BESIII Workshop on New Physics 2023

New physics at tau-charm factories

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A small (personal) selection of new physics (NP) that can be searched for at tau-charm energies:

- Charged Lepton Flavour Violation (CLFV)
- Tests of Lepton Flavour Universality (LFU)
- Light dark matter/dark sectors

Charged Lepton Flavour Violation

In the SM, electroweak interactions are *lepton flavour universal* and (with massless neutrinos) *lepton flavour conserving*

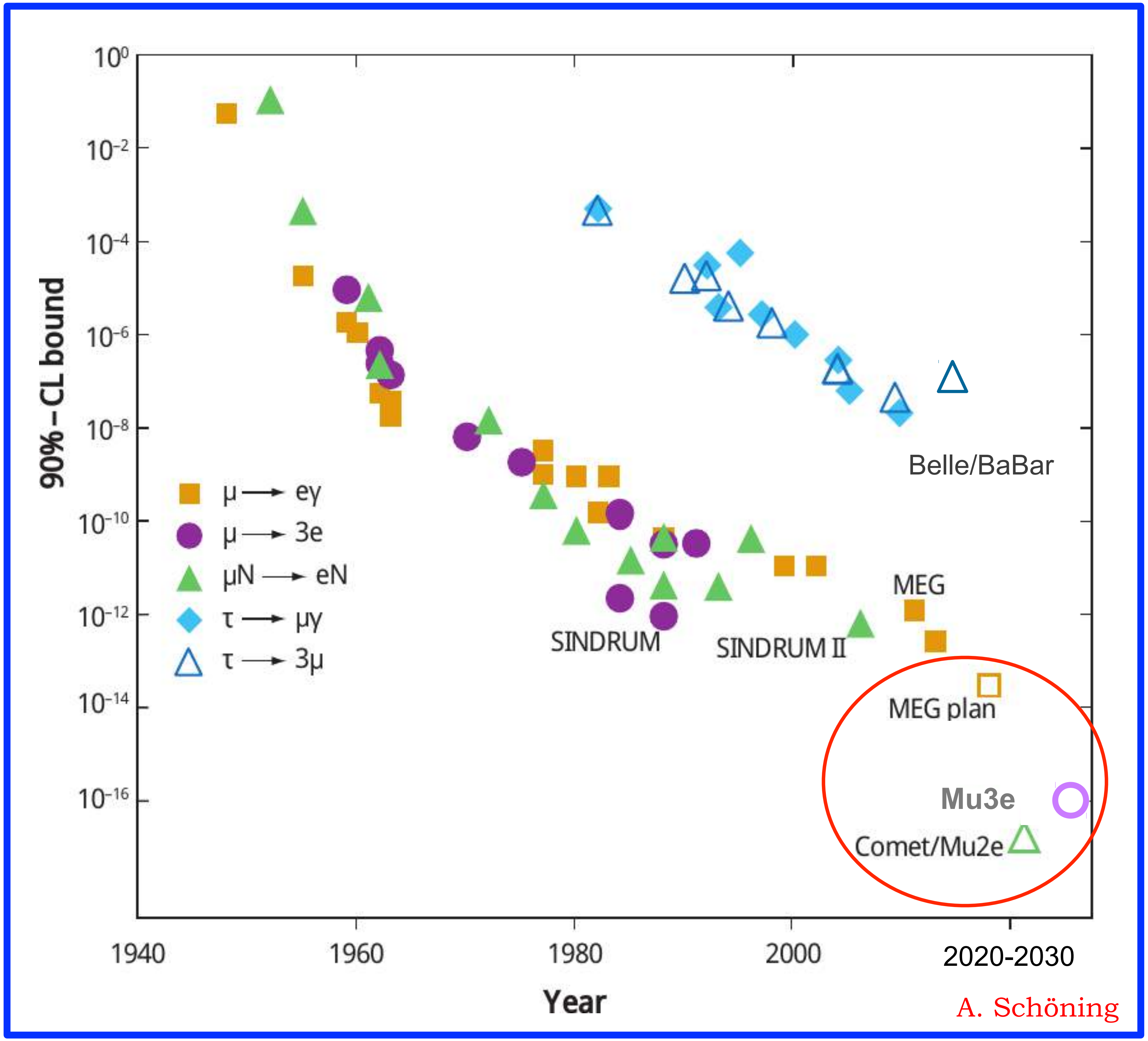
Neutrino masses/oscillations $\Longleftrightarrow \not{L}_e, \not{L}_\mu, \not{L}_\tau$

Lepton family numbers are not conserved: why not *charged* lepton flavour violation (CLFV): $\mu \to e\gamma, \quad \tau \to \mu\gamma, \quad \mu \to eee, \text{ etc.}\,?$

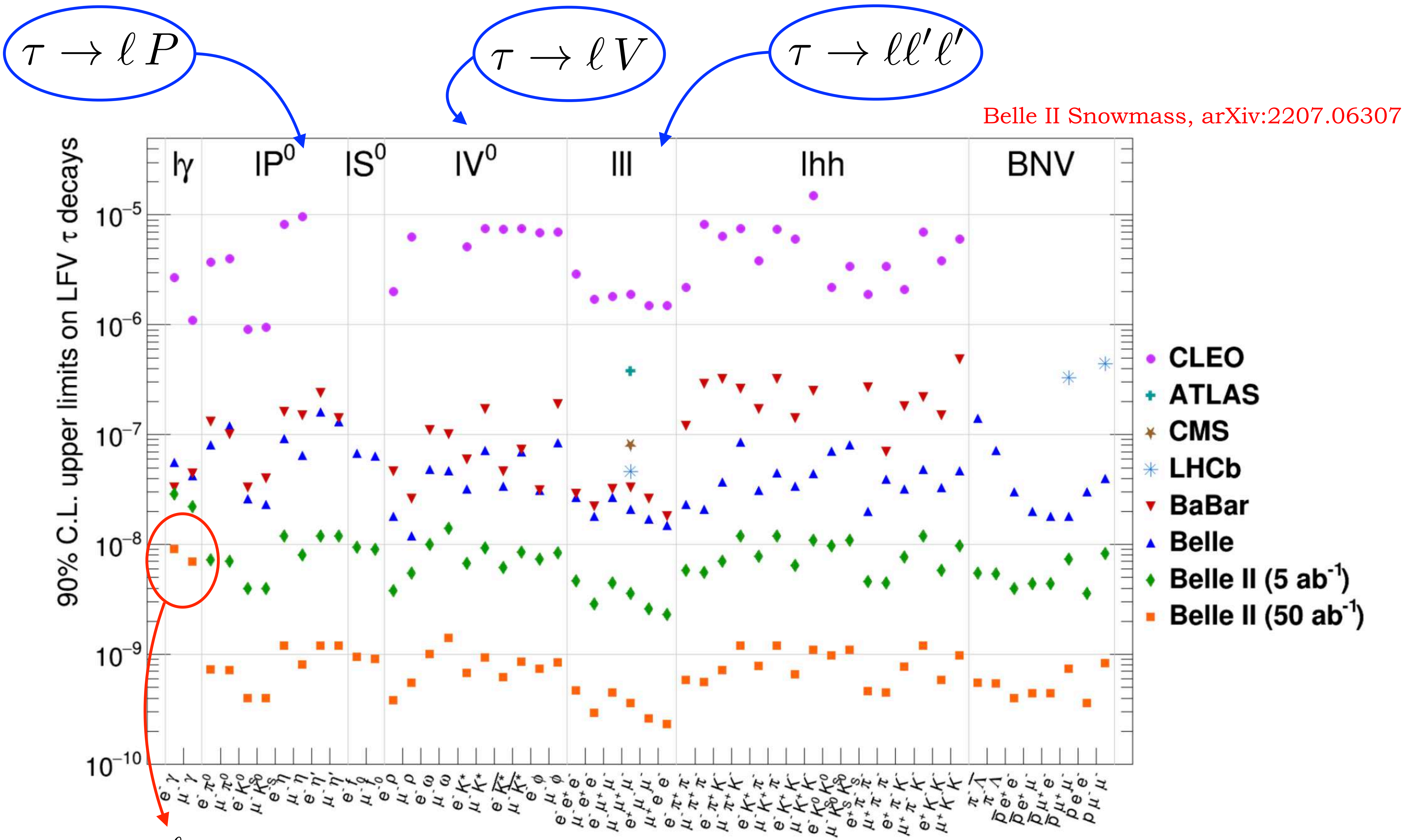
In the SM + neutrino masses, CLFV rates suppressed by a factor $\sim \left(\frac{\Delta m_\nu}{M_W}\right)^4 \approx 10^{-48}$

CLFV: clear signal of New Physics, stringent test of NP physics coupling to leptons, probe of scales way beyond the LHC reach

CLFV has been sought for more than 70 years...



Belle II prospects for tau LFV



$\tau \to \ell\gamma$ limited by ISR background ⟹ not a problem at tau-charm factories!

LFV quarkonium decays

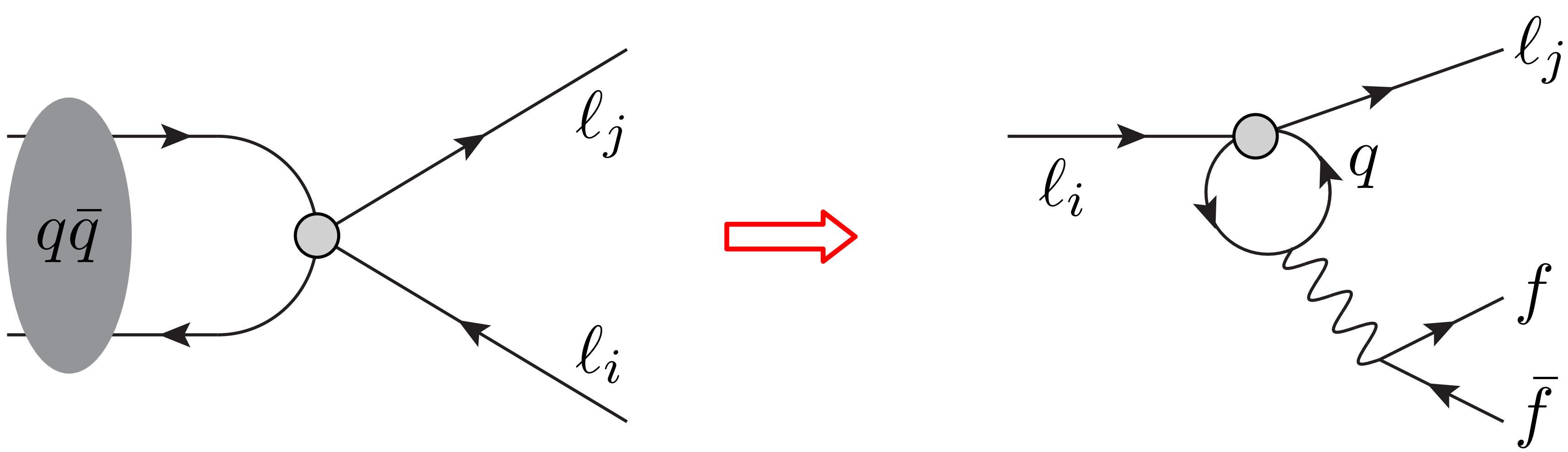
LFVQD	Present bounds on BR (90% CL)		
$J/\psi \to e\mu$	4.5×10^{-9}	BESIII (2022)	[16]
$\Upsilon(1S) \to e\mu$	3.6×10^{-7}	Belle (2022)	[17]
$\Upsilon(1S) \to e\mu\gamma$	4.2×10^{-7}	Belle (2022)	[17]
$J/\psi \to e\tau$	7.5×10^{-8}	BESIII (2021)	[18]
$\Upsilon(1S) \to e\tau$	2.4×10^{-6}	Belle (2022)	[17]
$\Upsilon(1S) \to e\tau\gamma$	6.5×10^{-6}	Belle (2022)	[17]
$\Upsilon(2S) \to e\tau$	3.2×10^{-6}	BaBar (2010)	[19]
$\Upsilon(3S) \to e\tau$	4.2×10^{-6}	BaBar (2010)	[19]
$J/\psi \to \mu\tau$	2.0×10^{-6}	BES (2004)	[20]
$\Upsilon(1S) \to \mu\tau$	2.6×10^{-6}	Belle (2022)	[17]
$\Upsilon(1S) \to \mu\tau\gamma$	6.1×10^{-6}	Belle (2022)	[17]
$\Upsilon(2S) \to \mu\tau$	3.3×10^{-6}	BaBar (2010)	[19]
$\Upsilon(3S) \to \mu\tau$	3.1×10^{-6}	BaBar (2010)	[19]

Table 1: Present 90% CL upper limits on vector quarkonium LFV decays. No limit is currently available for LFV decays of (pseudo)scalar or other vector resonances.

BESIII continues taking data, a high-lumi Super Tau-Charm Factory (STCF) is being discussed with c.o.m. E ~2-7 GeV that could produce ~10^{13} J/ψ (x1000 current BESIII), Belle II will collect x50-100 the data of Belle/BaBar

What can we learn from these processes?

- In principle, ideal modes to test $2q2\ell$ operators involving heavy quarks (that could stem *e.g.* from by *Z'*/LQs with MFV-like couplings)
- Searches for radiative modes and decays of (pseudo)scalar resonances would be sensitive to different LEFT operators than the vector ones
- The question is: can we find new physics searching for these modes?
- Tau/mu processes unavoidably induced: strong indirect constraints:



Effect summarised by the RGE running of the LEFT operators

Indirect constraints on quarkonium LFV

LEFT 2q2l ops:

$$\mathcal{L}_{2q2\ell} = C^{V,LL}_{eq,prst}(\bar{\ell}_p\gamma^\mu P_L\ell_r)(\bar{q}_s\gamma_\mu P_L q_t) + C^{V,RR}_{eq,prst}(\bar{\ell}_p\gamma^\mu P_R\ell_r)(\bar{q}_s\gamma_\mu P_R q_t)$$
$$+ C^{V,LR}_{eq,prst}(\bar{\ell}_p\gamma^\mu P_L\ell_r)(\bar{q}_s\gamma_\mu P_R q_t) + C^{V,LR}_{qe,prst}(\bar{q}_p\gamma_\mu P_L q_r)(\bar{\ell}_s\gamma^\mu P_R\ell_t)$$
$$+ \Big[C^{S,RL}_{eq,prst}(\bar{\ell}_p P_R\ell_r)(\bar{q}_s P_L q_t) + C^{S,RR}_{eq,prst}(\bar{\ell}_p P_R\ell_r)(\bar{q}_s P_R q_t)$$
$$+ C^{T,RR}_{eq,prst}(\bar{\ell}_p\sigma_{\mu\nu} P_R\ell_r)(\bar{q}_s\sigma^{\mu\nu} P_R q_t) + h.c.\Big],$$

Single operator at μ=[q$\bar{\text{q}}$ - M_Z]

Operator	Strongest constraint	Indirect upper limits on BR	
		$J/\psi \to \ell\ell'$	$\psi(2S) \to \ell\ell'$
$C^{V,LL}_{eu,\mu ecc}$	$\mu \to e$, Au	[1.6 - 0.07] $\times 10^{-15}$	[2.8 - 0.2] $\times 10^{-16}$
$C^{V,LR}_{eu,\mu ecc}$	$\mu \to e$, Au	[1.5 - 0.07] $\times 10^{-15}$	[2.8 - 0.2] $\times 10^{-16}$
$C^{T,RR}_{eu,\mu ecc}$	$\mu \to e\gamma$	[3.4 - 0.5] $\times 10^{-21}$	[7.8 - 1.4] $\times 10^{-22}$
$C_{e\gamma,\mu e}$	$\mu \to e\gamma$	[2.6 - 2.5] $\times 10^{-26}$	[6.3 - 0.5] $\times 10^{-27}$
$C^{V,LL}_{eu,\tau ecc}$	$\tau \to \rho e$	[6.6 - 0.1] $\times 10^{-9}$	[1.2 - 0.05] $\times 10^{-9}$
$C^{V,LR}_{eu,\tau ecc}$	$\tau \to \rho e$	[6.5 - 0.1] $\times 10^{-9}$	[1.2 - 0.04] $\times 10^{-9}$
$C^{T,RR}_{eu,\tau ecc}$	$\tau \to e\gamma$	[1.2 - 0.05] $\times 10^{-12}$	[2.3 - 0.2] $\times 10^{-13}$
$C_{e\gamma,\tau e}$	$\tau \to e\gamma$	[1.7 - 1.6] $\times 10^{-18}$	[4.7 - 3.5] $\times 10^{-19}$
$C^{V,LL}_{eu,\tau\mu cc}$	$\tau \to \rho\mu$	[4.5 - 0.09] $\times 10^{-9}$	[7.9 - 0.3] $\times 10^{-10}$
$C^{V,LR}_{eu,\tau\mu cc}$	$\tau \to \rho\mu$	[4.4 - 0.09] $\times 10^{-9}$	[7.9 - 0.3] $\times 10^{-10}$
$C^{T,RR}_{eu,\tau\mu cc}$	$\tau \to \mu\gamma$	[1.6 - 0.07] $\times 10^{-12}$	[2.9 - 0.3] $\times 10^{-13}$
$C_{e\gamma,\tau\mu}$	$\tau \to \mu\gamma$	[2.2 - 2.1] $\times 10^{-18}$	[6.1 - 4.5] $\times 10^{-19}$

(a) Vector and tensor operators. The operators $C^{V,RR}_{eu,ijcc}$, $C^{V,LR}_{ue,ccij}$, $C^{T,RR}_{eu,jicc}$ and $C_{e\gamma,ji}$ lead, respectively, to the same results as $C^{V,LL}_{eu,ijcc}$, $C^{V,LR}_{eu,ijcc}$, $C^{T,RR}_{eu,ijcc}$ and $C_{e\gamma,ij}$.

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Indirect constraints on quarkonium LFV

LEFT 2q2l ops:

$$\mathcal{L}_{2q2\ell} = C^{V,LL}_{eq,prst}\,(\bar{\ell}_p\gamma^\mu P_L\ell_r)(\bar{q}_s\gamma_\mu P_L q_t) + C^{V,RR}_{eq,prst}\,(\bar{\ell}_p\gamma^\mu P_R\ell_r)(\bar{q}_s\gamma_\mu P_R q_t)$$
$$+ C^{V,LR}_{eq,prst}\,(\bar{\ell}_p\gamma^\mu P_L\ell_r)(\bar{q}_s\gamma_\mu P_R q_t) + C^{V,LR}_{qe,prst}\,(\bar{q}_p\gamma_\mu P_L q_r)(\bar{\ell}_s\gamma^\mu P_R\ell_t)$$
$$+ \Big[C^{S,RL}_{eq,prst}\,(\bar{\ell}_p P_R\ell_r)(\bar{q}_s P_L q_t) + C^{S,RR}_{eq,prst}\,(\bar{\ell}_p P_R\ell_r)(\bar{q}_s P_R q_t)$$
$$+ C^{T,RR}_{eq,prst}\,(\bar{\ell}_p\sigma_{\mu\nu} P_R\ell_r)(\bar{q}_s\sigma^{\mu\nu} P_R q_t) + h.c.\Big]\,,$$

Operator	Str. const.	Indirect upper limits on BR		
		$J/\psi \to \ell\ell'\gamma$	$\eta_c \to \ell\ell'$	$\chi_{c0}(1P) \to \ell\ell'$
$C^{S,RR}_{eu,\mu ecc}$	$\mu \to e$, Au	$[1.5 - 1.4] \times 10^{-21}$	$[2.0 - 1.9] \times 10^{-20}$	$[3.4 - 3.2] \times 10^{-19}$
$C^{S,RL}_{eu,\mu ecc}$	$\mu \to e$, Au	$[1.5 - 1.4] \times 10^{-21}$	$[2.0 - 1.9] \times 10^{-20}$	$[3.4 - 3.2] \times 10^{-19}$
$C^{S,RR}_{eu,\tau ecc}$	$\tau \to e\gamma$	$[1.7 - 0.003] \times 10^{-10}$	$[6.8 - 0.01] \times 10^{-9}$	$[1.5 - 0.003] \times 10^{-7}$
$C^{S,RL}_{eu,\tau ecc}$	$\tau \to e\gamma$	$[2.0 - 0.09] \times 10^{-10}$	$[9.2 - 0.4] \times 10^{-9}$	$[1.3 - 0.08] \times 10^{-7}$
$C^{S,RR}_{eu,\tau\mu cc}$	$\tau \to \mu\gamma$	$[2.2 - 0.004] \times 10^{-10}$	$[8.7 - 0.02] \times 10^{-9}$	$[1.9 - 0.003] \times 10^{-7}$
$C^{S,RL}_{eu,\tau\mu cc}$	$\tau \to \mu\gamma$	$[2.6 - 0.1] \times 10^{-10}$	$[1.2 - 0.05] \times 10^{-8}$	$[1.7 - 0.1] \times 10^{-7}$

(b) Scalar operators. We find similar limits for $\psi(2S) \to \ell\ell'\gamma$, about a factor of $4\,(2)$ stronger for the $\mu e\,(\tau\ell)$ channels. See text for details on how the indirect upper limits have been estimated.

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Indirect constraints on quarkonium LFV

LEFT 2q2l ops:

$$\mathcal{L}_{2q2\ell} = C^{V,LL}_{eq,prst}\,(\bar\ell_p\gamma^\mu P_L\ell_r)(\bar q_s\gamma_\mu P_L q_t) + C^{V,RR}_{eq,prst}\,(\bar\ell_p\gamma^\mu P_R\ell_r)(\bar q_s\gamma_\mu P_R q_t)$$
$$+ C^{V,LR}_{eq,prst}\,(\bar\ell_p\gamma^\mu P_L\ell_r)(\bar q_s\gamma_\mu P_R q_t) + C^{V,LR}_{qe,prst}\,(\bar q_p\gamma_\mu P_L q_r)(\bar\ell_s\gamma^\mu P_R\ell_t)$$
$$+ \Big[C^{S,RL}_{eq,prst}\,(\bar\ell_p P_R\ell_r)(\bar q_s P_L q_t) + C^{S,RR}_{eq,prst}\,(\bar\ell_p P_R\ell_r)(\bar q_s P_R q_t)$$
$$+ C^{T,RR}_{eq,prst}\,(\bar\ell_p\sigma_{\mu\nu} P_R\ell_r)(\bar q_s\sigma^{\mu\nu} P_R q_t) + h.c.\Big]\,,$$

Operator	Str. const.	Indirect upper limits on BR		
		$\Upsilon(1S)\to\ell\ell'$	$\Upsilon(2S)\to\ell\ell'$	$\Upsilon(3S)\to\ell\ell'$
$C^{V,LL}_{ed,\mu ebb}$	$\mu\to e$, Au	$[1.1 - 0.08]\times10^{-12}$	$[9.9 - 0.8]\times10^{-13}$	$[1.1 - 0.1]\times10^{-12}$
$C^{V,LR}_{ed,\mu ebb}$	$\mu\to e$, Au	$[1.1 - 0.08]\times10^{-12}$	$[9.9 - 0.8]\times10^{-13}$	$[1.1 - 0.1]\times10^{-12}$
$C^{T,RR}_{ed,\mu ebb}$	$\mu\to e\gamma$	$[4.7 - 0.7]\times10^{-19}$	$[4.3 - 0.7]\times10^{-19}$	$[4.8 - 0.9]\times10^{-19}$
$C_{e\gamma,\mu e}$	$\mu\to e\gamma$	1.6×10^{-25}	1.5×10^{-25}	1.6×10^{-25}
$C^{V,LL}_{ed,\tau ebb}$	$\tau\to\rho e$	$[3.1 - 0.2]\times10^{-6}$	$[2.8 - 0.2]\times10^{-6}$	$[3.0 - 0.3]\times10^{-6}$
$C^{V,LR}_{ed,\tau ebb}$	$\tau\to\rho e$	$[3.1 - 0.2]\times10^{-6}$	$[2.8 - 0.2]\times10^{-6}$	$[3.0 - 0.3]\times10^{-6}$
$C^{T,RR}_{ed,\tau ebb}$	$\tau\to e\gamma$	$[4.0 - 0.6]\times10^{-11}$	$[3.7 - 0.6]\times10^{-11}$	$[4.1 - 0.8]\times10^{-11}$
$C_{e\gamma,\tau e}$	$\tau\to e\gamma$	1.4×10^{-17}	1.3×10^{-17}	1.4×10^{-17}
$C^{V,LL}_{ed,\tau\mu bb}$	$\tau\to\rho\mu$	$[2.1 - 0.2]\times10^{-6}$	$[1.9 - 0.2]\times10^{-6}$	$[2.1 - 0.2]\times10^{-6}$
$C^{V,LR}_{ed,\tau\mu bb}$	$\tau\to\rho\mu$	$[2.1 - 0.2]\times10^{-6}$	$[1.9 - 0.3]\times10^{-6}$	$[2.1 - 0.2]\times10^{-6}$
$C^{T,RR}_{ed,\tau\mu bb}$	$\tau\to\mu\gamma$	$[5.2 - 0.7]\times10^{-11}$	$[4.8 - 0.7]\times10^{-11}$	$[5.3 - 0.9]\times10^{-11}$
$C_{e\gamma,\tau\mu}$	$\tau\to\mu\gamma$	1.8×10^{-17}	1.6×10^{-17}	1.8×10^{-17}

(a) Vector and tensor operators. The operators $C^{V,RR}_{ed,ijbb}$, $C^{V,LR}_{de,bbij}$, $C^{T,RR}_{ed,jibb}$ and $C_{e\gamma,ji}$ lead, respectively to the same results as $C^{V,LL}_{ed,ijbb}$, $C^{V,LR}_{ed,ijbb}$, $C^{T,RR}_{ed,ijbb}$ and $C_{e\gamma,ij}$.

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LFV in the SM effective field theory

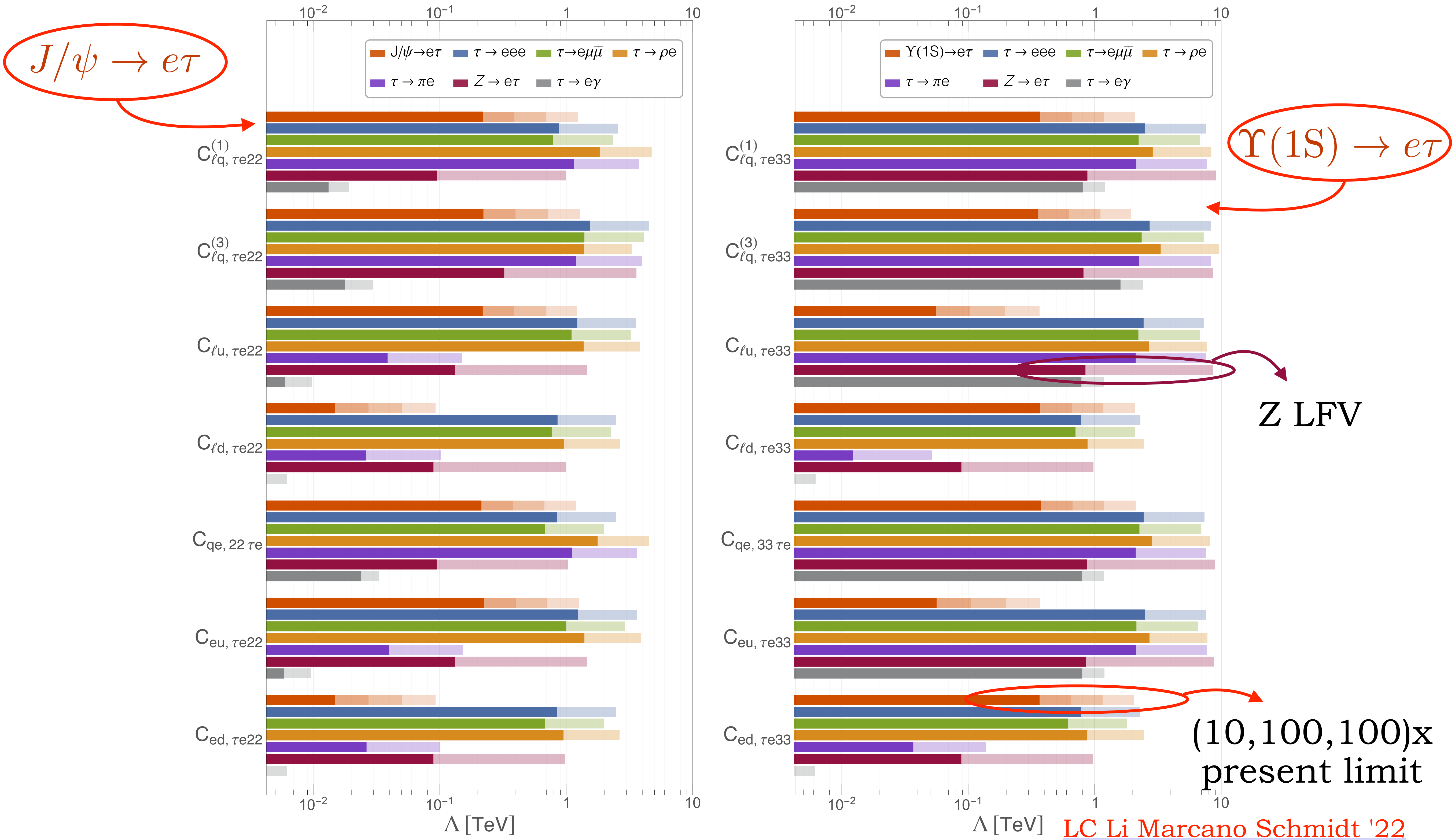
If NP scale $\Lambda \gg m_W$: $\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \dots$

Dimension-6 effective operators that can induce CLFV

4-leptons operators		Dipole operators	
$Q_{\ell\ell}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{L}_L\gamma^\mu L_L)$	Q_{eW}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\tau_I\Phi W^I_{\mu\nu}$
Q_{ee}	$(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R)$	Q_{eB}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\Phi B_{\mu\nu}$
$Q_{\ell e}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{e}_R\gamma^\mu e_R)$		
2-lepton 2-quark operators			
$Q_{\ell q}^{(1)}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{Q}_L\gamma^\mu Q_L)$	$Q_{\ell u}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{u}_R\gamma^\mu u_R)$
$Q_{\ell q}^{(3)}$	$(\bar{L}_L\gamma_\mu\tau_I L_L)(\bar{Q}_L\gamma^\mu\tau_I Q_L)$	Q_{eu}	$(\bar{e}_R\gamma_\mu e_R)(\bar{u}_R\gamma^\mu u_R)$
Q_{eq}	$(\bar{e}_R\gamma^\mu e_R)(\bar{Q}_L\gamma_\mu Q_L)$	$Q_{\ell edq}$	$(\bar{L}_L^a e_R)(\bar{d}_R Q_L^a)$
$Q_{\ell d}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{d}_R\gamma^\mu d_R)$	$Q_{\ell equ}^{(1)}$	$(\bar{L}_L^a e_R)\epsilon_{ab}(\bar{Q}_L^b u_R)$
Q_{ed}	$(\bar{e}_R\gamma_\mu e_R)(\bar{d}_R\gamma^\mu d_R)$	$Q_{\ell equ}^{(3)}$	$(\bar{L}_i^a\sigma_{\mu\nu}e_R)\epsilon_{ab}(\bar{Q}_L^b\sigma^{\mu\nu}u_R)$
Lepton-Higgs operators			
$Q_{\Phi\ell}^{(1)}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{L}_L\gamma^\mu L_L)$	$Q_{\Phi\ell}^{(3)}$	$(\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar{L}_L\tau_I\gamma^\mu L_L)$
$Q_{\Phi e}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}_R\gamma^\mu e_R)$	$Q_{e\Phi 3}$	$(\bar{L}_L e_R\Phi)(\Phi^\dagger\Phi)$

Grzadkowski et al. '10; Crivellin Najjari Rosiek '13

SMEFT running and SMEFT/LEFT matching induce stronger bounds:



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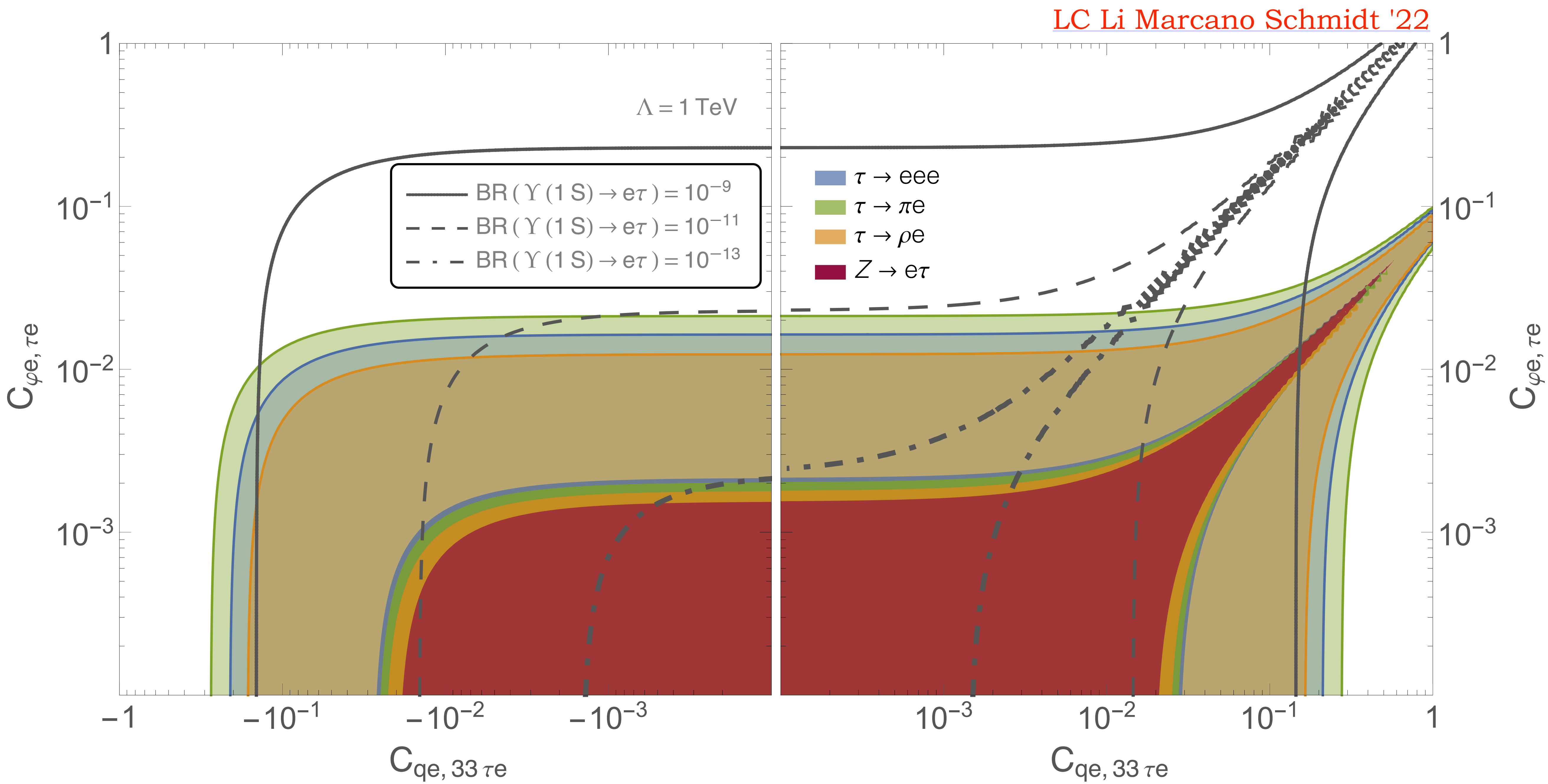
Flat directions are possible along which all indirect constraint vanish:



(similar situation for operators involving LH leptonic currents)

That's not the case for charmonium decays:

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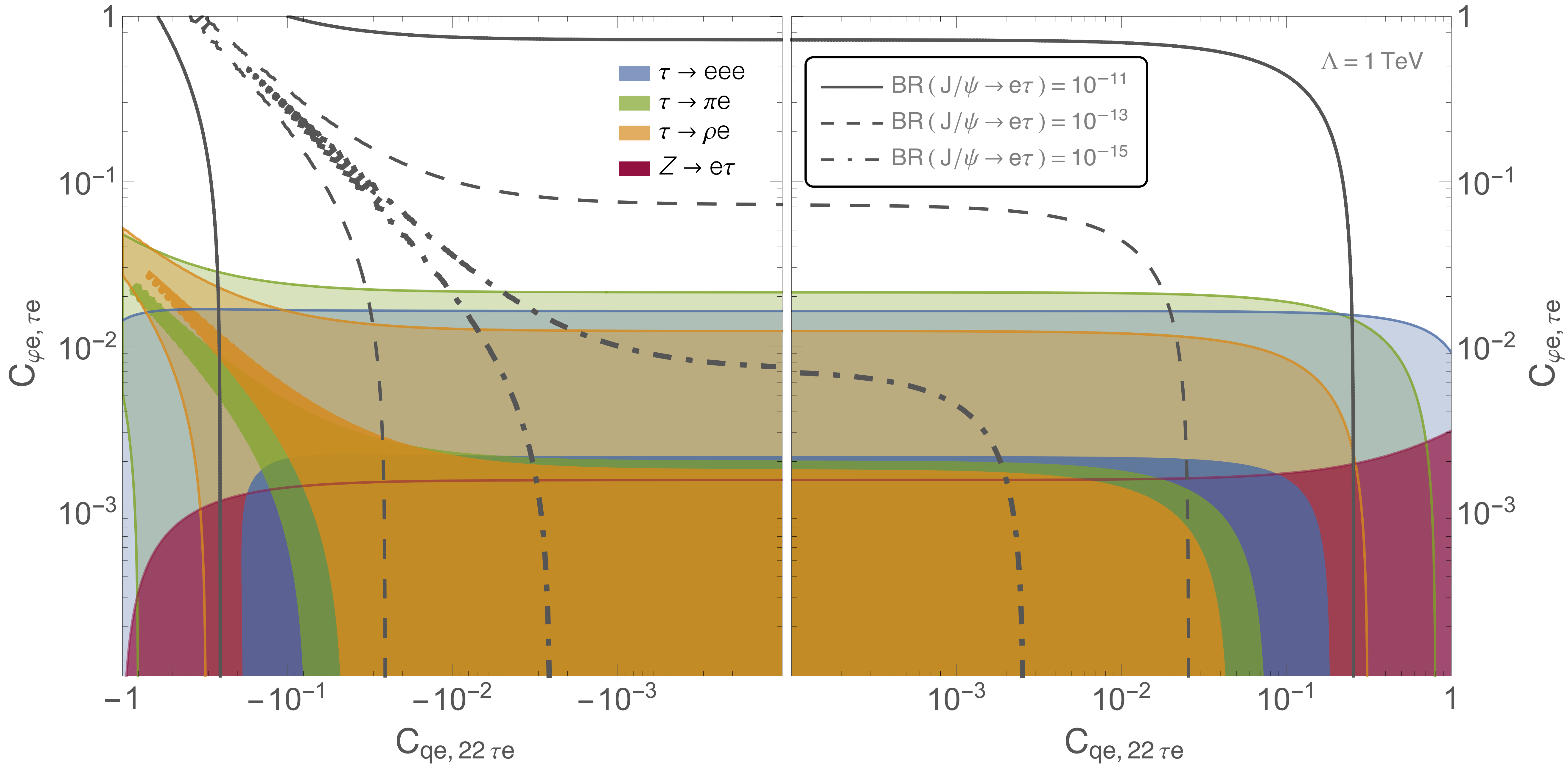


Quarkonium LFV: Summary

Searches for quarkonium LFV decays not sensitive to μ-e LFV due to strong indirect constraints (large widths penalise quarkonia)

In the most optimistic case, charmonium LFV rates are 1-2 orders below current BESIII bounds (partially within STFC sensitivity)

Indirect bounds on bottomonium LFV are at the level of present B-factory limits

SMEFT RGEs makes indirect bounds more important (especially for ops involving tops) → ~1000x increase of sensitivity needed

Flat directions are possible that only Υ LFV decays could probe

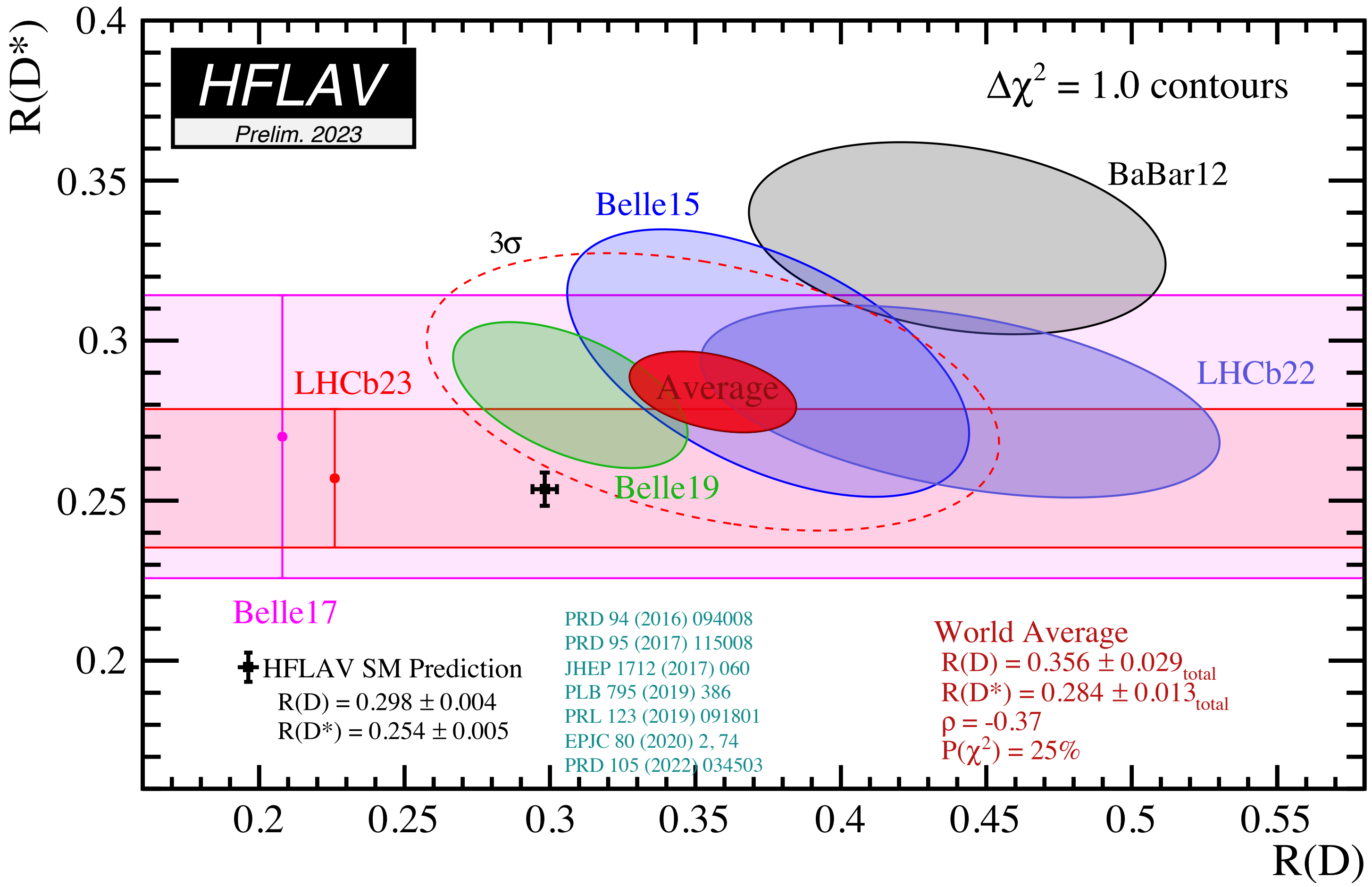
Lepton Flavour Universality

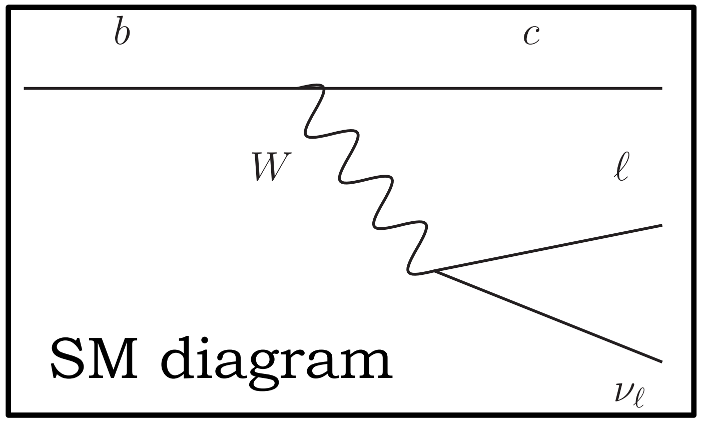
Gauge interactions are flavour blind: the SM predicts Lepton Flavour Universality (LFU) EW interactions

⇨ any deviation from LFU would be a clear indication of NP

Example: LFU tests in semileptonic (charged-current) B decays

$$R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}, \;\; \ell = e,\, \mu$$





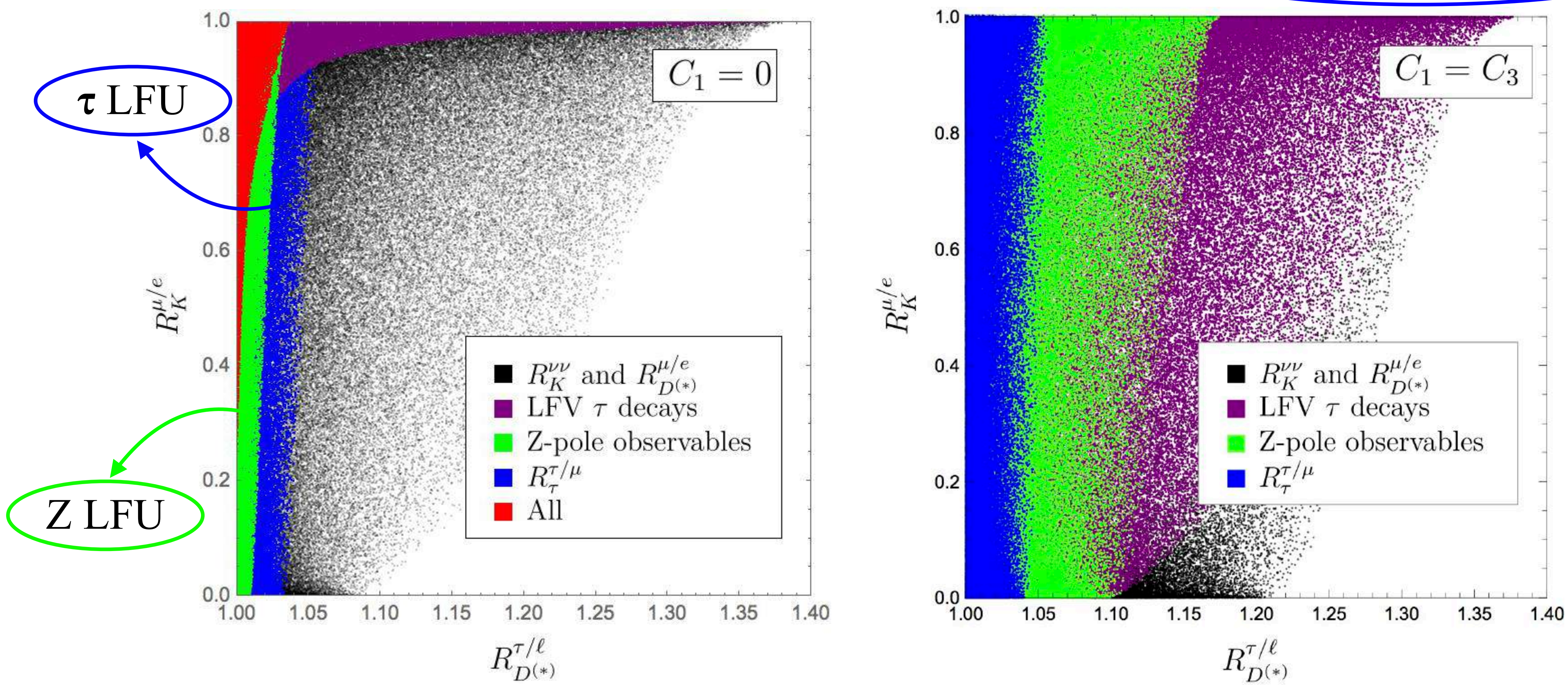
$\approx 3\sigma$ away from SM

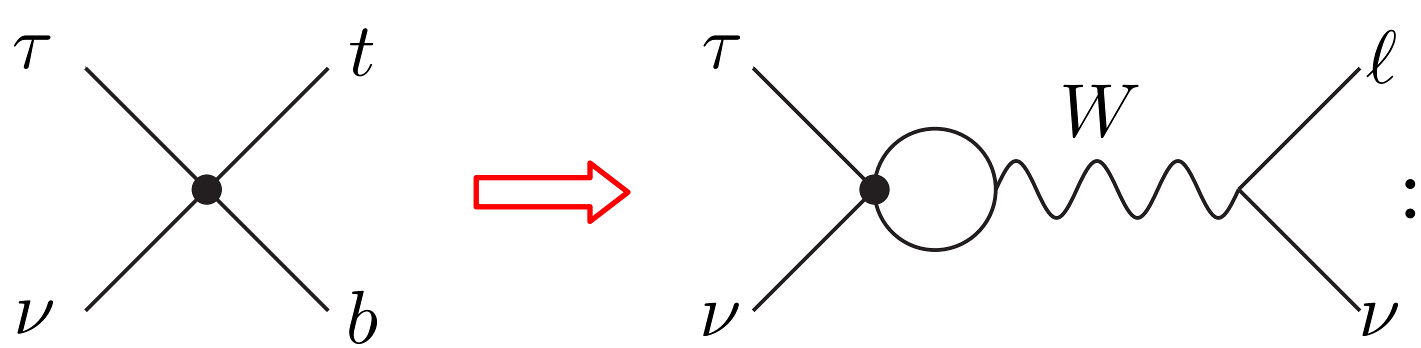
(would requires a 15-20% enhancement wrt the SM)

Constraints on B LFU from tau LFU

New physics inducing operators involving mainly 3rd family fermions

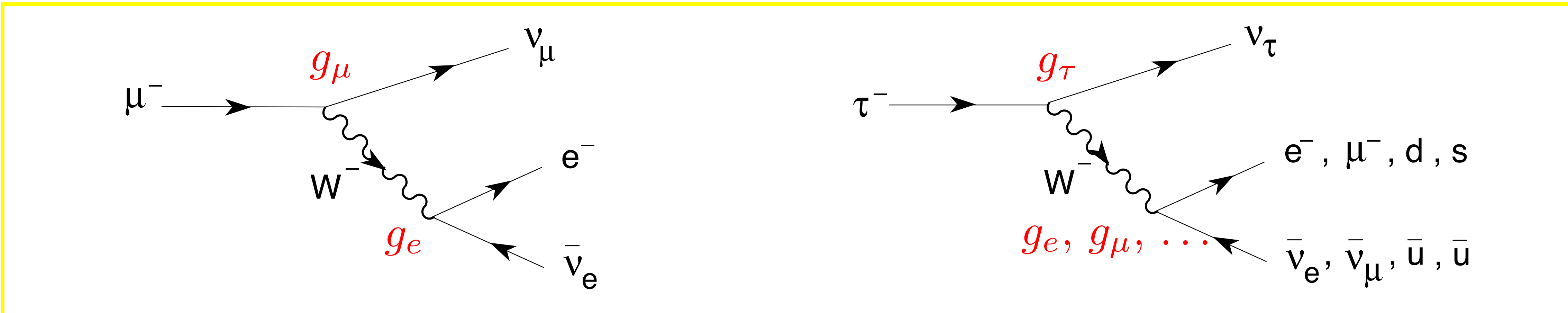
Ops with only 3rd family: $Q_{\ell q}^{(1)} = (\bar{L}_3 \gamma^\mu L_3)(\bar{Q}_3 \gamma_\mu Q_3)$, $Q_{\ell q}^{(3)} = (\bar{L}_3 \gamma^\mu \tau_I L_3)(\bar{Q}_3 \gamma_\mu \tau^I Q_3)$





$$\frac{\mathrm{BR}(\tau \to \ell \nu \bar{\nu})}{\mathrm{BR}(\mu \to e \nu \bar{\nu})}$$

Feruglio Paradisi Pattori ’16, ’17



phase-space factors

radiative corrections

$$\left(\frac{g_\mu}{g_e}\right)^2 = \frac{\mathrm{BR}(\tau \to \mu\nu\bar{\nu})}{\mathrm{BR}(\tau \to e\nu\bar{\nu})} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)} \frac{R_W^{\tau e}}{R_W^{\tau\mu}},$$

$$\left(\frac{g_\tau}{g_\ell}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{\mathrm{BR}(\tau \to \ell\nu\bar{\nu})}{\mathrm{BR}(\mu \to e\nu\bar{\nu})} \frac{f(m_e^2/m_\mu^2)}{f(m_\ell^2/m_\tau^2)} \frac{R_W^{\mu e} R_\gamma^\mu}{R_W^{\tau\ell} R_\gamma^\tau}, \quad (\ell = e, \mu)$$

Currently LFU tested with per mil level precision:

HFLAV '22: $\left(\frac{g_\mu}{g_e}\right) = 1.0009 \pm 0.0014$, $\left(\frac{g_\tau}{g_e}\right) = 1.0027 \pm 0.0014$, $\left(\frac{g_\tau}{g_\mu}\right) = 1.0019 \pm 0.0014$

[error budget: 1.1‰ from BRs, 0.9‰ from τ_τ, 0.2‰ from m_τ]

BESIII

If violation LFU is confirmed, we expect it to occur in the charm sector too!

$$R_{D_{(s)}} \equiv \frac{\Gamma(D_{(s)} \to \tau\nu)}{\Gamma(D_{(s)} \to \mu\nu)}, \qquad R_D^{\mathrm{SL}} \equiv \frac{\Gamma(D \to \pi\mu\nu)}{\Gamma(D \to \pi e\nu)}$$

SM

$$= \frac{m_\tau^2}{m_\mu^2}\left(\frac{m_{D_{(s)}}^2 - m_\tau^2}{m_{D_{(s)}}^2 - m_\mu^2}\right)^2 \approx 2.67\,(D),\ \ 9.74\,(D_s)$$

Observable	Current value	Current BESIII	Projected BESIII	Projected Belle II
$\mathrm{Br}(D \to \mu\nu)$	$(3.77 \pm 0.17) \times 10^{-4}$	4.5%	$1.9\% \oplus 1.3\% \to 2.3\%$	$3.0\% \oplus 1.8\% \to 3.5\%$
$\mathrm{Br}(D \to \tau\nu)$	$(1.20 \pm 0.27) \times 10^{-3}$	22.4%	$8\% \oplus 5\% \to 9.4\%$	$0.8\% \oplus 1.8\% \to 2.0\%$
R_D^μ	3.21 ± 0.77	24%	$8\% \oplus 5\% \to 9.4\%$	–
$\mathrm{Br}(D_s \to \mu\nu)$	$(5.51 \pm 0.16) \times 10^{-3}$	2.9%	$2.1\% \oplus 2.2\% \to 3.0\%$	$0.6\% \oplus 2.7\% \to 2.8\%$
$\mathrm{Br}(D_s \to \tau\nu)$	$(5.52 \pm 0.24) \times 10^{-2}$	4.3%	$1.6\% \oplus 2.4\% \to 2.9\%$	$0.3\% \oplus 1.0\% \to 1.0\%$
$R_{D_s}^\mu$	$10.2 \pm 0.5^\star$	$4.7\%^\star$	$2.6\% \oplus 2.8\% \to 3.8\%$	$0.9\% \oplus 3.2\% \to 3.3\%$

borrowed from S. Descotes-Genon

If violation LFU is confirmed, we expect it to occur in the charm sector too!

$$R_{D_{(s)}} \equiv \frac{\Gamma(D_{(s)} \to \tau\nu)}{\Gamma(D_{(s)} \to \mu\nu)}, \qquad R_D^{\rm SL} \equiv \frac{\Gamma(D \to \pi\mu\nu)}{\Gamma(D \to \pi e\nu)}$$

Adding NP contributions:

$$\mathcal{L}_{\rm eff} = -\frac{4G_F V_{cQ}}{\sqrt{2}}\Big[\Big(1+\epsilon_L^{(Q\tau)}\Big)\bar\tau\gamma_\mu P_L\nu_\tau\cdot\bar c\gamma^\mu P_L Q + \epsilon_R^{(Q\tau)}\bar\tau\gamma_\mu P_L\nu_\tau\cdot\bar c\gamma^\mu P_R Q$$
$$+\epsilon_T^{(Q\tau)}\,\bar\tau\sigma_{\mu\nu}P_L\nu_\tau\cdot\bar c\sigma^{\mu\nu}P_L Q + \epsilon_{S_L}^{(Q\tau)}\bar\tau P_L\nu_\tau\cdot\bar c P_L Q + \epsilon_{S_R}^{(Q\tau)}\bar\tau P_L\nu_\tau\cdot\bar c P_R Q\Big] + \text{h.c.}$$

$$\epsilon_P = \epsilon_{S_R} - \epsilon_{S_L}$$

$${\rm Br}(D_Q \to \tau\bar\nu_\tau) = \tau_{D_Q}\frac{m_{D_Q} m_\tau^2 f_D^2 G_F^2 |V_{cQ}|^2}{8\pi}\left(1-\frac{m_\tau^2}{m_{D_Q}^2}\right)^2\left|1+\epsilon_L^{(\tau)} + \frac{m_D^2}{m_\tau(m_Q+m_c)}\epsilon_P^{(\tau)}\right|^2$$

We can fix the coefficients to the best fit of the *B* charged-current anomalies and choose a *flavour structure* to relate $b \to c$ and $c \to u$

MFV: $\Delta R_{D_s} \lesssim \mathcal{O}(10^{-3})$, Anarchical: $\Delta R_{D_s} = \mathcal{O}(1-10)\%$

S. Descotes-Genon

Light dark sectors

Dark Matter exists! (About 27% of the energy of the universe)

Direct detection searches and LHC searches are giving increasingly tight constraints on WIMP models

It is the right time to consider *also* alternative paradigms, *e.g.* axions, dark photons, light DM/light dark sectors etc.

Axion-like-particles (ALPs), *often with flavour-violating couplings*, arise in any NP model with a spontaneously broken global U(1)

Flavour-violating axion-like-particles

- (Pseudo) Nambu-Goldstone bosons are naturally light and interact weakly with the SM (couplings suppressed by the U(1)-breaking scale)
- They can account for the observed DM (misalignment mechanism)
- Many well motivated scenarios (strong CP problem → PQ symmetry → axion, neutrino masses → lepton number → majoron, fermion hierarchies → family symmetry → familon, ...)
- Model-independently, the couplings to the SM fermions are of the form:

$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2 f_a}\, \bar{f}_i \gamma^\mu (C^V_{f_i f_j} + C^A_{f_i f_j}\gamma_5) f_j$$

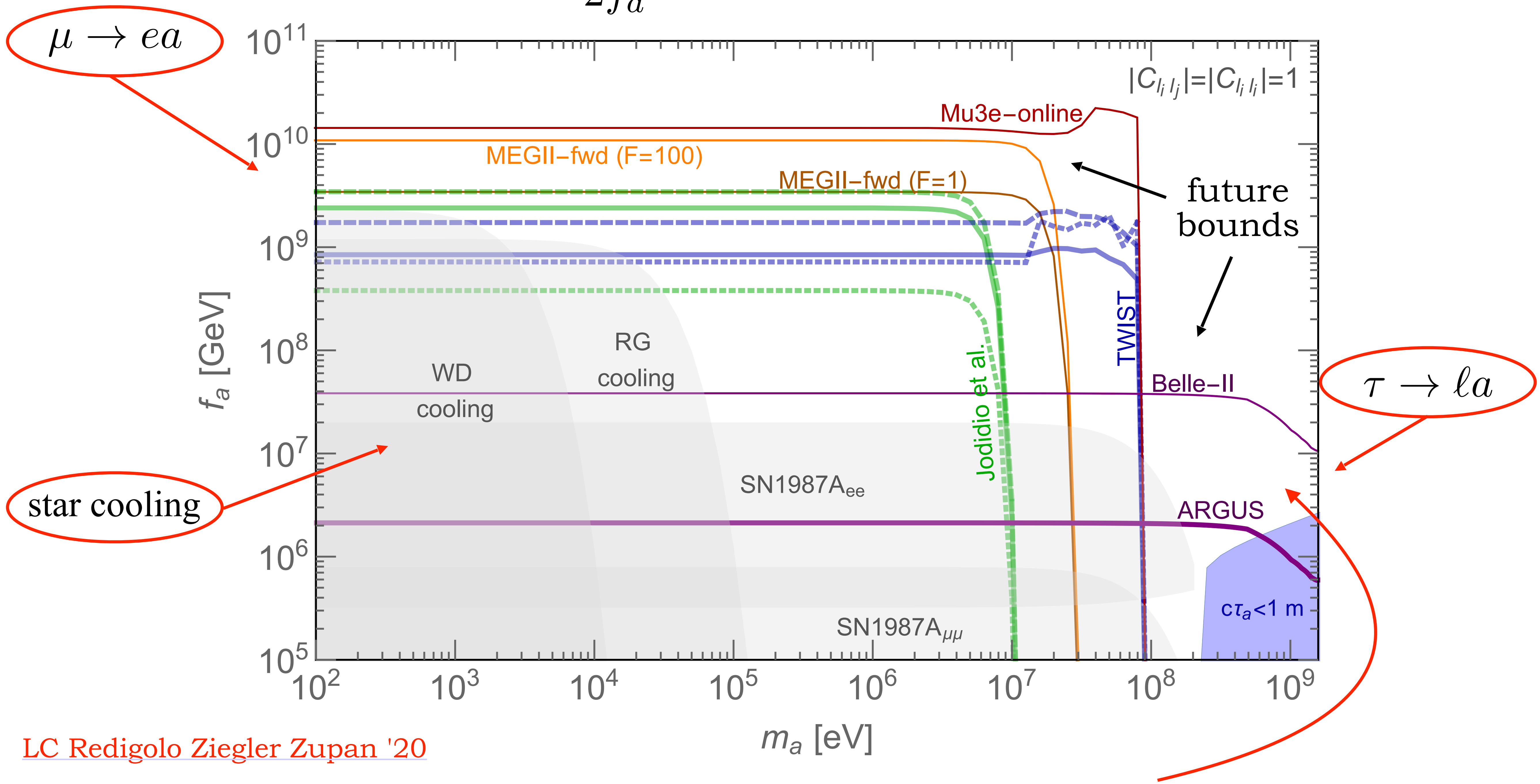
- Flavour-violating couplings can arise from loops or automatically if fermions have non- universal U(1) charges (e.g. “axiflavon” 1612.08040)

⇨ 2-body flavour-violating decays into a long-lived/invisible ALP:

$$K \to \pi a,\ D \to \pi a,\ B \to K a,\ \mu \to e a,\ \tau \to \mu a,\ \ldots$$

Lepton-flavour-violating invisible ALPs

$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2 f_a} \bar{f}_i \gamma^\mu (C^V_{f_i f_j} + C^A_{f_i f_j} \gamma_5) f_j$$



LC Redigolo Ziegler Zupan '20

If the ALP mass > m_μ, only constraints come from τ decays...

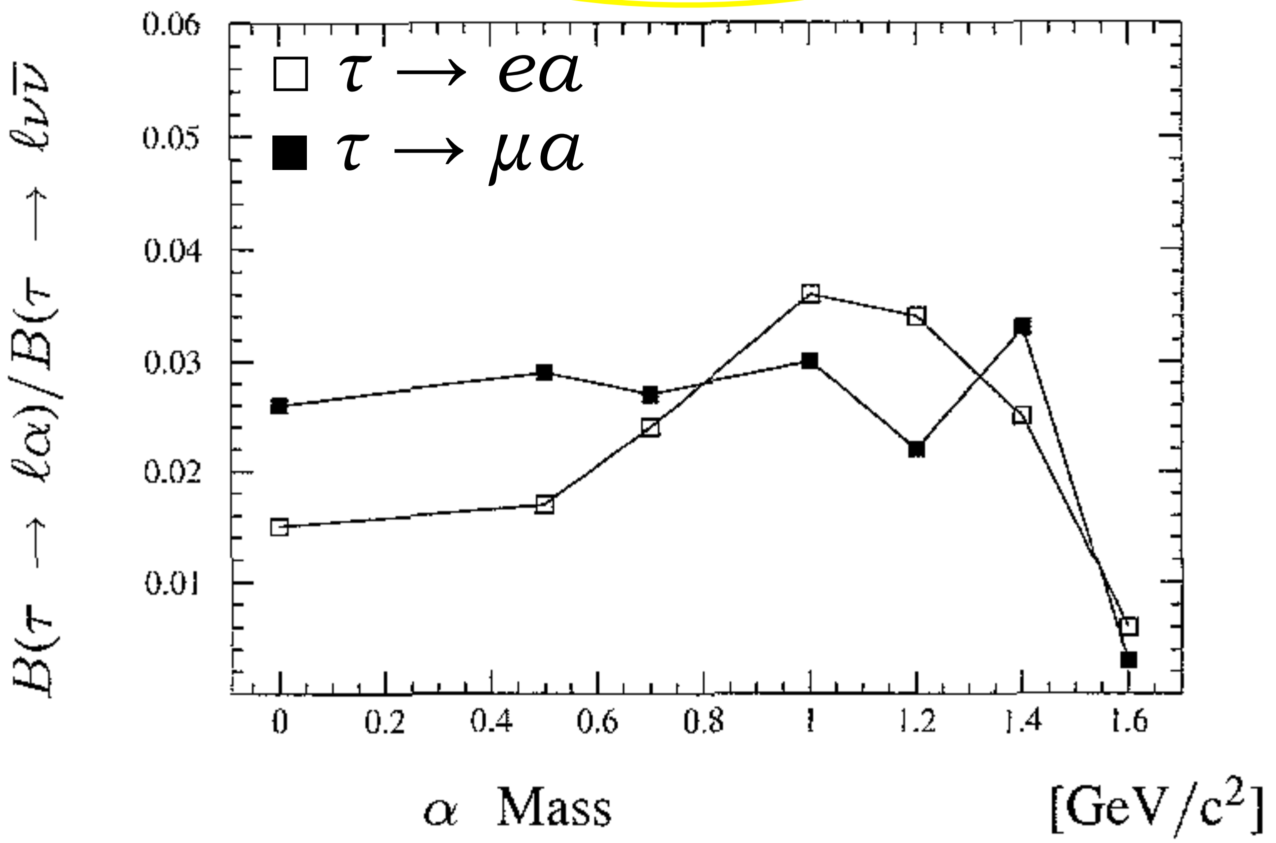
- ARGUS 1995

Z. Phys. C 68, 25–28 (1995)

A search for the lepton-flavour violating decays $\tau \longrightarrow e\alpha$, $\tau \longrightarrow \mu\alpha$

ARGUS Collaboration

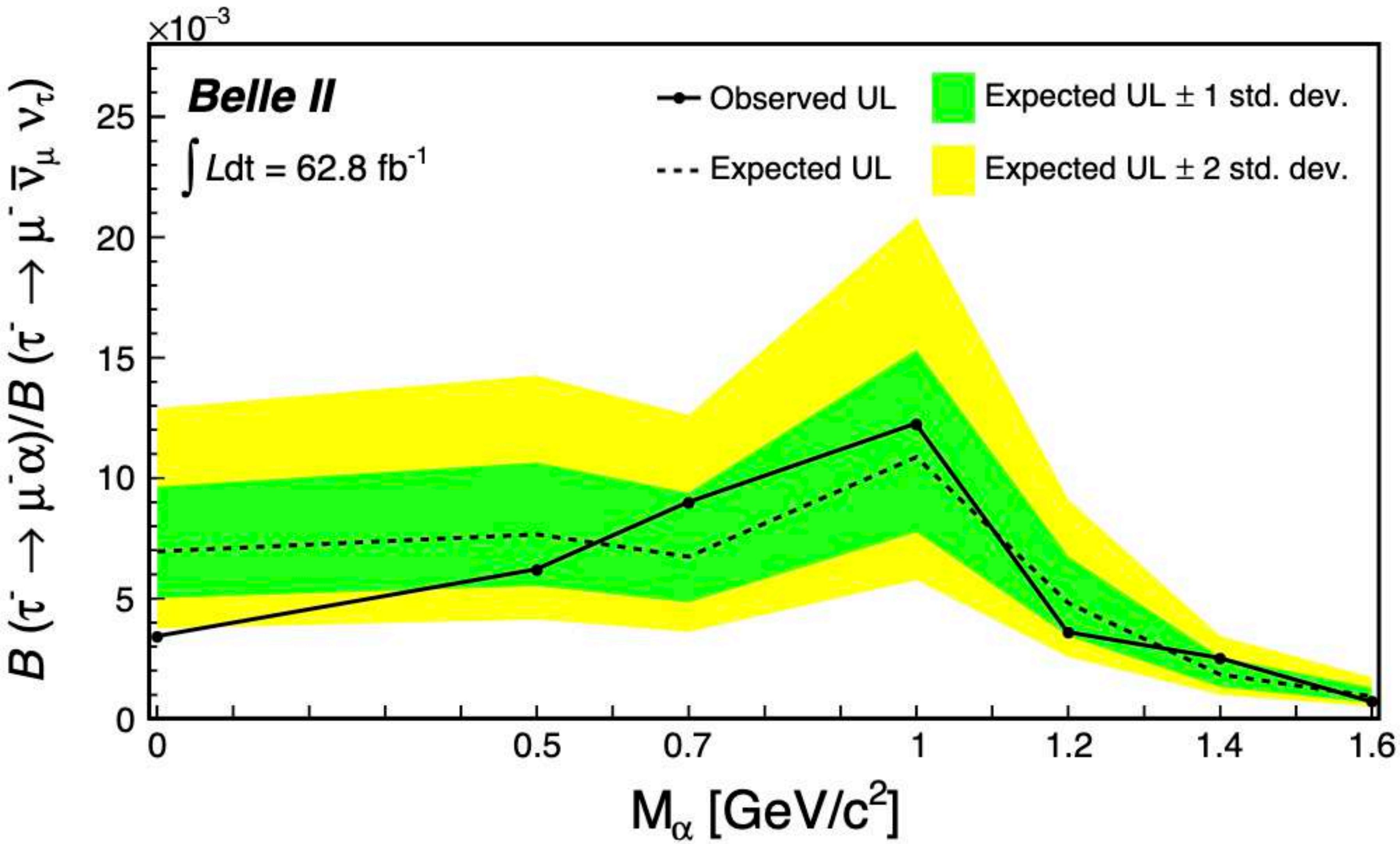
With 472 pb^{-1}:



$m_a \approx 0$:

$$\mathrm{BR}(\tau \to e\, a) < 2.7 \times 10^{-3} \quad (95\%\ \mathrm{CL}) \quad \Rightarrow \quad F_{\tau e} \gtrsim 4.3 \times 10^{6}\ \mathrm{GeV}\,,$$
$$\mathrm{BR}(\tau \to \mu\, a) < 4.5 \times 10^{-3} \quad (95\%\ \mathrm{CL}) \quad \Rightarrow \quad F_{\tau \mu} \gtrsim 3.3 \times 10^{6}\ \mathrm{GeV}\,.$$

- NEW! Belle II, Phys.Rev.Lett. 130 (2023)



$$m_a \approx 0, \quad \mathrm{BR}(\tau \to \mu a) \simeq 7 \times 10^{-4}, \quad \mathrm{BR}(\tau \to e a) \simeq 9 \times 10^{-4}$$

Large room for improvement: can BESIII/STCF play a role here?

Flavour-violating axions/ALPs couplings to quarks

$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2 f_a}\, \bar{f}_i \gamma^\mu (C^V_{f_i f_j} + C^A_{f_i f_j}\gamma_5) f_j$$

vector coupling → $P_1 \to P_2 + a \quad (D \to \pi + a)$

axial coupling → $P_1 \to V_2 + a \quad (D \to \rho + a)$

(because strong interactions conserve parity)

Decay	sd	cu	bd	bs
$\mathrm{BR}(P_1 \to P_2 + a)$	7.3×10^{-11} [89]	No analysis	4.9×10^{-5} [90]	4.9×10^{-5} [90]
$\mathrm{BR}(P_1 \to P_2 + a)_{\mathrm{recast}}$	No need	8.0×10^{-6} [93]	2.3×10^{-5} [92]	7.1×10^{-6} [91]
$\mathrm{BR}(P_1 \to P_2 + \nu\bar{\nu})$	$1.47^{+1.30}_{-0.89} \times 10^{-10}$ [89]	No analysis	0.8×10^{-5} [94]	1.6×10^{-5} [94]
$\mathrm{BR}(P_1 \to V_2 + a)$	3.8×10^{-5} [98]	No analysis	No analysis	No analysis
$\mathrm{BR}(P_1 \to V_2 + a)_{\mathrm{recast}}$	No need	No data	No data	5.3×10^{-5} [91]
$\mathrm{BR}(P_1 \to V_2 + \nu\bar{\nu})$	4.3×10^{-5} [98]	No analysis	2.8×10^{-5} [94]	2.7×10^{-5} [94]

No dedicated searches for D to axion decays

Recasting data from $D^+ \to \tau^+(\to \pi^+\nu)\,\nu$ (CLEO 2008):

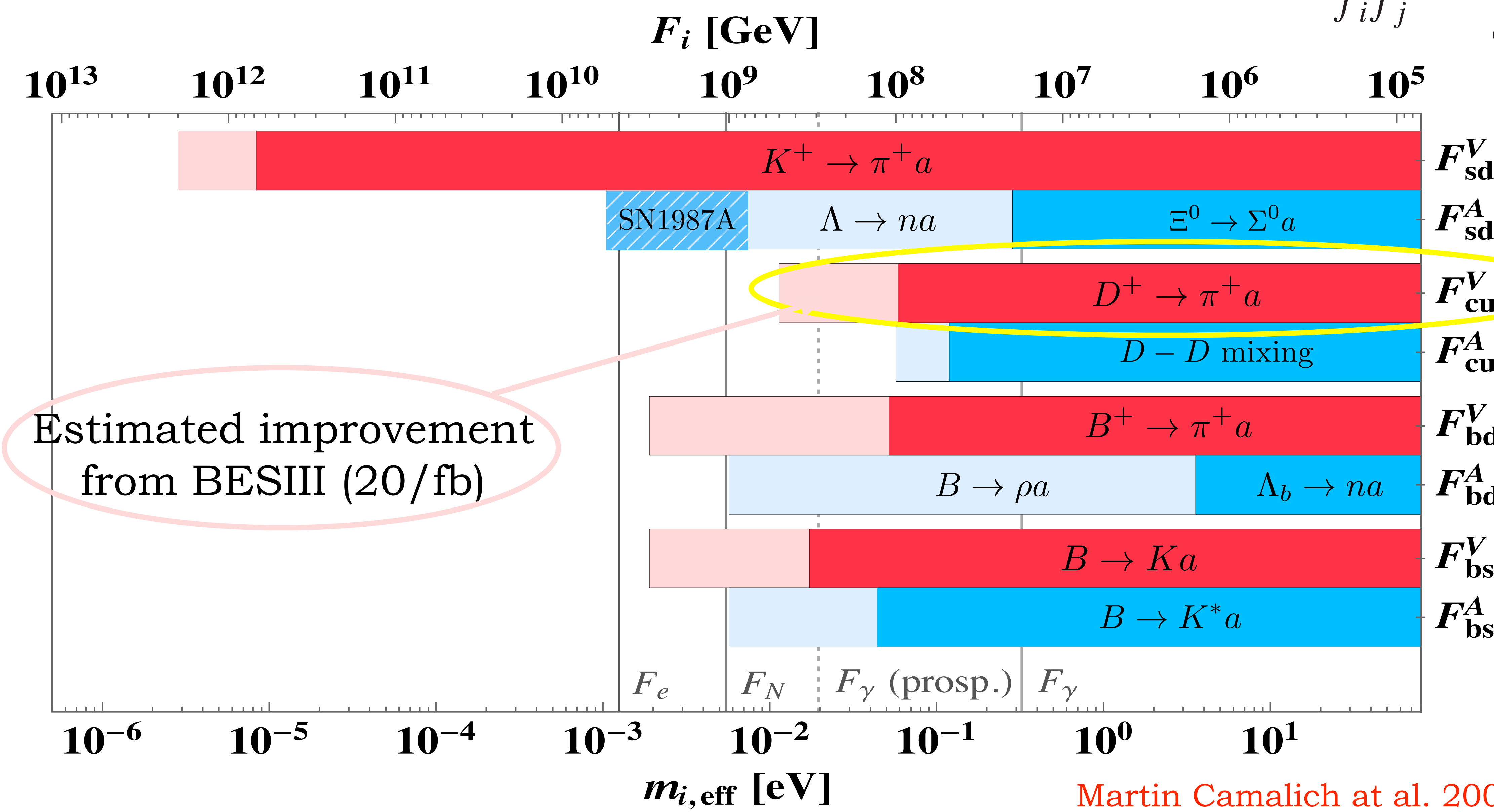
$$\mathrm{BR}(D^+ \to \pi^+ a) < 8 \times 10^{-6}$$

Martin Camalich at al. 2002.04623

Flavour-violating axions/ALPs couplings to quarks

$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2f_a}\,\bar{f}_i\gamma^\mu(C^V_{f_if_j} + C^A_{f_if_j}\gamma_5)f_j$$

$$F^{V,A}_{f_if_j} \equiv \frac{2f_a}{c^{V,A}_{f_if_j}}$$



Martin Camalich at al. 2002.04623

What about flavour-conserving couplings? E.g. to charm and muon in

$$D^+ \to \mu^+ \nu a \quad \text{or} \quad J/\psi \to \mu^+\mu^- a$$

Personal view about new physics searches at tau-charm energies:

J/ψ LFV rates seriously limited by indirect constraints (but it's important to keep searching for it: NP may evade our EFT approach)

Tests for LFU (e.g. in D decays) even more interesting than CLFV

Great potential for exploring light dark sectors in *semi-invisible* decays of tau, D, J/ψ … !

Thanks!

谢谢!

Additional slides

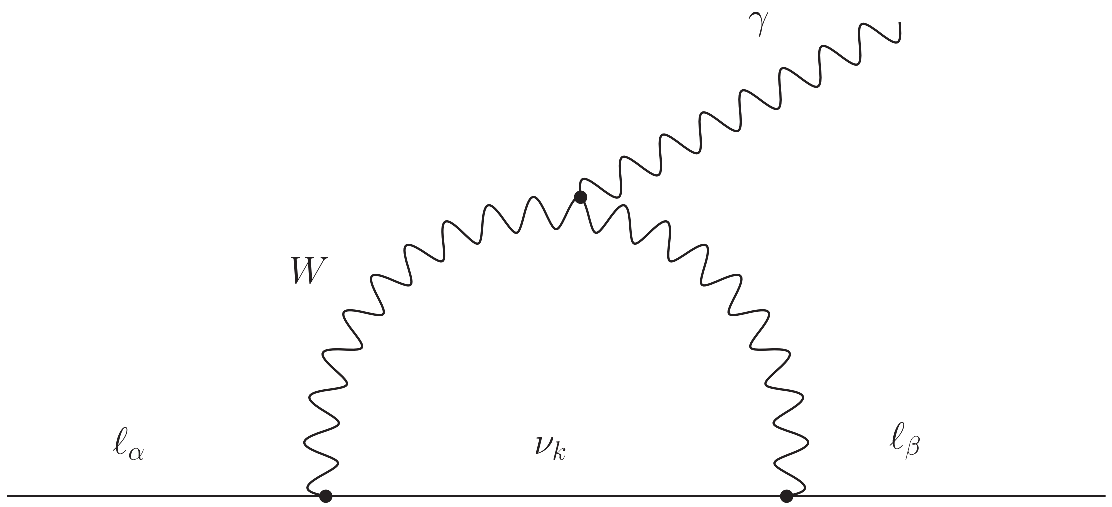
Why are we interested in CLFV?

- Neutrinos oscillate → Lepton family numbers are not conserved!
(while they would be exact global symmetries, if neutrinos were massless)

- Neutrino mass eigenstates couple to charged leptons of different flavours through the PMNS

- In the SM + massive neutrinos:

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu \bar{\nu})} = \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} U_{\alpha k} U^*_{\beta k} \frac{m^2_{\nu_k}}{M^2_W} \right|^2$$

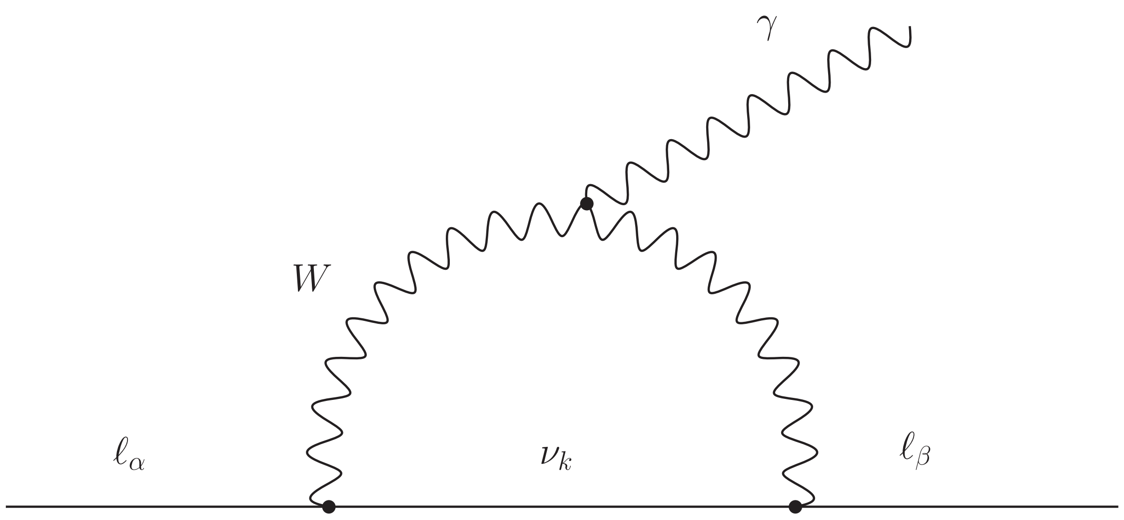


Cheng Li '77, '80; Petcov '77

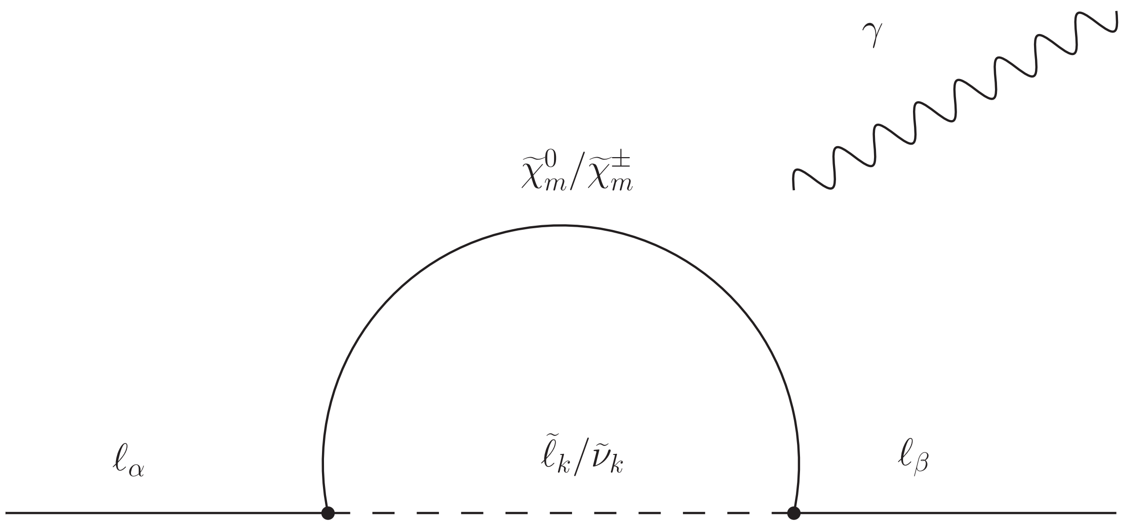
⇨ $\text{BR}(\mu \to e\gamma) \approx \text{BR}(\tau \to e\gamma) \approx \text{BR}(\tau \to \mu\gamma) = 10^{-55} \div 10^{-54}$

Large mixing, but huge suppression due to small neutrino masses

⇨ In presence of NP at the TeV we can expect large effects



e.g. SUSY



Borzumati Masiero '86;
Hisano et al. '95

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu \bar{\nu})} = \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} U_{\alpha k} U^*_{\beta k} \frac{m^2_{\nu_k}}{M^2_W} \right|^2$$

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu \bar{\nu})} \sim \frac{|\delta_{\alpha\beta}|^2}{G_F^2 \, m^4_{\text{SUSY}}}$$

- Unambiguous signal of New Physics (beyond neutrino masses)
- Stringent test of any NP coupling to leptons
- Probe of scales far beyond the LHC reach

⇨ For a pedagogical introduction (exp + th) cf. LC and Signorelli '17

… and we have experiments!

LFV observable	Present bounds		Expected future limits	
$\mathrm{BR}(\mu \to e\gamma)$	4.2×10^{-13}	MEG (2016) [28]	6×10^{-14}	MEG II [29]
$\mathrm{BR}(\mu \to eee)$	1.0×10^{-12}	SINDRUM (1988) [30]	10^{-16}	Mu3e [31]
$\mathrm{CR}(\mu \to e, \mathrm{Au})$	7.0×10^{-13}	SINDRUM II (2006) [32]		–
$\mathrm{CR}(\mu \to e, \mathrm{Al})$		–	6×10^{-17}	COMET/Mu2e [33, 34]
$\mathrm{BR}(Z \to e\mu)$	2.62×10^{-7}	ATLAS (2022) [35]	$10^{-8} - 10^{-10}$	FCC-ee/CEPC [36]
$\mathrm{BR}(\tau \to e\gamma)$	3.3×10^{-8}	BaBar (2010) [37]	9×10^{-9}	Belle II [25, 38]
$\mathrm{BR}(\tau \to eee)$	2.7×10^{-8}	Belle (2010) [39]	4.7×10^{-10}	Belle II [25, 38]
$\mathrm{BR}(\tau \to e\mu\mu)$	2.7×10^{-8}	Belle (2010) [39]	4.5×10^{-10}	Belle II [25, 38]
$\mathrm{BR}(\tau \to \pi e)$	8.0×10^{-8}	Belle (2007) [40]	7.3×10^{-10}	Belle II [25, 38]
$\mathrm{BR}(\tau \to \rho e)$	1.8×10^{-8}	Belle (2011) [41]	3.8×10^{-10}	Belle II [25, 38]
$\mathrm{BR}(Z \to e\tau)$	5.0×10^{-6}	ATLAS (2021) [42]	10^{-9}	FCC-ee/CEPC [36]
$\mathrm{BR}(\tau \to \mu\gamma)$	4.2×10^{-8}	Belle (2021) [43]	6.9×10^{-9}	Belle II [25, 38]
$\mathrm{BR}(\tau \to \mu\mu\mu)$	2.1×10^{-8}	Belle (2010) [39]	3.6×10^{-10}	Belle II [25, 38]
$\mathrm{BR}(\tau \to \mu ee)$	1.8×10^{-8}	Belle (2010) [39]	2.9×10^{-10}	Belle II [25, 38]
$\mathrm{BR}(\tau \to \pi\mu)$	1.1×10^{-7}	Babar (2006) [44]	7.1×10^{-10}	Belle II [25, 38]
$\mathrm{BR}(\tau \to \rho\mu)$	1.2×10^{-8}	Belle (2011) [41]	5.5×10^{-10}	Belle II [25, 38]
$\mathrm{BR}(Z \to \mu\tau)$	6.5×10^{-6}	ATLAS (2021) [42]	10^{-9}	FCC-ee/CEPC [36]

Table 2: Present 90% CL upper limits (95% CL for the Z decays) and future expected sensitivities for the set of LFV transitions relevant for our analysis.

→ searches for muon LFV will soon test new physics up to scales of the order of 10^7–10^8 GeV

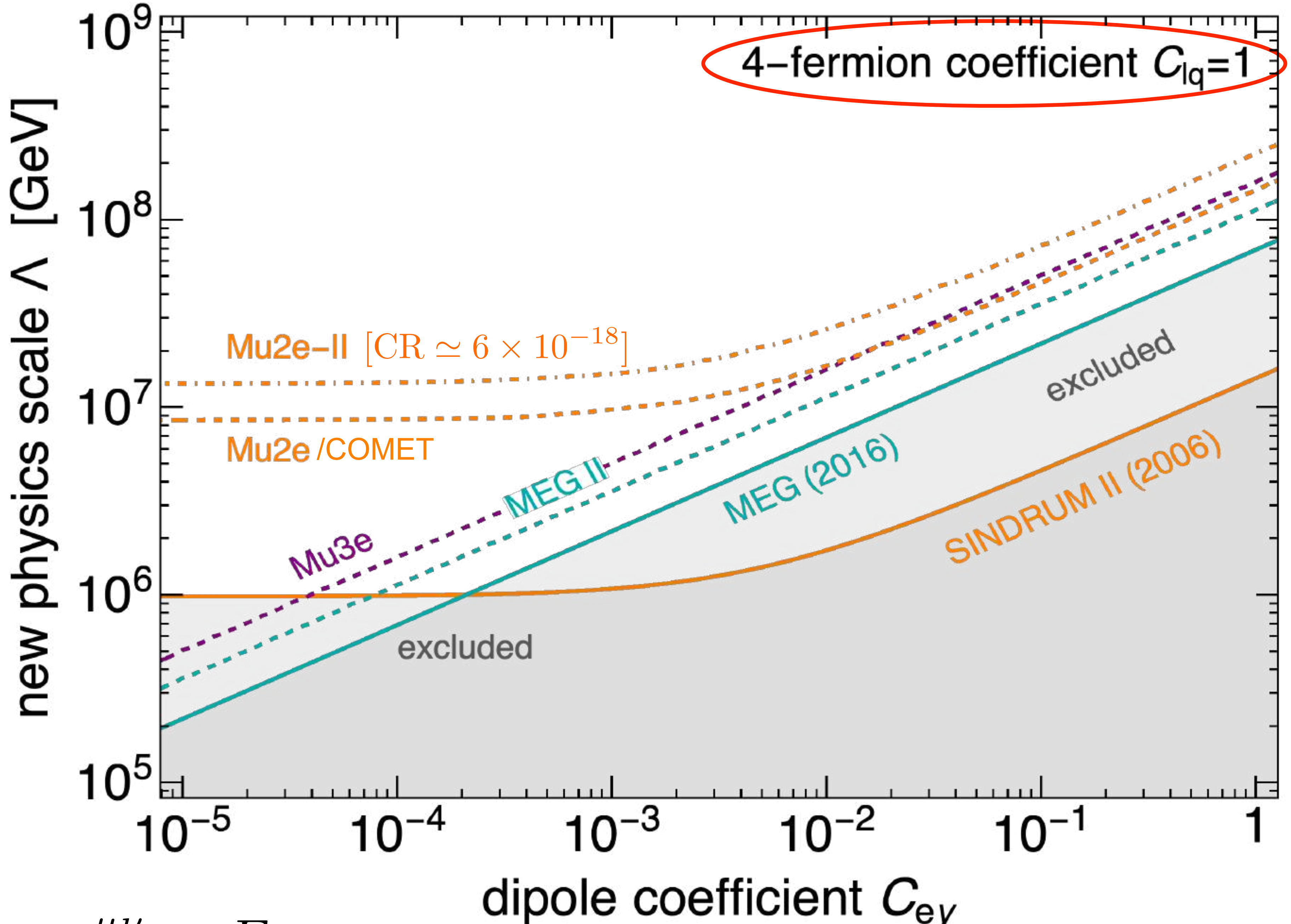
Probing very high-energy scales

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \dots$$

	$\lvert C_a\rvert$ [$\Lambda = 1$ TeV]	Λ (TeV) [$\lvert C_a\rvert = 1$]	CLFV Process
$C_{e\gamma}^{\mu e}$	2.1×10^{-10}	6.8×10^4	$\mu \to e\gamma$
$C_{\ell e}^{\mu\mu\mu e, e\mu\mu\mu}$	1.8×10^{-4}	75	$\mu \to e\gamma$ [1-loop]
$C_{\ell e}^{\mu\tau\tau e, e\tau\tau\mu}$	1.0×10^{-5}	312	$\mu \to e\gamma$ [1-loop]
$C_{e\gamma}^{\mu e}$	4.0×10^{-9}	1.6×10^4	$\mu \to eee$
$C_{\ell\ell, ee}^{\mu eee}$	2.3×10^{-5}	207	$\mu \to eee$
$C_{\ell e}^{\mu eee, ee\mu e}$	3.3×10^{-5}	174	$\mu \to eee$
$C_{e\gamma}^{\mu e}$	5.2×10^{-9}	1.4×10^4	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$
$C_{\ell q, \ell d, ed}^{e\mu}$	1.8×10^{-6}	745	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$
$C_{eq}^{e\mu}$	9.2×10^{-7}	1.0×10^3	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$
$C_{\ell u, eu}^{e\mu}$	2.0×10^{-6}	707	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$
$C_{e\gamma}^{\tau\mu}$	2.7×10^{-6}	610	$\tau \to \mu\gamma$
$C_{e\gamma}^{\tau e}$	2.4×10^{-6}	650	$\tau \to e\gamma$
$C_{\ell\ell, ee}^{\mu\tau\mu\mu}$	7.8×10^{-3}	11.3	$\tau \to \mu\mu\mu$
$C_{\ell e}^{\mu\tau\mu\mu, \mu\mu\mu\tau}$	1.1×10^{-2}	9.5	$\tau \to \mu\mu\mu$
$C_{\ell\ell, ee}^{e\tau ee}$	9.2×10^{-3}	10.4	$\tau \to eee$
$C_{\ell e}^{e\tau ee, eee\tau}$	1.3×10^{-2}	8.8	$\tau \to eee$

Example: dipole *and* 4-fermion operators

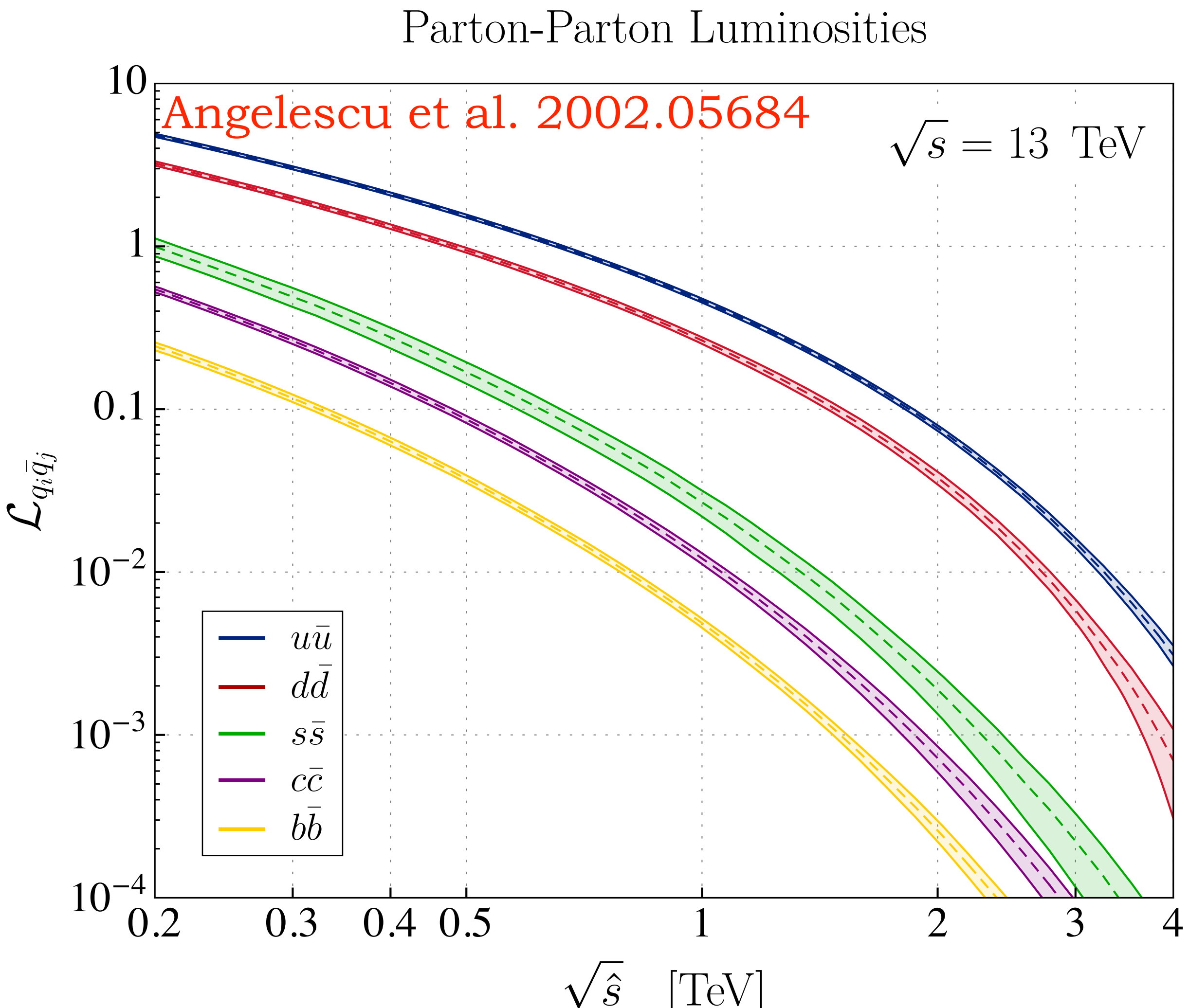
$$\frac{C_{\ell q}}{\Lambda^2}\,(\overline{e}_L\,\gamma^\mu\,\mu_L)\,(\overline{Q}\,\gamma_\mu Q)$$

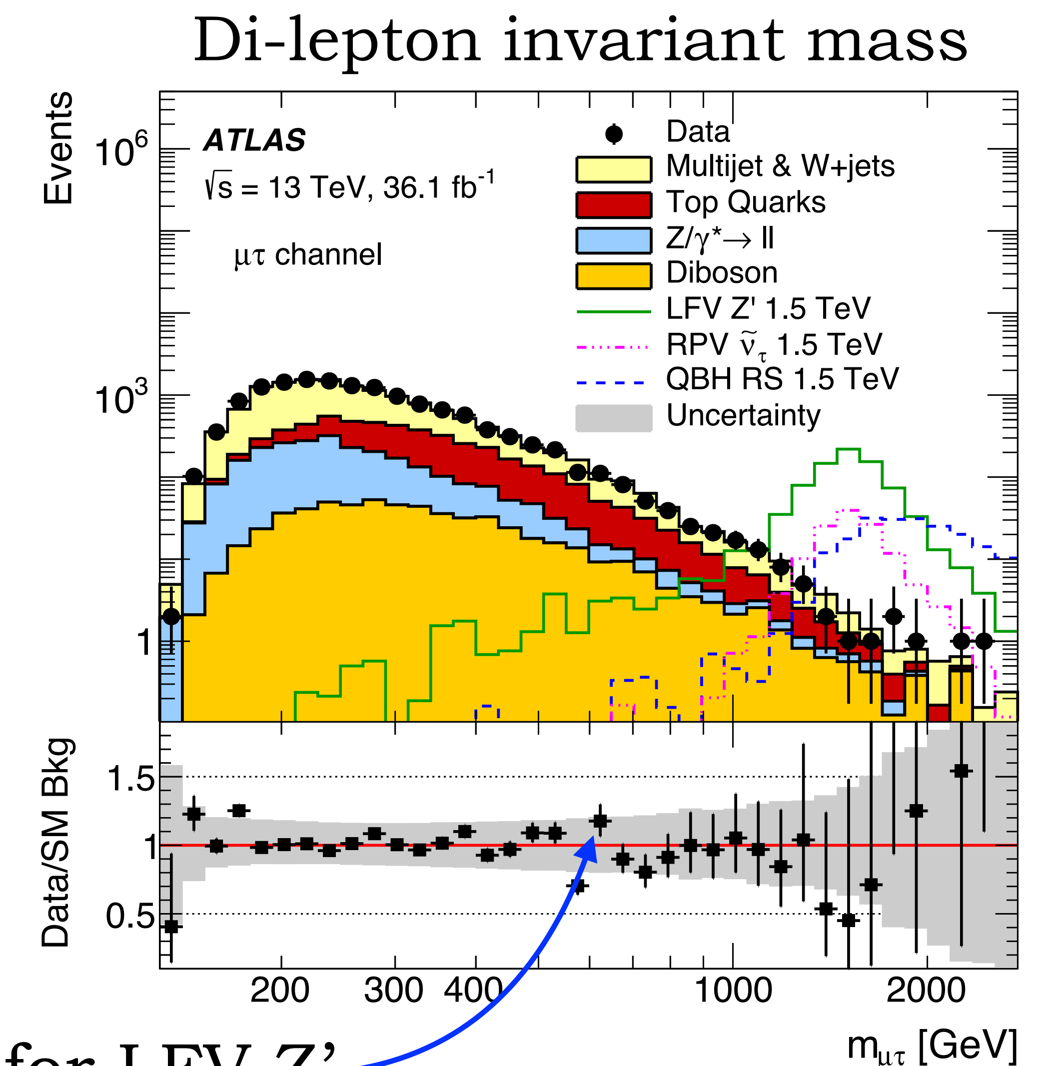


$$\frac{C_{e\gamma}}{\Lambda^2}\,\langle H\rangle\,\overline{e}_L\,\sigma^{\mu\nu}\,\mu_R\,F_{\mu\nu}$$

Mu2e-II Snowmass, arXiv:2203.07569

Many $\bar{c}c$ scatterings in pp collisions at the LHC





LHC di-lepton tails constrain $\bar{c}c\,\bar{\ell}_i\ell_j$ contact interactions up to Λ > 2-3 TeV

⇒ Indirect LHC bounds (if EFT is valid):

$$\mathrm{BR}(J/\psi \to e\mu) < 10^{-11},\quad \mathrm{BR}(J/\psi \to e\tau) < 6\times 10^{-11},\quad \mathrm{BR}(J/\psi \to \mu\tau) < 7\times 10^{-11}$$

Angelescu et al. 2002.05684

Comparison of indirect constraints