The Neutrino Option

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based on 1703.10924, 1809.03450, 1905.12642
with M. Trott, K. Moffat, S. Pascoli, S. Petcov, J. Turner

The issue: origin of the Higgs potential

The Higgs potential gives a successful parameterization of the electroweak symmetry breaking

$$V(H^\dagger H) = -\frac{m_H^2}{2}\,(H^\dagger\,H) + \lambda\,(H^\dagger\,H)^2$$

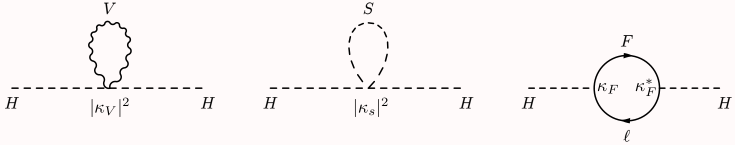
but it lacks **a dynamical origin**! $\longleftrightarrow$ several theoretical **problems**:

hierarchy, stability, triviality, phase transition? ...

The hierarchy problem in an EFT perspective

Brivio,Trott 1706.08945

Heavy new physics can give loop corrections to $(H^\dagger H)$



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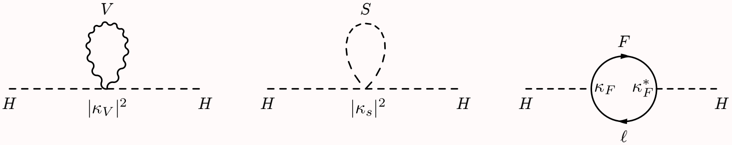

$\downarrow$ integrating it out

threshold matching contributions at $E < m_i$

[loops in DR+$\overline{MS}$ in the lim $v/m_i \to 0$]

$$\Delta V(H^\dagger H) \simeq H^\dagger H \left(\frac{3|\kappa_v|^2\ m_v^2\ N_v}{16\,\pi^2} + \frac{|\kappa_s|^2\ m_s^2\ N_s}{16\,\pi^2} - \frac{|\kappa_F|^2\ m_F^2\ N_F}{16\,\pi^2} \right) + \dots$$

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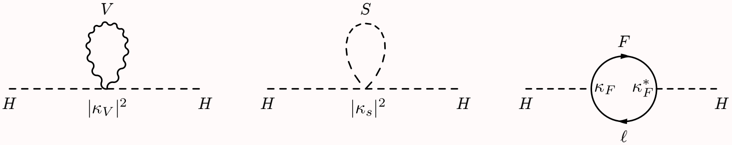

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these corrections are always proportional to the scale integrated out

$\to$ one of the main complications when UV completing the potential

Traditional solutions

Common approaches:

(a) SUSY way: extra symmetry to **force cancellations** among thresholds

(b) Composite way: shift symmetry to protect $H^\dagger H$

↓

potential **generated radiatively**.

$$V(H) \simeq \frac{g_{SM}^2 \Lambda^2}{8\pi^2}\left(-a\, H^\dagger H + b\, \frac{(H^\dagger H)^2}{f^2}\right)$$

Bellazzini,Csáki,Serra 1401.2457

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Bellazzini,Csáki,Serra 1401.2457

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Bellazzini,Csáki,Serra 1401.2457

- both require resonances not far from TeV scale
- the potential must be generated at once. That's not trivial!

tuning of a, b ↔ complex spectrum / symmetry setup

needed to get

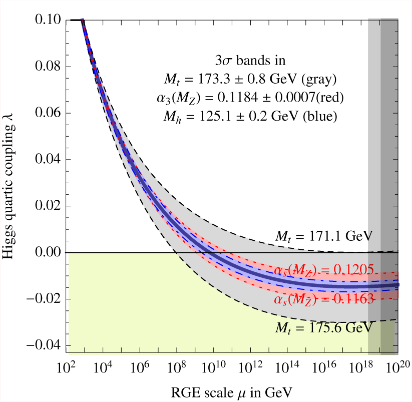
the right shape + $\mathbf{\frac{v^2}{f^2} = \frac{a}{b} \lesssim 1}$

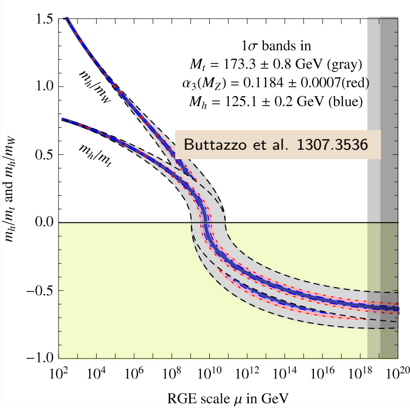
A change in perspective

Having measured the Higgs mass opens new possibilities!

An important one: controlling the **running** of the potential to very high energies.

Elias-Miro et al. 1112.3022, Degrassi et al,1205.6497, Espinosa et al. 1505.04825



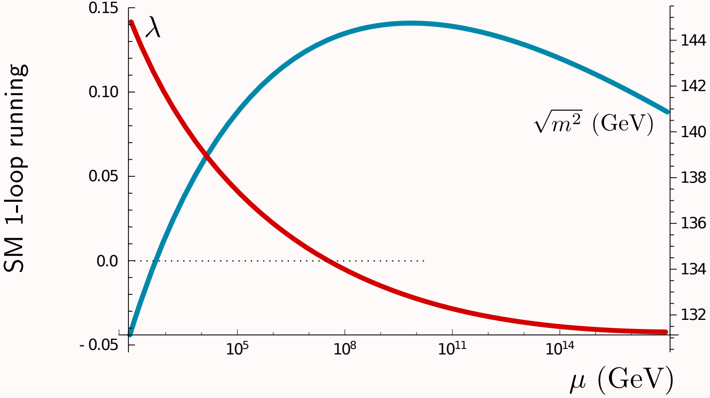


Buttazzo et al. 1307.3536

We can move the stabilization problem from the TeV to a much higher scale

Building the potential in the UV

idea: some very heavy UV sets the initial conditions at a high scale



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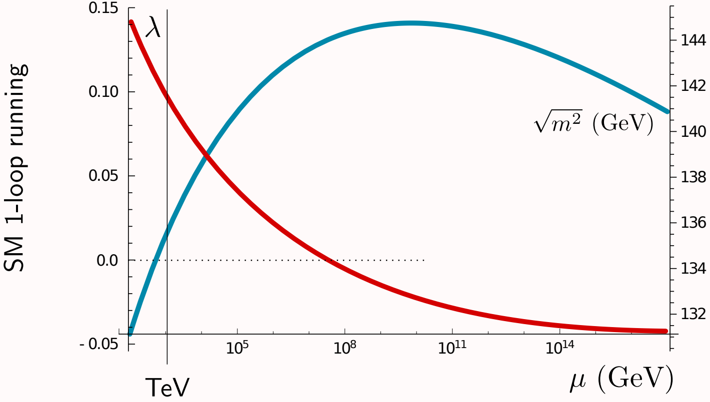

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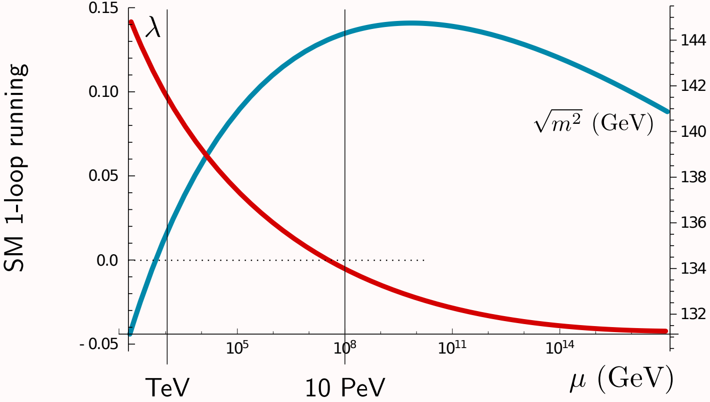

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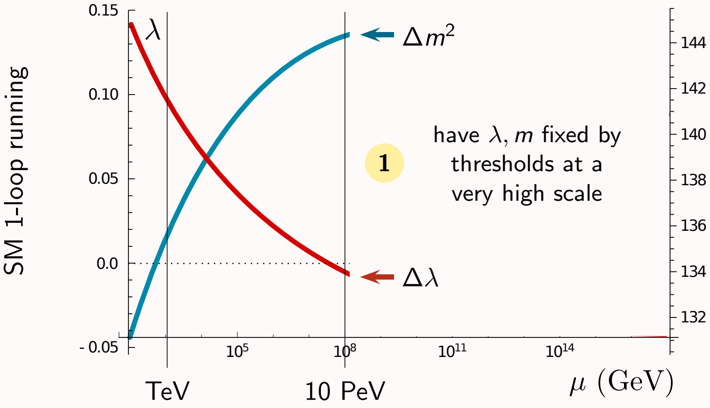

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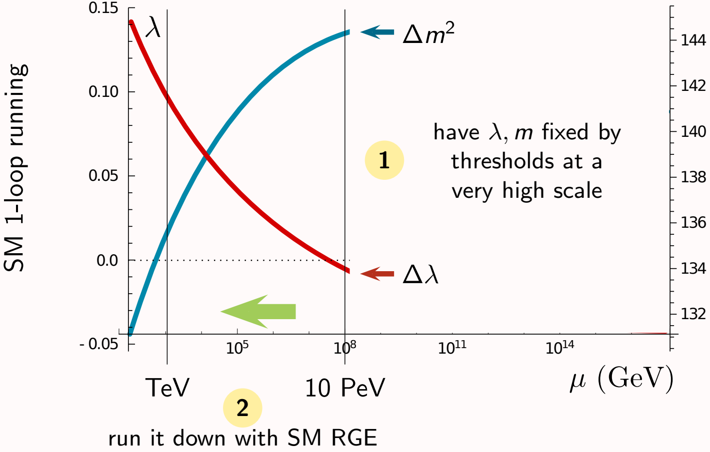


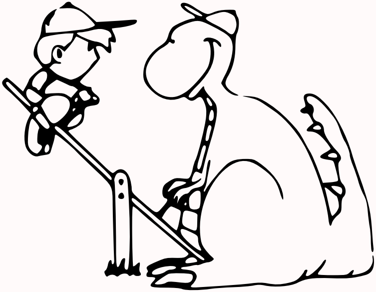
Can type I seesaw generate the Higgs potential?

$$\mathcal{L}_N = \frac{1}{2}\overline{N}(i\partial\!\!\!/ - M)N - \left[\overline{N}\,\omega\,\tilde{H}^\dagger \ell_L + \overline{\ell_L}\,\tilde{H}\,\omega^\dagger N\right]$$

Minkowski 1977
Gell-Mann,Ramond,Slansky 1979
Mohapatra,Senjanovic 1980
Yanagida 1980

with n Majorana neutrinos $N = N^c$:

M real, diagonal
ω $n \times 3$ matrix in flavor space



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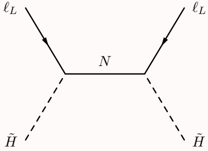
M ≫ v



$$m_\nu = \frac{v^2}{2}\,\omega^T M^{-1}\omega$$

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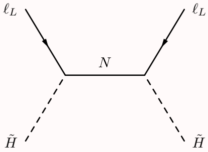

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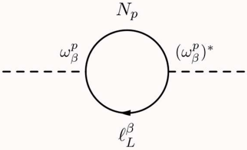
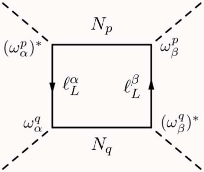


$$\Delta m_H^2 =\sim M^2 \frac{|\omega|^2}{8\,\pi^2}$$



$$\Delta\lambda \sim -\frac{5}{32\pi^2}|\omega|^4$$

(flavor indices omitted)

Vissani hep-ph/9709409
Casas et al hep-ph/9904295

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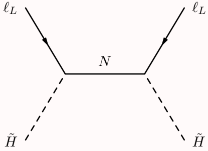
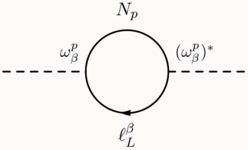
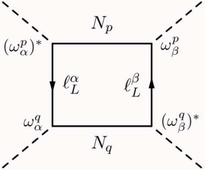
2 free quantities
in the UV
($\sim$ deg. M, no tunings)

M $\gg$ v







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3 constraints at the EW scale

(flavor indices omitted)

Vissani hep-ph/9709409
Casas et al hep-ph/9904295

Preliminary study

fix ω, M to generate

m_H

λ

$\longrightarrow$

check

m_ν

Brivio, Trott 1703.10924

Key assumptions

- start with nearly-vanishing classical potential at $\mu \gtrsim M$:

  approximate **scale invariance** + explicit breaking only from Majorana mass

- threshold contributions **from other NP** and **SM** contributions to the Coleman-Weinberg potential are subdominant.

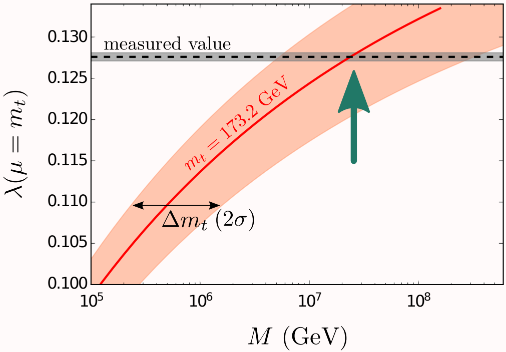
  SM: OK for $M|\omega| \gg v, \Lambda_{QCD}$.

Preliminary study: results

$\lambda(m_t)$ is not sensitive to $|\omega|$ but depends significantly on M

$\downarrow$

best fit $M \simeq 10^{7.4}$ GeV $\simeq 25$ PeV



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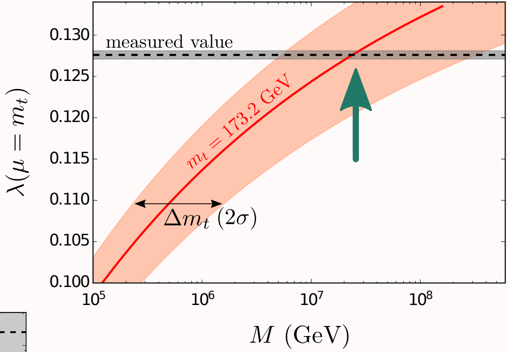

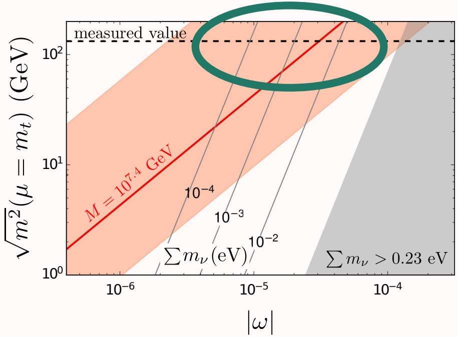

with fixed M, $m_H^2(m_t)$ determines uniquely $|\omega| \simeq 10^{-4.5}$

$\downarrow$

$$\sum |m_\nu| = \frac{3|\omega|^2}{2}\frac{v^2}{M} \simeq 3 \cdot 10^{-3}\ \text{eV}$$

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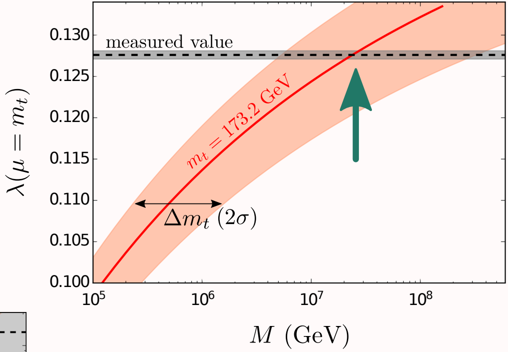

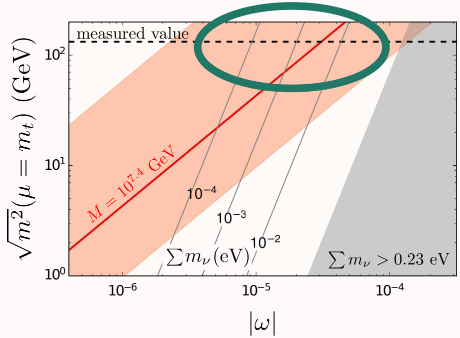

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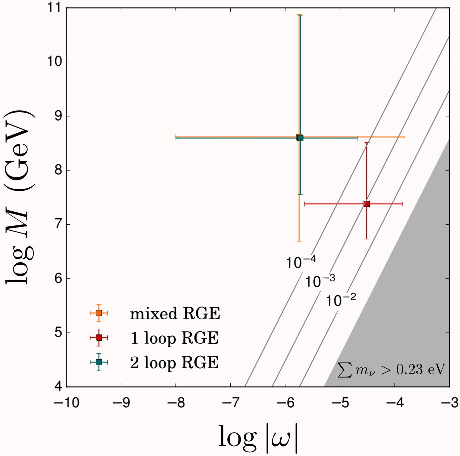
(Un)buried bodies

- High **numerical sensitivity** to m_t + RGE order
- Higher order RGEs point to lighter m_ν (too light!)
- ω too small for *thermal* leptogenesis Davoudiasl,Lewis 1404.6260
- Challenge:
  defining a **UV completion** with a classically vanishing potential and a generation mechanism for M
  Brdar,Emonds,Helmboldt,Lindner 1807.11490
  Brdar,Helmboldt,Kubo 1810.1230
  ⇝ Vedran's talk



Improved study

relax the assumption $\lambda_0 \simeq 0$

Brivio, Trott 1809.03450

simply start from a conformal potential $\mathbf{m^2_{H,0} \simeq 0}$

fix ω, M to generate

m_H

m_ν

in agreement with the measurements

$\longrightarrow$

use the freedom to fix

λ_0

to adjust the value of

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consider flavor effects

- choose seesaw with **2** heavy N $\rightarrow m_{\nu,\text{ lightest}} = 0$
- Δm^2_{ij}, θ_i, δ, α_i fully specified via Casas-Ibarra par. and varied in 3σ allowed range

Esteban et al. 1611.01514

Improved study results: ω, M

running effects have a small impact on both m_H, m_ν

Brivio,Trott 1809.03450

$$m_H^2 \simeq \frac{M^2|\omega|^2}{8\pi^2} \sim (10^2\,\mathrm{GeV})^2$$

$$m_\nu \simeq \frac{|\omega|^2 v^2}{2M} \gtrsim 0.01\,\mathrm{eV}$$

$\longrightarrow$

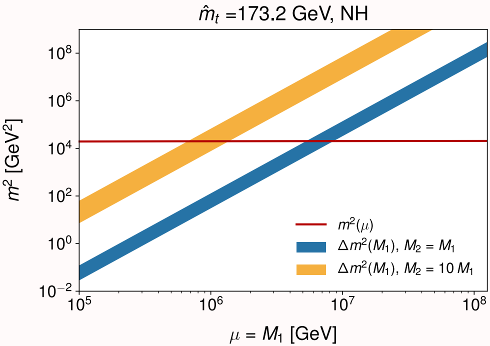
$$|\omega| \simeq \frac{1\,\mathrm{TeV}}{M}$$

$$M \lesssim 10^4\,\mathrm{TeV}$$

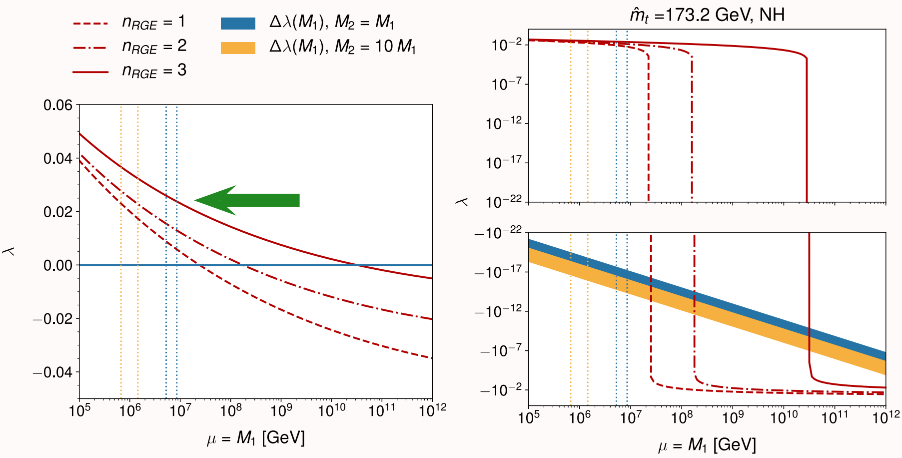
This result is **very stable** under variations of m_t and RGE running order!

$\downarrow$

prediction of this scenario



Improved study results: λ_0



the boundary condition for λ in the $\mu = M$ region selected by m_ν, m_H **cannot** be matched by the seesaw threshold contribution alone

Brivio, Trott 1809.03450

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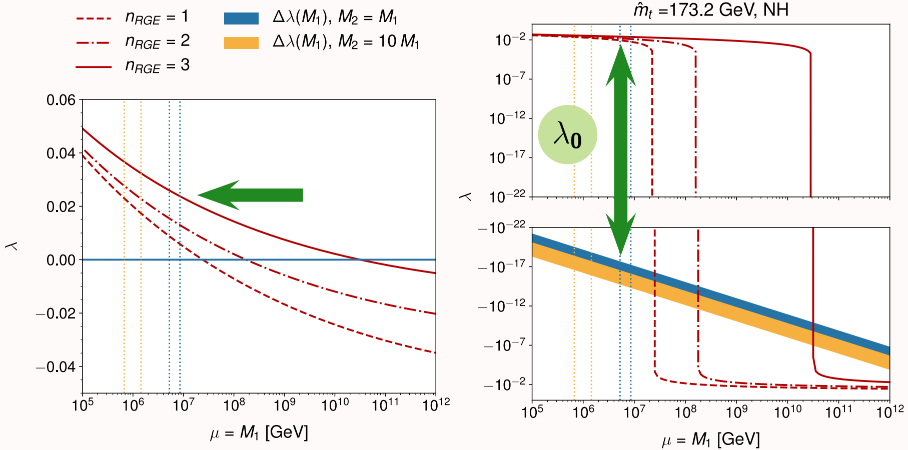

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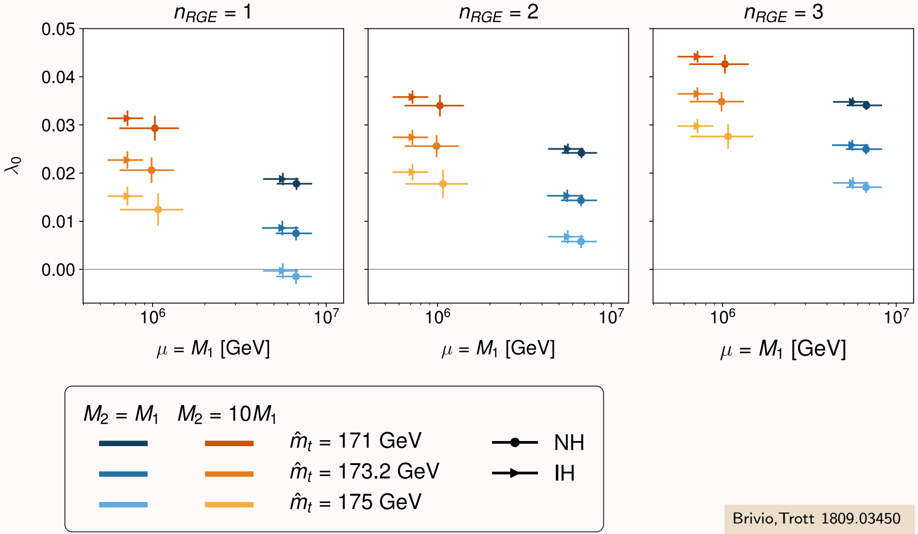
Brivio,Trott 1809.03450

Improved study results: λ_0

The value of λ_0 needed to obtain the SM potential depends on m_t, n_{RGE}



Brivio,Trott 1809.03450

What about leptogenesis?

- thermal
- thermal with enhanced R-matrices — Moffat,Pascoli,Petcov,Schulz,Turner 1804.05066

  $\rightsquigarrow$ Jessica's talk
- resonant — Pilaftsis,Underwood 0309342,0506107

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- resonant **?**

Moffat,Pascoli,Petcov,Schulz,Turner 1804.05066

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Pilaftsis,Underwood 0309342,0506107

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minimal case: $N_1, N_2, \quad M_i = 10^6 - 10^7$ GeV

Brivio,Moffat,Pascoli,Petcov,Turner 1905.12642
Brdar,Helmboldt,Iwamoto,Schmitz 1905.12634

resonant leptogenesis ↔ $\Delta M \sim \Gamma_N \ll \dfrac{M_1 + M_2}{2}$
→ asymmetry amplified by mixing among heavy states

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resonant leptogenesis $\leftrightarrow$ $\Delta M \sim \Gamma_N \ll \dfrac{M_1 + M_2}{2}$

→ asymmetry amplified by mixing among heavy states

are there points for which $\begin{cases} \Delta m_H^2 = m_H^2(\mu = M) \\ \eta_B = 6.1 \times 10^{-10} \end{cases}$ simultaneously?

λ_0 is irrelevant here → condition on M

Resonant leptogenesis in the Neutrino Option

(A) approximate solution of Boltzmann equations:

largest dependence on: M y

$$\Delta m_H^2 \;\sim\; \cosh(2y) M^3 \sum_i m_{\nu,i}$$

in Casas-Ibarra param. (NH):

$$R = \begin{pmatrix} 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \\ 1 & 0 & 0 \end{pmatrix}, \quad \theta = x + iy$$

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min M $\leftrightarrow$ max y

$$\eta_{B-L} \sim f_{res}(M_i, \Gamma_i) e^{-4y} \sin 2x$$

maximize η_{B-L} over other params

↓

maximize y

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$\min M \leftrightarrow \max y$	$\max M \leftrightarrow y = 0$
maximize $\eta_{B-L} \;\sim\; f_{res}(M_i, \Gamma_i) e^{-4y} \sin 2x$ over other params ↓ maximize y	η_B can always be matched adjusting phases. ↓ M fixed by m_H constraint

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maximize

$$\eta_{B-L} \sim f_{res}(M_i, \Gamma_i) e^{-4y} \sin 2x$$

over other params

$\downarrow$

maximize y

max M $\leftrightarrow$ $y = 0$

η_B can always be matched adjusting phases.

$\downarrow$

M fixed by m_H constraint

$M > 1.2 \times 10^6$ GeV, $y < 190.22^\circ$	[NH]	$M < 8.8 \times 10^6$ GeV
$M > 2.4 \times 10^6$ GeV, $y < 118.21^\circ$	[IH]	$M < 7.4 \times 10^6$ GeV

Resonant leptogenesis in the Neutrino Option

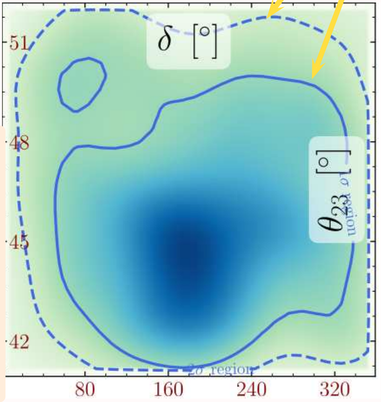
(B) numerical analysis with exact Boltzmann equations

fixed $M \rightarrow$ fix y from m_H constraint $\rightarrow$ scan over other parameters

2D projections @ min M:

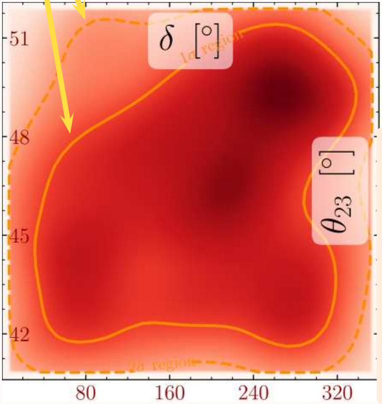
$1\sigma, 2\sigma$ compatible with η_B

NH



$M = 1.2 \times 10^6$ GeV, $y = 190.22^\circ$, $\theta_{12} = 33.63^\circ$, $\theta_{13} = 8.51^\circ$

IH

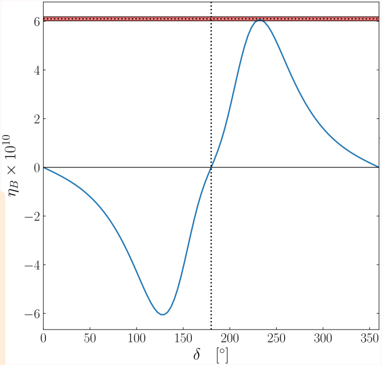


$M = 2.4 \times 10^6$ GeV, $y = 118.21^\circ$, $\theta_{12} = 33.63^\circ$, $\theta_{13} = 8.51^\circ$

Resonant leptogenesis in the Neutrino Option

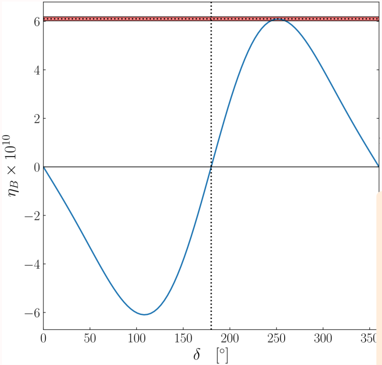
@ max M, $y = 0 \rightarrow$ ~~CP~~ only from SM phases $(\delta, \alpha, \alpha')$

NH



$M = 8.8 \times 10^6$ GeV
$y = 0,\ \alpha, \alpha' = 0$

IH



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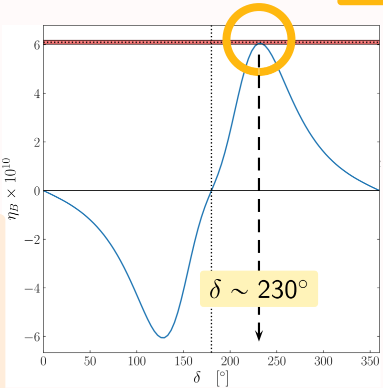
successful leptogenesis!

NH



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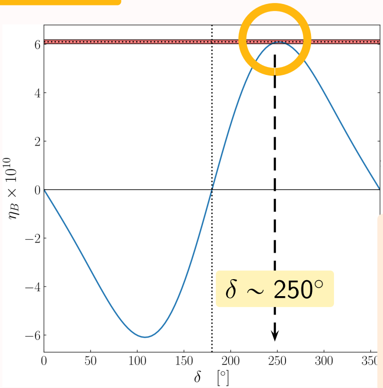

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- type I seesaw is minimal & compelling ☺
  but the key idea of generating the potential at high scale is general!
  can be also applied to other UVs