Phenomenology of Right-Handed Neutrinos in the Littlest Seesaw

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Advances in High Energy Physics and Cosmology
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22 Mar 2018

ongoing work with S. Molina-Sedgwick and Prof. S.F. King

Outline

- Background
  - Type-I Seesaw Mehchanism
  - Leptogenesis
  - Minimal Model: *The Littlest Seesaw*
- This Work: *Phenomenology of RH Neutrinos*
- Preliminary Results
- Outlook

Neutrino Physics and Cosmology

- Standard Model cannot explain neutrino masses and oscillations or the observed BAU

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s} > 0$$

- Possible solution: models that utilise a Type-I Seesaw mechanism

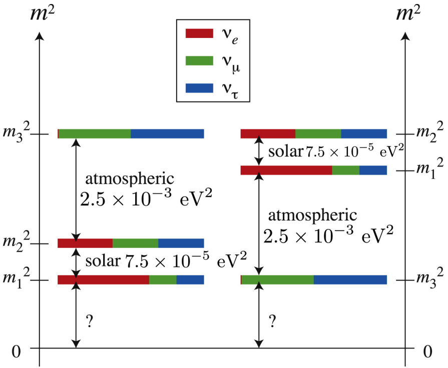

Figure: [King:1701.04413]

Type-I Seesaw Mechanism

- Extend the SM by a number of right-handed neutrinos - ν_R
- Give rise to additional terms in the Lagrangian:

$$\mathcal{L}_m^D = -Y_\nu \bar{\ell}_L \tilde{H} \nu_R + h.c. \quad \xrightarrow{EWSB} \quad -m_D \overline{\nu_L} \nu_R + h.c.$$

$$\mathcal{L}_m^M = -\frac{1}{2} M_R \overline{\nu_R^c} \nu_R + h.c.$$

- Collect such terms $\implies$ neutrino mass matrix:

$$\begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

- In the limit $M_R \gg m_D$, diagonalise to obtain light neutrino masses:

$$m_\nu = m_D M_R^{-1} m_D^T = v^2 Y_\nu M_R^{-1} Y_\nu^T$$

Leptogenesis

- Method of creating baryon asymmetry
- Generate a lepton asymmetry through the decay of lightest RHν into each lepton flavour

$$Y_{\Delta\alpha} = \eta_\alpha \epsilon_\alpha Y_{\nu_1}^{eq}$$

- Lepton asymmetry converted to baryon excess through sphaleron processes in the SM

$$Y_B = \frac{12}{37} \sum_\alpha Y_{\Delta\alpha}$$

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Extend the SM by **two** RH ν singlets: $\nu_R = \begin{pmatrix} \nu_R^{atm} \\ \nu_R^{sol} \end{pmatrix}$

$$-\mathcal{L}_{LS} = -\mathcal{L}_{SM} + (Y_\nu \bar{\ell}_L \tilde{H} \nu_R + \frac{1}{2} M_R \overline{\nu_R^c} \nu_R + h.c.)$$

N.B. Y_ν is a 2×3 matrix and M_R is 2×2

Constrained Sequential Dominance $\implies$ **heaviest** RHν gives dominant contribution to the **heaviest** LH neutrino mass

Two RHνs $\implies$ lightest LH neutrino is **massless**, $m_1 = 0$

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Fixes the absolute scale of neutrino masses

Constraints on Δm_{12} and Δm_{13} → constraints on $\mathbf{m_2}$ and $\mathbf{m_3}$

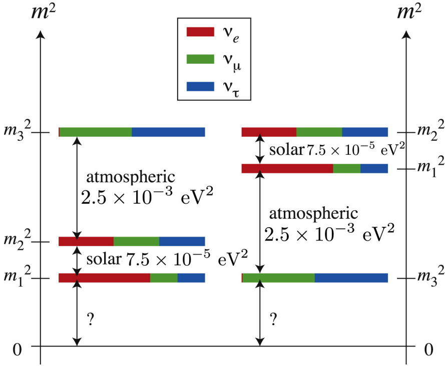

Figure: [King:1701.04413]

Four distinct cases of the LS, two of which relevant for leptogenesis.

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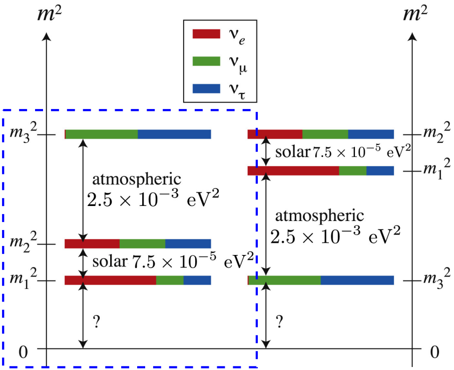

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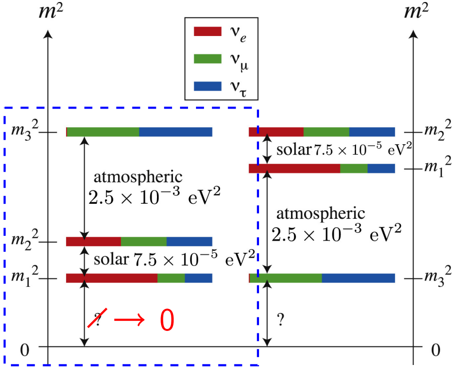

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Relevant Cases of the LS

- Case A:

$$Y_\nu^A = \begin{pmatrix} 0 & be^{i\eta/2} \\ a & nbe^{i\eta/2} \\ a & (n-2)be^{i\eta/2} \end{pmatrix}, \quad M_R^A = \begin{pmatrix} M_{atm} & 0 \\ 0 & M_{sol} \end{pmatrix}$$

- Case D:

$$Y_\nu^D = \begin{pmatrix} be^{i\eta/2} & 0 \\ (n-2)be^{i\eta/2} & a \\ nbe^{i\eta/2} & a \end{pmatrix}, \quad M_R^D = \begin{pmatrix} M_{sol} & 0 \\ 0 & M_{atm} \end{pmatrix}$$

RG Evolution

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- Evolve observables to low scales through **RG running**

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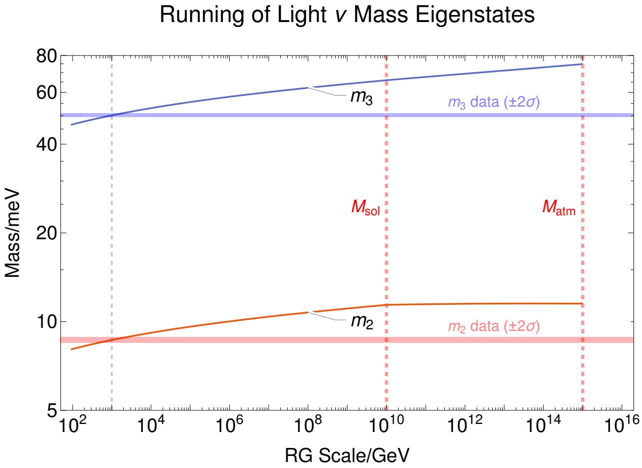


Case D:

$M_{atm} = 1.0 \times 10^{15}\,GeV$

$M_{sol} = 1.0 \times 10^{10}\,GeV$

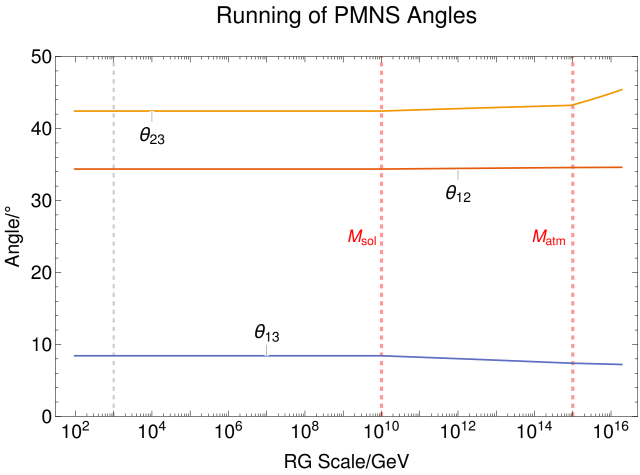
$a = 1.24691$

$b = 0.00114306$

$n = 3$

$\eta = -2\pi/3$

RG Evolution (2)



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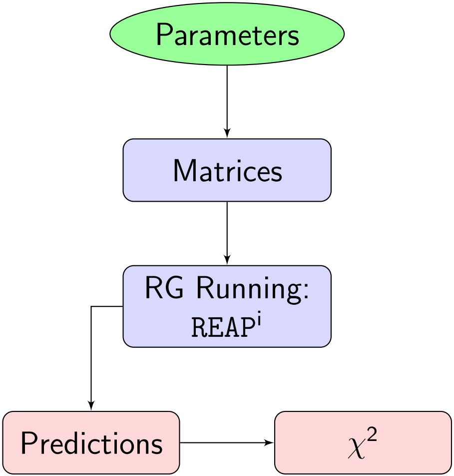
- **To accurately predict the masses of the RH neutrinos in the Littlest Seesaw**
- Use precision neutrino data and BAU from Leptogenesis

Observable	*Measured Value*
$sin^2(\theta_{12})$	$0.307^{+0.013}_{-0.012}$
$sin^2(\theta_{13})$	$0.02206^{+0.00075}_{-0.00075}$
$sin^2(\theta_{23})$	$0.538^{+0.033}_{-0.069}$
δ	$-126^{\circ}{}^{+43^{\circ}}_{-31^{\circ}}$
$\Delta m_{12}{}^2$	$7.40^{+0.21}_{-0.20} \times 10^{-5}\text{eV}^2$
$\Delta m_{13}{}^2$	$2.494^{+0.033}_{-0.031} \times 10^{-3}\text{eV}^2$
Y_B	$0.87^{+0.01}_{-0.01} \times 10^{-10}$

[Esteban et. al.(NuFit 3.2), arXiv:1611.01514]

[Plack Collaboration: arXiv:1303.5076]

This work



Scan over RH neutrino masses:

$$\begin{aligned} 1.0 \times 10^9 \leq M_1 &\leq 5.0 \times 10^{12} \\ 5M_1 \leq M_2 &\leq 1.0 \times 10^{16} \end{aligned}$$

a and *b* are left as free parameters.

n fixed to 3 [Geib et. al.:1709.07425]

η fixed to be $\pm 2\pi/3$

[i]Antusch et. al.:hep-ph/0501272.

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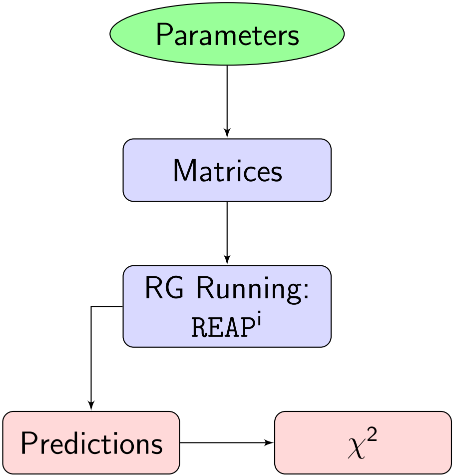

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Determine the best fit point for each case by minimising χ^2

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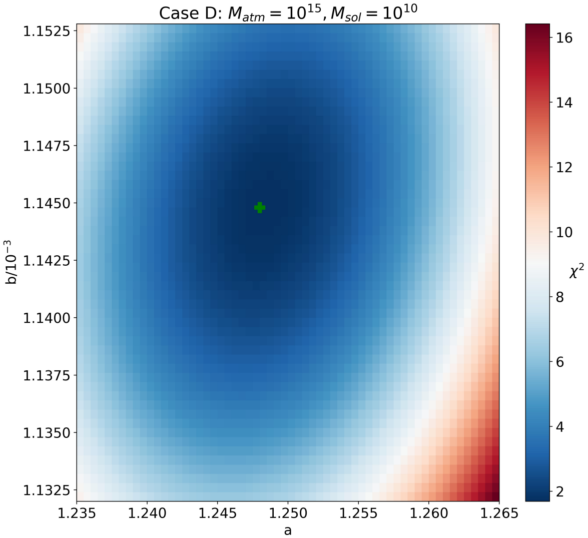
Checking Parameter Space

- Minimising χ^2 only useful if there is a **stable global minimum** in the parameter space
- Checked a/b parameter space (fix M_{atm} and M_{sol}) to ensure minimal χ^2 is stable



Preliminary Best Fit Points

Set of current best-fit points after a single coarse scan over M_{atm}, M_{sol}, a, b (**no leptogenesis**)

	Parameters				χ^2	χ^2_ν
	M_{atm}/GeV	M_{sol}/GeV	a	b		
A	1.0×10^{11}	1.0×10^{15}	0.0113	0.370534	7.31	3.66
D	1.0×10^{15}	1.0×10^{10}	1.24691	0.00114	**1.79**	**0.90**

Preliminary Best Fit Points: Case D

Concentrate on Case D, look at variation of χ^2 with RHν masses.
Varying M_{atm}:

Parameters				χ^2
M_{atm}/GeV	M_{sol}/GeV	a	b	
5.0×10^{12}	1.0×10^{10}	0.0782107	0.00108097	10.0119
1.0×10^{13}	1.0×10^{10}	0.110607	0.00108097	13.0470
5.0×10^{13}	1.0×10^{10}	0.251836	0.00109801	8.56636
1.0×10^{14}	1.0×10^{10}	0.35615	0.00109801	11.0418
5.0×10^{14}	1.0×10^{10}	0.839184	0.00111505	3.50215
1.0×10^{15}	1.0×10^{10}	0.836253	0.00114306	1.78567

Preliminary Best Fit Points: Case D

Concentrate on Case D, look at variation of χ^2 with RHν masses. Varying M_{sol}:

Parameters				χ^2
M_{atm}/GeV	M_{sol}/GeV	a	b	
1.0×10^{15}	1.0×10^{10}	0.836253	0.00114306	1.78567
1.0×10^{15}	5.0×10^{10}	0.836253	0.00257733	1.79572
1.0×10^{15}	1.0×10^{11}	1.24691	0.00367512	2.17086
1.0×10^{15}	5.0×10^{11}	1.24691	0.00828538	2.03957
1.0×10^{15}	1.0×10^{12}	1.24691	0.0117173	1.78793
1.0×10^{15}	5.0×10^{12}	1.24691	0.0264144	1.98070

Outlook

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- Hints that BAU constraint acting to fix lightest RH neutrino mass

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- Parameter fit to low scale observables

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Thank you for your attention!