Facultad de Ciencias | Universidad Autónoma de Madrid | Instituto de Física Teórica UAM-CSIC

PROBING NEW PHYSICS VIA LFV QUARKONIUM DECAYS

Xabier Marcano

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*with **Lorenzo Calibbi, Tong Li** and **Michael A. Schmidt***

QWG

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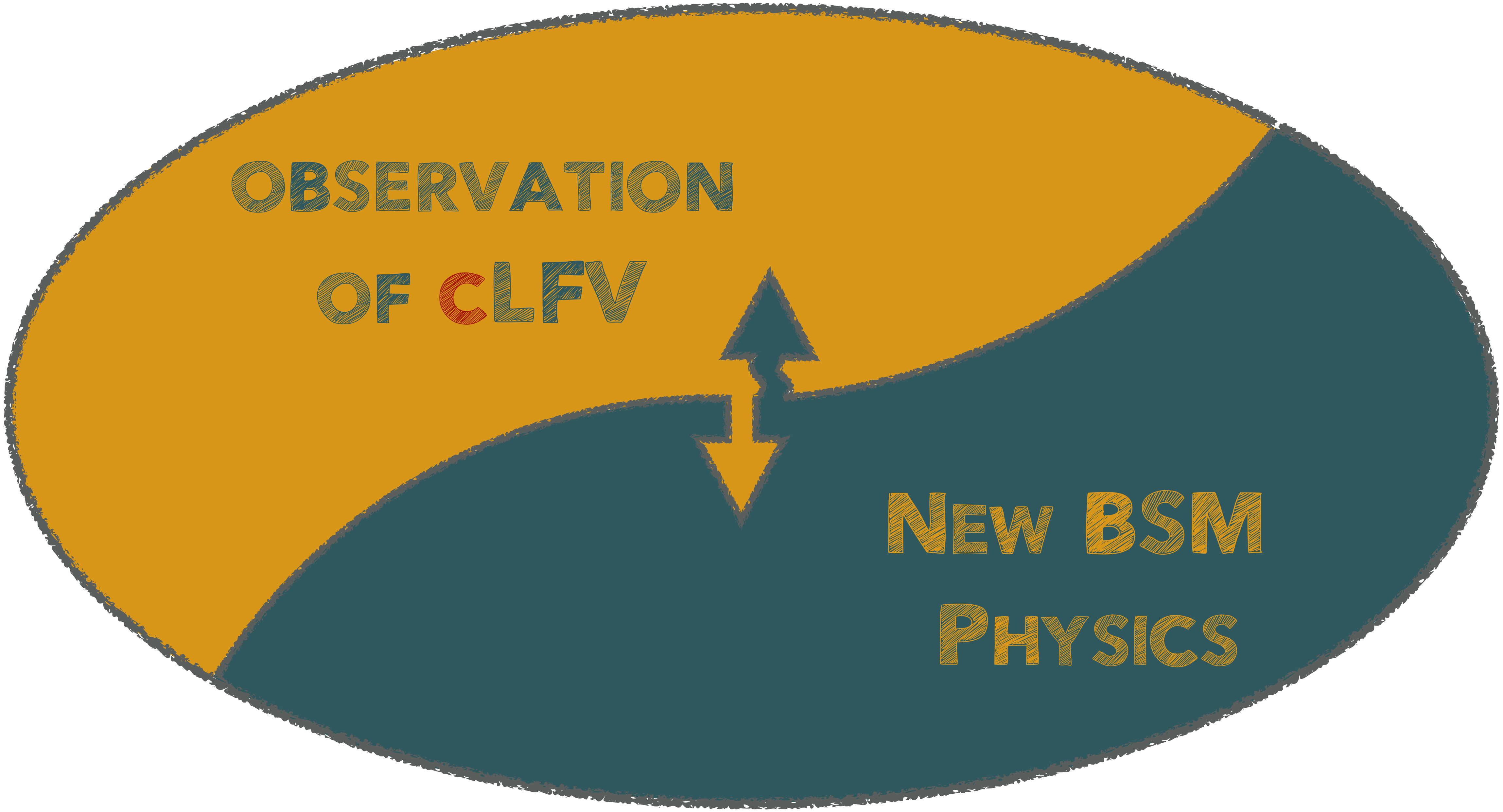
PheNumenal

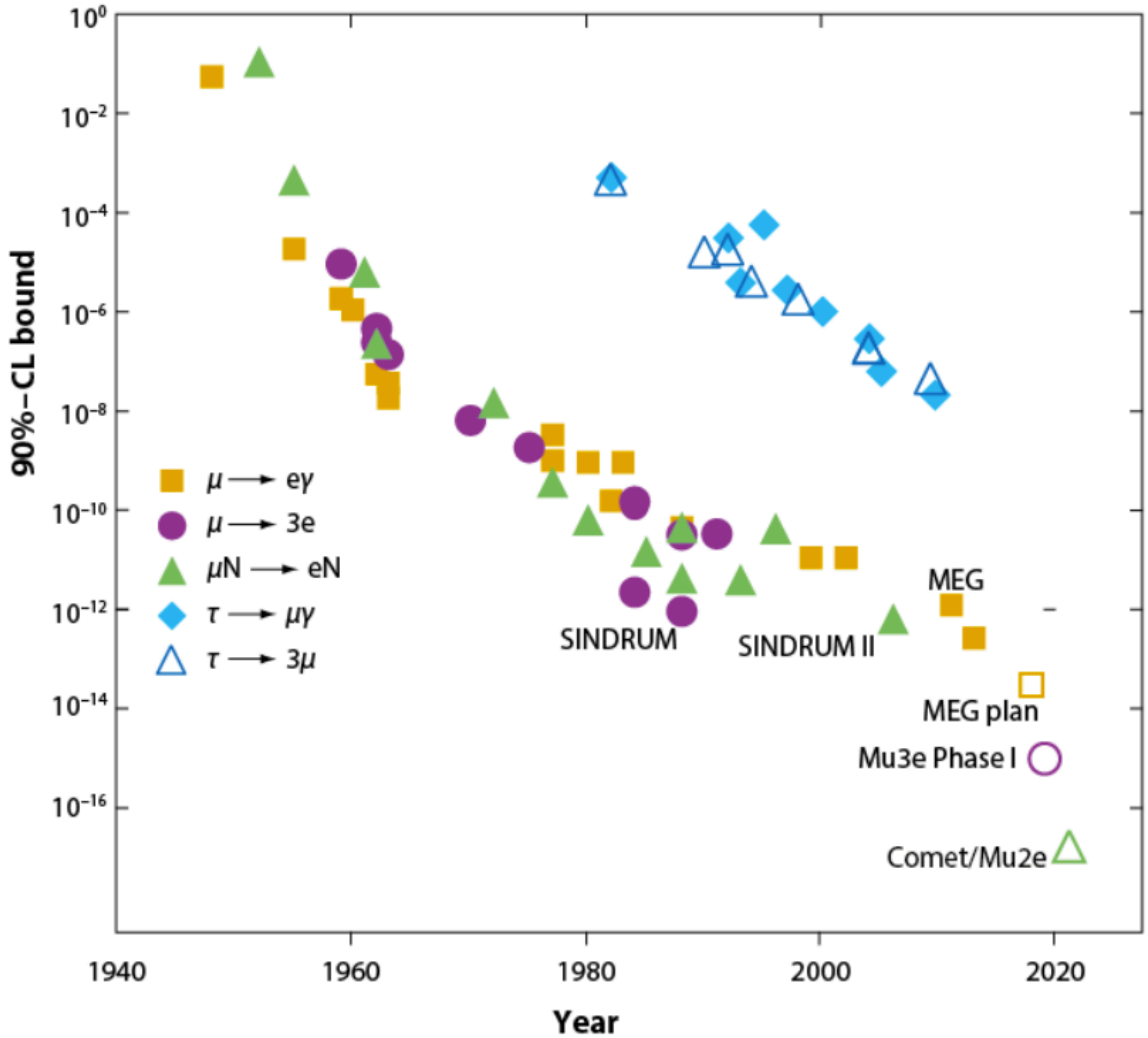
EXCELENCIA SEVERO OCHOA

WHY LEPTON FLAVOR VIOLATION?



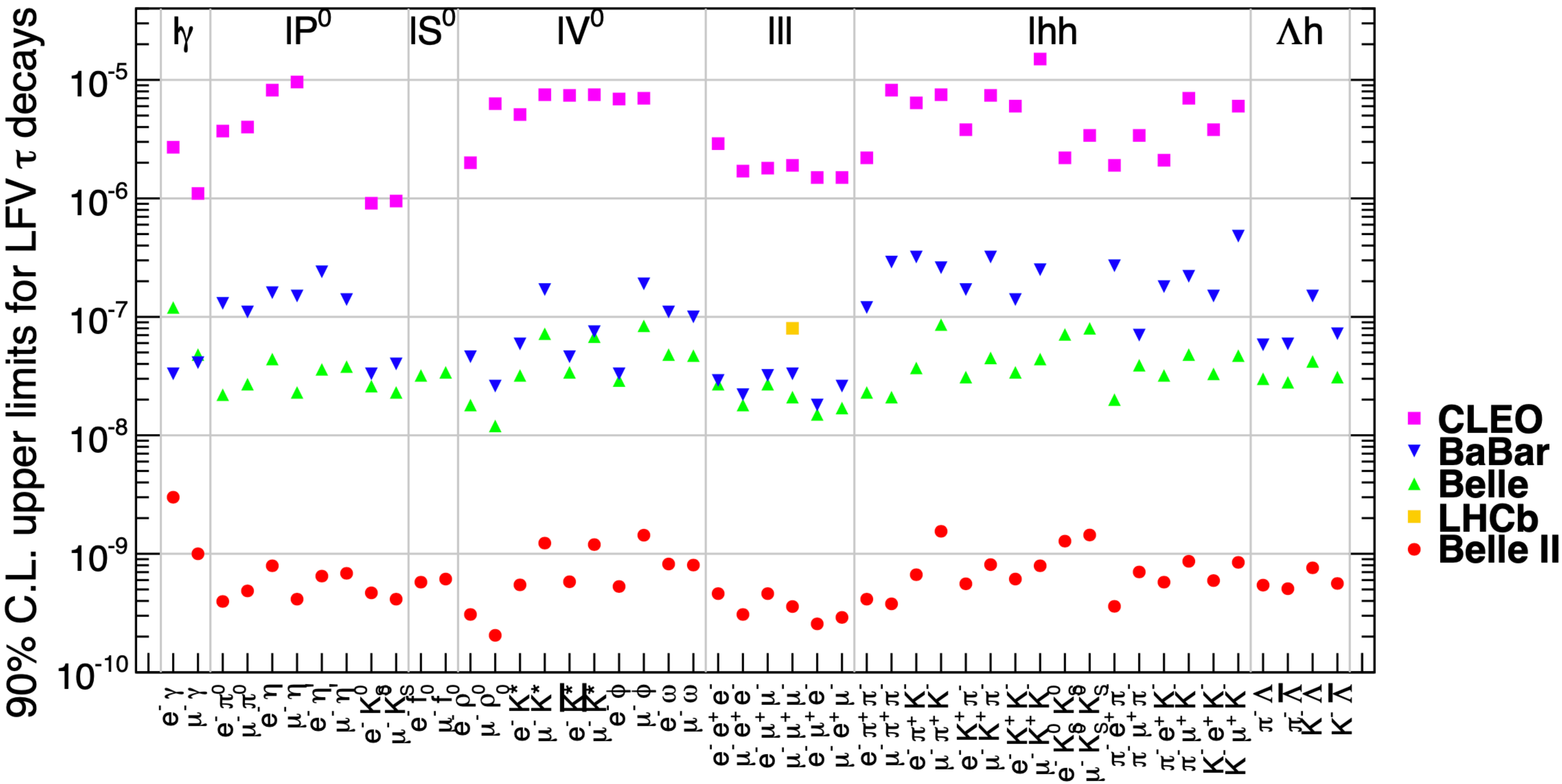
Long story

Bravar — ICHEP 2016

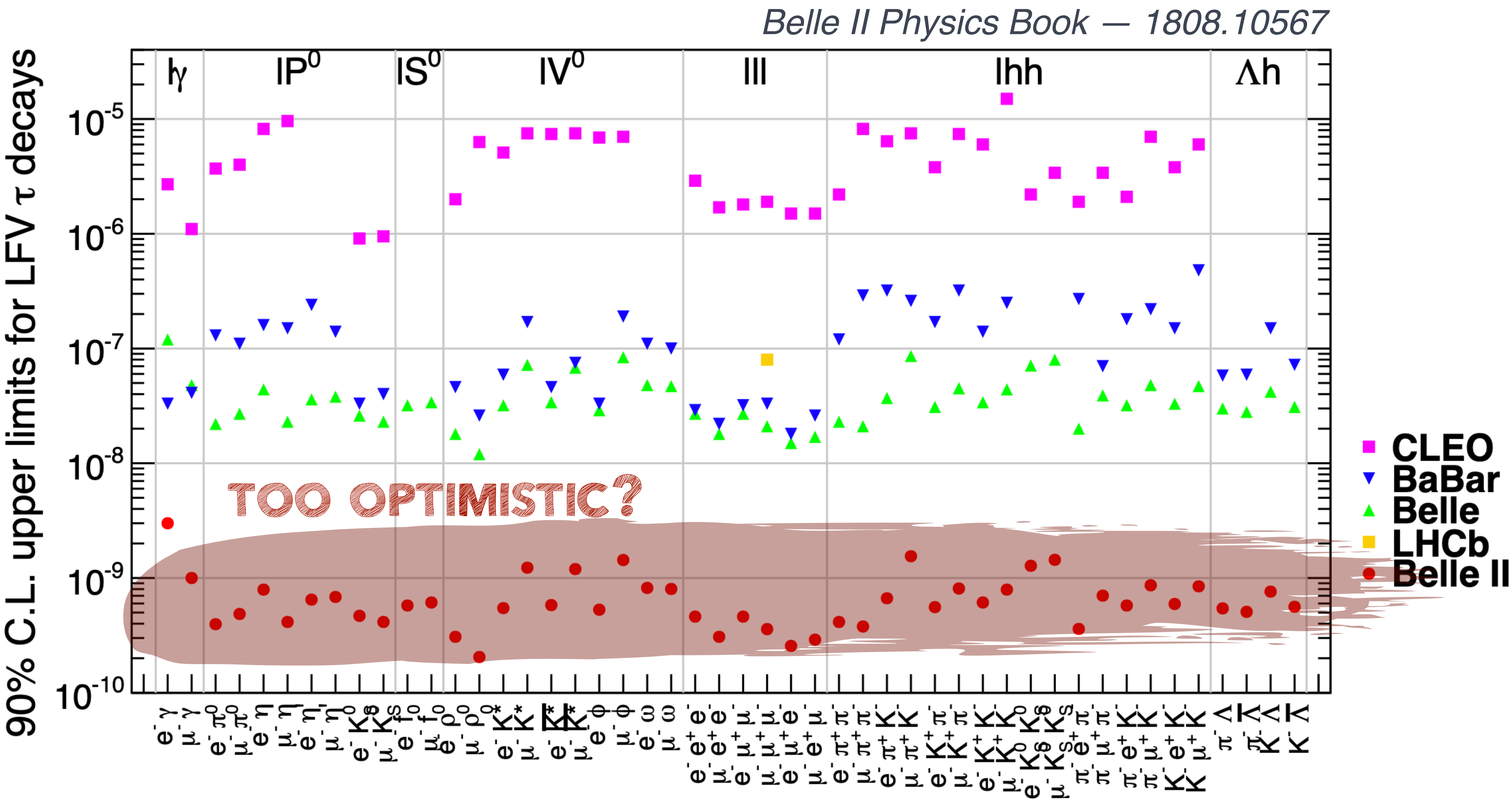


Long story

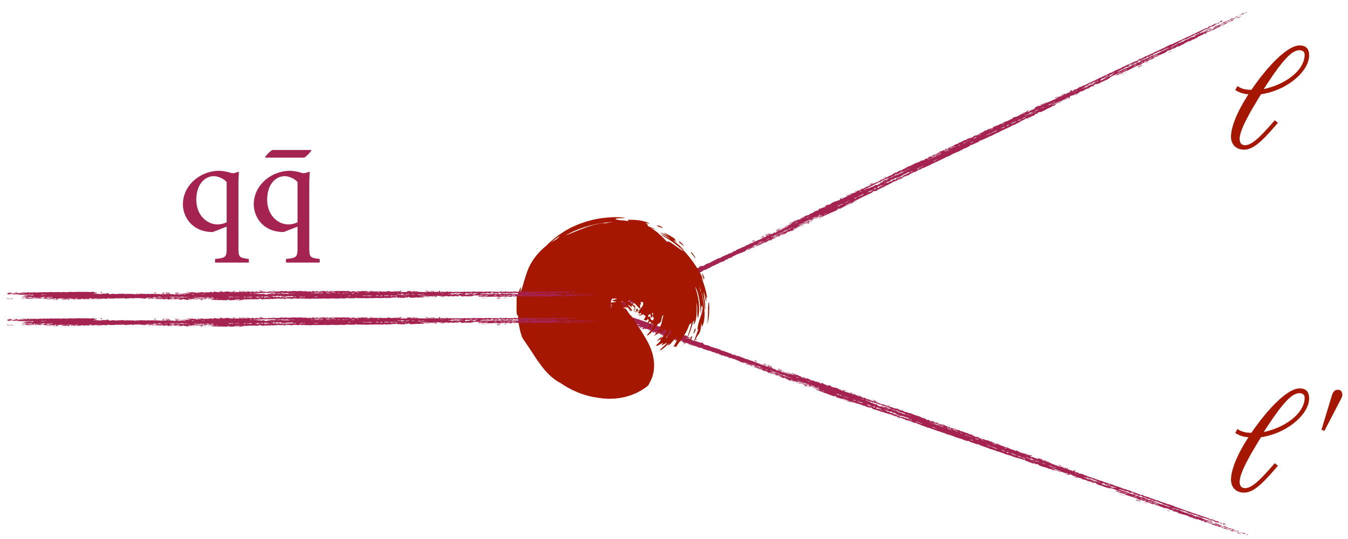
Belle II Physics Book — 1808.10567



LONG STORY


Belle II Physics Book — 1808.10567
90% C.L. upper limits for LFV τ decays
lγ
lP^0
lS^0
lV^0
lll
lhh
Λh
TOO OPTIMISTIC?
CLEO
BaBar
Belle
LHCb
Belle II

— LFV Quarkonium Decays —



Current Status on LFVQD

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]
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$J/\psi \to \mu\tau$	2.0×10^{-6}	BES (2004)	[20]
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- *See talk by Jingshu Li*
- *Refs as in 2207.10913*

Current Status on LFVQD

Vectorial Quarkonia

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Can we Probe New Physics via LFVQD?

Which Model?

Let's try to be model independent

— Effective Field Theory Analysis —

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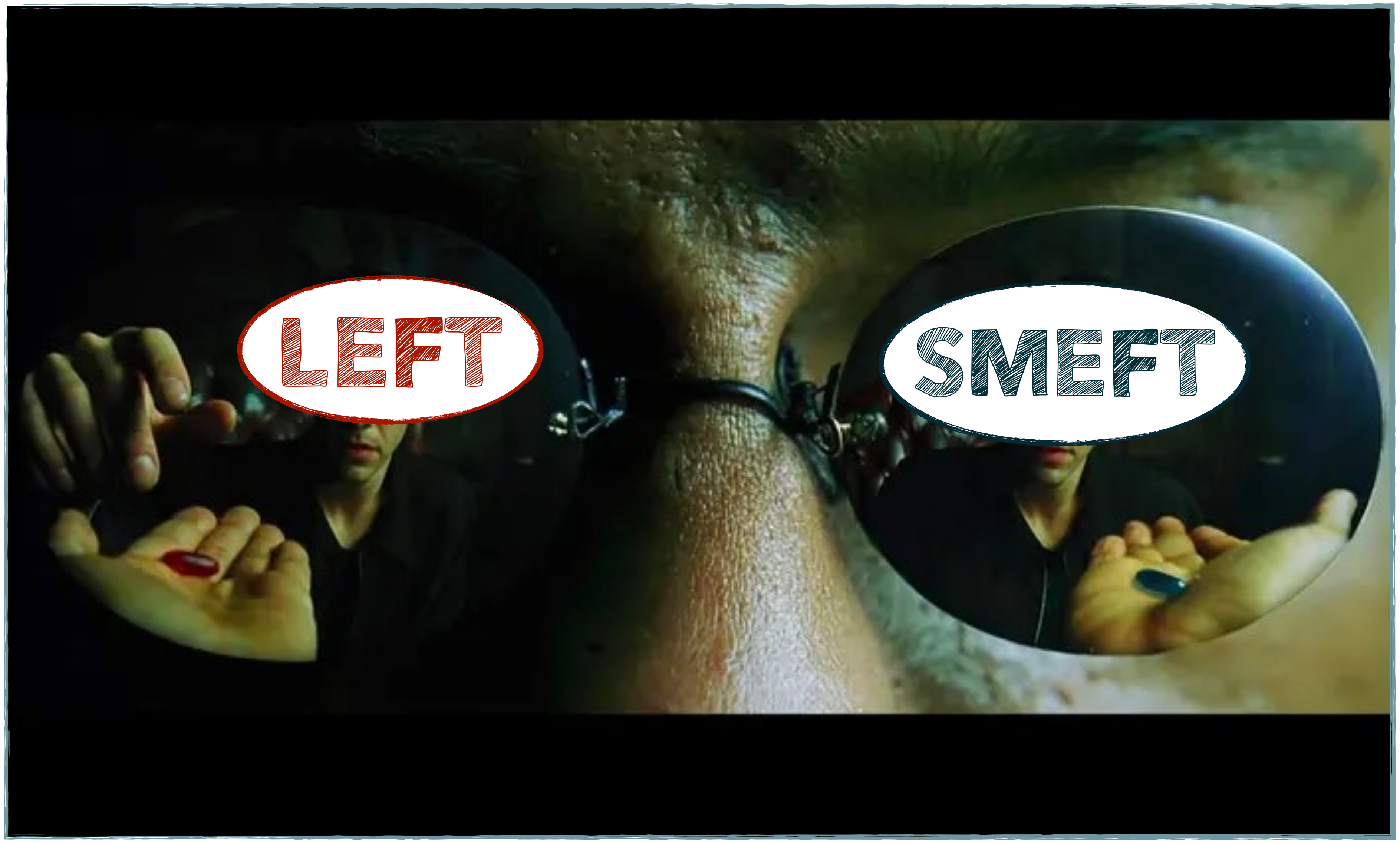
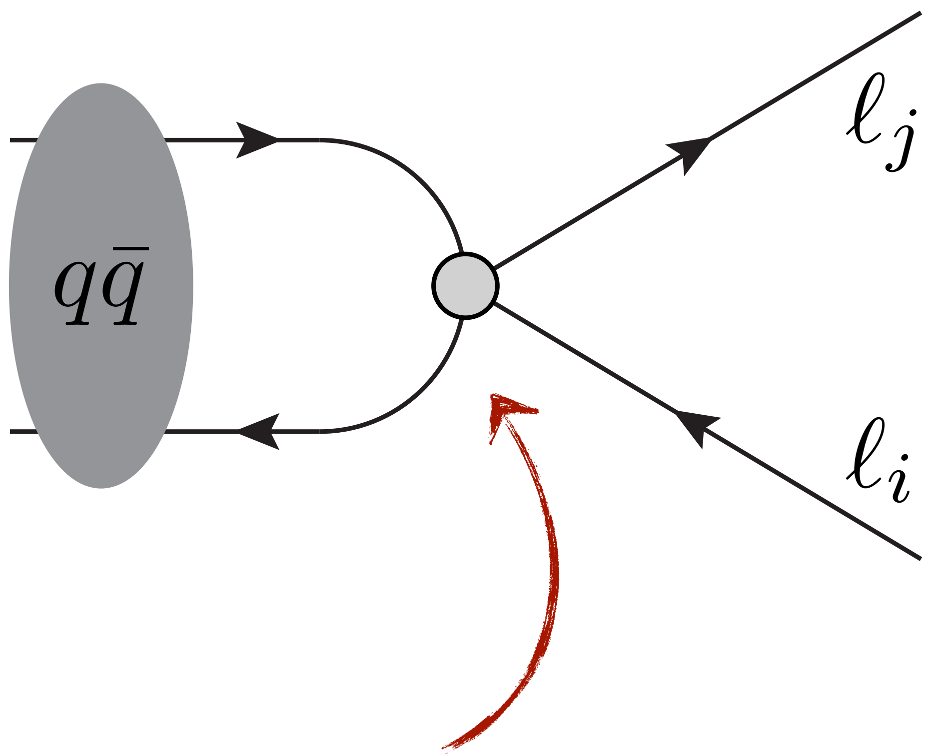
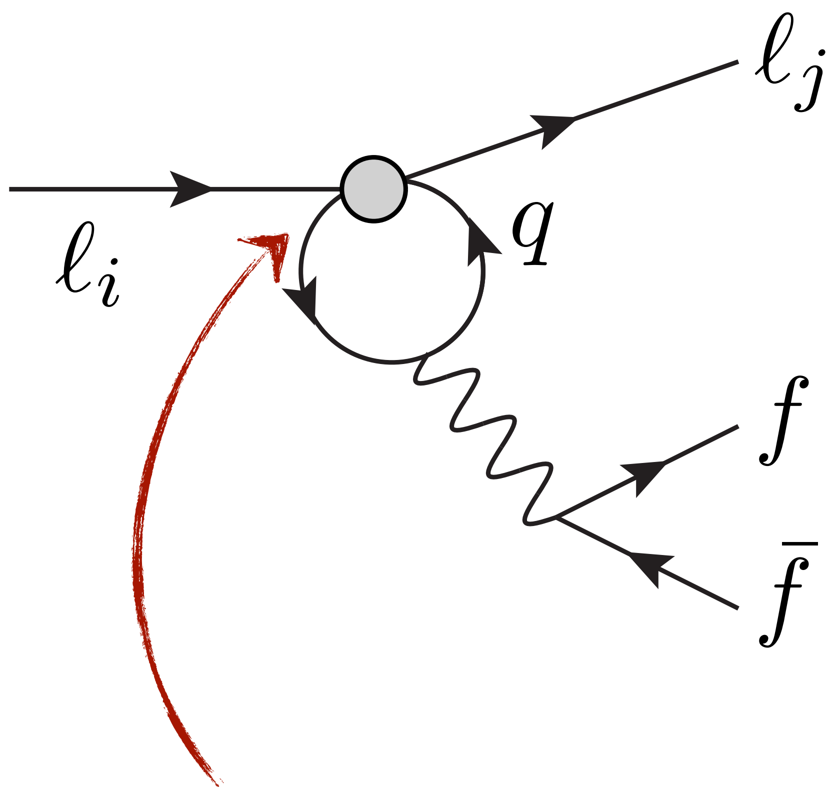
— Effective Field Theory Analysis —



- Defined below EW scale
- Four fermion operators: **2quark-2leptons** ***(S, V, T)***



Tree-level
LFVQD



Loop-level
other LFV processes

Indirect Upper Limits: Vectors

$c\bar{c}$

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

- Single operator analysis

  — warning! Wilson coefficients are scale dependent $C \equiv C(\mu)$ —

- Results for $\mu\tau$ similar to $e\tau$ (more in 2207.10913)

Indirect Upper Limits: Vectors

$c\bar{c}$

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

Too small

$BR(J/\psi \to e\mu) < 4.5 \times 10^{-9}$

- Single operator analysis

  — warning! Wilson coefficients are scale dependent $C \equiv C(\mu)$ —

- Results for $\mu\tau$ similar to $e\tau$ (more in 2207.10913)

Indirect Upper Limits: Vectors

$c\bar{c}$

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

Too small
$BR(J/\psi \to e\mu) < 4.5 \times 10^{-9}$

Not that far
$BR(J/\psi \to e\tau) < 7.5 \times 10^{-8}$

- Single operator analysis

  — warning! Wilson coefficients are scale dependent $C \equiv C(\mu)$ —

- Results for $\mu\tau$ similar to $e\tau$ (more in 2207.10913)

Indirect Upper Limits: Vectors

$b\bar{b}$

Operator	Str. const.	Indirect upper limits on BR		
		$\Upsilon(1S) \to \ell\ell'$	$\Upsilon(2S) \to \ell\ell'$	$\Upsilon(3S) \to \ell\ell'$
$C^{V,LL}_{ed,\tau ebb}$	$\tau \to \rho e$	$[3.1 - 0.2] \times 10^{-6}$	$[2.8 - 0.2] \times 10^{-6}$	$[3.0 - 0.3] \times 10^{-6}$
$C^{V,LR}_{ed,\tau ebb}$	$\tau \to \rho e$	$[3.1 - 0.2] \times 10^{-6}$	$[2.8 - 0.2] \times 10^{-6}$	$[3.0 - 0.3] \times 10^{-6}$
$C^{T,RR}_{ed,\tau ebb}$	$\tau \to e\gamma$	$[4.0 - 0.6] \times 10^{-11}$	$[3.7 - 0.6] \times 10^{-11}$	$[4.1 - 0.8] \times 10^{-11}$
$C_{e\gamma,\tau e}$	$\tau \to e\gamma$	1.4×10^{-17}	1.3×10^{-17}	1.4×10^{-17}

- More promising results: **BELLE/BABAR already at $\mathcal{O}(10^{-6})$ level**

Indirect Upper Limits: Vectors

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		$\Upsilon(1S) \to \ell\ell'$	$\Upsilon(2S) \to \ell\ell'$	$\Upsilon(3S) \to \ell\ell'$
$C^{V,LL}_{ed,\tau ebb}$	$\tau \to \rho e$	$[3.1 - 0.2] \times 10^{-6}$	$[2.8 - 0.2] \times 10^{-6}$	$[3.0 - 0.3] \times 10^{-6}$
$C^{V,LR}_{ed,\tau ebb}$	$\tau \to \rho e$	$[3.1 - 0.2] \times 10^{-6}$	$[2.8 - 0.2] \times 10^{-6}$	$[3.0 - 0.3] \times 10^{-6}$
$C^{T,RR}_{ed,\tau ebb}$	$\tau \to e\gamma$	$[4.0 - 0.6] \times 10^{-11}$	$[3.7 - 0.6] \times 10^{-11}$	$[4.1 - 0.8] \times 10^{-11}$
$C_{e\gamma,\tau e}$	$\tau \to e\gamma$	1.4×10^{-17}	1.3×10^{-17}	1.4×10^{-17}

- More promising results: **BELLE/BABAR already at $\mathcal{O}(10^{-6})$ level**

Vectorial quarkonia could probe new LEFT parameter space in $\ell\tau$ sector ✔

Indirect Upper Limits: Scalars

$c\bar{c}$

Operator	Str. const.	Indirect upper limits on BR		
		$J/\psi \to \ell\ell'\gamma$	$\eta_c \to \ell\ell'$	$\chi_{c0}(1P) \to \ell\ell'$
$C^{S,RR}_{eu,\tau ecc}$	$\tau \to e\gamma$	$[1.7 - 0.003] \times 10^{-10}$	$[6.8 - 0.01] \times 10^{-9}$	$[1.5 - 0.003] \times 10^{-7}$
$C^{S,RL}_{ed,\tau ecc}$	$\tau \to e\gamma$	$[2.0 - 0.09] \times 10^{-10}$	$[9.2 - 0.4] \times 10^{-9}$	$[1.3 - 0.08] \times 10^{-7}$

$b\bar{b}$

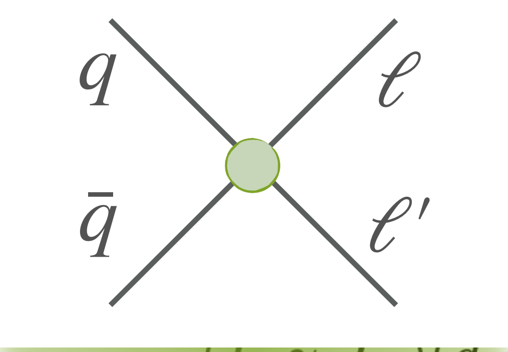
Operator	Str. const.	Indirect upper limits on BR		
		$\Upsilon(1S) \to \ell\ell'\gamma$	$\eta_b \to \ell\ell'$	$\chi_{b0}(1P) \to \ell\ell'$
$C^{S,RR}_{ed,\tau ebb}$	$\tau \to e\gamma$	$[7.6 - 0.1] \times 10^{-9}$	$[1.1 - 0.02] \times 10^{-6}$	$[2.8 - 0.05] \times 10^{-6}$
$C^{S,RL}_{ed,\tau ebb}$	$\tau \to e\gamma$	$[3.5 - 0.3] \times 10^{-8}$	$[5.3 - 0.4] \times 10^{-6}$	$[1.2 - 0.09] \times 10^{-5}$

- Few experimental results available
- Interesting as they **probe different operators than vectorial decays**

- Defined above EW scale

$2q2\ell$ operators			
$\mathcal{O}^{(1)}_{\ell q,prst}$	$(\bar{L}_p\gamma_\mu L_r)(\bar{Q}_s\gamma^\mu Q_t)$	$\mathcal{O}^{(3)}_{\ell q,prst}$	$(\bar{L}_p\gamma_\mu\tau^I L_r)(\bar{Q}_s\gamma^\mu\tau^I Q_t)$
$\mathcal{O}_{\ell u,prst}$	$(\bar{L}_p\gamma_\mu L_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{\ell d,prst}$	$(\bar{L}_p\gamma_\mu L_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{eu,prst}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{ed,prst}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{qe,prst}$	$(\bar{Q}_p\gamma^\mu Q_r)(\bar{e}_s\gamma_\mu e_t)$	$\mathcal{O}_{\ell edq,prst}$	$(\bar{L}_p e_r)(\bar{d}_s Q_t)$
$\mathcal{O}^{(1)}_{\ell equ,prst}$	$(\bar{L}^j_p e_r)\epsilon_{jk}(\bar{Q}^k_s u_t)$	$\mathcal{O}^{(3)}_{\ell equ,prst}$	$(\bar{L}^j_p\sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{Q}^k_s\sigma^{\mu\nu} u_t)$
4ℓ operators		**Dipole operators**	
$\mathcal{O}_{\ell\ell,prst}$	$(\bar{L}_p\gamma_\mu L_r)(\bar{L}_s\gamma^\mu L_t)$	$\mathcal{O}_{eW,pr}$	$(\bar{L}_p\sigma^{\mu\nu} e_r)\tau^I\varphi W^I_{\mu\nu}$
$\mathcal{O}_{ee,prst}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{eB,pr}$	$(\bar{L}_p\sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$
$\mathcal{O}_{\ell e,prst}$	$(\bar{L}_p\gamma_\mu L_r)(\bar{e}_s\gamma^\mu e_t)$		
Lepton-Higgs operators			
$\mathcal{O}^{(1)}_{\varphi\ell,pr}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{L}_p\gamma^\mu L_r)$	$\mathcal{O}^{(3)}_{\varphi\ell,pr}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{L}_p\gamma^\mu\tau^I L_r)$
$\mathcal{O}_{\varphi e,pr}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$	$\mathcal{O}_{e\varphi 3,pr}$	$(\bar{L}_p e_r\varphi)(\varphi^\dagger\varphi)$

- Defined above EW scale



	$2q2\ell$ operators		
$\mathcal{O}^{(1)}_{\ell q,prst}$	$(\bar{L}_p\gamma_\mu L_r)(\bar{Q}_s\gamma^\mu Q_t)$	$\mathcal{O}^{(3)}_{\ell q,prst}$	$\gamma^\mu\tau^I Q_t)$
$\mathcal{O}_{\ell u,prst}$	$(\bar{L}_p\gamma_\mu L_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{\ell d,prst}$	$(\bar{L}_p\gamma_\mu L_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{eu,prst}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{ed,prst}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{qe,prst}$	$(\bar{Q}_p\gamma^\mu Q_r)(\bar{e}_s\gamma_\mu e_t)$	$\mathcal{O}_{\ell edq,prst}$	$(\bar{L}_p e_r)(\bar{d}_s Q_t)$
$\mathcal{O}^{(1)}_{\ell equ,prst}$	$(\bar{L}^j_p e_r)\epsilon_{jk}(\bar{Q}^k_s u_t)$	$\mathcal{O}^{(3)}_{\ell equ,prst}$	$(\bar{L}^j_p\sigma_{\mu\nu}e_r)\epsilon_{jk}(\bar{Q}^k_s\sigma^{\mu\nu}u_t)$
	4ℓ operators		Dipole operators
$\mathcal{O}_{\ell\ell,prst}$	$(\bar{L}_p\gamma_\mu L_r)(\bar{L}_s\gamma^\mu L_t)$	$\mathcal{O}_{eW,pr}$	$(\bar{L}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$
$\mathcal{O}_{ee,prst}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{eB,pr}$	$(\bar{L}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$
$\mathcal{O}_{\ell e,prst}$	$(\bar{L}_p\gamma_\mu L_r)(\bar{e}_s\gamma^\mu e_t)$		
	Lepton-Higgs operators		
$\mathcal{O}^{(1)}_{\varphi\ell,pr}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{L}_p\gamma^\mu L_r)$	$\mathcal{O}^{(3)}_{\varphi\ell,pr}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{L}_p\gamma^\mu\tau^I L_r)$
$\mathcal{O}_{\varphi e,pr}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$	$\mathcal{O}_{e\varphi 3,pr}$	$(\bar{L}_p e_r\varphi)(\varphi^\dagger\varphi)$

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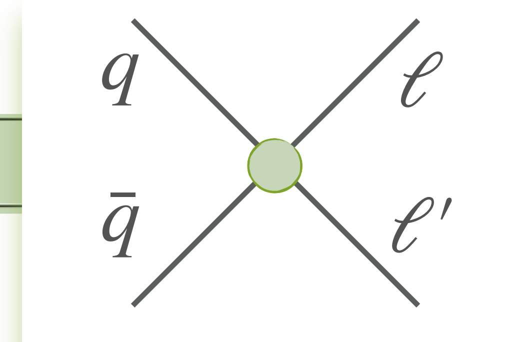
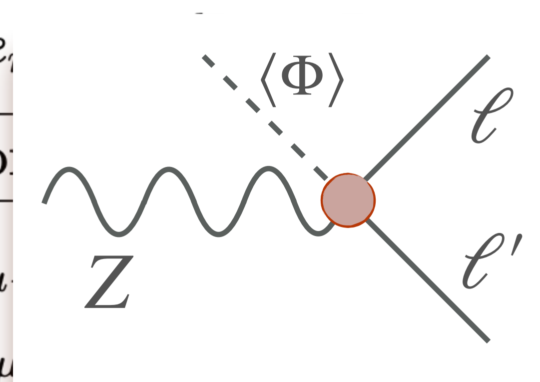
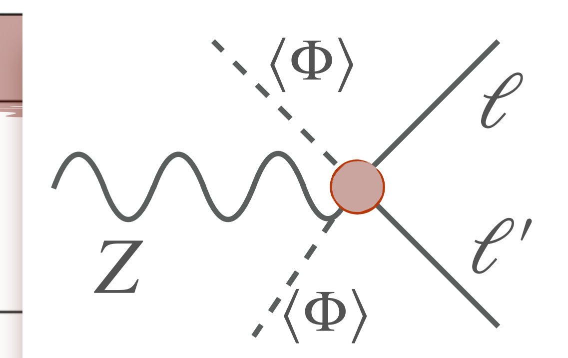
$\mathcal{O}_{eu,prst}$	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	$\mathcal{O}_{ed,prst}$	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$
$\mathcal{O}_{qe,prst}$	$(\bar Q_p\gamma^\mu Q_r)(\bar e_s\gamma_\mu e_t)$	$\mathcal{O}_{\ell edq,prst}$	$(\bar L_p e_r)(\bar d_s Q_t)$
$\mathcal{O}^{(1)}_{\ell equ,prst}$	$(\bar L^j_p e$	$^{(3)}_{\ell equ,prst}$	$(\bar L^j_p\sigma_{\mu\nu}e_r)\epsilon_{jk}(\bar Q^k_s\sigma^{\mu\nu}u_t)$
4ℓ operato		**Dipole operators**	
$\mathcal{O}_{\ell\ell,prst}$	$(\bar L_p\gamma_\mu$	$_{eW,pr}$	$(\bar L_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$
$\mathcal{O}_{ee,prst}$	$(\bar e_p\gamma_\mu$	$_{eB,pr}$	$(\bar L_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$
$\mathcal{O}_{\ell e,prst}$	$(\bar L_p\gamma_\mu L_r)(\bar e_s\gamma^\mu e_t)$		
Lepton-Higgs operators			
$\mathcal{O}^{(1)}_{\varphi\ell,pr}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar L_p\gamma^\mu L_r)$	$\mathcal{O}^{(3)}_{\varphi\ell,pr}$	$)$
$\mathcal{O}_{\varphi e,pr}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$	$\mathcal{O}_{e\varphi 3,pr}$	

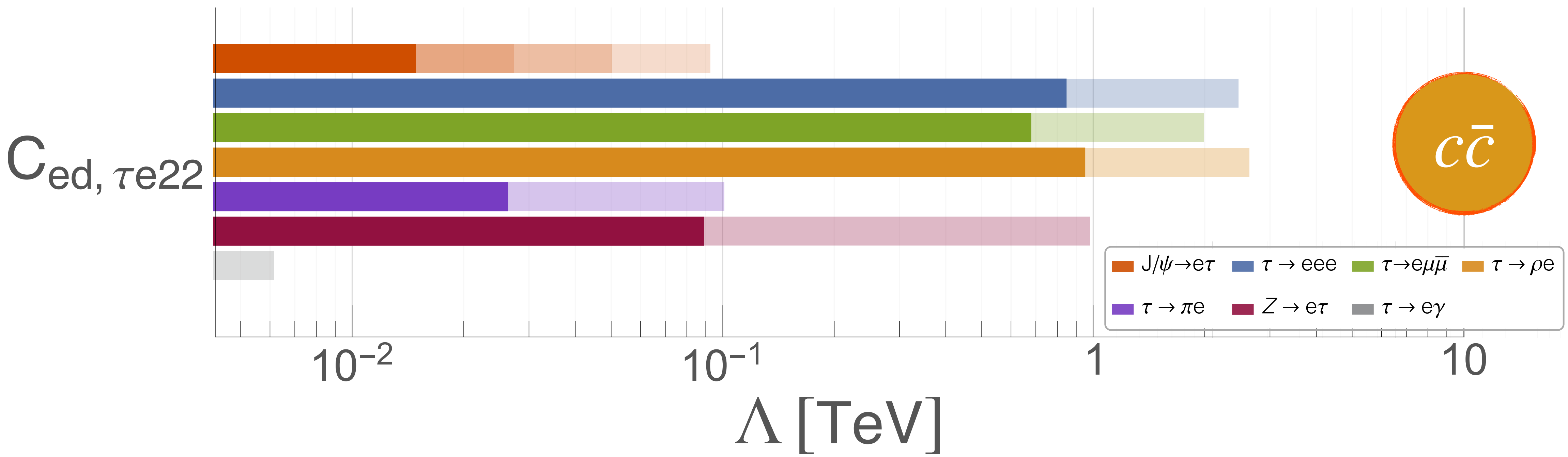


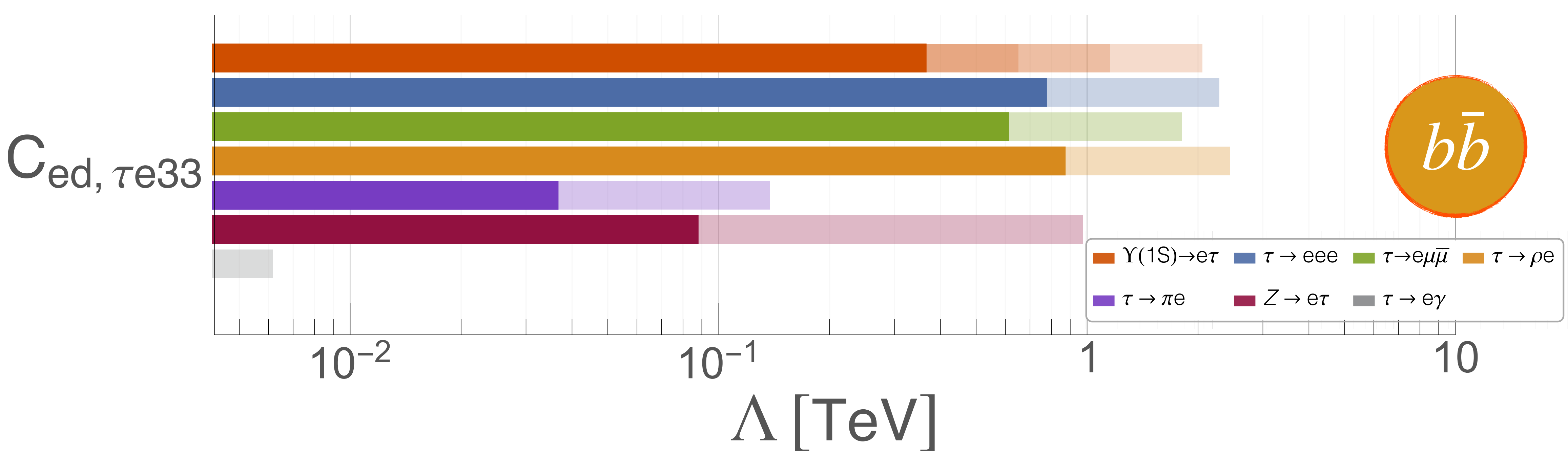




- **LFV Z decays also relevant** [see Calibbi, XM, Roy 2107.10273]

Sensitivity to New Physics Scale

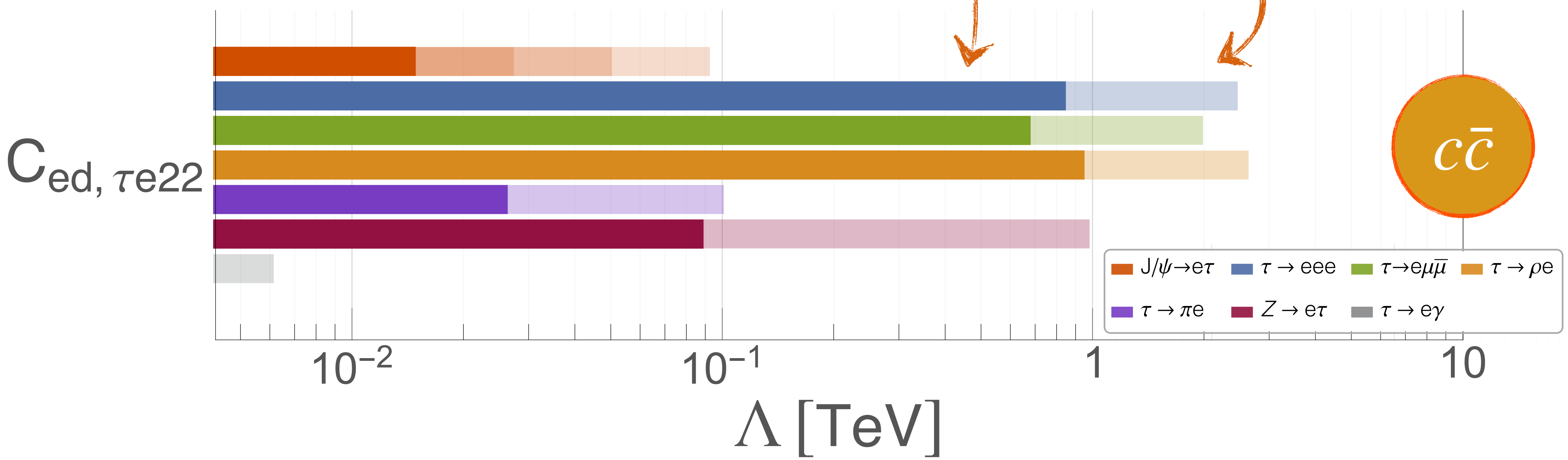


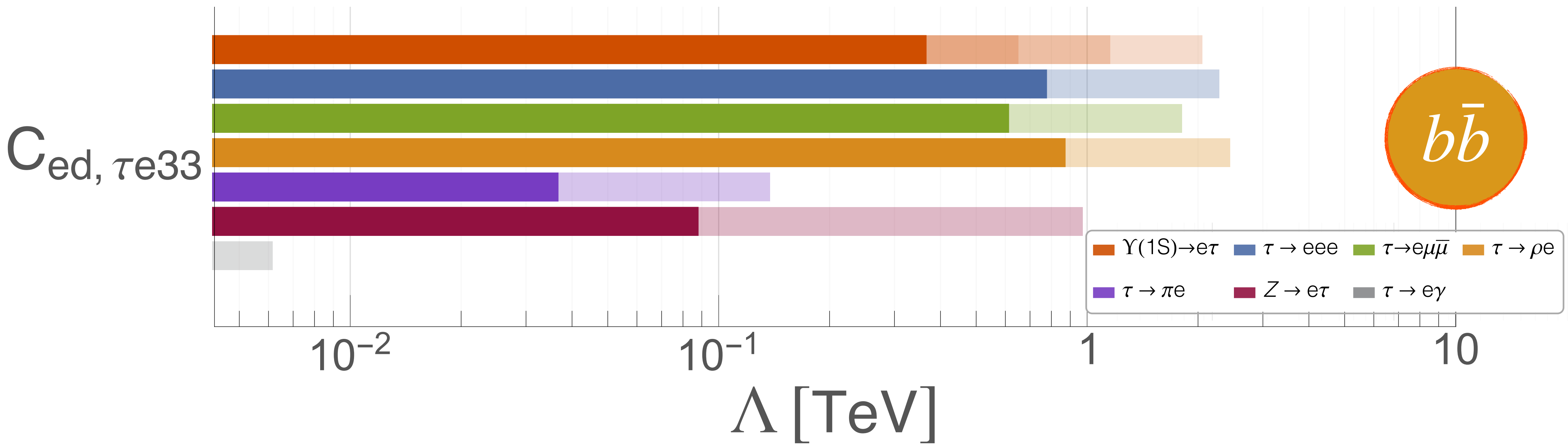


Sensitivity to New Physics Scale

NP scale probed by current experiments

Accesible at future experiments





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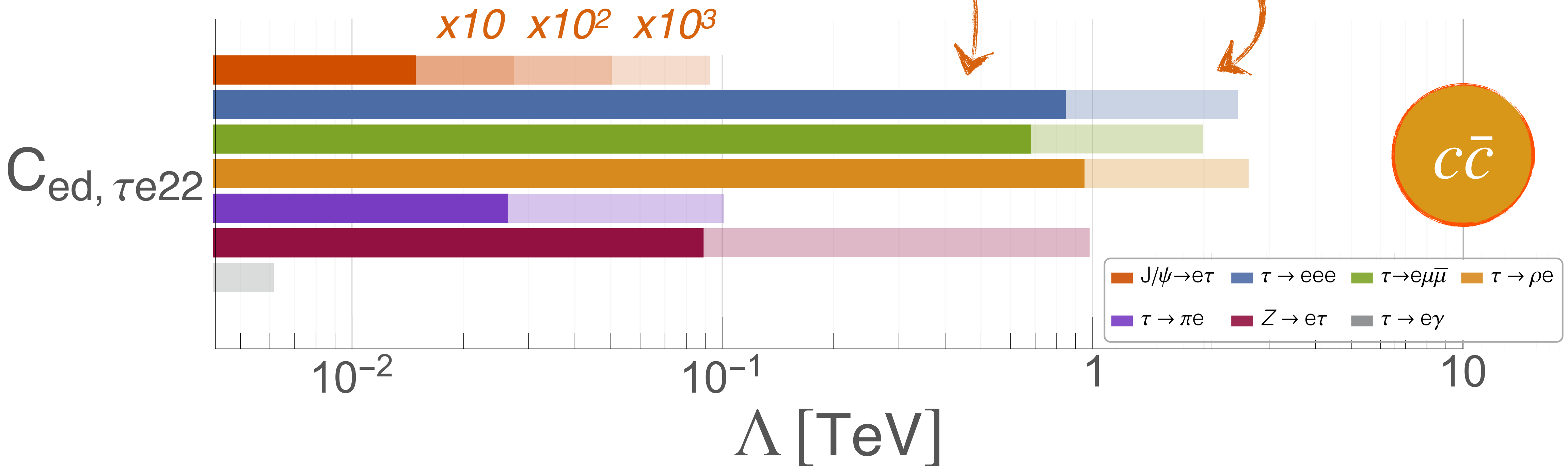
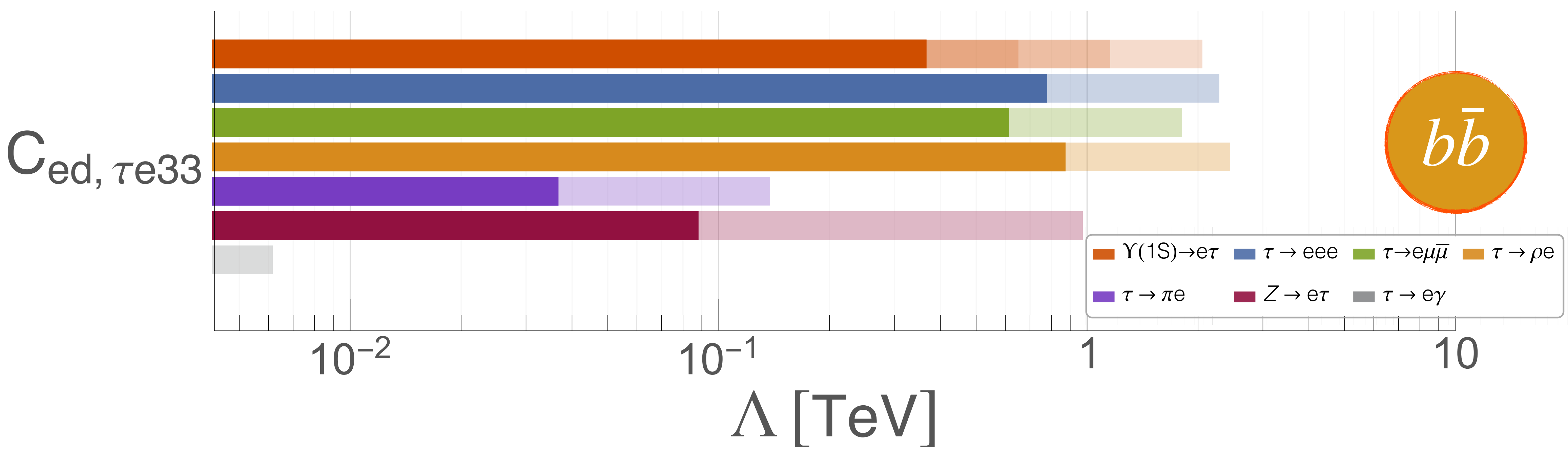
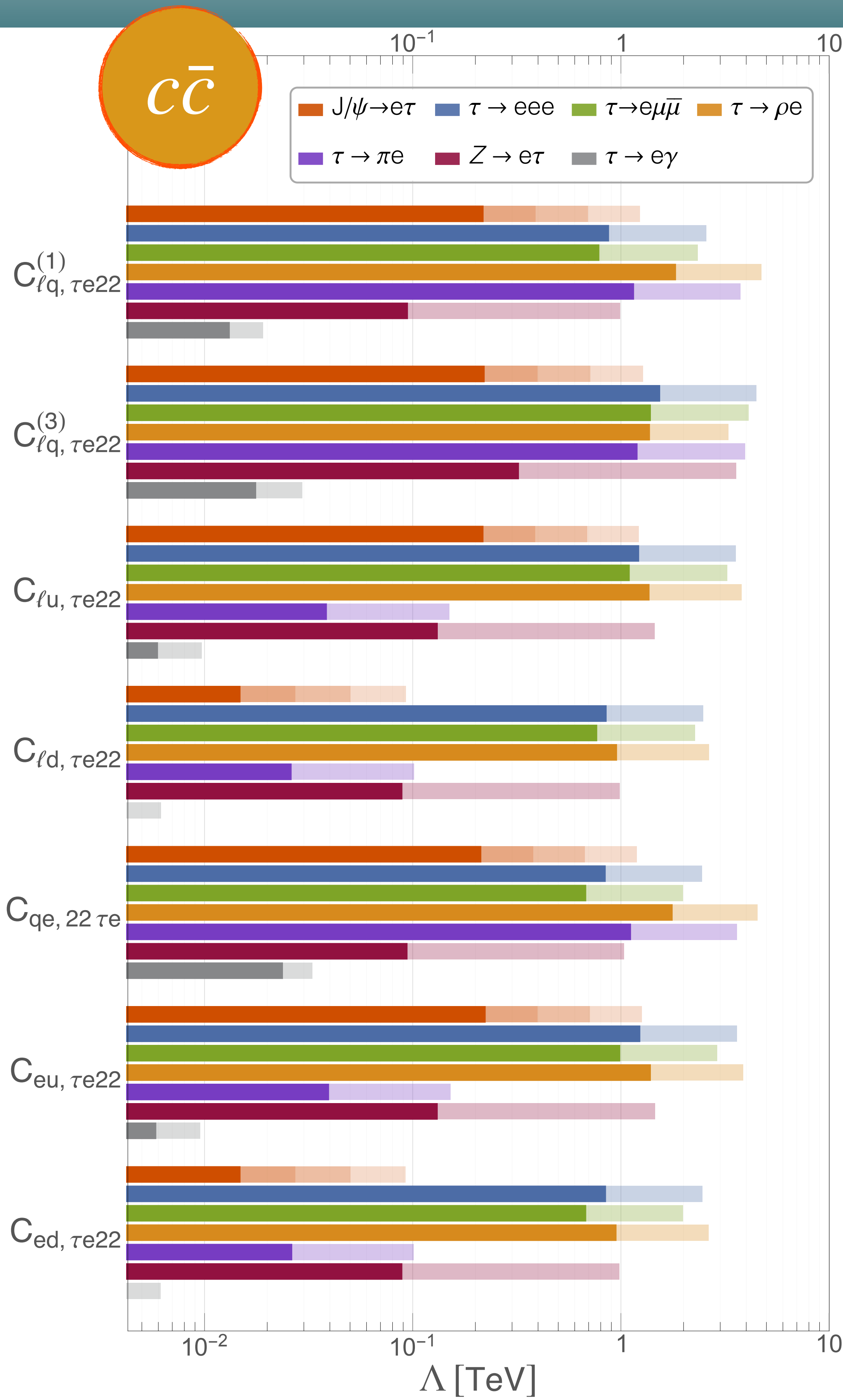
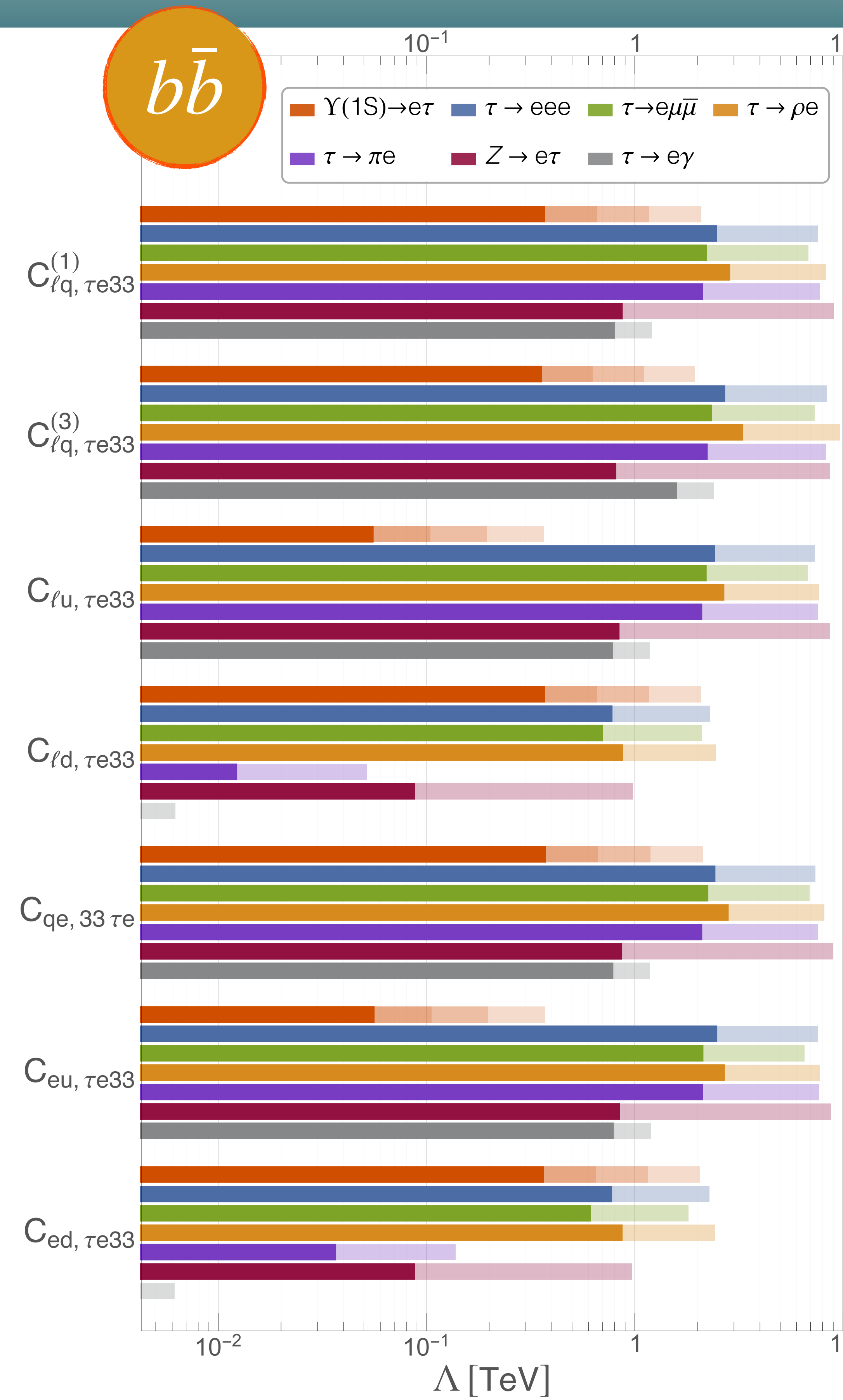




Sensitivity to New Physics Scale

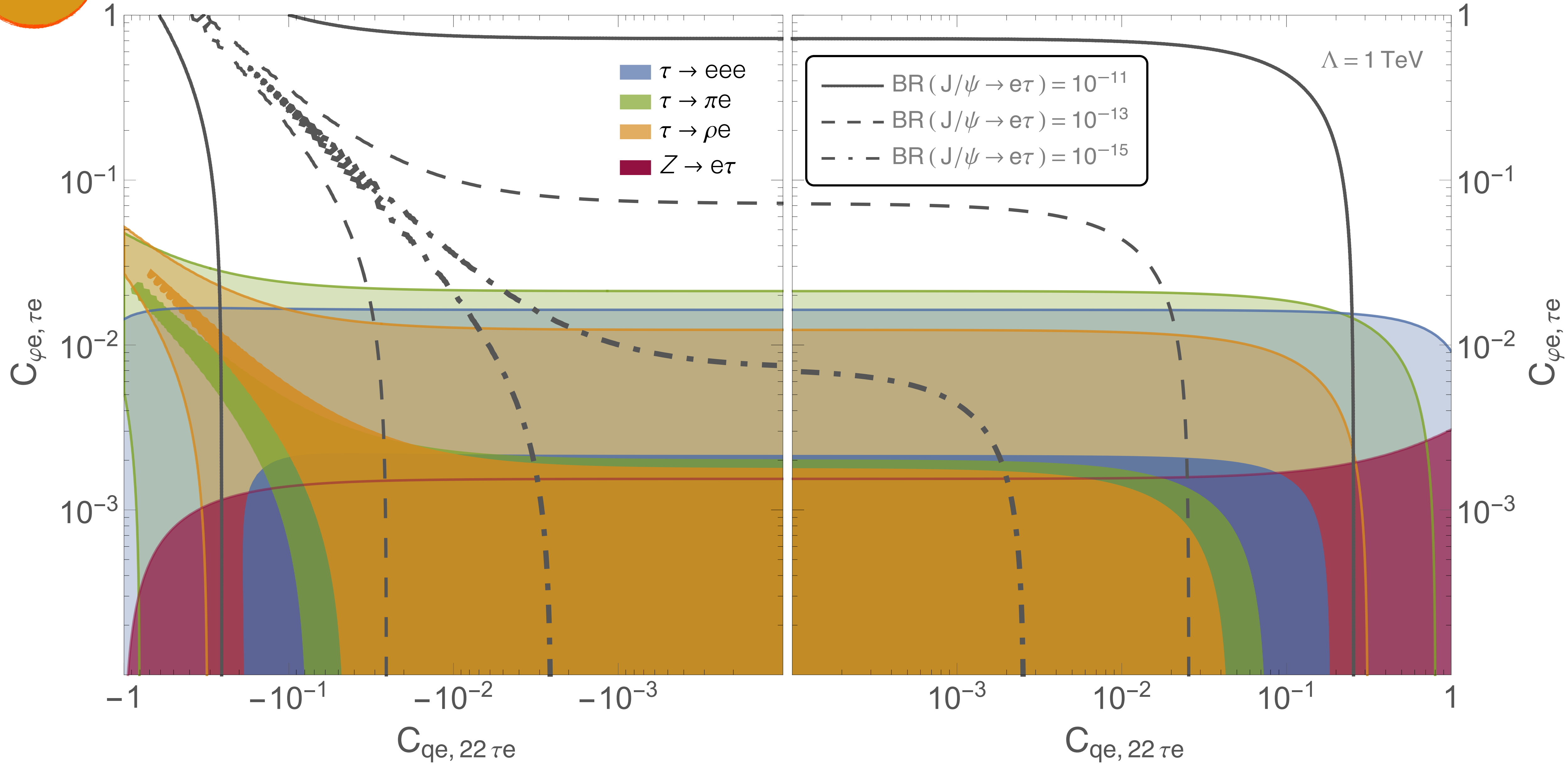




Beyond the Single Operator

$c\bar{c}$

Probing two effective operators at μ=Λ



Beyond the Single Operator

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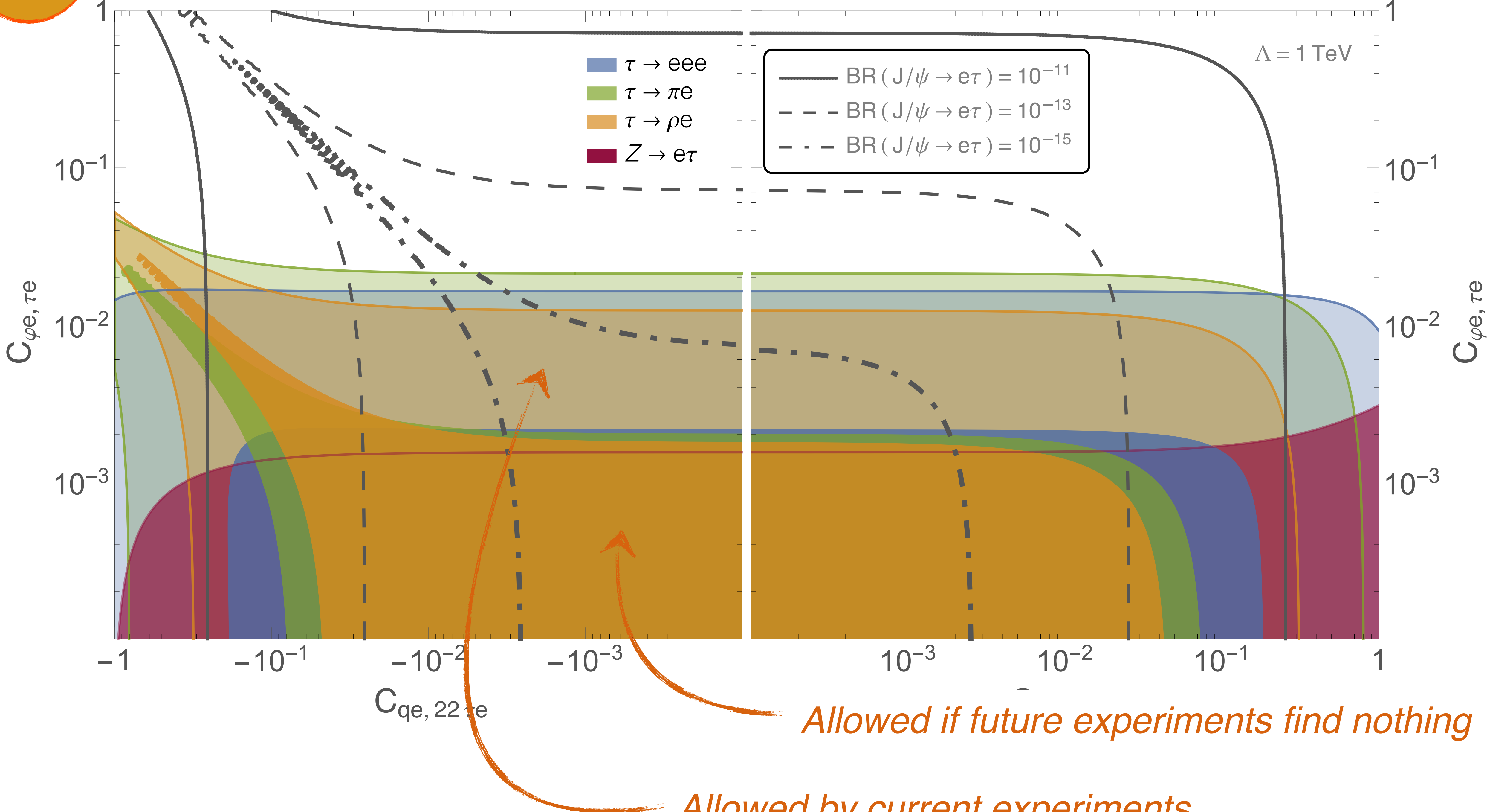
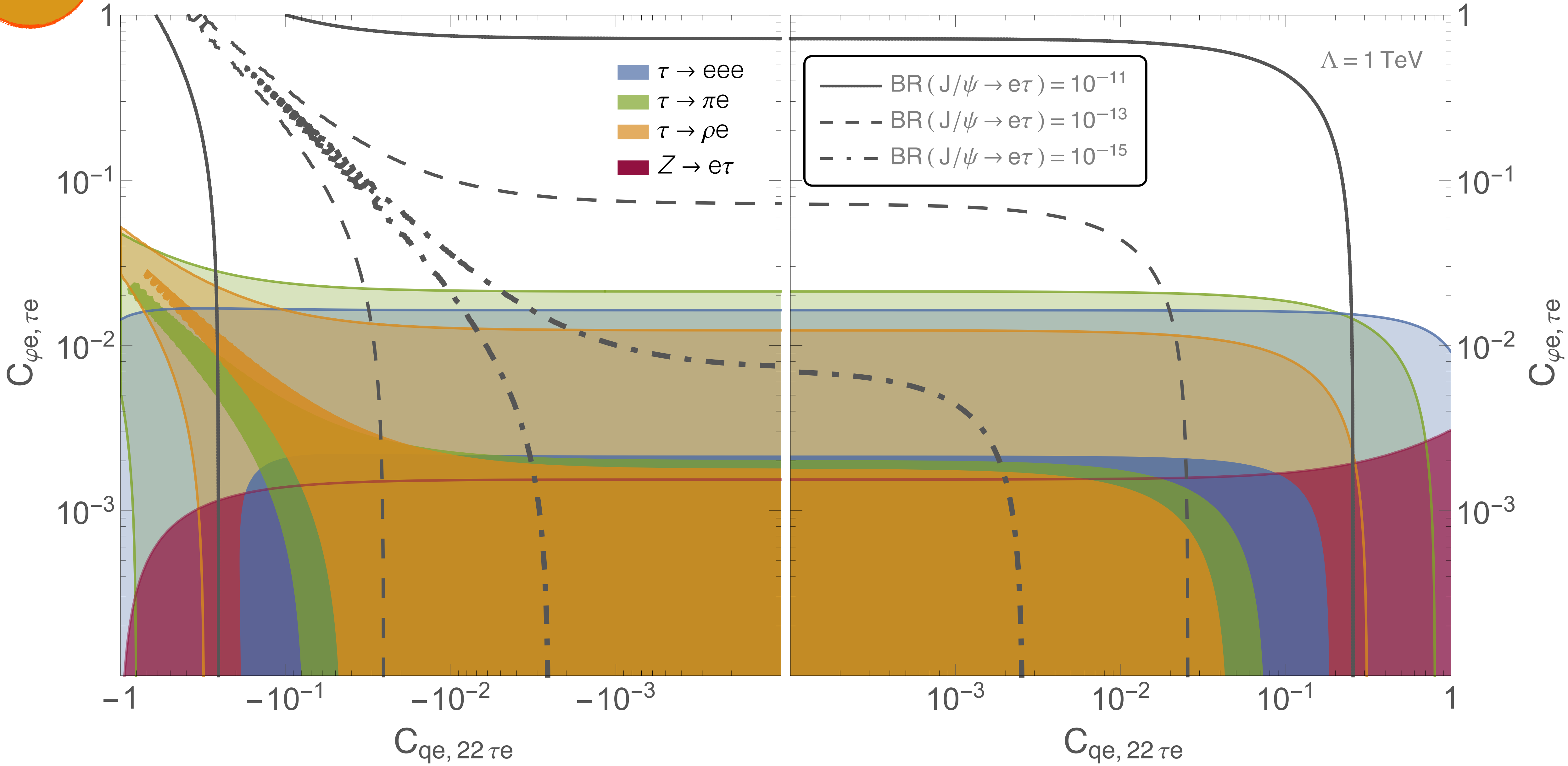
Probing two effective operators at μ=Λ



$c\bar{c}$

Probing two effective operators at μ=Λ

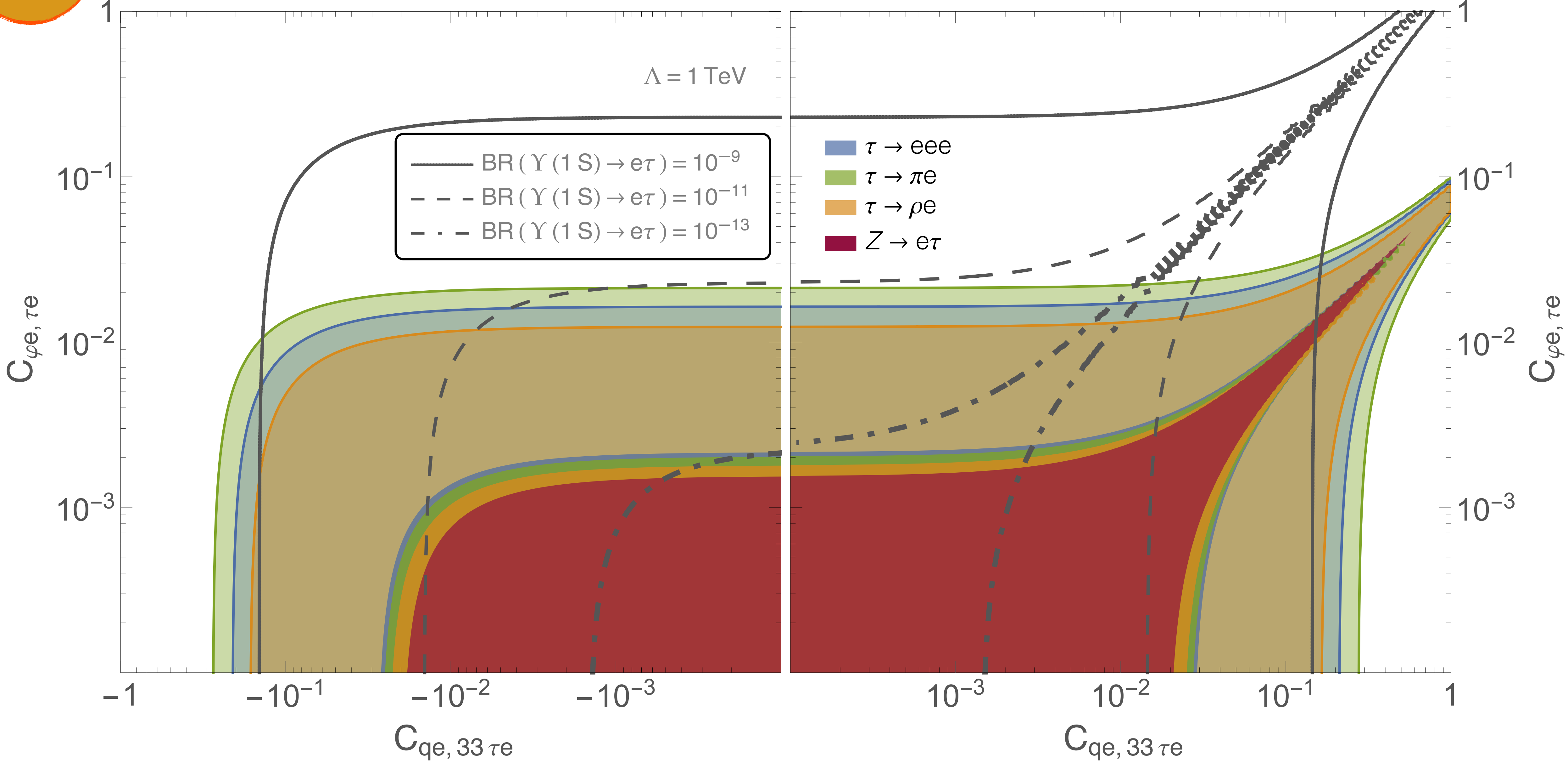


- *Potential 2D flat directions constrained by other observables*
- *Huge amount of fine tuning to avoid all low-energy constraints*

Beyond the Single Operator

$b\bar{b}$

Probing two effective operators at μ=Λ



- *Some particular flat directions for all constraints*

— LFVQD provide complementary information! —

Summary

— LFV quarkonium decays as a window to explore new physics —

- *These sensitivities compete with other LFV observables*

  — both at low- and high-energy —

- *We don't expect to see LFVQD in eμ channels*

  — Don't give up, prove us wrong!!! —

- *From our LEFT analysis*

  — LFVQD close to probe new parameter space —

- *From our SMEFT analysis*

  — More challenging, but still provides complementary information —

Thank you!

Funded by the European Union's Horizon Europe Programme under the Marie Skłodowska-Curie grant agreement no. 101066105-PheNUmenal. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

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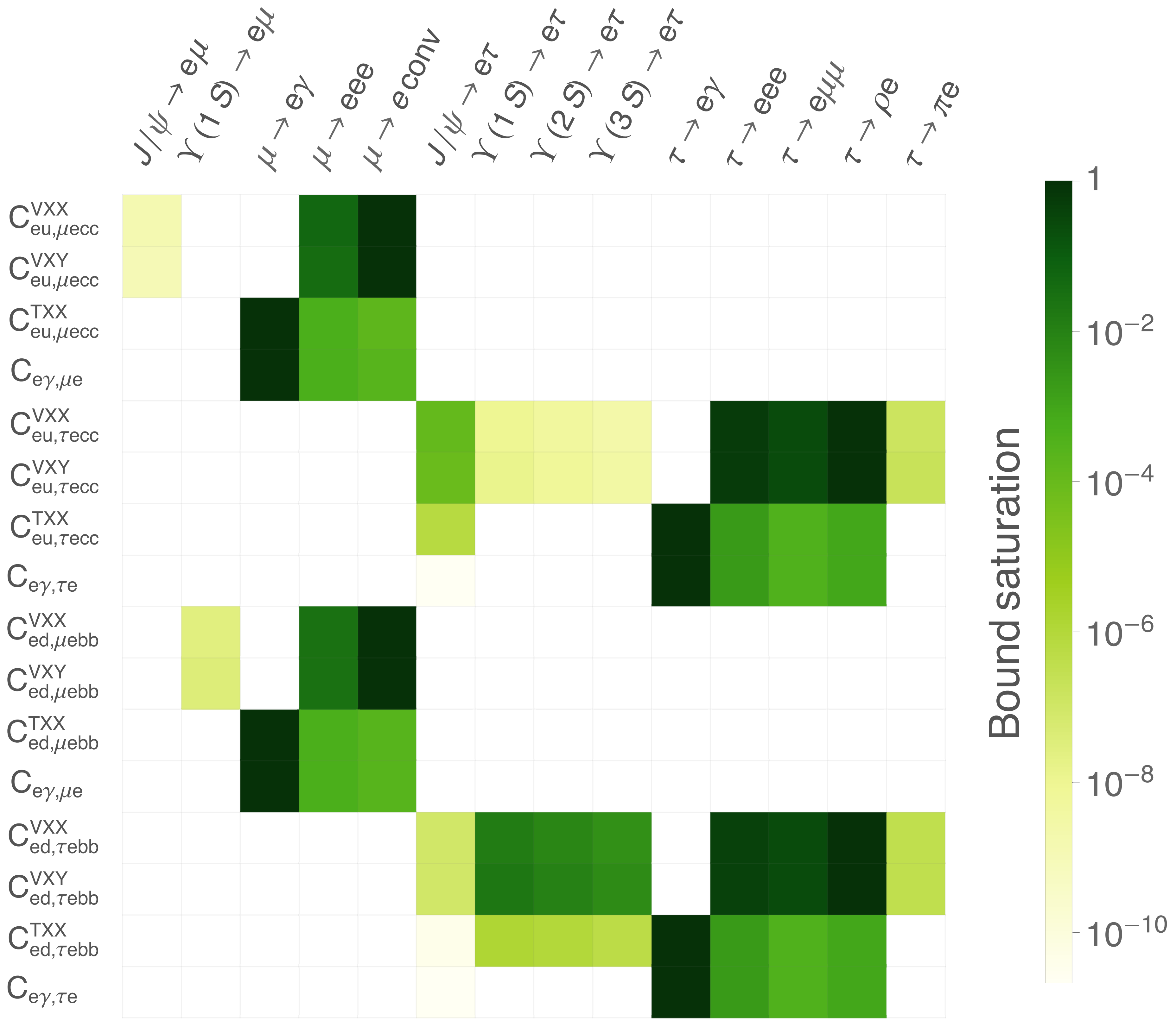
PheNUmenal

EXCELENCIA SEVERO OCHOA

Back up

LEFT: Full Picture of Bounds



SM Effective Field Theory

- *Add higher dimensional operators*

  — warning! Wilson coefficients are scale dependent $C \equiv C(\mu)$ *—*

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

- $Q_a^{(5)}$ *only 1: Weinberg operator*

  — neutrino masses —

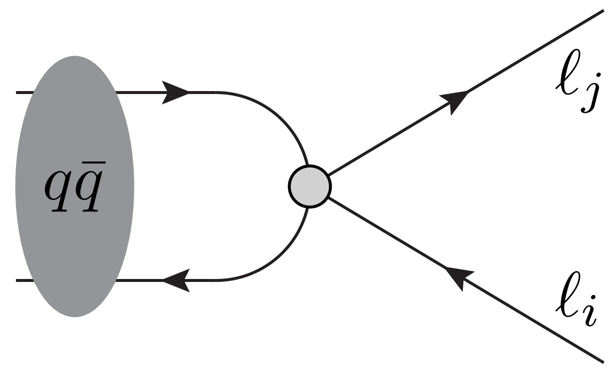
- $Q_a^{(6)}$ *59 operators* *[Buchmuller&Wyler'86, Grzadkowski et al' 10]*

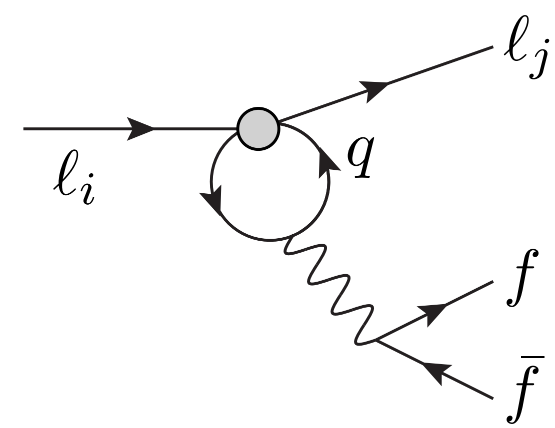
  — leading order for cLFV (some of them) —

- $Q_a^{(n\geq 7)}$ *just a lot*

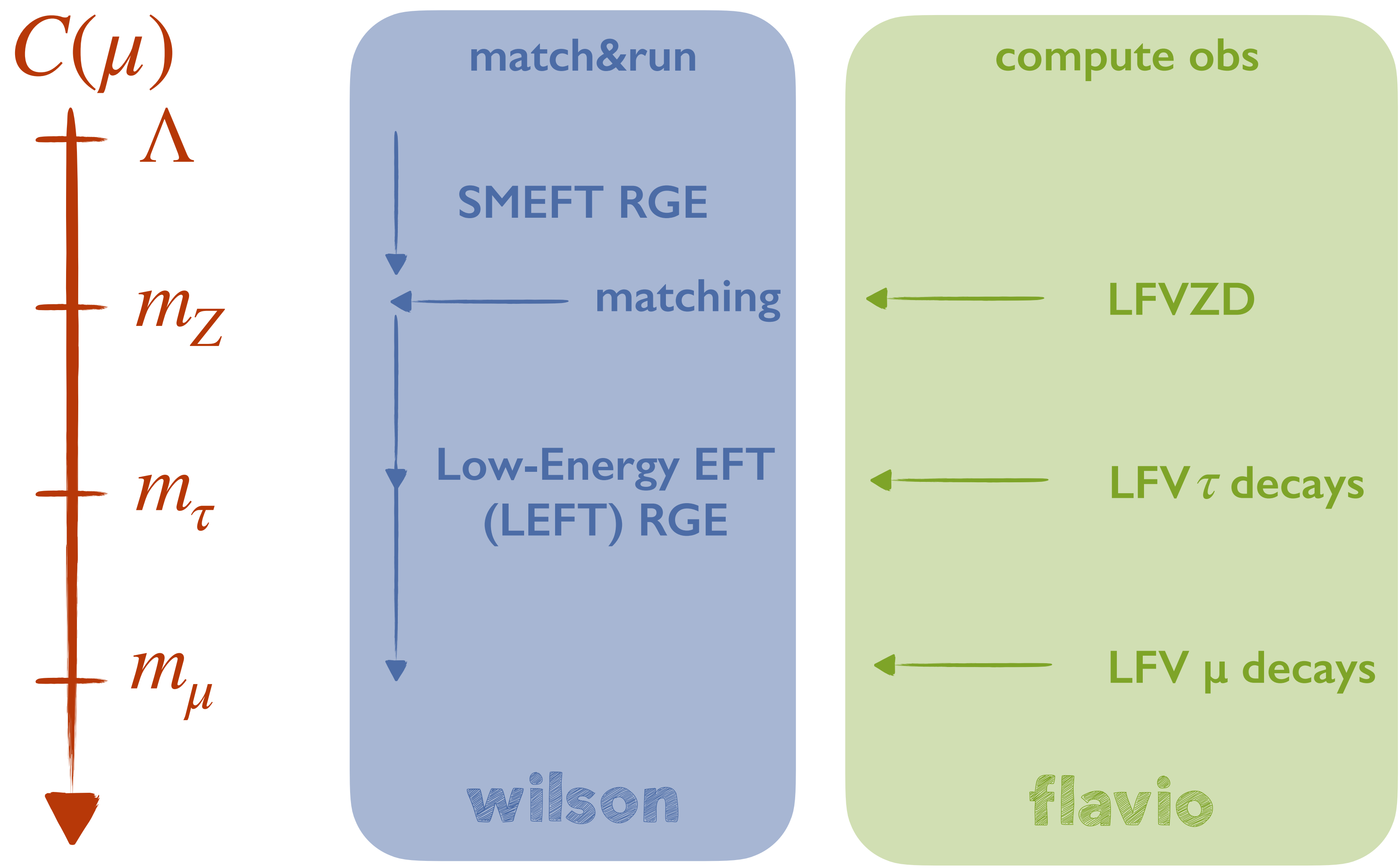
  — we neglect them —

INDIRECT CONSTRAINTS





- Same operators generate other **low-energy** cLFV observables



Low-Energy cLFV

LFV obs.	Present bounds (90% CL)		Expected future limits	
$\mathrm{BR}(\mu \to e\gamma)$	4.2×10^{-13}	MEG (2016) [63]	6×10^{-14}	MEG-II [64]
$\mathrm{BR}(\mu \to eee)$	1.0×10^{-12}	SINDRUM (1988) [65]	10^{-16}	Mu3e [66]
$\mathrm{CR}(\mu \to e, \mathrm{Au})$	7.0×10^{-13}	SINDRUM II (2006) [67]	–	–
$\mathrm{CR}(\mu \to e, \mathrm{Al})$	–	–	6×10^{-17}	COMET/Mu2e [68, 69]
$\mathrm{BR}(\tau \to e\gamma)$	3.3×10^{-8}	BaBar (2010) [70]	3×10^{-9}	Belle-II [71]
$\mathrm{BR}(\tau \to eee)$	2.7×10^{-8}	Belle (2010) [72]	5×10^{-10}	Belle-II [71]
$\mathrm{BR}(\tau \to e\mu\mu)$	2.7×10^{-8}	Belle (2010) [72]	5×10^{-10}	Belle-II [71]
$\mathrm{BR}(\tau \to \pi e)$	8.0×10^{-8}	Belle (2007) [73]	4×10^{-10}	Belle-II [71]
$\mathrm{BR}(\tau \to \rho e)$	1.8×10^{-8}	Belle (2011) [74]	3×10^{-10}	Belle-II [71]
$\mathrm{BR}(\tau \to \mu\gamma)$	4.2×10^{-8}	Belle (2021) [75]	10^{-9}	Belle-II [71]
$\mathrm{BR}(\tau \to \mu\mu\mu)$	2.1×10^{-8}	Belle (2010) [72]	4×10^{-10}	Belle-II [71]
$\mathrm{BR}(\tau \to \mu ee)$	1.8×10^{-8}	Belle (2010) [72]	3×10^{-10}	Belle-II [71]
$\mathrm{BR}(\tau \to \pi\mu)$	1.1×10^{-7}	Babar (2006) [76]	5×10^{-10}	Belle-II [71]
$\mathrm{BR}(\tau \to \rho\mu)$	1.2×10^{-8}	Belle (2011) [74]	2×10^{-10}	Belle-II [71]

Refs in arXiv: 2107.10273