IAS Program on High Energy Physics

Lepton-flavour-violating Z and quarkonium decays

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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

LFV decays of the Z

mainly based on LC, X. Marcano, J. Roy arXiv:2107.10273

Present limits on LFV Z decays

with 4×10^6 Zs

Mode	LEP bound (95% CL)	LHC bound (95% CL)
$\mathrm{BR}(Z \to \mu e)$	$< 1.7 \times 10^{-6}$	$< 7.5 \times 10^{-7}$
$\mathrm{BR}(Z \to \tau e)$	$< 9.8 \times 10^{-6}$	$< 5.0 \times 10^{-6}$
$\mathrm{BR}(Z \to \tau \mu)$	$< 1.2 \times 10^{-5}$	$< 6.5 \times 10^{-6}$

no candidates

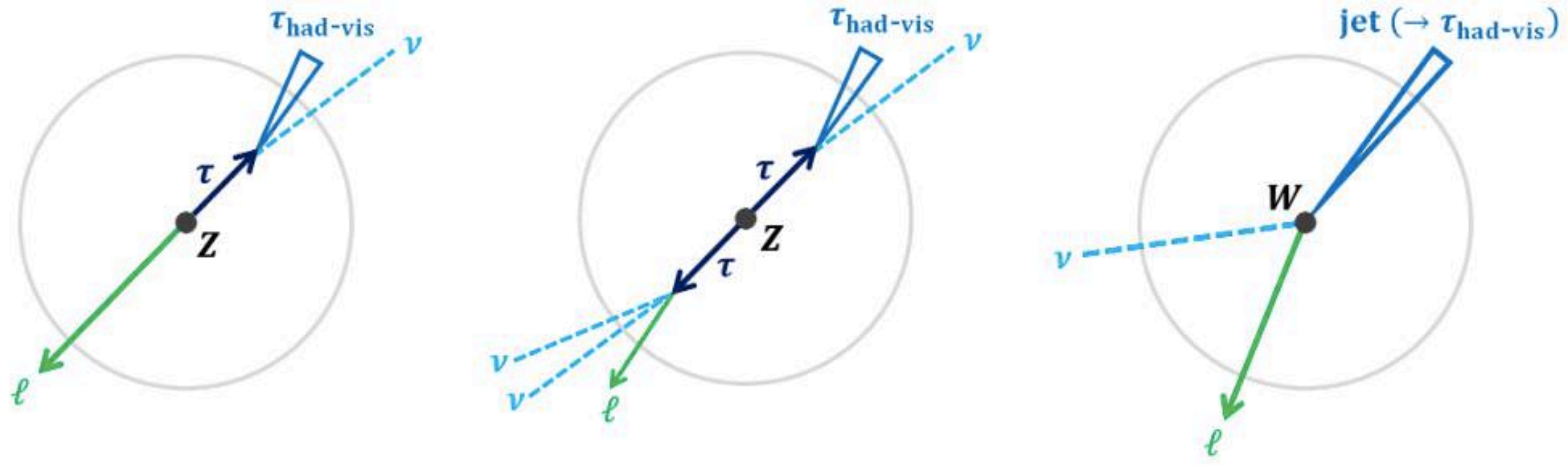
8 TeV, 20/fb

8+13 TeV, (20+139)/fb

OPAL '95, DELPHI '97

ATLAS '21 (2105.12491)

$Z\to\tau\tau$ bg



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$\mathrm{BR}(Z \to \tau \mu)$	$< 1.2 \times 10^{-5}$	$< 6.5 \times 10^{-6}$	8+13 TeV, (20+139)/fb

OPAL ’95, DELPHI ‘97

ATLAS ’21 (2105.12491)

$Z\to\tau\tau$ bg

- LHC searches limited by backgrounds (in particular $Z \to \tau\tau$): max ~10 improvement can be expected at HL-LHC (3000/fb)
- Operating as a “Tera-Z” factory (running at the Z pole and collecting ~10^{12} Zs) CEPC/FCC-ee can definitely reach better sensitivities

Z LFV prospects

A study in the context of the FCC-ee (5×10^{12} Zs):

- $Z \to \mu e$:

M. Dam @ Tau '18 & 1811.09408

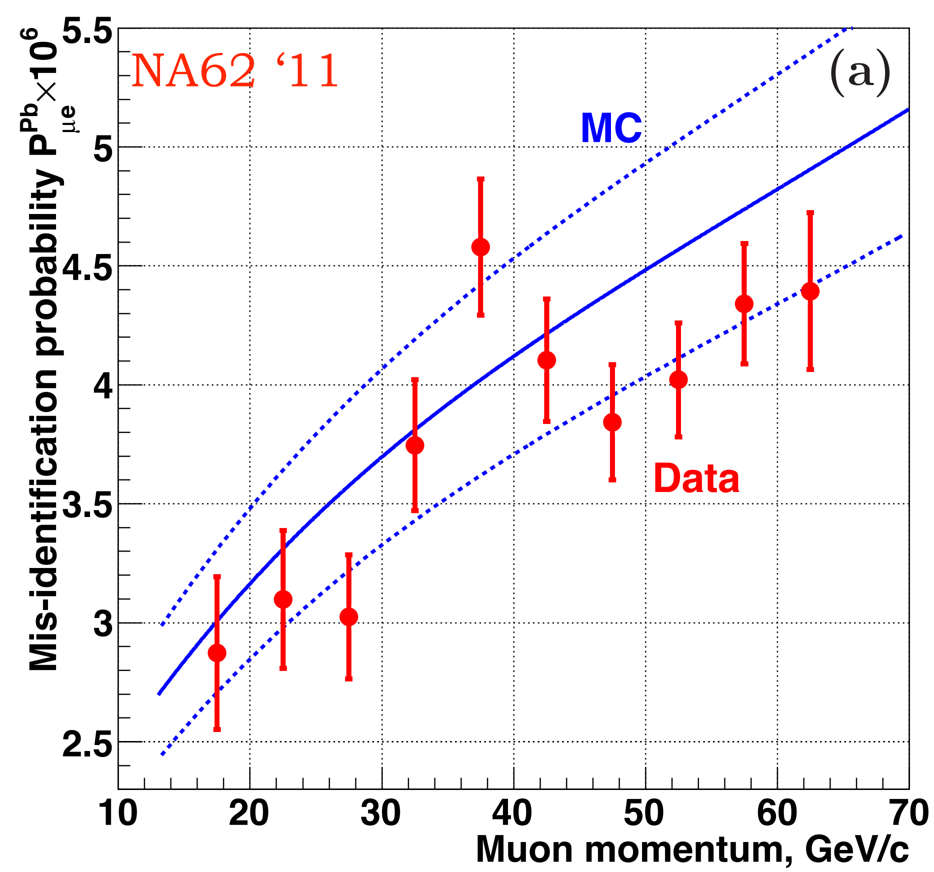
In contrast to the LHC, no background from $Z \to \tau\tau$:

Z mass constraint much more effective (collision energy is known)

→ background rate < 10^{-11} (with a 0.1% momentum resolution at ~45 GeV)

Main issue: muons can release enough brems. energy in the ECAL to be mis-id as electrons. Mis-id probability measured by NA62 for a LKr ECAL: 4×10^{-6} (for p_μ~45 GeV)

⇨ Bg. from $Z \to \mu\mu$ + mis-id μ (3×10^{-7} of all Z decays)



Sensitivity limited to: $\mathrm{BR}(Z \to \mu e) \sim 10^{-8}$

(Improved e/μ separation? Down to 10^{-10})

Z LFV prospects

A study in the context of the FCC-ee (5×10^{12} Zs):

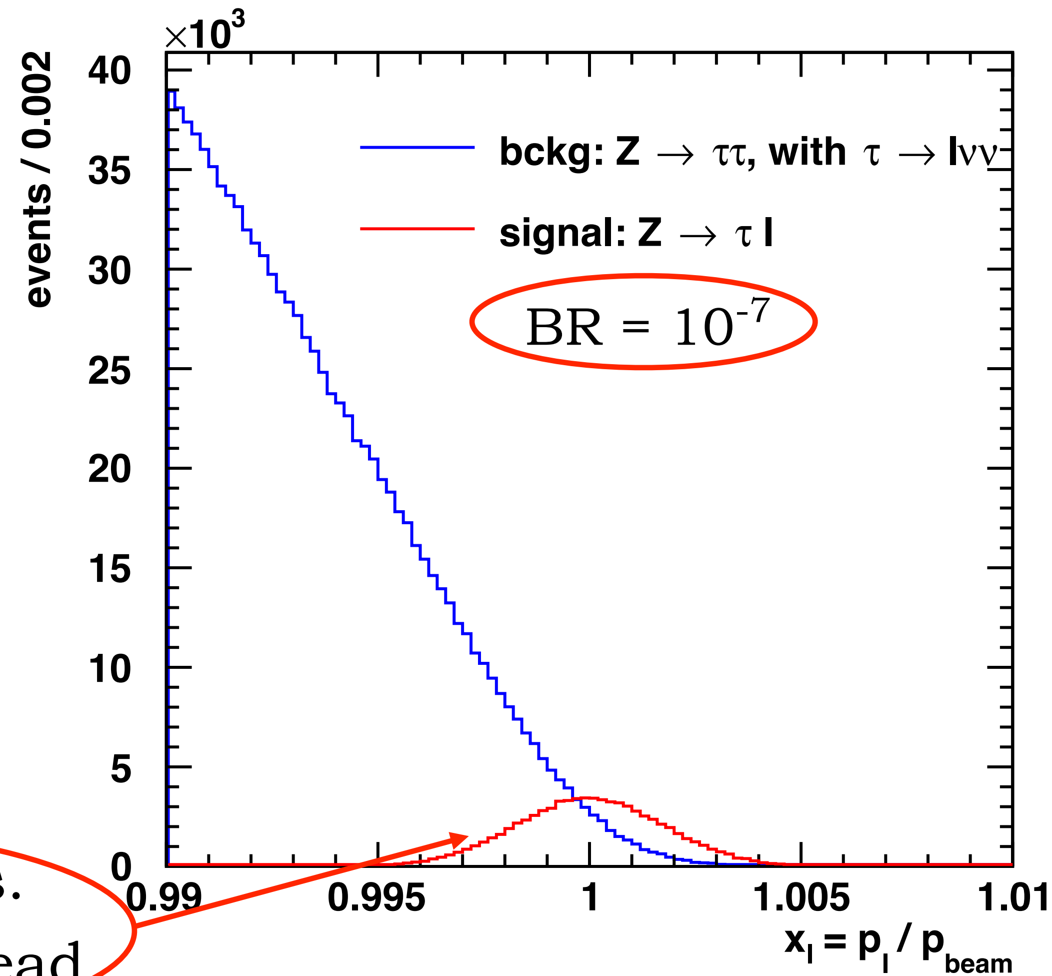
- $Z \to \ell\tau$:

M. Dam @ Tau ’18 & 1811.09408

To avoid mis-id, select one hadronic τ (≥3 prong, or reconstructed excl. mode)

Main background from $Z \to \tau\tau$ (with one leptonic τ decay)

Simulated signal & background:

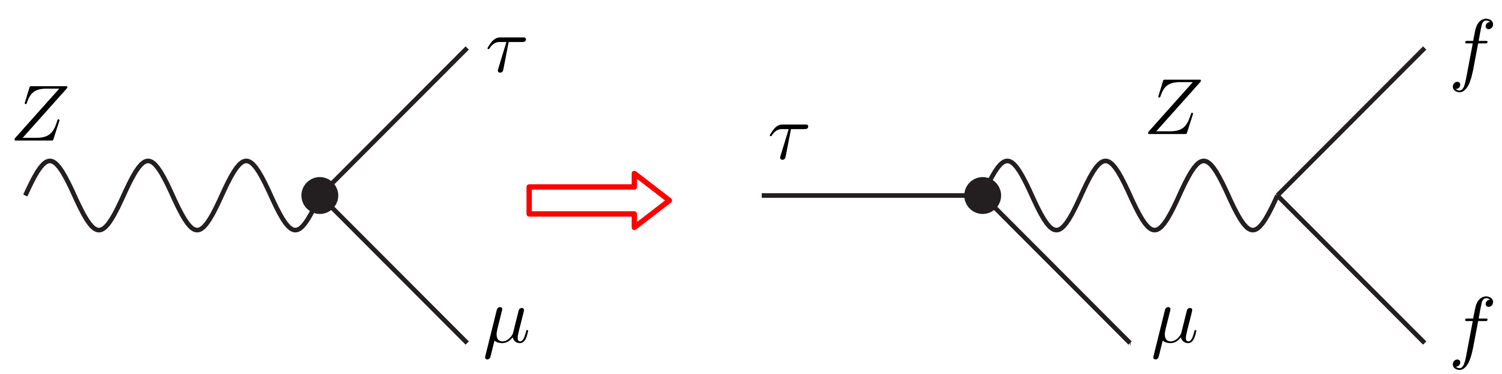


~10^{-3} momentum res.
& ~10^{-3} collision E spread

Sensitivity:
$\mathrm{BR}(Z \to \ell\tau) \sim 10^{-9}$

- CEPC/FCC-ee can improve on present LHC (future HL-LHC) bounds up to 4 (3) orders of magnitude, at least for the $Z \to \tau\ell$ modes
- The question is: can we find new physics searching for these modes?
- It depends on the indirect constraints from other processes
- In particular low-energy LFV decays are unavoidably induced

e.g. :



$\tau \to \mu\,\ell\ell$

$\tau \to \mu\,\pi$

$\tau \to \mu\,\rho$

$\dots$

Previous related studies:

Nussinov Peccei Zhang ’00; Delepine Vissani ’01; Gutsche et al. ’11; Crivellin Najjari Rosiek ’13; ...

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			
$Q^{(1)}_{\ell q}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{Q}_L\gamma^\mu Q_L)$	$Q_{\ell u}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{u}_R\gamma^\mu u_R)$
$Q^{(3)}_{\ell q}$	$(\bar{L}_L\gamma_\mu\tau_I L_L)(\bar{Q}_L\gamma^\mu\tau_I Q_L)$	Q_{eu}	$(\bar{e}_R\gamma_\mu e_R)(\bar{u}_R\gamma^\mu u_R)$
Q_{eq}	$(\bar{e}_R\gamma^\mu e_R)(\bar{Q}_L\gamma_\mu Q_L)$	$Q_{\ell edq}$	$(\bar{L}^a_L e_R)(\bar{d}_R Q^a_L)$
$Q_{\ell d}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{d}_R\gamma^\mu d_R)$	$Q^{(1)}_{\ell equ}$	$(\bar{L}^a_L e_R)\epsilon_{ab}(\bar{Q}^b_L u_R)$
Q_{ed}	$(\bar{e}_R\gamma_\mu e_R)(\bar{d}_R\gamma^\mu d_R)$	$Q^{(3)}_{\ell equ}$	$(\bar{L}^a_i\sigma_{\mu\nu}e_R)\epsilon_{ab}(\bar{Q}^b_L\sigma^{\mu\nu}u_R)$
Lepton-Higgs operators			
$Q^{(1)}_{\Phi\ell}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{L}_L\gamma^\mu L_L)$	$Q^{(3)}_{\Phi\ell}$	$(\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar{L}_L\tau_I\gamma^\mu L_L)$
$Q_{\Phi e}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}_R\gamma^\mu e_R)$	$Q_{e\Phi 3}$	$(\bar{L}_L e_R\Phi)(\Phi^\dagger\Phi)$

Grzadkowski et al. ’10; Crivellin Najjari Rosiek ‘13

The couplings of Z to leptons are protected by the SM gauge symmetry
→ LFV effects must be proportional to the EW breaking:

$$\mathrm{BR}(Z\to\ell\ell')\sim\mathrm{BR}(Z\to\ell\ell)\times C^2_{\mathrm{NP}}\left(\frac{v}{\Lambda_{\mathrm{NP}}}\right)^4$$

In the SM EFT, only 5 operators contribute at the tree level:

$$Q^{(1)}_{\Phi\ell}=(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar\ell_L\gamma^\mu\ell'_L),\qquad Q^{(3)}_{\Phi\ell}=(\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar\ell_L\tau_I\gamma^\mu\ell'_L),\qquad Q_{\Phi e}=(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar\ell_R\gamma^\mu\ell'_R)$$

$$Q_{eW}=(\bar\ell_L\sigma^{\mu\nu}\ell'_R)\tau_I\Phi\, W^I_{\mu\nu},\qquad Q_{eB}=(\bar\ell_L\sigma^{\mu\nu}\ell'_R)\Phi\, B_{\mu\nu}$$

$$\mathrm{BR}\left(Z\to\ell_i\ell_j\right)=\frac{m_Z}{12\pi\Gamma_Z}\left\{\left|g_{VR}\delta_{ij}+\delta g^{ij}_{VR}\right|^2+\left|g_{VL}\delta_{ij}+\delta g^{ij}_{VL}\right|^2+\frac{m_Z^2}{2}\left(\left|\delta g^{ij}_{TR}\right|^2+\left|\delta g^{ij}_{TL}\right|^2\right)\right\}$$

$$\mathcal{L}^Z_{\mathrm{eff}}=\Big[\left(g_{VR}\,\delta_{ij}+\delta g^{ij}_{VR}\right)\ \bar\ell_i\gamma^\mu P_R\ell_j\ +\ \left(g_{VL}\,\delta_{ij}+\delta g^{ij}_{VL}\right)\ \bar\ell_i\gamma^\mu P_L\ell_j\Big]Z_\mu\ +$$
$$\Big[\delta g^{ij}_{TR}\ \bar\ell_i\sigma^{\mu\nu}P_R\ell_j\ +\ g^{ij}_{TL}\ \bar\ell_i\sigma^{\mu\nu}P_L\ell_j\Big]Z_{\mu\nu}\ +\ h.c.\,,$$

The couplings of Z to leptons are protected by the SM gauge symmetry
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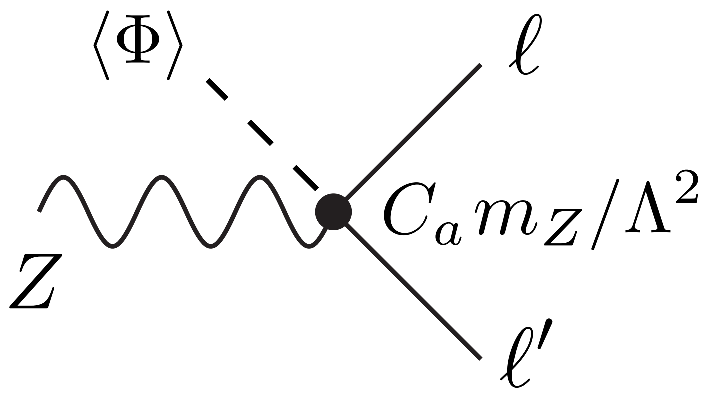
$$\mathrm{BR}\left(Z \to \ell_i \ell_j\right) = \frac{m_Z}{12\pi\Gamma_Z} \left\{ \left| g_{VR}\delta_{ij} + \delta g^{ij}_{VR} \right|^2 + \left| g_{VL}\delta_{ij} + \delta g^{ij}_{VL} \right|^2 + \frac{m_Z^2}{2} \left(\left| \delta g^{ij}_{TR} \right|^2 + \left| \delta g^{ij}_{TL} \right|^2 \right) \right\}$$

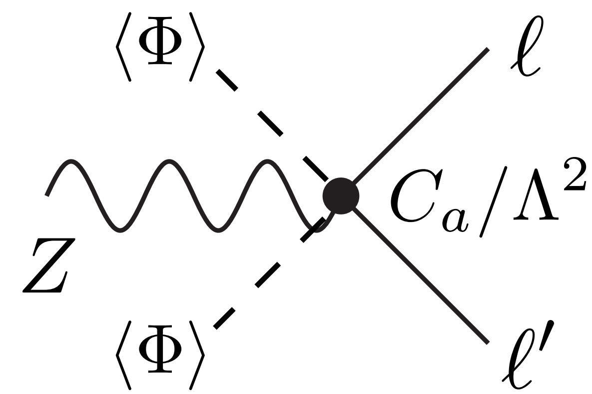
$$\delta g^{ij}_{VR} = -\frac{e v^2}{2 s_{\mathrm{w}} c_{\mathrm{w}} \Lambda^2} C^{ij}_{\varphi e}, \quad \delta g^{ij}_{VL} = -\frac{e v^2}{2 s_{\mathrm{w}} c_{\mathrm{w}} \Lambda^2} \left(C^{(1)\,ij}_{\varphi\ell} + C^{(3)\,ij}_{\varphi\ell} \right),$$

$$\delta g^{ij}_{TR} = \delta g^{ji\,*}_{TL} = -\frac{v}{\sqrt{2}\Lambda^2} \left(s_{\mathrm{w}} C^{ij}_{eB} + c_{\mathrm{w}} C^{ij}_{eW} \right),$$

Dipole operators:



Higgs-lepton operators:



$$Q^{(1)}_{\Phi\ell} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar\ell_L\gamma^\mu \ell'_L), \qquad Q^{(3)}_{\Phi\ell} = (\Phi^\dagger i \overleftrightarrow{D}^I_\mu \Phi)(\bar\ell_L\tau_I\gamma^\mu \ell'_L), \qquad Q_{\Phi e} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar\ell_R\gamma^\mu \ell'_R)$$

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If a single operator dominates, $Z \to \ell\ell'$ constrain NP scales up to

$$C_a = 1: \quad \Lambda \gtrsim 5\ \text{TeV} \quad (\text{Z} \to \mu\text{e}), \quad \Lambda \gtrsim 3\ \text{TeV} \quad (\text{Z} \to \tau\ell)$$

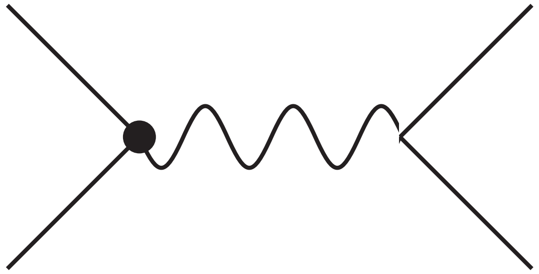
$$\delta g^{ij}_{VR} = -\frac{ev^2}{2s_w c_w \Lambda^2} C^{ij}_{\varphi e}, \quad \delta g^{ij}_{VL} = -\frac{ev^2}{2s_w c_w \Lambda^2}\left(C^{(1)\,ij}_{\varphi\ell} + C^{(3)\,ij}_{\varphi\ell}\right),$$

$$\delta g^{ij}_{TR} = \delta g^{ji\,*}_{TL} = -\frac{v}{\sqrt{2}\Lambda^2}\left(s_w C^{ij}_{eB} + c_w C^{ij}_{eW}\right),$$

- These operators give rise to low-energy lepton LFV too:

$$\mu e: \quad \mu \to e\gamma, \quad \mu \to eee, \quad \mu \to e \text{ in nuclei}$$

$$\tau\ell: \quad \tau \to \ell\gamma, \quad \tau \to \ell\ell'\ell', \quad \tau \to \ell\pi, \quad \tau \to \ell\rho, \ \ldots$$



- How large can LFV Z rates be without conflict with these bounds?
- To calculate this, we have to adopt the standard procedure:

(i) Running of the operators from **Λ** to the electroweak scale ~m_Z

→ operator mixing

(ii) Matching at m_Z to the low-energy EFT $\quad \mathcal{O}^{A,XY}_{\psi\chi,\alpha\beta\gamma\delta} = (\overline{\psi_\alpha}\Gamma_A P_X \psi_\beta)(\overline{\chi_\gamma}\Gamma_A P_Y \chi_\delta)$

(i.e. integrating out Higgs & EW gauge bosons)

(iii) QED×QCD running from m_Z down to $m_{\tau/\mu}$

(iv) Compute the low-energy observables

Let's start switching on *only one* operator at the time at the scale $\boldsymbol{\Lambda}$

Dipole operators can not play a major role, as they directly contribute to

$\ell \to \ell' \gamma$ through $\mathcal{L} \supset \frac{C_{e\gamma}}{\Lambda^2} \frac{v}{\sqrt{2}} (\bar{\ell}_L \sigma^{\mu\nu} \ell'_R) \, F_{\mu\nu}, \quad C_{e\gamma} \approx \cos\theta_W C_{eB} - \sin\theta_W C_{eW}$

⇨ if dominant LFV effects stem from C_{eB}, C_{eW} :

$\text{BR}(\mu \to e\gamma) \lesssim 4.2 \times 10^{-13}$ [MEG '16] $\Rightarrow$ $\text{BR}(Z \to \mu e) \lesssim 10^{-23} - 10^{-22}$

$\text{BR}(\tau \to e\gamma) \lesssim 3.3 \times 10^{-8}$ [BaBar '10] $\Rightarrow$ $\text{BR}(Z \to \tau e) \lesssim 10^{-15} - 10^{-14}$

$\text{BR}(\tau \to \mu\gamma) \lesssim 4.4 \times 10^{-8}$ [BaBar '10] $\Rightarrow$ $\text{BR}(Z \to \tau \mu) \lesssim 10^{-15} - 10^{-14}$

(BRs suppressed by the large Z width, compared to lepton decays)

One operator dominance: Higgs currents

Observable	Operator	Indirect Limit on LFVZD	Strongest constraint
$\mathrm{BR}(Z \to \mu e)$	$(Q_{\varphi\ell}^{(1)} + Q_{\varphi\ell}^{(3)})^{e\mu}$	3.7×10^{-13}	$\mu \to e$, Au
	$Q_{\varphi e}^{e\mu}$	9.4×10^{-15}	$\mu \to e$, Au
	$Q_{eB}^{e\mu}$	1.4×10^{-23}	$\mu \to e\gamma$
	$Q_{eW}^{e\mu}$	1.6×10^{-22}	$\mu \to e\gamma$
$\mathrm{BR}(Z \to \tau e)$	$(Q_{\varphi\ell}^{(1)} + Q_{\varphi\ell}^{(3)})^{e\tau}$	6.3×10^{-8}	$\tau \to \rho\, e$
	$Q_{\varphi e}^{e\tau}$	6.3×10^{-8}	$\tau \to \rho\, e$
	$Q_{eB}^{e\tau}$	1.2×10^{-15}	$\tau \to e\gamma$
	$Q_{eW}^{e\tau}$	1.3×10^{-14}	$\tau \to e\gamma$
$\mathrm{BR}(Z \to \tau\mu)$	$(Q_{\varphi\ell}^{(1)} + Q_{\varphi\ell}^{(3)})^{\mu\tau}$	4.3×10^{-8}	$\tau \to \rho\, \mu$
	$Q_{\varphi e}^{\mu\tau}$	4.3×10^{-8}	$\tau \to \rho\, \mu$
	$Q_{eB}^{\mu\tau}$	1.5×10^{-15}	$\tau \to \mu\gamma$
	$Q_{eW}^{\mu\tau}$	1.7×10^{-14}	$\tau \to \mu\gamma$

Wilson (Aebischer Kumar Straub ’18) and Flavio (Straub ’18) packages

One operator dominance: Higgs currents

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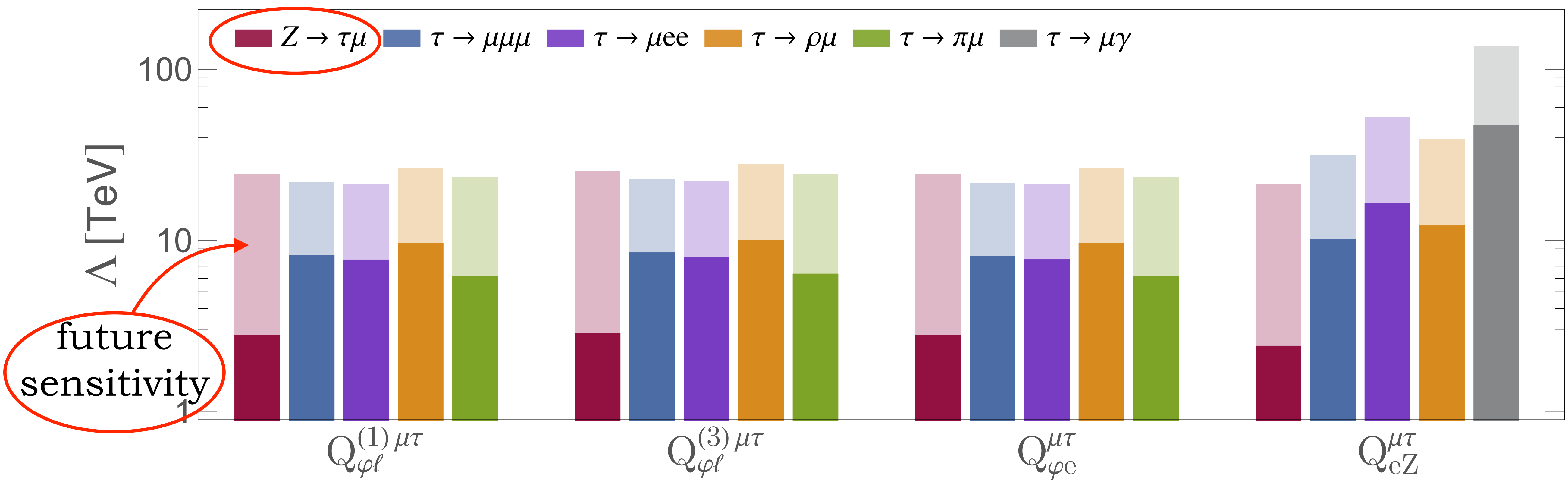
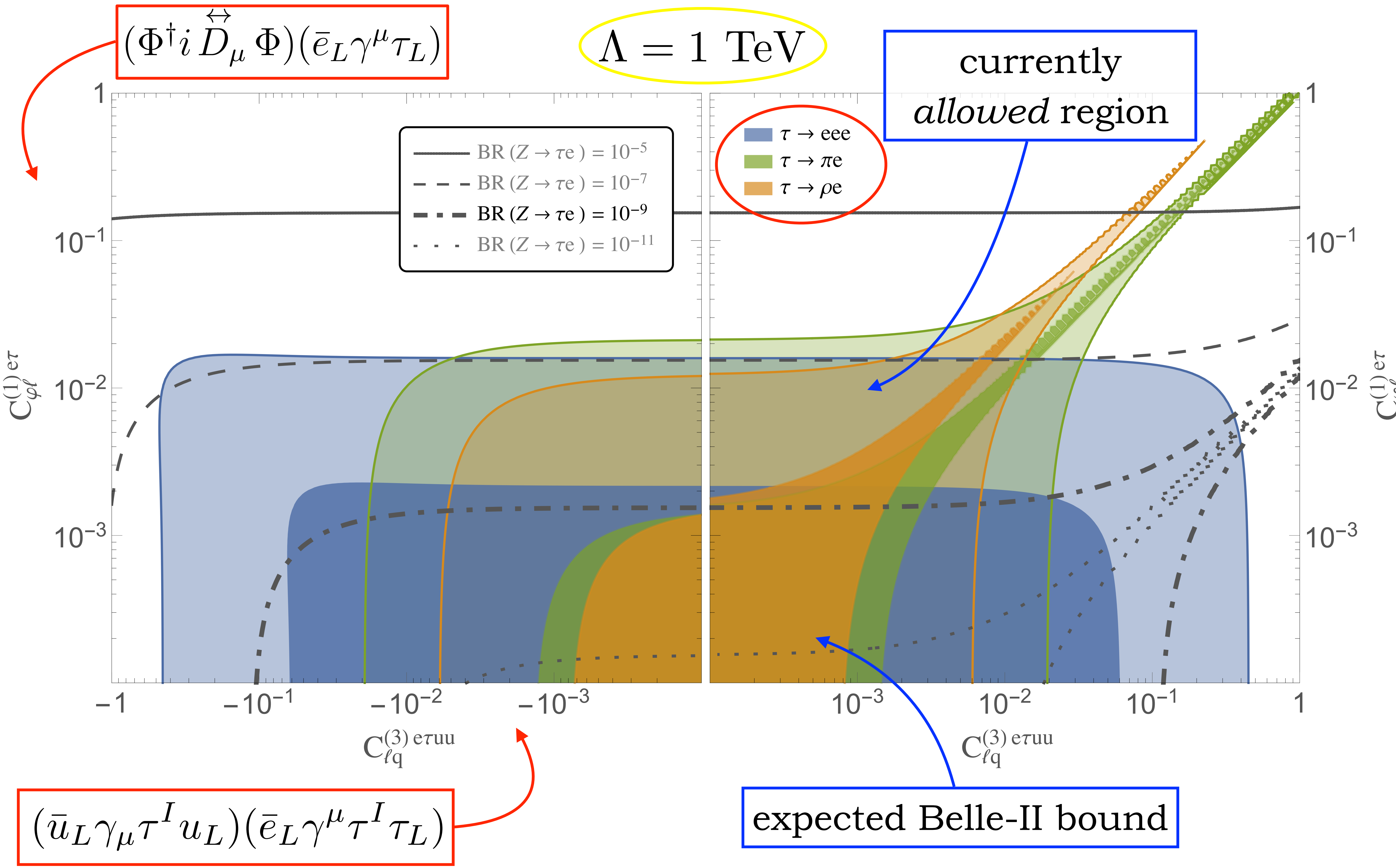
	$(Q_{\varphi\ell}^{(1)} + Q_{\varphi\ell}^{(3)})^{e\mu}$	3.7×10^{-13}	$\mu \to e$, Au

- A Tera Z can test LFV new physics scales searching for $Z \to \tau\,\ell$ at the level of what Belle II will do through LFV tau decays (or better)



Wilson (Aebischer Kumar Straub ’18) and Flavio (Straub ’18) packages

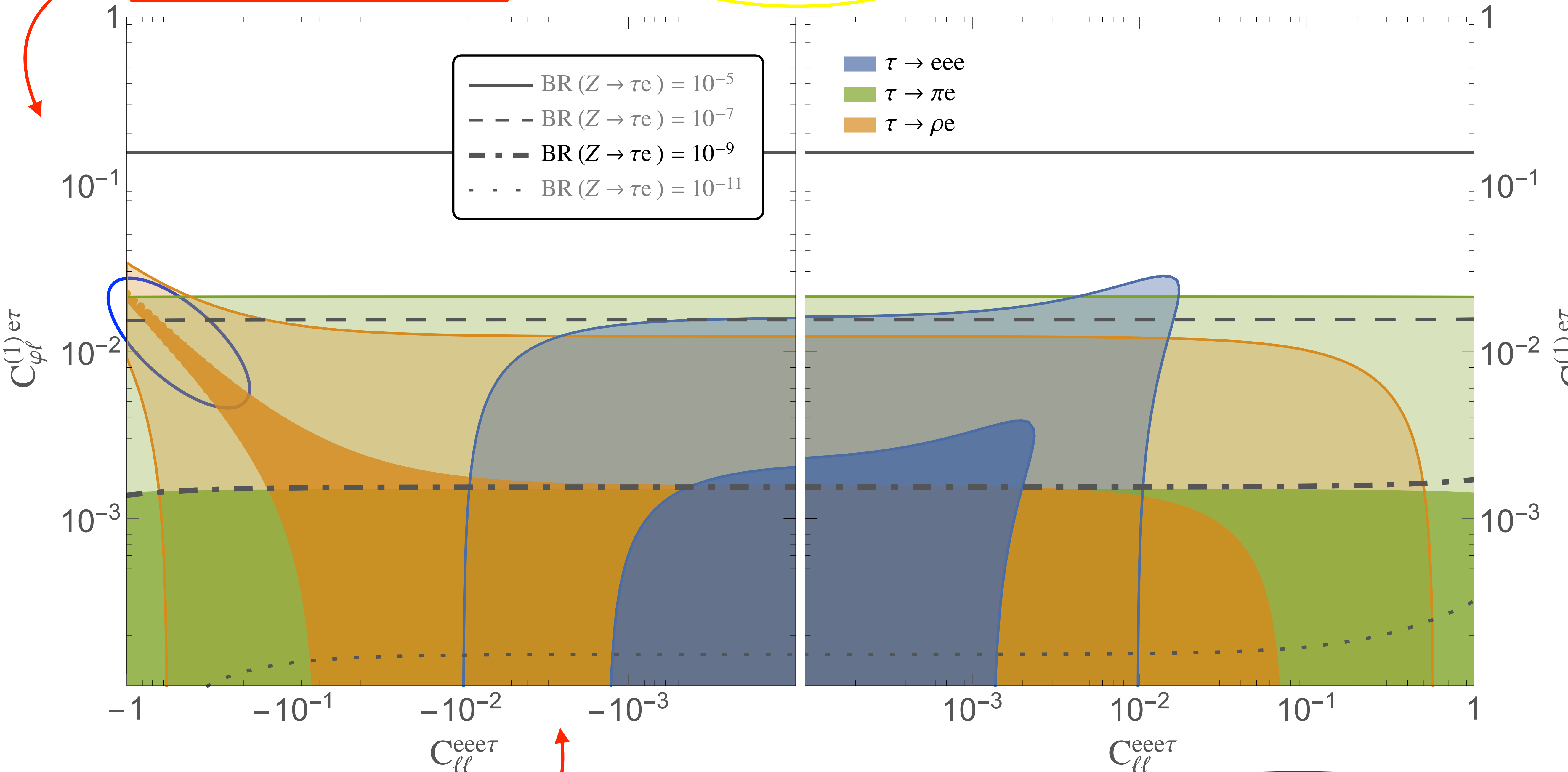
Two operators



Two operators

$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{e}_L \gamma^\mu \tau_L)$

$\Lambda = 1\ \text{TeV}$



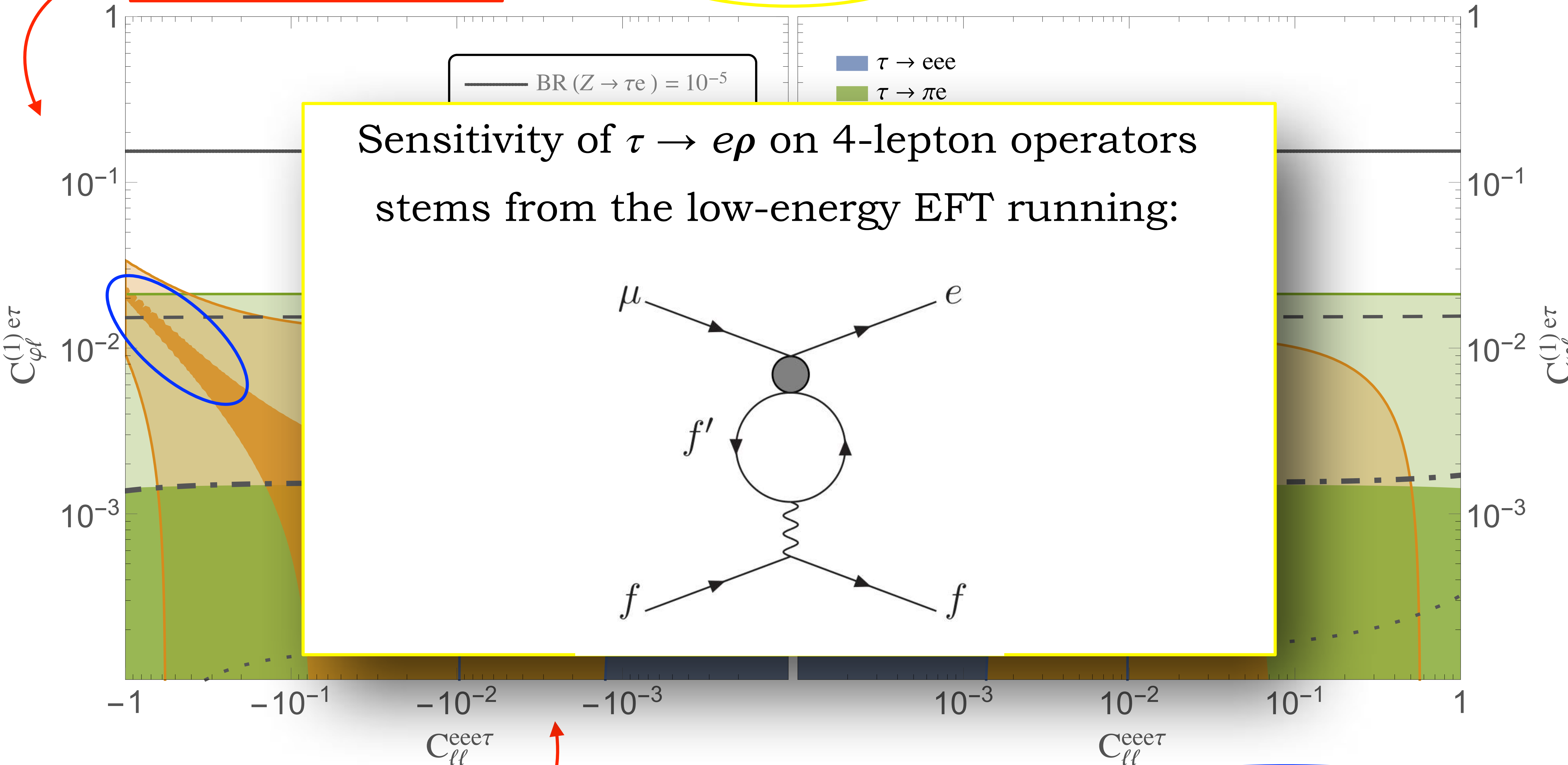
$(\bar{e}_L \gamma_\mu \tau_L)(\bar{e}_L \gamma_\mu e_L)$

4-lepton operators → cancellations possible only for some observables

Two operators

$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{e}_L \gamma^\mu \tau_L)$

$\Lambda = 1\ \text{TeV}$



Sensitivity of $\tau \to e\rho$ on 4-lepton operators stems from the low-energy EFT running:

$(\bar{e}_L \gamma_\mu \tau_L)(\bar{e}_L \gamma_\mu e_L)$

4-lepton operators → cancellations possible only for some observables

μ-e LFV in Z decays seems to be beyond CEPC sensitivity

SMEFT dipole operators severely constrained, unlike (2 combinations of) Higgs-lepton operators

$\mathrm{BR}(Z \to \tau\ell) \approx 10^{-7}$ still compatible with bounds from tau decays (future Belle-II limits may push the indirect limit down to 10^{-9})

Different operator dependence of different observables tends to cover possible cancellations in the NP parameter space

Still plenty of room to discover (tau) LFV at a Tera Z (and complementarity with B-factory searches)

LFV quarkonium decays

mainly based on LC, T. Li, X. Marcano, M. Schmidt arXiv:2207.10913

Experimental status and prospect: BESIII, STCF, Belle II...

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]

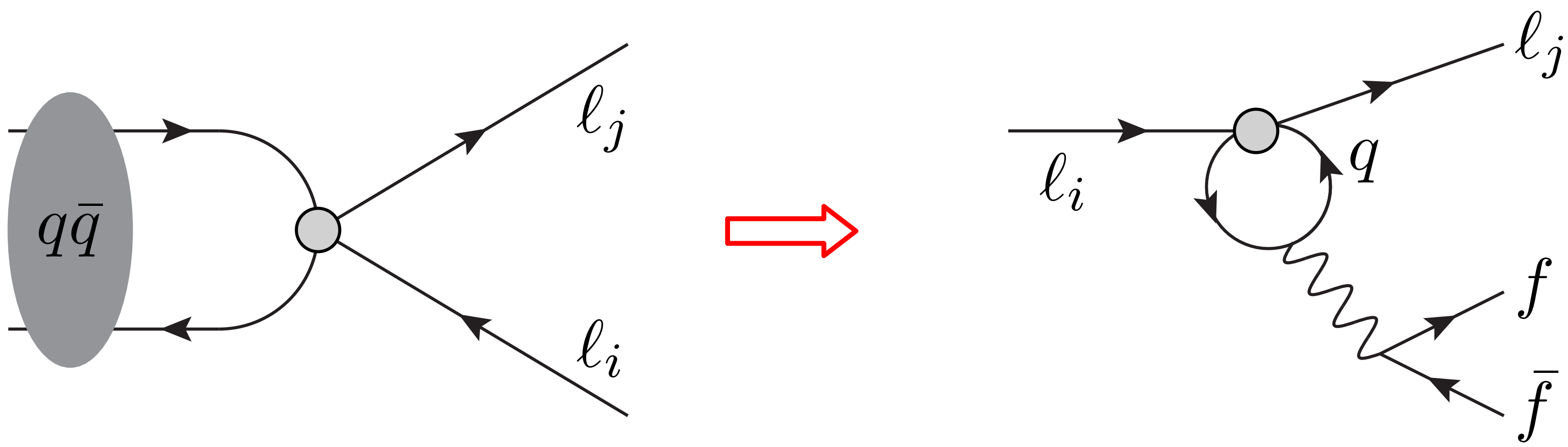
Table 1: Present 90% CL upper limits on vector quarkonium LFV decays. No limit is currently available for LFV decays of (pseudo)scalar or other vector resonances.

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 (1000x current BESIII), Belle II will collect 50-100x the data of Belle/BaBar

- 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

- Again, strongly limited by indirect constraints from tau/mu processes:



Effect summarised by the RGE running of the LEFT operators

Indirect constraints on quarkonium LFV

LEFT 2q2l ops:

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

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 $C_{e\gamma,ij}$.

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.

Indirect constraints on quarkonium LFV

LEFT 2q2l ops:

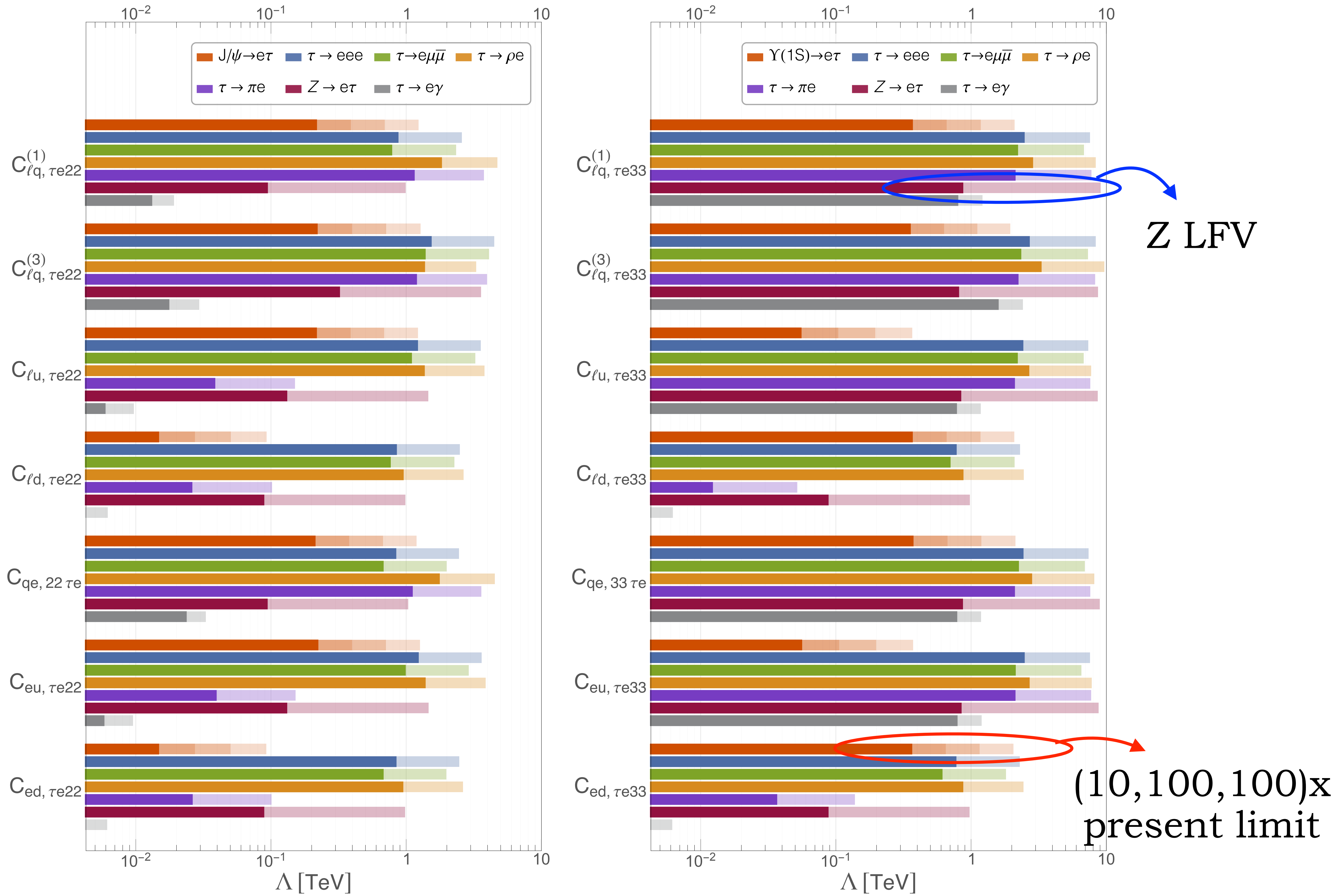
$$\mathcal{L}_{2q2\ell} = C^{V,LL}_{eq,prst}\,(\bar\ell_p\gamma^\mu P_L\ell_r)(\bar q_s\gamma_\mu P_L q_t) + C^{V,RR}_{eq,prst}\,(\bar\ell_p\gamma^\mu P_R\ell_r)(\bar q_s\gamma_\mu P_R q_t)$$
$$+ C^{V,LR}_{eq,prst}\,(\bar\ell_p\gamma^\mu P_L\ell_r)(\bar q_s\gamma_\mu P_R q_t) + C^{V,LR}_{qe,prst}\,(\bar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

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] $\times 10^{-12}$	[9.9 - 0.8] $\times 10^{-13}$	[1.1 - 0.1] $\times 10^{-12}$
$C^{V,LR}_{ed,\mu ebb}$	$\mu\to e$, Au	[1.1 - 0.08] $\times 10^{-12}$	[9.9 - 0.8] $\times 10^{-13}$	[1.1 - 0.1] $\times 10^{-12}$
$C^{T,RR}_{ed,\mu ebb}$	$\mu\to e\gamma$	[4.7 - 0.7] $\times 10^{-19}$	[4.3 - 0.7] $\times 10^{-19}$	[4.8 - 0.9] $\times 10^{-19}$
$C_{e\gamma,\mu e}$	$\mu\to e\gamma$	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] $\times 10^{-6}$	[2.8 - 0.2] $\times 10^{-6}$	[3.0 - 0.3] $\times 10^{-6}$
$C^{V,LR}_{ed,\tau ebb}$	$\tau\to\rho e$	[3.1 - 0.2] $\times 10^{-6}$	[2.8 - 0.2] $\times 10^{-6}$	[3.0 - 0.3] $\times 10^{-6}$
$C^{T,RR}_{ed,\tau ebb}$	$\tau\to e\gamma$	[4.0 - 0.6] $\times 10^{-11}$	[3.7 - 0.6] $\times 10^{-11}$	[4.1 - 0.8] $\times 10^{-11}$
$C_{e\gamma,\tau e}$	$\tau\to e\gamma$	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] $\times 10^{-6}$	[1.9 - 0.2] $\times 10^{-6}$	[2.1 - 0.2] $\times 10^{-6}$
$C^{V,LR}_{ed,\tau\mu bb}$	$\tau\to\rho\mu$	[2.1 - 0.2] $\times 10^{-6}$	[1.9 - 0.3] $\times 10^{-6}$	[2.1 - 0.2] $\times 10^{-6}$
$C^{T,RR}_{ed,\tau\mu bb}$	$\tau\to\mu\gamma$	[5.2 - 0.7] $\times 10^{-11}$	[4.8 - 0.7] $\times 10^{-11}$	[5.3 - 0.9] $\times 10^{-11}$
$C_{e\gamma,\tau\mu}$	$\tau\to\mu\gamma$	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 $C_{e\gamma,ij}$.

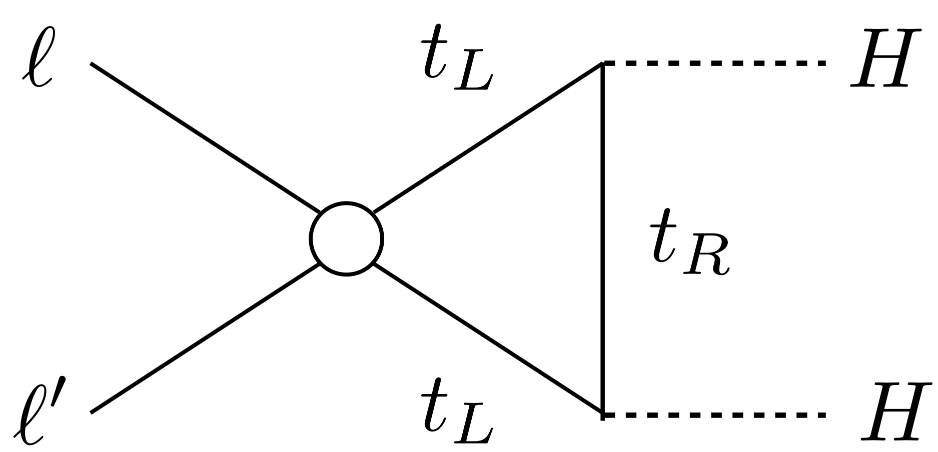
SMEFT analysis

SMEFT running and SMEFT/LEFT matching induce stronger bounds:



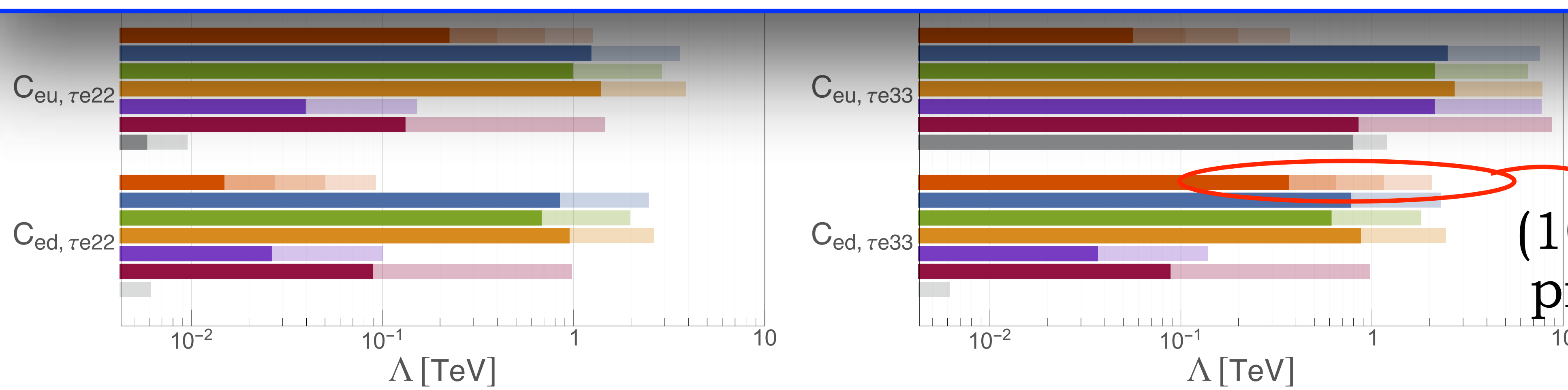
SMEFT running and SMEFT/LEFT matching induce stronger bounds:

SMEFT running induce large coefficients of Higgs-lepton ops (for 2q2l ops involving top quarks):



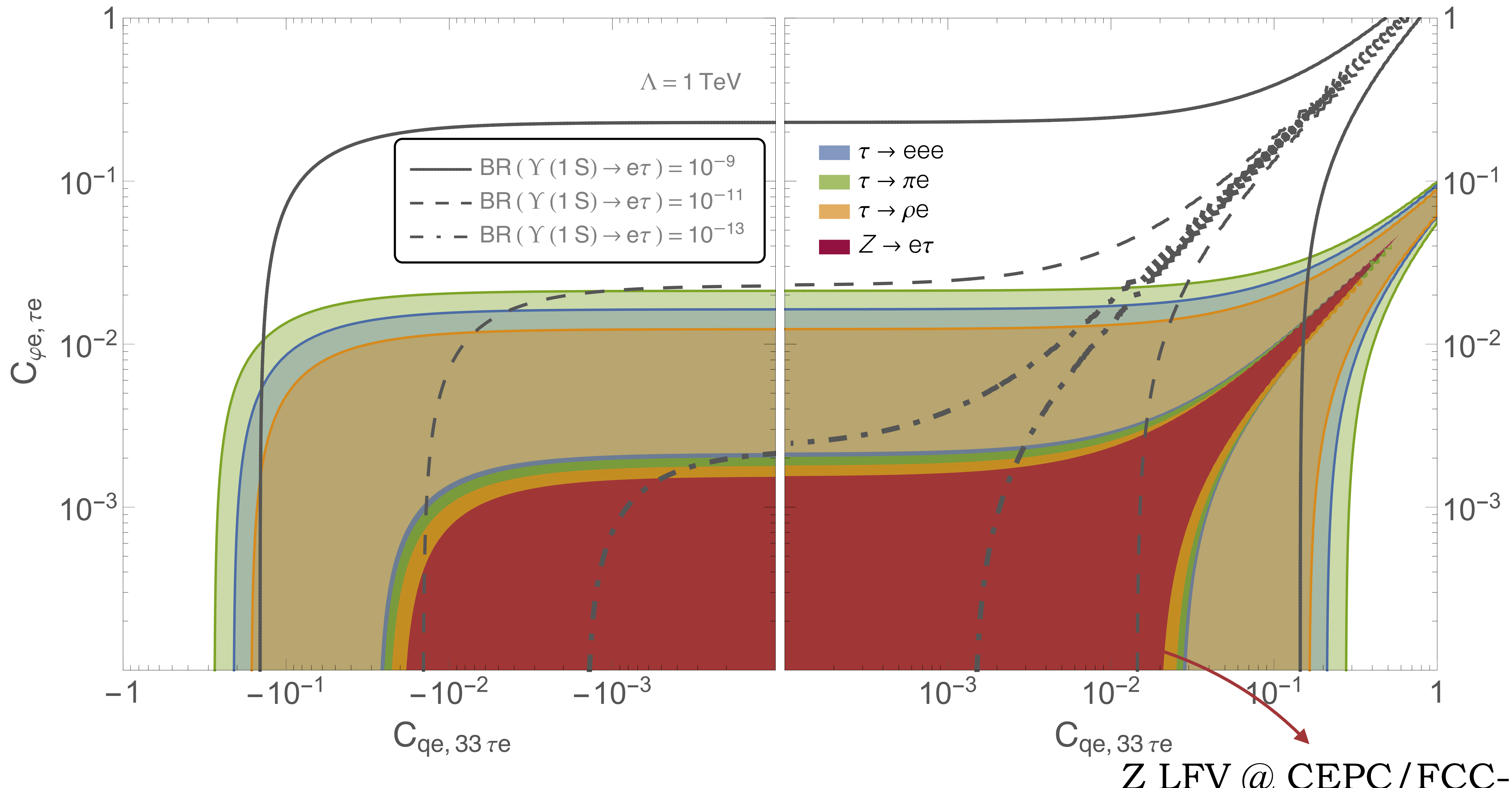
⇨ large effects for tau decays and Z LFV

LFV



(10,100,100)x present limit

Flat directions are possible along which all indirect constraint vanish:



(similar situation for operators involving LH leptonic currents)

Again, searches for quarkonium LFV decays are not sensitive to μ-e LFV due to the strong indirect constraints

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

谢谢大家！兔年快乐！

CEPC Physics Program

CEPC Operation mode		ZH	Z	W^+W^-	ttbar
		~ 240	~ 91.2	~ 160	~ 360
Run time [years]		7	2	1	-
CDR (30MW)	*L* / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	3	32	10	-
	[ab^{-1}, 2 IPs]	5.6	16	2.6	-
	Event yields [2 IPs]	**1×10^6**	**7×10^{11}**	**2×10^7**	-
Run time [years]		10	2	1	5
Latest (50MW)	*L* / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	8.3	192	27	0.83
	[ab^{-1}, 2 IPs]	20	96	7	1
	Event yields [2 IPs]	**4×10^6**	**4×10^{12}**	**5×10^7**	**5×10^5**

Large physics samples: ~10^6 Higgs, ~10^{12} Z, ~10^8 W bosons, ~10^6 top quarks

Talk by J. Guimarães Costa @ CEPC workshop 2022

The Z-peak run of CEPC/FCC-ee can deliver a few$\times 10^{12}$ visible Z decays

Plenty of flavour physics opportunities from $Z \to bb$, $Z \to cc$, $Z \to \tau\tau$:

Particle	Tera-Z	Belle II	LHCb
***b* hadrons**			
B^+	6×10^{10}	3×10^{10} ($50\,\text{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B^0	6×10^{10}	3×10^{10} ($50\,\text{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B_s	2×10^{10}	3×10^{8} ($5\,\text{ab}^{-1}$ on $\Upsilon(5S)$)	8×10^{12}
b baryons	1×10^{10}		1×10^{13}
Λ_b	1×10^{10}		1×10^{13}
***c* hadrons**			
D^0	2×10^{11}		
D^+	6×10^{10}		
D_s^+	3×10^{10}		
Λ_c^+	2×10^{10}		
τ^+	3×10^{10}	5×10^{10} ($50\,\text{ab}^{-1}$ on $\Upsilon(4S)$)	

for each 10^{12} Z decays

CEPC Study Group arXiv:1811.10545

see also the Snowmass report: The Physics potential of the CEPC

Advantages of a high-energy e^+e^- collider as flavour factory:

Luminosity

$\mathcal{L}$=100/ab, O(10^{12}) Z decays ⇒ O(10^{11}) bb, cc, and $\tau\tau$ pairs

Energy

besides producing states unaccessible at Belle II
$M_Z \gg 2m_b$, $2m_\tau$, $2m_c \Rightarrow$ surplus energy, boosted decay products
(better tracking and tagging, lower vertex uncertainty etc.)

Cleanliness

as for any leptonic machine, full knowledge of the initial state
(e.g. Z mass constraint on invariant masses more powerful)
⇒ it enables searches involving neutral/invisible particles

Summary of the tau and Z prospects

Measurement	Current [126]	FCC [115]	Tera-Z Prelim. [127]	Comments
Lifetime [sec]	$\pm 5 \times 10^{-16}$	$\pm 1 \times 10^{-18}$		from 3-prong decays, stat. limited
$\mathrm{BR}(\tau \to \ell\nu\bar{\nu})$	$\pm 4 \times 10^{-4}$	$\pm 3 \times 10^{-5}$		$0.1\times$ the ALEPH systematics
$\mathrm{m}(\tau)$ [MeV]	± 0.12	$\pm 0.004 \pm 0.1$		$\sigma(p_{\mathrm{track}})$ limited
$\mathrm{BR}(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$	$\mathcal{O}(10^{-10})$	same	bkg free
$\mathrm{BR}(\tau \to 3e)$	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau^\pm \to e\mu\mu)$	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau^\pm \to \mu ee)$	$< 1.8 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$	$\sim 2 \times 10^{-9}$	$\mathcal{O}(10^{-10})$	$Z \to \tau\tau\gamma$ bkg , $\sigma(p_\gamma)$ limited
$\mathrm{BR}(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$	$\sim 2 \times 10^{-9}$		$Z \to \tau\tau\gamma$ bkg, $\sigma(p_\gamma)$ limited
$\mathrm{BR}(Z \to \tau\mu)$	$< 1.2 \times 10^{-5}$	$\mathcal{O}(10^{-9})$	same	$\tau\tau$ bkg, $\sigma(p_{\mathrm{track}})$ & $\sigma(E_{\mathrm{beam}})$ limited
$\mathrm{BR}(Z \to \tau e)$	$< 9.8 \times 10^{-6}$	$\mathcal{O}(10^{-9})$		$\tau\tau$ bkg, $\sigma(p_{\mathrm{track}})$ & $\sigma(E_{\mathrm{beam}})$ limited
$\mathrm{BR}(Z \to \mu e)$	$< 7.5 \times 10^{-7}$	$10^{-8} - 10^{-10}$	$\mathcal{O}(10^{-9})$	PID limited
$\mathrm{BR}(Z \to \pi^+\pi^-)$			$\mathcal{O}(10^{-10})$	$\sigma(\vec{p}_{\mathrm{track}})$ limited, good PID
$\mathrm{BR}(Z \to \pi^+\pi^-\pi^0)$			$\mathcal{O}(10^{-9})$	$\tau\tau$ bkg
$\mathrm{BR}(Z \to J/\psi\gamma)$	$< 1.4 \times 10^{-6}$		$10^{-9} - 10^{-10}$	$\ell\ell\gamma$+$\tau\tau\gamma$ bkg
$\mathrm{BR}(Z \to \rho\gamma)$	$< 2.5 \times 10^{-5}$		$\mathcal{O}(10^{-9})$	$\tau\tau\gamma$ bkg, $\sigma(p_{\mathrm{track}})$ limited

From the Snowmass report: The Physics potential of the CEPC

Quarkonium LFV decay widths

LEFT 2q2l ops:

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

Vector resonances:

$$\mathrm{BR}(V\to\ell_i^-\ell_j^+) = \frac{m_V}{\Gamma_V}\frac{\lambda^{1/2}(1,y_i^2,y_j^2)}{16\pi}\Bigg[\frac{|V_L|^2+|V_R|^2}{12}\Big(2-y_i^2-y_j^2-(y_i^2-y_j^2)^2\Big)$$
$$+\frac{4}{3}\left(|T_L|^2+|T_R|^2\right)\Big(1+y_i^2+y_j^2-2(y_i^2-y_j^2)^2\Big)$$
$$+ y_iy_j\Big(\mathrm{Re}\big(V_LV_R^*\big)+16\,\mathrm{Re}\big(T_RT_L^*\big)\Big)$$
$$+2y_i\left(1+y_j^2-y_i^2\right)\,\mathrm{Re}\big(V_RT_R^*+V_LT_L^*\big)$$
$$+2y_j\left(1+y_i^2-y_j^2\right)\,\mathrm{Re}\big(V_LT_R^*+V_RT_L^*\big)\Bigg]\,,$$

$$V_L = f_Vm_V\left(C^{V,LL}_{eq,ijqq}+C^{V,LR}_{eq,ijqq}+\frac{2e^2Q_qQ_\ell\delta_{ij}}{m_V^2}\right),\qquad T_L = m_Vf_V^TC^{T,RR*}_{eq,jiqq}-eQ_qf_VC^*_{e\gamma,ji}\,,$$
$$V_R = f_Vm_V\left(C^{V,RR}_{eq,ijqq}+C^{V,LR}_{qe,qqij}+\frac{2e^2Q_qQ_\ell\delta_{ij}}{m_V^2}\right),\qquad T_R = m_Vf_V^TC^{T,RR}_{eq,ijqq}-eQ_qf_VC_{e\gamma,ij}\,,$$

Pseudoscalars:

$$\mathrm{BR}(P\to\ell_i^-\ell_j^+) = \frac{m_P}{\Gamma_P}\frac{\lambda^{1/2}(1,y_i^2,y_j^2)}{16\pi}\Big[\left(|S_L|^2+|S_R|^2\right)\,\left(1-y_i^2-y_j^2\right)-4y_iy_j\,\mathrm{Re}(S_LS_R^*)\Big]$$

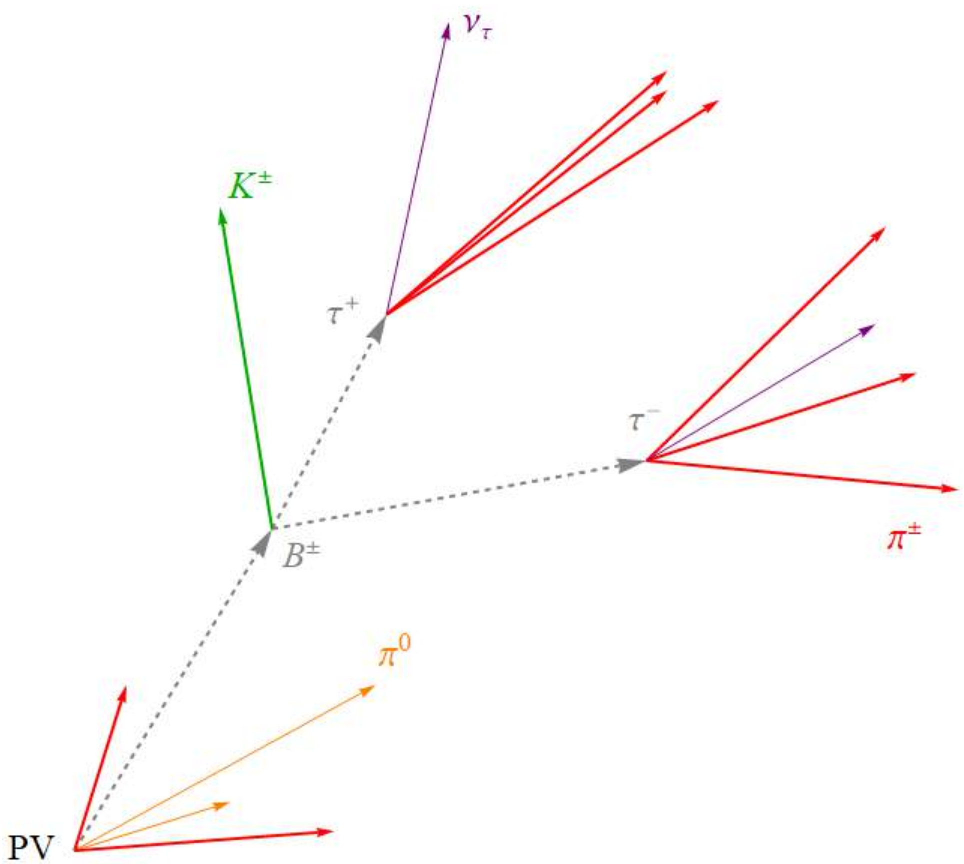
$$S_R = \frac{h_P}{4m_q}\left(C^{S,RR}_{eq,ijqq}-C^{S,RL}_{eq,ijqq}\right)-\frac{f_P}{2}\left[m_j\left(C^{V,LR}_{eq,ijqq}-C^{V,LL}_{eq,ijqq}\right)+m_i\left(C^{V,RR}_{eq,ijqq}-C^{V,LR}_{qe,qqij}\right)\right]$$
$$+\,i\frac{4\pi}{\alpha_s}a_PC_{eG\tilde G,ij}\,,$$
$$S_L = \frac{h_P}{4m_q}\left(C^{S,RL}_{eq,jiqq}-C^{S,RR}_{eq,jiqq}\right)^*-\frac{f_P}{2}\left[m_i\left(C^{V,LR}_{eq,ijqq}-C^{V,LL}_{eq,ijqq}\right)+m_j\left(C^{V,RR}_{eq,ijqq}-C^{V,LR}_{qe,qqij}\right)\right]$$
$$+\,i\frac{4\pi}{\alpha_s}a_PC^*_{eG\tilde G,ji}\,.$$

Example: $b \to s\tau\tau$

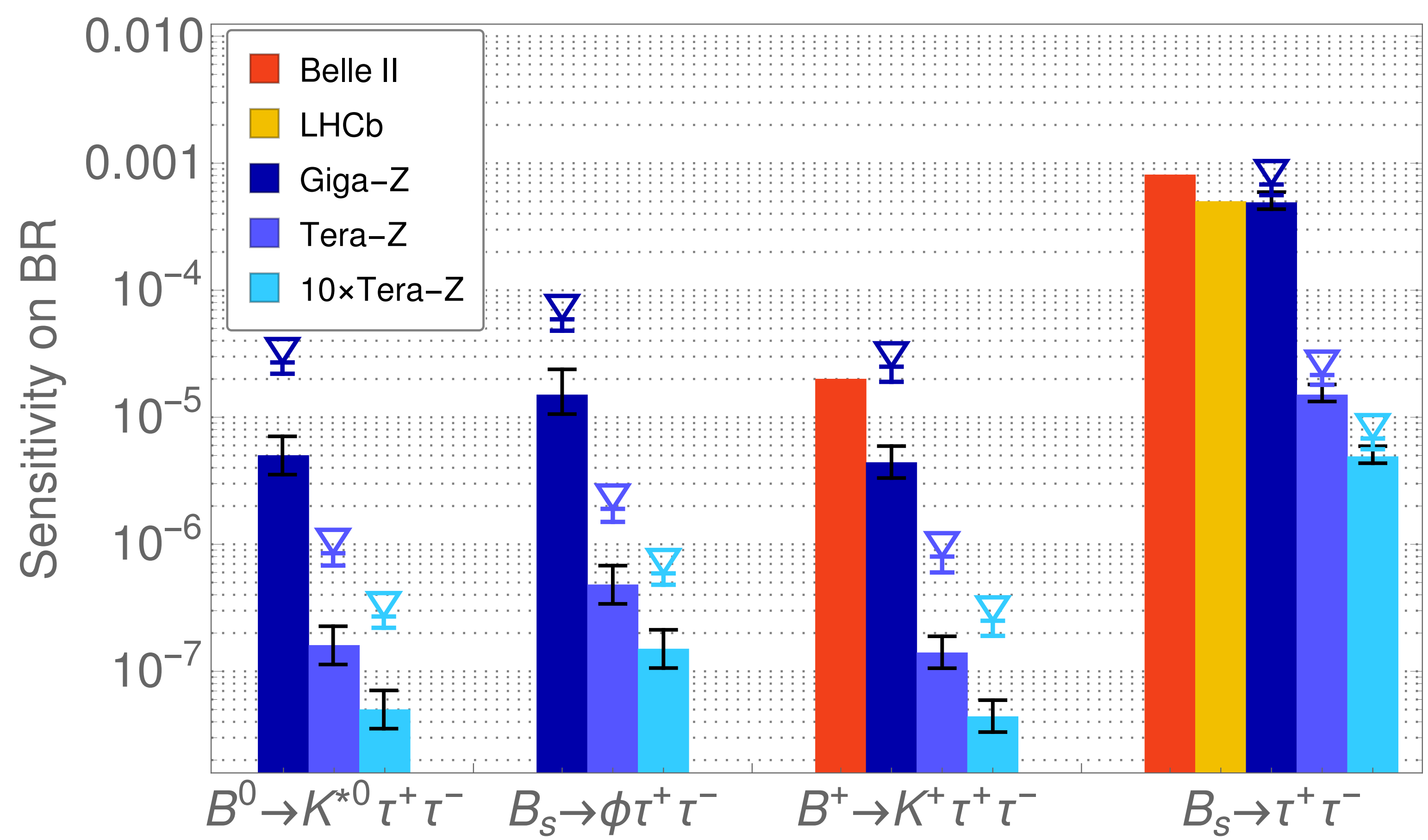
$$\text{BR}(B_s \to \tau\tau)_{\text{SM}} = (7.7 \pm 0.5) \times 10^{-7}$$ (Bobeth et al. 1311.0903)

$$\text{BR}(B \to K\tau\tau)_{\text{SM}} = (1.2 \pm 0.1) \times 10^{-7}$$ (Du et al. 1510.02349)

- Unobserved, weakly constrained (~10^{-4}-10^{-3} by Belle, Belle II can provide an O(10) increased sensitivity)
- They can have a large new-physics enhancement
- Tera Z prospects:



3-prong τ decays



Li L. and Liu T. '20

Example: $b \to s\nu\nu$

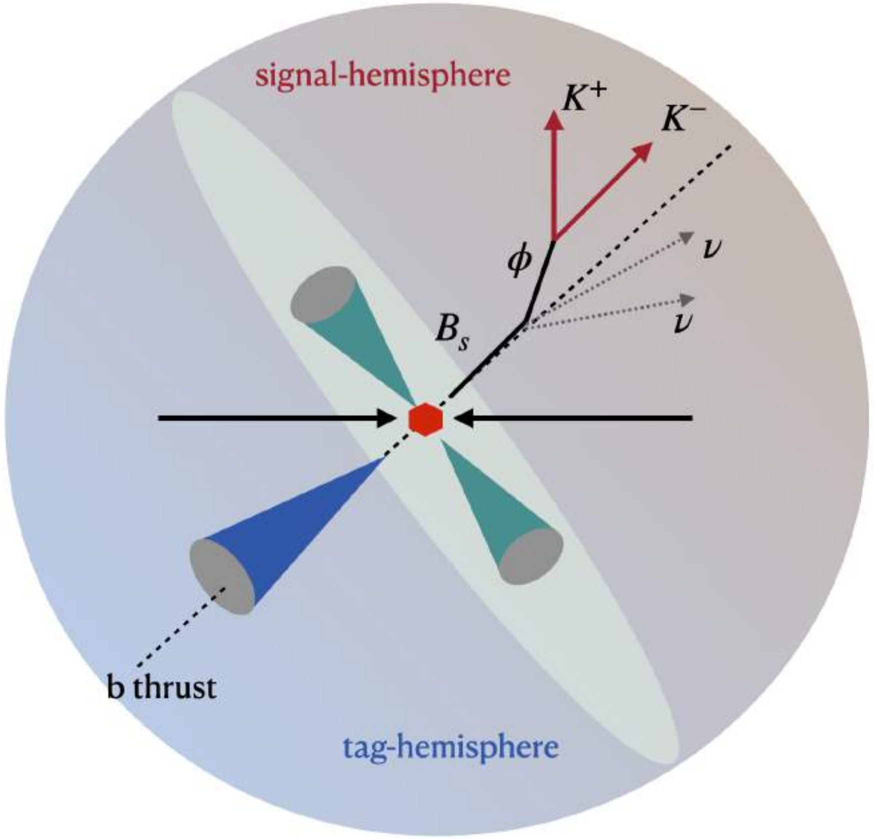
Li et al. '22

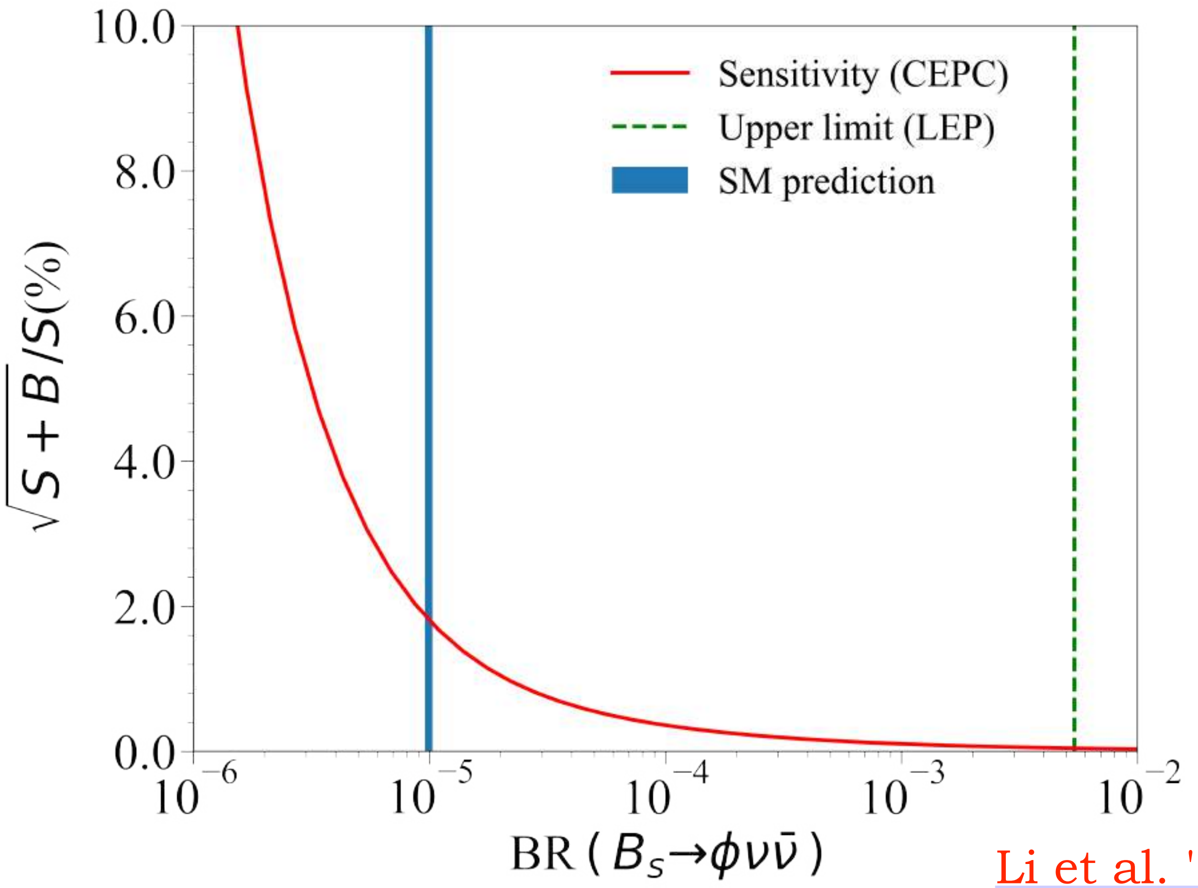
	Current Limit	Detector	SM Prediction
$\mathrm{BR}(B^0 \to K^0\nu\bar{\nu})$	$< 2.6 \times 10^{-5}$ [3]	BELLE	$(3.69 \pm 0.44) \times 10^{-6}$ [1]
$\mathrm{BR}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 1.8 \times 10^{-5}$ [3]	BELLE	$(9.19 \pm 0.99) \times 10^{-6}$ [1]
$\mathrm{BR}(B^\pm \to K^\pm\nu\bar{\nu})$	$< 1.6 \times 10^{-5}$ [4]	BABAR	$(3.98 \pm 0.47) \times 10^{-6}$ [1]
$\mathrm{BR}(B^\pm \to K^{*\pm}\nu\bar{\nu})$	$< 4.0 \times 10^{-5}$ [5]	BELLE	$(9.83 \pm 1.06) \times 10^{-6}$ [1]
$\mathrm{BR}(B_s \to \phi\nu\bar{\nu})$	$< 5.4 \times 10^{-3}$ [6]	DELPHI	$(9.93 \pm 0.72) \times 10^{-6}$

- Also these modes can be greatly enhanced by new physics responsible for the B anomalies

see e.g. LC Crivellin Ota '15

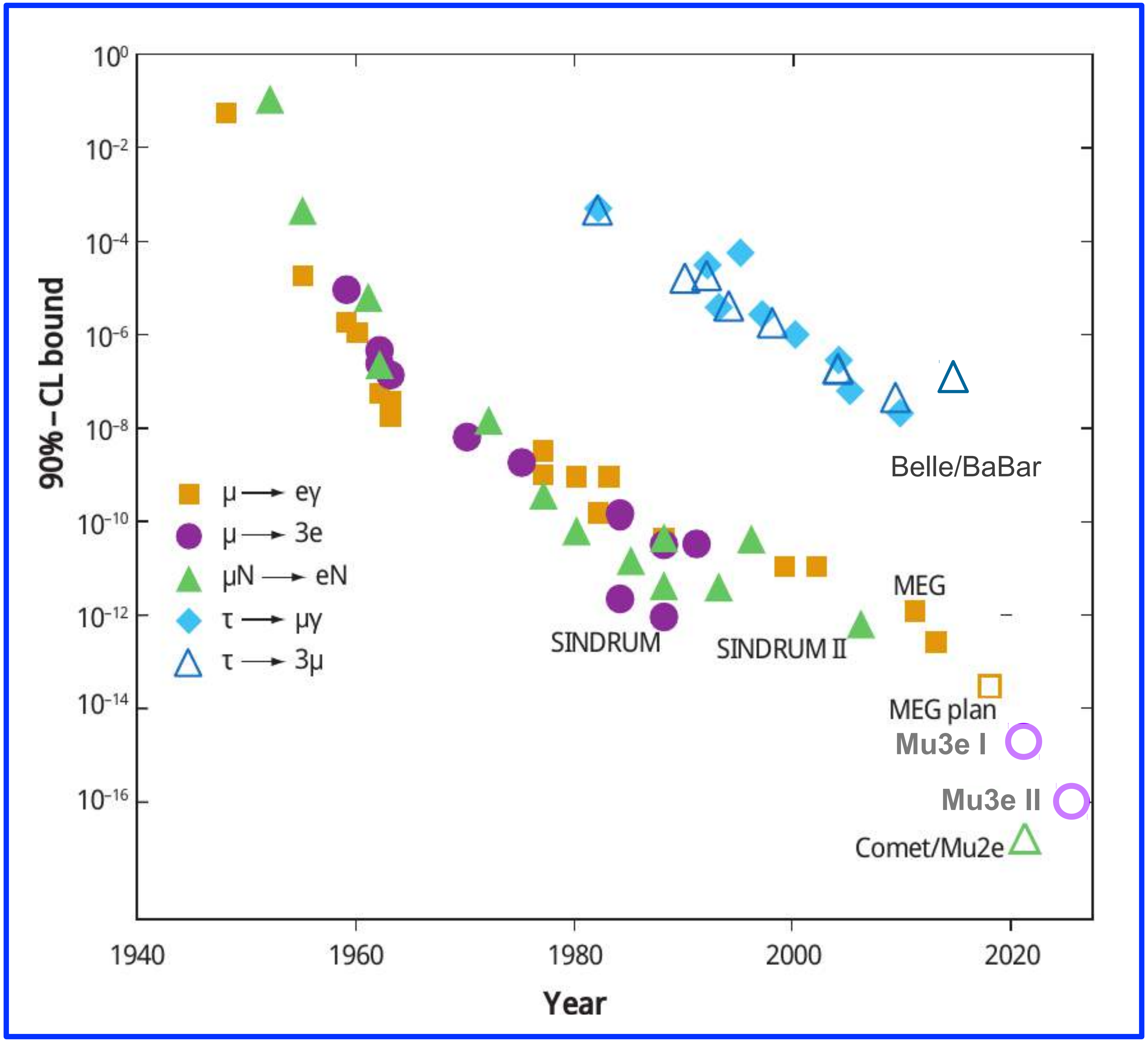
- A Tera Z can measure $B_s \to \phi\nu\nu$ with a percent level precision:



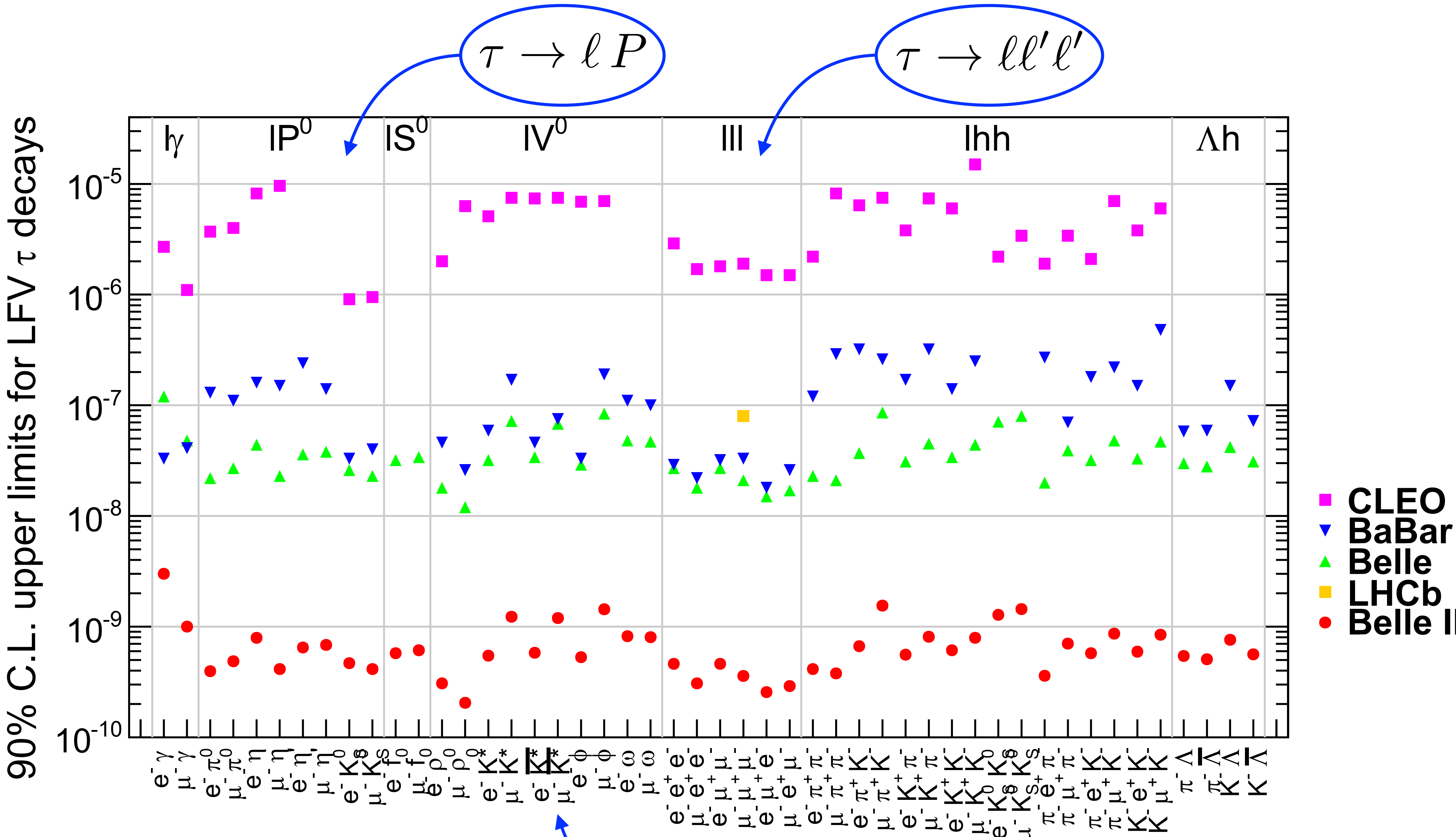


Li et al. '22

Present/future limits on LFV muon decays



Present/future limits on LFV tau decays



The Belle II Physics Book arXiv:1808.10567

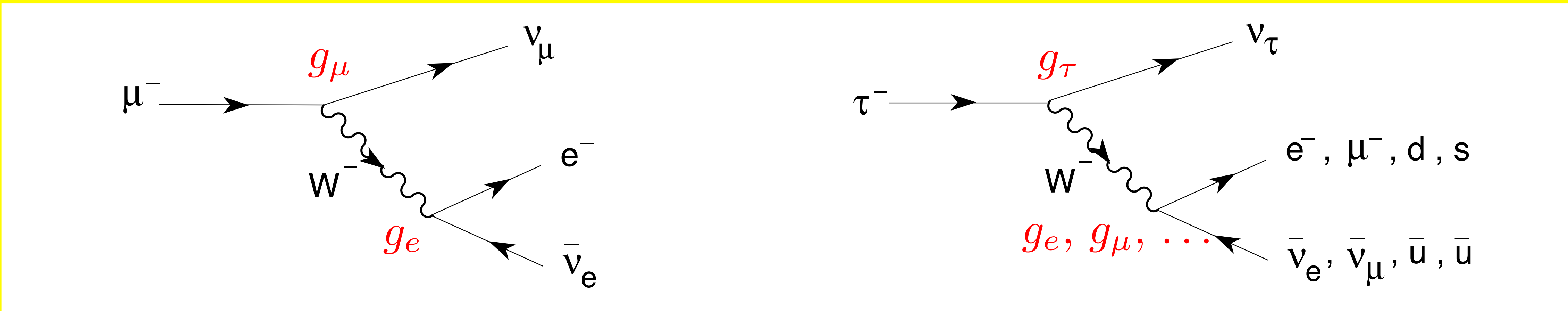
Universality presently tested at the per-mil level

LEP exps/SLD combination hep-ex:0509008

$$\frac{B(Z \to \mu^+\mu^-)}{B(Z \to e^+e^-)} = 1.0009 \pm 0.0028$$
$$\frac{B(Z \to \tau^+\tau^-)}{B(Z \to e^+e^-)} = 1.0019 \pm 0.0032$$

(1.7×10^7 Z decays at LEP + 6×10^5 Z decays with polarised beams at SLC)

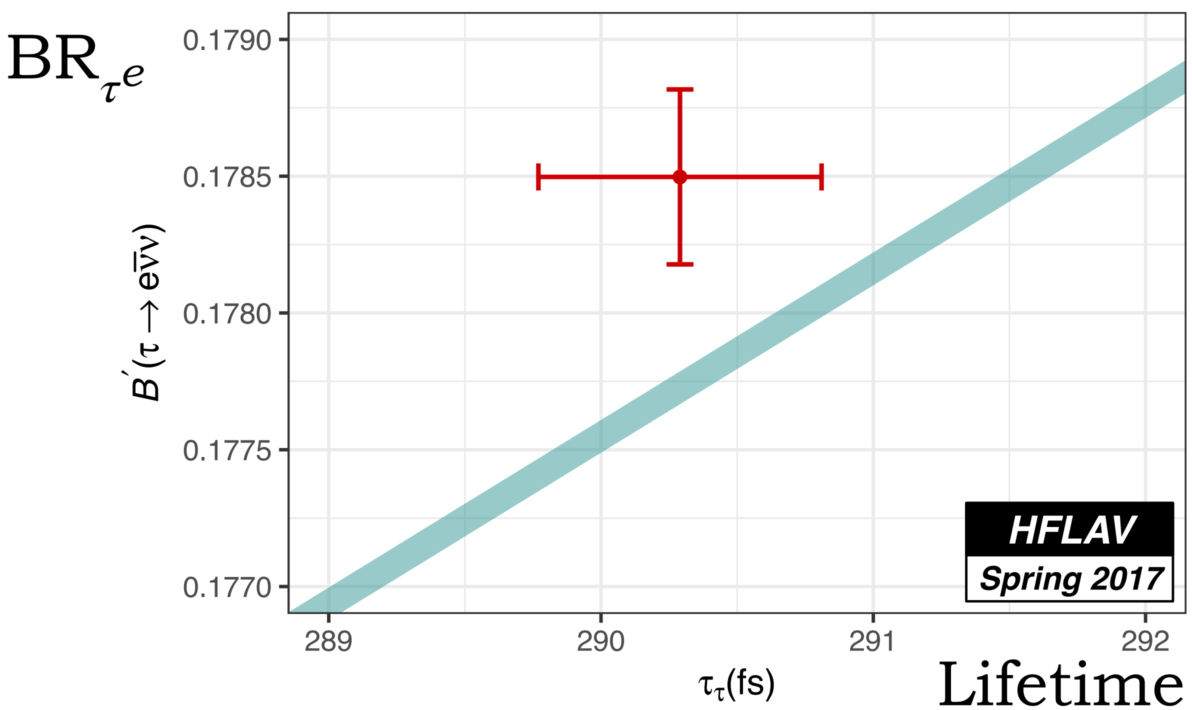
- Very important test in view of the LFU anomalies in B decays
- With 10^{12} Z, CEPC/FCC-ee has no problem of statistics
- Can systematics (lepton-id efficiencies? what else?) be controlled so as to measure BRs with e.g. 10^{-4} precision?



Neglecting radiative corrections:

$$\left(\frac{g_\mu}{g_e}\right)^2 = \frac{\mathrm{BR}(\tau\to\mu\bar{\nu}\nu)}{\mathrm{BR}(\tau\to e\bar{\nu}\nu)} \times \frac{f_{\tau e}}{f_{\tau\mu}} \qquad \left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{\mathrm{BR}(\tau\to e\bar{\nu}\nu)}{\mathrm{BR}(\mu\to e\bar{\nu}\nu)}$$

HFLAV '17: $g_\mu/g_e = 1.0019 \pm 0.0014$ $\quad g_\tau/g_\mu = 1.0010 \pm 0.0015$ $\quad g_\tau/g_e = 1.0029 \pm 0.0015$



Universality test uncertainty now limited by leptonic BRs

input	Δinput	Δtest	
τ_τ	0.090%	0.18%	← Belle
$\mathcal{B}_{\tau\to\mu,e}$	0.115%	0.23%	← LEP
m_τ	0.022%	0.009%	← BESIII

A. Lusiani @ Tau '18

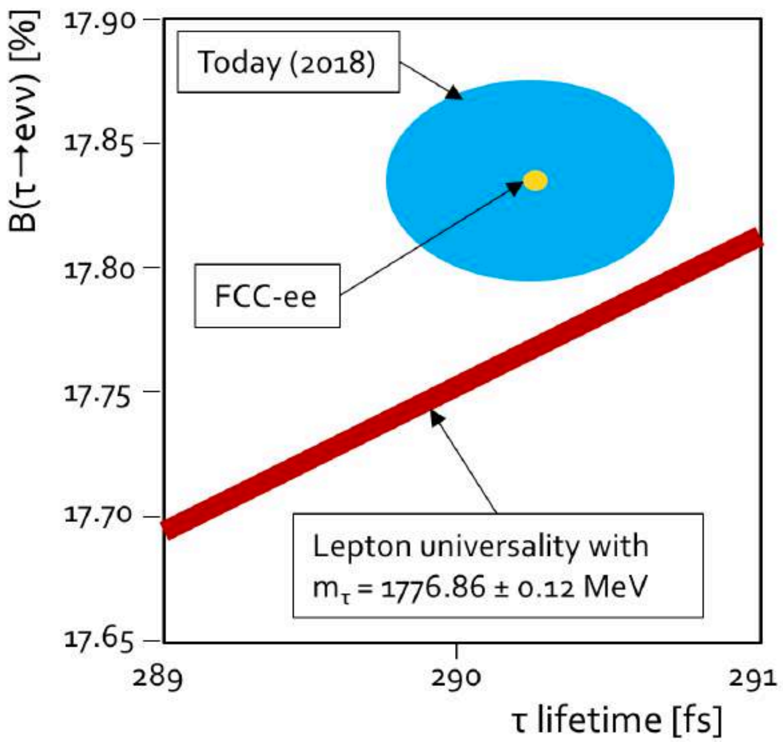
Preliminary study for the FCC-ee (10^{11} tau pairs):

Observable	Measurement	Current precision	FCC-ee **stat.**	**Possible syst.**	Challenge
m_τ [MeV]	Threshold / inv. mass endpoint	1776.86 **± 0.12**	**0.005**	**0.12**	Mass scale
τ_τ [fs]	Flight distance	290.3 **± 0.5 fs**	**0.005**	**< 0.040**	Vertex detector alignment
B($\tau\to e\nu\nu$) [%]	Selection of $\tau^+\tau^-$, identification of final state	17.82 **± 0.05**	**0.0001**	**No estimate; possibly 0.003**	Efficiency, bkg, Particle ID
B($\tau\to\mu\nu\nu$) [%]		17.39 **± 0.05**			

Lepton Universality Tests:

Quantity	Measurement	Current precision	FCC-ee precision
$\lvert g_\mu/g_e\rvert$	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	1.0018 **± 0.0015**	**Improvement by a factor 10 or more**
$\lvert g_\tau/g_\mu\rvert$	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	1.0030 **± 0.0015**	

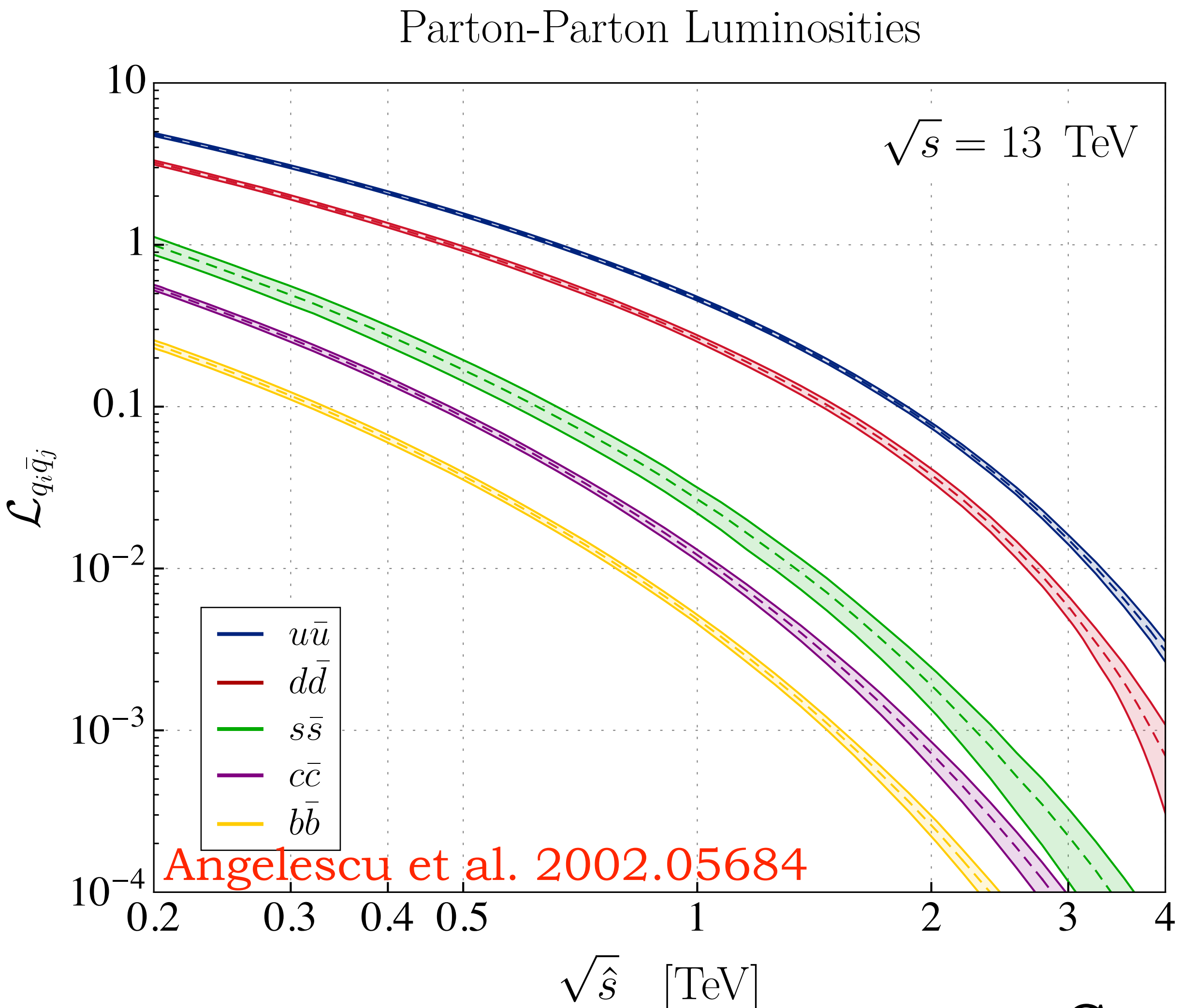
With the precise FCC-ee measurements of lifetime and BRs, m_τ could become the limiting measurement in the universality test



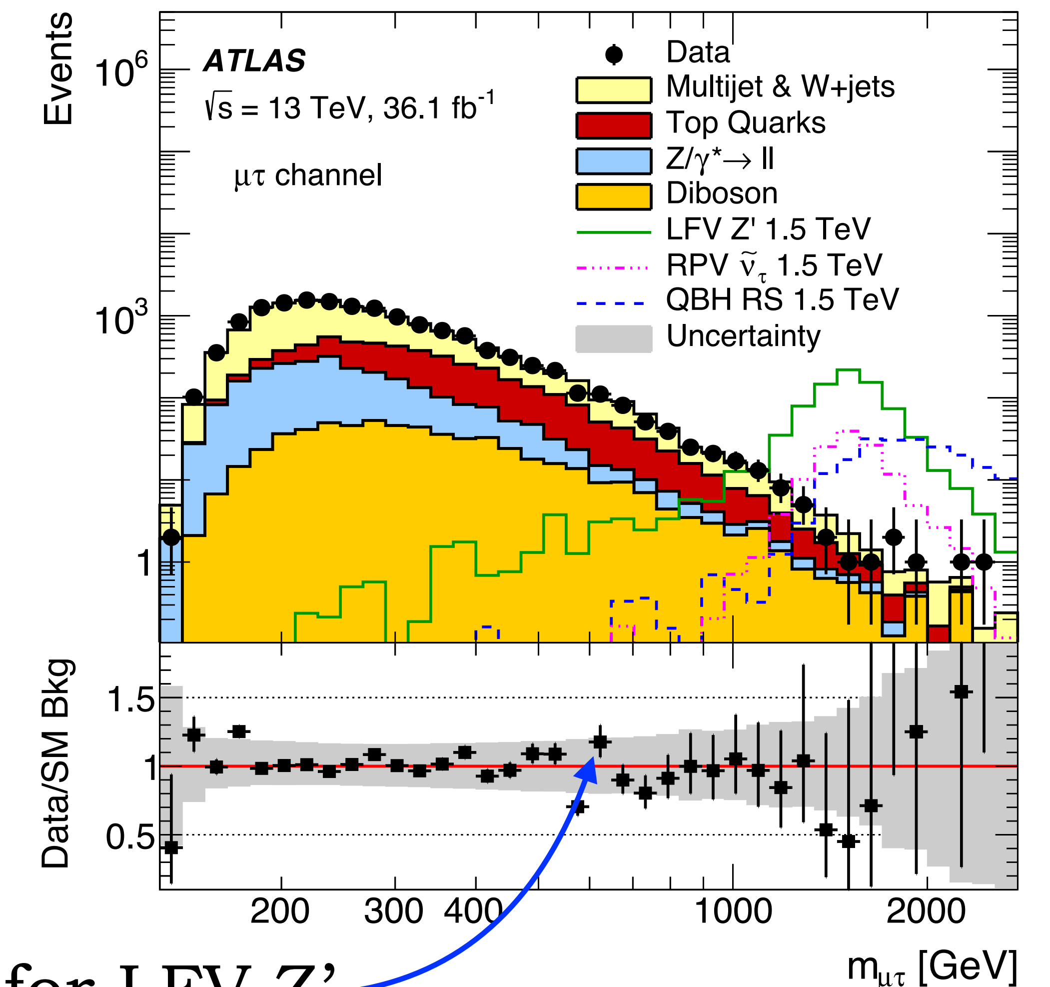
M. Dam @ Tau '18 & 1811.09408

Indirect constraints from searches for LFV at the LHC

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



Di-lepton invariant mass



Search for LFV Z'

ATLAS 1807.06573

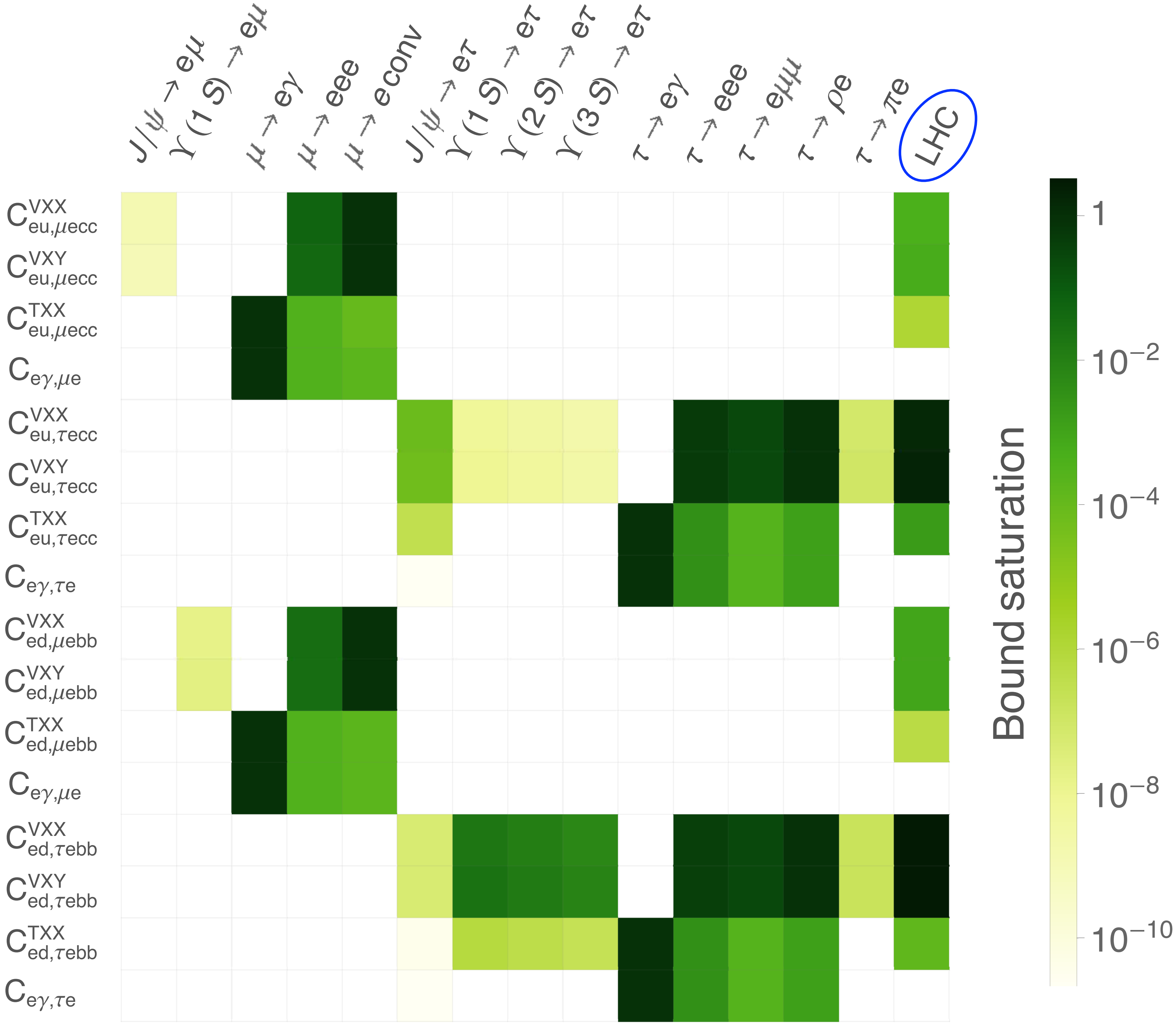
LHC di-lepton tails constrain $\bar{c}c\,\bar{\ell}_i\ell_j$ contact interactions up to Λ > 2-3 TeV

⇒ Indirect LHC bounds (if EFT is valid):

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

Angelescu et al. 2002.05684

Comparison of indirect constraints



That's not the case for charmonium decays: