to neutrino masses.



"Resonant" leptogenesis: Enhancement of CP violation due to through the mixing of (two) nearly degenerate heavy Majorana neutrinos.[2]

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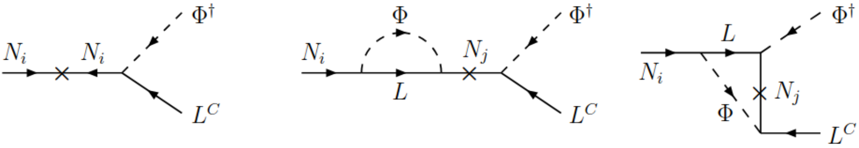

“Resonant” leptogenesis: Enhancement of CP violation due to through the mixing of (two) nearly degenerate heavy Majorana neutrinos.[2] $\Rightarrow$ Leptogenesis with small masses!

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Model – Yukawa structure

Tri-resonant model:

$$-\mathcal{L}^{\nu_R} = \boldsymbol{h}^{\nu}_{ij}\overline{L}_i\tilde{\Phi}\nu_{R,j} + \frac{1}{2}\overline{\nu}^{C}_{R,i}\left(\boldsymbol{m}_M\right)_{ij}\nu_{R,j} + \mathrm{H.c.}\ ,$$

$$\boldsymbol{h}^{\nu} = \boldsymbol{h}^{\nu}_0 + \delta\boldsymbol{h}^{\nu}\ .$$

$$\boldsymbol{h}^{\nu}_0 = \begin{pmatrix} a & a\,\omega & a\,\omega^2 \\ b & b\,\omega & b\,\omega^2 \\ c & c\,\omega & c\,\omega^2 \end{pmatrix}\ ,$$

with $\omega = exp\left(\frac{2\pi i}{3}\right)$; *i.e.* generator of $\mathbb{Z}_3$.[3]

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Reason: Tree-level and 1-loop neutrino masses vanish at leading order of $\boldsymbol{h}^{\nu}_0$. Dominant contribution comes from $\delta\boldsymbol{h}^{\nu}$.

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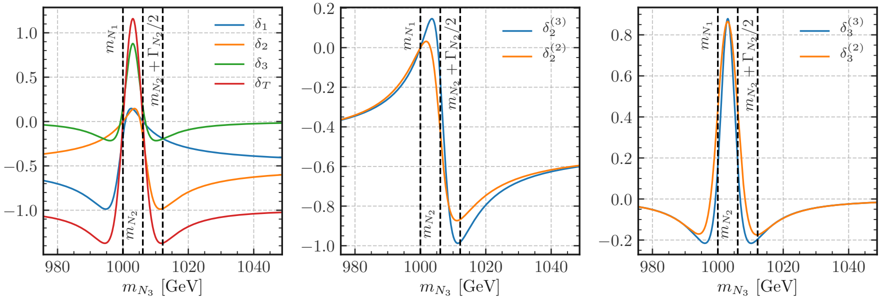
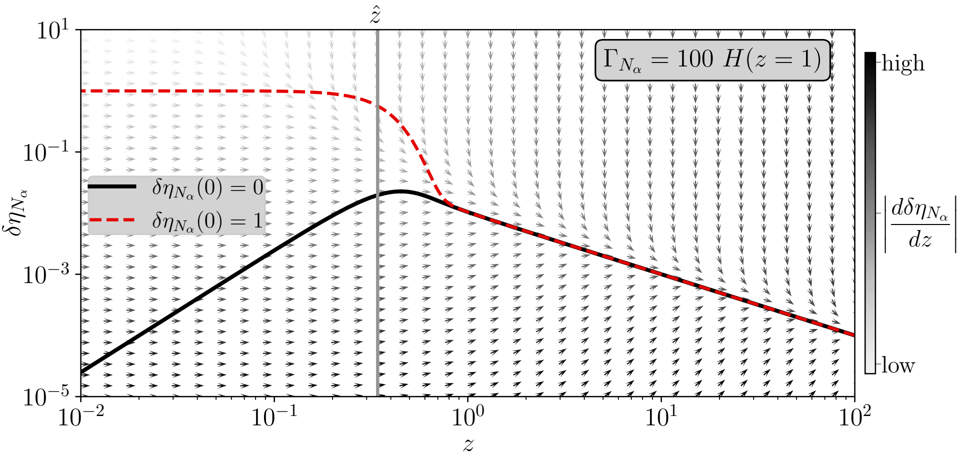
CP asymmetry, is enhanced if two right-handed neutrinos obey

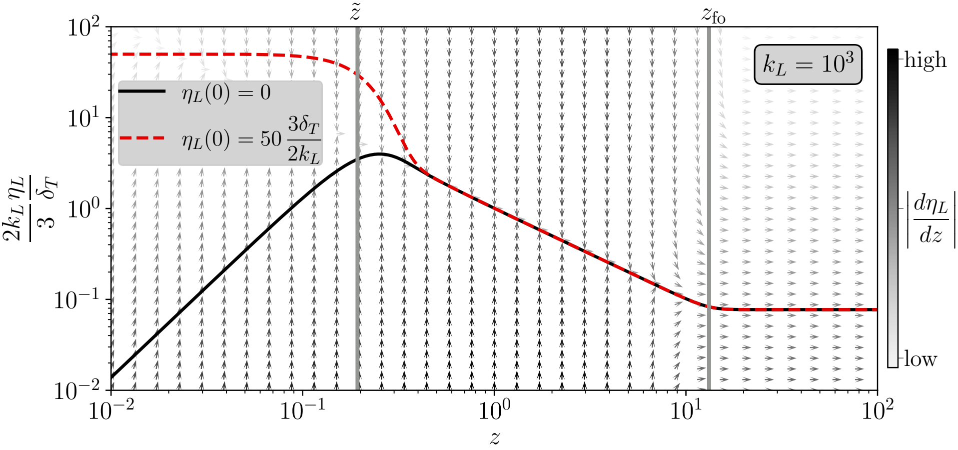
$$|m_{N_\alpha} - m_{N_\beta}| \sim \Gamma_\beta/2 \ .$$

Tri-resonant case produces even larger asymmetry:




$\hat{z}$
10^{1}
10^{-1}
10^{-3}
10^{-5}
$\delta\eta_{N_\alpha}$
$\Gamma_{N_\alpha} = 100\ H(z=1)$
$\delta\eta_{N_\alpha}(0) = 0$
$\delta\eta_{N_\alpha}(0) = 1$
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
z
high
low
$\left|\frac{d\delta\eta_{N_\alpha}}{dz}\right|$

Initial conditions: Leptons



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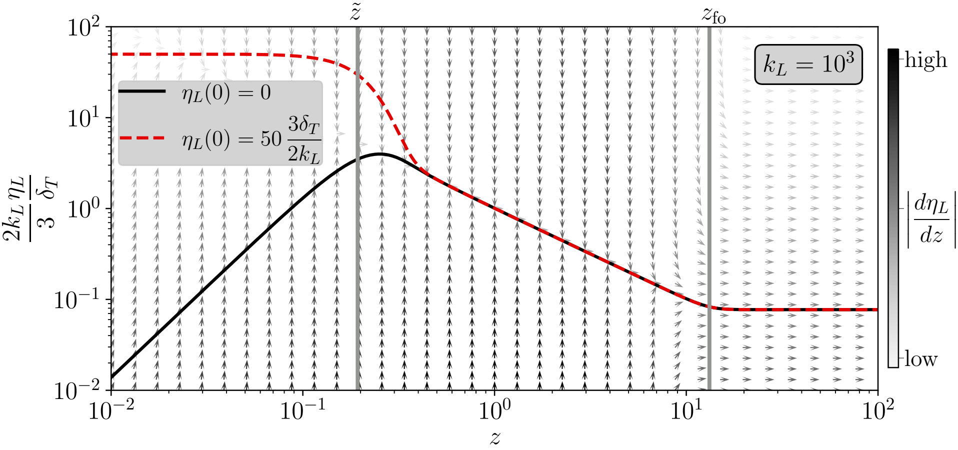

The initial conditions do not really matter!

Varying relativistic DOFs: The devil in details?

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$$\frac{d\delta\eta_N}{d\log z} \overset{z\ll 1}{\sim} -\frac{z^3}{2}\frac{\Gamma_N}{H(z=1)}\delta\eta_N + \frac{z^2}{2}(1+\delta\eta_N) - \frac{d\log h_{\rm eff}}{d\log T}(1+\delta\eta_N)$$

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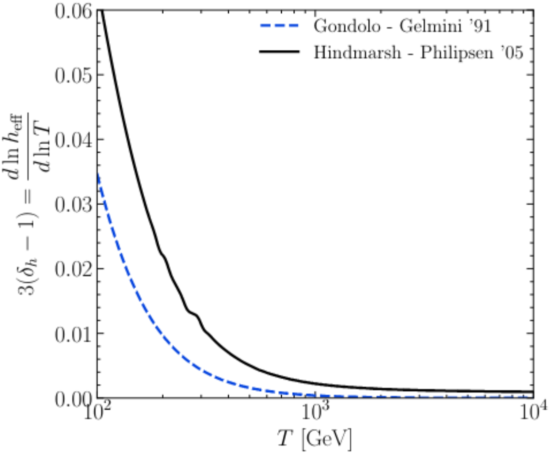
Varying relativistic DOFs: how?



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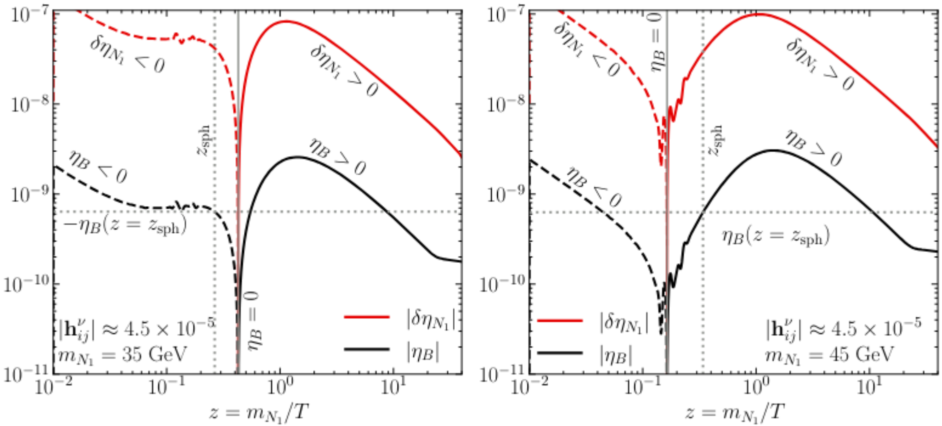
Varying relativistic DOFs: What about “attractors”?



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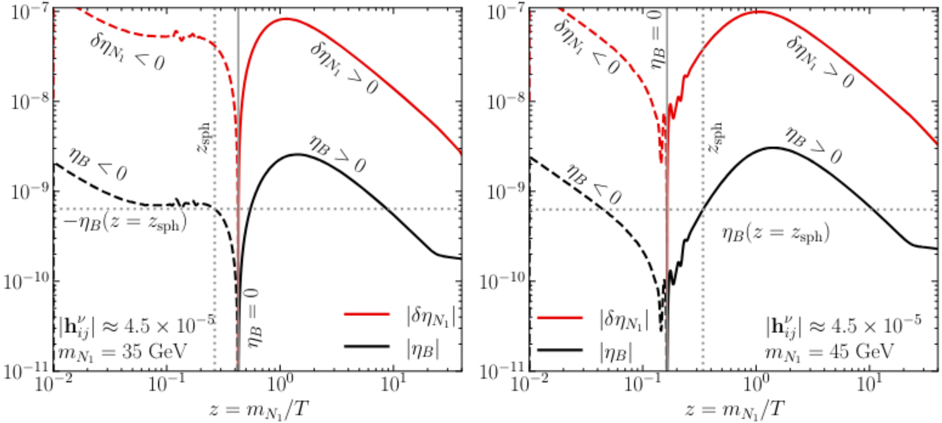

Baryon number is disturbed by $\dfrac{d\log h_{\rm eff}}{d\log T}$.

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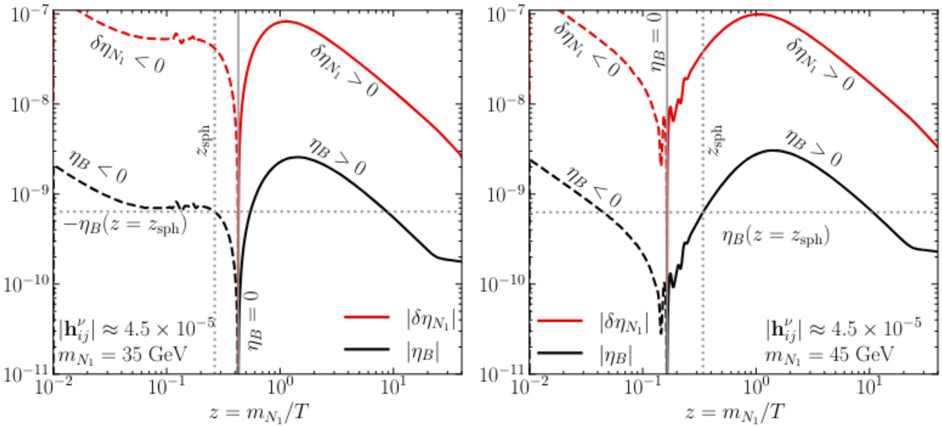
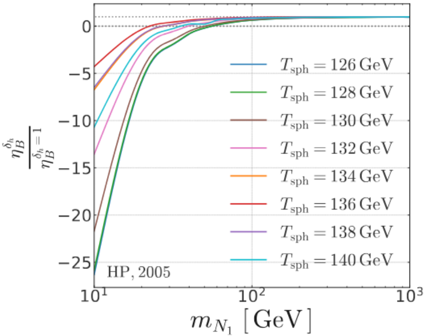
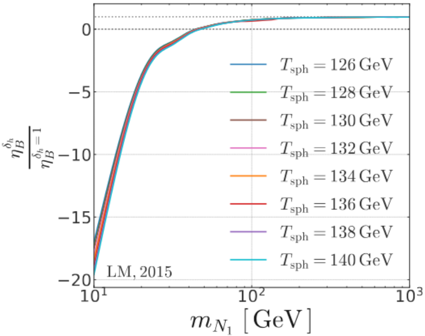


Baryon number is disturbed by $\dfrac{d \log h_{\rm eff}}{d \log T}$.

$\Rightarrow$ There may not be enough time to recover before $T_{\rm sph}$.

Varying relativistic DOFs: $T_{\rm sph}$ dependence?





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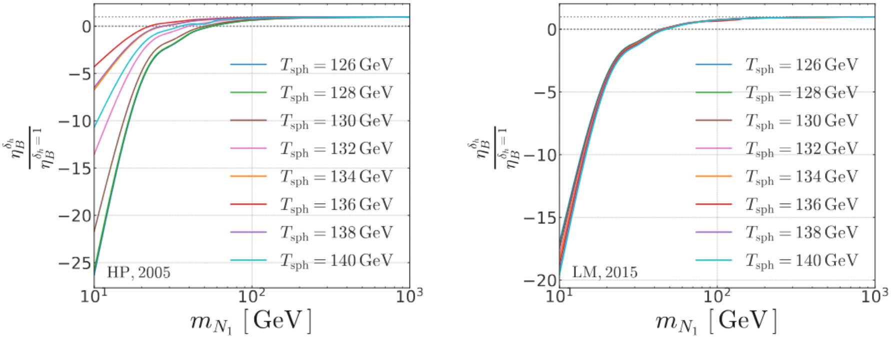

Also (sometimes) results in dependence on $T_{\rm sph}$.

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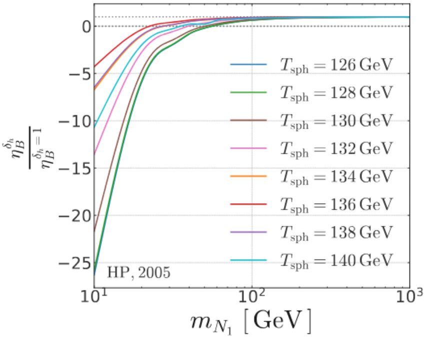
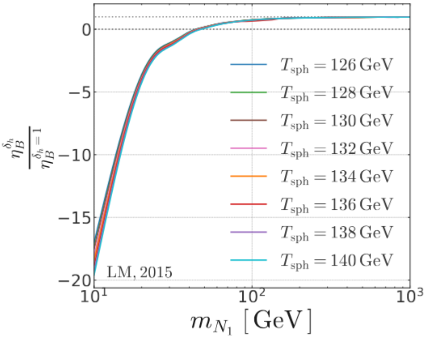
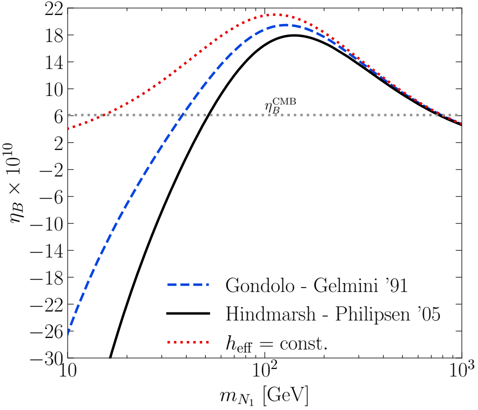


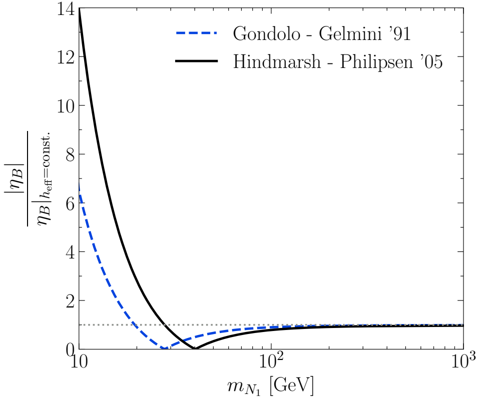


Also (sometimes) results in dependence on $T_{\rm sph}$.

$\Rightarrow$ We need accurate computation of both $\dfrac{d \log h_{\rm eff}}{d \log T}$ and $T_{\rm sph}$.

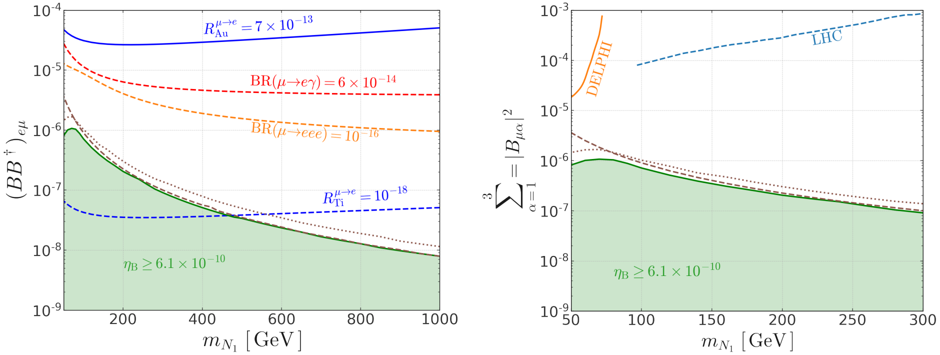
Varying relativistic DOFs: So what?





Final results

We solve the transport equations in the mass basis of the heavy neutrinos.[4]



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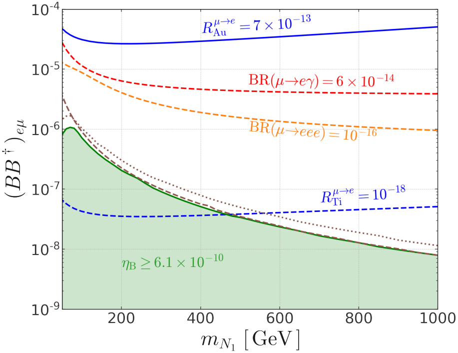

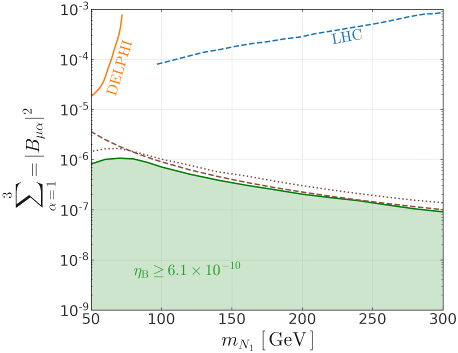

Possible probe: $\mu \to e$ transitions within Titanium.[5]

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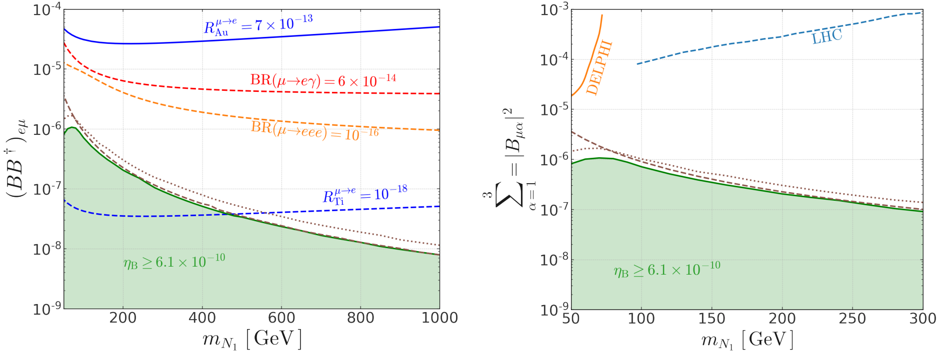

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Note the difference below $m_{N_1} \approx 100$ GeV.

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As for the future:

- Multi-resonant leptogenesis?
- Study known models including varying h_{eff}, to find how much they change.
- Extensions of TRL might introduce additional CP violations or mixing, making the parameter space better?

Thank you!