Determining the RH Neutrino Masses in the Littlest Seesaw

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

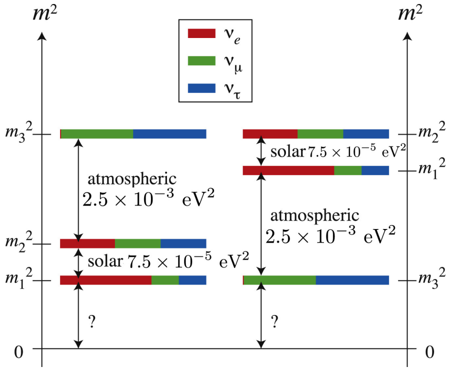
Neutrinos and Cosmology

- 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

$$m_{\nu_l} = v_\phi^2 \frac{Y_\nu^T Y_\nu}{M_R}$$



The Littlest Seesaw

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

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

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

Constrained Sequential Dominance $\implies$ one RHν gives dominant contribution to **atmospheric mass**, whilst the other RHν gives largest contribution to **solar mass**

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

S. F. King, Nucl. Phys. B **576** (2000) 85 [hep-ph/9912492].

Relevant Cases of the LS

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- 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:

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

S. F. King, JHEP **1307** (2013) 137 [arXiv:1304.6264 [hep-ph]].
S. F. King, JHEP **1602** (2016) 085 doi:10.1007/JHEP02(2016)085
S. F. King and C. Luhn, JHEP **1609** (2016) 023 [arXiv:1607.05276 [hep-ph]].

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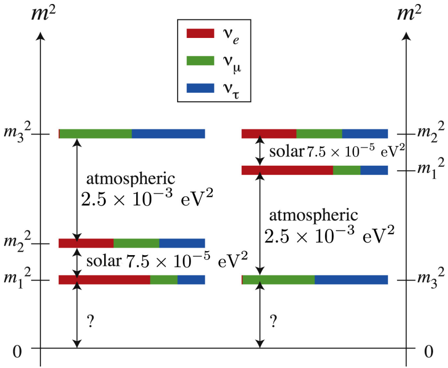
Fixes the absolute scale of neutrino masses



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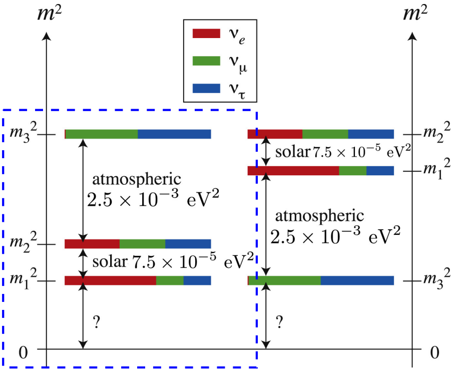

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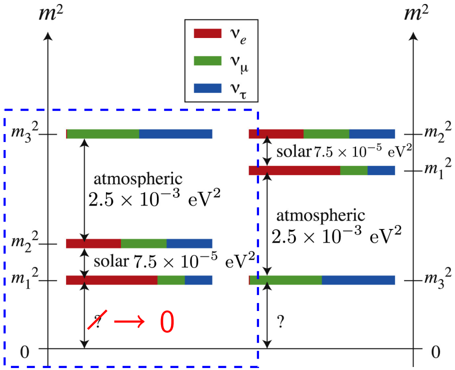

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This work: *Predictions for RHνs*

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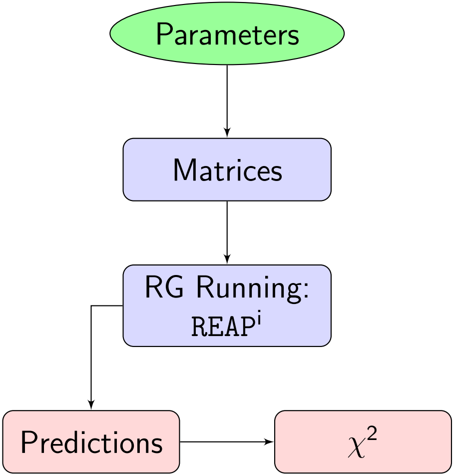
- **To accurately predict the masses of the RH neutrinos in the Littlest Seesaw**
- Fit high scale params to low scale neutrino data and BAU from Leptogenesis

Observable	Measured Value
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.6}$
$\delta/^\circ$	-126^{+43}_{-31}
$\Delta m_{12}{}^2/\text{eV}^2$	$7.40^{+0.21}_{-0.20} \times 10^{-5}$
$\Delta m_{13}{}^2/\text{eV}^2$	$2.494^{+0.033}_{-0.031} \times 10^{-3}$
Y_B	$0.87^{+0.01}_{-0.01} \times 10^{-10}$

NuFit 3.2 (I. Esteban et al.), JHEP **1701** (2017) 087 [arXiv:1611.01514]

Plack Collaboration (P.A.R. Ade et al.), Astron.Astrophys. **571** (2014) A16 [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.

$$n = 3, \qquad \eta = \pm 2\pi/3$$

T. Geib and S.F. King, Phys.Rev. **D97** (2018) no.7, 075010 [arXiv:1709.07425]

[i] S. Antusch et. al., JHEP **0503** 2005 024 [arXiv:hep-ph/0501272.]

This work

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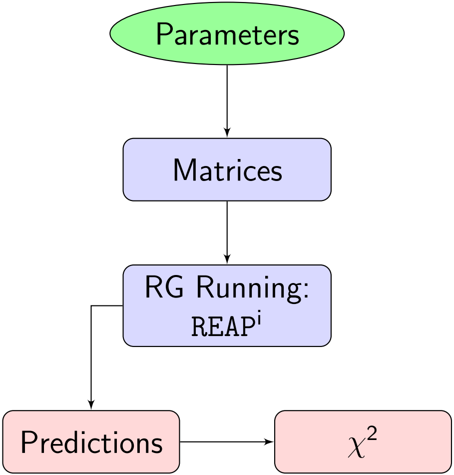

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Determine the best fit point for each case by minimising χ^2

[i] S. Antusch et. al., JHEP **0503** 2005 024 [arXiv:hep-ph/0501272.]

Benchmark Points

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	Case A BP	Case D BP
M_{atm}/GeV	5.051×10^{10}	1.357×10^{13}
M_{sol}/GeV	5.067×10^{13}	1.056×10^{10}
a	0.00805868	0.13484
b	0.082948	0.00115694
χ^2/d.o.f.	3.17/3	4.65/3

Table: Best fit points from parameter scan.

Predictions of Benchmark Points

	Case A BP	Case D BP	Experiment
$\theta_{12}/^\circ$	34.3	34.3	$33.62^{+0.78}_{-0.76}$
$\theta_{13}/^\circ$	8.59	8.58	$8.54^{+0.15}_{-0.15}$
$\theta_{23}/^\circ$	45.6	44.3	$47.2^{+1.9}_{-3.6}$
$\Delta m_{12}{}^2/10^{-5}\text{eV}^2$	7.35	7.32	$7.40^{+0.21}_{-0.20}$
$\Delta m_{31}{}^2/10^{-3}\text{eV}^2$	2.50	2.50	$2.494^{+0.033}_{-0.031}$
$\delta/^\circ$	−87.4	−92.9	-126^{+43}_{-31}
$Y_B/10^{-10}$	0.86	0.86	$0.87^{+0.01}_{-0.01}$
χ^2/d.o.f.	3.17/3	4.65/3	-

Table: Benchmark Point Observables

Conclusions

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- We extract 7 observables from 4 parameters: LS highly predictive
- **Indirectly predicted the RH neutrino masses**
- LS provides an excellent fit to neutrino and BAU data with a small number of parameters
- Cosmological constraints particularly important for neutrino models
- Future neutrino experiments (DUNE, HyperK etc.) will better test consistency of LS

Conclusions

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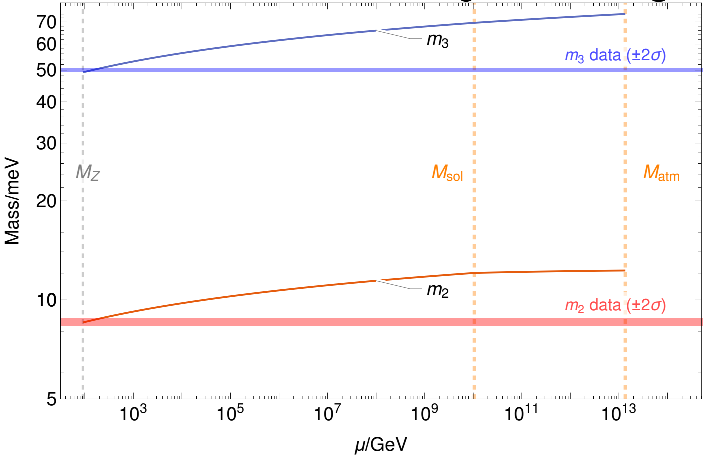
Thank you for your attention!

Observations

- SM extension with 2 new singlet fields
- Normal mass hierarchy with $m_1 = 0$.
- Close to maximal atmospheric mixing ($\theta_{23} \simeq \pi/4$)
  - NuFit3.0 (November '16) $\implies$ maximal atmospheric mixing was nearly excluded, Littlest Seesaw close to exclusion
  - NOVA reanalysis in NuFit3.2 (January '18) $\implies$ maximal atmospheric mixing consistent with current global fits

RG Evolution

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



S. F. King, J. Zhang and S. Zhou, JHEP **1612** (2016) 023 [arXiv:1609.09402 [hep-ph]].
T. Geib and S. F. King, Phys. Rev. D **97** (2018) no.7, 075010 [arXiv:1709.07425 [hep-ph]].

Leptogenesis

- Generate a lepton asymmetry through the decay of lightest RHν

$$Y_{\Delta\alpha} = \eta_\alpha \epsilon_\alpha Y_{N_1}^{eq}$$

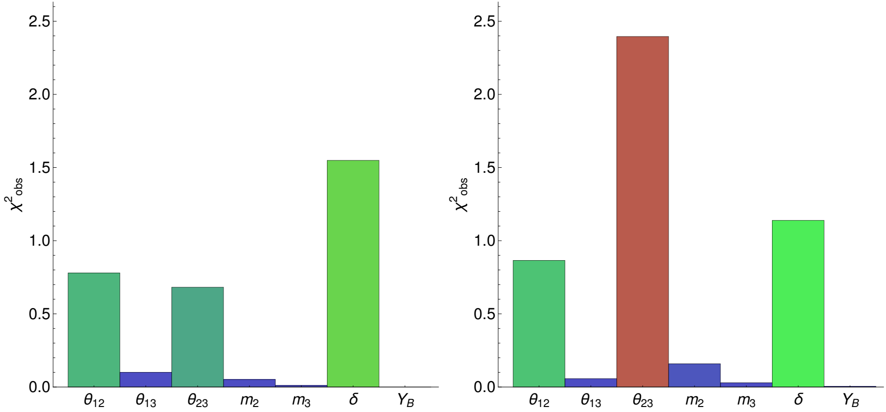
- Lepton asymmetry converted to baryon excess through sphaleron processes in the SM

$$Y_B = \frac{12}{37} \sum_{\alpha = e,\mu,\tau} Y_{\Delta\alpha}$$

$$\eta_\alpha = \text{efficiency factor}$$
$$\epsilon_\alpha = \text{decay asymmetry}$$
$$Y_{N1}^{eq} = \text{eq. density of RH}\nu$$

M. Fukugita and T. Yanagida, Phys. Lett. B **174** (1986) 45.
S. Antusch et al., Nuc. Phys. **B856** (2012) 180-209 [arXiv:1003.5132 [hep-ph]]

χ^2 Contributions



(a) Case A BP

(b) Case D BP