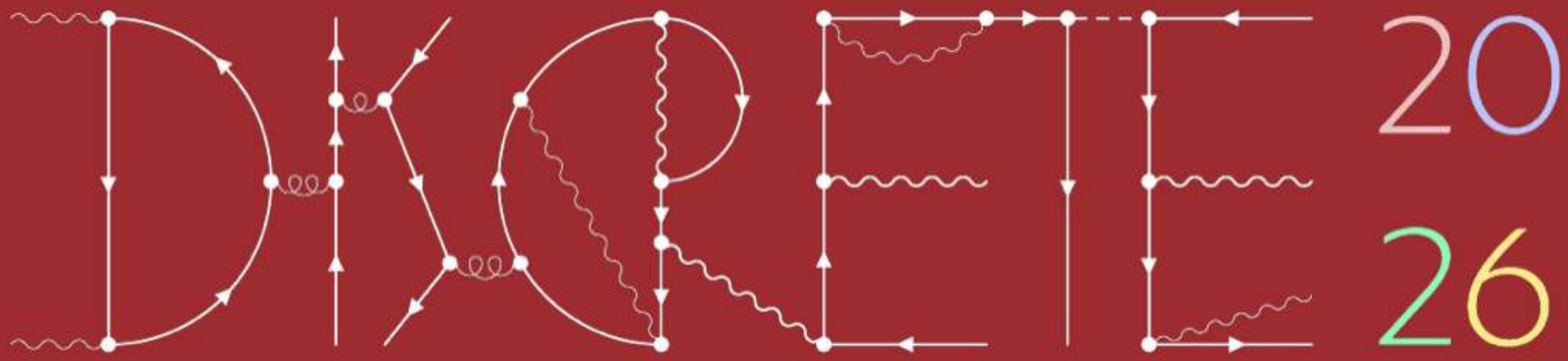


On phenomenological consequences of discrete flavour (and CP) symmetries

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Overview

- Introduction
- Idea of residual symmetries
- Selection rules for cLFV processes
- cLFV processes in inverse seesaw scenarios
- Other phenomenology
- Summary and outlook

Based on

Calibbi, CH, Schmidt, Vandeleur (2505.24350 [hep-ph])

Di Meglio, CH (2407.19734 [hep-ph], 2603.05360 [hep-ph])

CH, Kriewald, Orloff, Teixeira (2107.07537 [hep-ph])

CH, Molinaro (1602.04206 [hep-ph])

Drewes, Georis, CH, Klaric (2203.08538 [hep-ph], 2412.10254 [hep-ph])

Introduction

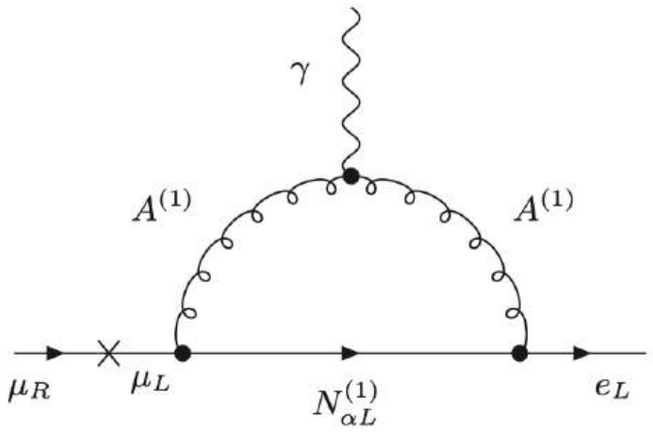
- Standard Model (SM) is very successful.
  Nevertheless, several phenomena are not explained within SM.
  - Replication of fermion generations
  - Fermion masses
  - Quark and lepton mixing
  - Baryon asymmetry of the Universe (BAU)
  - Dark Matter (DM)
  - …
- In the SM (without neutrino masses), charged lepton flavour violation (cLFV) is absent,
  e.g. $\mu \to e\gamma$ ✗

  $\mu - e$ conversion ✗

  $\tau \to \mu\mu\bar{\mu}$ ✗

Introduction

- However, in beyond SM (BSM) theories cLFV processes are often induced at a sizeable rate,
  e.g.



Control them well!

Correlations among them?

- … can be addressed with **flavour (and CP) symmetries and their residuals**
- … and more phenomenology as well such as predictions for neutrinoless double beta decay, correlation among CP violation at low and high energies, …

Idea of residual symmetries

Idea: Keep some residual symmetry among charged leptons and neutrinos, G_e and G_ν, with $G_e \neq G_\nu$

Mismatch of symmetries corresponds to lepton mixing

G_f and CP

charged leptons

G_e

U_e

neutrinos

$G_\nu = Z_2 \times$ CP

$U_\nu = \Omega_\nu R(\theta) K_\nu$

$$U_{PMNS} = U_e^\dagger \Omega_\nu R(\theta) K_\nu$$

see e.g. Feruglio/CH/Ziegler ('12)

Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]

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Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]

- $G_e = Z_3$ is often encountered (and $G_\nu = Z_2 \times Z_2$ or $G_\nu = Z_2 \times \mathrm{CP}$)

Example of a Z_3 among charged leptons (coined **lepton triality**, Ma ('10))

$$e^- \to e^- \qquad e^+ \to e^+$$
$$\mu^- \to \omega\, \mu^- \qquad \mu^+ \to \omega^2\, \mu^+$$
$$\tau^- \to \omega^2\, \tau^- \qquad \tau^+ \to \omega\, \tau^+$$

$$\omega = \exp\left(\frac{2\pi\, i}{3}\right) \qquad \text{3rd root of unity}$$

Typical A_4 and S_4 models leading to tri-bimaximal mixing have $G_e = Z_3$, see e.g. Altarelli/Feruglio ('05), He/Keum/Volkas ('06), Lam ('08)

Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]

- $G_e = Z_3$ is often encountered (and $G_\nu = Z_2 \times Z_2$ or $G_\nu = Z_2 \times \mathrm{CP}$)

Example of a Z_3 among charged leptons (coined **lepton triality**, Ma ('10))

$$Q_{Z_3}(e^-) = 0 \qquad Q_{Z_3}(e^+) = 0$$

$$Q_{Z_3}(\mu^-) = 1 \qquad Q_{Z_3}(\mu^+) = 2$$

$$Q_{Z_3}(\tau^-) = 2 \qquad Q_{Z_3}(\tau^+) = 1$$

Z_3 charge is modulo 3

Typical A_4 and S_4 models leading to tri-bimaximal mixing have $G_e = Z_3$, see e.g. Altarelli/Feruglio ('05), He/Keum/Volkas ('06), Lam ('08)

Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]

- It is known that it **forbids** cLFV processes such as

$$\mu \to e\,\gamma\,,\ \mu \to ee\bar{e} \text{ and } \mu - e \text{ conversion in nuclei N}$$

since

$$Q_{Z_3}(\mu^\pm) \neq Q_{Z_3}(e^\pm) \text{ and } Q_{Z_3}(\gamma) = 0\,,\ Q_{Z_3}(\text{quarks}) = 0$$

but **allows** for the tri-lepton tau lepton decays

$$\tau \to ee\bar{\mu} \text{ and } \tau \to \mu\mu\bar{e}$$

since

$$Q_{Z_3}(\tau^-) = 2\,Q_{Z_3}(e^-) + Q_{Z_3}(\mu^+) \text{ and } Q_{Z_3}(\tau^-) = 2\,Q_{Z_3}(\mu^-) + Q_{Z_3}(e^+)$$

see e.g. Feruglio/CH/Lin/Merlo ('08), Csaki/Delaunay/Grojean/Grossman ('08), Ma ('10), Holthausen/Lindner/Schmidt ('12), Pascoli/Zhou ('16), Bigaran et al. ('22), Lichtenstein/Schmidt/Valencia/Volkas ('23)

Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]

- $G_e = Z_3$ is not the only option
- Other known examples are:

  - $G_e = Z_4$ (and $G_\nu = Z_2 \times Z_2$) from S_4 leads to bimaximal mixing
    see e.g. de Adelhart Toorop/Feruglio/CH ('11)
  - $G_e = Z_5$ (and $G_\nu = Z_2 \times Z_2$ or $G_\nu = Z_2 \times CP$) from A_5 (and CP) leads to golden ratio(-like) mixing
    see e.g. Feruglio/Paris ('11), Di Iura/CH/Meloni ('15), Ballett/Pascoli/Turner ('15), Li/Ding ('15)
  - $G_e = Z_7$ can arise in scenarios with the flavour symmetry $PSL(2,7)$
    see e.g. de Adelhart Toorop/Feruglio/CH ('11)
  - further examples for G_e from $\Sigma(n\,\varphi)$
    see e.g. CH/Meroni/Vitale ('13)

Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]

- Do systematic search
  - Consider **small $G_e = Z_N$ with $N \leq 8$**
  - Take into account **all possible flavour charge assignments $Z_N(\alpha, \beta, \gamma)$**
    (α flavour charge of e, β of μ and γ of τ);
    also those where two flavours have the same charge,
    e.g. $Q_{Z_N}(e^-) = 0$, $Q_{Z_N}(\mu^-) = 0$ and $Q_{Z_N}(\tau^-) = 1$

Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]

- Do systematic search
  - Focus on **cLFV processes** (that conserve lepton number)
  - Use SMEFT operators and focus on their **flavour structure**

e.g. $\frac{1}{\Lambda^2}(\overline{\ell}_\mu \gamma_\nu \ell_e)(\overline{\ell}_\mu \gamma^\nu \ell_e) \to ee\mu^\dagger\mu^\dagger$

Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]

- Apply constraints
  - All operators conserve ***number of charged leptons***,

    i.e.

$$(n_e^- - n_e^+) + (n_\mu^- - n_\mu^+) + (n_\tau^- - n_\tau^+) \equiv \Delta n_e + \Delta n_\mu + \Delta n_\tau = 0$$

Example: $ee\mu^\dagger\tau^\dagger$ is characterised by $\{\Delta n_e, \Delta n_\mu, \Delta n_\tau\} = \{2, -1, -1\}$

  - All operators are ***invariant under residual symmetry*** $G_e = Z_N$

    i.e.

$$\alpha\,\Delta n_e + \beta\,\Delta n_\mu + \gamma\,\Delta n_\tau = 0 \mod N$$

with α flavour charge of e, β of μ and γ of τ

Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]

- Consequence
  - Possibility to reduce to two parameters $\delta_1 = \beta - \alpha$ and $\delta_2 = \gamma - \beta$ and the constraint

$$0 \mod N = \delta_1 \Delta n_\mu + (\delta_1 + \delta_2) \Delta n_\tau$$

so we have $N(\delta_1, \delta_2)$

Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]

- Output

Flavour charges	d_ℓ	Flavour structures
$\mathbf{2}(\mathbf{0},\mathbf{1})$	3	$e\mu^\dagger$
	6	$\mu\mu\tau^\dagger\tau^\dagger$
		$e\mu\tau^\dagger\tau^\dagger$
		$ee\tau^\dagger\tau^\dagger$
$3(0,1)$	3	$e\mu^\dagger$
	9	$\mu\mu\mu\tau^\dagger\tau^\dagger\tau^\dagger$
		$e\mu\mu\tau^\dagger\tau^\dagger\tau^\dagger$
		$ee\mu\tau^\dagger\tau^\dagger\tau^\dagger$
		$eee\tau^\dagger\tau^\dagger\tau^\dagger$
$\mathbf{3}(\mathbf{1},\mathbf{1})$	6	$e\mu\tau^\dagger\tau^\dagger$
		$e\mu^\dagger\mu^\dagger\tau$
		$ee\mu^\dagger\tau^\dagger$
	9	$\mu\mu\mu\tau^\dagger\tau^\dagger\tau^\dagger$
		$eee\tau^\dagger\tau^\dagger\tau^\dagger$
		$eee\mu^\dagger\mu^\dagger\mu^\dagger$

Flavour charges	d_ℓ	Flavour structures
$\mathbf{4}(\mathbf{1},\mathbf{1})$	6	$e\mu^\dagger\mu^\dagger\tau$
		$ee\tau^\dagger\tau^\dagger$
	9	$e\mu\mu\tau^\dagger\tau^\dagger\tau^\dagger$
		$eee\mu^\dagger\mu^\dagger\tau^\dagger$
	12	$\mu\mu\mu\mu\tau^\dagger\tau^\dagger\tau^\dagger\tau^\dagger$
		$eeee\mu^\dagger\mu^\dagger\mu^\dagger\mu^\dagger$
$\mathbf{5}(\mathbf{0},\mathbf{1})$	3	$e\mu^\dagger$
	15	$\mu\mu\mu\mu\mu\tau^\dagger\tau^\dagger\tau^\dagger\tau^\dagger\tau^\dagger$
		$e\mu\mu\mu\mu\tau^\dagger\tau^\dagger\tau^\dagger\tau^\dagger\tau^\dagger$
		$ee\mu\mu\mu\tau^\dagger\tau^\dagger\tau^\dagger\tau^\dagger\tau^\dagger$
		$eee\mu\mu\tau^\dagger\tau^\dagger\tau^\dagger\tau^\dagger\tau^\dagger$
		$eeee\mu\tau^\dagger\tau^\dagger\tau^\dagger\tau^\dagger\tau^\dagger$
		$eeeee\tau^\dagger\tau^\dagger\tau^\dagger\tau^\dagger\tau^\dagger$
$\mathbf{5}(\mathbf{1},\mathbf{1})$	6	$e\mu^\dagger\mu^\dagger\tau$
	9	$ee\mu\tau^\dagger\tau^\dagger\tau^\dagger$

Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]

- Translate **flavour structures** of SMEFT operators into **cLFV processes**

e.g.

$$e\mu^\dagger$$

$$\downarrow$$

$$\frac{1}{\Lambda^2}(\bar{\ell}_\mu \sigma^{\rho\nu} e_e)\,\varphi\, B_{\rho\nu} \text{ and } \frac{1}{\Lambda^2}(\bar{\ell}_\mu \sigma^{\rho\nu} e_e)\,\varphi\, W_{\rho\nu}$$

$$\downarrow$$

$$\frac{v}{\sqrt{2}\,\Lambda^2}(\bar{e}_{L\mu} \sigma^{\rho\nu} e_e)\, F_{\rho\nu}$$

$$\downarrow$$

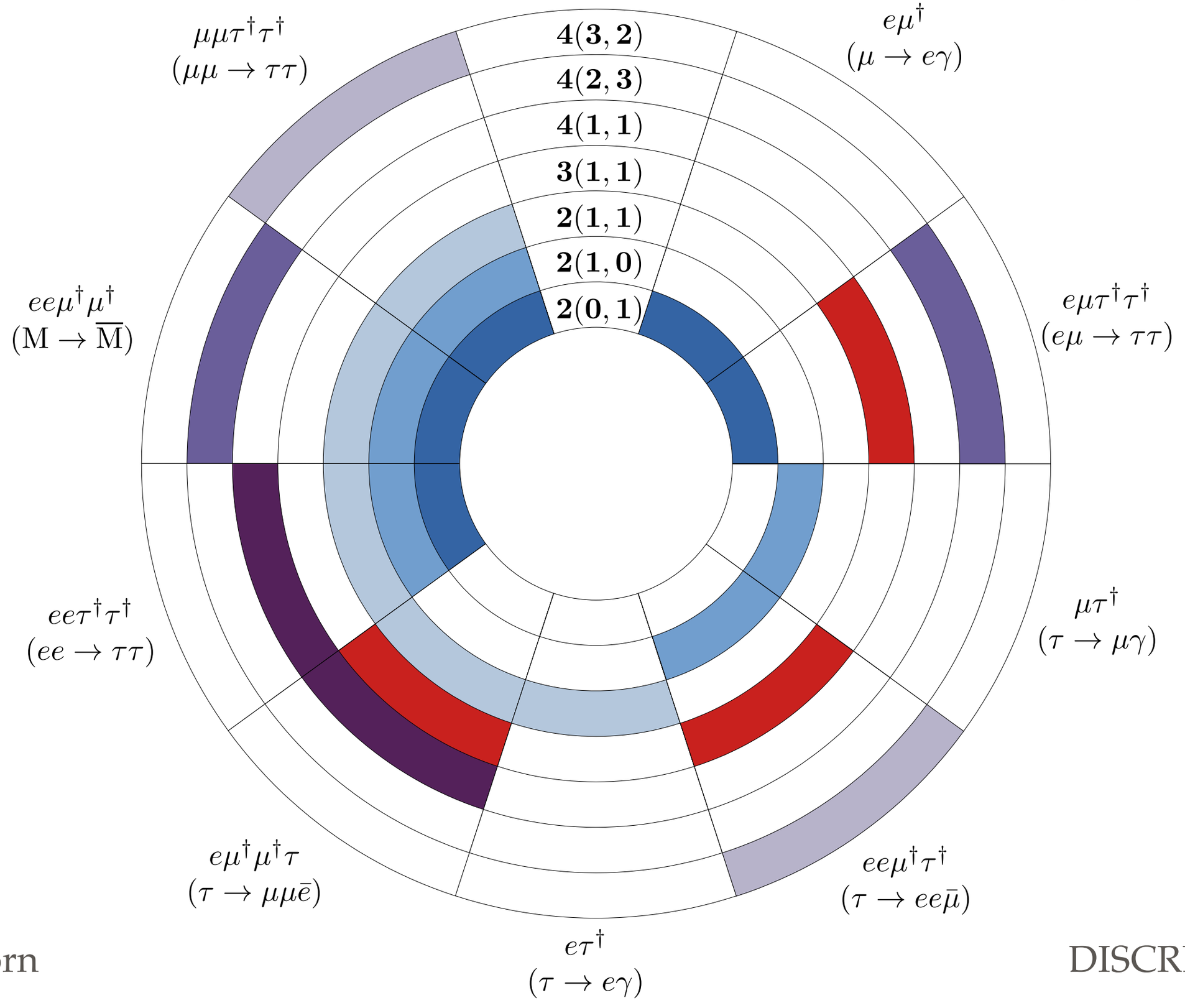
$$\mu \to e\,\gamma$$

- Consider SMEFT operators up to dimension 6, i.e. $d_\ell \leq 6$

[Calibbi, CH, Schmidt, Vandeleur ('25)]

Selection rules for cLFV processes

Coloured segments indicate allowed flavour structures

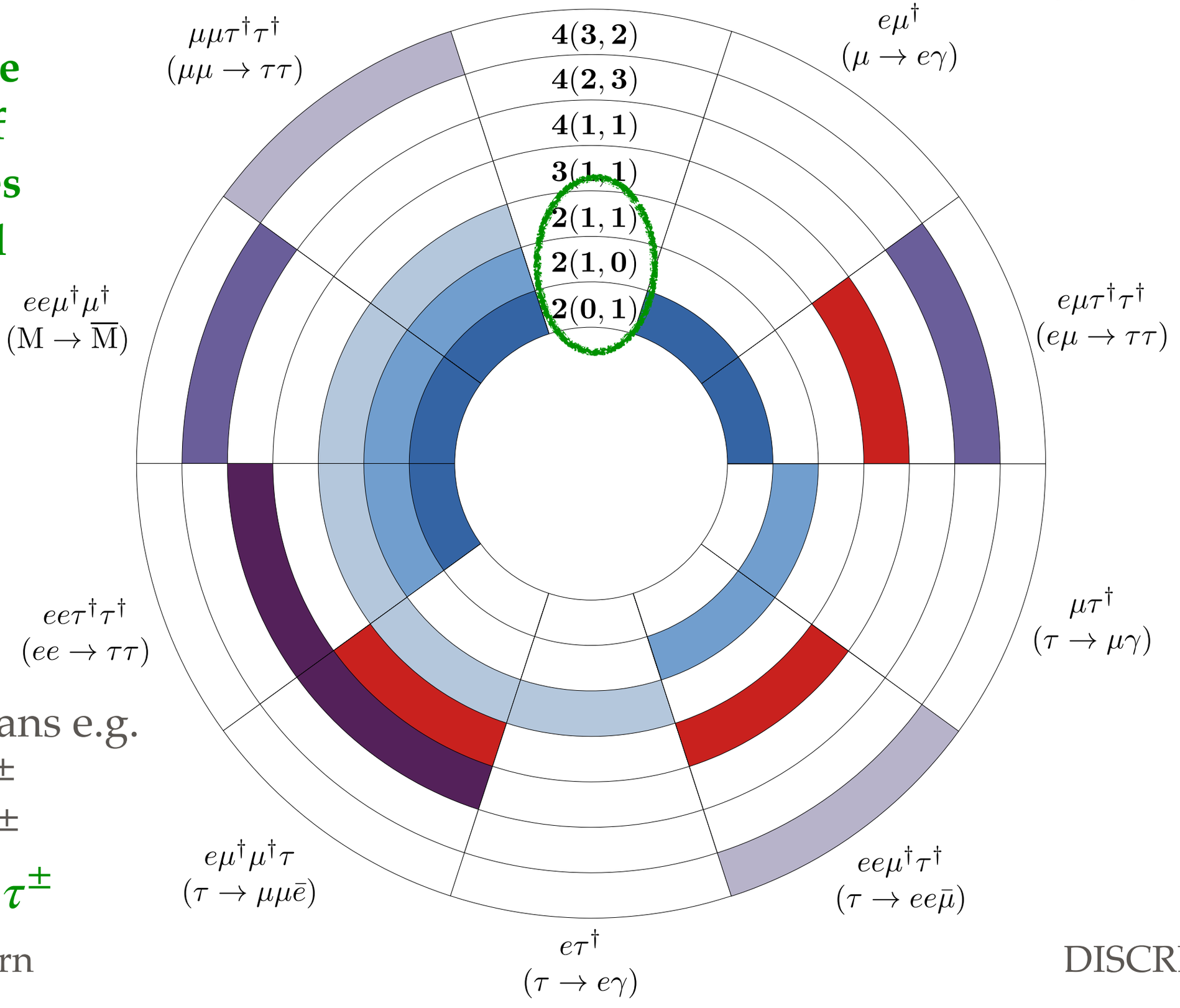


[Calibbi, CH, Schmidt, Vandeleur ('25)]

Selection rules for cLFV processes

Coloured segments indicate allowed flavour structures

up to five types of processes allowed



$\mathbf{2(0,1)}$ means e.g.

$e^\pm \to e^\pm$

$\mu^\pm \to \mu^\pm$

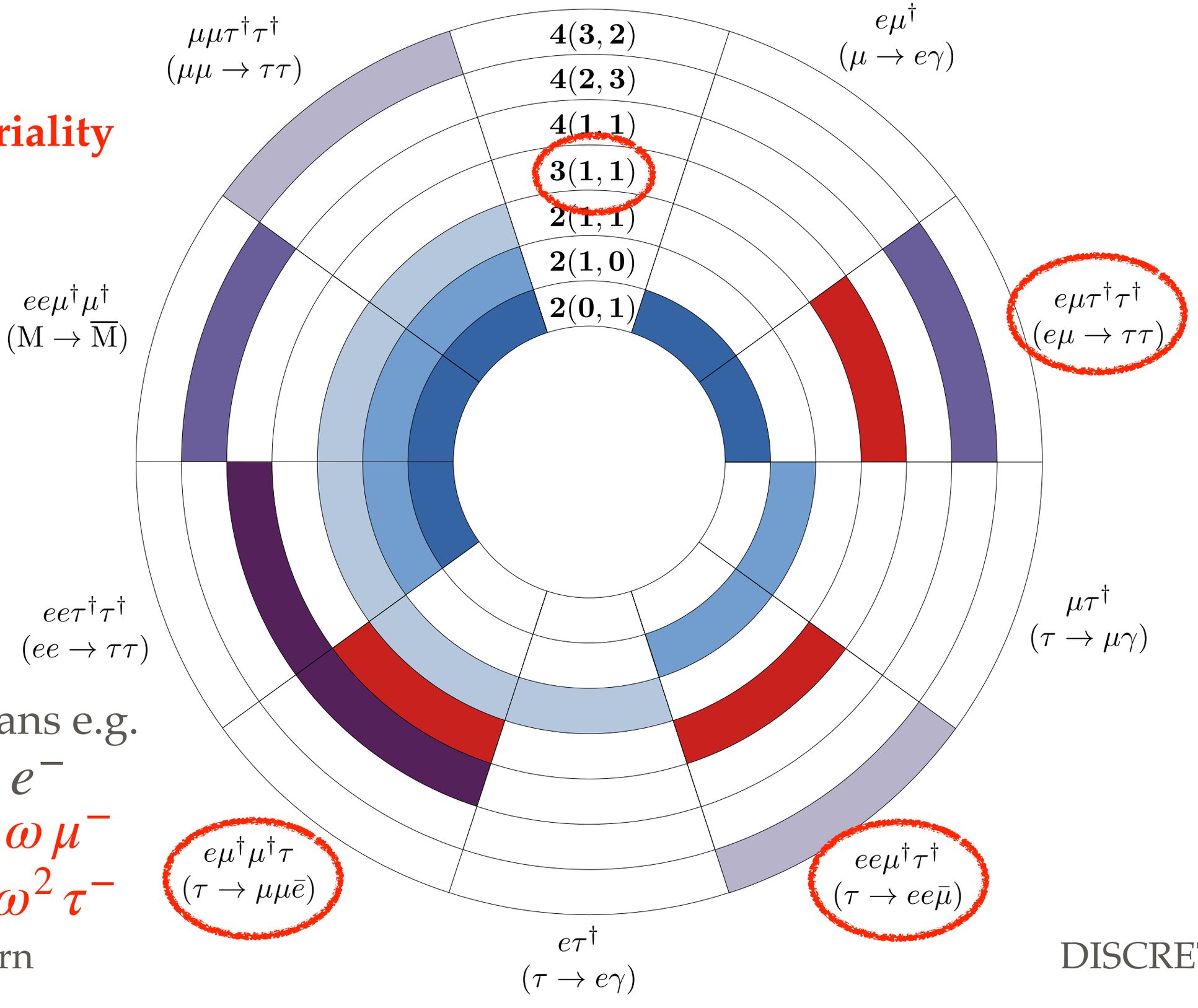
$\boldsymbol{\tau^\pm \to -\tau^\pm}$

[Calibbi, CH, Schmidt, Vandeleur ('25)]

Selection rules for cLFV processes

Coloured segments indicate allowed flavour structures

lepton triality



3(1, 1) means e.g.

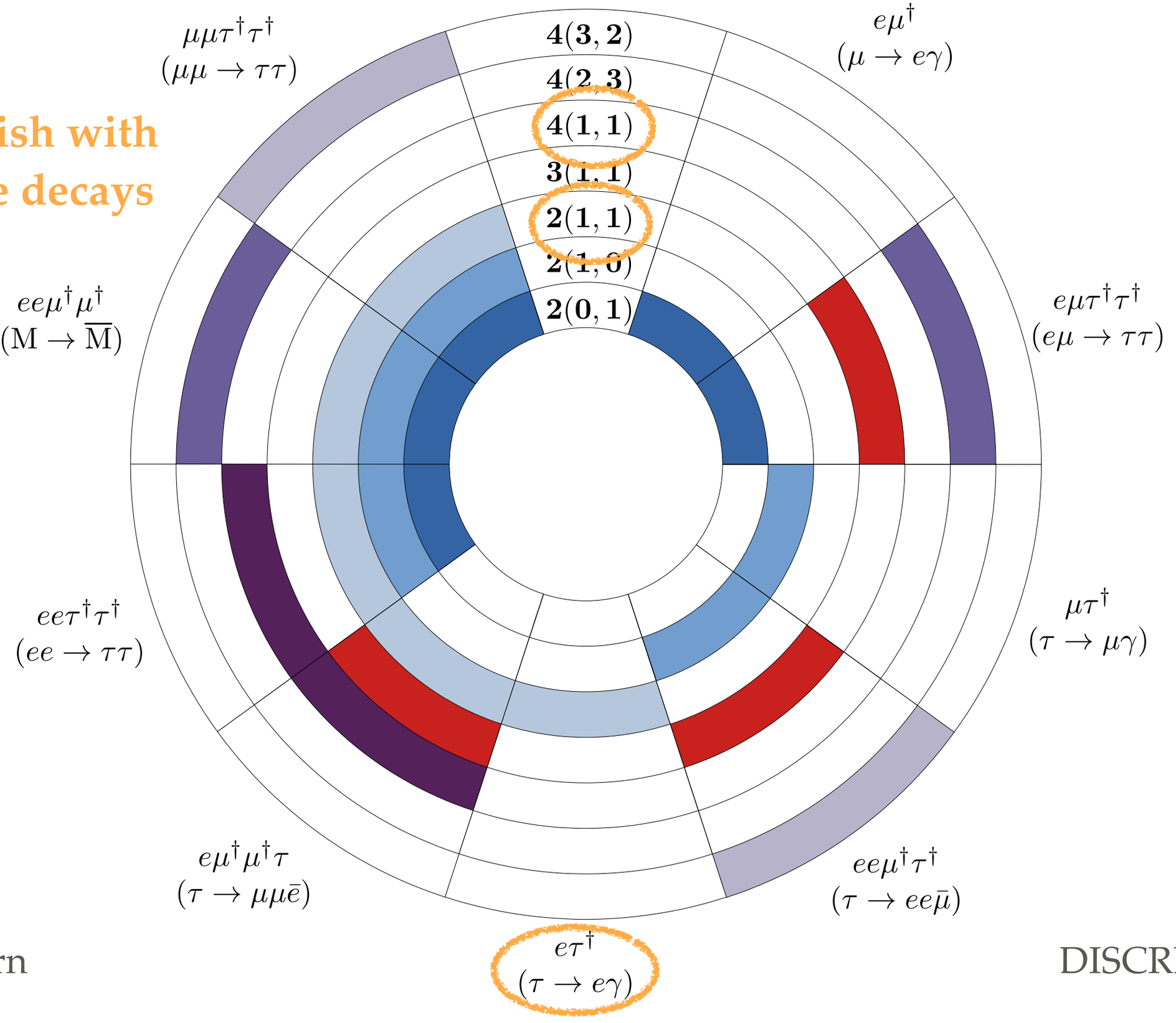
$$e^- \to e^-$$
$$\mu^- \to \omega\,\mu^-$$
$$\tau^- \to \omega^2\,\tau^-$$

[Calibbi, CH, Schmidt, Vandeleur ('25)]

Selection rules for cLFV processes

Coloured segments indicate allowed flavour structures

distinguish with radiative decays

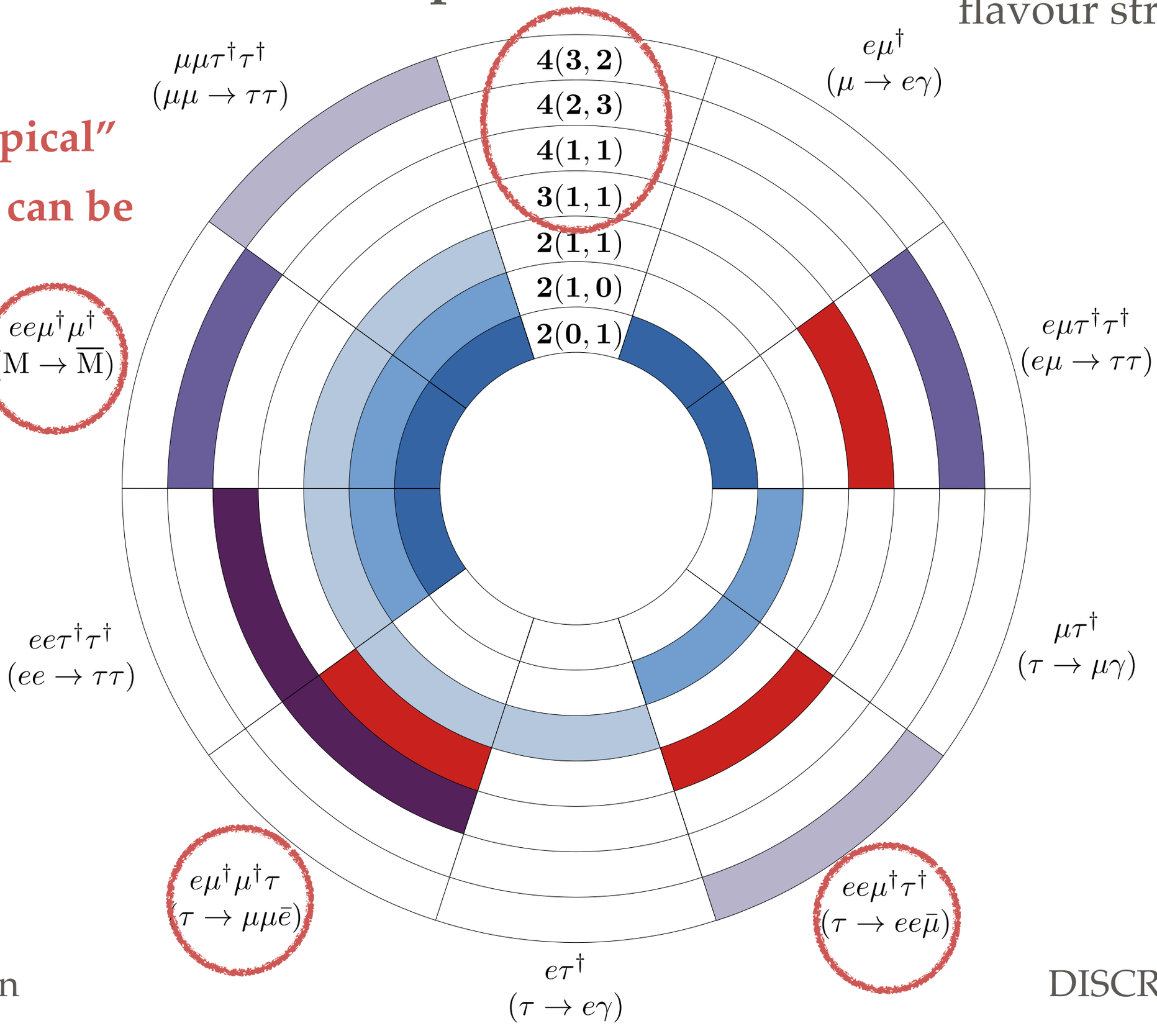


[Calibbi, CH, Schmidt, Vandeleur ('25)]

Selection rules for cLFV processes

Coloured segments indicate allowed flavour structures

"not so typical" processes can be crucial

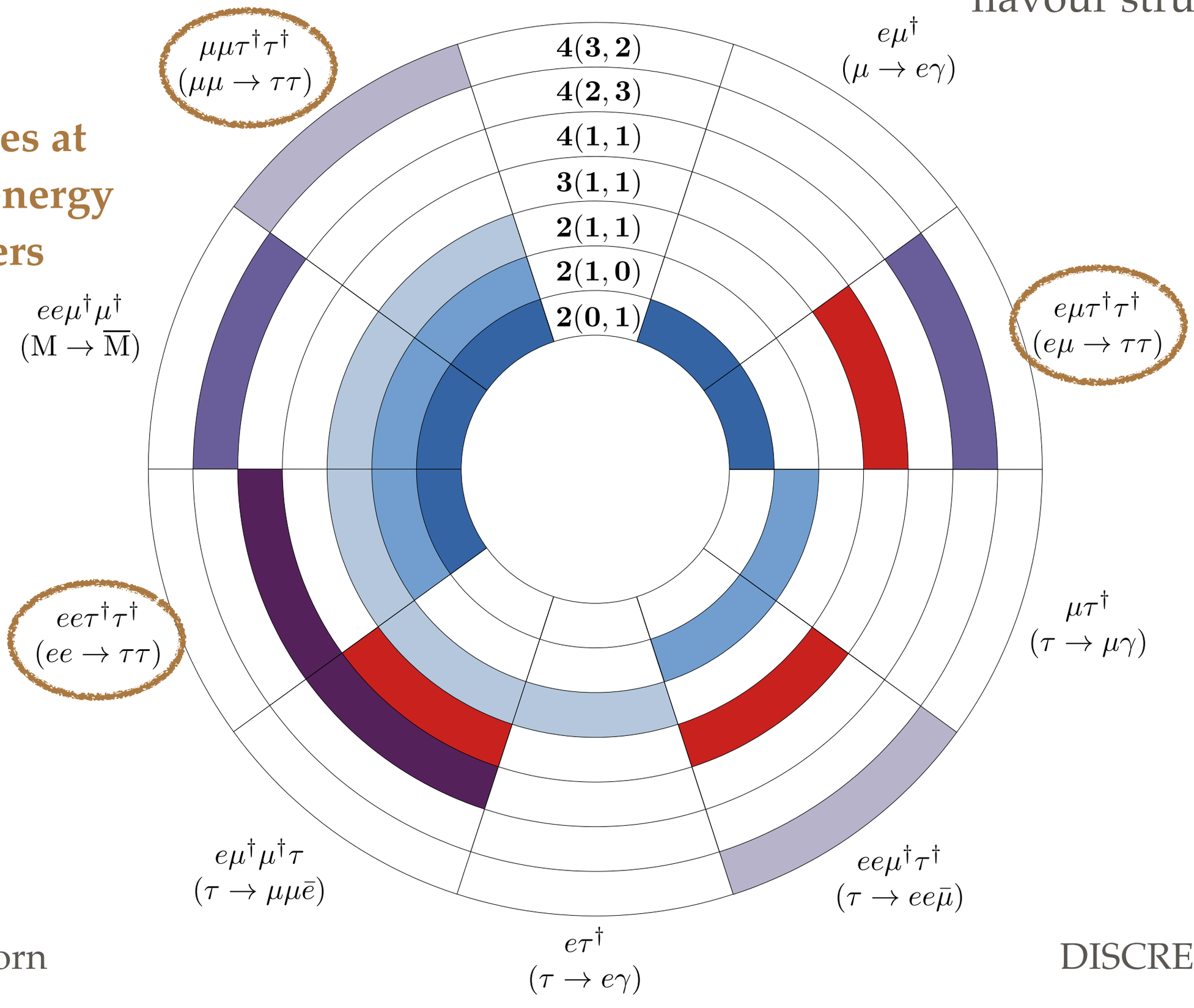


[Calibbi, CH, Schmidt, Vandeleur ('25)]

Selection rules for cLFV processes

Coloured segments indicate allowed flavour structures

cLFV searches at high-energy colliders



Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]

- Confront the results with current and future experimental limits
- Distinguish between **low-energy cLFV experiments** and possible **cLFV searches at high-energy colliders**
- In order to derive limits on the New Physics scale Λ make (theory-inspired) assumptions on origin of Wilson coefficients (WCs), e.g.

$$\frac{C}{\Lambda^2}(\bar{\ell}_\mu \gamma_\nu \ell_e)(\bar{\ell}_\mu \gamma^\nu \ell_e)$$

Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]

- Consider up to three scenarios — inspired by typical UV completions

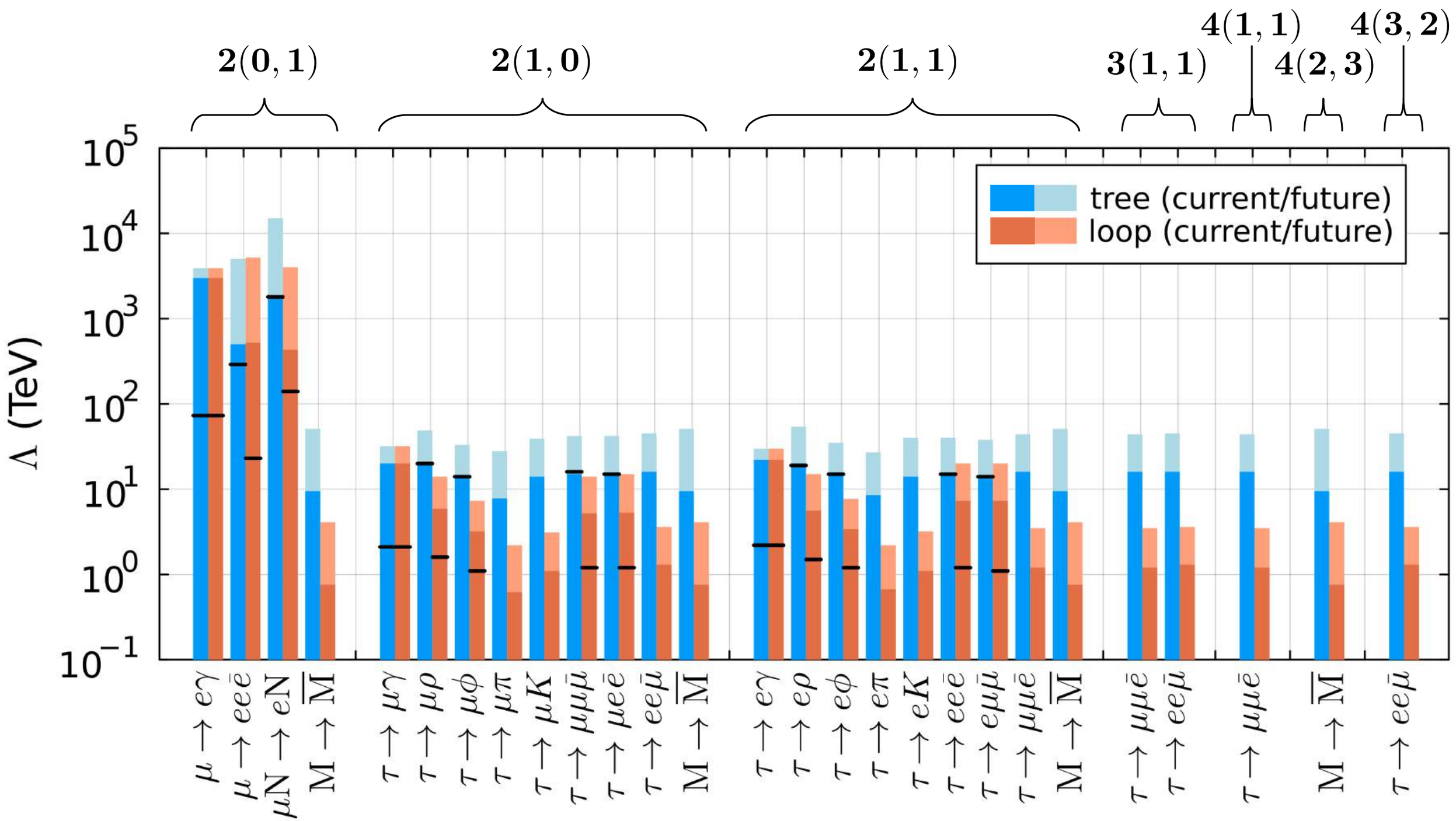
  - Scenario 1: **Tree-level new physics contributions**
    all allowed WCs are set to $C_x = 1$
    apart from the ones of the dipole operator $C_d = \dfrac{e}{16\,\pi^2} \approx 0.002$

  - Scenario 2: **One-loop new physics contributions**
    all WCs are set to $C_x = \dfrac{1}{16\,\pi^2} \approx 0.006$ and $C_d = \dfrac{e}{16\,\pi^2} \approx 0.002$

  - Scenario 3: **Dipole operators suppressed by Yukawa coupling**
    meaning $C_d = \dfrac{\sqrt{2}\,m_\ell\,e}{16\,\pi^2\,v}$

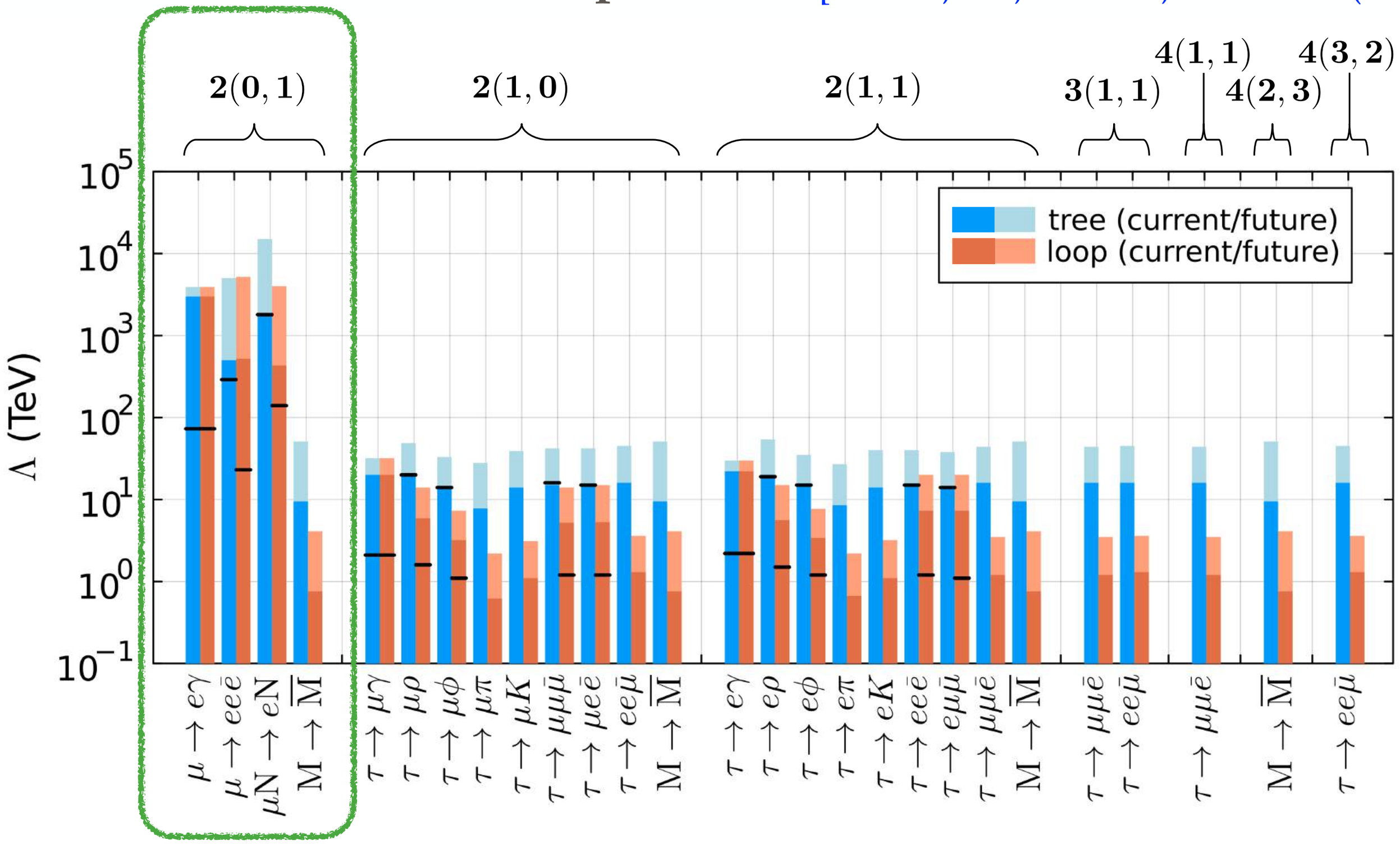
(formulae, see e.g. Calibbi/Marcano/Roy ('21))

Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]



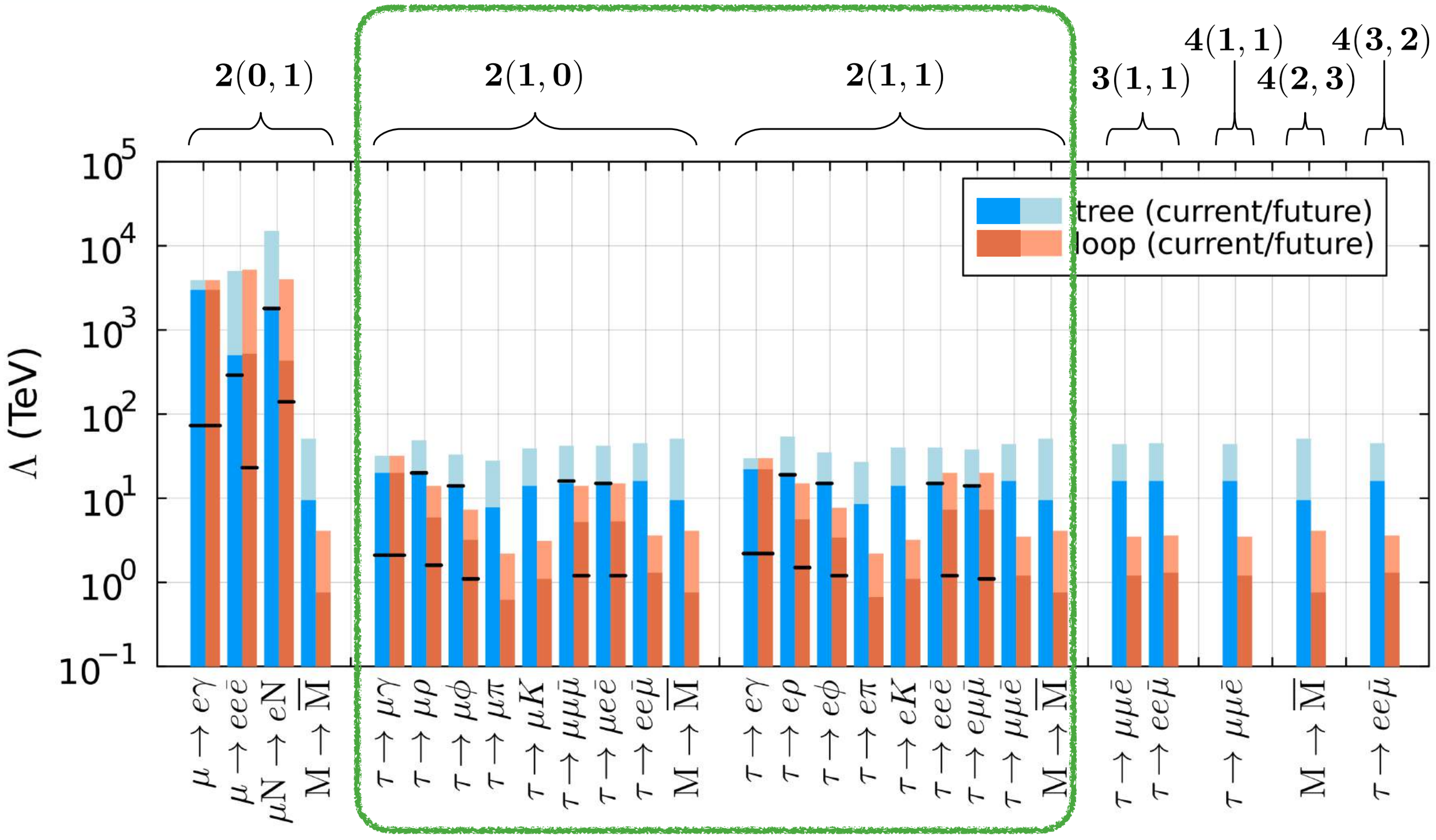
No RG running. No matching of SMEFT to LEFT.

Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]



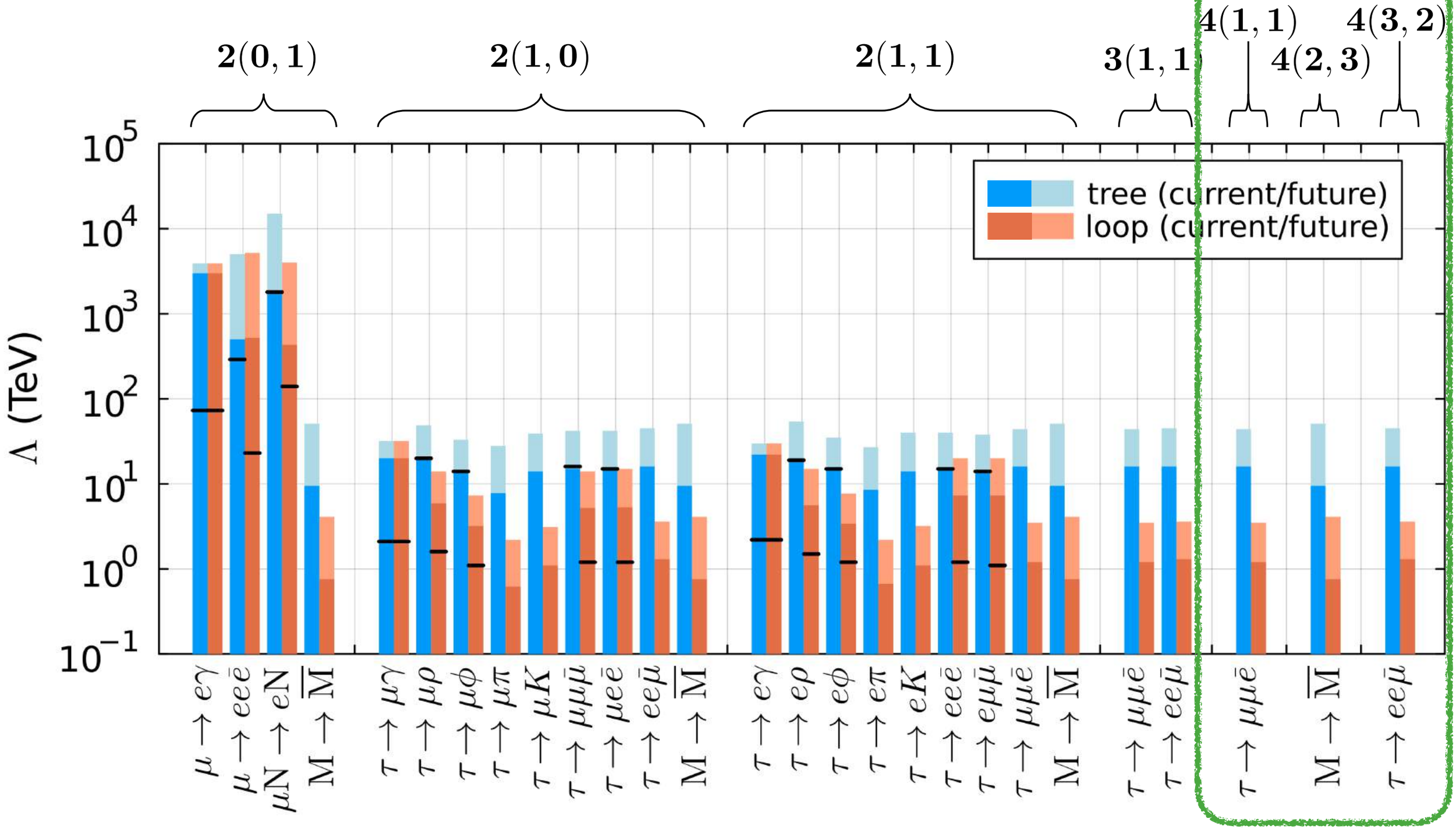
No RG running. No matching of SMEFT to LEFT.

Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]



No RG running. No matching of SMEFT to LEFT.

Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]



No RG running. No matching of SMEFT to LEFT.

Selection rules for cLFV processes [Calibbi, CH, Schmidt, Vandeleur ('25)]

What is not included?

- Breaking effects of residual symmetry G_e
  (shifts in flavon VEVs, cross-talk between different symmetry breaking sectors, etc.)
- Effects arising from concrete model realisation

Idea of residual symmetries

Idea: Keep some residual symmetry among charged leptons and neutrinos, G_e and G_ν, with $G_e \neq G_\nu$

Mismatch of symmetries corresponds to lepton mixing

G_f and CP

charged leptons

G_e

U_e

neutrinos

$G_\nu = Z_2 \times$ CP

$U_\nu = \Omega_\nu R(\theta) K_\nu$

$$U_{PMNS} = U_e^\dagger \Omega_\nu R(\theta) K_\nu$$

see e.g. Feruglio/CH/Ziegler ('12)

cLFV processes in inverse seesaw scenarios

Idea: Keep some residual symmetry among charged leptons and neutrinos, G_e and G_ν, with $G_e \neq G_\nu$

Mismatch of symmetries corresponds to lepton mixing

G_f and CP

$G_f = \Delta(3\,n^2)$ or $\Delta(6\,n^2)$

charged leptons

Minimal choice Z_3

G_e

U_e

3 different masses

neutrinos

Choice Z_2 and CP

$G_\nu = Z_2 \times$ CP

$U_\nu = \Omega_\nu R(\theta) K_\nu$

Majorana masses

Free parameter

$$U_{PMNS} = U_e^\dagger \Omega_\nu R(\theta) K_\nu$$

Size of masses not explained

see e.g. CH/Meroni/Molinaro ('14)

cLFV processes in inverse seesaw scenarios

- Consider a scenario of **(3,3) Inverse seesaw** mechanism,
  i.e. 3 generations of LH doublets,
  3 generations of N_i and S_j, all of them gauge singlets

$$-(y_D)_{\alpha i}\,\overline{L}^c_\alpha\,H\,N^c_i - (M_{NS})_{ij}\,\overline{N}_i\,S_j - \frac{1}{2}\,(\mu_S)_{kl}\,\overline{S}^c_k\,S_l + \text{h.c.}$$

Mass matrix of neutral states

$$\mathcal{M}_{\text{Maj}} = \begin{pmatrix} \mathbb{0} & m_D & \mathbb{0} \\ m_D^T & \mathbb{0} & M_{NS} \\ \mathbb{0} & M_{NS}^T & \mu_S \end{pmatrix} \quad \text{with} \quad m_D = y_D\,\frac{v}{\sqrt{2}}$$

- Light neutrino masses
  $|\mu_S| \ll |m_D| \ll |M_{NS}|$:

$$m_\nu = m_D \left(M_{NS}^{-1}\right)^T \mu_S\, M_{NS}^{-1}\, m_D^T$$

Mohapatra / Valle ('86),
Mohapatra (´86),
Bernabeu et al. (´87),
Gonzalez-Garcia / Valle (´89)

cLFV processes in inverse seesaw scenarios

- Heavy sterile states form pseudo-Dirac pairs
  $|\mu_S| \ll |m_D| \ll |M_{NS}|$:

$$V^T \begin{pmatrix} \mathbb{0} & M_{NS} \\ M_{NS}^T & \mu_S \end{pmatrix} V \approx \text{diag}\,(m_4, ..., m_9)$$

- Mixing matrix

$$\mathcal{U}^T \mathcal{M}_{\text{Maj}} \mathcal{U} = \mathcal{M}_{\text{Maj}}^{\text{diag}}$$

$$\mathcal{U} = \begin{pmatrix} \tilde{U}_\nu & S \\ T & V \end{pmatrix} \text{ and } \mathcal{M}_{\text{Maj}}^{\text{diag}} = \text{diag}\,(m_1, m_2, m_3, m_4, \ldots, m_9)$$

- For lepton mixing matrix we have

$$\tilde{U}_{\text{PMNS}} = \left(\mathbb{1} - \eta\right) U_0 \text{ with } \eta = \frac{1}{2} m_D^\star \left(M_{NS}^{-1}\right)^\dagger M_{NS}^{-1} m_D^T$$

$$\text{If } U_\ell = \mathbb{1} \text{ then } \tilde{U}_{\text{PMNS}} = U_\ell^\dagger \tilde{U}_\nu = \tilde{U}_\nu$$

cLFV processes in inverse seesaw scenarios

$$\mathcal{M}_{\rm Maj} = \begin{pmatrix} \mathbb{0} & m_D & \mathbb{0} \\ m_D^T & \mathbb{0} & M_{NS} \\ \mathbb{0} & M_{NS}^T & \mu_S \end{pmatrix} \quad \text{with} \quad m_D = y_D \frac{v}{\sqrt{2}}$$

- **Option 1** only the Majorana mass matrix μ_S of the singlets S_j breaks G_f and CP to G_ν

[CH, J. Kriewald, J. Orloff, A.M. Teixeira ('21)]

$$U_S^T \mu_S U_S = \begin{pmatrix} \mu_1 & 0 & 0 \\ 0 & \mu_2 & 0 \\ 0 & 0 & \mu_3 \end{pmatrix} \quad \text{and} \quad U_S = \Omega(\mathbf{3})\, R_{fh}(\theta_S)$$

together with

$$m_D = y_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \frac{v}{\sqrt{2}} \text{ with } y_0 > 0 \quad \text{and} \quad M_{NS} = M_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \text{ with } M_0 > 0$$

cLFV processes in inverse seesaw scenarios

$$\mathcal{M}_{\rm Maj} = \begin{pmatrix} \mathbb{0} & m_D & \mathbb{0} \\ m_D^T & \mathbb{0} & M_{NS} \\ \mathbb{0} & M_{NS}^T & \mu_S \end{pmatrix} \quad \text{with} \quad m_D = y_D \, \frac{v}{\sqrt{2}}$$

- **Option 2** only the Dirac neutrino mass matrix m_D breaks G_f and CP to G_ν

[F.P. Di Meglio, CH ('24)]

$$y_D = \Omega(\mathbf{3})^\star \, R_{ij}(\theta_L) \, \text{diag}(y_1, y_2, y_3) \, P_{kl}^{ij} \, R_{kl}(-\theta_R) \, \Omega(\mathbf{3}')^T$$

with 5 real parameters: 3 couplings y_1, y_2, y_3 and 2 angles θ_L and θ_R and

$$M_{NS} = M_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \text{and} \quad \mu_S = \mu_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

with $\quad M_0 > 0 \quad \text{and} \quad \mu_0 > 0$

cLFV processes in inverse seesaw scenarios

$$\mathcal{M}_{\rm Maj} = \begin{pmatrix} \mathbb{0} & m_D & \mathbb{0} \\ m_D^T & \mathbb{0} & M_{NS} \\ \mathbb{0} & M_{NS}^T & \mu_S \end{pmatrix} \quad \text{with} \quad m_D = y_D \frac{v}{\sqrt{2}}$$

- **Option 3** only the matrix M_{NS} breaks G_f and CP to G_ν

[F.P. Di Meglio, CH ('26)]

$$M_{NS} = \Omega(\mathbf{3})\, R_{ij}(\theta_N)\, \mathrm{diag}(M_1, M_2, M_3)\, P_{kl}^{ij}\, R_{kl}(-\theta_S)\, \Omega(\mathbf{3}')^\dagger$$

with 5 real parameters: 3 mass parameters M_1, M_2, M_3 and
2 angles θ_N and θ_S and

$$m_D = y_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \langle H \rangle \quad \text{with} \quad y_0 > 0 \qquad \mu_S = \mu_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \text{with} \quad \mu_0 > 0$$

cLFV processes in inverse seesaw scenarios

[CH, J. Kriewald, J. Orloff, A.M. Teixeira ('21)]

Option 1

- Lepton number and flavour breaking are **both** encoded in the matrix

$$U_S^T\,\mu_S\,U_S = \begin{pmatrix} \mu_1 & 0 & 0 \\ 0 & \mu_2 & 0 \\ 0 & 0 & \mu_3 \end{pmatrix} \quad \text{with} \quad U_S = \Omega(\mathbf{3})\,R_{fh}(\theta_S)$$

- Non-unitarity effects are **flavour-diagonal and flavour-universal**

$$\eta = \frac{y_0^2\,v^2}{4\,M_0^2}\,\mathbb{1} \equiv \eta_0\,\mathbb{1}$$

- Mass spectrum of heavy states is peculiar:
  they form **pseudo-Dirac pairs** with very small mass splitting
  and all three such pairs have a **common mass scale**

$$M_{h,i} = M_0 - \frac{\mu_i}{2} \;\text{ and }\; M_{h,i+3} = M_0 + \frac{\mu_i}{2} \;\text{ with }\; i = 1,2,3\,.$$

cLFV processes in inverse seesaw scenarios [CH, J. Kriewald, J. Orloff, A.M. Teixeira ('21)]

Option 1

- Lepton number and flavour breaking are **both** enc

$$U_S^T \mu_S U_S = \begin{pmatrix} \mu_1 & 0 & 0 \\ 0 & \mu_2 & 0 \\ 0 & & \end{pmatrix}$$

- Non-

Conclusion

Rates of charged lepton flavour violating processes

$\ell_\beta \to \ell_\alpha \gamma$ $\quad \ell_\beta \to 3\,\ell_\alpha$ $\quad \mu - e$ conversion

are very suppressed!

for general formulae see Alonso et al. ('12), Ilakovac/Pilaftsis ('95)

ion very small mass splitting

s have a **common mass scale**

$$M_{h,i} = M_0 - \frac{\mu_i}{2} \text{ and } M_{h,i+3} = M_0 + \frac{\mu_i}{2} \text{ with } i = 1,2,3\,.$$

cLFV processes in inverse seesaw scenarios [F.P. Di Meglio, CH ('24)]

Option 2

- Parameters of the scenario:
  2 scales: M_0 and μ_0
  5 real parameters: 3 couplings y_1, y_2, y_3 and 2 angles θ_L and θ_R
- Their role is
  M_0 mass of the 3 pseudo-Dirac pairs $150\,\text{GeV} \leq M_0 \leq 10\,\text{TeV}$
  μ_0 lepton number breaking parameter $100\,\text{eV} \leq \mu_0 \leq 100\,\text{keV}$
  y_f adjust light neutrino masses m_1, m_2, m_3 $4 \cdot 10^{-5} \lesssim y_f \lesssim 1.2$
  θ_L fitted to accommodate lepton mixing angles best
  θ_R free parameter $0 \leq \theta_R \leq 2\,\pi$
- Study of lepton mixing and charged lepton flavour violation for **Case 1) Case 2) Case 3 a) Case 3 b.1)**, analytically and numerically.

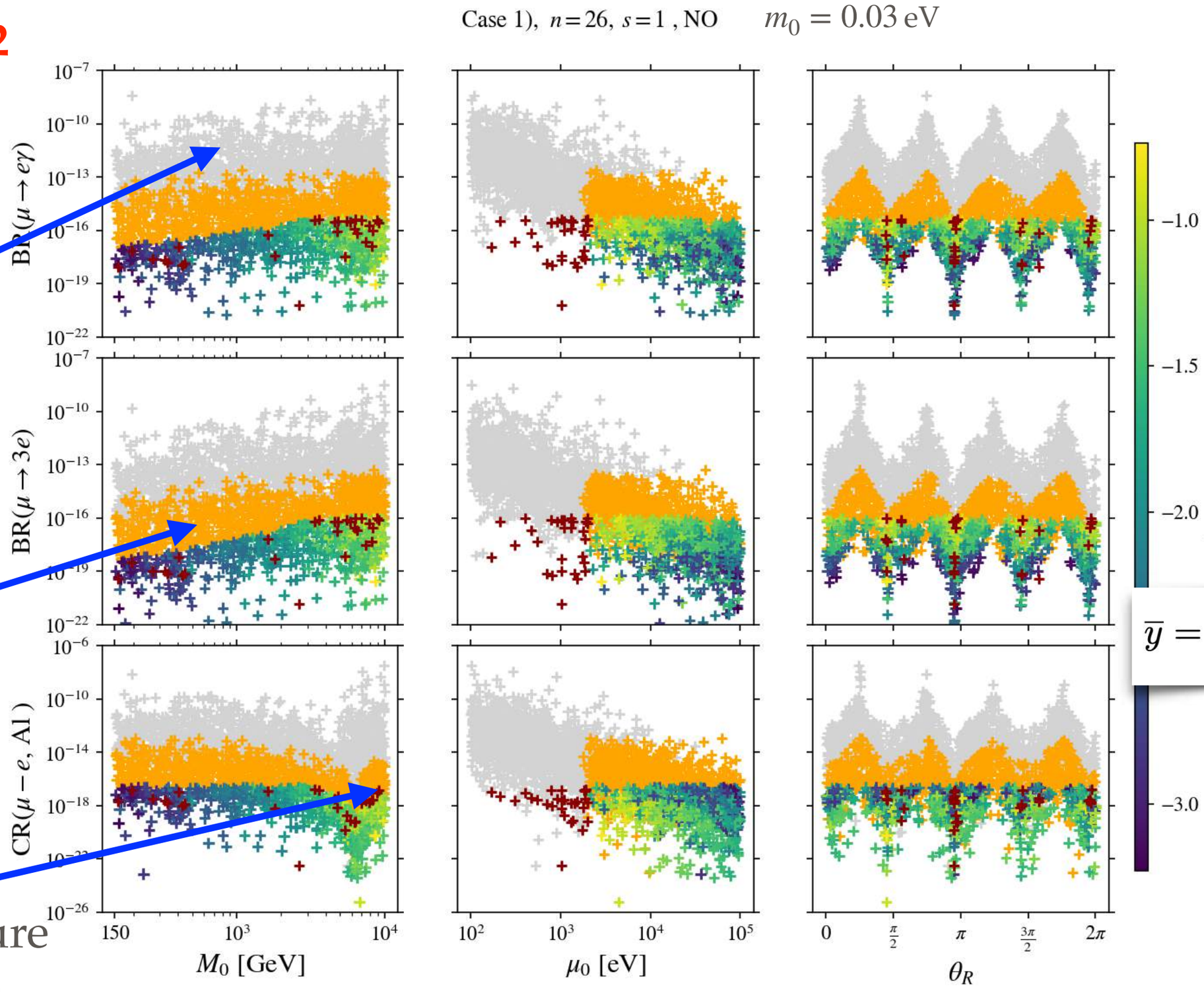
cLFV processes in inverse seesaw scenarios [F.P. Di Meglio, CH ('24)]

Option 2

cLFV future and η not OK

cLFV future not OK, but η OK

cLFV future OK, but η not OK



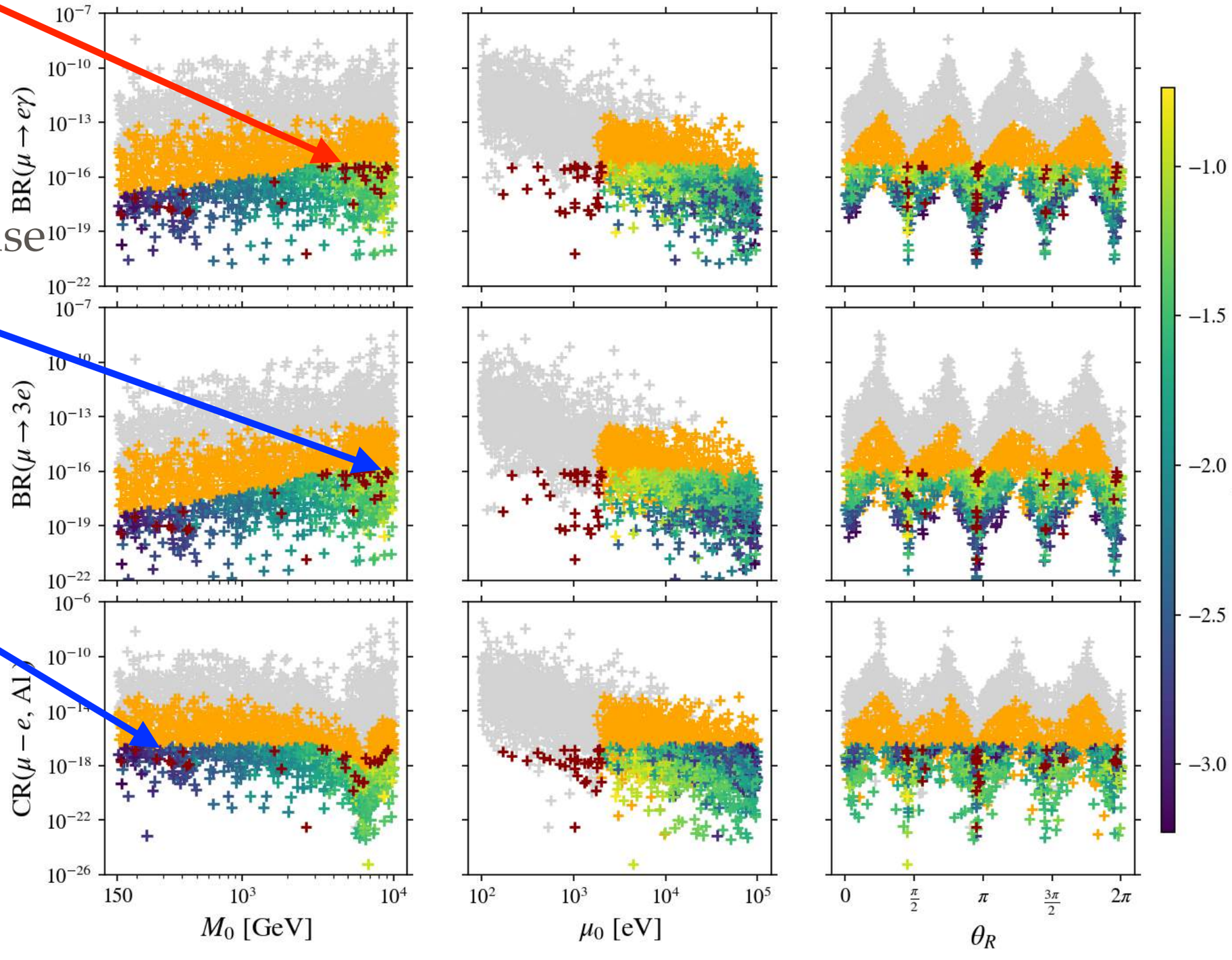
cLFV processes in inverse seesaw scenarios [F.P. Di Meglio, CH ('24)]

$\mathrm{BR}(\mu \to e\,\gamma) \lesssim 6 \times 10^{-16}$

Option 2

Mu3E Phase 2 bound reached

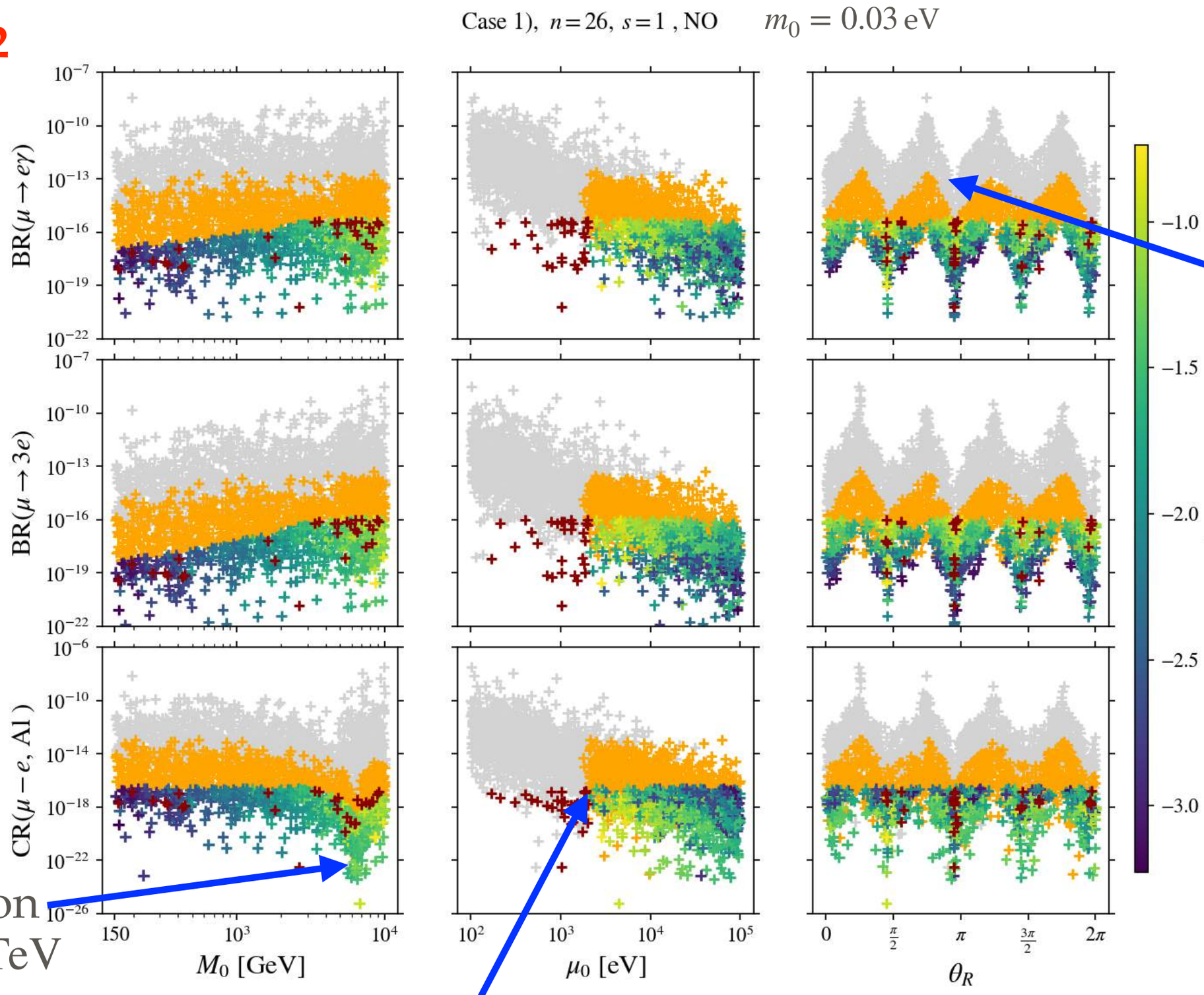
COMET bound reached



Results for IO and small m_0 also studied.

cLFV processes in inverse seesaw scenarios [F.P. Di Meglio, CH ('24)]

Option 2



θ_R dependence $\cos 2\theta_R \approx 0$ enhanced BRs, CR; for $|\cos 2\theta_R|$ large, suppressed

cancellation $M_0 \approx 6.5$ TeV

$\mu_0 \gtrsim 2$ keV

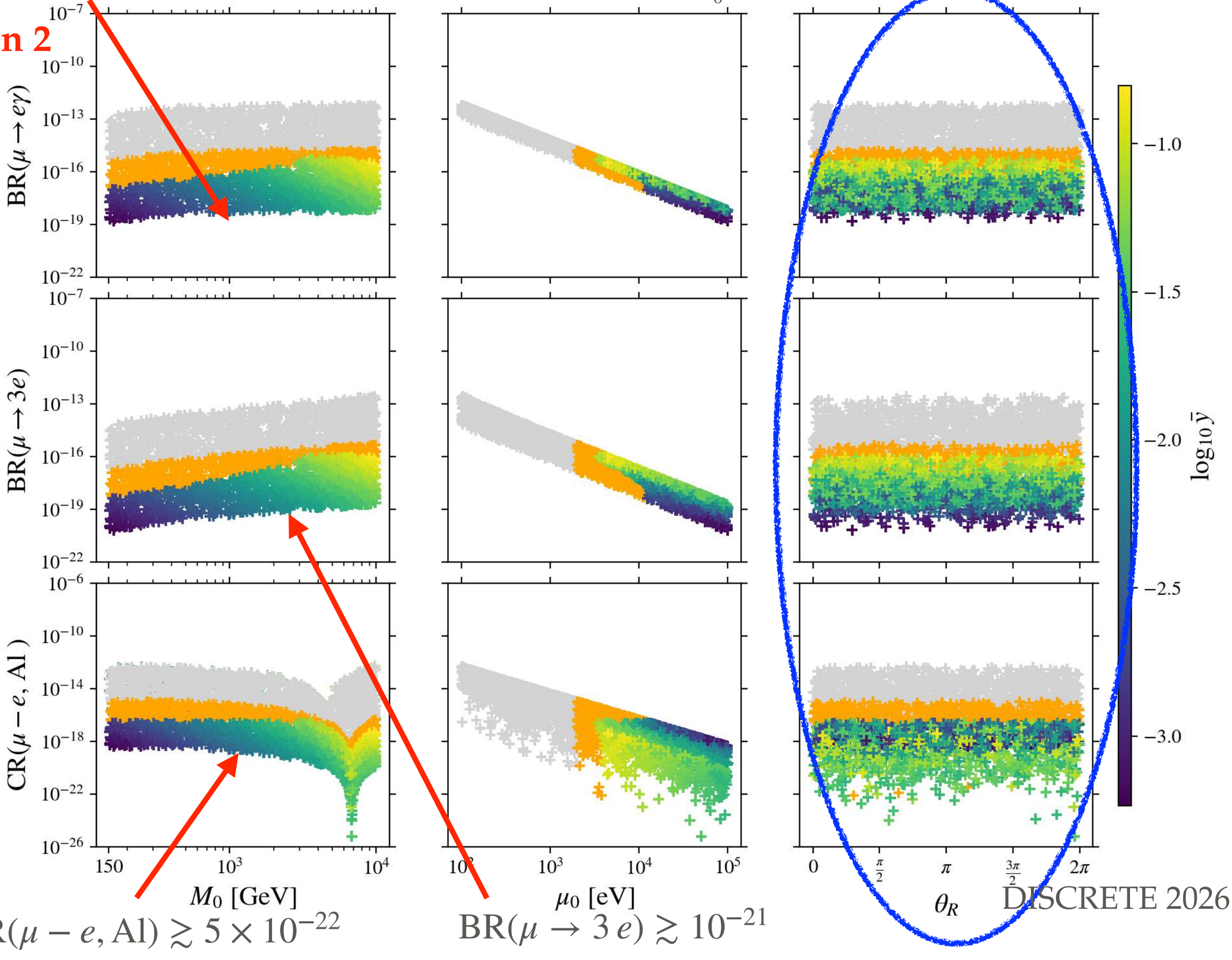
$\mathrm{BR}(\mu \to e\,\gamma) \gtrsim 10^{-19}$

Case 2), $n = 14$, $s = 1$, $t = 2\,(u = 0)$, NO

$m_0 = 0.03$ eV

no dependence on θ_R

Option 2



$\mathrm{CR}(\mu - e, \mathrm{Al}) \gtrsim 5 \times 10^{-22}$

$\mathrm{BR}(\mu \to 3\,e) \gtrsim 10^{-21}$

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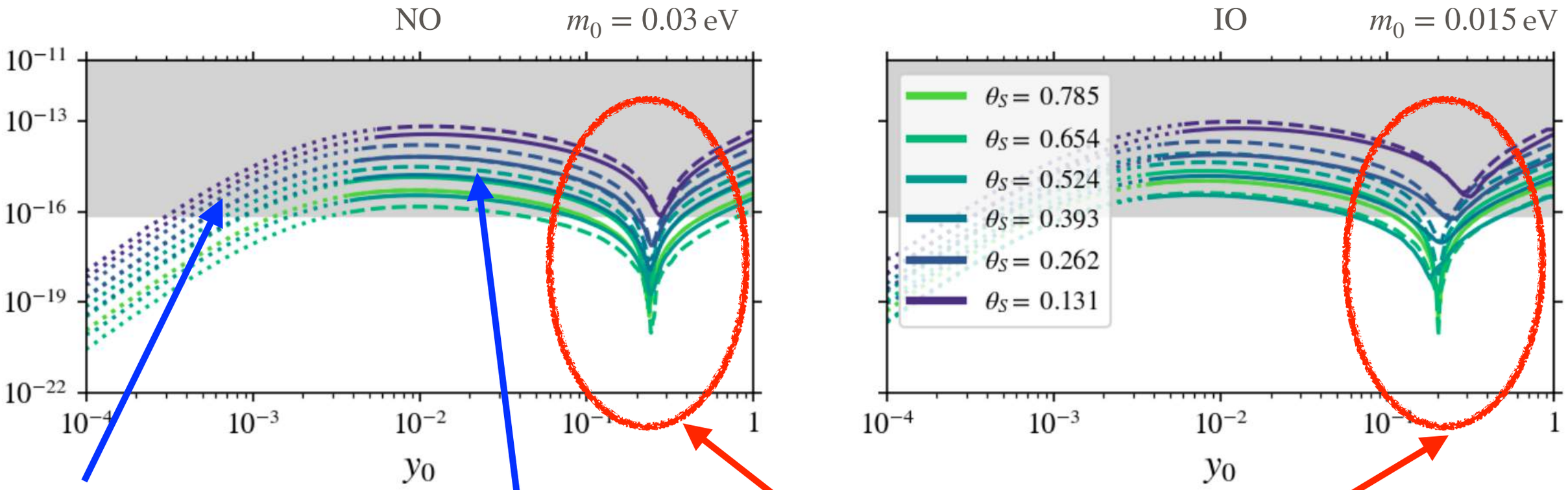
cLFV processes in inverse seesaw scenarios [F.P. Di Meglio, CH ('26)]

Option 3

- Parameters of the scenario:
  4 *scales*: M_1, M_2, M_3 and μ_0
  3 *real parameters*: 1 coupling y_0 and 2 angles θ_N and θ_S
- Their role is
  M_1, M_2, M_3 adjust light neutrino masses $150\,\text{GeV} \lesssim M_i \lesssim 700\,\text{TeV}$
  μ_0 lepton number breaking parameter $100\,\text{eV} \leq \mu_0 \leq 1\,\text{MeV}$
  y_0 overall scale of light neutrino masses $10^{-4} \leq y_0 \leq 1$
  θ_N fitted to accommodate lepton mixing angles best
  θ_S free parameter $0 \leq \theta_S \leq 2\,\pi$
- Study of lepton mixing and charged lepton flavour violation for **Case 1) Case 2) Case 3 a) Case 3 b.1)**, analytically and numerically.

cLFV processes in inverse seesaw scenarios [F.P. Di Meglio, CH ('26)]

$\mu_0 = 3\,\text{keV}$ **Option 3** Case 2), $n = 14\,, u = 1\,(s = 1\,, t = 1)$



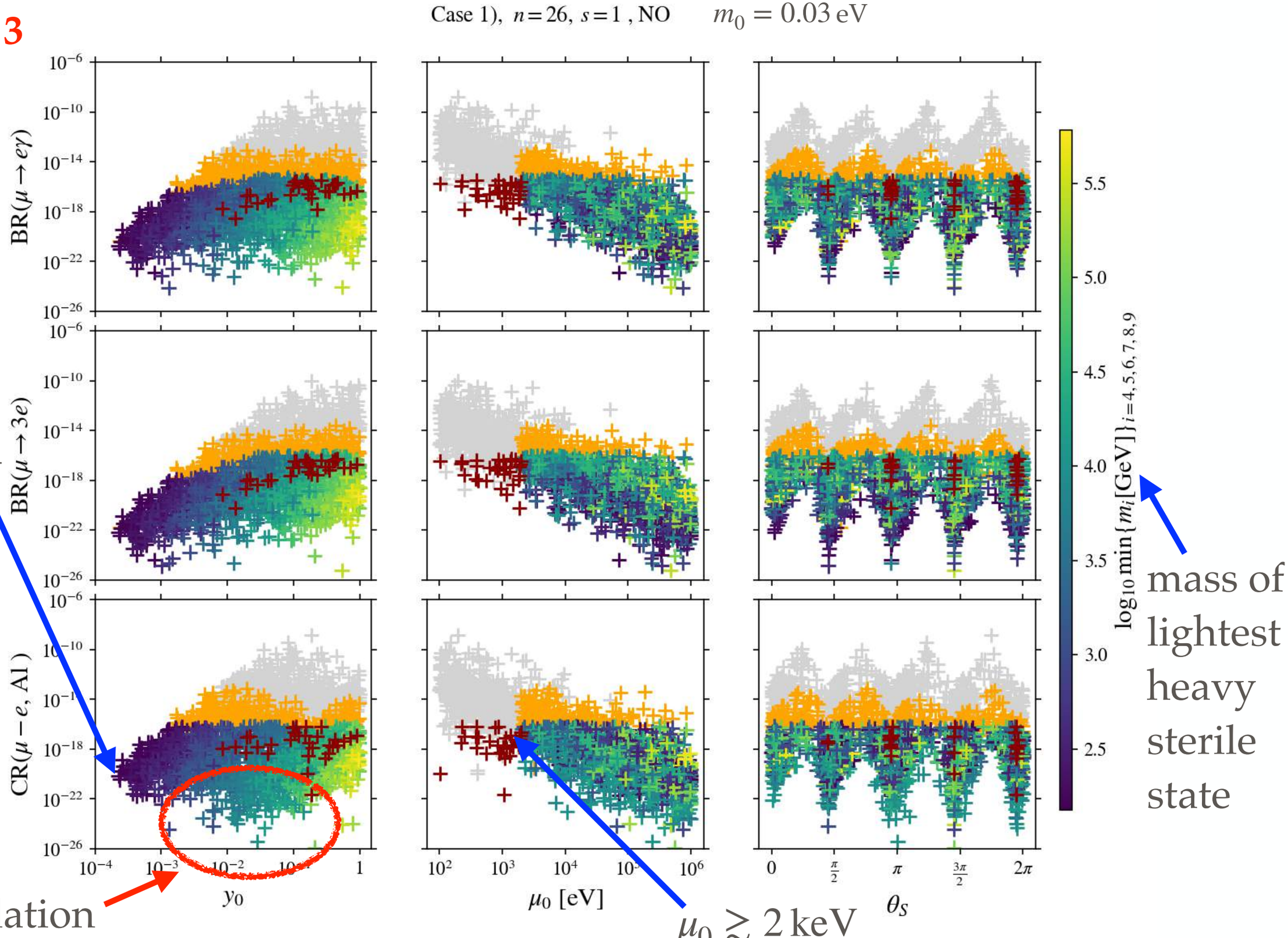
heavy sterile state(s) lighter than 150 GeV

different values of $\theta_N\,(\bar{\theta}_N)$

cancellation is not universal

cLFV processes in inverse seesaw scenarios [F.P. Di Meglio, CH ('26)]

Option 3



$y_0 \gtrsim 2 \times 10^{-4}$

cancellation

$\mu_0 \gtrsim 2\,\text{keV}$

mass of lightest heavy sterile state

cLFV processes in inverse seesaw scenarios

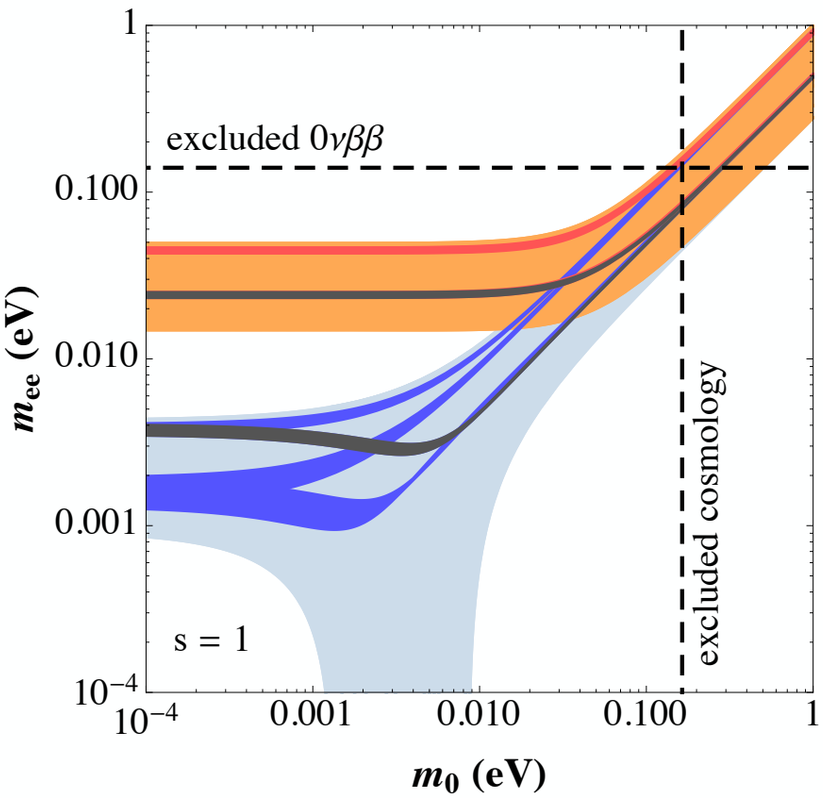
- No observable cLFV signals for option 1, but good prospects for option 2 and option 3
- Results for option 2 and option 3 are very similar, except that for $\mu - e$ conversion for option 2 there is an exact cancellation at a fixed value of the mass parameter M_0, whereas for option 3 this cancellation may not be exact and depends not only on mass parameters $M_{1,2,3}$
- Heavy sterile states are all (almost) degenerate in mass for option 1 and option 2, while for option 3 there are three pairs of (nearly) mass-degenerate pseudo-Dirac pairs
- Effects of non-unitarity are more general for option 2 and option 3 than for option 1, but of similar size (not observable in lepton mixing)

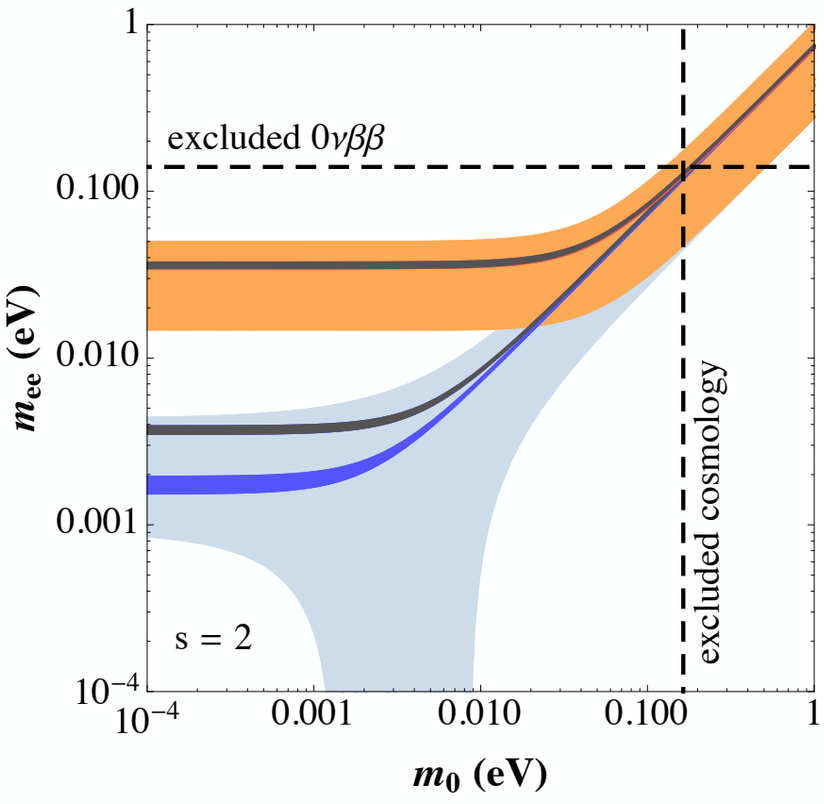
Other phenomenology

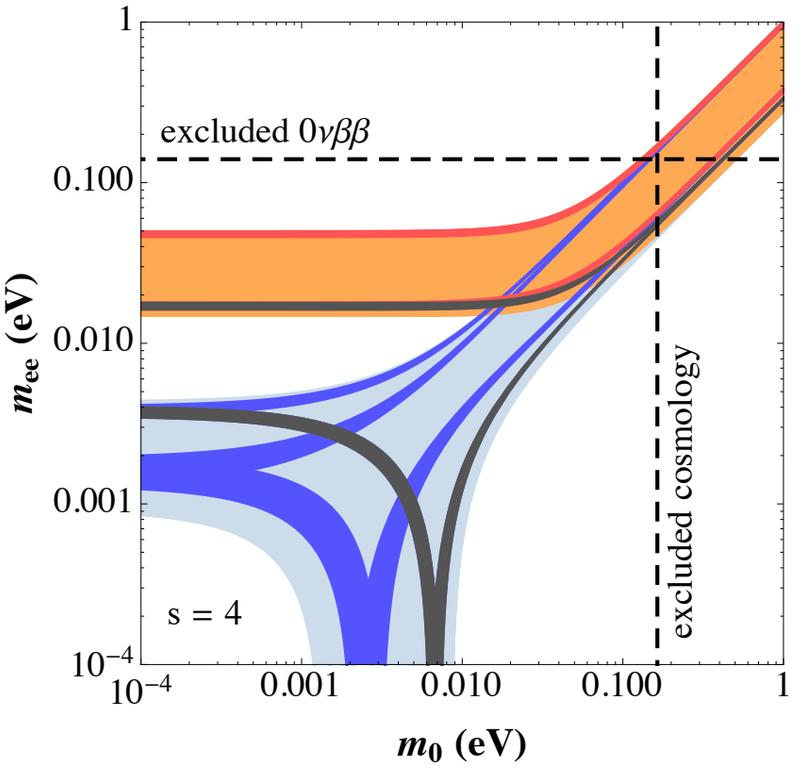
[CH, Molinaro ('16)]

Neutrinoless double beta decay

$$m_{ee} = \left|\cos^2\theta_{12}\,\cos^2\theta_{13}\,m_1 + \sin^2\theta_{12}\,\cos^2\theta_{13}\,e^{i\alpha}\,m_2 + \sin^2\theta_{13}\,e^{i\beta}\,m_3\right|$$





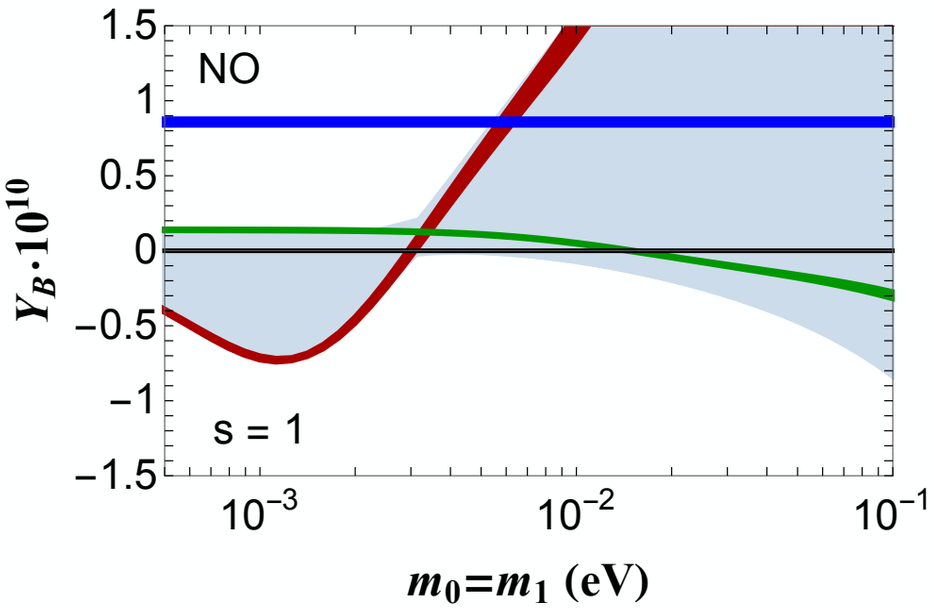


Case 3 b.1), $n = 8$, $m = 4$

Other phenomenology

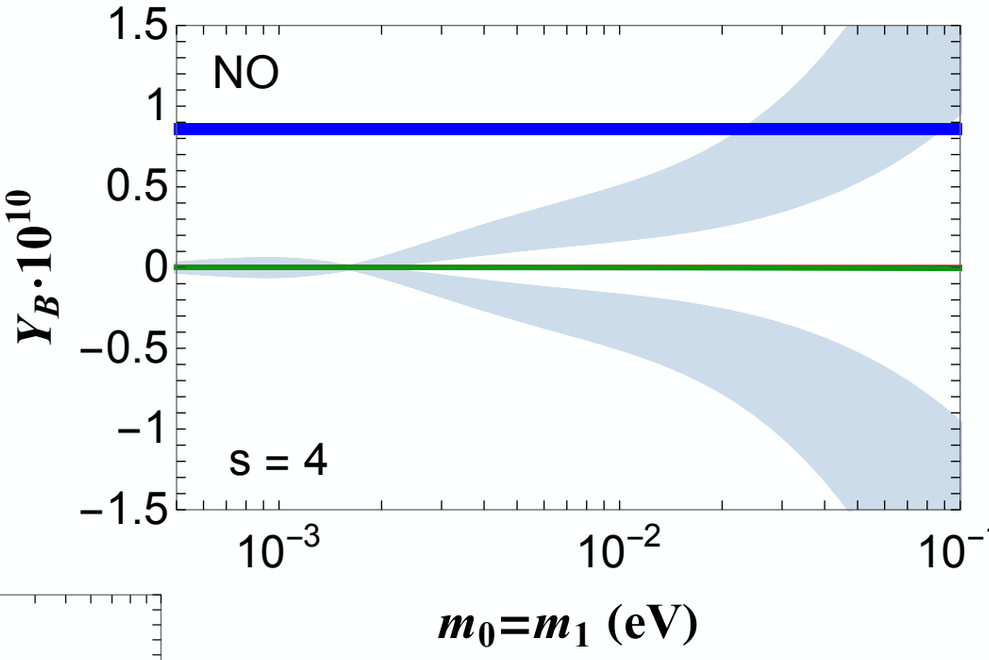
[CH, Molinaro ('16)]

Baryon asymmetry of the Universe

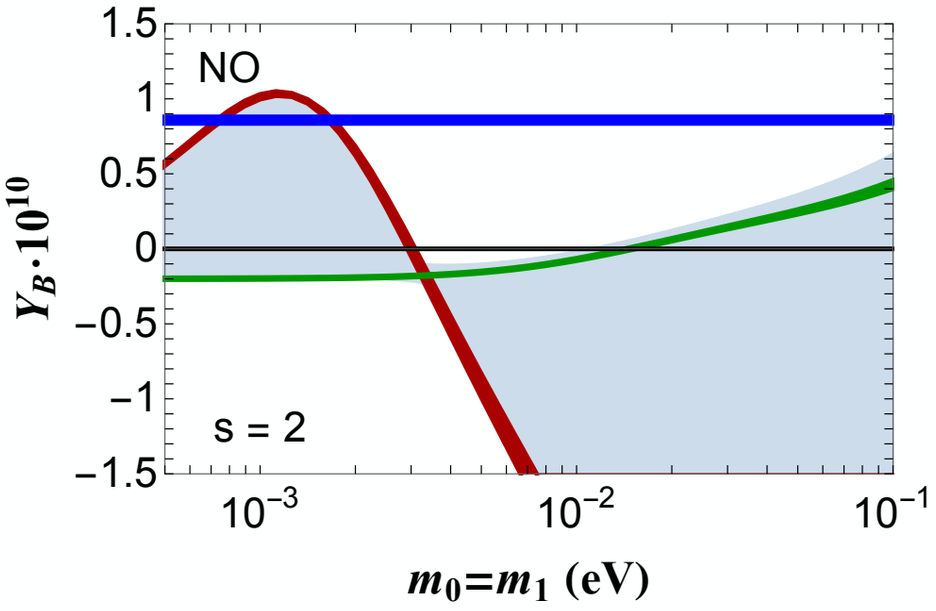


$\sin\alpha < 0$

$\sin\alpha > 0$



only $\sin\delta$ non-zero



Case 3 b.1), $n = 8$, $m = 4$

Summary

- Examples of how **flavour (and CP) symmetries** can constrain different **cLFV processes** — in SMEFT and in inverse seesaw scenario
- In SMEFT G_e among charged leptons leads to **selection rules**, e.g.
  - If the flavour charges of e and μ are different, $\mu \to e$ transitions are forbidden
  - If so, experimental constraints on cLFV tau lepton decays and muonium to antimuonium conversion, $M \to \overline{M}$, are crucial

Summary

- Examples of how **flavour (and CP) symmetries** can constrain different **cLFV processes** — in SMEFT and in inverse seesaw scenario
- In inverse seesaw scenario we can have **different options** corresponding to different way to realise G_ν among neutral states
  - **Option 1** (only μ_S breaks G_f and CP to G_ν)
    - cLFV processes strongly suppressed
  - **Option 2** (only m_D breaks G_f and CP to G_ν)
    - signals of cLFV processes ($\mu - e$ transitions) can be sizeable
  - **Option 3** (only M_{NS} breaks G_f and CP to G_ν)
    - signals of cLFV processes sizeable like for option 2, but cancellation in $\mu - e$ conversion not guaranteed nor universal

Summary

- Examples of how **flavour (and CP) symmetries** can constrain different **cLFV processes** — in SMEFT and in inverse seesaw scenario
- But flavour (and CP) symmetries can also have impact on **other phenomenology**, e.g.
  - predictions for neutrinoless double beta decay
  - correlation of low and high energy CP violation

Outlook

- **Selection rules**
  - also consider lepton number violating operators
  - extend to quark sector
- **Different options of inverse seesaw**
  - consider variants with more or less sterile states
  - study phenomenology of other seesaw types, e.g. linear seesaw
- **Other phenomenology**
  - analyse generation of baryon asymmetry of the Universe through different versions of leptogenesis
  - electric dipole moments of charged leptons

Many thanks for your attention!