Revisiting Lepton Flavour Universality in B decays

Andrea Pattori

LFV/LFUV, why and how?

Institut Henri Poincaré, 08.11.2016

based on: F. Feruglio, P. Paradisi, AP (arXiv:1605.00524)

Outline:

- About R_K and $R_{D^{(*)}}$

- Simultaneous explanation of R_K and $R_{D^{(*)}}$
    - crucial impact of 1-loop LFV/LFUV effects

- More about the relevance of the 1-loop effects

- Future perspectives and conclusions

Anomalies in B decays

Putative anomalies in B decays:

- $B \to K^{(*)}\ell^+\ell^-$
  - P'_5 and other smaller tensions for $B \to K^{(*)}\mu\mu$
  - LFU violation in R_K:

$$R_K = \frac{\mathcal{B}\left(B \to K\mu^+\mu^-\right)}{\mathcal{B}\left(B \to Ke^+e^-\right)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

- $\bar{B} \to D^{(*)}\ell\bar{\nu}$
  - LFU violation in R_D:

$$R^{\tau/\ell}_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu})_{\rm exp}/\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu})_{\rm SM}}{\mathcal{B}(\bar{B} \to D^{(*)}l\bar{\nu})_{\rm exp}/\mathcal{B}(\bar{B} \to D^{(*)}l\bar{\nu})_{\rm SM}}$$

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Common explanation?

- $B \to K^{(*)}\ell^+\ell^-$

$$\mathcal{O}_9 = \frac{\alpha}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma_\mu\ell) \qquad \mathcal{O}_9' = \frac{\alpha}{4\pi}(\bar{s}_R\gamma_\mu b_R)(\bar{\ell}\gamma_\mu\ell) \qquad \mathcal{O}_{7\gamma} = \frac{e}{4\pi^2}m_b(\bar{s}_L\sigma^{\mu\nu}b_R)F_{\mu\nu}$$

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How to address $b \to s$ anomalies

- $B \to K^{(*)}\ell^+\ell^-$

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$\Downarrow$

- ▹ $C_9^{NP} \neq 0$
- ▹ $C_9^{NP} = -C_{10}^{NP} \neq 0$

} good fits of: ▹ R_K ▹ P'_5 (et al.)

S. Descotes-Genon , L. Hofer, J. Matias, J. Virto (2015)

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$(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}_L\gamma_\mu\ell_L)$ ⇒ left-handed current

How to address $b \to d$ anomalies

- $\bar{B} \to D^{(*)} \ell \bar{\nu}$
  - Only 4 dimension-6 operators can address the R_D anomaly

$$\mathcal{O}_{lq}^{(3)} = (\bar{q}_L \gamma_\mu \sigma^a q_L)(\bar{\ell}_L \gamma_\mu \sigma^a \ell_L) \qquad \mathcal{O}_{lequ}^{(1)} = (\bar{\ell}_L e_R) i\sigma^2 (\bar{q}_L u_R)$$

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LH current

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- Is a LH quark-lepton current the way?
  - simultaneous explanation of R_K, R_D
  - bonus: relaxing P'_5 (et al.) tension(s)
  - well-motivated NP models behind it (vector leptoquark, Z')

Is it this simple?

- Simultaneous explanation of R_K and $R_{D(*)}$ anomalies:

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$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

~25%, 2.6σ

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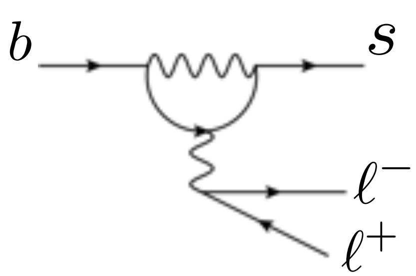
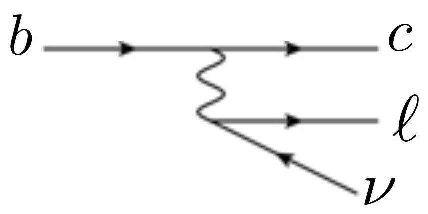
Problem: SM: 1-loop process



SM: tree-level process



R_K vs. $R_{D(*)}$

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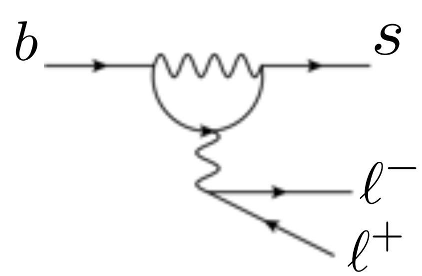

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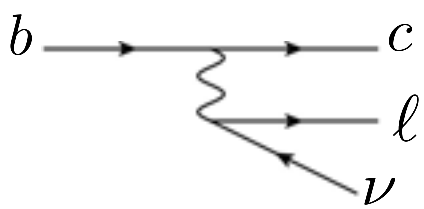


Solution:

1. Extend loop suppression to the NP sector
2. Rely on flavor symmetries (e.g *U(2)*)

typical assumption: NP couples mostly to the third generation quarks

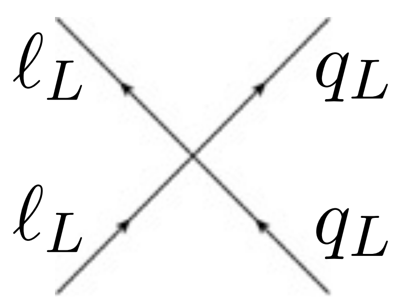
Tree-level analysis

- Left-handed vector currents
- Parametrical suppression of interaction with second-generation

Effective Lagrangian:

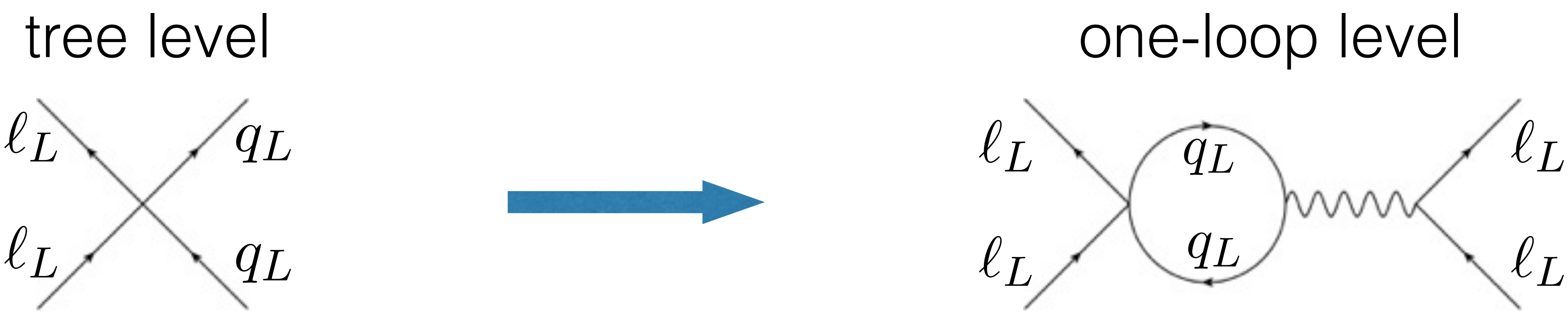
$$\mathcal{L}_{\rm eff} = \frac{C_1^{pqrs}}{\Lambda^2} \left(\bar{q}_{pL}\gamma^\mu q_{qL}\right)\left(\bar{\ell}_{rL}\gamma_\mu \ell_{sL}\right) + \frac{C_3^{pqrs}}{\Lambda^2} \left(\bar{q}_{pL}\gamma^\mu \tau^a q_{qL}\right)\left(\bar{\ell}_{rL}\gamma_\mu \tau^a \ell_{sL}\right)$$

tree level:



- fit $R_K, \; R_{D^{(*)}}^{\tau/\ell}$
- bounds from: $R_{D^{(*)}}^{\mu/e}, \; R_K^{\nu\nu} = \dfrac{\mathcal{B}(B \to K \nu\bar{\nu})}{\mathcal{B}(B \to K \nu\bar{\nu})_{\rm SM}}$
- benchmark: $\mathcal{B}(B \to K \tau\mu)$

What about loop contributions?



- New phenomenology, perhaps absent at tree level
- EW loop $\sim \dfrac{\alpha}{\pi} \sim 10^{-3}$, i.e. not so important, right?

What about loop contributions?

- New phenomenology, perhaps absent at tree level
- EW loop $\sim \frac{\alpha}{\pi} \sim 10^{-3}$, i.e. not so important, right? **No**

R_D (tree level in SM)		EW precision tests ($\sim 10^{-2} \div 10^{-3}$) LFV phenomenology
$\mathcal{O}(1)$ NP effect	→	$\sim 10^{-3}$ NP effect

Enhancements:
- Big logs $\sim \log\left(\frac{M_W^2}{\Lambda^2}\right)$
- big $\mathcal{O}(1)$ numerical factors

Our setup

- At NP scale Λ:

  1) Assume a basis where:

$$\mathcal{L}_{\rm eff} = \frac{C_1}{\Lambda^2}\left(\bar{q}_3\gamma^\mu P_L q_3\right)\left(\bar{\ell}_3\gamma_\mu P_L \ell_3\right) + \frac{C_3}{\Lambda^2}\left(\bar{q}_3\gamma^\mu \tau^a P_L q_3\right)\left(\bar{\ell}_3\gamma_\mu \tau^a P_L \ell_3\right)$$

  2) Go to mass basis through a rotation of generations 2-3:
    - two real parameters: θ_{bs}, $\theta_{\tau\mu}$ (assumed $\ll 1$)
    - no mixing with the 1^{st} generation

- RGE flow down to the EW scale (leading log) ← here new operators arise

- Matching to an EFT with broken *SU(2)*

- Computation of relevant observables

About Leading Log Approximation

- Eventually *Λ* ≈ *1÷3 TeV*

$$\left|\log\left(\frac{M_W^2}{\Lambda^2}\right)\right| \approx 5 \div 7$$

is it a “big” log?

⇒ it safely capture the order of magnitude of the effects

⇒ finite contributions might be *O(1)*

⇒ quantitatively correct, barring accidentally big cancellations

- Consider finite contributions? work in progress…

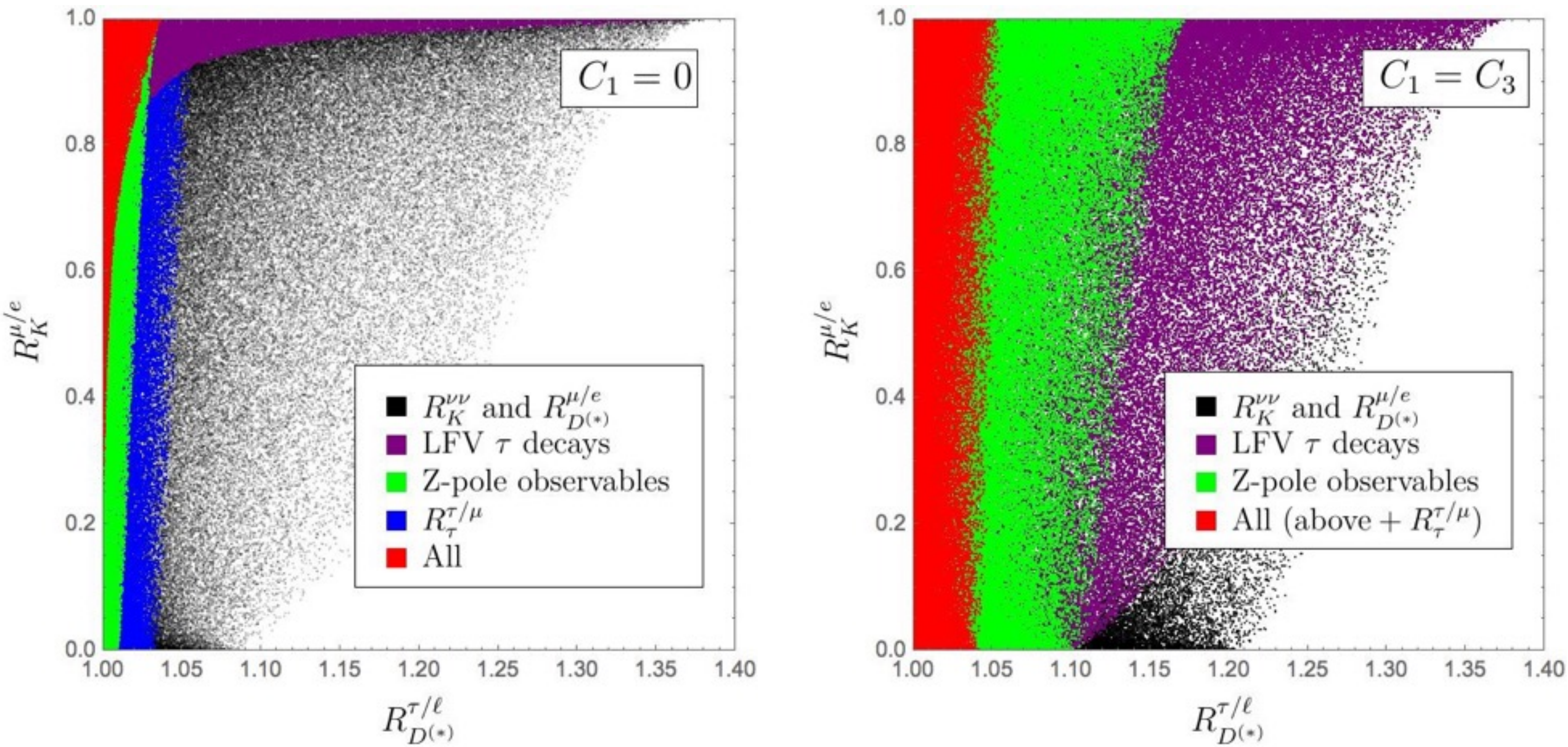
Relevant observables

- Relevant observables:
  - $R_D^{\mu/e}, R_K^{\nu\nu}$
  - LFV in τ decays: $\tau\to 3\mu$, $\tau\to\mu ee$, $\tau\to\mu\rho$, $\tau\to\mu\pi$
  - LFU in τ decays: $R_\tau^{\tau/\mu} = \dfrac{\mathcal{B}(\tau\to e\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\tau\to e\nu\bar{\nu})_{\rm SM}}{\mathcal{B}(\mu\to e\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\mu\to e\nu\bar{\nu})_{\rm SM}}$
  - Z pole observables: axial and vector lepton coupling

    invisible Z decay width

- We then scan over different C_1, C_3, θ_{bs}, $\theta_{\tau\mu}$

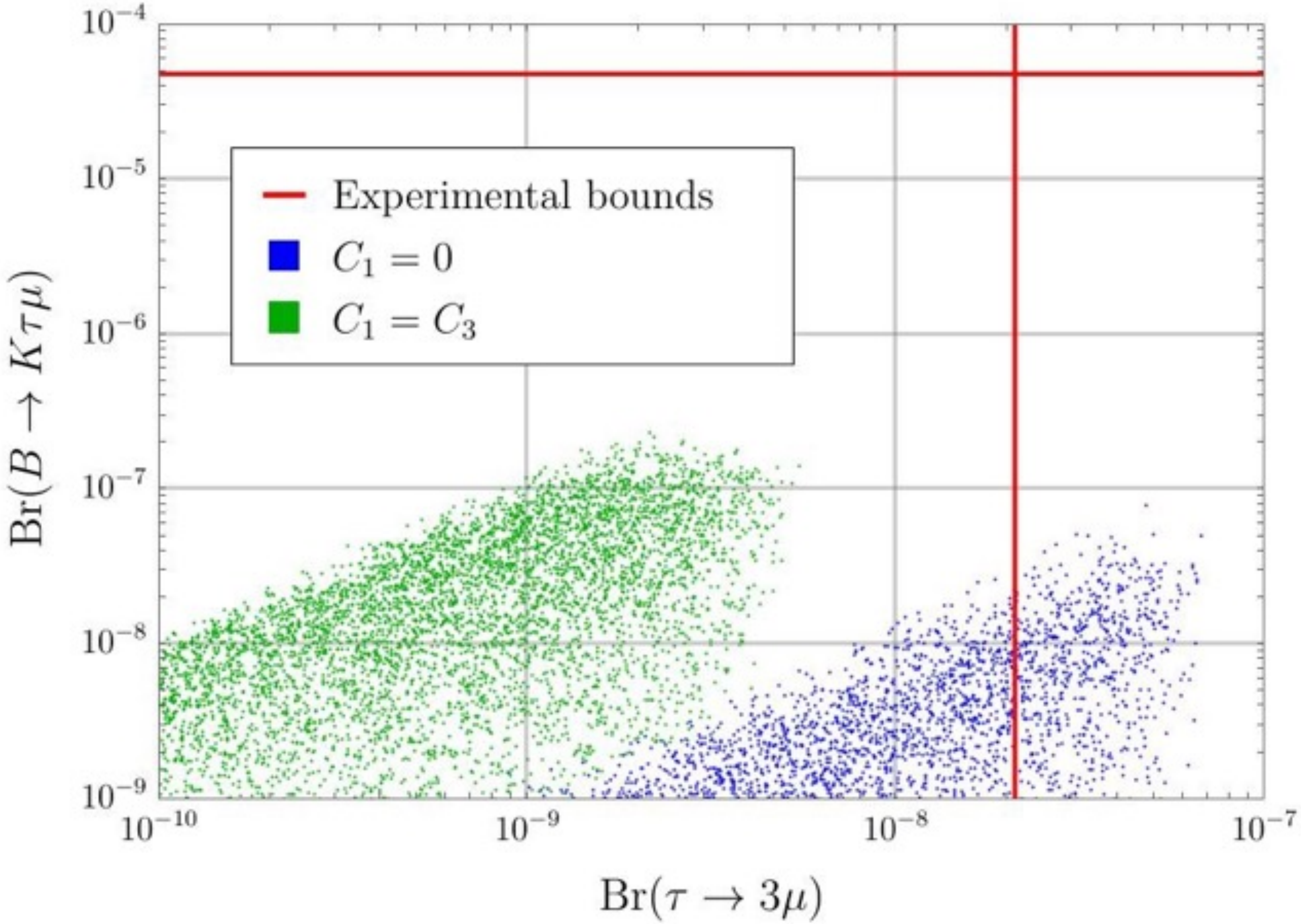
Results of the scan over the parameter space in our setup:



Simultaneous explanation of RD and RK through left-handed currents is ~~excluded~~ highly disfavoured

Results

Is $\mathcal{B}(\ B \to K\tau\mu\ )$ really <u>the</u> benchmark of these scenarios?



Scan over the parameter space, imposing:

- all discussed bounds
- R_K anomaly at 3σ
- <u>not</u> R_D

LFV τ decays are the most sensitive probes in these scenarios

What if…

- … we want to insist on LH current?

  ⇒ *Z’* models

What if…

- … we want to insist on LH current?

⇒ *Z'* models

⇒ either:

- tune additional tree-level contributions:

$$\left(\bar{\ell}_L\gamma_\mu\tau^a\ell_L\right)\left(\bar{\ell}_L\gamma_\mu\tau^a\ell_L\right)\;,\quad\left(H^\dagger\overleftrightarrow{D}^a_\mu H\right)\left(\bar{\ell}_L\gamma_\mu\tau^a\ell_L\right)$$

- very light *Z'* mass (200 - 300 GeV)

- cancellations with additional *Z''*

What if…

- … we are interested only in R_K?

⇒ LH currents not necessary:

$$\mathcal{O}_9 = \frac{\alpha}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma_\mu\ell) \qquad \mathcal{O}'_9 = \frac{\alpha}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma_\mu\ell)$$

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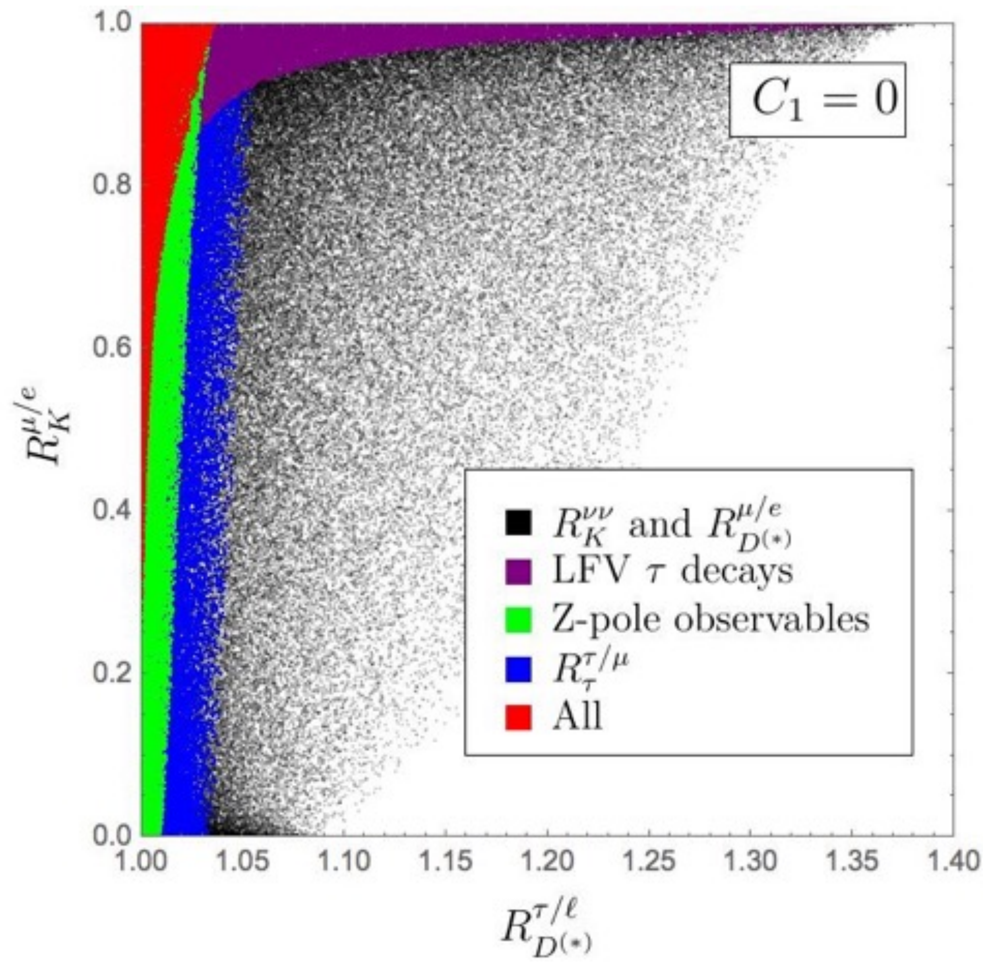
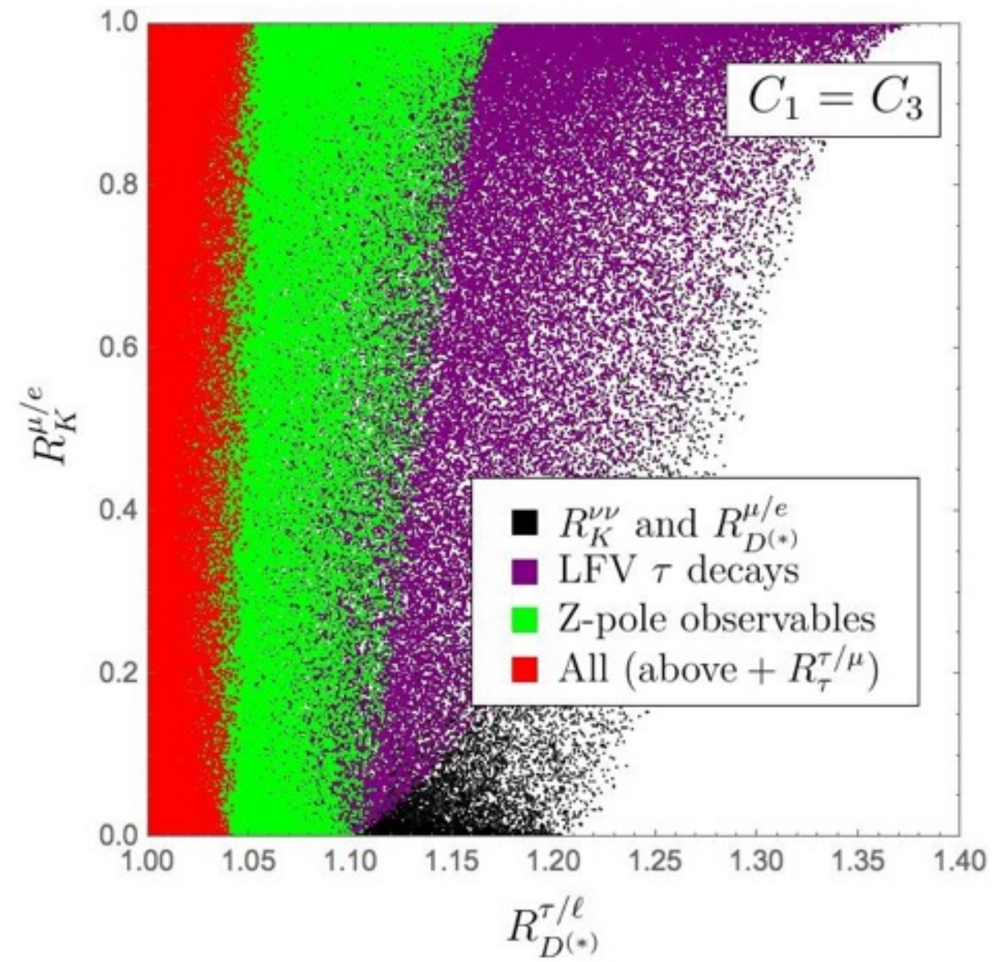
⇒ NP needed for R_K is small (compete with SM 1-loop)

⇒ loop effects are there, but not dangerous

What if…

- … we are interested only in R_D (still with LH currents)?





⇒ bounds from LFU violation are still there!

⇒ same caveats as before about Z' models

What if…

- … we are interested only in R_D (other operators)?

  ⇒ possible operators:

$$\mathcal{O}_{lq}^{(3)} = (\bar{q}_L \gamma_\mu \sigma^a q_L)(\bar{\ell}_L \gamma_\mu \sigma^a \ell_L) \qquad \mathcal{O}_{lequ}^{(1)} = (\bar{\ell}_L e_R) i\sigma^2 (\bar{q}_L u_R)$$

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  - loop effects: suppressed by lepton Yukawa ($y_\tau \approx 10^{-2}$)
  - severe bounds from high-p_T τ lepton searches at LHC

    D. Faroughy, A. Greljo, J. Kamenik, arXiv:1609.07138

  - impossible to accommodate R_K with the same operator(s)

Future perspectives

New experimental measurements coming soon:

- Updates for R_K
  - possibility to distinguish C_9 vs. C_{10}
- New measurements for $R_{D^{(*)}}$
  - independent channel (hadronic τ tagging)
- Measurement of R_{K^*}
  - more insights into the NP needed for the anomalies

Conclusions

- *B* anomalies extensively studied in literature
  - simultaneous R_K and $R_{D^{(*)}}$ explanation is appealing
  - typically achieved using LH currents
- crucial 1-loop effects in the leptonic sector
  - surprisingly overlooked so far
  - highly disfavour a LH current approach to $R_{D^{(*)}}$
  - $\tau \to 3\mu$ can be a more interesting than $B \to K\tau\mu$