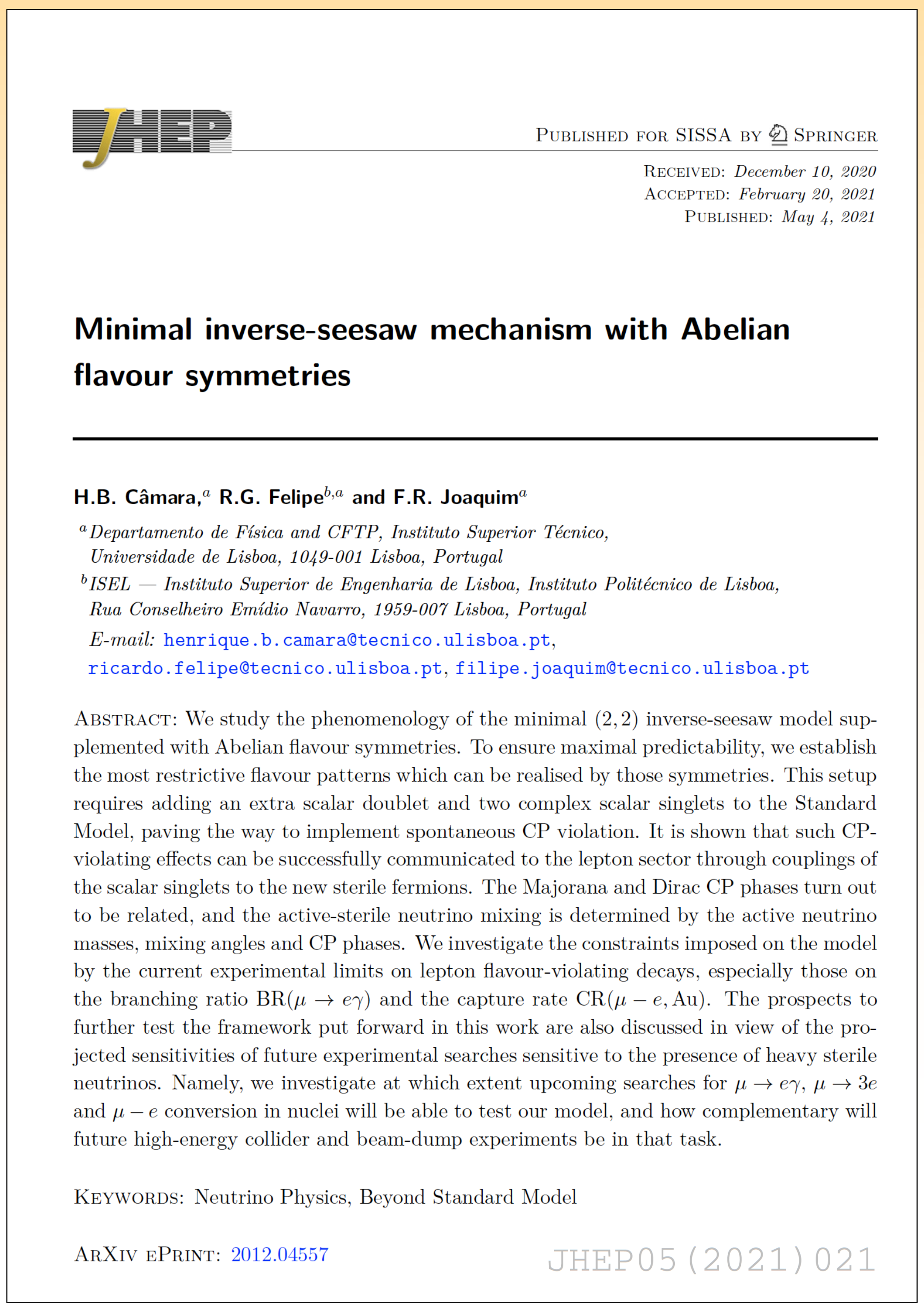
STERILE NEUTRINOS WITH INVERSE SEESAW AND ABELIAN FLAVOUR SYMMETRIES

Henrique B. Câmara, R.G. Felipe and F.R. Joaquim

Departamento de Física and CFTP
Instituto Superior Técnico, Universidade de Lisboa - Portugal

Invisibles Workshop 2021



PUBLISHED FOR SISSA BY SPRINGER
RECEIVED: *December 10, 2020*
ACCEPTED: *February 20, 2021*
PUBLISHED: *May 4, 2021*

Minimal inverse-seesaw mechanism with Abelian flavour symmetries

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

[a] *Departamento de Física and CFTP, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal*
[b] *ISEL — Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa, Rua Conselheiro Emídio Navarro, 1959-007 Lisboa, Portugal*
E-mail: henrique.b.camara@tecnico.ulisboa.pt, ricardo.felipe@tecnico.ulisboa.pt, filipe.joaquim@tecnico.ulisboa.pt

ABSTRACT: We study the phenomenology of the minimal $(2,2)$ inverse-seesaw model supplemented with Abelian flavour symmetries. To ensure maximal predictability, we establish the most restrictive flavour patterns which can be realised by those symmetries. This setup requires adding an extra scalar doublet and two complex scalar singlets to the Standard Model, paving the way to implement spontaneous CP violation. It is shown that such CP-violating effects can be successfully communicated to the lepton sector through couplings of the scalar singlets to the new sterile fermions. The Majorana and Dirac CP phases turn out to be related, and the active-sterile neutrino mixing is determined by the active neutrino masses, mixing angles and CP phases. We investigate the constraints imposed on the model by the current experimental limits on lepton flavour-violating decays, especially those on the branching ratio $\mathrm{BR}(\mu \to e\gamma)$ and the capture rate $\mathrm{CR}(\mu - e, \mathrm{Au})$. The prospects to further test the framework put forward in this work are also discussed in view of the projected sensitivities of future experimental searches sensitive to the presence of heavy sterile neutrinos. Namely, we investigate at which extent upcoming searches for $\mu \to e\gamma$, $\mu \to 3e$ and $\mu - e$ conversion in nuclei will be able to test our model, and how complementary will future high-energy collider and beam-dump experiments be in that task.

KEYWORDS: Neutrino Physics, Beyond Standard Model

ARXIV EPRINT: 2012.04557

JHEP05(2021)021

❑ INVERSE-SEESAW BASICS

Mohapatra; Mohapatra & Valle'86; Gonzalez-Garcia & Valle'89

Low-scale neutrino mass generation mechanism; Natural template for sizeable active-sterile neutrino mixing;

$\boxed{\mathrm{ISS}(n_R, n_s)}$: Two species of **sterile neutrinos**: $\nu_{Ri}\ (i=1,...,n_R),\ s_i\ (i=1,...,n_s)$

$$-\mathcal{L}^{\mathrm{ISS}}_{\mathrm{mass}} = \overline{e_L}\,\mathbf{M}_\ell\, e_R + \overline{\nu_L}\,\mathbf{M}_D \nu_R + \overline{\nu_R}\,\mathbf{M}_R s + \tfrac{1}{2}\overline{s^c}\ \mathbf{M}_s s + \mathrm{H.c.} \xrightarrow[(m_D,\mu_s \ll M)]{} \boxed{\begin{aligned} \mathbf{M}_{\mathrm{eff}} &= -\mathbf{M}_D^*\,(\mathbf{M}_R^T)^{-1}\,\mathbf{M}_s \mathbf{M}_R^{-1}\mathbf{M}_D^\dagger \\ \mathbf{U}_{\mathrm{Hl}} &\simeq \mathbf{V}_L^\dagger\,(0,\ \mathbf{M}_D(\mathbf{M}_R^\dagger)^{-1})\,\mathbf{U}_s \end{aligned}}$$

- **Minimal Inverse Seesaw ISS(2,2):**
  Abada & Lucente'14
  One massless neutrino; **17 parameters vs 7 observables**; Compatible with neutrino data.

❑ ABELIAN FLAVOUR SYMMETRIES

Maximally-restrictive flavour structure compatible with neutrino data **realisable** by Abelian symmetries

$$-\mathcal{L}_{\mathrm{Yuk.}} = \overline{\ell_L}\left(\mathbf{Y}_\ell^1\Phi_1 + \mathbf{Y}_\ell^2\Phi_2\right) e_R + \overline{\ell_L}\left(\mathbf{Y}_D^1\tilde{\Phi}_1 + \mathbf{Y}_D^2\tilde{\Phi}_2\right)\nu_R + \tfrac{1}{2}\overline{s^c}\left(\mathbf{Y}_s^1 S_1 + \mathbf{Y}_s^2 S_1^*\right) s + \overline{\nu_R}\left(\mathbf{Y}_R^1 S_2 + \mathbf{Y}_R^2 S_2^*\right) s + \mathrm{H.c.}$$

VEV configuration

$$\langle\phi_1^0\rangle = v\cos\beta \quad \langle\phi_2^0\rangle = v\sin\beta \quad \langle S_1\rangle = u_1 e^{i\xi} \quad \langle S_2\rangle = u_2$$

$$\boxed{5_1^\ell :}\quad \mathbf{M}_\ell = \begin{pmatrix} 0 & 0 & a_1 \\ 0 & m_{\ell_1}^2 & 0 \\ a_2 & 0 & a_4 \end{pmatrix} \longrightarrow \boxed{\text{6 distinct cases: }\mathrm{NO}_{e,\mu,\tau},\mathrm{IO}_{e,\mu,\tau}}$$

$$\mathbf{V}_L = \begin{pmatrix} \cos\theta_L & 0 & \sin\theta_L \\ 0 & 1 & 0 \\ -\sin\theta_L & 0 & \cos\theta_L \end{pmatrix} \qquad \mathbf{M}_{\mathrm{eff}} = e^{-i\xi}\begin{pmatrix} \frac{y^2}{x} + \frac{z^2}{w}e^{2i\xi} & y & ze^{2i\xi} \\ y & x & 0 \\ ze^{2i\xi} & 0 & we^{2i\xi} \end{pmatrix}$$

Flavour symmetry

$$\mathbf{G}_{\mathrm{F}} = \mathrm{U}(1) \times \mathbb{Z}_n \times \mathrm{U}(1)_{\mathrm{F}},\ n = 2,4$$

Only interesting case to study:

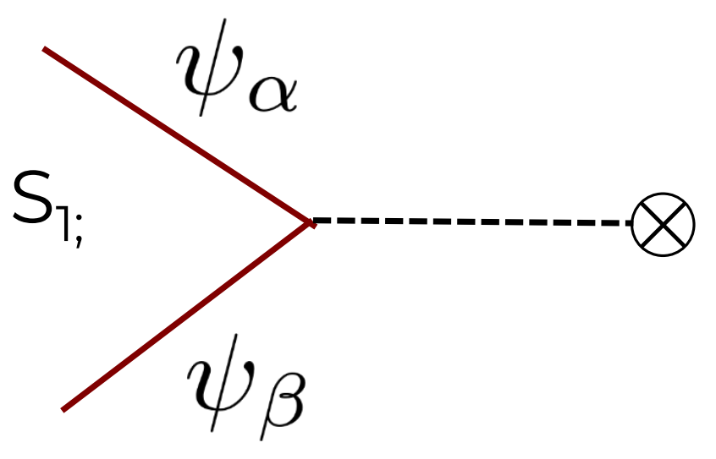
$(5^\ell_{1,\mathrm{I}}, \mathrm{T}_{45})$

Fields	Φ_1	Φ_2	S_1	S_2	ℓ_{e_L}	ℓ_{μ_L}	ℓ_{τ_L}	e_R	μ_R	τ_R	ν_{R_1}	ν_{R_2}	s_1	s_2
U(1)	0	0	0	1	1	1	1	1	1	1	1	1	0	0
$\mathrm{U}(1)_{\mathrm{F}}$	1	−1	2	0	0	2	−2	−3	3	−1	1	−1	−1	1
$\mathbb{Z}_2$	−	+	+	+	−	+	+	−	+	+	+	−	−	+

❑ HIGHLIGHTS

- Abelian symmetries allow to **reduce the number of parameters** leading to some **prediction;**
- All fermion **mass** terms are **generated dynamically**; **Spontaneous CPV** through the complex VEV of S_1;
- The effective light-neutrino mass matrix: **6 effective parameters vs 7 observables:**

$$(x, y, z, w, \theta_L, \xi) \longrightarrow \mathcal{O}_i \equiv (\Delta m^2_{21}, \Delta m^2_{31}, \theta_{ij}, \delta, \alpha)$$

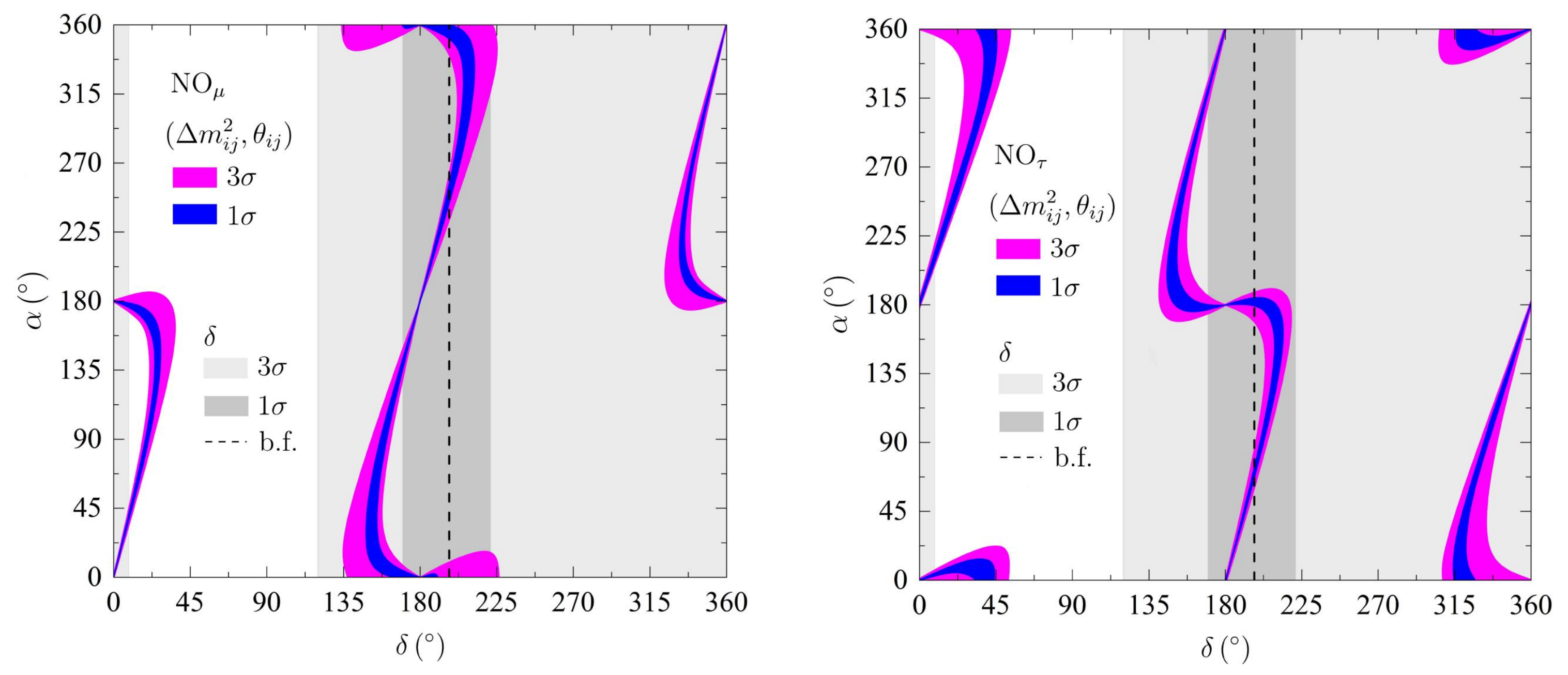


$$\langle\phi_a^0\rangle = v_a e^{i\theta_a} \qquad \langle S_a\rangle = u_a e^{i\xi_a} \longrightarrow$$

Mass matrices

$\mathbf{M}_\ell\,,\,\mathbf{M}_D$
$\mathbf{M}_R\,,\,\mathbf{M}_s$

❑ LEPTONIC CP VIOLATION

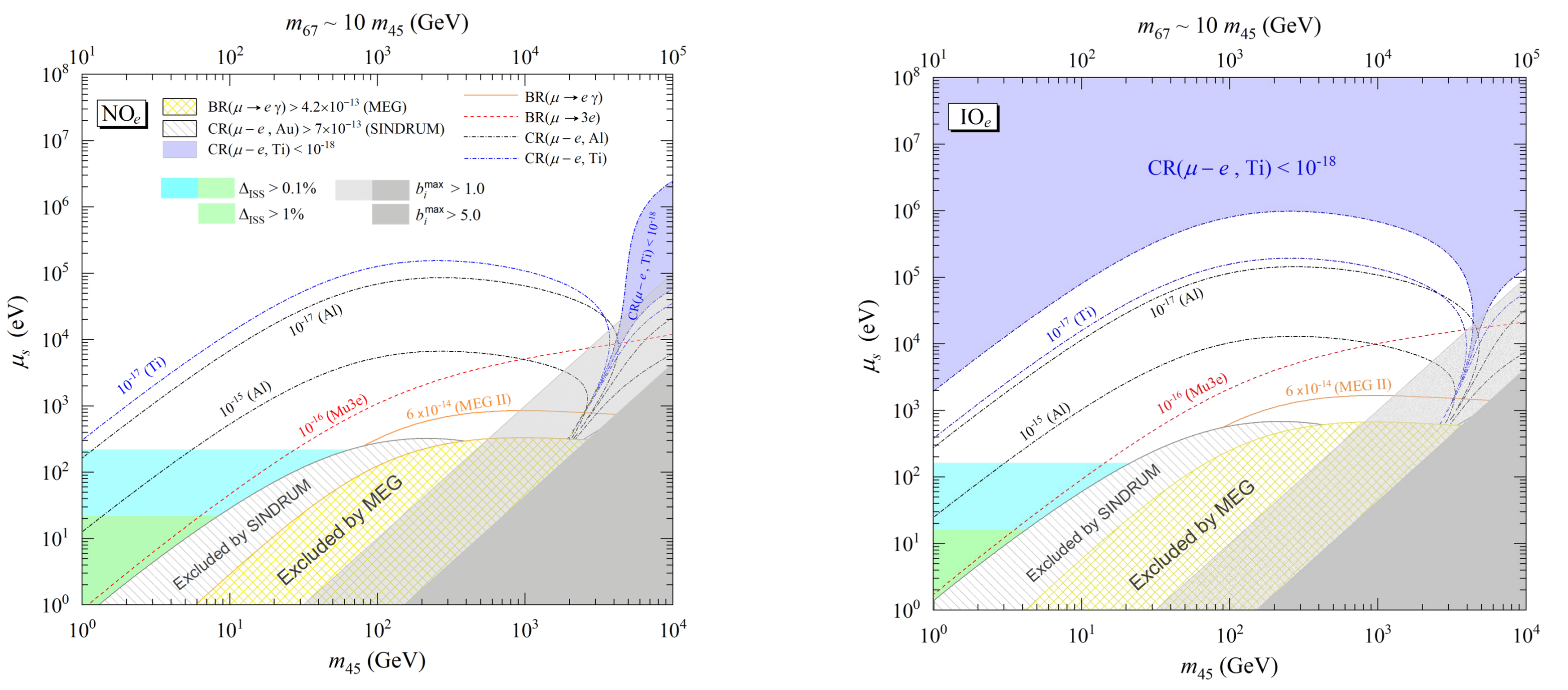


- Strong **correlation** between α and δ;
- **No Dirac CPV implies no Majorana CPV;** ⟶
- A measurement of δ in the intervals [45°, 135°] and [225°, 315°] would **exclude the NO$_\mu$ and NO$_\tau$ cases.**

$$\langle S_1\rangle = u_1 e^{i\xi}$$
$$\mathcal{J}^{\mathrm{CP}}_{\mathrm{Dirac}}\ ,\ \mathcal{J}^{\mathrm{CP}}_{\mathrm{Maj}} \propto \sin(2\xi)$$

as in Branco, Felipe, Joaquim, Serôdio (2012)

❑ LEPTON FLAVOUR VIOLATION

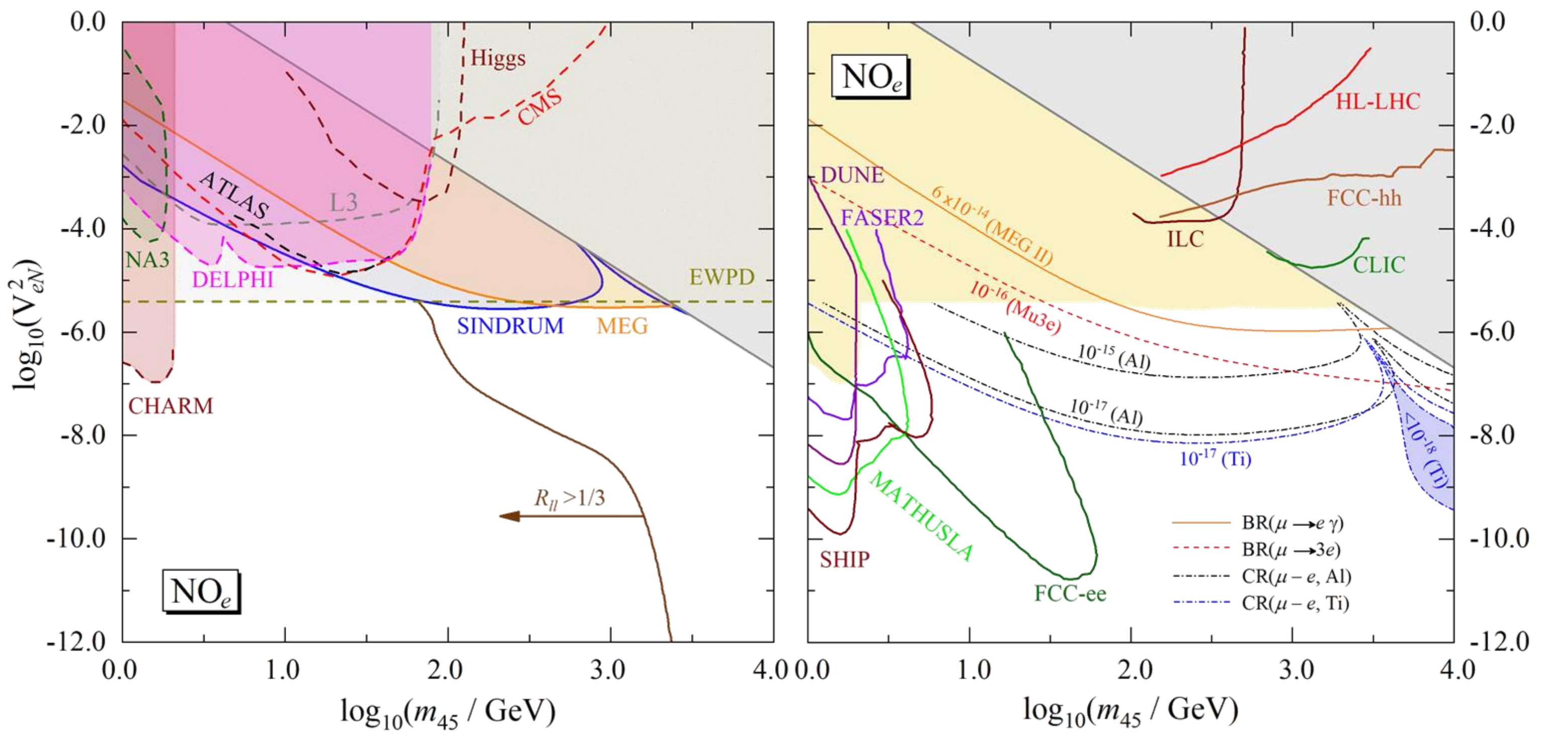


- For NO, almost the **whole parameter space** will be **scrutinized by future μ–e conversion experiments** (Mu2e, COMET, PRISM/PRIME);
- For IO, the prospects are less optimistic.

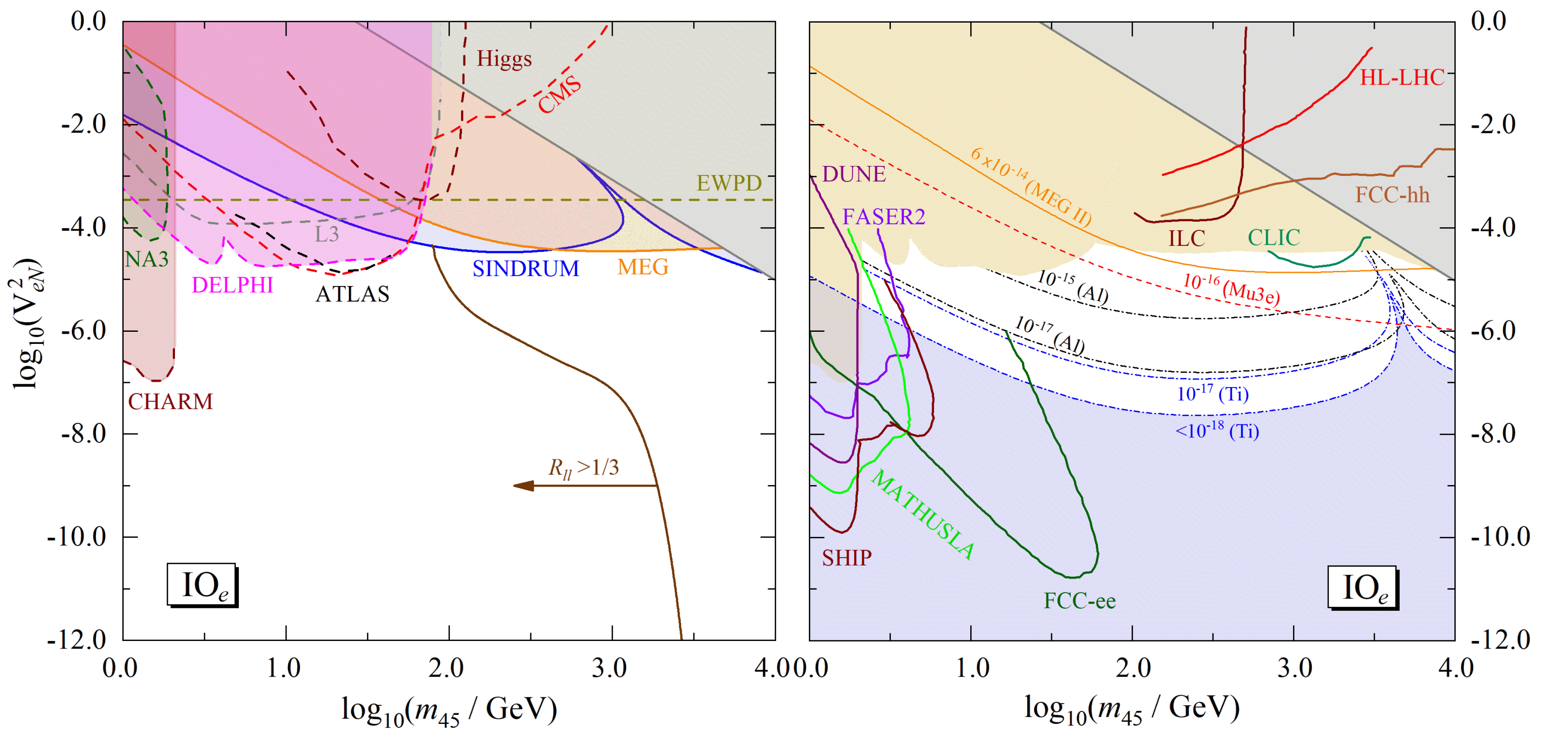
- **Parameter space**: sterile neutrino mass and LNV parameter (m_{45}, μ_s);
- **Muon LFV constraints.**

❑ STERILE NEUTRINO CONSTRAINTS

- **Parameter space**: sterile neutrino mass and active-sterile mixing (m_{45}, V^2_{eN});
- Current (left) and future (right) **constraints** from **LFV indirect searches** and **alternative probes:** beam-dump, hadron-collider, linear-collider, displaced-vertex experiments and electroweak precision data (EWPD).



- Current data implies an upper bound $V^2_{eN} \sim 10^{-6} - 10^{-5}$.
- Future probes will be sensitive to much smaller mixings. **LFV fully complementary to other searches**.



- **EWPD is less constraining** in the IO case.
- Future CLV probes will be sensitive to $V^2_{eN} \sim 10^{-7}$.

Acknowledgments: Projects: UIDB/00777/2020, UIDP/00777/2020.