A Minimal Explanation of Flavour Anomalies:

$R_{D^{(*)}}$, $R_{K^{(*)}}$, $(g\text{-}2)_\mu$ and CAA

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[D. Marzocca, ST] 2104.05730

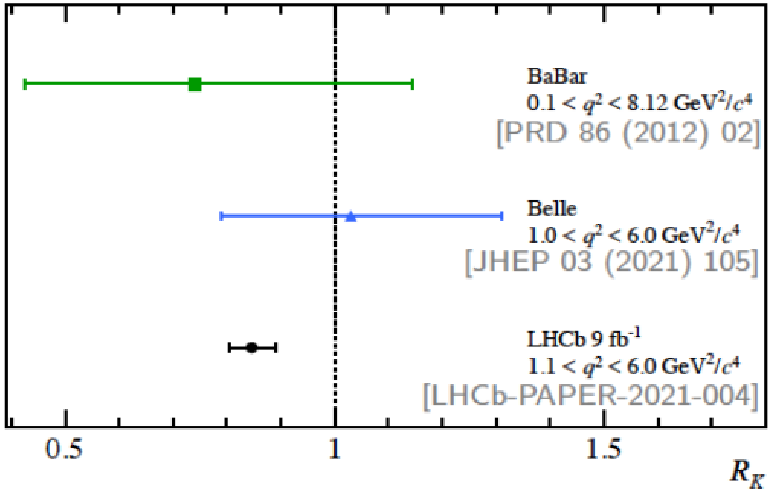
B-Physics Anomalies: neutral-current

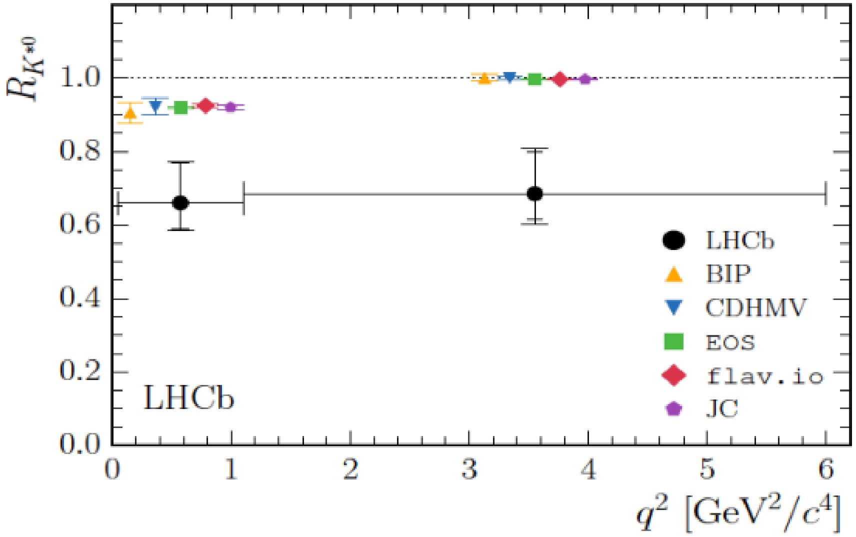
THE GOOD

- $b \to s\ell\ell$: Deficit of the charged-current transition in μ vs. e

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\overline{\mu})}{\mathcal{B}(B \to K^{(*)}e\bar{e})}$$

+ $B_s \to \mu^+\mu^-$, angular distributions of $B \to K^*\mu^+\mu^-$, various BRs





***B*-Physics Anomalies: neutral-current**

- R_K survived the latest update by the LHCb even after employing the full dataset of Run I and II independently at 3.1σ!

[LHCb] 2103.11769

- Fits obtained by varying one or two relevant NP WCs at a time yield pulls at a staggering 5σ level!

[Altmannshofer et al] 2103.13370

A recent analysis evaluated the global significant using a conservative & unbiased method and found a **global 3.9$\boldsymbol{\sigma}$** (still remarkable!)

[Lancierini et al] 2104.05631

- The anomalies implies violation of Lepton Flavor Universality (LFUV), which is an accidental symmetry of the SM.

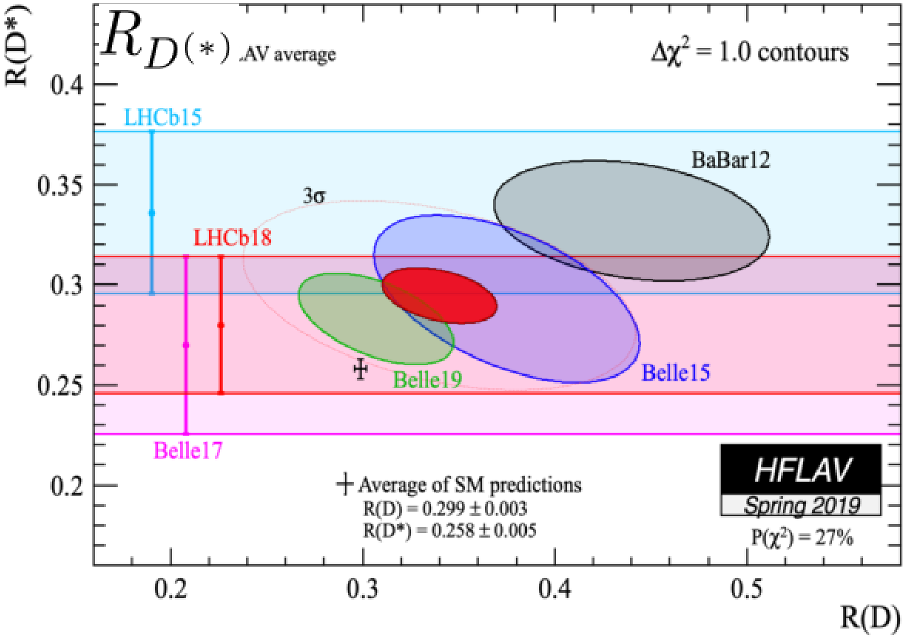
(if confirmed) definite NP signal of short-distance origin

B-Physics Anomalies: charged-current

THE (MAYBE NOT SO) GOOD

- $b \to c\tau\nu$: Enhancement of the charged-current transition in τ vs. ℓ

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\overline{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\overline{\nu})} \approx 3\sigma$$



- The results from BaBar (2012) drive mainly the CL (without it the pull is 2.2σ)
- R_D agrees with the SM in the latest Belle update, but it has never been measured by LHCb → in anticipation of an analysis?!

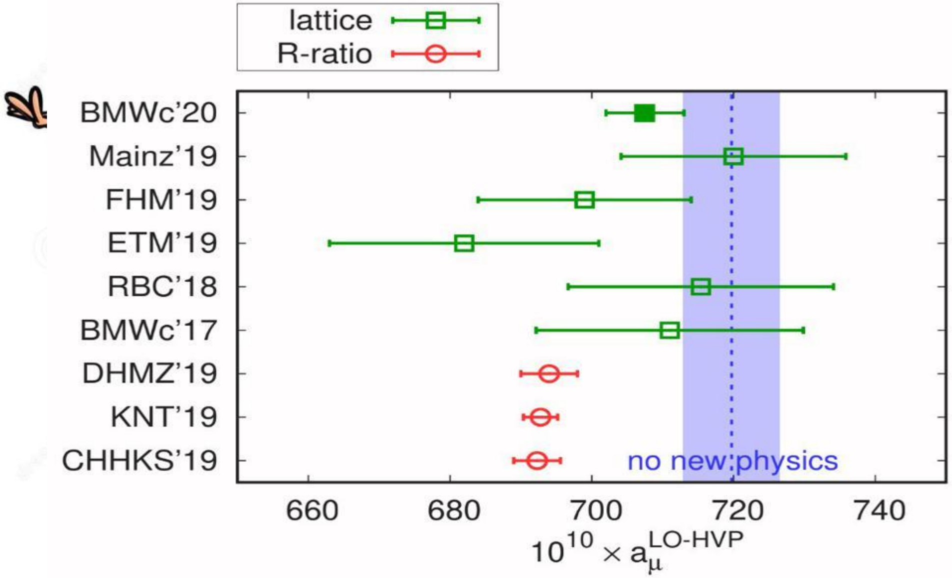
Anomalous magnetic moment of the muon

THE (NOT SO) BAD

- $(g\text{-}2)_\mu$: Deviation in the muon anomalous magnetic moment
- The longstanding BNL result was recently updated by FNAL, confirming the previous trend and increasing the significance to 4.2σ!!!

[Fermilab] 2104.03281

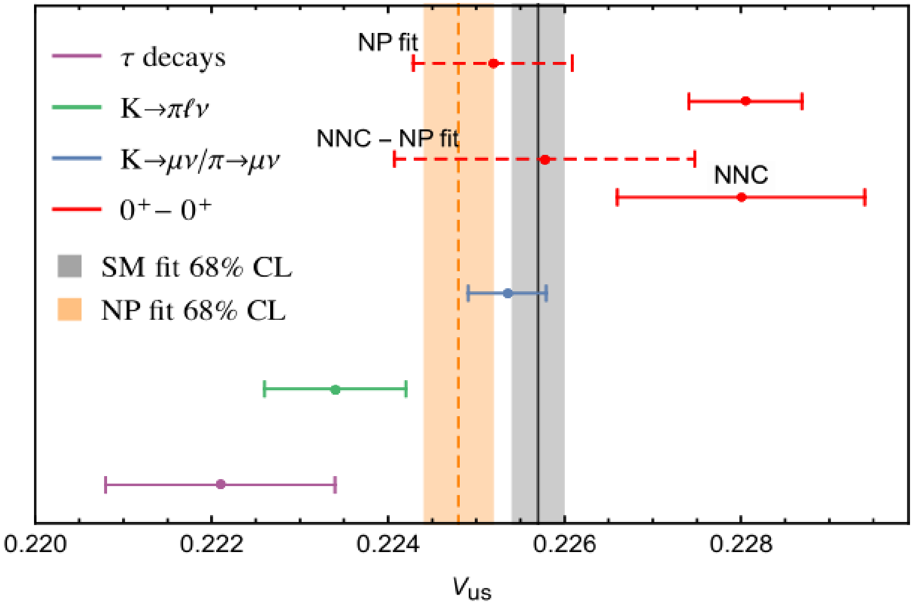
- BUT, recent lattice calculations yield SM prediction (almost) in agreement with experiment.



The Cabbibo-Angle Anomaly

AND THE UGLY

- CAA: Discrepancies between different determinations of V_{us}:



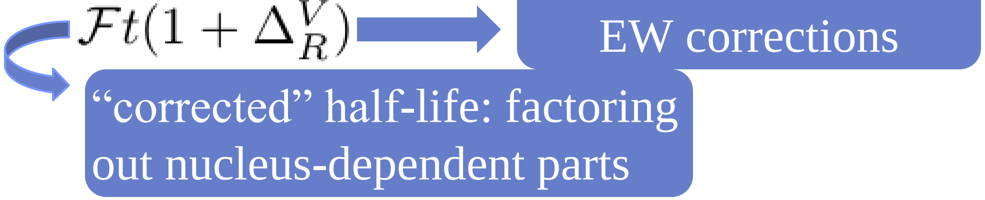
[Coutinho et al] 1912.08823

- Depending on the input from nuclear β decays we obtain 3-5σ!

[Grossman et al] 1911.07821

Excursion: nuclear *β* decays

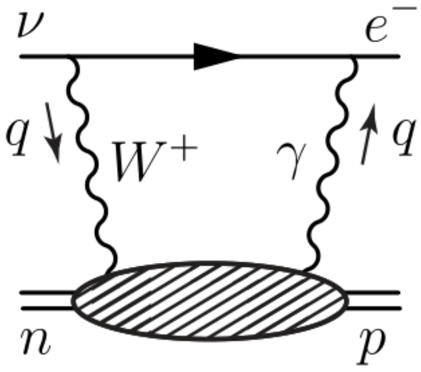
- Superallowed *β* decays are Fermi transitions (*S*=0, *ΔJ*=0) between isobaric analogue states with no parity change (*Δπ*=0).
- <u>Masterformula</u>: $|V_{ud}|^2 = \dfrac{2984.432(3)\,\mathrm{s}}{\mathcal{F}t(1+\Delta_R^V)}$



Universal contribution: EW corrections

"corrected" half-life: factoring out nucleus-dependent parts

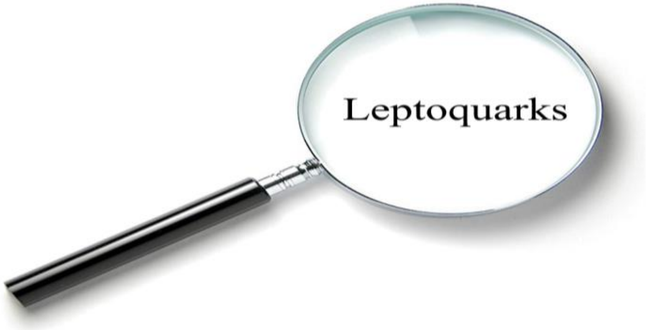
- What's **new**?



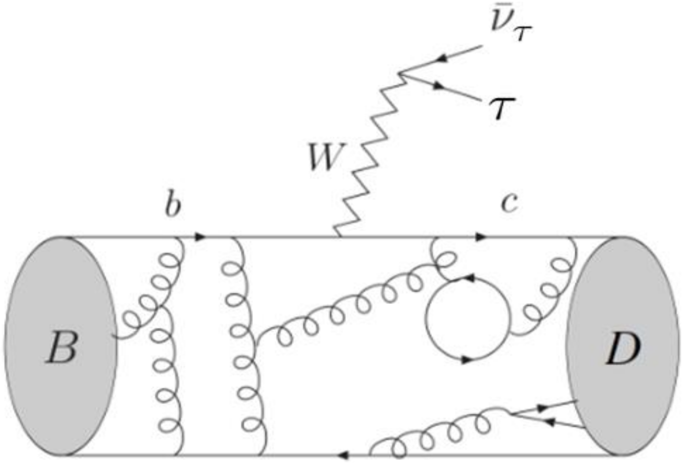
The uncertainty of Δ_R is dominated by the hadronic contribution to the $W\gamma$ box.
New analyses using dispersion relations and hybrid lattice QCD result in a shift of $|V_{ud}|$.

[Seng et al] 1812.03352, 2107.14708

[Czarnecki et al] 1907.06737



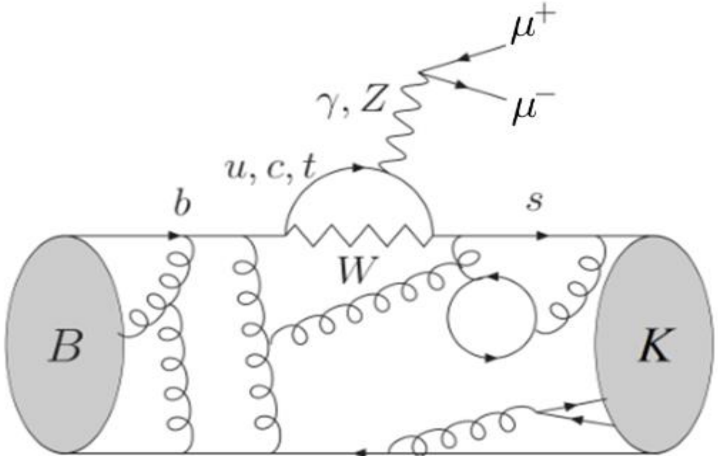
Following the trails…



- Tree-level process
- Mild CKM suppression

(presumably) tree-level NP effect induced by semi-leptonic 4-fermion opeators ⟹ Leptoquarks!

BONUS: *(g-2)*$_\mu$ with LQ chiral enhanced loops

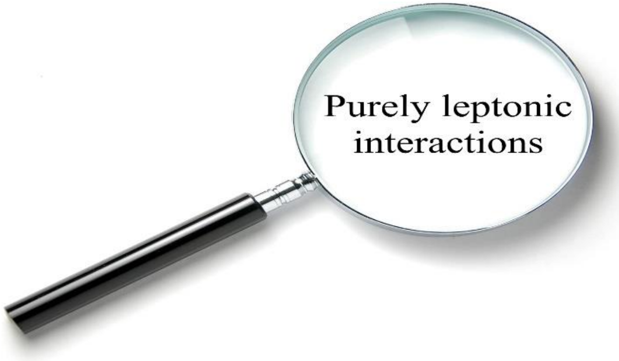


- Loop-level process
- CKM & GIM suppression

NP in (short-distance) WC of:

$$O_9^\mu = \bar{b}_L \gamma^\mu s_L \bar{\mu} \gamma_\mu \mu$$

$$O_{10}^\mu = \bar{b}_L \gamma^\mu s_L \bar{\mu} \gamma_\mu \gamma_5 \mu$$



Purely leptonic interactions

Following the trails…

- The tension between $V_{us}^{\rm CKM}$ and V_{us}^{β} can be alleviated by introducing a constructive interference in $\mu \to e\nu\nu$. In particular, one obtains:

$$V_{us}^{\beta} \equiv \sqrt{1-(V_{ud}^{\beta})^2-|V_{ub}|^2} \simeq V_{us}^{\rm CKM}\left[1+\left(\frac{V_{ud}^{\rm CKM}}{V_{us}^{\rm CKM}}\right)^2 \delta(\mu\to e\nu\nu)\right]$$

where $\delta(\ell \to \ell'\nu\nu) \equiv \mathcal{A}(\ell \to \ell'\nu\nu)_{\rm NP}/\mathcal{A}(\ell \to \ell'\nu\nu)_{\rm SM}$.

[Crivellin et al] 2012.09845

- Link between CAA and the *B*-Physics anomalies:

$$\frac{g_\tau}{g_e} = \left|\frac{1+\delta(\tau\to\mu\nu\nu)}{1+\delta(\mu\to e\nu\nu)}\right| \approx 2\sigma$$

[Feruglio et al] 1606.00524

Interplay with LQ anticipated already by the EFT analysis

The Model

- **NP particle content:** $S_1 \sim (\bar{\mathbf{3}}, \mathbf{1})_{1/3}\ , \qquad \phi^+ \sim (\mathbf{1}, \mathbf{1})_1\ .$
- The SM Lagrangian is augmented by the following Yukawa-type terms

$$\mathcal{L}_{S1+\phi} = \frac{1}{2}\lambda_{\alpha\beta}\bar{\ell}^c_\alpha \epsilon \ell_\beta \phi^+ + \lambda^{1L}_{i\alpha}\bar{q}^c_i \epsilon \ell_\alpha S_1 + \lambda^{1R}_{i\alpha}\bar{u}^c_i e_\alpha S_1 + \text{h.c.}$$

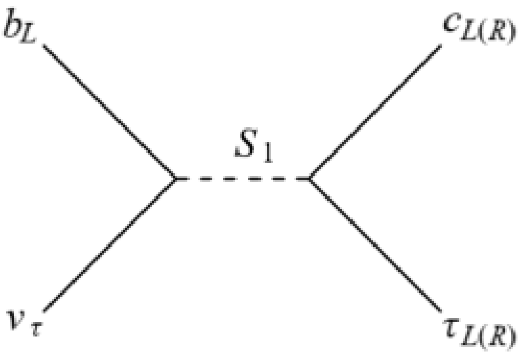
- We employ the following couplings:

$$\lambda \approx \begin{pmatrix} 0 & \lambda_{12} & \xcancel{\lambda_{13}} \\ -\lambda_{12} & 0 & \lambda_{23} \\ -\xcancel{\lambda_{13}} & -\lambda_{23} & 0 \end{pmatrix}, \quad \lambda^{1L} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & \xcancel{\lambda^{1L}_{s\mu}} & \lambda^{1L}_{s\tau} \\ 0 & \lambda^{1L}_{b\mu} & \lambda^{1L}_{b\tau} \end{pmatrix}, \quad \lambda^{1R} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & \lambda^{1R}_{c\mu} & \lambda^{1R}_{c\tau} \\ 0 & \lambda^{1R}_{t\mu} & \xcancel{\lambda^{1R}_{t\tau}} \end{pmatrix}.$$

$\mu \to e\gamma$

$\tau \to \mu\gamma$

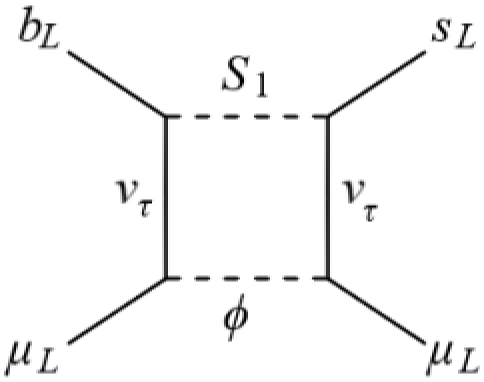
Solution to the Anomalies (diagrams)



- $b \to c\tau\nu$:

$$R_D \approx 0.299 - 0.235\frac{\lambda^{1L}_{b\tau}\lambda^{1R}_{c\tau}}{m_1^2}\left(1 + 0.05\log m_1^2\right)$$

$$R_{D^*} \approx 0.258 - 0.088\frac{\lambda^{1L}_{b\tau}\lambda^{1R}_{c\tau}}{m_1^2}\left(1 + 0.02\log m_1^2\right)$$



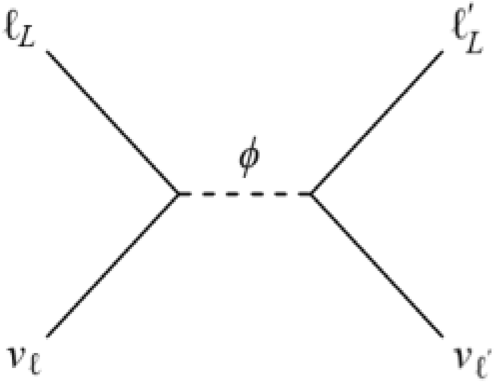
- $b \to s\ell\ell$: $\Delta C^{\mu}_{9,10} = (C_{LR} \pm C_{LL})/(2N_{sb})$

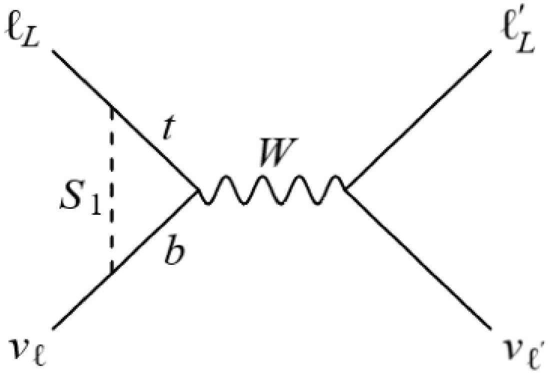
$$C_{LL} \approx -\lambda^{1L}_{b\tau}\lambda^{1L\,*}_{s\tau}\left(\frac{|\lambda^{1L}_{b\mu}|^2}{64\pi^2 M_1^2} + \frac{|\lambda_{\mu\tau}|^2\log M_1^2/M_\phi^2}{64\pi^2(M_\phi^2 - M_1^2)}\right)$$

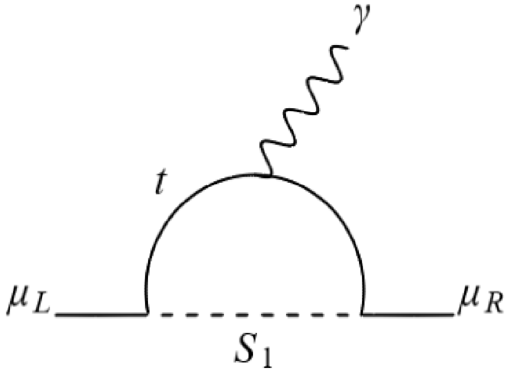
$$C_{LR} \approx -\frac{|\lambda^{1R}_{c\mu}|^2\lambda^{1L}_{b\tau}\lambda^{1L\,*}_{s\tau}}{64\pi^2 M_1^2}$$

Solution to the Anomalies (diagrams)

- CAA: $\delta(\mu \to e\nu\nu) \approx \frac{v^2|\lambda_{12}|^2}{4M_\phi^2} + \frac{3m_t^2|\lambda^{1L}_{b\mu}|^2}{32\pi^2 M_1^2}\left(\frac{1}{2} - \log\frac{M_1^2}{m_t^2}\right)$





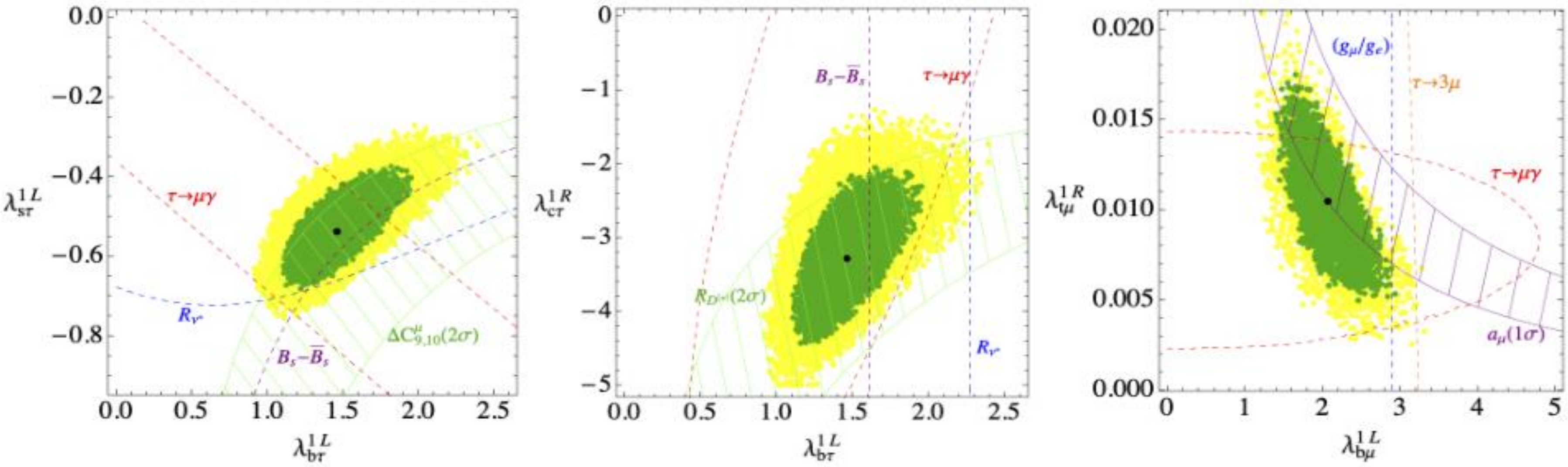


- *(g-2)$_\mu$:*

$$\Delta a_\mu \approx \frac{m_\mu m_t \lambda^{1L}_{b\mu}\lambda^{1R}_{t\mu}}{4\pi^2 M_1^2}\left(\log M_1^2/m_t^2 - \frac{7}{4}\right)$$

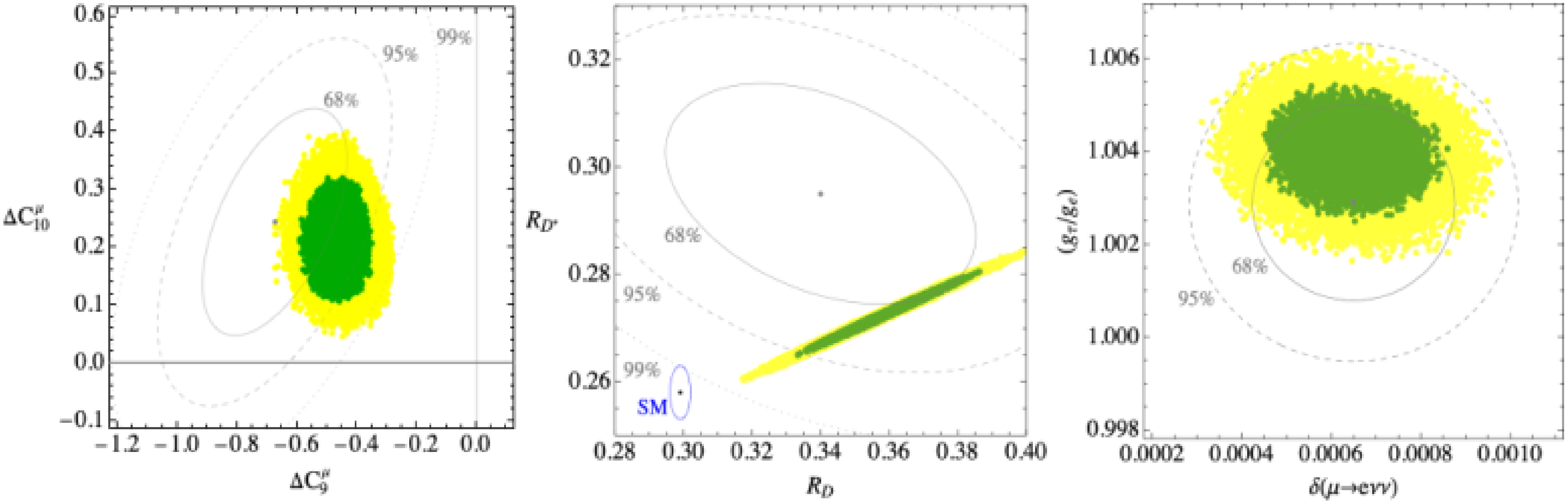
Model parameter space (at 2σ exclusion)

- We perform a χ^2 **minimization** with fixed masses, $M_1 = M_\phi = 5.5\mathrm{TeV}$.



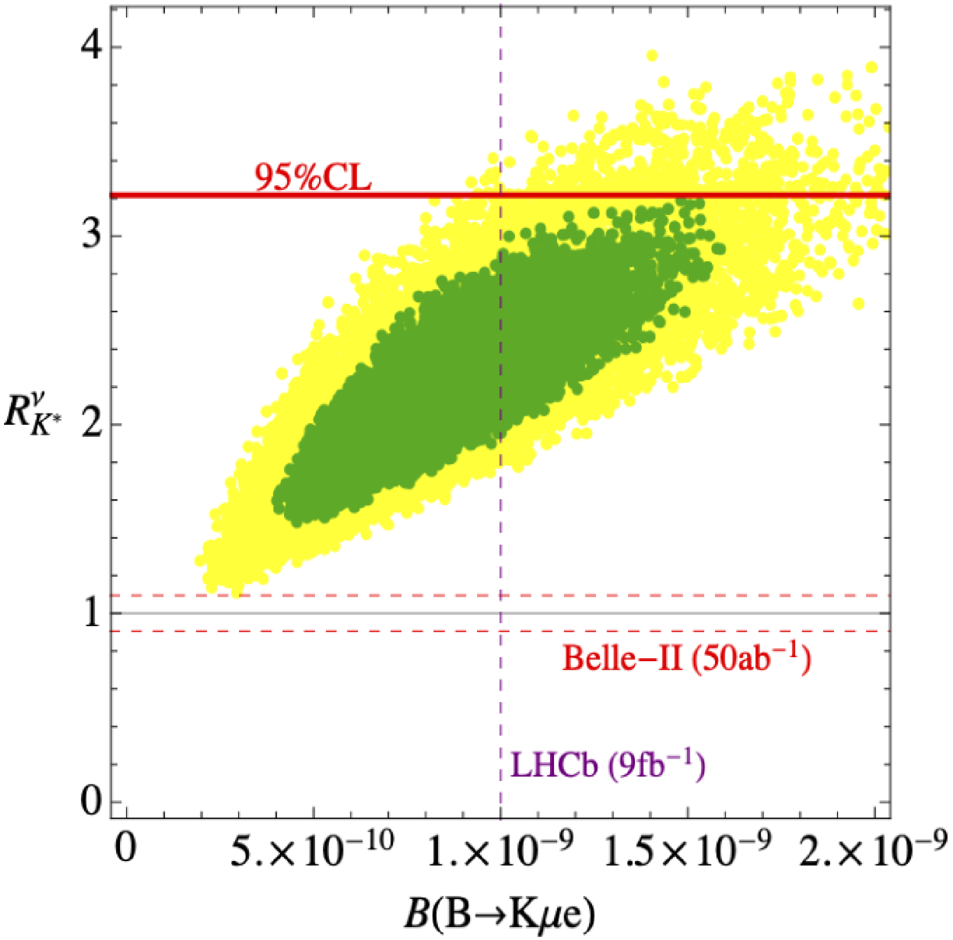
Solution to the Anomalies (fit)

$$\chi^2_{\rm SM} - \chi^2_{\rm best-fit} = 82$$



Future Prospects I

- The preferred region is close to B_s-mixing and $B \to K^{(*)}\nu\nu$ present bounds due to S_1 contributions.
- Unique signatures: $B \to K\mu e$ and $B_s \to \mu e$ (similar box that fixes C_9 & C_{10})
- No effects to $b \to s\tau\tau$.



Future Prospects II

- LFU ratios in τ decays (φ^+ at tree-level + S_1 at one-loop) :
  $\frac{g_\tau}{g_e}$ $\frac{g_\tau}{g_\mu}$ and $\frac{g_\mu}{g_e}$.
- LFV τ decays: $\tau \longrightarrow \mu\gamma$, $\tau \longrightarrow 3\mu$ and $\tau \longrightarrow \mu ee$ (via S_1 at one-loop)
  $\tau \longrightarrow e\gamma$, $\tau \longrightarrow 3e$ and $\tau \longrightarrow e\mu\mu$ (via φ^+ at one-loop)

  Belle-II
  & LHCb
- Masses too large for direct searches at LHC (maybe effects in high-energy tails of Drell-Yan). Ideal machines: FCC-hh for S_1 and a muon collider for φ^+.

Model-independent Prospects

- **Final verdict** on *B*-Physics anomalies: Belle-II with ~20ab^{-1}
- *(g-2)*$_\mu$ runs 2&3 already completed → statistical error will soon shrink further!
- CAA: (*theory*) advance understanding of the EW radiative corrections

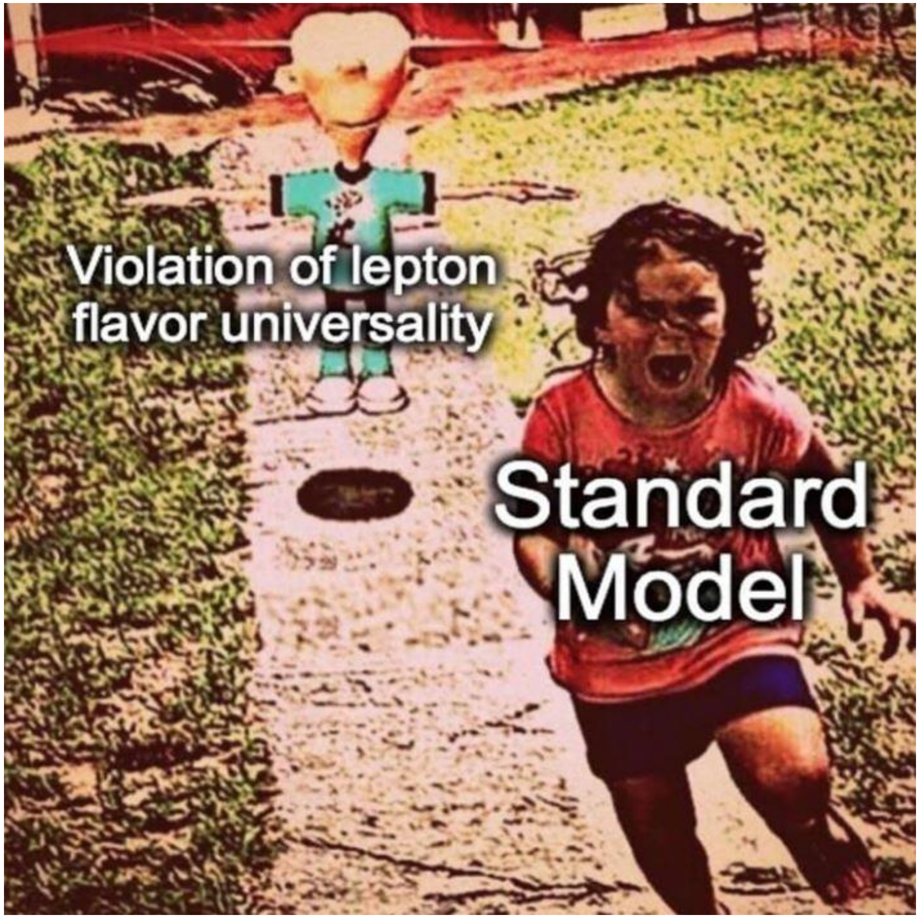
  (*exeriment*) improvement on $K \rightarrow \pi \ell \nu$ (LHCb, NA62, TREK etc.) & $K \rightarrow \mu\nu / K \rightarrow e\nu$ (J-PARC E36)

  Additionally, complementary observables can become competitive e.g. pion β decays $\pi^{\pm} \rightarrow \pi^0 e^{\pm} \nu_e$, neutron lifetime etc.

Conclusions

- Model-building invitation: Good reasons to consider all four major (>3σ) deviations from the SM in Flavour physics under the same NP (LFUV) framework.
- In this work we provide the first combined solution, respecting the rich set of phenomenological constraints.
- The particle content of the model ($S_1 + \varphi^+$) is (most probably) **the most minimal** one that can achieve this.
  Additionally, it features both LQ and purely leptonic interactions (=fresh new *market* direction vs the LQ *monopolies*).
- Many new and old interesting signatures (or model killers..)

Thank you!!!!

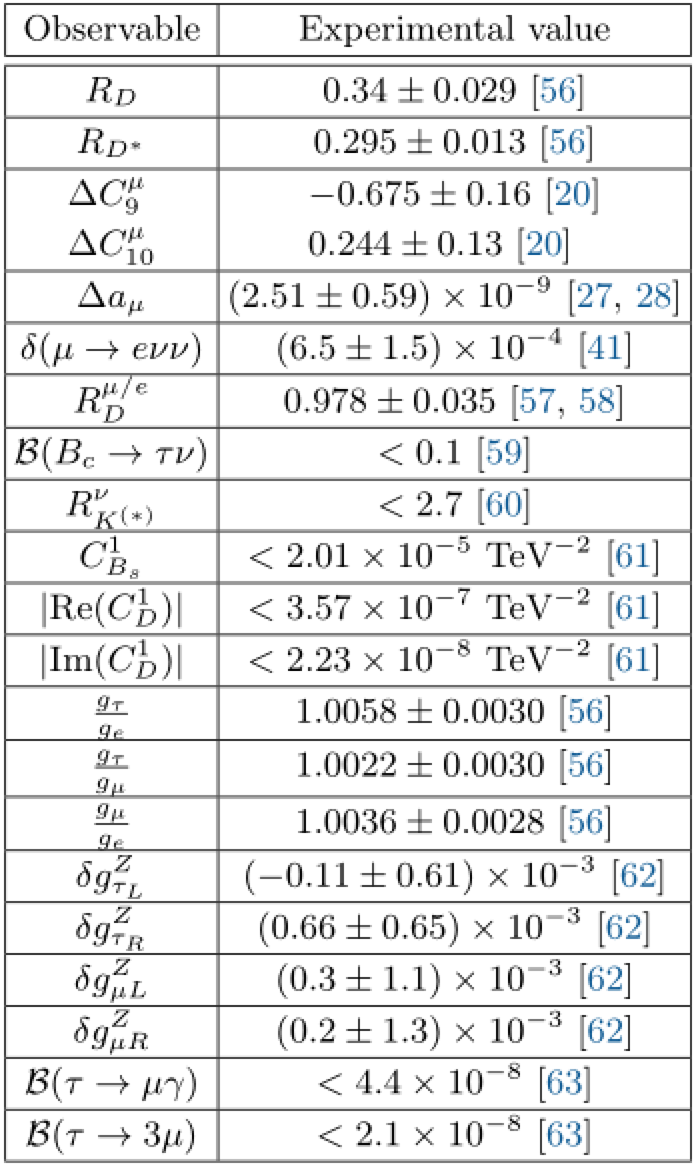


@largememecollider

QUESTIONS ???

Backup slides

Constraints:



Observable	Experimental value
R_D	0.34 ± 0.029 [56]
R_{D^*}	0.295 ± 0.013 [56]
ΔC_9^μ ΔC_{10}^μ	-0.675 ± 0.16 [20] 0.244 ± 0.13 [20]
Δa_μ	$(2.51 \pm 0.59) \times 10^{-9}$ [27, 28]
$\delta(\mu \to e\nu\nu)$	$(6.5 \pm 1.5) \times 10^{-4}$ [41]
$R_D^{\mu/e}$	0.978 ± 0.035 [57, 58]
$\mathcal{B}(B_c \to \tau\nu)$	< 0.1 [59]
$R_{K^{(*)}}^\nu$	< 2.7 [60]
$C_{B_s}^1$	$< 2.01 \times 10^{-5}\ \text{TeV}^{-2}$ [61]
$\lvert\text{Re}(C_D^1)\rvert$	$< 3.57 \times 10^{-7}\ \text{TeV}^{-2}$ [61]
$\lvert\text{Im}(C_D^1)\rvert$	$< 2.23 \times 10^{-8}\ \text{TeV}^{-2}$ [61]
$\frac{g_\tau}{g_e}$	1.0058 ± 0.0030 [56]
$\frac{g_\tau}{g_\mu}$	1.0022 ± 0.0030 [56]
$\frac{g_\mu}{g_e}$	1.0036 ± 0.0028 [56]
$\delta g_{\tau_L}^Z$	$(-0.11 \pm 0.61) \times 10^{-3}$ [62]
$\delta g_{\tau_R}^Z$	$(0.66 \pm 0.65) \times 10^{-3}$ [62]
$\delta g_{\mu L}^Z$	$(0.3 \pm 1.1) \times 10^{-3}$ [62]
$\delta g_{\mu R}^Z$	$(0.2 \pm 1.3) \times 10^{-3}$ [62]
$\mathcal{B}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$ [63]
$\mathcal{B}(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$ [63]

- Best-fit point:

$$\lambda_{e\mu} = 1.35\ , \quad \lambda_{\mu\tau} = 3.17\ ,$$
$$\lambda_{b\tau}^{1L} = 1.46\ , \quad \lambda_{s\tau}^{1L} = -0.54\ , \quad \lambda_{b\mu}^{1L} = 2.07\ ,$$
$$\lambda_{c\tau}^{1R} = -3.28\ , \quad \lambda_{t\mu}^{1R} = 0.01\ , \quad \lambda_{c\mu}^{1R} = 2.35\ .$$

(Wild) speculations

- The LQ S_1 and φ^+ share the quantum numbers of the right-handed sbottom and stau, respectively.
- The NP couplings λ and λ^{1L} would correspond then to the couplings λ and λ' of the RPV superpotential. The right-handed couplings λ^{1R} can only generated from non-holomorphic RPV terms.

[Trifinopoulos] 1904.12940

- Hint towards a RPV scenario with lighter 3rd generation superpartners?
- λ and λ^{1L} follow the $U(2)$ flavour symmetry that respects $SU(5)$ unification. λ^{1R} is more peculiar, but since it originates from a hidden sector maybe there is a flavourful dynamical way to reproduce the observed structure.

[Csaki et al] 1309.5957