SPONTANEOUS CP VIOLATION FROM *S*EVERAL ANGLES

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(*) Who is applying for postdocs

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Spontaneous CP violation

PHYSICAL REVIEW D VOLUME 8, NUMBER 4 15 AUGUST 1973

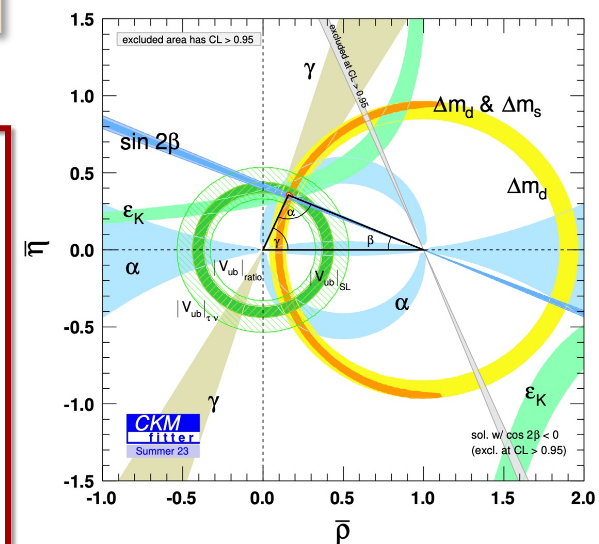
A Theory of Spontaneous T Violation*

T. D. Lee
Department of Physics, Columbia University, New York, New York 10027
(Received 11 April 1973)

A theory of spontaneous T violation is presented. The total Lagrangian is assumed to be invariant under the time reversal T and a gauge transformation (e.g., the hypercharge gauge), but the physical solutions are not. In addition to the spin-1 gauge field and the known matter fields, in its simplest form the theory consists of two complex spin-0 fields. Through the spontaneous symmetry-breaking mechanism of Goldstone and Higgs, the vacuum expectation values of these two spin-0 fields can be characterized by the shape of a triangle and their quantum fluctuations by its vibrational modes, just like a triangular molecule. T violations can be produced among the known particles through virtual excitations of the vibrational modes of the triangle which has a built-in T-violating phase angle. Examples of both Abelian and non-Abelian gauge groups are discussed. For renormalizable theories, all spontaneously T-violating effects are finite. It is found that at low energy, below the threshold of producing these vibrational quanta, T violation is always quite small.

First model of Spontaneous CP Violation (SCPV)
T. D. Lee (1973)

SCPV is only appealing if it can lead to **non-trivial CPV effects** in the fermion sector (CKM, PMNS,...)



HOW?

DIRECTLY

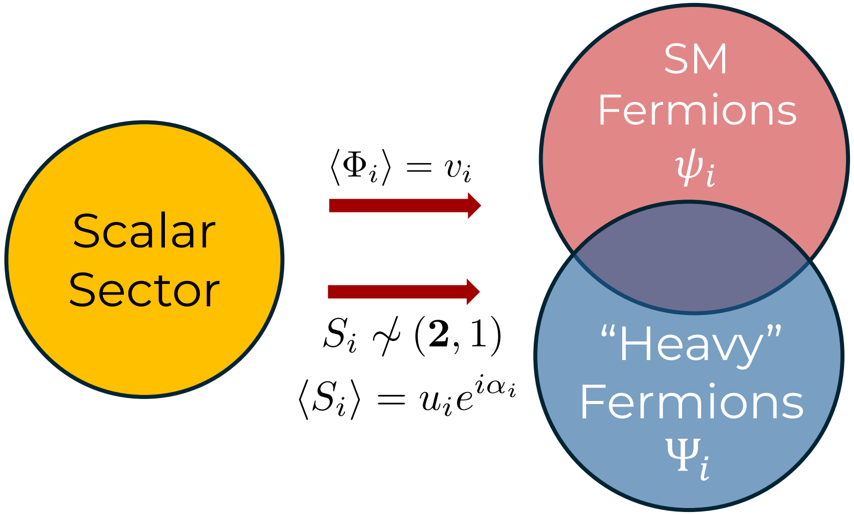
Scalar Sector → SM Fermion Sector

$\langle \Phi_i \rangle = v_i e^{\theta_i}$

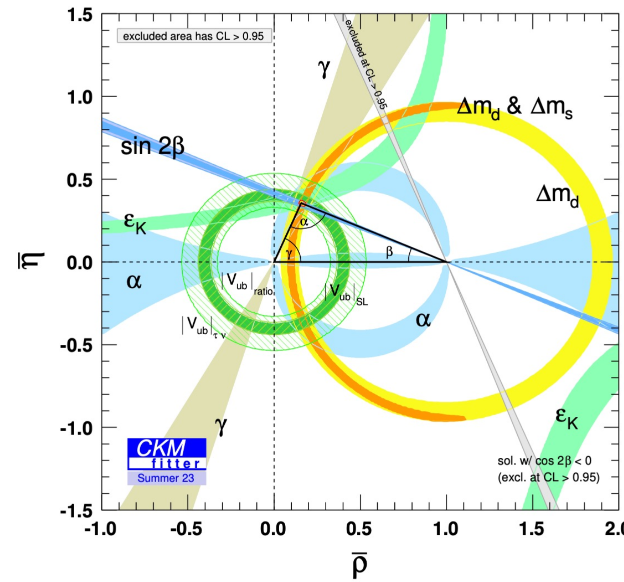
$\Phi_i \sim (\mathbf{2}, 1)$

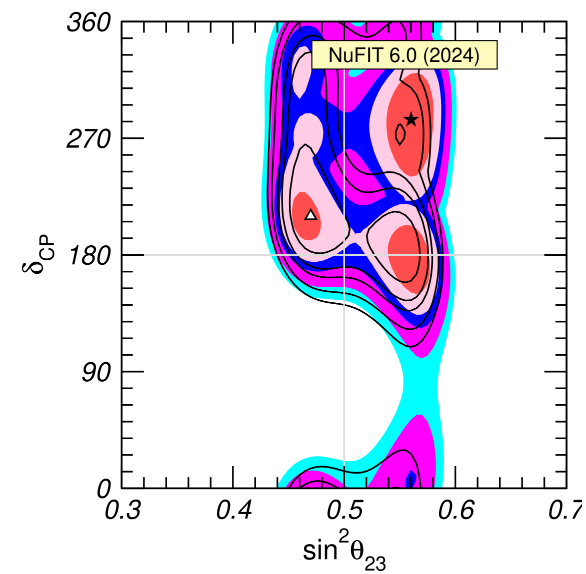
$Y^k_{ij} \psi_i \psi_j \Phi_k$ → **Non trivial CP phases in the observable sector**

CPV in the **"light SM sector"** via a **heavy-fermion** portal



CPV in the "light" sector





Heavy, light, heavy-light Yukawas

$$Y_{ij}^{(k)} \psi_i \psi_j \Phi_k + \tilde{Y}_{ij}^{(k)} \Psi_i \psi_j \Phi_k + \Gamma_{ij}^{(k)} \Psi_i \psi_j S_k + \ldots$$

CPV + some extra nice things...

Spontaneous CP violation

Physics Letters B
Volume 267, Issue 1, 5 September 1991, Pages 95-99

A minimal model with natural suppresion of strong *CP* violation

Luis Bento [a] *, Gustavo C. Branco [b], Paulo A. Parada [b]

A Common Origin for all CP Violations

G. C. Branco *,[1] P. A. Parada,[2] and M. N. Rebelo *[1]
[1] *Departamento de Física and Grupo Teórico de Física de Partículas, Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisboa, Portugal.*
[2] *Departamento de Física, Universidade da Beira Interior, Rua Marquês d'Ávila e Bolama, 6200 Covilhã, e Grupo Teórico de Física de Partículas, Instituto Superior Técnico, Lisboa, Portugal*
(Dated: March 22, 2022)

We put forward the conjecture that all CP violating phenomena may have a common origin. In order to illustrate our idea, we present a minimal model where CP is spontaneously broken at a high energy scale, through the phase in the vacuum expectation value of a complex scalar singlet. This single phase is the origin of both low energy CP violation in the quark and leptonic sectors, as well as leptogenesis. We also show that in this framework the strong CP problem may be solved in a simple way through the introduction of a Z_4 symmetry which allows for the implementation of the Nelson-Barr mechanism.

(BPR Model) Z_4 SYMMETRY:

$$D^0 \to -D^0 \;,\; S \to -S \;,\; \nu_R^0 \to i\nu_R^0 \;,\; \psi_l^0 \to i\psi_l^0 \;,\; e_R^0 \to ie_R^0$$

$$\mathcal{L}_q = \overline{\psi_q^0} G_u \phi u_R^0 + \overline{\psi_q^0} G_d \tilde{\phi} d_R^0 + \left(f_q S + {f_q}' S^*\right) \overline{D_L^0} d_R^0 + \tilde{M}\, \overline{D_L^0} D_R^0 + \text{ h.c.}$$

$$\mathcal{L}_l = \overline{\psi_l^0} G_l \phi e_R^0 + \overline{\psi_l^0} G_\nu \tilde{\phi} \nu_R^0 + \frac{1}{2} \nu_R^{0T} C \left(f_\nu S + + f_\nu' S^*\right) \nu_R^0 + \text{ h.c.}$$

$$V = V_{SM} + \left(\mu^2 + \lambda_1 S^* S + \lambda_2 \phi^\dagger \phi\right)\left(S^2 + S^{*2}\right) + \lambda_3 \left(S^4 + S^{*4}\right)$$

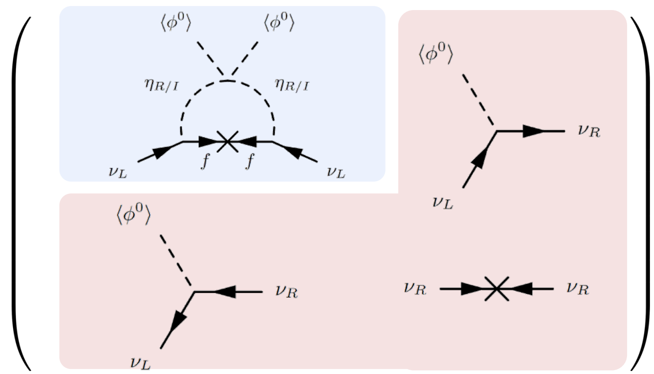
$$\langle \phi^0 \rangle = \frac{v}{\sqrt{2}} \;,\; \langle S \rangle = \frac{V \exp(i\alpha)}{\sqrt{2}}$$

→ **CPV in the "light" quark and neutrino sectors**

Rojas, Srivastava, Valle'19

	ν_R	η	f
$SU(2)_L$	1	2	1
$U(1)_Y$	0	1/2	0
$\mathcal{Z}_2$	+	−	−
Multiplicity	1	1	1

$\mathbf{M}_\nu =$



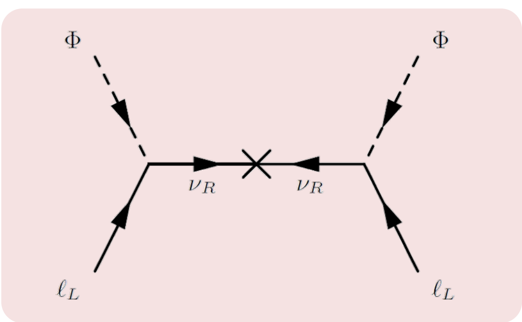
$$-\mathcal{L} = \overline{\ell_L}\mathbf{Y}_\nu^*\tilde{\Phi}\nu_R + \frac{1}{2}M_R\overline{\nu_R}\nu_R^c + \overline{\ell_L}\mathbf{Y}_f^*\tilde{\eta}f + \frac{1}{2}M_f\overline{f}f^c + \text{H.c.}$$

Generates the **atmospheric** neutrino mass scale

Generates the **solar** neutrino mass scale

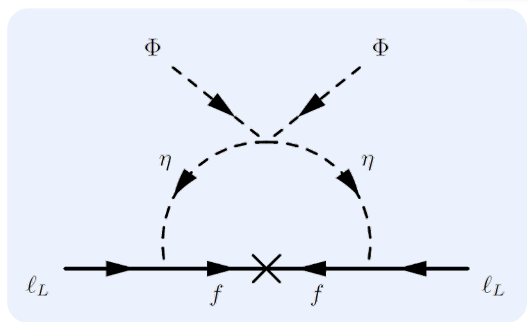
At the effective level:

$$= -\frac{v^2}{2}\frac{\mathbf{Y}_\nu\mathbf{Y}_\nu^T}{M_R} + \mathcal{F}\left(M_f, m_{\eta_R^0}, m_{\eta_I^0}\right)M_f\mathbf{Y}_f\mathbf{Y}_f^T$$



Type-I seesaw contribution

Minkowski'77; M. Gell- Mann, P. Ramond and R. Slansky'79); T. Yanagida'79; S.L. Glashow'80; Mohapatra and G. Senjanovic'80; Schechter & Valle'80.



Scotogenic contribution

Tao, PRD 54 (1996) 5693; Ma, PRD 73 (2006) 077301

- **Economical framework** for neutrino masses and mixing (one massless neutrino)
- **Scalar or fermion DM**
- **New LFV contributions** mediated by dark fermions/scalars

Minimal S-STI model with SCPV

Barreiros, FRJ, Srivastava & Valle
JHEP 04 (2021) 249

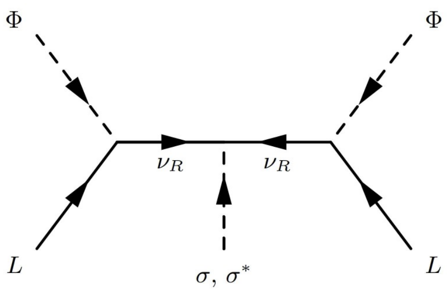
Scoto-seesaw + SCPV from a scalar singlet $\langle\sigma\rangle = ue^{i\theta}$

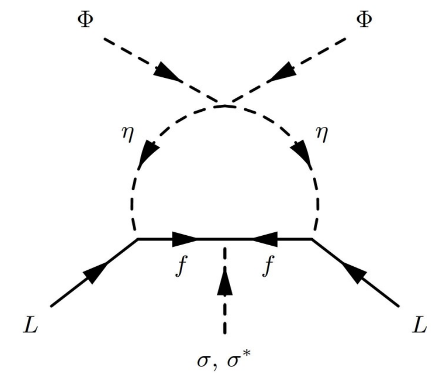
$$\frac{1}{2}(y_R\sigma + \tilde{y}_R\sigma^*)\overline{\nu_R}\nu_R^c + \frac{1}{2}\left(y_f\sigma + \tilde{y}_f\sigma^*\right)\bar{f}\,f^c + \text{ H.c.}$$

$$\mathbf{M}_\nu = -v^2 e^{i(\theta_f - \theta_R)}\frac{\mathbf{Y}_\nu\mathbf{Y}_\nu^T}{|M_R|} + \mathcal{F}(|M_f|, m_{\eta_R}, m_{\eta_I})|M_f|\mathbf{Y}_f\mathbf{Y}_f^T$$

$$|M_{R,f}|^2 = \left[y_{R,f}^2 + \tilde{y}_{R,f}^2 + 2y_{R,f}\tilde{y}_{R,f}\cos(2\theta_{R,f})\right]u^2$$

$$\tan(\theta_f - \theta_R) = \frac{\left(y_f\tilde{y}_R - y_R\tilde{y}_f\right)\sin(2\theta)}{y_R y_f + \tilde{y}_R\tilde{y}_f + \left(y_R\tilde{y}_f + y_f\tilde{y}_R\right)\cos(2\theta)}$$





Minimal scoto-seesaw

$1\ \nu_R + 1\ f$

(too many parameters, no predictions in the)

+

Abelian Flavour symmetries

↓

Two massless neutrinos and/or vanishing mixing angles

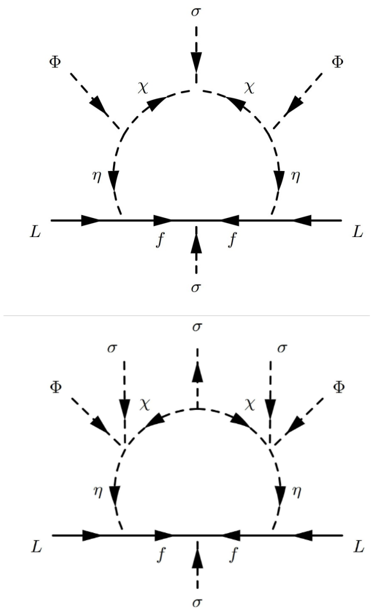
Minimal model that leads to predictions in the neutrino sector:

Z_8 flavour symmetry + 2 ν_R + 1 f

↓ $\langle\sigma\rangle = ue^{i\theta}$

Z_2 DM symmetry

Lowest-order contributions



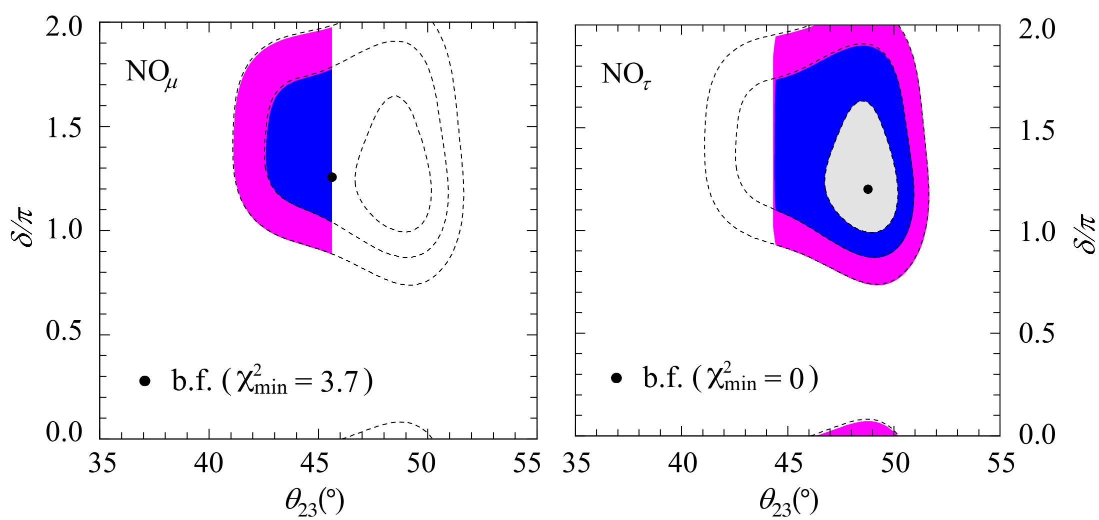
Flavour Structures:

$$\mathbf{Y}_\nu = \begin{pmatrix} \times & 0 \\ 0 & \times \\ \times & 0 \end{pmatrix}, \quad \mathbf{Y}_f = \begin{pmatrix} \times \\ 0 \\ \times \end{pmatrix}, \quad \mathbf{Y}_\ell = \begin{pmatrix} \times & 0 & \times \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix}, \quad \mathbf{M}_R = \begin{pmatrix} 0 & \times \\ \cdot & \times \end{pmatrix}$$

	Fields	$\mathrm{SU(2)_L \otimes U(1)_Y}$	$\mathcal{Z}_8^{e-\mu} \to \mathcal{Z}_2^D$	$\mathcal{Z}_8^{\mu-\tau} \to \mathcal{Z}_2^D$	$\mathcal{Z}_8^{e-\tau} \to \mathcal{Z}_2^D$
Fermions	L_e, e_R	$(\mathbf{2},-1/2),(\mathbf{1},0)$	$\omega^6 \equiv -i \to +1$	$\omega^0 \equiv 1 \to +1$	$\omega^6 \equiv -i \to +1$
	L_μ, μ_R	$(\mathbf{2},-1/2),(\mathbf{1},0)$	$\omega^6 \equiv -i \to +1$	$\omega^6 \equiv -i \to +1$	$\omega^0 \equiv 1 \to +1$
	L_τ, τ_R	$(\mathbf{2},-1/2),(\mathbf{1},0)$	$\omega^0 \equiv 1 \to +1$	$\omega^6 \equiv -i \to +1$	$\omega^6 \equiv -i \to +1$
	ν_R^1	$(\mathbf{1},0)$	$\omega^6 \equiv -i \to +1$	$\omega^6 \equiv -i \to +1$	$\omega^6 \equiv -i \to +1$
	ν_R^2	$(\mathbf{1},0)$	$\omega^0 \equiv 1 \to +1$	$\omega^0 \equiv 1 \to +1$	$\omega^0 \equiv 1 \to +1$
	f	$(\mathbf{1},0)$	$\omega^3 \to -1$	$\omega^3 \to -1$	$\omega^3 \to -1$
Scalars	Φ	$(\mathbf{2},1/2)$	$\omega^0 \equiv 1 \to +1$	$\omega^0 \equiv 1 \to +1$	$\omega^0 \equiv 1 \to +1$
	σ	$(\mathbf{1},0)$	$\omega^2 \equiv i \to +1$	$\omega^2 \equiv i \to +1$	$\omega^2 \equiv i \to +1$
	η	$(\mathbf{2},1/2)$	$\omega^5 \to -1$	$\omega^5 \to -1$	$\omega^5 \to -1$
	χ	$(\mathbf{1},0)$	$\omega^3 \to -1$	$\omega^3 \to -1$	$\omega^3 \to -1$

In cases $NO_{\mu,\tau}$ the model predicts the octant of the atmospheric mixing angle

In the remaining cases the model does not constrain the mixing parameters.



Flavour and DM in the S-ST2 model

Barreiros, Câmara, Felipe and FRJ, JHEP 08 (2022) 030

JHEP

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Flavour and dark matter in a scoto/type-II seesaw model

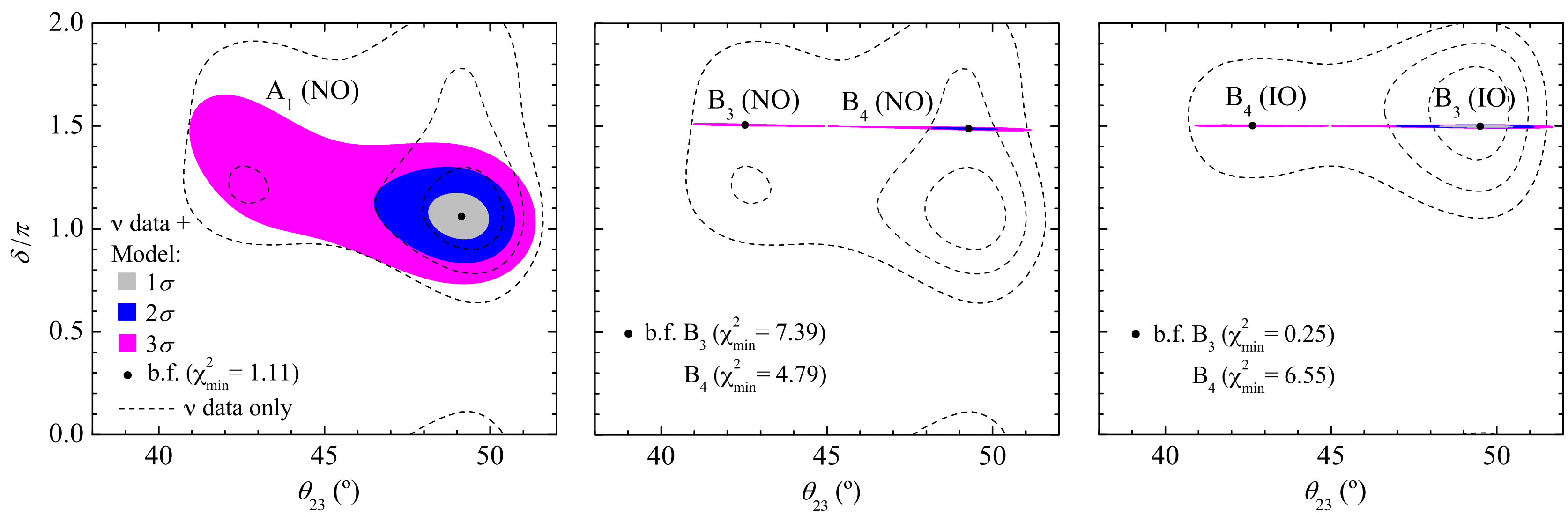
JHEP08(2022)030

D.M. Barreiros, H.B. Câmara and F.R. Joaquim

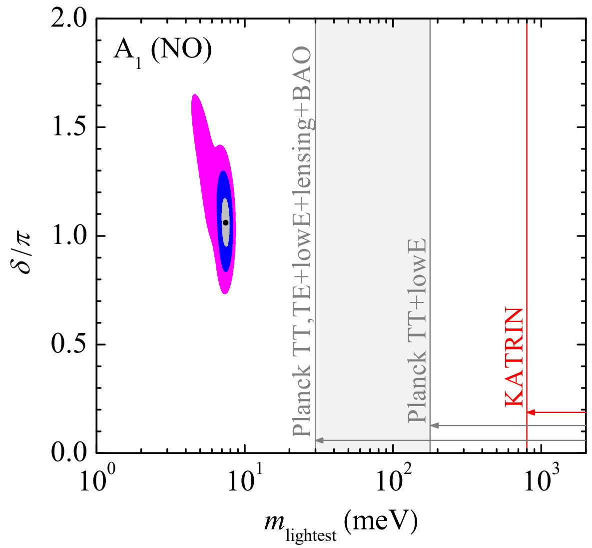
	Fields	$\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$	$\mathcal{Z}_8^{e-\mu} \to \mathcal{Z}_2$	$\mathcal{Z}_8^{e-\tau} \to \mathcal{Z}_2$	$\mathcal{Z}_8^{\mu-\tau} \to \mathcal{Z}_2$
Fermions	ℓ_{eL}, e_R	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$1 \to +$	$1 \to +$	$\omega^2 \to +$
	$\ell_{\mu L}, \mu_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^6 \to +$	$\omega^2 \to +$	$1 \to +$
	$\ell_{\tau L}, \tau_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^2 \to +$	$\omega^6 \to +$	$\omega^6 \to +$
	f	$(\mathbf{1}, 0)$	$\omega^3 \to -$	$\omega^3 \to -$	$\omega^3 \to -$
Scalars	Φ	$(\mathbf{2}, 1/2)$		$1 \to +$	
	Δ	$(\mathbf{3}, 1)$		$1 \to +$	
	σ	$(\mathbf{1}, 0)$		$\omega^2 \to +$	
	η_1	$(\mathbf{2}, 1/2)$		$\omega^3 \to -$	
	η_2	$(\mathbf{2}, 1/2)$		$\omega^5 \to -$	

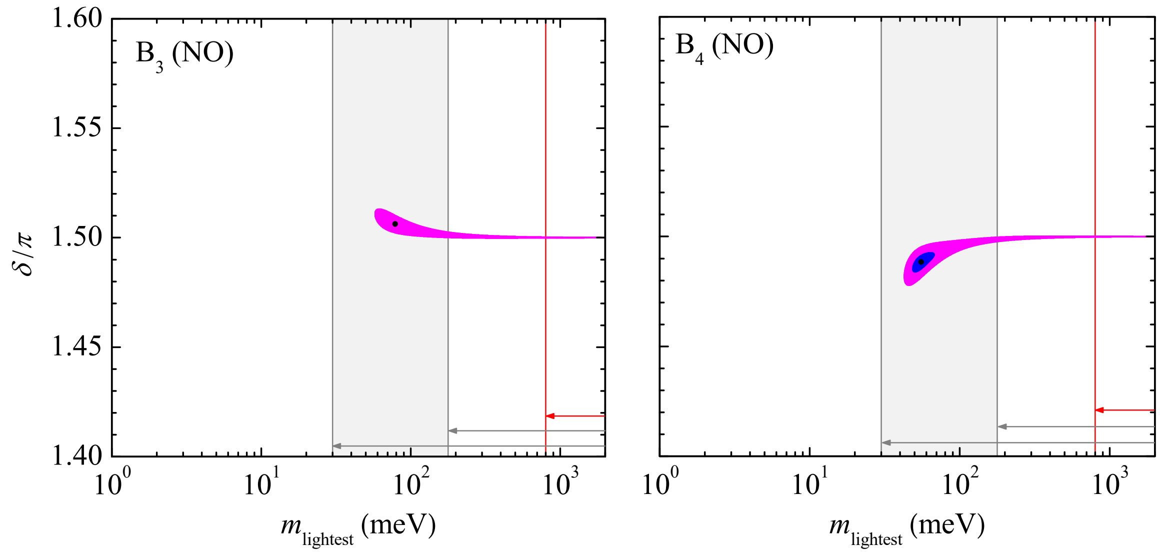
Very restricted flavour structure for the effective neutrino mass texture

$$\mathcal{Z}_8^{e-\mu} \to \mathrm{B}_4 : \begin{pmatrix} \times & \times & 0 \\ . & \times & \times \\ . & . & 0 \end{pmatrix}, \mathcal{Z}_8^{e-\tau} \to \mathrm{B}_3 : \begin{pmatrix} \times & 0 & \times \\ . & 0 & \times \\ . & . & \times \end{pmatrix}, \mathcal{Z}_8^{\mu-\tau} \to \mathrm{A}_1 : \begin{pmatrix} 0 & 0 & \times \\ . & \times & \times \\ . & . & \times \end{pmatrix}$$

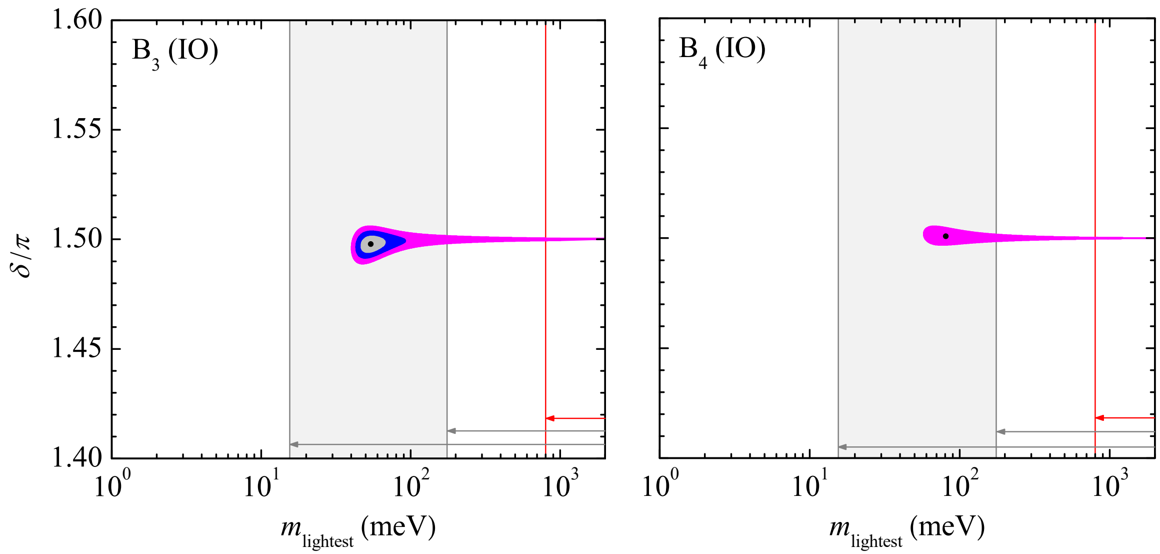


Barreiros, Câmara, Felipe and FRJ,
JHEP 08 (2022) 030





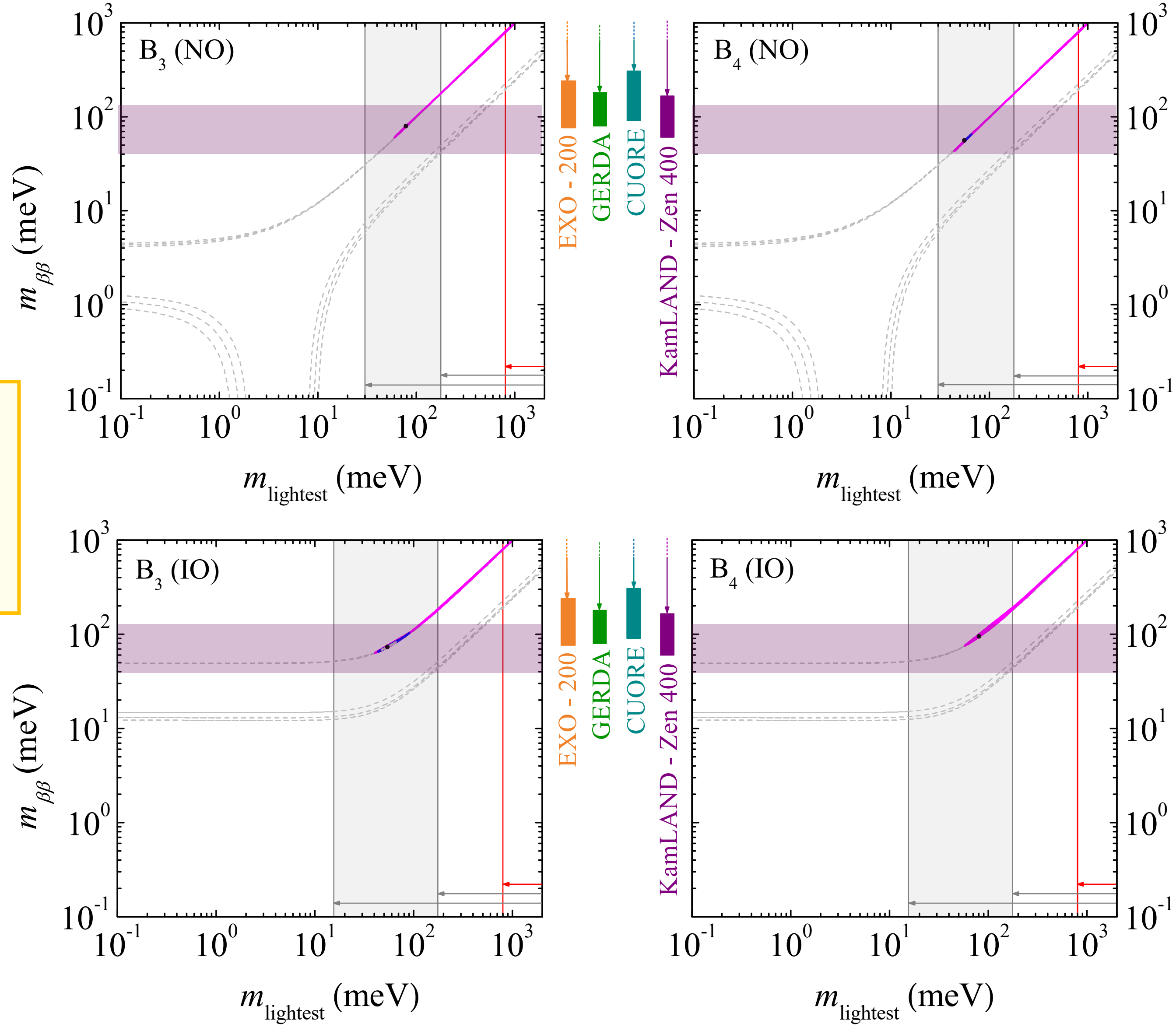
- Case A1 **is compatible** with the current bounds coming from cosmology. A **direct measurement** of neutrino mass by KATRIN **would exclude this case**.
- For the remaining cases, the lower bound on the **lightest neutrino mass** in tension with bounds from cosmology



Best present limit from **KamLAND-Zen**

$$m_{\beta\beta} < 0.036 - 0.156$$

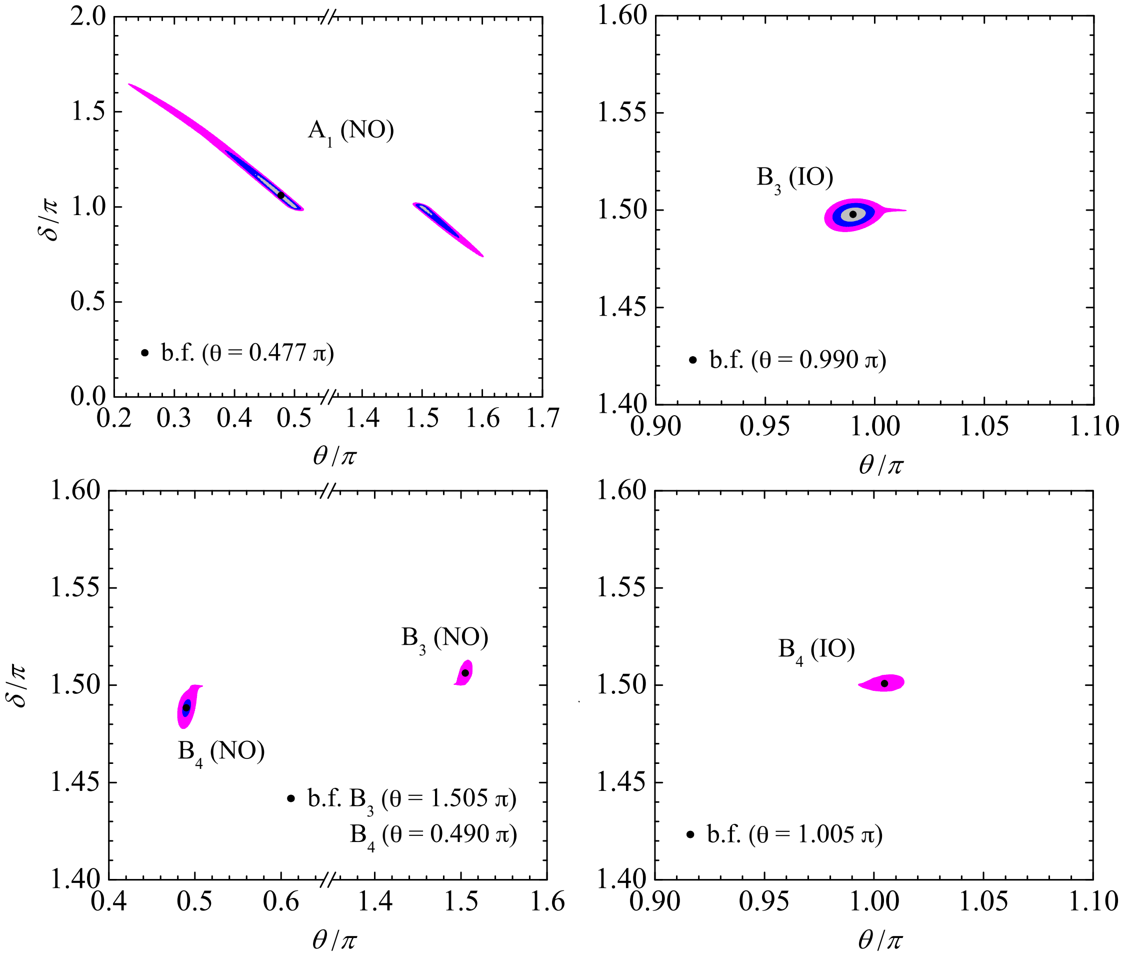
Abe et al.; PRL 130 (2023) 051801



Flavour and DM in the S-ST2 model

The σ **VEV phase** is determined by **neutrino data !!!**

$$\langle\sigma\rangle = u e^{i\theta} \longrightarrow \cot\text{an}\,\theta = -\frac{1}{\sin\xi}\left[\cos\xi - \frac{\left|\left(\widehat{\mathbf{M}}_\nu\right)_{12}\right|^2}{\left|\left(\widehat{\mathbf{M}}_\nu\right)_{11}\right|\left|\left(\widehat{\mathbf{M}}_\nu\right)_{22}\right|}\mathcal{R}\right]$$

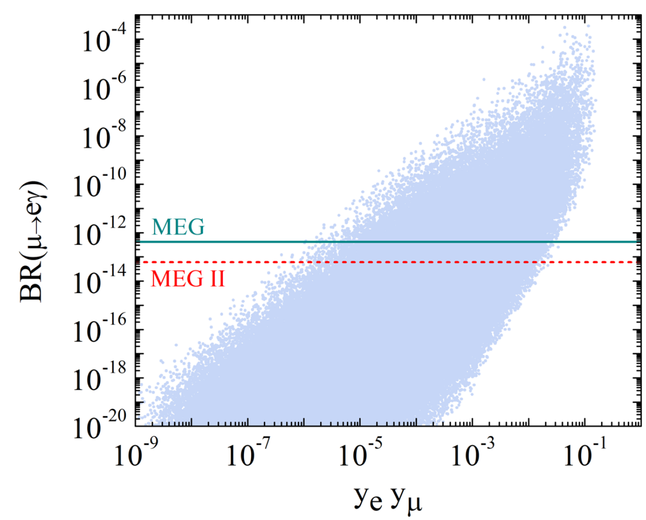


LFV radiative and 3-body decays

$$\mathbf{Y}_f^1 = \begin{pmatrix} y_e \\ 0 \\ 0 \end{pmatrix}, \mathbf{Y}_f^2 = \begin{pmatrix} 0 \\ y_\mu \\ 0 \end{pmatrix}$$

$$\mathbf{Y}_\Delta = \begin{pmatrix} y_1 & 0 & 0 \\ 0 & 0 & y_2 \\ 0 & y_2 & 0 \end{pmatrix} e^{-i\theta}$$

Contributions to LFV processes induced by dark fields and scalars from the triplet



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Barreiros, Câmara, Felipe and FRJ, JHEP 08 (2022) 030

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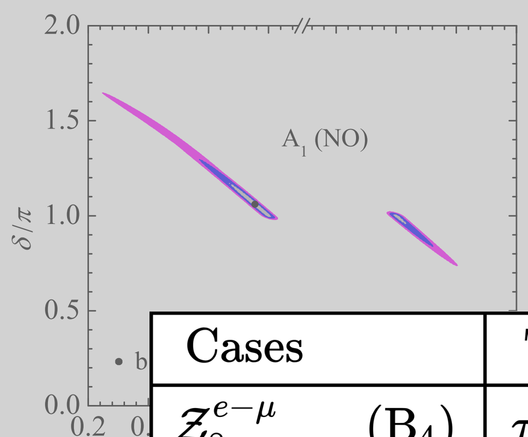
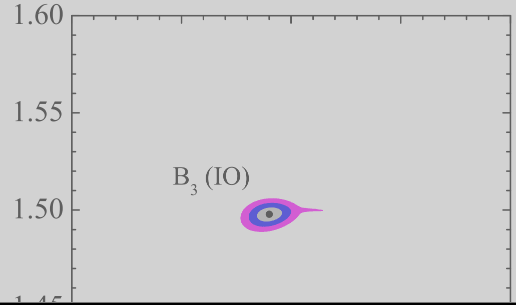
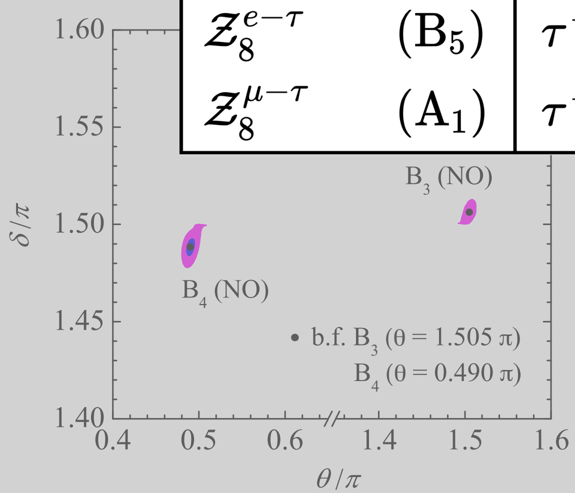
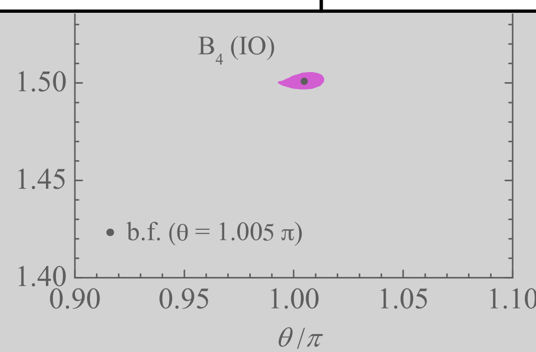








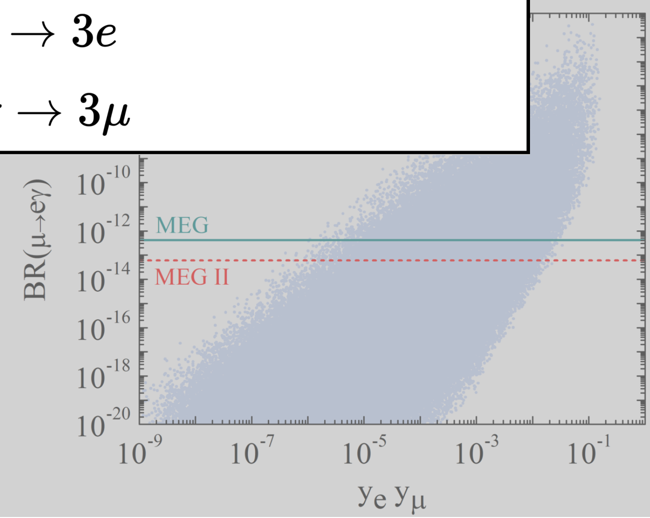
Cases		Type-II seesaw	Scotogenic
$\mathcal{Z}_8^{e-\mu}$	(B_4)	$\tau^- \to \mu^+ e^- e^-$	$\mu \to e\gamma, \mu \to 3e, \mu - e$ conversion
$\mathcal{Z}_8^{e-\tau}$	(B_5)	$\tau^- \to \mu^+ e^- e^-$	$\tau \to e\gamma, \tau \to 3e$
$\mathcal{Z}_8^{\mu-\tau}$	(A_1)	$\tau^- \to e^+ \mu^- \mu^-$	$\tau \to \mu\gamma, \tau \to 3\mu$

LFV radiative and 3-body decays

$$\mathbf{Y}_f^1 = \begin{pmatrix} y_e \\ 0 \\ 0 \end{pmatrix}, \mathbf{Y}_f^2 = \begin{pmatrix} 0 \\ y_\mu \\ 0 \end{pmatrix}$$

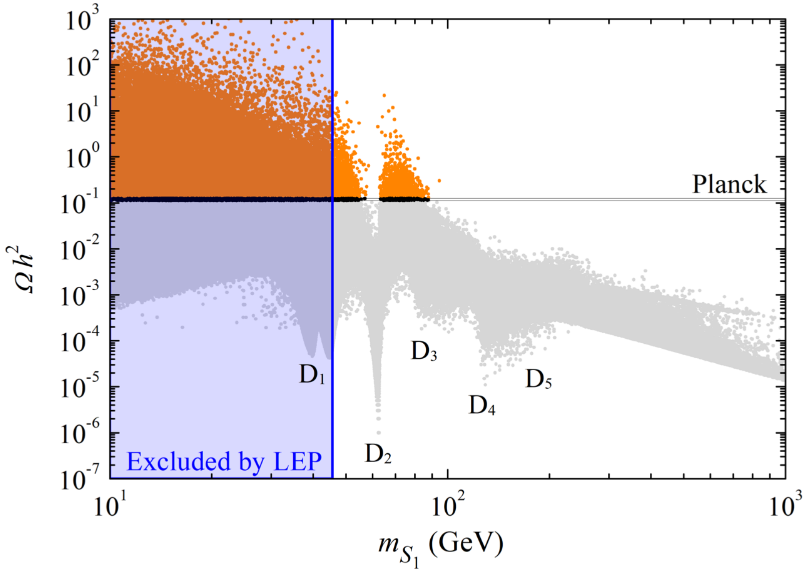
$$\mathbf{Y}_\Delta = \begin{pmatrix} y_1 & 0 & 0 \\ 0 & 0 & y_2 \\ 0 & y_2 & 0 \end{pmatrix} e^{-i\theta}$$

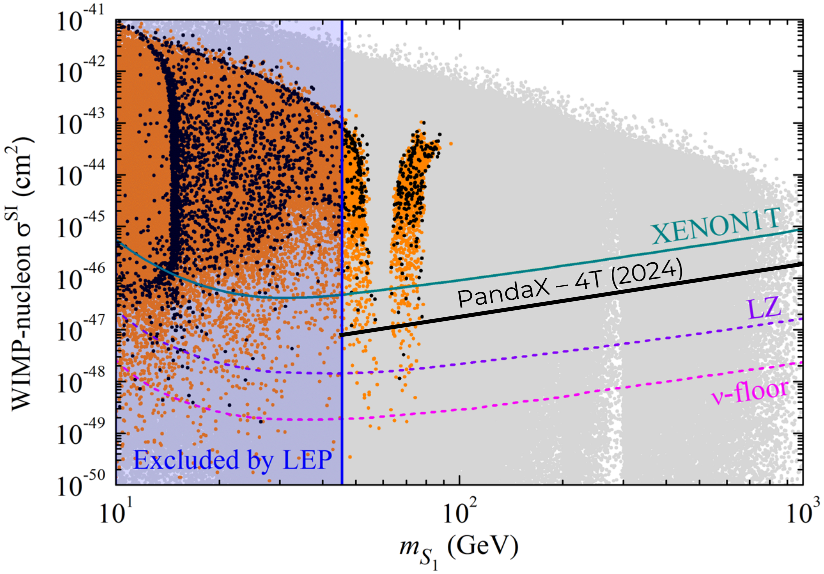
Contributions to LFV ... y dark ... m the

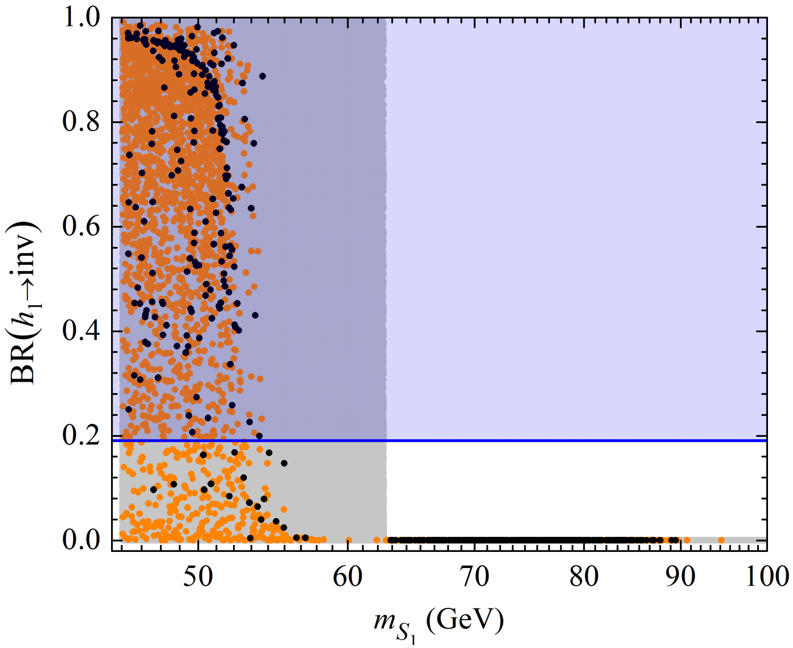


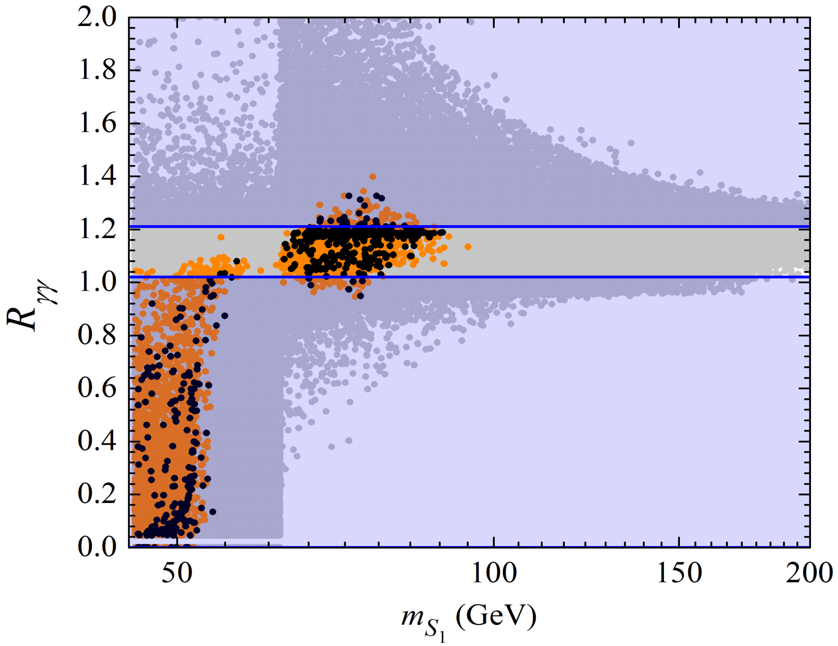
Flavour and DM in the S-ST2 model

Barreiros, Câmara, Felipe and FRJ, JHEP 08 (2022) 030









Dark-seeded solution to the SCP problem

Câmara, FRJ and Valle, PRD 108 (2023) 9, 095003

PHYSICAL REVIEW D **108,** 095003 (2023)

Dark-sector seeded solution to the strong *CP* problem

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[2]*AHEP Group, Institut de Física Corpuscular–CSIC/Universitat de València, Parc Científic de Paterna. C/ Catedrático José Beltrán, 2 E-46980 Paterna (Valencia), Spain*

(Received 13 March 2023; accepted 27 September 2023; published 2 November 2023)

$$-\mathcal{L}_{\rm Yuk} \supset \mathbf{Y}_u \overline{q_L}\tilde{\Phi} u_R + \mathbf{Y}_d \overline{q_L}\Phi d_R + \mathbf{Y}_\xi \overline{D_{2L}} d_R \xi + \mathbf{Y}_\chi \overline{D_{1L}} d_R \chi^* + \text{ H.c.}$$

$$-\mathcal{L}_{\rm Yuk} \supset y_\chi \overline{B_L} D_{2R}\chi + y_\xi \overline{B_L} D_{1R}\xi^* + y'_\chi \overline{D_{2L}} B_R \chi^* + y'_\xi \overline{D_{1L}} B_R \xi + \text{ H.c.}$$

$$-\mathcal{L}_{\rm mass} = m_B \overline{B_L} B_R + m_{D_{1,2}} \overline{D_{1,2L}} D_{1,2R} + \text{ H.c.}$$

	Fields	$G_{\rm SM}$	$\mathcal{Z}_8 \to \mathcal{Z}_2$
Fermions	q_L	$(\mathbf{3},\mathbf{2},1/6)$	$\omega^2 \to +$
	u_R	$(\mathbf{3},\mathbf{1},2/3)$	$\omega^2 \to +$
	d_R	$(\mathbf{3},\mathbf{1},-1/3)$	$\omega^2 \to +$
	$B_{L,R}$	$(\mathbf{3},\mathbf{1},-1/3)$	$\omega^6 \to +$
	$D_{1L,1R}$	$(\mathbf{3},\mathbf{1},-1/3)$	$\omega^7 \to -$
	$D_{2L,2R}$	$(\mathbf{3},\mathbf{1},-1/3)$	$\omega^3 \to -$
Scalars	Φ	$(\mathbf{1},\mathbf{2},1/2)$	$1 \to +$
	σ	$(1,1,0)$	$\omega^2 \to +$
	χ	$(1,1,0)$	$\omega^3 \to -$
	ξ	$(1,1,0)$	$\omega \to -$

Tree-level quark mass matrix

$$\mathcal{M}_d^{(0)} = \begin{pmatrix} \mathbf{M}_d & 0 \\ 0 & m_B \end{pmatrix}$$

$$\bar{\theta} = \arg[\det(\mathbf{M}_u)] + \arg[\det(\mathcal{M}_d)] = 0$$

and CKM is real

@ one loop: $\mathcal{M}_d = \mathcal{M}_d^{(0)} + \Delta\mathcal{M}_d$

$$\Delta\mathcal{M}_d^{(1)} = \begin{pmatrix} 0 & 0 \\ \Delta\mathbf{M}_{Bd} & \Delta m_B \end{pmatrix}$$

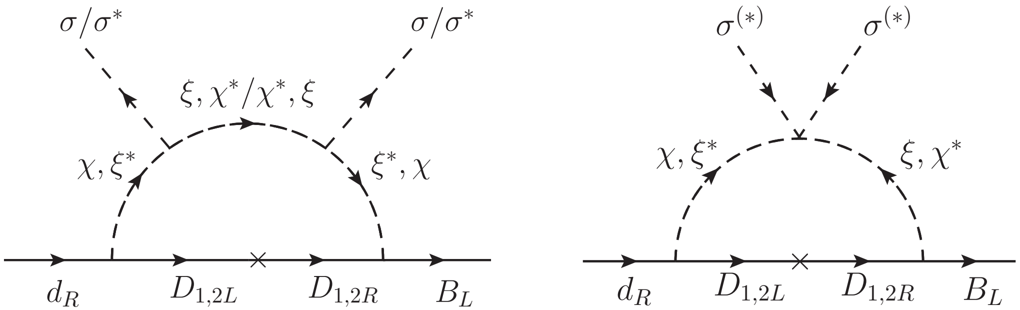
In terms of operators:

$$\Delta\mathcal{M}_d^{(1)} = \begin{pmatrix} 0 & 0 \\ \overline{B_L} d_R \sigma^{(*)2} & \overline{B_L} B_R (\Phi^\dagger\Phi), \overline{B_L} B_R |\sigma|^2 \end{pmatrix}$$

COMPLEX $\Delta\mathbf{M}_{Bd}$ ⟶ **COMPLEX CKM!**

Câmara, FRJ and Valle,
PRD 108 (2023) 9, 095003

$$\bar{\theta} = \arg[\det(\mathbf{M}_u)] + \arg[\det(\mathcal{M}_d)] = 0$$ @ one loop

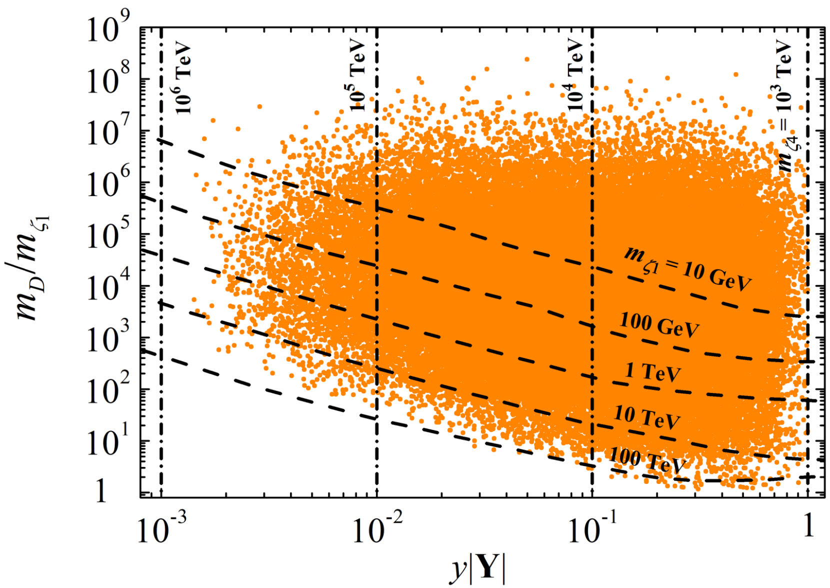


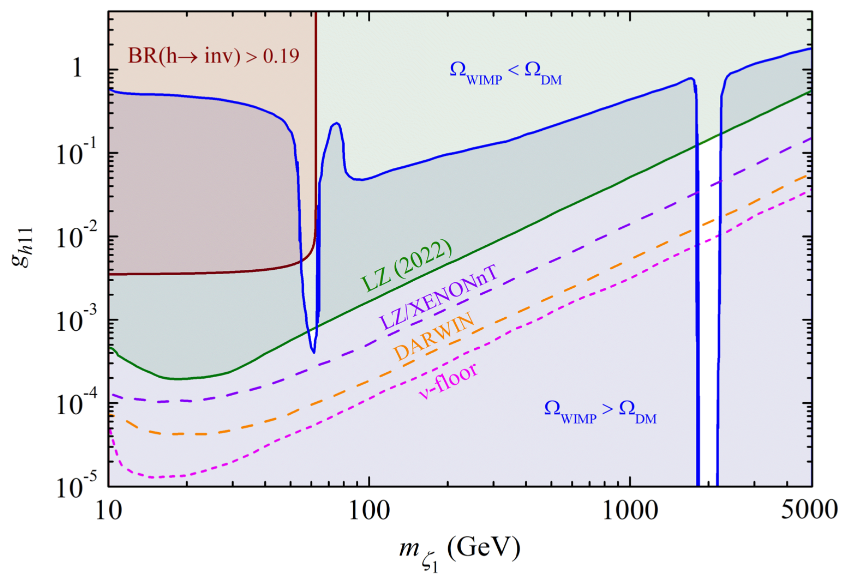
ONE-LOOP CONTRIBUTIONS TO $\Delta\mathbf{M}_{Bd}$:

$$|\Delta\mathbf{M}_{Bd}| \sim \frac{1}{16\pi^2}\lambda_{\sigma\zeta\zeta}|\mathbf{Y}_\zeta|y_\zeta\frac{v_\sigma^2}{m_\zeta^2}m_D$$

$$|\Delta\mathbf{M}_{Bd}| \sim \frac{1}{16\pi^2}|\mathbf{Y}_\zeta|y_\zeta\frac{\mu_\zeta^2}{m_\zeta^2}\frac{v_\sigma^2}{m_\zeta^2}m_D$$

LIGHT-QUARK MASSES: $$\mathbf{M}^2_{\text{light}} \simeq \mathbf{M}_d\mathbf{M}_d^T - \frac{\mathbf{M}_d\Delta\mathbf{M}^\dagger_{Bd}\Delta\mathbf{M}_{Bd}\mathbf{M}_d^T}{\tilde{m}_B^2}$$





Singlet-assisted Leptogenesis with SCPV

Published for SISSA by Springer

Scalar-singlet assisted leptogenesis with CP violation from the vacuum

D. M. Barreiros,[a] H. B. Câmara,[a] R. G. Felipe[b,a] and F. R. Joaquim[a]

CPV needed for Leptogenesis to work is communicated to the RH neutrino sector at high scales through the VEVs of scalar singlets:

$$u_i > \Lambda_{\text{Leptog.}} \gg v$$

HEAVY SCALAR SINGLETS: $S_k = \frac{1}{\sqrt{2}}\left(u_k e^{i\theta_k} + S_{\mathrm{R}k} + i S_{\mathrm{I}k}\right)$

LIGHT SCALAR DOUBLETS: $\Phi_a = \begin{pmatrix} \phi_a^+ \\ \phi_a^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi_a^+ \\ v_a e^{i\varphi_a} + \phi_{\mathrm{R}a}^0 + i\phi_{\mathrm{I}a}^0 \end{pmatrix}$

θ_k

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

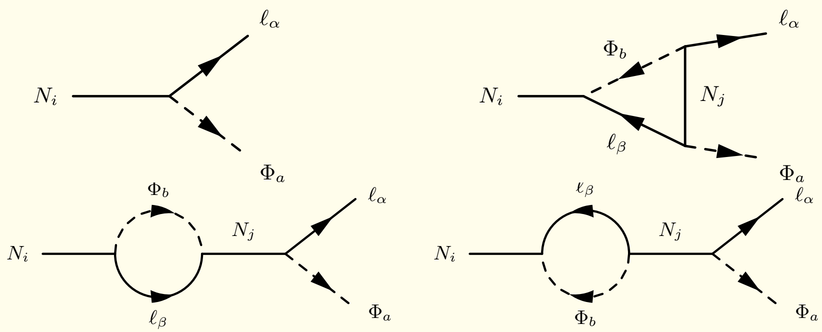
$$\mathbf{M}_R = \mathbf{M}_R^0 + \frac{u_k}{\sqrt{2}}\left(\mathbf{Y}_R^k e^{i\theta_k} + \mathbf{Y}_R^{\prime k} e^{-i\theta_k}\right)$$

In the N mass basis →

$$\mathbf{Y}^{a*}\overline{\ell_L} N \Phi_a : \mathbf{Y}^{a*} = \mathbf{V}_L^\dagger \mathbf{Y}_D^{a*} \mathbf{U}_R$$

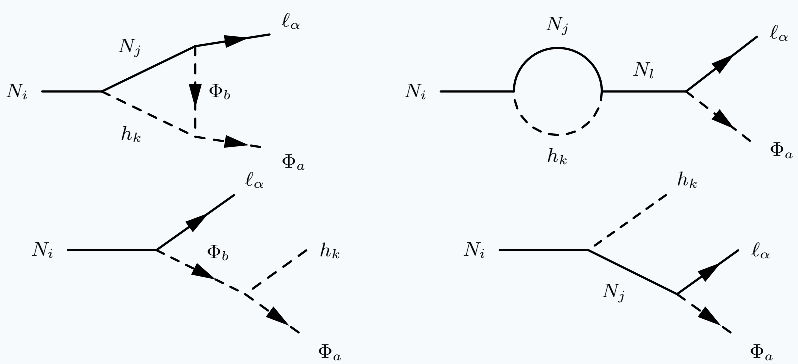
Singlet-assisted Leptogenesis with SCPV

Barreiros, Câmara, Felipe and FRJ, JHEP 01 (2023) 010



$$\varepsilon^a_{i\alpha} = \frac{\Gamma(N_i \to \Phi_a \ell_\alpha) - \Gamma\left(N_i \to \Phi_a^\dagger \bar{\ell}_\alpha\right)}{\sum_{\beta=e,\mu,\tau}\sum_{b=1}^{n_H}\left[\Gamma(N_i \to \Phi_b \ell_\beta) + \Gamma\left(N_i \to \Phi_b^\dagger \bar{\ell}_\beta\right)\right]}$$

Fukujita & Yanagida'86; Covi, Roulet Vissani'96;



$$\varepsilon^a_{i\alpha} \simeq \frac{\sum_{k=1}^{2n_S}\left[\Gamma(N_i \to \Phi_a \ell_\alpha h_k) - \Gamma\left(N_i \to \Phi_a^\dagger \bar{\ell}_\alpha h_k\right)\right]}{\sum_{\beta=e,\mu,\tau}\sum_{b=1}^{n_H}\left[\Gamma(N_i \to \Phi_b \ell_\beta) + \Gamma\left(N_i \to \Phi_b^\dagger \bar{\ell}_\beta\right)\right]}$$

M. Le Dall and A. Ritz, PRD 90 (2014)

HIGGS PORTAL LG

A simple realisation with **high-energy SCPV**

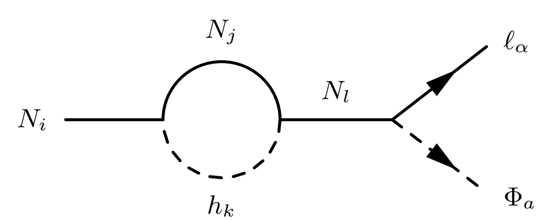
	Fields	$SU(2)_L \otimes U(1)_Y$	$\mathcal{Z}_8^e$	$\mathcal{Z}_8^\mu$	$\mathcal{Z}_8^\tau$
Fermions	ℓ_{eL}	$(\mathbf{2}, -1/2)$	ω^5	ω^7	ω^6
	$\ell_{\mu L}$	$(\mathbf{2}, -1/2)$	ω^7	ω^5	ω^5
	$\ell_{\tau L}$	$(\mathbf{2}, -1/2)$	ω^6	ω^6	ω^7
	e_R	$(\mathbf{1}, -1)$	ω^4	ω^7	ω^6
	μ_R	$(\mathbf{1}, -1)$	ω^7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

Only one case compatible with neutrino data: $\mathcal{Z}_8^\mu$

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

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

In this minimal setup, only the **new wavefunction diagrams** are relevant

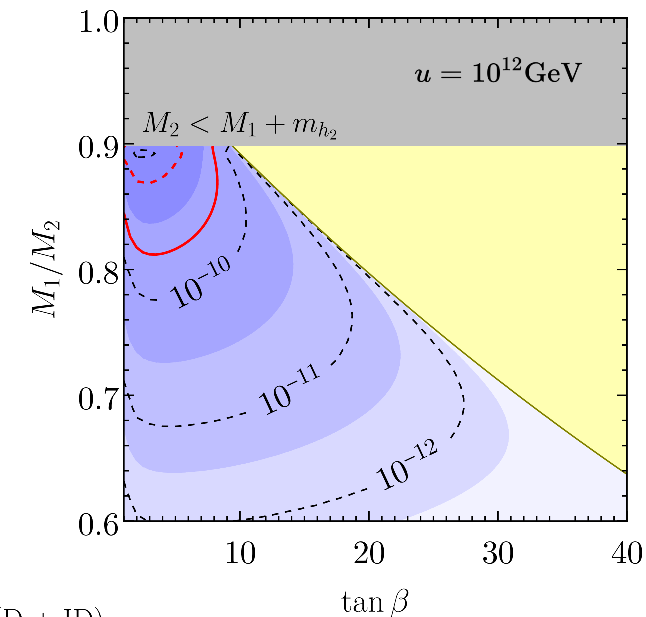


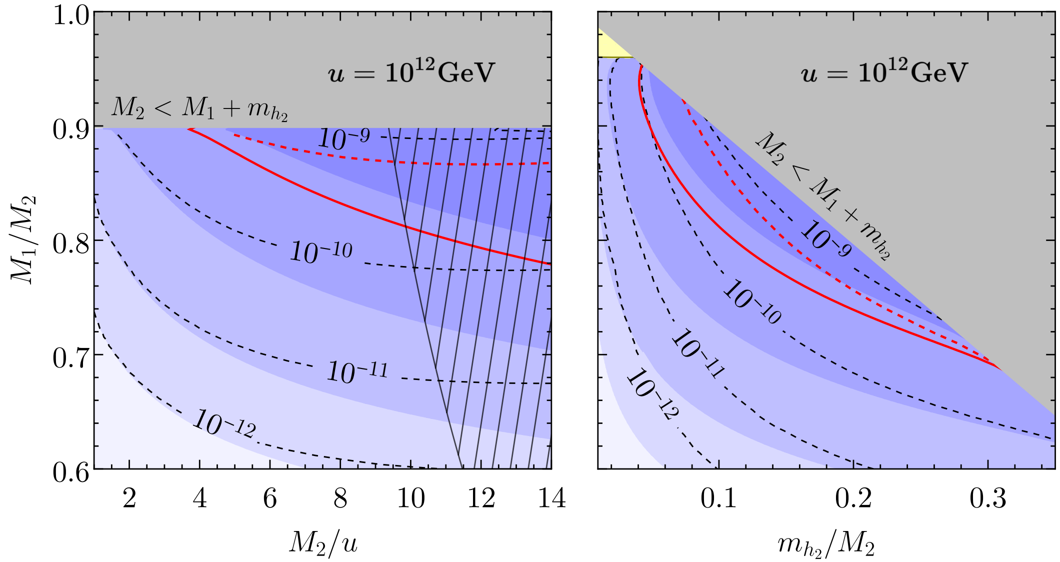
Barreiros, Câmara, Felipe and FRJ, JHEP 01 (2023) 010

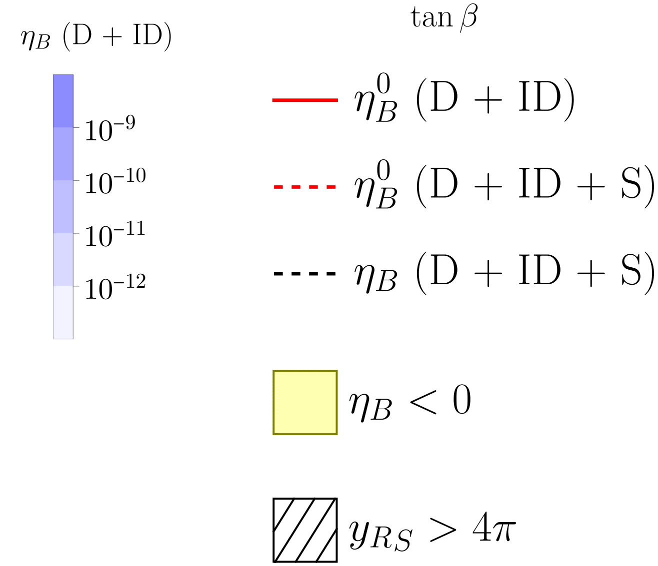
- Best-fit neutrino parameters for IO

Case	θ_{12} ($^\circ$)	θ_{13} ($^\circ$)	θ_{23} ($^\circ$)	δ/π	α/π	$m_{\beta\beta}$ (meV)	m_β (meV)	$\sum_i m_i$ (meV)
$\mathcal{Z}_8^\mu$(IO)	35.48	8.60	49.62	1.88	0.92	16.6	49.2	99.7

Case	θ/π	θ_L/π	(x,y,z)(meV)
$\mathcal{Z}_8^\mu$(IO)	1.89	7.29×10^{-2}	(0.325, 32.8, 0.426)







- The BAU can be obtained for $M_1/M_2 \gtrsim 0.8$

Conclusions

- **SCPV** is very appealing from the theory point of view.
- **In the standard paradigm** SCPV comes from doublets.
- **SCPV from the Scalar Singlet Portal** coupled to a heavy fermion sector has some nice features:
  - **Seesaw induced** low-energy CPV (e.g. scoto-seesaw)
  - Connections with Dark matter and **SCP problems**
  - **Singlet-assisted** leptogenesis
- Implementation in the framework of **low-energy** neutrino mass generation mechanisms.

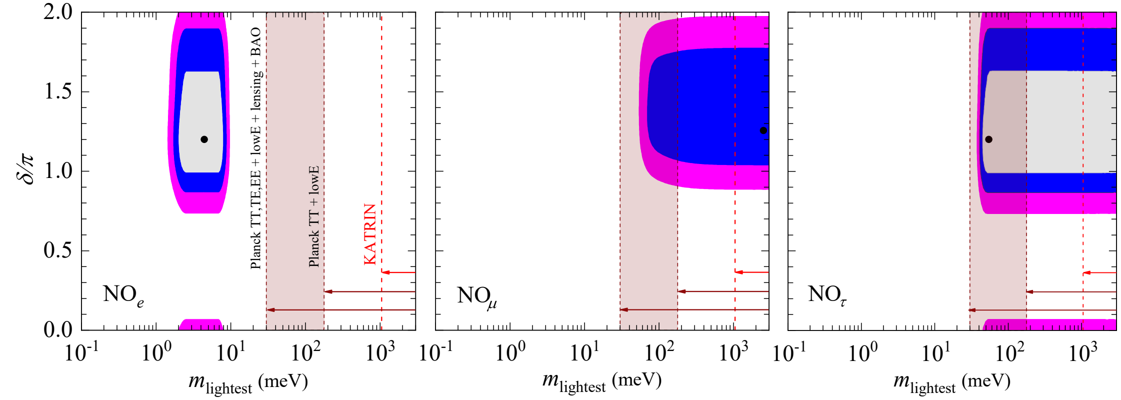
Câmara and FRJ, JHEP 05 (2021) 021

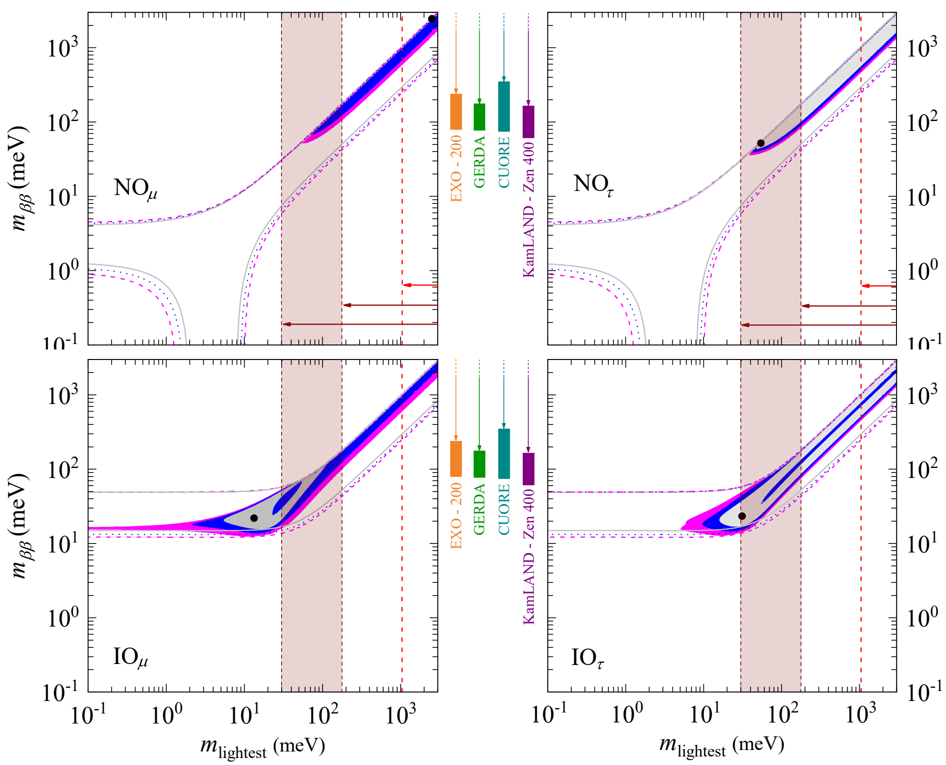
Thank you!

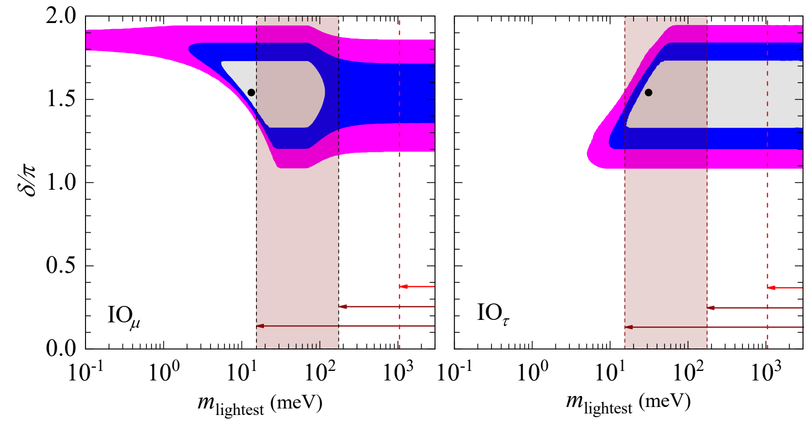
Minimal S-STI model with SCPV

Barreiros, FRJ, Srivastava & Valle
JHEP 04 (2021) 249

Neutrinoless double beta decay
$\beta\beta_{0\nu}$







Lower bound on the **lightest neutrino mass** in tension with bounds from cosmology