FLASY 22 – 9th Workshop on Flavour Symmetries and Consequences in Accelerators and Cosmology

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Leptogenesis assisted by complex scalar singlet

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Motivation

The Standard Model cannot explain:

- **Neutrino flavour oscillations** (imply existence of neutrino masses and lepton mixing)
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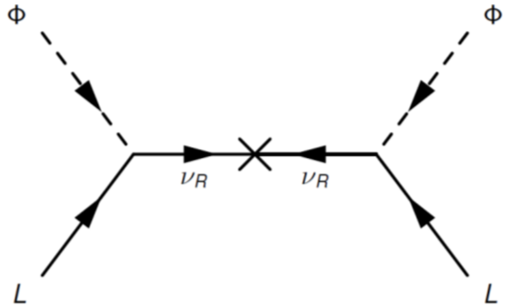

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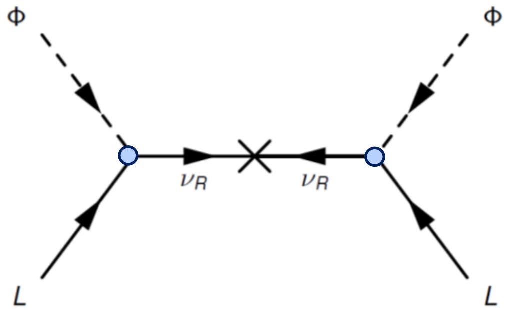

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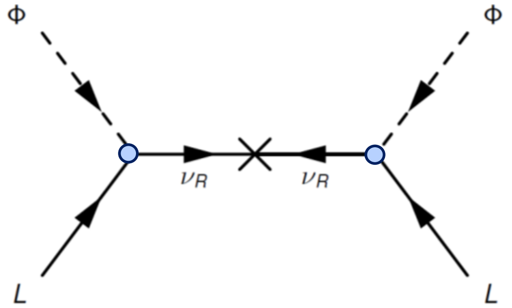

CP violation from complex Yukawa couplings

Our approach:

Complex scalar singlet extension of type-I seesaw model

Can **CP be spontaneously broken** by the complex VEV of complex scalar singlets and explain **CP violation both at the leptogenesis scale and electroweak scale**?

Scalar singlet extended Type-I Seesaw Model

Add to the SM $\boldsymbol{n_R}$ **RH neutrinos**, $\boldsymbol{n_H}$ **scalar doublets** and $\boldsymbol{n_S}$ **complex scalar singlets**:

$$-\mathcal{L}_{\text{Yuk.}} = \overline{\ell}_L \mathbf{Y}_\ell^a \Phi_a e_R + \overline{\ell}_L \mathbf{Y}_D^{a*} \tilde{\Phi}_a \nu_R + \frac{1}{2} \overline{\nu_R} \left(\mathbf{M}_R^0 + \mathbf{Y}_R^k S_k + \mathbf{Y}_R'^k S_k^* \right) \nu_R^c + \text{H.c.}$$

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Scalar singlets acquire VEV at $T \gg v_{\text{EW}}$

$$\langle S_k \rangle = \frac{u_k \, e^{i\theta_k}}{\sqrt{2}}$$

Heavy-neutrino mass generation

$$\mathbf{M}_R = \mathbf{M}_R^0 + \frac{u_k}{\sqrt{2}} \left(\mathbf{Y}_R^k e^{i\theta_k} + \mathbf{Y}_R'^k e^{-i\theta_k} \right)$$

CP violation is dynamically **generated from the vacuum** and transmitted to the heavy-neutrino mass matrix at high energies

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Scalar doublets acquire VEV at the EW scale

$$\langle \Phi_a^0 \rangle = \frac{v_a}{\sqrt{2}}$$

Charged-lepton and light-neutrino mass generation

$$\mathbf{M}_\ell = \frac{v_a}{\sqrt{2}} \mathbf{Y}_\ell^a \qquad \mathbf{M}_\nu = -\frac{v_a^2}{2} \mathbf{Y}_D \mathbf{M}_R^{-1} \mathbf{Y}_D^T$$

CP violation is communicated to leptonic sector at low energies

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CP violation is communicated to leptonic sector at low energies

SCPV is the **source of CP violation** both at **high energies** ($\varepsilon_{\text{CP}} \neq 0$ at leptogenesis scale) and **low energies** (non-trivial Dirac and Majorana phases at the EW scale)

New interactions

Complex scalar singlet extension of the Type-I Seesaw:

Yukawa and mass terms

$$\overline{\ell}_L \mathbf{Y}_D^a \tilde{\Phi}_a \nu_R + \frac{1}{2}\overline{\nu_R}\left(\mathbf{M}_R^0 + \mathbf{Y}_R^k S_k + \mathbf{Y}_R'^k S_k^*\right)\nu_R^c + \text{H.c.}$$

Scalar interactions

$$\mu_{ab,i}(\Phi_a^\dagger \Phi_b) S_i + \mu_{ijk} S_i^* S_j S_k + \mu'_{ijk} S_i S_j S_k + \text{H.c.}$$

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using:

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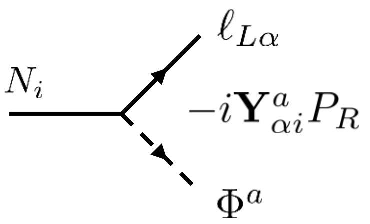
Usual



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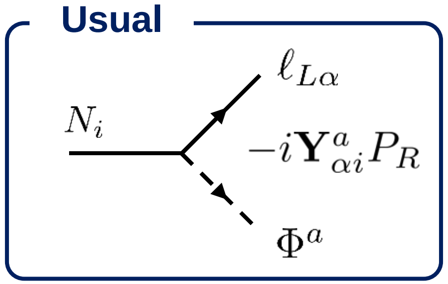

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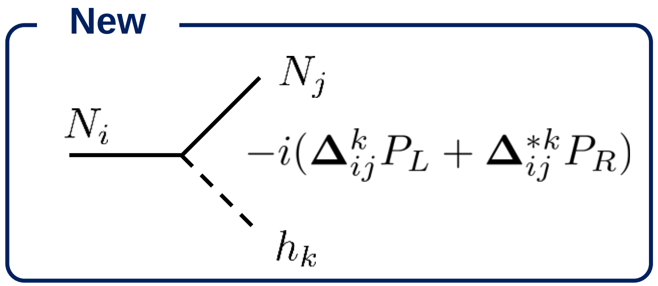
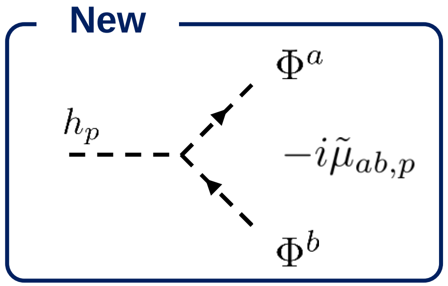
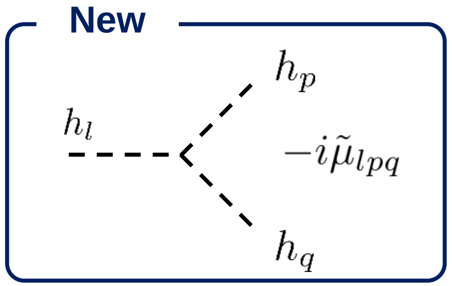


$$\boldsymbol{\Delta}^k = f(\mathbf{V}, \mathbf{U_R}, \mathbf{Y}_R, \mathbf{Y}'_R)$$



$$\tilde{\mu}_{ab,p} = f'(\mu_{ab,i}, \mathbf{V})$$



$$\tilde{\mu}_{lpq} = f''(\mu_{ijk}, \mu'_{ijk}, \mathbf{V})$$

Leptogenesis assisted by complex scalar singlet

Lepton asymmetry is dynamically generated via **out-of-equilibrium decays** of the heavy neutrinos added to the SM, and later transformed into baryon asymmetry via **sphaleron processes**

Yanagida, Fukugita (1986)

Key ingredients for Leptogenesis

Sakharov (1967)

Baryon number violation	CP Violation	Departure from thermal equilibrium
↓	↓	↓
Lepton to baryon asymmetry conversion factor from (B+L)-violating sphaleron transitions	**CP asymmetry**	**Efficiency factors**
$a_{\rm sph} \equiv \frac{B}{B-L} = \frac{24+4n_H}{66+13n_H}$	$\varepsilon^a_{i\alpha} = \frac{\Gamma(N_i \to \Phi_a \ell_\alpha) - \Gamma(N_i \to \Phi_a^\dagger \overline{\ell}_\alpha)}{\sum_\beta \sum_b \left[\Gamma(N_i \to \Phi_b \ell_\beta) + \Gamma(N_i \to \Phi_b^\dagger \overline{\ell}_\beta)\right]}$	$\hat{\mathcal{L}} f_\varphi = \hat{\mathcal{C}} f_\varphi$

New complex scalar singlet contributions (CP asymmetry and efficiency factors)

Sierra, Tórtola, Valle, Vicente (2014), Le Dall, Ritz (2014), Alanne, Huggle, Platscher (2019)

CP asymmetries

Flavoured CP asymmetry:

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Contributions:

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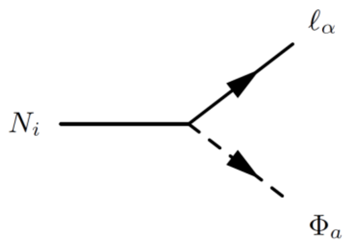
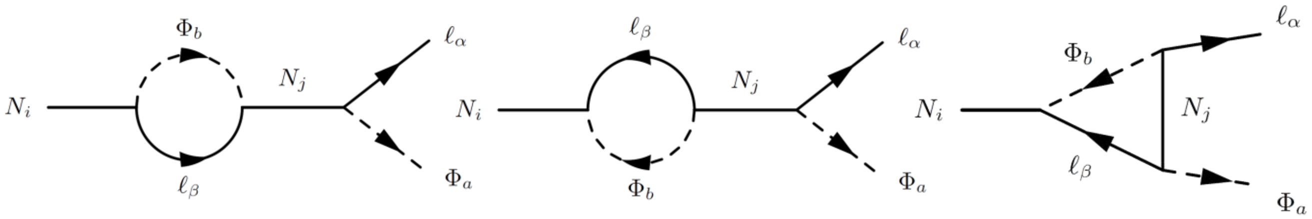
Type-I seesaw		

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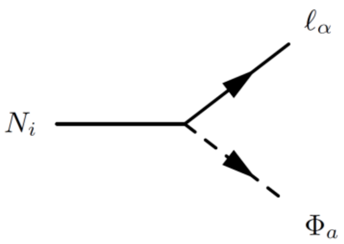
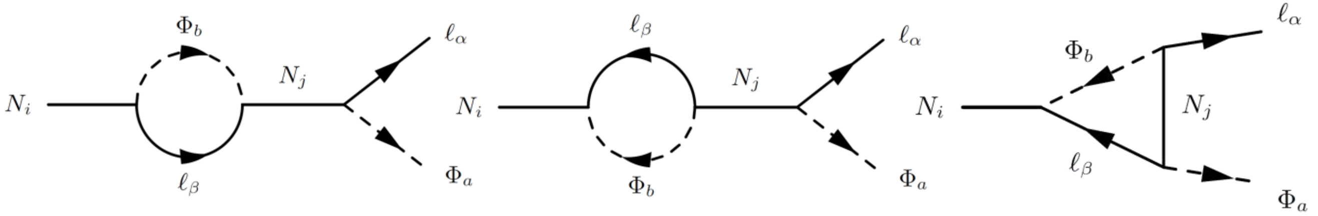
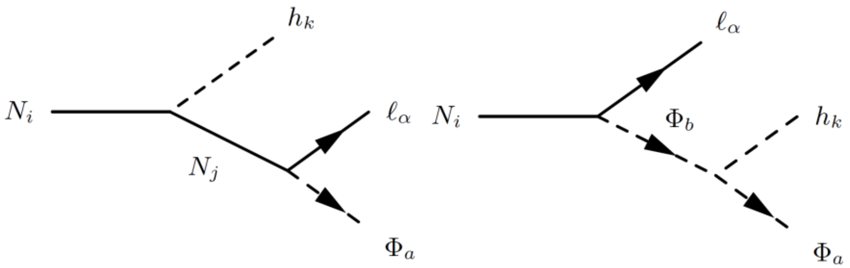
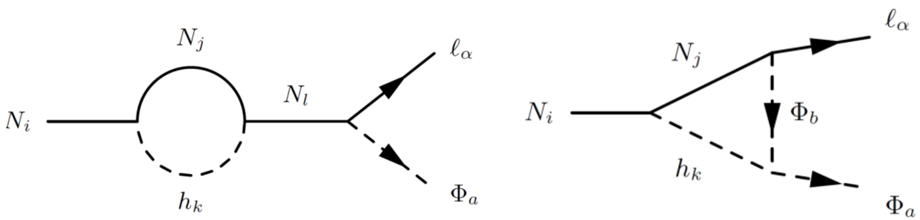
Type-I seesaw		
New		

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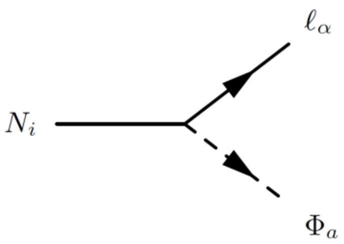
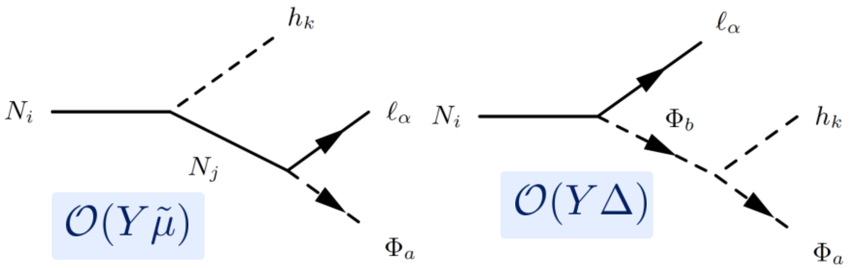


$\mathcal{O}(Y^2)$

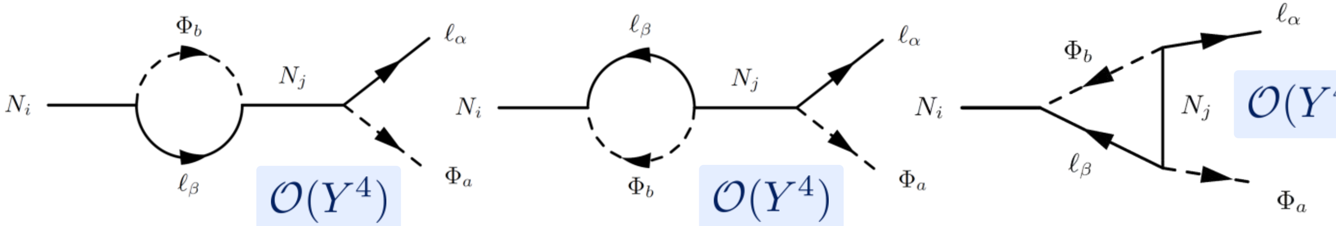
New



$\mathcal{O}(Y\tilde{\mu})$ $\mathcal{O}(Y\Delta)$

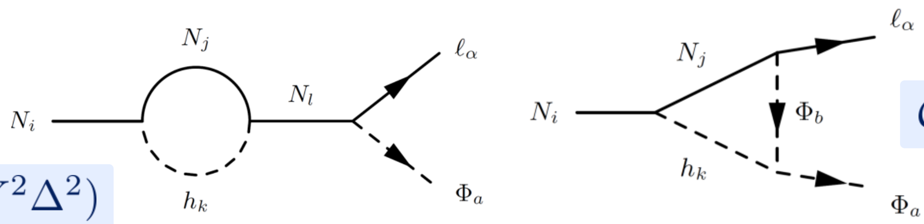
One-loop level

Type-I seesaw



$\mathcal{O}(Y^4)$ $\mathcal{O}(Y^4)$ $\mathcal{O}(Y^4)$

New



$\mathcal{O}(Y^2\Delta^2)$ $\mathcal{O}(Y^2\tilde{\mu}\Delta)$

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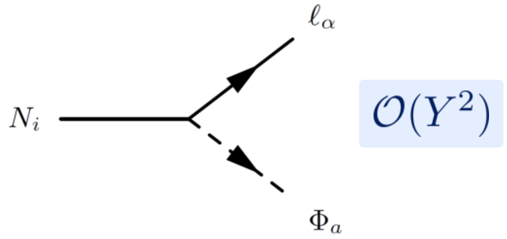

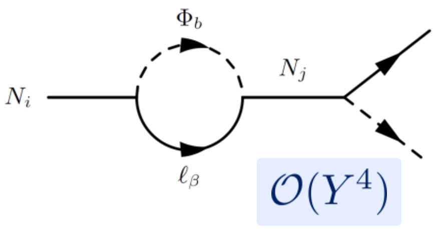

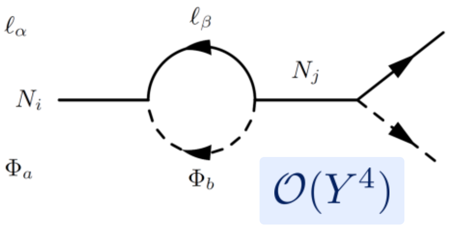

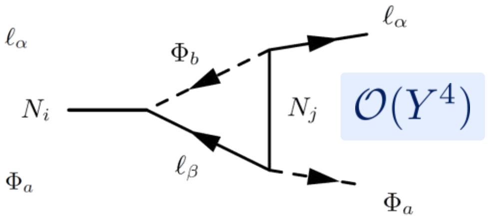

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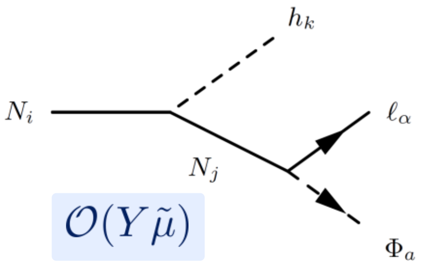

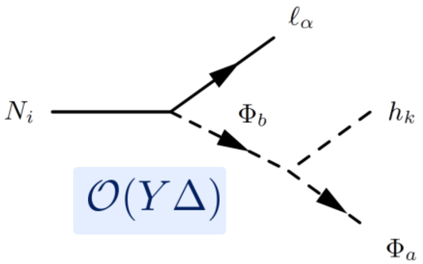

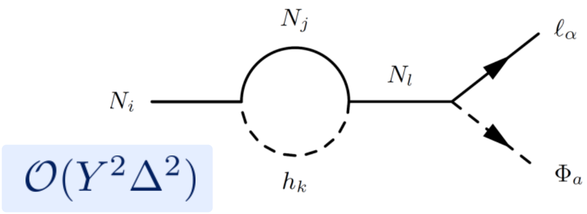

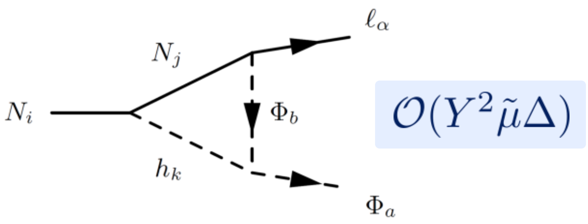

$$\varepsilon^a_{i\alpha} = \varepsilon^a_{i\alpha}(\text{type-I}) + \underbrace{\varepsilon^a_{i\alpha}(\text{3-body decay}) + \varepsilon^a_{i\alpha}(\text{wave}) + \varepsilon^a_{i\alpha}(\text{vertex})}_{}$$

Presence of new scalar singlets

Le Dall, Ritz (2014)

Unflavoured Boltzmann equations

Considering $n_R = 2$ and $M_2 > M_1$:

$$\frac{dN_{N_1}}{dz} = -(D_1 + \frac{N_{N_2}^{\rm eq}}{N_{N_1}^{\rm eq}} D_{21} + S_1)(N_{N_1} - N_{N_1}^{\rm eq}) + D_{21}(N_{N_2} - N_{N_2}^{\rm eq}) - S_{11}[(N_{N_1})^2 - (N_{N_1}^{\rm eq})^2] - S_{12}(N_{N_1} N_{N_2} - N_{N_1}^{\rm eq} N_{N_2}^{\rm eq})$$

$$\frac{dN_{N_2}}{dz} = -(D_2 + D_{21} + S_2)(N_{N_2} - N_{N_2}^{\rm eq}) + \frac{N_{N_2}^{\rm eq}}{N_{N_1}^{\rm eq}} D_{21}(N_{N_1} - N_{N_1}^{\rm eq}) - S_{22}[(N_{N_2})^2 - (N_{N_2}^{\rm eq})^2] - S_{12}(N_{N_1} N_{N_2} - N_{N_1}^{\rm eq} N_{N_2}^{\rm eq})$$

$$\frac{dN_{B-L}}{dz} = -\sum_{i=1}^{2} \epsilon_i D_i (N_{N_i} - N_{N_i}^{\rm eq}) - W N_{B-L}$$

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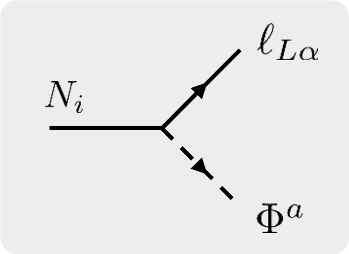
$\Delta L = 1$ decays (D_i)



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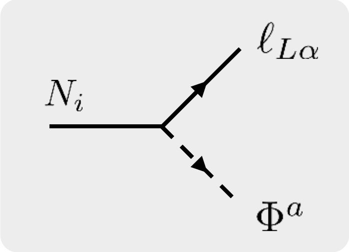

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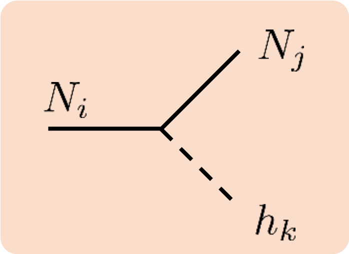

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decays
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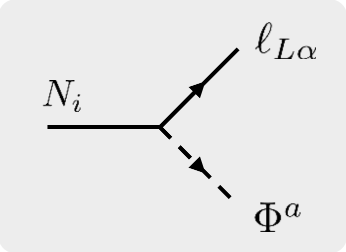
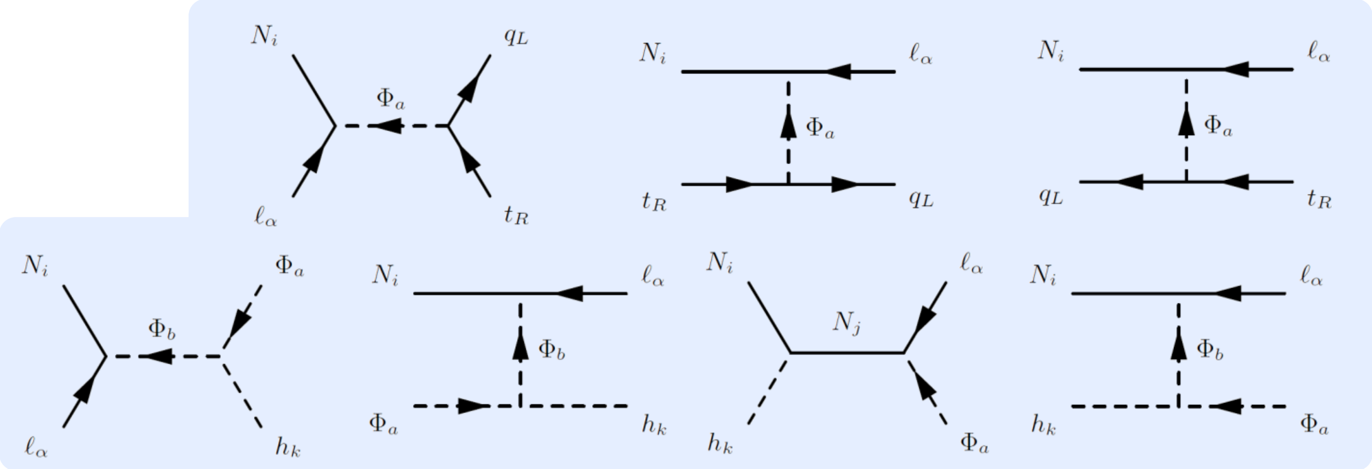


$\Delta L = 1$
scatterings
(S_i)



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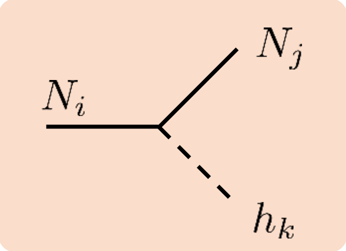
decays
(D_{ij})



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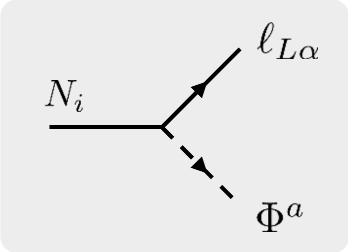
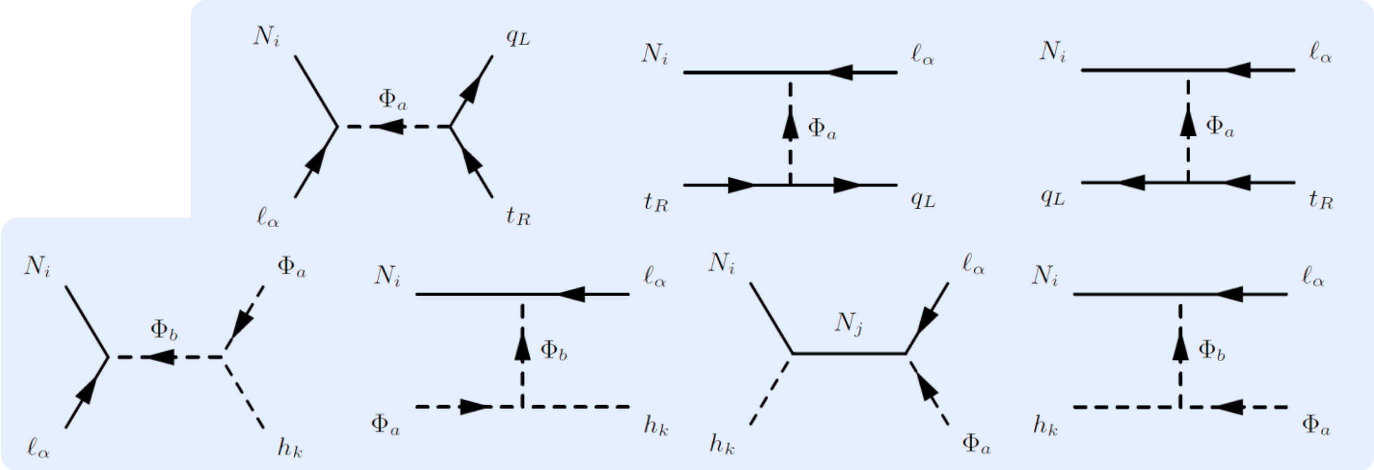
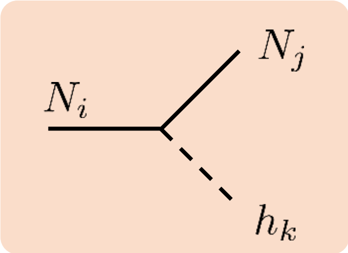


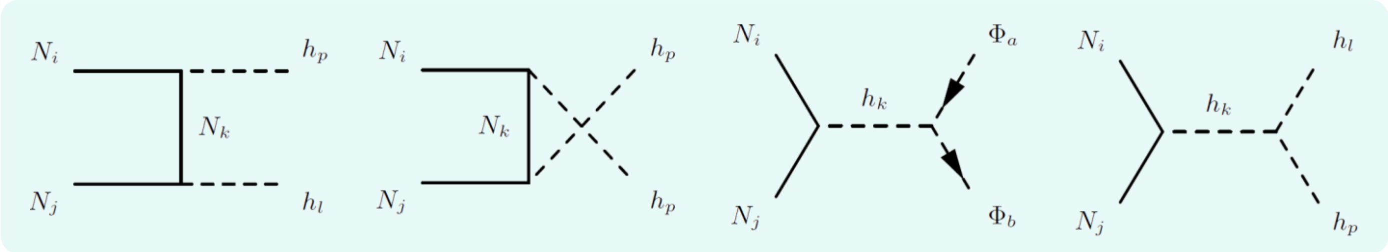
$\Delta L = 1$ scatterings (S_i)



$\Delta L = 0$ decays (D_{ij})



$\Delta N = 2$ scatterings (S_{ij})



An illustrative model

Extending the SM with **2 RH neutrinos**, **1 scalar doublet** and **1 scalar singlet** along with a discrete flavour symmetry to **minimize the number of free parameters**

	Fields	$SU(2)_L \otimes U(1)_Y$	$\mathcal{Z}_8^e$	$\mathcal{Z}_8^\mu$	$\mathcal{Z}_8^\tau$
Fermions	ℓ_{eL}	$(\mathbf{2}, -1/2)$	ω^5	ω^7	ω^6
	$\ell_{\mu L}$	$(\mathbf{2}, -1/2)$	ω^7	ω^5	ω^5
	$\ell_{\tau L}$	$(\mathbf{2}, -1/2)$	ω^6	ω^6	ω^7
	e_R	$(\mathbf{1}, -1)$	ω^4	ω^7	ω^6
	μ_R	$(\mathbf{1}, -1)$	ω^7	ω^4	ω^4
	τ_R	$(\mathbf{1}, -1)$	ω^6	ω^6	ω^7
	ν_{R_1}	$(\mathbf{1}, 0)$	ω^6	ω^6	ω^6
	ν_{R_2}	$(\mathbf{1}, 0)$	1	1	1
Scalars	Φ_1	$(\mathbf{2}, 1/2)$	1		
	Φ_2	$(\mathbf{2}, 1/2)$	ω		
	S	$(\mathbf{1}, 0)$	ω^2		

$$\langle \phi_1^0 \rangle = \frac{v_1}{\sqrt{2}} \ , \ \langle \phi_2^0 \rangle = \frac{v_2}{\sqrt{2}} \ , \ \langle S \rangle = \frac{u e^{i\theta}}{\sqrt{2}}$$

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$\Downarrow\ \mathcal{Z}_8^\tau$

$$\mathbf{Y}_\ell^1 = \begin{pmatrix} y_1 & 0 & 0 \\ 0 & y_3 & 0 \\ 0 & 0 & 0 \end{pmatrix},\ \mathbf{Y}_\ell^2 = \begin{pmatrix} 0 & y_2 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_4 \end{pmatrix},\ \mathbf{Y}_D^1 = \begin{pmatrix} 0 & 0 \\ y_{D_2} & 0 \\ 0 & 0 \end{pmatrix},\ \mathbf{Y}_D^2 = \begin{pmatrix} 0 & y_{D_1} \\ 0 & 0 \\ y_{D_3} & 0 \end{pmatrix},$$

$$\mathbf{M}_R^0 = \begin{pmatrix} 0 & 0 \\ . & m_R \end{pmatrix},\ \mathbf{Y}'_R = \begin{pmatrix} 0 & y_{R_S} \\ . & 0 \end{pmatrix},\ \mathbf{Y}_R = \begin{pmatrix} 0 & 0 \\ . & 0 \end{pmatrix}$$

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At the effective level (charged-lepton mass basis):

$$\mathbf{M}_\nu = \begin{pmatrix} -e^{-i\theta} y \sqrt{\frac{z}{x}} \sin(2\theta_L) + z s_L^2 & e^{-i\theta} y \sqrt{\frac{z}{x}} \cos(2\theta_L) - \frac{z}{2} \sin(2\theta_L) & e^{-i\theta} y c_L - \sqrt{xz} s_L \\ . & e^{-i\theta} y \sqrt{\frac{z}{x}} \sin(2\theta_L) + z c_L^2 & e^{-i\theta} y s_L + \sqrt{xz} c_L \\ . & . & x \end{pmatrix}$$

$$x = \frac{v_2^2}{u^2} \frac{m_R y_{D_3}^2}{y_{R_S}^2},\ y = \frac{v_2^2}{\sqrt{2} u} \frac{y_{D_1} y_{D_3}}{y_{R_S}},$$

$$z = \frac{v_1^2}{u^2} \frac{m_R y_{D_2}^2}{y_{R_S}^2}$$

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- CP is **spontaneously broken** by the complex VEV of S and is **successfully transmitted to the leptonic sector**
- A minimal scalar potential which allows to implement SCPV must contain a **phase sensitive** term of the type $\boldsymbol{S^4} + \mathbf{H.c.}$
- New Z_8 discrete symmetry leads to **low-energy constrains** for neutrino masses and lepton mixing
- Phase $\boldsymbol{\theta}$ **is source of CPV at low-energies** and leads to **non-zero CP asymmetries in the early Universe**

Branco *et al.* (1999, 2003)

Neutrino sector predictions

High-energy parameters

$$\mathbf{M}_\nu = \begin{pmatrix} -e^{-i\theta} y\sqrt{\frac{z}{x}}\sin(2\theta_L) + z s_L^2 & e^{-i\theta} y\sqrt{\frac{z}{x}}\cos(2\theta_L) - \frac{z}{2}\sin(2\theta_L) & e^{-i\theta} y c_L - \sqrt{xz}\, s_L \\ \cdot & e^{-i\theta} y\sqrt{\frac{z}{x}}\sin(2\theta_L) + z c_L^2 & e^{-i\theta} y s_L + \sqrt{xz}\, c_L \\ \cdot & \cdot & x \end{pmatrix}$$

matching

Low-energy parameters

$$\widehat{\mathbf{M}}_\nu = \mathbf{U}^* \mathrm{diag}(m_1, m_2, m_3)\mathbf{U}^\dagger$$

$$\mathbf{U} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}e^{i\delta} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

Rodejohann, Valle (2011)

Using the global fit of neutrino oscillation data: Salas *et al.* (2021)

Case	θ/π	θ_L/π	(x,y,z) (meV)	θ_{23} (°)	δ/π	α/π	$m_{\beta\beta}$ (meV)	m_β (meV)	$\sum_i m_i$ (meV)
$\mathcal{Z}_8^\mu$ (IO)	0.11	7.29×10^{-2}	(0.325, 32.8, 0.426)	49.62	1.88	0.92	16.6	49.2	99.7
$\mathcal{Z}_8^\tau$ (IO)	1.92	6.36×10^{-2}	(0.431, 37.8, 0.321)	48.64	1.08	1.04	12.6		

- Only cases $\boldsymbol{Z_8^\mu}$ **and** $\boldsymbol{Z_8^\tau}$ are **compatible with neutrino oscillation data** at the 3σ level and only for **inverted ordering** (IO)
- **SCPV phase** $\boldsymbol{\theta}$ is **fixed** by **low-energy parameters** due to the constraints imposed by the **underlying** $\boldsymbol{Z_8}$ **symmetry**

CP asymmetry contributions

Reconstructed Yukawa couplings (in the charged-lepton and heavy-neutrino mass basis for case Z_8^{τ}):

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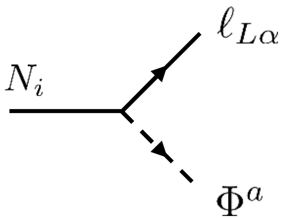
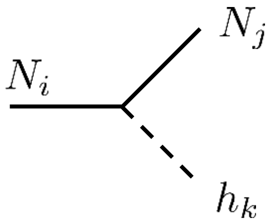


$$\mathbf{Y}^1 = \frac{\sqrt{z}\sqrt{M_1}}{v_1}\frac{\sqrt{2}}{\sqrt{1-r_{12}}}\begin{pmatrix} -s_L e^{i\theta} & -\sqrt[4]{r_{12}} s_L e^{i\theta} \\ c_L e^{i\theta} & \sqrt[4]{r_{12}} c_L e^{i\theta} \\ 0 & 0 \end{pmatrix}, \quad \mathbf{Y}^2 = \frac{\sqrt{x}\sqrt{M_1}}{v_2}\frac{\sqrt{2}}{\sqrt{1-r_{12}}}\begin{pmatrix} \frac{y}{x}\left(1-\sqrt{r_{12}}\right) c_L & -\frac{y}{x}\left(1-\sqrt{r_{12}}\right) c_L \\ \frac{y}{x}\left(1-\sqrt{r_{12}}\right) s_L & -\frac{y}{x}\left(1-\sqrt{r_{12}}\right) s_L \\ e^{i\theta} & \sqrt[4]{r_{12}} e^{i\theta} \end{pmatrix}$$



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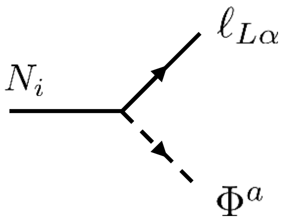

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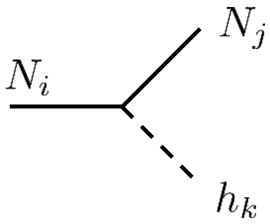

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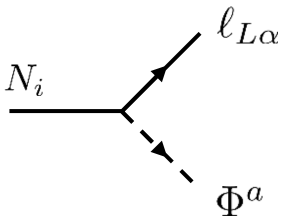

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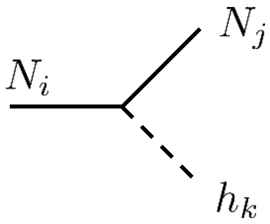

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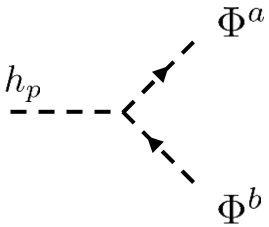

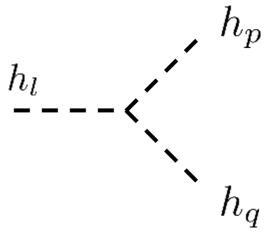

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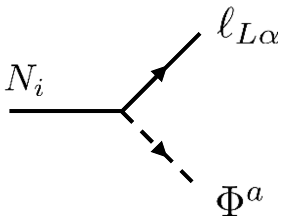

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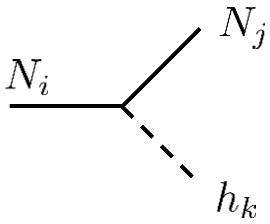

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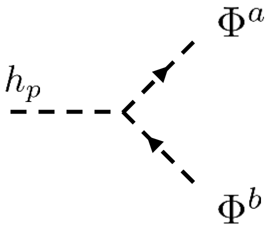

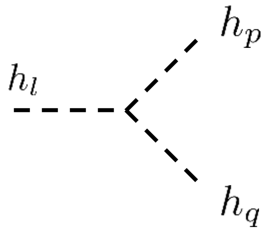

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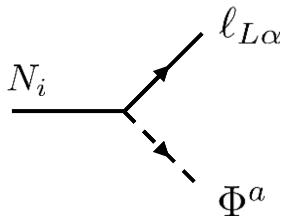

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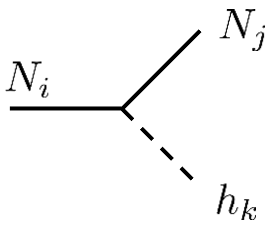

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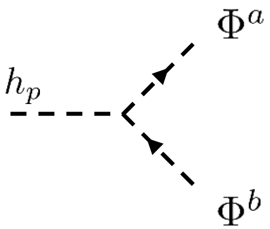

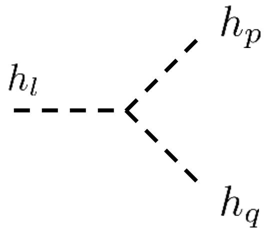

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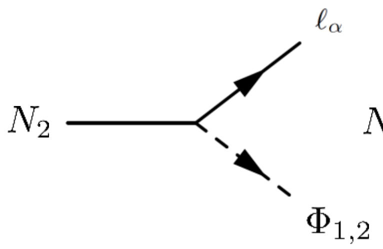

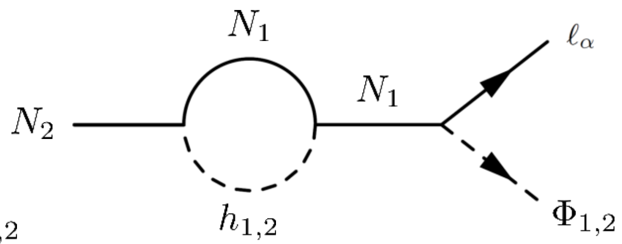

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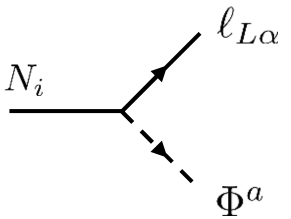

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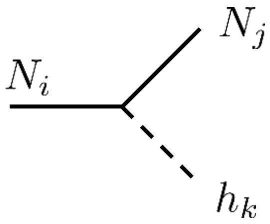

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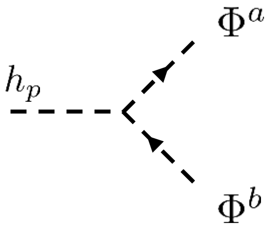

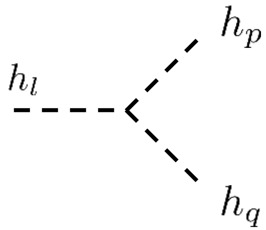

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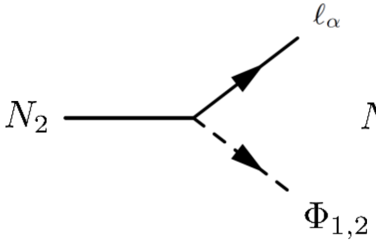

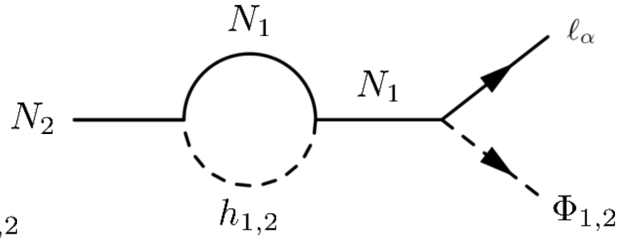

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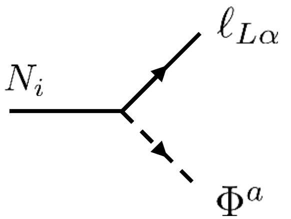

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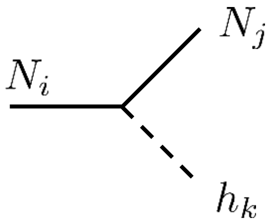

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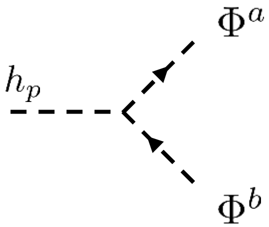

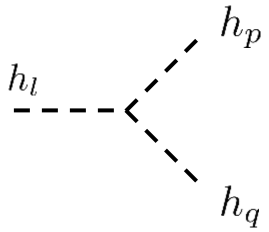

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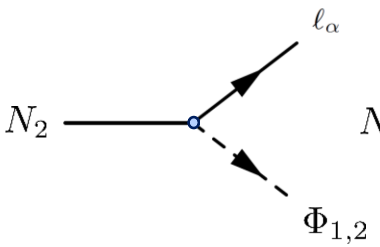

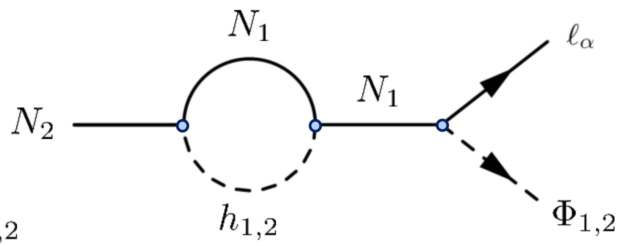

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CPV phase

Scalar mixing: $\theta_S = f(m_{h_1}, m_{h_2}, \theta)$

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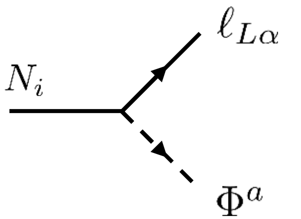
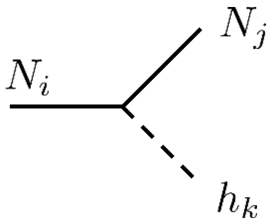
$$r_{12} = \frac{M_1}{M_2}$$



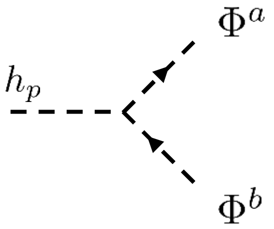
$$\mathbf{Y}^1 = \frac{\sqrt{z}\sqrt{M_1}}{v_1}\frac{\sqrt{2}}{\sqrt{1-r_{12}}}\begin{pmatrix} -s_L e^{i\theta} & -\sqrt[4]{r_{12}}\, s_L e^{i\theta} \\ c_L e^{i\theta} & \sqrt[4]{r_{12}}\, c_L e^{i\theta} \\ 0 & 0 \end{pmatrix}, \quad \mathbf{Y}^2 = \frac{\sqrt{x}\sqrt{M_1}}{v_2}\frac{\sqrt{2}}{\sqrt{1-r_{12}}}\begin{pmatrix} \frac{y}{x}\left(1-\sqrt{r_{12}}\right) c_L & -\frac{y}{x}\left(1-\sqrt{r_{12}}\right) c_L \\ \frac{y}{x}\left(1-\sqrt{r_{12}}\right) s_L & -\frac{y}{x}\left(1-\sqrt{r_{12}}\right) s_L \\ e^{i\theta} & \sqrt[4]{r_{12}}\, e^{i\theta} \end{pmatrix}$$

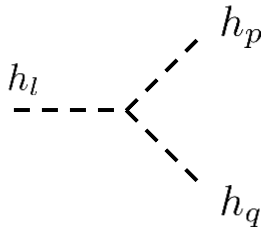


$$\mathbf{\Delta}^1 = \frac{M_2}{u}\frac{\sqrt[4]{r_{12}}}{1+\sqrt{r_{12}}}\begin{pmatrix} -2\sqrt[4]{r_{12}} & 1-\sqrt{r_{12}} \\ \cdot & 2\sqrt[4]{r_{12}} \end{pmatrix} e^{-i(\theta_S-\theta)}, \quad \mathbf{\Delta}^2 = -i\mathbf{\Delta}^1$$

Usual type-I seesaw diagrams do not contribute to $\varepsilon_{\mathrm{CP}}$!

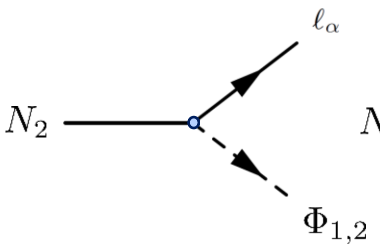
\+ Z_8 symmetry forbids cubic couplings and thus, $\tilde{\mu}_{ab,k} = 0$ and $\tilde{\mu}_{lpq} = 0$

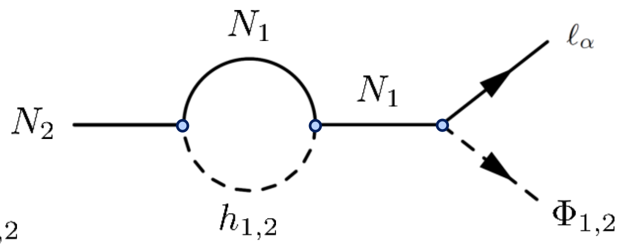




New 3-body decay and vertex diagrams do not contribute to $\varepsilon_{\mathrm{CP}}$!

Only contributions to the CP asymmetry:





$$\varepsilon_{\mathrm{CP}} \equiv \varepsilon_2 = \frac{1}{8\pi}\frac{M_2^2}{u^2}\frac{r_{12}\left[1-\sqrt{r_{12}}\right]\left[v_1^2(1-\sqrt{r_{12}})^2y^2 - v_1^2\sqrt{r_{12}}x^2 - v_2^2\sqrt{r_{12}}xz\right]}{\left[1+\sqrt{r_{12}}\right]^2\left[v_1^2 r_{12}x^2 + v_1^2(\sqrt{r_{12}}-1)^2y^2 + v_2^2 r_{12}xz\right]}$$
$$\times \sin[2(\theta_S-\theta)]\left[\mathcal{F}^{2111}_{\mathrm{w},LR} - \mathcal{F}^{2121}_{\mathrm{w},LR} - \mathcal{F}^{2111}_{\mathrm{w},RL} + \mathcal{F}^{2121}_{\mathrm{w},RL}\right]$$

CPV phase

Scalar mixing: $\theta_S = f(m_{h_1}, m_{h_2}, \theta)$

Loop factors: $\mathcal{F}_w = f'(m_{h_1}, m_{h_2}, M_1, M_2)$

CP asymmetry results (preliminary)

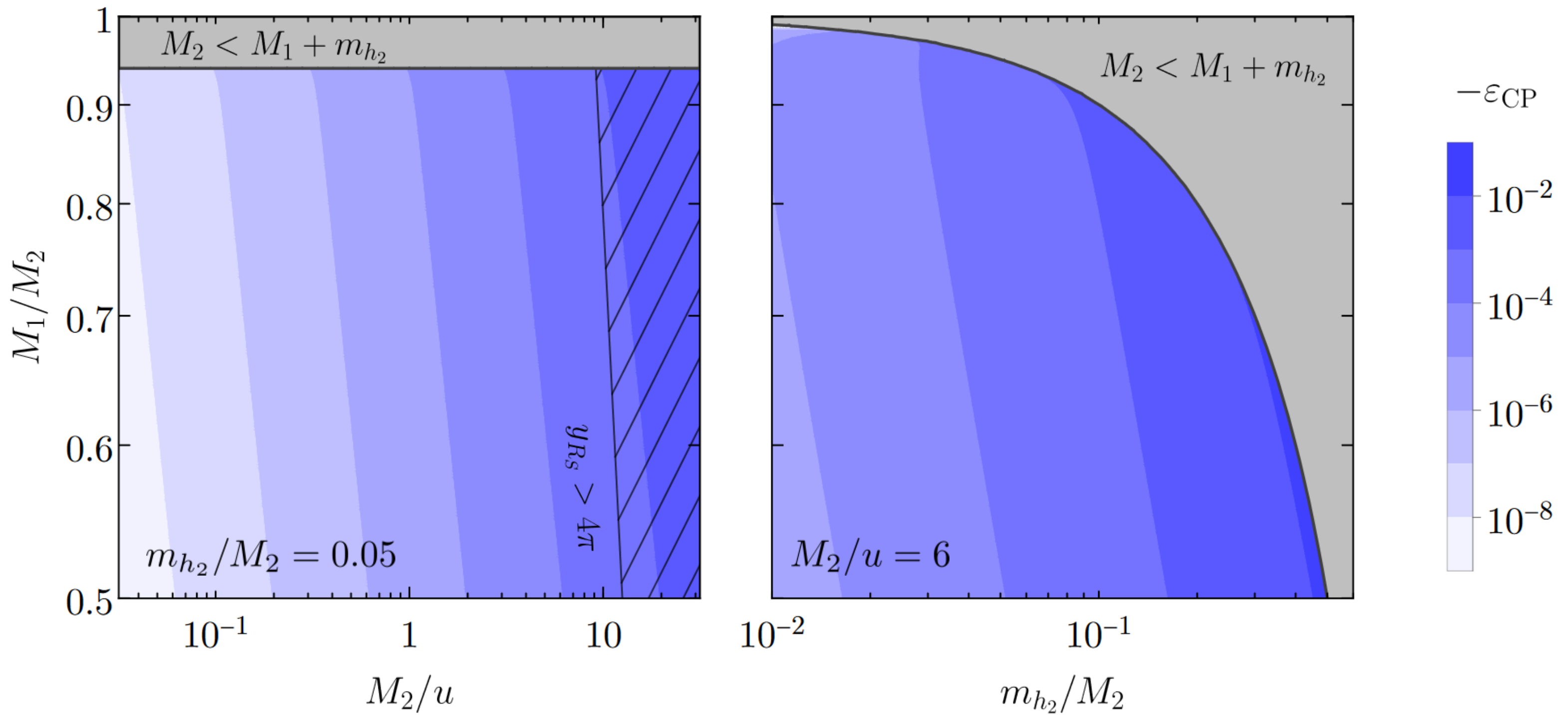
$$\varepsilon_{\rm CP} = \frac{1}{8\pi}\frac{M_2^2}{u^2}\frac{r_{12}\left[1-\sqrt{r_{12}}\right]\left[v_1^2(1-\sqrt{r_{12}})^2y^2 - v_1^2\sqrt{r_{12}}x^2 - v_2^2\sqrt{r_{12}}xz\right]}{\left[1+\sqrt{r_{12}}\right]^2\left[v_1^2 r_{12}x^2 + v_1^2(\sqrt{r_{12}}-1)^2y^2 + v_2^2 r_{12}xz\right]}\sin[2(\theta_S-\theta)]\left[\mathcal{F}^{2111}_{{\rm w},LR} - \mathcal{F}^{2121}_{{\rm w},LR} - \mathcal{F}^{2111}_{{\rm w},RL} + \mathcal{F}^{2121}_{{\rm w},RL}\right]$$

Case Z_8^τ (IO)

Preliminary results

Constraints:

- Kinematics: $M_2 > M_1 + m_{h_2}$
- Perturbativity: $|y_{D_i}|, |y_{R_s}|, |\lambda_i| < 4\pi$
- Constraints from requiring the scalar potential to be bounded from below
- **Neutrino low-energy parameters** are **fixed** to the model's **best-fit** value
- $v_1 = v_2 = 246$ GeV, $u = 10^{12}$ GeV
- $\frac{m_{h_1}}{m_{h_2}} = 10^{-4}$



Results:

- Case Z_8^μ predicts $\boldsymbol{\varepsilon_{\rm CP} > 0}$ (for $\boldsymbol{\theta \sim 0.11\,\pi}$)
- Case Z_8^τ predicts $\boldsymbol{\varepsilon_{\rm CP} < 0}$ (for $\boldsymbol{\theta \sim 1.92\,\pi}$)

BAU results (preliminary)

The results for the BAU are obtained by **numerically solving the BEs** in the **unflavoured temperature regime** ($T \gtrsim 10^{12}$ GeV)

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 9.40 \times 10^{-3} N^f_{B-L}$$

$$\eta_B^0 = (6.12 \pm 0.04) \times 10^{-10}$$

Planck Collaboration (2018)

Constraints:

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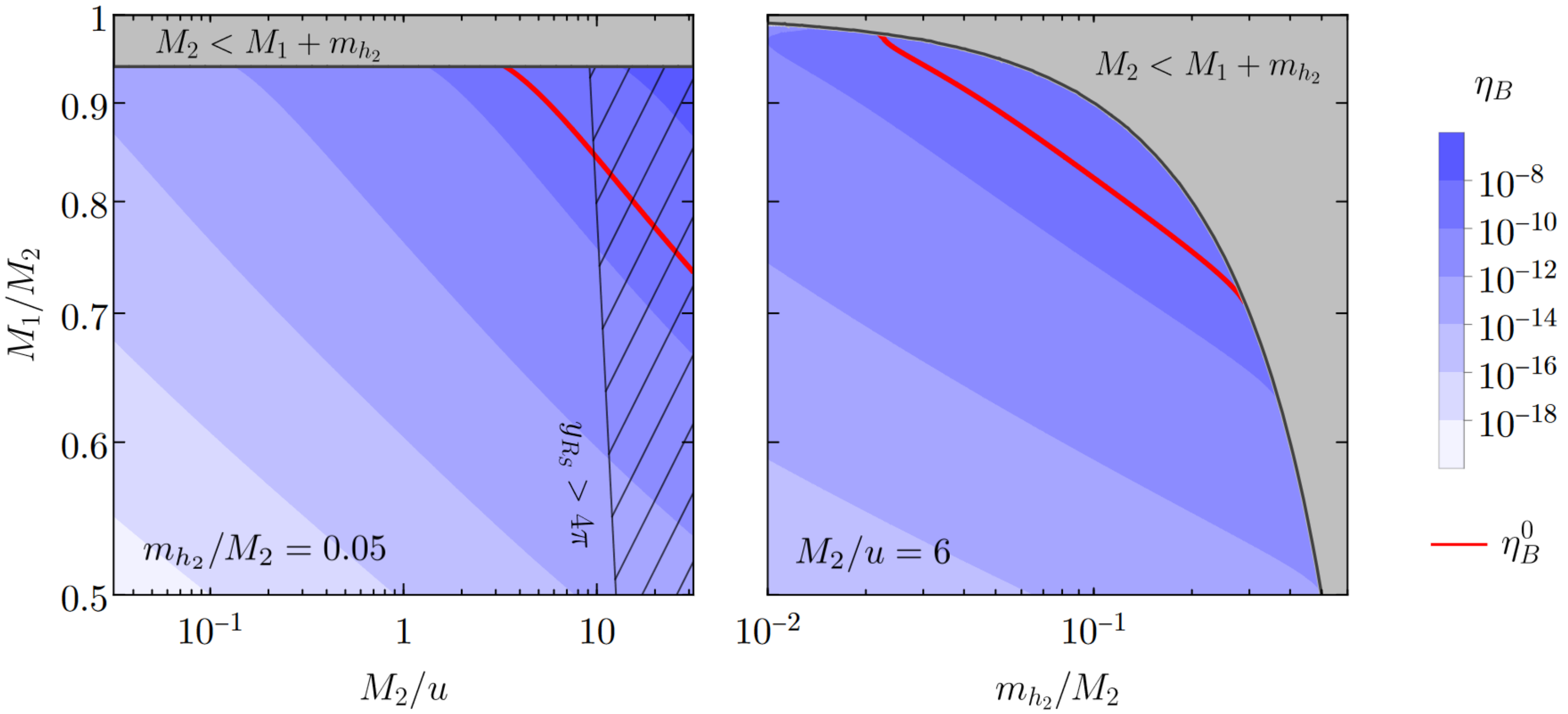
- $v_1 = v_2 = 246$ GeV, $u = 10^{12}$ GeV
- $\frac{m_{h_1}}{m_{h_2}} = 10^{-4}$
- Only **decays and inverse decays** are included in the analysis so far

Results:

- Case $\boldsymbol{Z_8^\mu}$ **predicts** $\boldsymbol{\eta_B < 0}$ (for $\theta \sim 0.11\,\pi$) and thus **excluded**
- Case $\boldsymbol{Z_8^\tau}$ **predicts** $\boldsymbol{\eta_B > 0}$ (for $\theta \sim 1.92\,\pi$) and the observed abundance is achieved for $M_1 \gtrsim 0.72\, M_2$, $M_2 \gtrsim 2\, u$, $m_{h_2} \gtrsim 2 \times 10^{-2} M_2$

Case Z_8^τ (IO)

Preliminary results



Concluding remarks

- We explore the possibility for **spontaneously CP violation** in the **complex scalar extension of the type-I seesaw model** to be the source of both **Dirac and Majorana CP violation**, at the electroweak scale, and **high-energy CP violation**, at the leptogenesis scale

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- We generalise CP asymmetry calculation for **arbitrary number** of RH neutrinos, complex scalars and scalar doublets added to the SM

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- For illustration, we study an extension of the SM with **one complex singlet**, **two RH neutrinos** and a **new scalar doublet**, where the parameters in the Lagrangian are constrained by the presence of a $\boldsymbol{Z_8}$ **flavour symmetry**
  - The Z_8 symmetry highly constrains the neutrino parameter space and leads to a **direct relation between the low-energy parameters and the SCPV phase**
  - The **only allowed CP asymmetry contribution** comes from the $h_{1,2}$ scalar mediated **wave diagram**, being the usual type-I seesaw diagrams, and new 3-body decay and vertex contributions forbidden
  - After **solving the BEs** by considering the effects of **decays and inverse decays**, we achieve the **observed BAU for** $\boldsymbol{M_1 \gtrsim 0.72\, M_2,\ M_2 \gtrsim 2\, u,\ m_{h_2} \gtrsim 2 \times 10^{-2} M_2}$
  - Next steps: complete our analysis by including scattering terms in the BEs

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Thank you!

Backup Slides

Spontaneous CP Violation

	Fields	$SU(2)_L \otimes U(1)_Y$	$\mathcal{Z}_8^e$	$\mathcal{Z}_8^\mu$	$\mathcal{Z}_8^\tau$
Scalars	Φ_1	$(\mathbf{2}, 1/2)$		1	
	Φ_2	$(\mathbf{2}, 1/2)$		ω	
	S	$(\mathbf{1}, 0)$		ω^2	

Scalar Potential

$$V(\Phi_1,\Phi_2,S) = m_1^2(\Phi_1^\dagger\Phi_1) + m_2^2(\Phi_2^\dagger\Phi_2) + m_{12}^2\left[(\Phi_1^\dagger\Phi_2) + (\Phi_2^\dagger\Phi_1)\right] + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+ \lambda_{1S}(\Phi_1^\dagger\Phi_1)|S|^2 + \lambda_{2S}(\Phi_2^\dagger\Phi_2)|S|^2 + m_S^2|S|^2 + m_S'^2\left(S^2 + S^{*2}\right) + \frac{\lambda_S}{2}|S|^4 + \lambda_S'\left(S^4 + S^{*4}\right)$$

⇩

From the minimisation conditions for

$$\langle\phi_1^0\rangle = \frac{v_1}{\sqrt{2}}\ ,\ \langle\phi_2^0\rangle = \frac{v_2}{\sqrt{2}}\ ,\ \langle S\rangle = \frac{ue^{i\theta}}{\sqrt{2}}$$

CP violating solution:

$$m_S^2 = -\frac{u^2}{2}(\lambda_S - 4\lambda_S')\ ,\ \cos(2\theta) = -\frac{m_S'^2}{2u^2\lambda_S'}$$

corresponds to the global minimum for $\left(m_S'^4 - 4u^4\lambda_S'^2\right)/(4\lambda_S') > 0$

Existence of non-zero vacuum phase at the potential global minimum ⇒ $\theta \neq k\,\pi$ is allowed!