The 2020 international workshop on the high energy
Circular Electron Positron Collider

Probing new physics with LFV Z decays at the CEPC

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based on work in progress with **Xabier Marcano** and **Joydeep Roy**

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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 $\sim \left(\frac{\Delta m_\nu}{M_W}\right)^4 \Rightarrow \ \mathrm{BR}(Z \to \ell\ell') \approx 10^{-50}$

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

for a pedagogical introduction → LC & Signorelli '17

Present limits on LFV Z decays

with 4×10^6 Zs

Mode	LEP bound (95% CL)	LHC bound (95% CL)	
$\mathrm{BR}(Z\to\mu e)$	$< 1.7\times10^{-6}$ no candidates	$< 7.5\times10^{-7}$	8 TeV, 20/fb
$\mathrm{BR}(Z\to\tau e)$	$< 9.8\times10^{-6}$	$< 8.1\times10^{-6}$	8+13 TeV, (20+140)/fb
$\mathrm{BR}(Z\to\tau\mu)$	$< 1.2\times10^{-5}$	$< 9.5\times10^{-6}$	
	OPAL '95, DELPHI '97	ATLAS '14, '20 (2010.02566)	

$Z\to\tau\tau$ 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 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

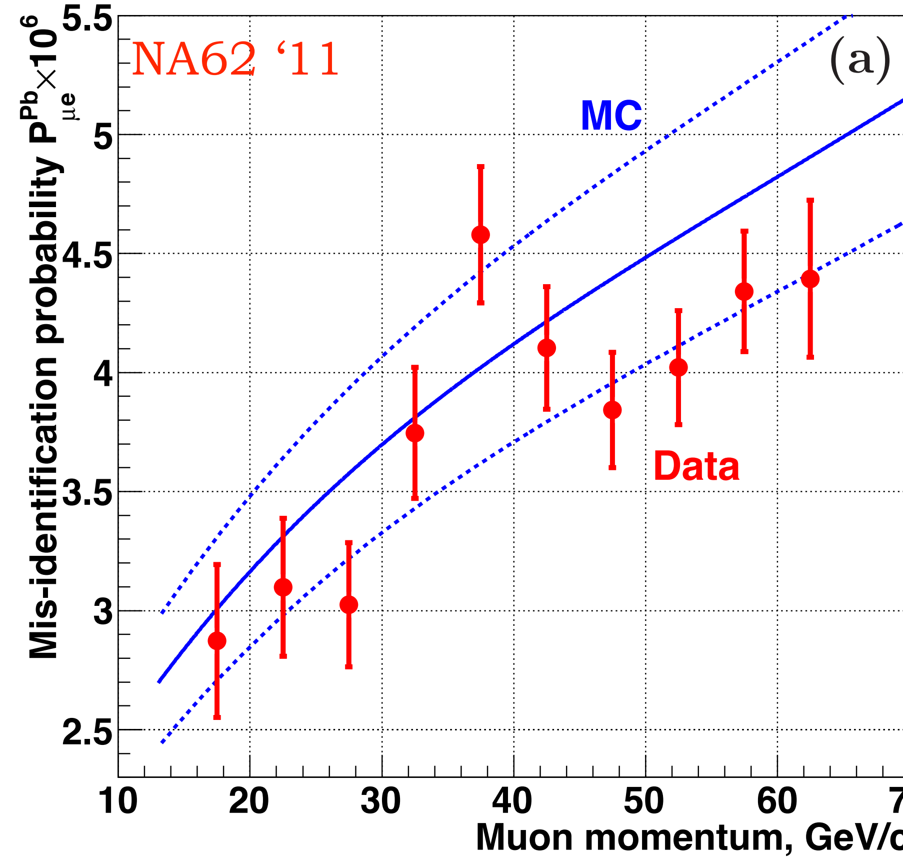
In contrast to the LHC, no background from $Z \to \tau\tau$:

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})

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

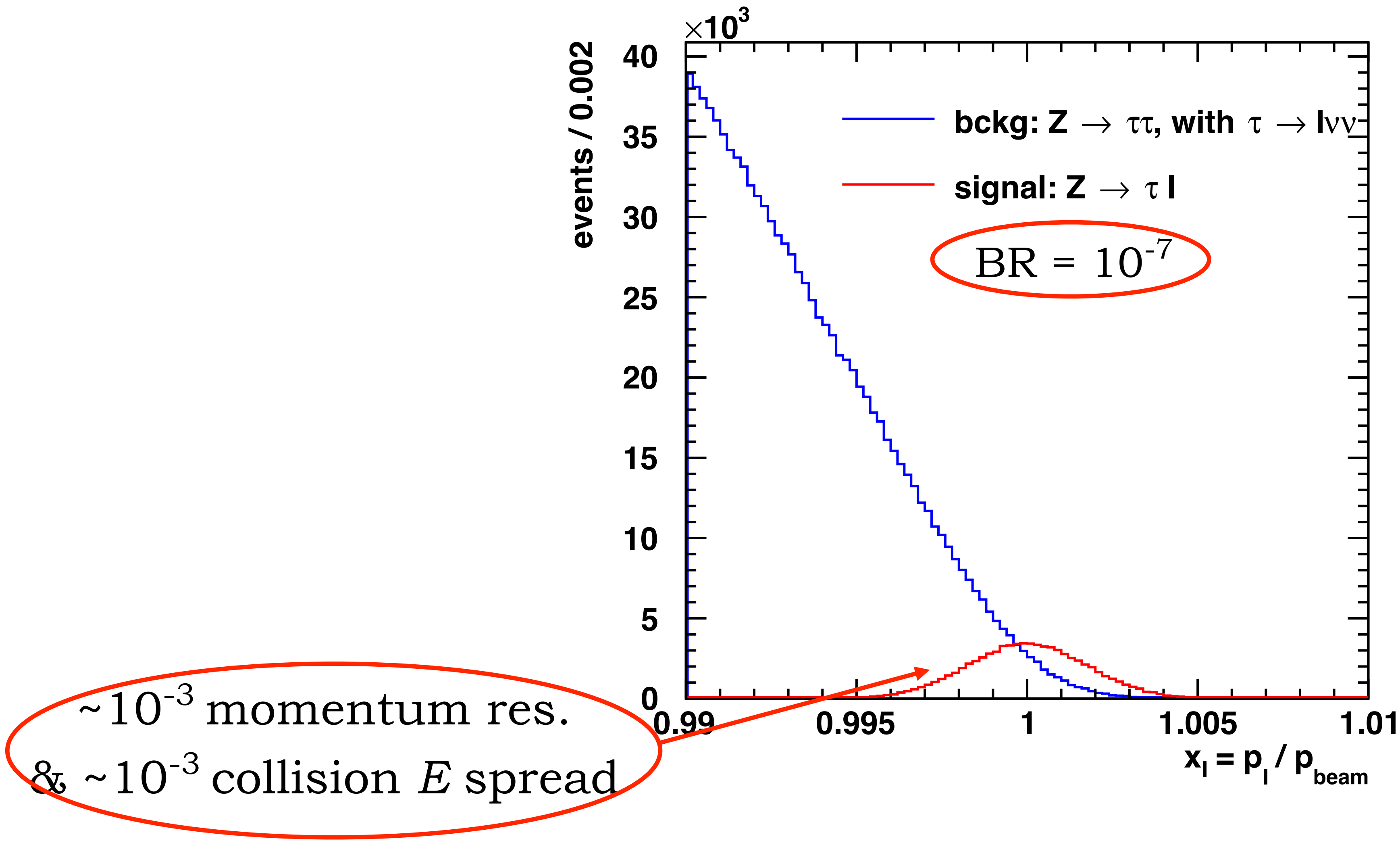
- $Z \to \ell\tau$:

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:

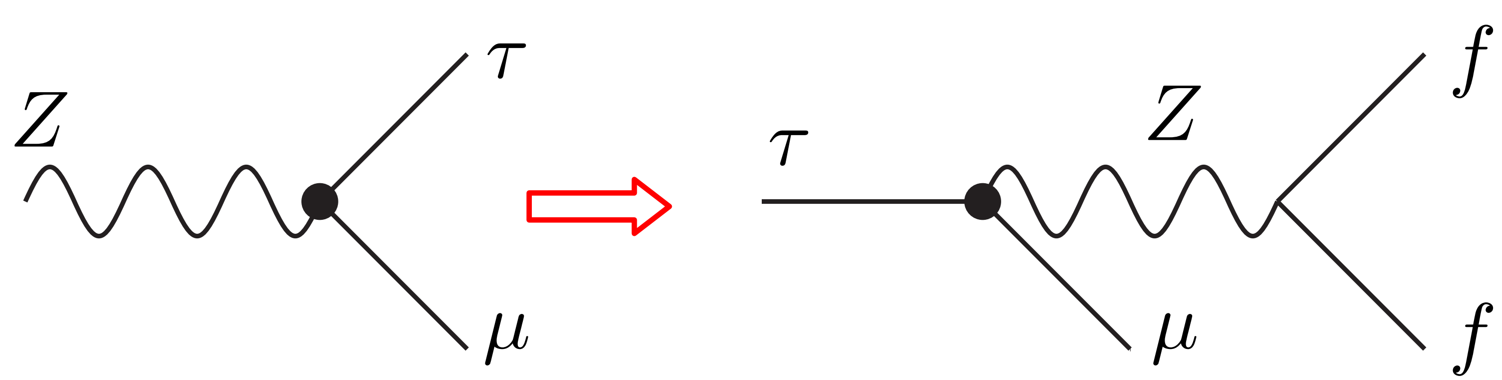


Sensitivity:

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

- CEPC 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 CEPC searches find new physics with these modes?
- It depends on the indirect constraints from other processes
- In particular low-energy LFV processes are unavoidably induced

E.g. :



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

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

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

$\dots$

Previous model-independent 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			
$Q_{\ell q}^{(1)}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{Q}_L\gamma^\mu Q_L)$	$Q_{\ell u}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{u}_R\gamma^\mu u_R)$
$Q_{\ell q}^{(3)}$	$(\bar{L}_L\gamma_\mu\tau_I L_L)(\bar{Q}_L\gamma^\mu\tau_I Q_L)$	Q_{eu}	$(\bar{e}_R\gamma_\mu e_R)(\bar{u}_R\gamma^\mu u_R)$
Q_{eq}	$(\bar{e}_R\gamma^\mu e_R)(\bar{Q}_L\gamma_\mu Q_L)$	$Q_{\ell edq}$	$(\bar{L}^a_L e_R)(\bar{d}_R Q^a_L)$
$Q_{\ell d}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{d}_R\gamma^\mu d_R)$	$Q_{\ell equ}^{(1)}$	$(\bar{L}^a_L e_R)\epsilon_{ab}(\bar{Q}^b_L u_R)$
Q_{ed}	$(\bar{e}_R\gamma_\mu e_R)(\bar{d}_R\gamma^\mu d_R)$	$Q_{\ell equ}^{(3)}$	$(\bar{L}^a_i\sigma_{\mu\nu}e_R)\epsilon_{ab}(\bar{Q}^b_L\sigma^{\mu\nu}u_R)$
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

Z LFV in the SM EFT

The couplings of Z to leptons are protected by the SM gauge symmetry
$\rightarrow$ 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:

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

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

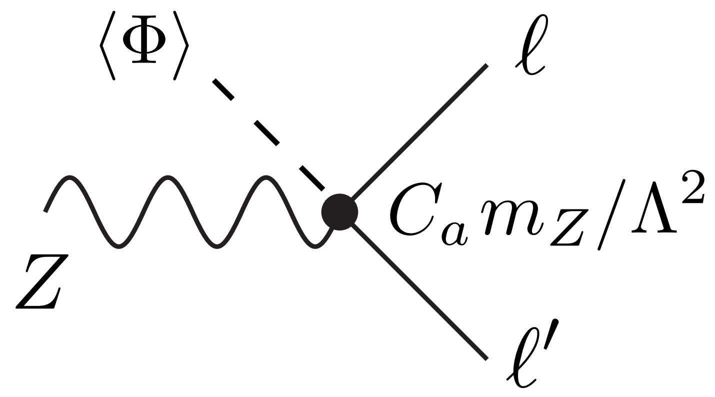
$$\mathrm{Br}\left[Z^0 \to \ell^\pm_f \ell^\mp_i\right] = \frac{m_Z}{24\pi\Gamma_Z}\left[\frac{m_Z^2}{2}\left(\left|C^{ZR}_{fi}\right|^2 + \left|C^{ZL}_{fi}\right|^2\right) + \left|\Gamma^{ZL}_{fi}\right|^2 + \left|\Gamma^{ZR}_{fi}\right|^2\right]$$

$$\Gamma^{ZL}_{fi} = \frac{e}{2s_W c_W}\left(\frac{v^2}{\Lambda^2}\left(C^{(1)fi}_{\varphi l} + C^{(3)fi}_{\varphi l}\right) + \left(1 - 2s_W^2\right)\delta_{fi}\right) \qquad \Gamma^{ZR}_{fi} = \frac{e}{2s_W c_W}\left(\frac{v^2}{\Lambda^2} C^{fi}_{\varphi e} - 2s_W^2 \delta_{fi}\right)$$

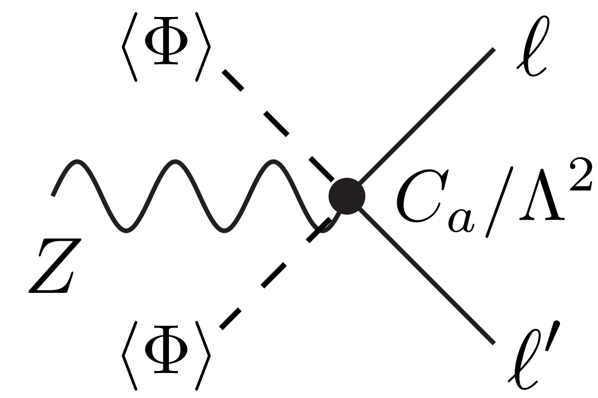
$$C^{ZR}_{fi} = C^{ZL\star}_{if} = -\frac{v}{\sqrt{2}\Lambda^2} = \left(s_W C^{fi}_{eB} + c_W C^{fi}_{eW}\right)$$

Crivellin Najjari Rosiek 1312.0634

Dipole operators:



Higgs-lepton operators:



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

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

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

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

$$\Gamma^{ZL}_{fi} = \frac{e}{2 s_W c_W}\left(\frac{v^2}{\Lambda^2}\left(C^{(1)fi}_{\varphi l} + C^{(3)fi}_{\varphi l}\right) + \left(1 - 2 s_W^2\right)\delta_{fi}\right) \qquad \Gamma^{ZR}_{fi} = \frac{e}{2 s_W c_W}\left(\frac{v^2}{\Lambda^2} C^{fi}_{\varphi e} - 2 s_W^2 \delta_{fi}\right)$$

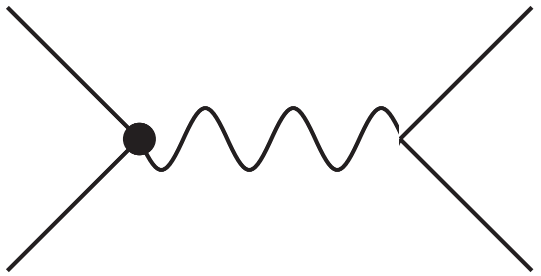
$$C^{ZR}_{fi} = C^{ZL\star}_{if} = -\frac{v}{\sqrt{2}\Lambda^2} = \left(s_W C^{fi}_{eB} + c_W C^{fi}_{eW}\right)$$

Crivellin Najjari Rosiek 1312.0634

- 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:

$\rightarrow$ operator mixing

e.g.

$$16\pi^2 \frac{dC^{Hl(1)}_{\alpha\beta}}{d\log\mu} = 2(Y_e^\dagger Y_e C^{Hl(1)})_{\alpha\beta} + \frac{9}{2}(Y_e^\dagger Y_e C^{Hl(3)})_{\alpha\beta} + 2\left(C^{Hl(1)} Y_e^\dagger Y_e\right)_{\alpha\beta} + \frac{9}{2}\left(C^{Hl(3)} Y_e^\dagger Y_e\right)_{\alpha\beta}$$
$$+ 2\chi C^{Hl(1)}_{ab} + \frac{1}{3} g_1^2 C^{Hl(1)}_{\alpha\beta} + \frac{2}{3} g_1^2 \mathrm{tr}[C^{Hl(1)}]\delta_{\alpha\beta} - 6(C^{W\dagger}C^{W})_{\alpha\beta} \,,$$

$$16\pi^2 \frac{dC^{ll}_{\alpha\beta\gamma\delta}}{d\log\mu} = \frac{1}{2}\left(C^{Hl(3)}_{\alpha\beta} - C^{Hl(1)}_{\alpha\beta}\right)(Y_e^\dagger Y_e)_{\gamma\delta} - C^{Hl(3)}_{\alpha\delta}(Y_e^\dagger Y_e)_{\gamma\beta} - \frac{1}{6}\left(g_2^2 C^{Hl(3)}_{\alpha\beta} + g_1^2 C^{Hl(1)}_{\alpha\beta}\right)\delta_{\gamma\delta}$$
$$+ \frac{1}{2}(Y_e^\dagger Y_e)_{\alpha\beta}\left(C^{Hl(3)}_{\gamma\delta} - C^{Hl(1)}_{\gamma\delta}\right) - (Y_e^\dagger Y_e)_{\alpha\delta} C^{Hl(3)}_{\gamma\beta} - \frac{1}{6}\delta_{\alpha\beta}\left(g_1^2 C^{Hl(1)}_{\gamma\delta} + g_2^2 C^{Hl(3)}_{\gamma\delta}\right)$$
$$+ \frac{g_2^2}{3}\left(C^{Hl(3)}_{\alpha\delta}\delta_{\gamma\beta} + C^{Hl(3)}_{\gamma\beta}\delta_{\alpha\delta}\right) - 2C^{W\dagger}_{\alpha\gamma}C^{W}_{\beta\delta} \,,$$

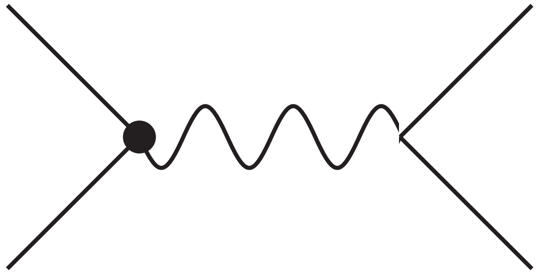
$\cdots$

4 leptons operators induced at 1 loop

Jenkins Manohar Trott '13 (x2); Alonso et al. '13

- 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:

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

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

e.g. Jenkins Manohar Stoffer '17; Davidson '16; Coy Frigerio '18; ...

⇨ e.g. $C^{V,LL}_{ee,\alpha\beta\gamma\delta} = C^{ll}_{\alpha\beta\gamma\delta} + \frac{1}{2}\left(-1+2s_w^2\right)\left[\left(C^{Hl(1)}_{\alpha\beta} + C^{Hl(3)}_{\alpha\beta}\right)\delta_{\gamma\delta} + \delta_{\alpha\beta}\left(C^{Hl(1)}_{\gamma\delta} + C^{Hl(3)}_{\gamma\delta}\right)\right]$

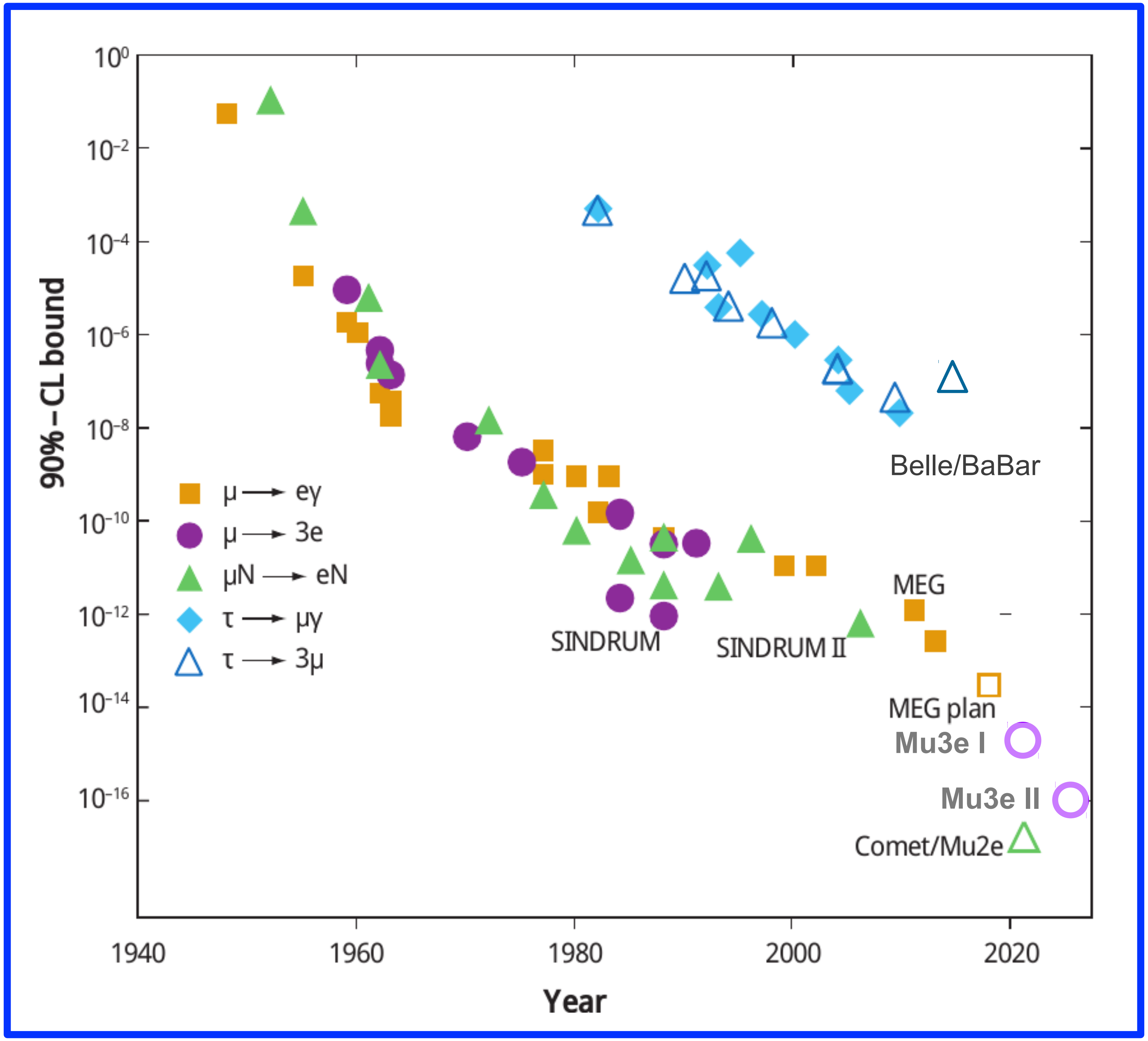
(iii) QED×QCD running from m_Z down to $m_{\tau/\mu}$

e.g. Crivellin Davidson Pruna Signer '17; Jenkins Manohar Stoffer '17

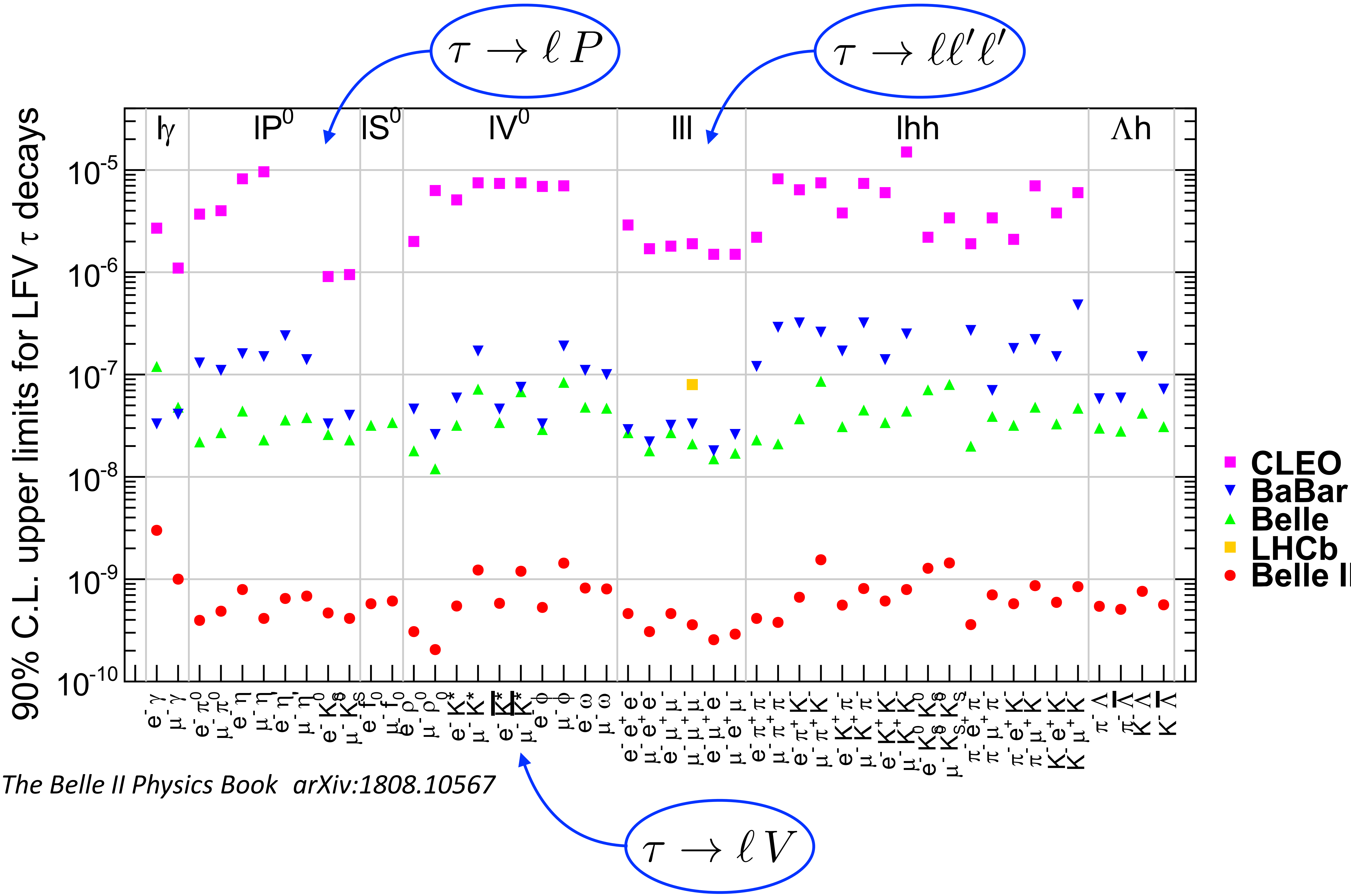
(iv) Compute the low-energy observables

Celis Cirigliano Passemar '13; Crivellin at al.'13; Pruna Signer '14; Crivellin at al. '17; Aebischer et al. '18; ...

Present/future limits on LFV muon decays



Present/future limits on LFV tau decays



The Belle II Physics Book arXiv:1808.10567

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

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} :

$\mathrm{BR}(\mu \to e\gamma) \lesssim 4.2 \times 10^{-13}$	[MEG '16]	$\Rightarrow$	$\mathrm{BR}(Z \to e\mu) \lesssim 10^{-22} - 10^{-21}$
$\mathrm{BR}(\tau \to e\gamma) \lesssim 3.3 \times 10^{-8}$	[BaBar '10]	$\Rightarrow$	$\mathrm{BR}(Z \to \tau e) \lesssim 10^{-14} - 10^{-13}$
$\mathrm{BR}(\tau \to \mu\gamma) \lesssim 4.4 \times 10^{-8}$	[BaBar '10]	$\Rightarrow$	$\mathrm{BR}(Z \to \tau\mu) \lesssim 10^{-14} - 10^{-13}$

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

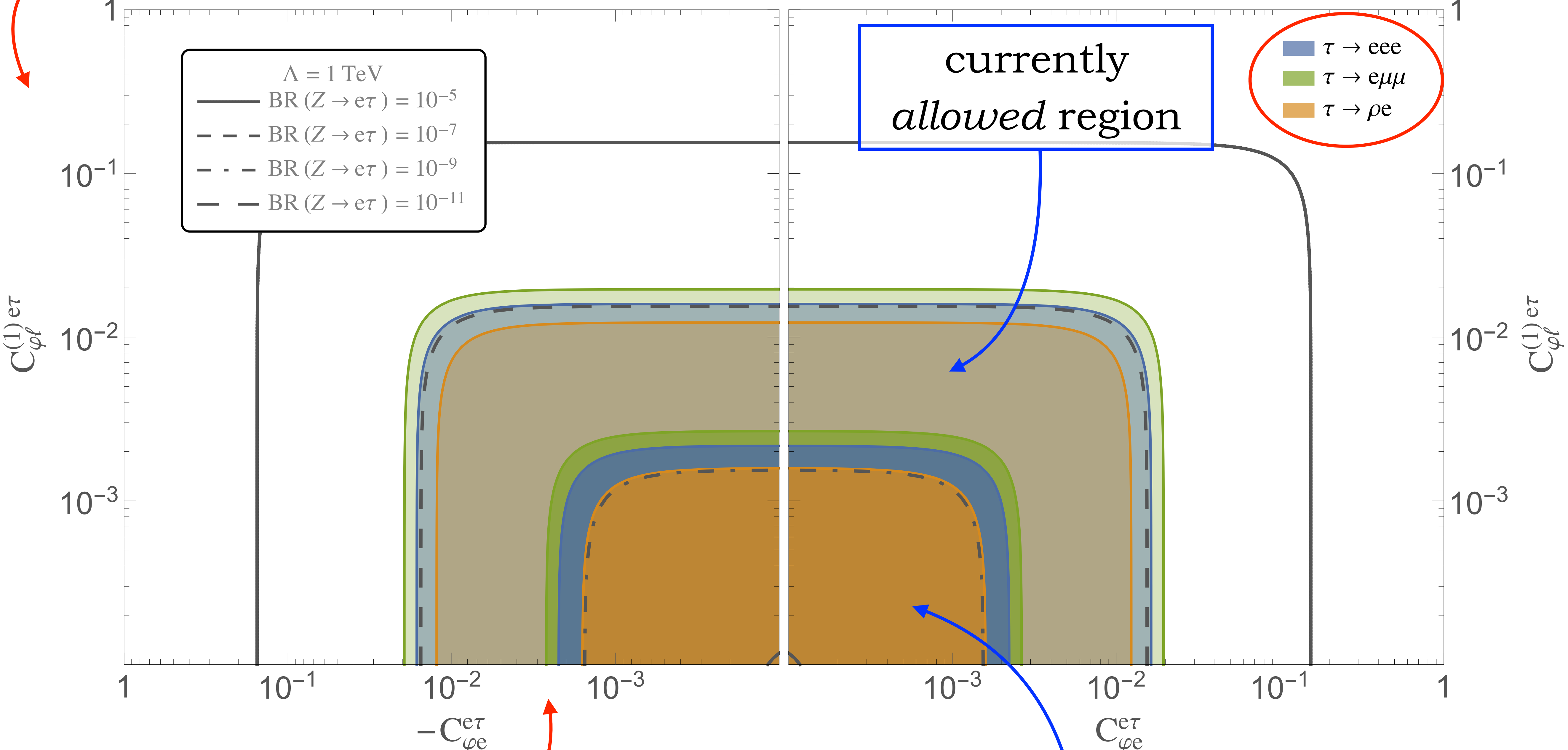
One operator dominance: Higgs currents

	Indirect limits on $\mathrm{BR}(Z \to \ell\ell')$ from single operators		
	Operator	Limit	Strongest constraint
$Q_{\Phi\ell}^{(1)}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{e}_L \gamma^\mu \mu_L)$	$\mathrm{BR}(Z \to \mu e) \lesssim 3.7 \times 10^{-13}$	$\mu \to eee$
	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{e}_L \gamma^\mu \tau_L)$	$\mathrm{BR}(Z \to \tau e) \lesssim 8.5 \times 10^{-8}$	$\tau \to \rho\, e$
	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{\mu}_L \gamma^\mu \tau_L)$	$\mathrm{BR}(Z \to \tau \mu) \lesssim 6.6 \times 10^{-8}$	$\tau \to \rho\, \mu$
$Q_{\Phi\ell}^{(3)}$	$(\Phi^\dagger i \overleftrightarrow{D}^I_\mu \Phi)(\bar{e}_L \tau_I \gamma^\mu \mu_L)$	$\mathrm{BR}(Z \to \mu e) \lesssim 3.7 \times 10^{-13}$	$\mu \to eee$
	$(\Phi^\dagger i \overleftrightarrow{D}^I_\mu \Phi)(\bar{e}_L \tau_I \gamma^\mu \tau_L)$	$\mathrm{BR}(Z \to \tau e) \lesssim 8.5 \times 10^{-8}$	$\tau \to \rho\, e$
	$(\Phi^\dagger i \overleftrightarrow{D}^I_\mu \Phi)(\bar{\mu}_L \tau_I \gamma^\mu \tau_L)$	$\mathrm{BR}(Z \to \tau \mu) \lesssim 6.6 \times 10^{-8}$	$\tau \to \rho\, \mu$
$Q_{\Phi e}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{e}_R \gamma^\mu \mu_R)$	$\mathrm{BR}(Z \to \mu e) \lesssim 6.5 \times 10^{-12}$	$\mu \to eee$
	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{e}_R \gamma^\mu \tau_R)$	$\mathrm{BR}(Z \to \tau e) \lesssim 9.8 \times 10^{-8}$	$\tau \to \rho\, e$
	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{\mu}_R \gamma^\mu \tau_R)$	$\mathrm{BR}(Z \to \tau \mu) \lesssim 7.6 \times 10^{-8}$	$\tau \to \rho\, \mu$

above refs + Wilson (Aebischer Kumar Straub ’18) and Flavio (Straub ’18) packages

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

$\Lambda = 1$ TeV



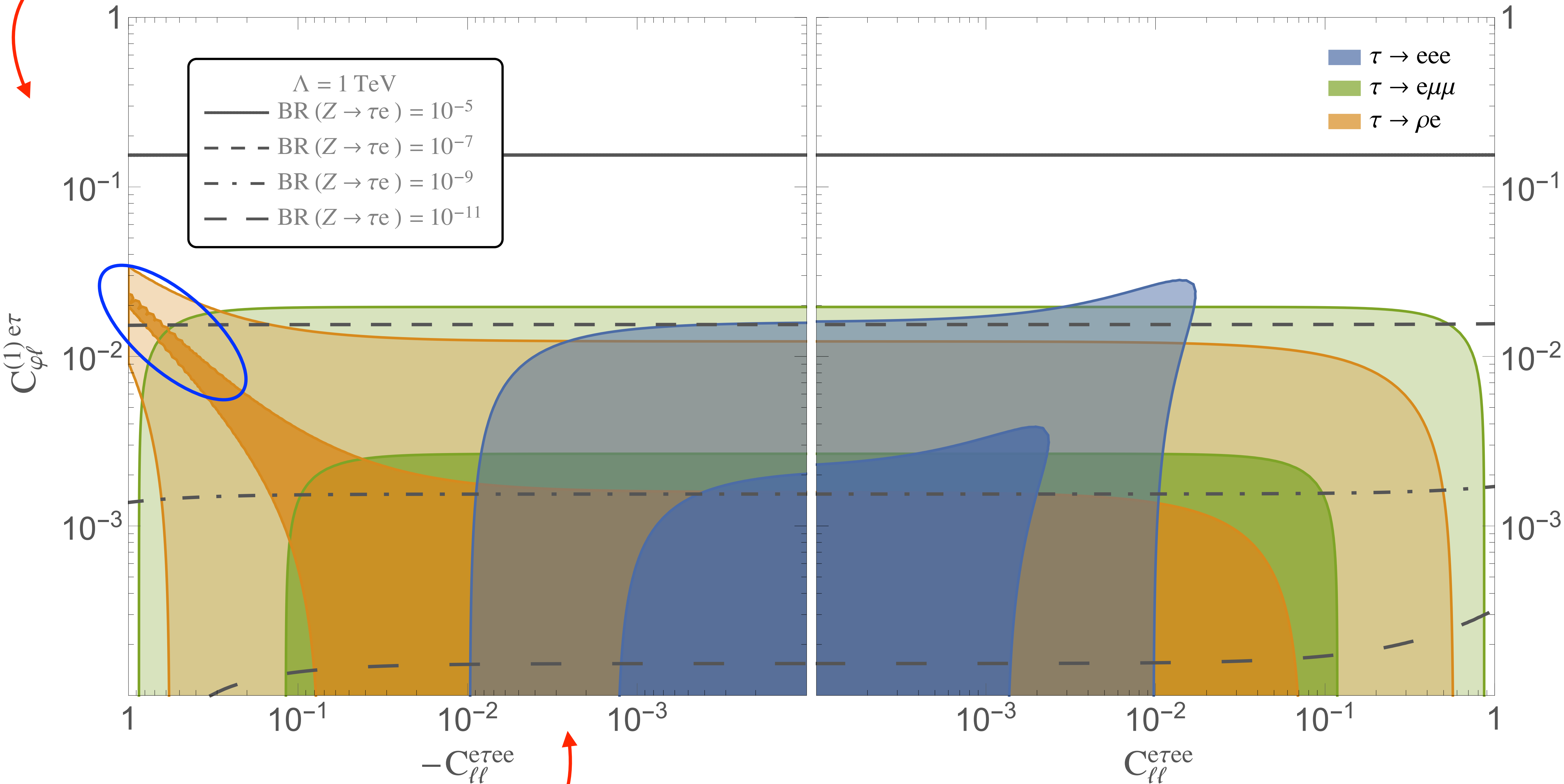
$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{e}_R \gamma^\mu \tau_R)$

expected Belle-II bound

Two operators

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

$\Lambda = 1$ TeV



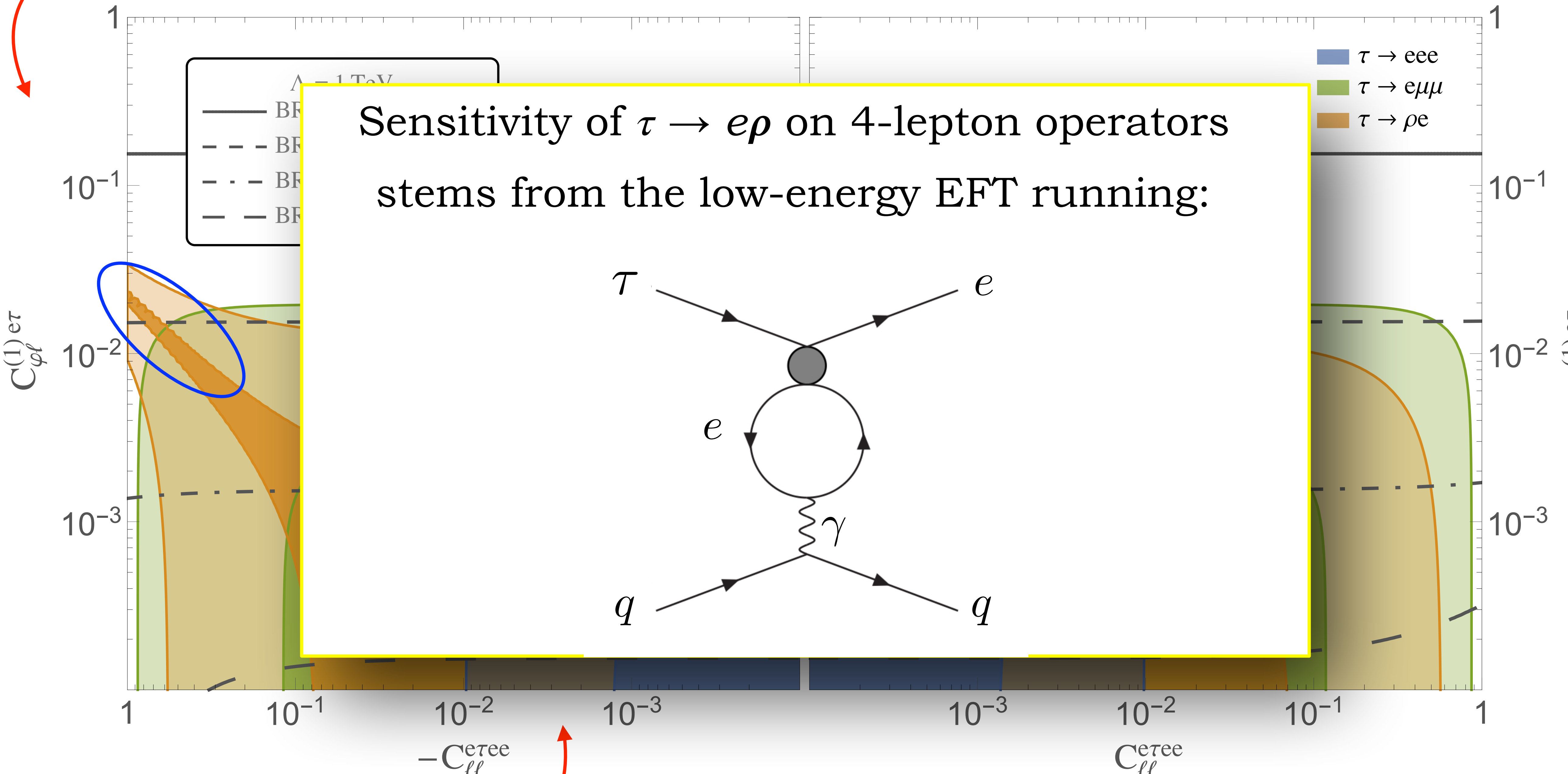
$(\bar{e}_L \gamma_\mu \tau_L)(\bar{e}_L \gamma_\mu e_L)$

4-lepton operator → cancellations are possible for some observables

Two operators

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

$\Lambda = 1$ TeV



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

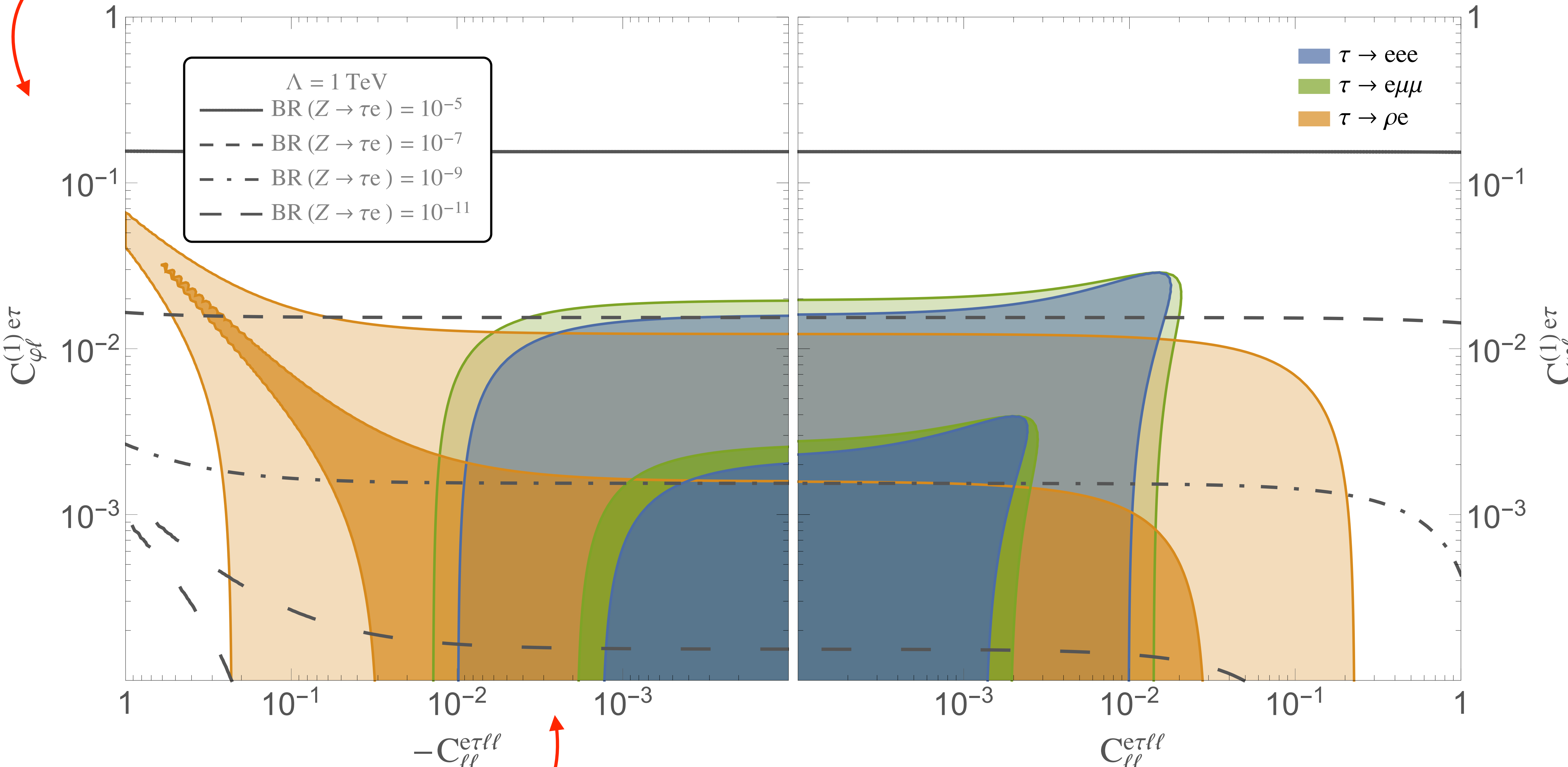
$(\bar{e}_L \gamma_\mu \tau_L)(\bar{e}_L \gamma_\mu e_L)$

4-lepton operator → cancellations are possible for some observables

Two operators

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

$\Lambda = 1$ TeV



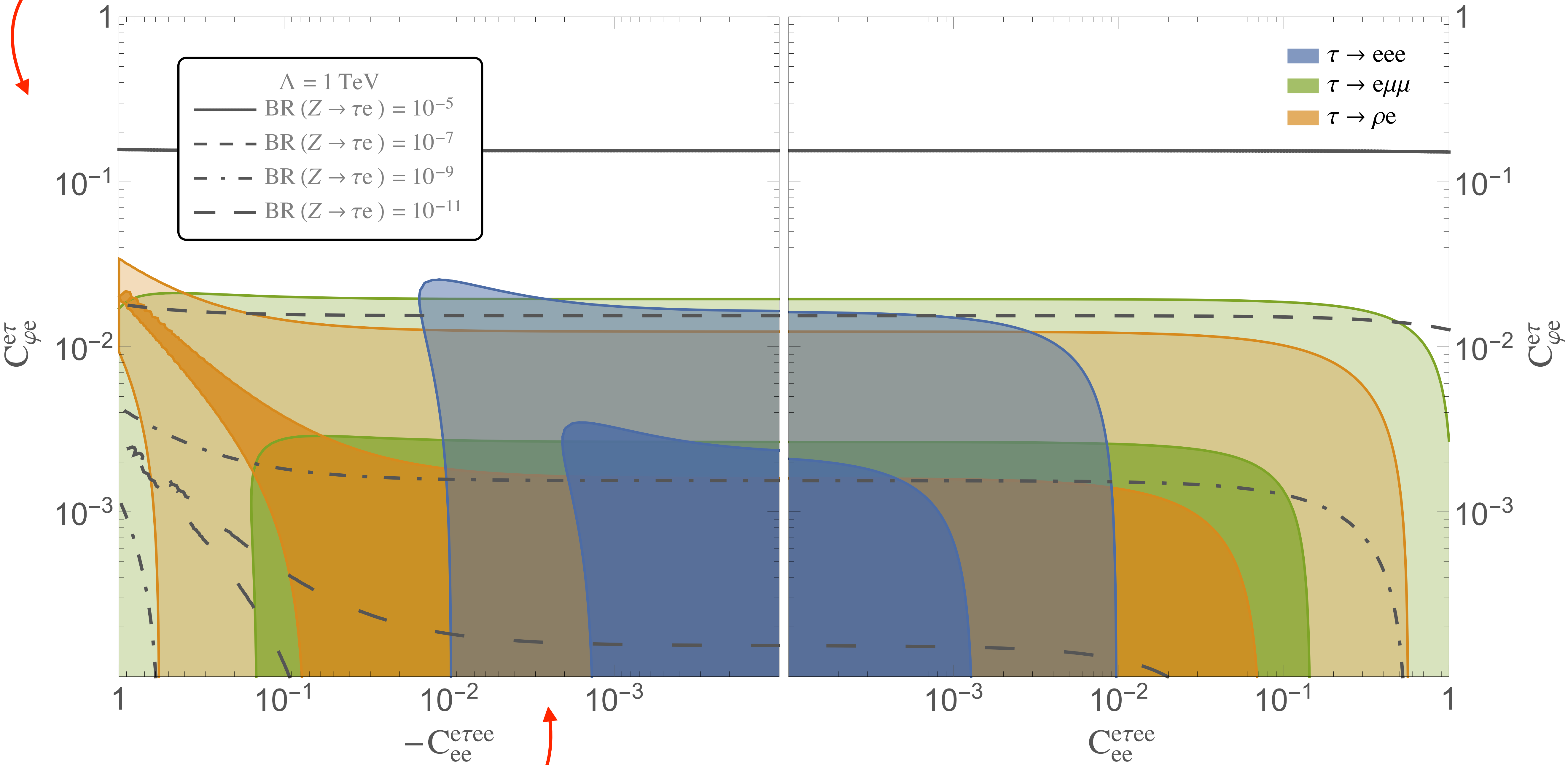
$(\bar{e}_L \gamma_\mu \tau_L)(\bar{\ell}_L \gamma_\mu \ell_L)$

LFU current: $C_{\ell\ell}^{e\tau ee} = C_{\ell\ell}^{e\tau\mu\mu} = C_{\ell\ell}^{e\tau\tau\tau}$

Two operators

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

$\Lambda = 1$ TeV



$(\bar{e}_R \gamma_\mu \tau_R)(\bar{e}_R \gamma_\mu e_R)$

RH operators

Conclusions

Preliminary results: systematical study on the way…

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

$\mathrm{BR}(Z \to \tau\ell) \approx 10^{-7}$ 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 the CEPC (and complementarity with B-factory searches)

谢谢大家!

Thank you!