WIFAI 2025: Workshop Italiano sulla Fisica ad Alta Intensità

Predictions for cLFV processes from symmetries

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WIFAI 2025, Bari, Italy, 11.-14.11.2025

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EXCELENCIA SEVERO OCHOA

Overview

- Introduction
- Idea of residual symmetries
- Systematic search
- Allowed cLFV processes
- Experimental constraints and prospects
- Beyond this study
- 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)
  - …
- In the SM, charged lepton flavour violation (cLFV) is absent, e.g.

$\mu \to e\gamma$ ✖

$\mu - e$ conversion ✖

$\tau \to 3\,\mu$ ✖

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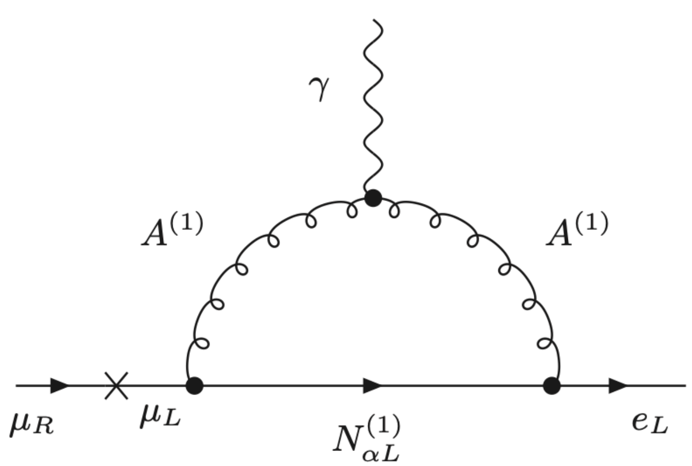
- In the SM, charged lepton flavour violation (cLFV) is absent.
- Additionally, in beyond SM (BSM) theories cLFV processes are often induced at a sizeable rate,
  e.g.



Control them well!

Correlations among them?

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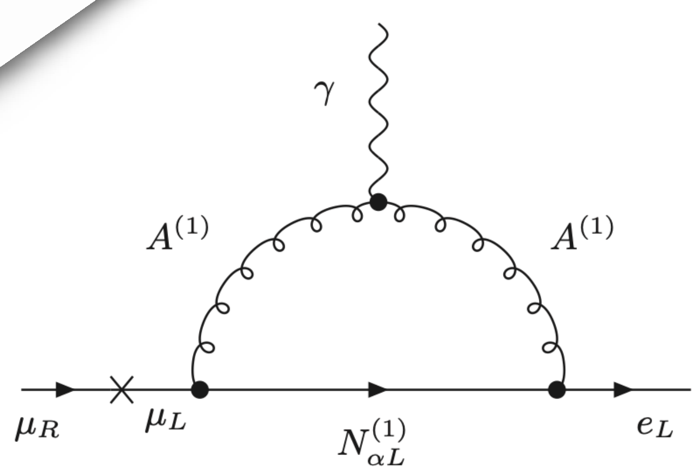
… can be addressed by flavour (and CP) symmetries



Control them well!

Correlations among them?

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

$$
\begin{tikzcd}
 & G_f \text{ and CP} \arrow[dl] \arrow[dr] & \\
\begin{array}{c}\text{charged leptons}\\ G_e \\ U_e\end{array} \arrow[dr] & & \begin{array}{c}\text{neutrinos}\\ G_\nu = Z_2 \times \text{CP} \\ U_\nu = \Omega_\nu R(\theta) K_\nu\end{array} \arrow[dl] \\
 & U_{PMNS} = U_e^\dagger \Omega_\nu R(\theta) K_\nu &
\end{tikzcd}
$$

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

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G_f and CP

$\swarrow \qquad \searrow$

charged leptons		neutrinos
G_e		$G_\nu = Z_2 \times$ CP
U_e		$U_\nu = \Omega_\nu R(\theta) K_\nu$

$\searrow \qquad \swarrow$

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

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

Idea of residual symmetries

- $G_e = Z_3$ is often encountered (and $G_\nu = Z_2 \times Z_2$)

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

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

$$\omega = \exp\left(\frac{2\pi i}{3}\right)$$ 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)

Idea of residual symmetries

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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)

Idea of residual symmetries

- 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)

Idea of residual symmetries

- $G_e = Z_3$ 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)

Systematic search

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

Systematic search

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- Are residuals of some discrete group that fits in $U(3)$, maybe also $SU(3)$ (affects the possibilities for Q_{Z_N} of e, μ and τ)

Systematic search

- Consider **small $G_e = Z_N$ with $N \leq 8$** (also discussed direct products)
- 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. $Q_{Z_N}(e^-) = 0$, $Q_{Z_N}(\mu^-) = 0$ and $Q_{Z_N}(\tau^-) = 1$

Systematic search

- Interested in studying **cLFV processes**, **lepton number is conserved**

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

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

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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 $N(\delta_1, \delta_2)$

- $N(\delta_1, \delta_2)$ does not uniquely specify **flavour charge assignment**
- At this stage e, μ and τ can be permuted

Systematic search

- 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
$\mathbf{2(0,1)}$	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	$\mu\mu\mu\tau^\dagger\tau^\dagger\tau^\dagger$
		$e\mu\mu\tau^\dagger\tau^\dagger\tau^\dagger$
		$ee\mu\tau^\dagger\tau^\dagger\tau^\dagger$
		$eee\tau^\dagger\tau^\dagger\tau^\dagger$
$\mathbf{3(1,1)}$	6	$e\mu\tau^\dagger\tau^\dagger$
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		$eee\tau^\dagger\tau^\dagger\tau^\dagger$
		$eee\mu^\dagger\mu^\dagger\mu^\dagger$

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

$$e\mu^\dagger$$

$$\downarrow$$

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

$$\downarrow$$

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

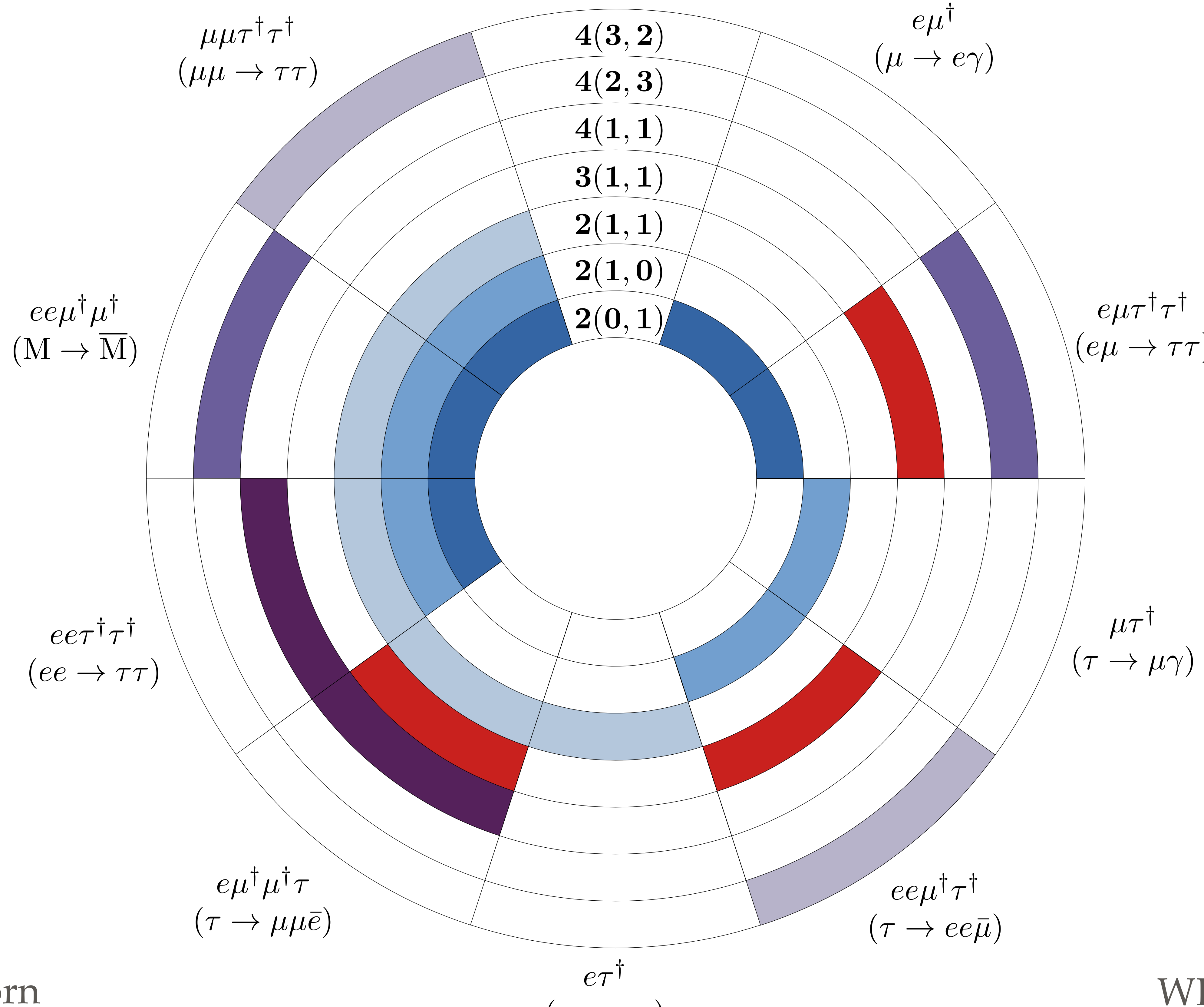
$$\downarrow$$

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

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

Allowed cLFV processes

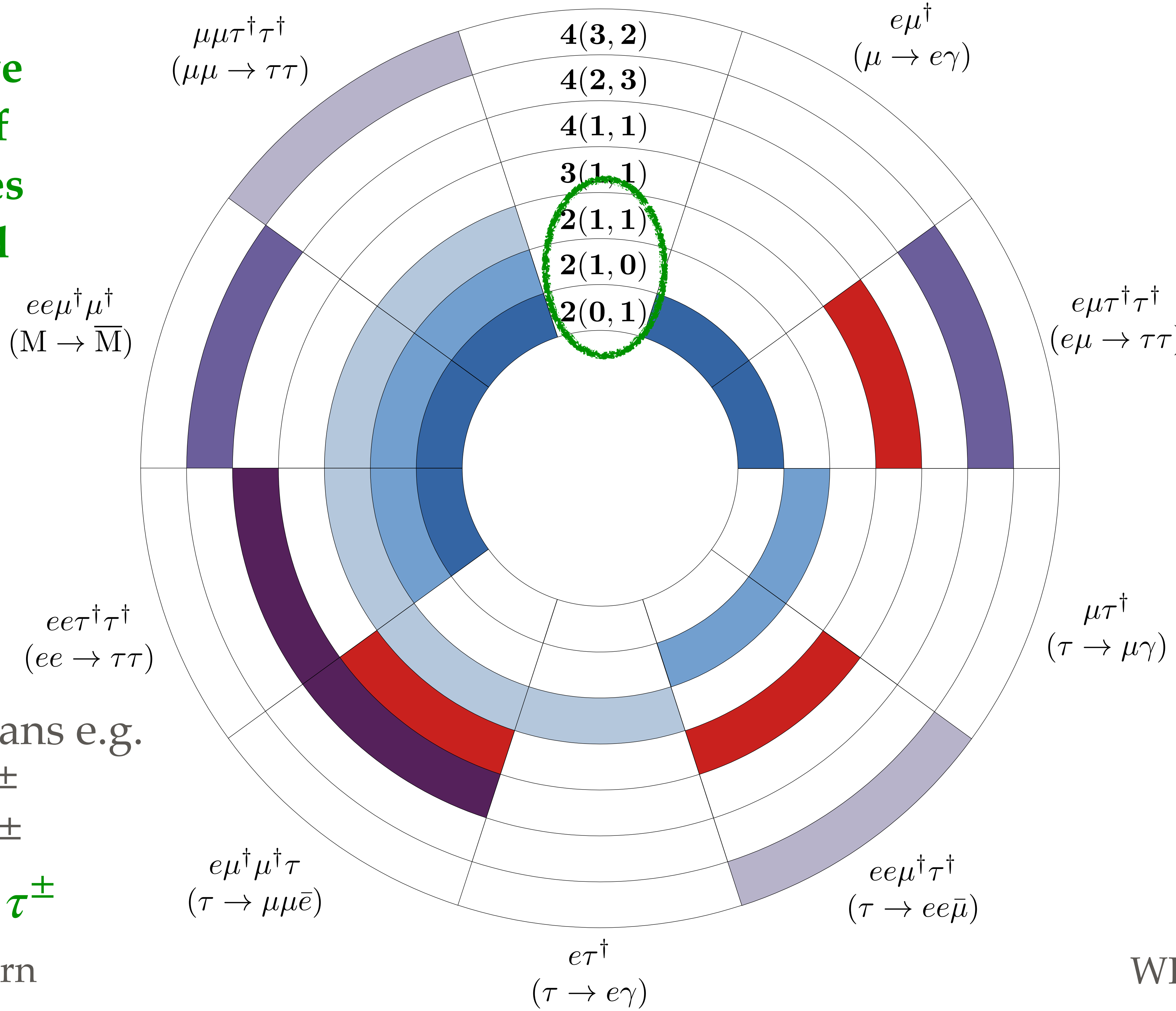
Coloured segments indicate allowed flavour structures



Allowed cLFV processes

Coloured segments indicate allowed flavour structures

up to five types of processes allowed



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

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

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

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

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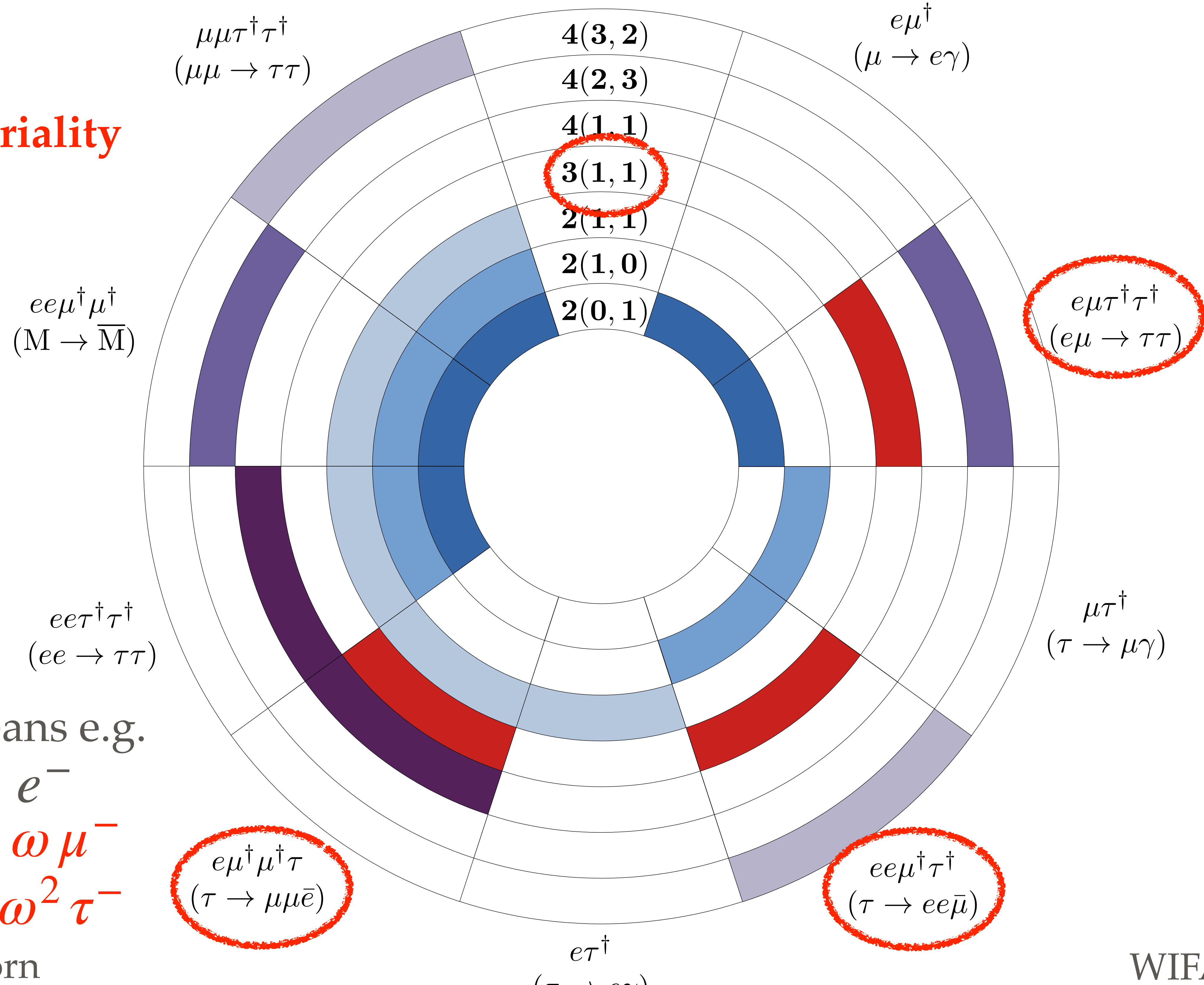
Allowed cLFV processes

Coloured segments indicate allowed flavour structures

lepton triality



$\mathbf{3(1,1)}$ means e.g.

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

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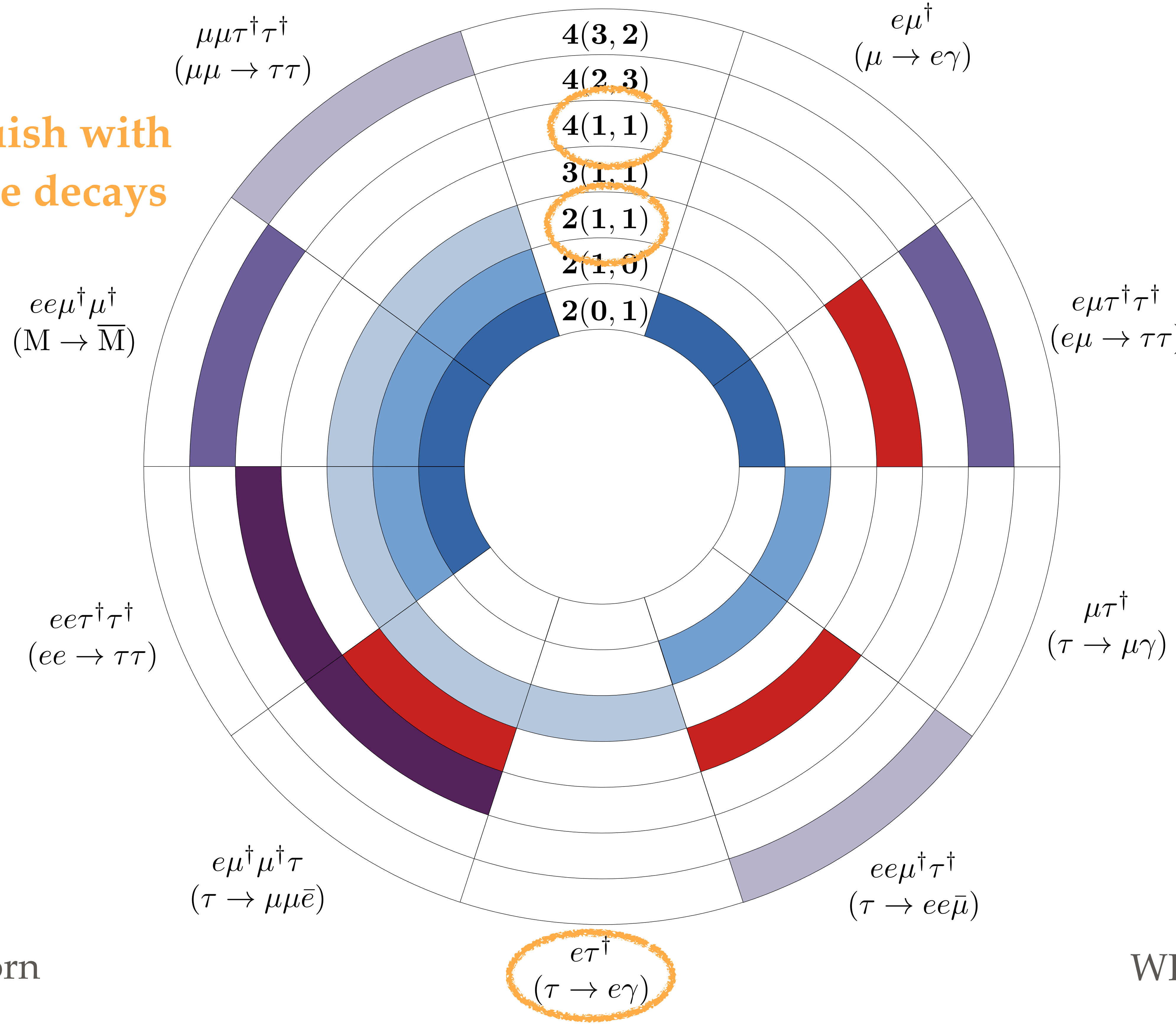
Allowed cLFV processes

Coloured segments indicate allowed flavour structures

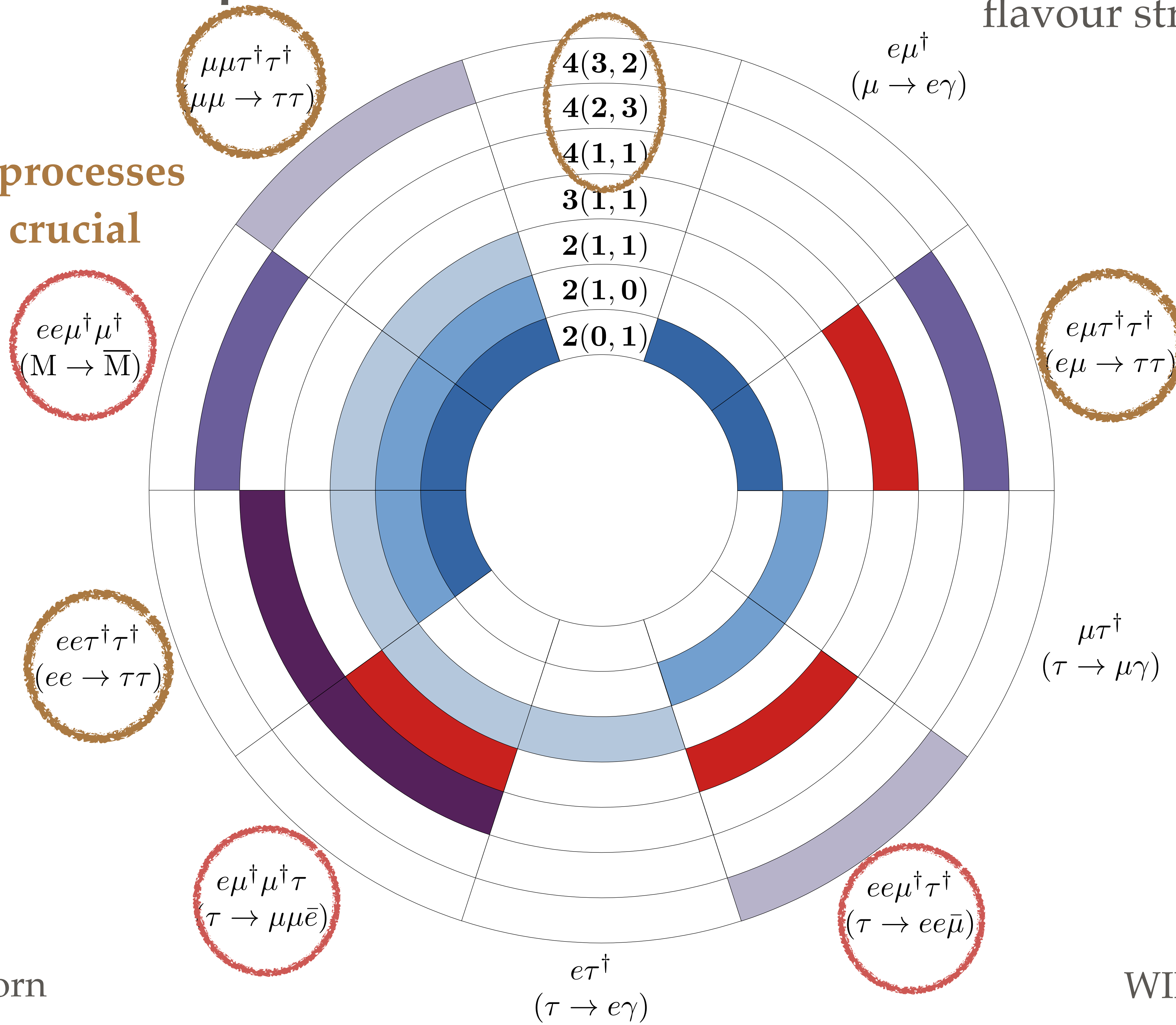
distinguish with radiative decays



Allowed cLFV processes

Coloured segments indicate allowed flavour structures

“exotic” processes can be crucial



Experimental constraints and prospects

- 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.

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

Experimental constraints and prospects

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

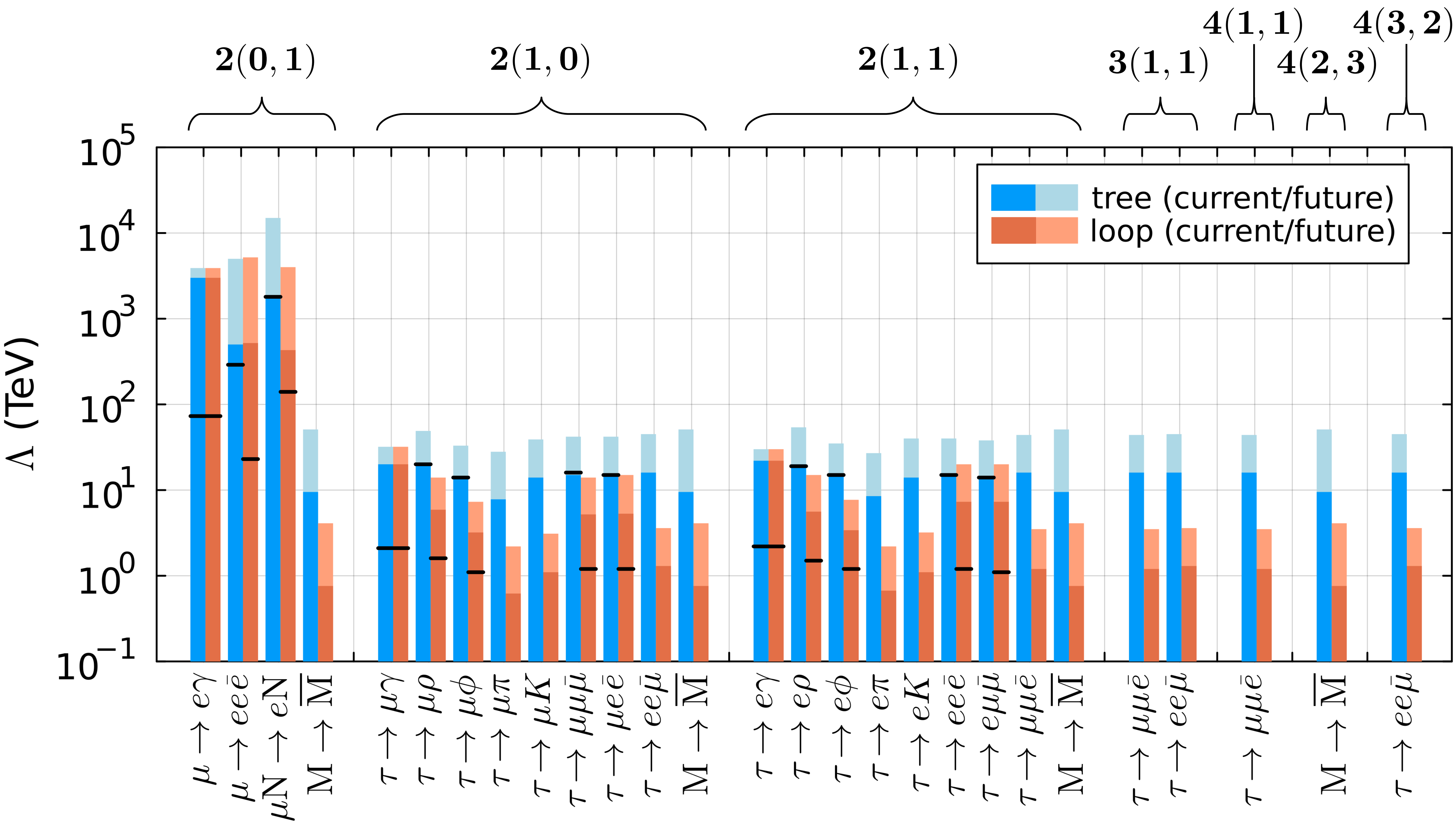
  - Scenario 1: **Tree-level new physics contributions**
    all allowed WCs are set to $C_x = 1$
    apart from the ones of the dipole operator $C_d = \dfrac{e}{16\,\pi^2} \approx 0.002$

  - 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 $C_d = \dfrac{\sqrt{2}\, m_\ell\, e}{16\,\pi^2\, v}$

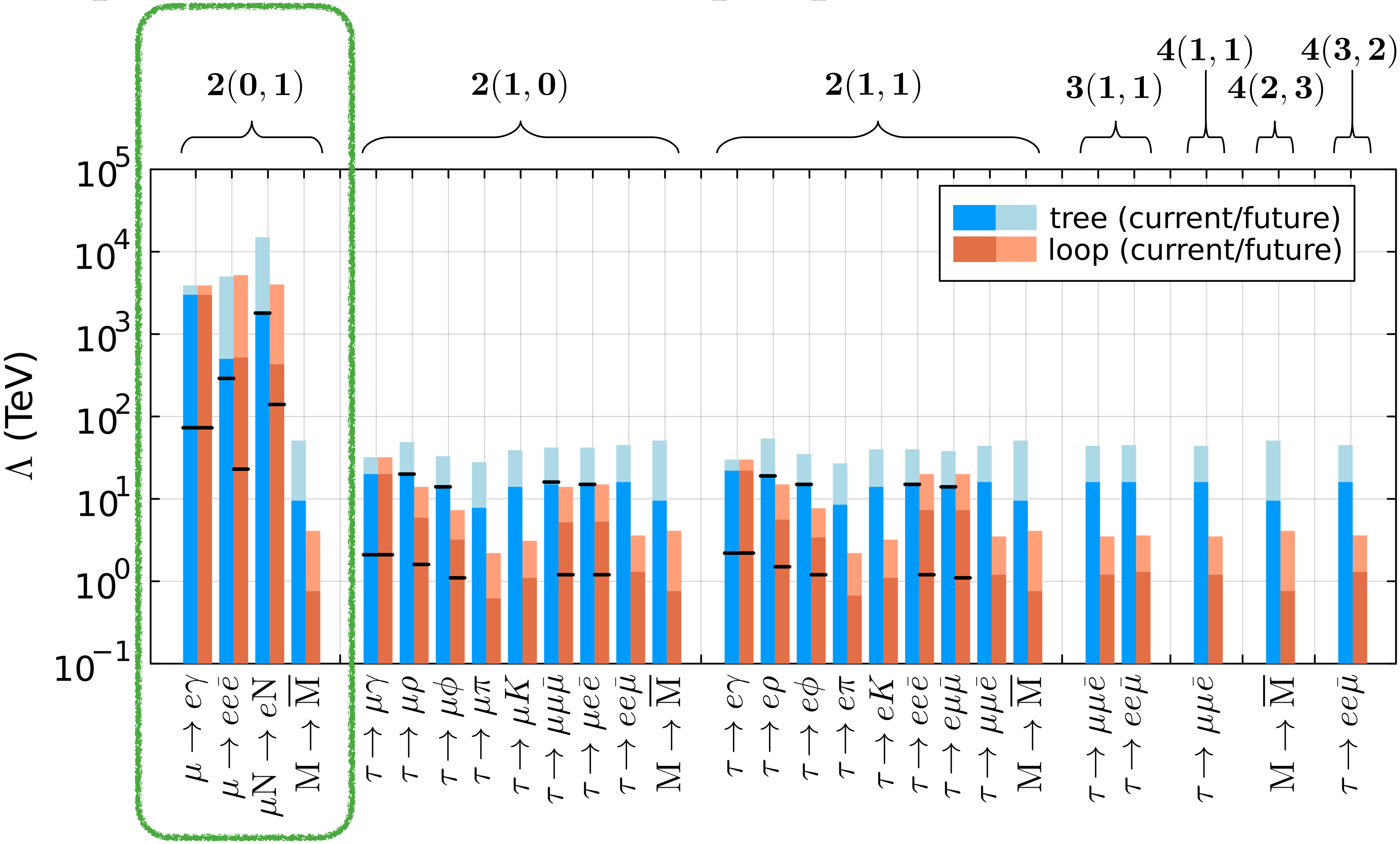
(formulae, see e.g. Calibbi/Marcano/Roy ('21))

Experimental constraints and prospects



No RG running. No matching of SMEFT to LEFT.

Experimental constraints and prospects



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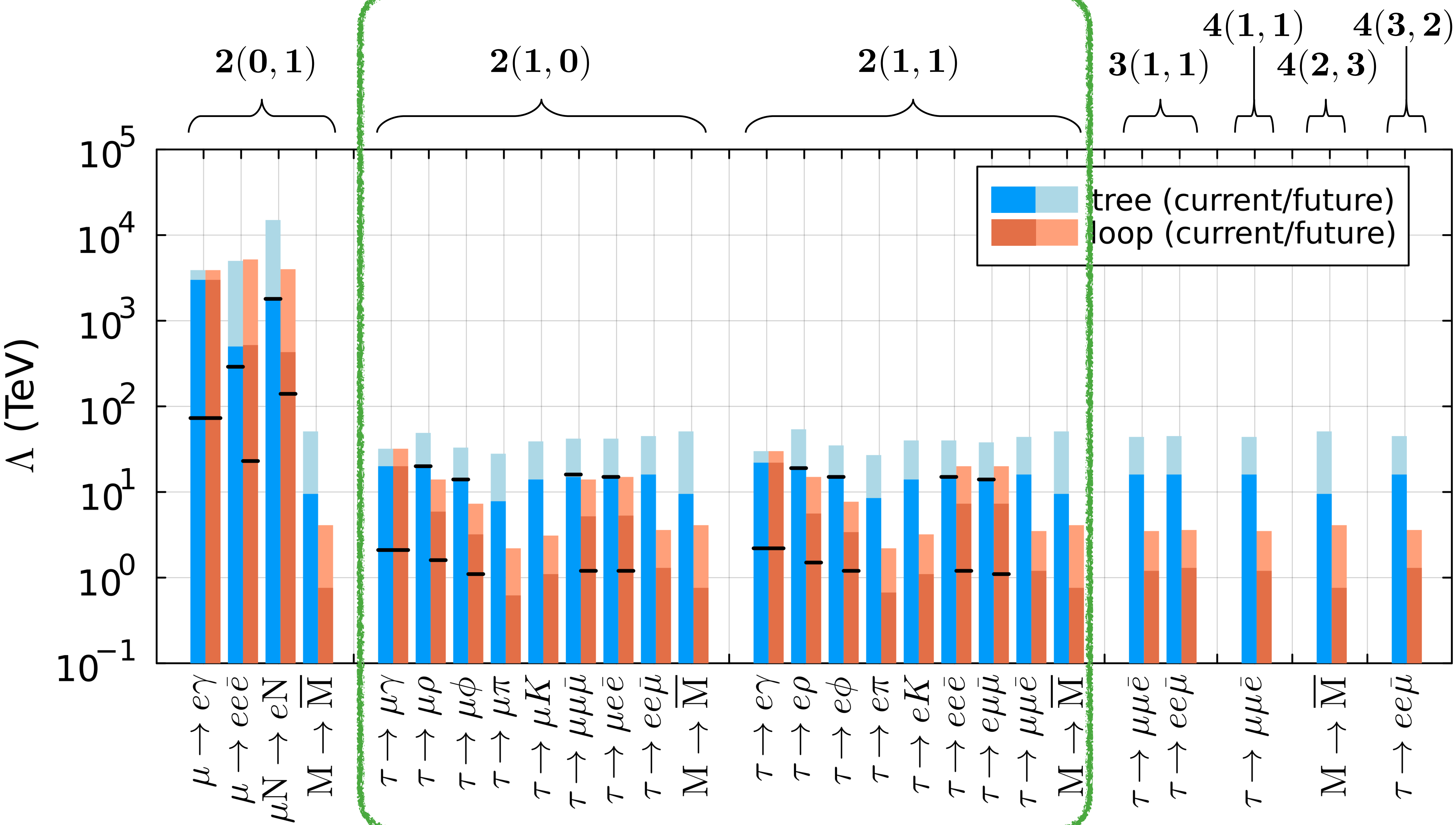

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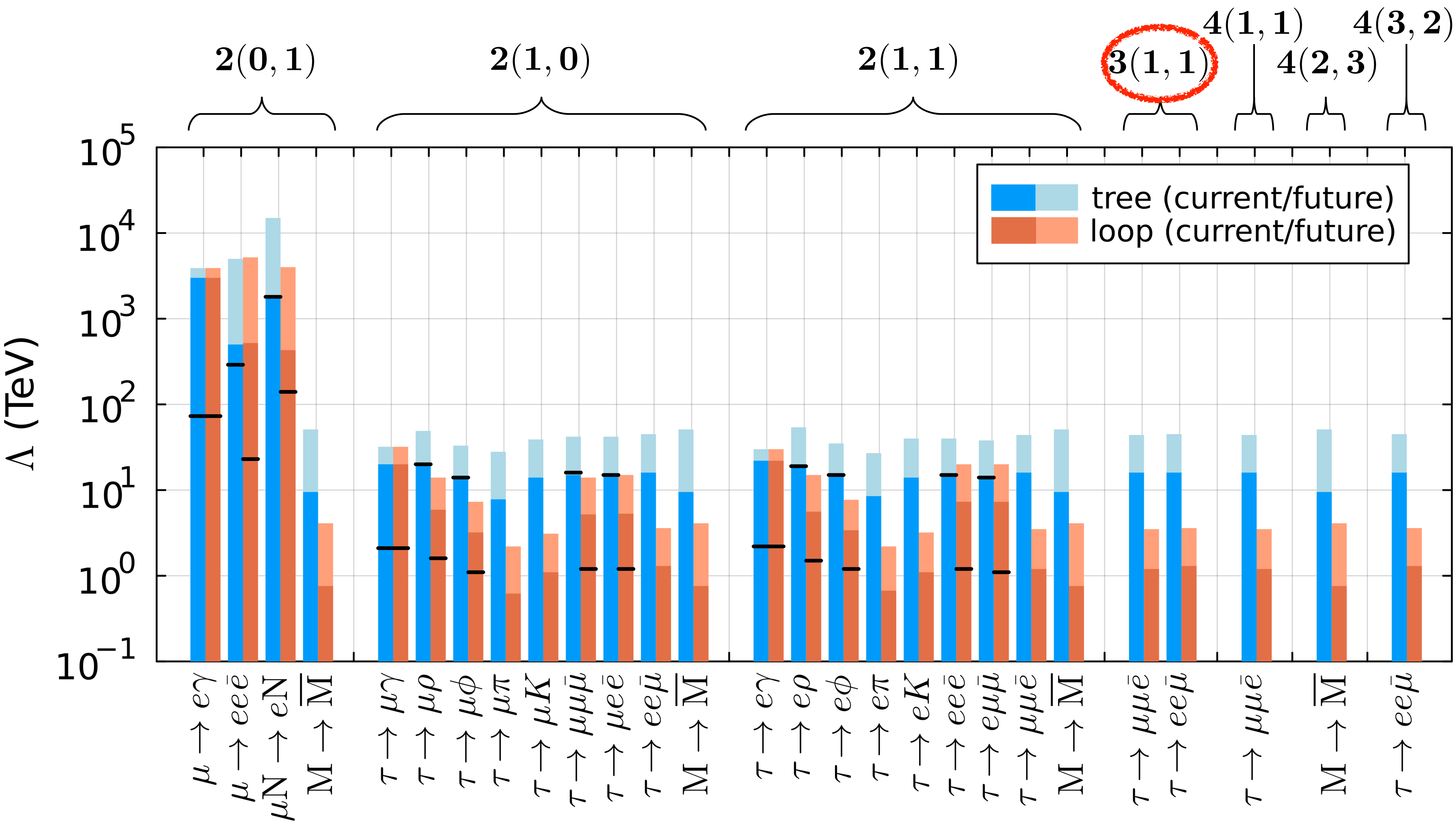
Experimental constraints and prospects

lepton triality



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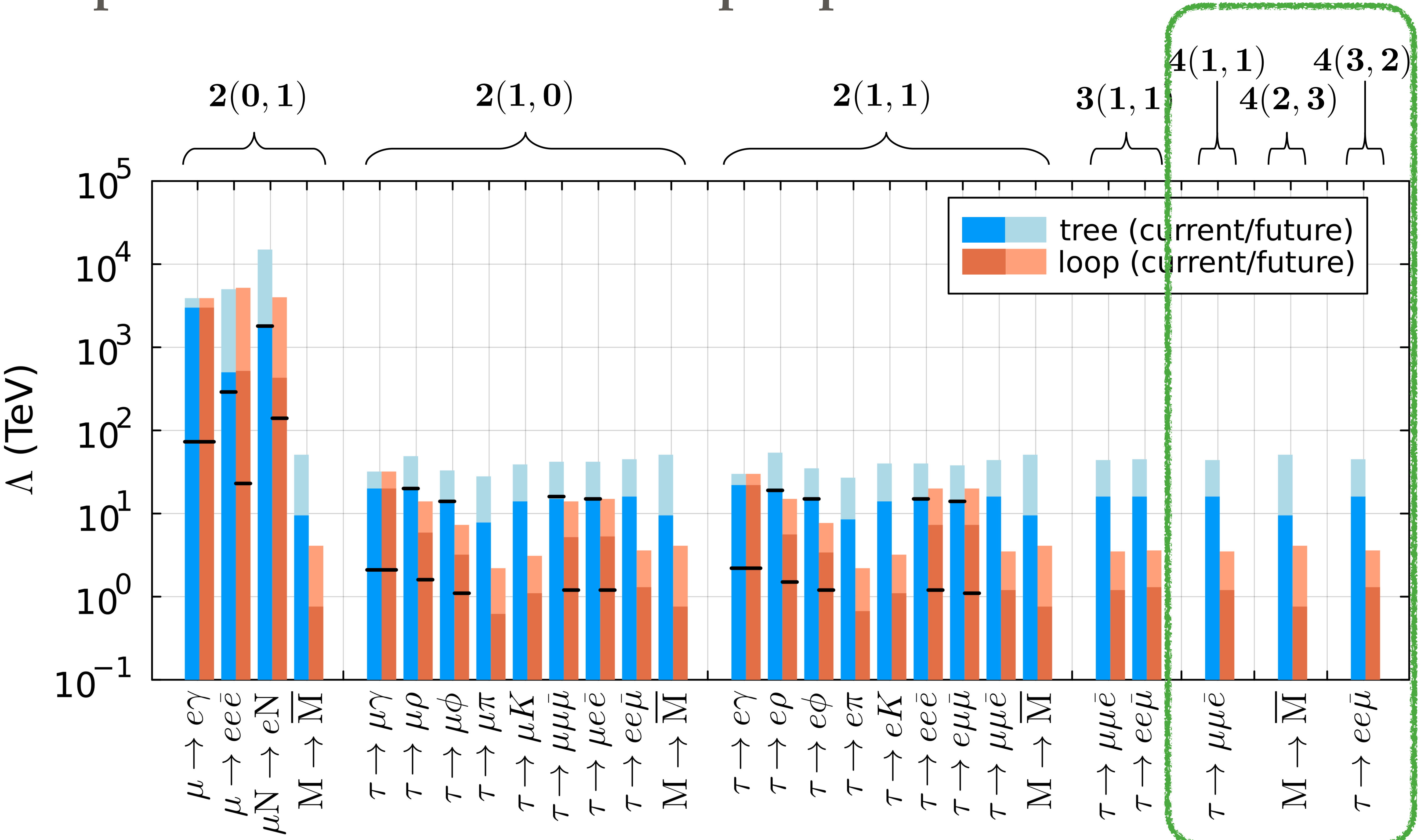
Experimental constraints and prospects



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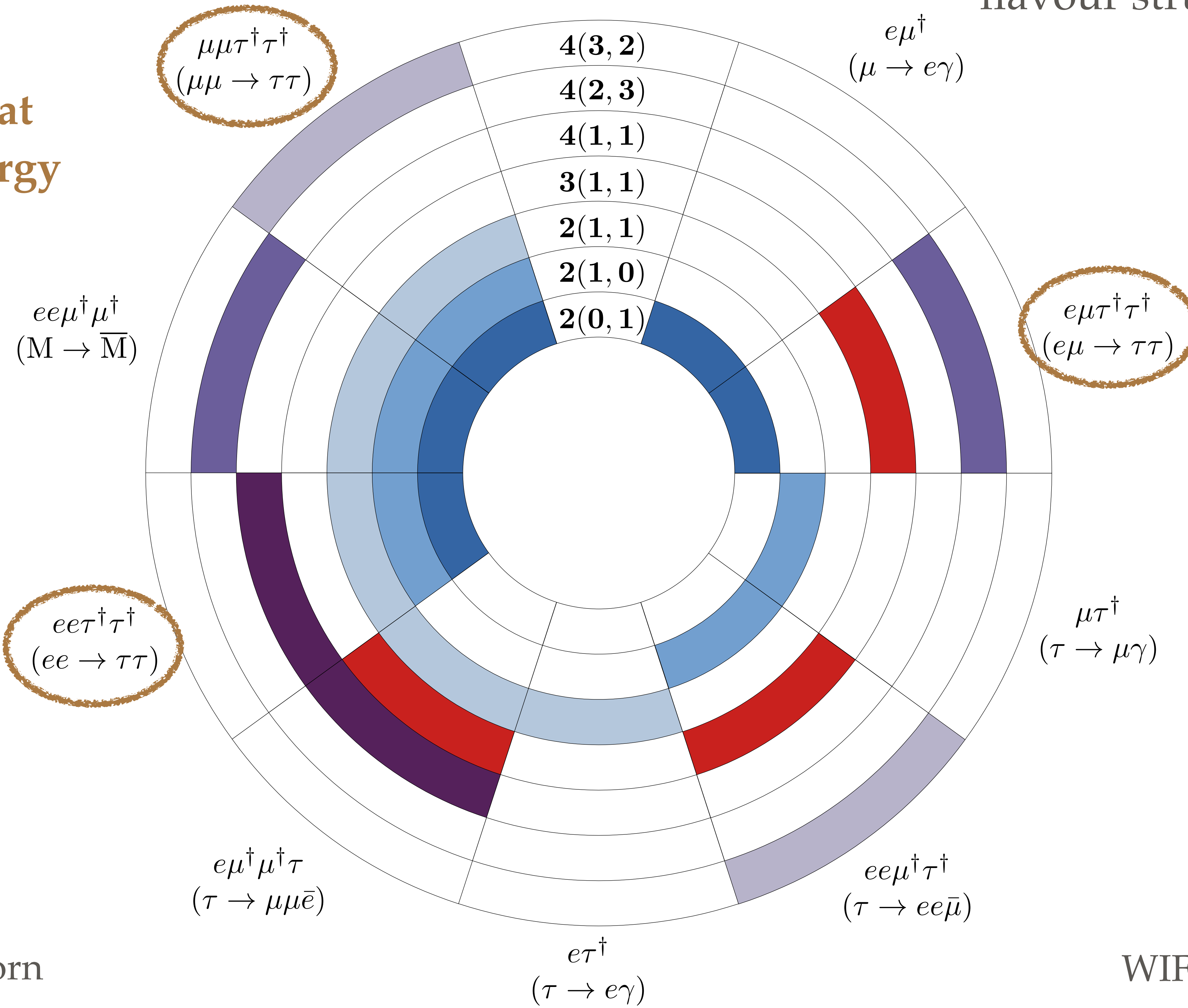
Allowed cLFV processes

Coloured segments indicate allowed flavour structures

cLFV searches at high-energy colliders



Experimental constraints and prospects

- 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)

- Other possible probe are 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)

Beyond this study

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 BR($\tau \rightarrow \mu\mu\bar{e}$)

Beyond this study

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)

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 up and down quarks; potentially with the 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!

Back-up slides

Systematic search

- Consider **small $G_e = Z_N$ with $N \leq 8$** (also discussed direct products)
- 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. $Q_{Z_N}(e^-) = 0$, $Q_{Z_N}(\mu^-) = 0$ and $Q_{Z_N}(\tau^-) = 1$

  $\rightarrow$ consequences

  - Flavour charge assignments that require embedding in $U(3)$ are encountered,

    e.g. $Q_{Z_3}(e^-) = 0$, $Q_{Z_3}(\mu^-) = 0$ and $Q_{Z_3}(\tau^-) = 2$ in $G_e = Z_3$
  - Also $G_e = Z_2$ is included in the search

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 $N(\delta_1, \delta_2)$

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

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

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 $N(\delta_1, \delta_2)$

- $N(\delta_1, \delta_2)$ 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: $3\,\alpha + 2\,\delta_1 + \delta_2 = 0 \mod N$

Systematic search

- Output

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	$\Lambda_{\mathrm{T}}\,(\Lambda_{\mathrm{T}\chi})$	$\Lambda_{\mathrm{L}}\,(\Lambda_{\mathrm{L}\chi})$	Constraint	Λ_{T}	Λ_{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

$\mathbf{2(1,1)}$	$e\tau^\dagger$	$\mathrm{BR}(\tau \to e\gamma)$	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
$\mathbf{3(1,1)}$	$e\mu^\dagger\mu^\dagger\tau$	$\mathrm{BR}(\tau \to \mu\mu\bar{e})$	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
$\mathbf{4(1,1)}$	$e\mu^\dagger\mu^\dagger\tau$	$\mathrm{BR}(\tau \to \mu\mu\bar{e})$	1.7×10^{-8} [69]	16	1.2	2.6×10^{-10} [72]	44	3.5
$\mathbf{4(2,3)}$	$ee\mu^\dagger\mu^\dagger$	$\mathrm{P}(\mathrm{M} \to \overline{\mathrm{M}})$	8.2×10^{-11} [61]	9.5	0.76	10^{-13} [62]	51	4.1
$\mathbf{4(3,2)}$	$ee\mu^\dagger\tau^\dagger$	$\mathrm{BR}(\tau \to ee\bar{\mu})$	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	$\Lambda_{\rm T}$	Constraint	$\Lambda_{\rm T}$
$\mathbf{2(a,b)}^{\ddagger}$, $\mathbf{4(3,2)}$	$\mu\mu\tau^\dagger\tau^\dagger$	$\sigma(\mu^+\mu^+ \to \tau^+\tau^+)$	–	–	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 $\mathbf{2(1,1)}$.