Predicting Right-Handed Neutrino Masses from the Littlest Seesaw and Leptogenesis

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

Outline

- Background
  - Seesaw Models: Type-I
  - The Littlest Seesaw
  - Leptogenesis
- This Work: *Predictions for RH neutrinos*
- Preliminary Results
- Outlook

Why Seesaw Models?

- Standard Model cannot explain neutrino masses and oscillations or the observed BAU
- Need extension theory in order to be consistent with data
- Possible solution: models that utilise a Type-I Seesaw mechanism

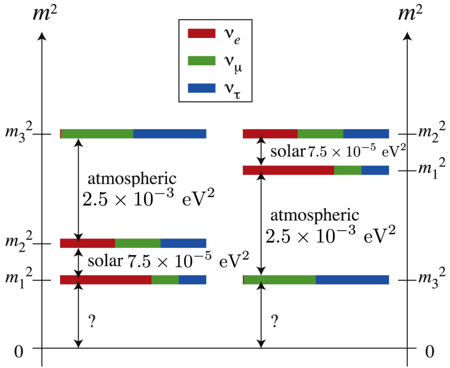

Figure: [King:1701.04413]

The Type-I Seesaw

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

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

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

- Collect terms together $\implies$ 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 $M_R \gg m_D$, approximately diagonalise to obtain light neutrino masses:

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

The Littlest Seesaw

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**, $m_1 = 0$

The Littlest Seesaw

Fixes the absolute scale of neutrino masses

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

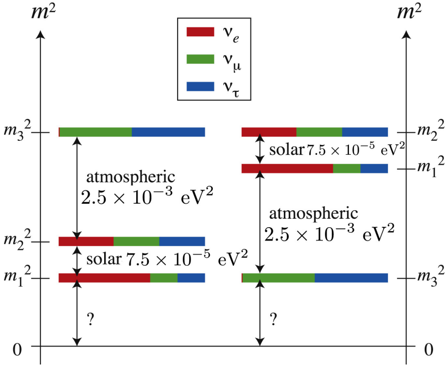

Figure: [King:1701.04413]

Four distinct cases of the LS, labelled A through D.

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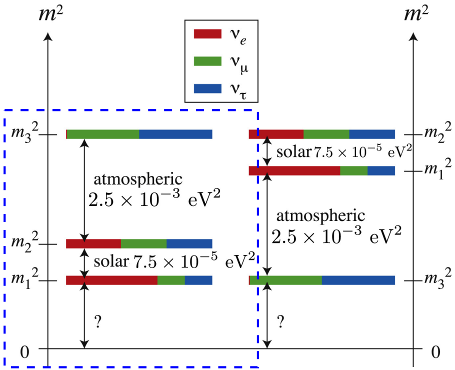

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The Littlest Seesaw

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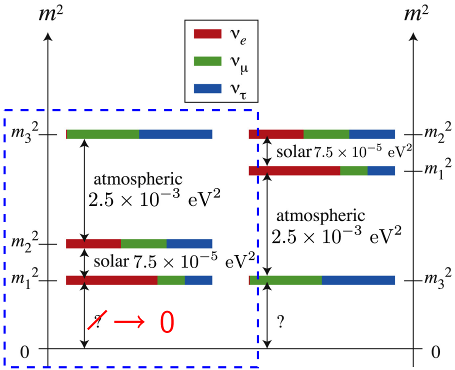

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Four distinct cases of the LS, labelled A through D.

The Littlest Seesaw: A and B

- 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 B:

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

η is a complex phase and n is the order of CSD.

The Littlest Seesaw: C and D

- Case C:

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

- Case D:

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

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RG Evolution

- Theory defined at $\mu = \Lambda_{GUT}$, data available at low energies
- Evolve observables to low scales through **RG running**

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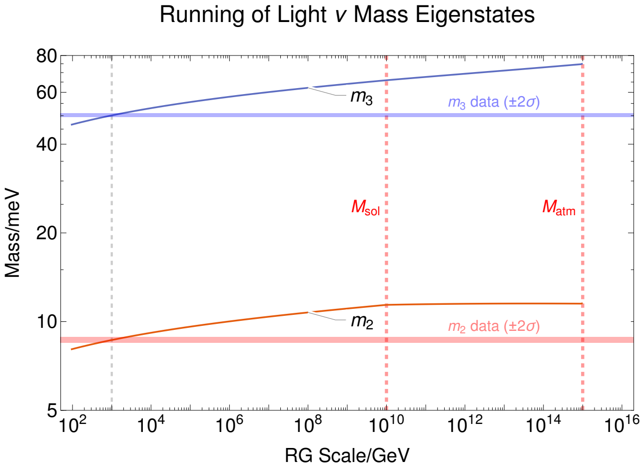


Case D:

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

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

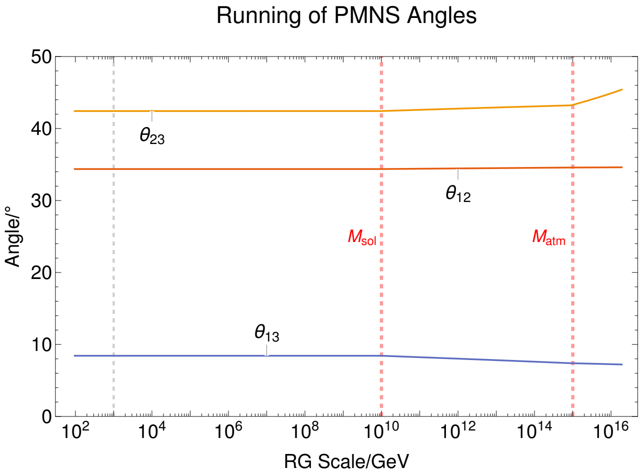
$a = 1.24691$

$b = 0.00114306$

$n = 3$

$\eta = -2\pi/3$

RG Evolution (2)



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Leptogenesis

- Observed asymmetry normalised to the entropy density of the universe:

$$Y_B \simeq (0.87 \pm 0.03) \times 10^{-10}$$

- Leptogenesis: **mechanism for generating a BAU**
- Type-I seesaw models are able to generate a lepton asymmetry through the decay of the lightest RHν
- Lepton asymmetry converted to baryon inbalance through sphaleron processes in the SM

This work: *Predictions for RHνs*

- **Can we accurately predict the masses of the RH neutrinos in the Littlest Seesaw?**

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- Use precision neutrino data

Observable	*Measured Value*
$sin^2(\theta_{12})$	$0.306^{+0.012}_{-0.012}$
$sin^2(\theta_{13})$	$0.02166^{+0.00075}_{-0.00075}$
$sin^2(\theta_{23})$	$0.441^{+0.027}_{-0.021}$
δ	$-99^{\circ}{}^{+51^{\circ}}_{-59^{\circ}}$
$\Delta {m_{12}}^2$	$7.50^{+0.19}_{-0.17} \times 10^{-5}\text{eV}^2$
$\Delta {m_{13}}^2$	$2.524^{+0.039}_{-0.040} \times 10^{-3}\text{eV}^2$

[Esteban et. al.(NuFit 3.0): 1611.01514]

This work: *Predictions for RHνs*

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

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[Spergel et. al.: astro-ph/06033449]

This work

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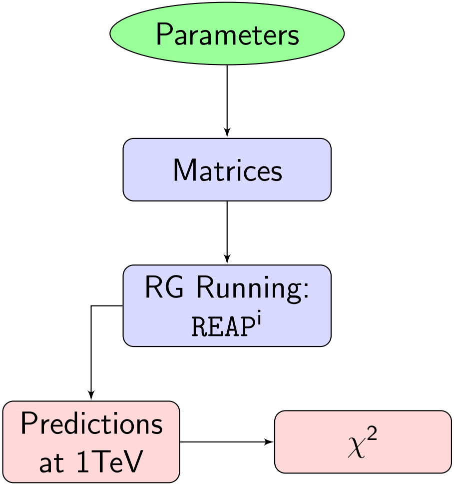

Scan over RH neutrino masses:

$$1.0 \times 10^9 \leq M_{atm} \leq 5.0 \times 10^{15}$$
$$1.0 \times 10^9 \leq M_{sol} \leq 5.0 \times 10^{15}$$

a and b are left as free parameters.

n fixed to be 3 and η fixed to be $\pm 2\pi/3$

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

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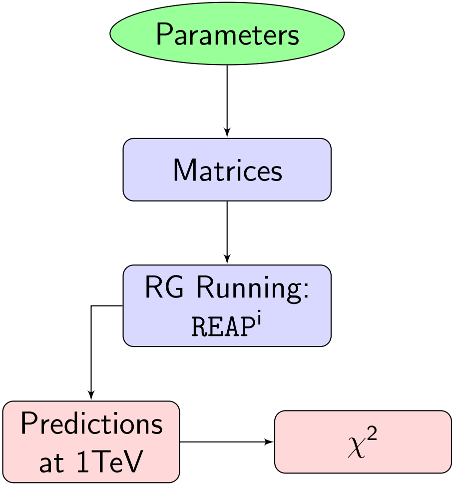

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n fixed to be 3 and η fixed to be $\pm 2\pi/3$

Grid over parameter space, determine the best fit point for each case by minimising χ^2

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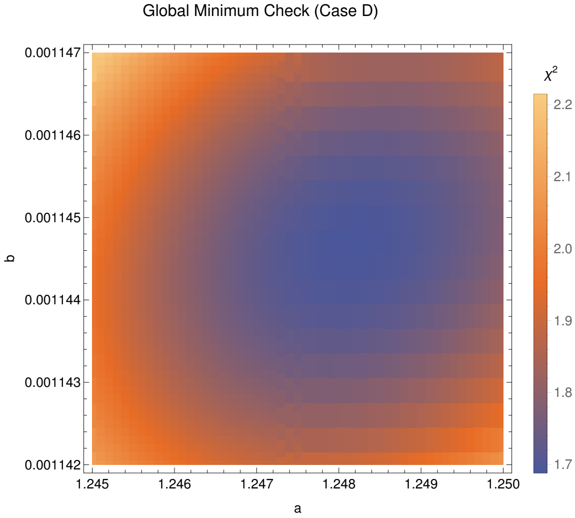
Checking 2D Parameter Space

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



Preliminary Best Fit Points

Set of current best-fit points after a single coarse scan (no leptogenesis)

	Parameters				χ^2
	M_{atm}/GeV	M_{sol}/GeV	a	b	
Case A	1.0×10^{11}	1.0×10^{15}	0.0113	0.370534	7.31496
Case B	1.0×10^{10}	1.0×10^{15}	0.00354	0.370534	4.93358
Case C	1.0×10^{15}	1.0×10^{10}	1.24691	0.00114	3.46989
Case D	1.0×10^{15}	1.0×10^{10}	1.24691	0.00114	**1.78567**

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

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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

- Neutrino data seems to be fixing heaviest RH neutrino mass

- Include leptogenesis observables/data into our χ^2 fitting $\Longrightarrow$ constraints on lighter RH neutrino
- Perform more rigorous fitting by 'homing in' on desirable areas of the parameter space
- Possible use of Markov Chain Monte Carlo (MCMC) methods to find best fit in desirable region

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Thank you for your attention