A Challenge to Lepton Universality

R_K@LHCb $\neq 1$

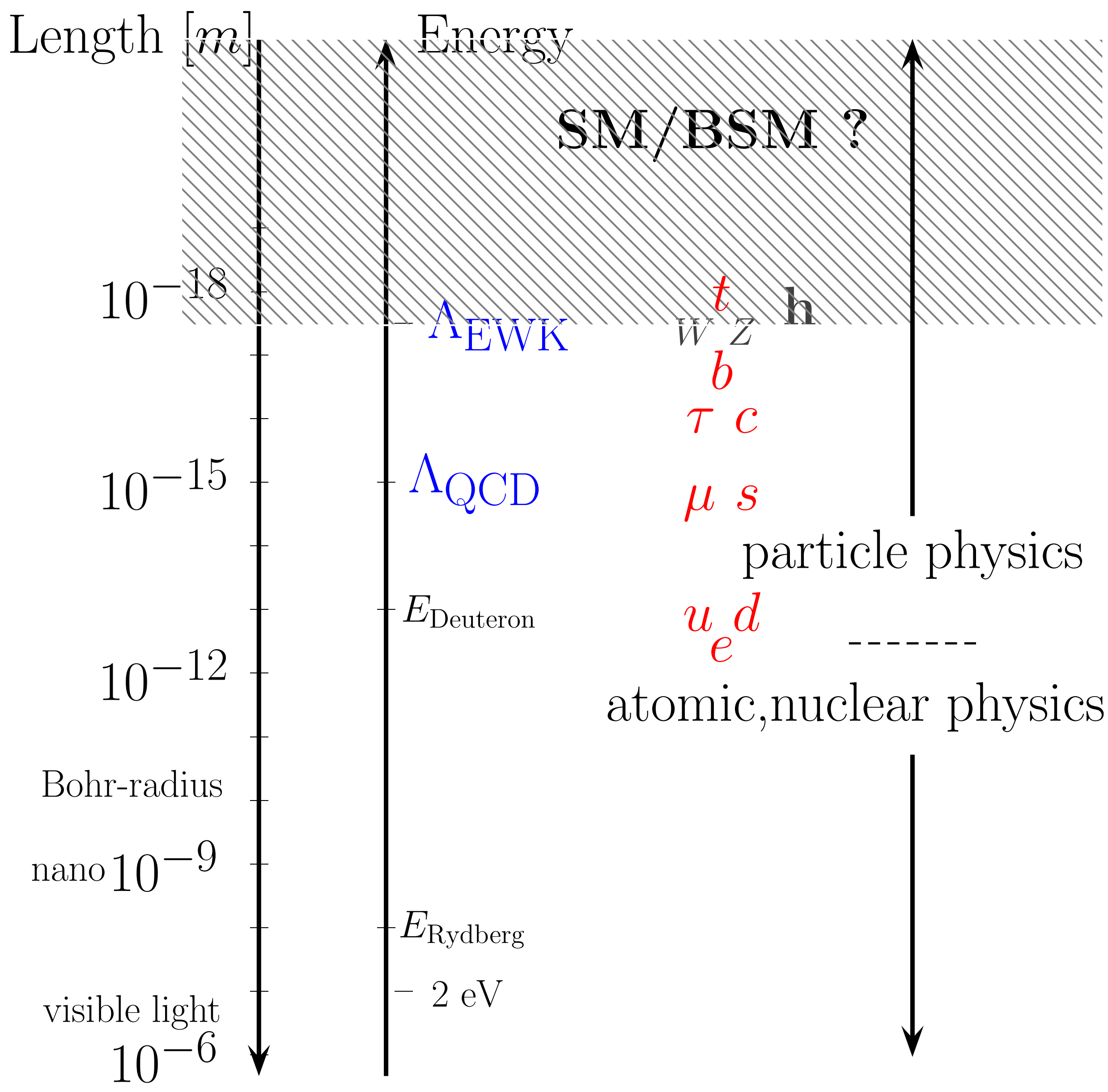
http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.113.151601,

arXiv:1406.6482 [hep-ex]

physics highlight: http://physics.aps.org/articles/v7/102

Gudrun Hiller, Dortmund

Exploring Physics at Highest Energies



FCNCs are suppressed in SM by i) weak loop, ii) CKM and iii) GIM. These mechanisms do not have to be at work in BSM, so FCNCs are a great place to look for BSM effects.

$s \to d$: $K^0 - \bar{K}^0$, $K \to \pi\nu\bar{\nu}$

$c \to u$: $D^0 - \bar{D}^0$, ΔA_{CP}

$b \to d$: $B^0 - \bar{B}^0$, $B \to \rho\gamma$, $b \to d\gamma$, $B \to \pi\mu\mu$

$b \to s$: $B_s - \bar{B}_s$, $b \to s\gamma$, $B \to K_s\pi^0\gamma$, $b \to sll$, $B \to K^{(*)}ll$ (precision, angular analysis, R_K), $B_s \to \mu\mu$

$t \to c, u$, $l \to l'$: not observed

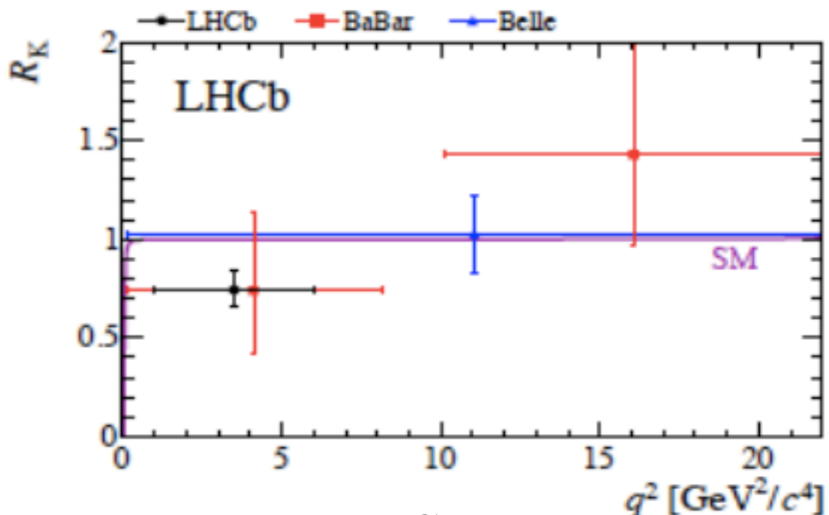
in red: THIS TALK!

$$R_K = \frac{\mathcal{B}(\bar{B}\to\bar{K}\mu\mu)}{\mathcal{B}(\bar{B}\to\bar{K}ee)}$$

idea: $R_H^{\rm SM} = 1+$ tiny for $H = K, K^*, X_s, ..$ GH, Krüger, hep-ph/0310219

refined, cuts, correlations, models: 0709.4174 Bobeth etal

early data: Belle 0904.0770, BaBar 1204.3933, consistent with SM



latest data: LHCb 1406.6482 $R_K^{LHCb} \simeq 3/4 \pm 0.1$: 2.6 σ, BSM huge!

theory: 1406.6681 1407.7044 1408.1627 1408.4097 1409.0882 ....

R_K measurement

$B^\pm \to K^\pm ee$ and $B^\pm \to K^\pm \mu\mu$ events at LHCb. Full data set, $3\mathrm{fb}^{-1}$, from 7 and 8 TeV LHC run.

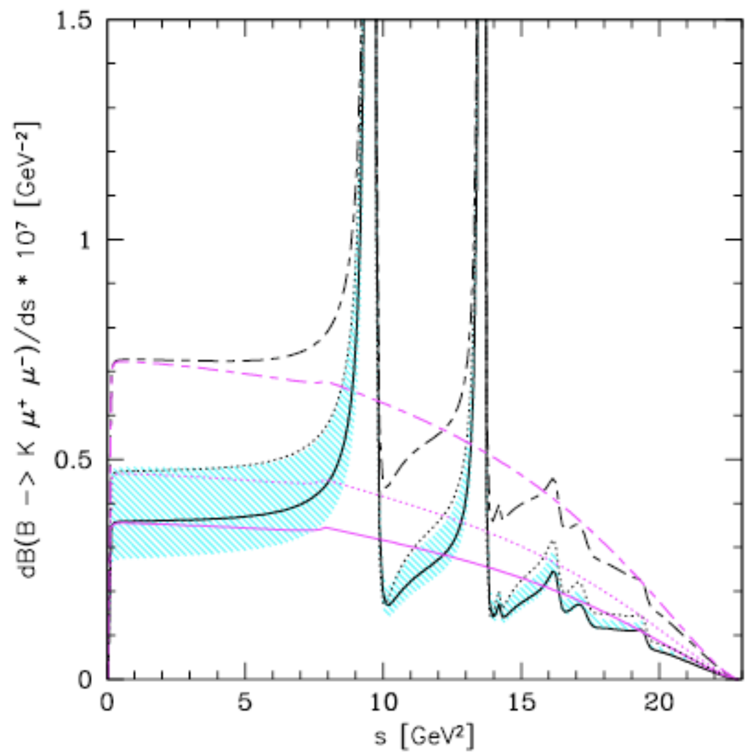


Fig from 9910221, solid: SM, dotted and dot-dashed: susy

Select low dilepton mass window: $1 \leq q^2 < 6\,\mathrm{GeV}^2$ below J/Ψ.

situation for numerator $\mu\mu$ and denominator ee of R_K separately:

	LHCb[a]	SM[b]
$\mathcal{B}(B \to K\mu\mu)_{[1,6]}$	$(1.21 \pm 0.09 \pm 0.07) \cdot 10^{-7}$	$(1.75^{+0.60}_{-0.29}) \cdot 10^{-7}$
$\mathcal{B}(B \to Kee)_{[1,6]}$	$(1.56^{+0.19+0.06}_{-0.15-0.04}) \cdot 10^{-7}$	same
$R_K\|_{[1,6]}$	$0.745 \pm^{0.090}_{0.074} \pm 0.036$	$\simeq 1$

[a] 1209.4284 (μ) and 1406.6482 (e) [b] Bobeth, GH, van Dyk ’12, form factors from 1006.4945

Individual branching ratios make presently no case for new physics, although muons are a bit below SM. The Ratio R_K is much cleaner.

Probing Lepton e vs μ universality with R_K

.. which was the idea behind R_K in first place:

Lepton-universal effects – including hadronic ones – drop out in ratios of branching fractions GH,Krüger'03

$$R_K^{LHCb} = \frac{\mathcal{B}(\bar{B} \to \bar{K}\mu\mu)}{\mathcal{B}(\bar{B} \to \bar{K}ee)}$$

$R_K^{\rm SM} = 1$ up to kinematic corrections $\mathcal{O}(m_\mu^2/m_b^2)$ and electromagnetic logs (depending on exp. cuts) $\mathcal{O}(\frac{\alpha_e}{4\pi} Log(m_e/m_b))$ at O(permille) level.

$$R_K^{LHCb} = 0.745 \pm^{0.090}_{0.074} \pm 0.036\,, \qquad \text{1406.6482 hep-ex}$$

2.6σ: if taken at face value this implies lepton-nonuniversal new physics in the flavor sector.

Probing Lepton e vs μ universality with R_K

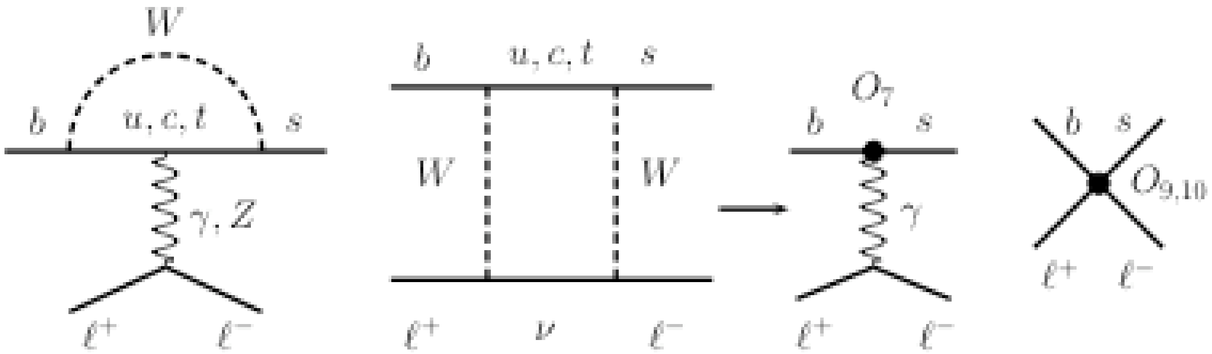
Comments:

–$R_K = 0.745 \pm^{0.090}_{0.074} \pm 0.036 < 1$ implies suppressed muons and/or enhanced electrons, that is, BSM in electrons, or muons, or both.

– $R_K \simeq 3/4$ is almost an order 1 effect. Yet, it is not excluded by other data essentially because R_K is so clean and the effect, lepton-nonuniversality in $b \to s$, is quite specific.

– Ongoing precision fits in $B \to K^{(*)}\ell\ell$ decays (Babar,Belle,CDF, ATLAS,CMS,LHCb) 1307.5683, 1308.1501, 1310.2478 dominated from hadron colliders hence give essentially lepton-specific constraints for $\ell = \mu$.

– Electrons much more difficult for LHCb than muons:
$B \to K\mu\mu$: ~ 1226 events, $B \to Kee$: $\sim O(200)$ events.



Construct EFT $\mathcal{H}_{\rm eff} = -4\frac{G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i C_i(\mu)O_i(\mu)$ at dim 6

V,A operators $\mathcal{O}_9 = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \ell]\,, \quad \mathcal{O}'_9 = [\bar{s}\gamma_\mu P_R b]\,[\bar{\ell}\gamma^\mu \ell]$

$$\mathcal{O}_{10} = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \gamma_5 \ell]\,, \quad \mathcal{O}'_{10} = [\bar{s}\gamma_\mu P_R b]\,[\bar{\ell}\gamma^\mu \gamma_5 \ell]$$

S,P operators $\mathcal{O}_S = [\bar{s}P_R b]\,[\bar{\ell}\ell]\,, \quad \mathcal{O}'_S = [\bar{s}P_L b]\,[\bar{\ell}\ell]\,,$ ONLY O_9, O_{10} are SM, all other BSM

$$\mathcal{O}_P = [\bar{s}P_R b]\,[\bar{\ell}\gamma_5 \ell]\,, \quad \mathcal{O}'_P = [\bar{s}P_L b]\,[\bar{\ell}\gamma_5 \ell]$$

and tensors $\mathcal{O}_T = [\bar{s}\sigma_{\mu\nu} b]\,[\bar{\ell}\sigma^{\mu\nu}\ell]\,, \quad \mathcal{O}_{T5} = [\bar{s}\sigma_{\mu\nu} b]\,[\bar{\ell}\sigma^{\mu\nu}\gamma_5\ell]$

lepton specific $C_i O_i \to C_i^\ell O_i^\ell$, $\ell = e, \mu, \tau$

Barring the presence of several different types of operators, hence allowing for tuning, there are the following model-independent explanations for R_K:

i) V,A operators with muons

ii) V,A operators with electrons

iii) S,P operators electrons (disfavored at 1 σ and requires cancellations, testable with $\bar{B} \to \bar{K}ee$ angular distributions)

Tensors and S,P muons are excluded.

R_K-interpretations

Model-independent interpretations with V,A interactions: arXiv:1408.1627, 1406.6681

$$0.7 \lesssim \mathrm{Re}[X^e - X^\mu] \lesssim 1.5\,,$$
$$X^\ell = C_9^{\mathrm{NP}\ell} + C_9'^{\ell} - (C_{10}^{\mathrm{NP}\ell} + C_{10}'^{\ell})\,, \quad \ell = e, \mu\,.$$

– The required NP is large, almost $O(1)$ of SM $C_9^{\mathrm{SM}} \simeq -C_{10}^{\mathrm{SM}} \simeq 4.2$.

– Since the SM couples V-A-like, the leading constraints on X^ℓ from SM-NP-interference have V-A structure for the leptons; there's no sensitivity to V+A (right-handed) leptons at this level.

Lets use the chiral basis:

$$\mathcal{O}^{\ell}_{LL} \equiv (\mathcal{O}^{\ell}_{9} - \mathcal{O}^{\ell}_{10})/2\,, \quad \mathcal{O}^{\ell}_{LR} \equiv (\mathcal{O}^{\ell}_{9} + \mathcal{O}^{\ell}_{10})/2\,,$$
$$\mathcal{O}^{\ell}_{RL} \equiv (\mathcal{O}'^{\ell}_{9} - \mathcal{O}'^{\ell}_{10})/2\,, \quad \mathcal{O}^{\ell}_{RR} \equiv (\mathcal{O}'^{\ell}_{9} + \mathcal{O}'^{\ell}_{10})/2\,.$$

R_K sensitive to left-handed leptons:

$$C^{\ell}_{LL} = C^{\ell}_{9} - C^{\ell}_{10}\,, \quad C^{\ell}_{RL} = C'^{\ell}_{9} - C'^{\ell}_{10}\,.$$

right-handed leptons: $C^{\ell}_{LR} = C^{\ell}_{9} + C^{\ell}_{10}$, $C^{\ell}_{RR} = C'^{\ell}_{9} + C'^{\ell}_{10}$

This suggests to use in global fits invariant-constraints such as
$C^{\mathrm{NP}\ell}_{9} = -C^{\mathrm{NP}\ell}_{10}\,, \quad C^{\mathrm{NP}\prime\ell}_{9} = -C^{\mathrm{NP}\prime\ell}_{10}$.

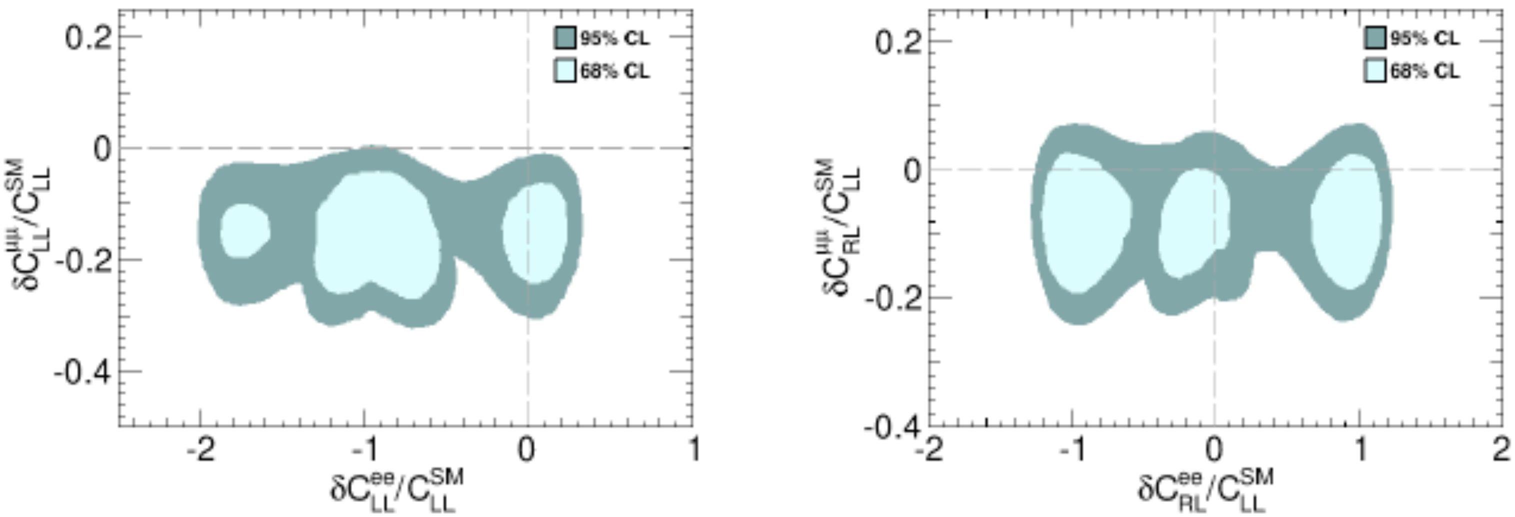


Fig from 1410.4545 – global fit including R_K

– Bounds stronger for $\mu\mu$ (y-axis) than for ee (x-axis).

– Both left-handed quarks C_{LL} (left-handed plot) and right-handed quarks C_{RL} (right-handed plot) can be sizable.

R_K -interpretations – $SU(2)_L$ muons

If we assume new physics in muons alone employ $\mathcal{B}(\bar{B}_s \to \mu\mu)$

$$\frac{\mathcal{B}(\bar{B}_s \to ee)^{\rm exp}}{\mathcal{B}(\bar{B}_s \to ee)^{\rm SM}} < 3.3 \cdot 10^6 \,, \quad \frac{\mathcal{B}(\bar{B}_s \to \mu\mu)^{\rm exp}}{\mathcal{B}(\bar{B}_s \to \mu\mu)^{\rm SM}} = 0.79 \pm 0.20 \quad \text{is suppressed currently} \,.$$

$$\begin{aligned} 0.0 &\lesssim {\rm Re}[C^\mu_{LR} + C^\mu_{RL} - C^\mu_{LL} - C^\mu_{RR}] \lesssim 1.9 \,, \quad (\mathcal{B}(B_s \to \mu\mu)) \\ 0.7 &\lesssim -{\rm Re}[C^\mu_{LL} + C^\mu_{RL}] \lesssim 1.5 \,. \qquad (R_K) \end{aligned}$$

This isolates C^μ_{LL} as the only single operator (particle) interpretation of R_K. Note: this is V-A. Iff $\mathcal{B}(\bar{B}_s \to \mu\mu)$ would be enhanced this would isolate $C^\mu_{RL} \simeq -1$, V+A! $b \to see$ way less constrained.

V,A muons and V,A electrons can be realized with leptoquark models

GH, Schmaltz arXiv:1408.1627, Phys. Rev. D 90, 054014 (2014)

A model with C^e_{RL} (includes R-parity violating MSSM):

$\mathcal{L} = -\lambda_{d\ell}\,\varphi\,(\bar{d}P_L\ell)$ with leptoquark $\varphi(3,2)_{1/6}$ with mass M.

$\mathcal{H}_{\rm eff} = -\frac{|\lambda_{d\ell}|^2}{M^2}(\bar{d}P_L\ell)\,(\bar{\ell}P_R d) = \frac{|\lambda_{d\ell}|^2}{2M^2}[\bar{d}\gamma^\mu P_R d]\,[\bar{\ell}\gamma_\mu P_L\ell]$
from tree level φ exchange and fierzing.

In terms of the usual Wilson coefficients:

$C'^e_{10} = -C'^e_9 = \frac{\lambda_{se}\lambda^*_{be}}{V_{tb}V^*_{ts}}\frac{\pi}{\alpha_e}\frac{\sqrt{2}}{4M^2G_F} = -\frac{\lambda_{se}\lambda^*_{be}}{2M^2}(24\mathrm{TeV})^2$
R_K-benchmark: $C'^e_9 = -C'^e_{10} \simeq 1/2$ follows $M^2/\lambda_{se}\lambda^*_{be} \simeq (24\mathrm{TeV})^2$

Viable parameters of the (scalar) leptoquarks read

$$1\,\text{TeV} \lesssim M \lesssim 48\,\text{TeV}$$
$$2 \cdot 10^{-3} \lesssim |\lambda_{se}\lambda^*_{be}| \lesssim 4$$
$$4 \cdot 10^{-4} \lesssim |\lambda_{qe}| \lesssim 5$$

– $SU(2)$ implies corresponding effects in $b \to s\nu\nu$ (only electron-neutrinos affected, signal diluted over 3 species). $\mathcal{B}(B \to K\nu\nu)$ reduced by 5 %, $\mathcal{B}(B \to K^*\nu\nu)$ enhanced by 5 %, F_L enhanced by 2 % w.r.t SM.

– Further correlation with B_s mixing, $b \to s\gamma$, and direct searches.

– Decay modes of φ-dublet: $\varphi^{2/3} \to b\, e^+ \;, \quad \varphi^{-1/3} \to b\, \nu$

A LL muon leptoquark model

$$\mathcal{L} = -\lambda_{b\mu}\,\varphi^*\,q_3\ell_2 - \lambda_{s\mu}\,\varphi^*\,q_2\ell_2, \qquad \varphi(3,3)_{-1/3}$$

$$\mathcal{H}_{\rm eff} = -\frac{\lambda^*_{s\mu}\lambda_{b\mu}}{M^2}\left(\tfrac{1}{4}[\bar{q}_2\tau^a\gamma^\mu P_L q_3]\,[\bar{\ell}_2\tau^a\gamma_\mu P_L\ell_2] + \tfrac{3}{4}[\bar{q}_2\gamma^\mu P_L q_3]\,[\bar{\ell}_2\gamma_\mu P_L\ell_2]\right)$$

gives $C_9^{{\rm NP}\mu} = -C_{10}^{{\rm NP}\mu} = \frac{\pi}{\alpha_e}\frac{\lambda^*_{s\mu}\lambda_{b\mu}}{V_{tb}V^*_{ts}}\frac{\sqrt{2}}{2M^2G_F} \simeq -0.5$ and similar mass range as other model.

Decay modes of φ-triplet:

$$\begin{array}{rcl} \varphi^{2/3} & \to & t\,\nu \\ \varphi^{-1/3} & \to & b\,\nu\;,\;t\,\mu^- \\ \varphi^{-4/3} & \to & b\,\mu^- \end{array}$$

The $U(1)_{\tau-\mu}$-extension of SM 1403.1269 Altmannshofer etal also violates lepton-universality. (V,A-muons-type i) model, no BSM in ee.)

C (LH-quark currents) versus C' (RH quark currents)?

Long story in interpreting $B \to K^{(*)}\mu\mu$ data/global fits as hadronic uncertainties (power corrections, resonances) could shadow BSM.

e.g. Camalich, Jäger '12, Lyon, Zwicky'14, .. in global fits 1307.5683, 1308.1501, 1310.2478, ...

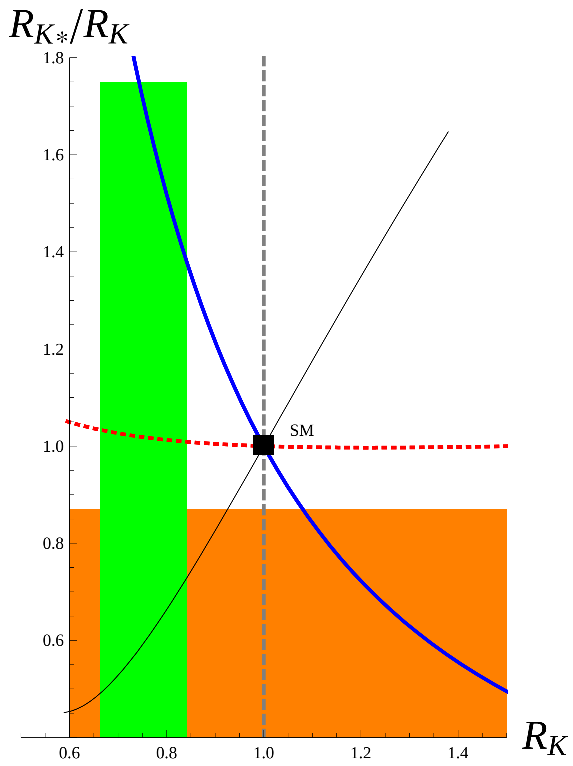
By parity and lorentz invariance, the C, C' enter decay amplitudes $B \to K\ell\ell$ etc as GH, Schmaltz 1411.4773 (today)

$$\begin{aligned} C + C' : &\quad K, K^*_\perp, \ldots \\ C - C' : &\quad K_0(1430), K^*_{0,\|}, \ldots \end{aligned}$$

so different ratios R_K, R_{K^*} etc are complementary. It follows that double ratios R_{K^*}/R_K are cleanly probing right-handed currents! In addition, since K^* is dominated by $'0'$ and $'\,\|'$ polarization, the complementarity between R_K and R_{K^*} (similarly R_φ) is maximal.

predictions: $R_K = R_\eta$, $R_{K^*} = R_\varphi$, and correlations between R_H. Measure two R_H (with $C \pm C'$) and predict all of them !

Diagnosing lepton-nonuniversality



Green band: R_K 1 sigma LHCb. Curves: different BSM scenarios. red dashed: pure C_{LL}. Black solid: $C_{LL} = -2C_{RL}$. Blue: C_{RL}. Orange band is prediction for R_{K^*} (not significantly measurend) based on R_K and $B \to X_s \ell\ell$: $R_{X_s}^{\text{Belle}'09} = 0.42 \pm 0.25\,, \quad R_{X_s}^{\text{BaBar}'13} = 0.58 \pm 0.19$.

- If LHCb's measurement of R_K substantiates it implies that there is more difference between a muon and an electron than their mass. Lepton-universality, a feature of the $SU(3)_C \times SU(2)_L \times U(1)_Y$ SM appears to be violated in $b \to s$ FCNC transitions.

- Current data allow for model-independent explanations, as well as model frameworks such as leptoquarks. There is no conflict with other measurements nor with model-building.

- Explanations imply correlations with other FCNC processes as well as predictions for direct searches, that can be tested in the future.

STAY TUNED