LUV / LFV in meson and baryon decays
– TH overview –

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Overview

- *Models explaining b → s and b → c data*
- *Which of these models also predict LFV*
- *New observables*
- *LUV / LFV in Kaon decays*

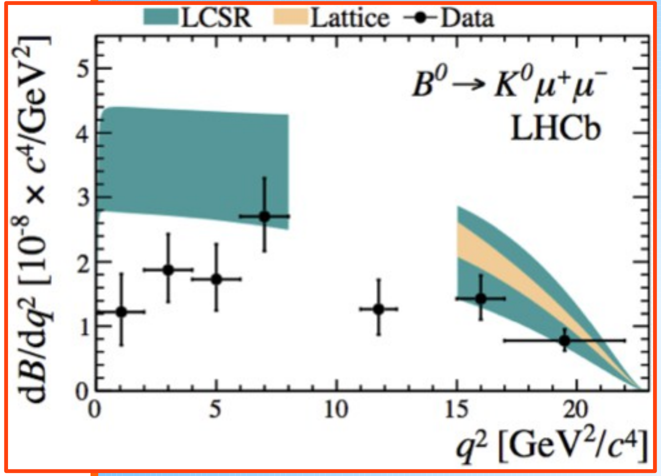
Collider Data

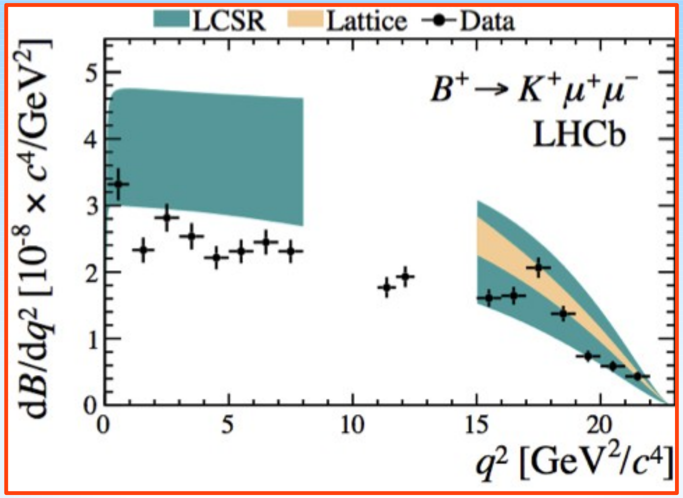
- *No direct evidence of BSM at colliders*
- *A coherent set of discrepancies in B decays*

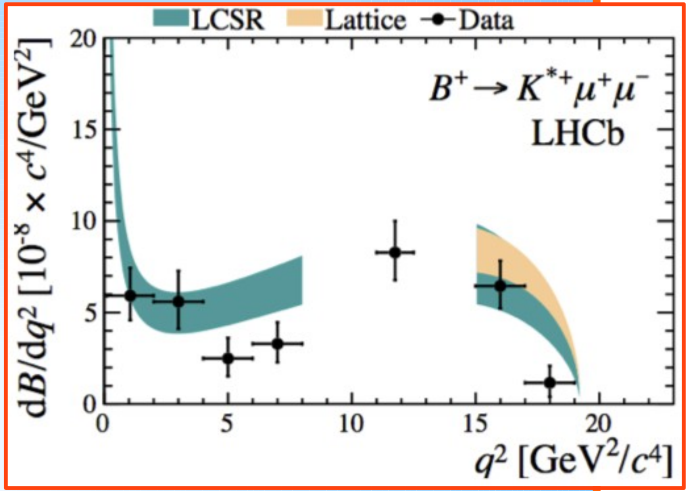
❶ *$b \to s\, \mu\mu$ BR data < SM*

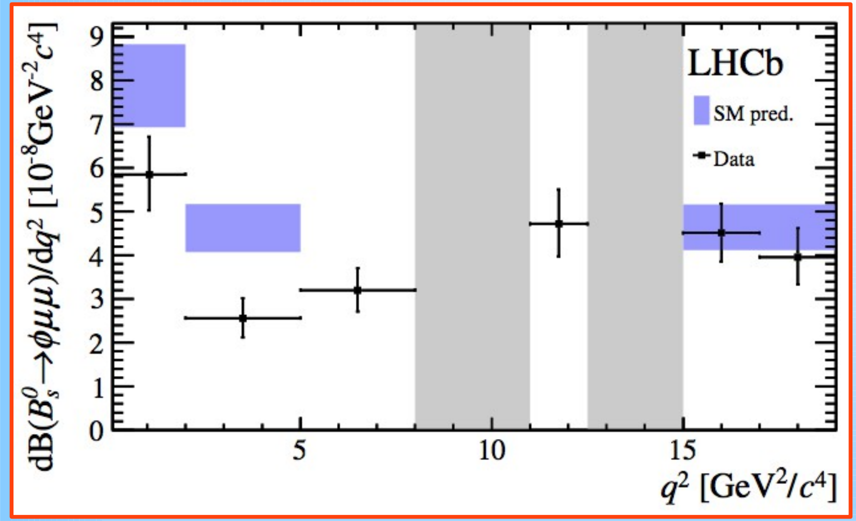
Challenge: B → light meson f.f.'s

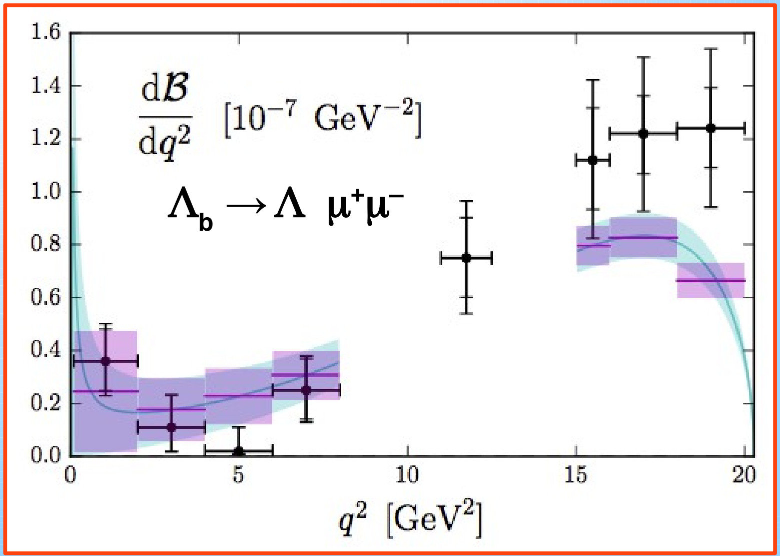
$b \to s\,\mu\mu$ BR data < SM











Collider Data

- *No direct evidence of BSM at colliders*
- *A coherent set of discrepancies in B decays*

❶ $b \to s \mu\mu$ *BR data < SM*

Challenge: B → light meson f.f.'s

❷ $B \to K^* \mu\mu$ *angular data*

Challenge: charm loops

❸ $b \to s \mu\mu$ / $b \to s\, ee$ *ratios*

Challenge: (mostly) stats

loop processes

❹ $b \to c\, \tau\nu$ / $b \to c\, \ell\nu$ *ratios*

Challenge: stats + syst

tree processes

Combined TH explanations

- *Taken together, the above datasets display a remarkable degree of coherence*

- *From a BSM perspective, natural to expect modifications in both $b \to s$ and $b \to c$ datasets (related by the SM $SU(2)_L$ symmetry)*

- *The only (known) viable, simultaneous, single-mediator explanation of all datasets is the U_1 leptoquark*

Note: *here "single-mediator" refers to the mediator(s) entering the amplitudes for R_K and R_D. From a UV-complete perspective, the U_1 can hardly come alone.*

Non-U1-LQ-alone TH explanations

Many models offering alternative R_K & R_D explanations exist, but mostly use ≥ 1 mediators

LQs other than the U_1 alone

[Marzocca, 1803.10972; Popov+, 1905.06339; Bigaran+, 1906.01870; Balaji+,1911.08873; Crivellin+, 1912.04224; Saad+, 2004.07880; Bhupal Dev+, 2004.09464; Saad, 2005.04352; Kowalska+, 2007.03567; Gherardi+,2008.09548]

Non-LQ scalar / vector sectors

[Boucenna+, 1608.01349; Li+, 1807.08530; Marzo+, 1901.08290; Borah+, 2007.13778; Babu+, 2009.01771]

x-dims

[Megias+, 1707.08014; Blanke-Crivellin, 1801.07256]

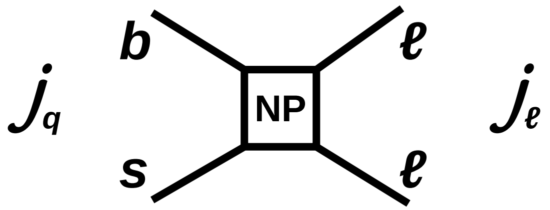
RPV SUSY

[Trifinopoulos, 1904.12940; Altmannshofer+, 2002.12910]

Why LeptoQuarks

- $R_K \approx 0.85$

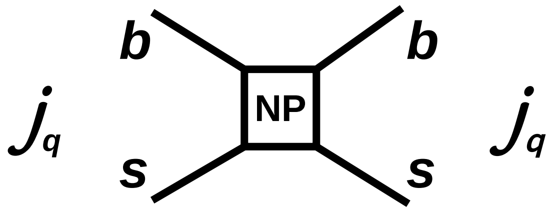
O(15%) effects in



At the same time:

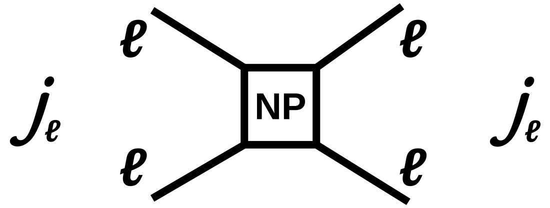
- $\Delta M_s \approx (\Delta M_s)_{SM}$

small corrections to



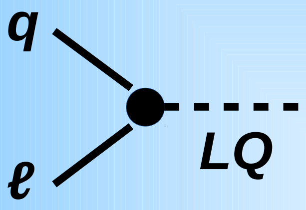
- $\ell \to \ell' + X$
  < *current limits*

and small corrections to

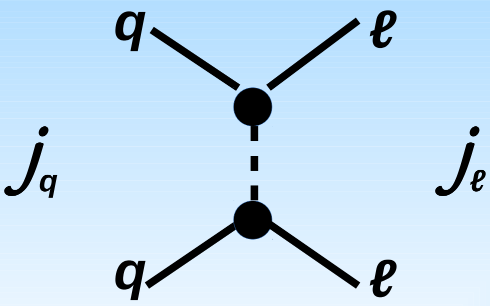


Why LeptoQuarks

Take

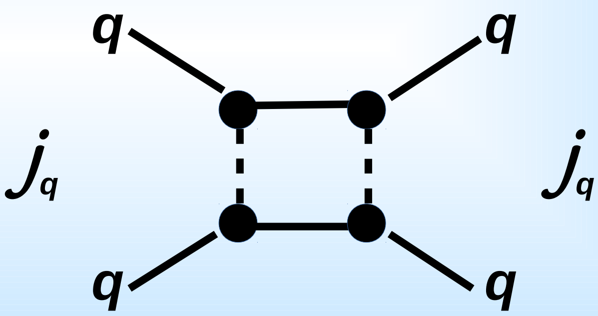


then



is tree

but



is loop-suppressed

(at least for “genuine” LQs [Dorsner et al., ‘16, Davidson et al., ‘93])

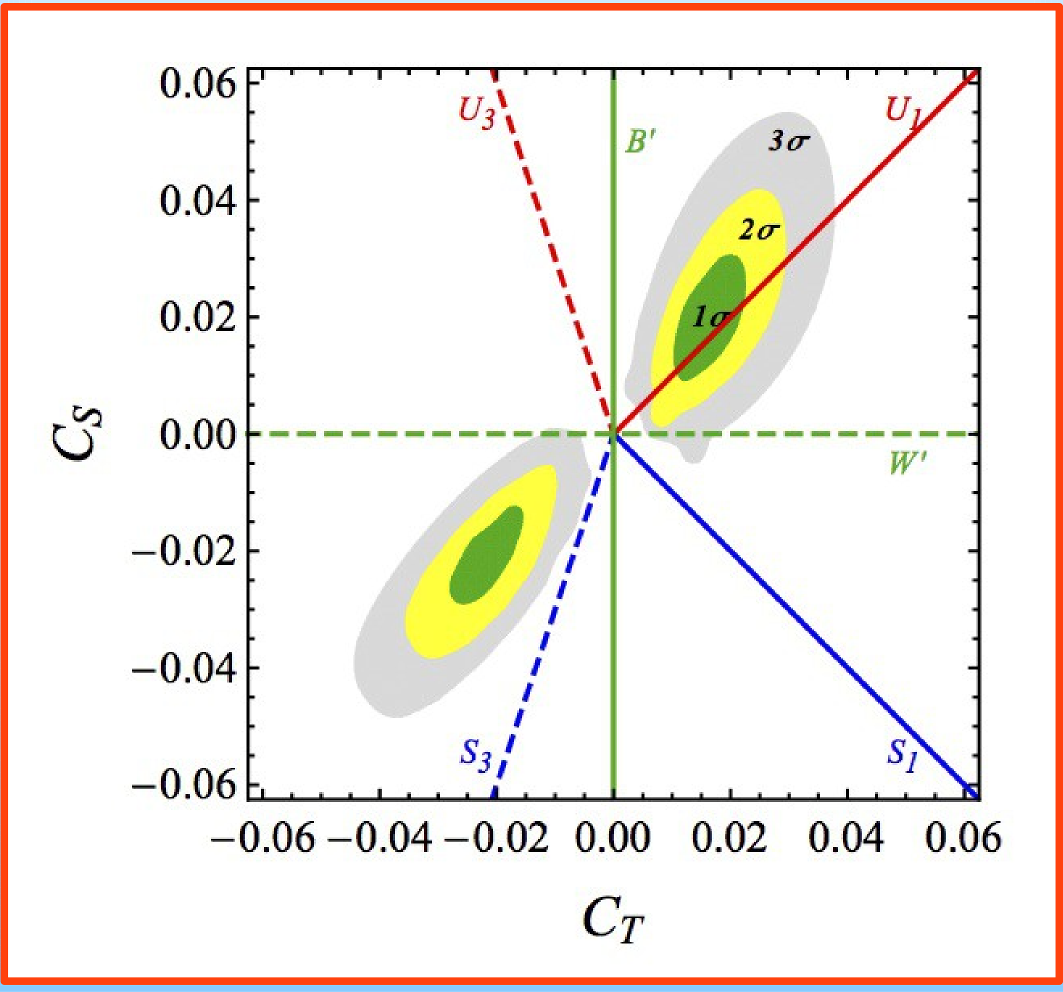
The U_1 LQ

- It was realized that the vector *LQ* $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$

  [*Alonso, Grinstein, Martin-C, 1407.7044; Calibbi, Crivellin, Ota, 1506.02661*]

  would simultaneously explain all B discrepancies

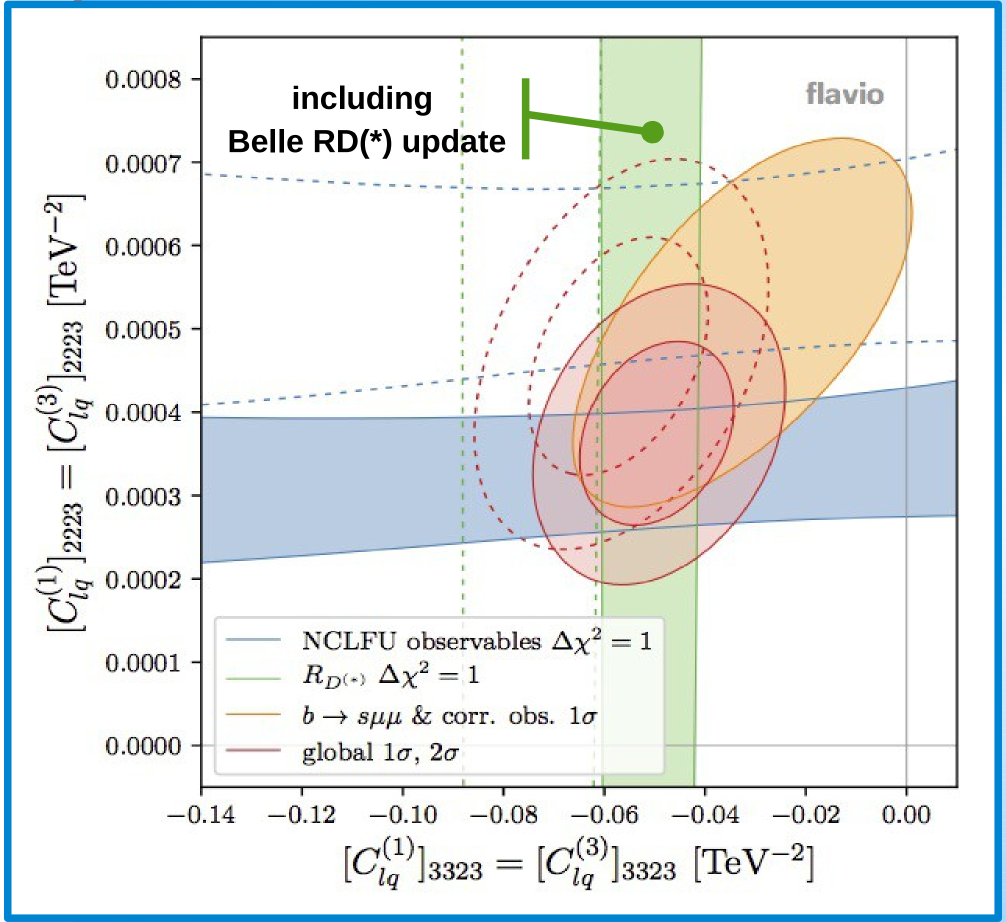
  [*Buttazzo, Greljo, Isidori, Marzocca, 1706.07808*]

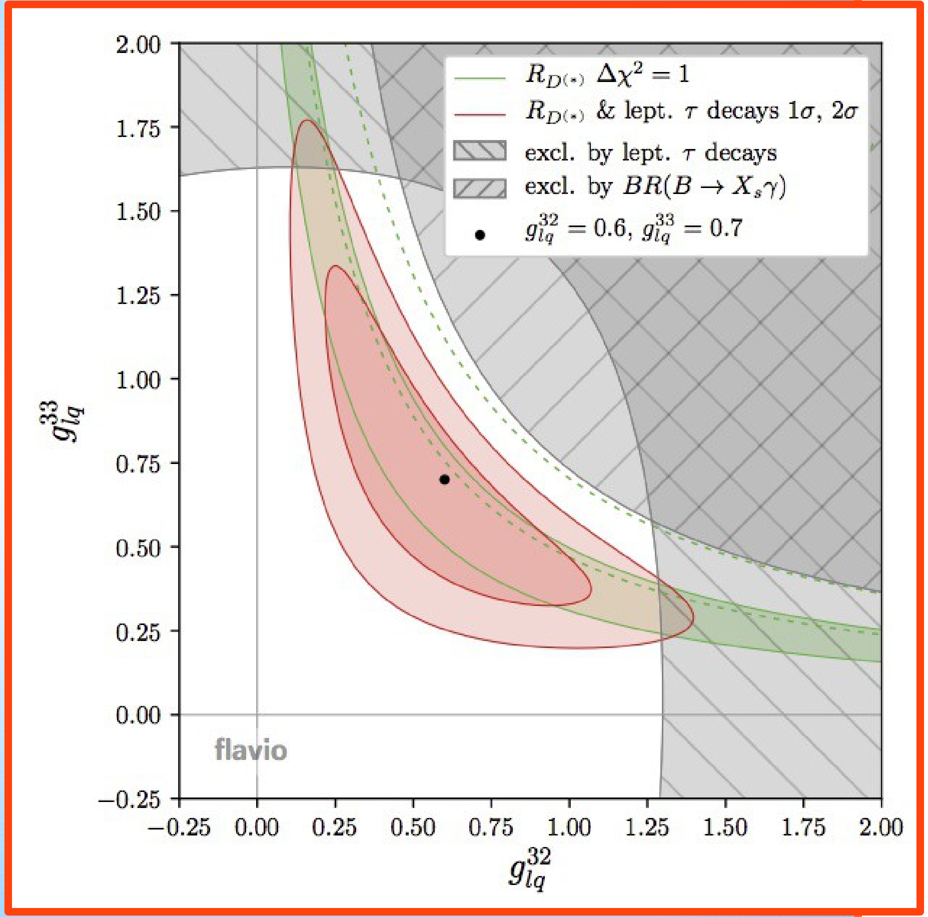


The U_1 LQ

- This explanation has become even more consistent with recent data

[*Aebischer et al., 1903.10434*]


including Belle RD(*) update



The U_1 LQ and UV completions

- As a massive vector boson, the U_1 requires a UV completion

as

- a composite vector boson [*Barbieri, Murphy, Senia , 1611.04930*]
- a gauge boson of a spont.-broken gauge sym.

Pati-Salam's *"Lepton number as the 4th color"* natural starting point

Problem: push the scale of RH currents up, but not the U_1 scale

- Consider $SU(4) \times SU(3)' \times SU(2)_L \times U(1)_X$

[*Georgi, Nakai , 1606.05865*][*Diaz, Schmaltz, Zhong, 1706.05033*]
[*Di Luzio, Greljo, Nardecchia, 1708.08450*]

The SM arises after

$$SU(4) \times SU(3)' \times U(1)_X \longrightarrow SU(3)_c \times U(1)_Y$$

Which models also predict LFV?

Any of them, unless the dynamics responsible for LUV implies some symmetry that prevents LFV

Model zero

- *All b → s data are explained at one stroke if one assumes*
  - $(V-A)_q \times (V-A)_\ell$ *structure*
  - *with Wilson-coeff. shift much larger for* $\mu\mu$ *than for ee*

- *Such pattern can be obtained from a purely 3rd-generation interaction of the kind* [Glashow *et al.*, 1411.0565]

$$H_{\mathrm{NP}} = G \left(\bar{b}'_L \gamma^\lambda b'_L\right) \left(\bar{\tau}'_L \gamma_\lambda \tau'_L\right)$$

with $G = 1/\Lambda^2_{\mathrm{NP}} \ll G_F$

Model zero

- ***Note:*** *primed fields in* $H_{\mathrm{NP}} = G\left(\bar{b}'_L \gamma^\lambda b'_L\right)\left(\bar{\tau}'_L \gamma_\lambda \tau'_L\right)$
  - *Above the EWSB scale, fields are in the "gauge" basis, not the mass eigenbasis*
  - *Mass-basis unitary transformations induces LUV and LFV effects*

mass basis

$$\begin{aligned} b'_L &\equiv (d'_L)_3 = \left(U^d_L\right)_{3i} \boxed{(d_L)_i} \\ \tau'_L &\equiv (\ell'_L)_3 = \left(U^\ell_L\right)_{3i} \boxed{(\ell_L)_i} \end{aligned}$$

- *One can then parametrically relate measured LUV ($R_{K(*)}$) to LFV decays such as* $B \to (K)\, \tau\mu$ [Glashow *et al.*, 1411.0565]

$$BR\left(B^+ \to K^+ \ell_1^\pm \ell_2^\mp\right) \simeq \overset{\textbf{= 2\%}}{\boxed{2\frac{\left(\sqrt{R_K}-1\right)^2}{R_K}}} \cdot \mathrm{func.}\left(U^\ell_L \text{ ratios}\right) \cdot \overset{\textbf{= 4×10}^{-7}}{\boxed{BR\left(B^+ \to K^+ \mu\mu\right)}}$$

⇨ *BRs ~ 10^{-8} expected, for generic choices of U matrices*

Lepton-decay LFV

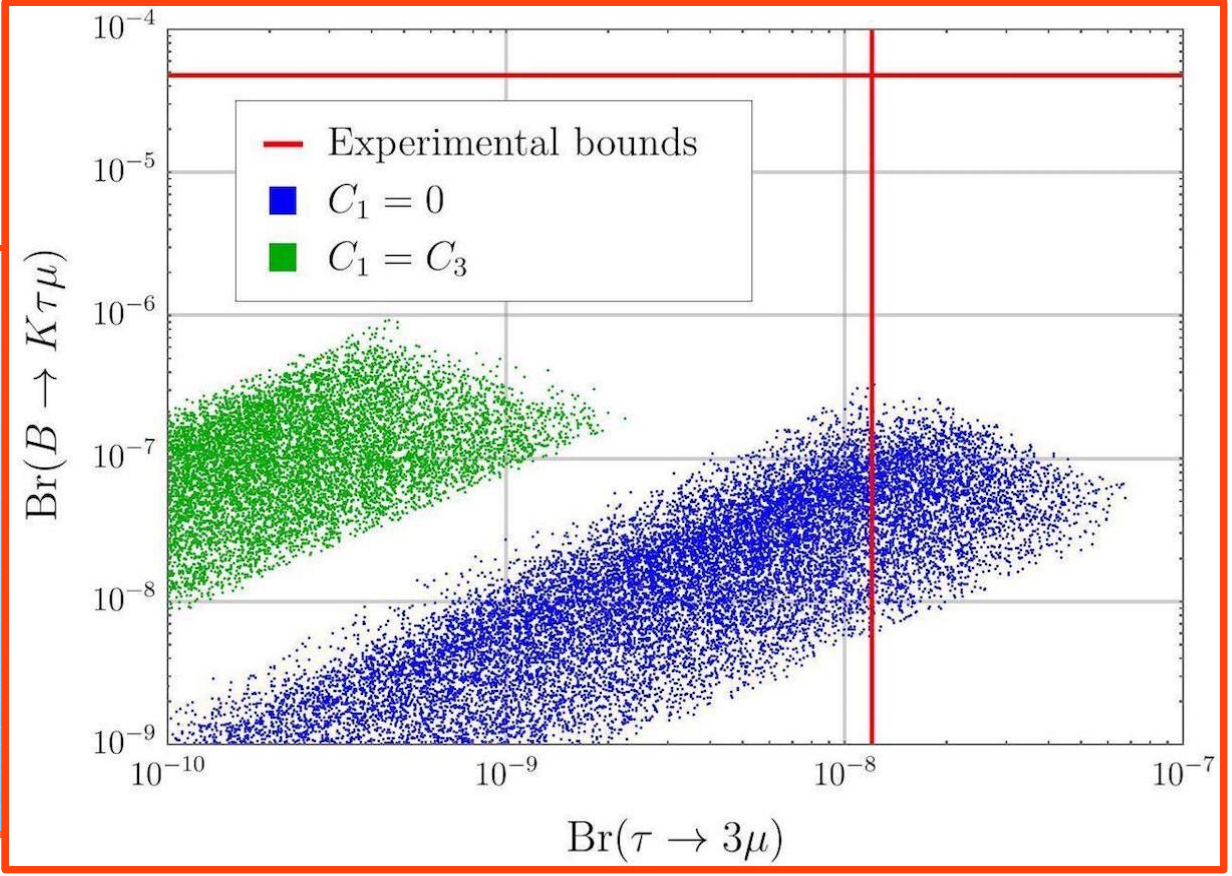
[Feruglio, Paradisi, Pattori, '16, '17]

- *Actually certain LFV decays represent strong constraints*

- *Given, at the UV matching scale*

$$\mathcal{L}^0_{NP}(\Lambda) = \frac{1}{\Lambda^2}\left(C_1\ \bar{q}'_{3L}\gamma^\mu q'_{3L}\ \bar{\ell}'_{3L}\gamma_\mu \ell'_{3L} + C_3\ \bar{q}'_{3L}\gamma^\mu \tau^a q'_{3L}\ \bar{\ell}'_{3L}\gamma_\mu \tau^a \ell'_{3L}\right)$$

close the quark loop
& attach a gauge boson
→ two further leptons



LFV in explicit UV-complete models

- *It was shown that explicit UV-complete constructions of the U_1 LQ generally predict B-decay LFV while fulfilling lept.-LFV limits*
- *Example:*
  PS^3 models, in the IR reducing to 4321 models, i.e. yielding the U_1 LQ
- *Unambiguous prediction: large $\tau \to \mu$ effective coupling due to assumed $U(2)^5$ flavor sym, and its breaking pattern*

[Bordone, Cornella, Fuentes-M, Isidori, *'18*]

$$\mathcal{B}(B_s \to \tau^+\mu^-) \approx 2 \times 10^{-4} \left(\frac{\Delta R_K}{0.3}\right)^2 \left(\frac{0.1}{s_\tau}\right)^2 ,$$

$$\mathcal{B}(B \to K^*\tau^+\mu^-) \approx 1.5 \times 10^{-6} \left(\frac{\Delta R_K}{0.3}\right)^2 \left(\frac{0.1}{s_\tau}\right)^2 ,$$

$$\mathcal{B}(B^+ \to K^+\tau^+\mu^-) \approx 2 \times 10^{-5} \left(\frac{\Delta R_K}{0.3}\right)^2 \left(\frac{0.1}{s_\tau}\right)^2 ,$$

to compare e.g. with

$BR(B^+ \to K^+ \mu^- \tau^+) < 3.9 \times 10^{-5}$

[LHCb, *2003.04352*]

More observables

Many nice ideas, most of which actually applicable in the short-medium term

- *Measure more LUV ratios*
- *New optimized ratios minimizing f.f. uncertainties*
- *Extract long-distance effects from data*
- *New decays sensitive to $C_{9,10}$ (e.g. of baryons)*
- *…*

Will focus on a single example which generated new activity encompassing exp, precision perturbation TH, and LQCD

An example: $B_s \to \mu\mu\ \gamma$

- *The additional photon lifts chirality suppression*

  For light leptons: enhancement w.r.t. purely leptonic mode

  ee channel: enhancement is 5 orders of magnitude

- $B_s \to \ell\,\ell\ \gamma$ *offers sensitivity to* C_7 , C_9 , C_{10} *(and primed)*

- *Direct measurement (= with* γ *detection) quite challenging at hadron colliders:*
  - *No tracking for photons*
  - *Plenty of photons from* π^0 *'s*

- *No PDG entry on* $B_s \to \ell\,\ell\ \gamma$

$B_s \to \mu\mu\ \gamma$: "indirect" measurement

Basic Idea [Dettori, DG, Reboud, 2017]

Extract $B_s \longrightarrow \mu\mu\ \ \gamma$ from $B_s \longrightarrow \mu\mu$ event sample, by enlarging $m_{\mu\mu}$ below B_s peak

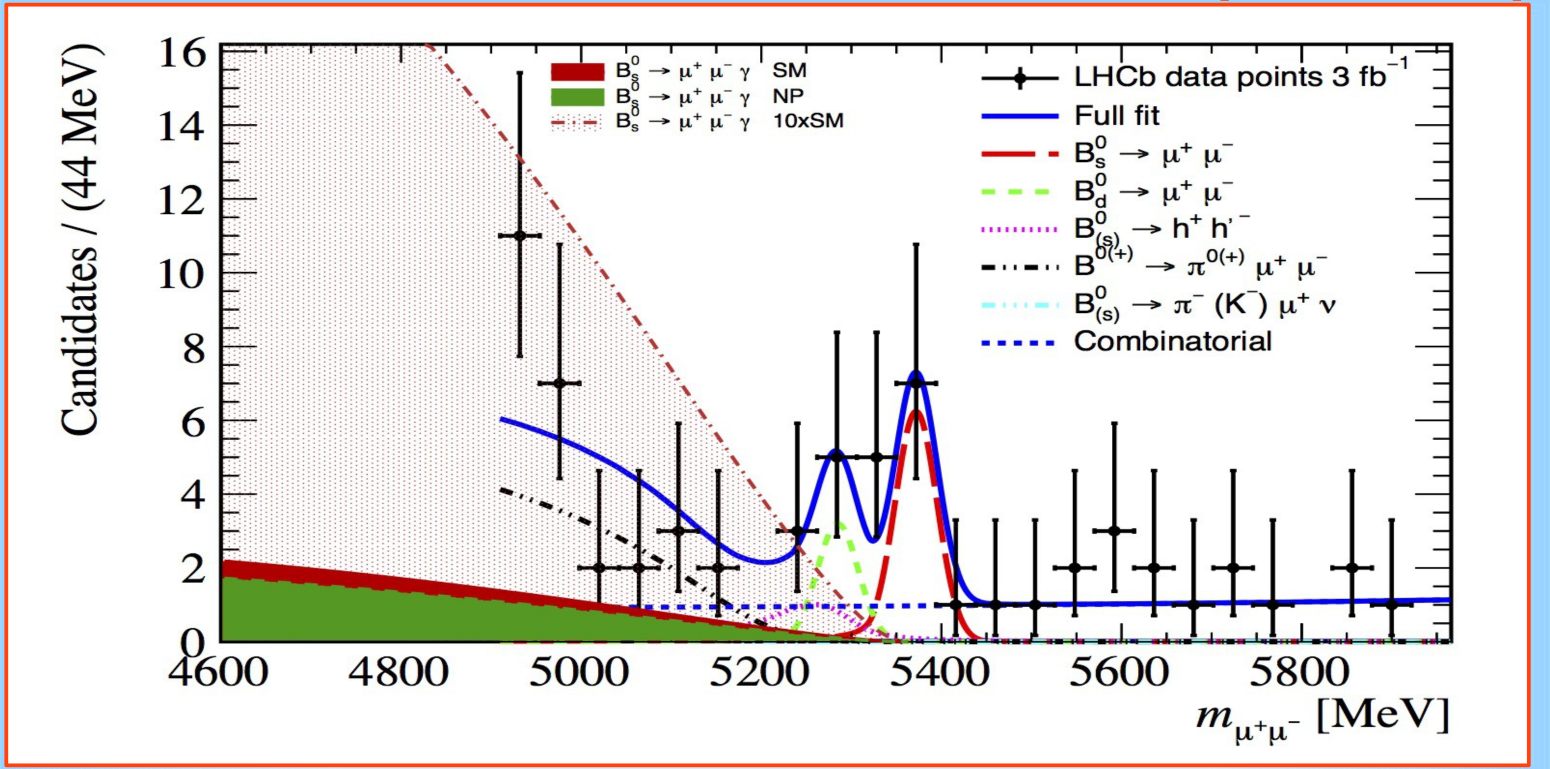
- *One can relate the $m_{\mu\mu}$ energy imbalance to the energy of the additional, undetected γ*
- *Essential precondition: controlling all other backgrounds*

Approach merges the advantages of both decays:

- *Exploits rich and ever increasing $B_s \longrightarrow \mu\mu$ dataset*
- *… to access $B_s \longrightarrow \mu\mu\ \ \gamma$, that probes flavour anomalies more thoroughly*

$B_s \to \mu\mu\ \gamma$: how a measurement looks like

[Dettori et al., 2017]



- $B_s \to \mu\mu\ \gamma$ *yield (expectedly) large*
- *By construction, method accesses high-*q^2 *part of spectrum*
  - *most sensitive to* C_9 & C_{10}
  - *preferred* q^2 *for LQCD* $B \to \gamma$ *matrix elements (missing!)*

Radiative leptonic f. f.'s in LQCD

Novel ideas & applications, both at low q^2 (large E_γ) and high q^2 (small E_γ)

Large E_γ

The required correlator (weak & e.m. current insertion between a B and the vac) has the desired large-Euclidean-t behavior provided $|\mathbf{p}_\gamma| \neq 0$

[Kane, Lehner, Meinel, Soni, *'19*]

Radiative leptonic f. f.'s in LQCD

Novel ideas & applications, both at low q^2 (large E_γ) and high q^2 (small E_γ)

Small E_γ [RM123, '*15*] [1st application ($K_{\ell 2}$), RM123, '*17*]

As $E_\gamma \to 0$ one needs to sum virtual QED corrs. with real emission to cancel IR divergences.

⇨ *Novel method to define IR-safe LQCD quantities*

- *Use the continuum, scalar-QED width to cancel IR divergences for each γ momentum of the LQCD-calculated width*
- *Main assumption: scalar QED (= pointlike mesons)*
  This implies a cutoff on $E_\gamma \ll \Lambda_{\mathrm{QCD}}$

$B_s \to \mu\mu\gamma$ with energetic γ

[Beneke-Bobeth-Wang, '20]

- *For energetic γ, one can adopt a large E_γ, large m_b expansion.*

⇨ *Calculation of f.f.'s using SCET + resonance parameterization*

- *Restriction to $q^2 < 6$ GeV^2 to avoid charmonium*

☞ *Resonant contributions at $q^2 \sim 1$ GeV^2 anyway:*
ϕ (for B_s), ϱ, ω (for B_d).

Breit-Wigner-like ansatz to include these contributions
[Krueger, Sehgal, '96]

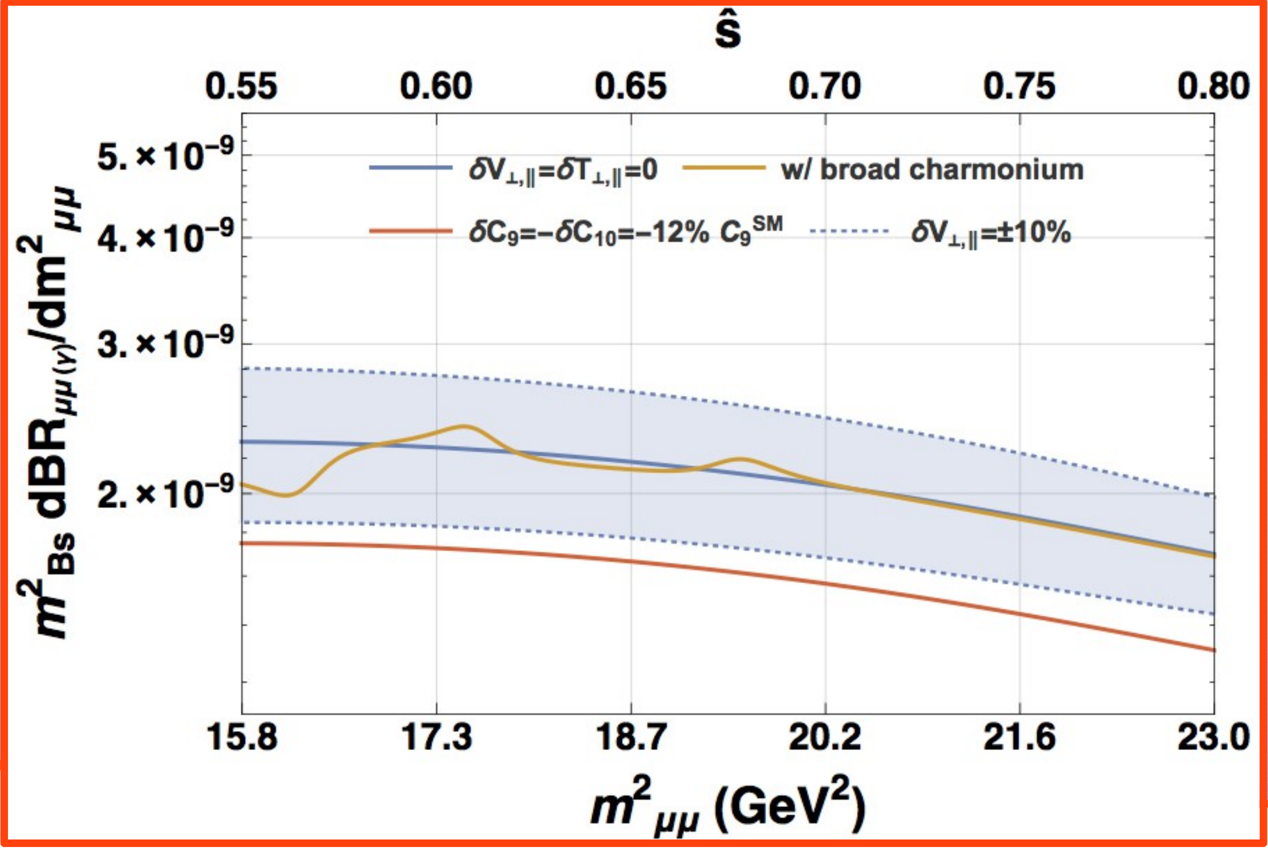
- *Prediction*

$$\langle\mathcal{B}\rangle_{[4m_\mu^2,\,6.0]} = \left(12.51^{+3.83}_{-1.93}\right)\cdot 10^{-9}, \qquad \langle\mathcal{B}\rangle_{[2.0,\,6.0]} = \left(0.30^{+0.25}_{-0.14}\right)\cdot 10^{-9}$$

i.e. prediction completely dominated by the resonant regions

$B_s \to \mu\mu\gamma$: full spectrum

- *In [DG, Reboud, Zwicky, '17] resonant ansatz used to rewrite low-q^2 BR in terms of the measured BR($B_s \to \phi\gamma$)*
- *Then main focus on large-q^2 region, above narrow charmonium. Broad-charmonium pollution estimated with similar resonant ansatz*



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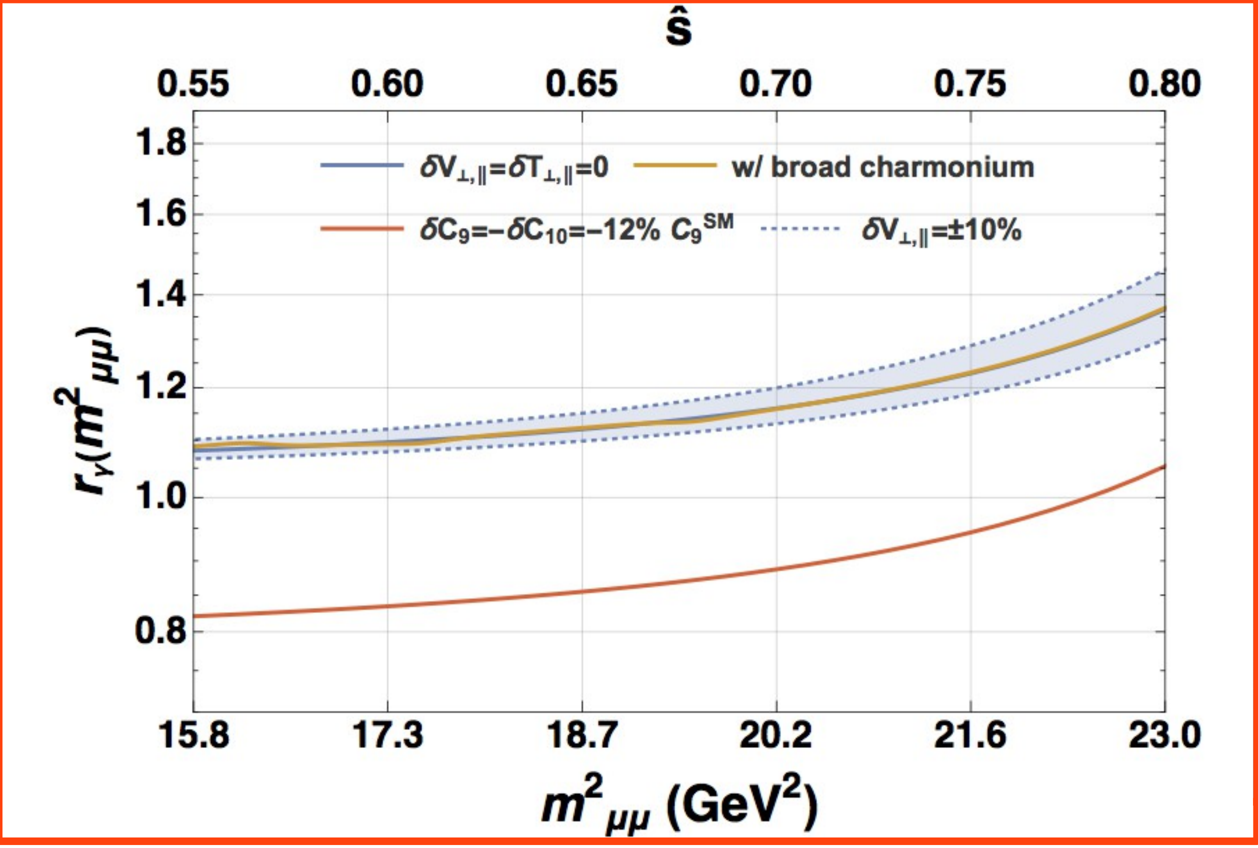
- *Then main focus on large-q^2 region, above narrow charmonium. Pollution substantially tamed in suitable ratio observable*



$$r_\gamma \equiv \frac{d\,BR(B_s \to \mu\mu\gamma)/dq^2}{d\,BR(B_s \to ee\gamma)/dq^2}$$

LUV / LFV

in Kaon decays

Main point

- *The putative new dynamics in B decays may yield correlated effects in suitable K decays.*

- *Especially interesting examples include*

$$K \to \pi \nu \bar{\nu} \qquad\qquad K \to (\pi)\mu e$$

- *It turns out that B-physics machines can offer complementary info on these decays w.r.t. Kaon machines, because of*
  - *the large amounts of Kaons produced*
  - *the excellent decay-reconstruction capabilities (e.g. for K_S)*

Why correlated effects

- *The new physics for B decays can usually be described by*

$$\mathcal{L}_{\rm eff} \supset \frac{C^{(a)}_{ijkl}}{\Lambda^2}\, \mathcal{O}^{(a)}_{ijkl}$$

two-quark { i, j }
two-lepton { k, l }
operators

- *New scale Λ may be fixed by size of observed discrepancies (typically Λ = few to 10 x few TeV)* [Di Luzio, Nardecchia, *1706.01868*]

- *The C couplings encode flavor structure. If dynamics tree-level:*

$C_{ijkl} \sim \lambda^{(q)}_{ij}\, \lambda^{(\ell)}_{kl}$ *for new colorless massive bosons*

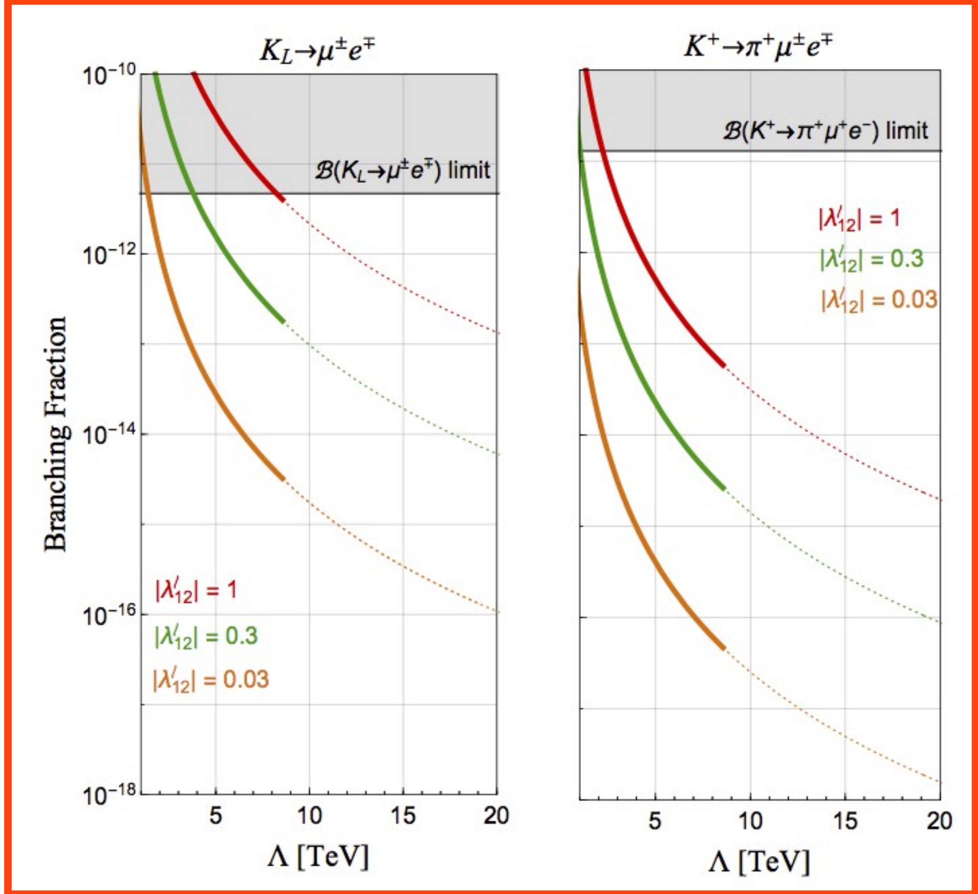
$C_{ijkl} \sim \lambda^{(q\ell)}_{il}\, (\lambda^{(q\ell)}_{jk})^*$ *for leptoquarks*

In many motivated scenarios, the λ's entering B decays and those entering K decays are highly correlated

Example 1

- *LHCb may well improve existing limits on* $K_L \to \mu e$ *and* $K^+ \to \pi^+ \mu e$

[Borsato *et al.*, *1808.02006*][Alves Jr. *et al.*, *1808.03477*]



TH assumptions

- *(V–A) × (V–A), SU(2)$_L$-invariant* $qq\ell\ell$ Hamiltonian adopted in [Buttazzo *et al.*, *1706.07808*] to explain *B* anomalies
- *CKM-like ansatz for the* $\lambda^{(q)}$ *coupling*
- *Agnostic on the* $\lambda^{(\ell)}$ *coupling*

Example 2

- *Assuming a general, SU(2)$_L$-invariant $qq\ell\ell$ Hamiltonian the effects in $R_{K(*)}$ are generally correlated with those in* $b \to s\ \nu\bar{\nu}$

[Buras *et al.*, *1409.4557*]

- *Assuming also that flavor couplings are ruled by MFV results in much wider correlations between effects in*

$B \to h_s\ \nu\bar{\nu}$ *(h_s= K, K*, X_s)* ⇔ $K \to \pi\ \nu\bar{\nu}$

[Descotes-G *et al.*, *2005.03734*]

Example 3

- *B-physics anomalies suggest BSM physics dominantly coupled to 3rd gen. of left-handed fermions* [Glashow *et al.*, *1411.0565*]

- *Effects / constraints involving lighter gen.'s are nicely compatible with*

  $$U(2)^5 = U(2)_q \times U(2)_\ell \times U(2)_u \times U(2)_d \times U(2)_e$$

  that distinguishes the 1st & 2nd from the 3rd one

  [Barbieri *et al.*, *1105.2296, 1512.01560*][Blankenburg *et al.*, *1204.0688*]

- $K \to \pi \nu \bar{\nu}$ *are the only Kaon decays with 3rd-gen. leptons*
  Use of the above sym gives rise to a beautiful triple correlation

[Bordone *et al.*, *1705.10729*]

$$\frac{\Delta\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})}{\Delta\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})} \approx \frac{2}{3} \times \frac{\theta_q}{\cos\phi_q} \times \frac{1 - 12\,[R_{D^{(*)}} - 1]\theta_q^2 f_q}{1 - 15[R_{D^{(*)}} - 1]\,\frac{\theta_q f_q}{\cos\phi_q}}$$

Conclusions

- *Plenty of models explaining R_K and R_D alike*

  One leading "paradigm" : Leptoquarks

- *LUV and LFV are two sides of the same broken symmetry*
  (unless the LUV dynamics implies a symmetry that prevents LFV)

  So most of the above models also predict LFV

- *Interestingly, B discrepancies can be tested, soon, in plenty of ways thanks to a synergy of exp, precision perturbation TH, and LQCD*

- *Also interestingly, K physics offers nice complementary probes*

- *And also interestingly, these probes are accessible, too*