Testable Baryogenesis and Leptonic CP Violation in Seesaw Models

Jordi Salvado

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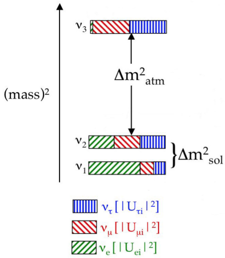
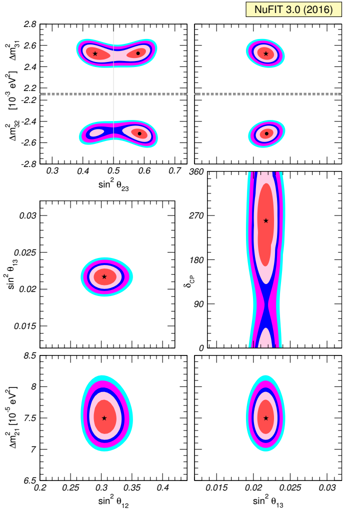
Based on arXiv:1606.06719 and arXiv:1611.05000

Neutrinos are massive



$$\Delta m^2_{\rm sol} = 7.50\times10^{-5}{\rm eV}^2$$

$$|\Delta m^2_{\rm atm}| = 2.534\times10^{-3}{\rm eV}^2$$



NuFIT 3.0 (2016)

$$|U|_{3\sigma} = \begin{pmatrix} 0.800 \to 0.844 & 0.515 \to 0.581 & 0.139 \to 0.155 \\ 0.229 \to 0.516 & 0.438 \to 0.699 & 0.614 \to 0.790 \\ 0.249 \to 0.528 & 0.462 \to 0.715 & 0.595 \to 0.776 \end{pmatrix}$$

[B. Kayser, hep-ph/0506165 (2004)]

[M.C. Gonzalez-Garcia et. al. JHEP 01 (2017) 087 www.nu-fit.org]

Seesaw Type-I

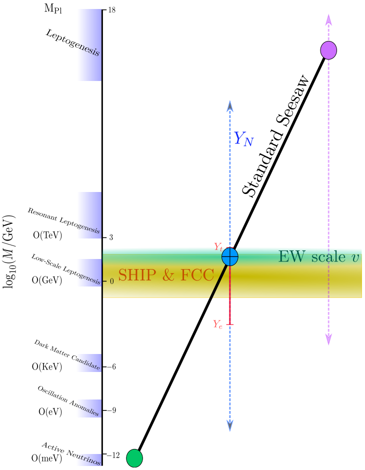
$$\mathcal{L} = \mathcal{L}_{SM} - \sum_{\alpha,i} \bar{L}^{\alpha} Y^{\alpha i} \tilde{\Phi} \nu_R^i - \sum_{i,j=1}^{3} \frac{1}{2} \bar{\nu}_R^{ic} M_N^{ij} \nu_R^j + h.c..$$

- Neutrino Masses suggest a NEW PHYSICS scale.
- We focus in the simplest model type-I seesaw
- $Y_N = O(1) \rightarrow$ Hierarchy problem and not testable.

$$m_\nu = Y_N^T \frac{v^2}{M_N} Y_N$$

Minkowski; Yanagida; Glashow; Gell-Mann,

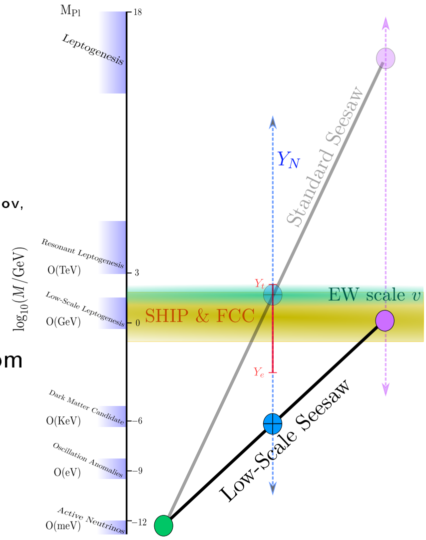
Ramond Slansky; Mohapatra, Senjanovic...



Low-Scale Seesaw (testable)

- Testable in collider (SHIP and FCC)
- Interesting cosmological implications: Leptogenesis (Akhmedov, Rubakov, Smirnov)
- Potential implications in neutrino-less double β decay.
- Small Yukawas, but not so far from the SM.

$$m_\nu = Y_N^T \frac{v^2}{M_N} Y_N$$



Parametrization of the Model

- We set the minimal models with 2 heavy sterile neutrinos.
- Casas-Ibarra parametrization helps us to parametrize the model easily imposing what we know about the light sector.

$$U_{\alpha h} = i U_{\text{PMNS}} \sqrt{m_l}\, R^{\dagger}(z) M^{-1/2}$$

- We set U_{PMNS} angles and m_l square differences to the current best fit(NOT the PHASE, ORDERING).

$$\{\delta, \phi_1, \gamma, \theta, M_1, M_2\}$$

Cosmological Implications

- The heavy steriles are too heavy and unstable to directly affect any CMB or LSS cosmology.

BUT before EW phase transition we have:

- Baryon number violation, in our case lepton number violation + sphalerons
- Loss of thermal equilibrium, the steriles interact very weekly.
- C and CP violation processes, here they come from oscillations.

The model acomplish three Sakharov conditions

(Andrei Sakharov 1967)

therefore it will produce primordial asymetry

(Akhmedov, Rubakov, Smirnov)

Formalism: Oscillations plus interactions in a primordial plasma

Rafelt-Sigle equations for neutrinos plus the lepton chemical potentials.

$$
\begin{aligned}
xH_u \frac{dr_N}{dx} &= -i[\langle H\rangle, r_N] - \frac{\langle\gamma_N^{(0)}\rangle}{2}\{Y^\dagger Y, r_N - 1\} + \langle\gamma_N^{(1)}\rangle Y^\dagger \mu Y - \frac{\langle\gamma_N^{(2)}\rangle}{2}\{Y^\dagger \mu Y, r_N\} \\
xH_u \frac{dr_{\bar N}}{dx} &= -i[\langle H^*\rangle, r_{\bar N}] - \frac{\langle\gamma_N^{(0)}\rangle}{2}\{Y^T Y^*, r_{\bar N} - 1\} + \langle\gamma_N^{(1)}\rangle Y^T \mu Y^* \\
&+ \frac{\langle\gamma_N^{(2)}\rangle}{2}\{Y^T \mu Y^*, r_{\bar N}\}, \\
xH_u \frac{d\mu_{B/3-L_\alpha}}{dx} &= \frac{\int_k \rho_F}{\int_k \rho_F'}\Bigg\{ \frac{\langle\gamma_N^{(0)}\rangle}{2}(Y r_N Y^\dagger - Y^* r_{\bar N} Y^T)_{\alpha\alpha}. \\
&+ \mu_\alpha \left(\frac{\langle\gamma_N^{(2)}\rangle}{2}(Y r_N Y^\dagger + Y^* r_{\bar N} Y^T)_{\alpha\alpha} - \langle\gamma_N^{(1)}\rangle \mathrm{Tr}[Y Y^\dagger I_\alpha] \right) \Bigg\}, \\
\mu_\alpha &= -\sum_\beta C_{\alpha\beta}\mu_{B/3-L_\beta}.
\end{aligned}
$$

- Thermal quantum field theory effects.
- Almost all depends on time "x": Numerically hard problem!

Considerations in the derivation

- Fermi-Dirac or Bose-Einstein statistics is kept throughout.
- Collision terms include $2 \leftrightarrow 2$ scatterings at tree level with top quarks and gauge bosons, as well as $1 \leftrightarrow 2$ scatterings including the resummation of scatterings mediated by soft gauge bosons.
- Leptonic chemical potentials are kept in all collision terms to linear order
- Include spectator processes

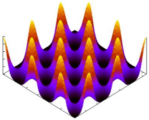
If we have tools to solve the equations we can compare with observations

Baryon asymetry is very well measured:

$$Y_B^{\rm exp} \simeq 8.65(8) \times 10^{-11}.$$

- Essentially the same technical problem that doing a CMB-LSS precision cosmology fit.
- TOOLS:
  1. Bayesian Inference(Multinest)
  2. Hard Numerical Computations (SQuIDS)

SQuIDS
Simple Quantum Integro Differential Solver



https://github.com/jsalvado/SQuIDS

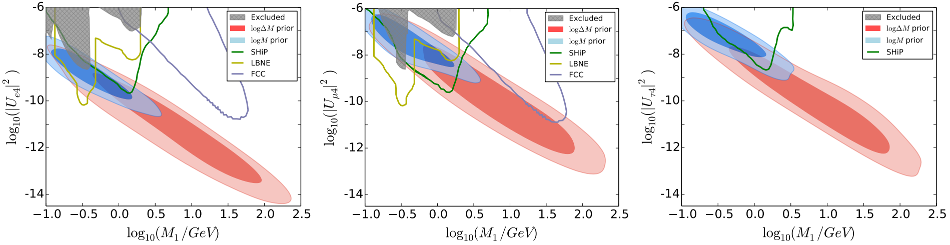
https://github.com/JohannesBuchner/MultiNest

Analysis details

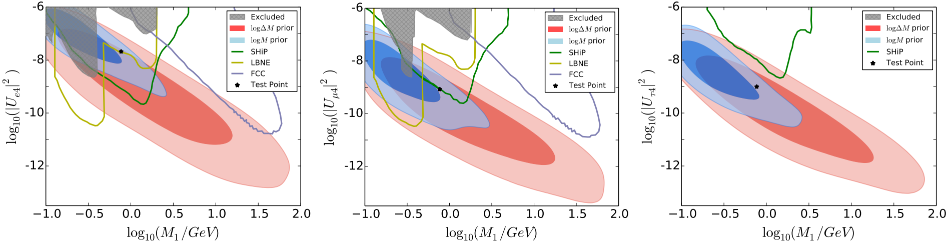
Flat priors in the Casas-Ibarra parameters $\{\delta, \phi_1, \gamma, \theta, M_1, M_2\}$ except:

1. Flat prior in $\log_{10}\left(\frac{M_1}{\mathrm{GeV}}\right)$ and $\log_{10}\left(\frac{M_2}{GeV}\right)$
2. Flat prior in $\log_{10}\left(\frac{M_1}{\mathrm{GeV}}\right)$ and $\log_{10}\left(\frac{|M_2 - M_1|}{\mathrm{GeV}}\right)$

Normal Ordering



Inverted Ordering



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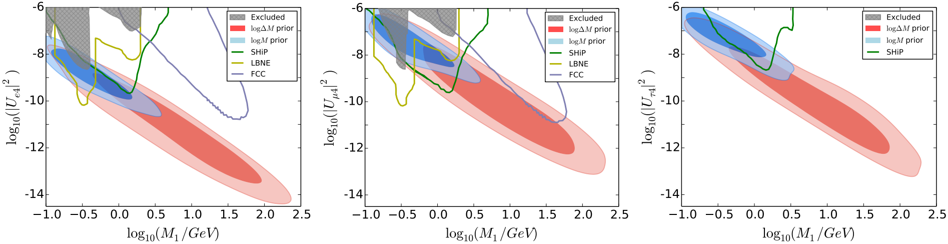
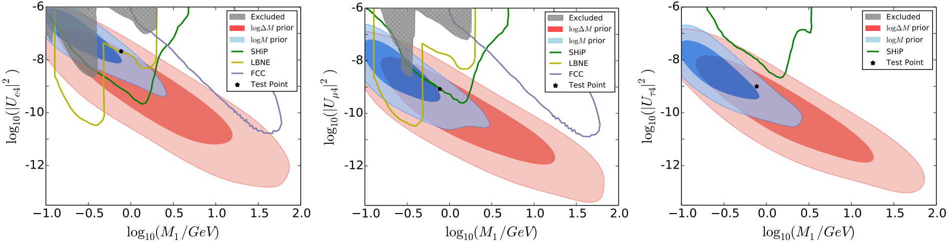
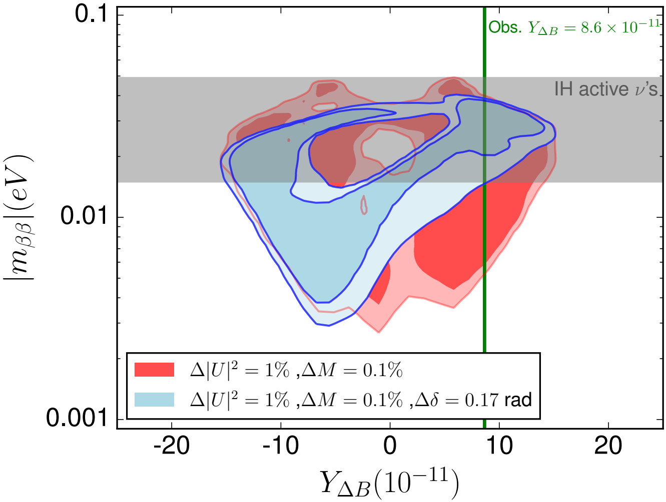


Inverted Ordering



What if we really measure something* in SHiP

Forecast for SHIP (with and without a measure δ_{CP}



What else can we learn: CP discovery potential

Assumptions:

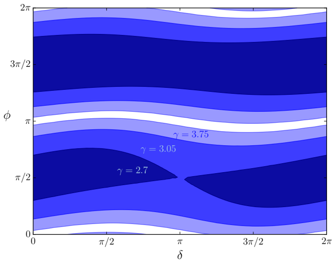
1. SHiP or FCC measures one of the steriles.
2. The steriles are the main contribution in generating the light neutrino masses by the low scale seesaw.

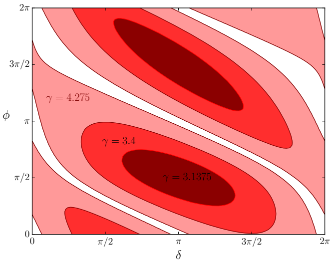
Goal:

- Quantify the potential to exclude any of the CP conserving points(NULL HYPOTHESIS):

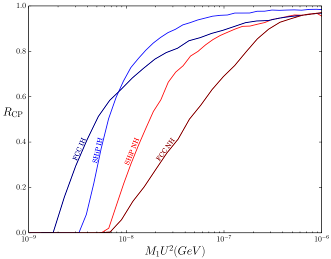
$$(\delta, \phi_1) = \{(0,0), (0,\pi), (\pi,0), (\pi,\pi)\}$$

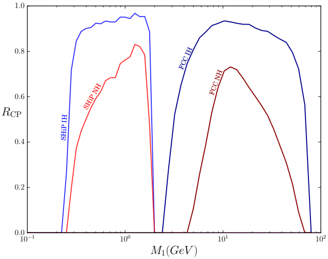
5σ contours for different gammas, Inverted and Normal





R_{CP} in terms of M_1U^2 and M_1 for SHiP and FCC-ee.





Conclusions

- We used state of the art computation and numerical tools in low scale leptogeneis.
- The precise measurement of the asymmetry is very relevant:
  - Not very degenerate values are preferred.
  - Important overlapping with the sensitivity regions of SHiP and FCC.
- A measurement of SHiP, δ_{CP} and $m_{\beta\beta}$ may give a prediction for the primordial asymmetry(Testable)
- A SHiP or FCC measurement has strong power to prove CP violation in the leptonic sector.