Neutrino mass and leptogenesis in a hybrid seesaw model with a spontaneously broken CP

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Introduction

Apart from the experimental challenges to determine the neutrino oscillation parameters, the origin of a Dirac CP phase ($\delta_{\rm CP}$) in the neutrino mixing matrix is of a theoretical importance to understand how neutrinos oscillate differently from anti-neutrinos which remains unknown as of now. This work provides a possible framework of the origin of $\delta_{\rm CP}$ via the mechanism of spontaneous CP violation (SCPV) first proposed in the context of two Higgs doublet models. In the model, the mechanism of SCPV is achieved by a complex vev of a singlet and the phase is propagated from the scalar sector to the neutrino sector leading to effective complex Yukawa couplings required to generate a non-zero $\delta_{\rm CP}$. The model provides a minimal framework of seesaw neutrino masses satisfying observed oscillation data, as well as leads to a non-vanishing asymmetry parameter which triggers leptogenesis.

Spontaneous CP violation (SCPV)

CP violation

- Explicit (complex parameters in the Lagrangian)
- Spontaneous
- Geometric (depends on the choice of vacuum)

Necessary condition: A non-zero relative phase between the orientation of vacuum expectation values (vev) of the scalar fields.

Objective

Build a minimal model that generates a CP phase spontaneously in the electroweak (EW) sector and is responsible for $\delta_{\rm CP}$ in the neutrino mass matrix and drive leptogenesis.

- ☞ Minimal in terms of field content and free parameters
- ☞ All the couplings are set to real
- ☞ A single phase is generated in the EW sector
- ☞ Gets propagated in the neutrino sector to generate $\delta_{\rm CP}$
- ☞ Reproduce correct BAU through leptogenesis

Singlet Doublet Triplet model (SDT)

Singlet σ obtains a complex vev $\langle\sigma\rangle = v_\sigma\, e^{i\theta_\sigma}$

$\lambda_{\sigma H\Delta}\left[\sigma H^{\mathsf T} i\tau_2 \Delta^\dagger H + \text{ h.c.}\right]$
$V_\mu^{\rm soft} = \mu\left[H^{\mathsf T} i\tau_2 \Delta^\dagger H + \text{ h.c.}\right]$

Triplet Δ develops a complex vev $\langle\delta_0\rangle = v_\Delta\, e^{i\theta_\Delta}$

$-\mathcal{L}_Y \supset \frac{1}{2}\mathcal{Y}_{\Delta\alpha\beta} L_\alpha^T\, \mathcal{C} i\tau_2 \Delta L_\beta + \text{ h.c.}$

Singlet Yukawa couplings $-\mathcal{L}_Y \supset \frac{1}{2} y_R \sigma^* \overline{N_R} N_R^c + \text{ h.c.}$

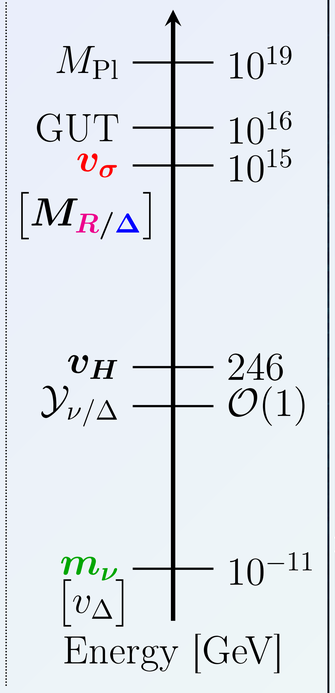
Complex mass matrix for RHN $M_R = |M_R|\, e^{i\theta_R}$

$-\mathcal{L}_Y \supset \mathcal{Y}_{\nu\alpha 1} \overline{L}_\alpha \widetilde{H} N_R + \text{ h.c.}$

$\theta_{\rm eff} = \theta_\Delta + \theta_R$

$M_\nu = \mathcal{Y}_\Delta \frac{v_\Delta}{\sqrt{2}} e^{i\theta_{\rm eff}} - \frac{v_H^2}{2|M_R|}\mathcal{Y}_\nu\, \mathcal{Y}_\nu^{\mathsf T}$

$\theta_{\rm eff}$ also appears in Leptogenesis



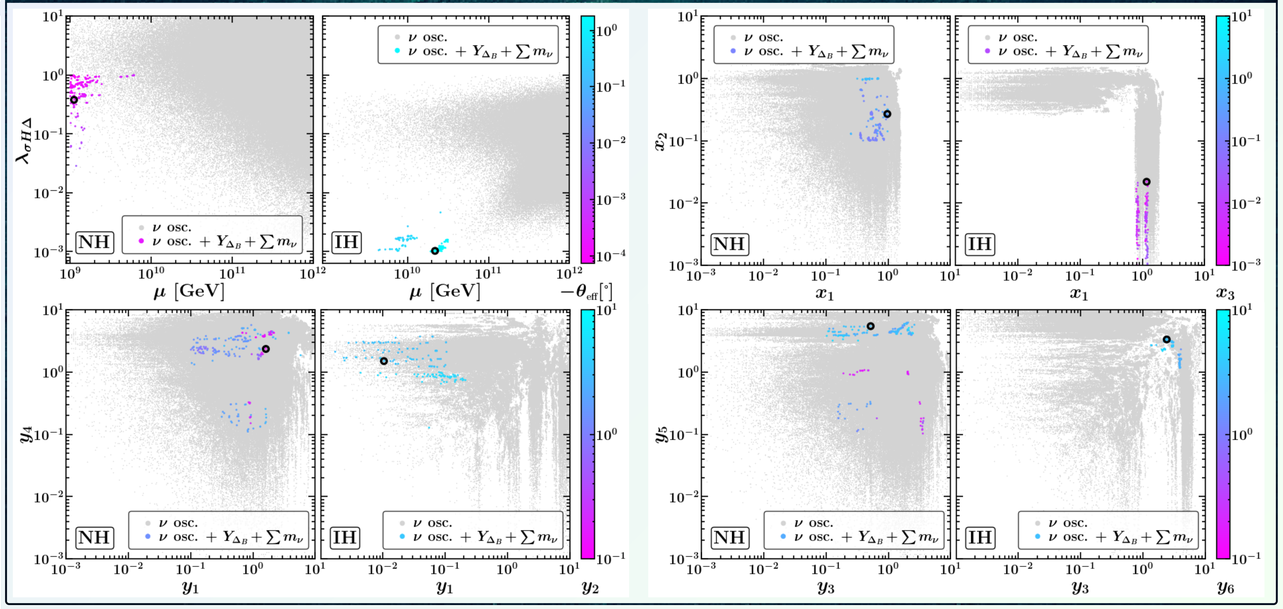
Asymmetry parameter

$$\epsilon_N^\Delta = -\frac{1}{16\pi^2\Gamma_N}\sum_{il}\mathcal{I}m[\mathcal{Y}_{\nu i}\mathcal{Y}_{\nu l}(\mathcal{Y}_{\Delta il}e^{i\theta_{\rm eff}})^*\widetilde{\mu}^*]\left[1-\frac{M_\Delta^2}{|M_R|^2}\log\left(1+\frac{|M_R|^2}{M_\Delta^2}\right)\right]$$

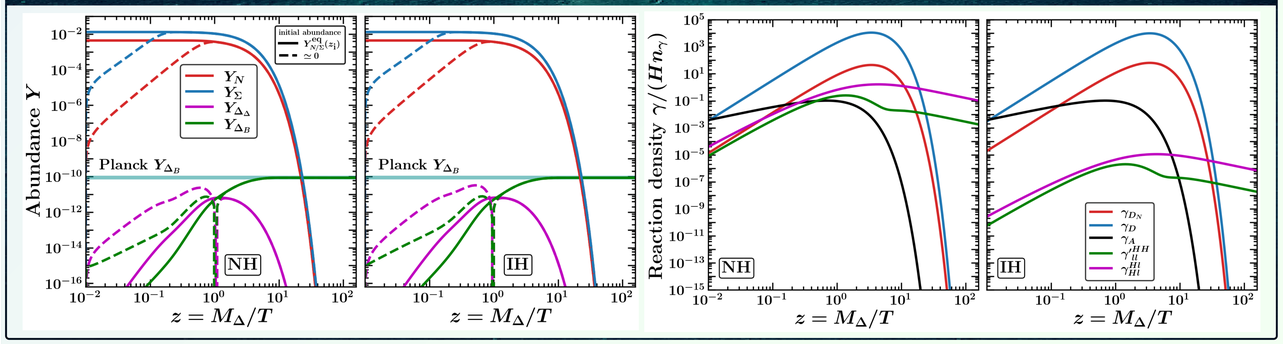
$$\epsilon_\Delta^N = \frac{1}{64\pi^2\Gamma_\Delta}\sum_{il}\mathcal{I}m[\mathcal{Y}_{\nu i}^*\mathcal{Y}_{\nu l}^*(\mathcal{Y}_{\Delta il}e^{i\theta_{\rm eff}})\widetilde{\mu}]\left[\frac{|M_R|}{M_\Delta}\log\left(1+\frac{M_\Delta^2}{|M_R|^2}\right)\right]$$

with $\theta_{\rm eff} = \widetilde{\theta} - \theta_\sigma$,
$\widetilde{\mu}e^{i\widetilde{\theta}} = \mu + \frac{v_\sigma}{\sqrt{2}}e^{i\theta_\sigma}\lambda_{\sigma H\Delta}$

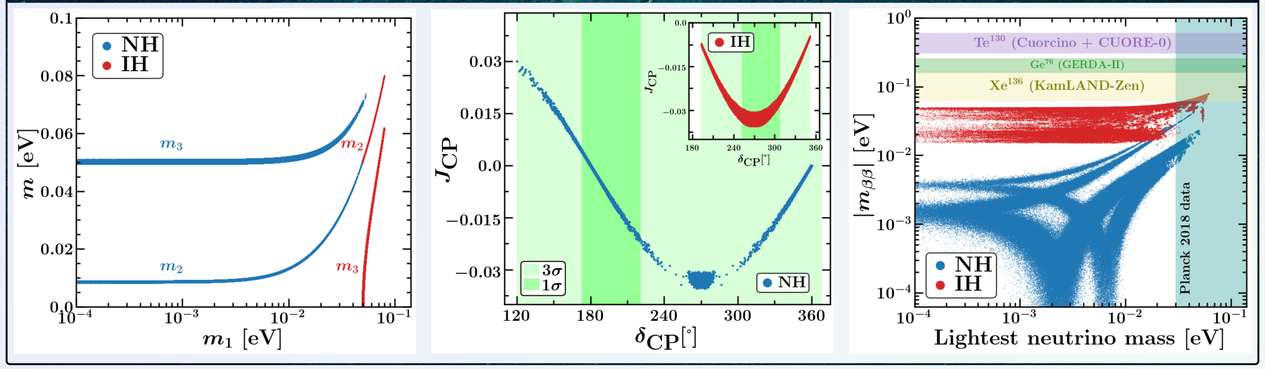
Parameter space



Evolution of various abundances



Neutrino oscillation data



Minimal model

Additonal field		Degrees of freedom			No. of free parameters			SCPV	Neutrino osc. data	Lepto-genesis
Scalar(s)	Fermion(s)	Scalar	Fermion	Total	Potential	Fermion	Total			
-	$2N_R$	-	2	2	-	$6+3$	9	✗	✓	✓
-	$3N_R$	-	3	3	-	$9+6$	15	✗	✓	✓
Δ	-	6	-	6	6	12	18	✗	✓	✗
2Δ	-	12	-	12	17	12	29	✓	✓	✓
σ, Δ	N_R	$2+6$	1	9	12	$3+1$	16	✓	✓	✓

References

R. Pramanick, T. S. Ray and A. Shaw, *Neutrino mass and leptogenesis in a hybrid seesaw model with a spontaneously broken CP*, JHEP 06 (2023) 099 [2211.04403]