FLASY

11TH WORKSHOP

Flavor Symmetries and Consequences in Accelaratores and Cosmology

ROME 2025

Selection rules for cLFV processes from residual flavour groups

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EXCELENCIA SEVERO OCHOA

Overview

- Introduction
- Idea of residual symmetries
- Systematic search
- Allowed cLFV processes
- Experimental constraints and prospects
- Summary and outlook

Based on

Lorenzo Calibbi, CH, Michael A. Schmidt, James Vandeleur (2505.24350 [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)
  - …

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- Additionally, beyond SM (BSM) theories can have a rich phenomenology.
  - Processes forbidden/highly suppressed in SM can be in reach
  - Flavour and CP violation needs to be kept under control
  - Possible correlations among different signals

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  - … and CP violation needs to be kept under control
  - …ssible correlations among different signals

… can be addressed by flavour (and CP) symmetries

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)

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G_e

U_e

Minimal choice Z_3

(3 different masses)

neutrinos

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- Indeed, the minimal choice Z_3 is often encountered (and $G_\nu = Z_2 \times Z_2$)

Typical A_4 and S_4 models leading to tri-bimaximal mixing

see e.g. Altarelli/Feruglio ('05), He/Keum/Volkas ('06), Lam ('08)

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  Also four interesting mixing patterns (Case 1) through Case 3 b.1)) arising from $G_f = \Delta(3\,n^2)$ and $G_f = \Delta(6\,n^2)$ and CP require Z_3 as residual group among charged leptons (and $G_\nu = Z_2 \times CP$)

  see e.g. CH / Meroni / Molinaro ('14), Ding / King / Neder ('14)

Idea of residual symmetries

- Indeed, the minimal choice Z_3 is often encountered (and $G_\nu = Z_2 \times Z_2$)
- This Z_3 symmetry has been coined **lepton triality**
  $e \sim 1$, $\mu \sim \omega$ and $\tau \sim \omega^2$ with ω being the 3rd root of unity, $\omega = e^{\frac{2\pi i}{3}}$
  correspond to Z_3 charge 0 for e, 1 for μ and 2 for τ (modulo 3)
  see e.g. Ma ('10)

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

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

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

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

  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)

Idea of residual symmetries

- Indeed, the minimal choice Z_3 is often encountered (and $G_\nu = Z_2 \times Z_2$)
- However, it is definitely not the only possibility

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)

Systematic search

- Consider **small** $G_e = Z_N$ with $N \leq 8$ (also discussed direct products)

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- Are residuals of some discrete group that fits in $U(3)$, maybe also $SU(3)$
- Take into account **all possible flavour charge assignments** (α, β, γ);

  also those where two flavours have the same charge,

  e.g. $Q(e) = 0$, $Q(\mu) = 0$ and $Q(\tau) = 1$

  $\rightarrow$ consequences

  - Flavour charge assignments that require embedding in $U(3)$
    are encountered, e.g. $Q(e) = 0$, $Q(\mu) = 0$ and $Q(\tau) = 2$ in $G_e = Z_3$
  - Also $G_e = Z_2$ is included in the search

Systematic search

What is not included?

- Breaking effects of residual symmetry G_e
  (shifts in flavon VEVs, cross-talk between different symmetry breaking sectors, etc.)

  $\rightarrow$ consequences

  e.g. in case of lepton triality $\tau \rightarrow \mu\mu\bar{\mu}$ becomes allowed, but its BR should be more suppressed than $\tau \rightarrow \mu\mu\bar{e}$

Systematic search

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

$\rightarrow$ consequences

e.g. in case of lepton triality BR $(\tau \to \mu\mu\bar{e}) \gg$ BR $(\tau \to ee\bar{\mu})$

in SUSY version of well-known A_4 model

see e.g. Muramatsu/Nomura/Shimizu ('16)

but conclusion depends on whether certain flavon components mix or not

see e.g. Pascoli/Zhou ('16)

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- Use SMEFT operators and focus on their **flavour structure**

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

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- 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 $\{\Delta n_e, \Delta n_\mu, \Delta n_\tau\} = \{2, -1, -1\}$ and fulfils the equation

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- 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

Systematic search

- Denote particular flavour charge assignment as $Z_N(\alpha, \beta, \gamma)$
- Labelling can be reduced with the two constraints 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 $N(\delta_1, \delta_2)$

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- $N(\delta_1, \delta_2)$ does not uniquely specify flavour charge assignment, e.g.

$$\left.\begin{array}{l} \mathbb{Z}_3(0,0,1) \\ \mathbb{Z}_3(1,1,2) \\ \mathbb{Z}_3(2,2,0) \end{array}\right\} \to 3(0,1)$$

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- $N(\delta_1, \delta_2)$ does not uniquely specify flavour charge assignment
- At this stage e, μ and τ can be permuted
- We put flavour charge assignments compatible with $SU(3)$ in **boldface**, but $\boldsymbol{N(\delta_1, \delta_2)}$ does not mean all corresponding flavour charge assignments have this property,

  e.g. $\mathbf{4(0,1)}$ corresponds to $\mathbf{Z_4(1,1,2)}$, but also $Z_4(0,0,1)$

  Additional condition: $$3\,\alpha + 2\,\delta_1 + \delta_2 = 0 \mod N$$

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- Several equivalences among the flavour charge assignments: common factors, permutations, complex conjugation

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- Several equivalences among the flavour charge assignments: common factors, permutations, complex conjugation
- For flavour structures: Hermitian conjugation, trivial flavour structures (e.g. $ee^\dagger$), combinations of invariant flavour structures are not included

Systematic search

- Systematic scan over all possible flavour charge assignments $Z_N(\alpha, \beta, \gamma)$

$$0 \leq \alpha \leq \beta \ , \quad 0 \leq \beta \leq \gamma \ , \quad 0 \leq \gamma \leq N-1$$

- Scan over flavour structures $\{\Delta n_e, \Delta n_\mu, \Delta n_\tau\}$

$$0 \leq \Delta n_e \leq N \ , \quad -N \leq \Delta n_\mu \leq N \ , \quad \Delta n_\tau = -\Delta n_e - \Delta n_\mu$$

Systematic search

- 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	$\mu\mu\mu\tau^\dagger\tau^\dagger\tau^\dagger$
		$eee\tau^\dagger\tau^\dagger\tau^\dagger$
		$eee\mu^\dagger\mu^\dagger\mu^\dagger$

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$\mathbf{4}(\mathbf{1},\mathbf{1})$	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	$ee\mu\tau^\dagger\tau^\dagger\tau^\dagger$

Allowed cLFV processes

- Translate flavour structures of SMEFT operators into cLFV processes

  e.g. $$e\mu^\dagger$$

$$\downarrow$$

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

$$\downarrow$$

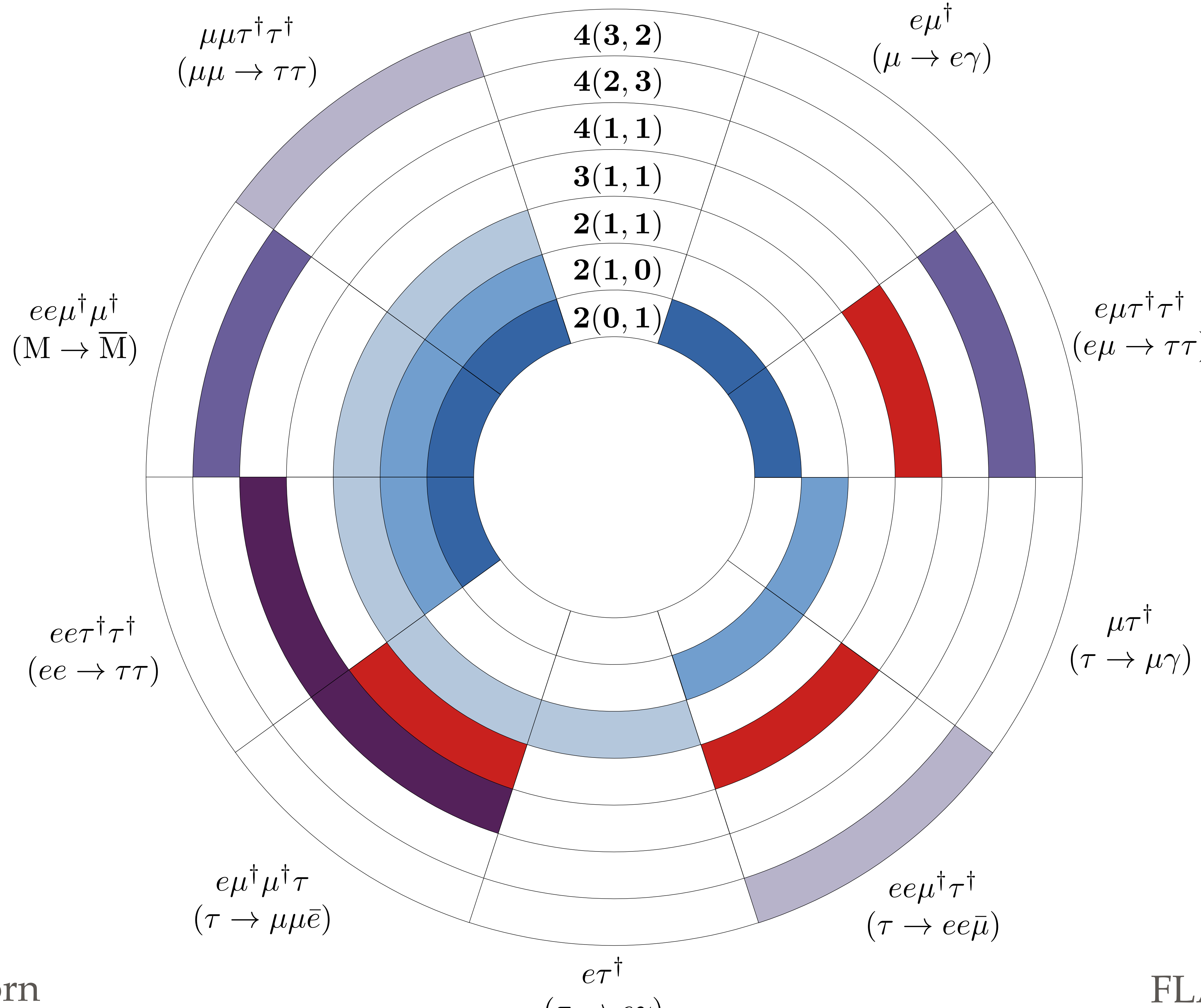
$$\frac{v}{\sqrt{2}\,\Lambda^2}\,(\overline{e}_{L\mu}\,\sigma^{\rho\nu} e_e)\,F_{\rho\nu}$$

$$\downarrow$$

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

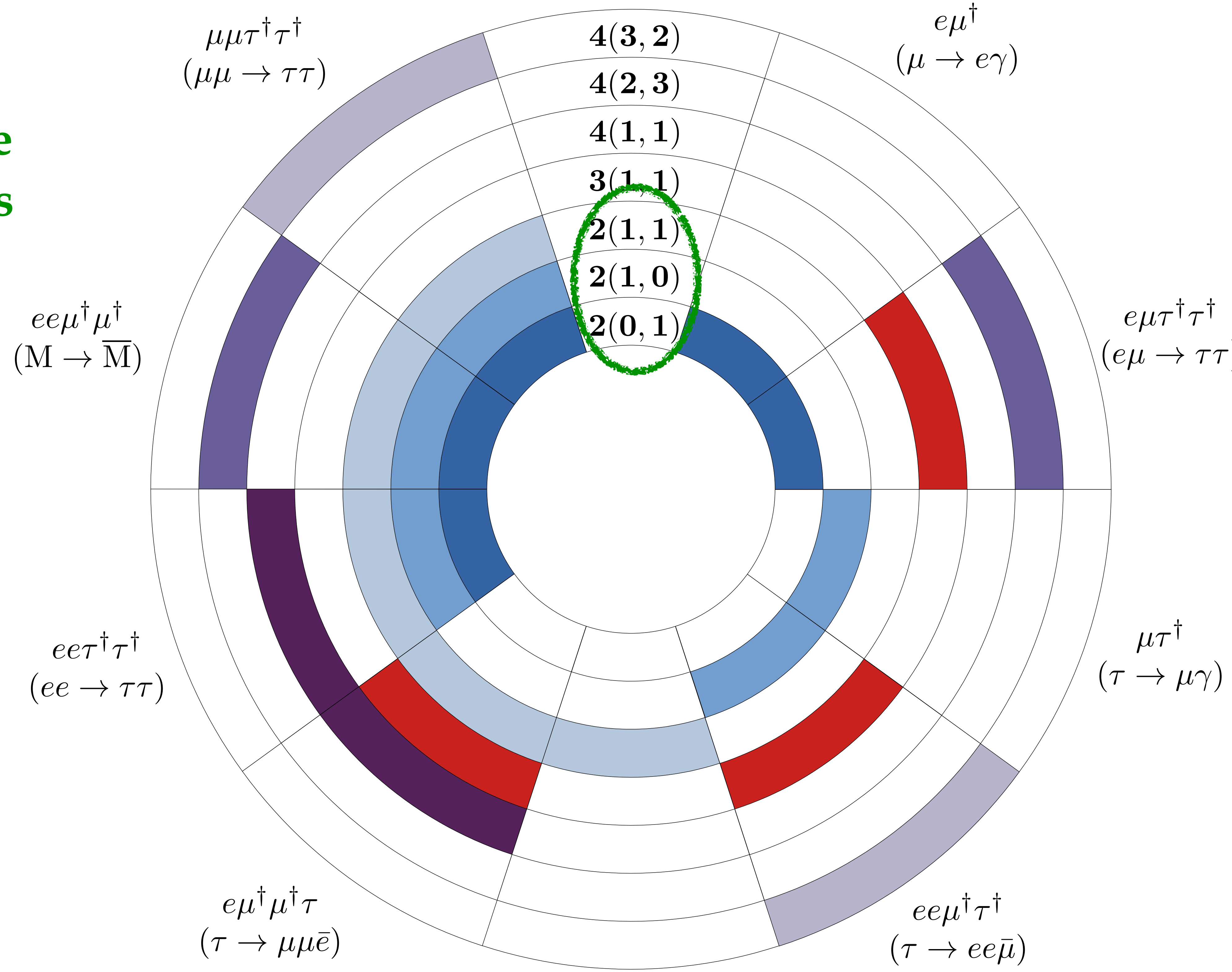
- Consider SMEFT operators up to dimension 6, i.e. $d_\ell \leq 6$

Allowed cLFV processes



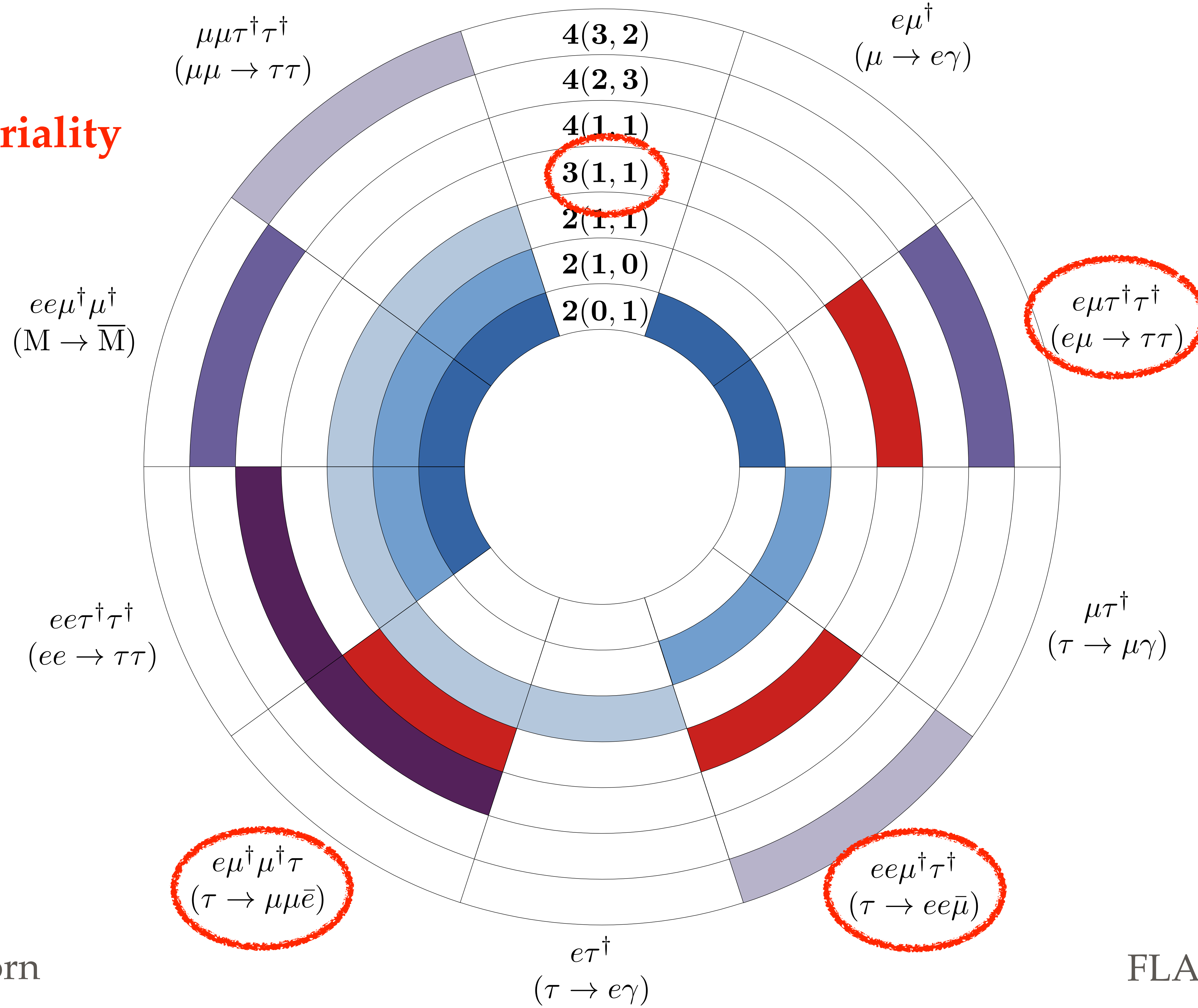
Allowed cLFV processes

up to five processes



Allowed cLFV processes

lepton triality



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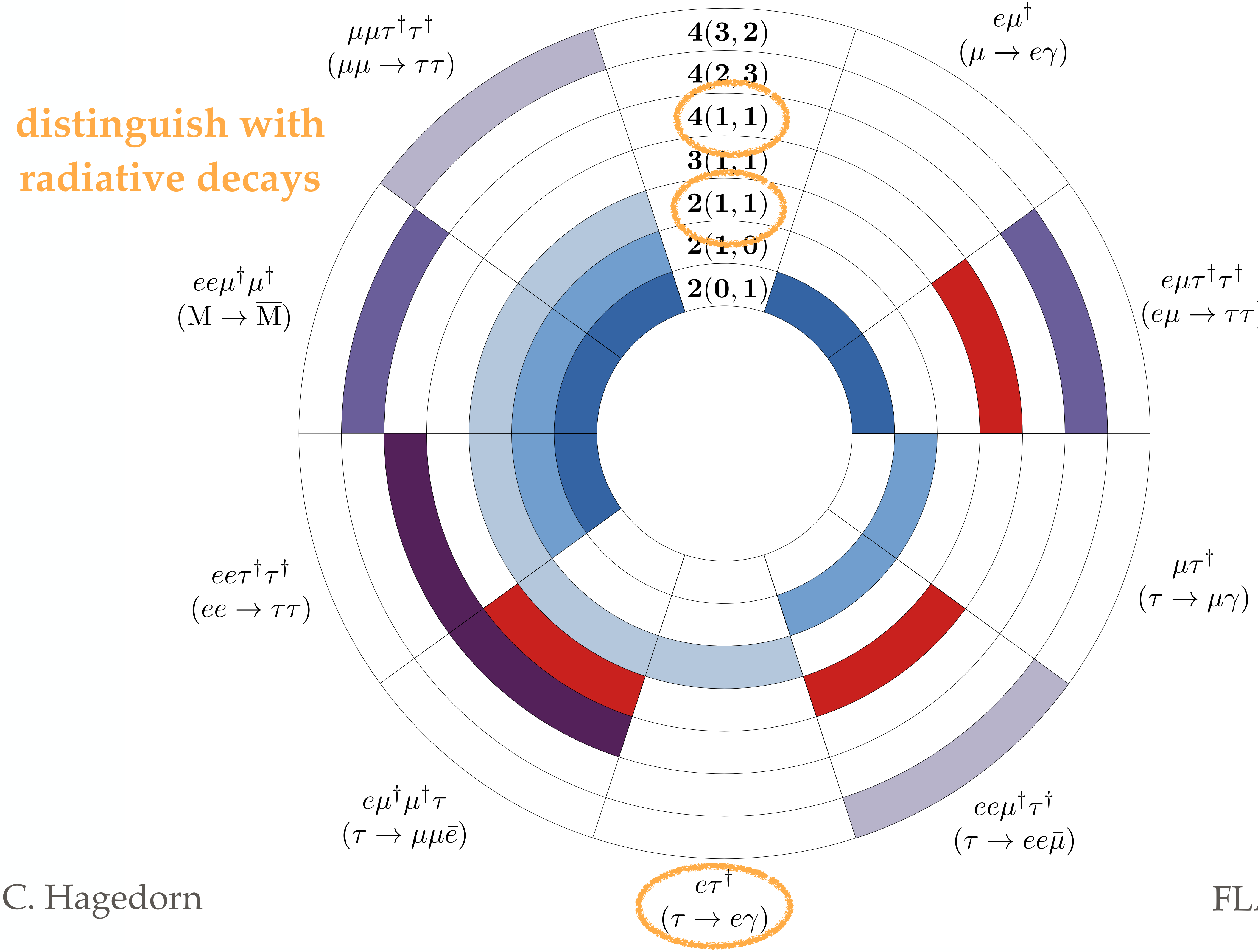
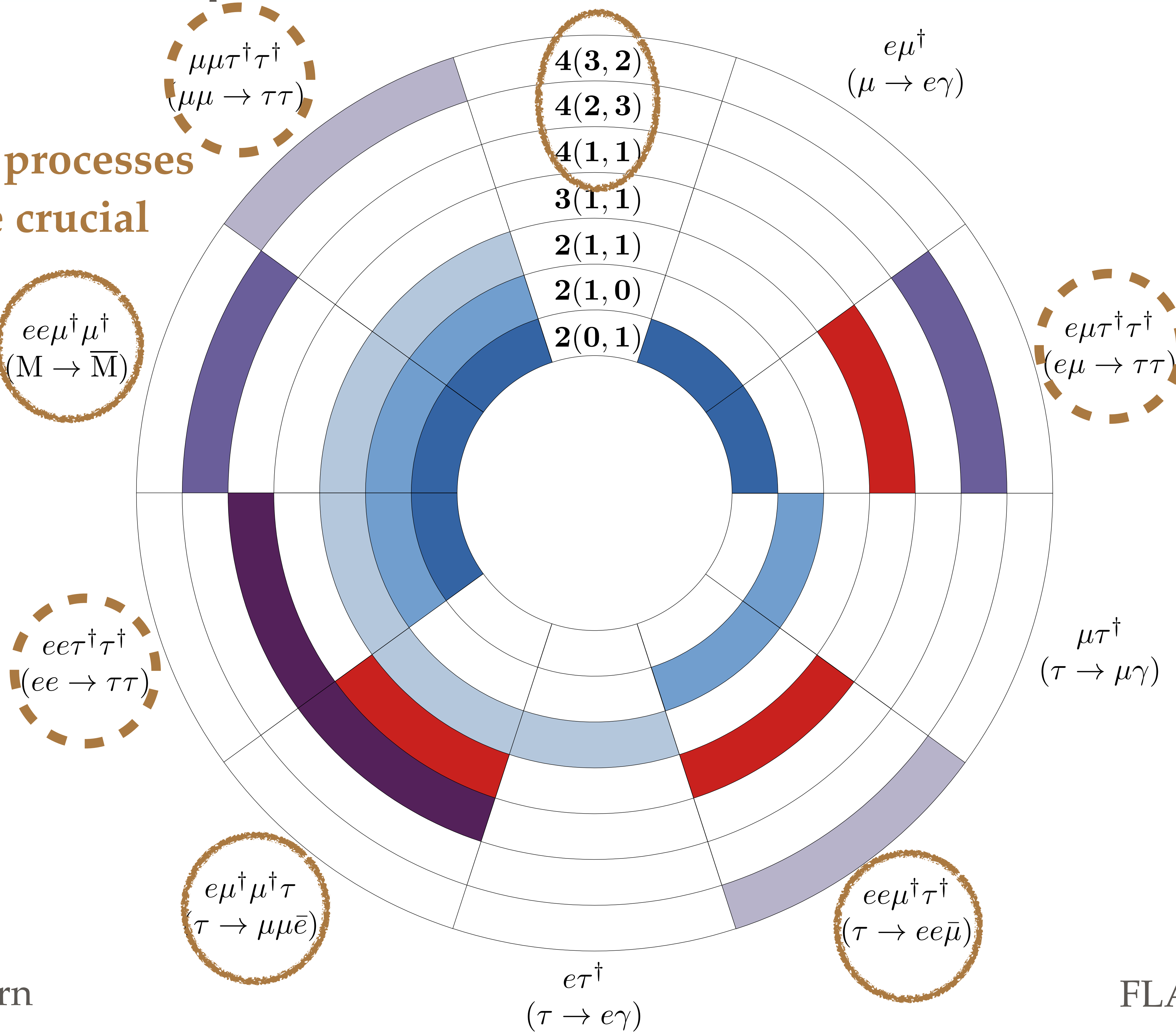


Allowed cLFV processes

"exotic" processes can be crucial



Experimental constraints and prospects

- Confront the results with current and future experimental limits

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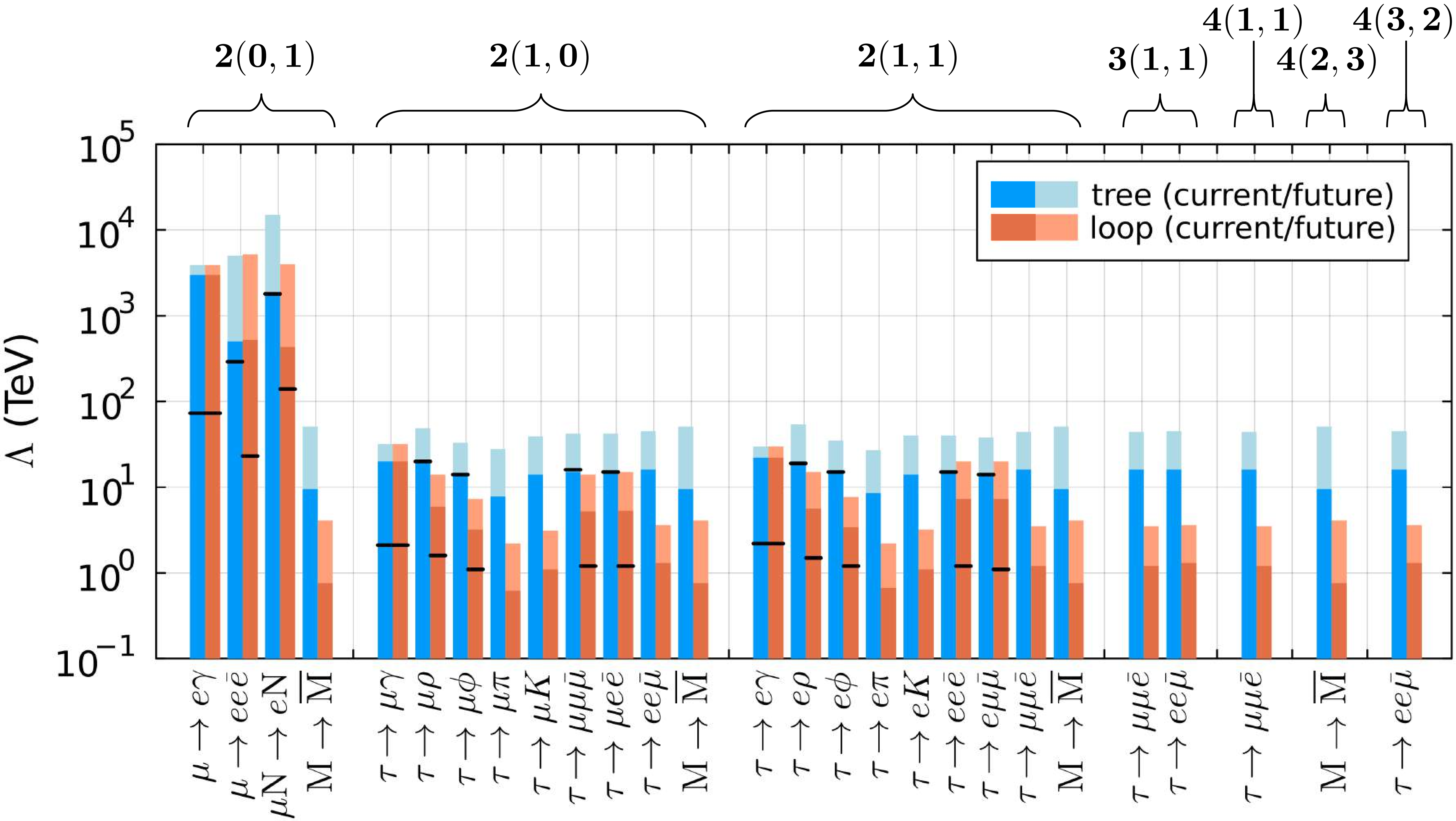
- Confront the results with current and future experimental limits
- Distinguish between low-energy cLFV experiments and possible cLFV searches at high-energy colliders
- Consider up to three scenarios — inspired by typical UV completions
  - Scenario 1: **Tree-level new physics contributions**
    all allowed Wilson coefficients (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 $C_d = \dfrac{\sqrt{2}\, m_\ell\, e}{16\,\pi^2\, v}$

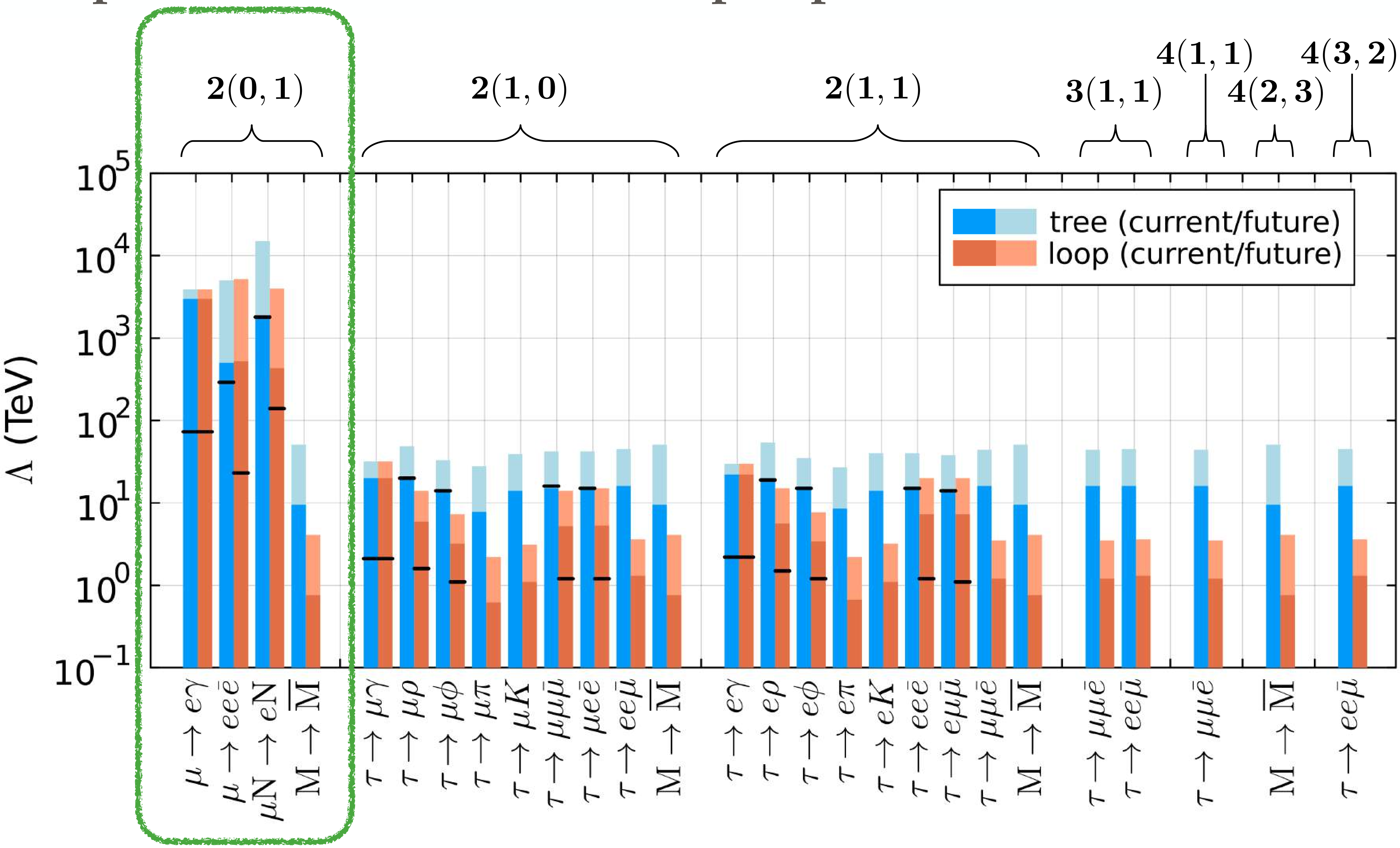
(formulae, see e.g. Calibbi/Marcano/Roy ('21))

Experimental constraints and prospects



No RG running. No matching of SMEFT to LEFT.

Experimental constraints and prospects



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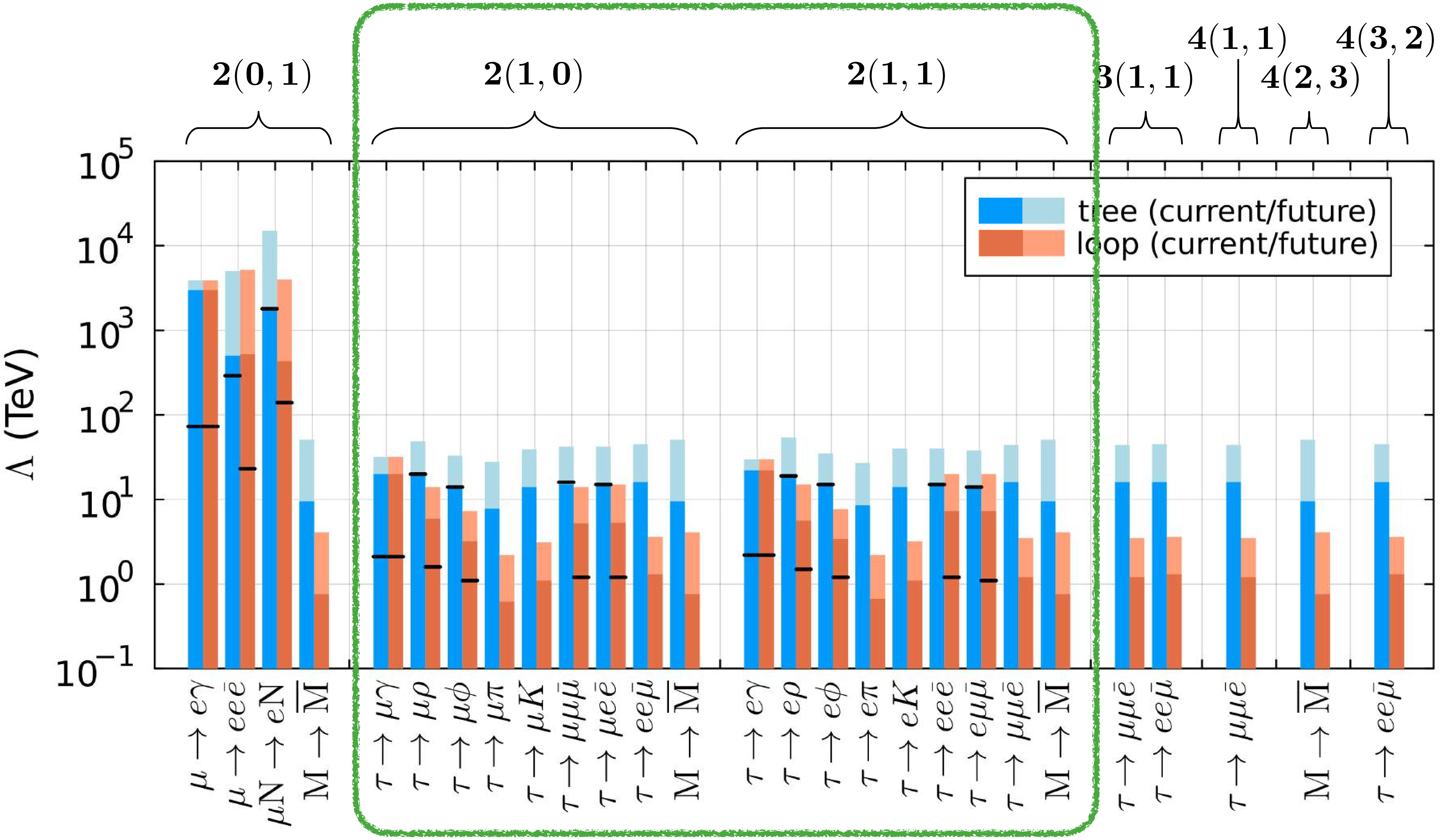

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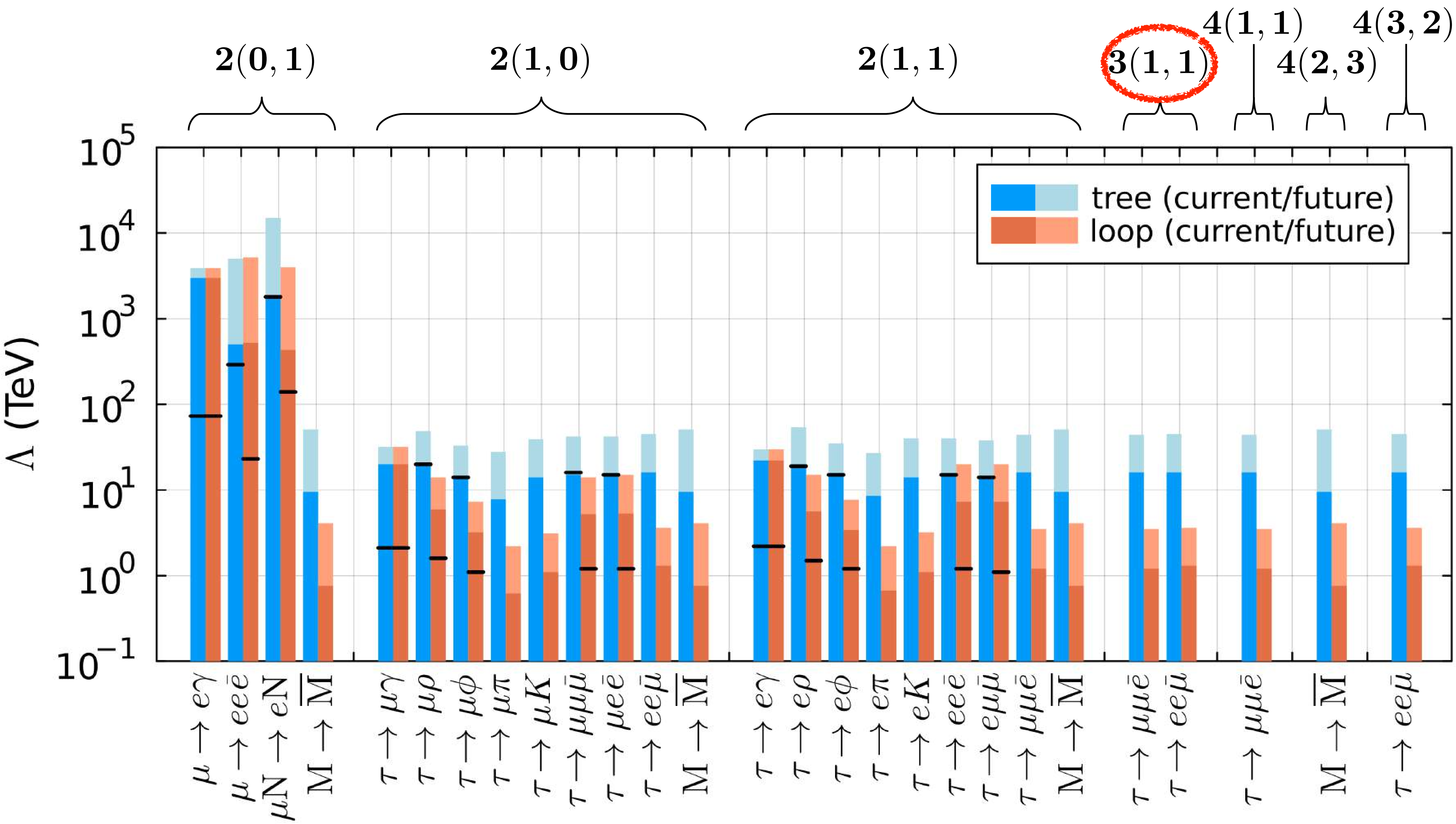
Experimental constraints and prospects

lepton triality



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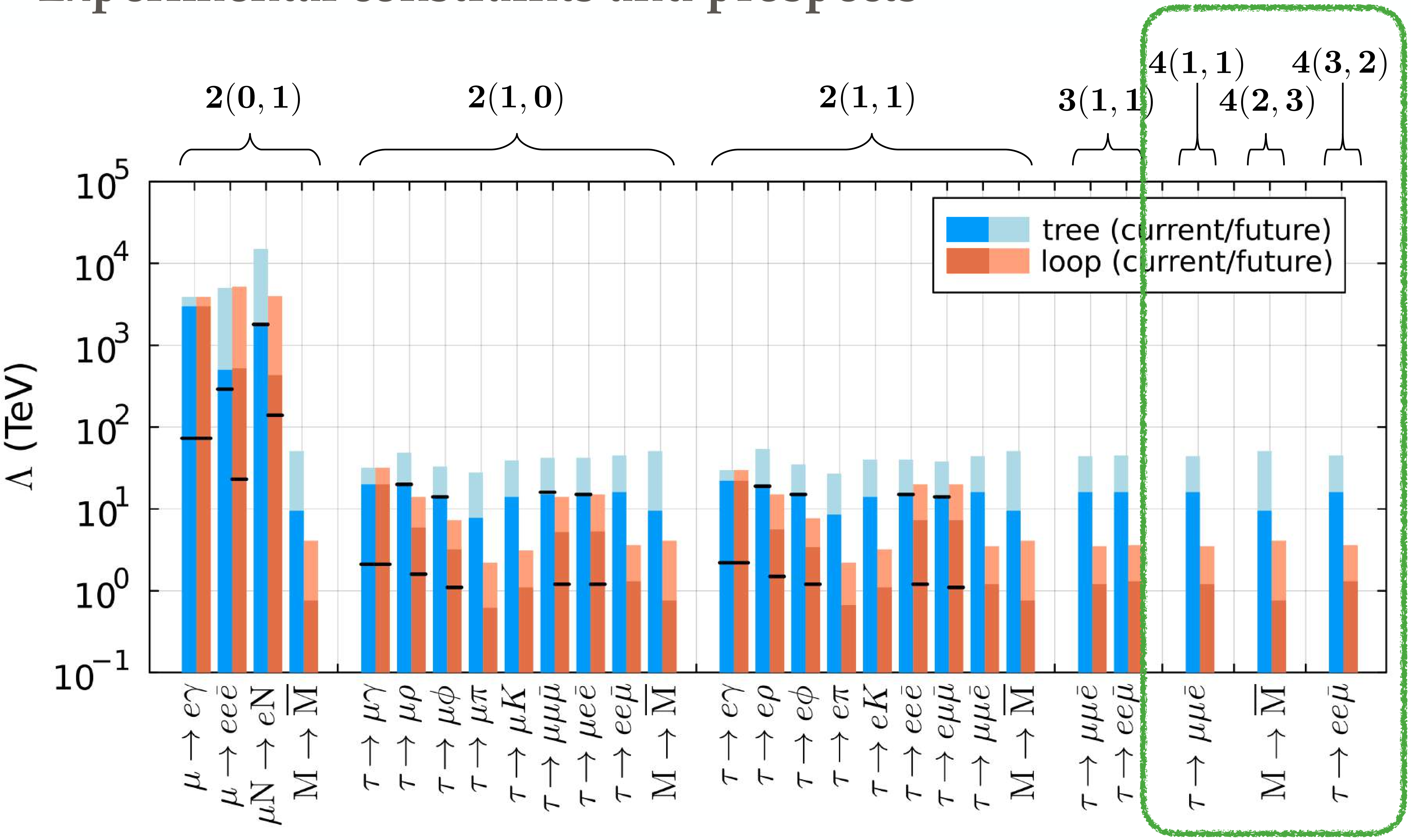

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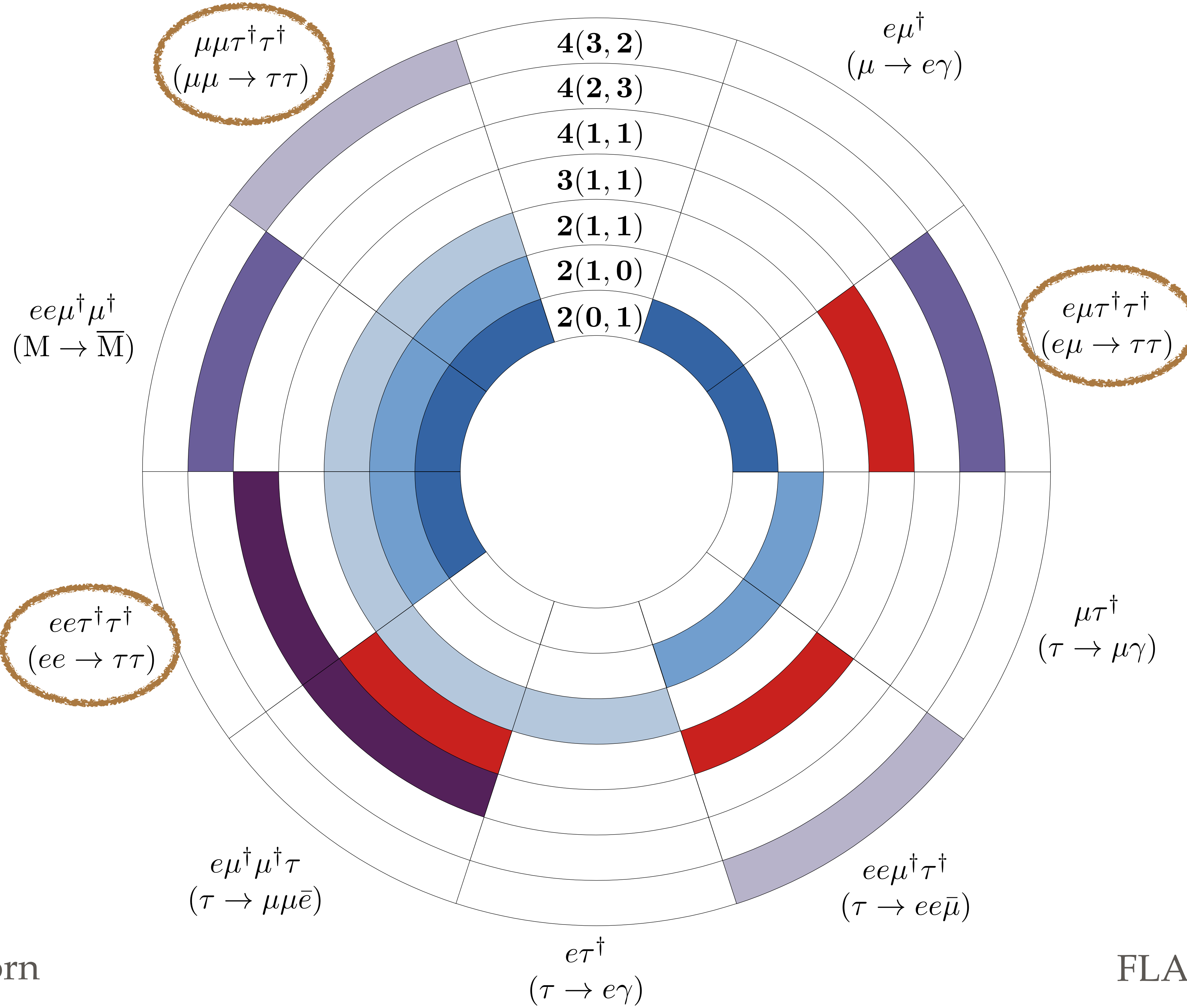
Allowed cLFV processes



Experimental constraints and prospects

- Comment on possible cLFV searches at high-energy colliders
- Test SMEFT operators with same sign tau leptons via scattering

$$e^\pm e^\pm \to \tau^\pm \tau^\pm \,, \quad e^\pm \mu^\pm \to \tau^\pm \tau^\pm \,, \quad \mu^\pm \mu^\pm \to \tau^\pm \tau^\pm$$

- With proposed experiment μTRISTAN testable Hamada et al. ('22)

$$\sigma(\mu^+\mu^+ \to \tau^+\tau^+) = \frac{s}{2\pi}\frac{|C_x|^2}{\Lambda^4} \simeq 25\,\mathrm{fb}\left(\frac{\sqrt{s}}{2\,\mathrm{TeV}}\right)^2\left(\frac{10\,\mathrm{TeV}}{\Lambda/\sqrt{|C_x|}}\right)^4$$

For $\sqrt{s} = 2\,\mathrm{TeV}$ and $C_x = 1$ limit on new physics scale is

$$\Lambda \approx 30\,\mathrm{TeV}$$

see e.g. Fridell/Kitano/Takai ('23)

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- Other possible probe four-body Z boson decays, e.g. $Z \to \tau\tau\bar{e}\bar{e}$, but constraints on Λ are (very) weak

see e.g. Heeck/Sokhashvili ('24)

Summary

- Derived **selection rules for cLFV processes** arising from residual symmetry $G_e = Z_N$ with $N \leq 8$
- **Focussing on SMEFT operators with dimension six or less** all possible flavour charge assignments turn out to be equivalent to one for $G_e = Z_N$ with $N \leq 4$
- 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, see $G_e = Z_3$ and $G_e = Z_4$

Outlook

- Consider **concrete models** with studied residual group G_e
- Analyse SMEFT operators with **lepton number violation**
- Apply **same logic to quark sector** and discuss quark flavour violation
  - Use G_e also for quarks, potentially with same flavour charge assignment
  - Or assume different residual symmetries for up and down quarks — that in general also differ from G_e

Many thanks for your attention!

… one last point

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S. Simón-Díaz, A. Bonanos, S. Ekström, M. Urbaneja, A. Barnes

Thermodynamics and Kinetics of Chemical Reaction Networks: From Cell Metabolism to Design Principles for Synthetic Life **7 - 18 September**
D. Busiello, D. Lacoste, T. Kobayashi, P. Schwille, U. Gerland

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Flavour charges	d_ℓ	Flavour structures
$6(0,1)$	3	$e\mu^\dagger$
	18	$\mu^6(\tau^\dagger)^6$
		$e\mu^5(\tau^\dagger)^6$
		$e^2\mu^4(\tau^\dagger)^6$
		$e^3\mu^3(\tau^\dagger)^6$
		$e^4\mu^2(\tau^\dagger)^6$
		$e^5\mu(\tau^\dagger)^6$
		$e^6(\tau^\dagger)^6$
$\mathbf{6}(\mathbf{1},\mathbf{1})$	6	$e(\mu^\dagger)^2\tau$
	9	$e^3(\tau^\dagger)^3$
	12	$e^2\mu^2(\tau^\dagger)^4$
		$e^4(\mu^\dagger)^2(\tau^\dagger)^2$
	15	$e\mu^4(\tau^\dagger)^5$
		$e^5(\mu^\dagger)^4\tau^\dagger$
	18	$\mu^6(\tau^\dagger)^6$

Flavour charges	d_ℓ	Flavour structures
$\mathbf{7}(\mathbf{1},\mathbf{2})$	9	$e\mu^2(\tau^\dagger)^3$
		$e^2(\mu^\dagger)^3\tau$
		$e^3\mu^\dagger(\tau^\dagger)^2$
	15	$e(\mu^\dagger)^5\tau^4$
		$e^4\mu(\tau^\dagger)^5$
		$e^5(\mu^\dagger)^4\tau^\dagger$
	21	$\mu^7(\tau^\dagger)^7$
		$e^7(\tau^\dagger)^7$
		$e^7(\mu^\dagger)^7$
$\mathbf{8}(\mathbf{0},\mathbf{1})$	3	$e\mu^\dagger$
	24	$\mu^8(\tau^\dagger)^8$
		$e\mu^7(\tau^\dagger)^8$
		$e^2\mu^6(\tau^\dagger)^8$
		$e^3\mu^5(\tau^\dagger)^8$
		$e^4\mu^4(\tau^\dagger)^8$
		$e^5\mu^3(\tau^\dagger)^8$
		$e^6\mu^2(\tau^\dagger)^8$

Allowed cLFV processes

Restrictions from single flavour structure		
$e\mu^\dagger$ - $N(0,a)$	$ee\mu^\dagger\mu^\dagger$ - $2N(N,a)$	$ee\mu^\dagger\tau^\dagger$ - $N(N-a,2a)$
$\mu\tau^\dagger$ - $N(a,0)$	$\mu\mu\tau^\dagger\tau^\dagger$ - $2N(a,N)$	$e\mu^\dagger\mu^\dagger\tau$ - $N(a,a)$
$e\tau^\dagger$ - $N(a,N-a)$	$ee\tau^\dagger\tau^\dagger$ - $2N(a,N-a)$	$e\mu\tau^\dagger\tau^\dagger$ - $N(2a,N-a)$

a is an integer

Allowed cLFV processes

Restrictions from single flavour structure		
$e\mu^\dagger$ - $N(0,a)$	$ee\mu^\dagger\mu^\dagger$ - $2N(N,a)$	$ee\mu^\dagger\tau^\dagger$ - $N(N-a,2a)$
$\mu\tau^\dagger$ - $N(a,0)$	$\mu\mu\tau^\dagger\tau^\dagger$ - $2N(a,N)$	$e\mu^\dagger\mu^\dagger\tau$ - $N(a,a)$
$e\tau^\dagger$ - $N(a,N-a)$	$ee\tau^\dagger\tau^\dagger$ - $2N(a,N-a)$	$e\mu\tau^\dagger\tau^\dagger$ - $N(2a,N-a)$

a is an integer

Experimental constraints and prospects

$N(\delta_1, \delta_2)$		Observable	Current (Λ in TeV)			Future (Λ in TeV)		
			Constraint	$\Lambda_{\rm T}$ ($\Lambda_{{\rm T}\chi}$)	$\Lambda_{\rm L}$ ($\Lambda_{{\rm L}\chi}$)	Constraint	$\Lambda_{\rm T}$	$\Lambda_{\rm L}$
$\mathbf{2}(\mathbf{0},\mathbf{1})$	$e\mu^\dagger$	$\mathrm{BR}(\mu \to e\gamma)$	1.5×10^{-13} [53]	3000 (73)	3000 (73)	6×10^{-14} [54]	3900	3900
		$\mathrm{BR}(\mu \to ee\bar{e})$	1.0×10^{-12} [55]	500 (290)	520 (23)	10^{-16} [56]	5000	5200
		$\mathrm{CR}(\mu\,\mathrm{Au} \to e\,\mathrm{Au})$	7×10^{-13} [57]	1800 (1800)	430 (140)	–	–	–
		$\mathrm{CR}(\mu\,\mathrm{Al} \to e\,\mathrm{Al})$	–	–	–	6×10^{-17} [58, 59]	15000	4000
	$ee\mu^\dagger\mu^\dagger$	$\mathrm{P}(\mathrm{M} \to \overline{\mathrm{M}})$	8.2×10^{-11} [61]	9.5	0.76	10^{-13} [62]	51	4.1
$\mathbf{2}(\mathbf{1},\mathbf{0})$	$\mu\tau^\dagger$	$\mathrm{BR}(\tau \to \mu\gamma)$	4.2×10^{-8} [65]	20 (2.1)	20 (2.1)	6.9×10^{-9} [72]	32	32
		$\mathrm{BR}(\tau \to \mu\rho)$	1.7×10^{-8} [66]	21 (20)	5.9 (1.6)	5.5×10^{-10} [72]	49	14
		$\mathrm{BR}(\tau \to \mu\phi)$	2.3×10^{-8} [66]	14 (14)	3.2 (1.1)	8.4×10^{-10} [72]	33	7.3
		$\mathrm{BR}(\tau \to \mu\pi)$	1.1×10^{-7} [63]	7.8	0.62	7.1×10^{-10} [72]	28	2.2
		$\mathrm{BR}(\tau \to \mu K)$	2.3×10^{-8} [68]	14	1.1	4.0×10^{-10} [72]	39	3.1
		$\mathrm{BR}(\tau \to \mu\mu\bar{\mu})$	1.9×10^{-8} [70]	16 (16)	5.3 (1.3)	3.6×10^{-10} [72]	42	14
		$\mathrm{BR}(\tau \to \mu e\bar{e})$	1.8×10^{-8} [69]	15 (15)	5.3 (1.2)	2.9×10^{-10} [72]	42	15
	$ee\mu^\dagger\mu^\dagger$	$\mathrm{P}(\mathrm{M} \to \overline{\mathrm{M}})$	8.2×10^{-11} [61]	9.5	0.76	10^{-13} [62]	51	4.1
	$ee\mu^\dagger\tau^\dagger$	$\mathrm{BR}(\tau \to ee\bar{\mu})$	1.5×10^{-8} [69]	16	1.3	2.3×10^{-10} [72]	45	3.6

Experimental constraints and prospects

$\mathbf{2}(\mathbf{1},\mathbf{1})$	$e\tau^\dagger$	$\mathrm{BR}(\tau\to e\gamma)$	3.3×10^{-8} [67]	22 (2.2)	22 (2.2)	9.0×10^{-9} [72]	30	30
		$\mathrm{BR}(\tau\to e\rho)$	2.2×10^{-8} [66]	20 (19)	5.6 (1.5)	3.8×10^{-10} [72]	54	15
		$\mathrm{BR}(\tau\to e\phi)$	2.0×10^{-8} [66]	15 (15)	3.4 (1.2)	7.4×10^{-10} [72]	35	7.7
		$\mathrm{BR}(\tau\to e\pi)$	8.0×10^{-8} [64]	8.5	0.67	7.3×10^{-10} [72]	27	2.2
		$\mathrm{BR}(\tau\to eK)$	2.6×10^{-8} [68]	14	1.1	4.0×10^{-10} [72]	40	3.2
		$\mathrm{BR}(\tau\to ee\bar{e})$	2.7×10^{-8} [69]	15 (15)	7.3 (1.2)	4.7×10^{-10} [72]	40	20
		$\mathrm{BR}(\tau\to e\mu\bar{\mu})$	2.7×10^{-8} [69]	14 (14)	7.3 (1.1)	4.5×10^{-10} [72]	38	20
	$ee\mu^\dagger\mu^\dagger$	$\mathrm{P}(\mathrm{M}\to\overline{\mathrm{M}})$	8.2×10^{-11} [61]	9.5	0.76	10^{-13} [62]	51	4.1
	$e\mu^\dagger\mu^\dagger\tau$	$\mathrm{BR}(\tau\to\mu\mu\bar{e})$	1.7×10^{-8} [69]	16	1.2	2.6×10^{-10} [72]	44	3.5
$\mathbf{3}(\mathbf{1},\mathbf{1})$	$e\mu^\dagger\mu^\dagger\tau$	$\mathrm{BR}(\tau\to\mu\mu\bar{e})$	1.7×10^{-8} [69]	16	1.2	2.6×10^{-10} [72]	44	3.5
	$ee\mu^\dagger\tau^\dagger$	$\mathrm{BR}(\tau\to ee\bar{\mu})$	1.5×10^{-8} [69]	16	1.3	2.3×10^{-10} [72]	45	3.6
$\mathbf{4}(\mathbf{1},\mathbf{1})$	$e\mu^\dagger\mu^\dagger\tau$	$\mathrm{BR}(\tau\to\mu\mu\bar{e})$	1.7×10^{-8} [69]	16	1.2	2.6×10^{-10} [72]	44	3.5
$\mathbf{4}(\mathbf{2},\mathbf{3})$	$ee\mu^\dagger\mu^\dagger$	$\mathrm{P}(\mathrm{M}\to\overline{\mathrm{M}})$	8.2×10^{-11} [61]	9.5	0.76	10^{-13} [62]	51	4.1
$\mathbf{4}(\mathbf{3},\mathbf{2})$	$ee\mu^\dagger\tau^\dagger$	$\mathrm{BR}(\tau\to ee\bar{\mu})$	1.5×10^{-8} [69]	16	1.3	2.3×10^{-10} [72]	45	3.6

Experimental constraints and prospects

$N(\delta_1, \delta_2)$		Observable	Current (Λ in TeV)		Future (Λ in TeV)	
			Constraint	Λ_{T}	Constraint	Λ_{T}
$\mathbf{2(a,b)}^{\ddagger}$, $\mathbf{4(3,2)}$	$\mu\mu\tau^\dagger\tau^\dagger$	$\sigma(\mu^+\mu^+ \to \tau^+\tau^+)$	–	–	0.3 fb [83]	30
		$\mathrm{BR}(Z \to \tau\tau\bar{\mu}\bar{\mu})$	2×10^{-3} [31]	0.001	10^{-12} [31]	0.25
$\mathbf{2(a,b)}^{\ddagger}$, $\mathbf{4(1,1)}$	$ee\tau^\dagger\tau^\dagger$	$\mathrm{BR}(Z \to \tau\tau\bar{e}\bar{e})$	2×10^{-3} [31]	0.001	10^{-12} [31]	0.25
$\mathbf{2(0,1)}$, $\mathbf{3(1,1)}$, $\mathbf{4(2,3)}$	$e\mu\tau^\dagger\tau^\dagger$	$\mathrm{BR}(Z \to \tau\tau\bar{e}\bar{\mu})$	2×10^{-3} [31]	0.001	10^{-12} [31]	0.21

‡ $\mathbf{2(a,b)}$ stands for $\mathbf{2(0,1)}$, $\mathbf{2(1,0)}$ and $\mathbf{2(1,1)}$.