CEPC Physics Workshop

Flavour Physics Opportunities for Tau and Z

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Peking University, CHEP, July 2nd 2019

Introduction and Motivations

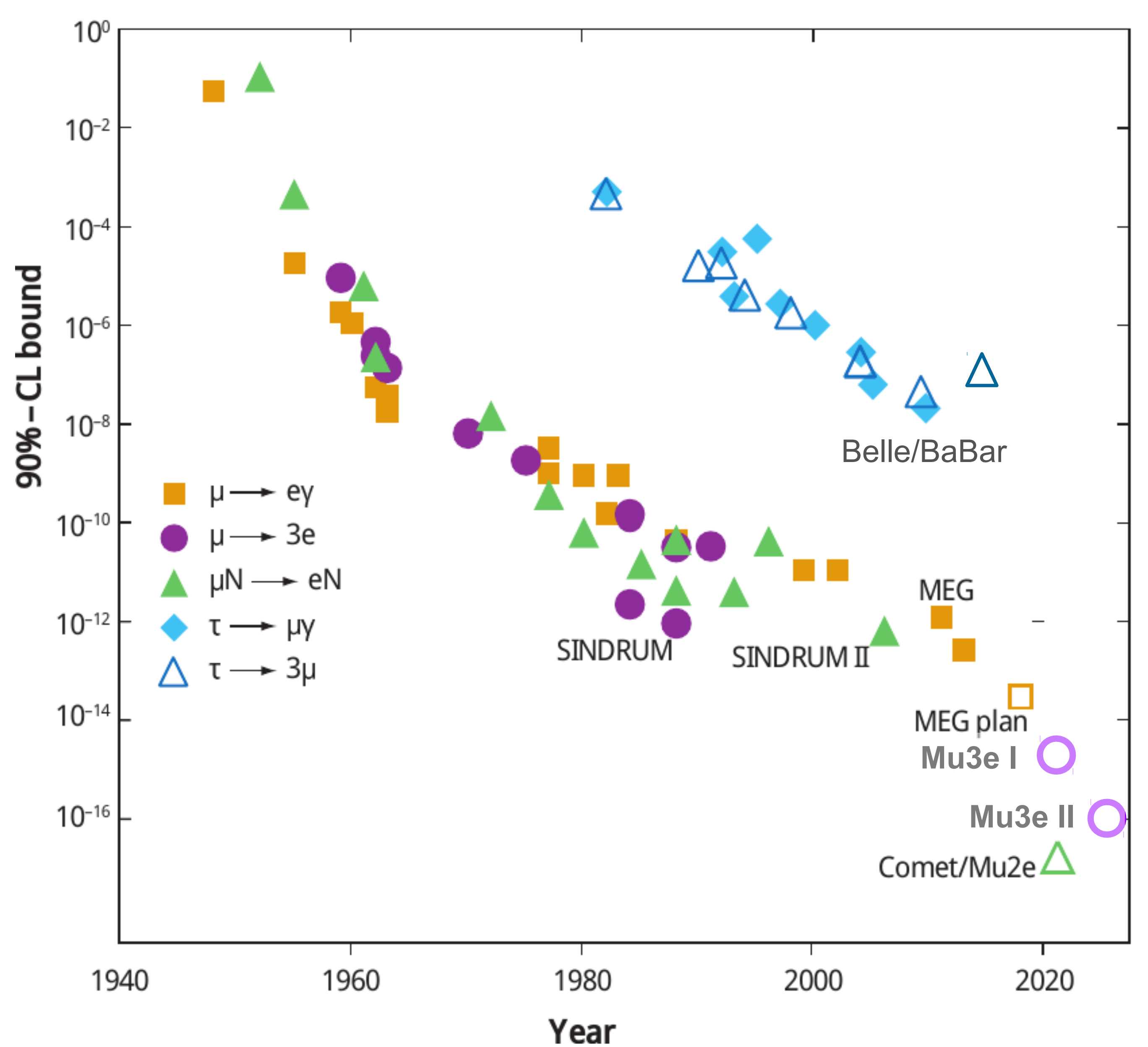
Tau flavour physics

WG: LC, E. Passemar (Indiana U) & E. Stamou (Chicago U)

Z flavour physics

WG: W. Altmannshofer (UC Santa Cruz) & LC

Charged Lepton Flavor Violation?



Sought for more than 70 years…

In the SM fermion masses, thus the *flavour sector*, stems from the Yukawa interactions:

$$-\mathcal{L}_Y = (Y_u)_{ij}\,\overline{Q}_{L\,i}\,u_{R\,j}\,\widetilde{\Phi} + (Y_d)_{ij}\,\overline{Q}_{L\,i}\,d_{R\,j}\,\Phi + (Y_e)_{ij}\,\overline{L}_{L\,i}\,e_{R\,j}\,\Phi + h.c.$$

Rotations to the fermion mass basis: $Y_f = V_f \hat{Y}_f W_f^\dagger, \qquad f = u, d, e$

Unitary rotation matrices, couplings to photon and Z remain flavour-diagonal:

$$e\,\bar{f}\gamma_\mu f A^\mu \qquad\qquad (g_L\,\bar{f}_L\gamma_\mu f_L + g_R\,\bar{f}_R\gamma_\mu f_R)Z^\mu$$

→ flavour-universal couplings to gauge bosons

Couplings to the Higgs also flavour-conserving (aligned to the mass matrix):

$$\frac{m_f}{v}\,\bar{f}_L f_R\,h$$ (but not flavour-universal!)

No (tree-level) flavour-changing neutral currents
Gauge interactions flavour-univeral

Standard Model: LFU and no LFV

In the SM fermion masses, thus the *flavour sector*, stems from the Yukawa interactions:

$$-\mathcal{L}_Y = (Y_u)_{ij}\, \overline{Q}_{L\,i}\, u_{R\,j}\, \widetilde{\Phi} + (Y_d)_{ij}\, \overline{Q}_{L\,i}\, d_{R\,j}\, \Phi + (Y_e)_{ij}\, \overline{L}_{L\,i}\, e_{R\,j}\, \Phi + h.c.$$

Rotations to the fermion mass basis: $Y_f = V_f \hat{Y}_f W_f^\dagger, \quad f = u, d, e$

Flavour violation occurs in charged currents only:

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \left(\overline{u}_L \gamma^\mu (V_u^\dagger V_d) d_L + \overline{\nu}_L \gamma^\mu (V_\nu^\dagger V_e) e_L \right) W_\mu^+ + h.c.$$

but flavour-universal!

$$V_{\rm CKM} \equiv V_u^\dagger V_d \qquad\qquad U_{\rm PMNS} \equiv V_\nu^\dagger V_e$$

However, if neutrinos are massless, we can choose:

$$V_\nu = V_e$$

No LFV (Y_e only 'direction' in the leptonic flavour space)

- Neutrinos oscillate → *Lepton family numbers are not conserved!*

We have to introduce neutrino mass terms:

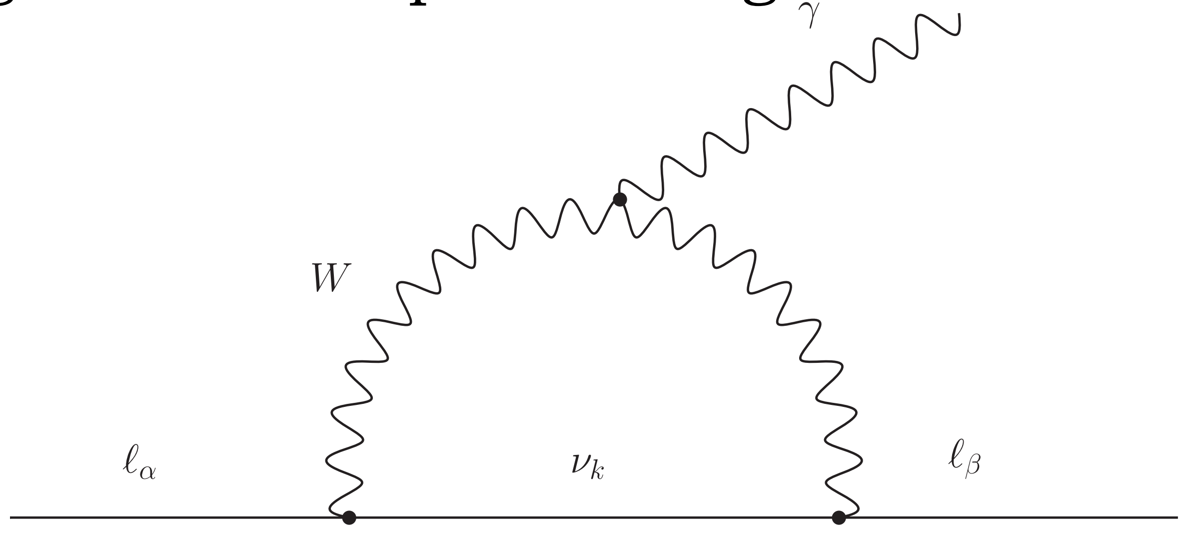
Dirac: $$\mathcal{L}_D = -(Y_\nu)_{ij}\,\overline{\nu}_{R\,i}\,\widetilde{\Phi}^\dagger\,L_{L\,j} + \text{h.c.} \quad\Longrightarrow\quad (m_\nu^D)_{ij} = \frac{v}{\sqrt{2}}(Y_\nu)_{ij}.$$

or Majorana: $$\mathcal{L} \supset \frac{C_{ij}}{\Lambda}\left(\overline{L^c_{L\,i}}\,\tau_2\Phi\right)\left(\Phi^T\tau_2 L_{L\,j}\right) + \text{h.c.} \quad\Longrightarrow\quad (m_\nu^M)_{ij} = \frac{C_{ij}v^2}{\Lambda}$$

- PMNS becomes ‘physical’: neutrino mass eigenstates couple to charged leptons of different flavours

- In the SM + massive neutrinos:

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

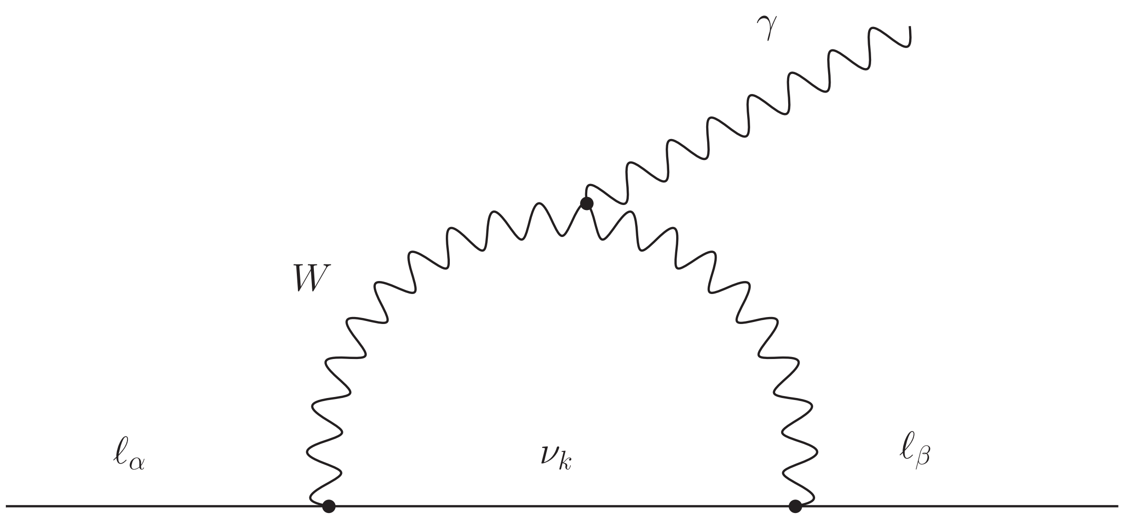


Cheng Li ’77, ’80; Petcov ‘77

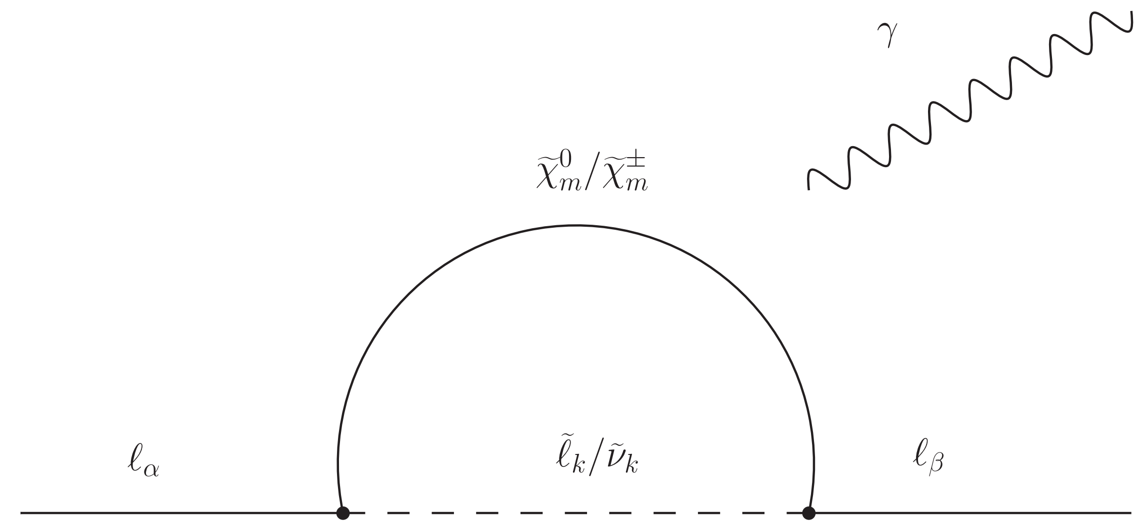
⟹ $$\text{BR}(\mu\to e\gamma)\approx\text{BR}(\tau\to e\gamma)\approx\text{BR}(\tau\to\mu\gamma) = 10^{-55}\div 10^{-54}$$

Large mixing, but huge ‘accidental’ (?) suppression due to small neutrino masses

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



e.g. SUSY



Borzumati Masiero ‘86;
Hisano et al. ‘95

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

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

- Unambiguous signal of New Physics
- Stringent test of NP coupling to leptons
- It probes scales far beyond the LHC reach

Two classes of anomalies:

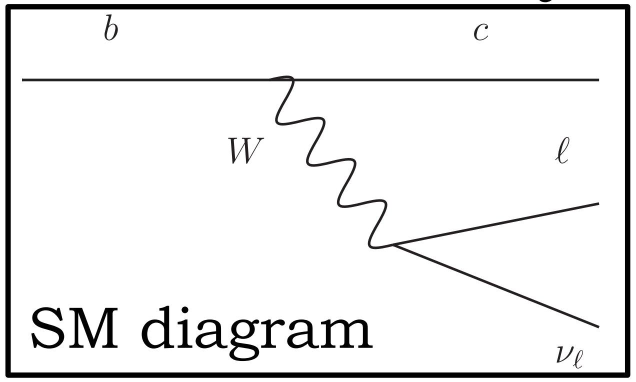
I. In charged-current processes of the type $b \to c\ell\nu$

II. In neutral-current $b \to s\ell^+\ell^-$ transitions

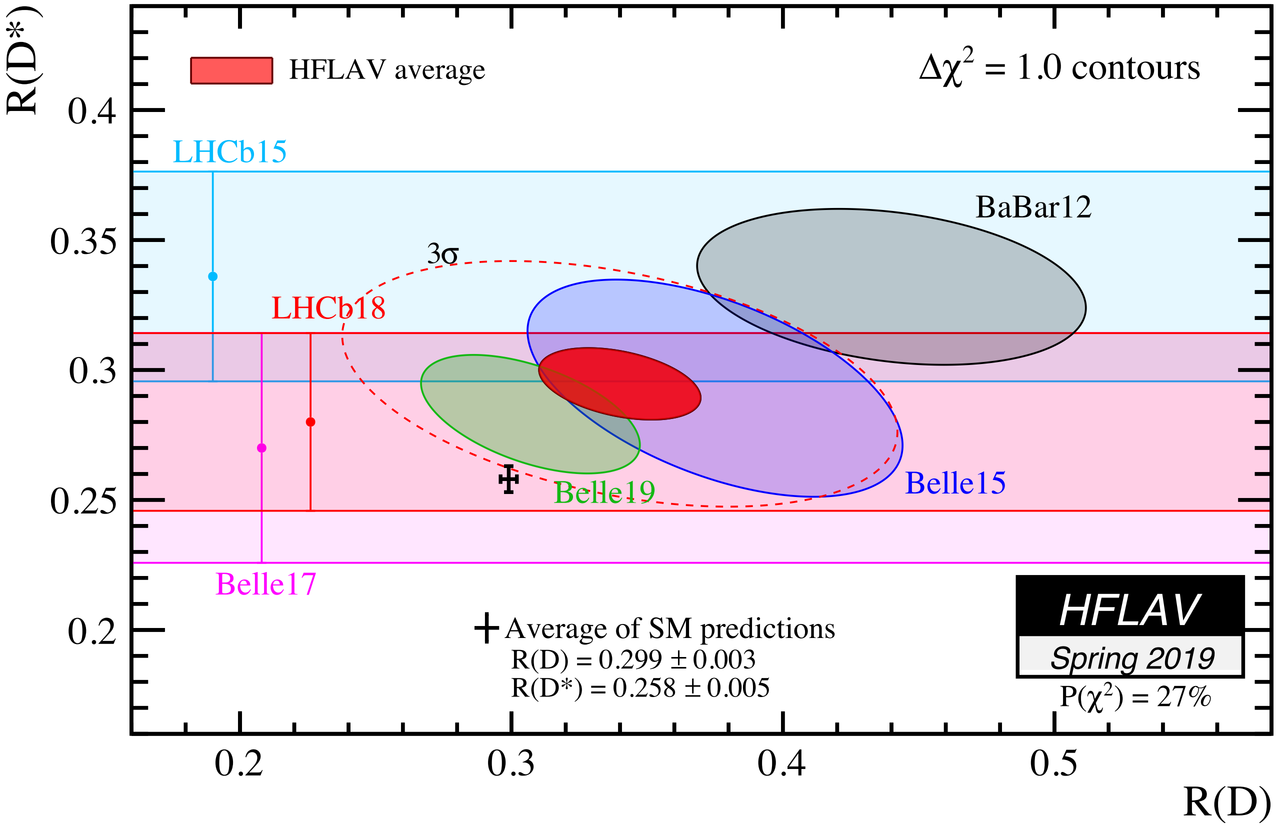
Class I.

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

Test of the Lepton Flavour Universality of SM couplings →



$\approx 3\sigma$ from the SM



requires a 15-20% enhancement wrt the SM

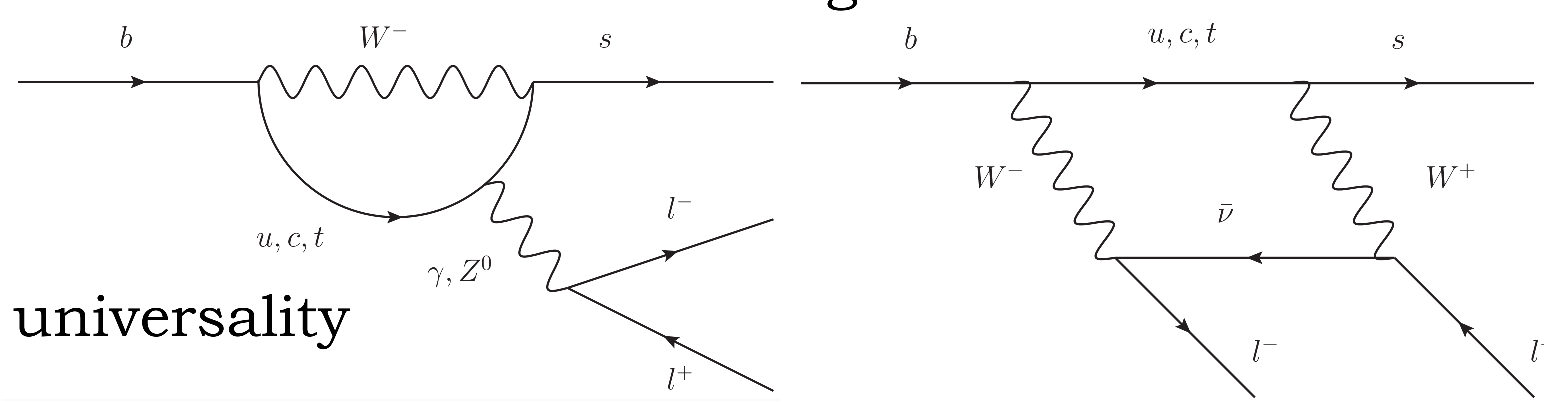
Two classes of anomalies:

I. In charged-current processes of the type $b \to c\ell\nu$

II. In neutral-current $b \to s\ell^+\ell^-$ transitions

Class II.

SM diagrams:



$$R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$

=1+-0.01 in the SM: lepton flavour universality

Bordone et al. '16

LHCb measurements ($1.1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2$):

$$R_K = 0.846\,^{+0.060}_{-0.054}\,^{+0.016}_{-0.014}\,, \qquad R_{K^*} = 0.685^{+0.113}_{-0.069} \pm 0.047 \qquad \approx 2.5\sigma \text{ off}$$

LHCb '19 LHCb '17

Few sigma discrepancies in other obs with larger hadronic uncertainties:

Angular observables in $B \to K^*\mu^+\mu^-$

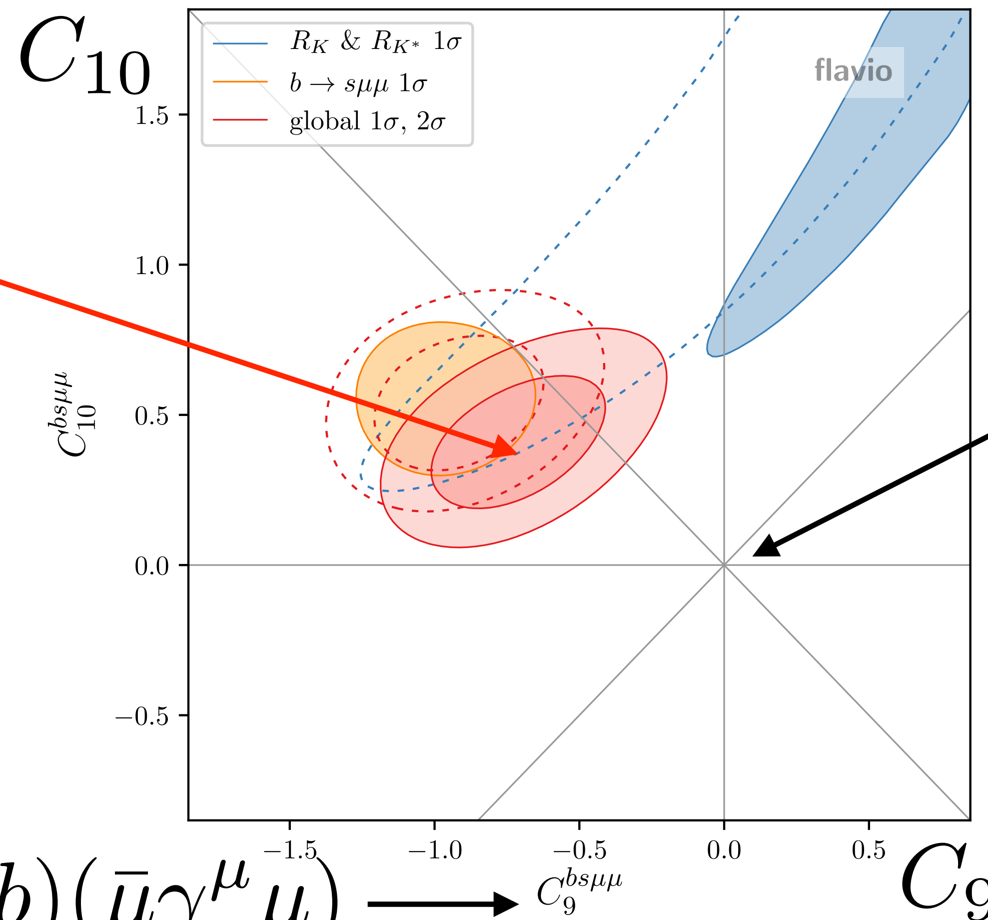
Some $b \to s\mu^+\mu^-$ BRs

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

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

Best fit

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



SM point

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

Aebischer et al. '19

Fits to the data: non-standard contributions preferred at the 4-5σ level

Aebischer et al. '19, Algueró et al. '19, Arbey et al. '19, Ciuchini et al. '19, Kowalska et al . '19, + 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. :

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

$\Rightarrow$ $b \to s\mu\mu$ $\qquad$ $\sim V_{cb} \times V_{tb}$

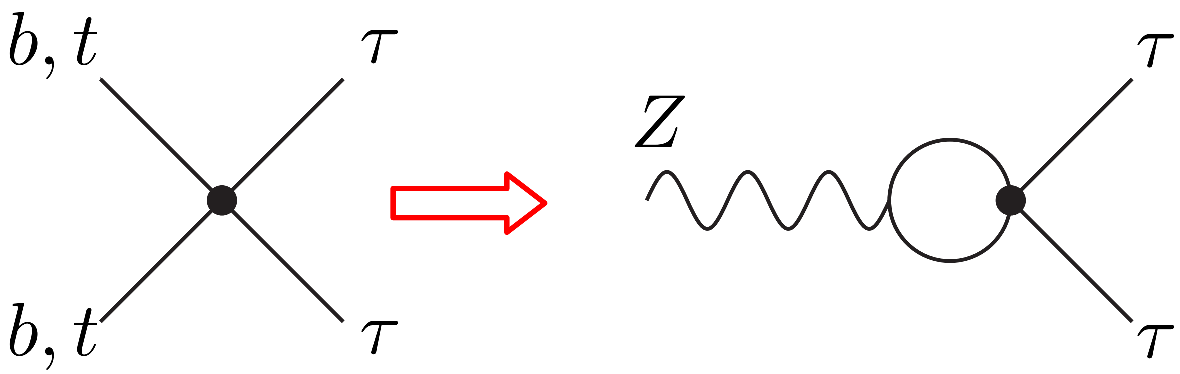
Both kinds of anomalies can be fitted. However...

Radiatively generated LFV and LFUV effects

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

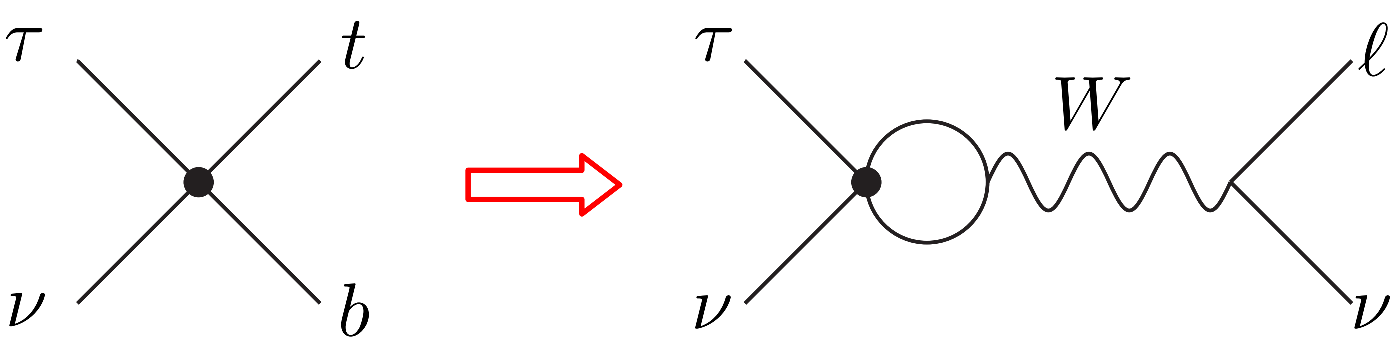
Important radiative effects:

Feruglio Paradisi Pattori '16 & '17



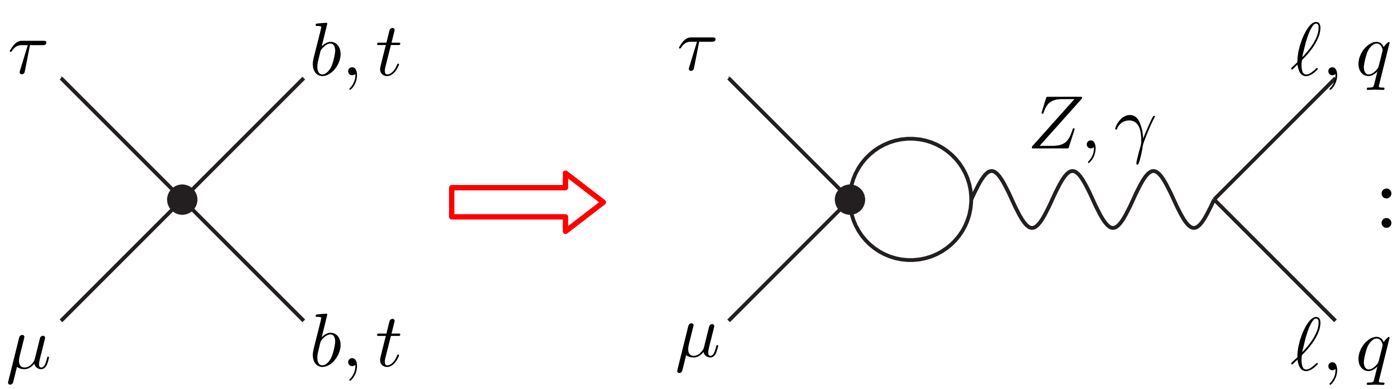
: $$\frac{\mathrm{BR}(Z \to \tau\tau)}{\mathrm{BR}(Z \to ee)}$$

(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)

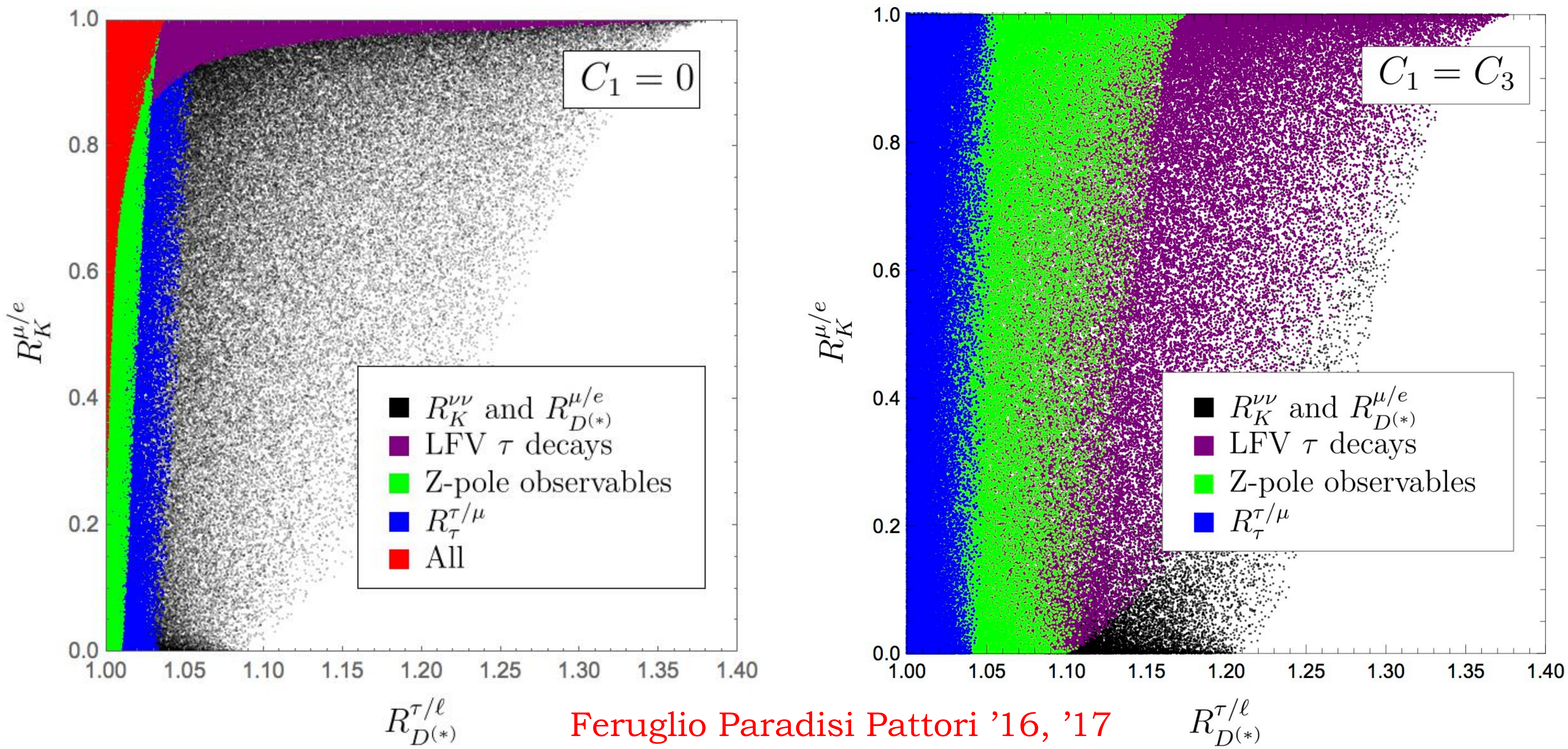


: $\tau \to \mu\ell\ell \quad \tau \to \mu\pi \quad \tau \to \mu\rho$

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
⇒ crucial test of the B anomalies!
(true also for more general flavour structures)

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Z flavour physics

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τ Data Samples

ALEPH:	$3.3 \cdot 10^5$	reconstructed τ decays
BaBar / Belle:	$1.4 \cdot 10^9$	$\tau^+\tau^-$ pairs
Belle-II:	$4.6 \cdot 10^{10}$	$\tau^+\tau^-$ pairs
sτcF:	$2.1 \cdot 10^{10}$	$\tau^+\tau^-$ pairs (10^8 near threshold)

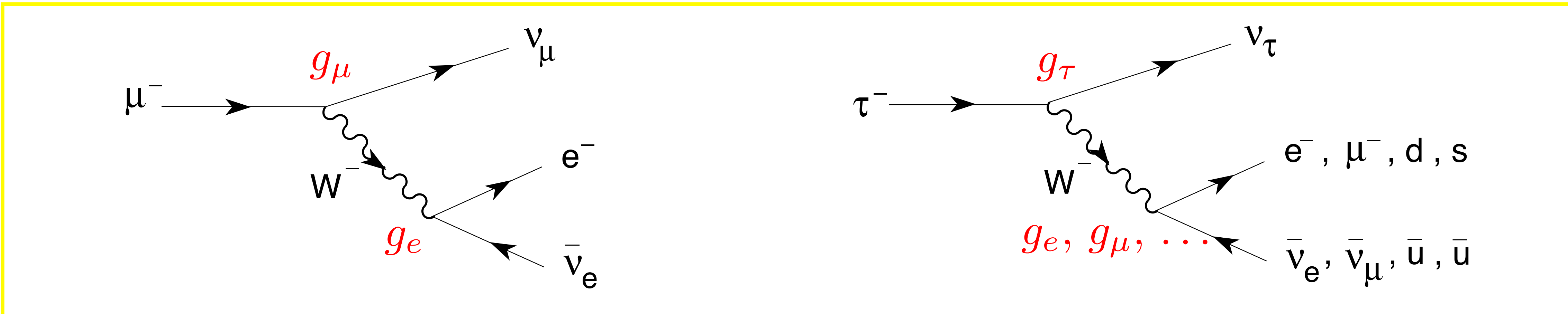
Proposed Super Tau-Charm

A. Pich @ Future Tau-Charm Factory '18

CEPC potential as a "Tera-Z factory":

$$\mathrm{BR}(Z \to \tau^+\tau^-) \simeq 3.4\%$$

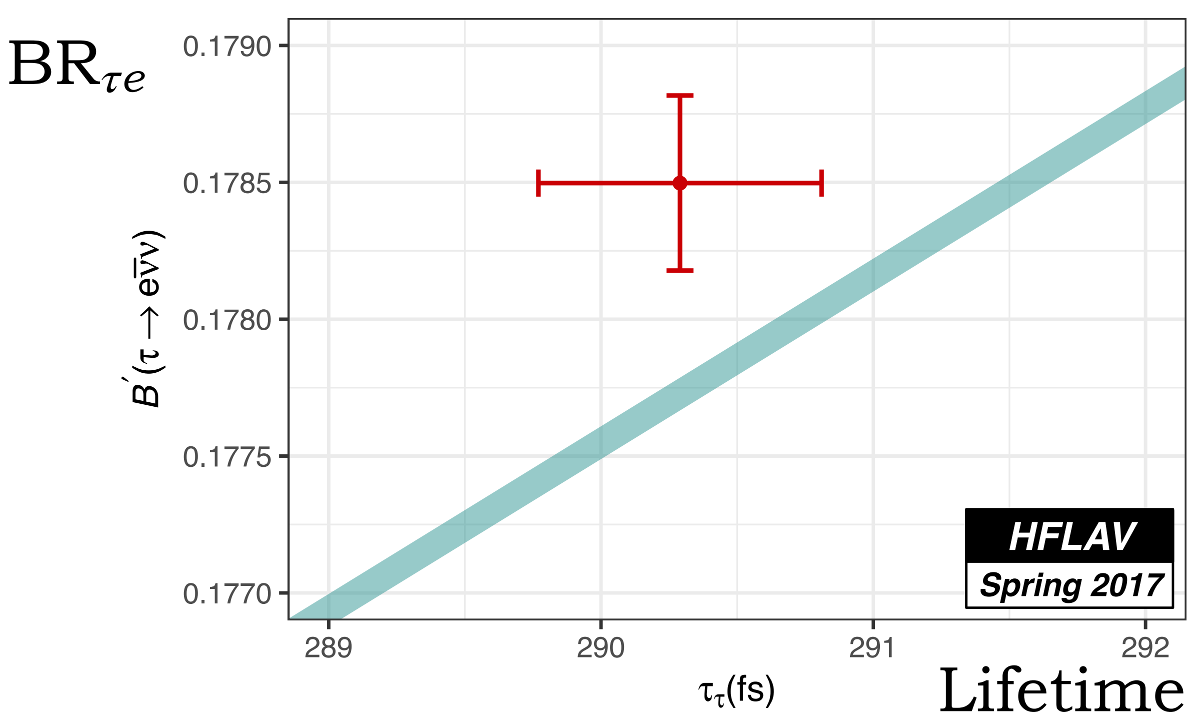
$$10^{12}\ Z \quad \Longrightarrow \quad 3 \times 10^{10}\ \tau^+\tau^-$$



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: $g_\mu/g_e = 1.0019\pm0.0014$ $\quad g_\tau/g_\mu = 1.0010\pm0.0015$ $\quad g_\tau/g_e = 1.0029\pm0.0015$



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

Tau LFU prospects

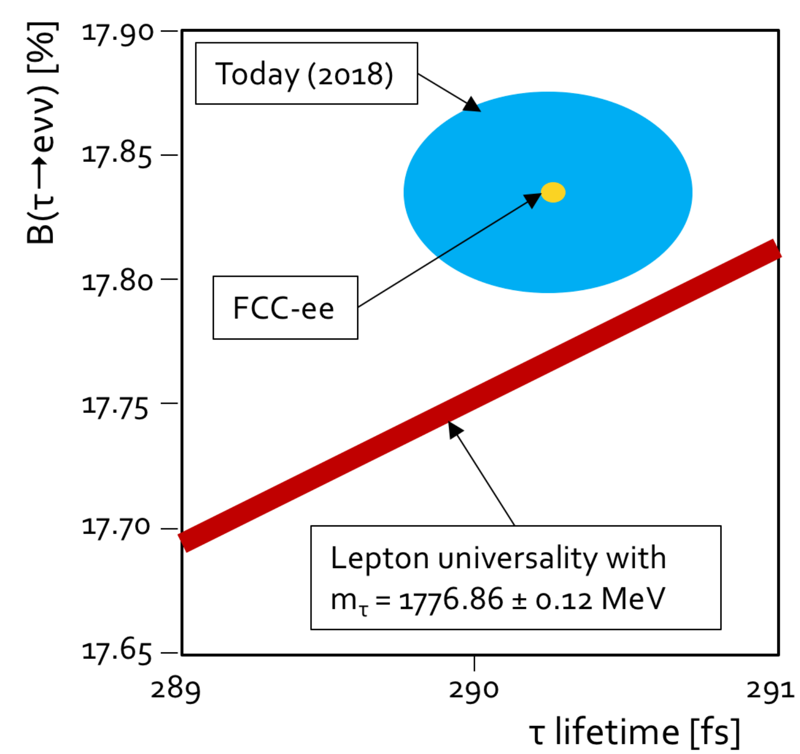
Preliminary study for the FCC-ee (10^{11} tau pairs):

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(τ→eνν) [%]	Selection of $\tau^+\tau^-$, identification of final state	17.82 **± 0.05**	**0.0001**	**No estimate; possibly 0.003**	Efficiency, bkg, Particle ID
B(τ→μνν) [%]		17.39 **± 0.05**			

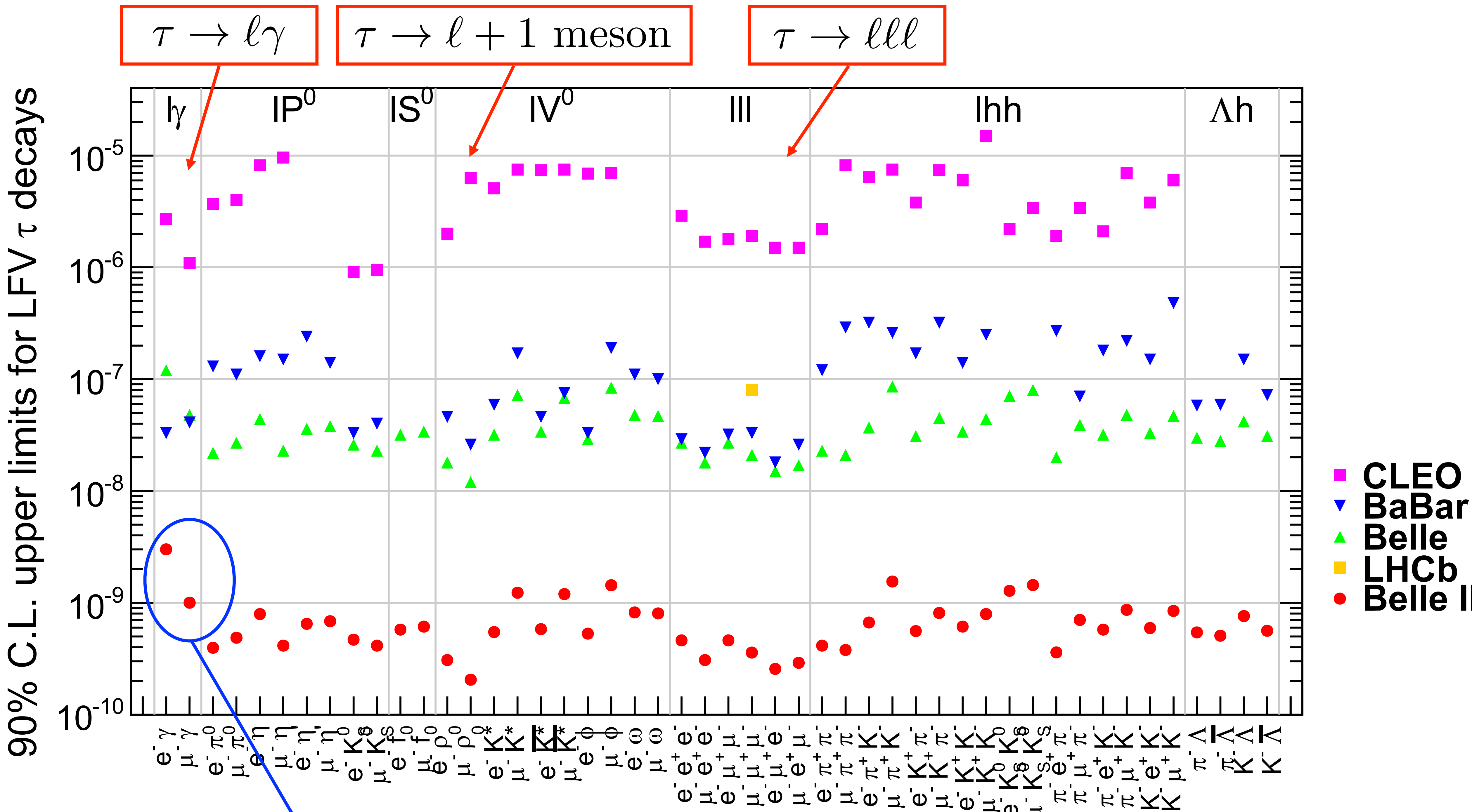
Lepton Universality Tests:

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



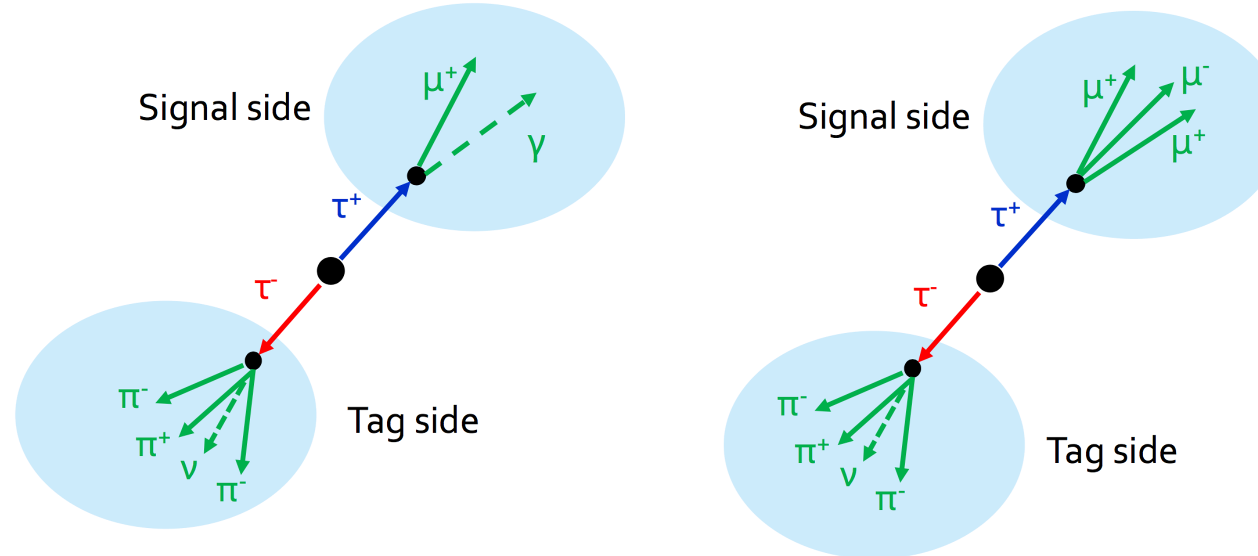
The Belle II Physics Book arXiv:1808.10567

Radiative modes affected by ISR photon background:
Expected sensitivity too optimistic?

- $\tau \to \ell\ell\ell$: *background-free* at the B-factories (with 4-7×10^8 tau pairs)

  If this is the case (?), CEPC can give (3×10^{10} pairs and search effic. ≈10%):

$$\mathrm{BR}(\tau \to \ell\ell\ell) \lesssim 4 \times 10^{-10}$$



Comparable to Belle II reach

(Q: is it really background free at Tera-Z?)

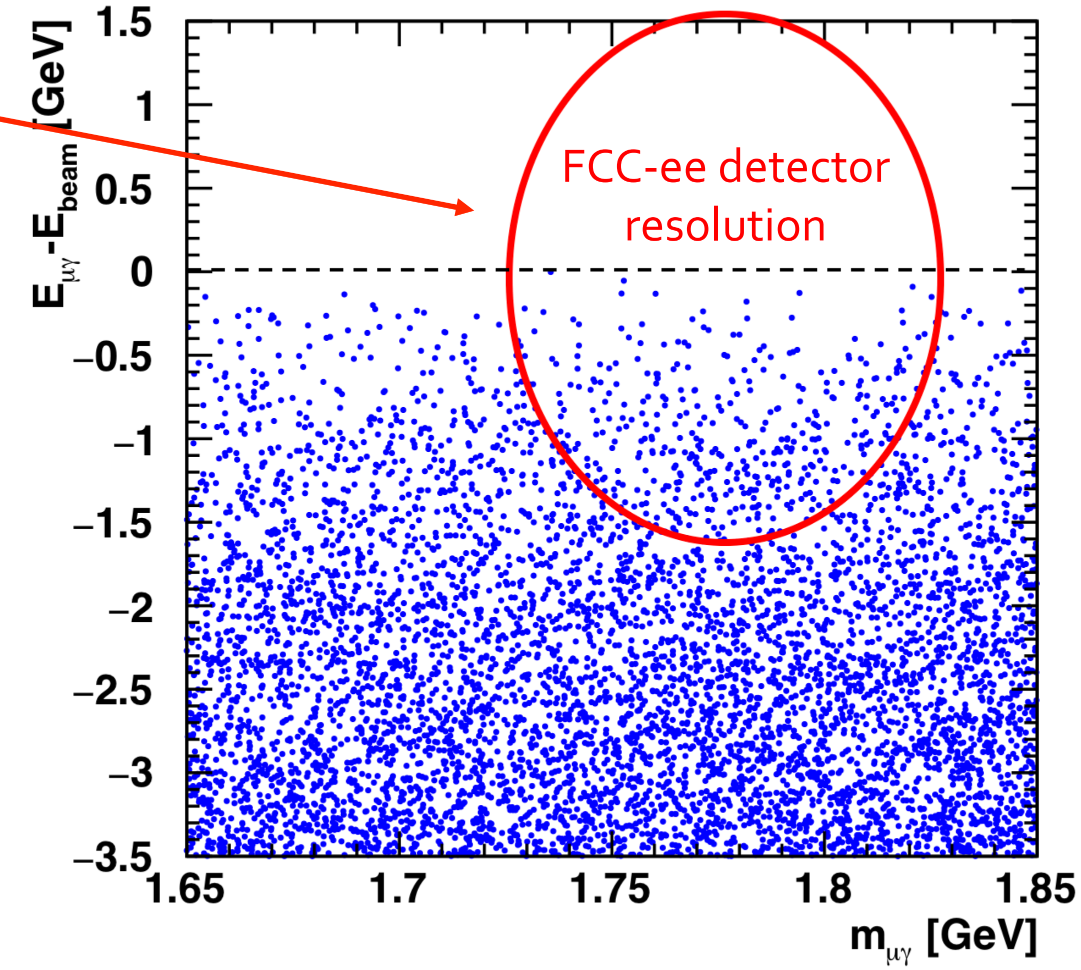
- $\tau \to \ell\gamma$: limited by radiative events bg (leptonic tau decays + ISR or FSR γ) Simulation performed for FCC-ee.

  M. Dam @ Tau '18 & 1811.09408

  Rescaling by the CEPC number of taus:

$$\mathrm{BR}(\tau \to \ell\gamma) \lesssim 3 \times 10^{-9}$$

(again at the level of Belle II expectation)



Write-up ongoing

Other obs are being considered: CPV in tau decays, tau EDM, ...

Ideal wish list:

LFU: Estimate of systematics in leptonic tau BRs measurement

LFV: Signal & background simulations (in particular 3-body decays)

Personal (more *realistic*) view:

LFU tests should be the priority $\rightarrow$ let's discuss about systematics!

LFV already taken care of by Belle II (and we can rely on FCC)

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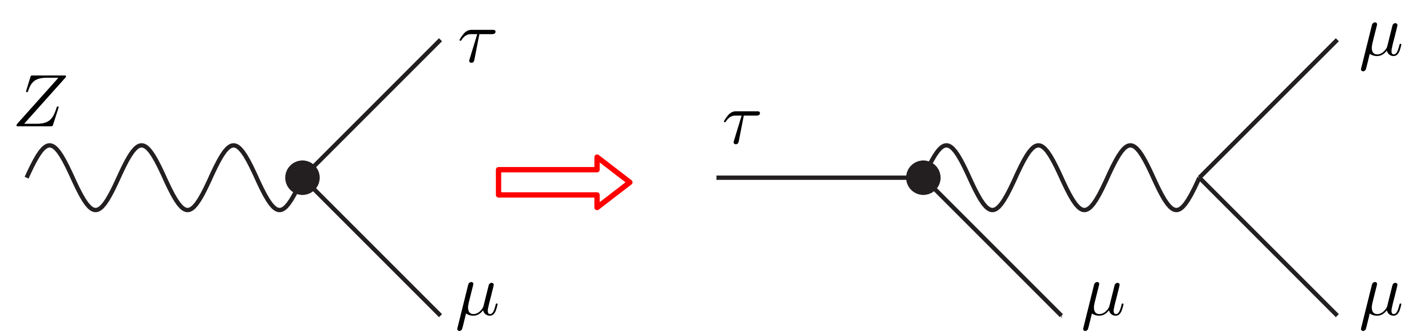
Z LFV decays

4×10^6 Z → LEP bounds	LHC bounds
no candidates → $\mathrm{BR}(Z \to \mu e) < 1.7 \times 10^{-6}$	$\mathrm{BR}(Z \to \mu e) < 7.5 \times 10^{-7}$ ← 8 TeV, 20/fb
Z→ττ bg. → $\mathrm{BR}(Z \to \tau e) < 9.8 \times 10^{-6}$	$\mathrm{BR}(Z \to \tau e) < 5.8 \times 10^{-5}$ ← 13 TeV, 36/fb
$\mathrm{BR}(Z \to \tau\mu) < 1.2 \times 10^{-5}$	$\mathrm{BR}(Z \to \tau\mu) < 1.3 \times 10^{-5}$ ← 8+13 TeV comb.
OPAL '95, DELPHI '97	ATLAS '14, '18

- LHC searches limited by backgrounds (in particular $Z \to \tau\tau$): max ~10 improvement can be expected at HL-LHC (3000/fb)
- CEPC can definitely reach better sensitivities
- Severe indirect constraints from low-energy LFV observables, e.g.:

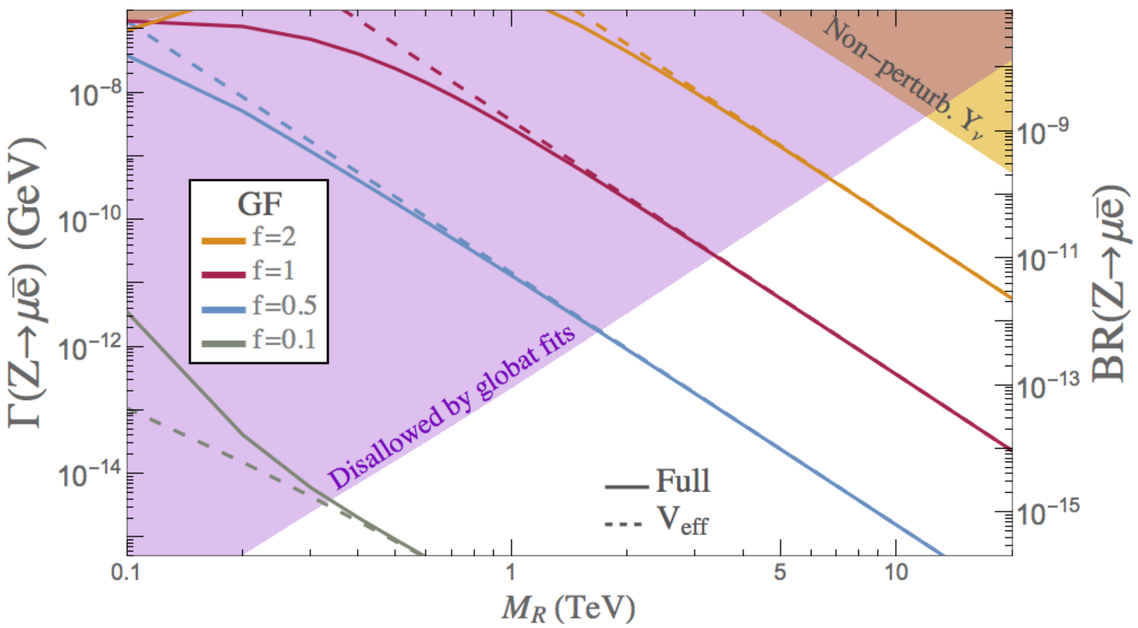


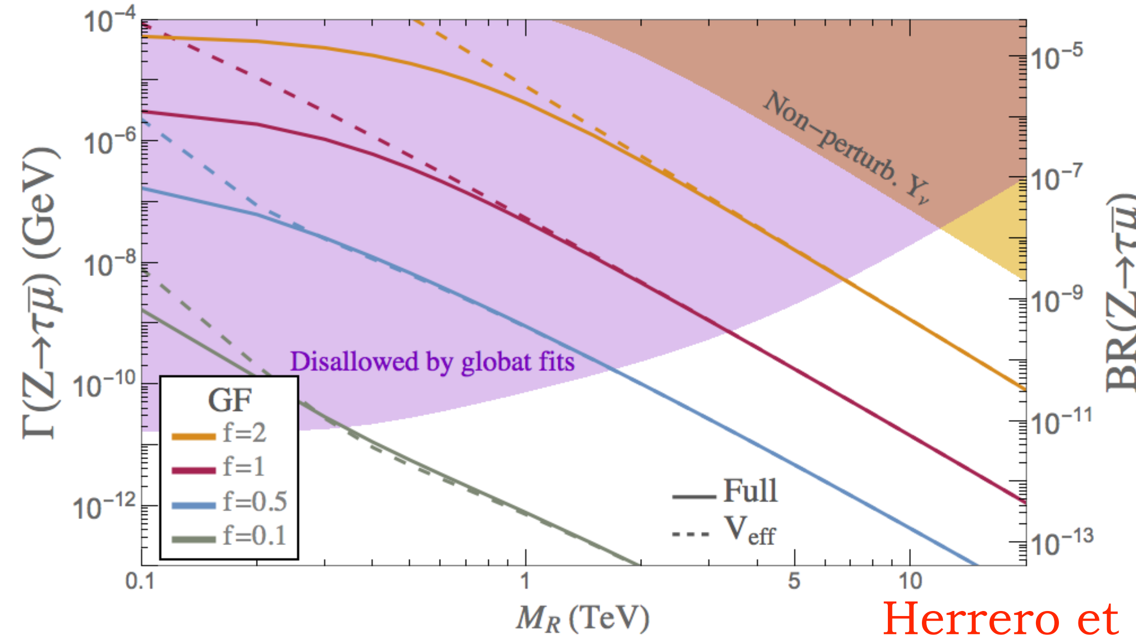
Is Z LFV still interesting?

Z LFV decays

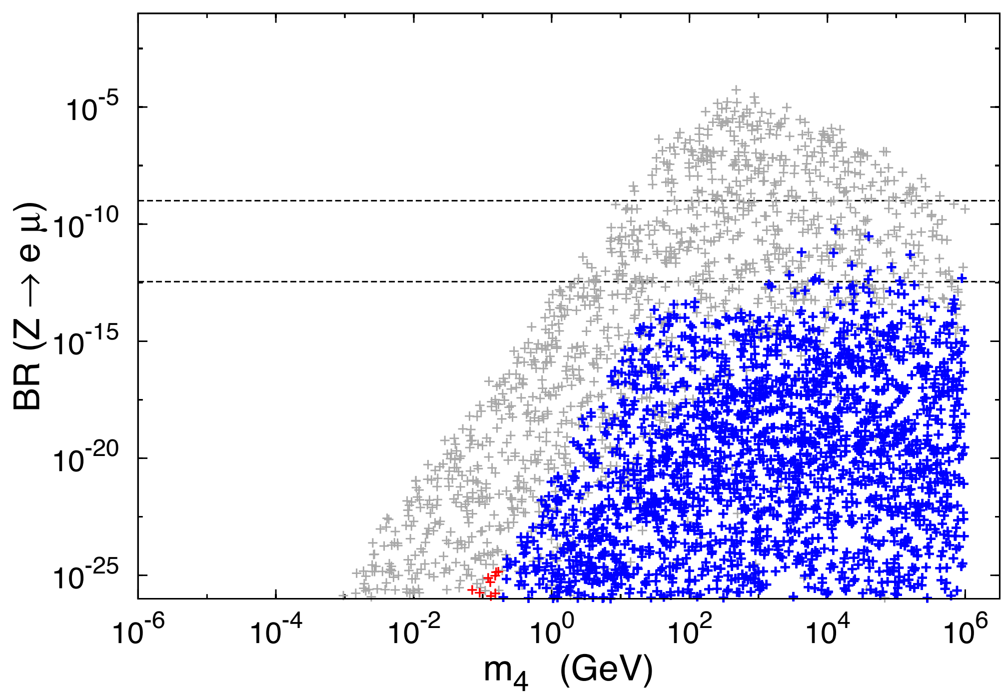
Model-independent study ongoing…

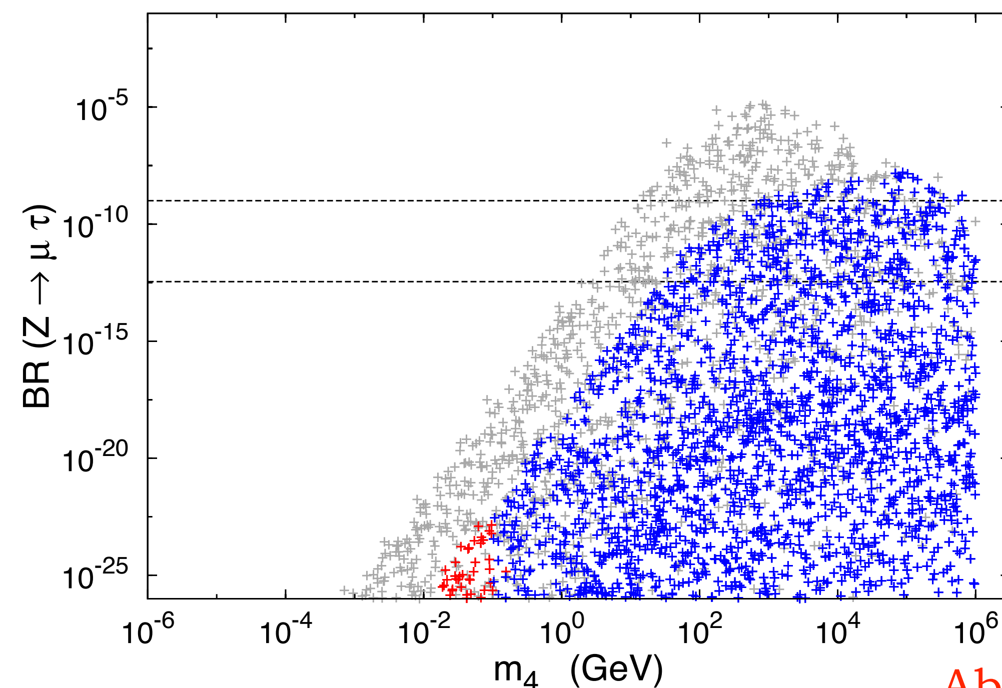
Examples within heavy sterile neutrino models:





Herrero et al. '18





Abada et al. '14

In some cases, $Z\to\tau\,\ell$ can supersede low-energy bounds!

Z LFV prospects

A study in the context of the FCC-ee:

- $Z \to \mu e$:

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)

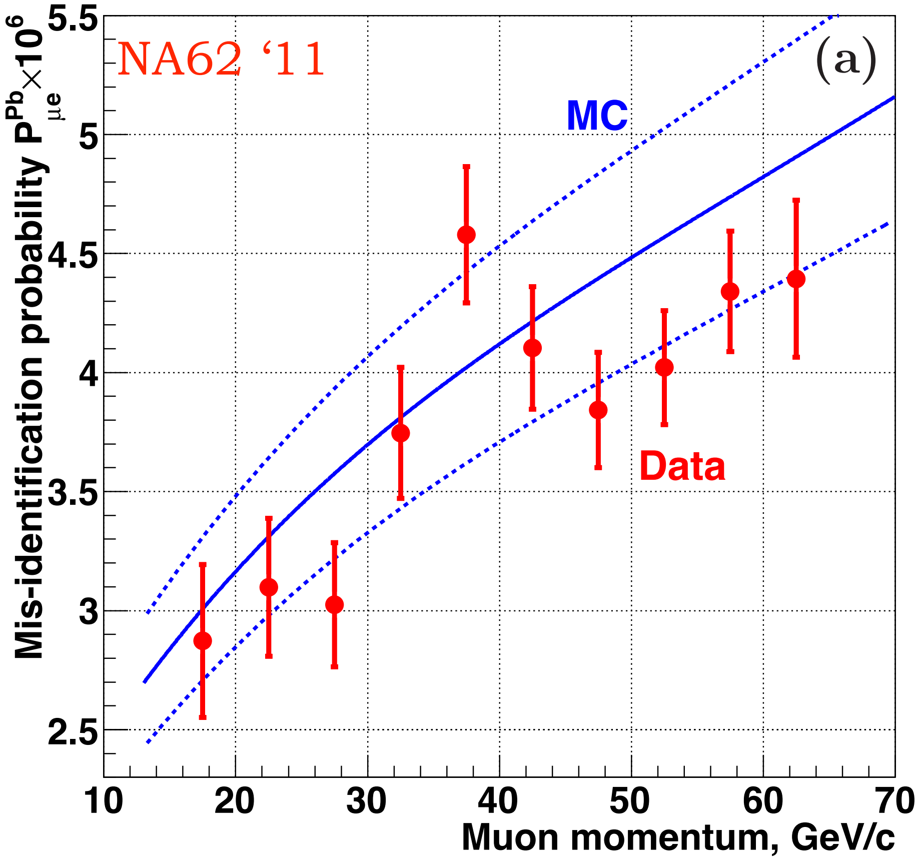
Main issue: muons can release enough energy in the ECAL to be mis-id as electrons.

Mis-id probability measured by NA62 for a LKr ECAL: 4×10^{-6} (for p_μ~45 GeV)

⇨ Bg. from Z → $\mu\mu$ + 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:

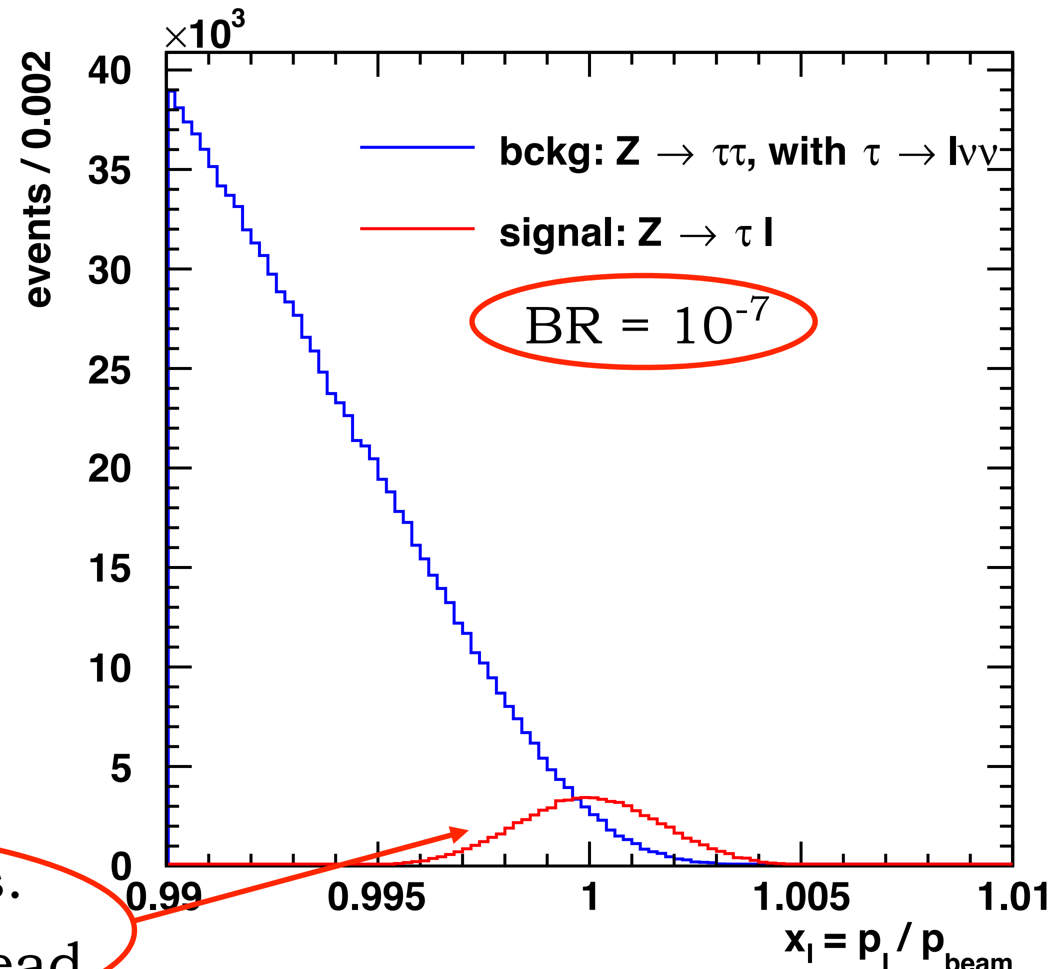
- $Z \to \ell\tau$:

M. Dam @ Tau '18 & 1811.09408

To avoid mis-id, select one hadronic $\boldsymbol{\tau}$ (>3 prong, or reconstructed excl. mode)

Main background from $Z \to \boldsymbol{\tau\tau}$ (with one leptonic $\boldsymbol{\tau}$ decay)

Simulated signal & background:



~10^{-3} momentum res.

& ~10^{-3} collision E spread

Sensitivity:

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

Z LFU tests

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 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?

⇨ We need your input!

(Q: *Is any EW precision expert studying this*?)

Z WG outlook

Ideal wish list:

LFV: Study of the muon mis-id for μ-e

Signal & background study for ℓ-τ

LFU: Estimate of the achievable precision given the systematics

Personal (more *realistic*) view:

$Z \to \mu e$ is a nice process *but*

barring extreme tuning indirect bounds overwhelming

(sensitivity on $\mu \to e$ LFV will improve > ×1000 within a decade!)

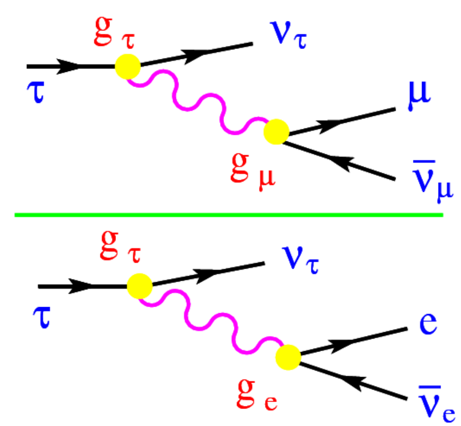
For $Z \to \ell\tau$ we can readapt FCC-ee simulation

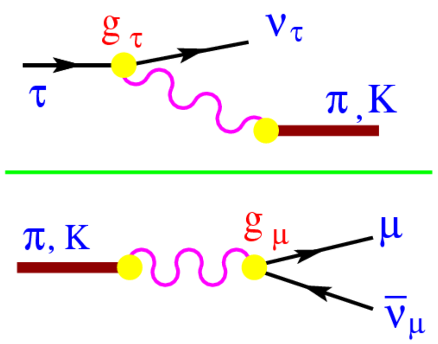
The priority should be to focus Z LFU assessment!

谢 谢！

Thank you!

Charged Current Universality





$|g_\mu / g_e|$

$B_{\tau\to\mu}/B_{\tau\to e}$	1.0018 ± 0.0014
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0003 ± 0.0012
$B_{K\to\mu}/B_{K\to e}$	0.9978 ± 0.0020
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.0010 ± 0.0025
$B_{W\to\mu}/B_{W\to e}$	0.996 ± 0.010

$|g_\tau / g_\mu|$

$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0011 ± 0.0015
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.9962 ± 0.0027
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.9858 ± 0.0070
$B_{W\to\tau}/B_{W\to\mu}$	1.034 ± 0.013

$|g_\tau / g_e|$

$B_{\tau\to\mu}\ \tau_\mu/\tau_\tau$	1.0030 ± 0.0015
$B_{W\to\tau}/B_{W\to e}$	1.031 ± 0.013

A. Pich @ Future Tau-Charm Factory ’18

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

- **World average**
  - **$B(\tau\to e\nu\nu) = 17.82 \pm 0.05$ %** ; **$B(\tau\to \mu\nu\nu) = 17.39 \pm 0.05$ %**
- Dominated by ALEPH
  - **$B(\tau\to e\nu\nu) = 17.837 \pm 0.072_{stat} \pm 0.036_{syst}$ %** ; **$B(\tau\to \mu\nu\nu) = 17.319 \pm 0.070_{stat} \pm 0.032_{syst}$ %**
- Three uncertainty contributions were dominant in the Aleph measurement
  - Selection efficiency: 0.021 / 0.020 %
  - Non-$\tau^+\tau^-$ background: 0.029 / 0.020 %
  - Particle ID: 0019 / 0.021 %
  - All of these are limited by statistics: size of test samples, etc.
- Prospects at FCC-ee
  - Enormous statistics:

$\delta_{stat} = 0.0001$ %

  - Systematic uncertainty is hard to (gu)estimate at this point.
    - Depends intimately on the detailed performance of the detector(s)
      - At the end of the day, between LEP experiments, δ_{syst} varied by up to a factor 3
        - Lesson: Design your detector with care!

Let me put here as *a placeholder* a suggested factor 10 improvement wrt ALEPH:

$\delta_{syst} = 0.003$ %

M. Dam @ Tau '18