The 8th China LHC Physics Workshop (CLHCP2022)

Flavour Physics @ Tera Z

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Nanjing Normal University, November 25th 2022

CEPC Flavor White Paper

in preparation

Today, I can only mention few selected topics (guided by personal bias)

For a number of excellent talks, check out the flavour session of the recent international CEPC workshop

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 can deliver a few $\times10^{12}$ 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 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}
B^0	6×10^{10}	3×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}
B_s	2×10^{10}	3×10^{8} (5 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 ab^{-1} on $\Upsilon(4S)$)	

for each 10^{12} Z decays

CEPC Study Group arXiv:1811.10545

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

$M_Z \gg 2m_b$, $2m_\tau$, $2m_c$ ⇒ 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

What flavour physics can we study at a Tera Z?

flavour-violating Z decays

forbidden processes [lepton flavour (universality) violation, lepton/baryon number violation...]

precise measurements [CKM UT angles, CPV...]

rare decays [(semi-)leptonic B decays...]

charm physics

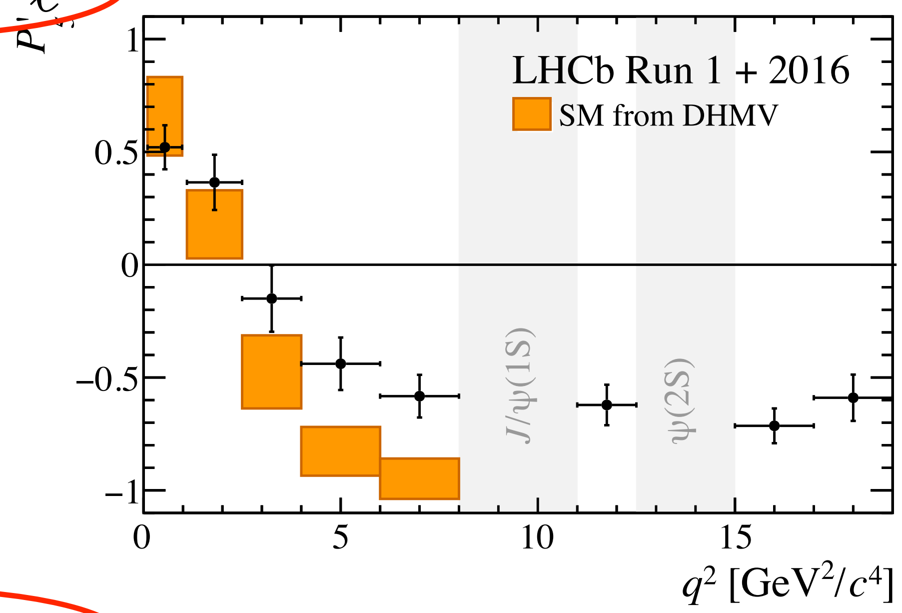
exotic hadrons [tetraquarks, molecules...]

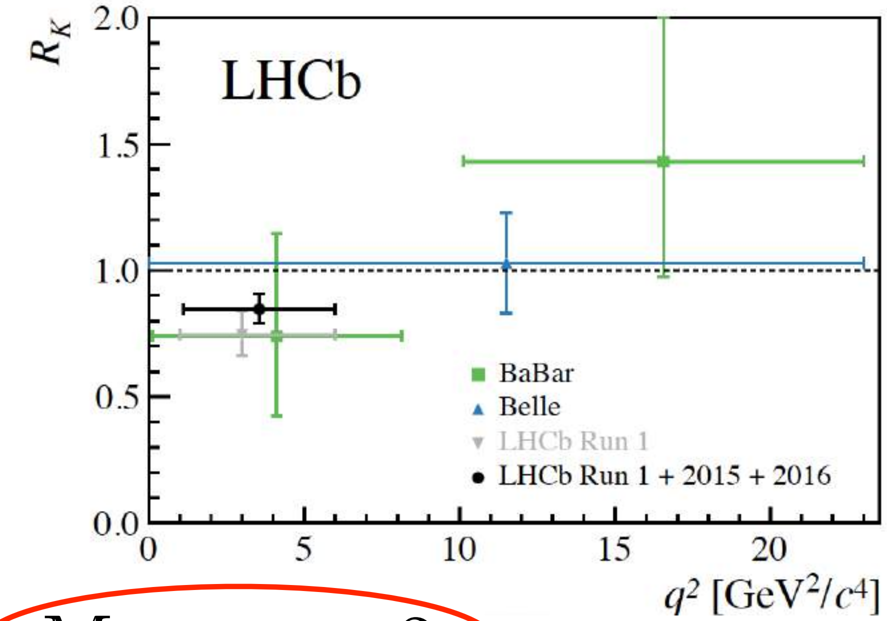
tau physics

... in one word *everything*

Possible motivation: hints of LFU violation, muon g-2 etc.

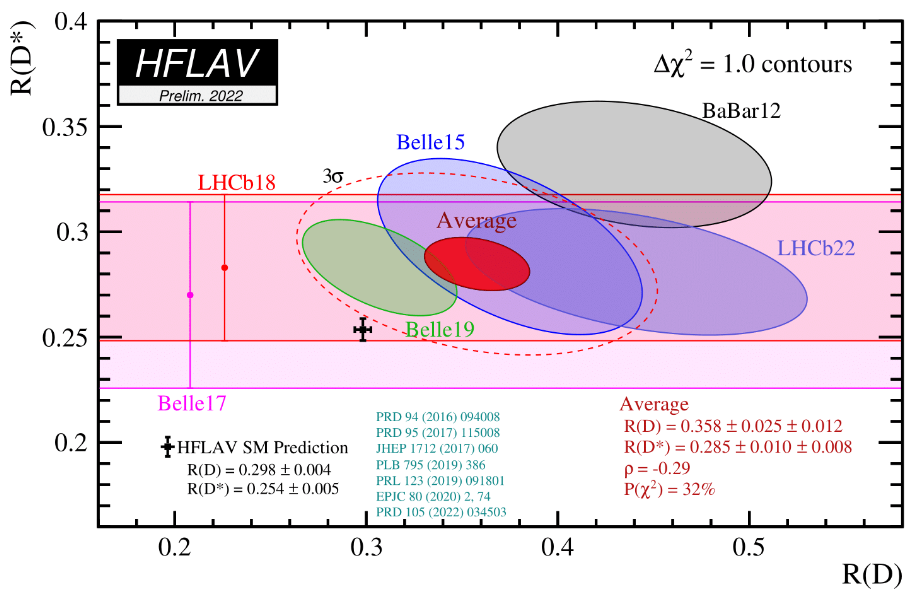
$b \to s\ell^+\ell^-$

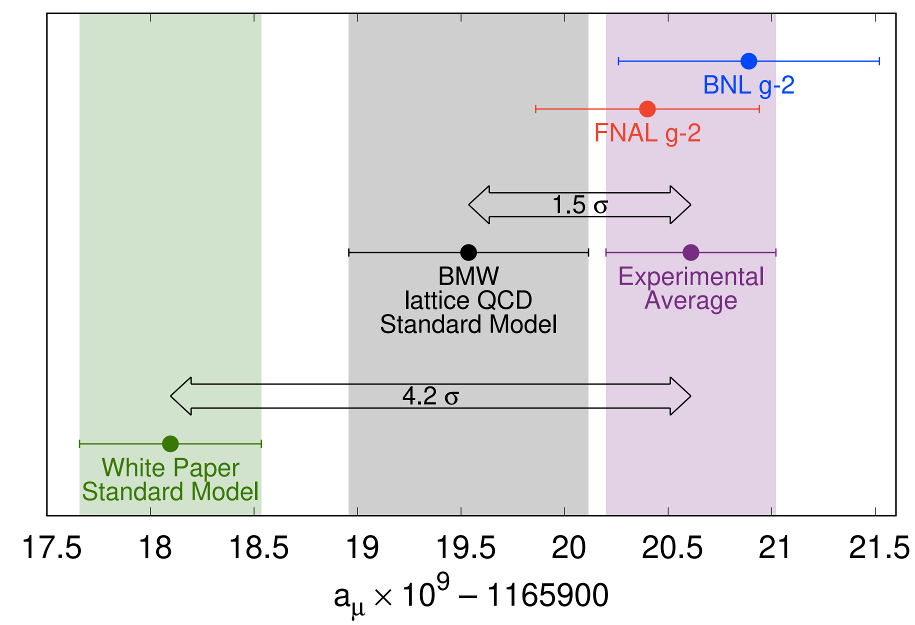




$b \to c\,\ell\nu$

Muon $g-2$





- They would point to new physics coupling preferably to muons (and *also* τ ?) at scales < O(10-100) TeV   Di Luzio Nardecchia '17   Allwicher et al. '21
- Expected LFV/LFUV effects in $b \to s\tau\tau$, $b \to s\tau\mu$, $b \to s\nu\nu$, τ/Z decays . . .

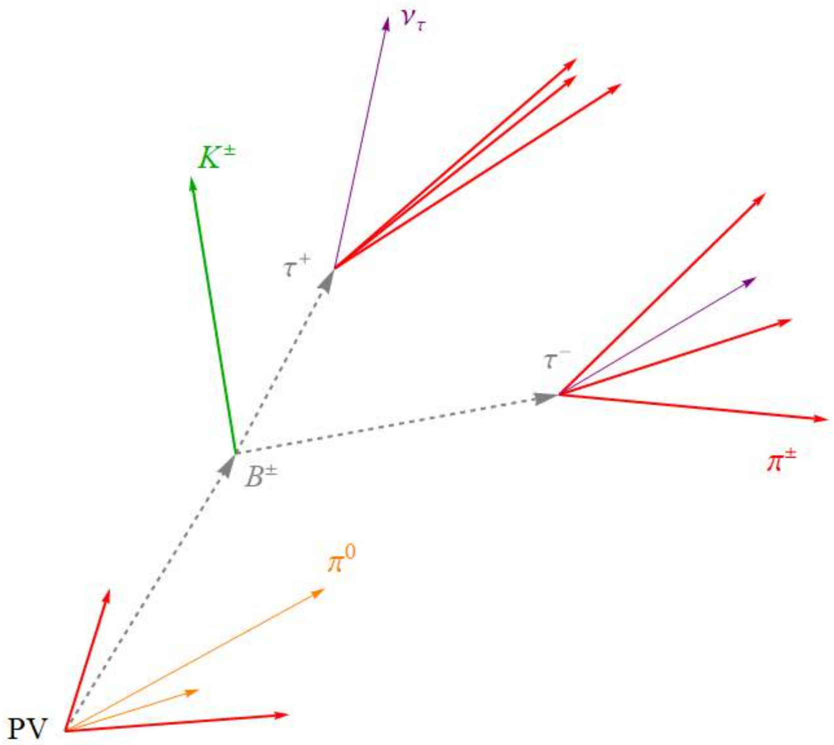
see e.g. Feruglio Paradisi Pattori '16 & '17

$b \to s\tau\tau$

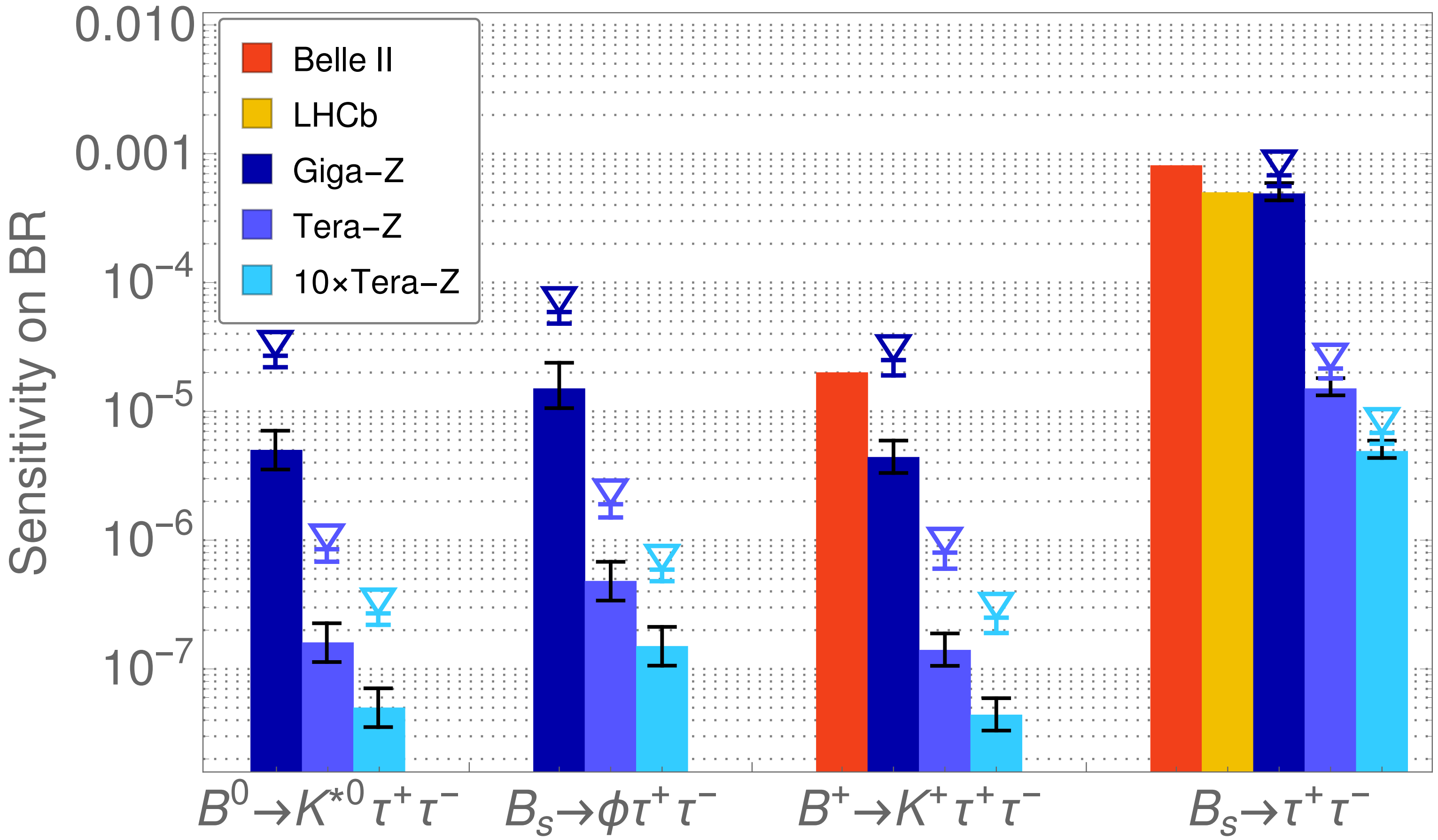
$$\text{BR}(B_s \to \tau\tau)_{\text{SM}} = (7.7 \pm 0.5) \times 10^{-7} \quad \text{(Bobeth et al. 1311.0903)}$$

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

- Unobserved, weakly constrained (~10^{-4}-10^{-3} by Belle, Belle II can provide an O(10) increased sensitivity)
- They can have huge new-physics enhancement (especially in theories addressing the B physics anomalies)
- Tera Z prosp:



3-prong τ decays



Li L. and Liu T. '20

$b \to s\nu\nu$

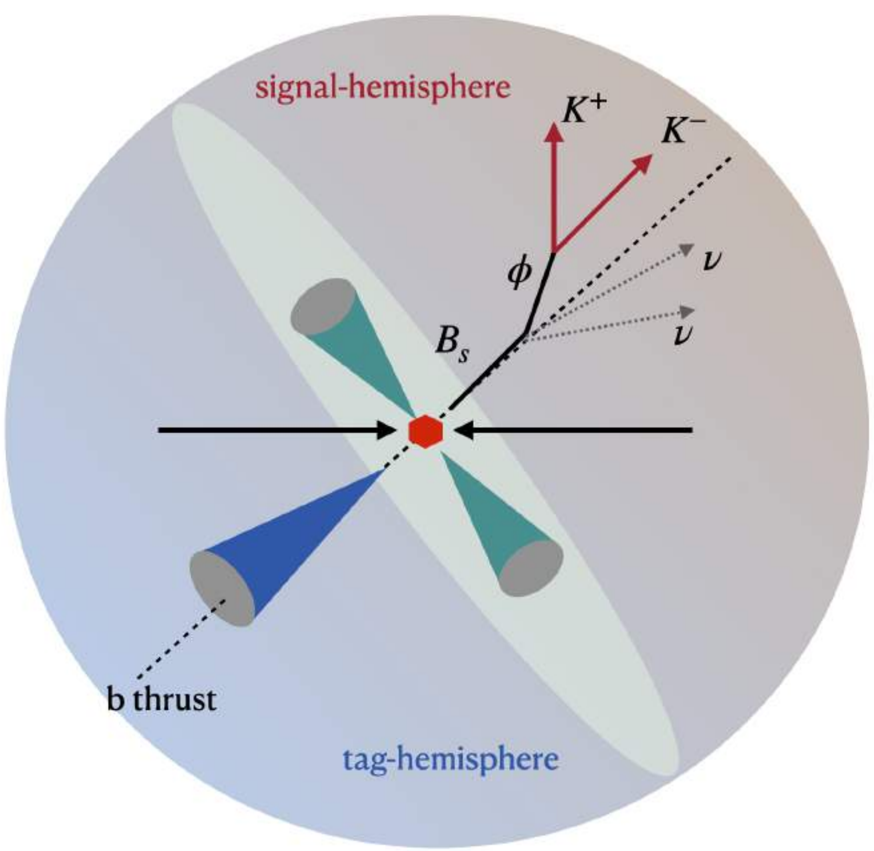
Li et al. '22

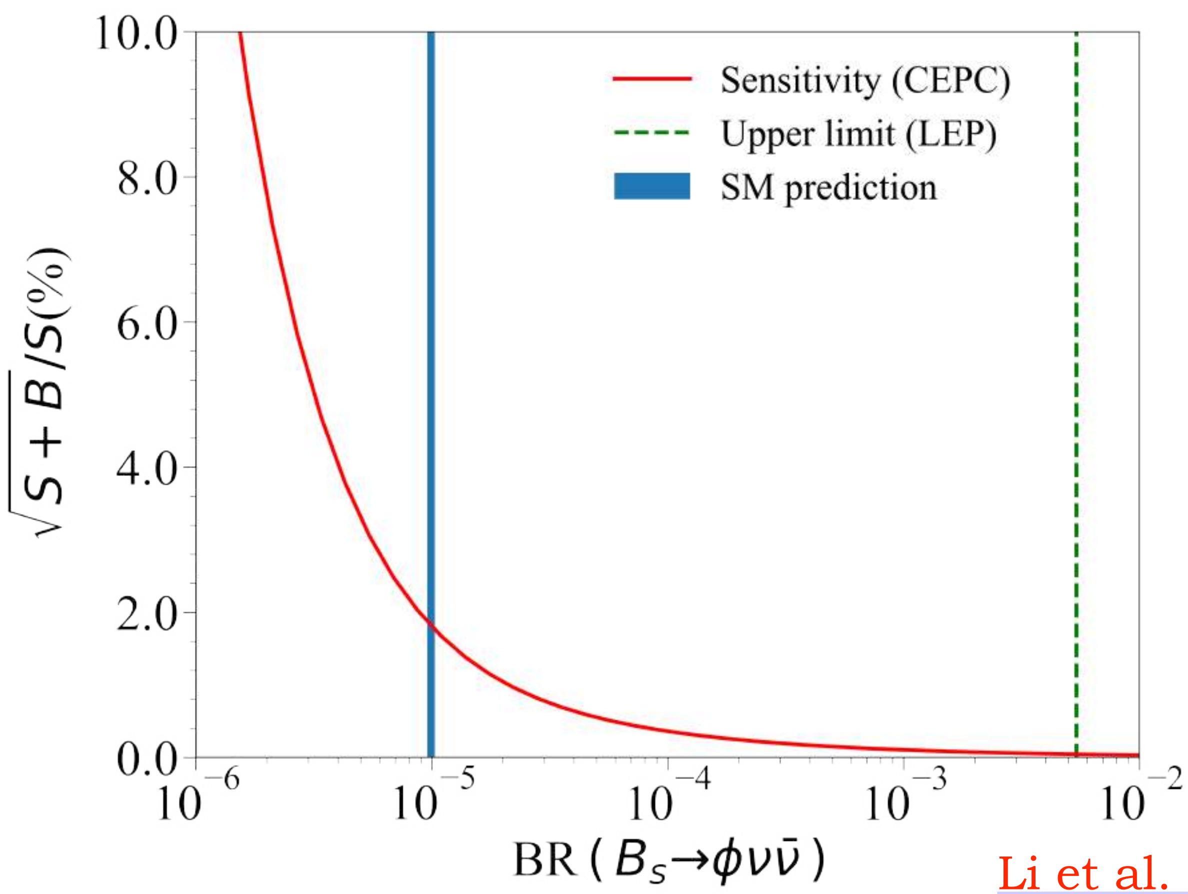
	Current Limit	Detector	SM Prediction
$\mathrm{BR}(B^0 \to K^0 \nu\bar{\nu})$	$< 2.6 \times 10^{-5}$ [3]	BELLE	$(3.69 \pm 0.44) \times 10^{-6}$ [1]
$\mathrm{BR}(B^0 \to K^{*0} \nu\bar{\nu})$	$< 1.8 \times 10^{-5}$ [3]	BELLE	$(9.19 \pm 0.99) \times 10^{-6}$ [1]
$\mathrm{BR}(B^\pm \to K^\pm \nu\bar{\nu})$	$< 1.6 \times 10^{-5}$ [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:



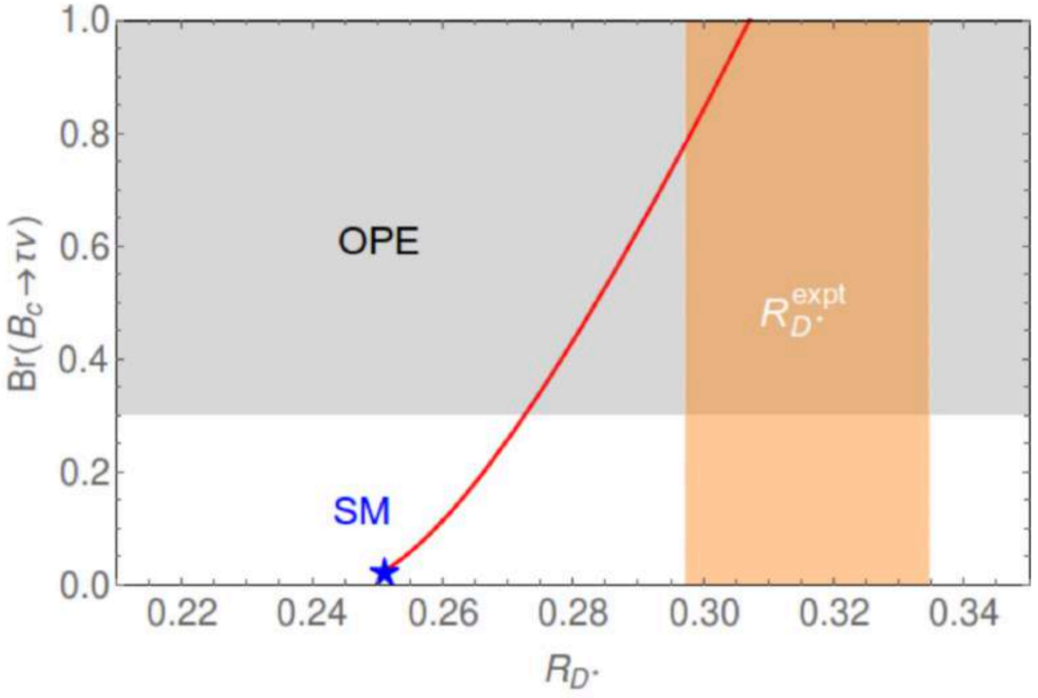


Li et al. '22

$B_c \to \tau\nu$

- Key observable to test the LFU anomalies in charged-current B decays

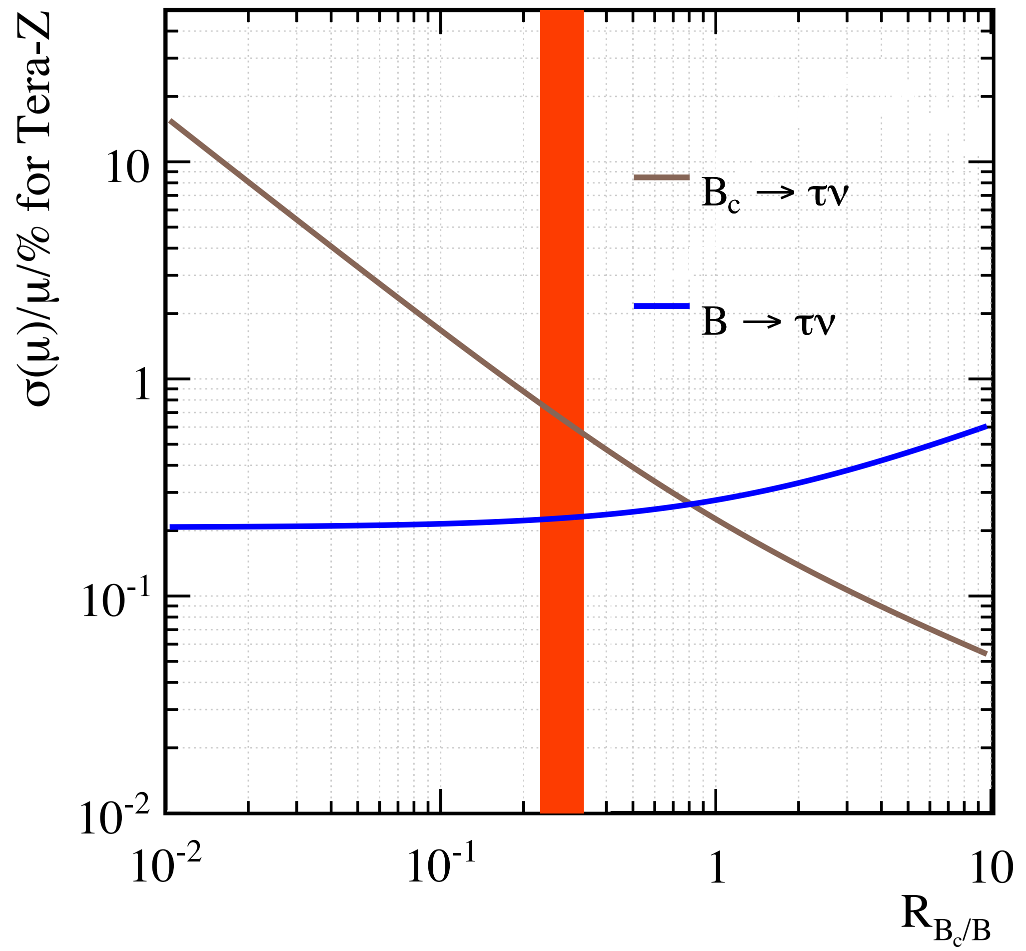
Alonso et al. '16



- SM prediction for the BR ~ 2%, beyond the reach of LHCb

- Tera Z could measure with percent level accuracy (thus providing also a percent level accurate measurement of V_{cb})

Zheng et al. '20



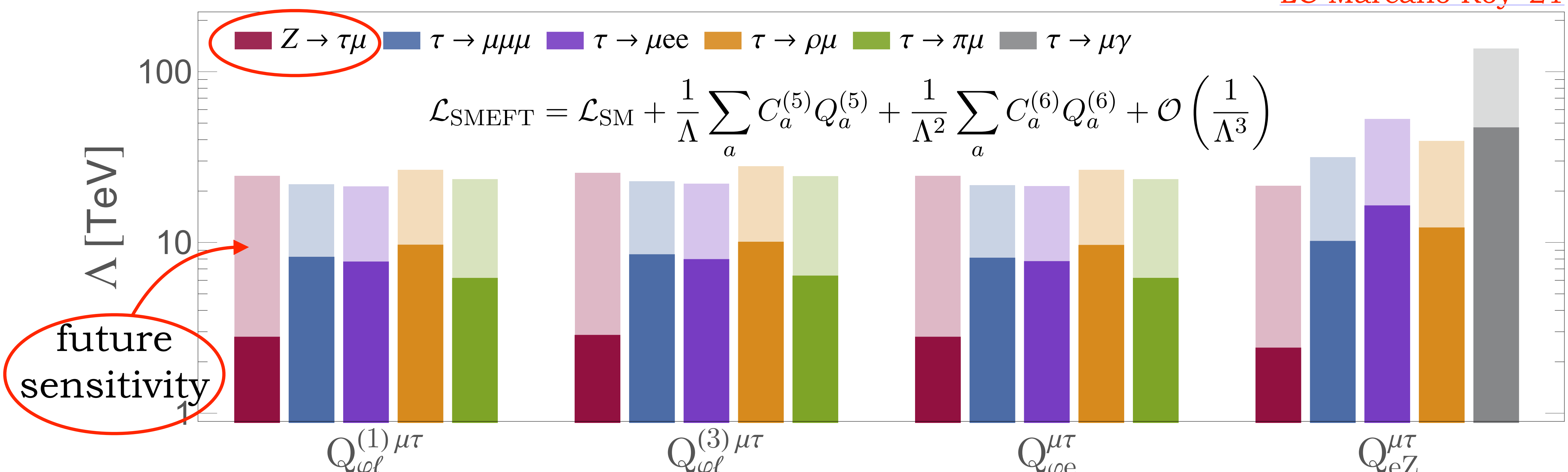
Lepton Flavour Violation in Z decays

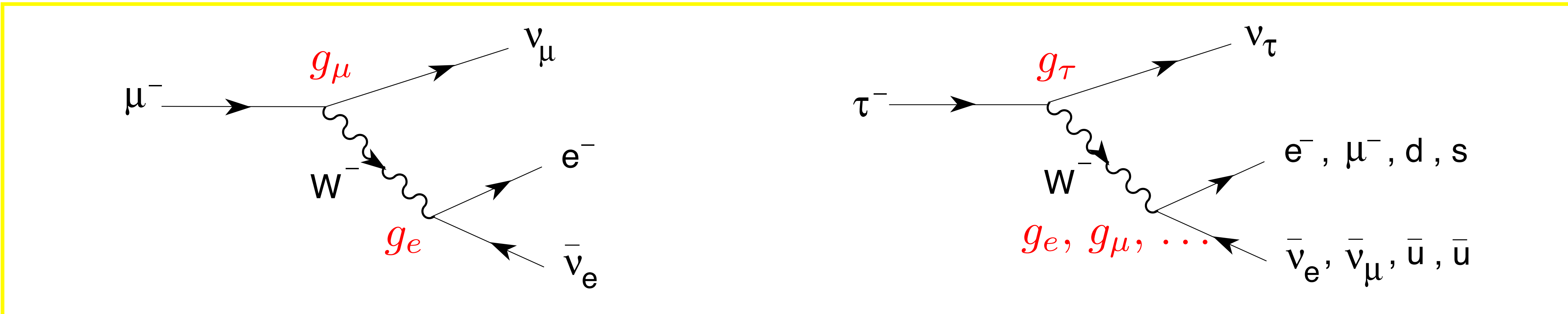
Mode	LEP bound (95% CL)	LHC bound (95% CL)	CEPC/FCC-ee exp.
BR($Z \to \mu e$)	1.7×10^{-6} [2]	7.5×10^{-7} [3]	$10^{-8} - 10^{-10}$
BR($Z \to \tau e$)	9.8×10^{-6} [2]	5.0×10^{-6} [4, 5]	10^{-9}
BR($Z \to \tau \mu$)	1.2×10^{-5} [6]	6.5×10^{-6} [4, 5]	10^{-9}

M. Dam '18

- LHC searches limited by backgrounds (in particular $Z \to \tau\tau$): max ~10 improvement can be expected at HL-LHC (3000/fb)
- 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)

LC Marcano Roy '21

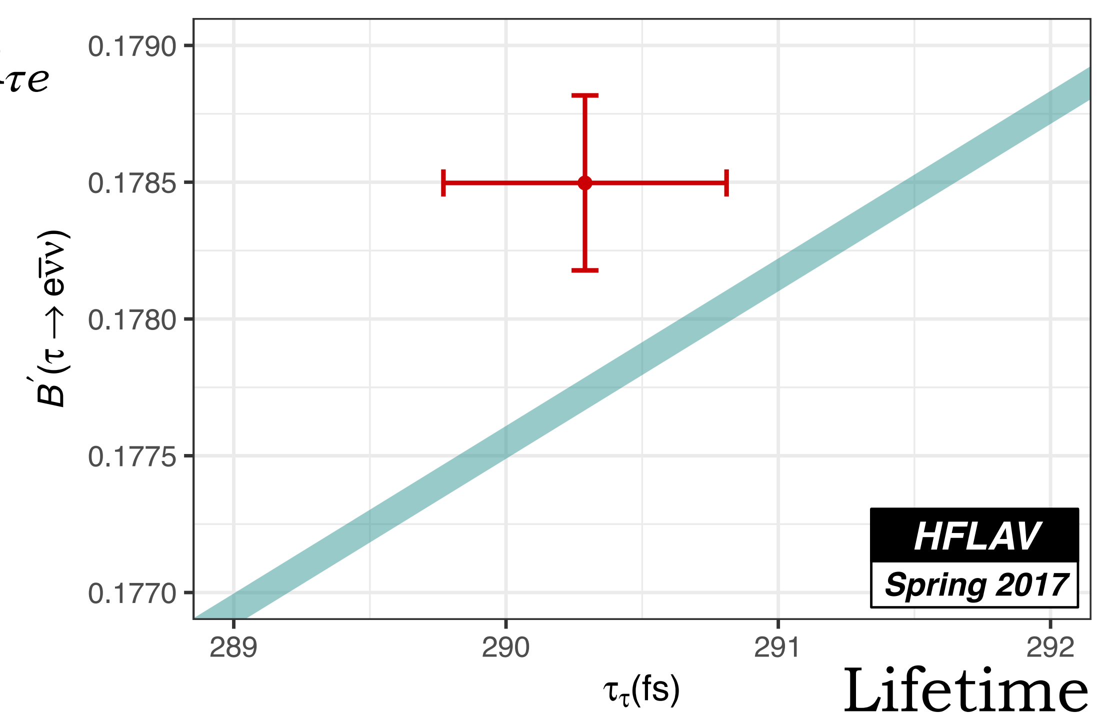




Neglecting radiative corrections:

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

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

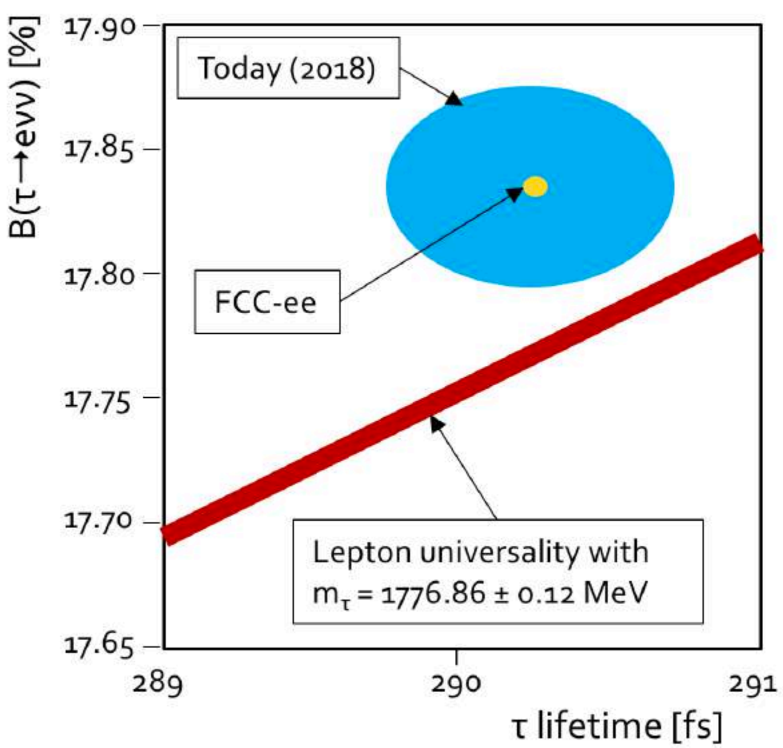
Preliminary study for the FCC-ee (10^{11} tau pairs):

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

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

The Z-pole run of the CEPC would offer
plenty of flavour physics opportunities

O(10^{12}) Z decays would enable us to study many processes with a much higher precision than (or inaccessible to) other experiments

If the current anomalies will be confirmed,
new physics is "behind the corner"

However, it may be out of the reach of the LHC, we need to discriminate among the possible new physics options elsewhere

Tera Z provides a unique opportunity to study Z LFV decays, rare B decays, tests of LFU in tau decays or B_c decays etc.

谢谢大家!

Thank you!

Additional slides

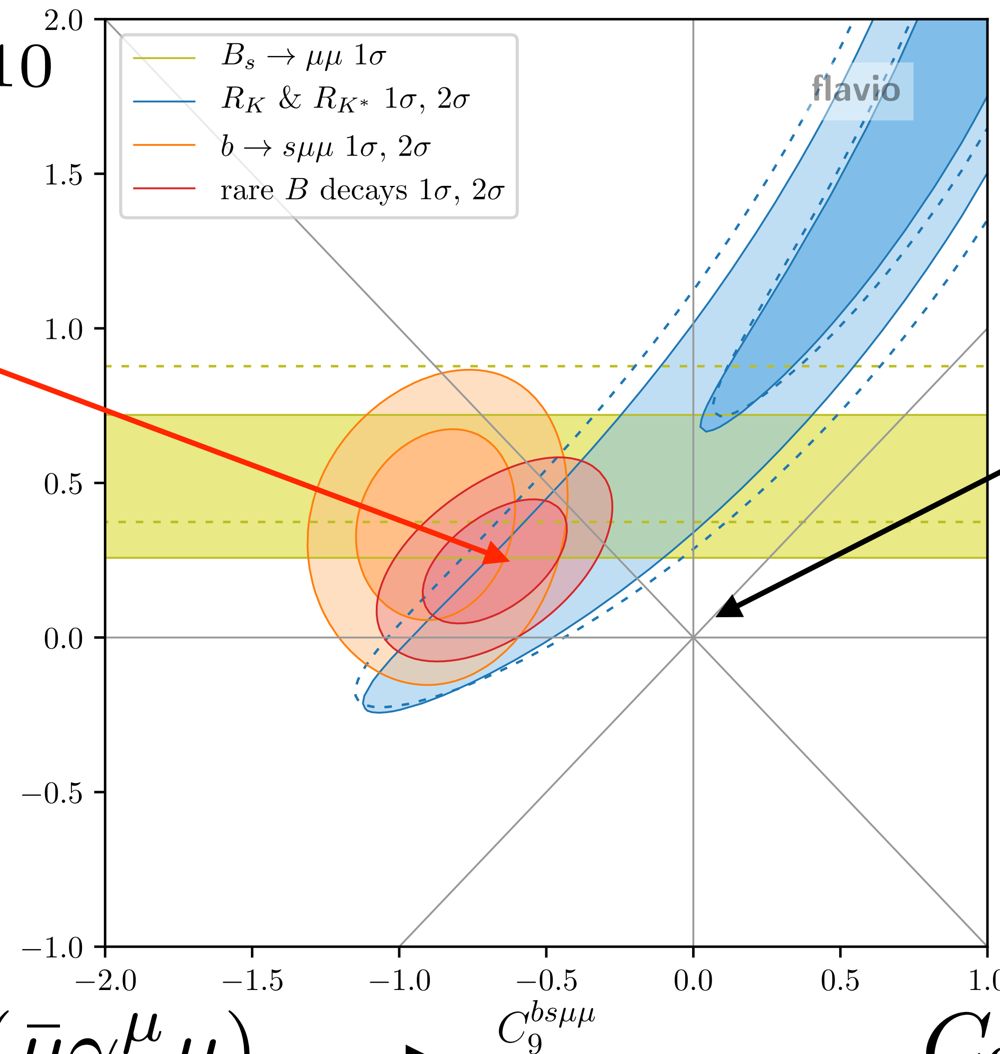
It seems that we have to fit a deficit of muon events

$$\mathcal{O}_9^{\ell(\prime)} \sim (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10}^{\ell(\prime)} \sim (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

C_{10}

Best fit

New physics contribution to $(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$ →



SM point

Altmannshofer Stangl
arXiv: 2103.13370

New physics contribution to (negative) $(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$ → C_9

Fits to the data: non-standard contributions preferred at the ~5σ level

Geng Li-Sheng et al. ’21, Cornella et al. ’21, Algueró et al. ’21, Ciuchini et al. ’20 + many older refs.

Where do O_9 and O_{10} come from?

SU(2)-invariant operators ('SM EFT'):

Differ by SU(2) contractions:

$$(Q^{(1)}_{\ell q})_{\mu\mu bs} = (\bar{L}^a_{L\,2}\,\gamma^\mu\,L^a_{L\,2})(\bar{Q}^b_{L\,2}\,\gamma_\mu\,Q^b_{L\,3})$$ "singlet-singlet"

$$(Q^{(3)}_{\ell q})_{\mu\mu bs} = \sum_{I=1,3}(\bar{L}^a_{L\,2}\,\gamma^\mu(\tau_I)_{ab}\,L^b_{L\,2})(\bar{Q}^c_{L\,2}\,\gamma_\mu(\tau_I)_{cd}\,Q^d_{L\,3})$$ "triplet-triplet"

They both give C_9=-C_{10}

it gives also rise to charged-current, it can address also $R_{D(*)}$

One can attempt to explain class 1 and 2 anomalies simultaneously

Relevant constraints from $B \to K^{(*)}\nu\bar{\nu}$ which can be however relaxed if C_S=C_T

Alonso Grinstein Camalich '15
LC Crivellin Ota '15

Simultaneous explanation of the anomalies

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

(in the interaction basis)

Flavour structure justified by:

- Theoretical considerations (SM hierarchies, MFV paradigm, …)
- Observed anomalies (3rd generation affected more than 2nd generation, 2nd generation more than 1st generation)

Glashow Guadagnoli Lane '14, Bhattacharya et al. '14, LC Crivellin Ota '15, Feruglio Paradisi Pattori '16,'17 …

Operators involving 2nd generations generated by rotations to the mass basis:

$$Y^f = V^{f\dagger} \hat{Y}^f W^f, \qquad f = u, d, e$$

Giving e.g. :

$$C_S (\bar{L}_3 \gamma^\mu L_3)(\bar{Q}_3 \gamma_\mu Q_3) \longrightarrow C_S V_{23}^{d} V_{33}^{d\,*} |V_{23}^{e}|^2 \; (\bar{L}_2 \gamma^\mu L_2)(\bar{Q}_2 \gamma_\mu Q_3)$$

$\Rightarrow \; b \to s\mu\mu$ $\qquad$ $V_{23}^{d} V_{33}^{d\,*} \sim V_{cb} \times V_{tb}$

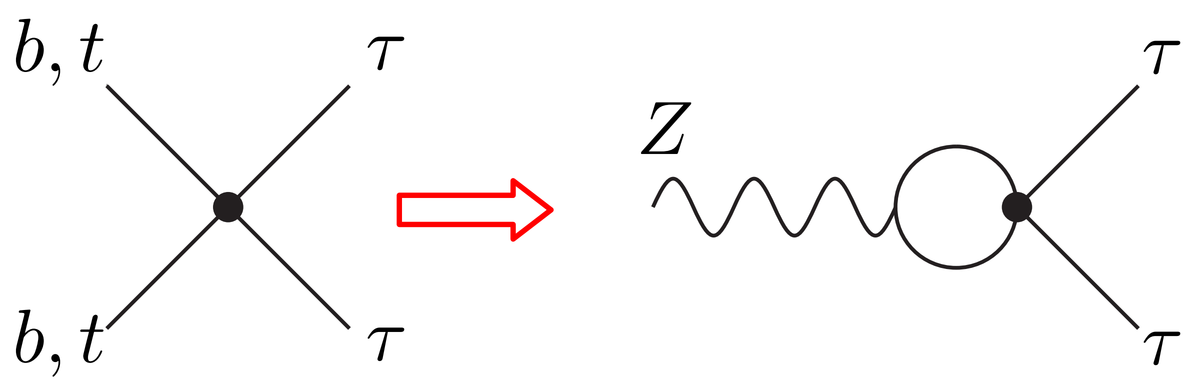
Both kinds of anomalies can be fitted. However…

Radiatively generated LFV and LFUV effects

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

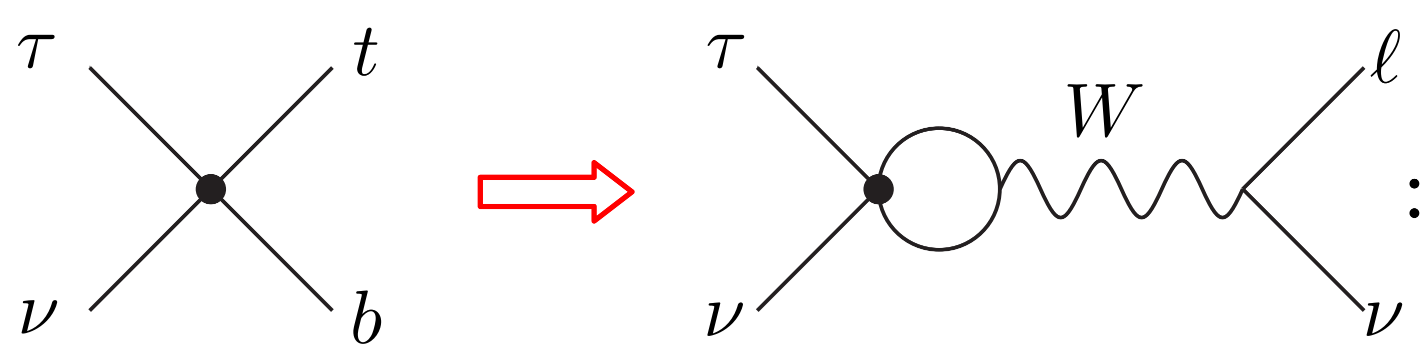
Important radiative effects:

Feruglio Paradisi Pattori '16 & '17



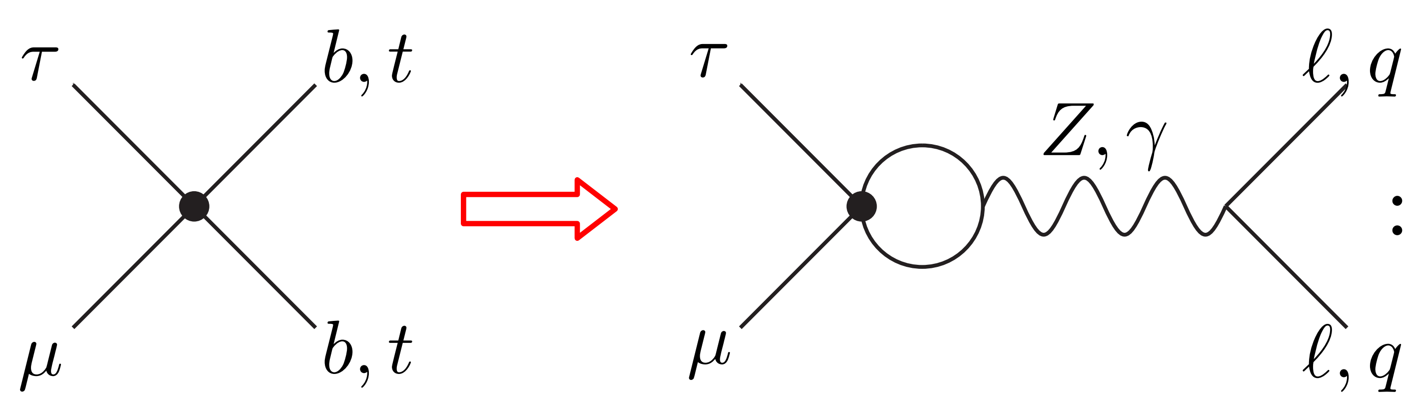
: $$\frac{\mathrm{BR}(Z \to \tau\tau)}{\mathrm{BR}(Z \to ee)}$$

(LFU in Z couplings tested at the permil level)



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

(LFU in tau decays tested below the percent level)

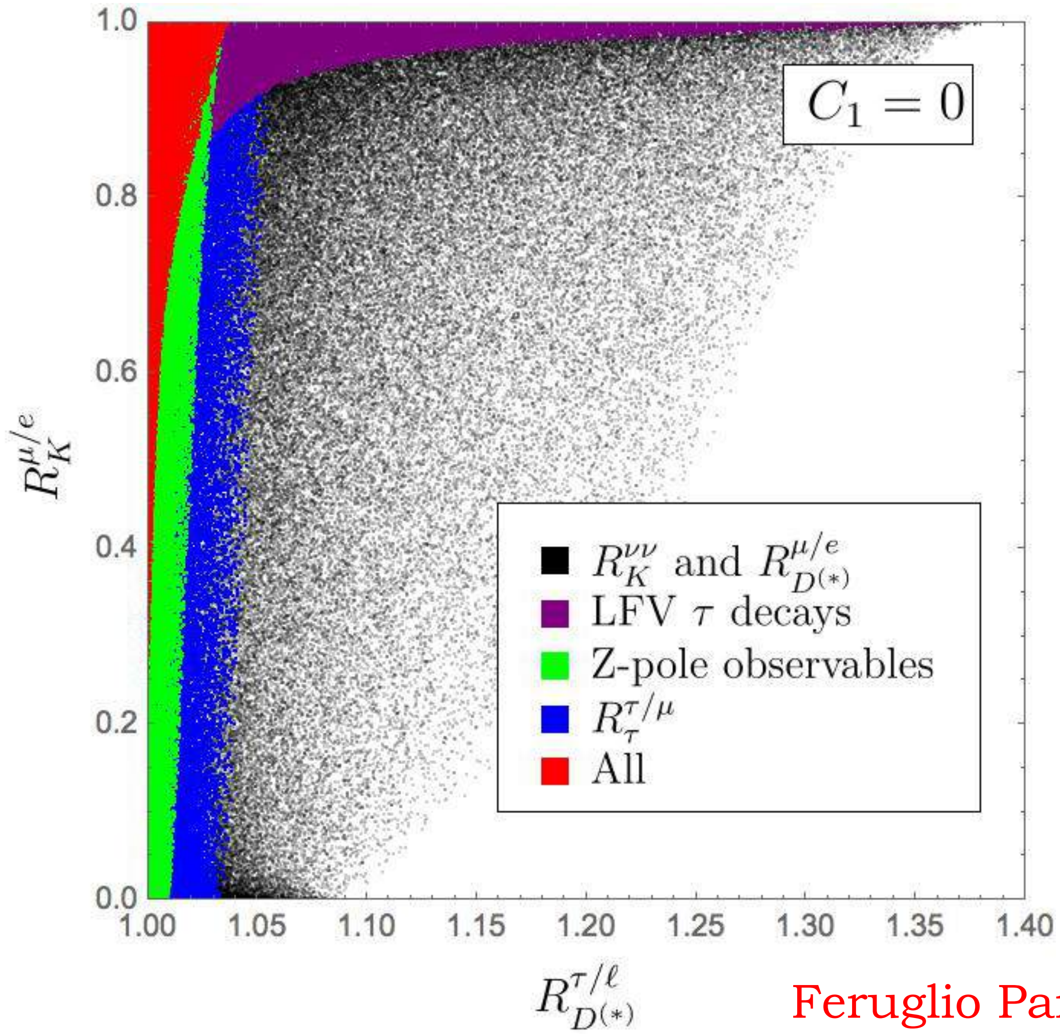


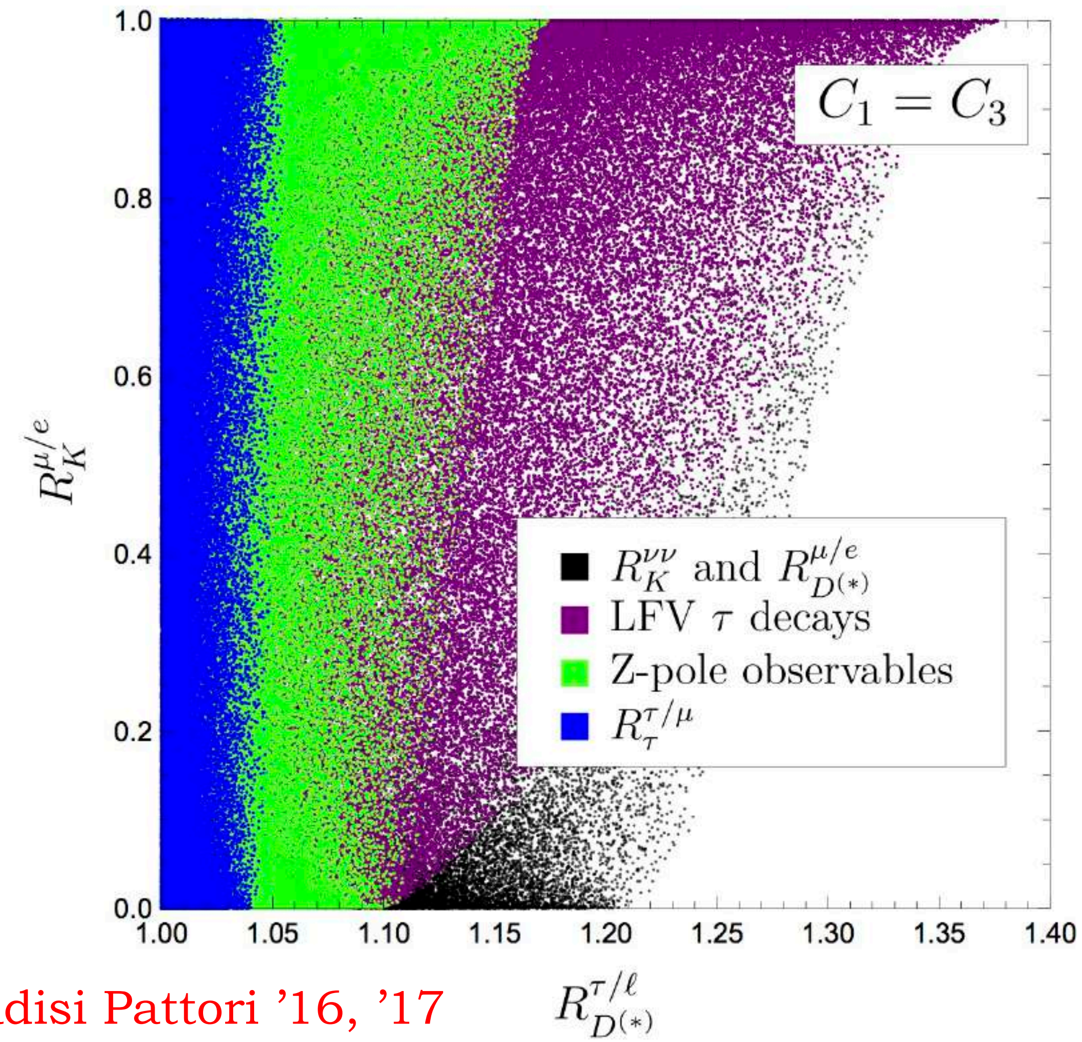
: $\tau \to \mu\ell\ell \quad \tau \to \mu\pi \quad \tau \to \mu\rho$

Tau CLFV!

Radiatively generated LFV and LFUV effects

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





Feruglio Paradisi Pattori '16, '17

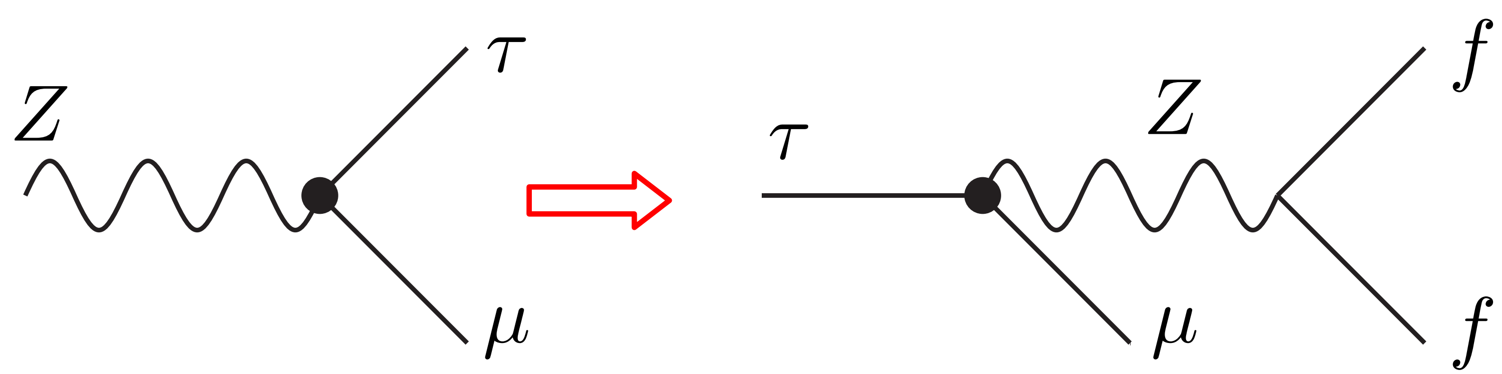
We need a more general flavour structure to explain all anomalies

Buttazzo et al. '17

Z and Tau LFU (and LFV) observables are a limiting factor
$\Rightarrow$ crucial test of the B anomalies!
(true also for more general flavour structures)

- 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. :



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

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

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

$\ldots$

Previous model-independent studies:

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

Z LFV prospects

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}	$\tau \to \mu\gamma$

Table 4: Indirect upper limits on $\mathrm{BR}(Z \to \ell_i \ell_j)$ considering a single operator at the scale $\mu = m_Z$. The last column shows which low-energy observable gives the strongest constraint.

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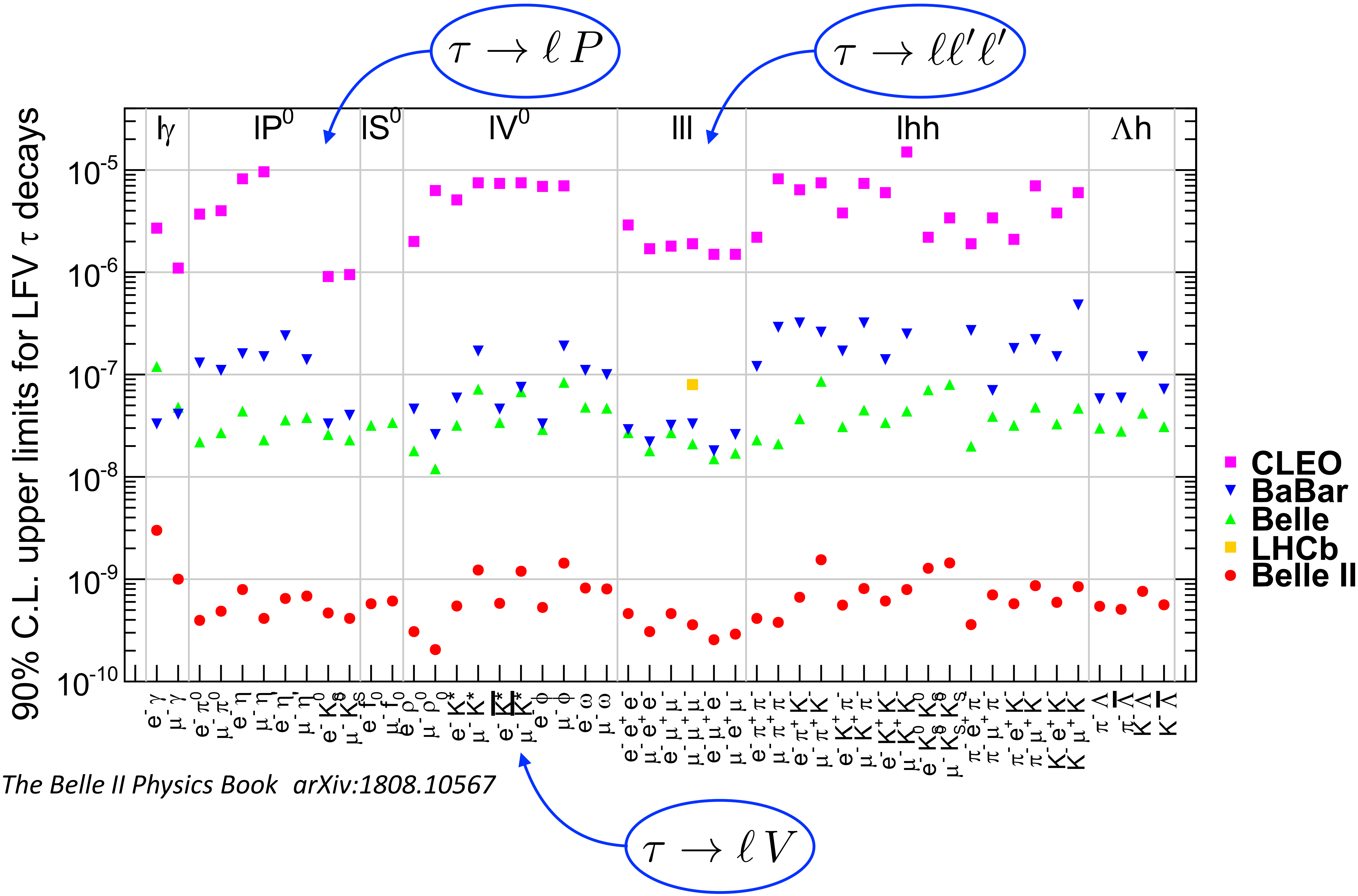
Present/future limits on LFV tau decays



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